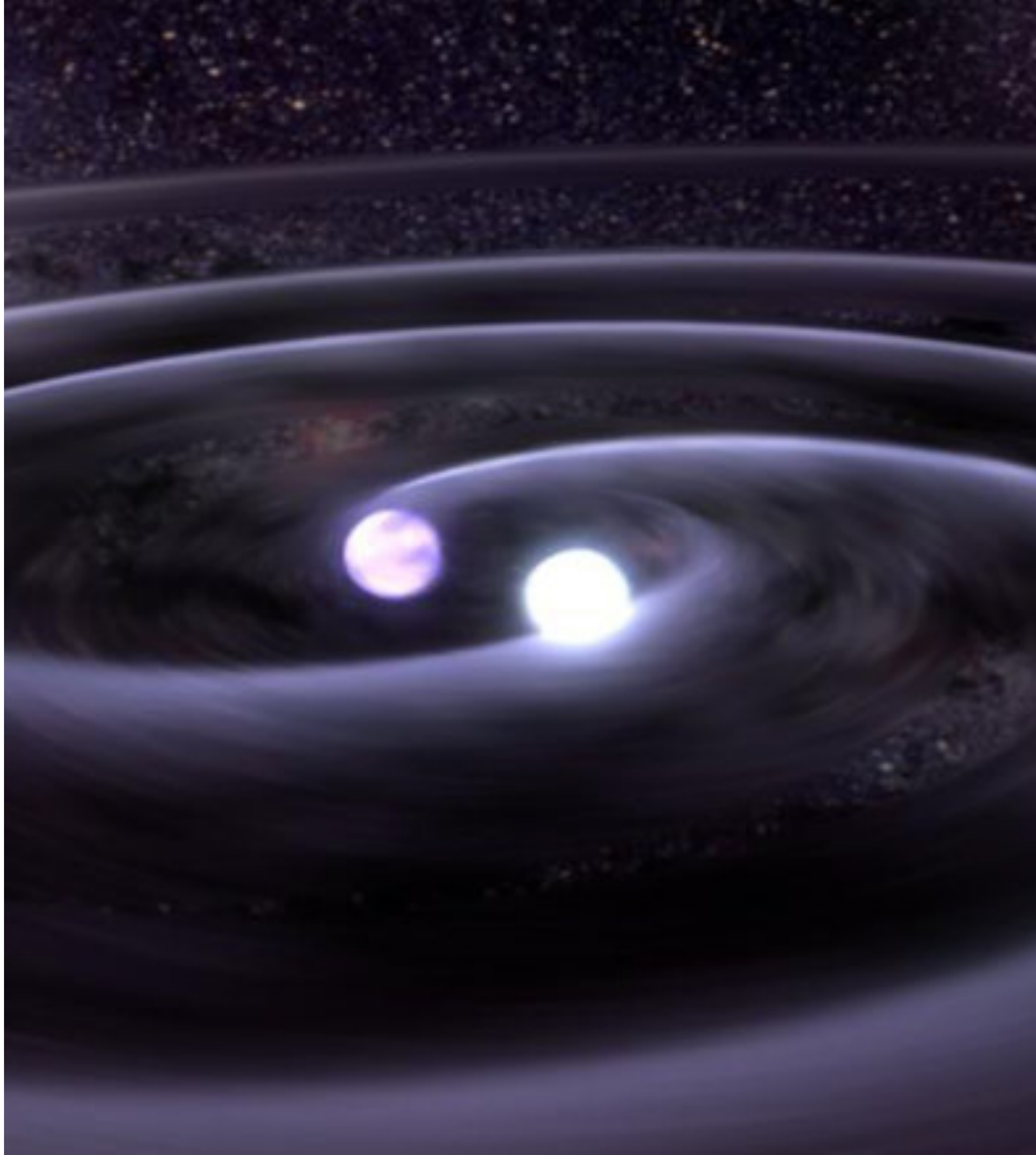
PHY 4905 | Modern Astrophysics

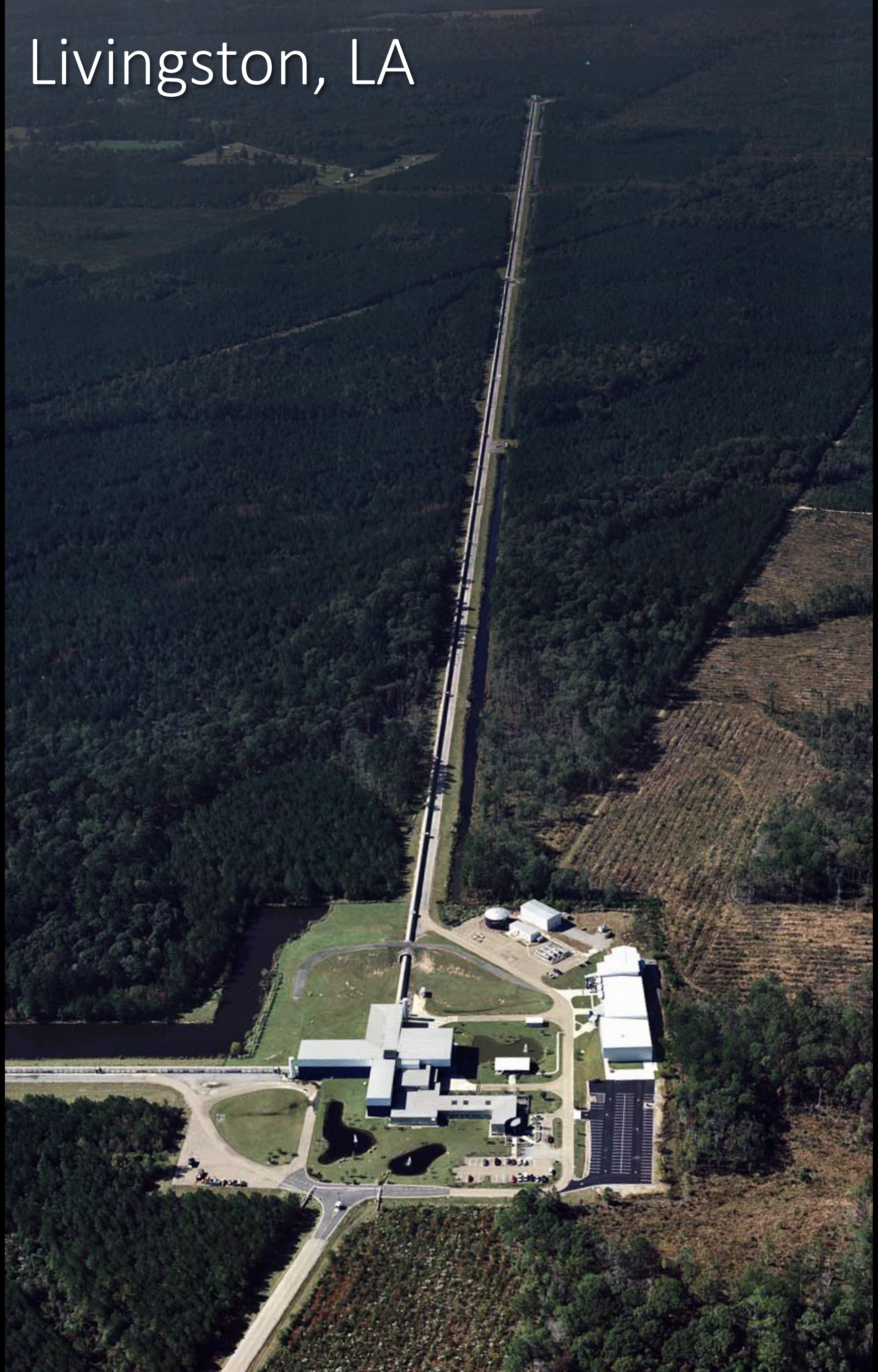
Lecture XXXV.

