Astrofisica Nucleare e Subnucleare

Gravitational Waves

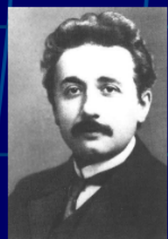
What are Gravitational Waves ?

Gravitational Waves (GW) are ripples of space-time

Theory of GW :

1. Einstein equations: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$
2. Far from sources: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$
3. Linearization: $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
4. Gauge TT: $$\nabla^2 h_{\mu\nu}^{TT} = 0$$

Propagation of some tensor field – *h* - on flat space-time



Prediction in 1916 !

Gravitational Wave general properties

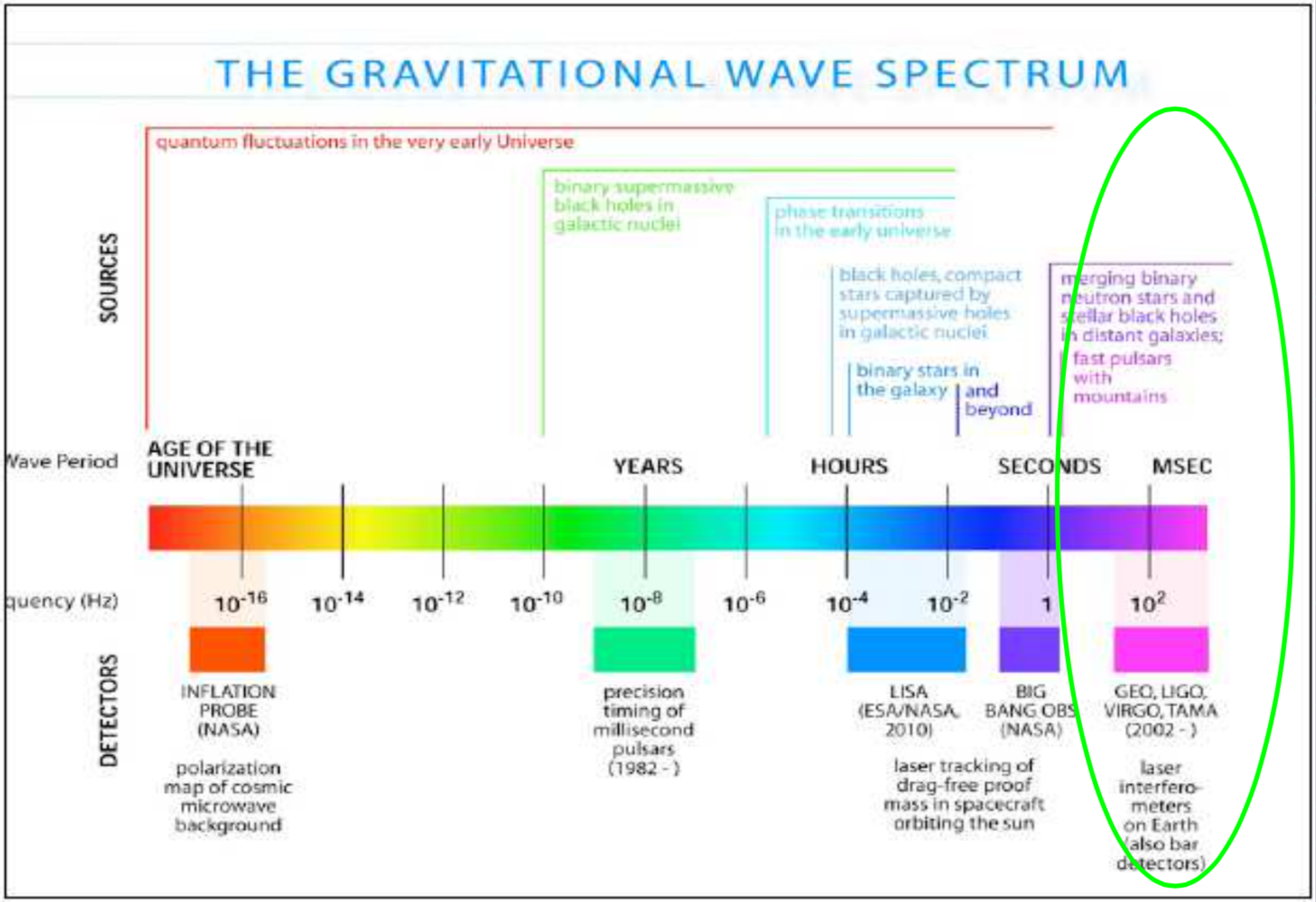
- GW propagate at speed of light
- GW have two polarizations "+" and "x"
- GW emission is quadrupolar at lowest order

Example: plane wave propagating along z axis with 2 polarization amplitudes h_+ and h_x:

$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Corresponding *Graviton* properties:

- Graviton has null mass
- Graviton has spin 2


THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
BIG BANG OBS (NASA)
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interferometers on Earth (also bar detectors)

Gravitational Wave emission

(*quadrupole formalism*)

Emission equation in the TT Gauge: $\nabla^2 h_{\mu\nu}^{TT} = -\frac{16\pi G}{c^4} T_{\mu\nu}$

Retarded solution: $h_{\mu\nu}^{TT}(\vec{x},t) = \frac{2G}{Rc^4}\, \ddot{Q}_{\mu\nu}^{TT}(t - R/c)$

Hence: $h_{+}^{TT}(\vec{x},t) = \frac{G}{Rc^4}\left[\ddot{Q}_{11}^{TT} - \ddot{Q}_{22}^{TT}\right](t-R/c)$ $h_{\times}^{TT}(\vec{x},t) = \frac{2G}{Rc^4}\left[\ddot{Q}_{12}^{TT}\right](t-R/c)$

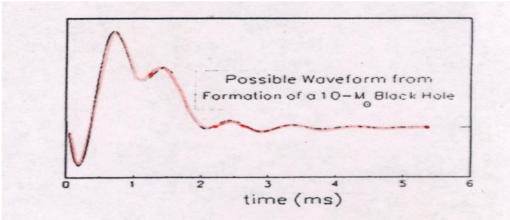
Where the ***reduced quadrupole*** moment:

$$Q_{\mu\nu}^{TT} = \iiint d^3x\, \rho\, (x_\mu\, x_\nu - \tfrac{1}{3}\delta_{\mu\nu} r^2)$$

Regular quadrupole (inertia) moment: $q_{\mu\nu} = \iiint d^3x\, \rho\, x_\mu x_\nu$

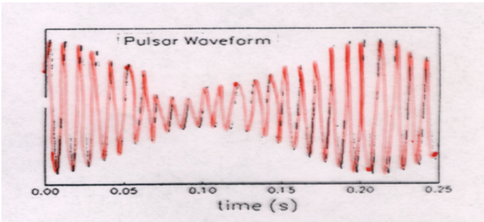
$\rho \sim T_{00}/c^2$: density of the source

Tipi di segnale



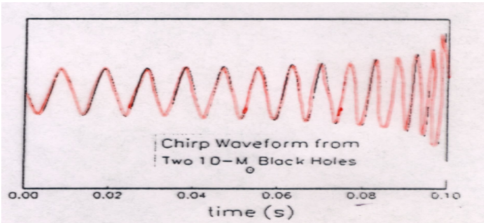
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density



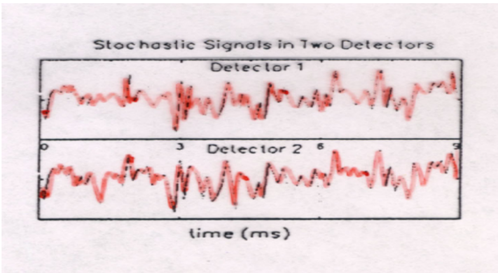
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution



COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

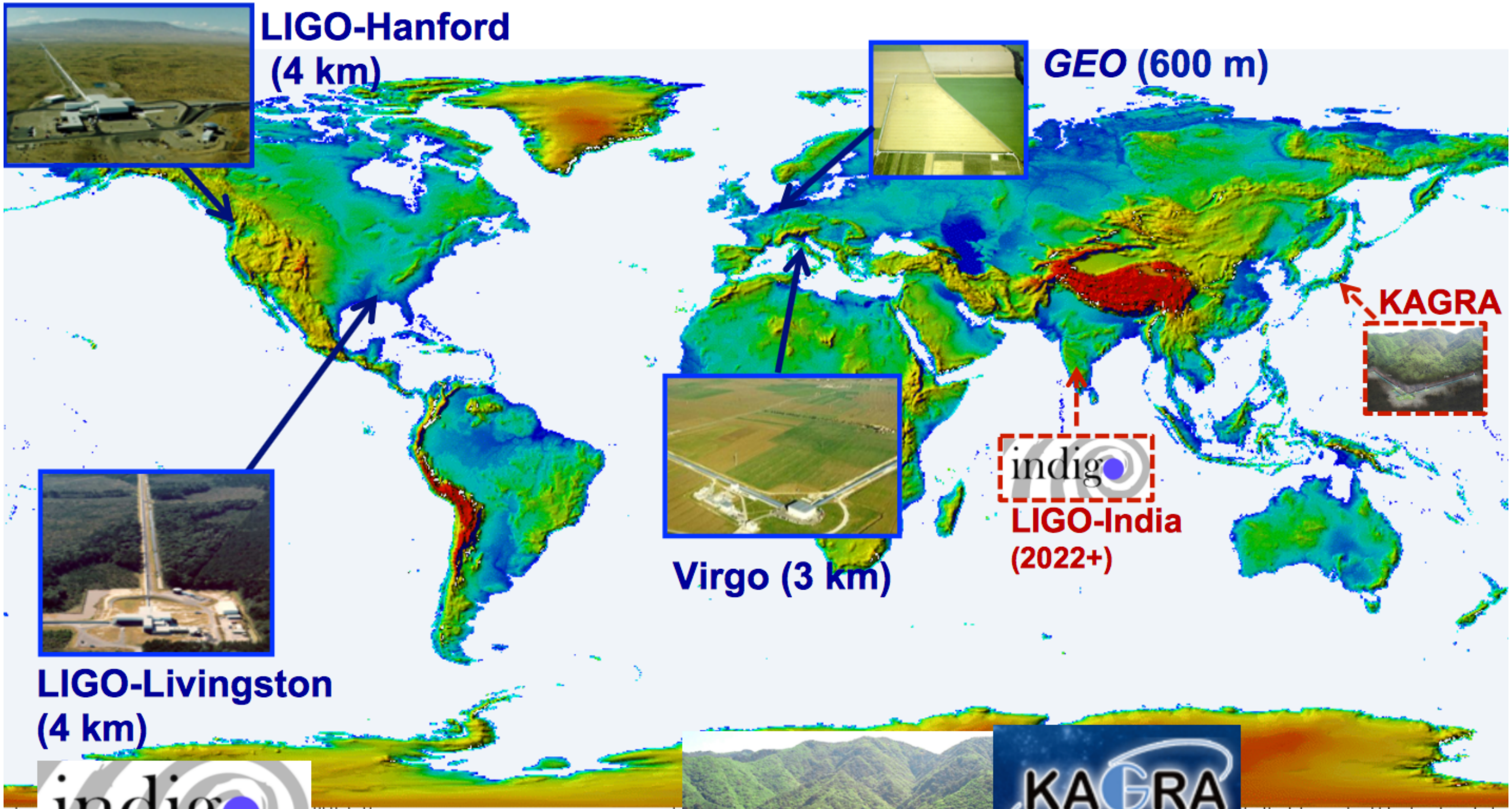
Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

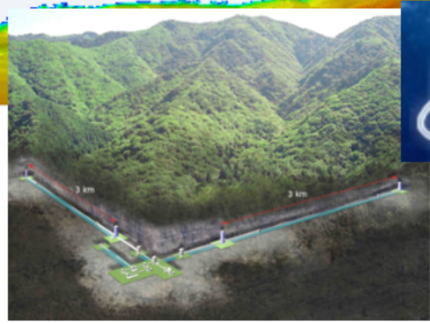
Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

Near Future Gravitational Wave Detectors



indigo

Move one of the two LIGO detectors in Hanford to India



KAGRA

Underground detector in the Kamioka mine: 3km length,
– Cryogenic mirrors (2nd phase)

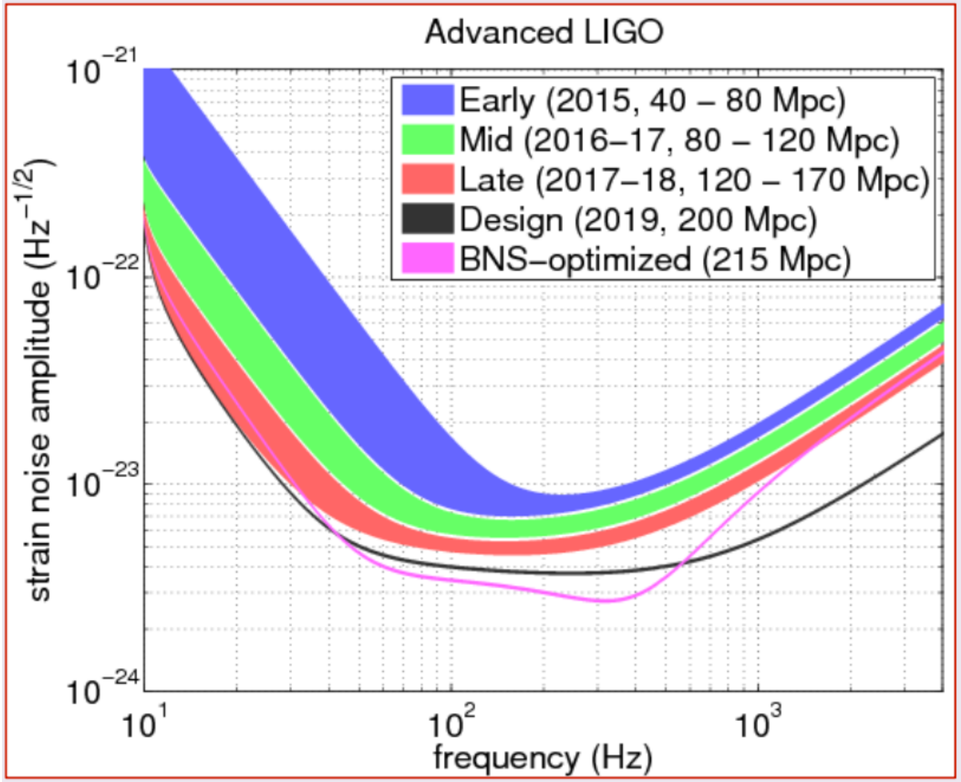
Exercise #3

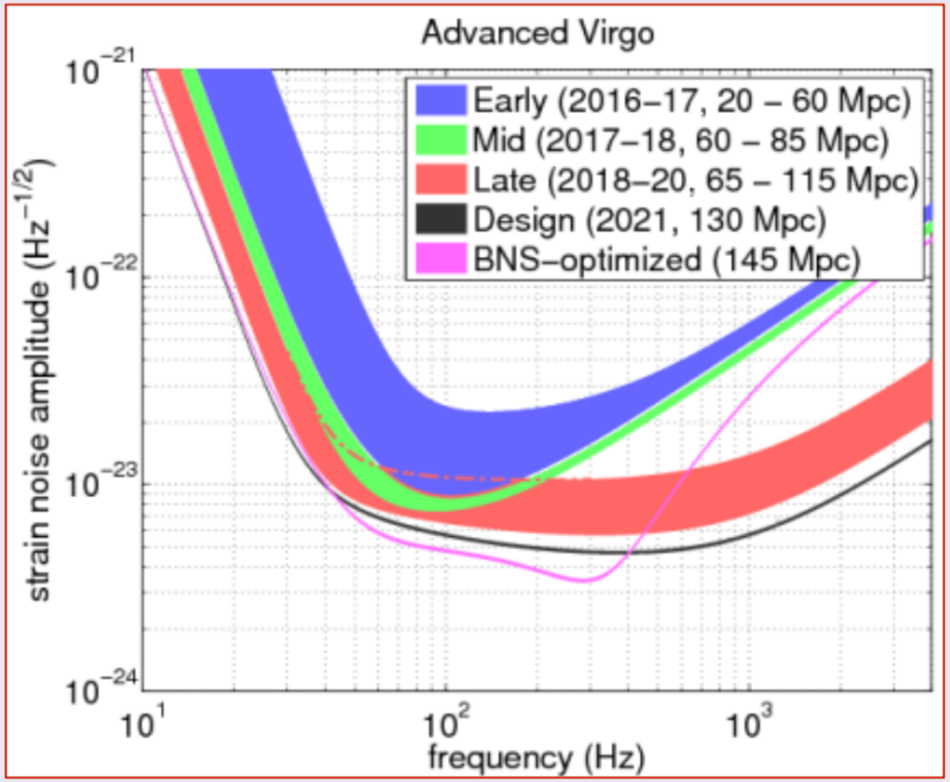
- Find recent information on the status of LIGO, Virgo, KAGRA
- Find the status of eLISA GW observatory
- Find the status of PTA GW methods

Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

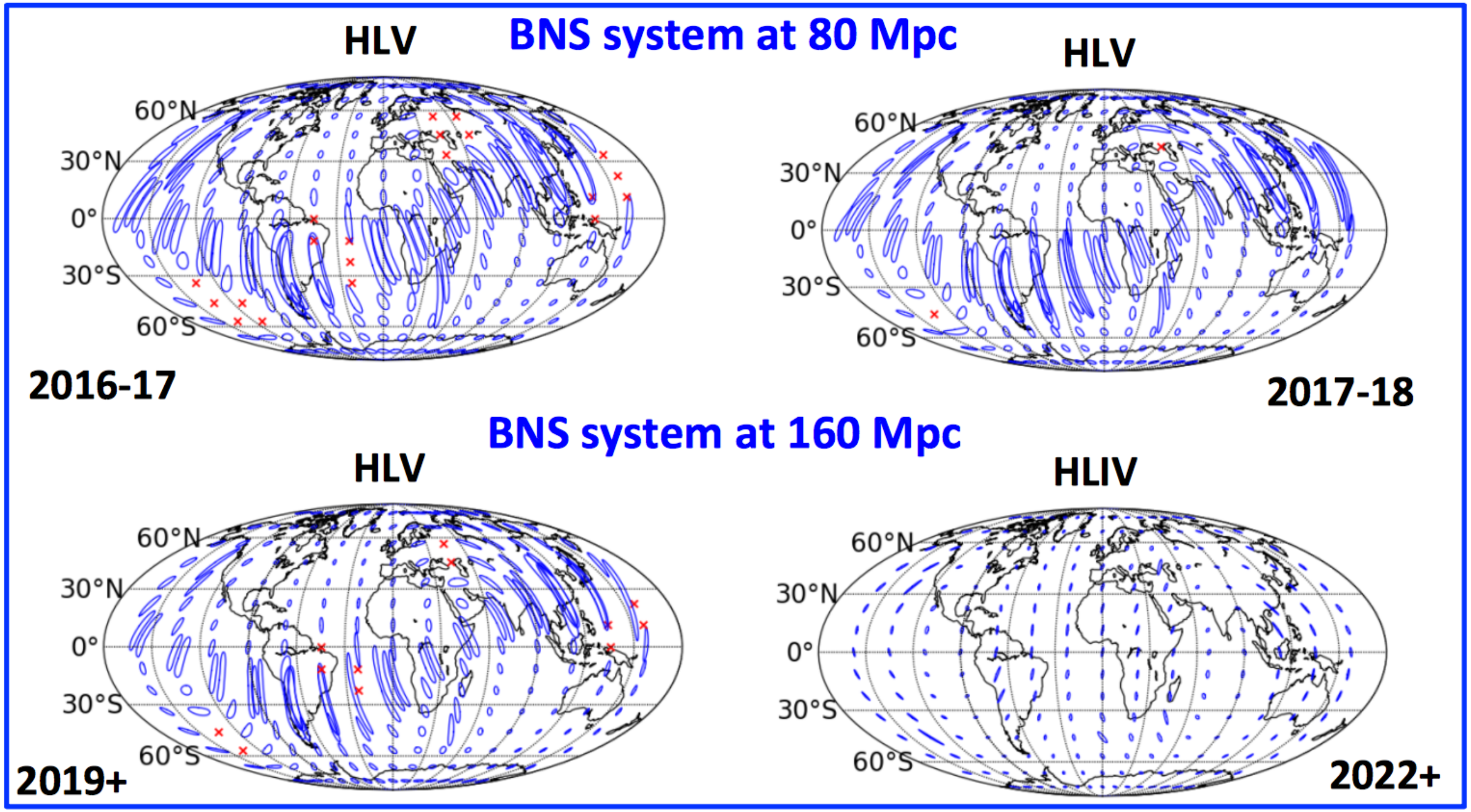
Progression of sensitivity and range for Binary Neutron Stars





Larger GW-detectable Universe

Sky Localization of Gravitational-Wave Transients



→ 90% confidence localization areas

X → signal not confidently detected

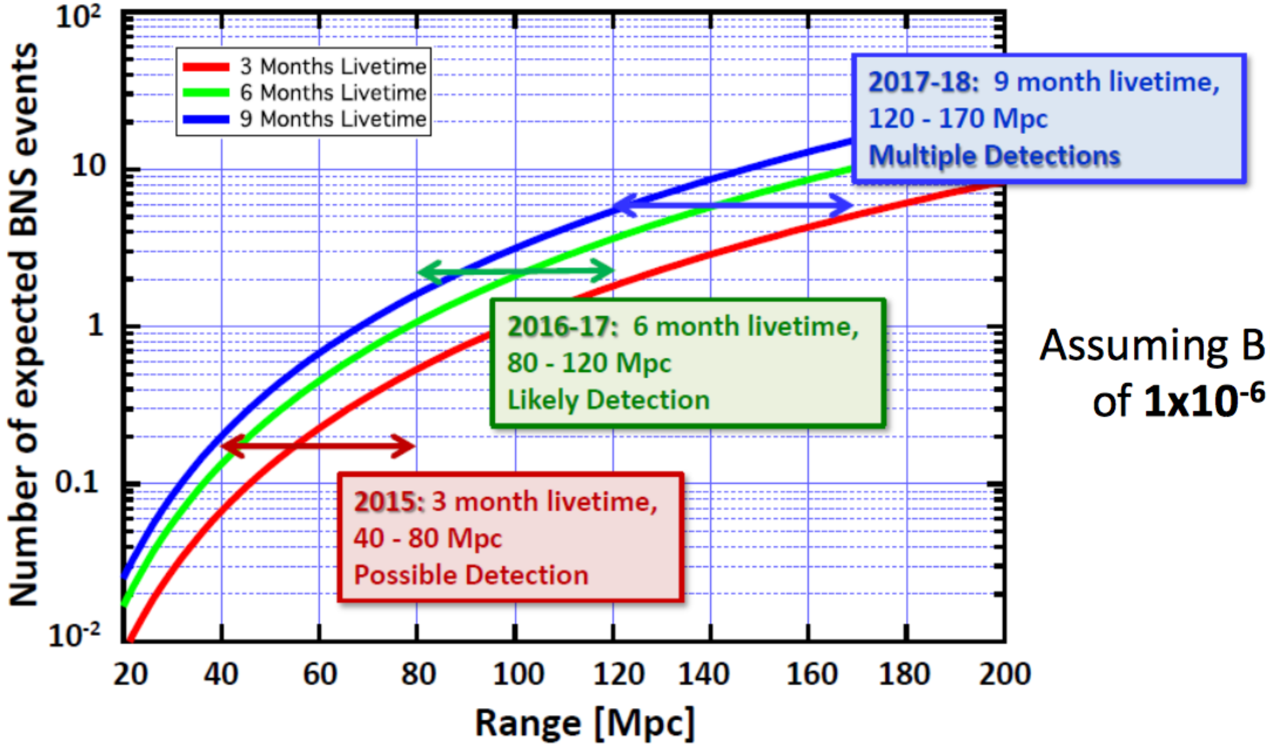
Position uncertainties with areas of **tens to hundreds of sq. degrees**

