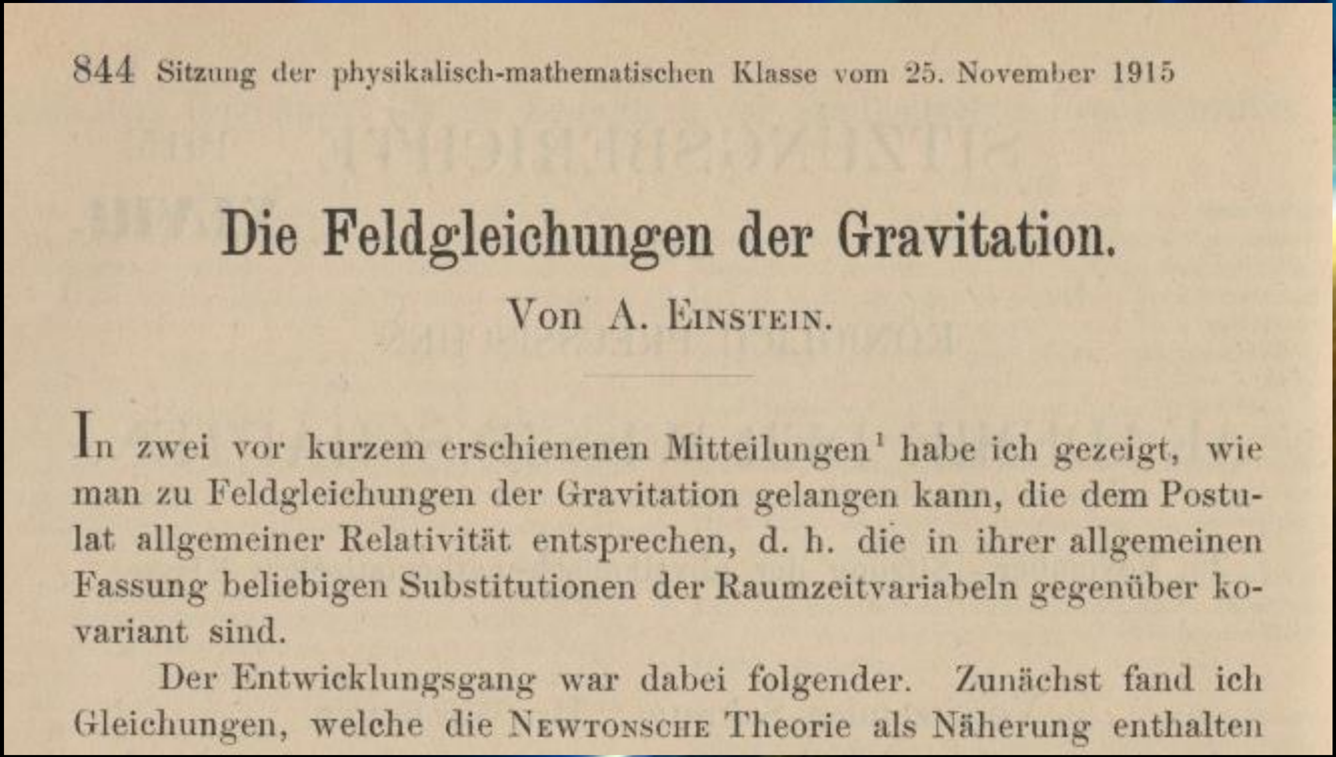
Gravitational-wave astrophysics

Marco Cavaglià, University of Mississippi
for the LIGO Scientific Collaboration and the Virgo Collaboration

2016: One hundred (one) years of General Relativity



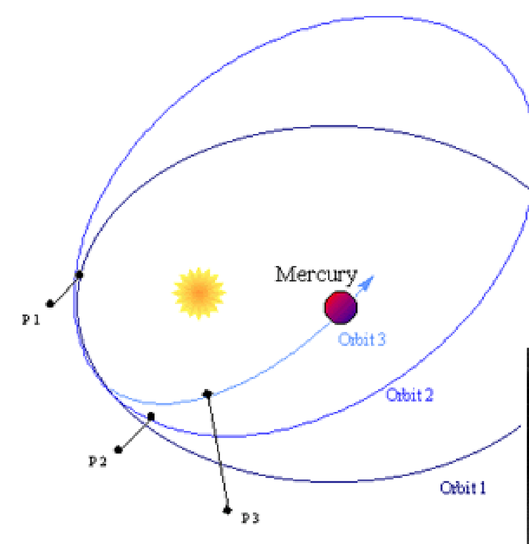
844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

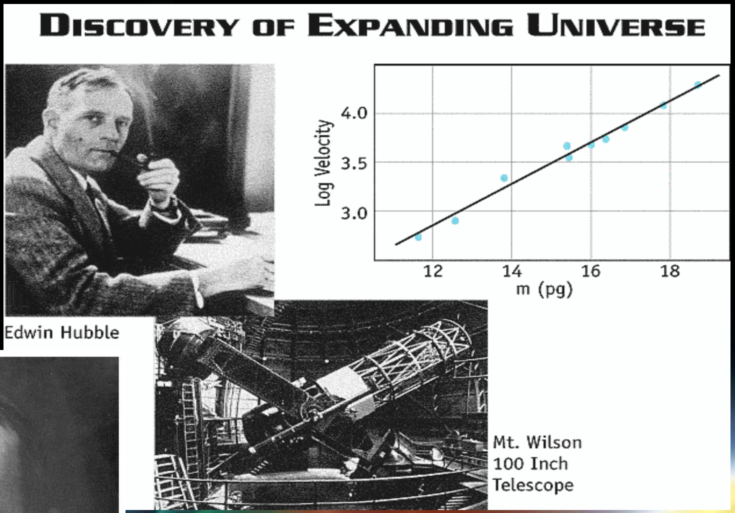
Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten





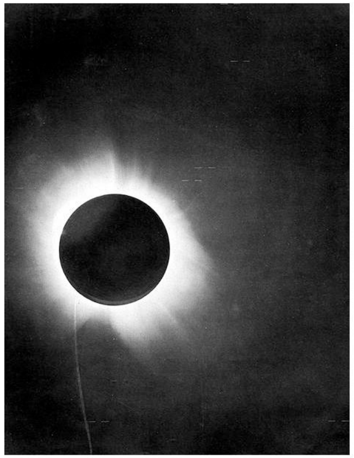
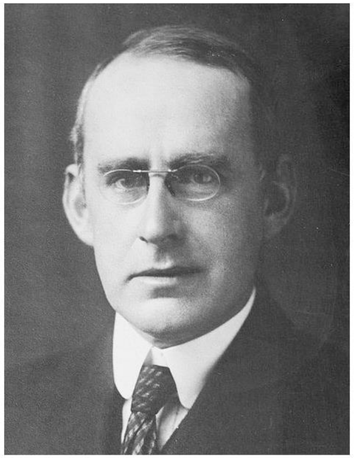
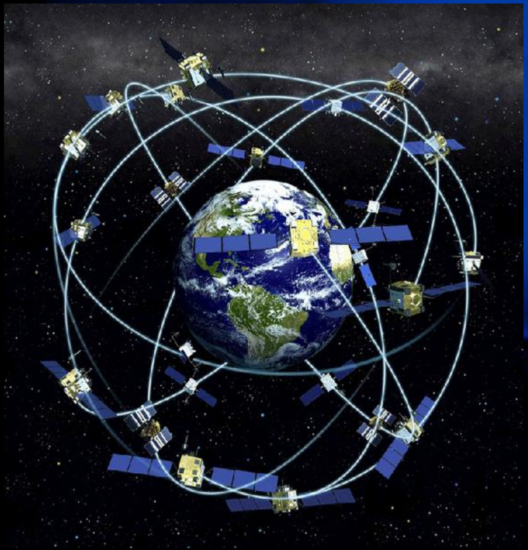


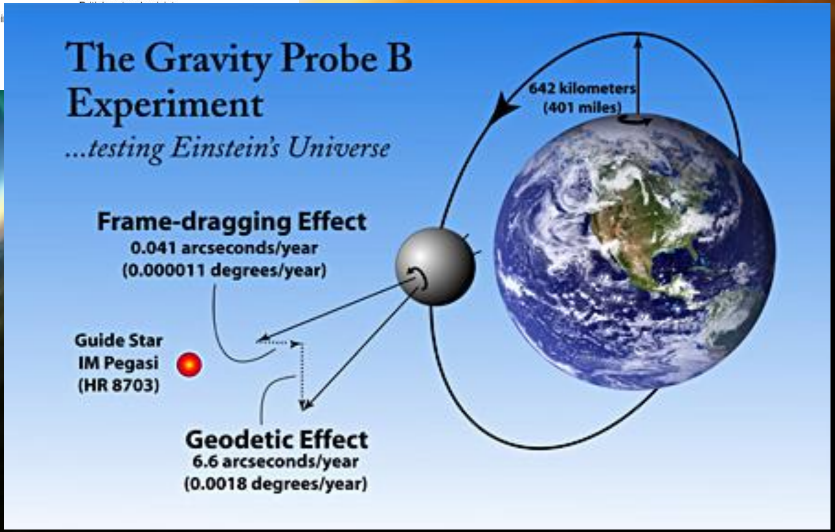
Plate 1, May 29, 1919, Sir Arthur Stanley Eddington Principe Expedition
From:
"A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations Made at the Total Eclipse of May 29, 1919" Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character (1920): 291-333, on 332, submitted by F. W. Dyson, A. S. Eddington, and C. Davidson.



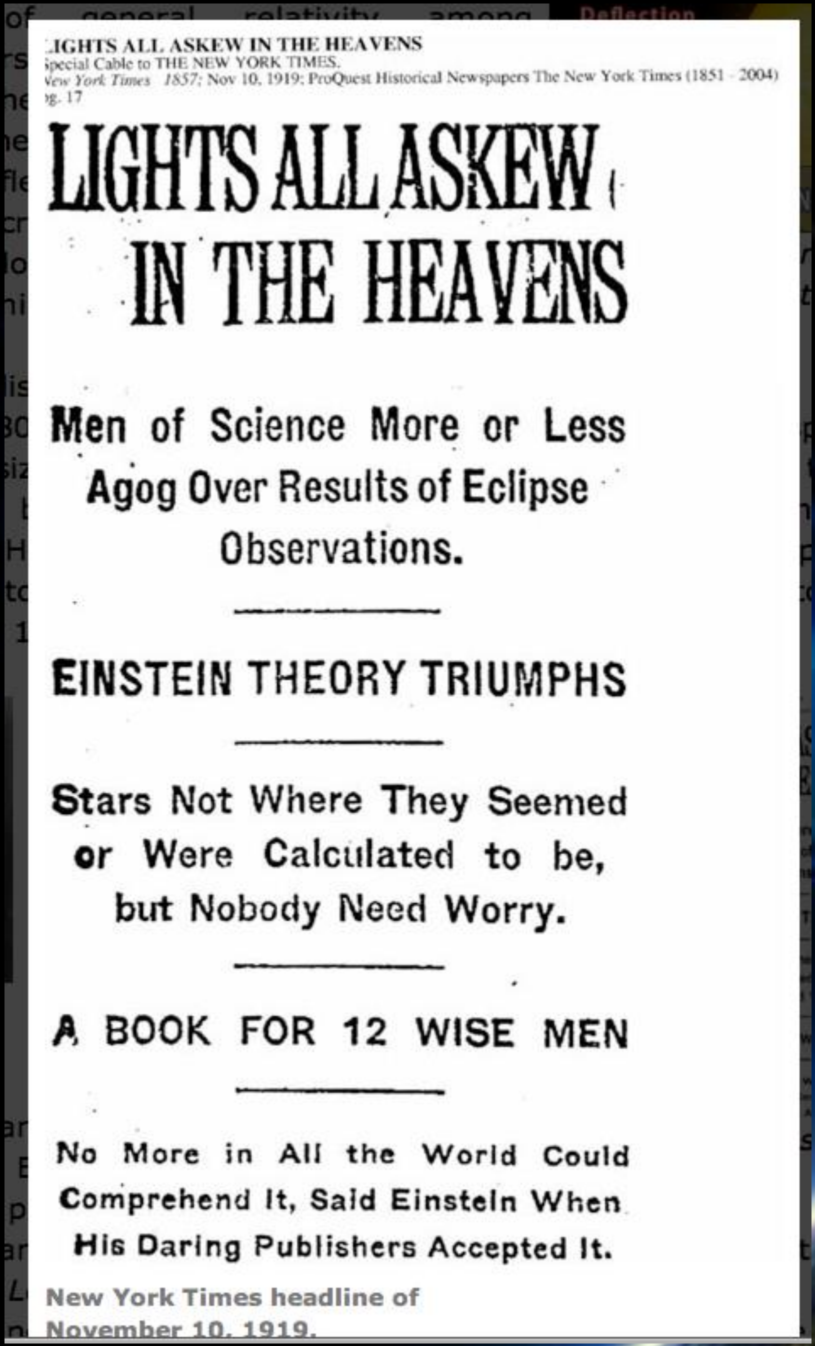
Sir Arthur Stanley Eddington (1882 - 1944)

Preemi





One hundred (one) years of successes



IGHTS ALL ASKEW IN THE HEAVENS
pecial Cable to THE NEW YORK TIMES.
ew York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
g. 17

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

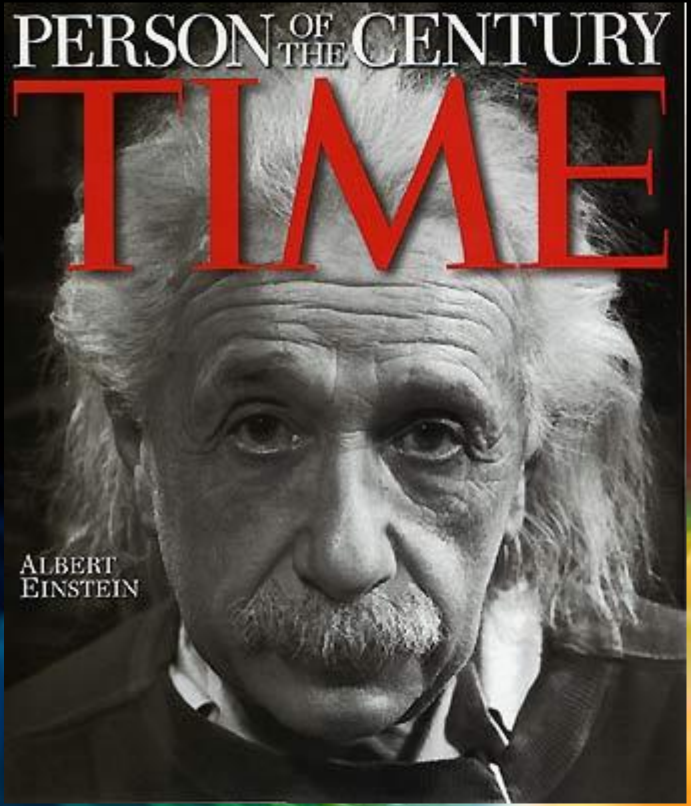
EINSTEIN THEORY TRIUMPHS

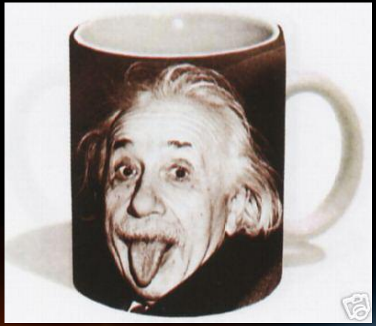
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

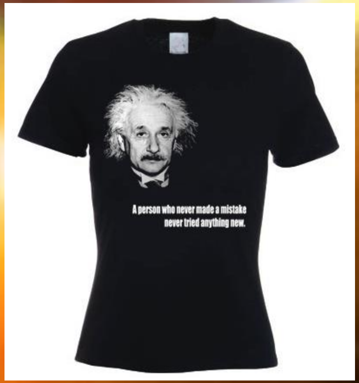
A BOOK FOR 12 WISE MEN

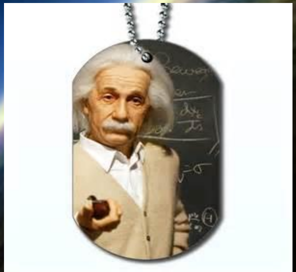
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times headline of November 10, 1919.



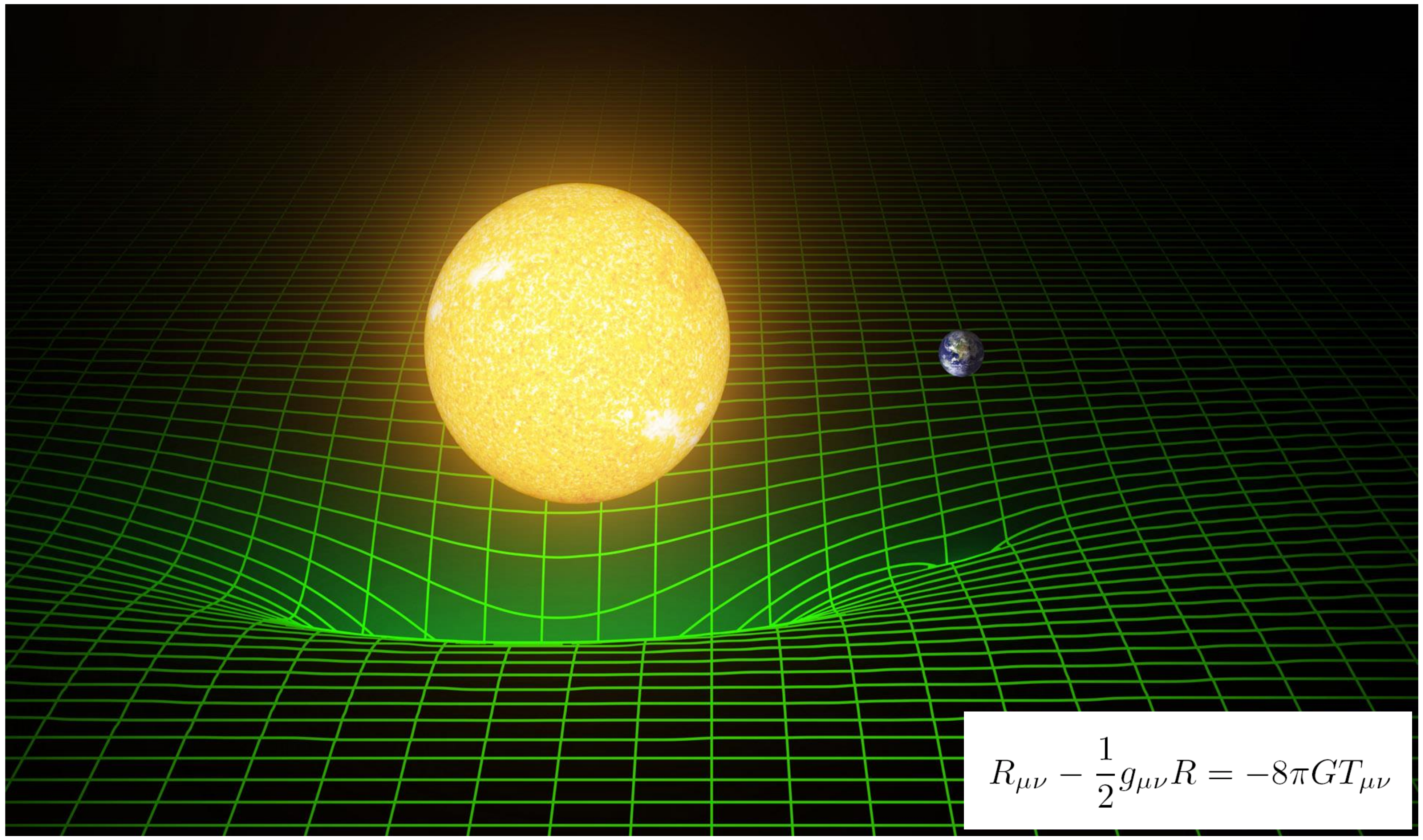




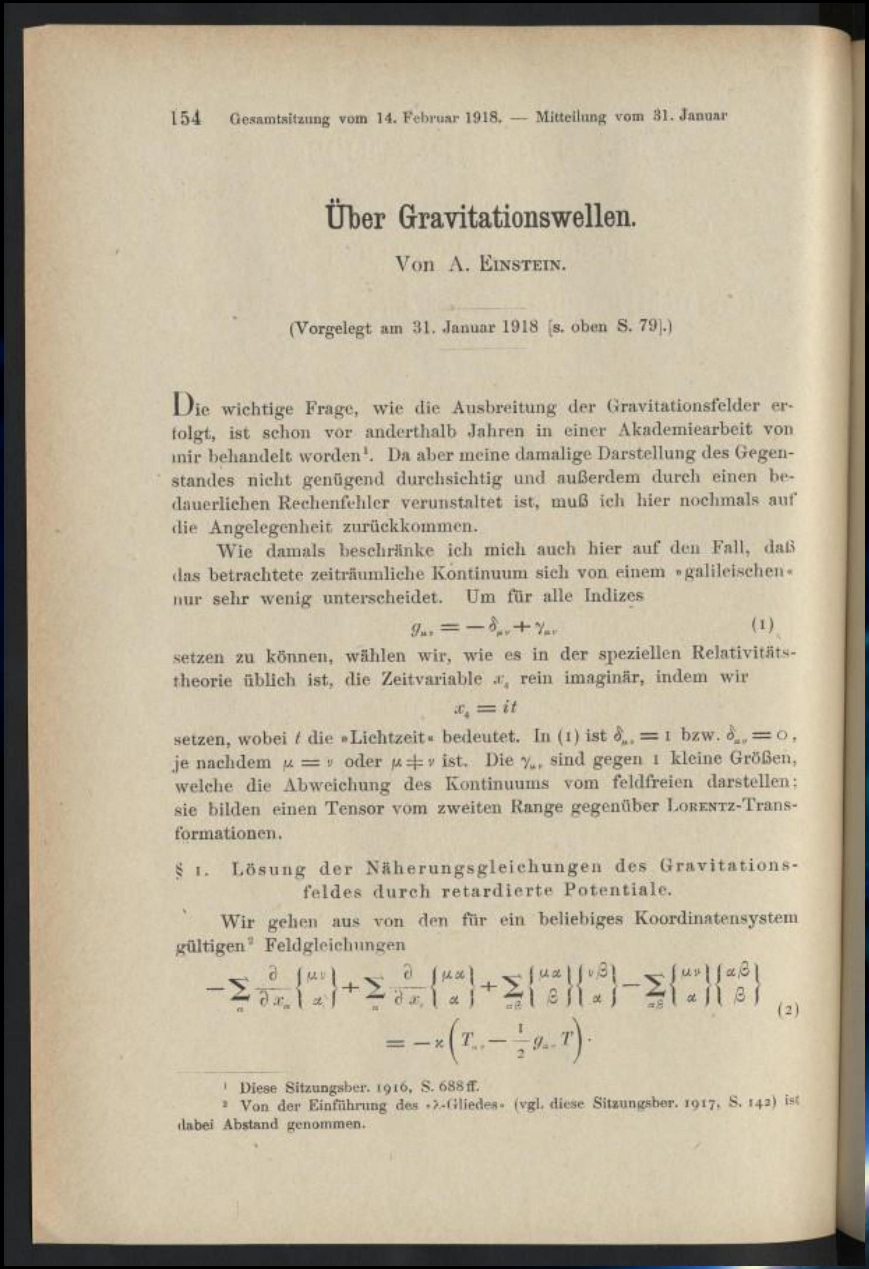


“Matter tells space time how to curve, and curved space time tells matter how to move.”

- John Wheeler



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu}$$



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

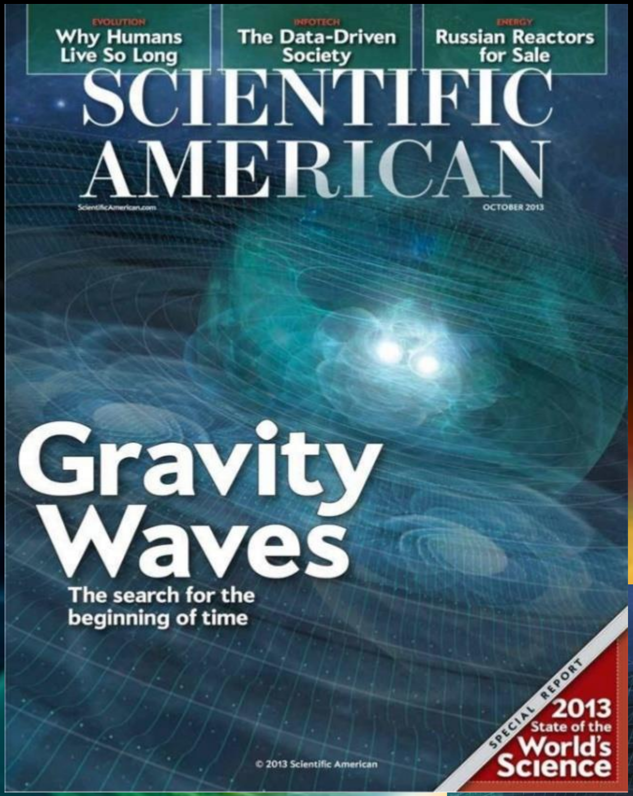
Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

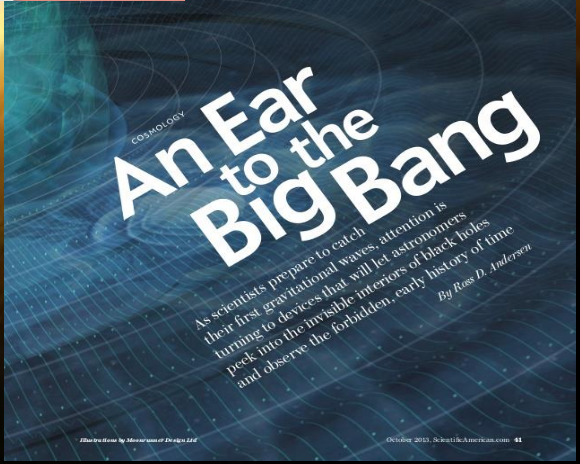
$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu}\begin{Bmatrix}\mu\alpha\\ \alpha\end{Bmatrix} + \sum_{\alpha\beta}\begin{Bmatrix}\mu\alpha\\ \beta\end{Bmatrix}\begin{Bmatrix}\nu\beta\\ \alpha\end{Bmatrix} - \sum_{\alpha\beta}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}\begin{Bmatrix}\alpha\beta\\ \beta\end{Bmatrix} = -\varkappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right). \tag{2}$$

---

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.