Gravitational Waves

UNIVERSITY of FLORIDA

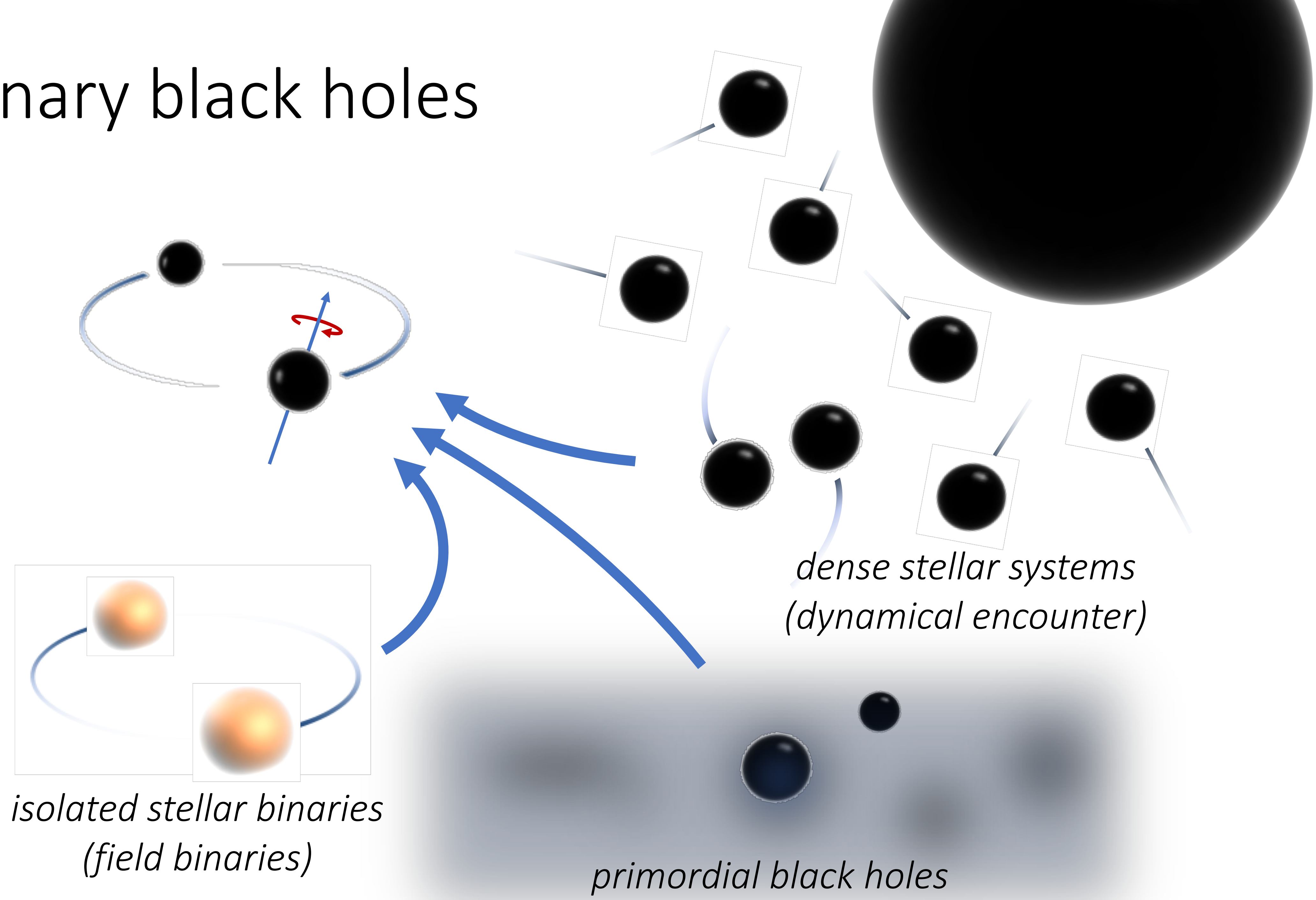
Imre Bartos | Fall 2018



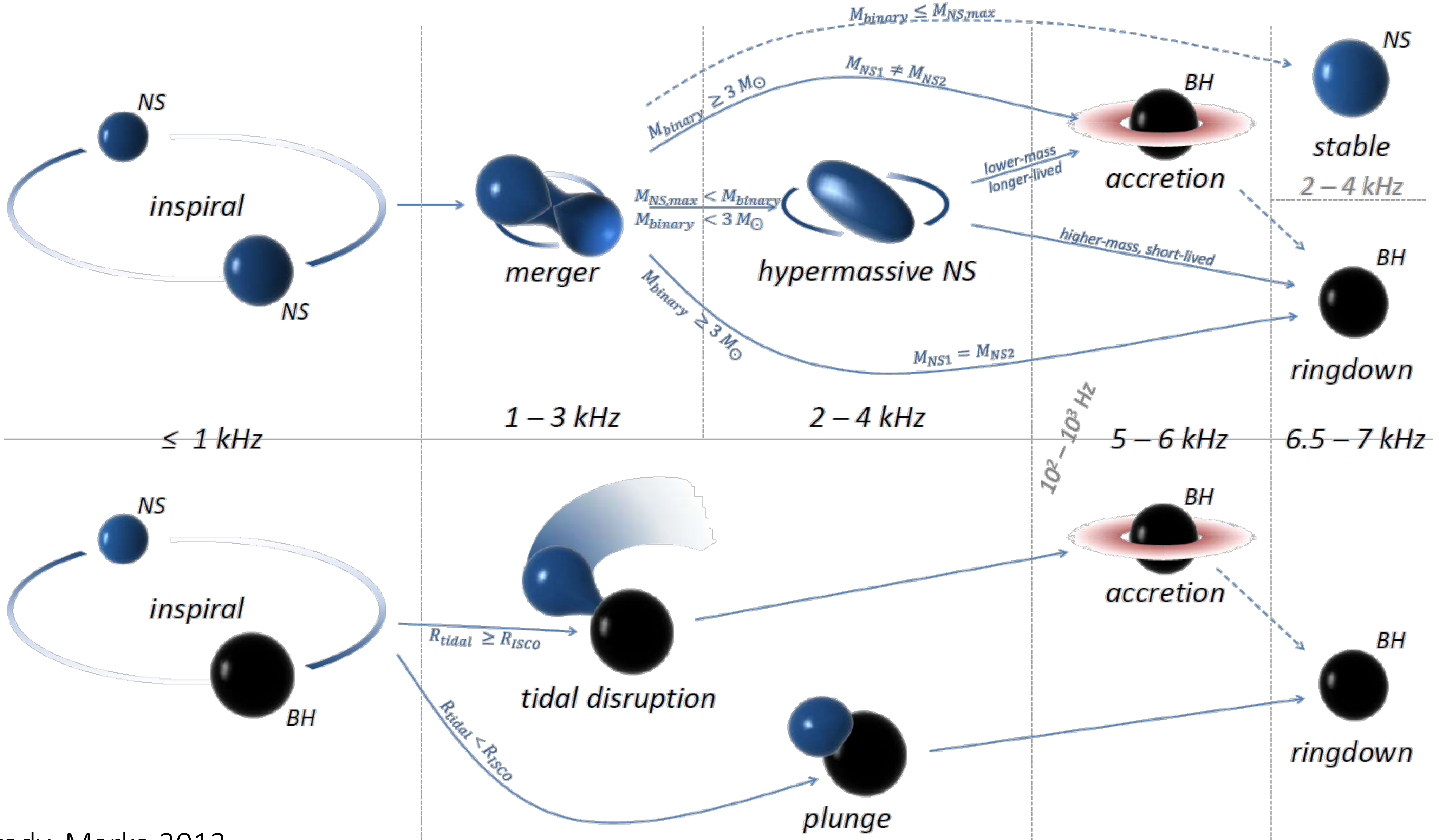


Credit: LIGO

binary black holes



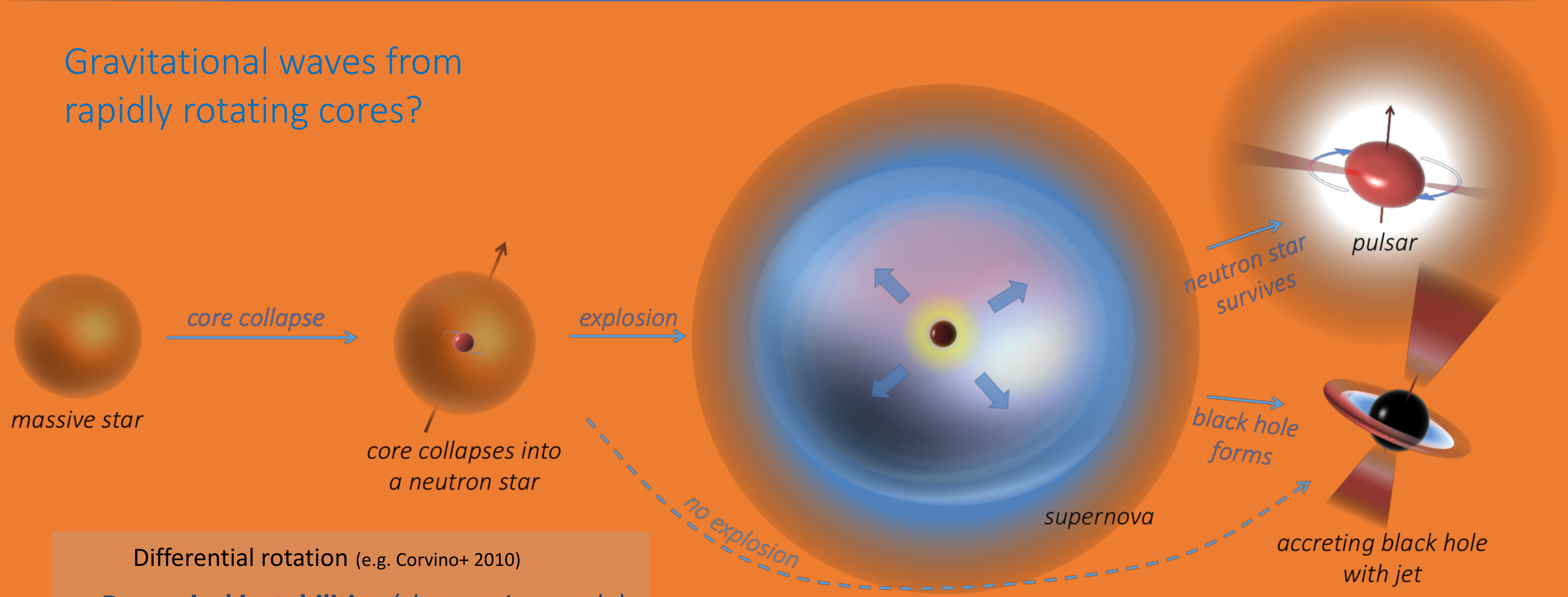
progenitor: neutron star mergers



Bartos, Brady, Marka 2013

Stellar core collapse

Gravitational waves from rapidly rotating cores?



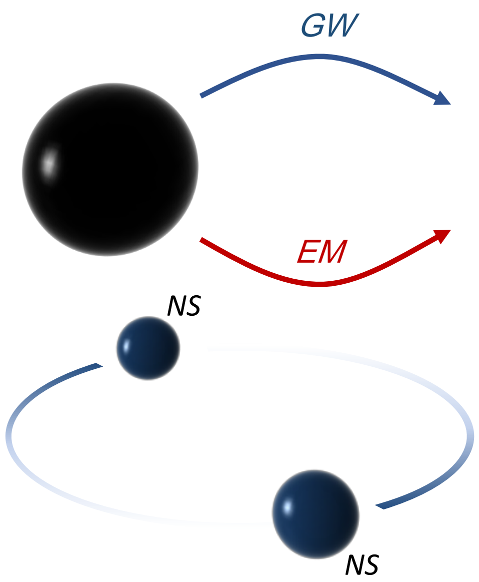
Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

Fallback accretion? *(Piro & Thrane, 2012)*

Science targets

Fundamental physics

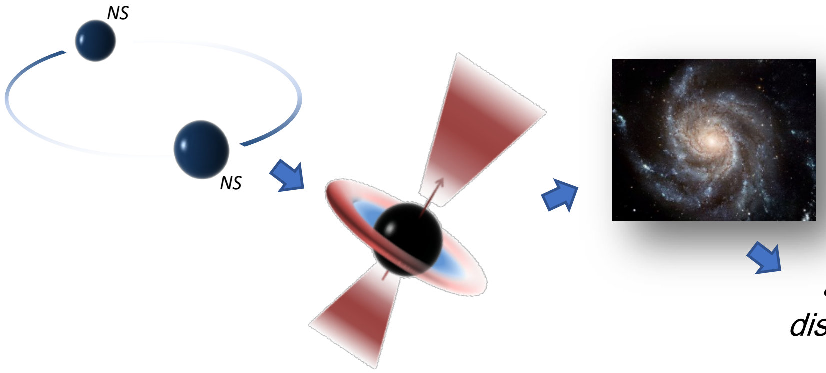


speed of gravity

tests of general relativity

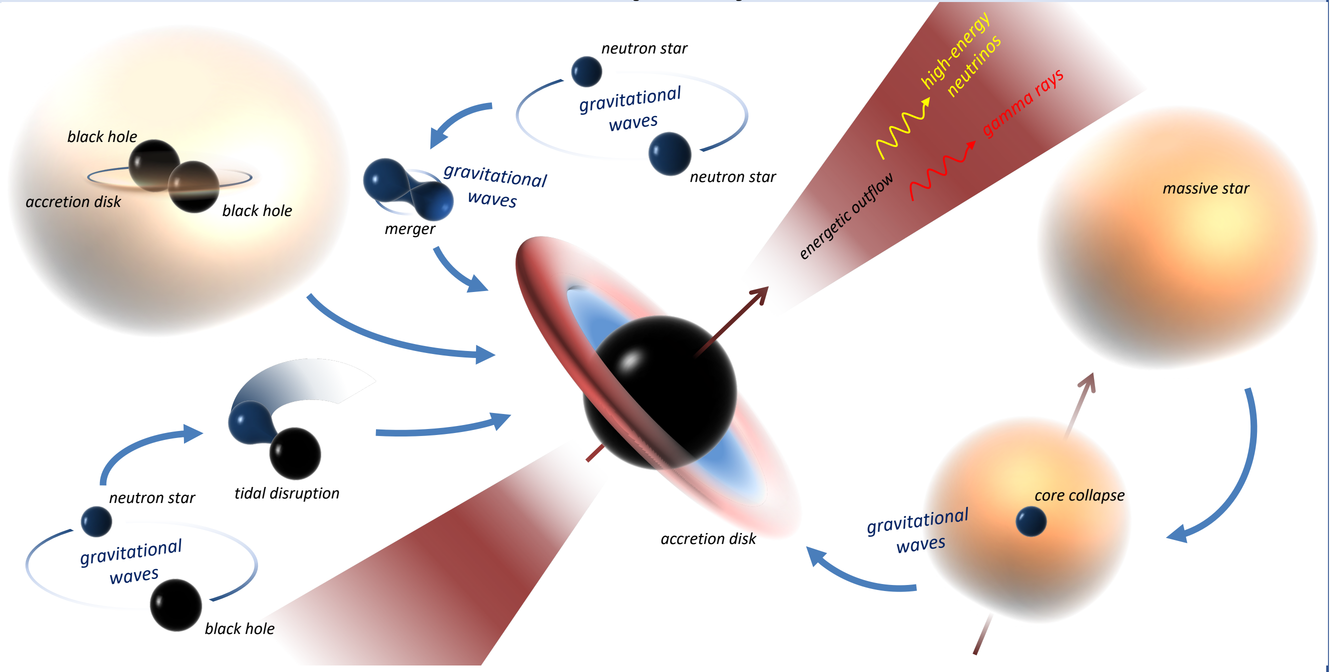
equation of state
of supranuclear matter

Cosmology



alternative
distance ladder

Astrophysics



- *Black hole accretion*
- *Cosmic particle acceleration*
- *Stellar core collapse*
- *Compact binary formation channels*
- *Intermediate mass black holes*
- *Origin of heavy elements*
- *Environment in galactic nuclei*
- *Relativistic outflows*
- *…*

Search for gravitational waves

Rotating source:

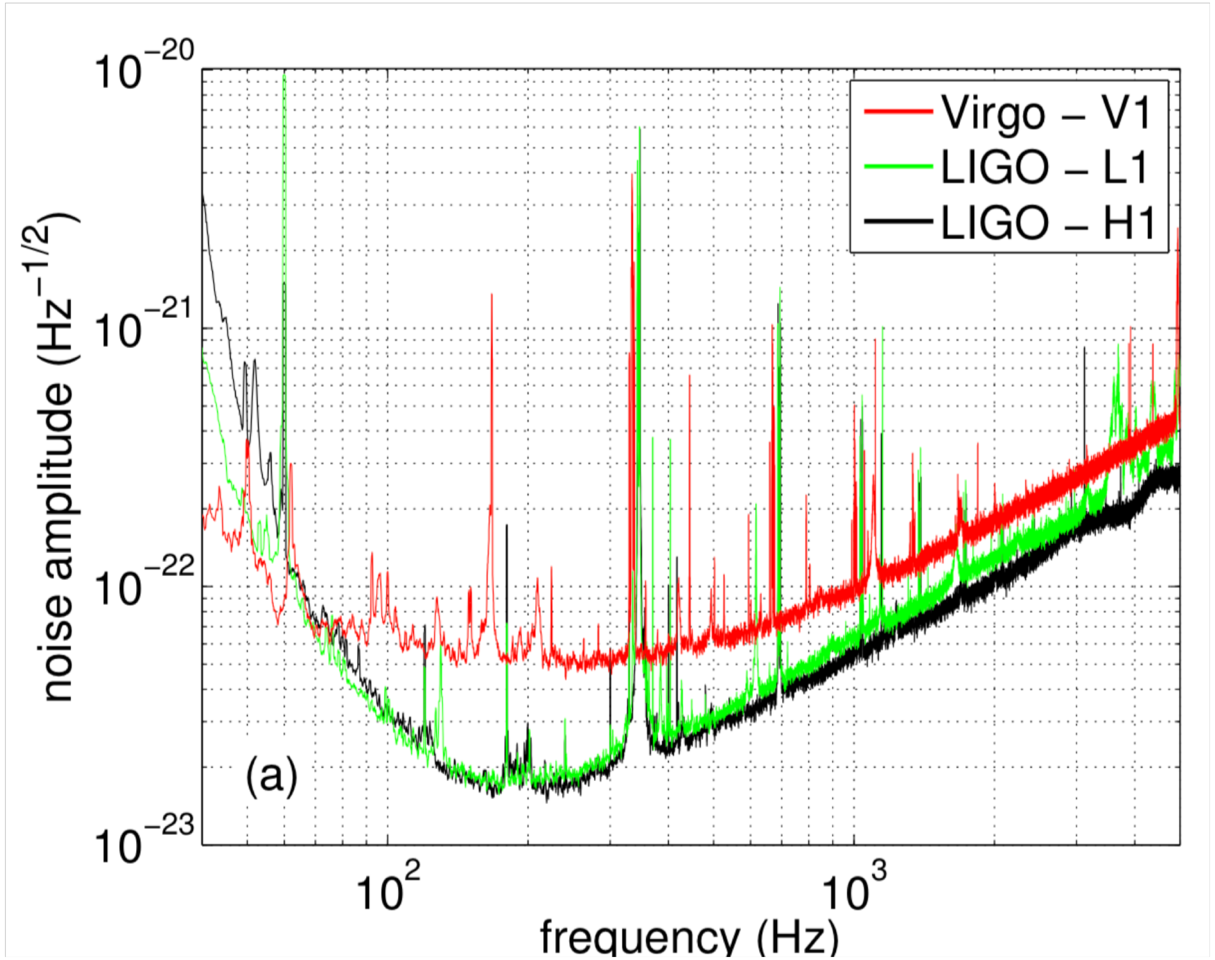
$$h_+(t) = \frac{1}{2}(1+\cos^2(\iota))\,A(t)\cos\Phi(t)$$
$$h_\times(t) = \cos(\iota)\,A(t)\sin\Phi(t)\,,$$