Summary of plausible observing scenario

LSC & Virgo collaboration arXiv:1304.0670

aLIGO/Virgo Range	Rate	Localization

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

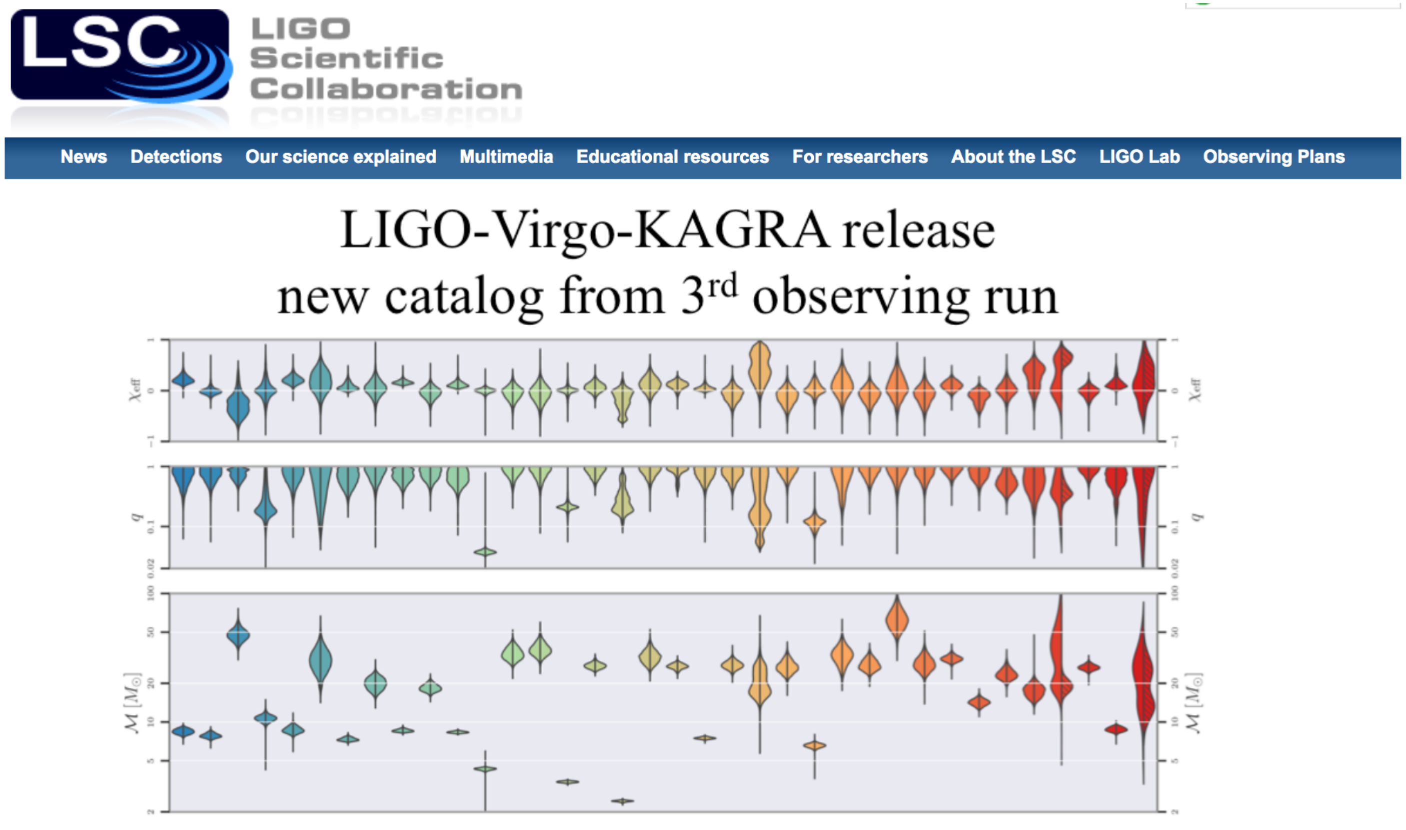


Assuming BNS merger rate of **1x10^{-6}** Mpc^{-3} year^{-1}

Exercise #3

http://www.ligo.org

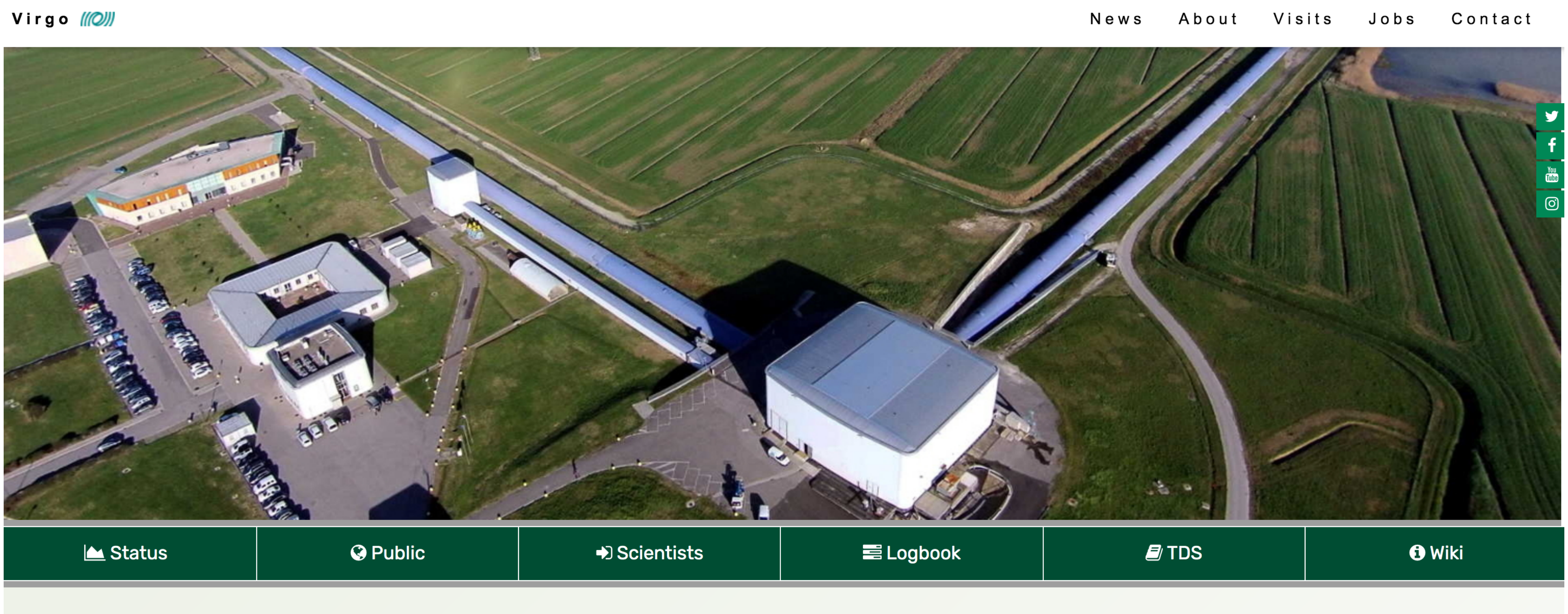
- Find recent information on the status of LIGO, Virgo, KAGRA



http://www.virgo-gw.eu

Exercise #3

- Find recent information on the status of LIGO, Virgo, KAGRA



Exercise #3

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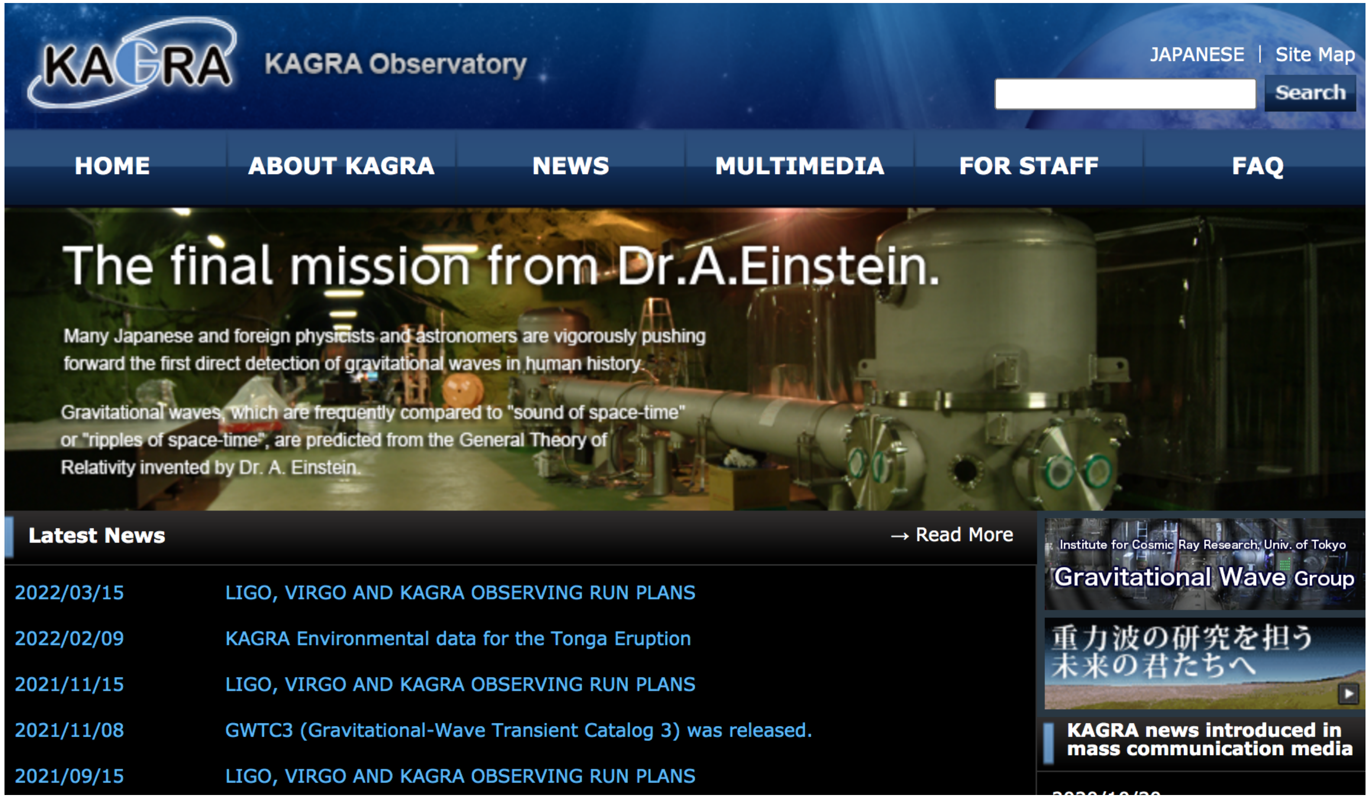


https://gwcenter.icrr.u-tokyo.ac.jp/en/

Exercise #3

- Find recent information on the status of LIGO, Virgo, KAGRA

Living Reviews in Relativity
https://doi.org/10.1007/s41114-020-00026-9

REVIEW ARTICLE

Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA

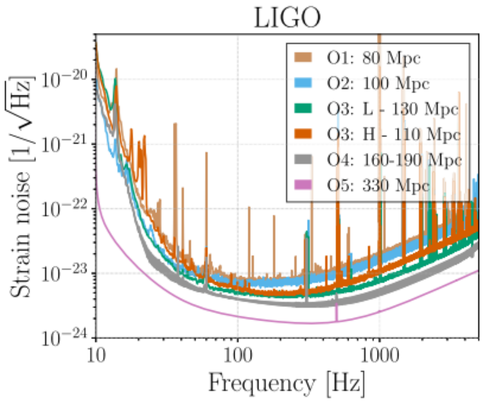
Abbott, B. P. et al. (KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration)*

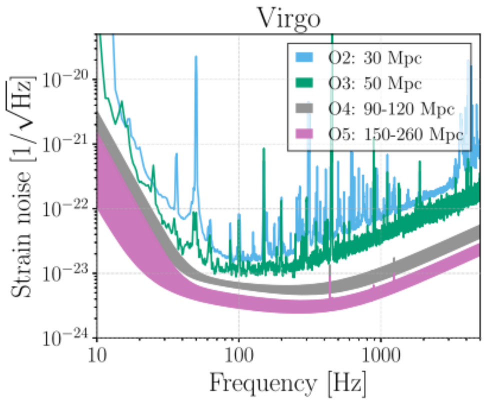
Received: 1 October 2019 / Accepted: 27 May 2020

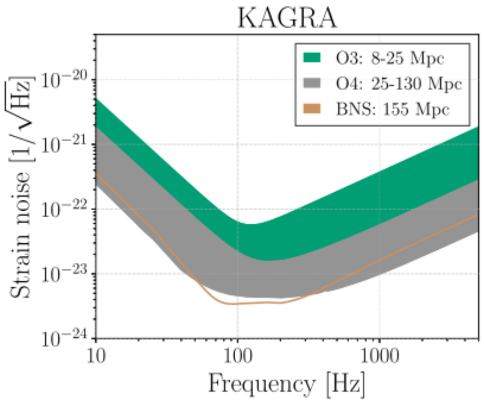
https://arxiv.org/abs/1304.0670

Exercise #3

- Find recent information on the status of LIGO, Virgo, KAGRA







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- Find recent information on the status of LIGO, Virgo, KAGRA

Table 2 Achieved and projected detector sensitivities for a $1.4\,M_\odot + 1.4\,M_\odot$ BNS system, a $30\,M_\odot + 30\,M_\odot$ BBH system, a $1.4\,M_\odot + 10\,M_\odot$ NSBH system, and for two unmodeled burst signals

		O1	O2	O3	O4	O5
BNS range (Mpc)	aLIGO	80	100	110–130	160–190	330
	AdV	–	30	50	90–120	150–260
	KAGRA	–	–	8–25	25–130	130+
BBH range (Mpc)	aLIGO	740	910	990–1200	1400–1600	2500
	AdV	–	270	500	860–1100	1300–2100
	KAGRA	–	–	80–260	260–1200	1200+
NSBH range (Mpc)	aLIGO	140	180	190–240	300–330	590
	AdV	–	50	90	170–220	270–480
	KAGRA	–	–	15–45	45–290	290+
Burst range (Mpc) $[E_{GW} = 10^{-2}\,M_\odot c^2]$	aLIGO	50	60	80–90	110–120	210
	AdV	–	25	35	65–80	100–155
	KAGRA	–	–	5–25	25–95	95+
Burst range (kpc) $[E_{GW} = 10^{-9}\,M_\odot c^2]$	aLIGO	15	20	25–30	35–40	70
	AdV	–	10	10	20–25	35–50
	KAGRA	–	–	0–10	10–30	30+

https://arxiv.org/abs/1304.0670

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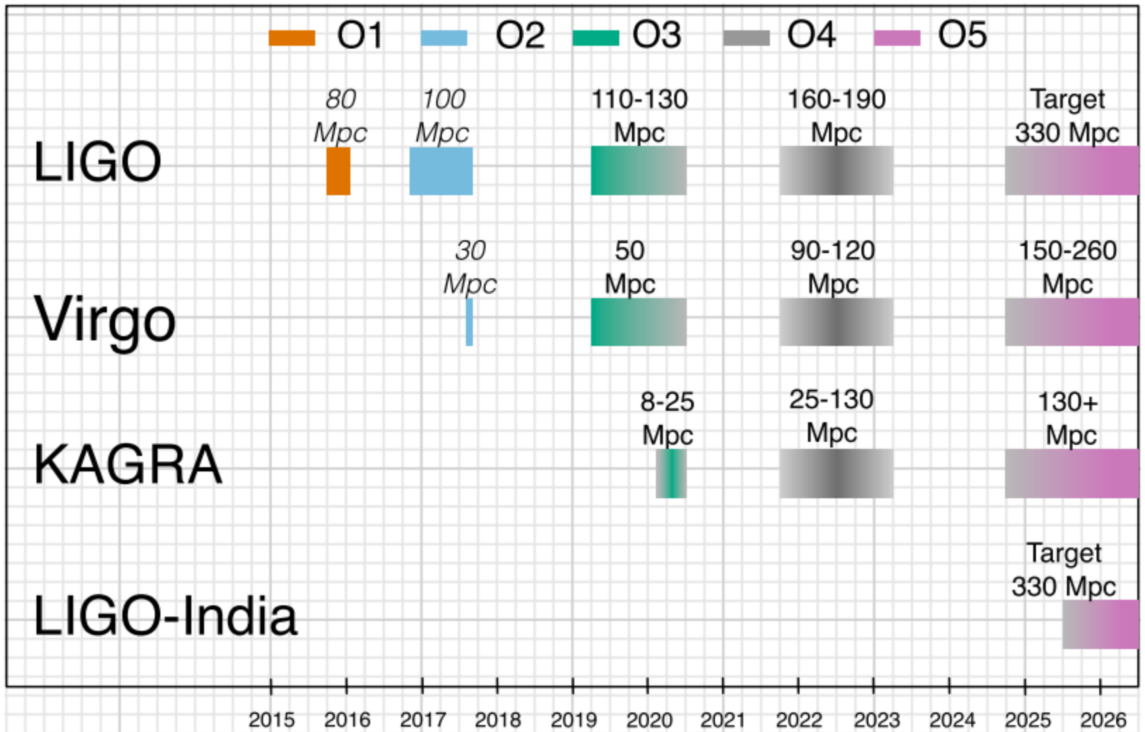

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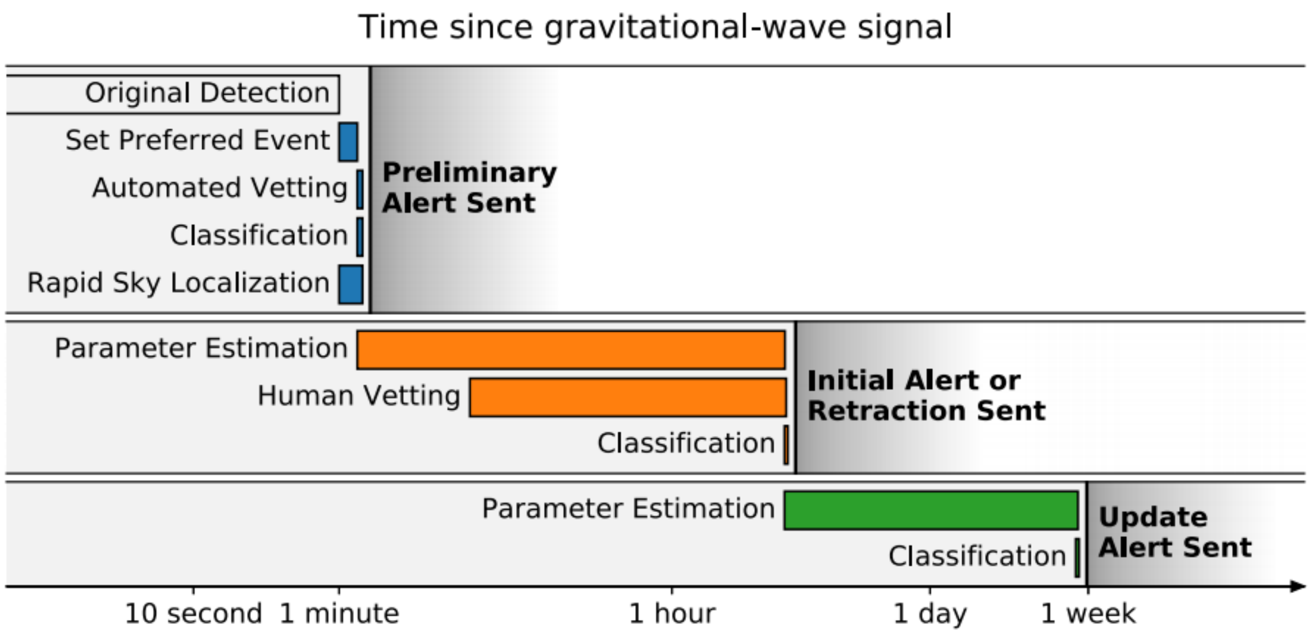

https://arxiv.org/abs/1304.0670

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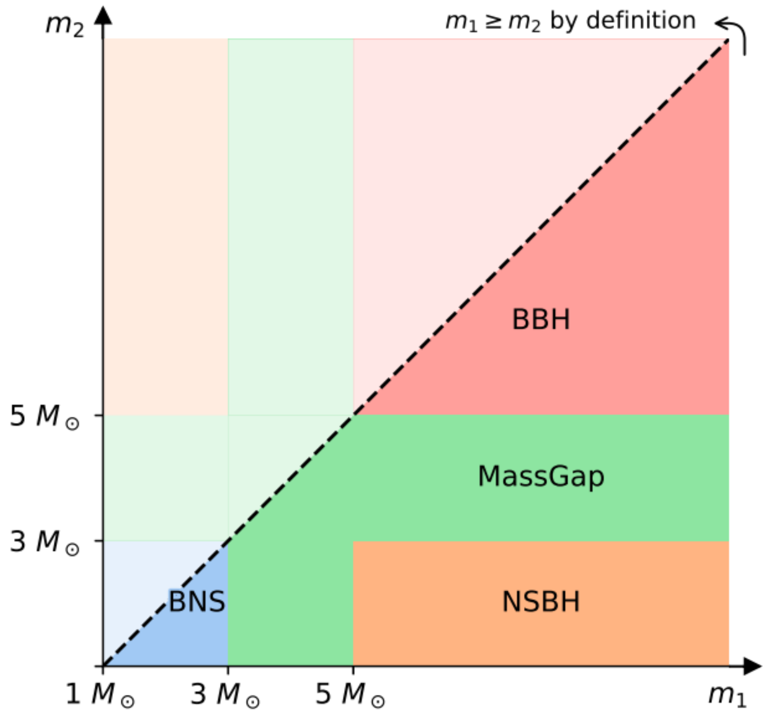
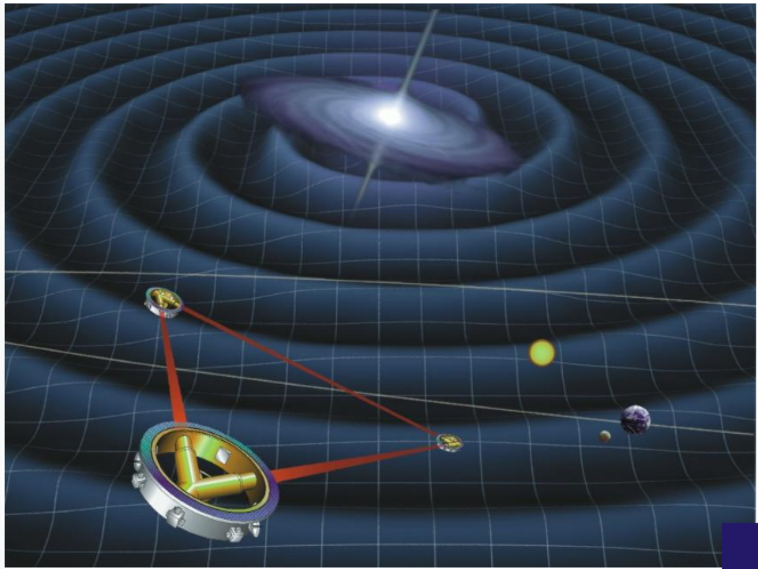


https://arxiv.org/abs/1304.0670

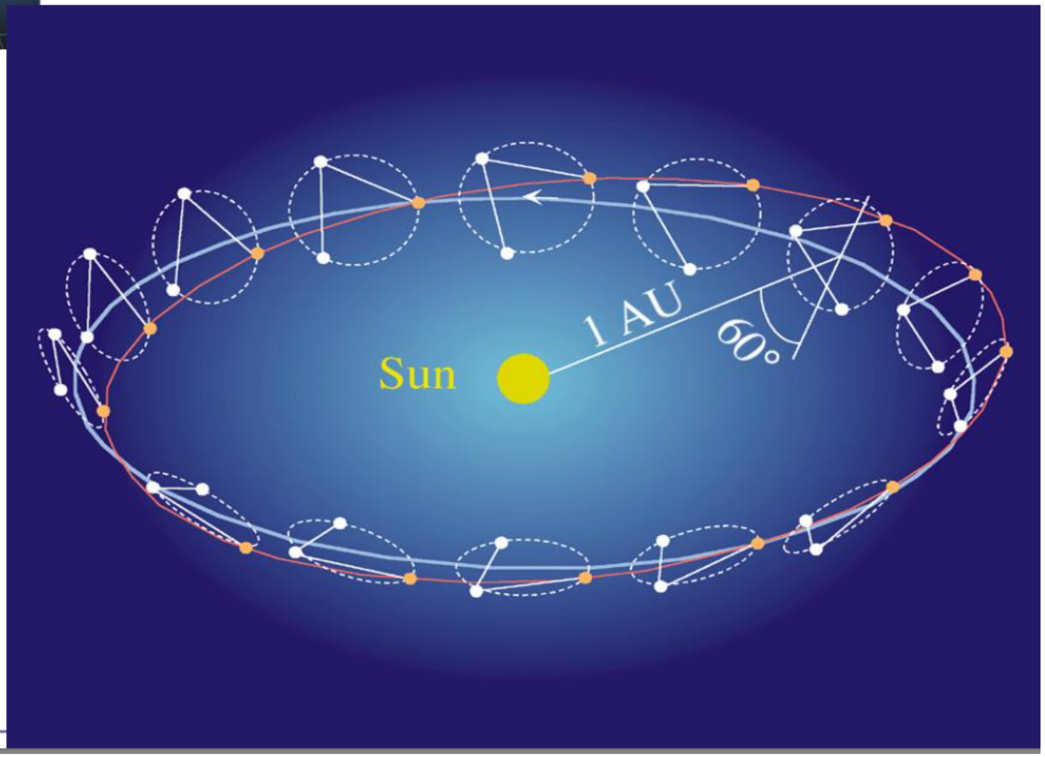
Exercise #3

- Find the status of eLISA GW observatory
  – https://www.elisascience.org

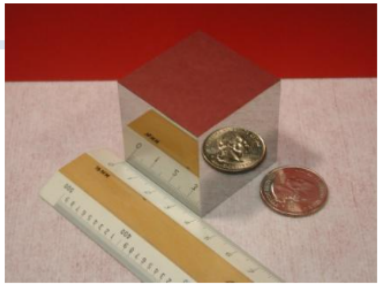
Gravitational wave antenna in space - LISA