COSMOLOGY

An Ear to the Big Bang

As scientists prepare to catch their first gravitational waves, attention is turning to devices that will let astronomers peek into the invisible interiors of black holes and observe the forbidden, early history of time

By Ross D. Andersen

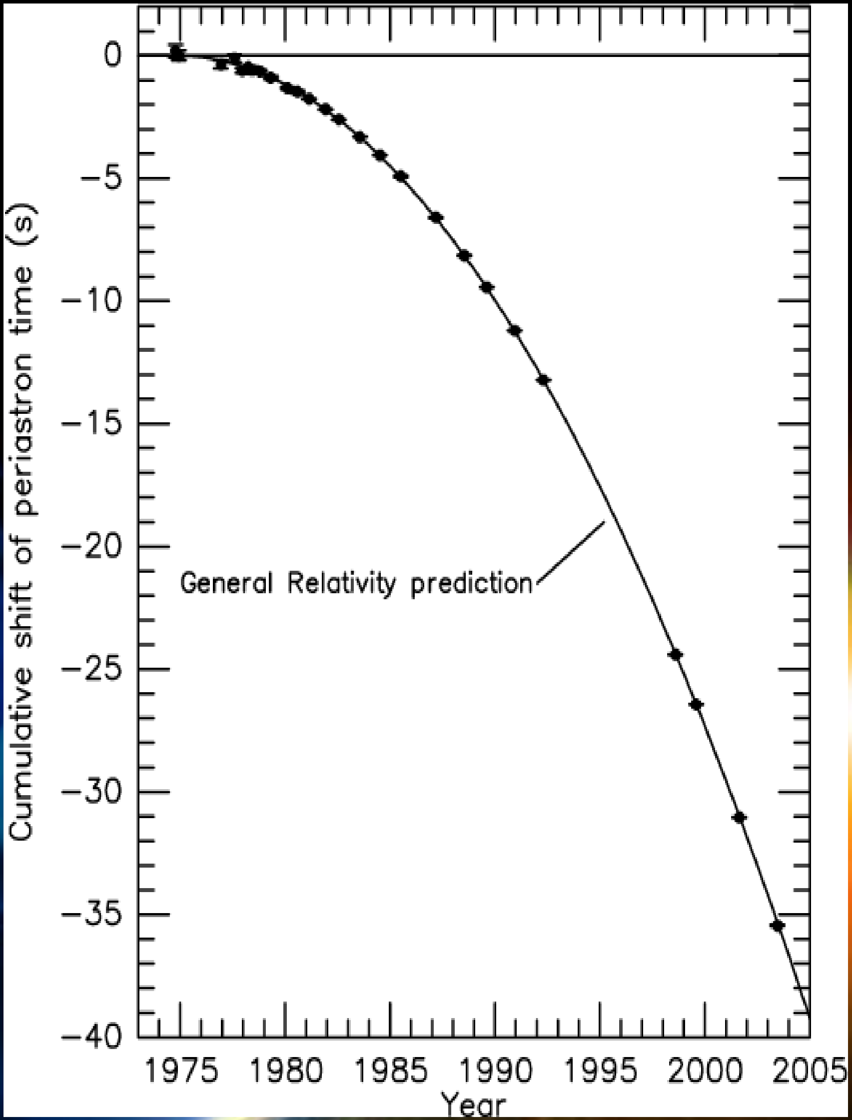
Illustrations by Moonrunner Design Ltd

October 2013, ScientificAmerican.com 41

Einstein's Last Great Prediction...

1980’s: Indirect evidence for gravitational waves

The Nobel Prize in Physics 1993 was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



J.H. Taylor and J. Weisberg, “A New Test of General Relativity: Gravitational Radiation and the Binary Pulsar PSR 1913+16,” Astrophys. J. 253, 908 (1982).

…but until now they had never been directly detected.

Republican American
FRIDAY, FEBRUARY 12, 2016 FINAL $1

NAUGY FALLS
NAUGATUCK'S ANTOINE SISTRUNK SCORES 13 IN 80-78 LOSS TO TORRINGTON, PAGE 9B

UCONN STUNNED
TEMPLE'S AMAZING RALLY LIFTS OWLS TO 63-58 WIN, PAGE 12B

Student discipline to go quiet

CoCo Key hotel up for sale

COMMUNITY NEWS, PAGE 8D

SHOPPING FOR A VEHICLE?

Bill to legalize pot fil
Lawmaker proposes allowing recreational use in

EINSTEIN WAS RIGHT!
A CENTURY AFTER HE PREDICTED GRAVITATIONAL WAVES, SCIENTISTS PROVE IT IN A GROUNDBREAKING DISCOVERY

INSIDE
POTENT PLAY
ORANGE SHOOTERS RED HOT ON COLD NIGHT IN SYRACUSE

A NEW CLUE
FIND THE HIDDEN MEDALLION AND WIN UP TO $2,500.

THE POST-STANDARD
FRIDAY, FEBRUARY 12, 2016
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COSMIC BREAKTHROUGH
SU SCIENTISTS ON TEAM THAT CONFIRMS EINSTEIN'S GRAVITY RIPPLES AND IN SPACE-TIME

DRIVING WITH SNOW ON YOUR CAR? NY LAWMAKERS PROPOSE FINES

Philadelphia Inquirer
Winner of 20 Pulitzer Prizes

Deal would halt Syria fighting
World powers acted to allow humanitarian access to besieged areas.

'Einstein Would Be Beaming'

CAMPAIGN 2016
Clinton, Sanders cordial but firm
The candidates agreed on much, but grew heated in discussing support for President Obama.

MANUFACTURERS HELD LIABLE FOR FOULED WATER IN HOOSICK FALLS PAGE A2

THE POST STAR
Friday, February 12, 2016
poststar.com
2009 Pulitzer Prize winner

THUNDER
Team gets new players ready
PAGE C1

ONE-OF-A-KIND HEIRLOOM
Quilt traces 170 years of family's history
PAGE B1

MURDER-SUICIDE
Police confirm details of Colonie house fire
PAGE B3

Felon steals to the north
Serial burglar from Florida winds up in Saratoga County

SCIENTIFIC BREAKTHROUGH
Music to their ears
Scientists detect gravity ripples that Einstein predicted

Rap sheet to be cited
Prosecutors prep for Bennett's trial in child death case

BUNE-REVIEW
Safety tech takes the wheel at Pittsburgh Auto Show B8

pel grad aided in breakthrough

Discovery opens ears to cosmos

Riverhawks' Levi McBride is a monster on the mat

Kennewick High's Madhatters plan concert Feb. 18-20

Tri-City Herald

SANDERS, CLINTON COURT VOTERS

OCCUPIERS TURN THEMSELVES IN

THEORY OF RELATIVITY CONFIRMED
Gravitational waves detected at LIGO

IT IS THE FIRST TIME THE UNIVERSE HAS SPOKEN TO US THROUGH GRAVITATIONAL WAVES.

The Clarion-Ledger

USA TODAY
Revolutionary discovery

MARVEL'S ANTIHERO
GNC LOOKS FOR BETTER YEAR IN '16
OVER THE SALARY CAP?

Pittsburgh Post-Gazette
ONE OF AMERICA'S GREAT NEWSPAPERS
$1.50 229 YEARS OF SERVICE FRIDAY, FEBRUARY 12, 2016 VOL. 89, NO. 196, 2/12/16 FINAL

Clinton accuses Sanders of false promises
Candidates pointed but polite at debate

Gravitational waves discovery a 'new window' into universe
Finding confirms Einstein's general theory of relativity

Picking a major can be daunting

PLAY BALL! LSU softball team begins season with lofty goals

Baton Rouge on tap this weekend

THE ADVOCATE
BATON ROUGE • LOUISIANA

'WE CAN HEAR THE UNIVERSE'
Livingston's LIGO confirms gravitational waves finding

Trump fires up big crowd in BR

Edwards gives rare TV address on budget
Governor predicts dire cuts unless shortfall plugged

DHH investigating two possible cases of Zika
Louisiana patients had traveled to Caribbean

ZIKA VIRUS CASES IN THE U.S.

BRAINERD DISPATCH
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'HOLY GRAIL OF SCIENCE'

SANTA FE NEW MEXICAN
Friday, February 12, 2016

Deeper cuts needed to counter 'free fall,' Smith says

Council candidates discuss tax hike possibility at forum

With faint chirp, scientists prove Einstein correct

LANL crew had faith discovery was matter of time

The Boston Globe
FRIDAY, FEBRUARY 12, 2016

Rivals debate their support for Obama

A whisper from across the universe

Deal set for truce, aid drops in Syria
US-Russia plan puts humane efforts first

The New York Times

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

Long in Clinton's Corner, Blacks Notice Sanders

The Bakersfield Californian
FRIDAY, FEBRUARY 12, 2016 • BAKERSFIELD.COM

MAKING WAVES
Gravitational waves, that is: New scientific observation affirms Einstein's general theory of relativity
USA TODAY | 30

Lawsuit disputes union access to farms

THE MONITOR
FRIDAY, FEBRUARY 12, 2016
SERVING THE RIO GRANDE VALLEY SINCE 1909

Collaboration proves Einstein correct

Former LIGO director reflects on historic wave detection

Bishop Flores grateful to join Pope in

USA TODAY WEEKEND
FEBRUARY 12 - 14, 2016

GRAVITATIONAL WAVES CONFIRMED

'A WHOLE NEW WINDOW ON THE UNIVERSE'

RUSSIA, U.S. REACH DEAL IN SYRIA WAR

White House bans guns — finally

The Columbus Dispatch
FRIDAY, FEBRUARY 12, 2016

achete-wielding man injures 4

Democrats polite but pointed

'Until this moment, we had our eyes on the sky and we couldn't hear the music. The skies will never be the same.'
Szabolcs Marka

A FORCE AWAKENS
As Einstein said, scientists detect ripples in gravity

Intruder assaults wom makes off with items.

School vouch bill stalls, but could resurfa

BACK ON TRACK

Daily Press
FRIDAY, FEBRUARY 12, 2016

CNU POLL SHOWS GUN RIGHTS WEIGH HEAVILY ON VIRGINIA VOTERS' MINDS

'A WINDOW ONTO THE UNIVERSE'
Einstein's gravitational waves found, with help from W&M physicist

HAMPTON SYMPOSIUM STRESSES 'URGENCY' OF CURBING VIOLENCE AMONG BLACK MALES

The Huntsville Times

UAH 'AT THE CENTER' OF CONFIRMING EINSTEIN'S THEORY OF RELATIVITY

Huntsville ready to welcome Uber, Lyft and Zipcar

Lawmakers hold key to building mega-prisons

The Washington Post

U.S., Russia agree to a halt in Syrian war

Fault line spotlighted in Wis. debate

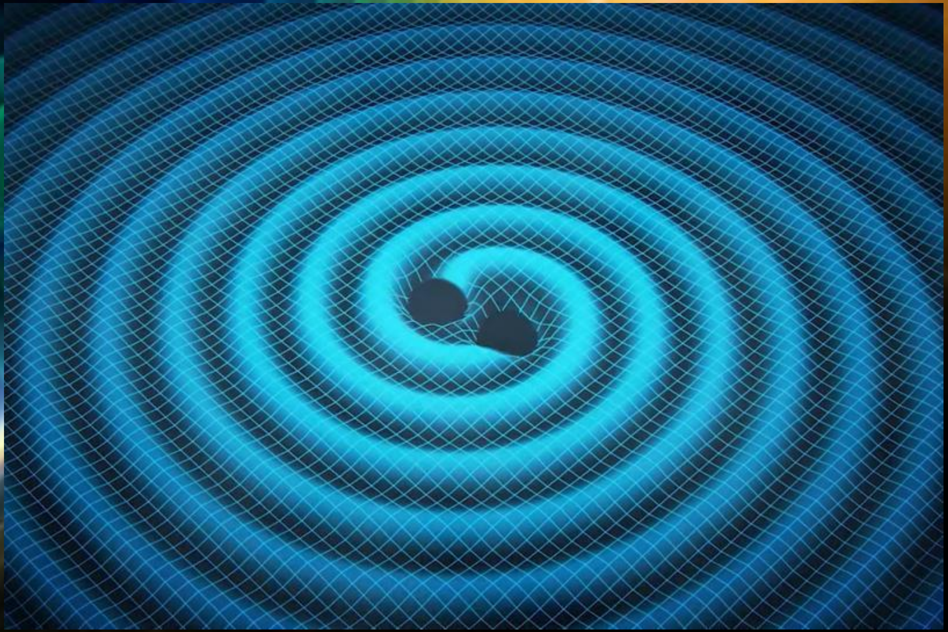
Oregon siege ends as four surrender

Gravitational waves Einstein foresaw are detected

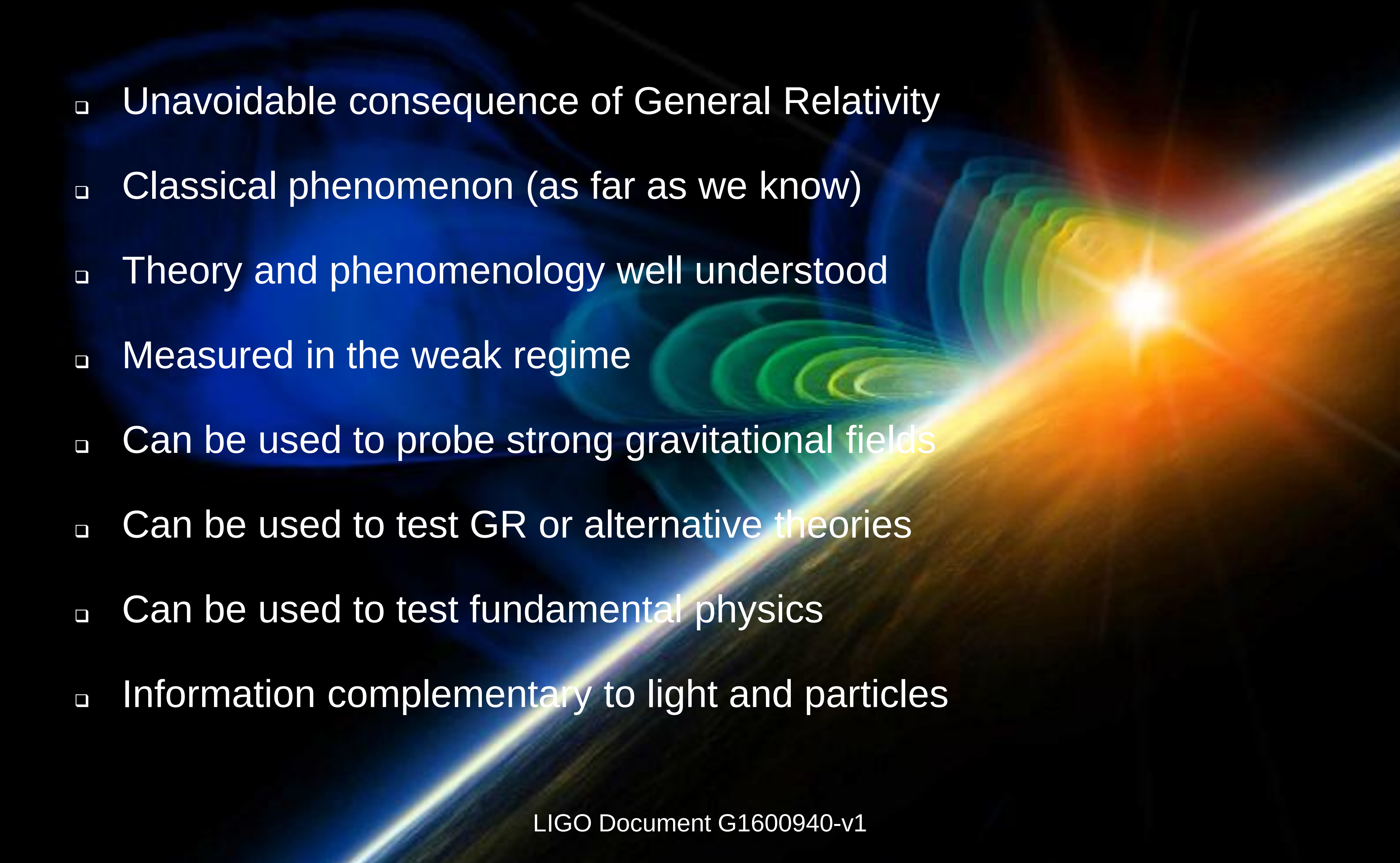
A gravitational wave is a propagating disturbance of the space-time

When masses move rapidly, the space-time becomes stirred by their motion:

Gravitational waves start traveling outward with the speed of light



Gravitational waves in a nutshell



- 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

A bit of theory

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -8\pi G T_{\mu\nu}$$

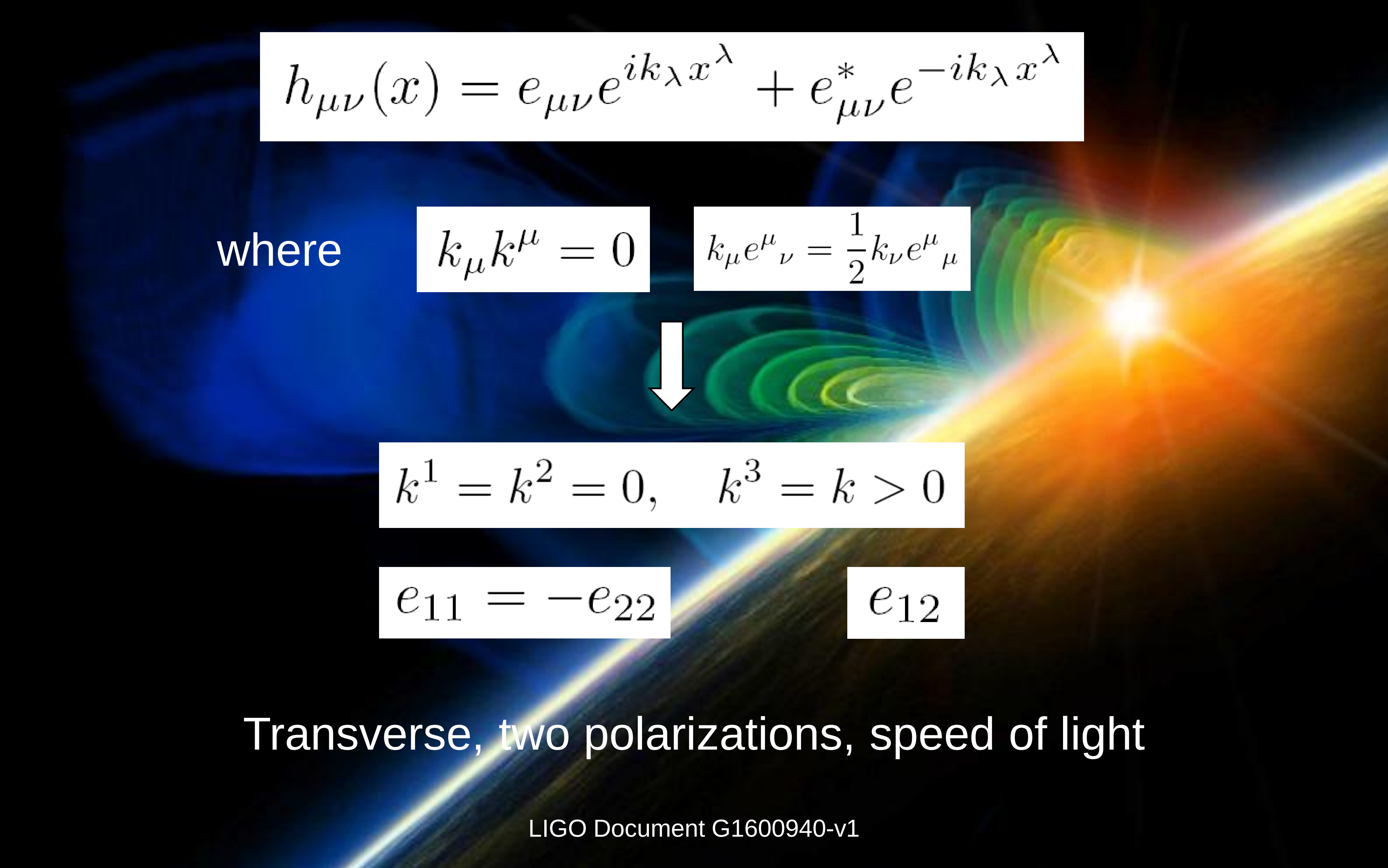
Weak field limit:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

↓

$$\Box^2 h_{\mu\nu} = -16\pi G S_{\mu\nu}$$

Vacuum solution



$$h_{\mu\nu}(x) = e_{\mu\nu} e^{ik_\lambda x^\lambda} + e^*_{\mu\nu} e^{-ik_\lambda x^\lambda}$$

where $k_\mu k^\mu = 0$ $\quad k_\mu e^\mu{}_\nu = \frac{1}{2} k_\nu e^\mu{}_\mu$

$$\Downarrow$$

$$k^1 = k^2 = 0, \quad k^3 = k > 0$$

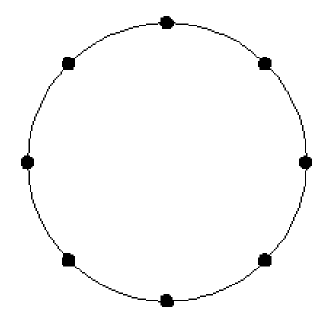
$e_{11} = -e_{22}$ $\qquad e_{12}$

Transverse, two polarizations, speed of light

What is the effect of a gravitational wave?

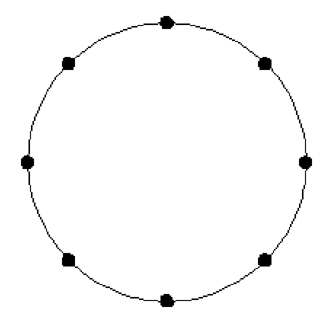
"+" polarization:

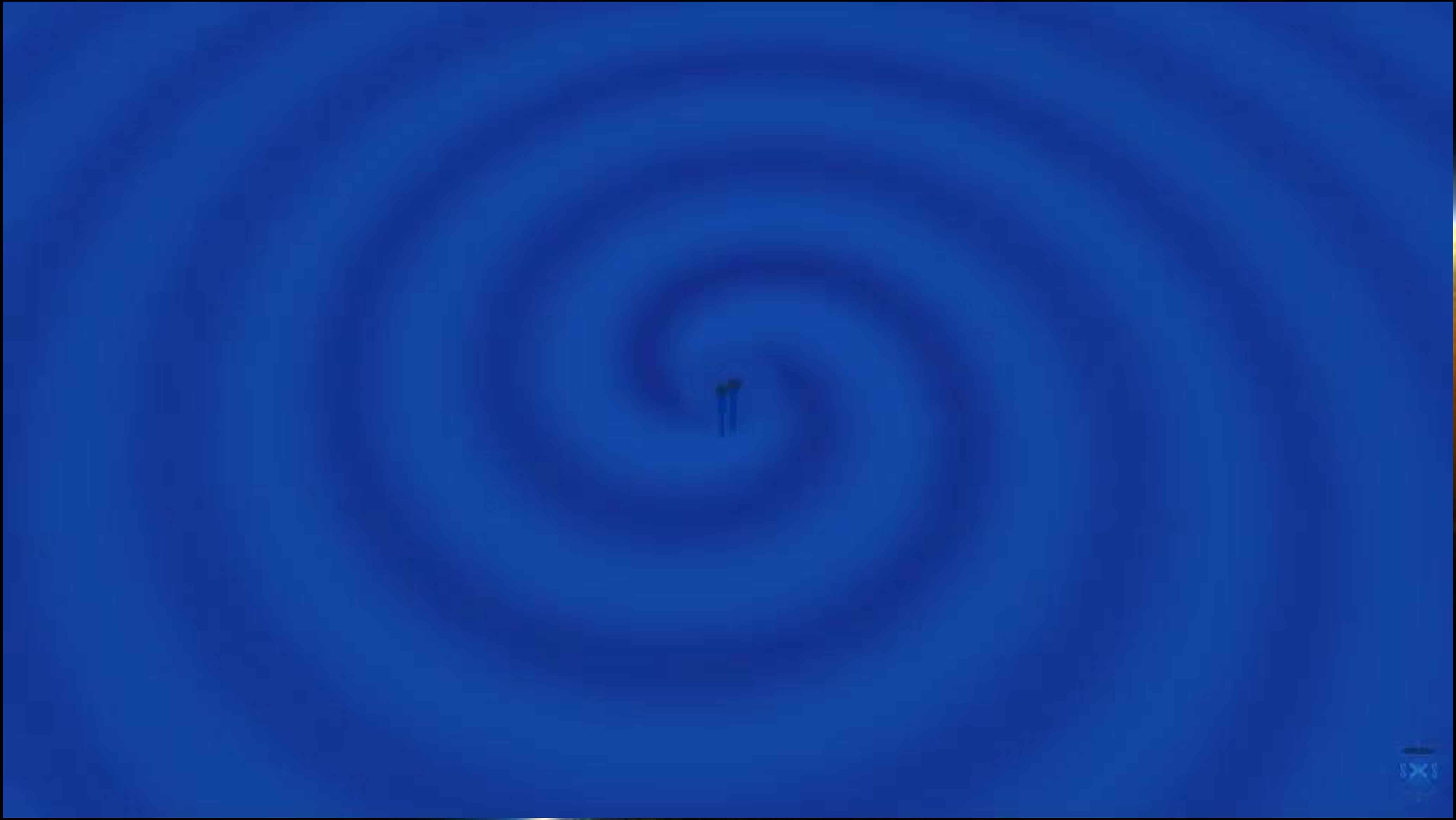
$$h_+(t-z) = h^{TT}_{xx} = -h^{TT}_{yy}$$

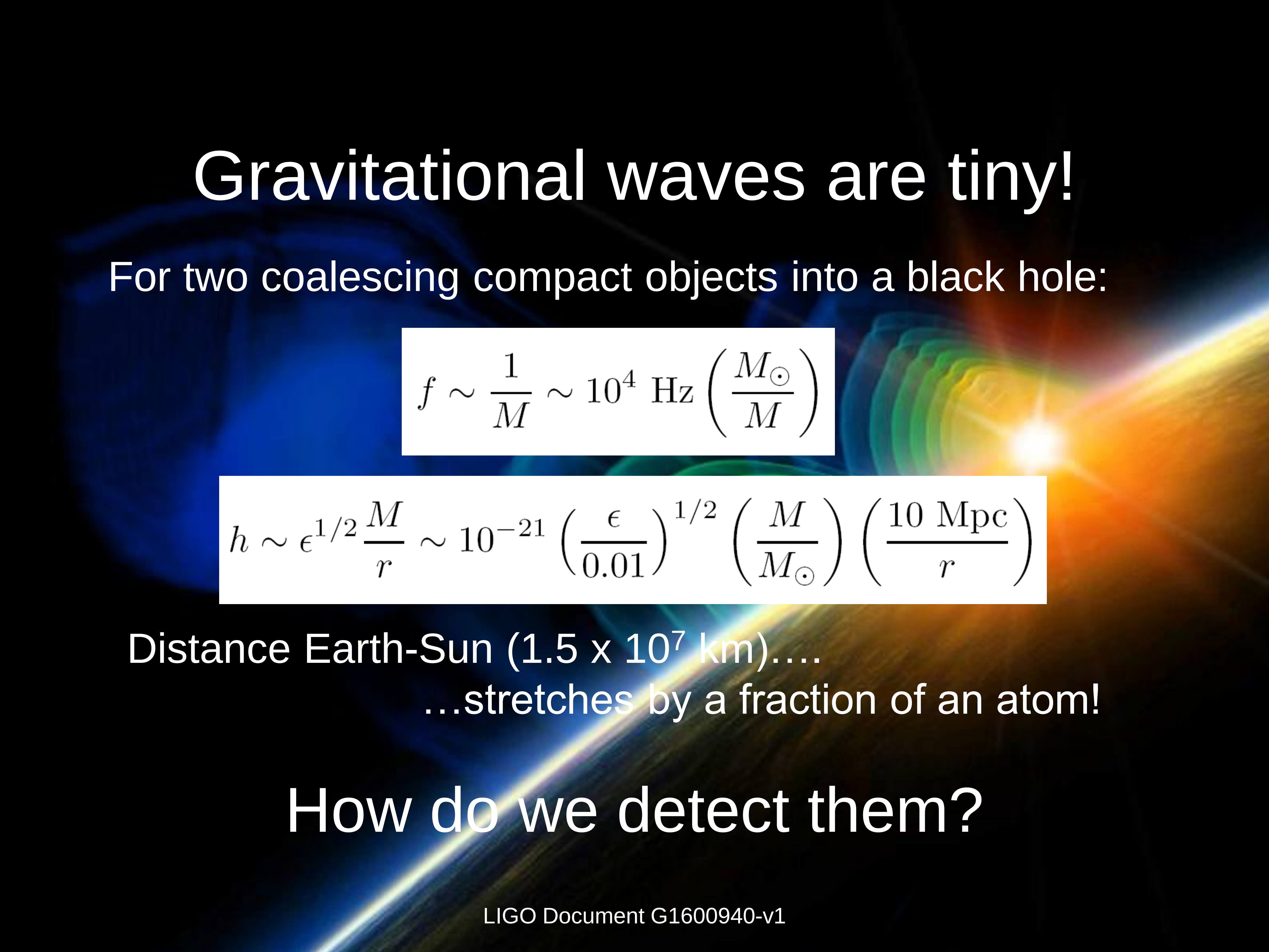


"x" polarization:

$$h_\times(t-z) = h^{TT}_{xy} = h^{TT}_{yx}$$







Gravitational waves are tiny!

