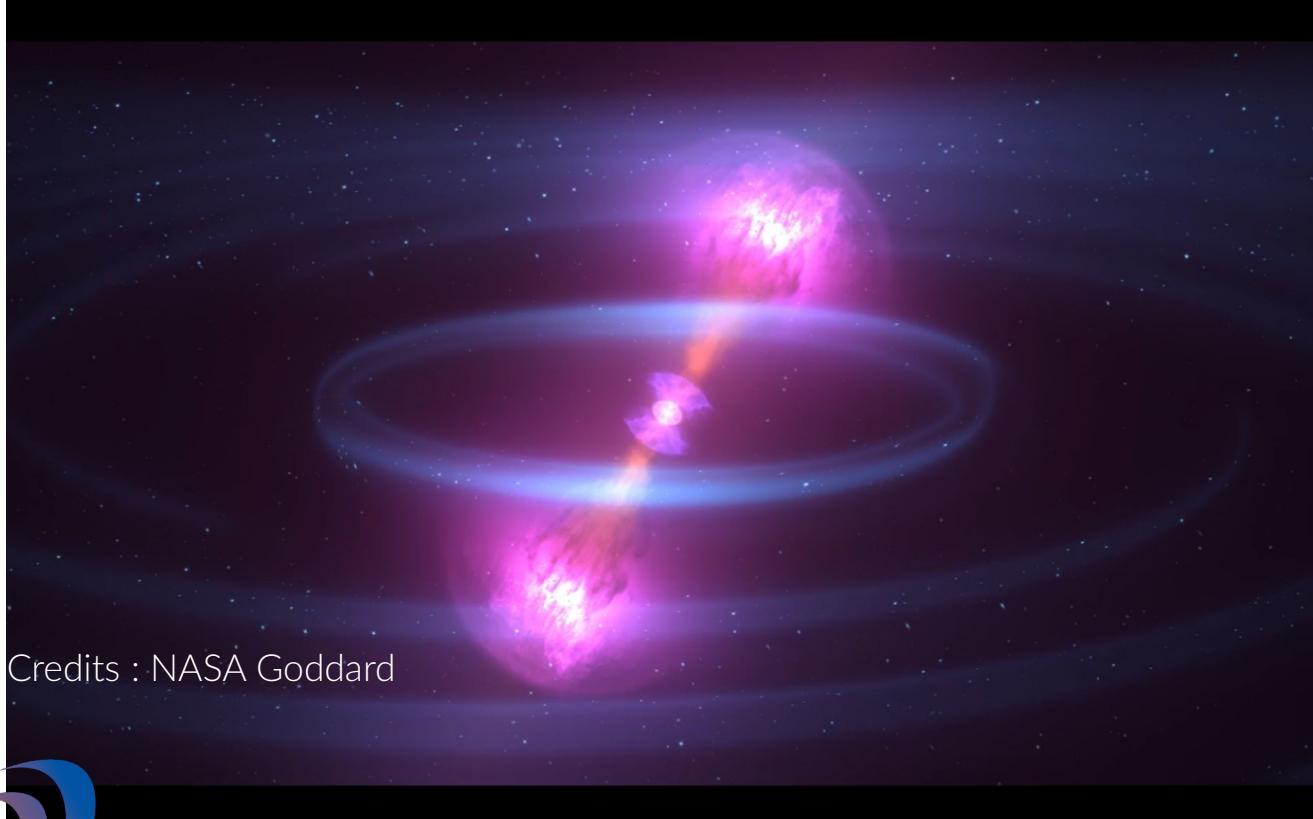


L'avènement de l'astrophysique multi-messager avec les ondes gravitationnelles



Eric Chassande-Mottin
AstroParticule et Cosmologie (APC)
CNRS Univ Paris Diderot

Plan de la présentation

- Introduction sur les ondes gravitationnelles
- DéTECTEURS et observations jusqu'ici
- GW170817 et l'astronomie multi-messager
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- Perspectives

Le Monde

WEEKEND

CULTURE & IDEES
EUROPE LE SECRET MARCHANDAGE DES NORMES DIESEL

SamEDI 13 Février 2016 - 27e édition - N°57140 - 4,20 € - France métropolitaine - www.lemonde.fr - Rédacteur : Hubert Desco-Mery



Les petits calculs d'un remaniement

François Hollande a choisi un remaniement, le tac-tus et l'art de faire les choses différentes pour ne pas porter la moitié du parti de la majorité avant 2017

L'arrivée de trois ministres écologistes, dont une femme au sein de la majorité, a déclenché un coup sévère au parti de Cécile Duflot.

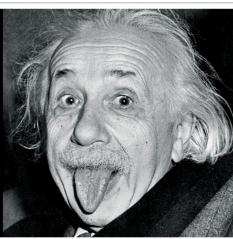
Le retour de l'ancien premier ministre Bernard Marais, après son départ à Quesnoy, tient à la volonté de rassurer la gauche qui a choisi le président

Plus qu'un gouvernement de combat, c'est un gouvernement de contacts qui a choisi le président

► 100 PAGES ET 14

Einstein avait raison

Le physicien avait prédit 100 ans des effets de gravité en vu, la preuve directe est maintenant faite



Pourquoi les banques sont attaquées en Bourse

Les banques mondiales, Deutsche Bank en tête, ont accusé un manque de respect des investisseurs et répondu aux revendications de ces derniers. Les résultats sont décevants et des négociations houleuses ont lieu pour éviter une perte importante des propres ressources. Les résultats sont également décevants et des négociations houleuses ont lieu pour éviter une perte importante des propres ressources.

► 100 PAGES ET 14

UN AIR DE LEHMAN BROTHERS

COMICS
LE GRAND BAZAR
DU TRAVAIL
DU DIMANCHE

CULTURE
LE THÉâTRE
DE L'EUROPE
AUX EUROPÉENS

CULTURE & IDEES
L'URGENCE CLIMATIQUE:
FAUT-IL ÊTRE URGENT
POUR ÊTRE URGENT?

SPORT & FINANCE
PROFESSION GLADIATEUR

Plan russe-américain pour une trêve en Syrie

Sergueï Lavrov et John Kerry ont effectué un accès humanitaire aux villes assaillies



MIGRANTS

L'Etat va raser LA MOTTE DE LA « JUNGLE » DE CALAS

PARIS/FRANCE

L'aéroport de Paris-Charles de Gaulle a été évacué et fermé pour préparer la démolition de la jungle de Calais, une zone où des milliers de migrants vivent dans des conditions déplorables. L'agence de l'ONU pour les réfugiés a déclaré que plus de 10 000 personnes étaient actuellement coincées dans ce campement. Le maire de Calais, Jean-Louis Schaffrand, a déclaré que la ville devait être débarrassée de la jungle, mais que les autorités locales devraient trouver une solution alternative pour les migrants.

BACCHANALES MODERNES !

Le nu, l'ivresse et la danse

DANS L'ART

12 février
23 mai 2016

Exposition à la Galerie des Arts, à Paris, jusqu'au 23 mai 2016. Entrée : 10 euros. Accès : 10 euros.

► 100 PAGES ET 2-3

► 100 PAGES ET 2-3

The New York Times

VOL. CLXV - NO. 57140 + NEW YORK, FRIDAY, FEBRUARY 12, 2016

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHODOROW AND PATRICK CHALEY MILWAUKEE — Hillary Clinton painted a rosy picture of her double-digit deficit in the New Hampshire primary, then easily challenged the trillion-dollar plan of her Democratic rival at their presidential debate on Thursday night, a move that gave him as a big talker who needed to “live up to his words.”