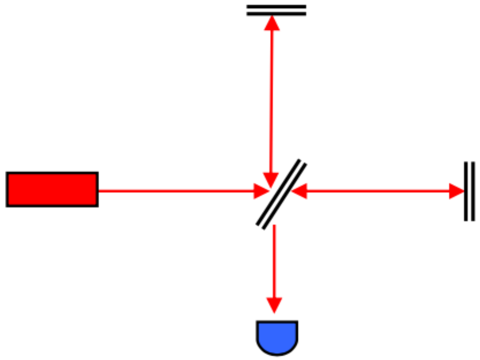
- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between NASA and ESA*

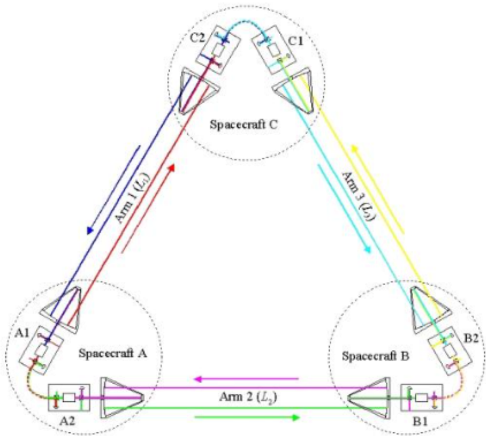


LISA interferometry

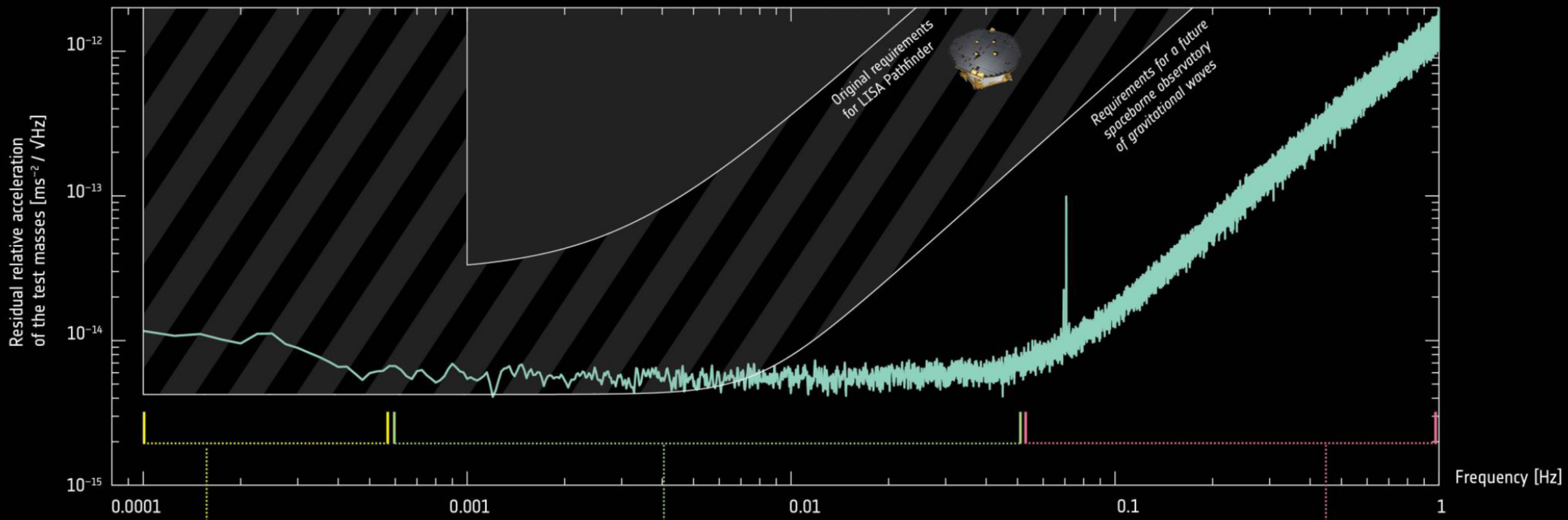


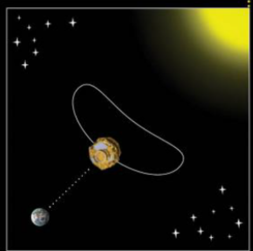
- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
  - Arm lengths change continuously
  - Light travel time ~17 seconds
  - Constellation is rotating and translating in space





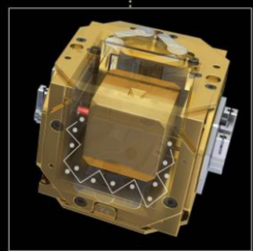
→ LISA PATHFINDER EXCEEDS EXPECTATIONS





Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.

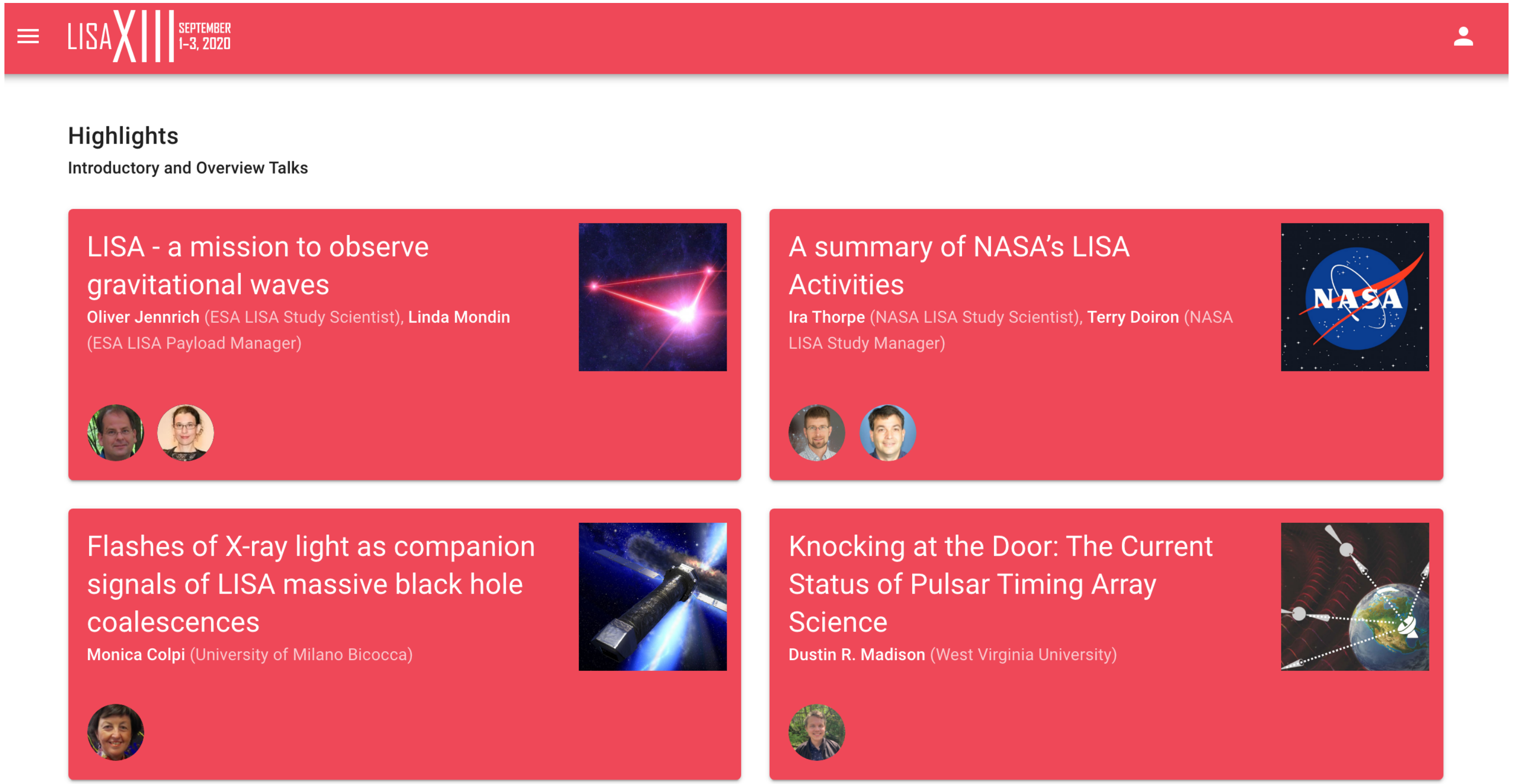
Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

Exercise #3

- Find the status of eLISA GW observatory
  - https://www.elisascience.org



https://lisasymposium13.lisamission.org/agenda/highlights/

Exercise #3

- Find the status of PTA GW methods
  – http://ipta4gw.org/

International Pulsar Timing Array Data Release Gravitational Waves Meetings Outreach People

A Global, Galactic-Scale Gravitational Wave Detector

Press Release: IPTA strengthens evidence of signal that may hint at gravitational waves

We are pleased to share a press release describing results from the gravitational-wave search of our latest IPTA data release (Data Release 2, or DR2).

Read More ...

IPTA Statement on the DR2 Press Release

The International Pulsar Timing Array (IPTA) is a consortium of consortia[1] , comprised of the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), the Indian Pulsar Timing Array Project (InPTA, and the Parkes Pulsar Timing Array (PPTA). The goal of the IPTA is to detect and characterize the low-frequency gravitational wave universe through timing a global array of approximately 100 millisecond pulsars using the largest radio telescopes in the world. Through sharing resources and creating combined pulsar timing data sets, the IPTA is constructing the most sensitive low-frequency gravitational wave detector possible. Sharing resources will also help to reach other IPTA goals, for example, establishing a pulsar-based reference timescale.

What is a PTA?

PTA = Pulsar Timing Array

Term first described by Romani (1989) and Foster & Backer (1990)

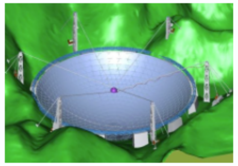
First major realisation of a PTA was the Parkes Pulsar Timing Array project started by R. Manchester

Main goals: 1) **detect gravitational waves**, 2) search for irregularities in terrestrial time standards and 3) improve the Solar System planetary ephemeris

Numerous secondary goals …

PTAs in 2015

EPTA



CPTA

ASKAP

Meerkat

SKA

IPTA

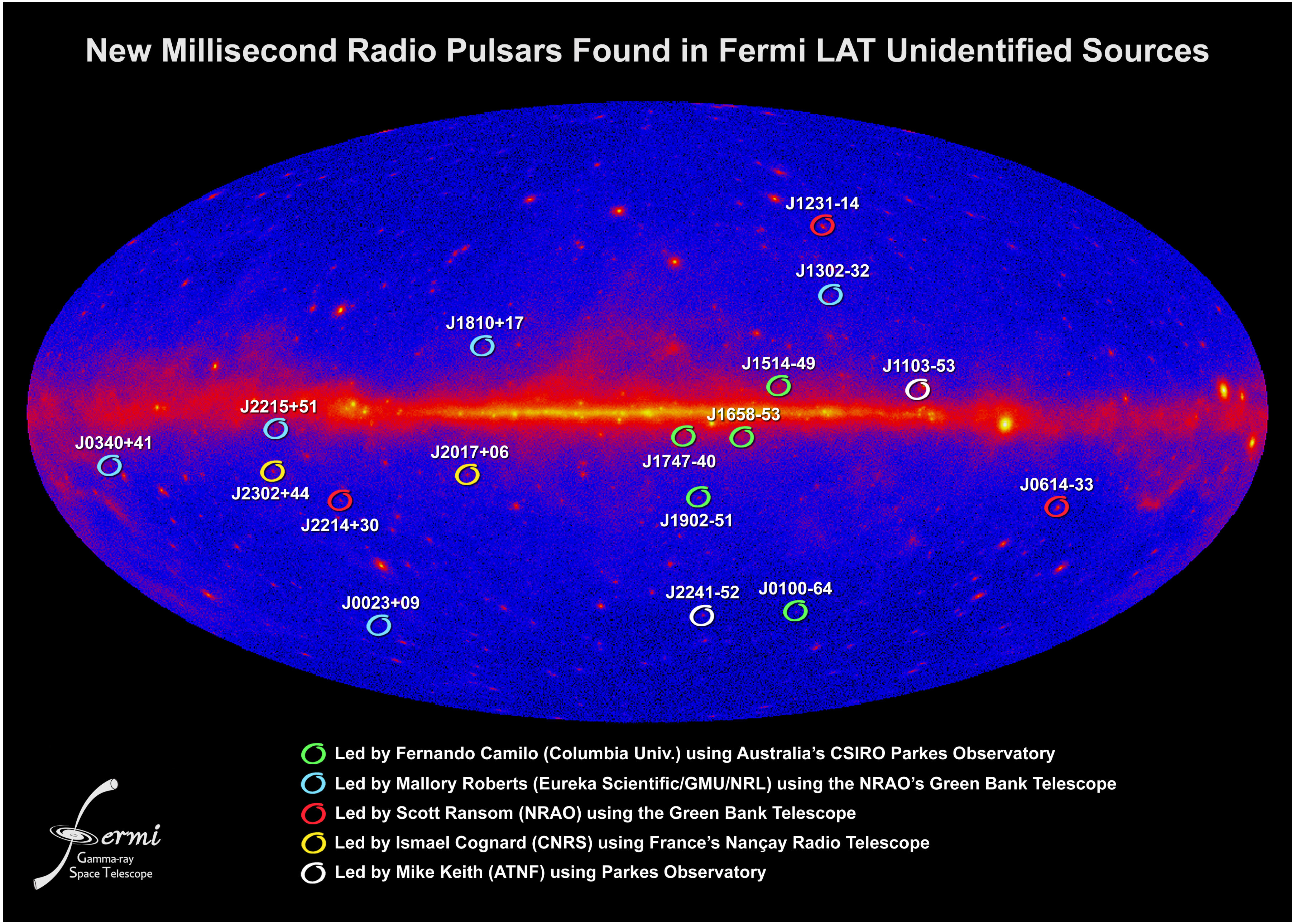
Interest in pulsar community

Interest in gravitational wave community

NANOGrav

PPTA

CSIRO



Fermi Large Area Telescope first year map of the gamma-ray sky at energies above 100 MeV with the locations of the new millisecond pulsars shown. The symbols are color coded according to the discovery team: red led by Scott Ransom (NRAO) using NRAO's Green Bank Telescope (GBT), cyan led by Mallory Roberts (Eureka Scientific/GMU/NRL) also using the GBT, green led by Fernando Camilo (Columbia University) using Australia's CSIRO Parkes Observatory, white led by Mike Keith (ATNF) also using Parkes, and yellow led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope. (Credit: NASA/DOE/Fermi LAT Collaboration)

Exercise #3

- Find the status of PTA GW methods
  - http://ipta4gw.org/

Accessibility menu

CSIRO

Australia Telescope National Facility

Search

ATNF Home | About ATNF | Facilities | Science & Technology | Online Resources | Outreach

IPTA Catch-up meeting 2020

A virtual meeting instead of the in-person IPTA 2020 conference

UTC: 22nd and 23rd September

The IPTA 2020 in-person meeting has been postponed until 2021. Instead we will hold a short, virtual "catch-up" meeting.

Dates, Times and Presentations

Links will be provided here to recordings of each of the presentations.

Joining the meeting

Zoom details have been sent by email. Please discuss the live presentations and the contributed talks/posters/pdfs on the IPTA slack channel at #ipta_virtual_meeting_2020 and #talks. Please check your email for details on how to join this channel.

Contributed presentations, posters and discussion

Any IPTA member may record a short (<10 minute) presentation or submit slides or a poster. Please contact George Hobbs for more details. These talks will be made available here.

Author(s)	Style	Presentation/poster
Bence Becsy, Neil Cornish	Poster	Joint search for bright binaries and a stochastic background in PTA Data
Andrew Casey-Clyde, Chiara Mingarelli, Kris Pardo	Presentation	Constraining Supermassive Black Hole Binary Populations with PTAs
Katie Cella, Stephen Taylor, Luke Kelley	Slides	Host Galaxy Properties of PTA Detectable SMBHBs Using Illustris
Malgorzata Curylo, Tomasz Bulik	Poster	Probing black hole merger history with gravitational waves
Shantanu Desai	Set of slides	Galactic and Extra-galactic Shapiro delay
Timothy Dolch	pptx	Deconvolving Pulsar Signals with Cyclic Spectroscopy: A Systematic Evaluation
Jeffrey Hazborn	10 minute presentation (hosted on YouTube)	Model Dependence of Bayesian Gravitational Wave Background Statistics for PTAs

https://www.atnf.csiro.au/research/conferences/2020/ipta/

Exercise #3

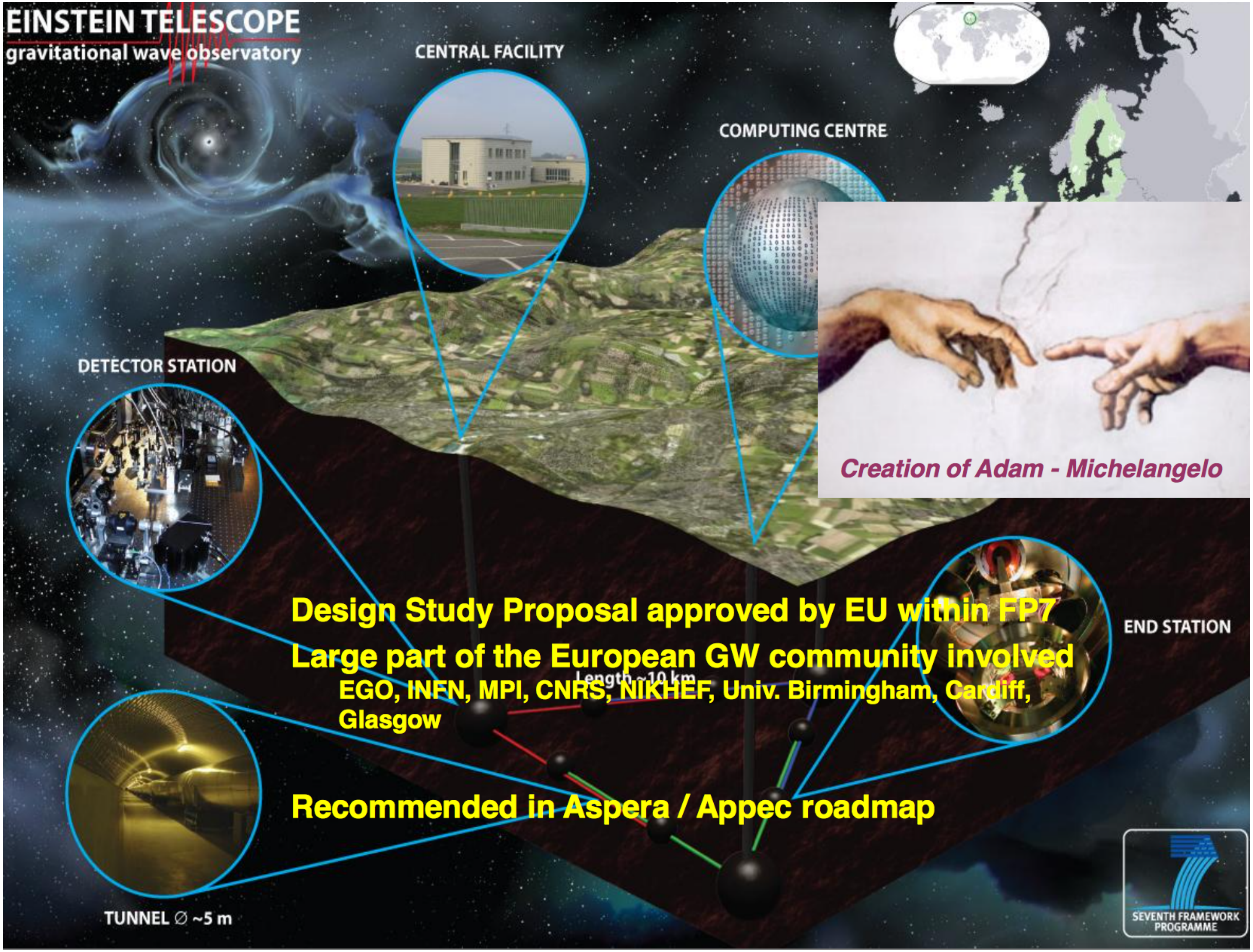
- Find the status of PTA GW methods
  - http://ipta4gw.org/

IPTA 2021 Science Week at a glance

Click on the full schedule links for full program details and connection details.

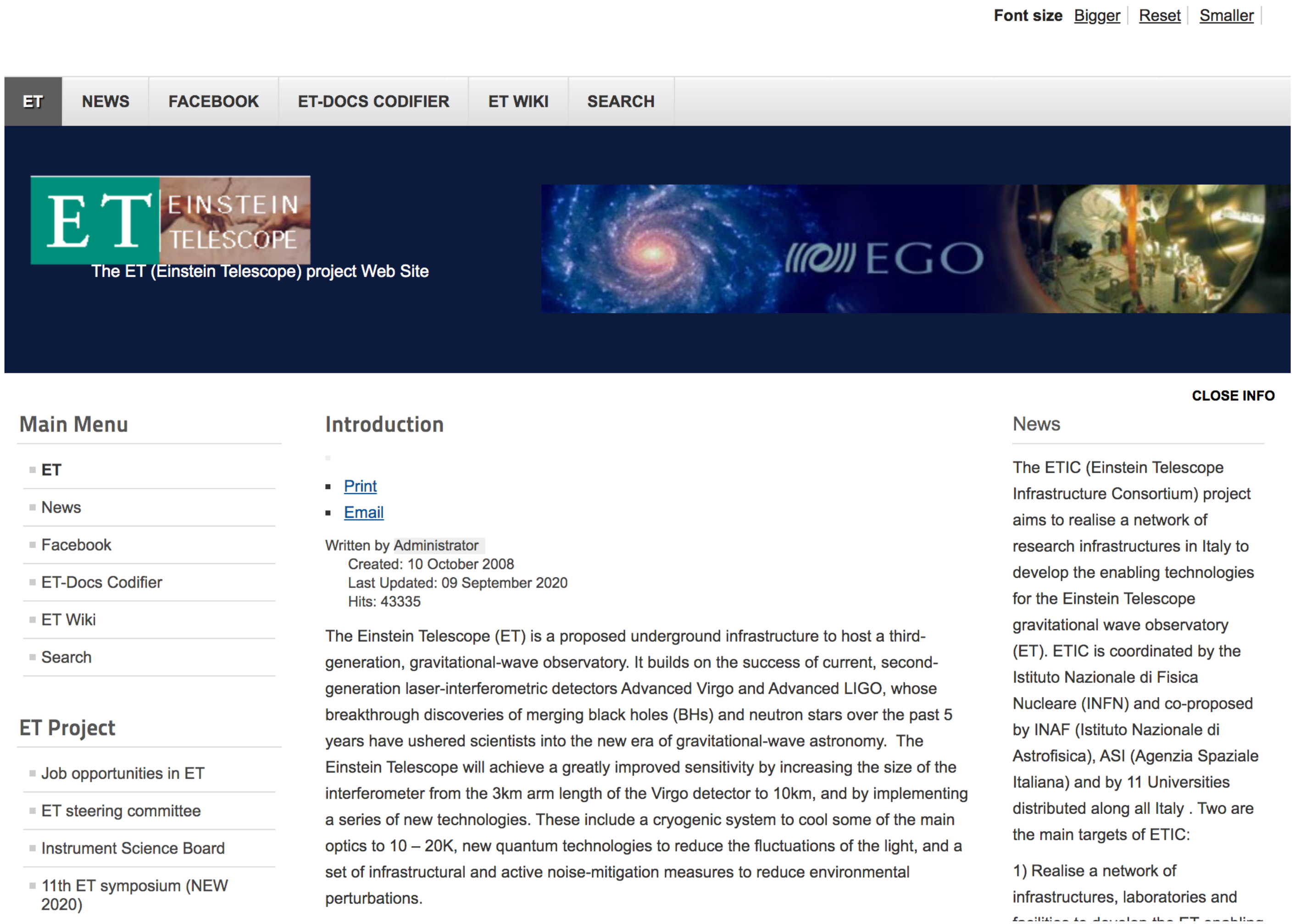
Day	Topics	Start times	Full schedule link
Monday 21st June	Session 1: Overview and PTA Updates Session 2: Overview and PTA Updates Session 3: Pulsar searching	07:00 UTC 15:00 UTC 23:00 UTC	Monday full schedule
Tuesday 22nd June	Session 4: Pulsar timing Session 5: Pulsar timing Session 6: Pulsar timing	07:00 UTC 15:00 UTC 23:00 UTC	Tuesday full schedule
Wednesday 23rd June	Session 7: EPO/Noise budget Session 8: Noise budget Session 9 GW detection	07:00 UTC 15:00 UTC 23:00 UTC	Wednesday full schedule
Thursday 24th June	Session 10: Facilities/GW detection Session 11: Facilities/GW Detection Session 12: GW Detection/DEI	07:00 UTC 15:00 UTC 23:00 UTC	Thursday full schecdule
Friday 25th June	Session 13: New PTAs/GW sources Session 14: GW sources	07:00 UTC 15:00 UTC	Friday full schedule

https://github.com/hannahm8/IPTA2021-ScienceWeekSchedule/wiki/The-week-at-a-glance


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
Creation of Adam - Michelangelo
END STATION
Design Study Proposal approved by EU within FP7
Large part of the European GW community involved
EGO, INFN, MPI, CNRS, NIKHEF, Univ. Birmingham, Cardiff, Glasgow
Length ~10 km
Recommended in Aspera / Appec roadmap
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

The Einstein Telescope

http://www.et-gw.eu/



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ET EINSTEIN TELESCOPE

The ET (Einstein Telescope) project Web Site

EGO

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ET Project

- Job opportunities in ET
- ET steering committee
- Instrument Science Board
- 11th ET symposium (NEW 2020)

Introduction

- Print
- Email

Written by Administrator
Created: 10 October 2008
Last Updated: 09 September 2020
Hits: 43335

The Einstein Telescope (ET) is a proposed underground infrastructure to host a third-generation, gravitational-wave observatory. It builds on the success of current, second-generation laser-interferometric detectors Advanced Virgo and Advanced LIGO, whose breakthrough discoveries of merging black holes (BHs) and neutron stars over the past 5 years have ushered scientists into the new era of gravitational-wave astronomy. The Einstein Telescope will achieve a greatly improved sensitivity by increasing the size of the interferometer from the 3km arm length of the Virgo detector to 10km, and by implementing a series of new technologies. These include a cryogenic system to cool some of the main optics to 10 – 20K, new quantum technologies to reduce the fluctuations of the light, and a set of infrastructural and active noise-mitigation measures to reduce environmental perturbations.