For two coalescing compact objects into a black hole:

$$f \sim \frac{1}{M} \sim 10^4\ \mathrm{Hz} \left(\frac{M_\odot}{M}\right)$$

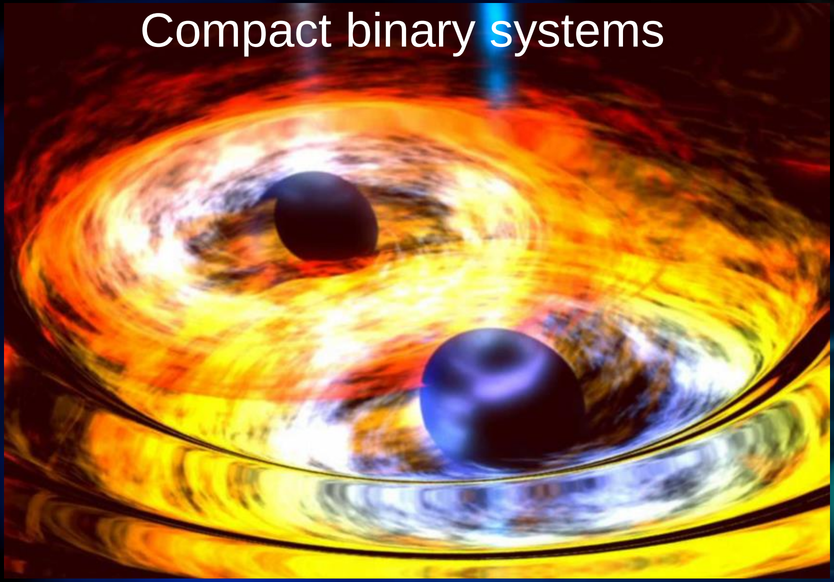
$$h \sim \epsilon^{1/2} \frac{M}{r} \sim 10^{-21} \left(\frac{\epsilon}{0.01}\right)^{1/2} \left(\frac{M}{M_\odot}\right) \left(\frac{10\ \mathrm{Mpc}}{r}\right)$$

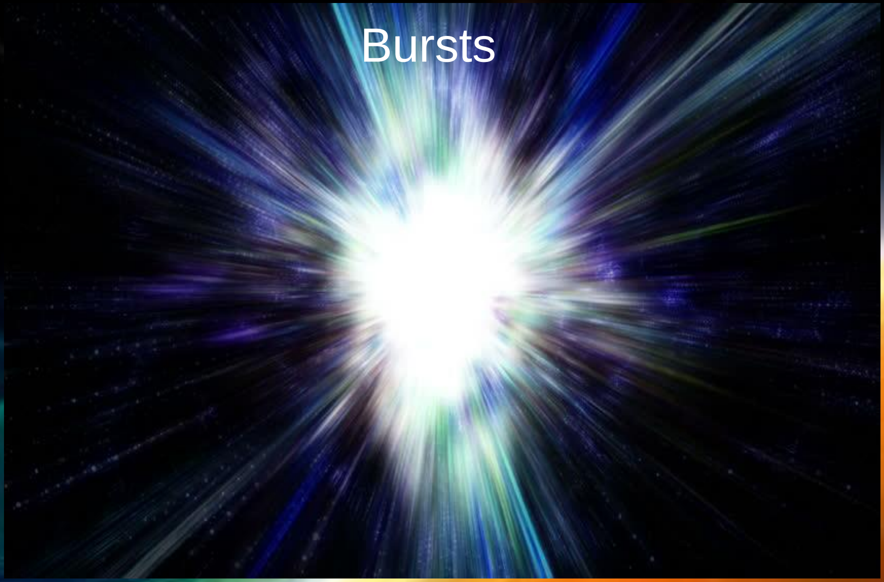
Distance Earth-Sun (1.5 x 10^7 km)….

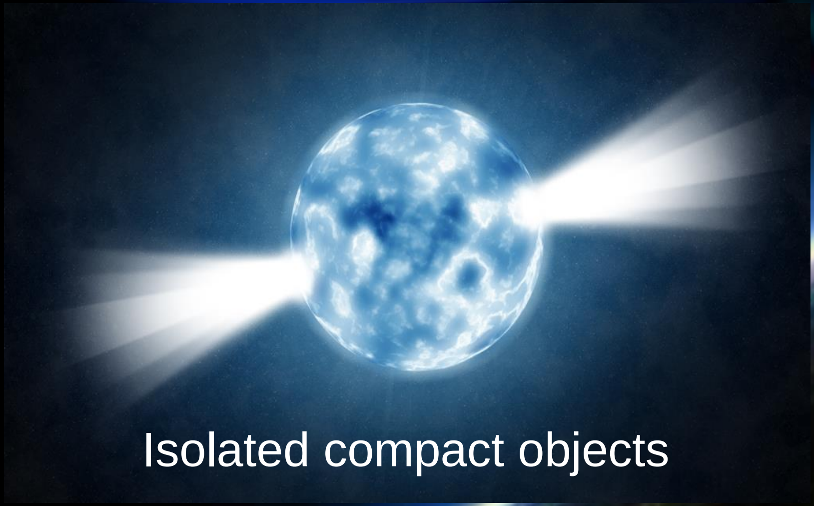
…stretches by a fraction of an atom!

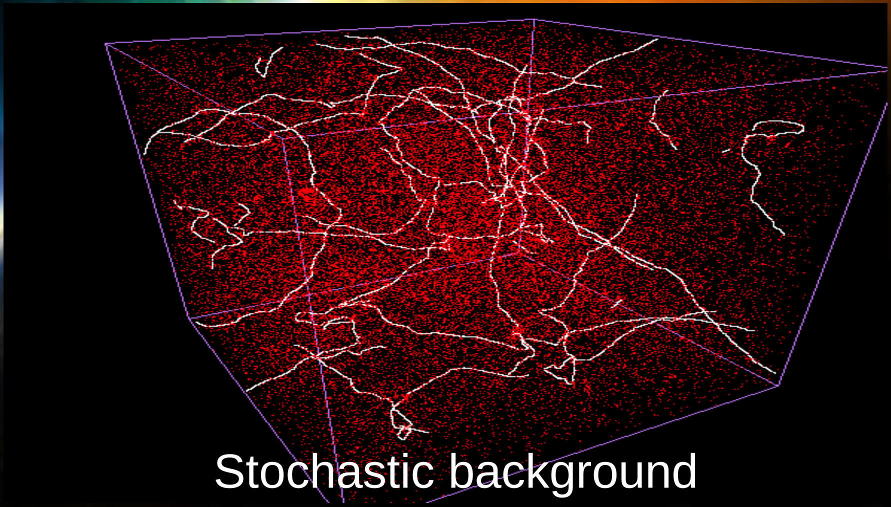
How do we detect them?

Sources we can probe

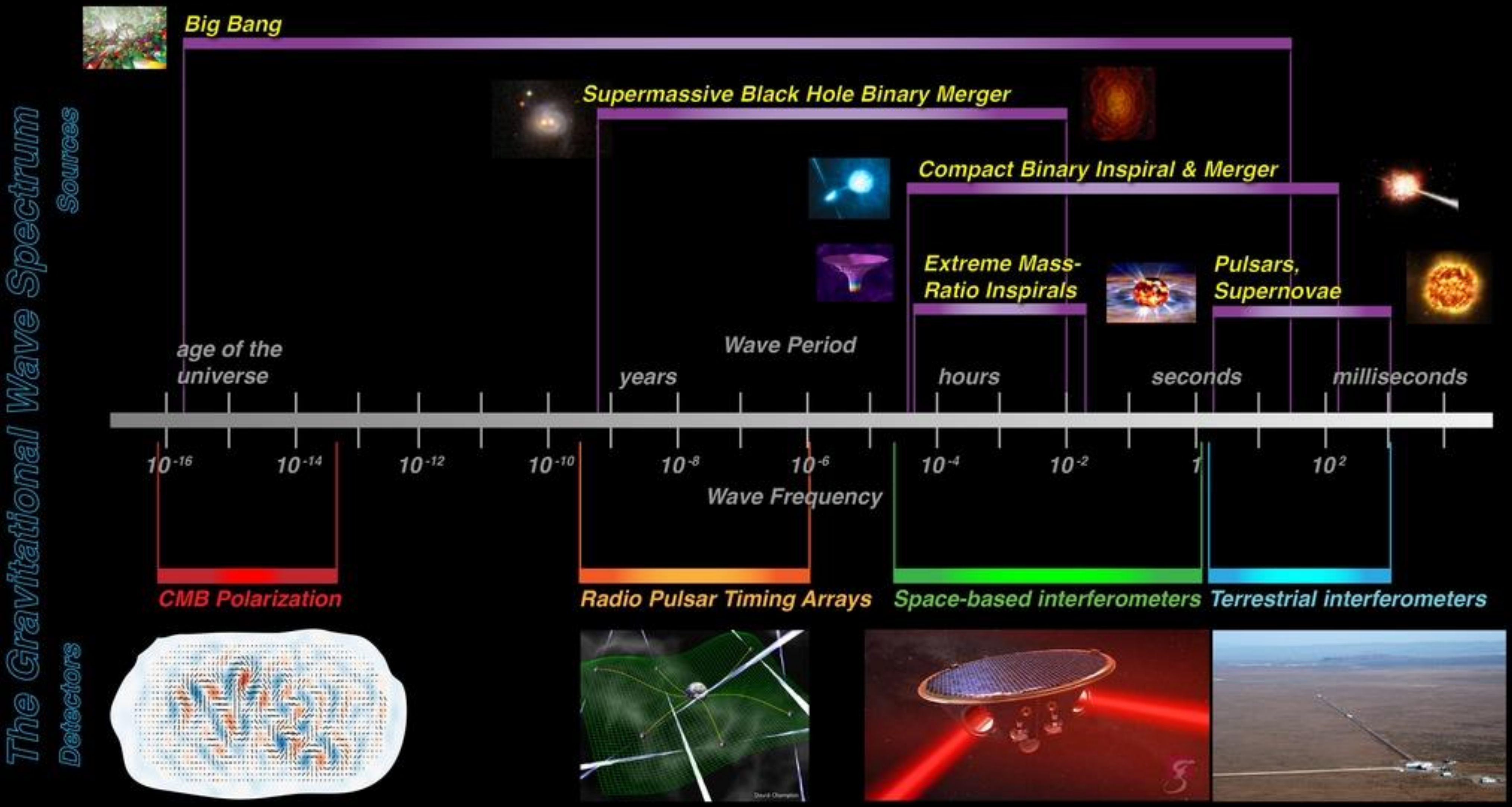

Compact binary systems


Bursts

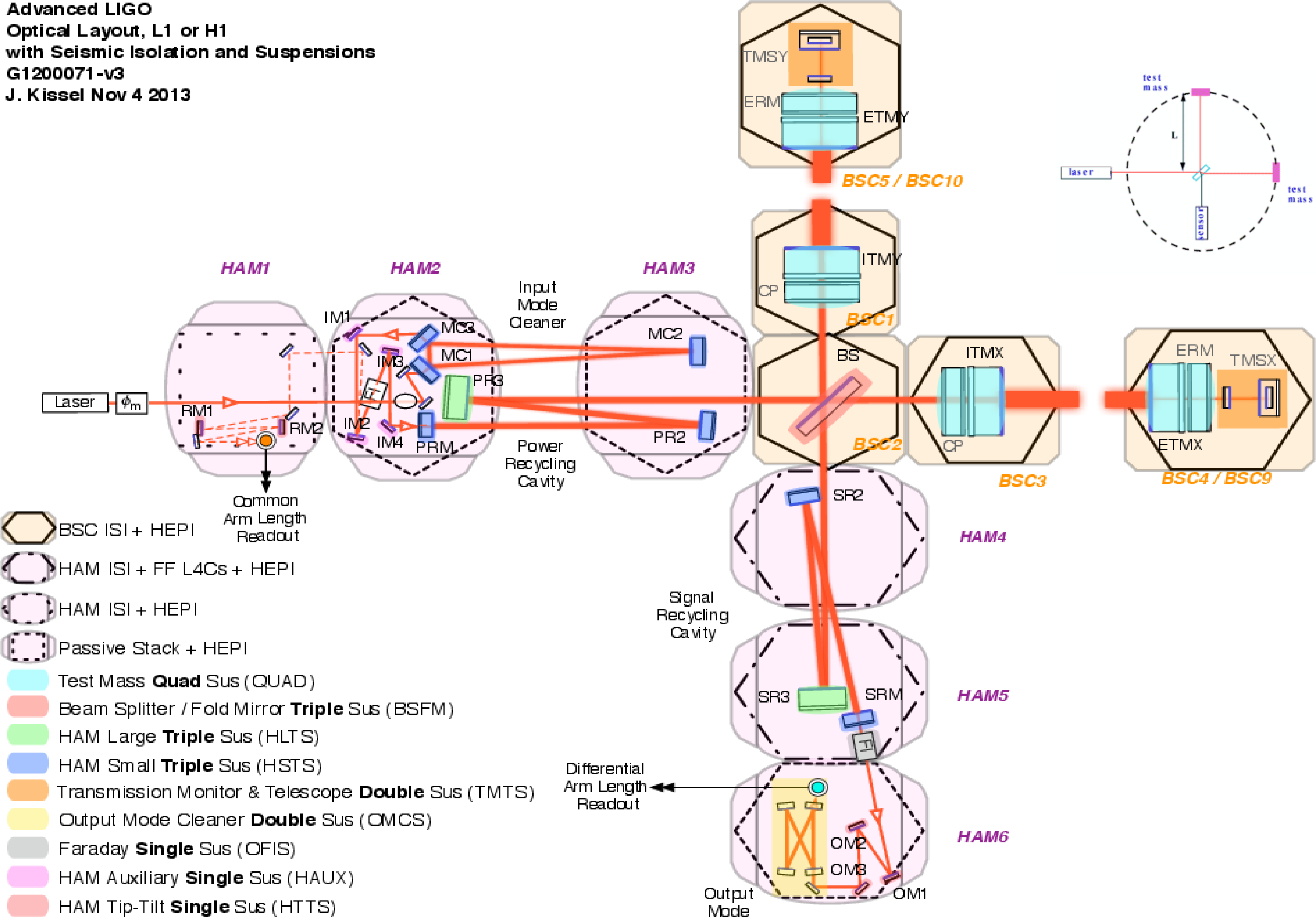

Isolated compact objects


Stochastic background

The gravitational-wave spectrum



Laser Interferometer Gravitational-wave Observatory



Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013

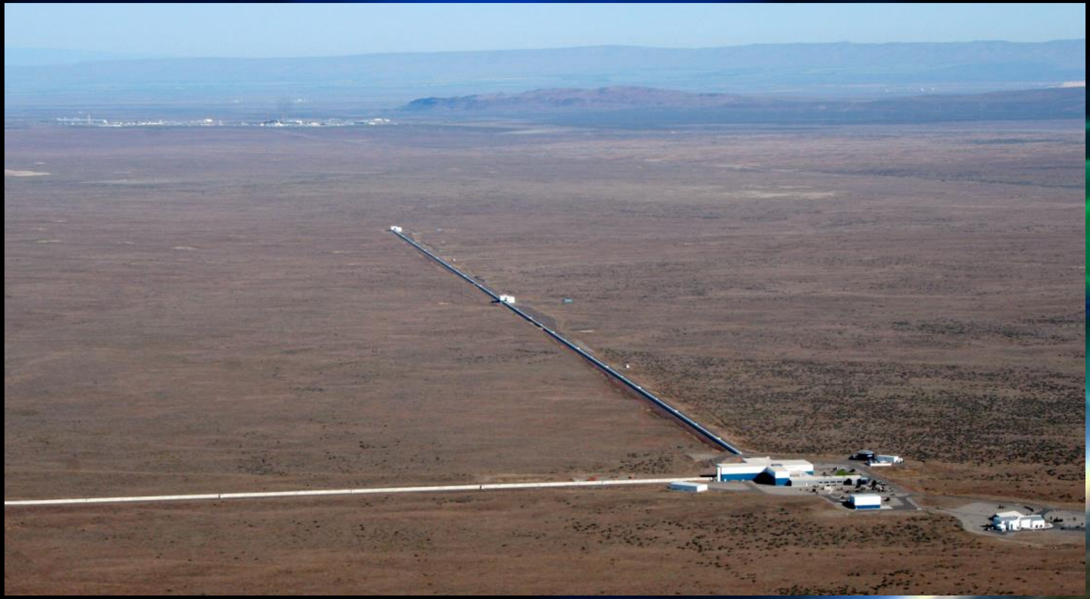


Photo credits: LIGO Laboratory; Kai Staats.

What it looks like from the outside

What it looks like from the inside

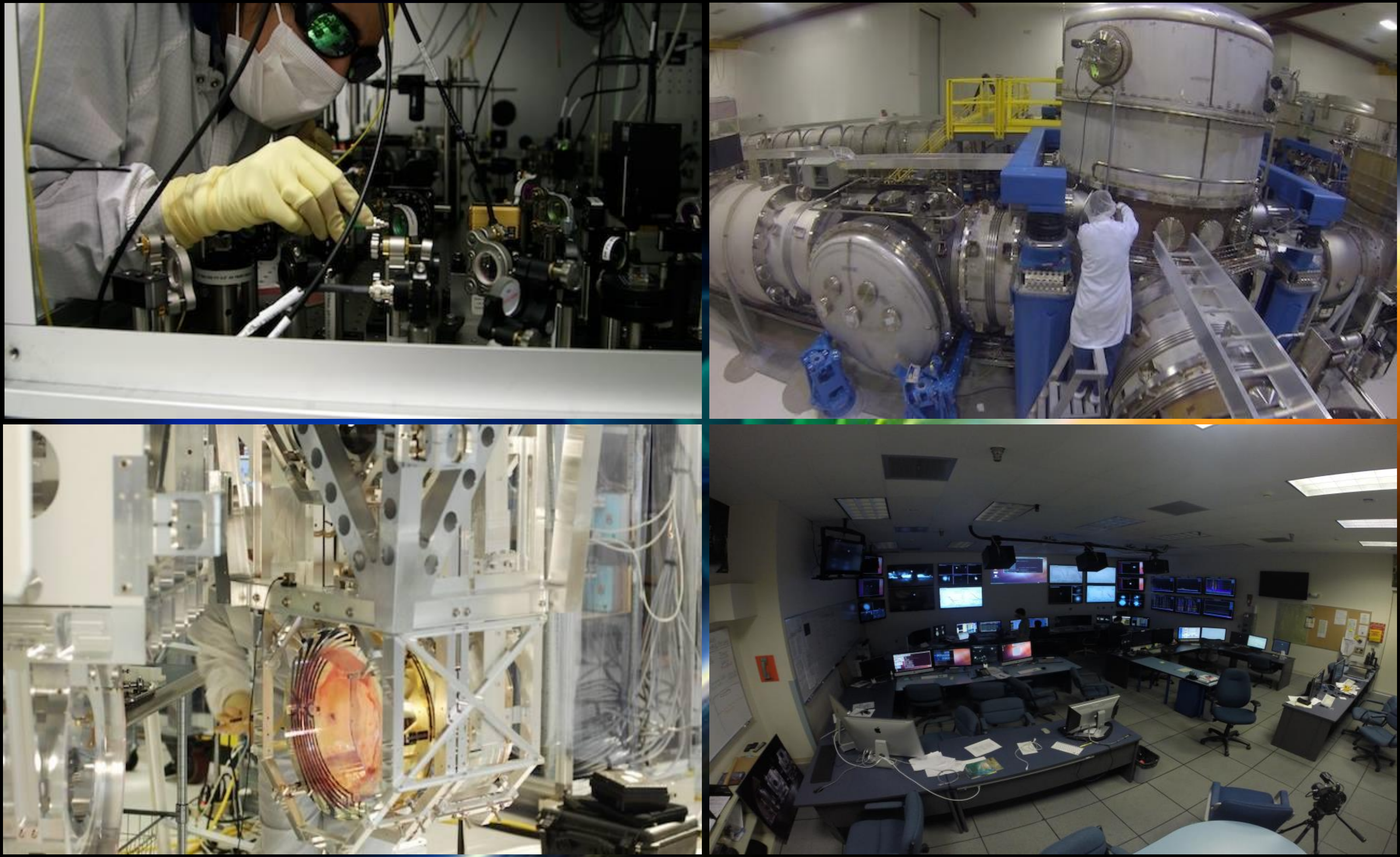


Photo credits: Kai Staats.

LIGO Scientific Collaboration

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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
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Goddard Space Flight Center
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ICTP-SAIFR
IndIGO
IAP-Russian Acad. of Sciences
Inst. Nacional Pesquisas Espaciais
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
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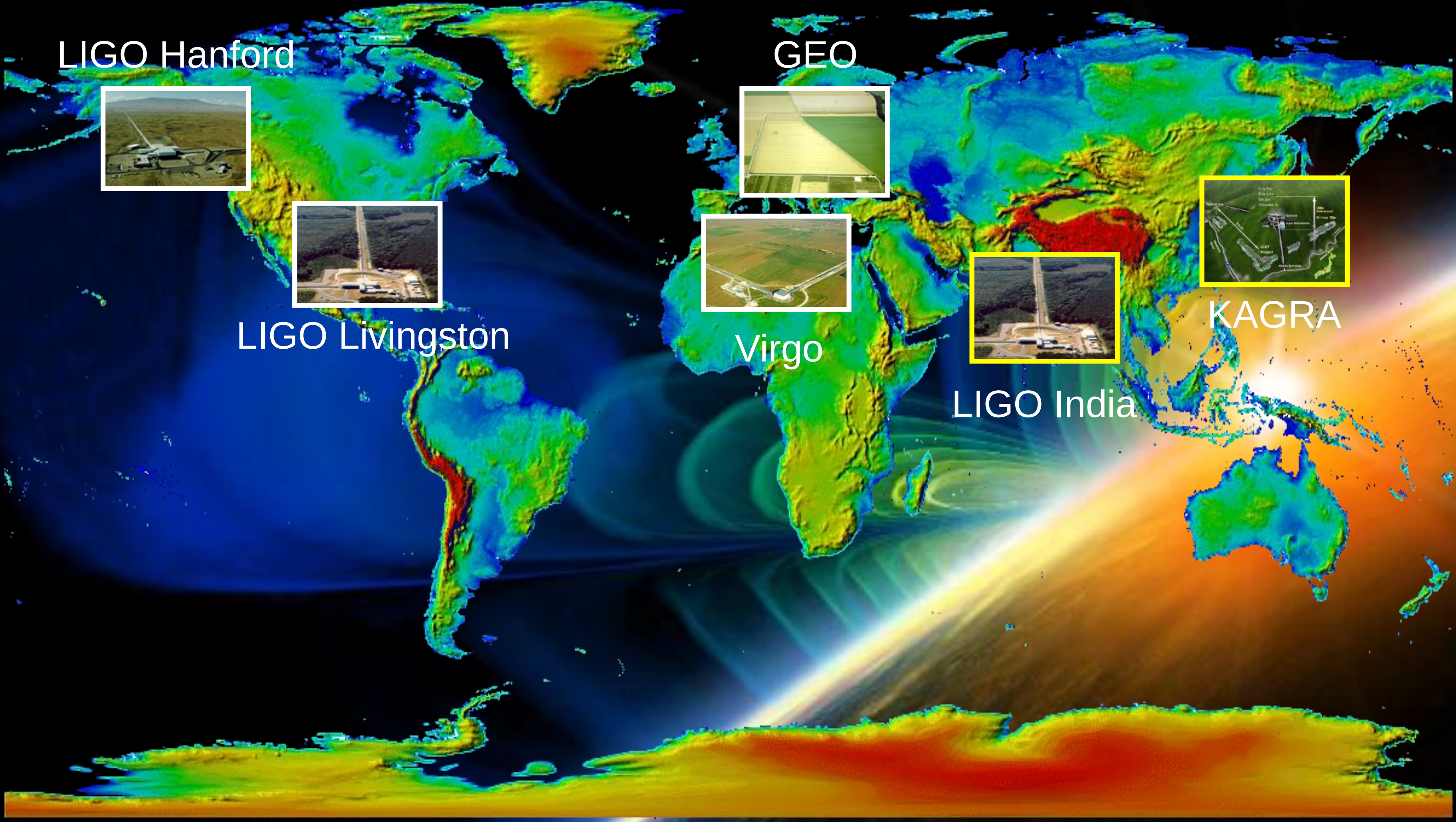
Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

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

Photo credits: Kai Staats.