► 100 PAGES ET 2-3



WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A Ripple in Spacetime

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

By DENNIS OVERBYE

A team of scientists announced today that they had detected and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that confirmed the validity of Einstein's general theory of relativity.

► 100 PAGES ET 2-3

Long in Clinton's Corner, Blacks Notice Sanders

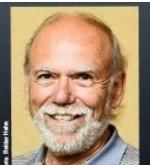
Courted Hard in South Carolina, Loyalties

Last Occupier In Rural Oregon Is Coaxed Out

► 100 PAGES ET 2-3



Rainer Weiss
LIGO/VIRGO Collaboration



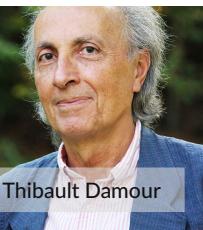
Barry C. Barish
LIGO/VIRGO Collaboration



Kip S. Thorne
LIGO/VIRGO Collaboration



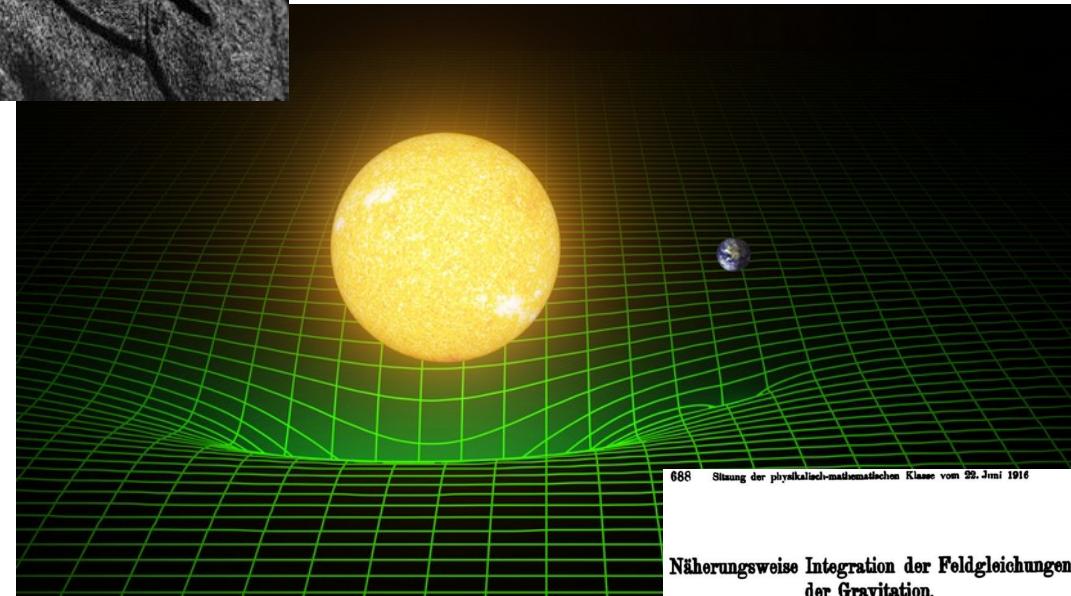
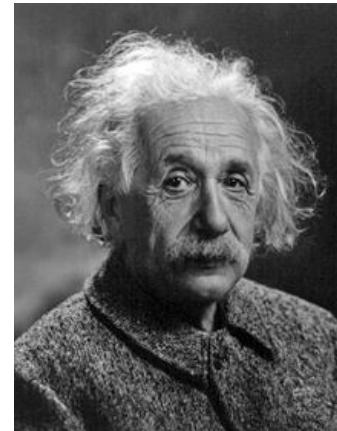
Alain Brillet



Thibault Damour

Space-time in general relativity

- Space-time is a **deformable and dynamical object**
- Gravity is a geometrical effect that emerges from space-time curvature



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. EINSTEIN.

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

1915

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_0 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