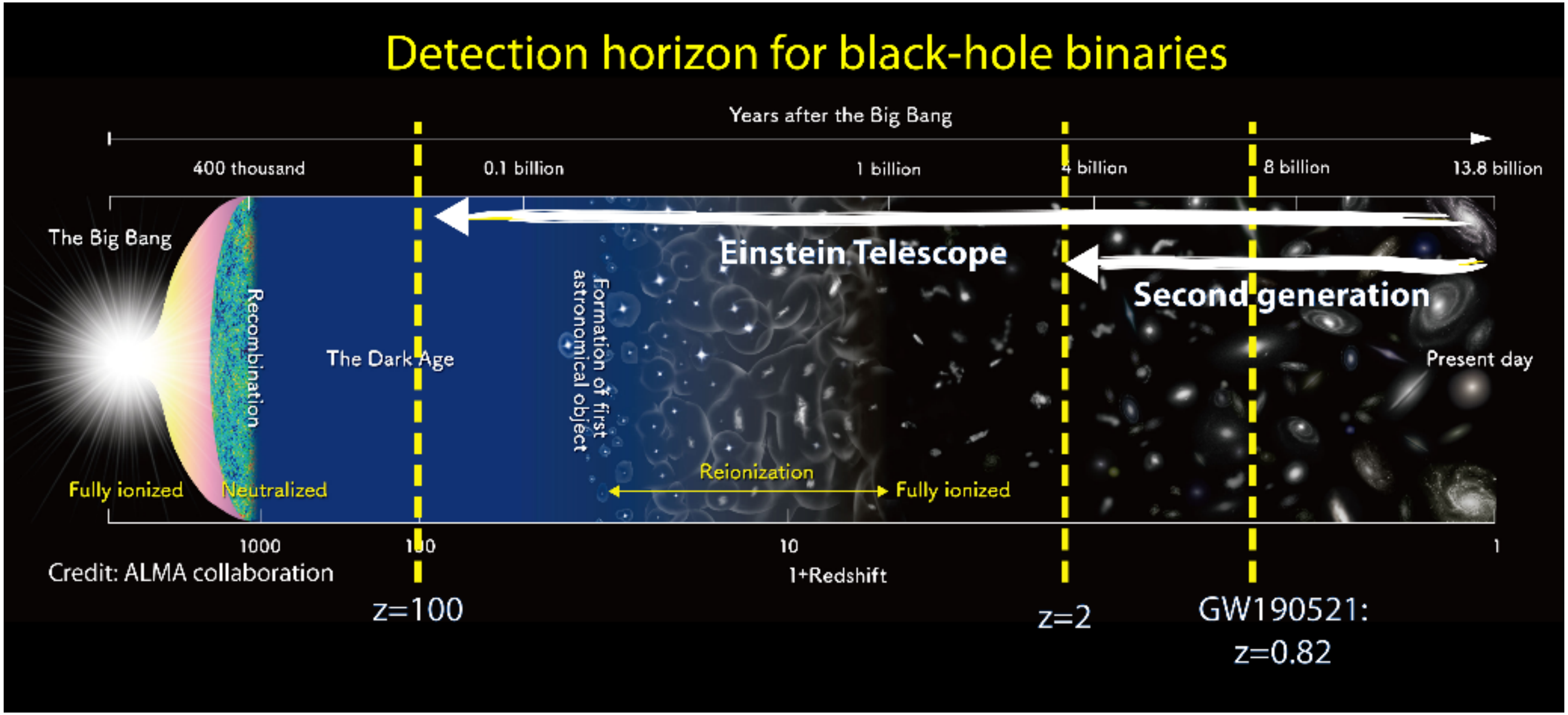
News

The ETIC (Einstein Telescope Infrastructure Consortium) project aims to realise a network of research infrastructures in Italy to develop the enabling technologies for the Einstein Telescope gravitational wave observatory (ET). ETIC is coordinated by the Istituto Nazionale di Fisica Nucleare (INFN) and co-proposed by INAF (Istituto Nazionale di Astrofisica), ASI (Agenzia Spaziale Italiana) and by 11 Universities distributed along all Italy . Two are the main targets of ETIC:

1) Realise a network of infrastructures, laboratories and

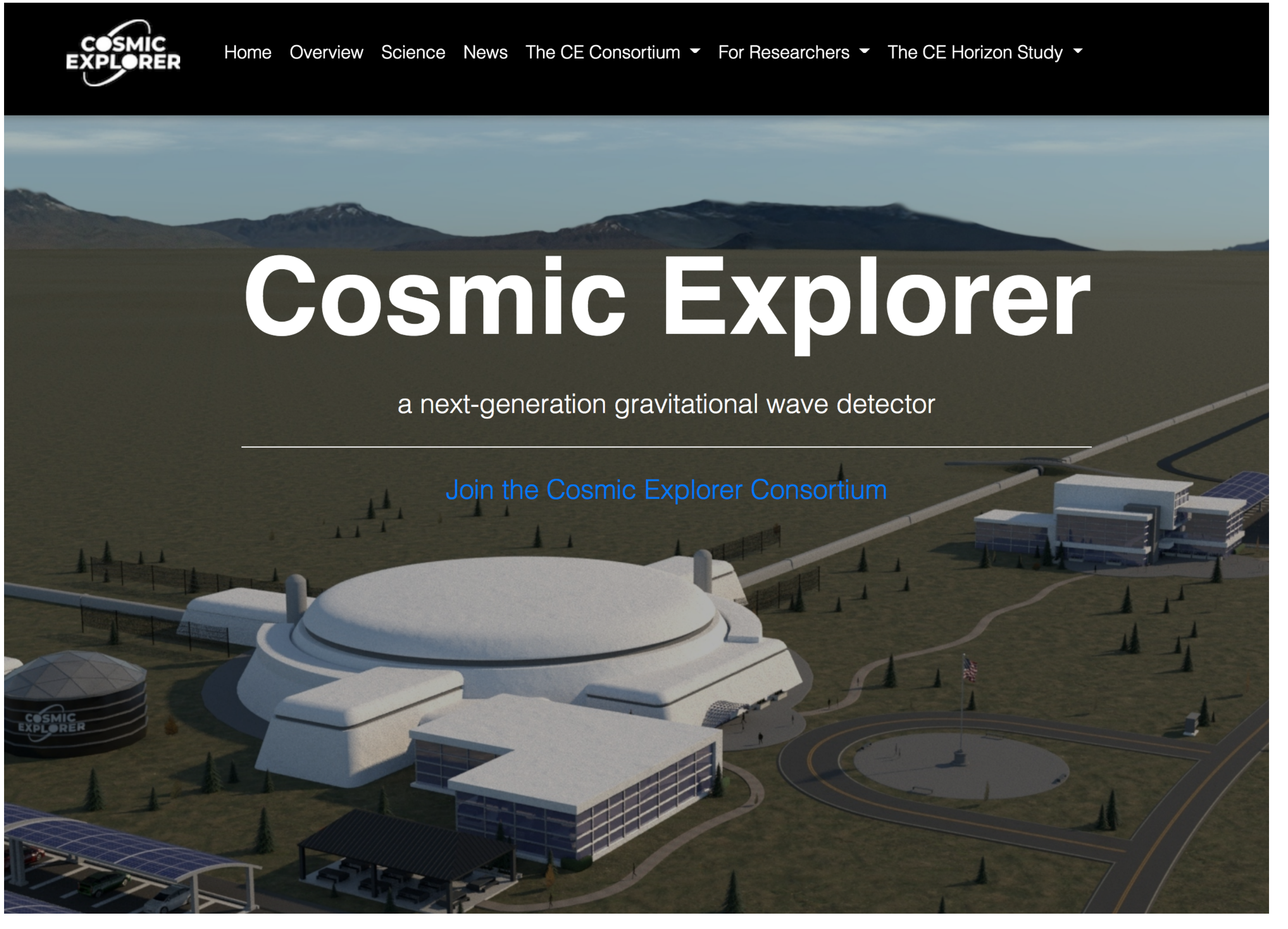
The Einstein Telescope

http://www.et-gw.eu/



The Cosmic Explorer

https://cosmicexplorer.org/



Astrofisica Nucleare e Subnucleare

GRB and GW

Advanced Era GW-detectors (ADE)

LIGO-H

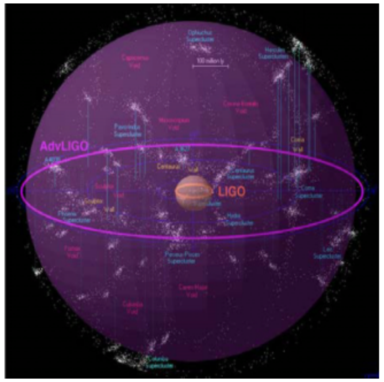
LIGO-L

Virgo

LIGO and **Virgo** detectors
are currently being **upgraded**

⬇

boost of sensitivity
by a **factor of ten**
(of 10^3 in number of detectable sources)



Advanced era
Detection rates of compact binary coalescences

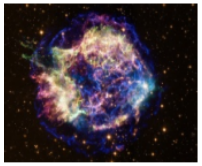
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(Abadie et al. 2010, CQG 27)

Mass: NS = 1.4 Mo
BH = 10 Mo

Advanced era
Sky location and orientation averaged range

197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH



Core-Collapse Supernovae

2-4 yr^{-1} EM-observed within **20 Mpc**

Rate of GW-detectable events unknown

GW-signal detectable **< Milky Way** (Ott et al. 2012, Phy.R.D.)
few Mpc (Fryer et al. 2002, ApJ, 565)

Optimistic models **10 - 100 Mpc** (Piro & Pfahl 2007)
(Fryer & New 2011)

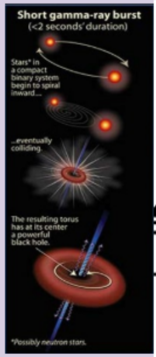
Electromagnetic emission

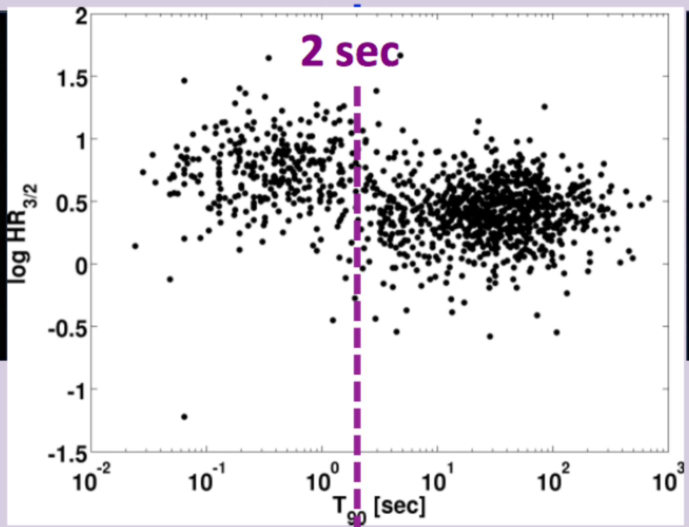
Merger of NS-NS / NS-BH

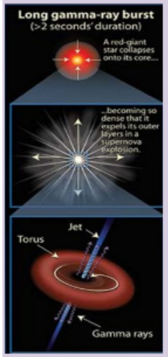
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB







Long Soft GRB

Kilonovae

(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c

Short GRBs: how many on-axis/off-axis

Observed on-axis SHORT GRBs

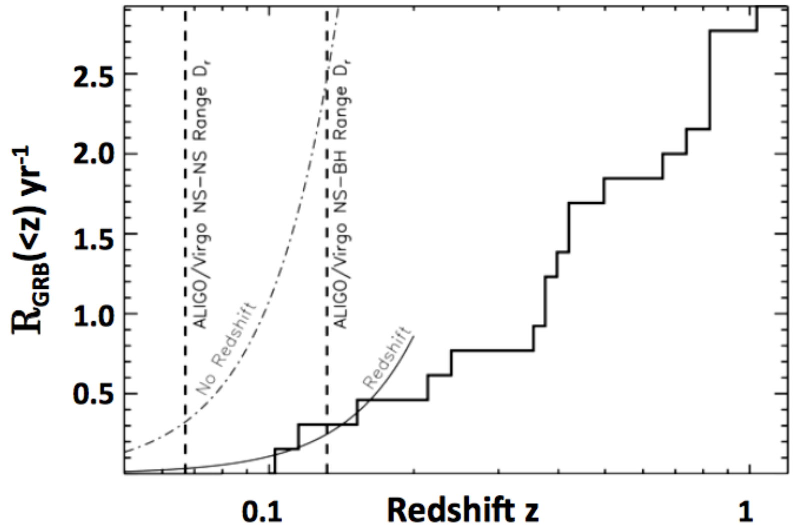
So far **~100** of which **~20** at known distance

<z>=0.5 = 3 Gpc

zmin = 0.12 = 560 Mpc

Energy = 10^{48-52} erg

GW/on-axis short GRB detection rate



All-sky gamma-ray monitor

→ **0.3 short GRBs per year** (NS-NS range)

→**3 short GRBs per year** (NS-BH range)

Metzger & Berger 2012, ApJ 746

*The **number of off-axis wrt on-axis** short GRB depend on the **beaming angle** that is very poorly constrained: **only two measures** → 7 and 14 degree*

Advanced LIGO and Virgo NS-NS detection rate based on short GRB observations

Assuming that the progenitor of all the short GRBs observed are NS-NS merger:

Short GRB observations → NS-NS merger rate

$$R_{NS\text{-}NS} = R_{GRB}/(1-\cos(\theta))$$

$R_{NS\text{-}NS}$

8 -1100 $Gpc^{-3} yr^{-1}$ (Coward et al. 2012)

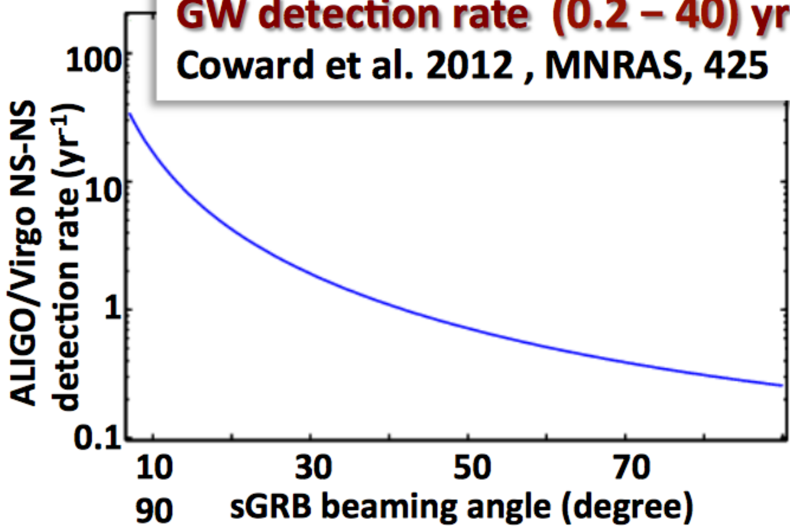
92–1154 $Gpc^{-3} yr^{-1}$ (Siellez et al. 2013)

Theoretical prediction

10-10000 $Gpc^{-3} yr^{-1}$ (Abadie et al. 2010)

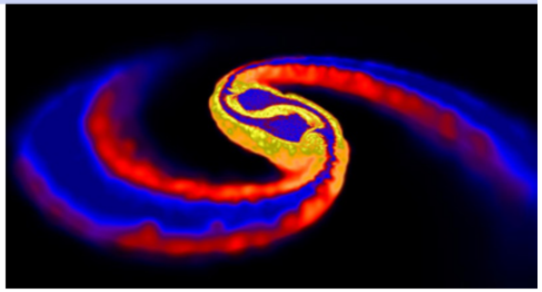
GW detection rate (0.2 – 40) yr^{-1}

Coward et al. 2012 , MNRAS, 425

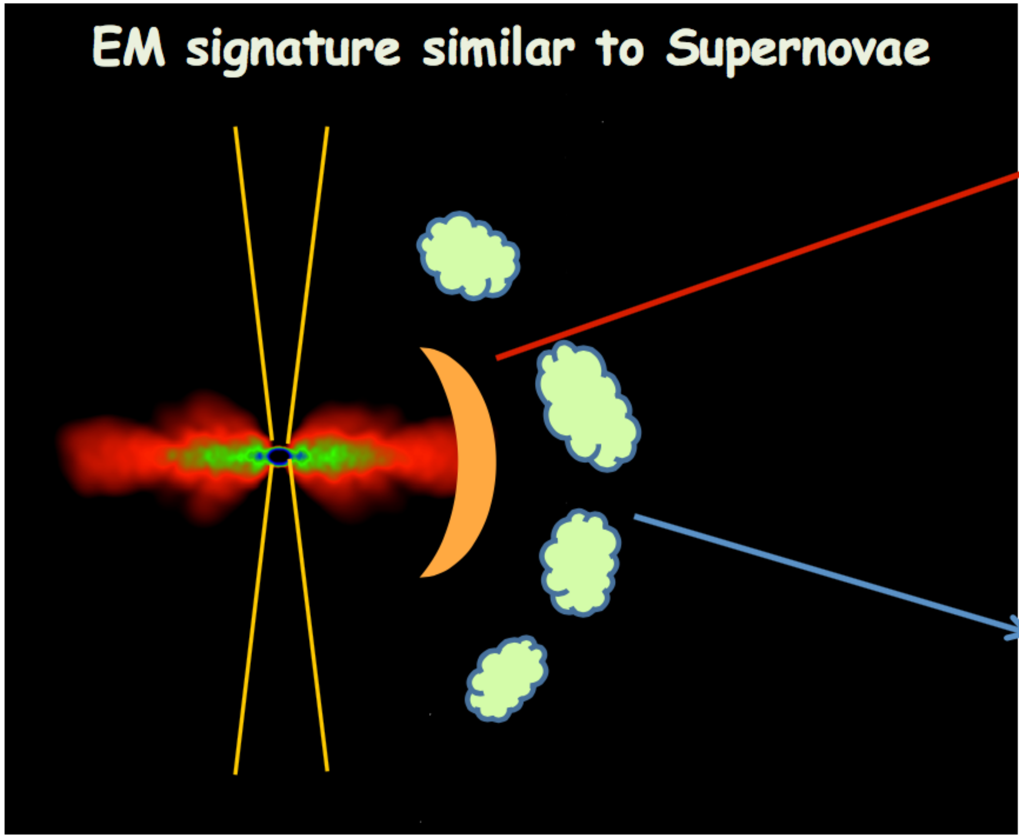


Kilonovae

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected**
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.2 c)**



(Piran et al. 2013, MNRAS, 430; Rosswog et al. 2013 , MNRAS, 430)



Macronova – Kilonova

short lived IR-UV signal (days) powered by the radioactive decay of heavy elements synthesized in the ejected outflow

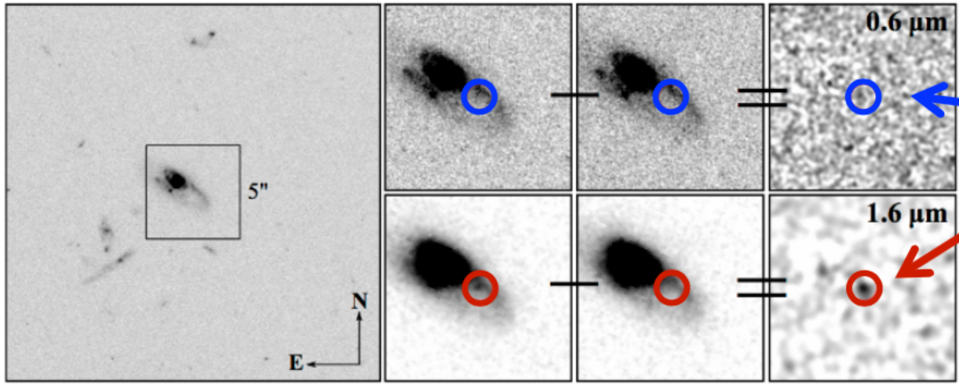
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;
Piran et al. 2013, MNRAS, 430

RADIO REMNANT

long lasting radio signals (years)
produced by interaction of ejected sub-relativistic outflow with surrounding matter **Piran et al. 2013, MNRAS, 430**