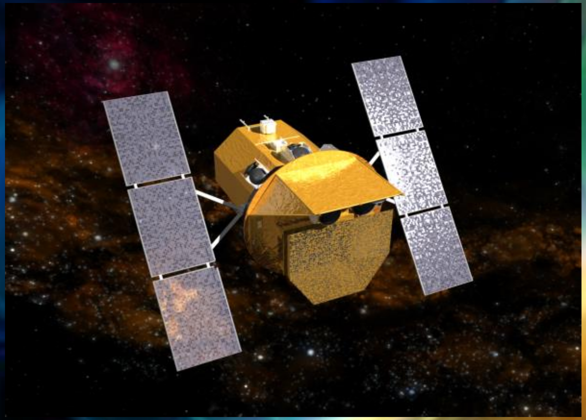


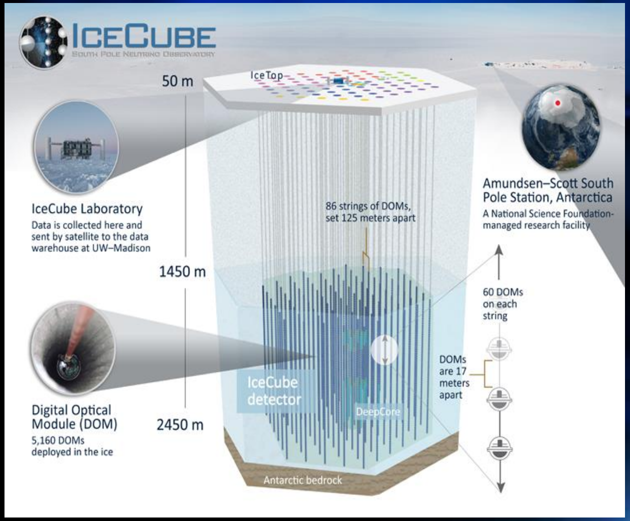
International network

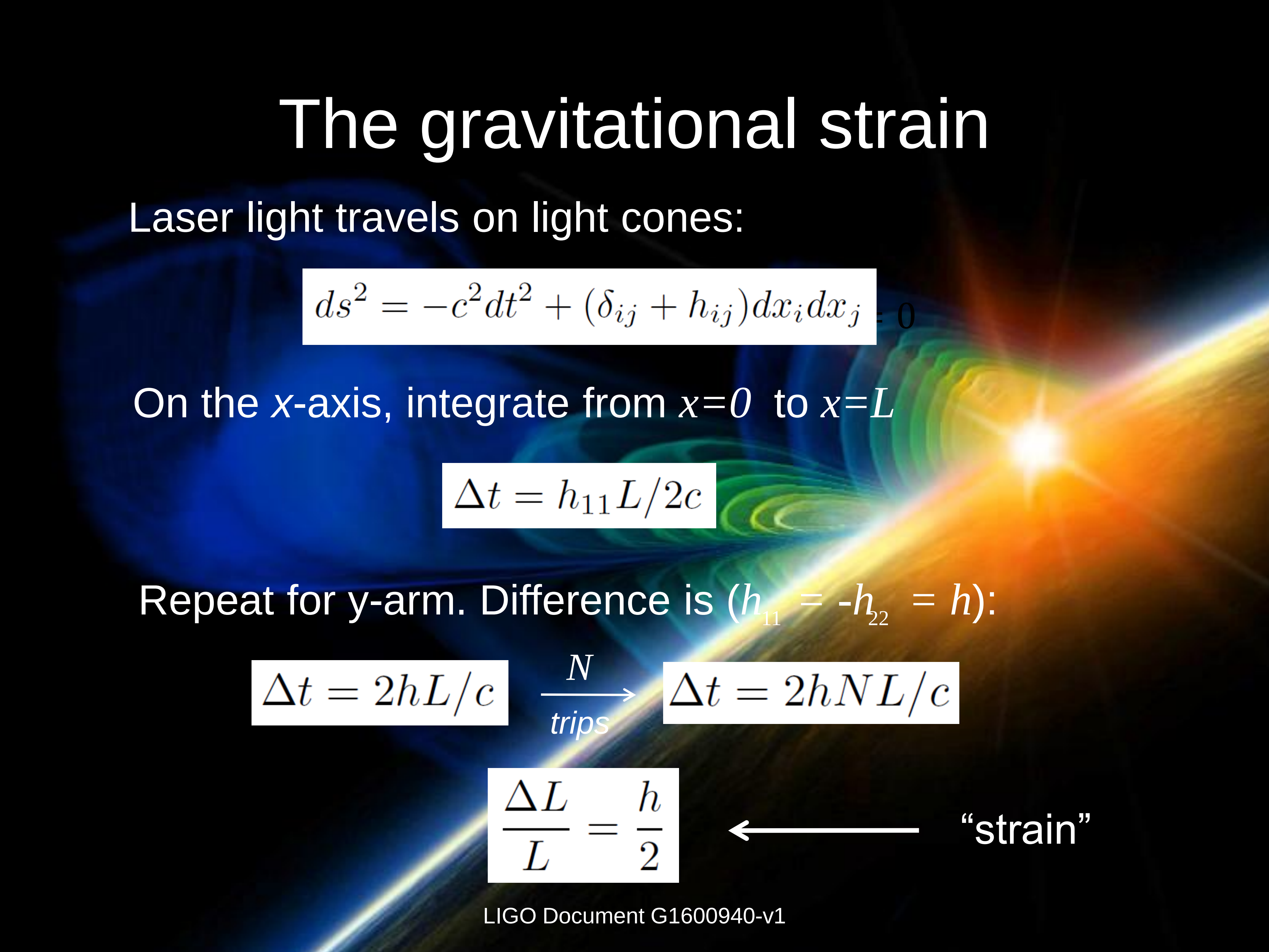
Partners

75+ agreements with astronomers for electromagnetic follow-up

MOUs with Icecube, Antares for neutrino follow-up







The gravitational strain

Laser light travels on light cones:

$$ds^2 = -c^2dt^2 + (\delta_{ij} + h_{ij})dx_i dx_j = 0$$

On the *x*-axis, integrate from $x=0$ to $x=L$

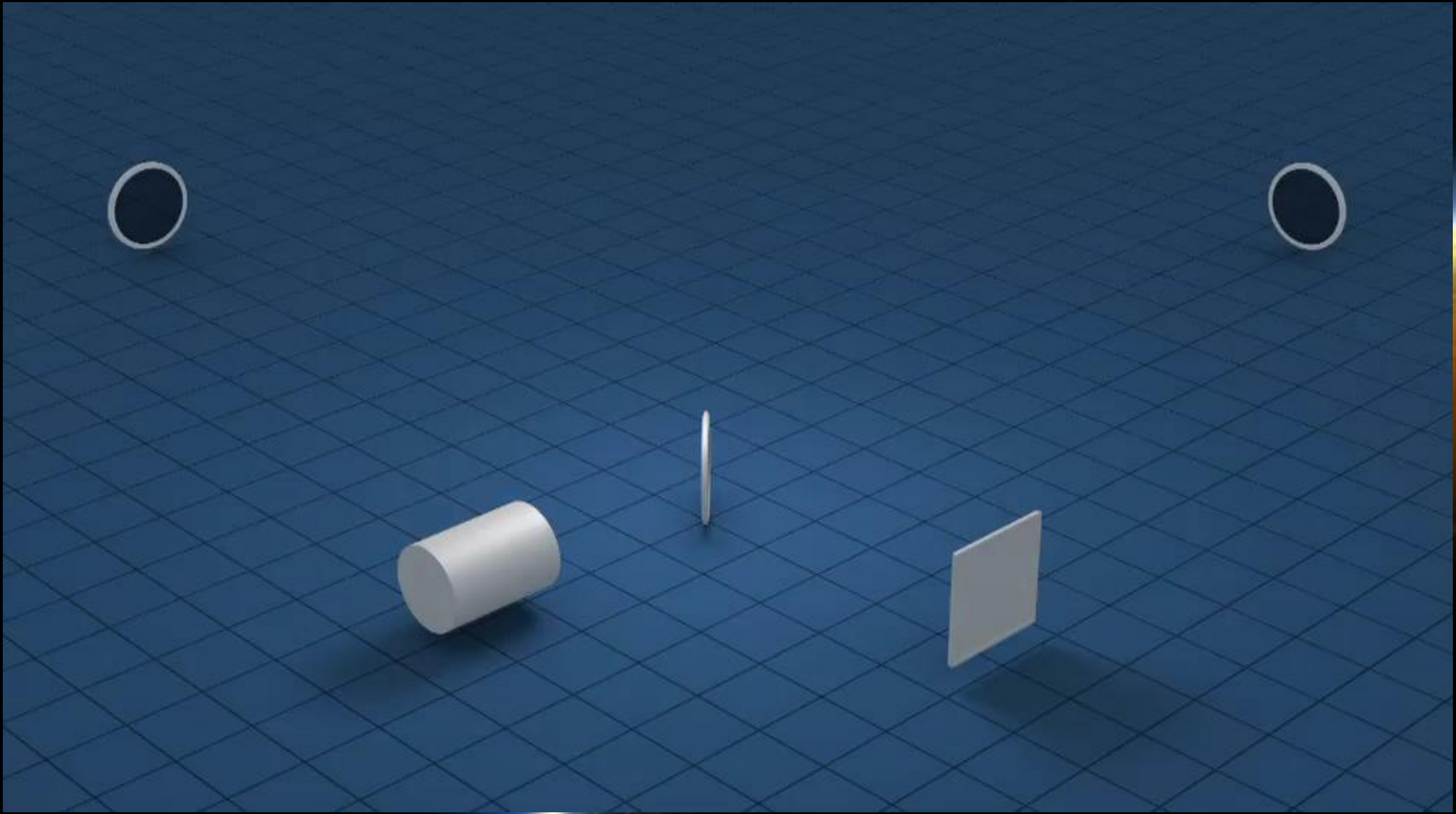
$$\Delta t = h_{11}L/2c$$

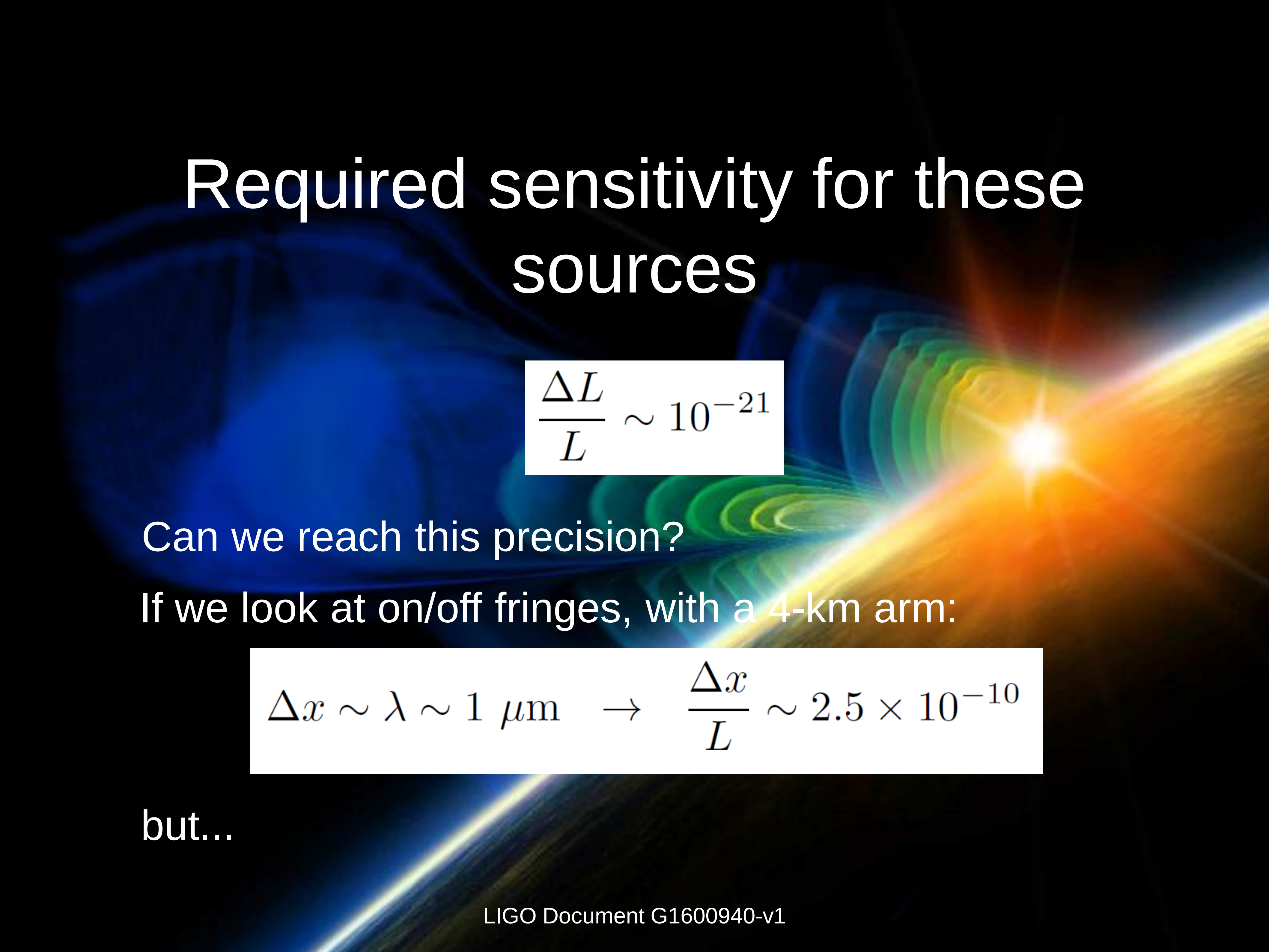
Repeat for y-arm. Difference is ($h_{11} = -h_{22} = h$):

$$\Delta t = 2hL/c \xrightarrow[\text{trips}]{N} \Delta t = 2hNL/c$$

$$\frac{\Delta L}{L} = \frac{h}{2}$$

← “strain”





Required sensitivity for these sources

$$\frac{\Delta L}{L} \sim 10^{-21}$$

Can we reach this precision?

If we look at on/off fringes, with a 4-km arm:

$$\Delta x \sim \lambda \sim 1\ \mu\mathrm{m} \quad \rightarrow \quad \frac{\Delta x}{L} \sim 2.5 \times 10^{-10}$$

but...

Required sensitivity for these sources

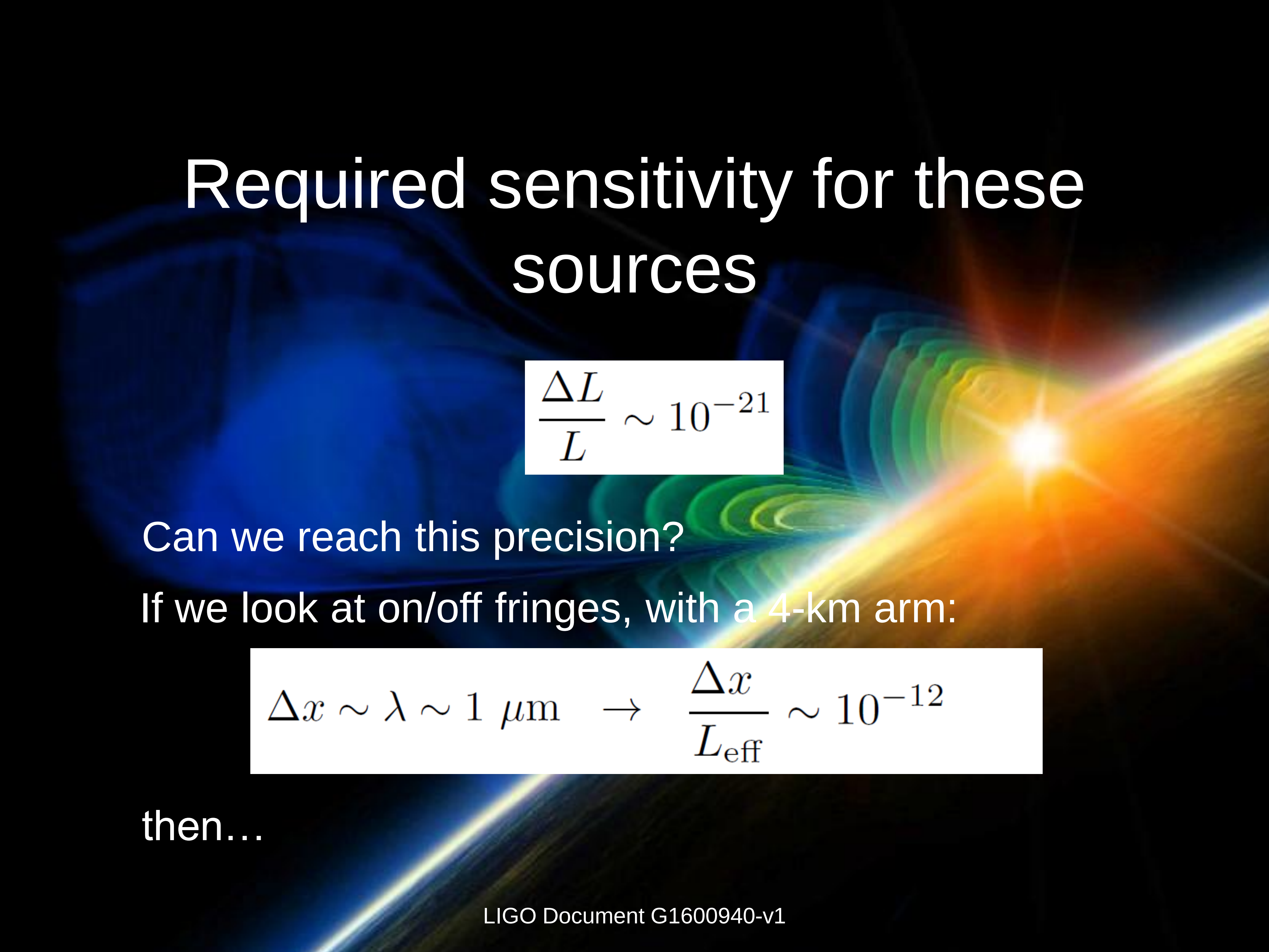
$$\frac{\Delta L}{L} \sim 10^{-21}$$

Can we reach this precision?

If we look at on/off fringes, with a 4-km arm:

$$\Delta x \sim \lambda \sim 1\ \mu\mathrm{m} \quad \rightarrow \quad \frac{\Delta x}{L} \sim 2.5 \times 10^{-10}$$

…first build up power in the arms



Required sensitivity for these sources

$$\frac{\Delta L}{L} \sim 10^{-21}$$

Can we reach this precision?

If we look at on/off fringes, with a 4-km arm:

$$\Delta x \sim \lambda \sim 1\ \mu\mathrm{m} \quad \rightarrow \quad \frac{\Delta x}{L_{\mathrm{eff}}} \sim 10^{-12}$$

then…

Average flux of photons

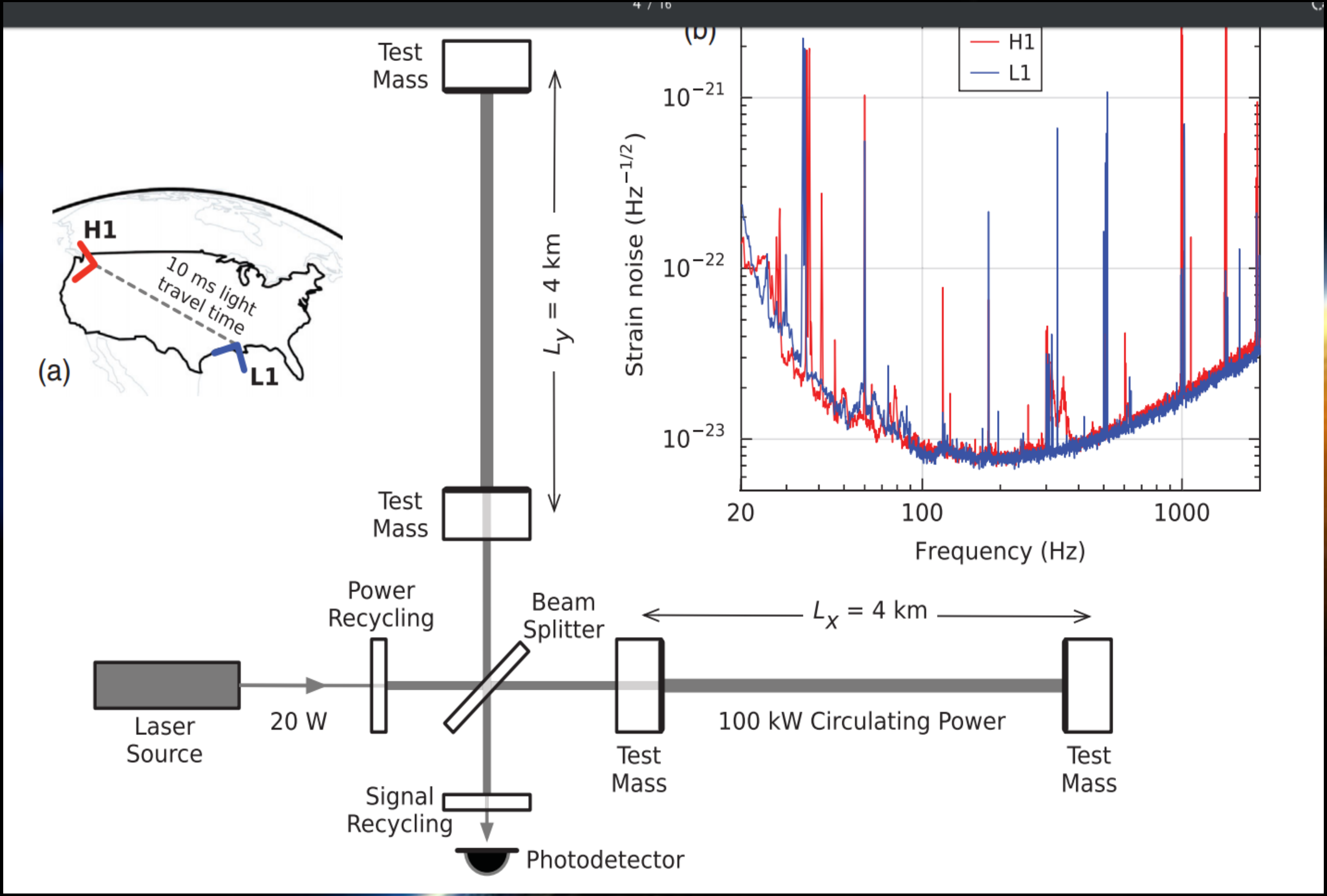
$$\bar{N} = \frac{\lambda}{2\pi\hbar c} P$$

Fluctuations (shot noise):

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}}$$

200 W of laser light carries 10^{19} photons per second, giving a sensitivity of

$$\frac{\Delta N}{N} \sim 3 \times 10^{-10} \quad \rightarrow \quad h \sim \frac{\Delta x}{L_{\mathrm{eff}}} \frac{\Delta N}{N} \sim 3 \times 10^{-22}$$

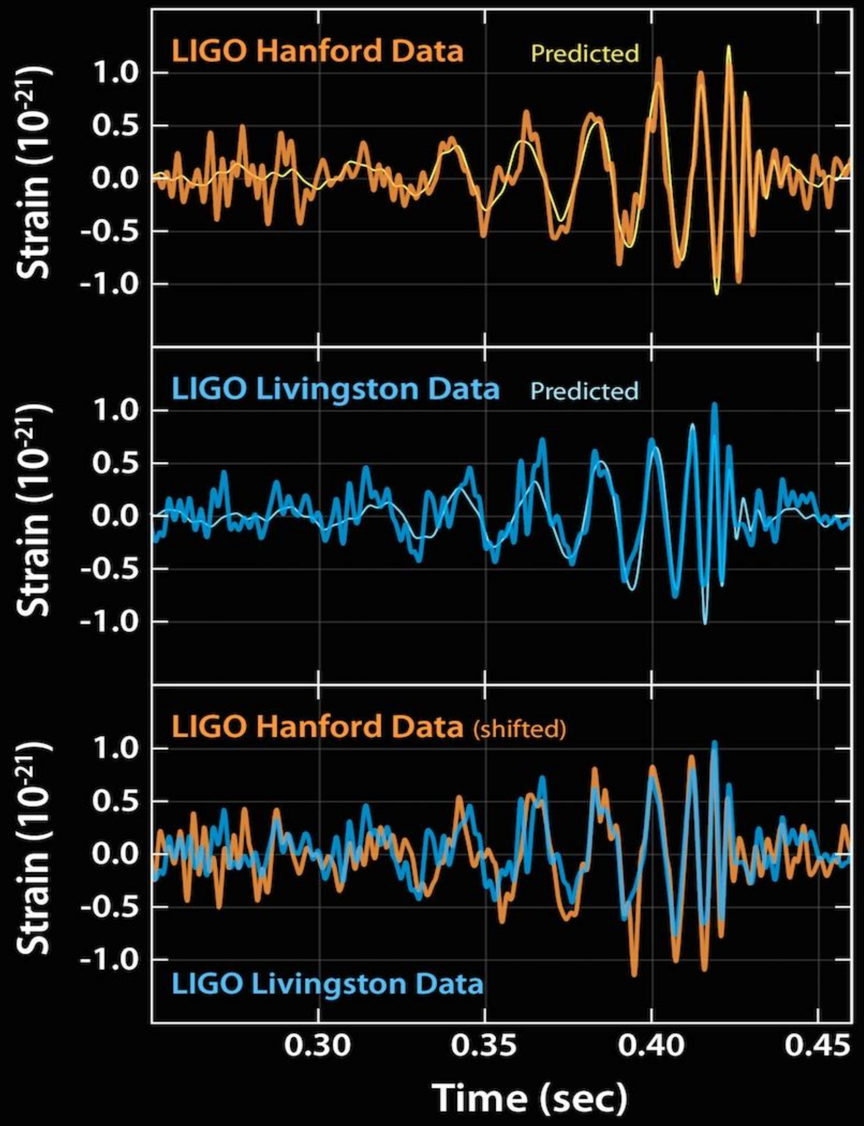


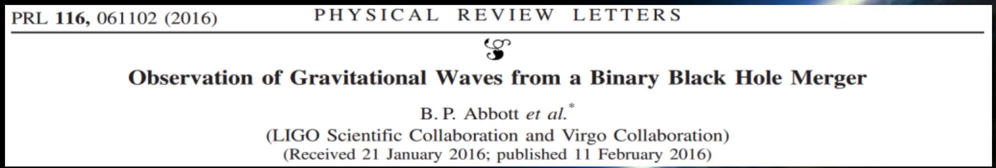
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

LIGO Document G1600940-v1

LIGO's first detection
GW150914: September 14, 2015, 9:50:45 UTC

- 7 ms delay between arrival times at Livingston and Hanford
- Filtered to remove low frequency fluctuations and single frequency lines
- Hanford's data inverted to account for orientation of detectors