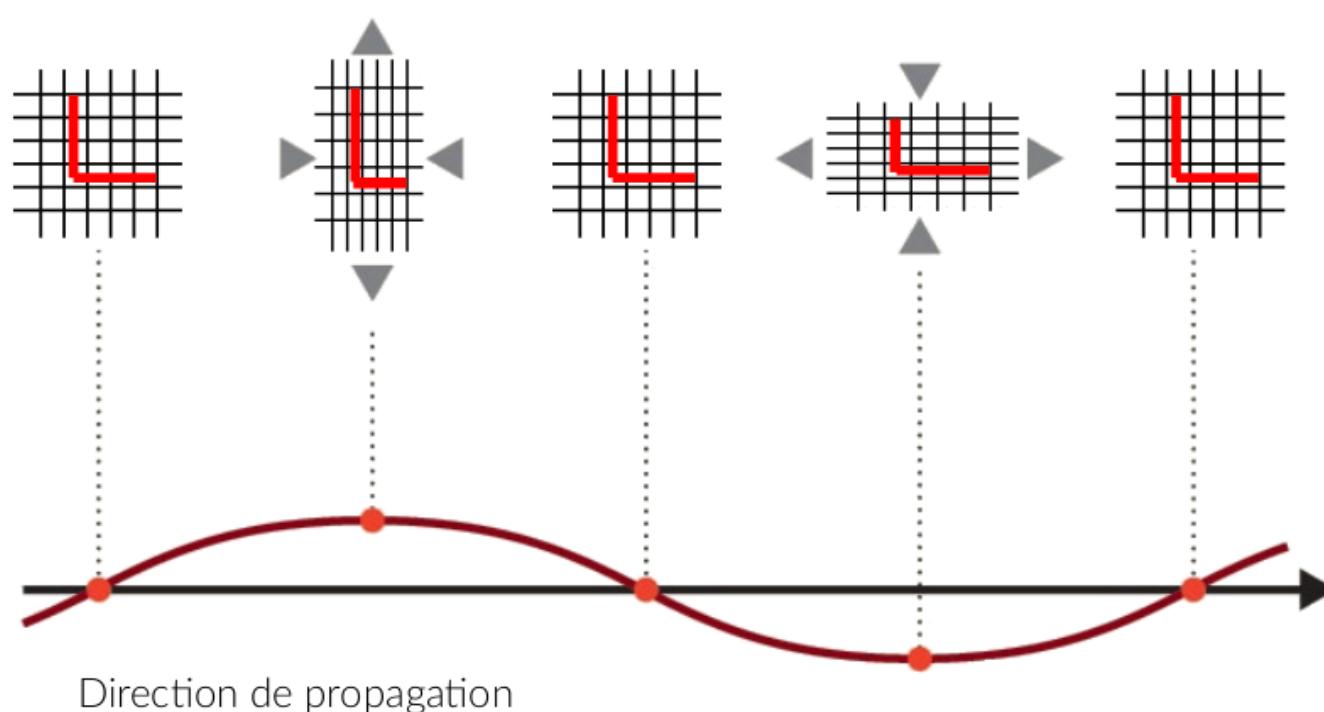
Gravitational waves

Einstein's equations → **wave equation !**

for small perturbations of flat space-time metric

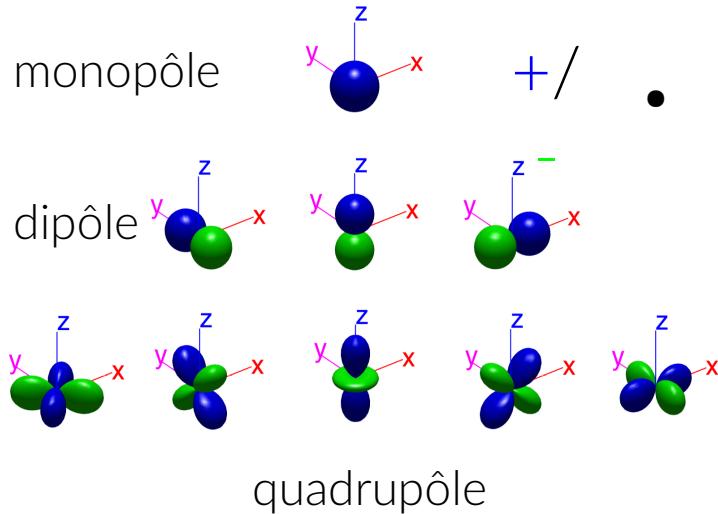
There are **waves of space and time**

Gravitational waves are **transverse**



Gravitational wave amplitude h = no dimension

Sources of gravitational waves



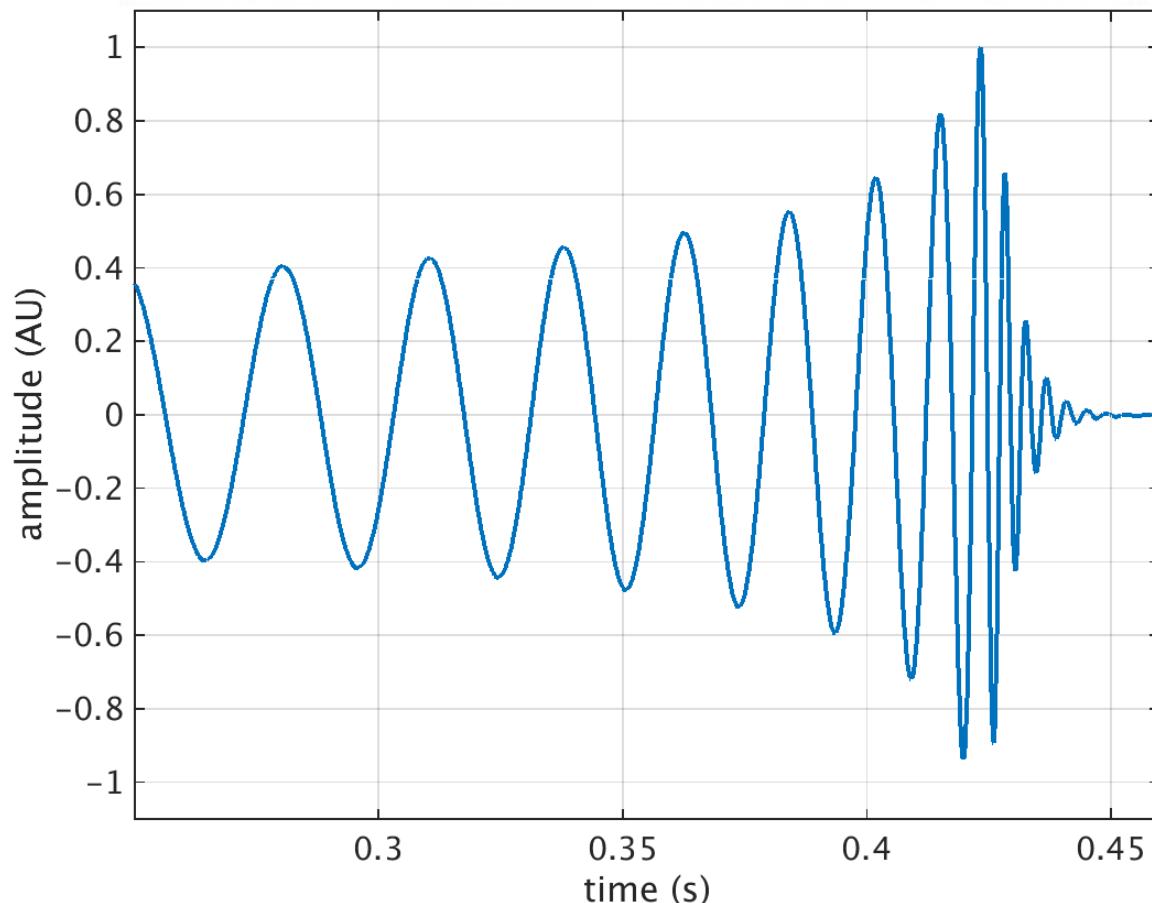
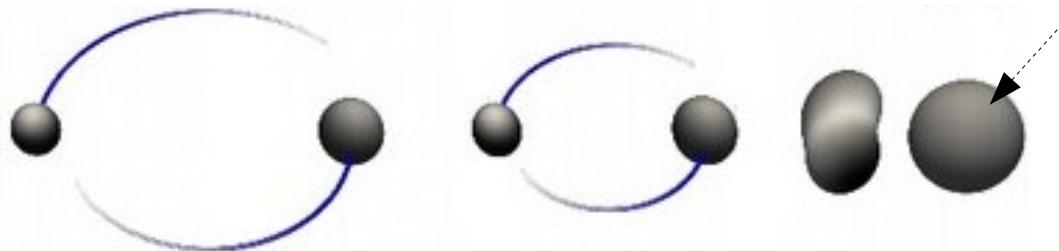
- Electromagnetic waves → **accelerated charges**
 - Variations of the electrostatic dipole
 - Gravitational waves → **accelerated masses**
 - Gravitational dipole is constant (momentum is conserved)
 - Variations of **gravitational quadrupole**
 - No emission for spherical objects
- source non axi-symmetry is required**