Possible HST kilonova detection for short GRB 130603B after 9.4 days

Tanvir et al. 2013, Nature ,500



HST two epochs (9d, 30d) observations

F606W/optical

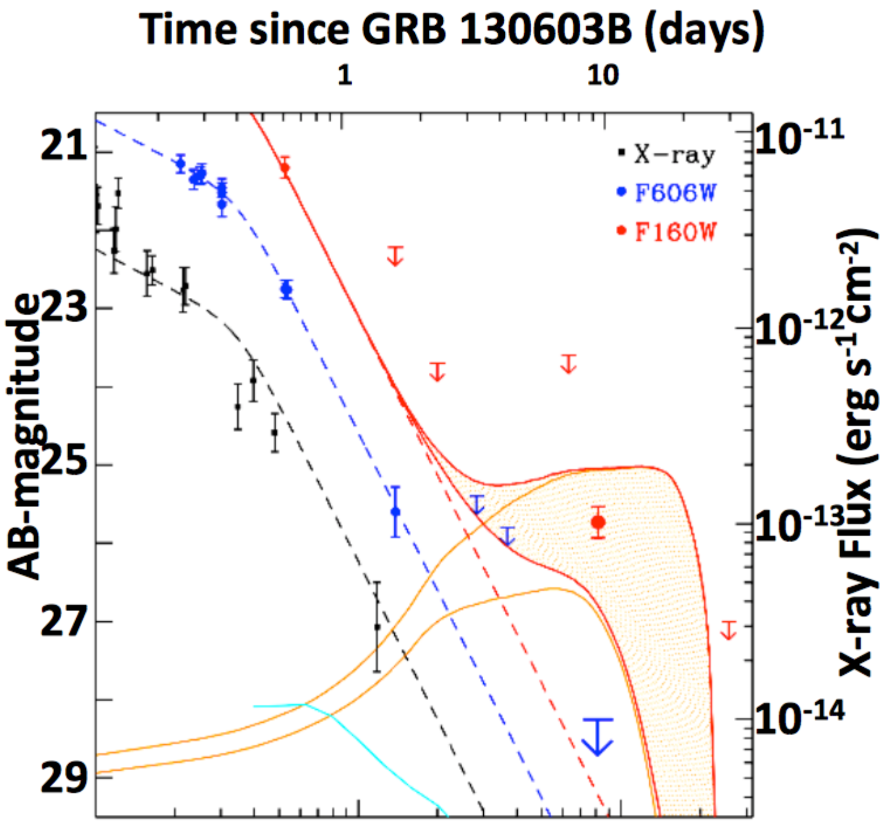
NIR/F160W

Afterglow and host galaxy z=0.356

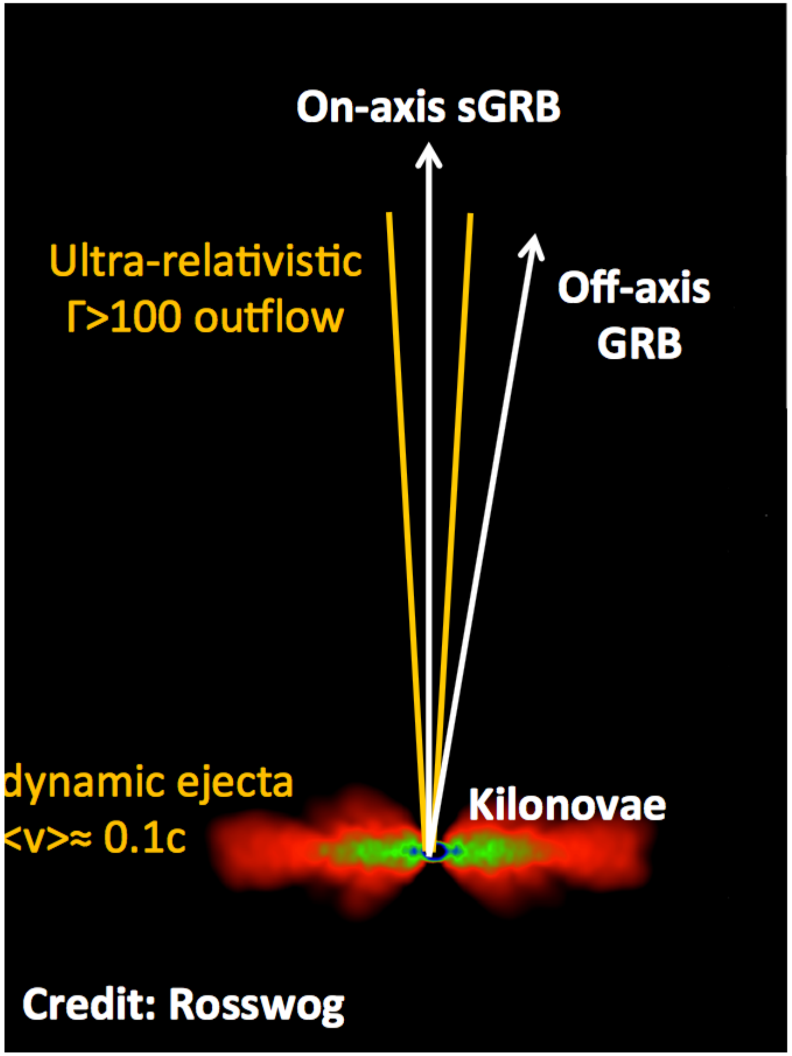
Orange curves → kilonova NIR model
ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model



EM signals from NS-NS/NS-BH merger and massive star core-collapse



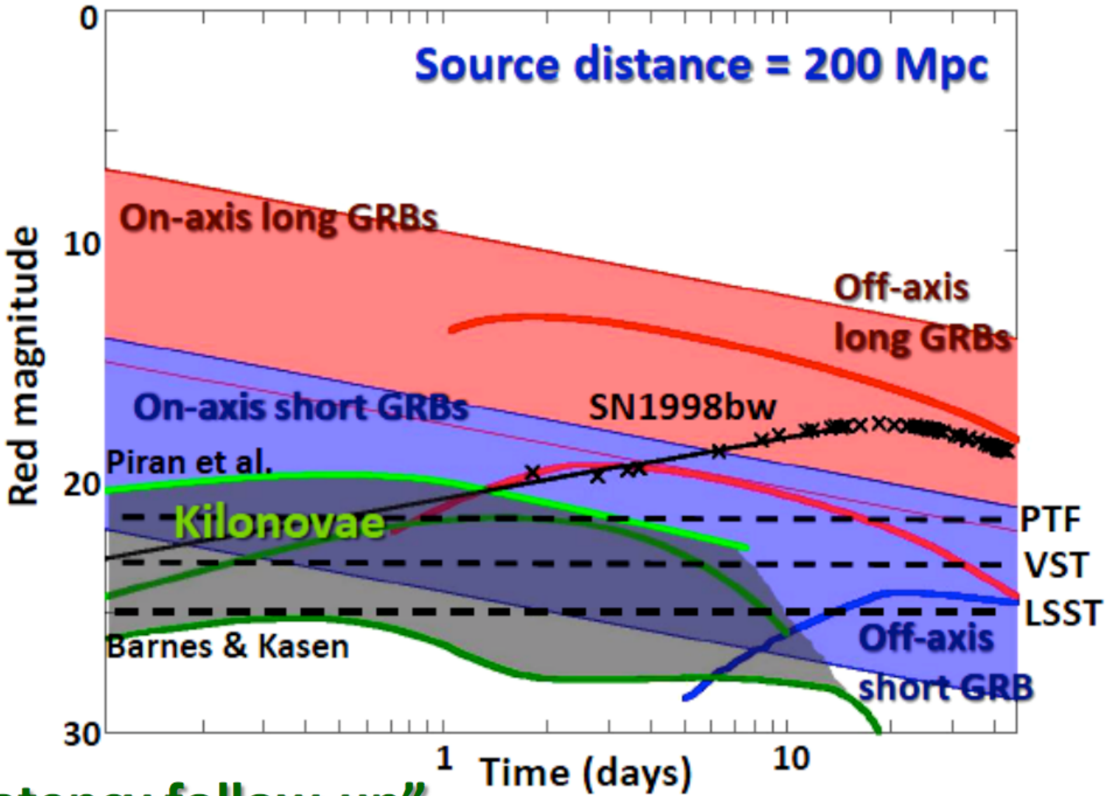
❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"GRB Triggered analysis"**

❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

"Low-latency EM follow-up"

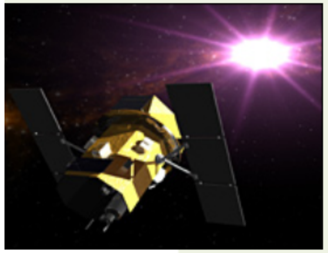


❖ **Radio:**

GW trigger → radio search **"High-latency follow-up"**

Blind radio search → GW search **"Triggered off-line analysis"**

GRB prompt emission → TRIGGERED GW SEARCH

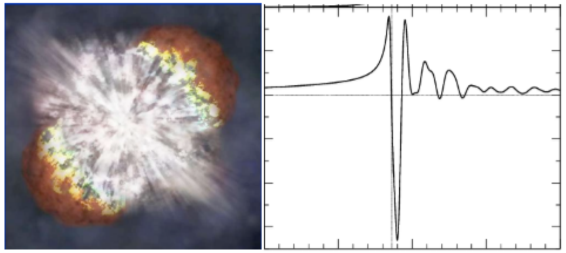


Known **GRB event time** and **sky position:**

→ **reduction in search parameter space**

→ **gain in search sensitivity**

GW transient searches

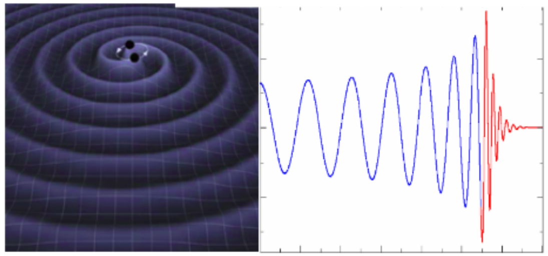


Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

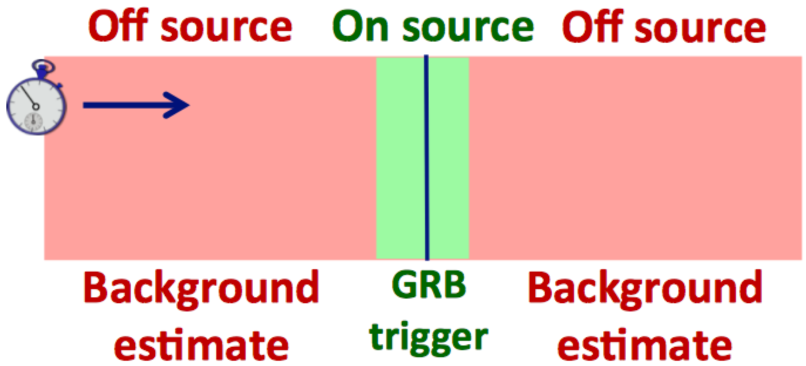
→ **Excess power**



Compact Binary Coalescence

Known waveform

→ **Matched filter**



Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010** while 2 or 3 LIGO/Virgo detectors were taken good data

No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

Astrophysical non-detection results for single events

Short GRB070201 / GRB051103

➢ gamma-ray emission:

→GRB070201 sky position overlaps with M31 (Andromeda, **770 kpc**)

→ GRB051103 sky position overlaps with M81 (**3.6 Mpc**)

➢ Non detection of GWs from binary coalescence

→ compact binary progenitor in M31excluded at 99% c.l.

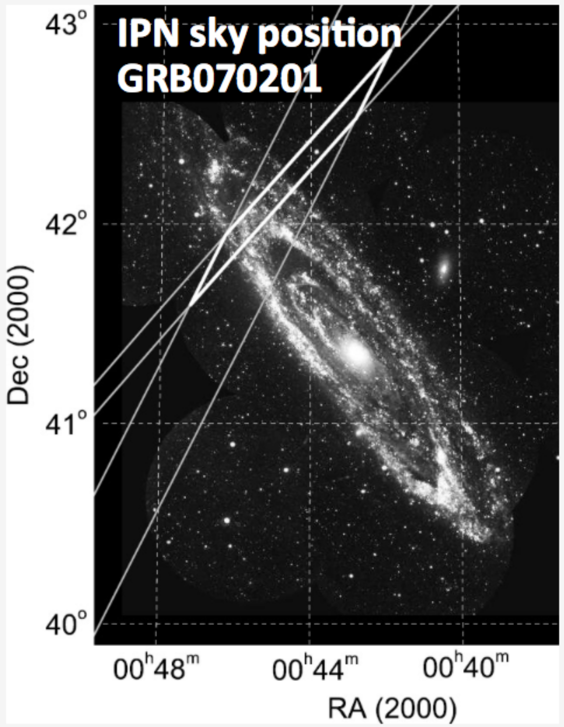
→ comapct binary progenitor in M81excluded at 98% c.l.

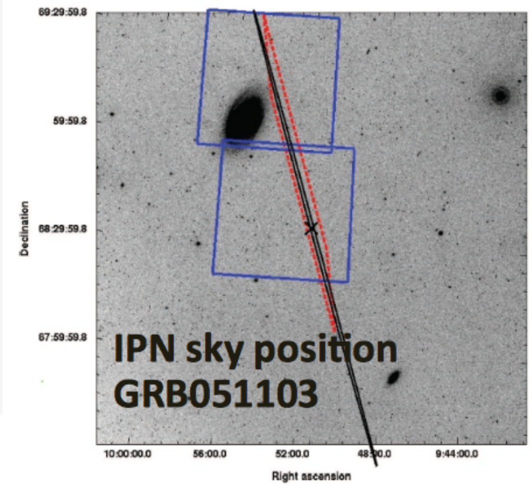
➢ Non detection of GW burst sets limits on emitted energy compatible with:

→ **soft gamma-ray repeater giant flare**

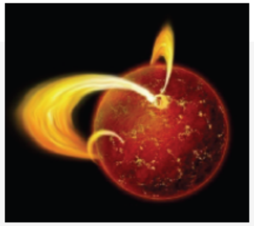
→ **coalescence in galaxy more distant than M31/M81**

Abbott et al 2008, ApJ, 681; Abadie et al. 2012, ApJ, 755





Other EM Triggered GW Searches



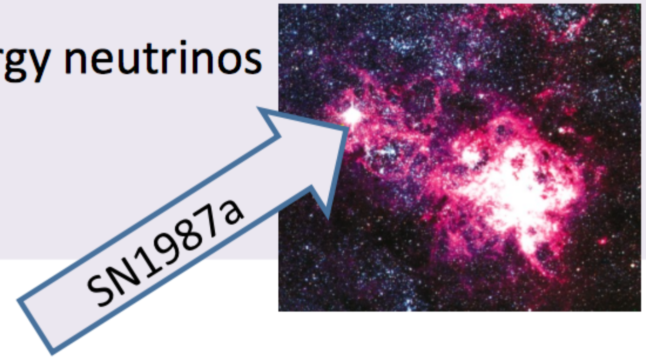
Soft Gamma Ray Repeaters & Anomalous X-ray Pulsars

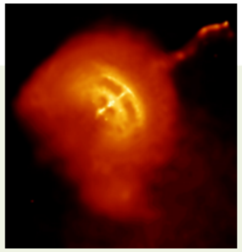
- Magnetars which emit **hard X-ray/gamma repetitive 0.1 sec flares** (10^{42} erg/s) & **giant flares** (10^{47} erg/s)
- Maximum **energy available for GWs:**
  → Crust-cracking **10^{-7} -10^{-4} $M_o c^2$**
  → Magnetic rearrangement **10^{-9}-10^{-6} $M_o c^2$**

Abbott et al. 2008, PRL, 21110
Abbott et al. 2009, ApJ, 701
Abadie et al. 2011, ApJ, 734

Core-Collapse Supernovae

- Energy in GW **10^{-8} -10^{-4} $M_o c^2$**
- 2-4 yr^{-1} EM-observed within 20 Mpc
- Challenges in EM: **nightly/weekly optical/X-ray survey** of nearby galaxies
- Low-energy neutrinos





Pulsar glitches:

sudden increase in the NS rotational phase, frequency or frequency derivatives observable in **radio and gamma-ray pulsars**

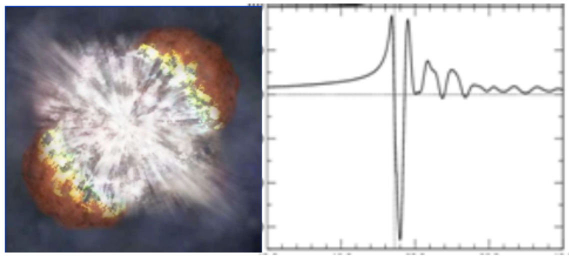
Expected energy in GW: **10^{-16} -10^{-12} $M_o c^2$**

Abadie et al.2011PhRvD,83

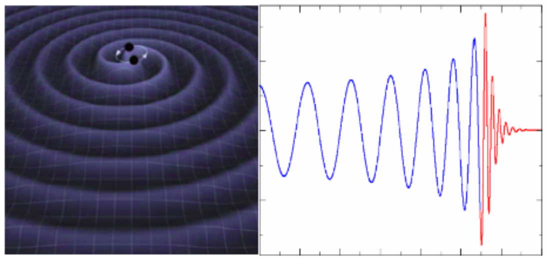
2009-2010 first Electromagnetic follow-up of candidate GW events

Low-latency GW data analysis pipelines

GW transient searches



Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ Excess power



Compact Binary Coalescence
Known waveform
→ Matched filter

enabled us to:

1) identify GW candidates in "real time"

2) obtain prompt EM observations

Abadie et al. 2012, A&A 539

Abadie et al. 2012, A&A 541

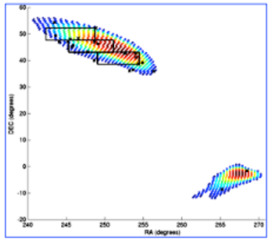
GW triggers

Sky Pointing Position

EM facilities

LIGO-H LIGO-L

Virgo



Event validation

"Search Algorithms" to identify the GW-triggers

"Software" to identify GW-trigger for the EM follow-up:

- select statistically significant triggers wrt background
- determine telescope pointing

~ 10 min. → ~ 30 min.

Advanced detector era latency expected to be improved to few minutes!

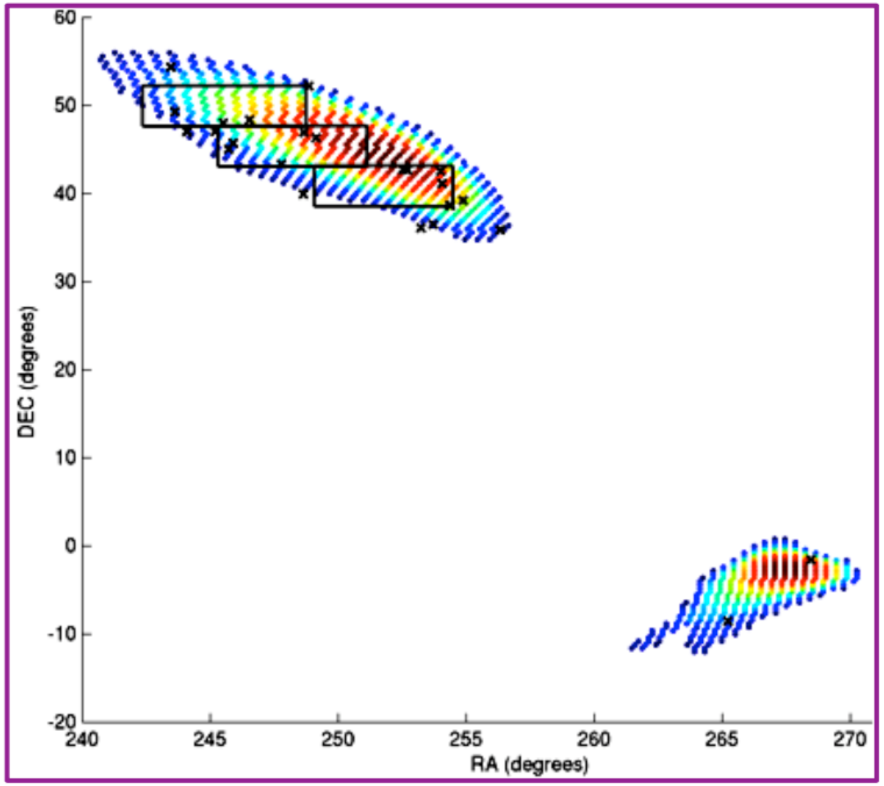
Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541
Evans et al. 2012, ApJS 203
Aasi et al. 2014, ApJS, 211

Additional priors to improve the localization accuracy and increase the chance to observe the EM counterpart

To determine each telescope pointing position:

The probability skymap of each GW trigger was 'weighted'

→ taking into account **luminosity** and **distance of galaxies within the LIGO/Virgo horizon** for binary containing a NS 50 Mpc



Galaxy targeting strategy

Astrofisica Nucleare e Subnucleare
Gravitational Waves Science

GW Science

Academic Training Lecture Regular Programme

Gravitational Waves: The Present and the Future (1/3)

by Jo van den Brand (NIKHEF, Amsterdam, The Netherlands)

Wednesday 9 Oct 2019, 11:00 → 12:00 Europe/Rome

222/R-001 (CERN)

Description	Gravitational waves detection and measurements, the discovery of which was announced to the world in 2016, is a fast moving field. Several events have been detected in LIGO and LIGO+VIRGO, and in spectacular coincidence with gamma ray burst detectors. Clearly we are just at the start of this fast developing discipline. These lectures will discuss the experimental aspects of gravitational wave detection, the information gathered from the present experimental results and the road ahead for these experiments.
	CERN_Academic_L... Recording
From the same series	2 3
Organized by	Jamie Boyd / 90 Participants

https://indico.cern.ch/event/806259/

GW Science

A primer on LIGO and Virgo gravitational wave science

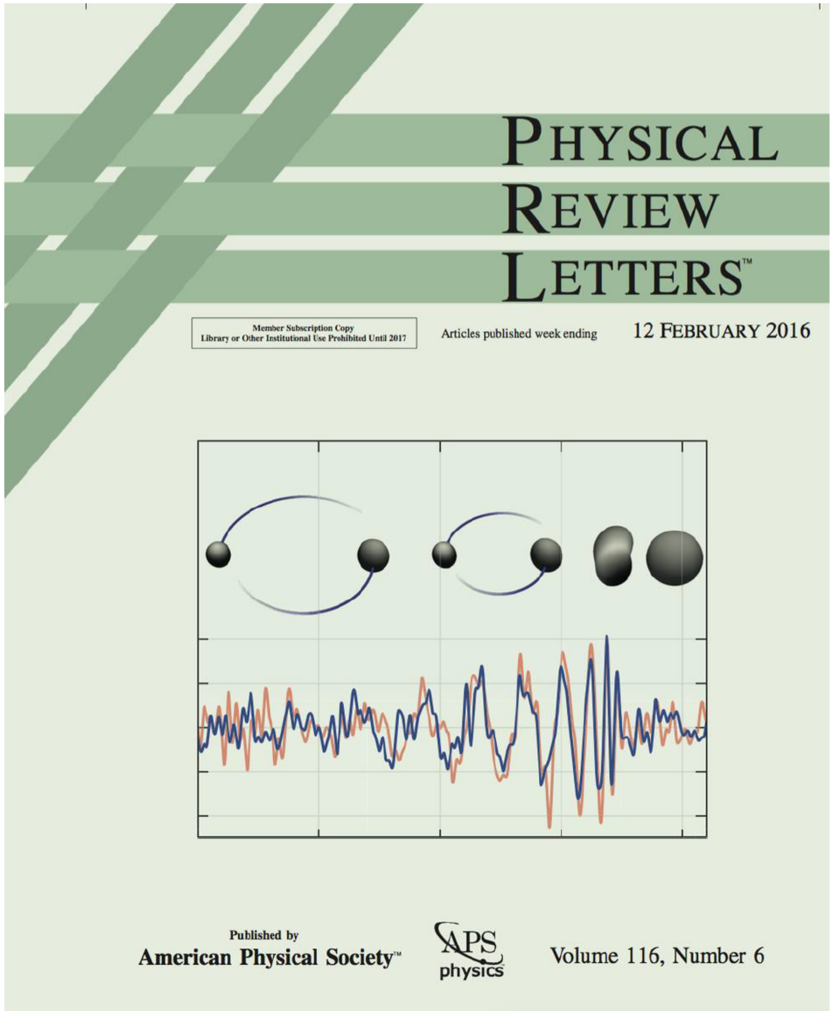
Jo van den Brand, Nikhef and VU University Amsterdam, Maastricht University, jo@nikhef.nl
CERN Academic Lectures, Geneva, October 9-11, 2019