Root-sum-square amplitude:

$$h_{\rm rss} = \int_{-\infty}^{\infty} dt\,\left[h_+^2(t) + h_\times^2(t)\right]$$
$$= 2\int_0^{\infty} df\,\left[|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right]$$

Radiated GW energy:

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} r^2 f_0^2 h_{\rm rss}^2$$



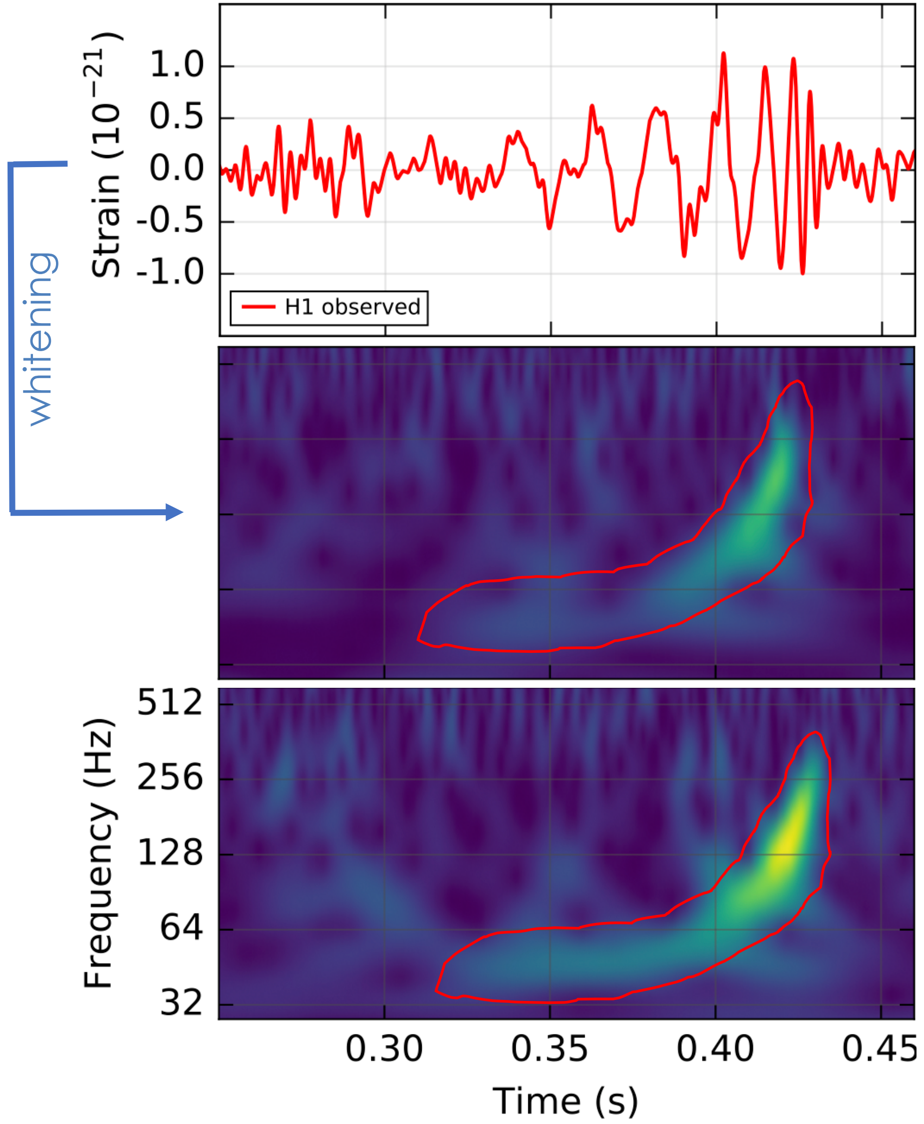
Signal to noise ratio:

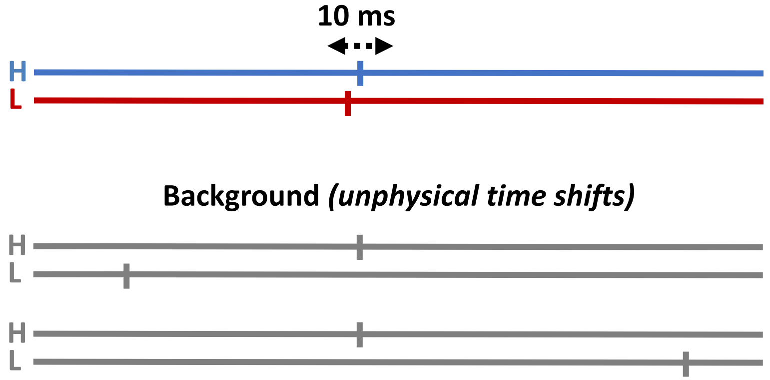
$$\rho^2 = 2\int_{-\infty}^{\infty} df\,\frac{|F_+\tilde{h}_+(f) + F_\times\tilde{h}_\times(f)|^2}{S(f)}$$

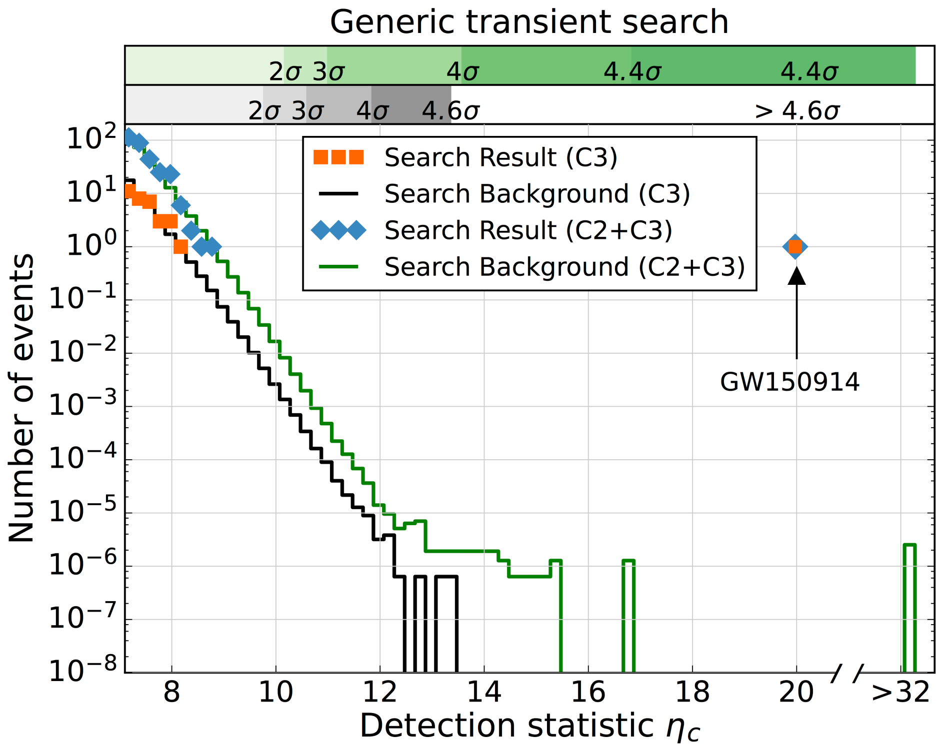
Gravitational wave sources and searches

1. Transient, unmodeled (e.g. supernova) Prof. Klimenko
2. Transient, modeled (e.g. binary black hole merger) (Prof. Klimenko)
3. Continuous (e.g. deformed rotating neutron star)
4. Stochastic (e.g. many distant events that are individually unresolvable)

Generic transient search

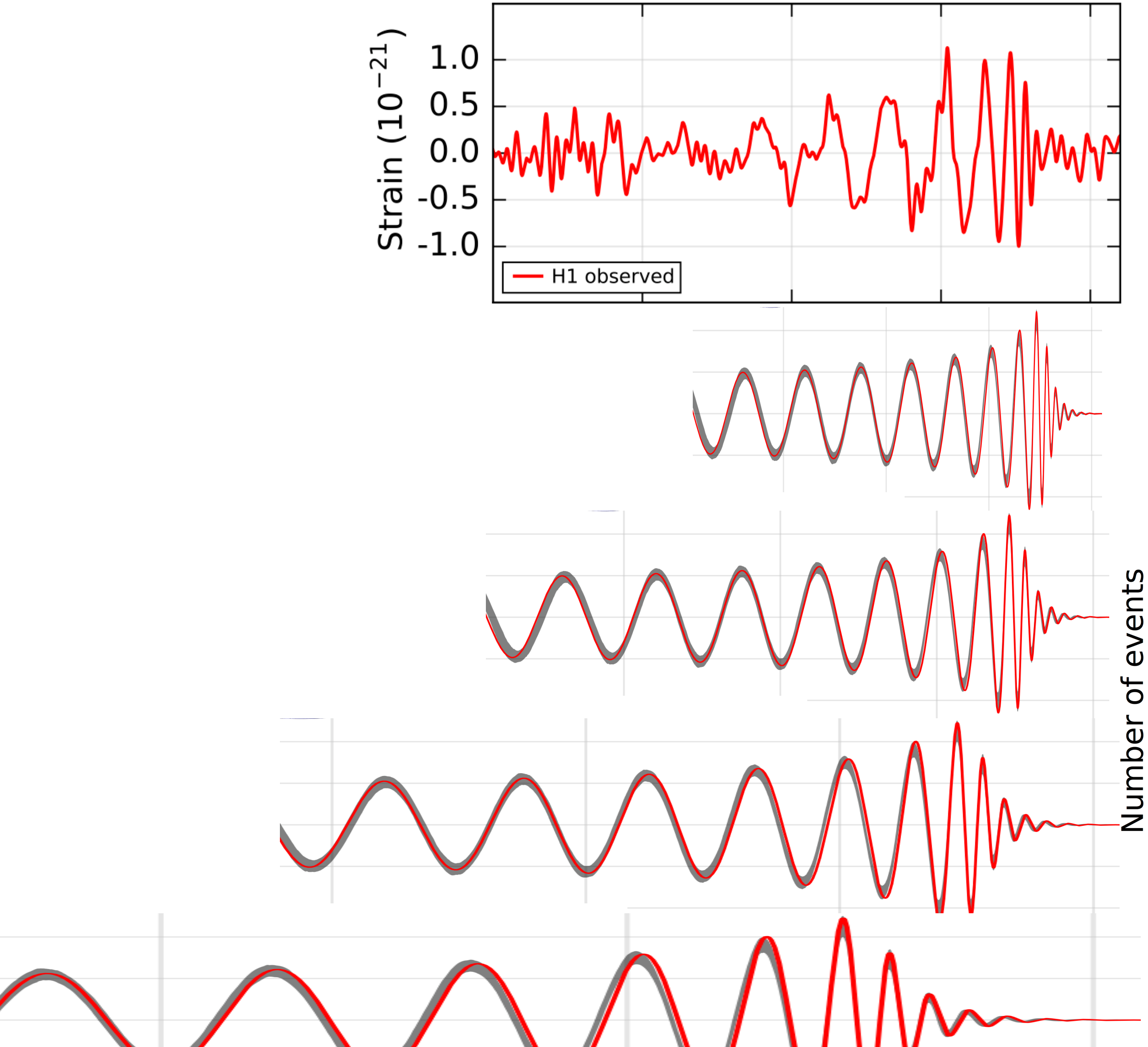






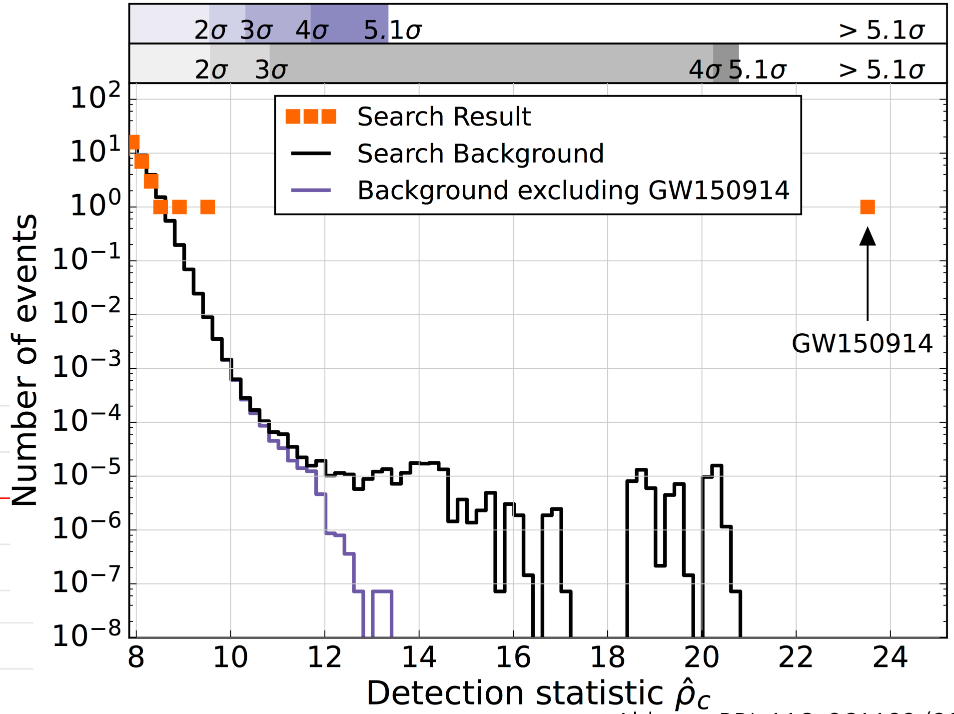
Abbott+ PRL 116, 061102 (2016)