Black hole binary merger

inspiral

merger

ringdown



Characteristic waveform
signature

$$f_{\text{GW}} \approx 2f_{\text{orbital}}$$

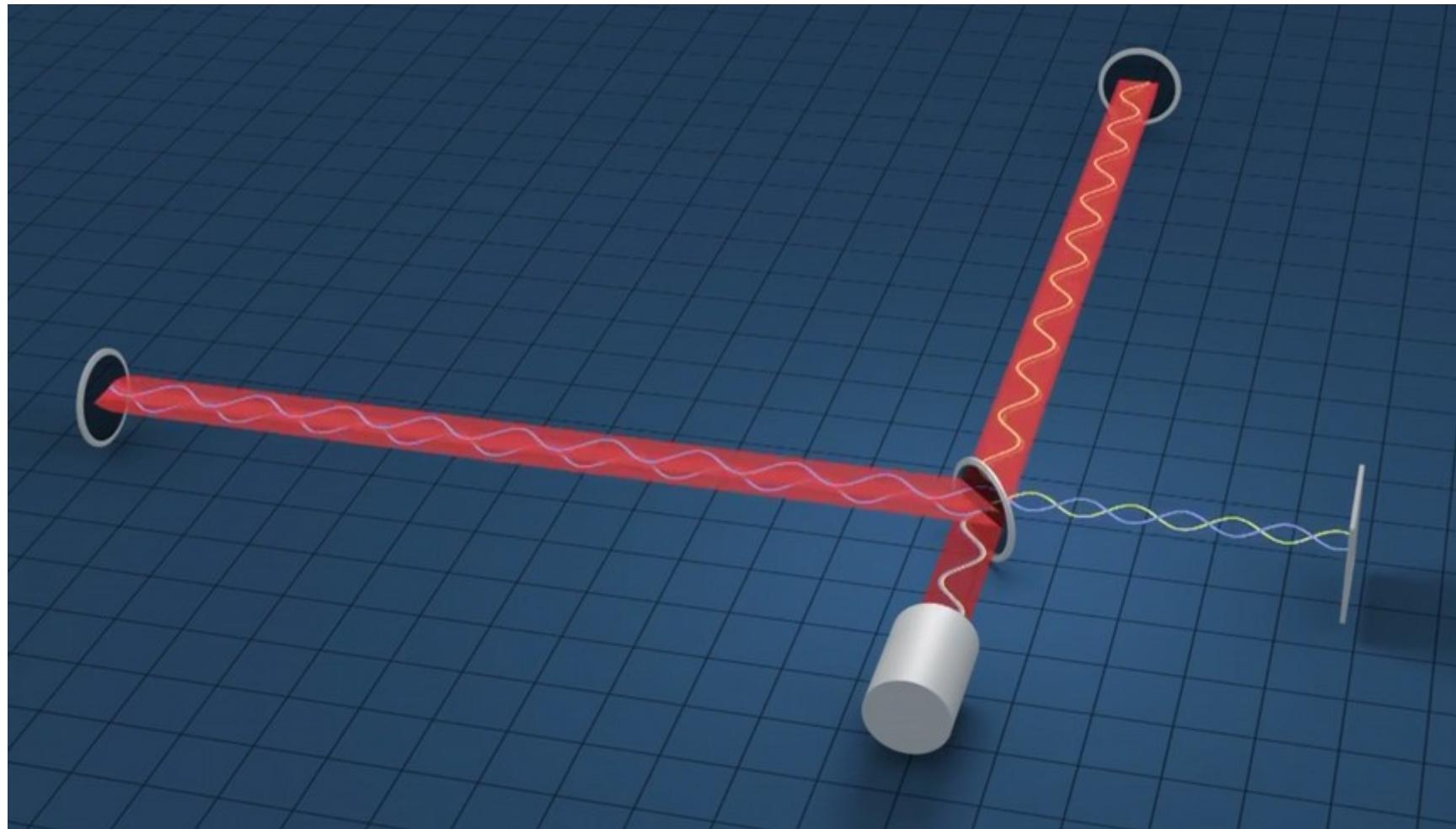
Chirp mass \mathcal{M}

$$h_{\text{typ}} \sim 10^{-21}$$

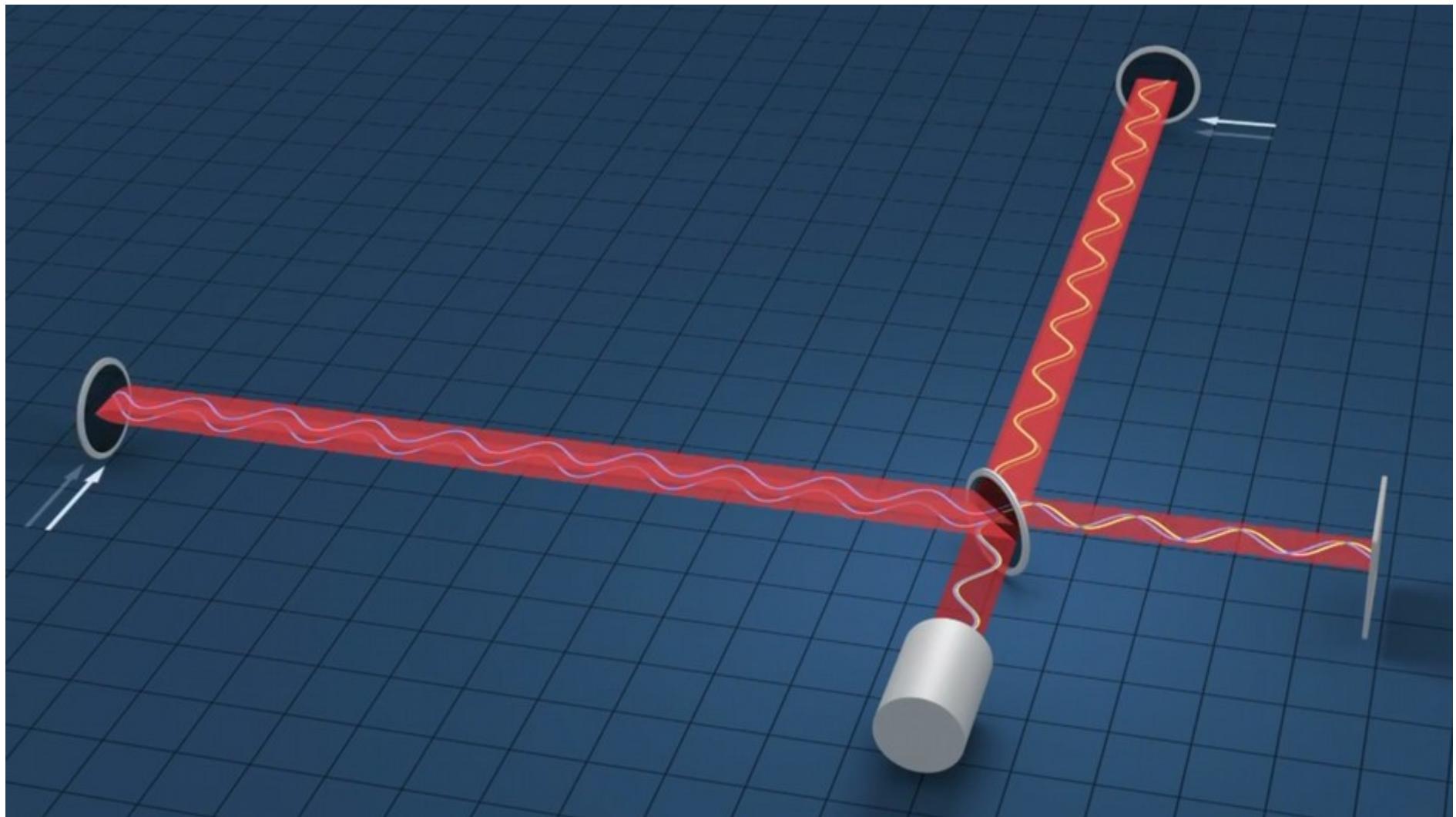
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Michelson interferometer



Michelson interferometer





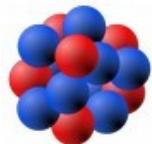
LIGO (Etats unis)