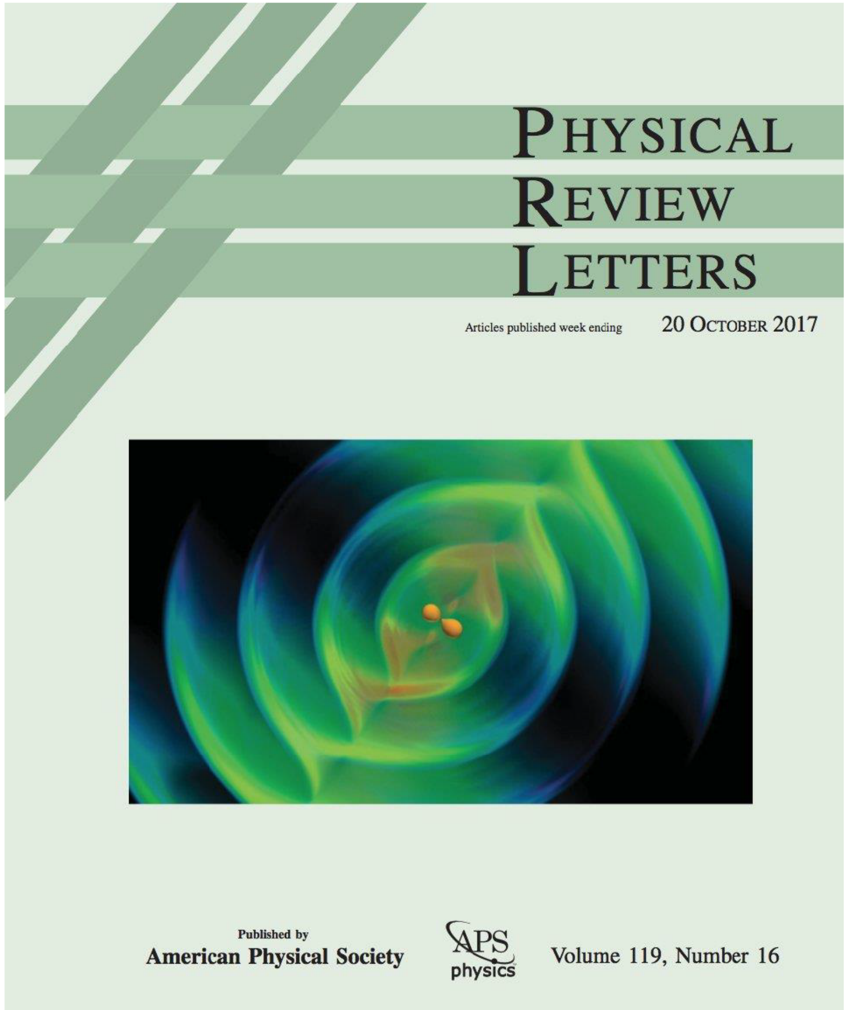
LSC LIGO Scientific Collaboration

Advanced Virgo

https://indico.cern.ch/event/806259/

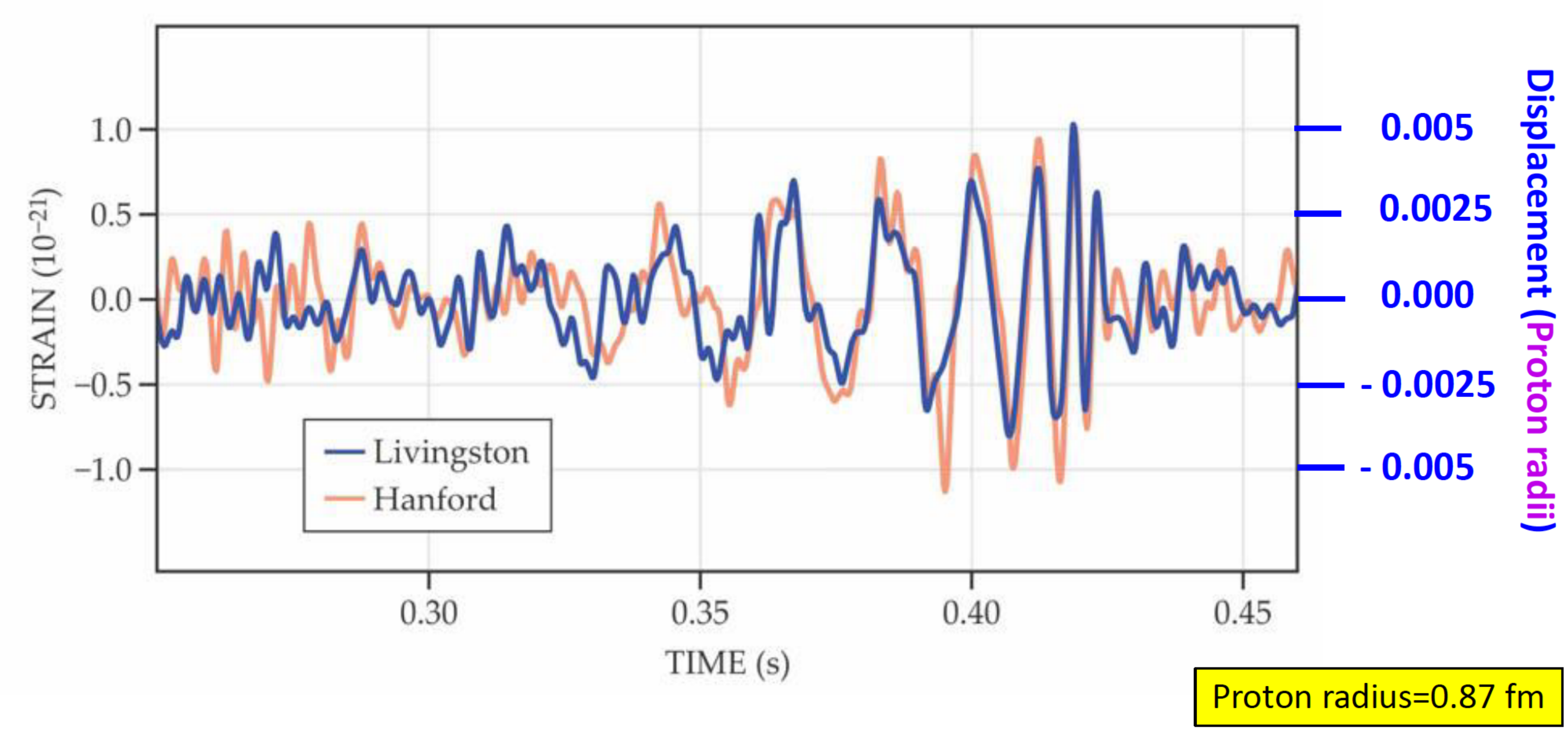
First gravitational wave detection with GW150914 and first binary neutron star GW170817





Event GW150914

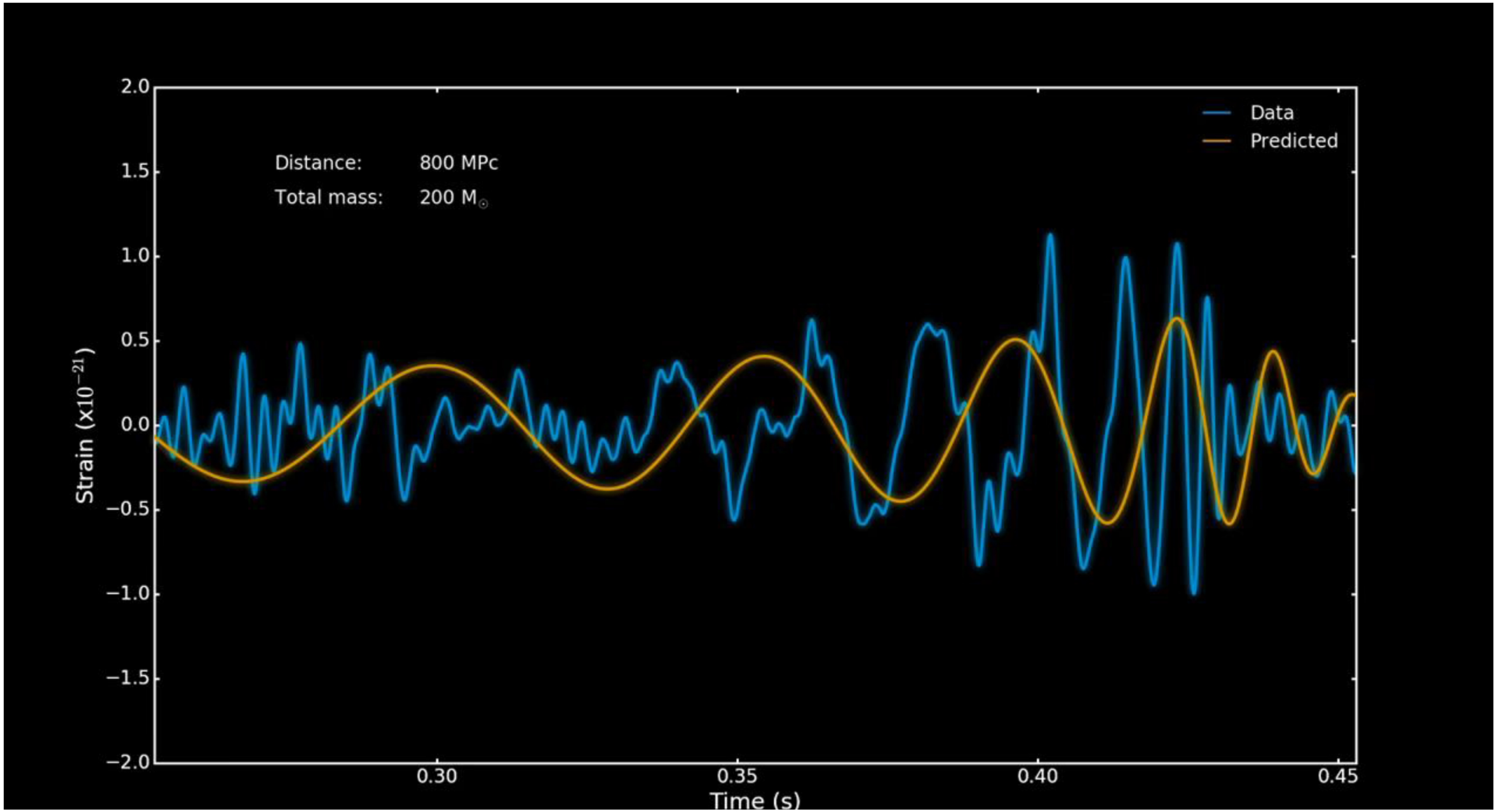
On September 14th 2015 the gravitational waves generated by a binary black hole merger, located about 1.4 Gly from Earth, crossed the two LIGO detectors displacing their test masses by a small fraction of the radius of a proton



Measuring intervals must be smaller than 0.01 seconds

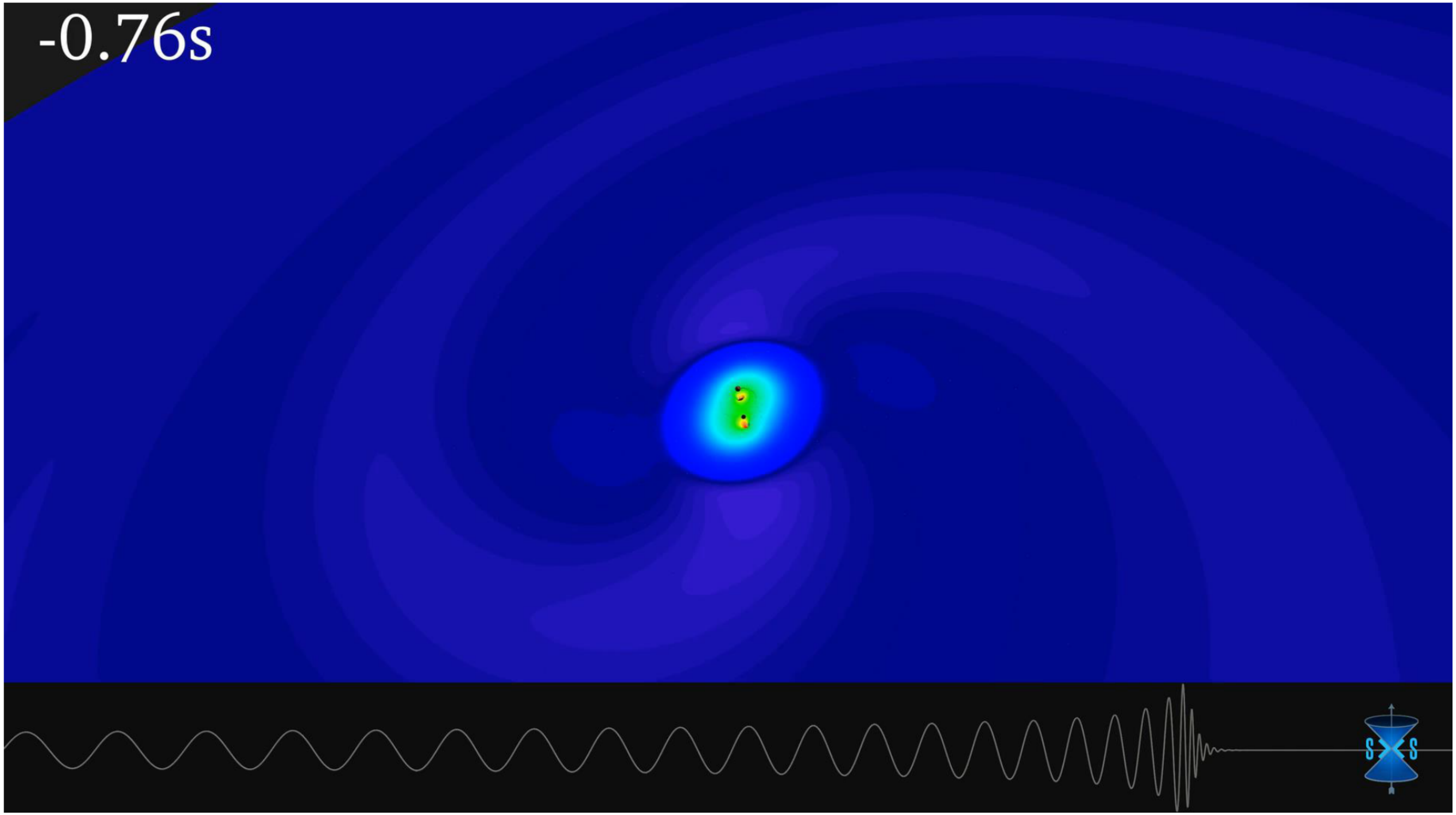
Parameter estimation: GW150914

Once a gravitational wave signal has been identified in the our data, the next step is to measure the properties of the system. This is done by comparing the signal to millions of different waveforms predicted by general relativity and seeing which match the data



Numerical relativity

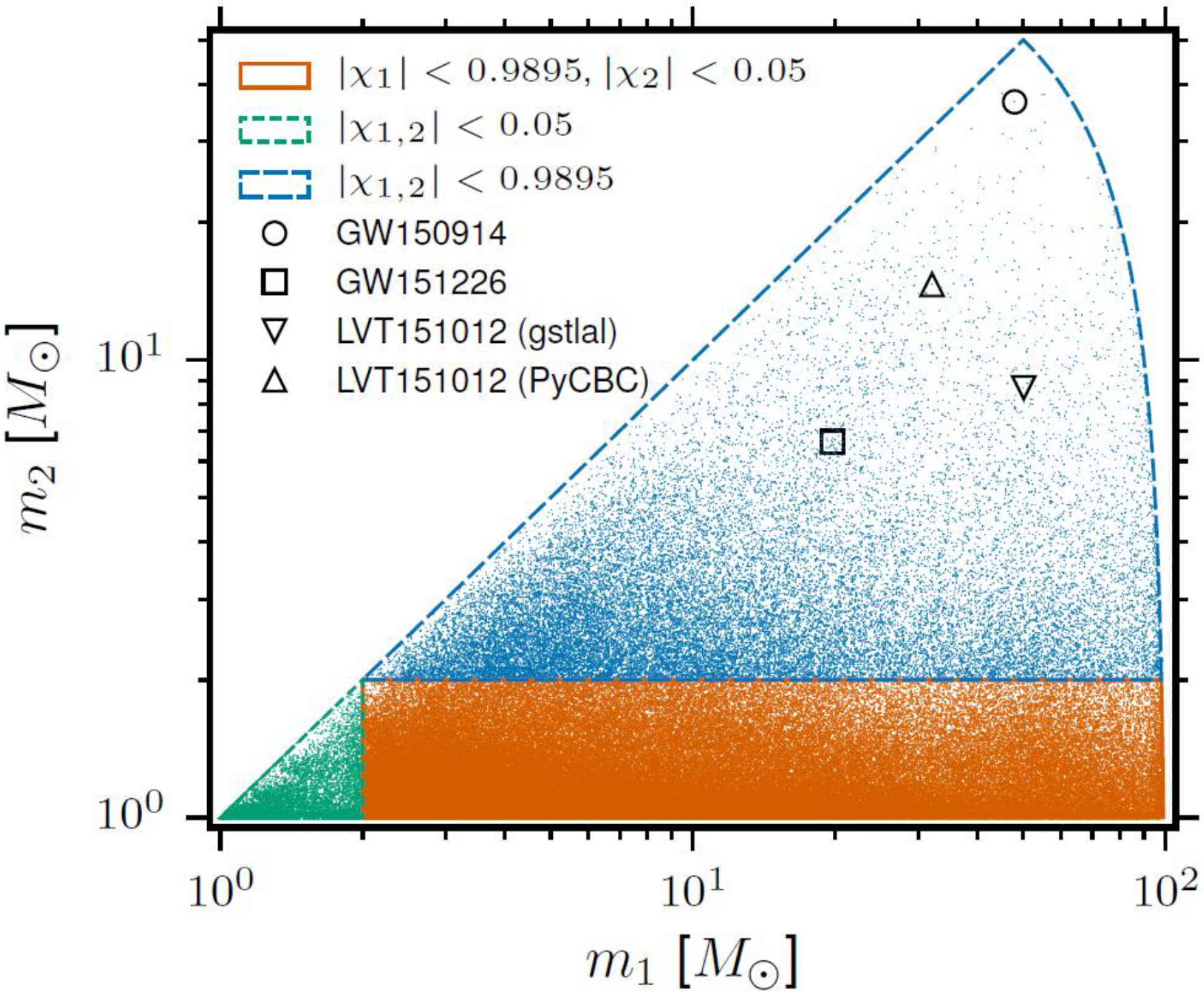
Numerical relativity example for GW150914: parameters can be determined by matching millions of trial waveforms in 15-dimensional parameter space

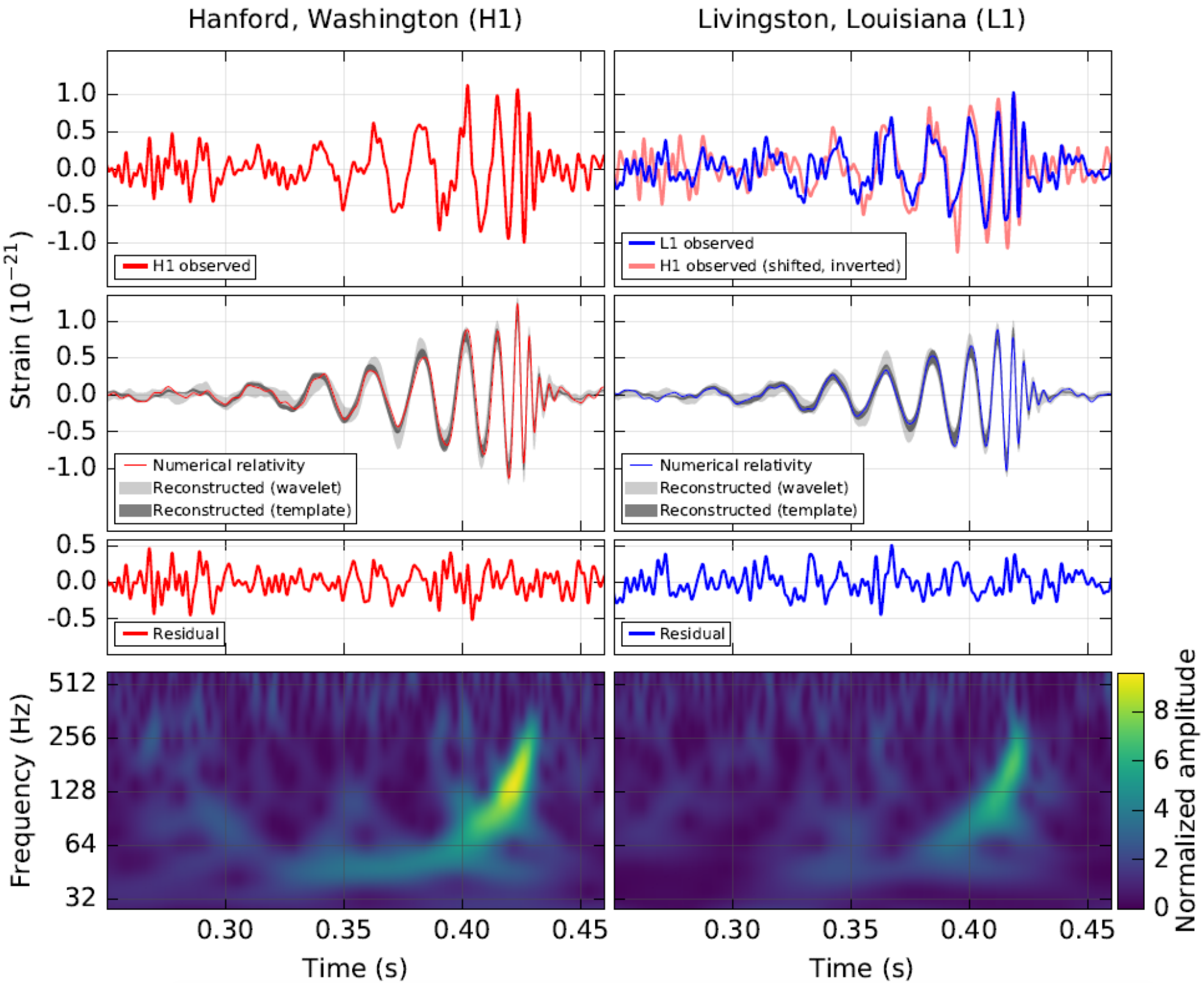


Discovery of gravitational waves

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

"Testing General Relativity" analysis pipelines developed at Nikhef





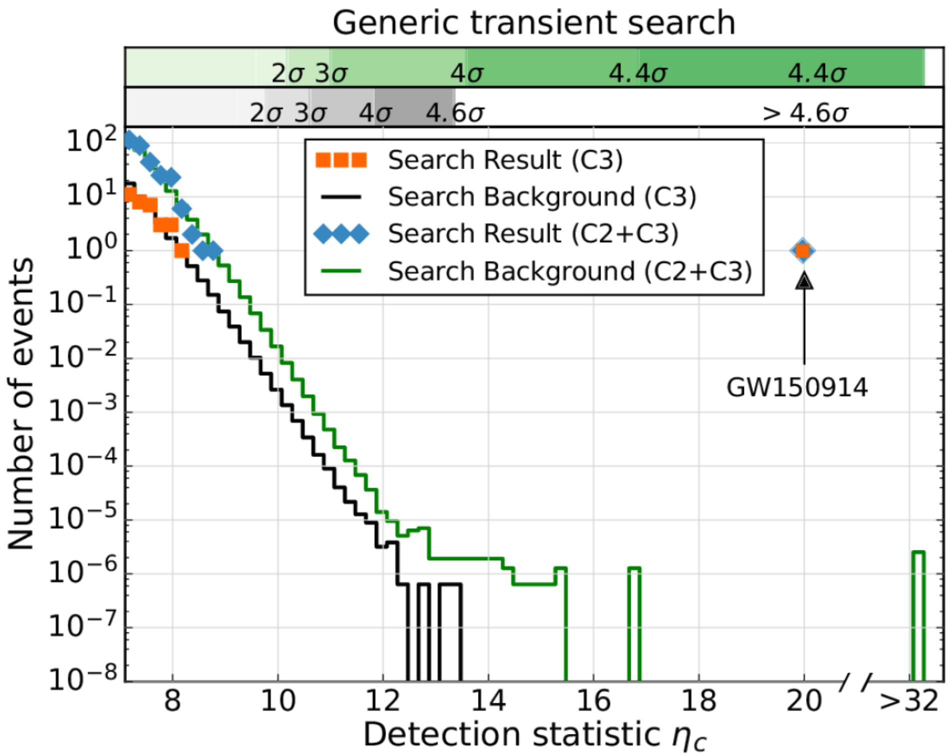
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

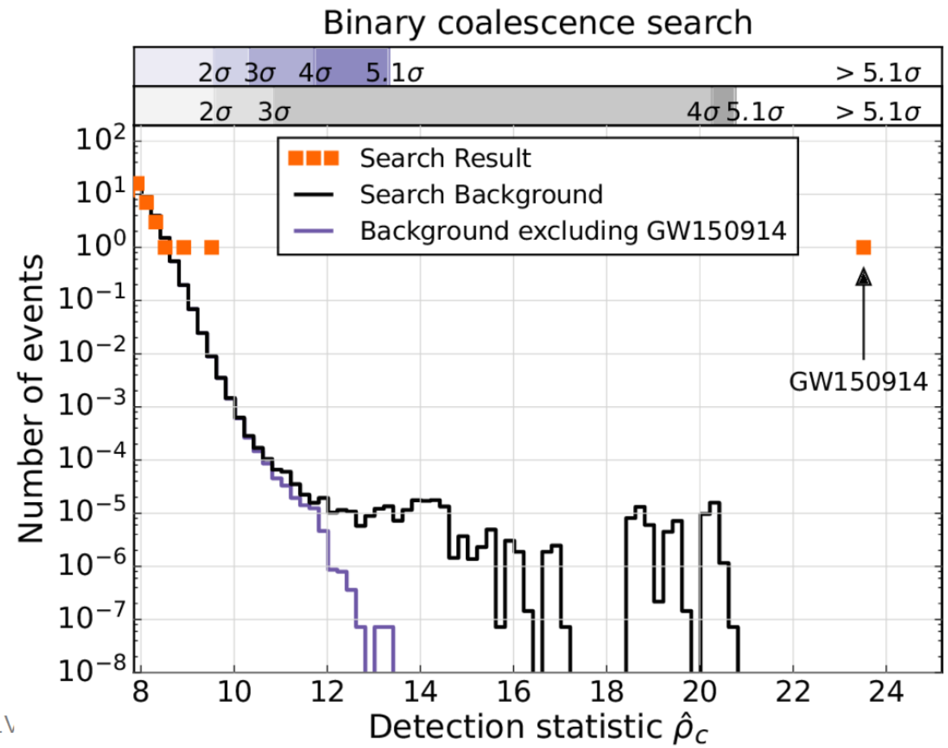
Observation of GW from a Binary Black Hole merger

First direct detection of GW and the first observation of a binary black hole merger. Two types of searches have been used: unmodeled and modeled. Detector noise is non-stationary and non-Gaussian. Empirical determination with time-shift technique. Trials factor 3

Modeled search” (which makes use of waveform predictions)
uses 16 days of coincident Livingston-Hanford data