Binary coalescence search



15 (+2) parameters

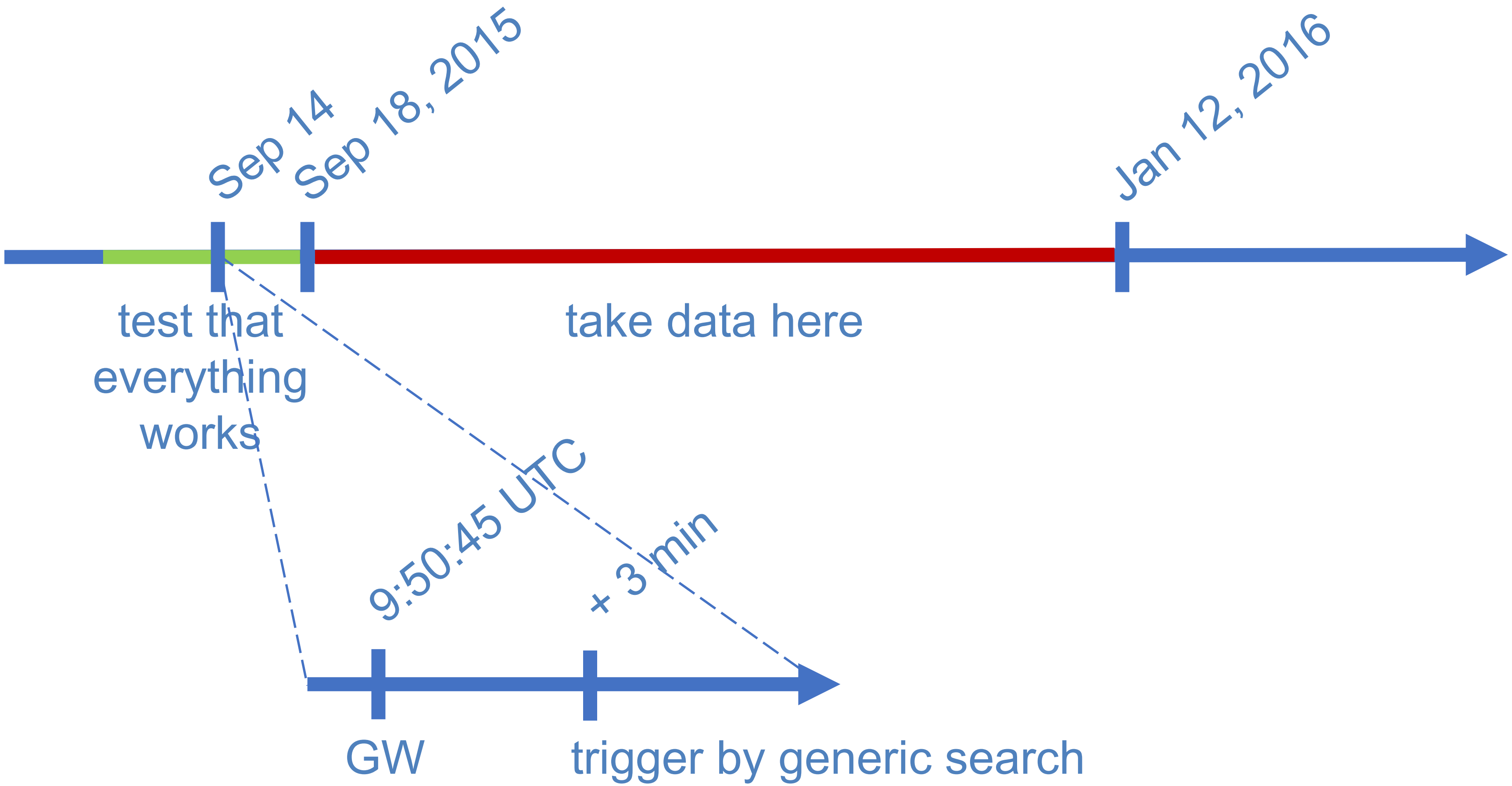
masses (2)
distance (1)
direction (2)
orientation (2)
spin (6)
time (1)
phase (1)
+ eccentricity (2)
+ calibration uncertainty (~10%)



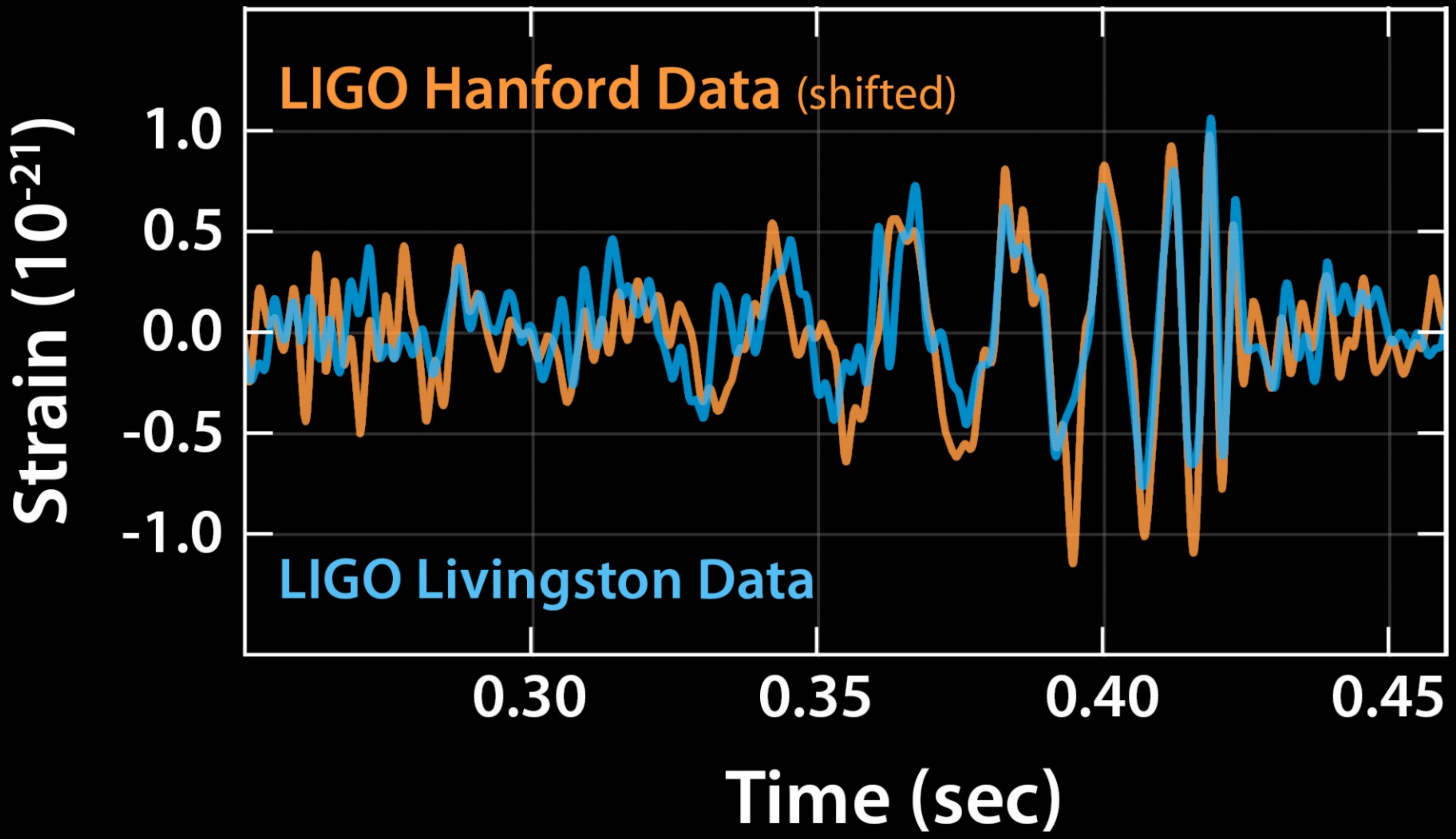
Abbott+ PRL 116, 061102 (2016)