Virgo (Italie)

$$h = \frac{\delta\ell}{L} \sim 10^{-21}$$

$$\delta\ell \sim 10^{-18} m$$
$$L = 3 \text{ km}$$



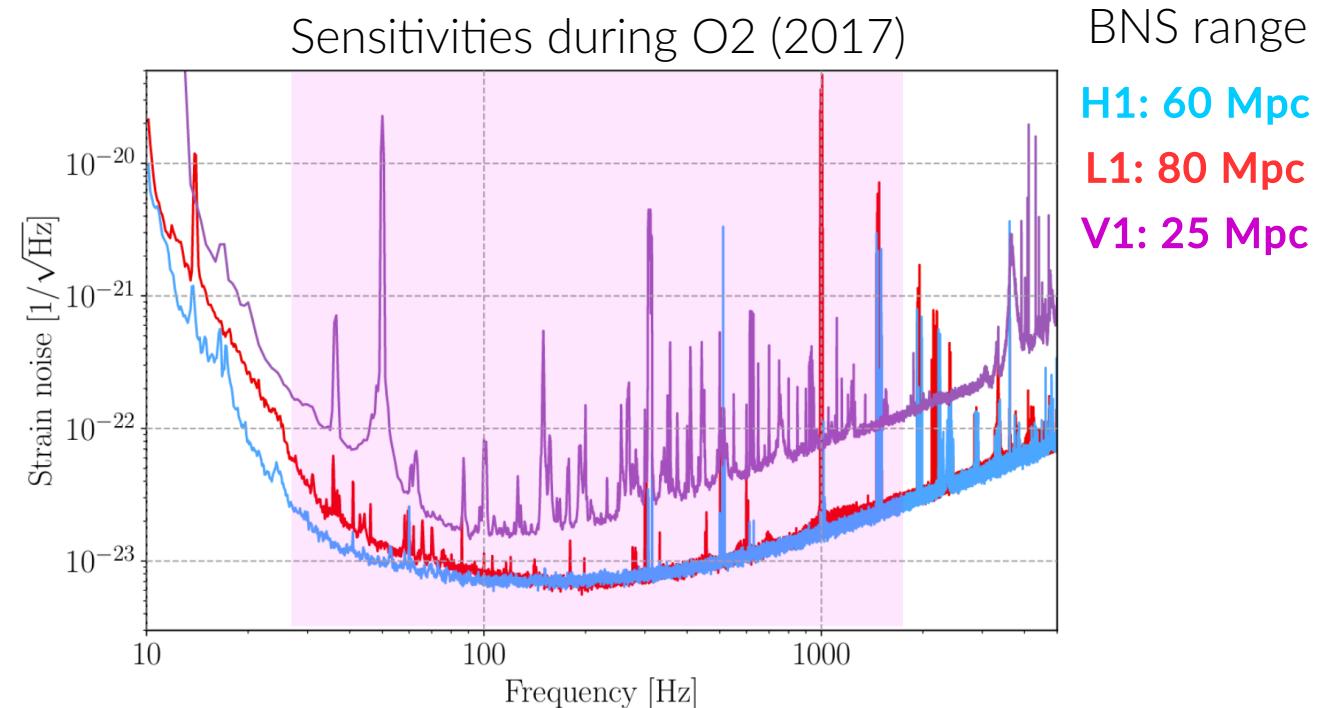
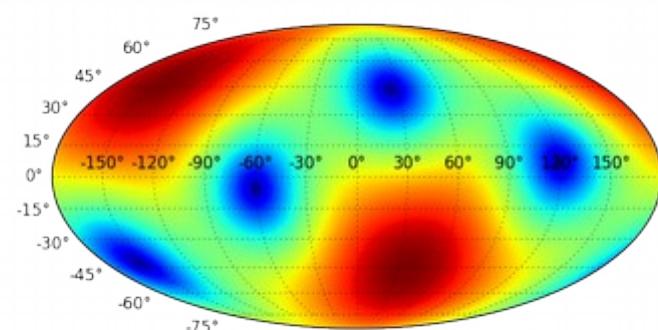
Radius of atomic nuclei

$10^{-15} m$ ($\times 1000$)



~3000 km
(10 light-ms)

~10000 km
(30 light-ms)





2015 2016 2017 2018 2019 2020



LIGO only



O1

4 months
~50 days
coincident



O2



6 months
~ 100 days
coincident

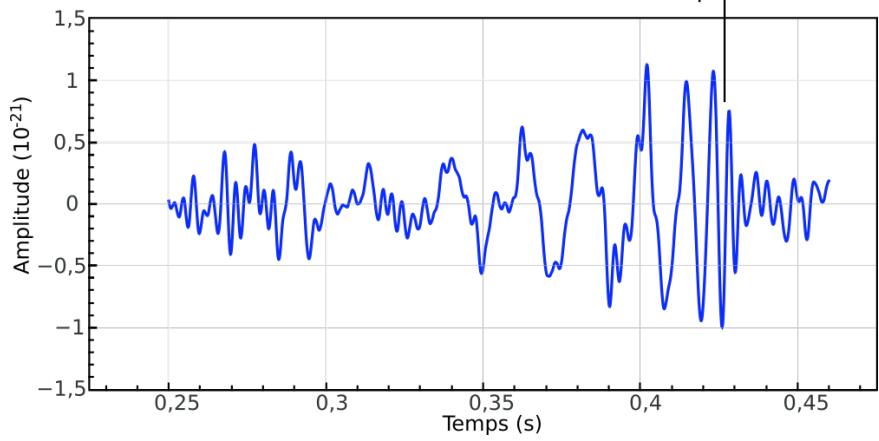
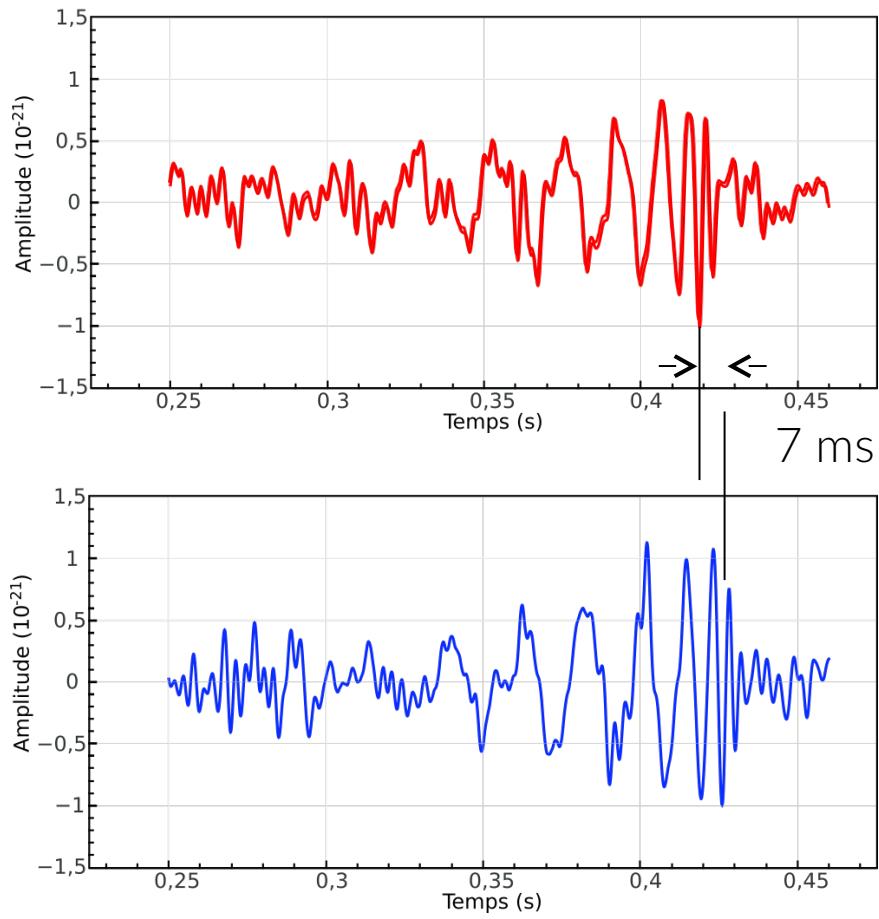
LIGO & Virgo