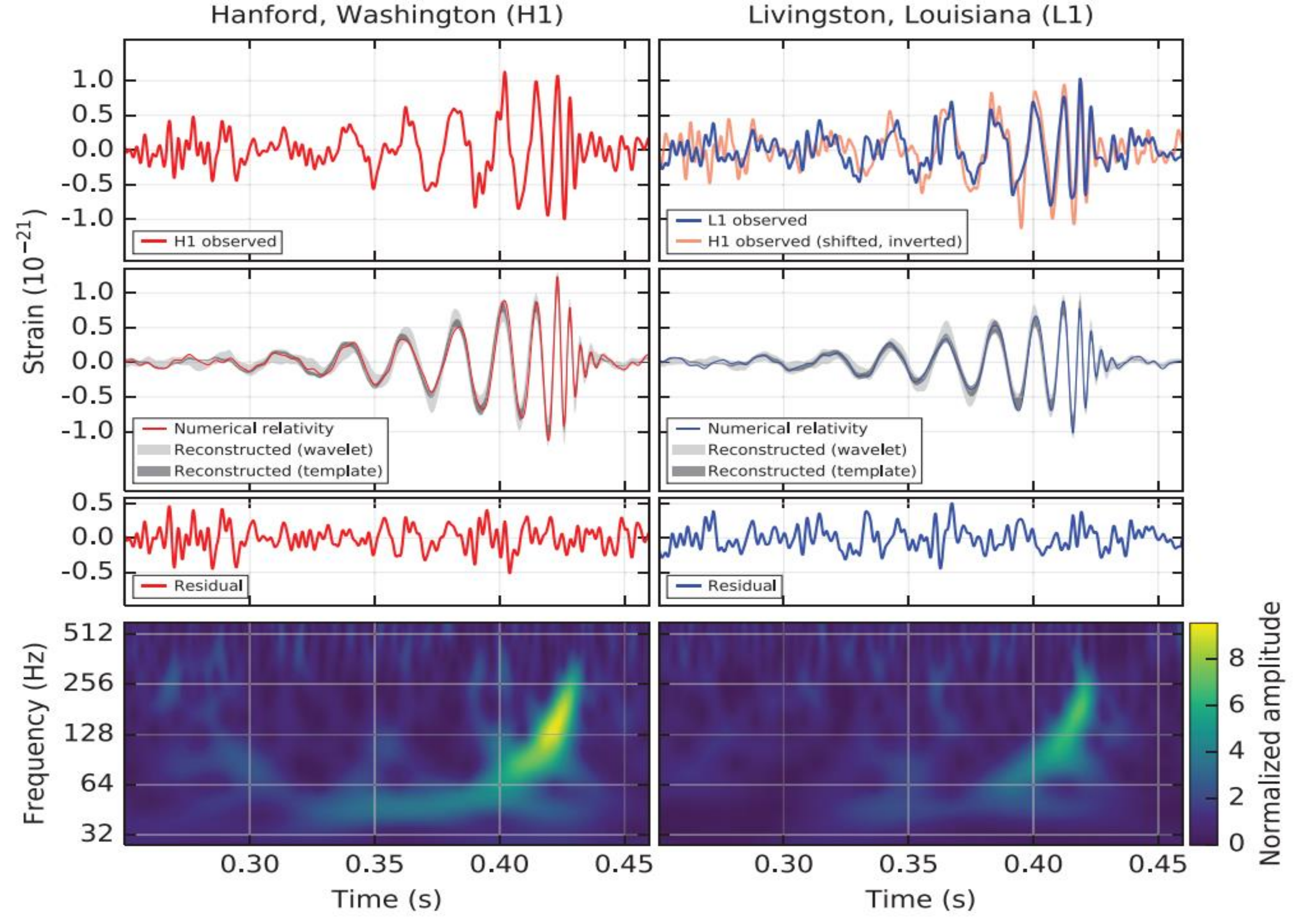



PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS

Observation of Gravitational Waves from a Binary Black Hole Merger

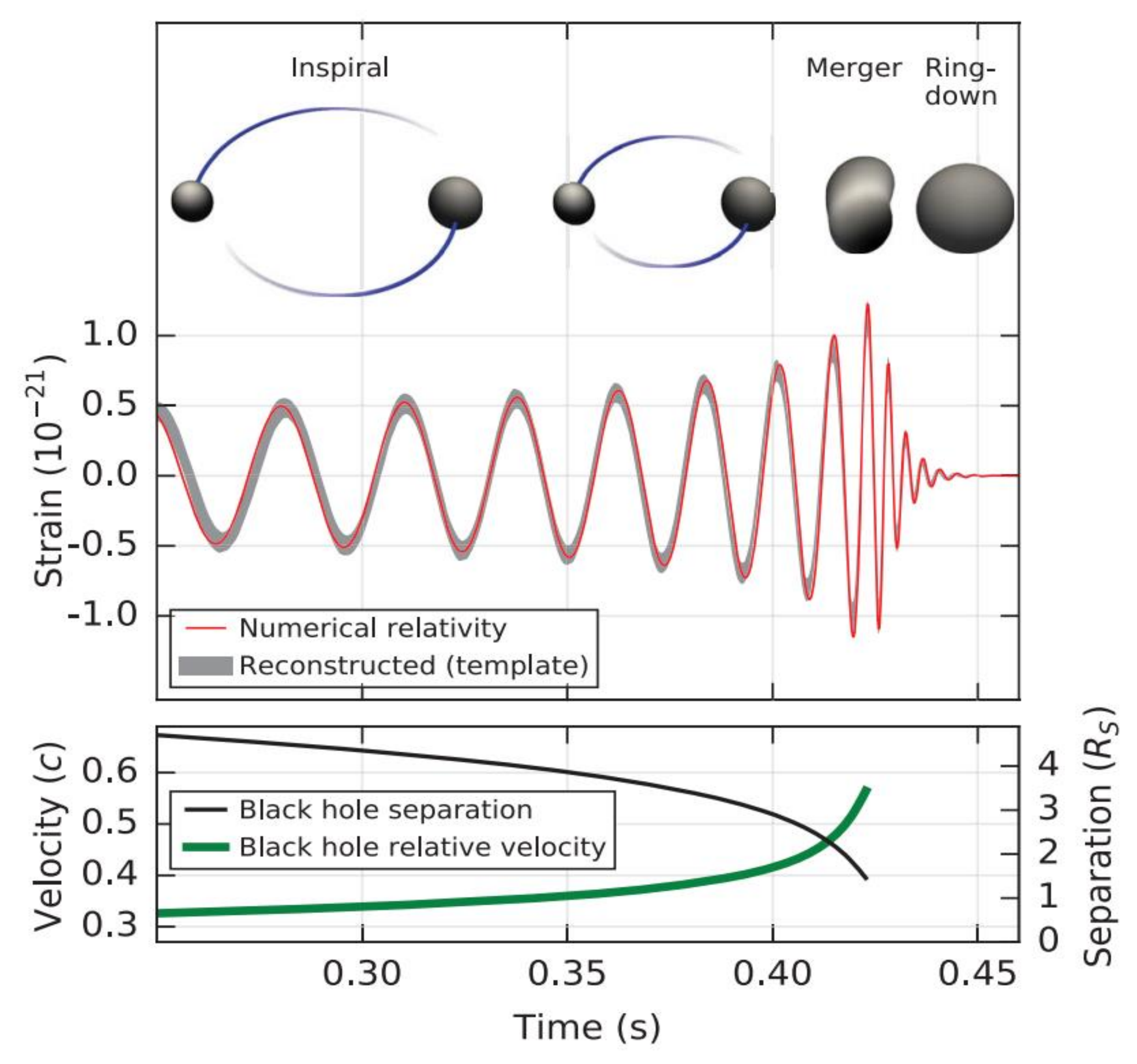
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



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

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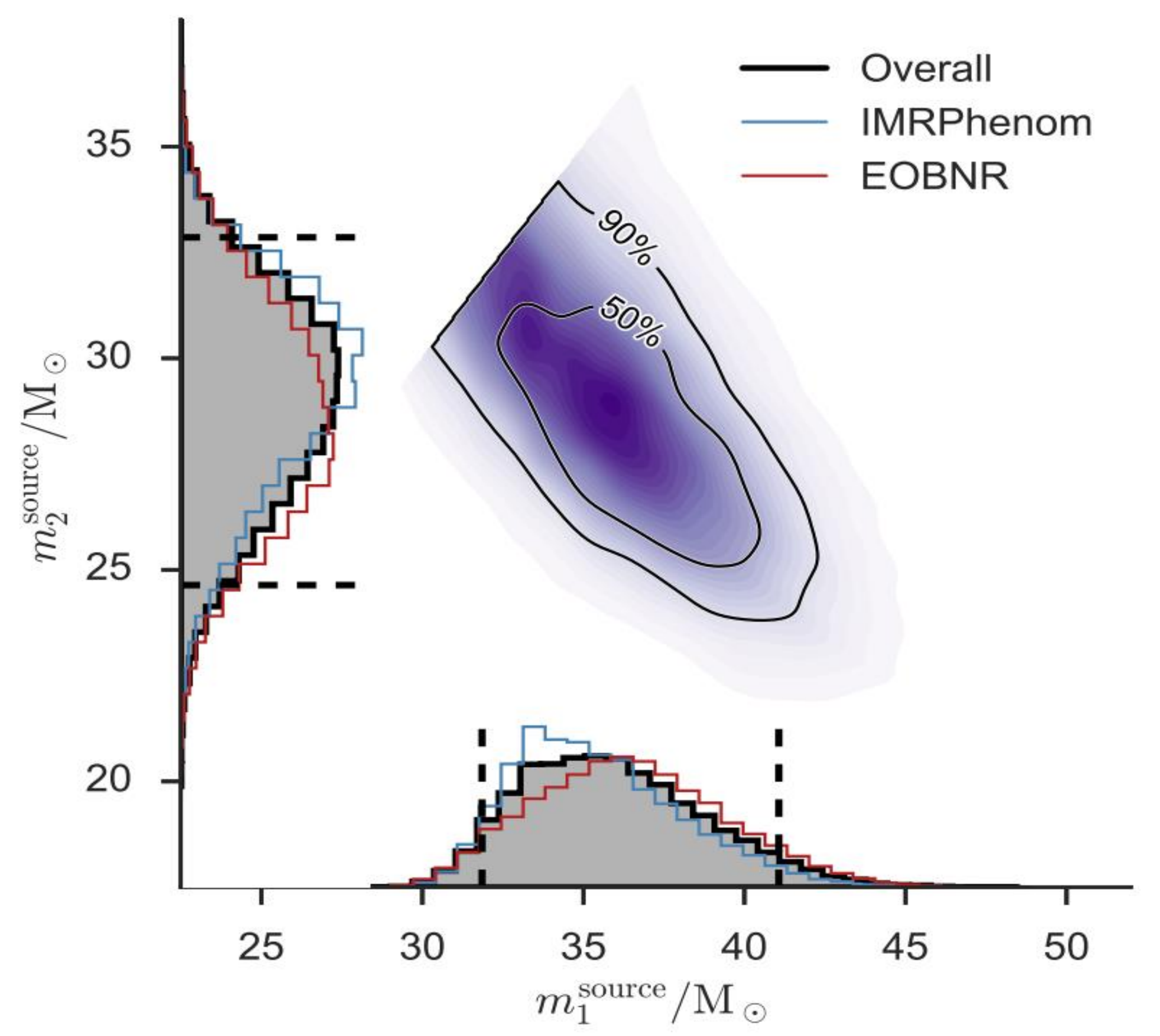
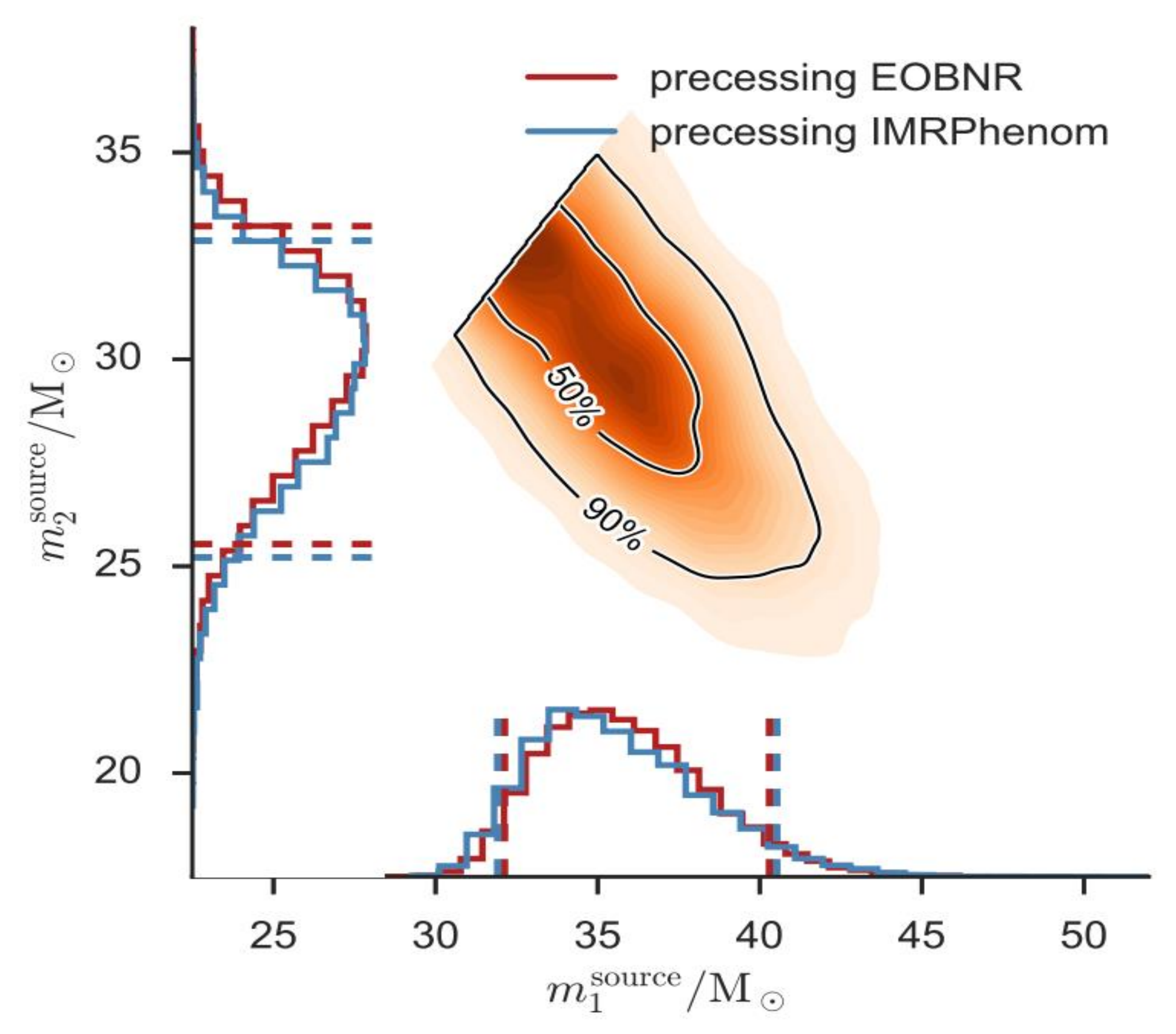
Black hole masses



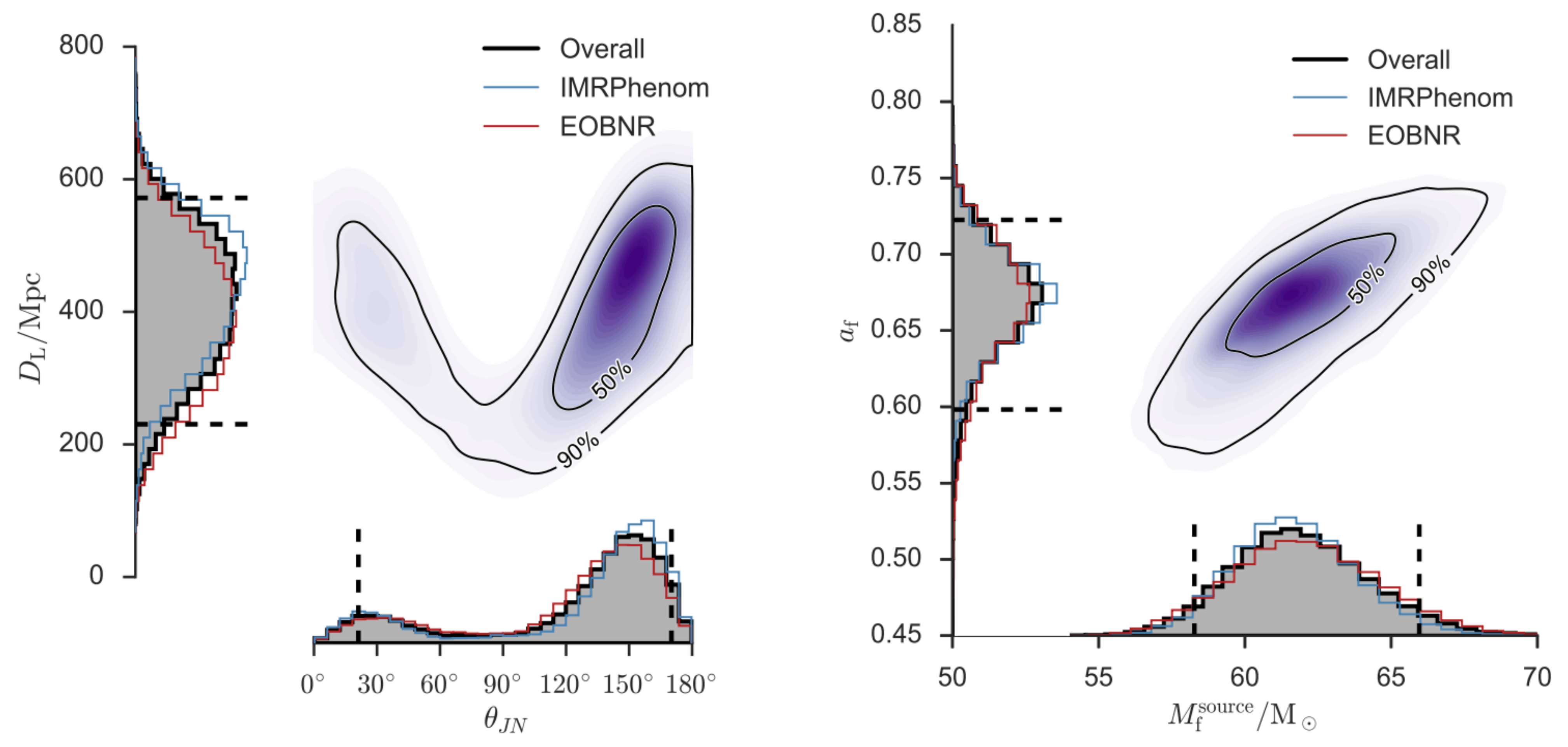
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Black hole masses



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv 1606.01210.

Distance and final black hole



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

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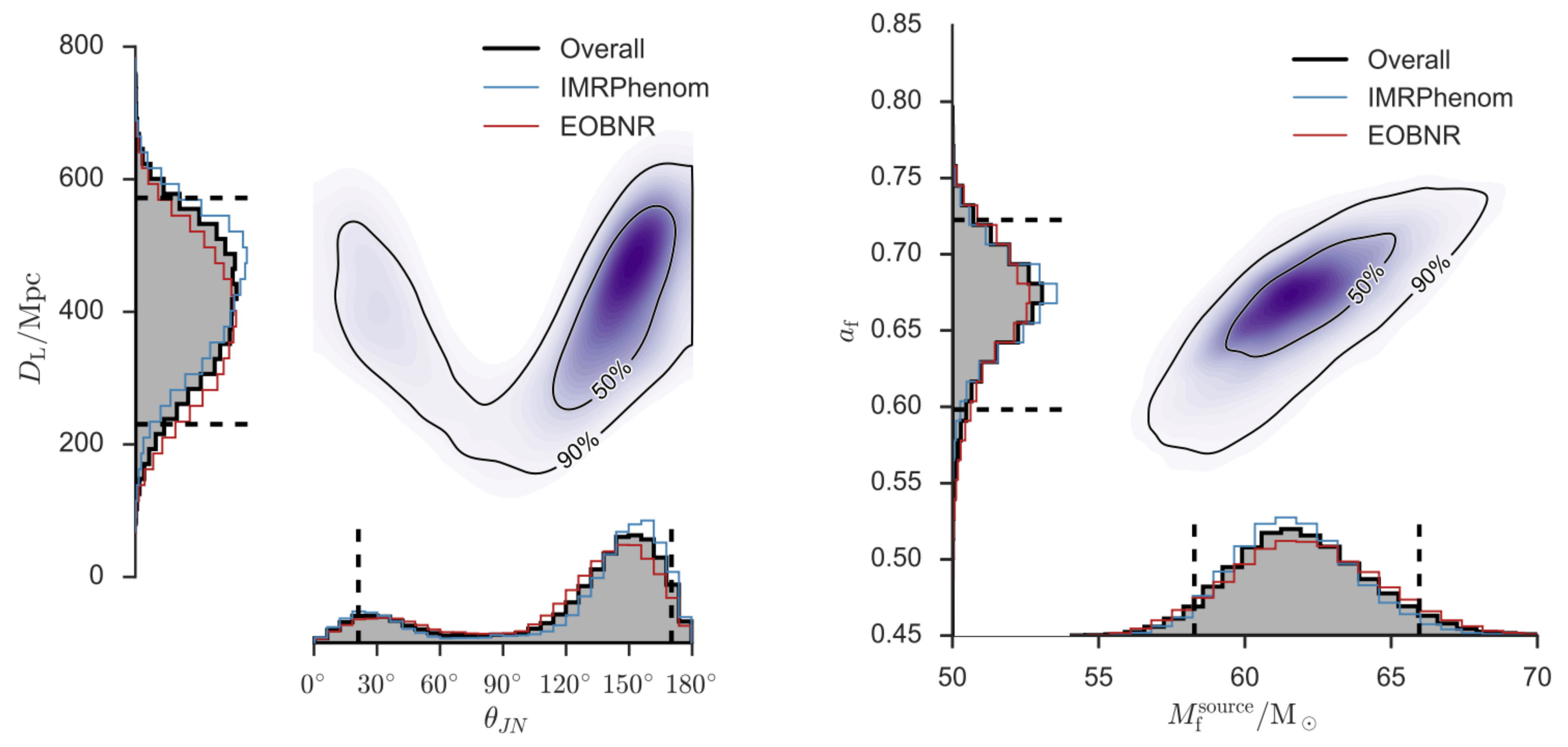

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

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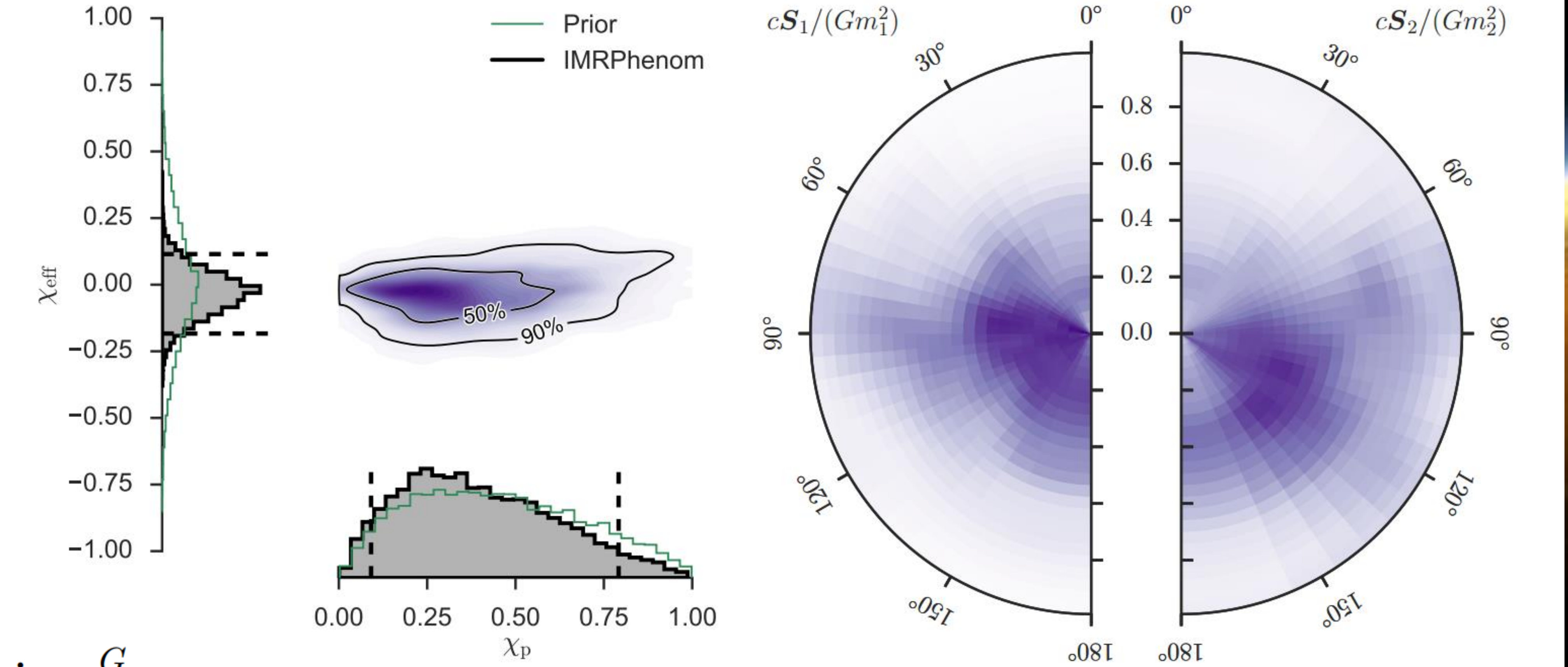
Spins