September 14th, 2015

timeline

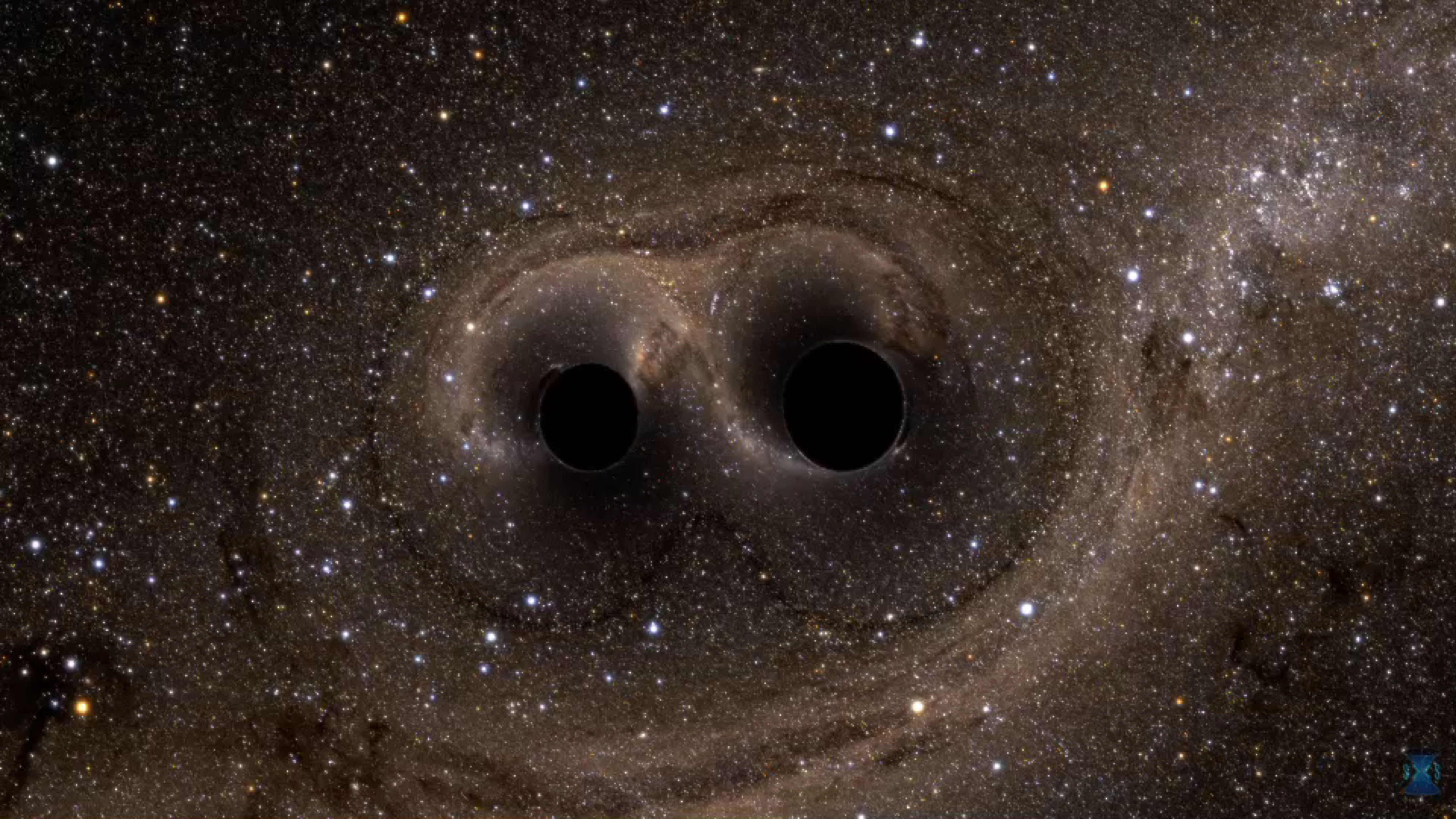


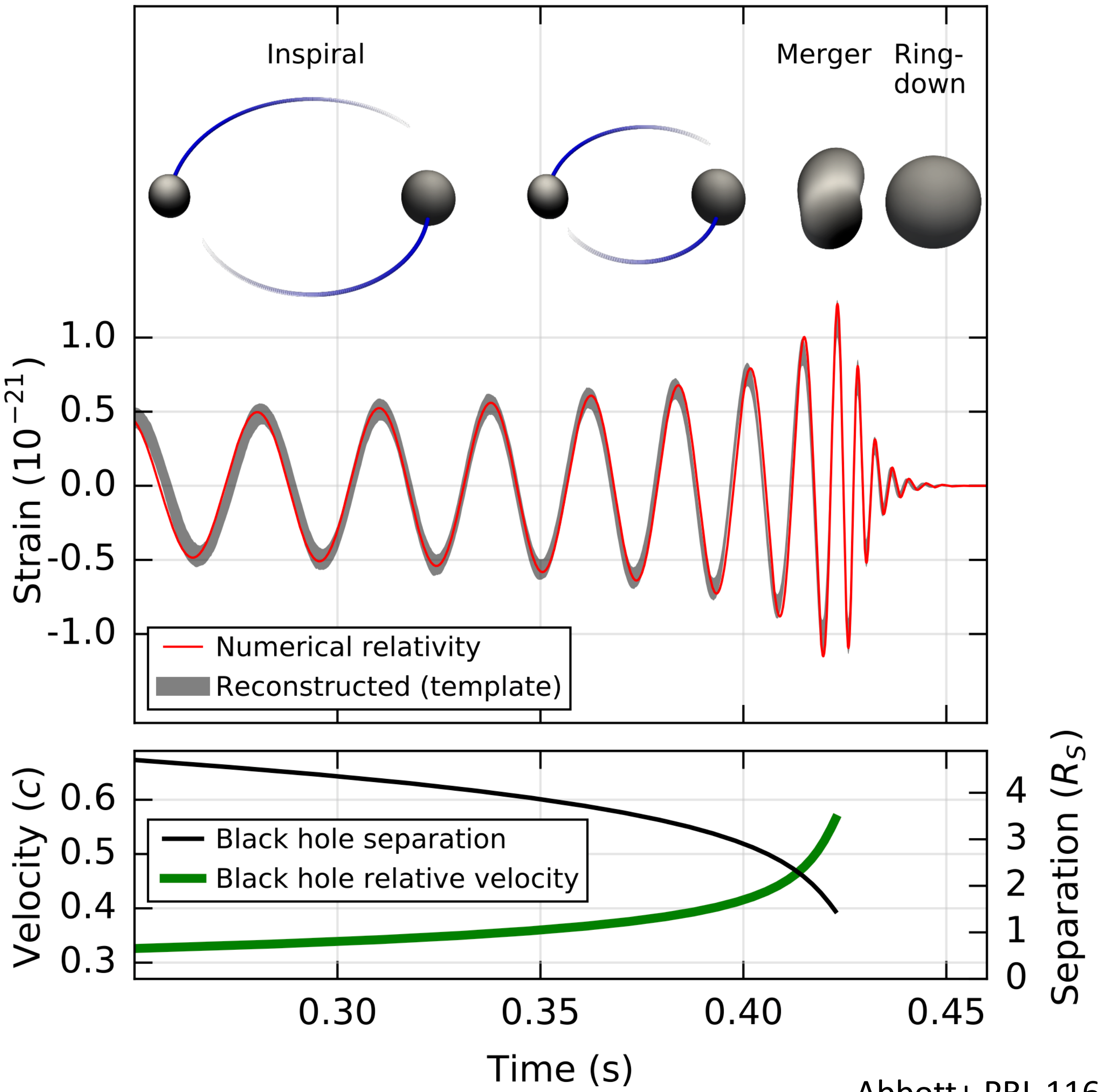
Sep 14
Sep 18, 2015
Jan 12, 2016
test that everything works
take data here
9:50:45 UTC
+ 3 min
GW
trigger by generic search



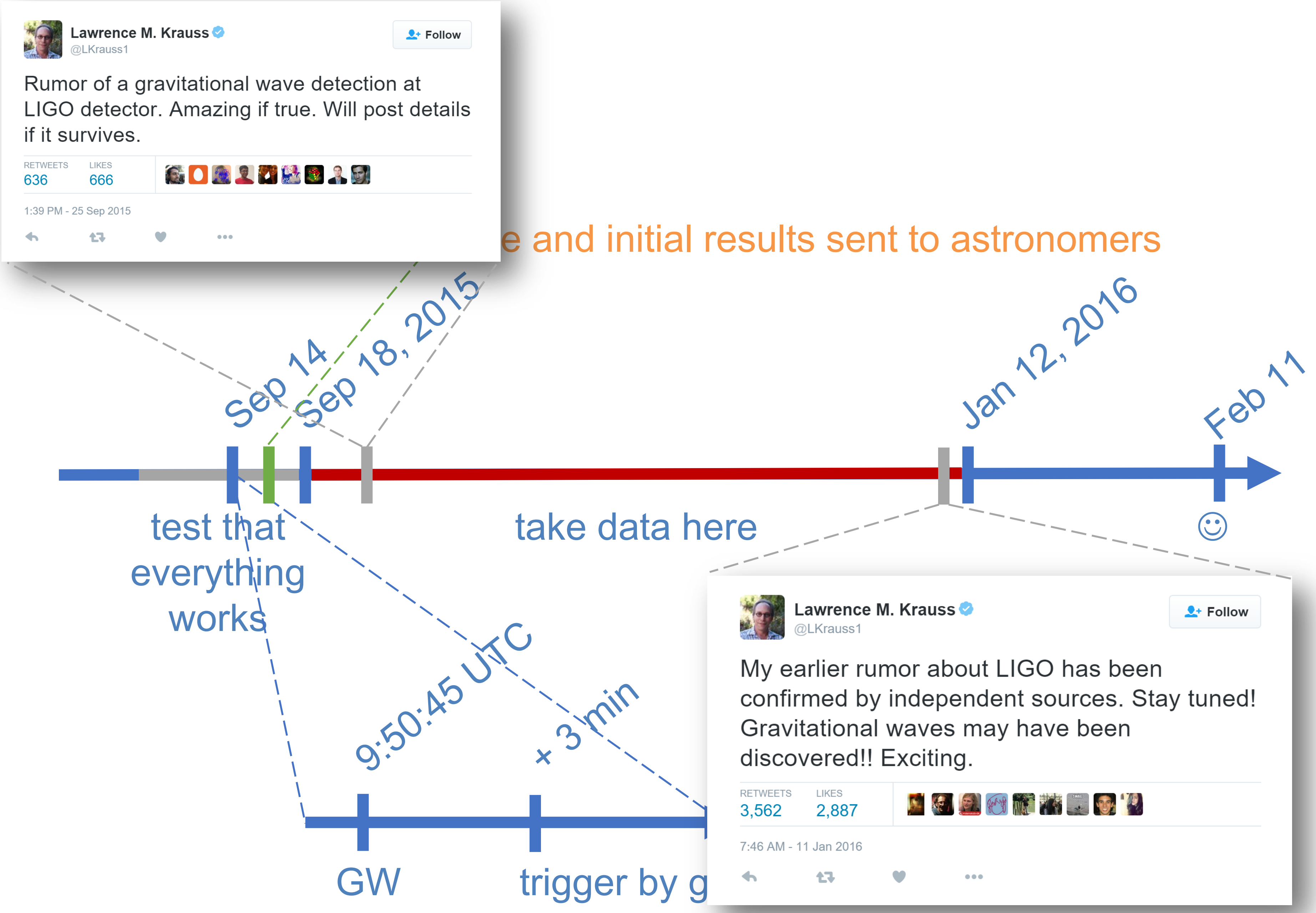
Abbott+ PRL 116, 061102 (2016)

Courtesy of Corey Gray





Abbott+ PRL 116, 061102 (2016)



Lawrence M. Krauss
@LKrauss1
Follow
Rumor of a gravitational wave detection at LIGO detector. Amazing if true. Will post details if it survives.
RETWEETS 636
LIKES 666
1:39 PM - 25 Sep 2015
e and initial results sent to astronomers
Sep 14
Sep 18, 2015
Jan 12, 2016
Feb 11
test that everything works
take data here
☺
9:50:45 UTC
+ 3 min
GW
trigger by g
Lawrence M. Krauss
@LKrauss1
Follow
My earlier rumor about LIGO has been confirmed by independent sources. Stay tuned! Gravitational waves may have been discovered!! Exciting.
RETWEETS 3,562
LIKES 2,887
7:46 AM - 11 Jan 2016

What have we discovered?

- Einstein was right
- First signal: “I come from a black hole”

“All the News That’s Fit to Print”

The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed

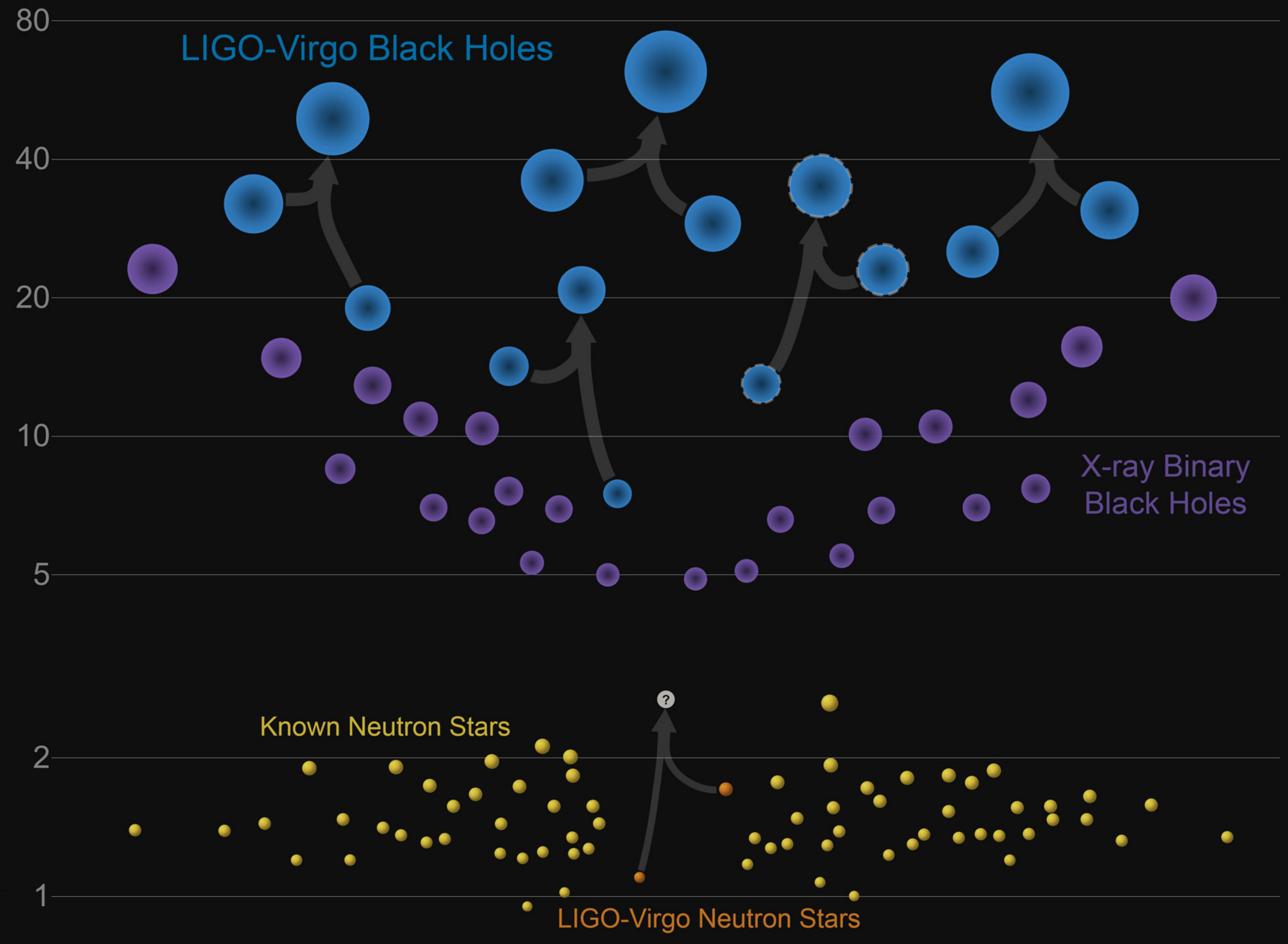
WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