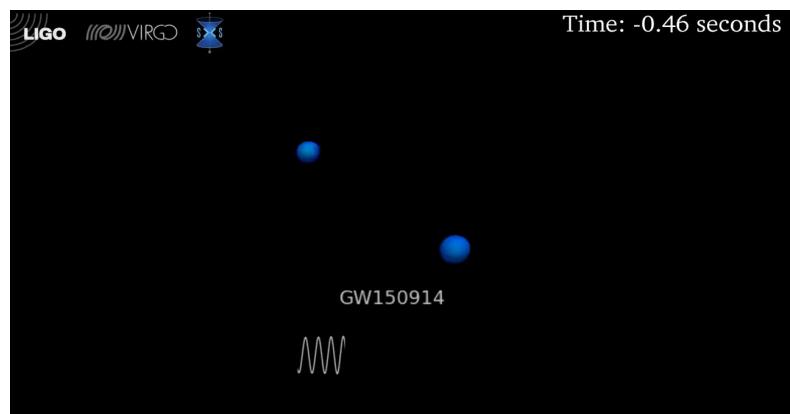
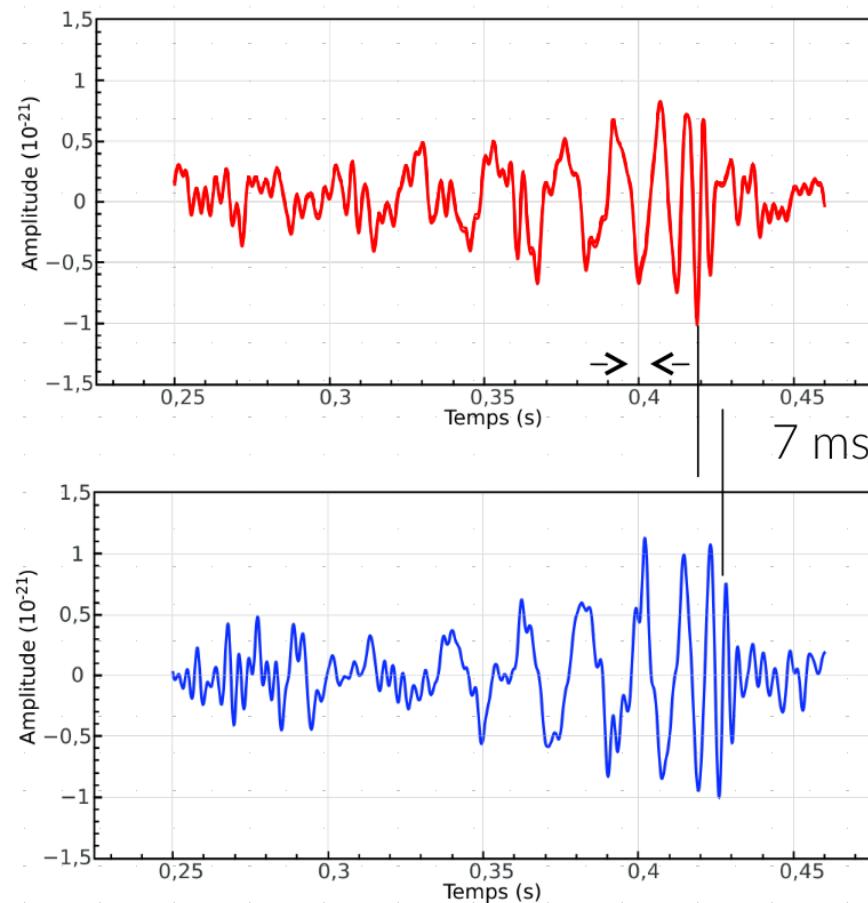
O3