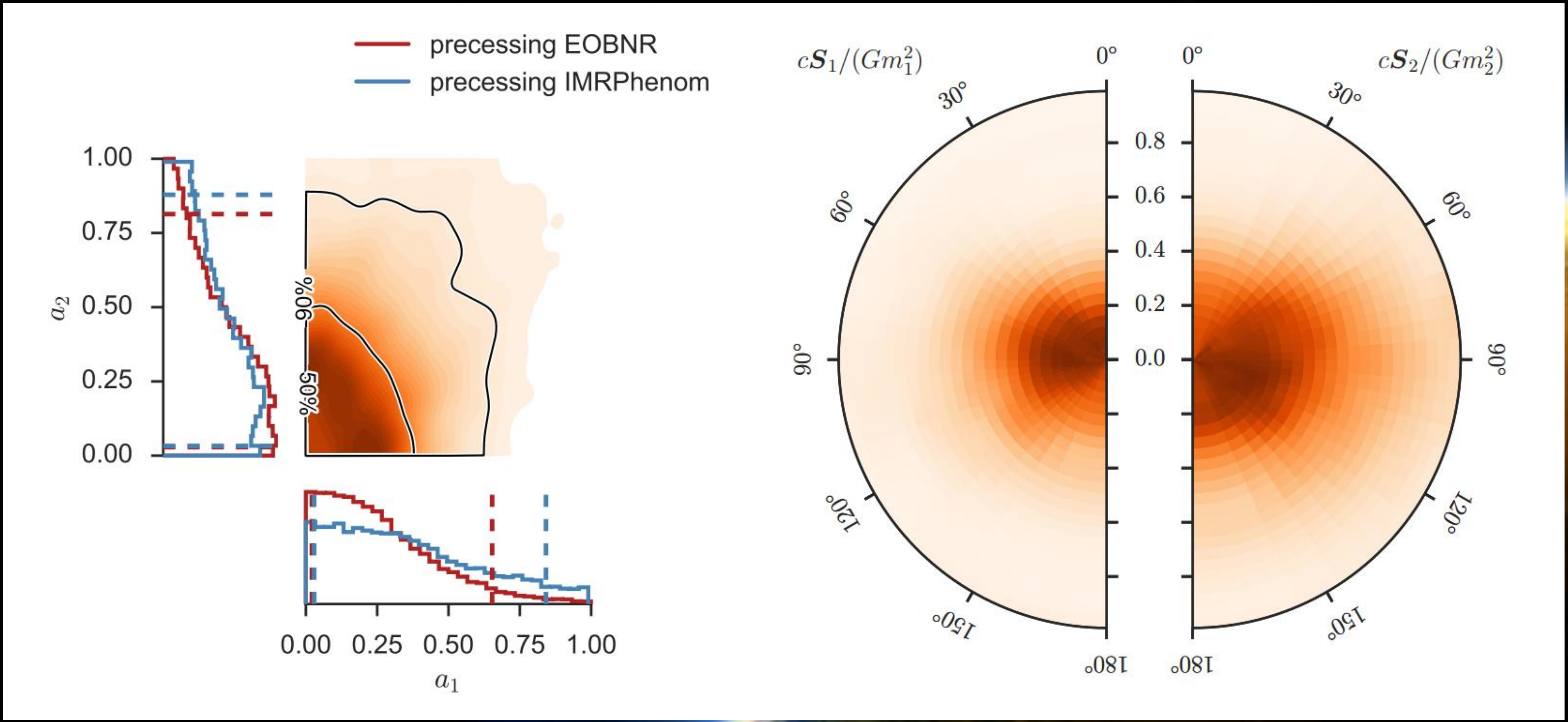
$$\dot{\boldsymbol{L}} = \frac{G}{c^2 r^3}(B_1 \boldsymbol{S}_{1\perp} + B_2 \boldsymbol{S}_{2\perp}) \times \boldsymbol{L}$$

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

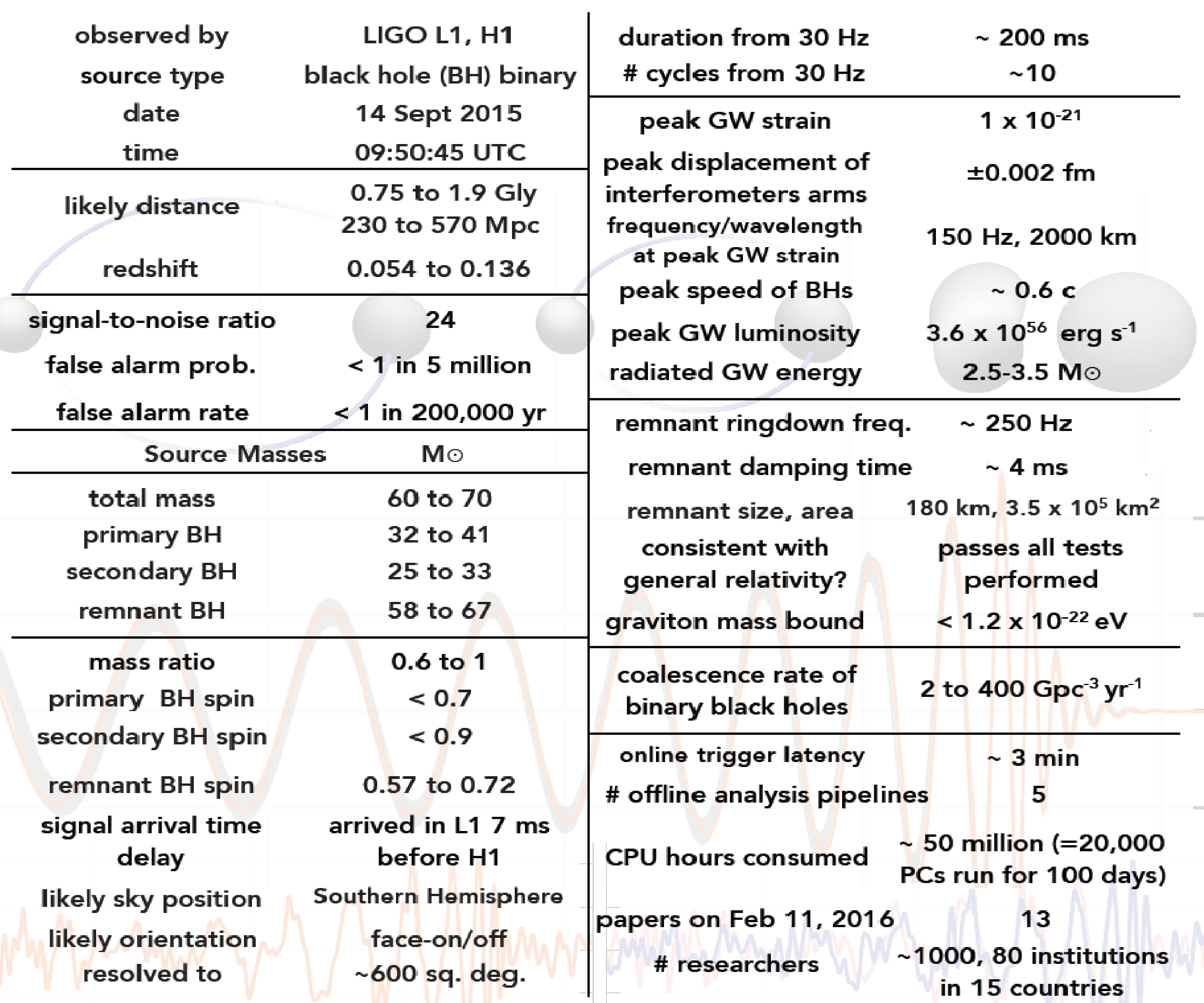
$$\chi_{\mathrm{eff}} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M} \quad \chi_{\mathrm{p}} = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

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

Spins

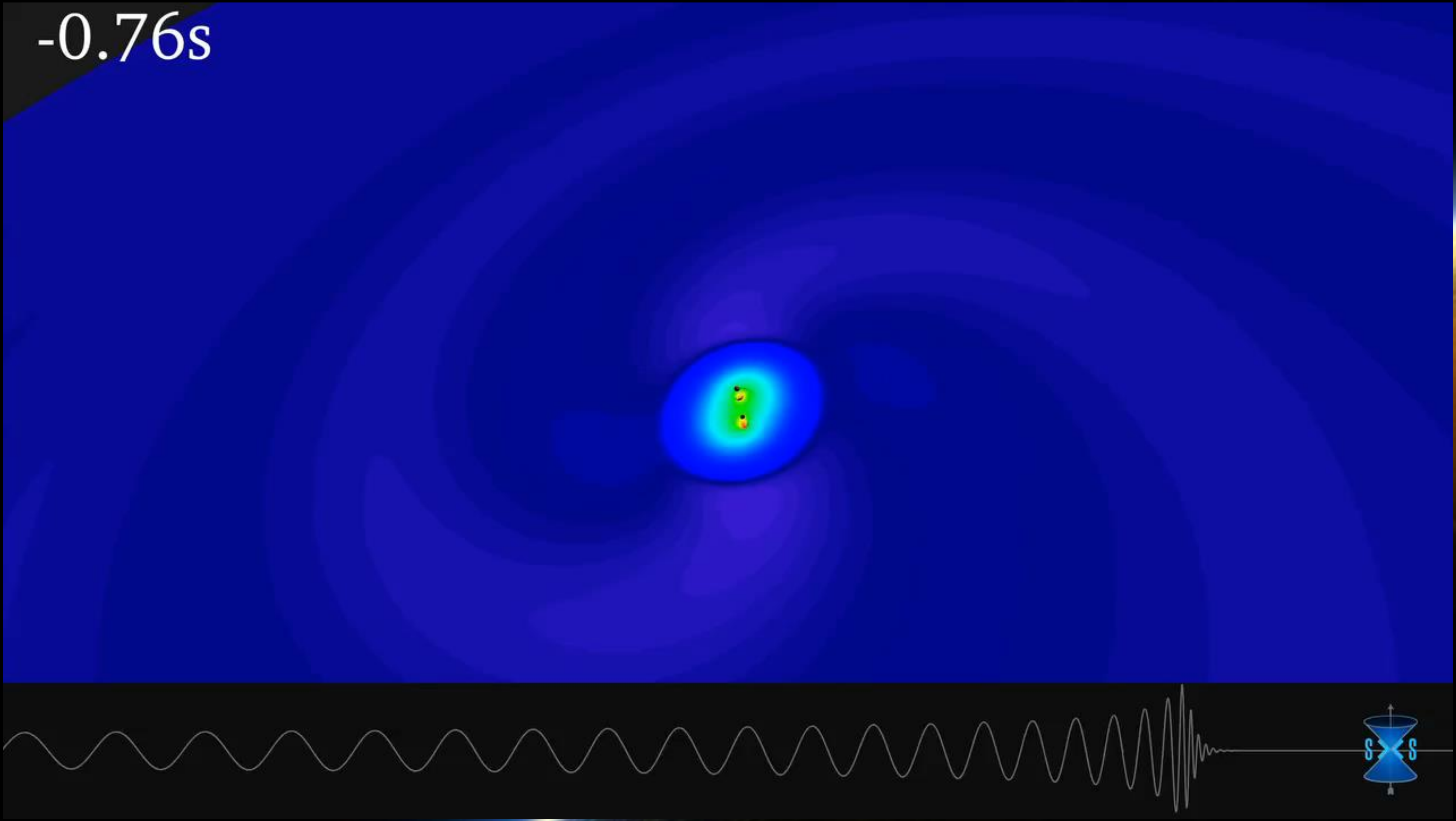


B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv 1606.01210.

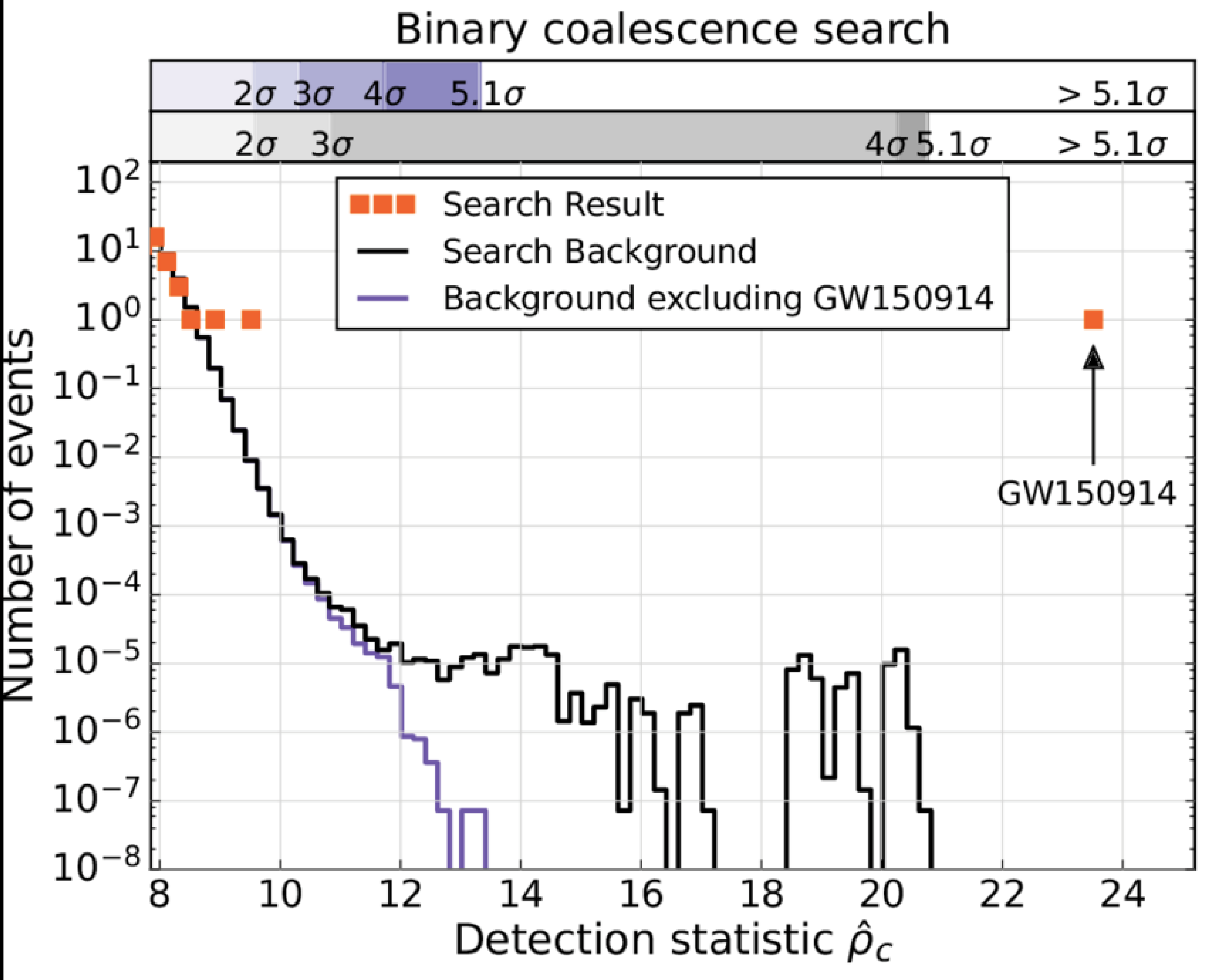


observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	$M_\odot$
total mass	60 to 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 $M_\odot$
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


-0.76s

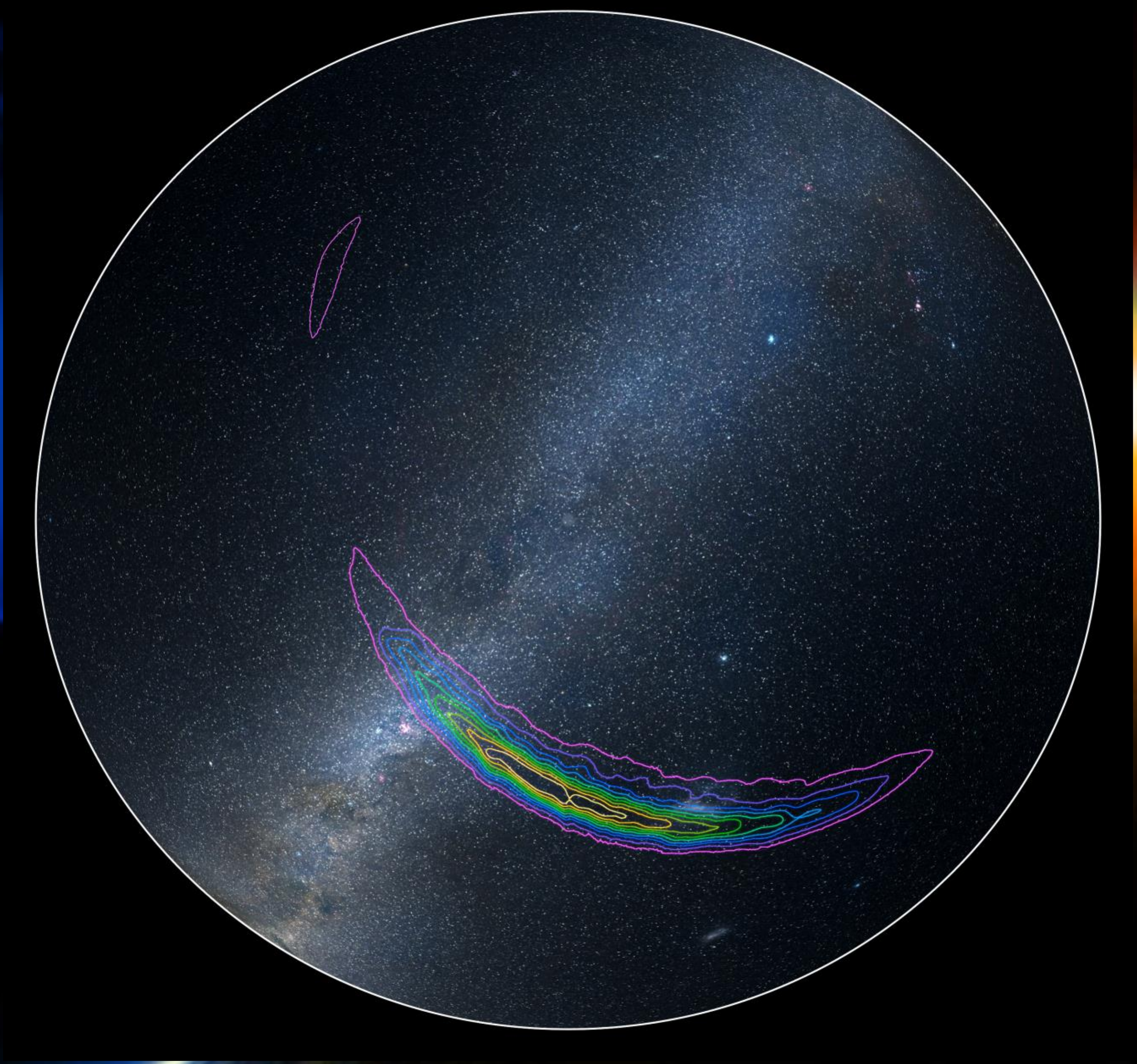
GW150914 statistical significance



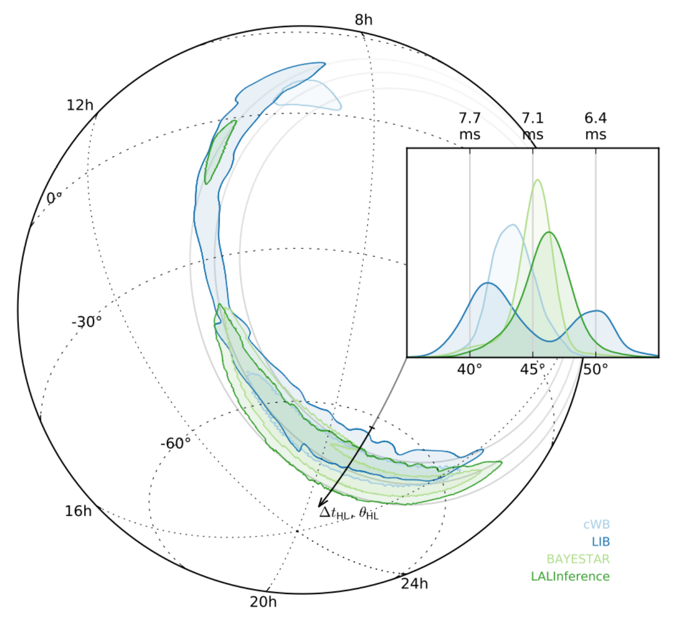
- False alarm rate is less than 1 event per 203,000 years
- A significance of > 5.1 sigma

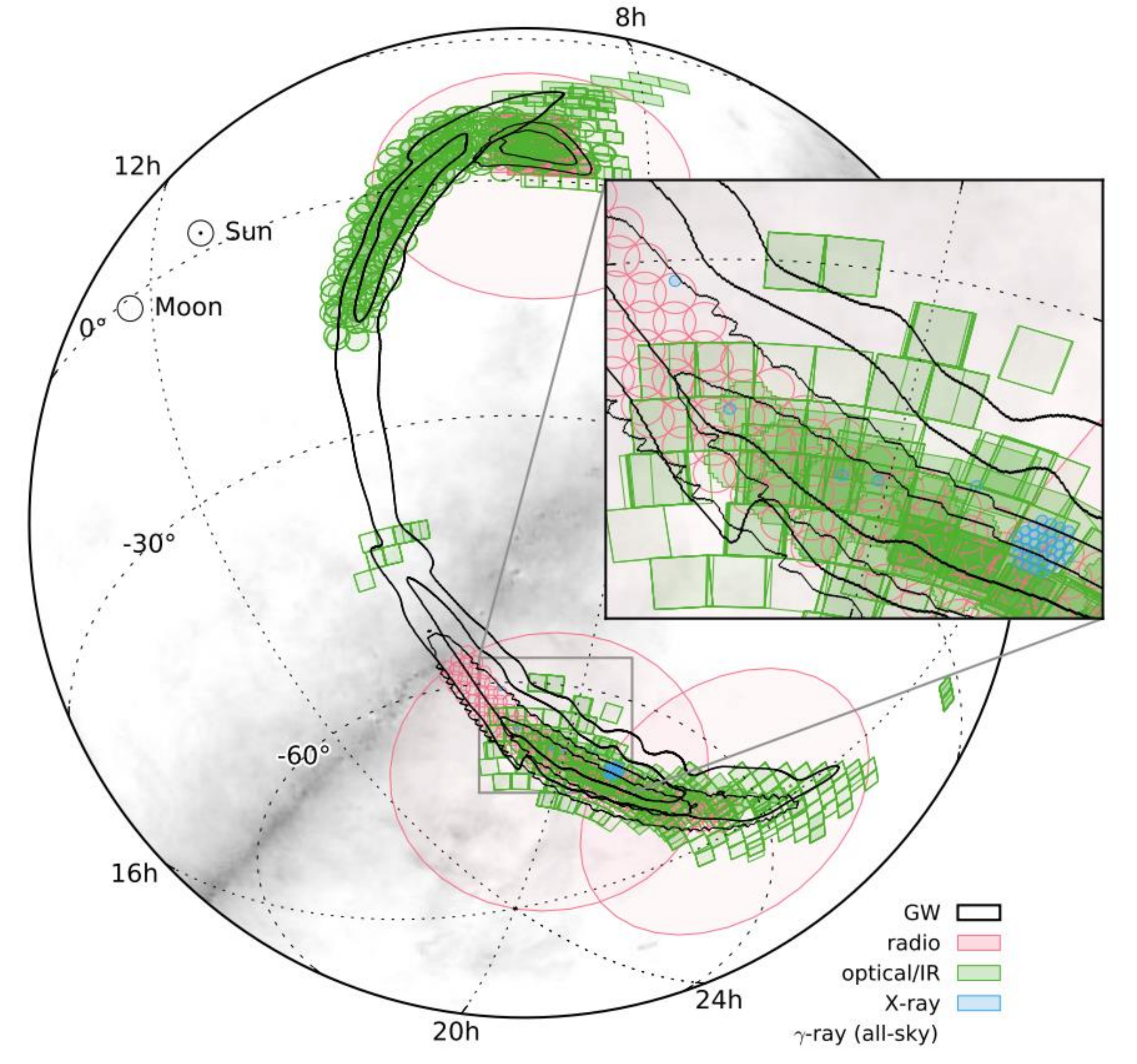
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

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

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Astrophysical implications

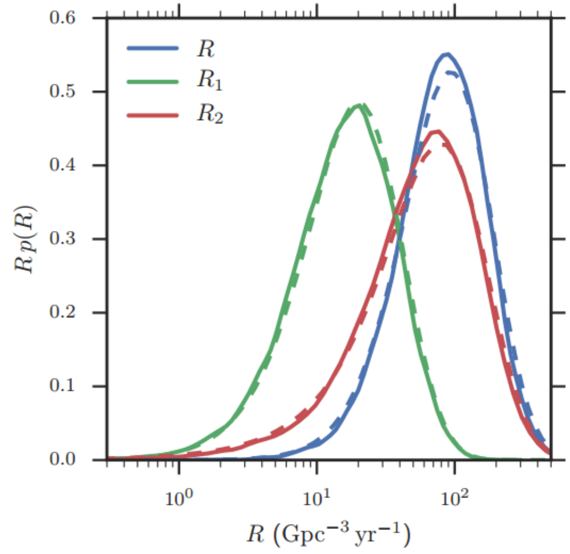
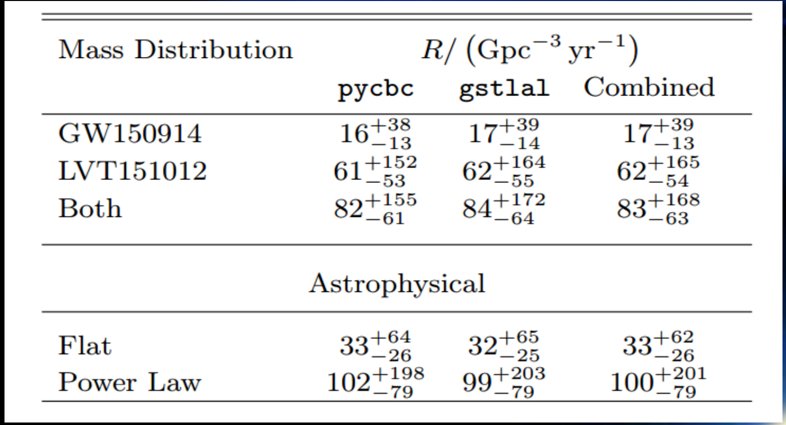
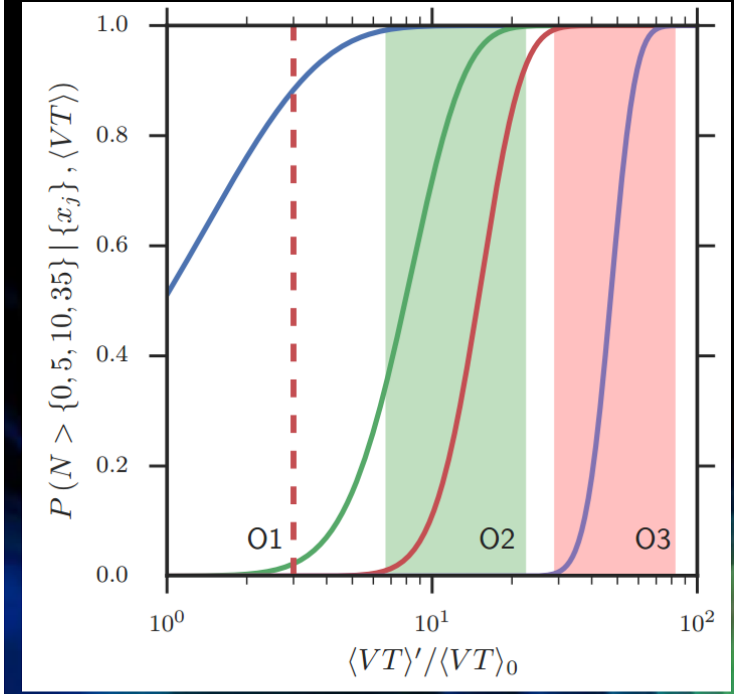