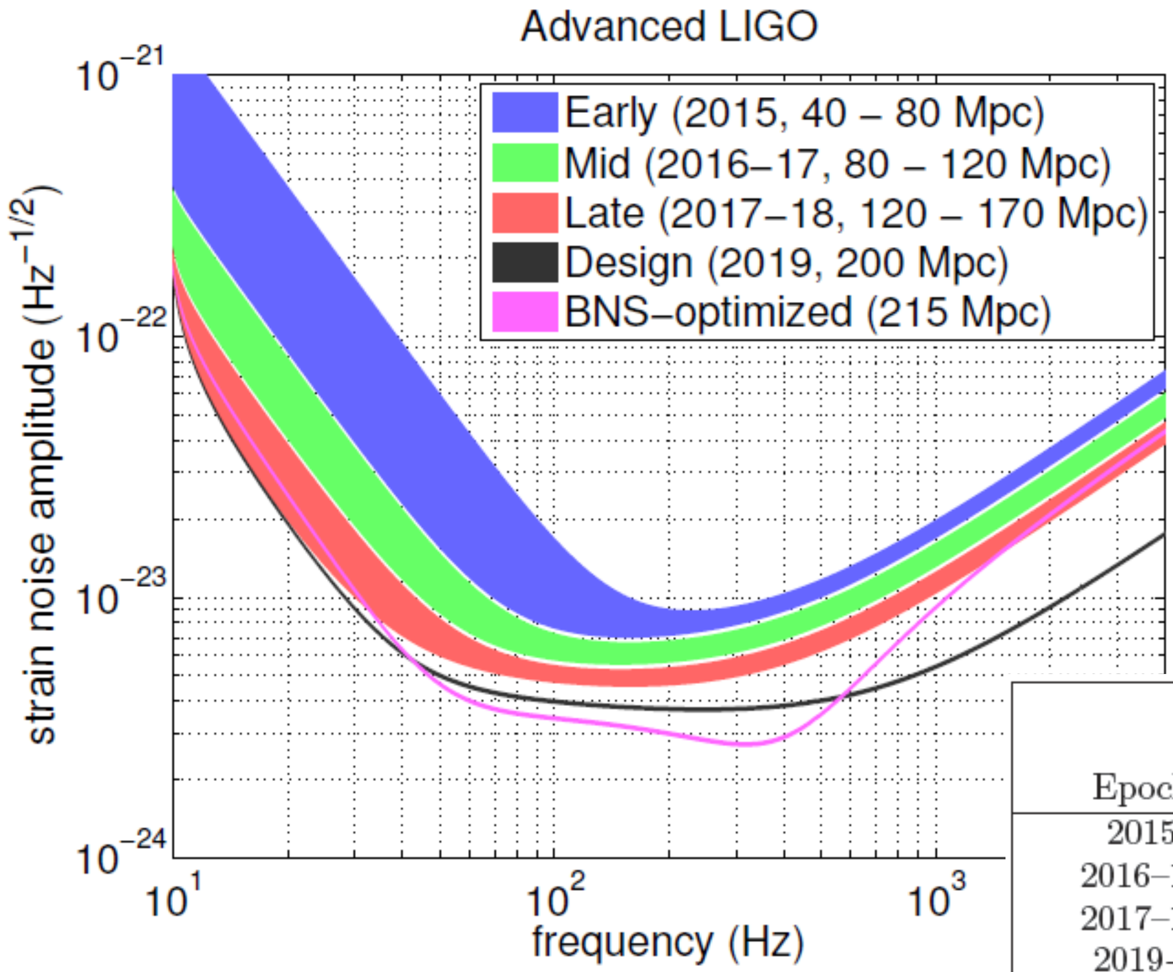
By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard



80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
?

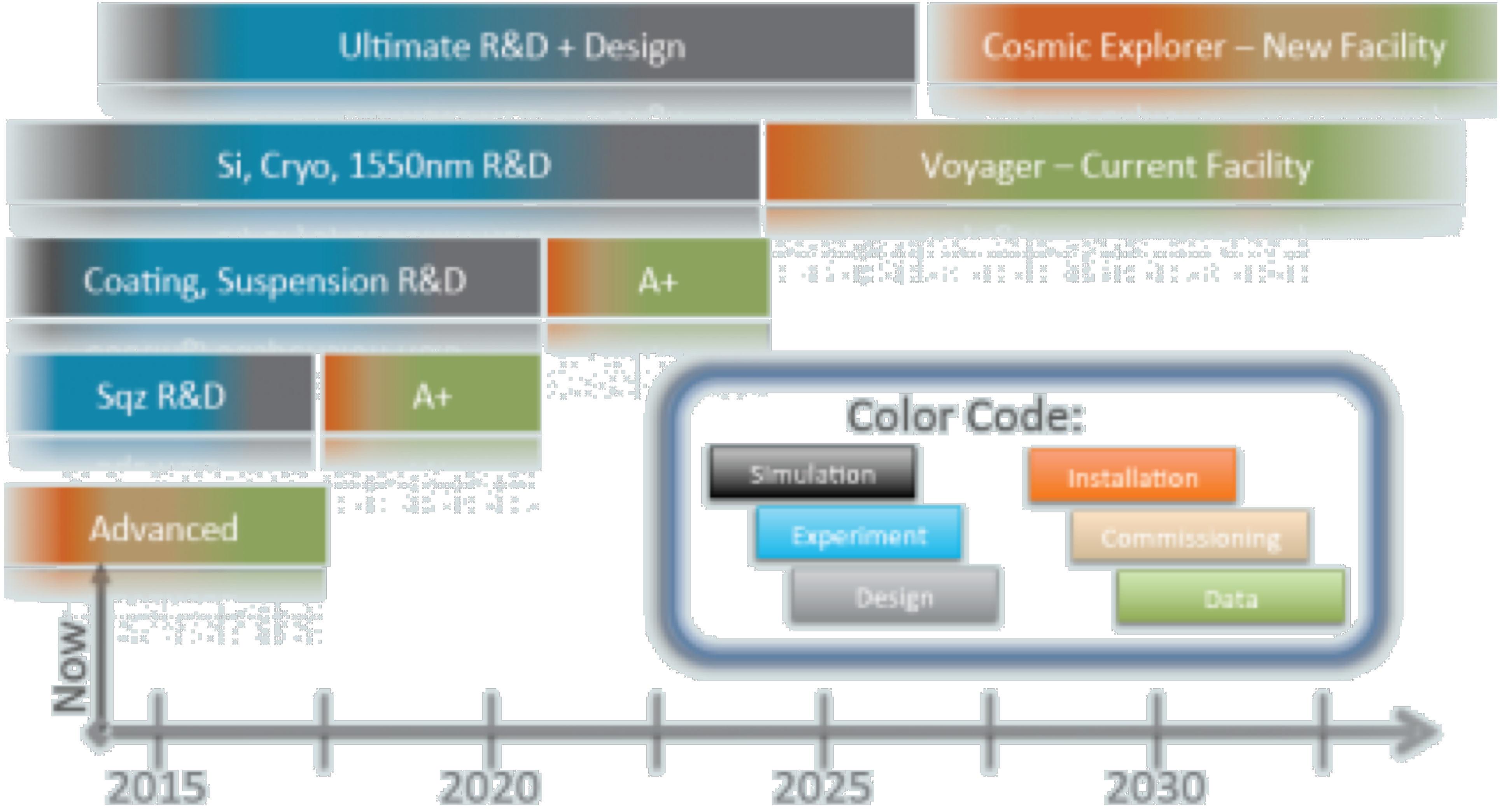
Sensitivity Timeline



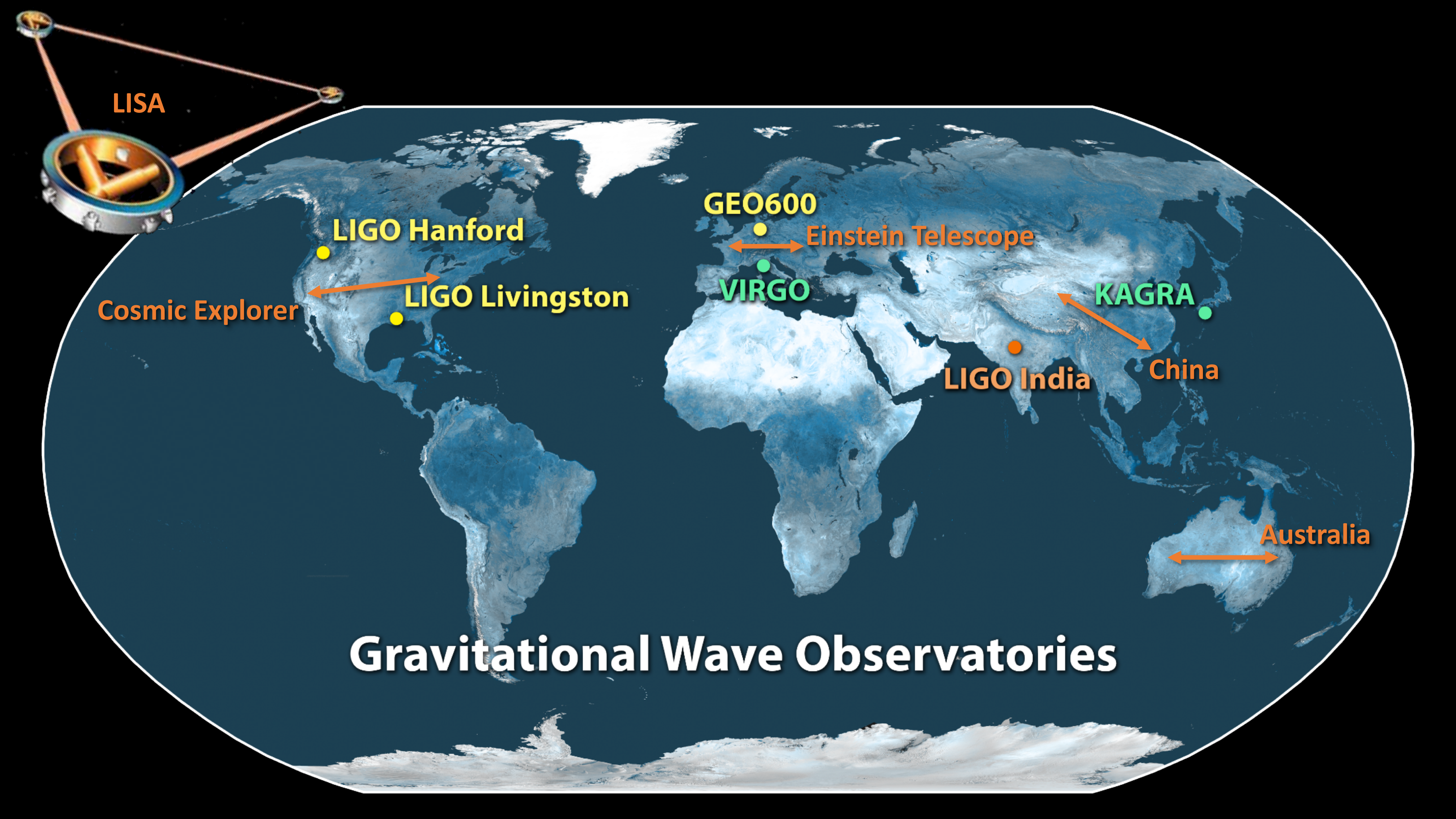
Epoch	Estimated Run Duration
2015	3 months
2016–17	6 months
2017–18	9 months
2019+	(per year)
2022+ (India)	(per year)

Aasi+ Living Reviews in Relativity, vol. 19, no. 1 (2016)