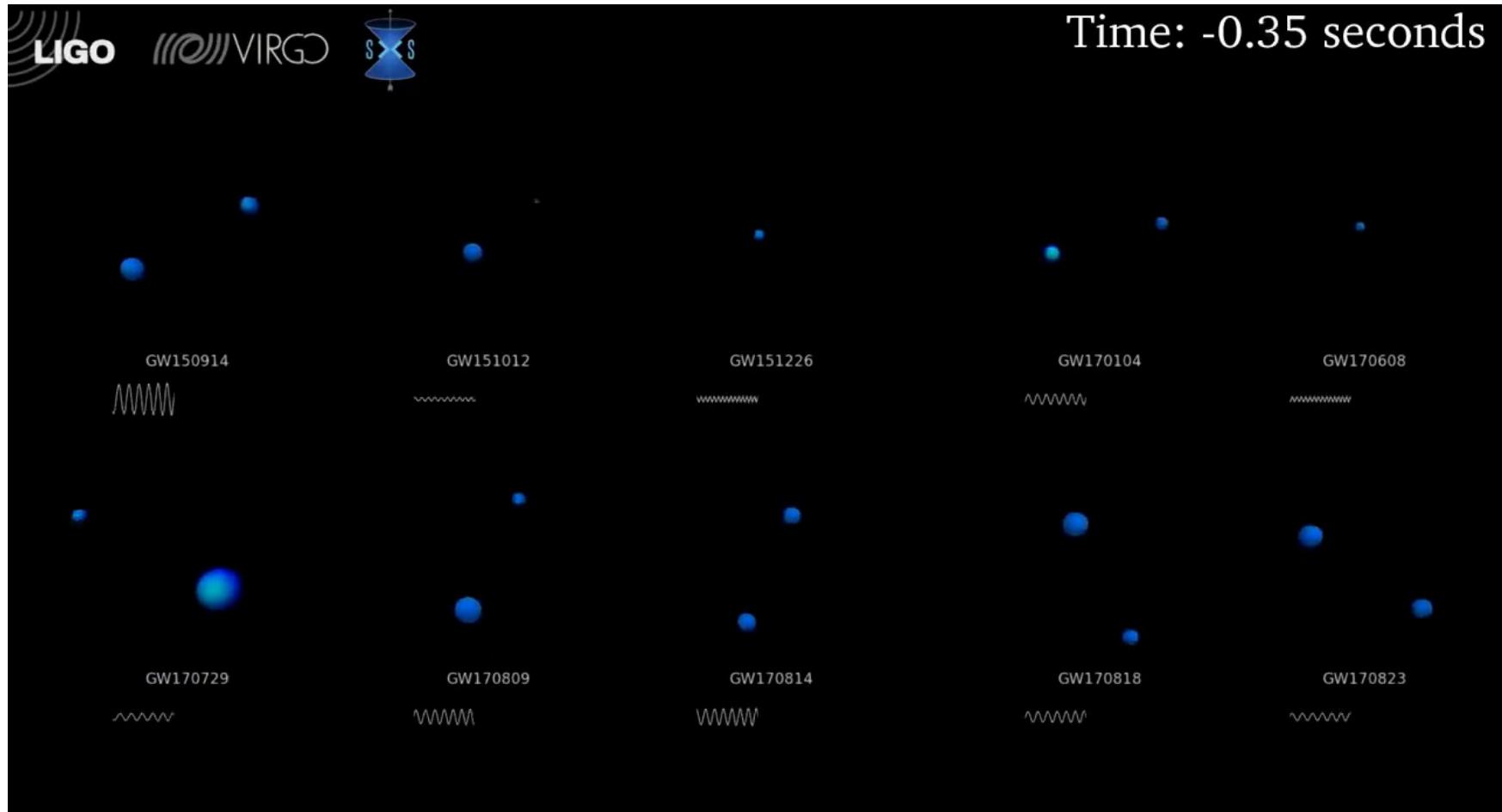
1 yr from Apr 2019

Sep 14, 2015



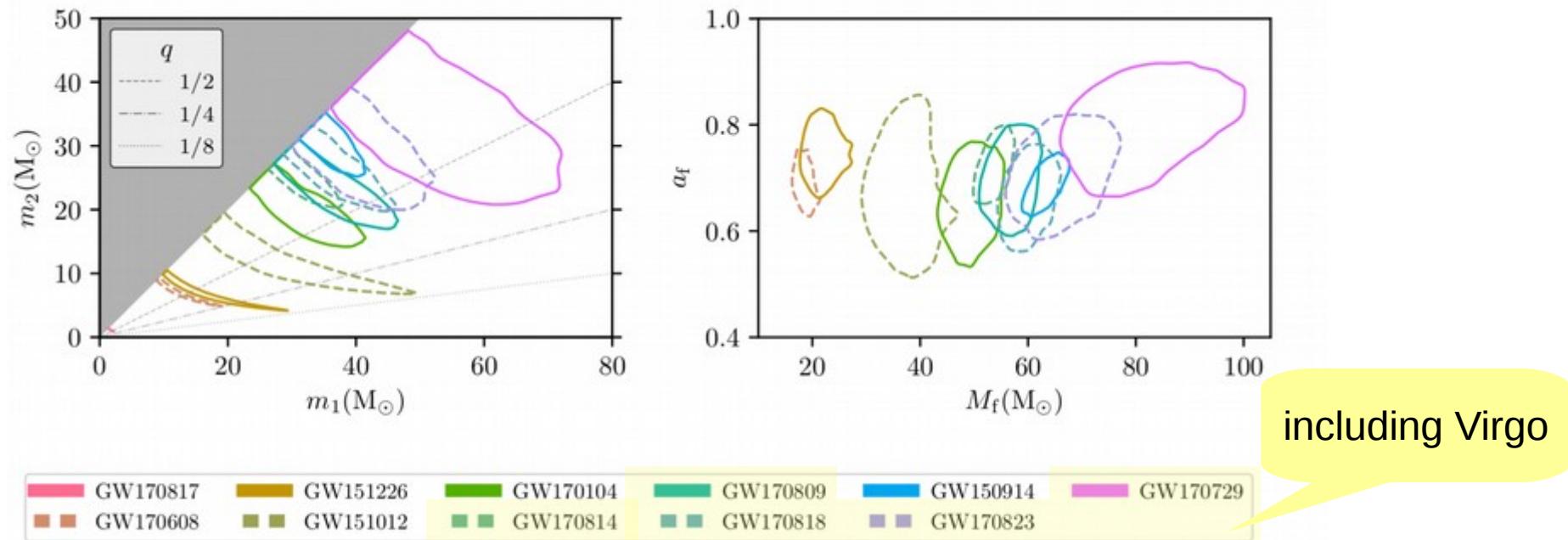
Sep 14, 2015





Catalog GWTC#1

- 10 binary black hole mergers



- population of objects hidden to conventional astronomy

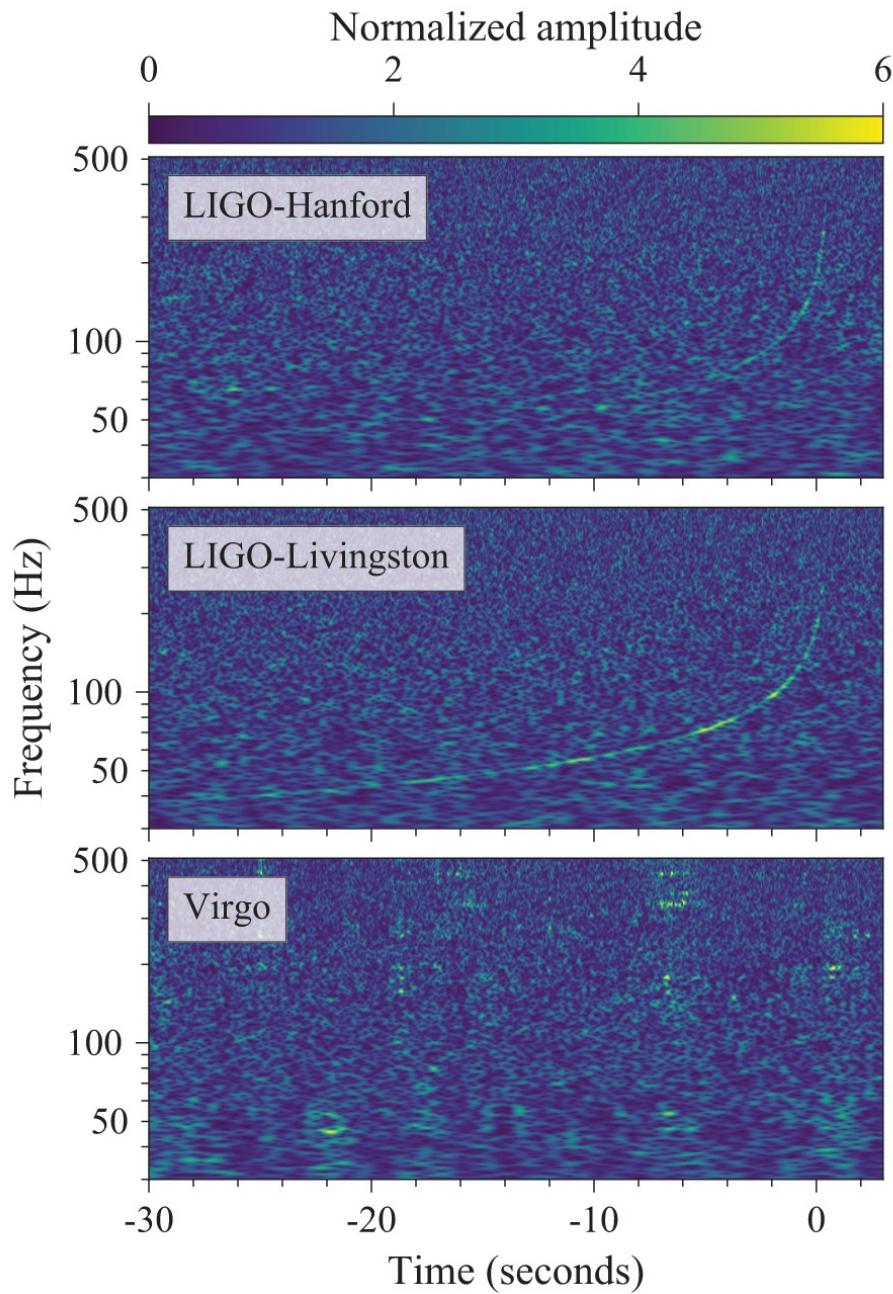
arXiv:1811.12907, <https://www.gw-openscience.org/catalogs/>

[Cf aussi l'article de J Garcia Bellido et S Clesse dans Pour la science, fév 2018]