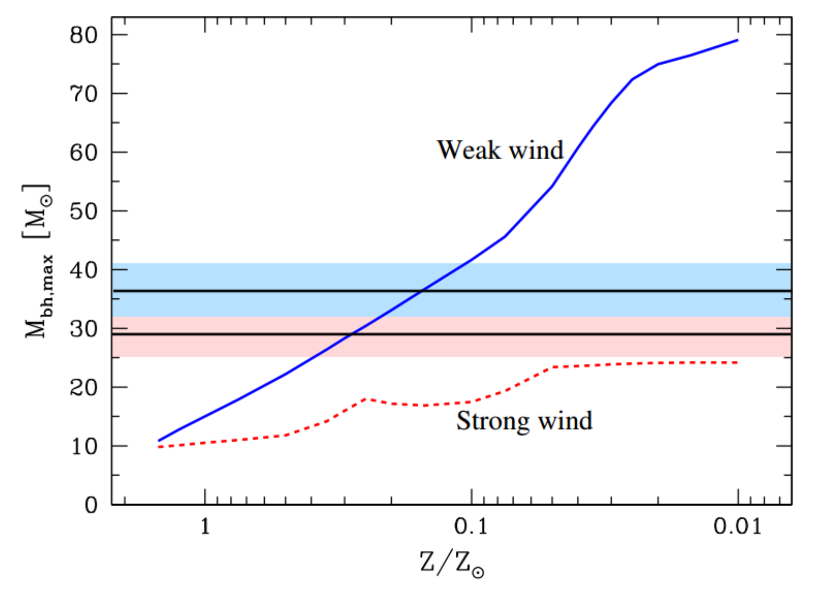
Figure 4. The posterior density on the rate of GW150914-like BBH inspirals, R_1 (green), LVT151012-like BBH inspirals, R_2 (red), and the inferred total rate, $R = R_1 + R_2$ (blue). The median and 90% credible levels are given in Table 1. Solid lines give the rate inferred from the `pycbc` trigger set,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

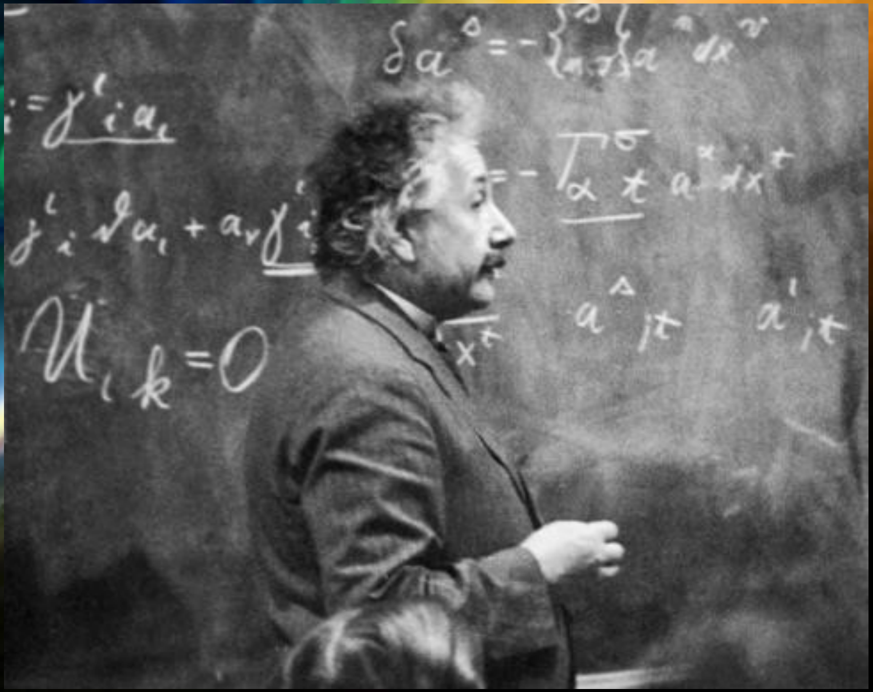




B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) ApJL, 818, L22, 2016

General Relativity tests

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

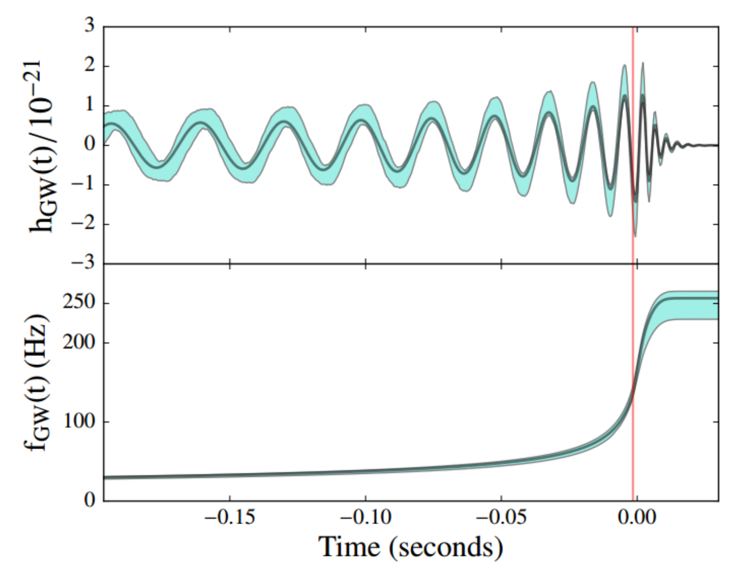


IMR consistency tests

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

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

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



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841
LIGO Document G1600940-v1

IMR consistency tests

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

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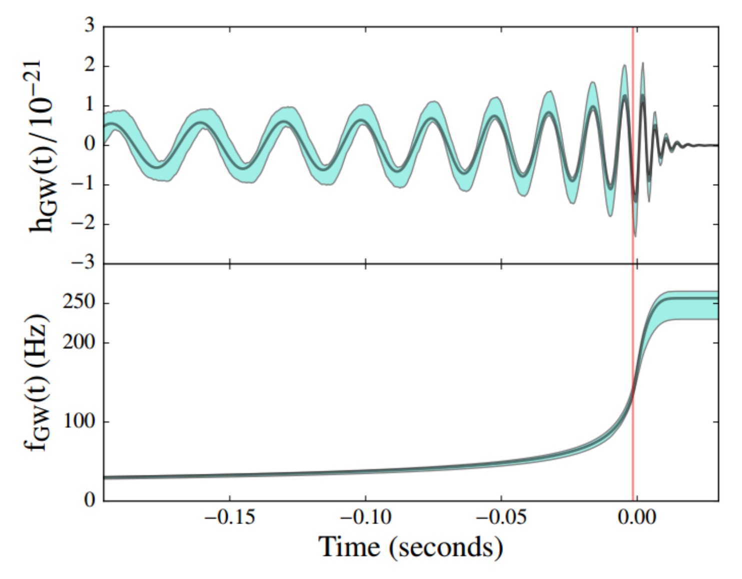


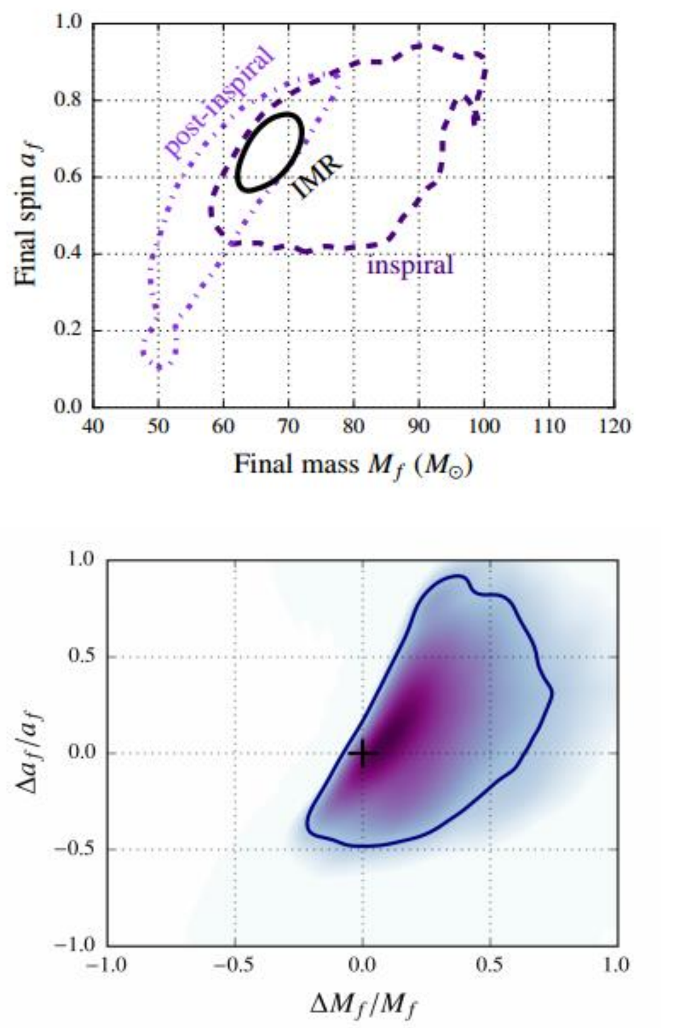


FIG. 3. *Top panel*: 90% confidence regions on the joint posterior distributions for the mass M_f and dimensionless spin a_f of the final compact object predicted from the inspiral (dark violet, dashed) and measured from the post-inspiral (violet, dot-dashed), as well as the result from a full inspiral-merger-ringdown (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 G1600940-v1

QNM tests

Can we probe the event horizon from the ringdown?

QNM tests

Can we probe the event horizon from the ringdown?

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

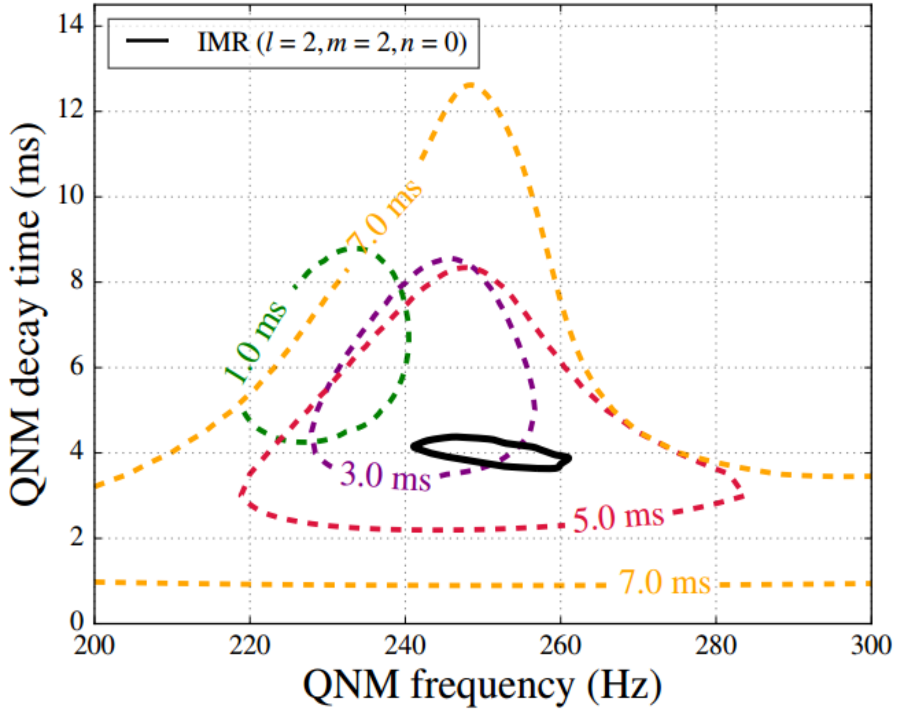
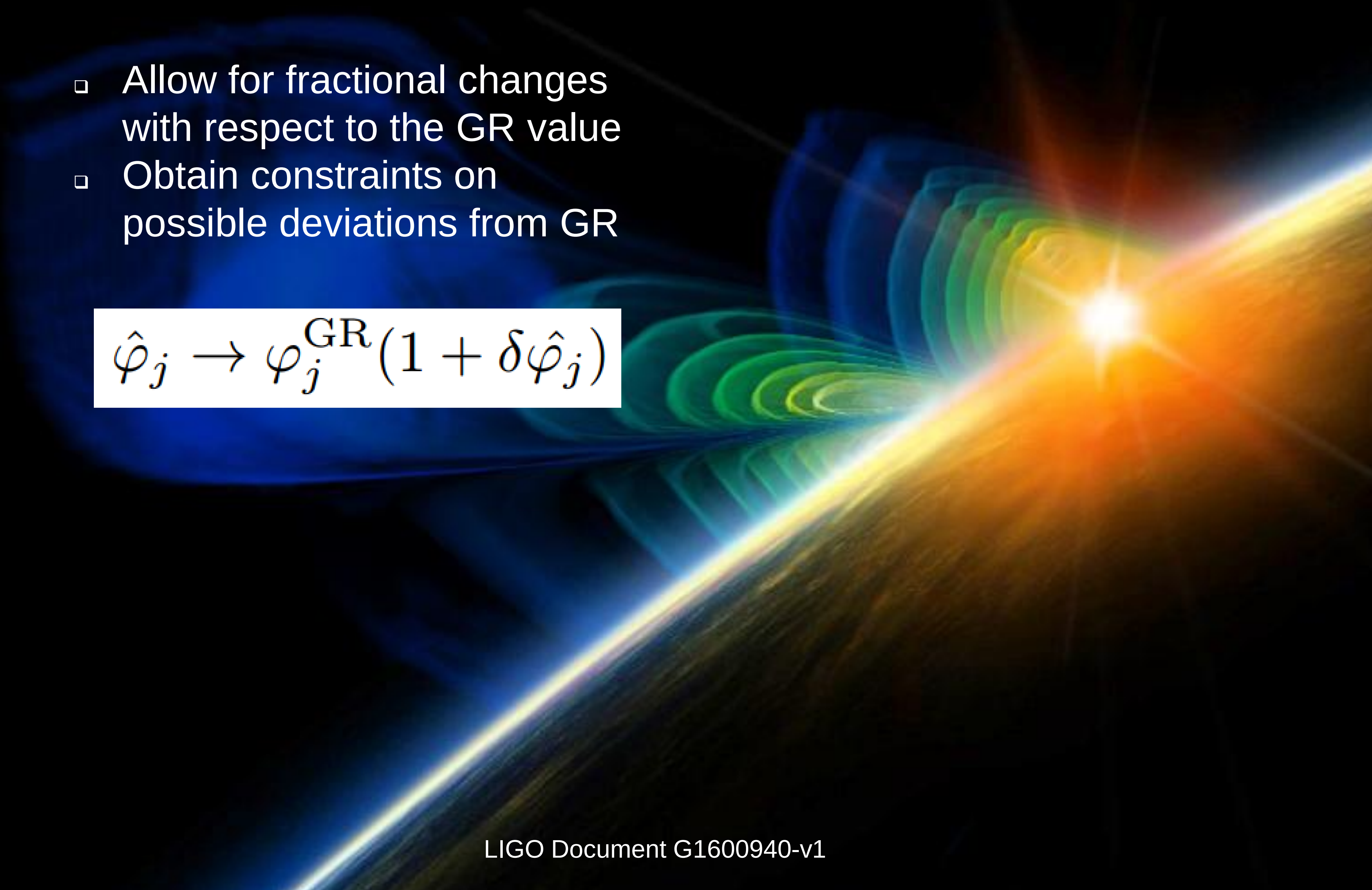


FIG. 4. We show the posterior 90% confidence regions from Bayesian parameter estimation for a damped-sinusoid model, assuming different start-times $t_0 = t_M + 1, 3, 5, 7$ ms, labeled by offset from the merger time $t_{\rm M}$ of the most-probable waveform from GW150914. The black solid line shows contours 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) Phys.Rev.Lett. 116 (2016) no.22, 221101

Deviations from GR waveforms



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

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

Deviations from GR waveforms

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

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

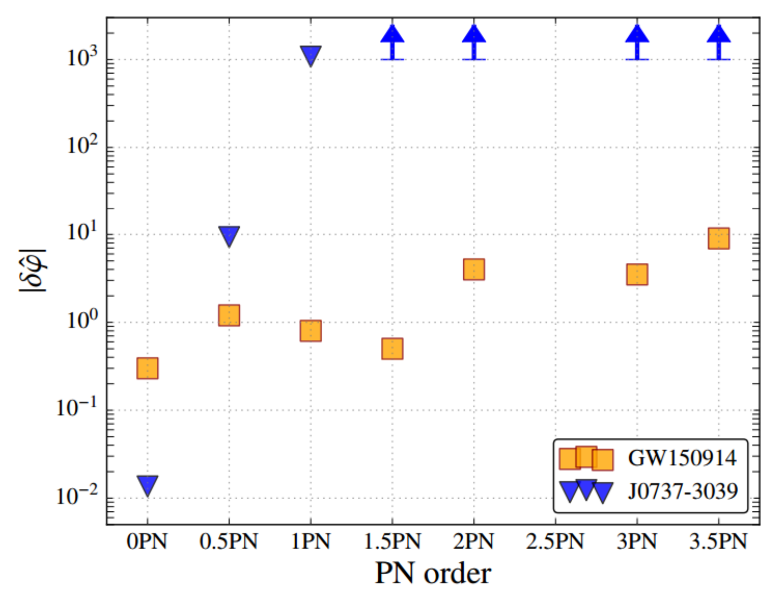
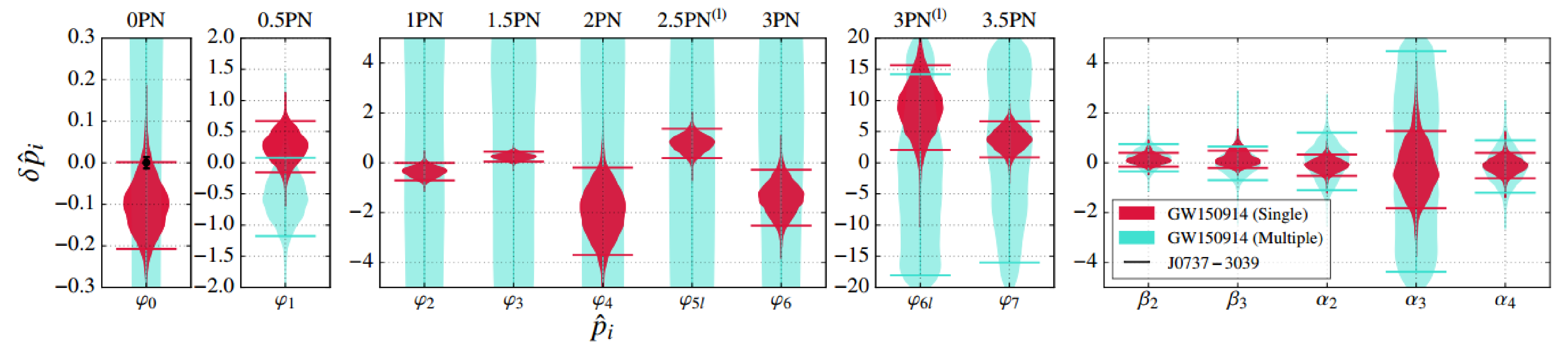


FIG. 6. 90% upper bounds on the fractional variations for the known PN coefficients compared to their known value in GR.



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys.Rev.Lett. 116 (2016) no.22, 221101

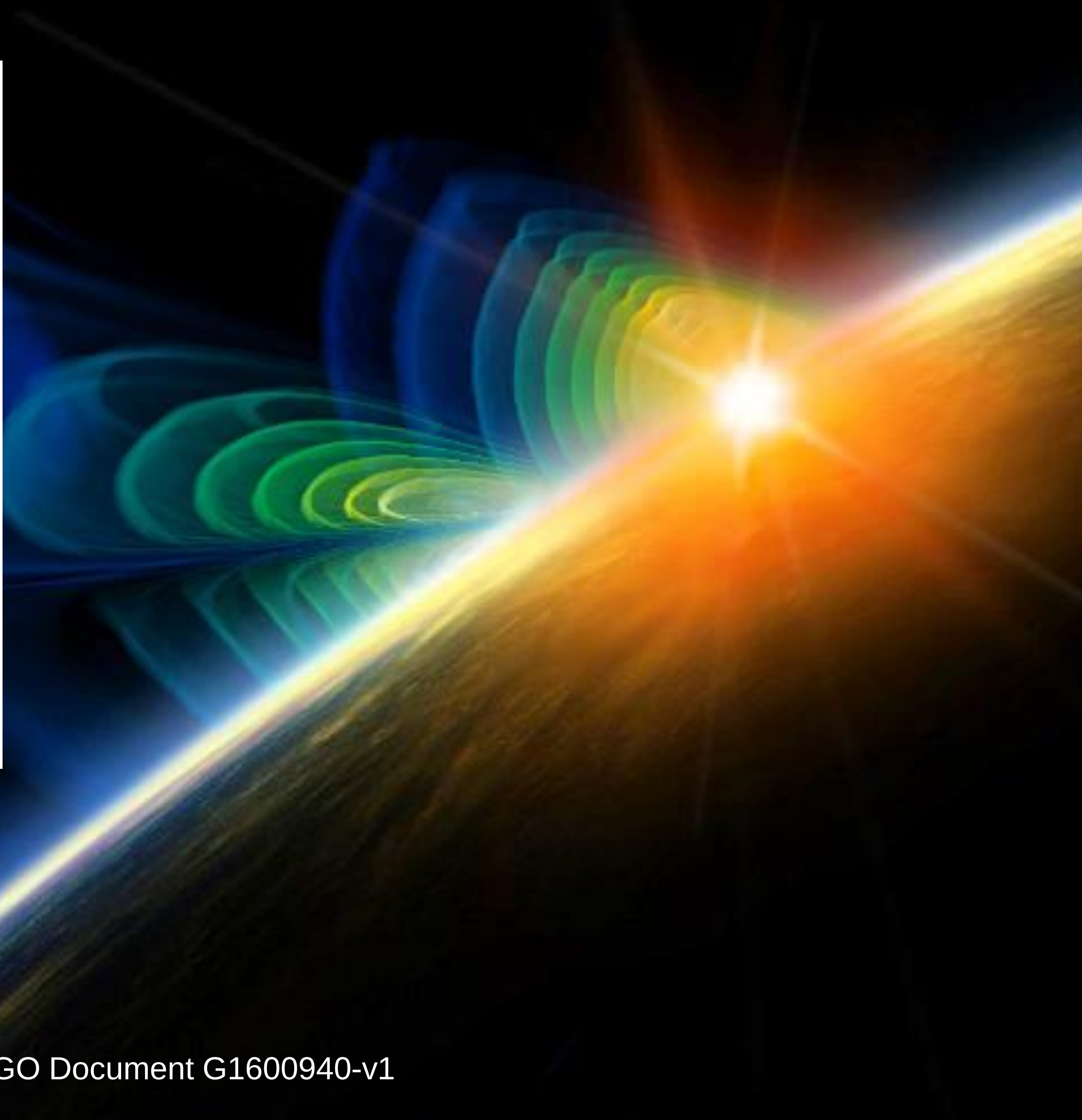
Graviton Compton length

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

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

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

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



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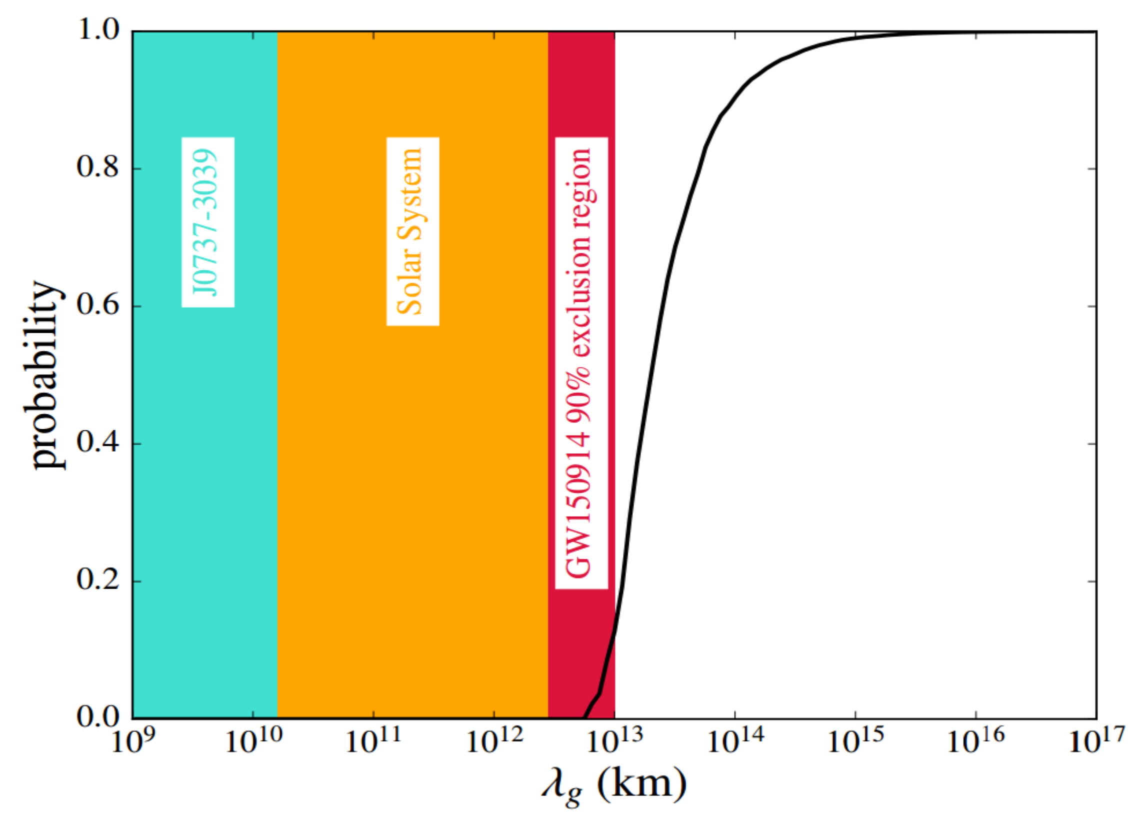
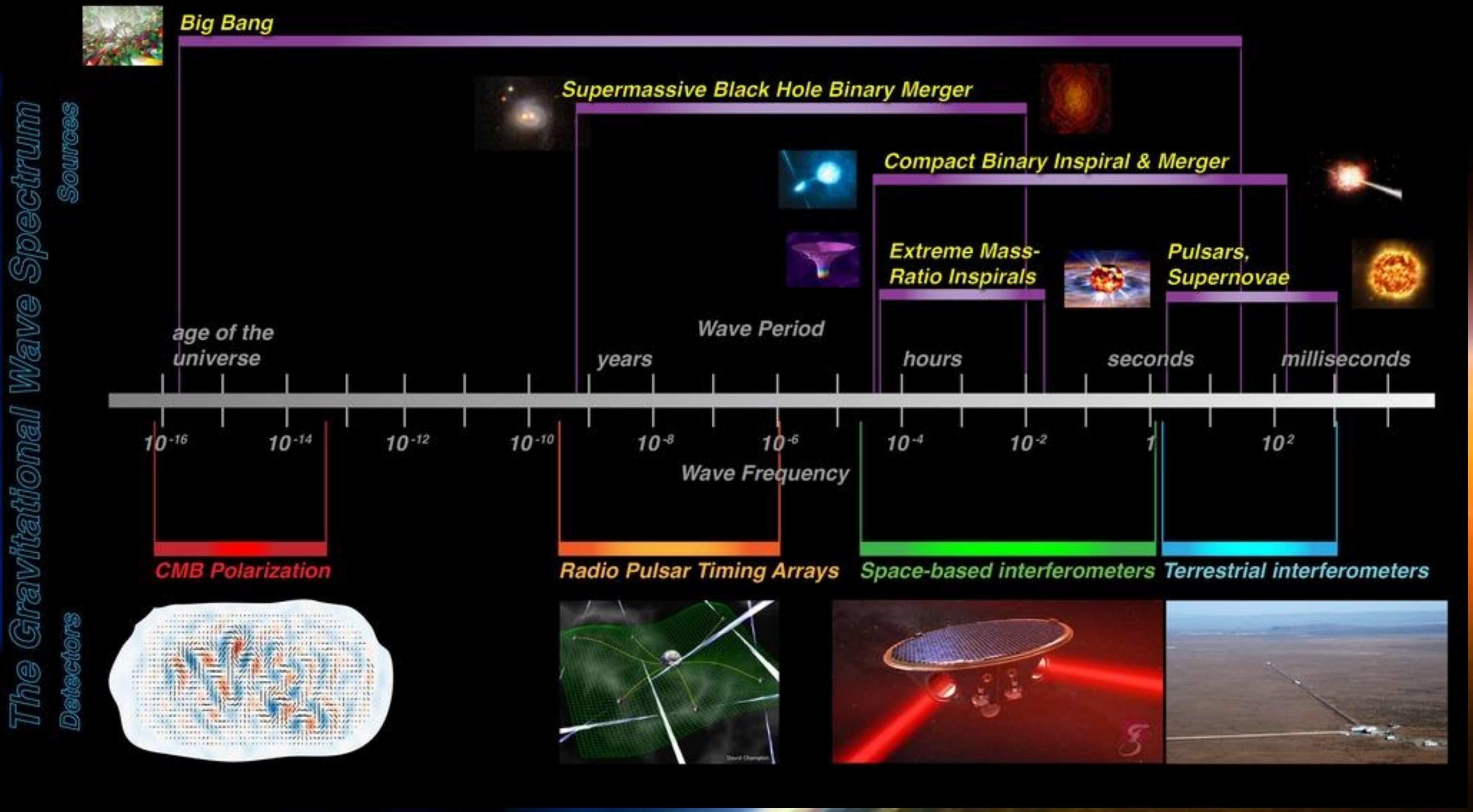