LIGO upgrade timeline

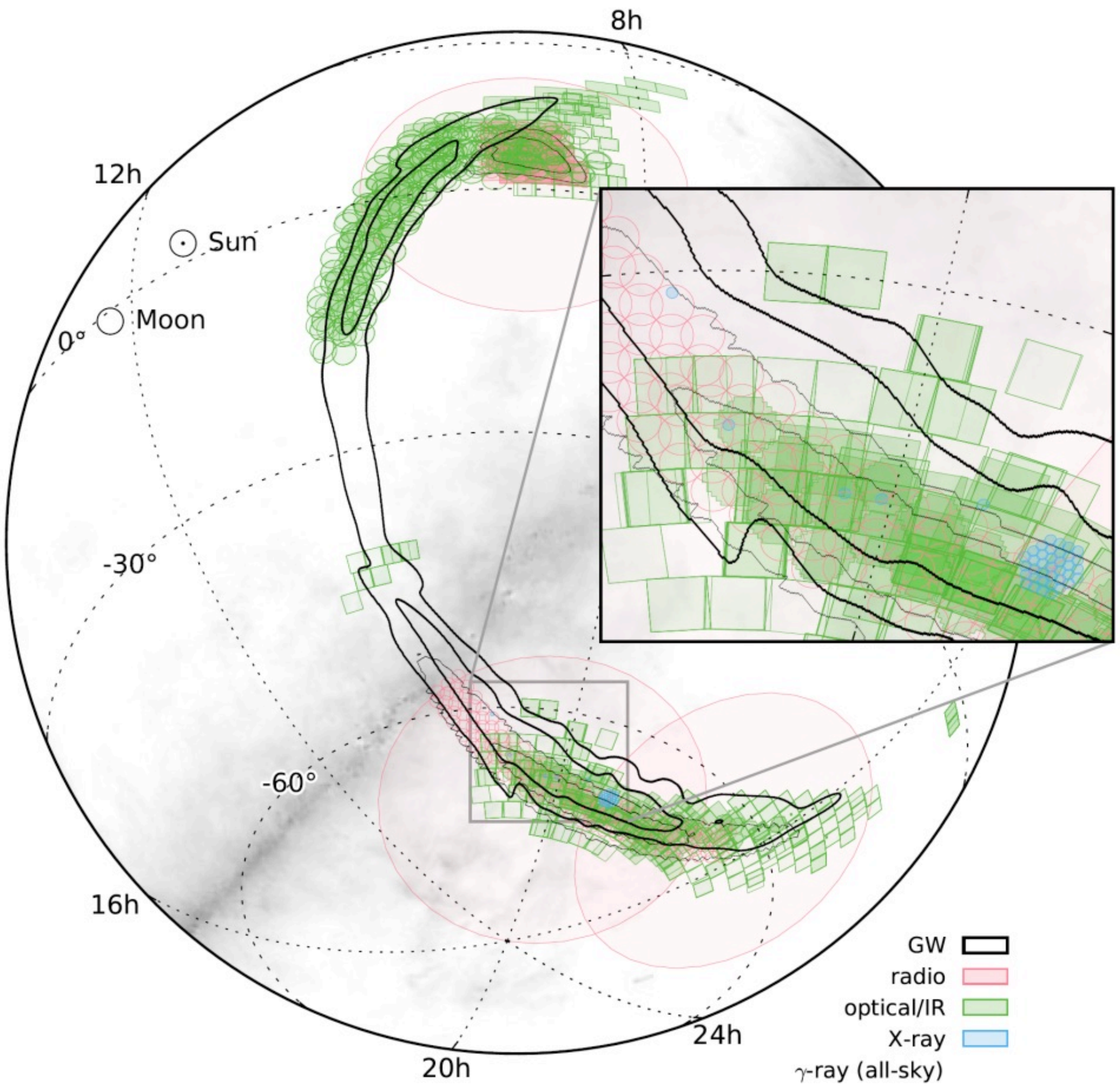


T1400316/004, Instrument Science White Paper

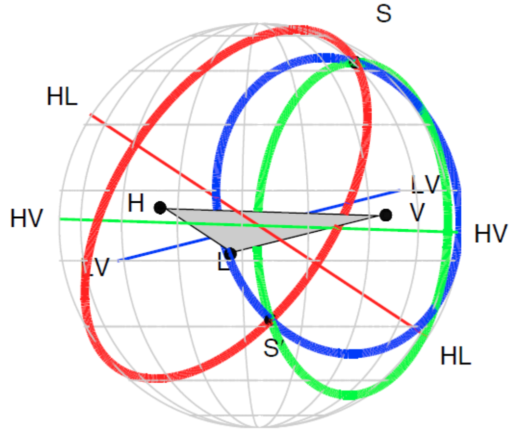


LISA
GEO600
LIGO Hanford
Einstein Telescope
Cosmic Explorer
LIGO Livingston
VIRGO
KAGRA
LIGO India
China
Australia
Gravitational Wave Observatories

localization



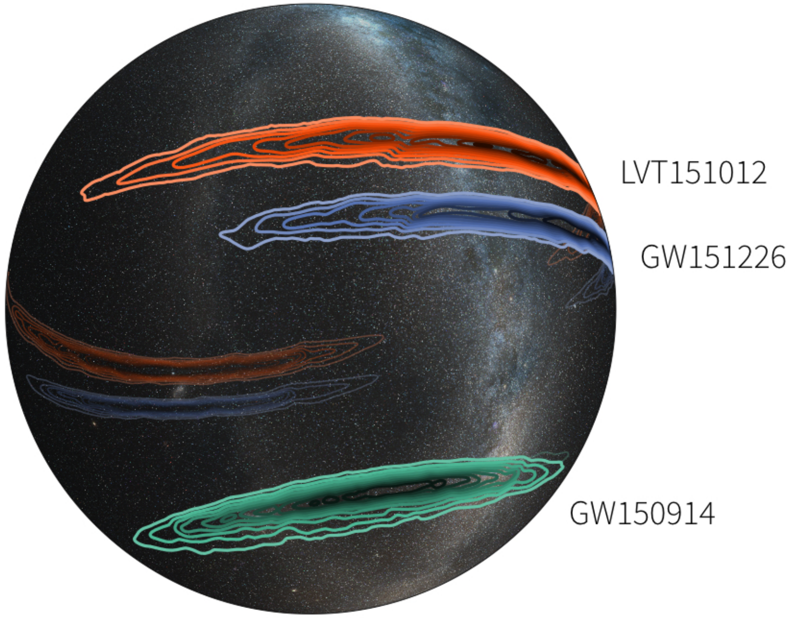
Abbott et al. 2016 (1602.08492)



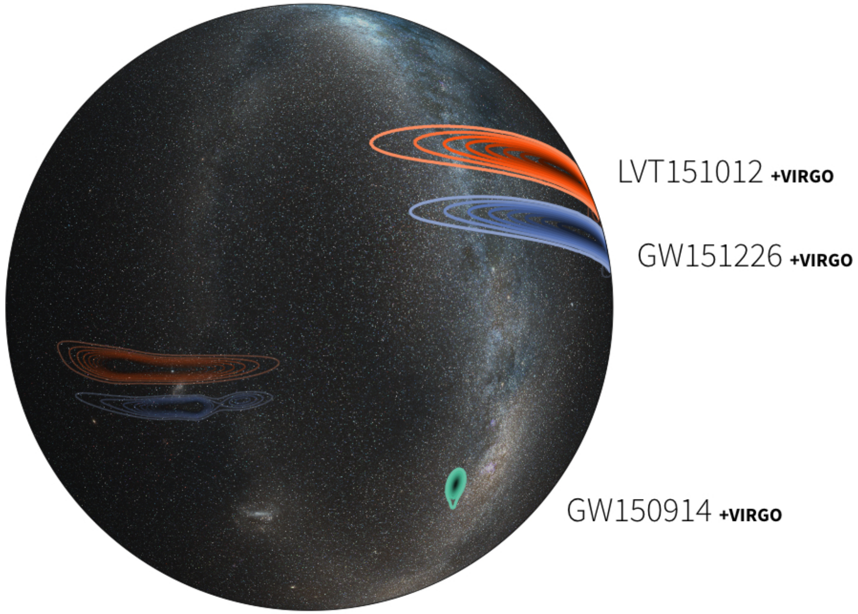
Chatterji+ PRD 2006

- 100-1000 deg^2
- Improves with more detectors
- Difficult to cover for many optical observatories
- Significant transient foreground (SNe)
- 1/month FAR LIGO triggers

MORE DETECTORS NEEDED



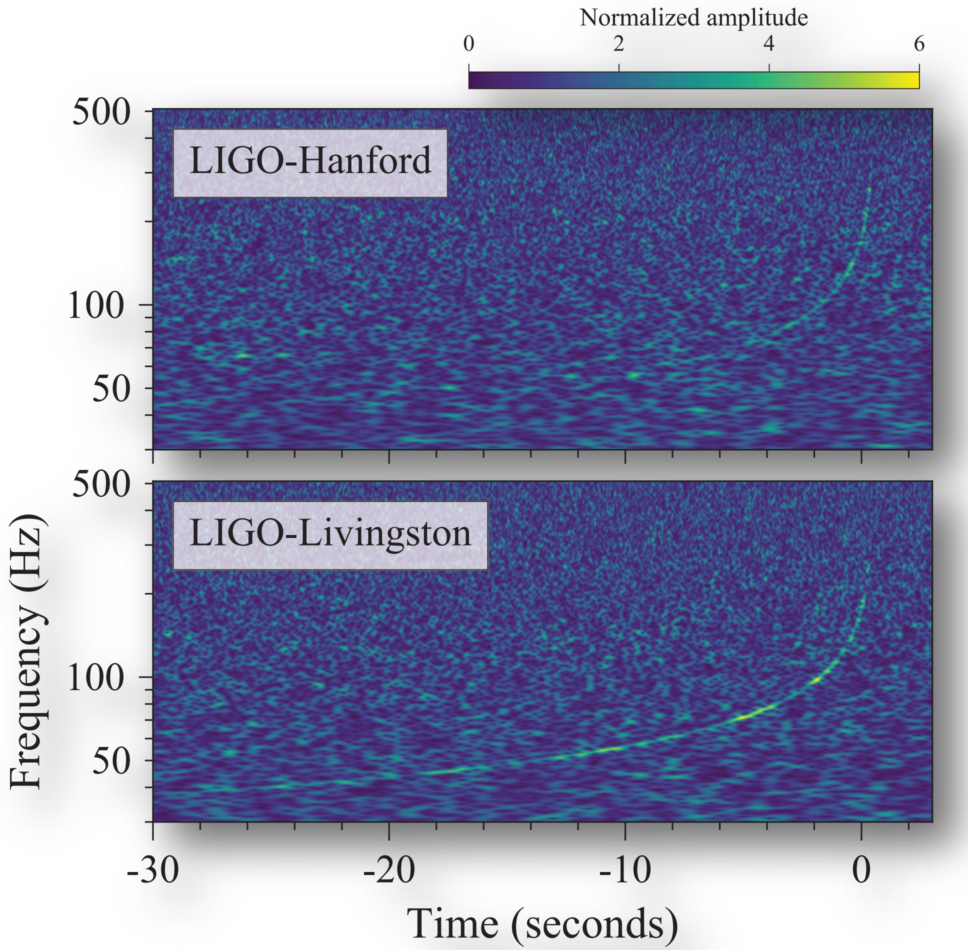
Actual estimates

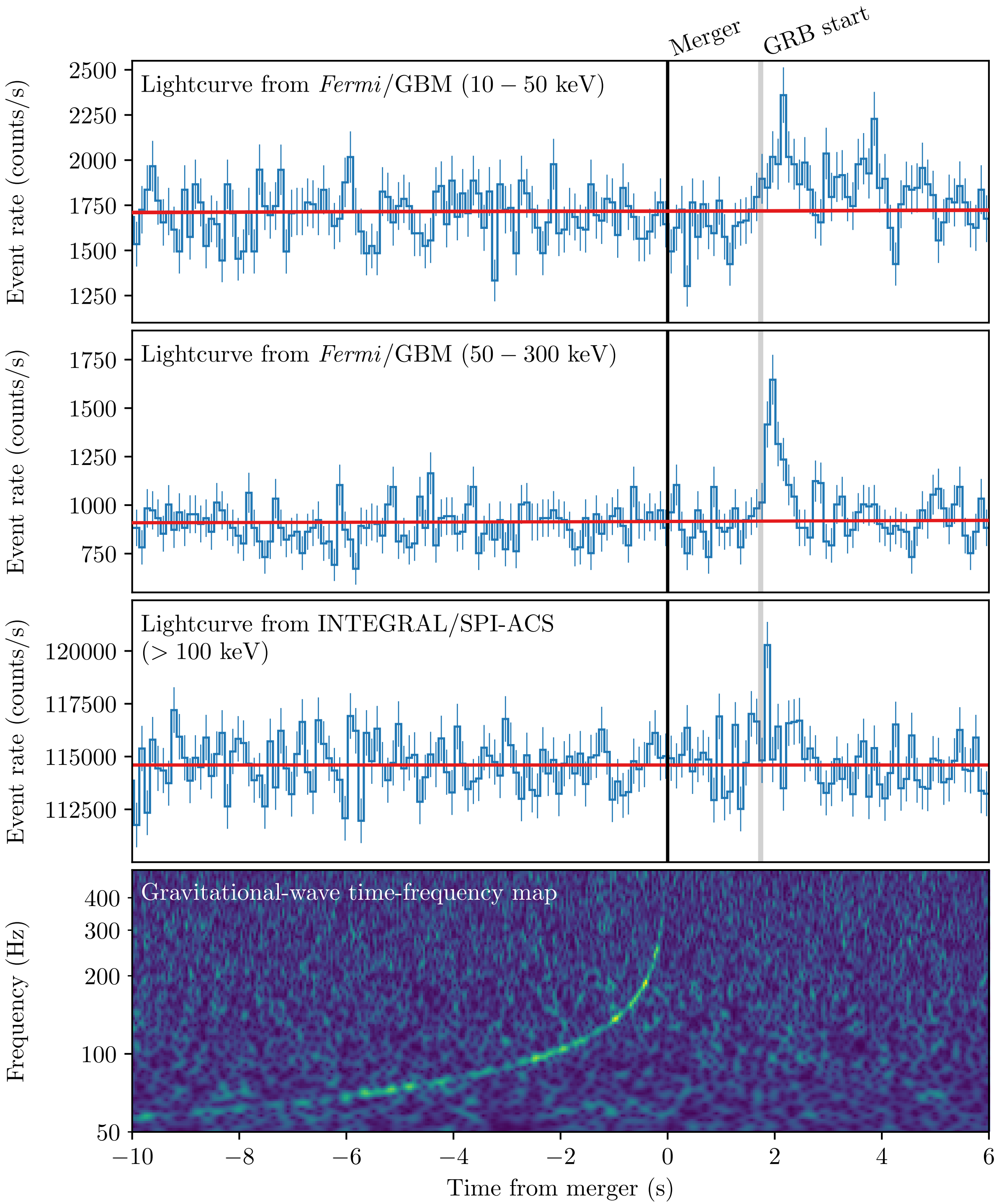


Simulated estimates with Virgo

3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (green), and GW151226 (blue), and the candidate LVT151012 (red). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region. Image credit: LIGO/Axel Mellinger.