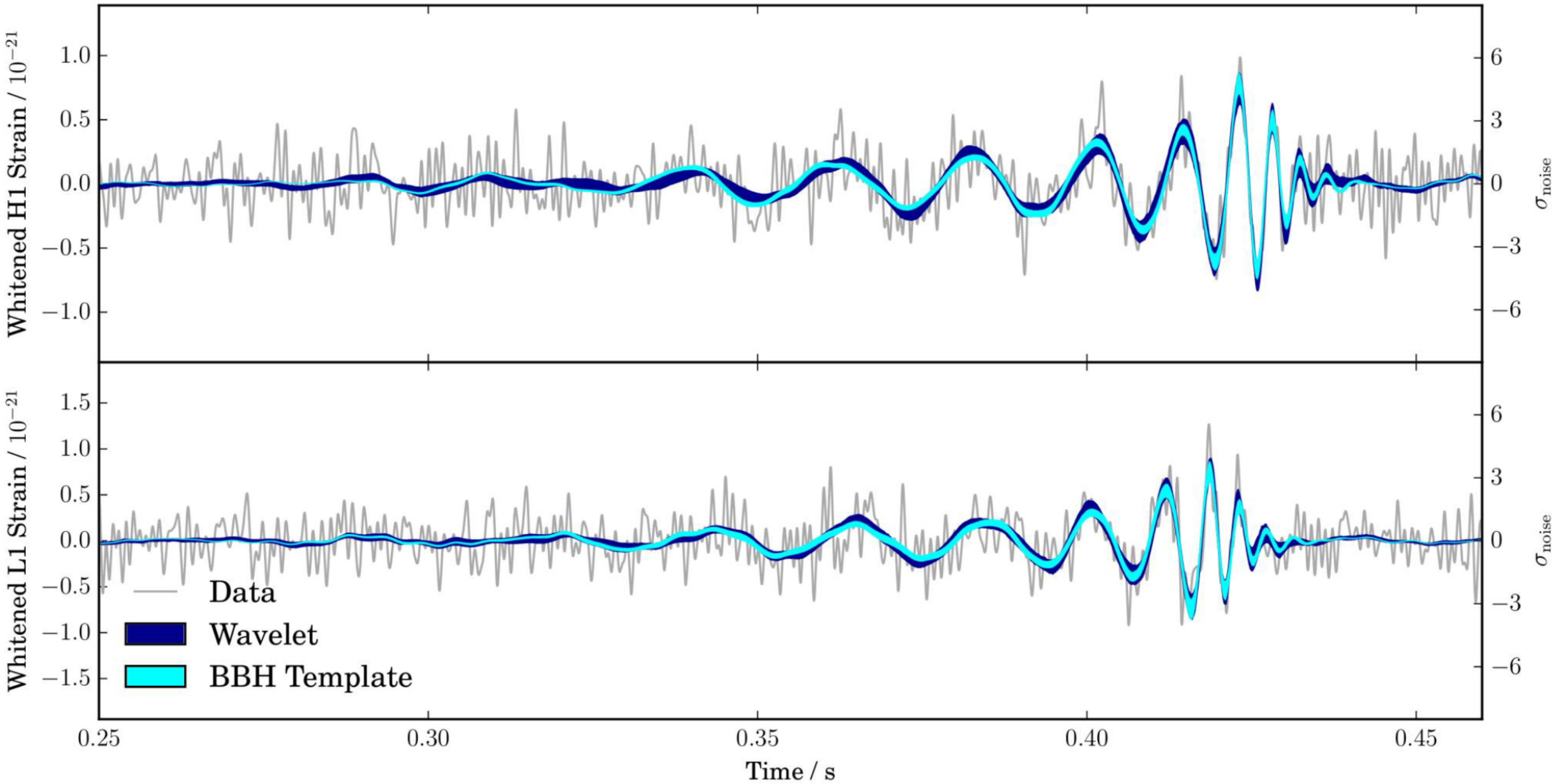
- False alarm rate < 1 in 203,000 years
- Significance > 5.1σ





Recovered gravitational waveforms

Wavelet estimate for the waveform without assuming a particular source in comparison to results if we assume the event is a binary black hole (BBH) as predicted by general relativity



See "*Properties of the Binary Black Hole Merger GW150914*" http://arxiv.org/abs/1602.03840

The basic physics of binary black hole merger GW150914

https://arxiv.org/abs/1608.01940

The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from this inspiral phase

- Total mass $M = M_1 + M_2$
- Reduced mass $\mu = M_1 M_2 / M$
- Chirp mass $M_S^{5/3} = \mu M^{2/3}$

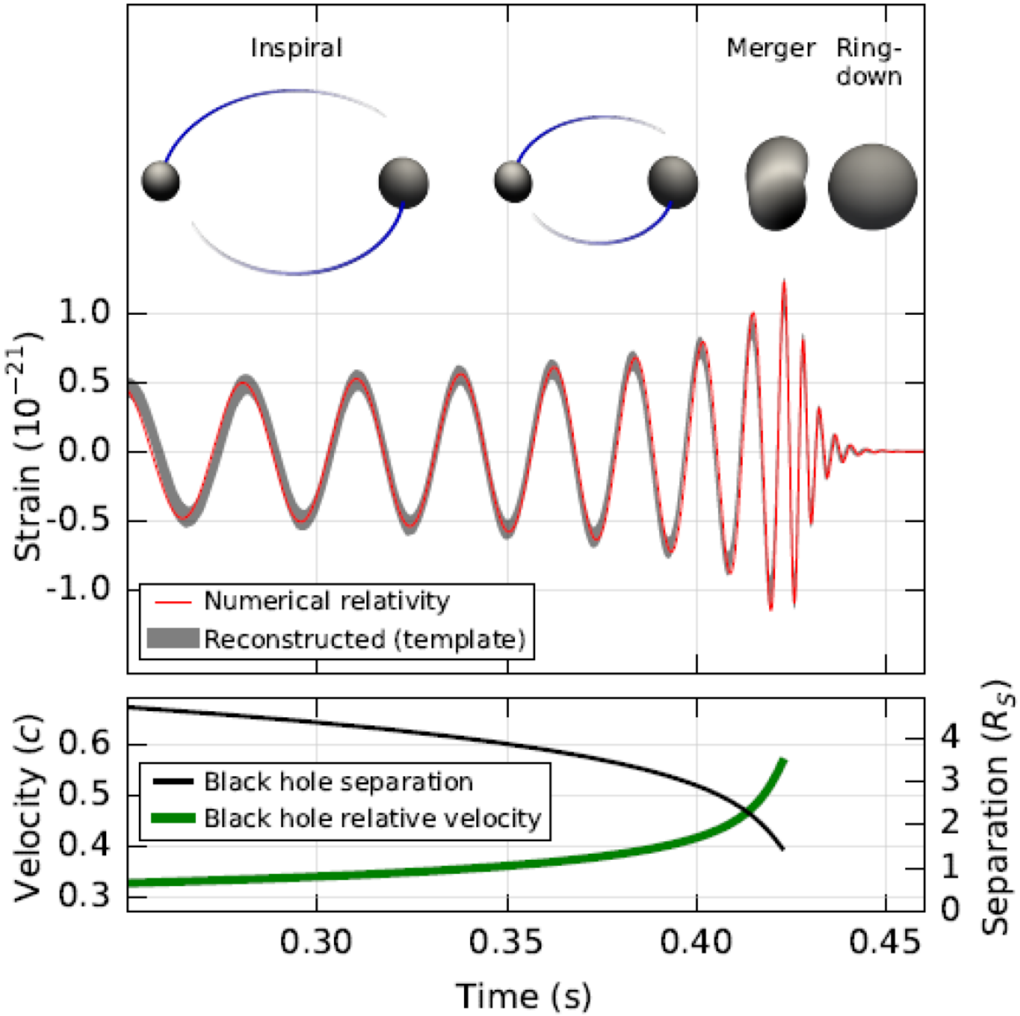
- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$

- Speed $\frac{v}{c} = \left(\frac{GM\pi f}{c^3}\right)^{1/3}$
- Separation $R_S = \frac{2GM}{c^2}$

- Orbital phase (post Newtonian expansion)

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

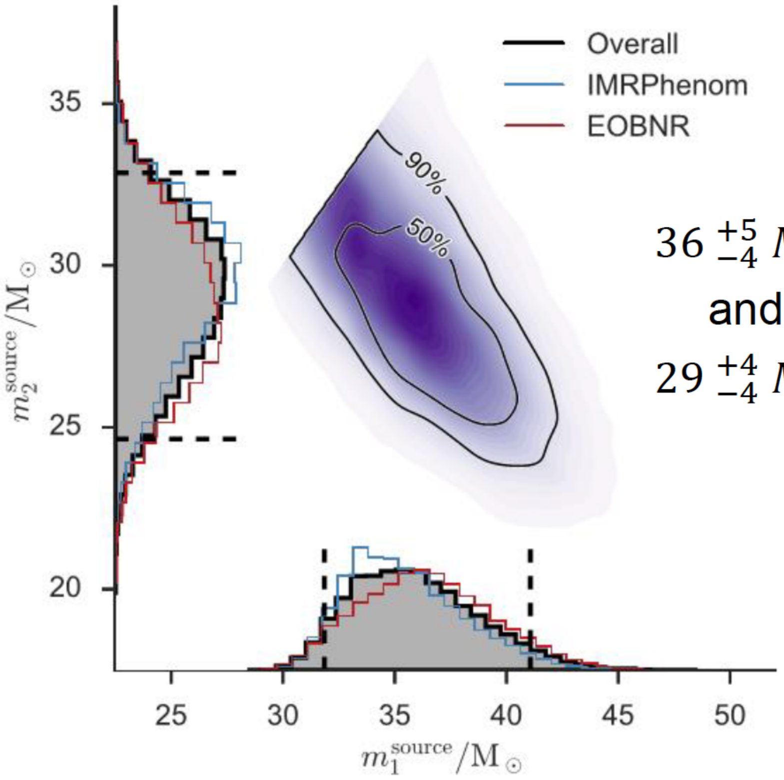
- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$



Some properties of GW150914

These are surprising heavy for stellar-remnant black holes

Masses



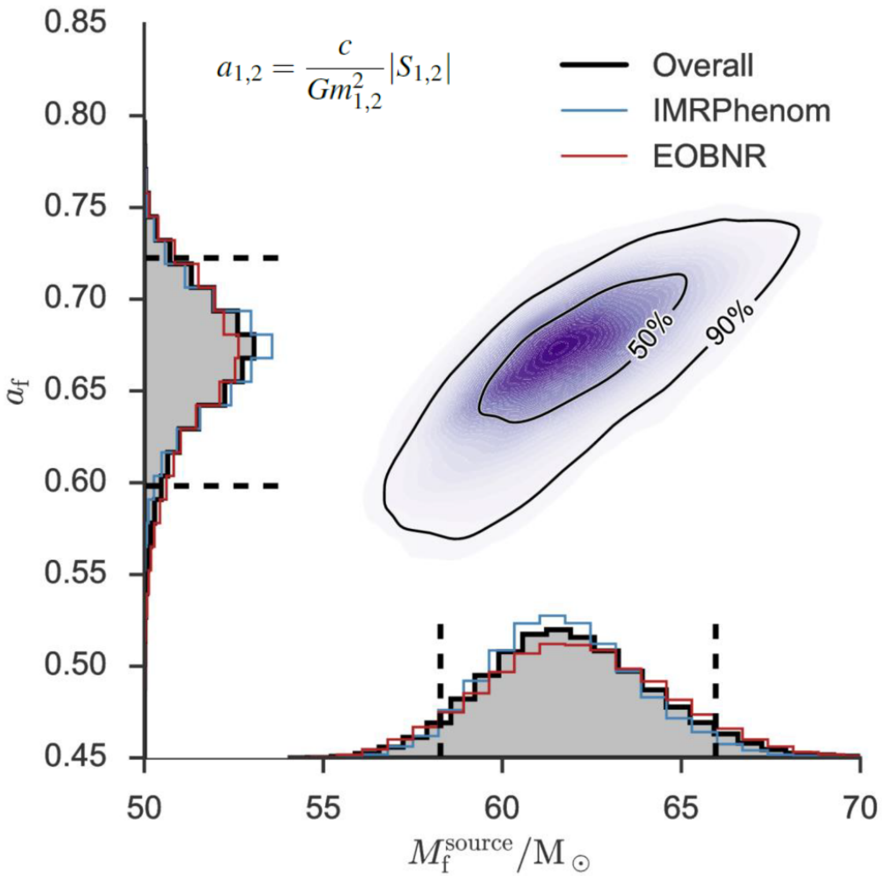
$36\,^{+5}_{-4}\,M_\odot$
and
$29\,^{+4}_{-4}\,M_\odot$

[Abbott et al. 2016, ApJL 833, L1]

- Final BH mass: $62 \pm 4\ M_\odot$
- Energy radiated: $3.0 \pm 0.5\ M_\odot c^2$
- Peak power $\sim 200\ M_\odot c^2/s$!
- Distance: $410\ ^{+160}_{-180}\ \mathrm{Mpc}$
  $= 1.3 \pm 0.5$ billion light-years
- ➔ Redshift $z \approx 0.09$
- We can't tell if the initial black holes had any "spin" (intrinsic angular momentum), but the spin of the final BH is $0.67\ ^{+0.05}_{-0.07}$ of maximal spin allowed by GR ($\frac{Gm^2}{c}$)

Source parameters for GW150914

Mass and spin of the final black hole (90% probability intervals). Different curves show results of different models.



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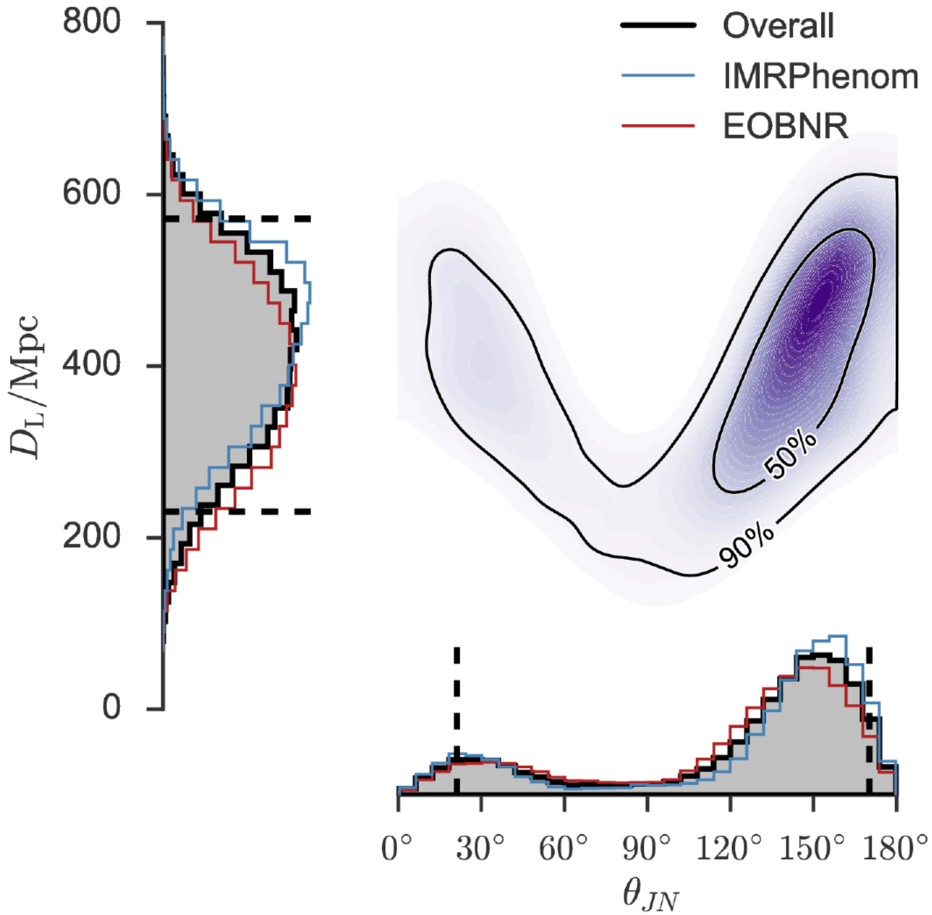
Energy radiated: 3.0 ± 0.5 solar masses. Peak power at merger: 200 solar masses per second

See "*Properties of the Binary Black Hole Merger GW150914*" http://arxiv.org/abs/1602.03840

Luminosity distance to the source for GW150914

Estimated luminosity distance and binary inclination angle. An inclination of $\theta_{JN} = 90^\circ$ means we are looking at the binary (approximately) edge-on. Again 90% credible level contours



Polarization can be used to break the degeneracy between distance and inclination

$$h_+ = \frac{2\nu M}{d}[\pi M f(t)]^{2/3}\left(1+\cos^2\iota\right)\cos[2\varphi(t)]$$

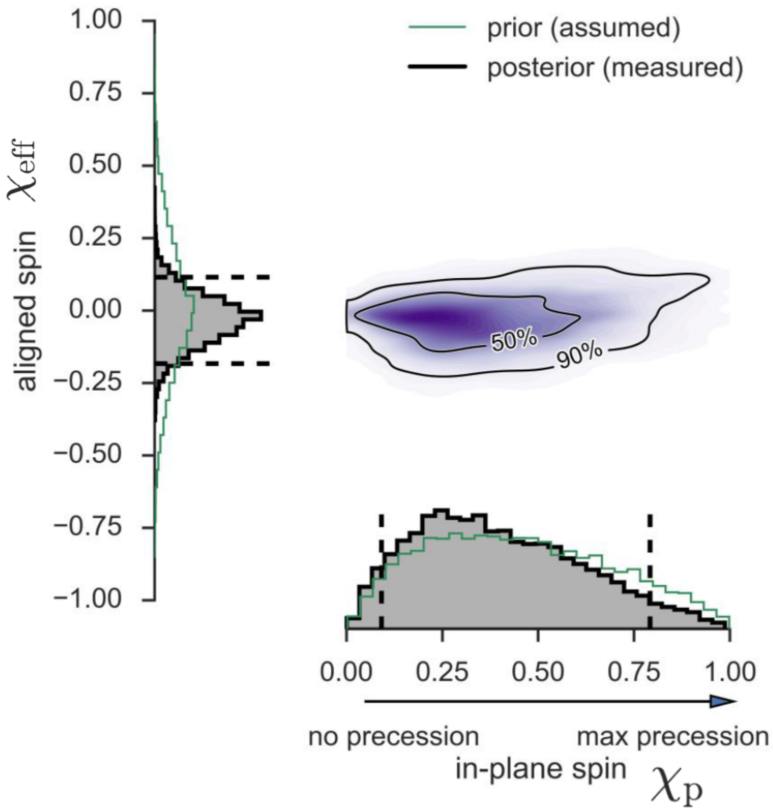
$$h_\times = \frac{4\nu M}{d}[\pi M f(t)]^{2/3}\cos\iota\,\sin[2\varphi(t)]$$

To measure the polarization components, we need a third detector, i.e. Virgo, oriented at about 45 degrees with respect to LIGO

See "*Properties of the Binary Black Hole Merger GW150914*" http://arxiv.org/abs/1602.03840

Combinations of component spins for GW150914

GW150914 suggests that the individual spins were either small, or they were pointed opposite from one another, cancelling each other's effect



Effective spin parameter

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

Precession in BBH

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

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

Effective precession spin parameter

$$\chi_p = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

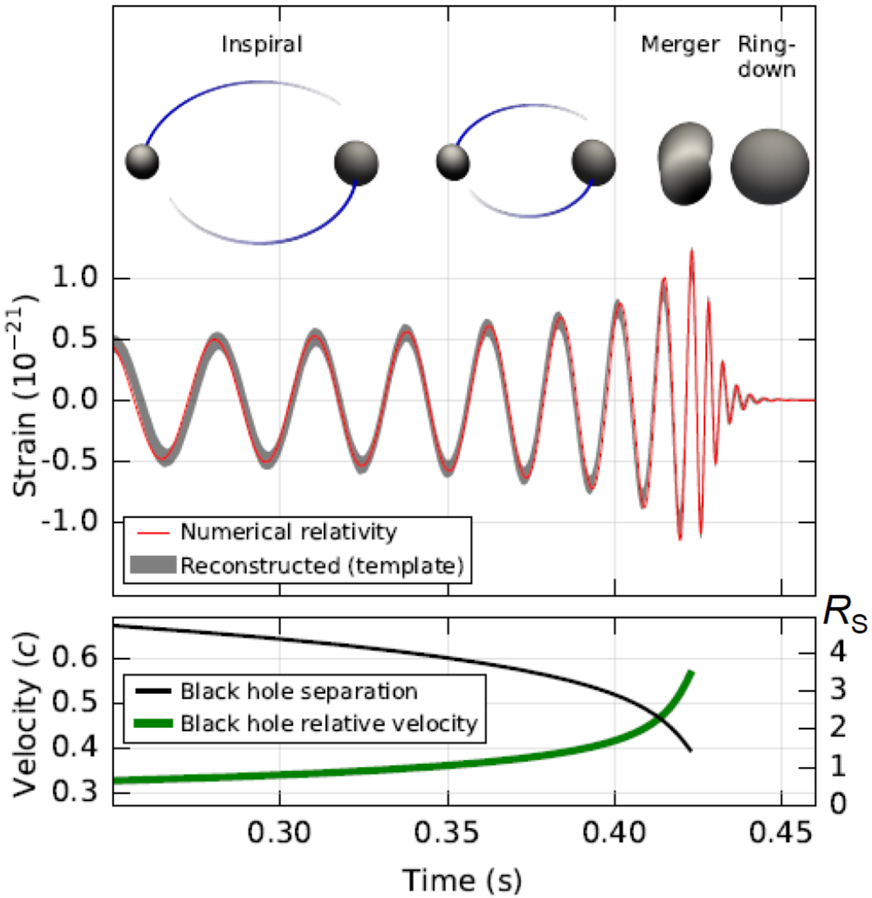
$\chi_p = 0$ aligned-spin (non-precessing) system

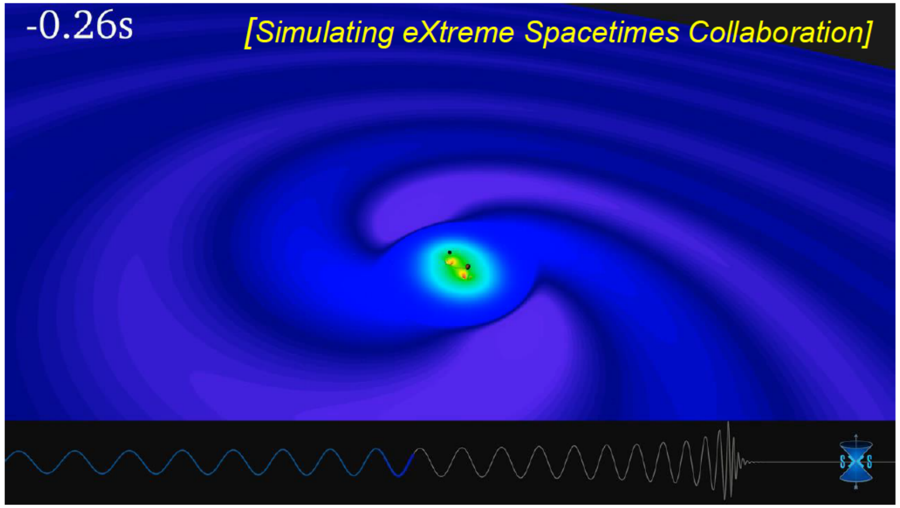
$B_1 = 2 + 3q/2$ and $B_2 = 2 + 3/(2q)$, and $i = \{1, 2\}$

See “*Properties of the Binary Black Hole Merger GW150914*” http://arxiv.org/abs/1602.03840

Binary black hole merger GW150914 observed with LIGO

The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from inspiral and ringdown phase





- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Orbital phase (post Newtonian expansion)

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$

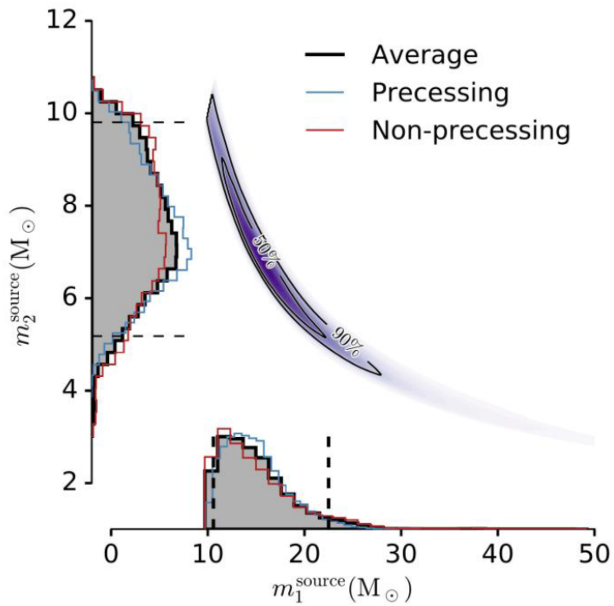
Properties of GW151226

GW151226 has lower mass than GW150914… and non-zero spin!