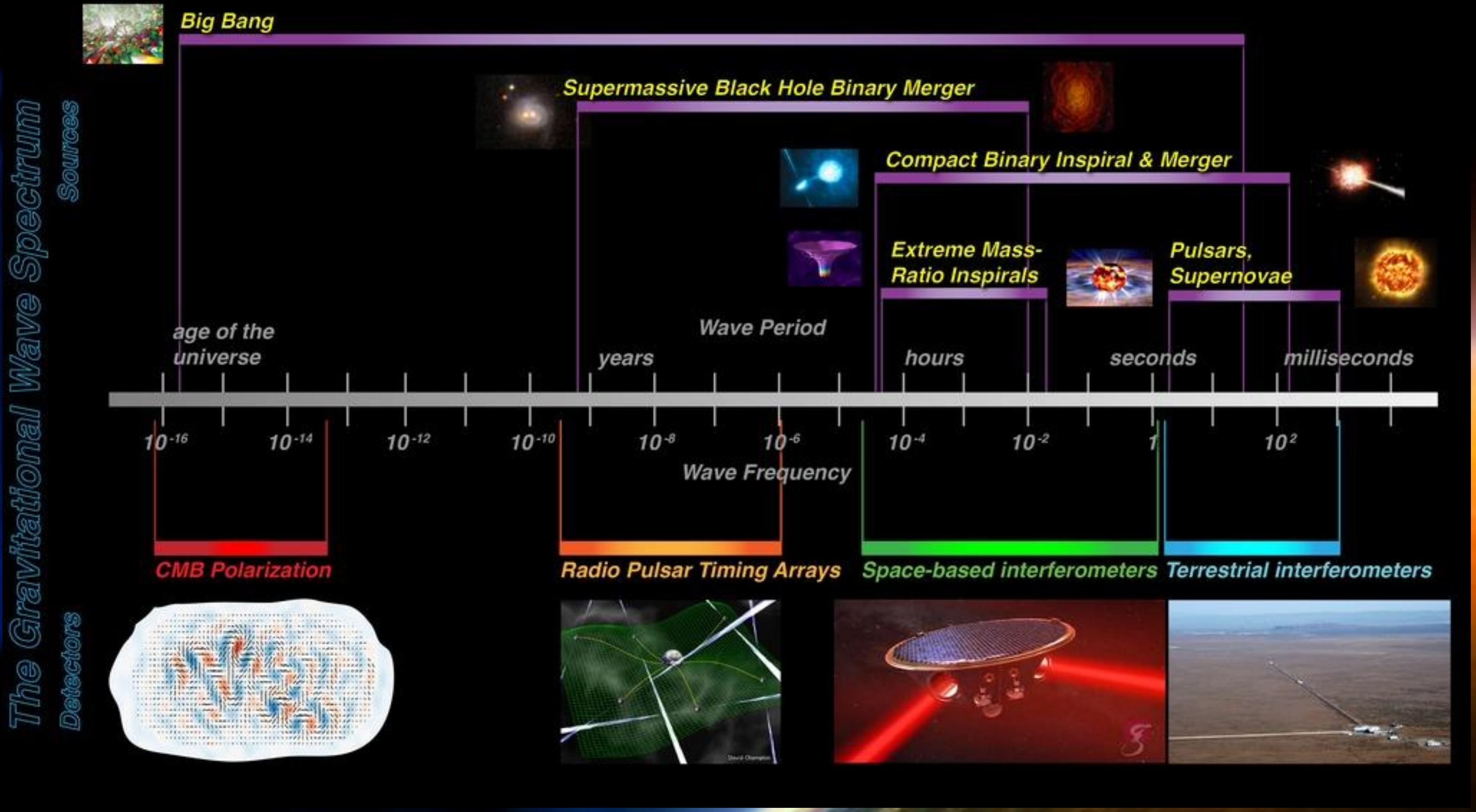
Limit on graviton mass: $m_g \leq 1.2 \times 10^{-22}$ eV/c^2

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys.Rev.Lett. 116 (2016) no.22, 221101

LIGO has opened a new window on the universe



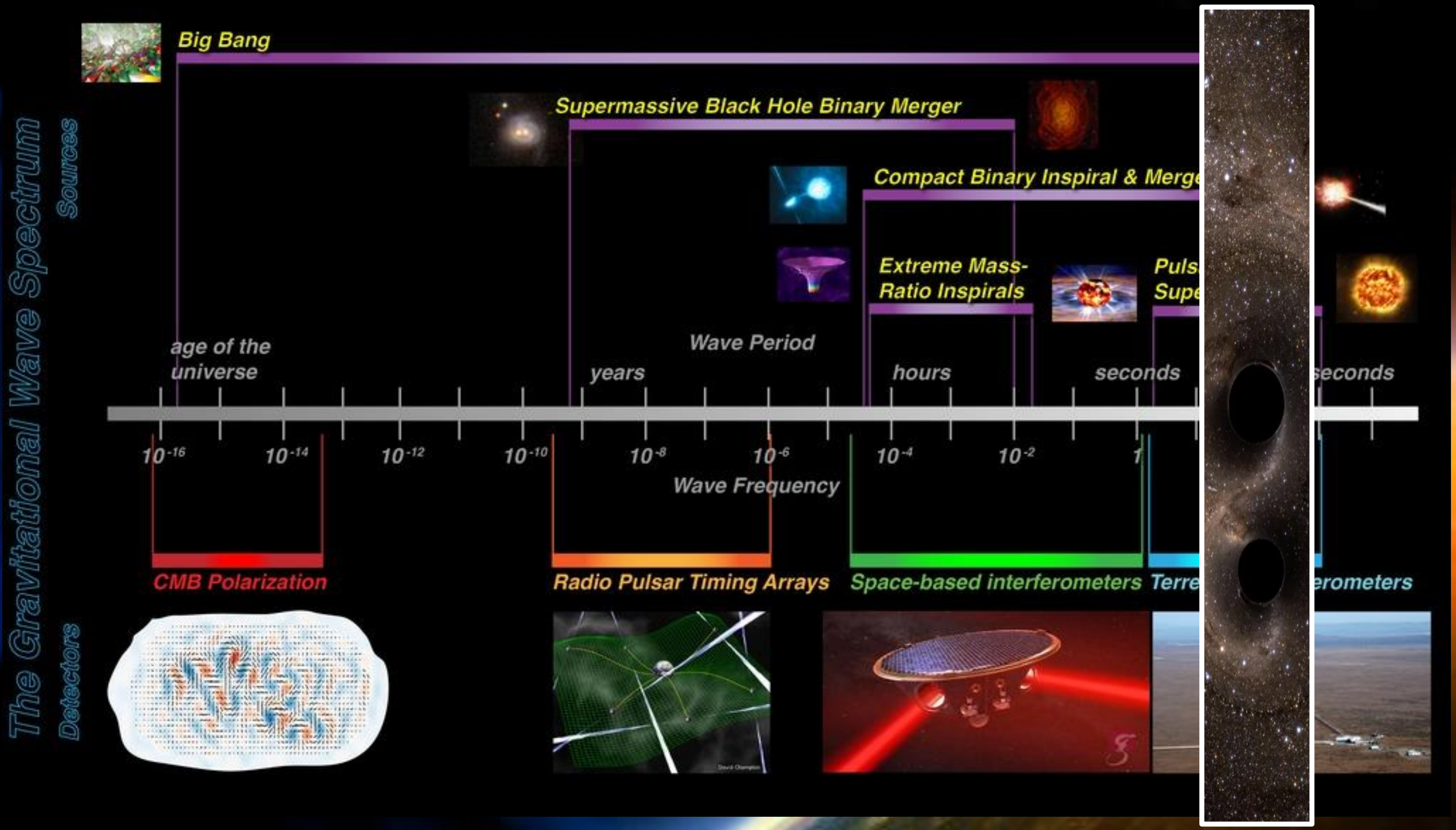
LIGO has opened a new window on the universe



In the next 5 years, it is likely we will have:

- Hundreds of compact binary coalescence and other source detections
- SNR ~ 100 (GW150914 is ~ 24)
- Observation of fine details of these systems (number, distances, masses, spins, EoS, environment...)

LIGO has opened a new window on the universe



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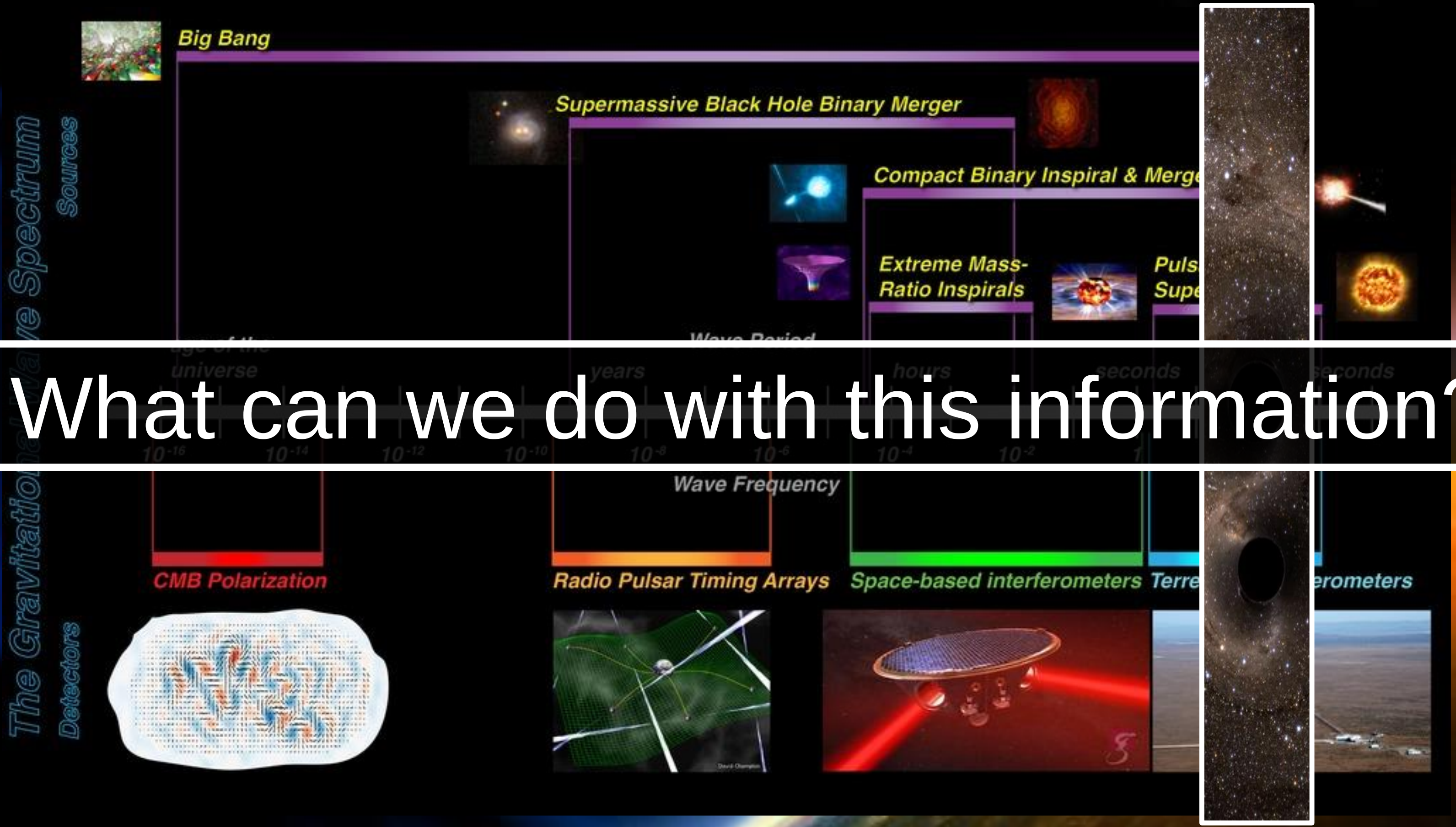

What can we do with this information?

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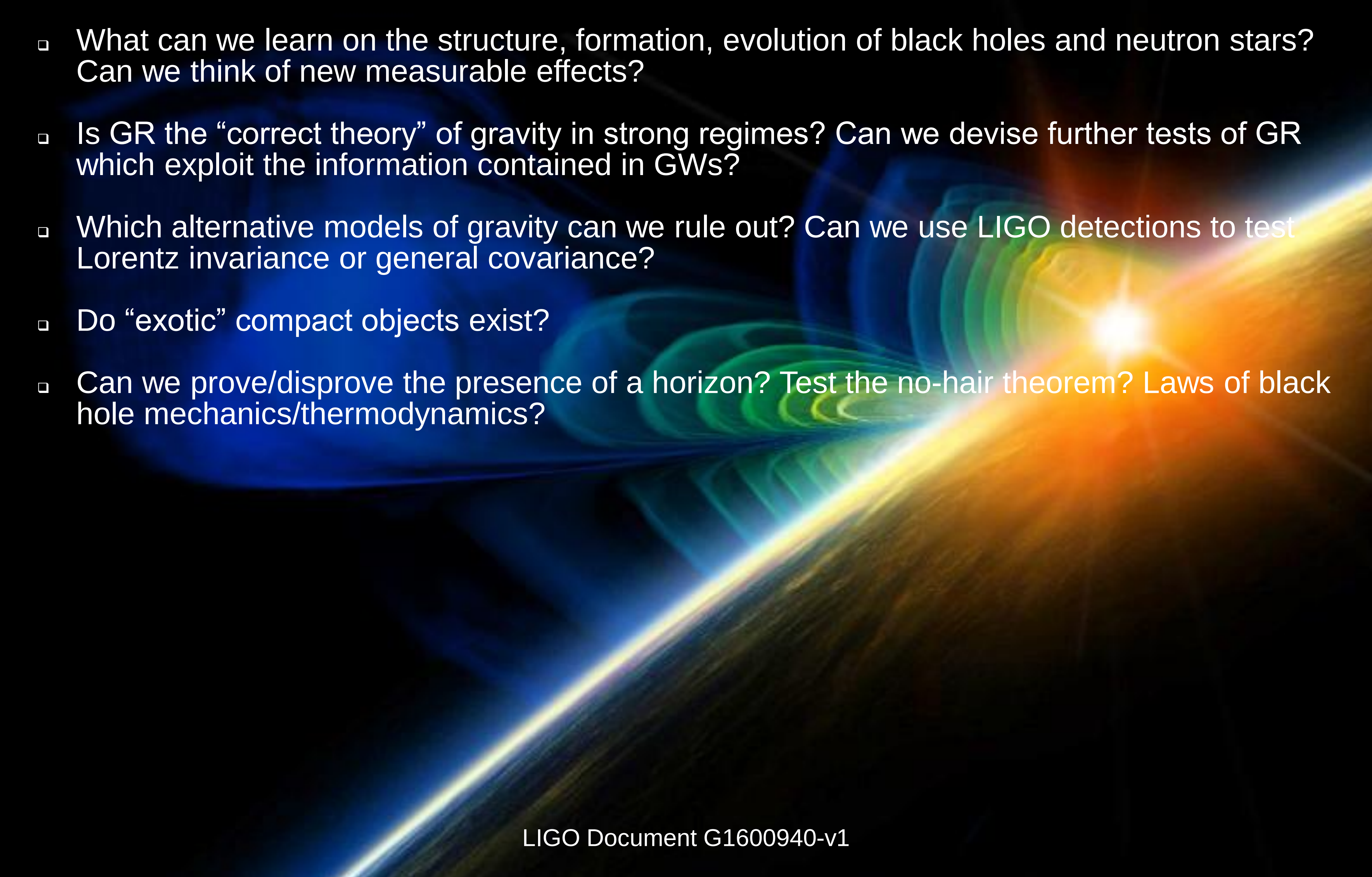

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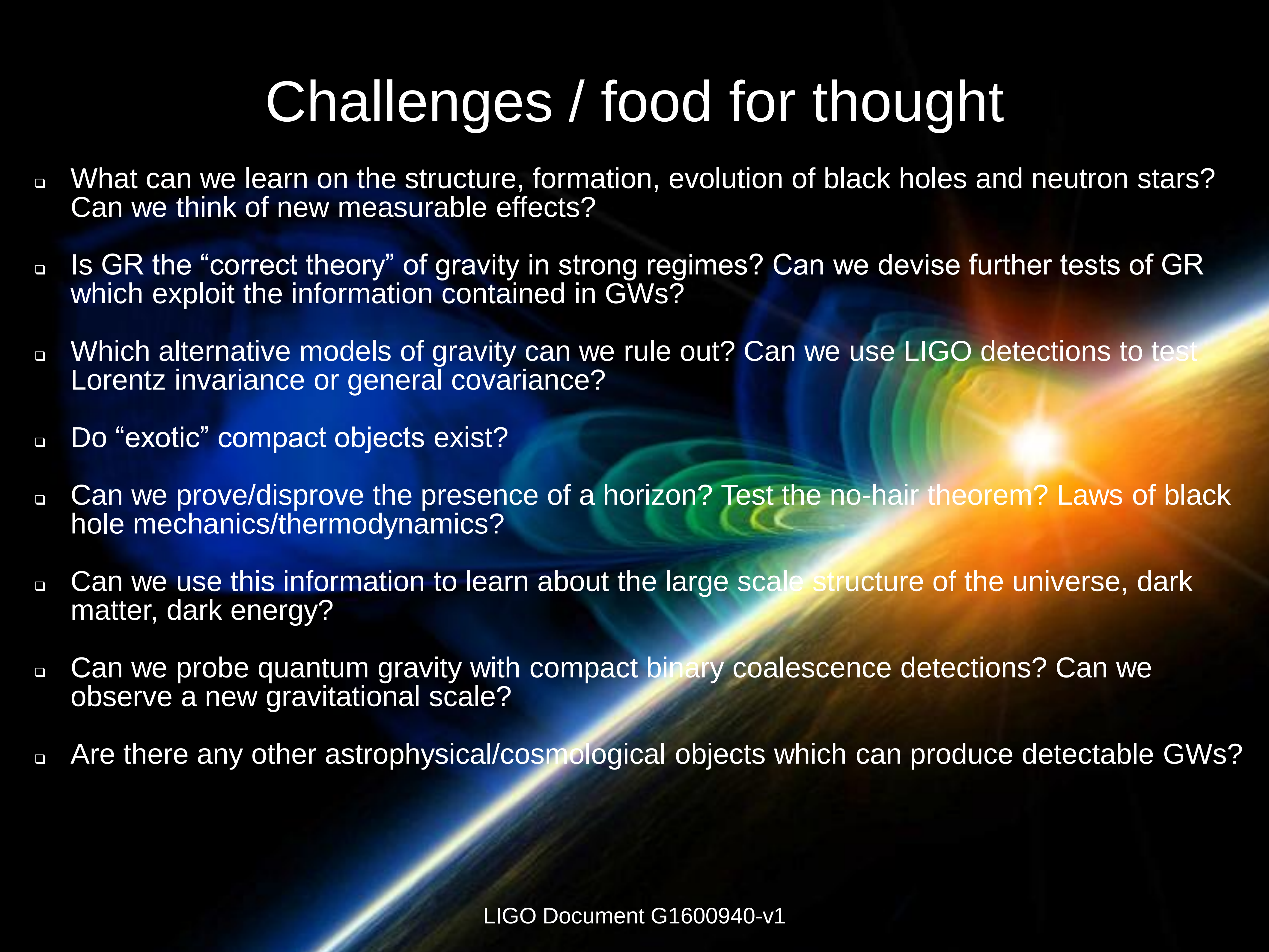

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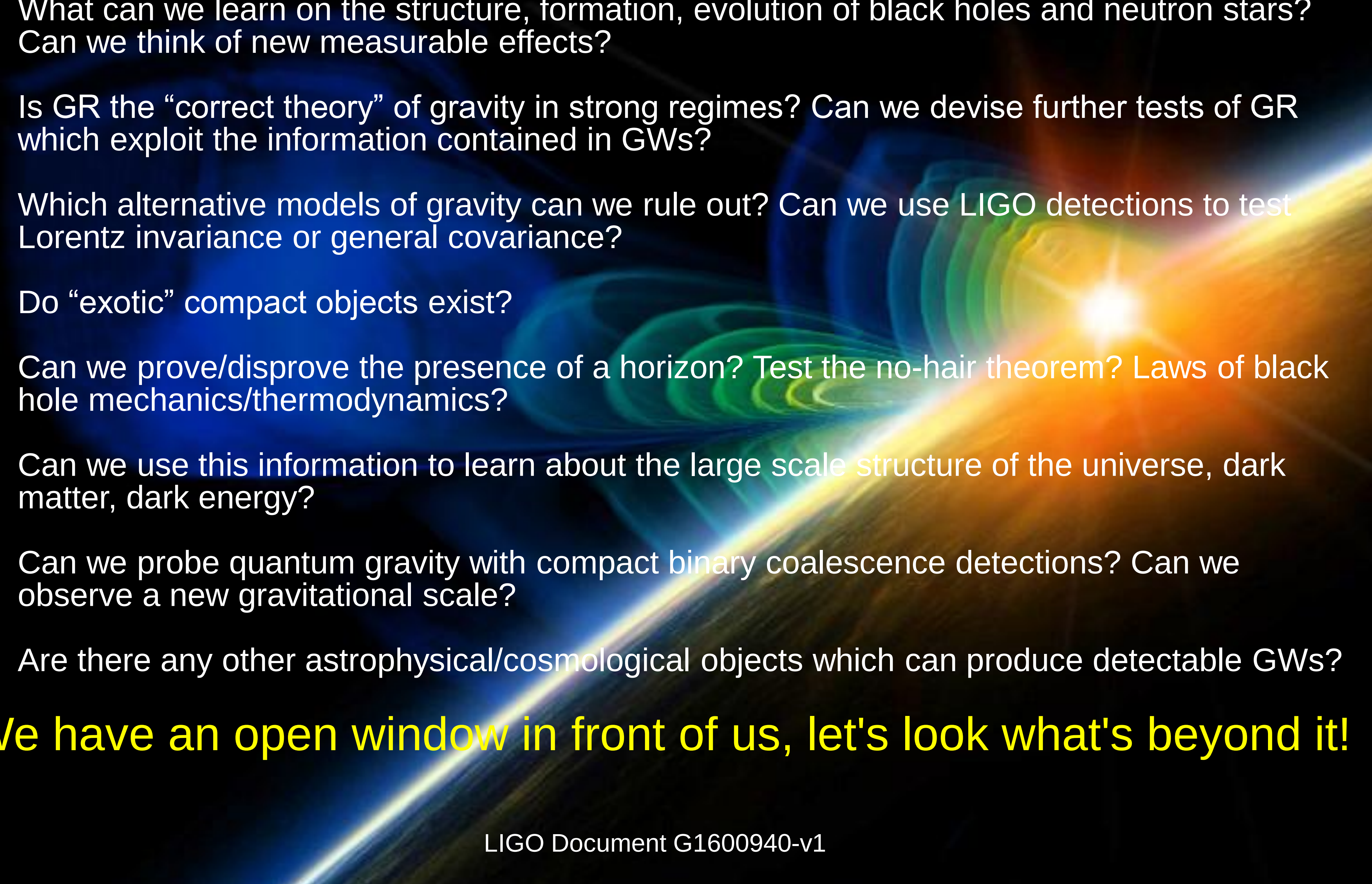

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We have an open window in front of us, let's look what's beyond it!