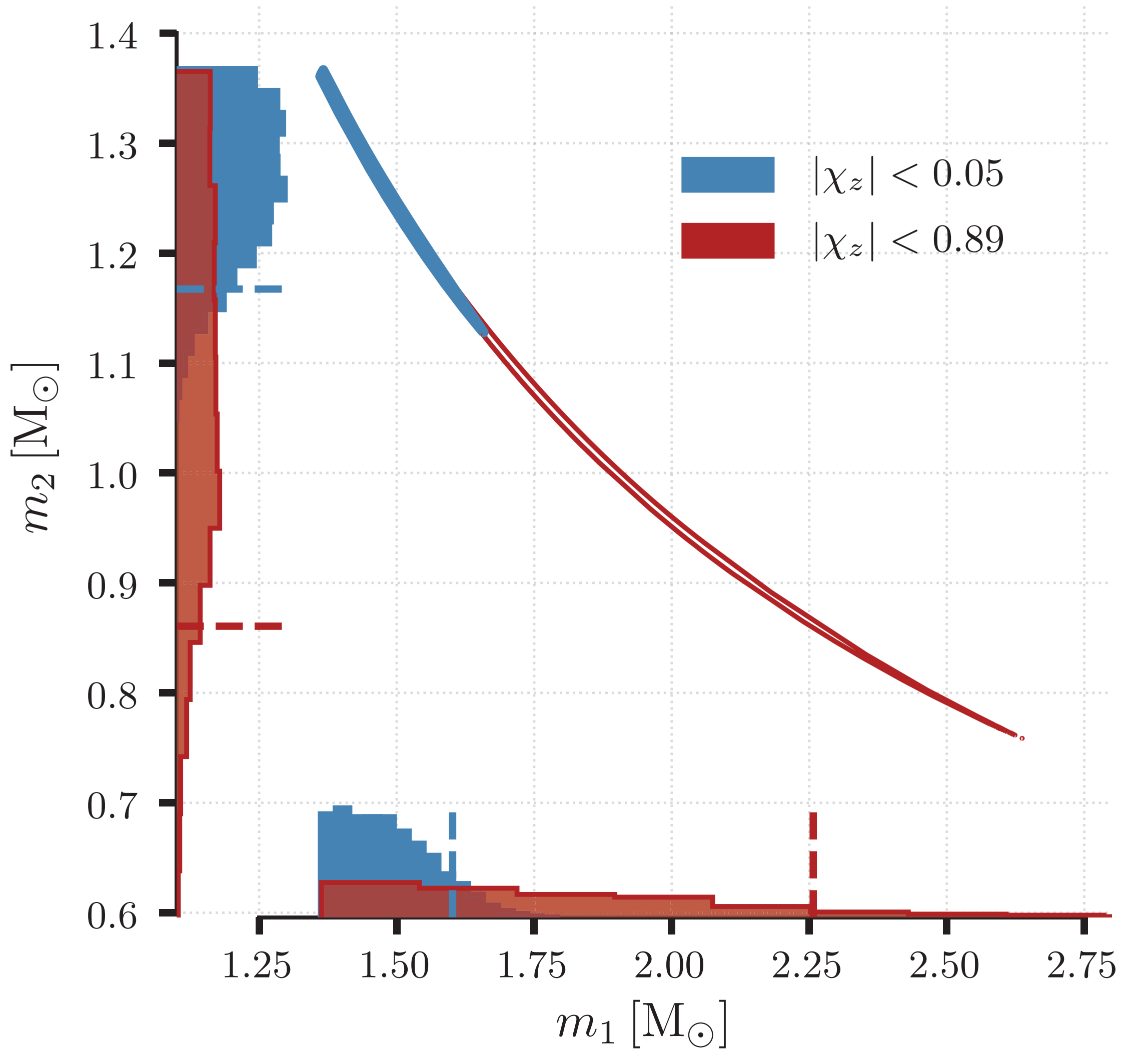
August 17, 2017





- Gravitational-wave trigger in LIGO-Hanford only
- Livingston – noise transient
- No signal in Virgo
- Consistent with BNS merger
- 1.7s later --- GRB alert from Fermi
- Weak GRB (~10^{-7} erg cm^{-2})

Information in Gravitational Waves



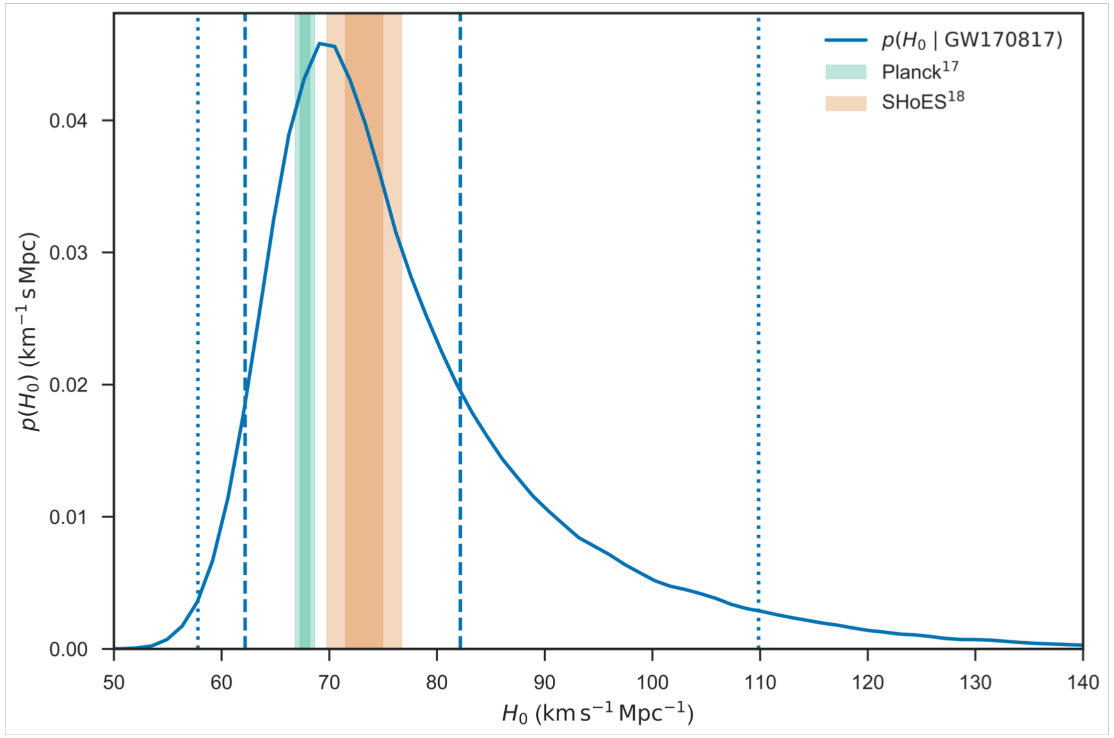
	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$
Using NGC 4993 location	$\lesssim 28°$

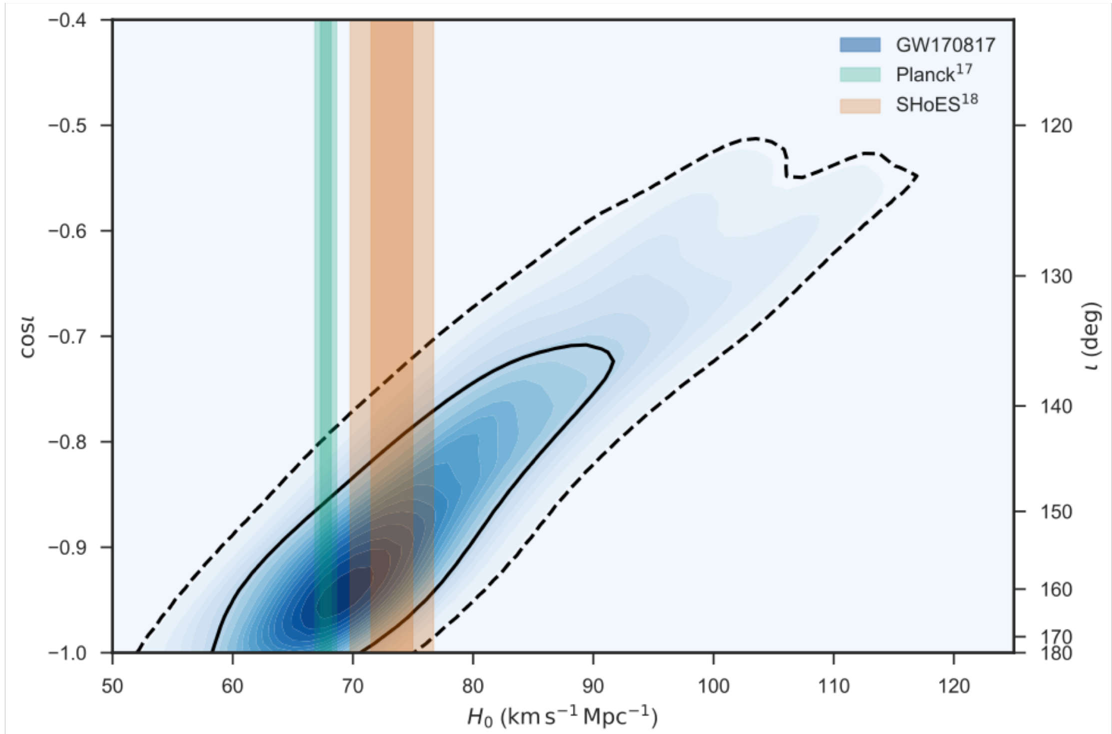
$$R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

- More common than we expected
- Consistent with galactic BNS observations
- Tidal effects are not taken into account
- Neutron star maximum mass: ~2.2 Msun

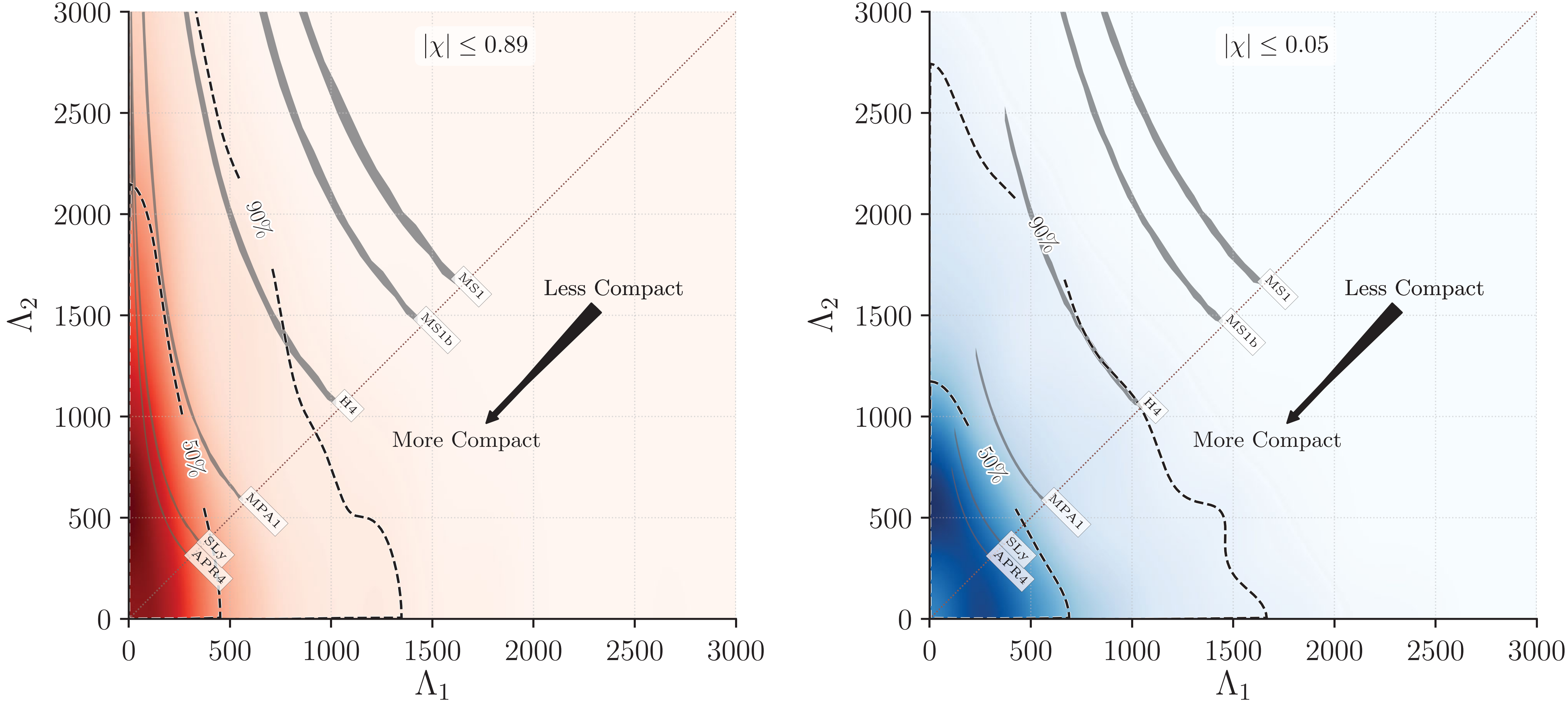
Constraints on Cosmology with Gravitational Waves

- <u>Uncertainty:</u>
  - Inclination
  - Peculiar velocity of host galaxy
  - Natal kick
- More and more distant detections will significantly shrink this uncertainty





LIGO+ Nature 2017



LIGO+Virgo PRL 2017