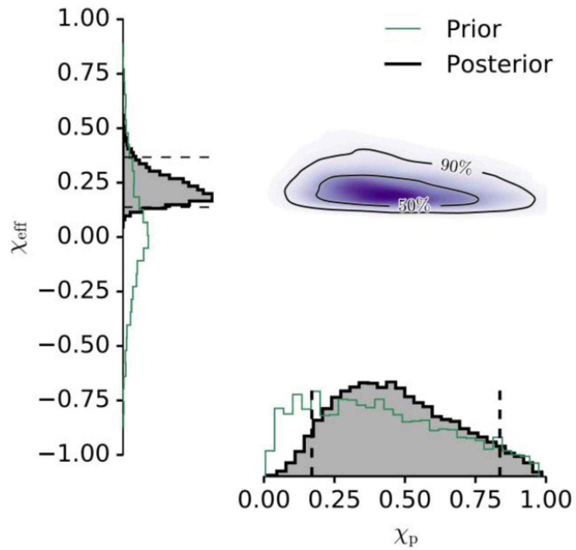
[Abbott et al. 2016, PRL 116, 241103]

Initial masses: $14.2^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\, M_\odot$
Final BH mass: $20.8^{+6.1}_{-1.7}\, M_\odot$
Energy radiated: $1.0^{+0.1}_{-0.2}\, M_\odot c^2$

Luminosity distance: 440^{+180}_{-190} Mpc



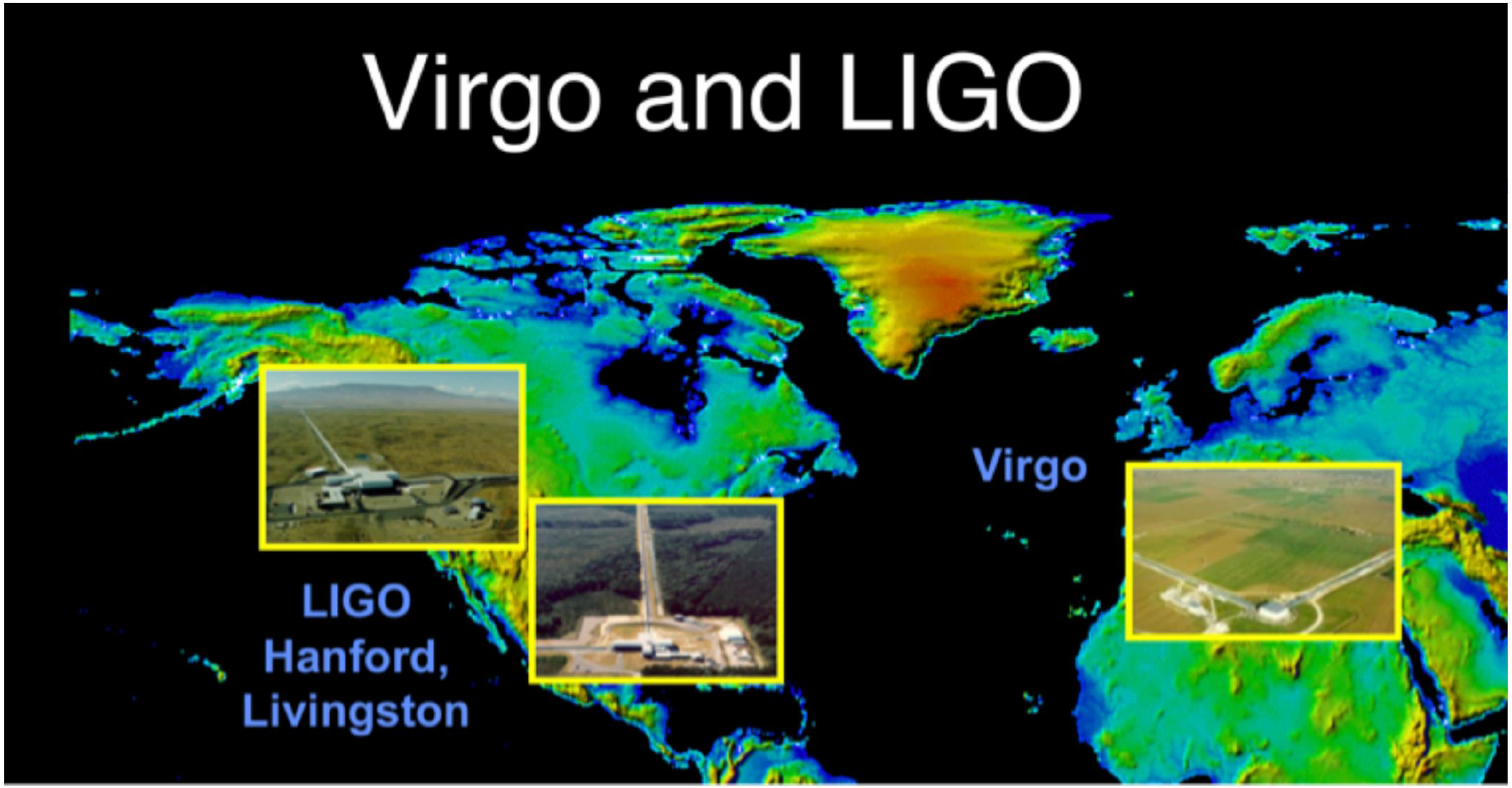
Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)



LIGO and Virgo detector joint data taking in August 2017

Observe together as a Network of GW detectors. LVC have integrated their data analysis

LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU already for more than a decade
KAGRA in Japan is expected to join in 2019. LIGO India will join in 2024



Scientific achievements: properties of binary systems

"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", LIGO Virgo Collaboration, [arXiv:1811.12907](https://arxiv.org/abs/1811.12907)

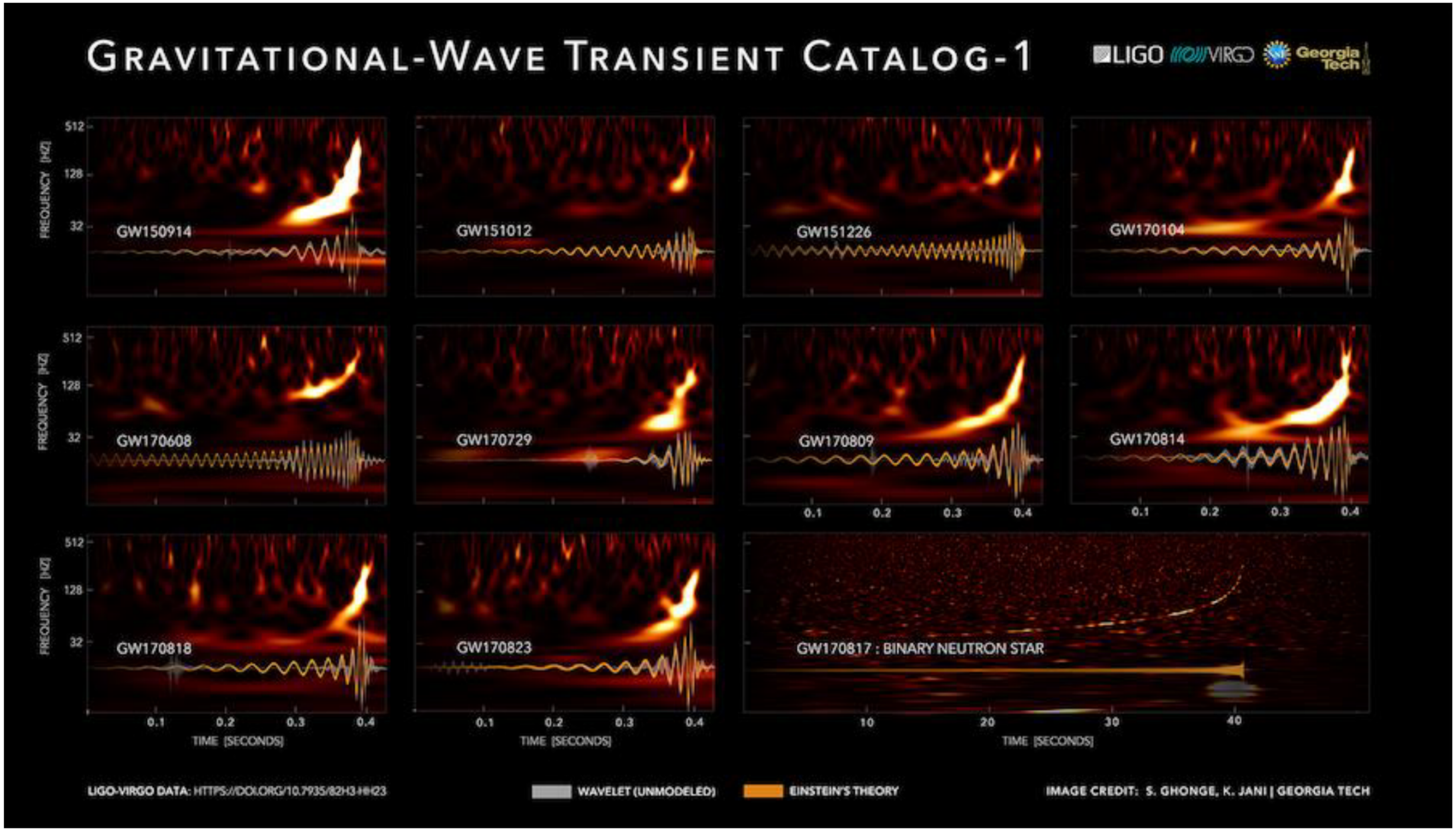


Table of O1 and O2 triggers with source properties

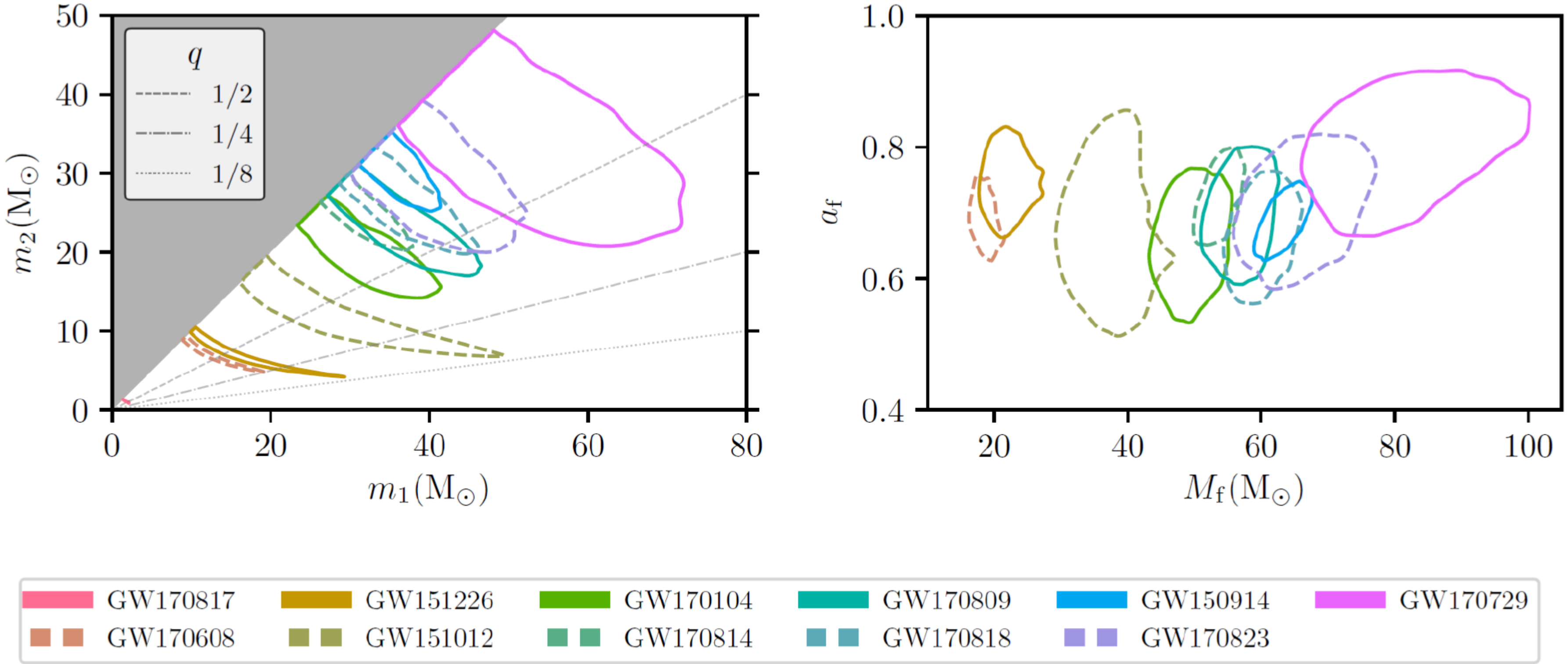
See arXiv:1811.12907

Virgo data contributed to Parameter Estimation of 5 events

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_{\mathrm{f}}/M_\odot$	a_{f}	$E_{\mathrm{rad}}/(M_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$D_{\mathrm{L}}/\mathrm{Mpc}$	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	194
GW151012	$23.2^{+14.0}_{-5.4}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.2}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.7}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1491
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1075
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.4^{+5.2}_{-3.9}$	$0.66^{+0.09}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.2^{+0.7}_{-1.0} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	912
GW170608	$11.2^{+5.4}_{-1.9}$	$7.5^{+1.5}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.04^{+0.19}_{-0.06}$	$17.9^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.8^{+0.1}_{-0.1}$	$3.4^{+0.5}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	524
GW170729	$50.7^{+16.3}_{-10.2}$	$34.4^{+8.9}_{-10.2}$	$35.8^{+6.3}_{-4.9}$	$0.37^{+0.21}_{-0.26}$	$80.3^{+14.5}_{-10.3}$	$0.81^{+0.07}_{-0.13}$	$4.9^{+1.6}_{-1.7}$	$4.2^{+0.8}_{-1.5} \times 10^{56}$	2760^{+1290}_{-1350}	$0.48^{+0.18}_{-0.21}$	1069
GW170809	$35.2^{+8.3}_{-5.9}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.17}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	310
GW170814	$30.7^{+5.5}_{-2.9}$	$25.6^{+2.8}_{-4.0}$	$24.3^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.6^{+3.2}_{-2.5}$	$0.73^{+0.07}_{-0.05}$	$2.8^{+0.4}_{-0.3}$	$3.7^{+0.5}_{-0.5} \times 10^{56}$	560^{+140}_{-210}	$0.12^{+0.03}_{-0.04}$	99
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	22
GW170818	$35.5^{+7.5}_{-4.7}$	$26.9^{+4.4}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.7}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-370}	$0.20^{+0.07}_{-0.07}$	35
GW170823	$39.5^{+10.1}_{-6.6}$	$29.4^{+6.5}_{-7.1}$	$29.3^{+4.2}_{-3.1}$	$0.08^{+0.19}_{-0.22}$	$65.6^{+9.3}_{-6.5}$	$0.71^{+0.08}_{-0.09}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1860^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1780

Properties of black holes and neutron stars from transients

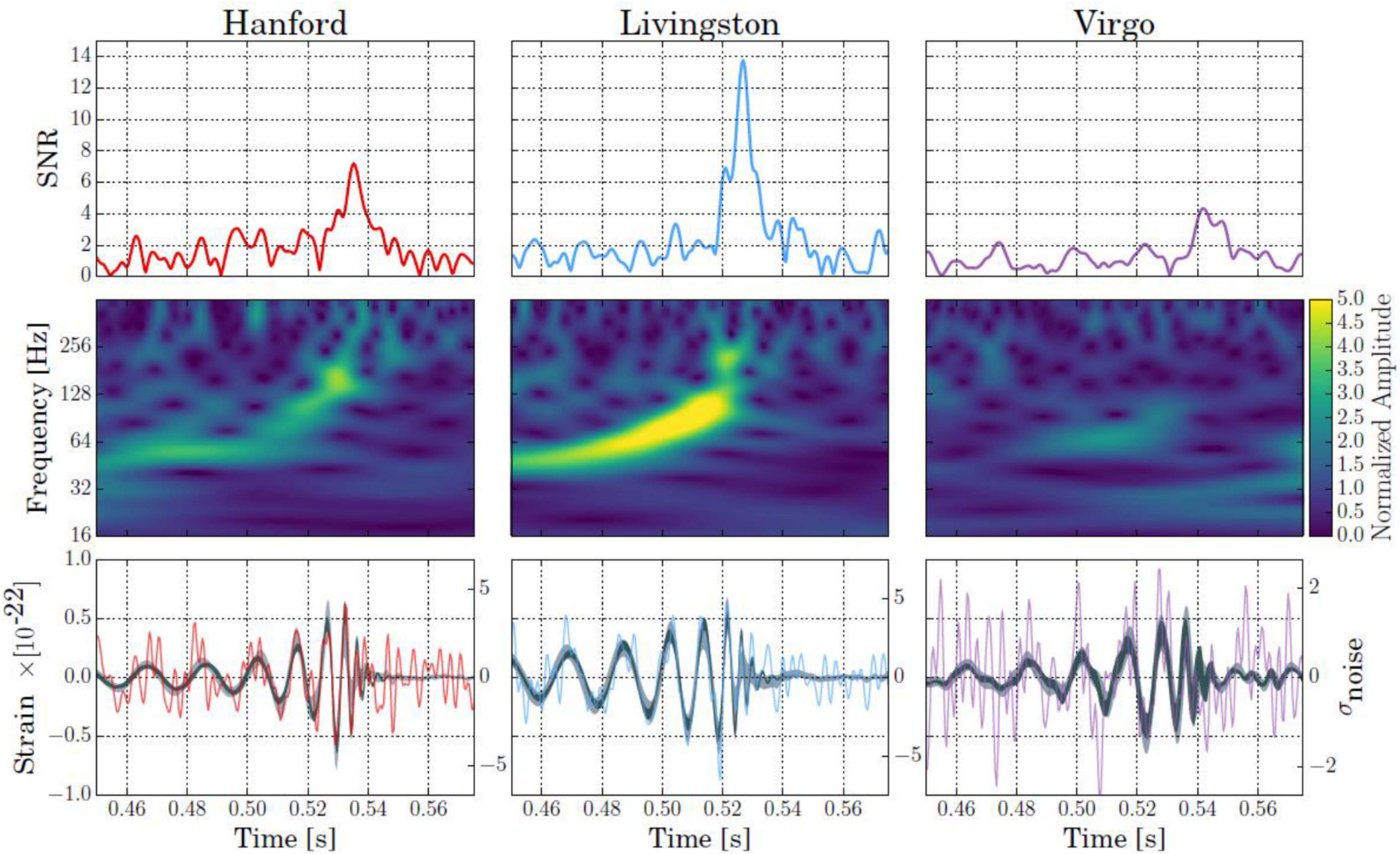
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms



"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", The LIGO Virgo Collaboration, arXiv:1811.12907

First triple detection by Virgo and LIGO: GW170814

August 14, 2017 three detectors observed BBH. Initial black holes were 31 and 25 solar mass, while the final black hole featured 53 solar masses. About 3 solar mass radiated as GWs



Advanced Virgo

Publications of the LIGO Scientific Collaboration and Virgo Collaboration

Note: The LSC and Virgo collaborations have been co-authoring observational result papers since 2010. Beginning in 2021, the KAGRA collaboration too is co-authoring observational results from the full O3 run.

Highlighting: Event discoveries Multi-messenger

Click on any keyword to filter on that keyword | Click to toggle doi information | BibTeX file for these papers

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public DCC
Mar 21, 2022 *Recent*	**Search for gravitational waves associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO-Virgo Observing Run O3a** (*by LSC, Virgo and KAGRA*)	O3 FRBs	summary	*Submitted to ApJ*	2203.12038	P2100124
Mar 2, 2022 *Recent*	**First international joint observation of an underground gravitational-wave observatory, KAGRA, with GEO 600** (*by LSC, Virgo and KAGRA*)	O3 CBC Burst	summary	*Submitted to PTEP*	2203.01270	P2100286
Jan 25, 2022	**Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.10104	P2100405
Jan 3, 2022	**All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.00697	P2100367
Dec 21, 2021	**Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run** (*by LSC, Virgo, KAGRA plus 28 radio astronomers and NICER science team members*)	O3 CW	summary	*Accepted by ApJ*	2112.10990	P2100267
Dec 13, 2021	**Tests of General Relativity with GWTC-3** (*by LSC, Virgo and KAGRA*)	O3 CBC TGR	summary	*Submitted to PRD*	2112.06861	P2100275
Nov 30, 2021	**Search of the Early O3 LIGO Data for Continuous Gravitational Waves from the Cassiopeia A and Vela Jr. Supernova Remnants** (*by LSC and Virgo*)	O3 CW	summary	*Accepted by PRD*	2111.15116	P2100298
Nov 30, 2021	**All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2111.15507	P2100343
Nov 25, 2021	**Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to ApJ*	2111.13106	P2100049
Nov 7, 2021	**Constraints on the cosmic expansion history from the third LIGO-Virgo-KAGRA Gravitational-Wave Transient Catalog** (*by LSC, Virgo and KAGRA*)	O3 Cosmology	summary	*Submitted to ApJ*	2111.03604	P2100185
Nov 7, 2021	**GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run** (*by LSC, Virgo and KAGRA*)	O3 CBC GWTC	summary	*Submitted to PRX*	2111.03606	P2000318

https://pnp.ligo.org/ppcomm/Papers.html

LIGO Scientific Collaboration

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SUMMARIES OF LSC/LVK SCIENTIFIC PUBLICATIONS

For each of our new research articles, we feature a summary of the paper's key points written for the general public. Simply click on any of the titles for an online version, or on the '[flyer]' links for a downloadable file in PDF format. Translations into several languages are also available for some of these summaries. Where not noted separately, translations can be accessed through their language acronyms (e.g. 'es' for Spanish, also see details in the sidebar) or from the top of the English online versions. Most recent papers, and their summaries, are written together by the LIGO Scientific Collaboration (LSC), the Virgo Collaboration and the KAGRA Collaboration, forming the LVK collaboration.

LATEST DETECTIONS

GWTC-3 (Nov 07, 2021)

GWTC-3, a third catalog of gravitational-wave detections **[flyer]**

Also in: Catalan [ca] | Chinese (simplified) [zh-Hans] | Chinese (traditional) [zh-Hant] | French [fr] | German [de] | Italian [it] | Japanese [ja] | Polish [pl] | Spanish [es]

Companion papers: (also available in some other languages):

- Uncovering the population properties of black holes and neutron stars following LIGO and Virgo's third observing run **[flyer]** | [fr] | [ja] | [pl] | [zh-Hant]
- Improving measurements of the cosmic expansion with gravitational waves **[flyer]** | [fr] | [el] | [es] | [ja] | [zh-Hant]
- Searching for quiet gravitational waves produced by gamma-ray bursts in O3b **[flyer]** | [fr] | [it] | [zh-Hant]
- Does Einstein's Theory of Gravity Hold Up to the Latest LIGO/Virgo/KAGRA Observations? (published Dec 13, 2021) **[flyer]** | [fr] | [el] | [it] | [zh-Hans]

GWTC-2.1 (Aug 02, 2021)

GWTC-2.1: Extended catalog of Binary Mergers Observed by LIGO and Virgo During the First Half of the Third Observing Run **[flyer]**

Also in: Italian [it] | Japanese [ja]

GW200105 and GW200115 (Jun 29, 2021)

A new source of gravitational waves: neutron star–black hole binaries **[flyer]**

Also in: Blackfoot [bla] | Catalan [ca] | Chinese (traditional) [zh-Hant] | French [fr] | German [de] | Greek [el] | Italian [it] | Japanese [ja] | Polish [pl] | Portuguese [pt] | Spanish [es]

LOOKING DOWN A DETECTOR ARM

Visitors at LIGO Hanford Observatory gaze down the site's X arm. Half of the 4-kilometer length of the arm is visible in the photo. (Credit: LIGO Laboratory)

TRANSLATIONS: LANGUAGE KEYS

For most summaries, we list the available translations by their ISO 639-1 / ISO 639-2 keys, as listed below. Translations are a volunteer effort and different sets of languages are available for each summary. You can search for the key of your language, in square brackets – for instance [fr] for French – on this page to find all science summaries that have been translated into it.

- **[bla]**: Blackfoot
- **[bn]**: Bengali (Bangla / বাংলা)
- **[ca]**: Catalan (Català)
- **[de]**: German (Deutsch)
- **[el]**: Greek (Ellinika / Ελληνικά)
- **[es]**: Spanish (Español / Castellano)
- **[fr]**: French (Français)

https://www.ligo.org/science/outreach.php