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Aug 17, 2017



$$\tau \propto \mathcal{M}_{\text{det}}^{-5/3}$$

chirp mass

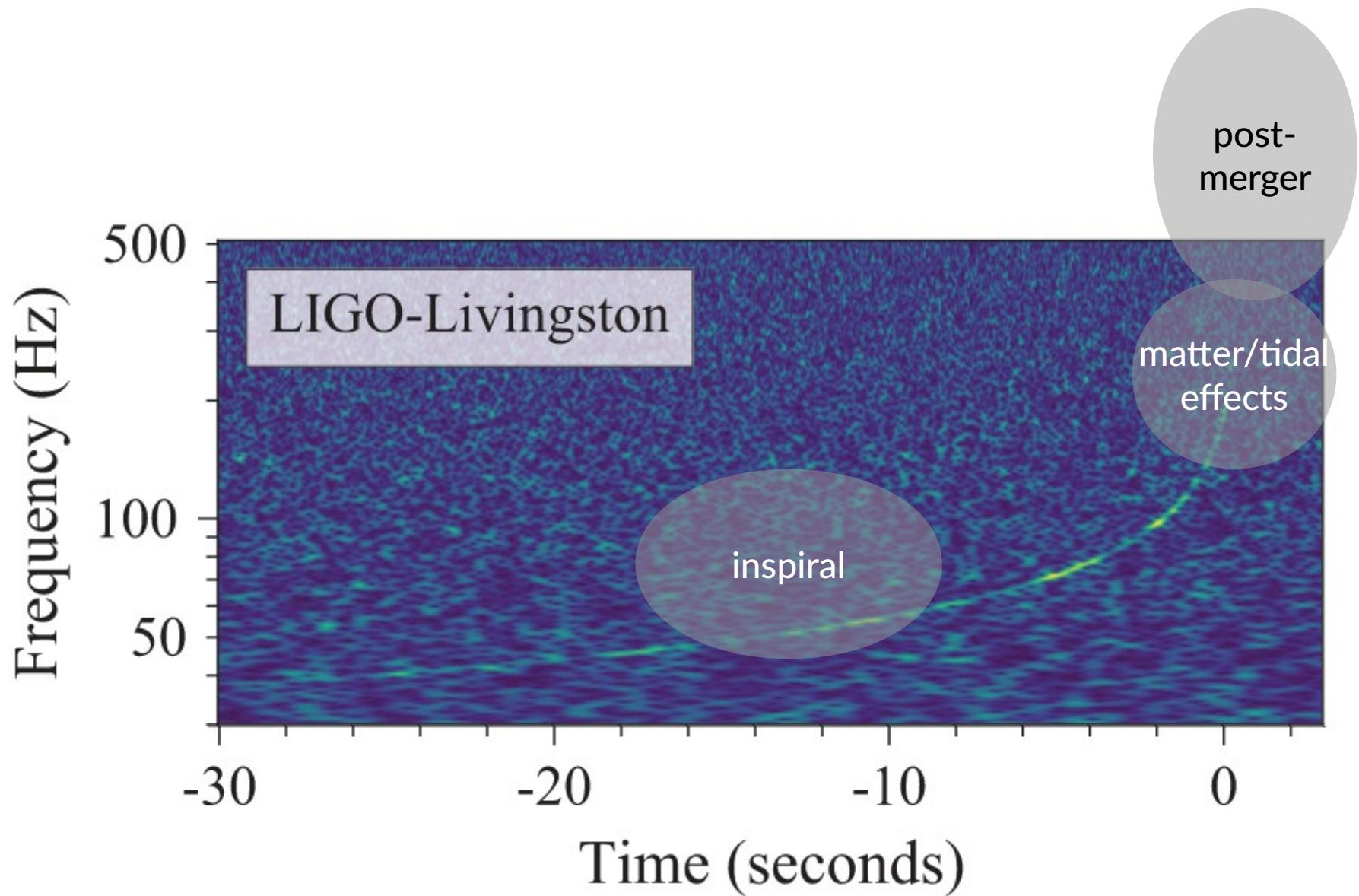
$$\tau \lesssim 1 \text{ s} \quad \text{for BBH}$$

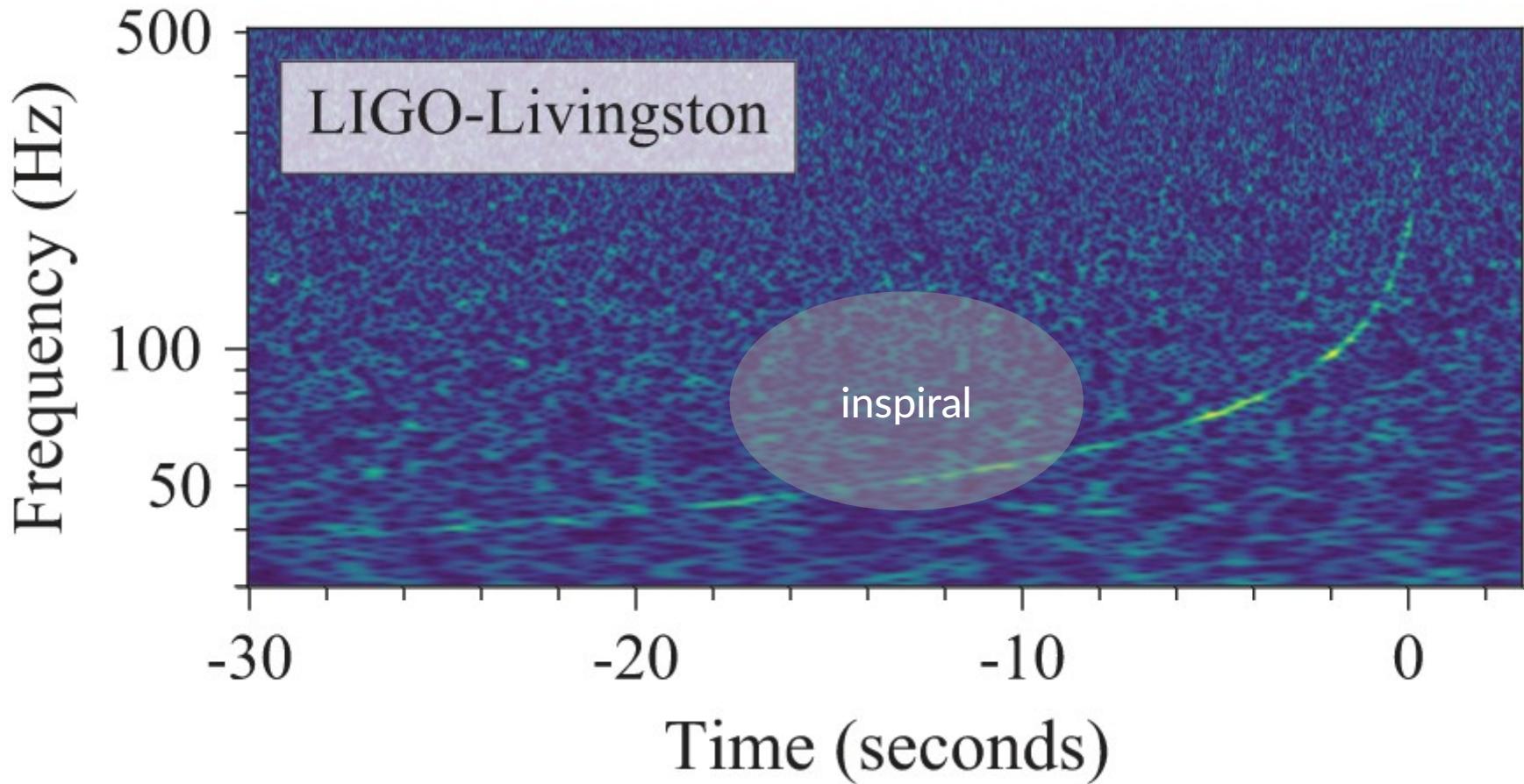
GW170817

$$\tau \sim 100 \text{ s}$$

$$\mathcal{M}_{\text{det}} \sim 1 M_{\odot}$$

A lot of science with one signal





From signal phase, chirp mass estimate

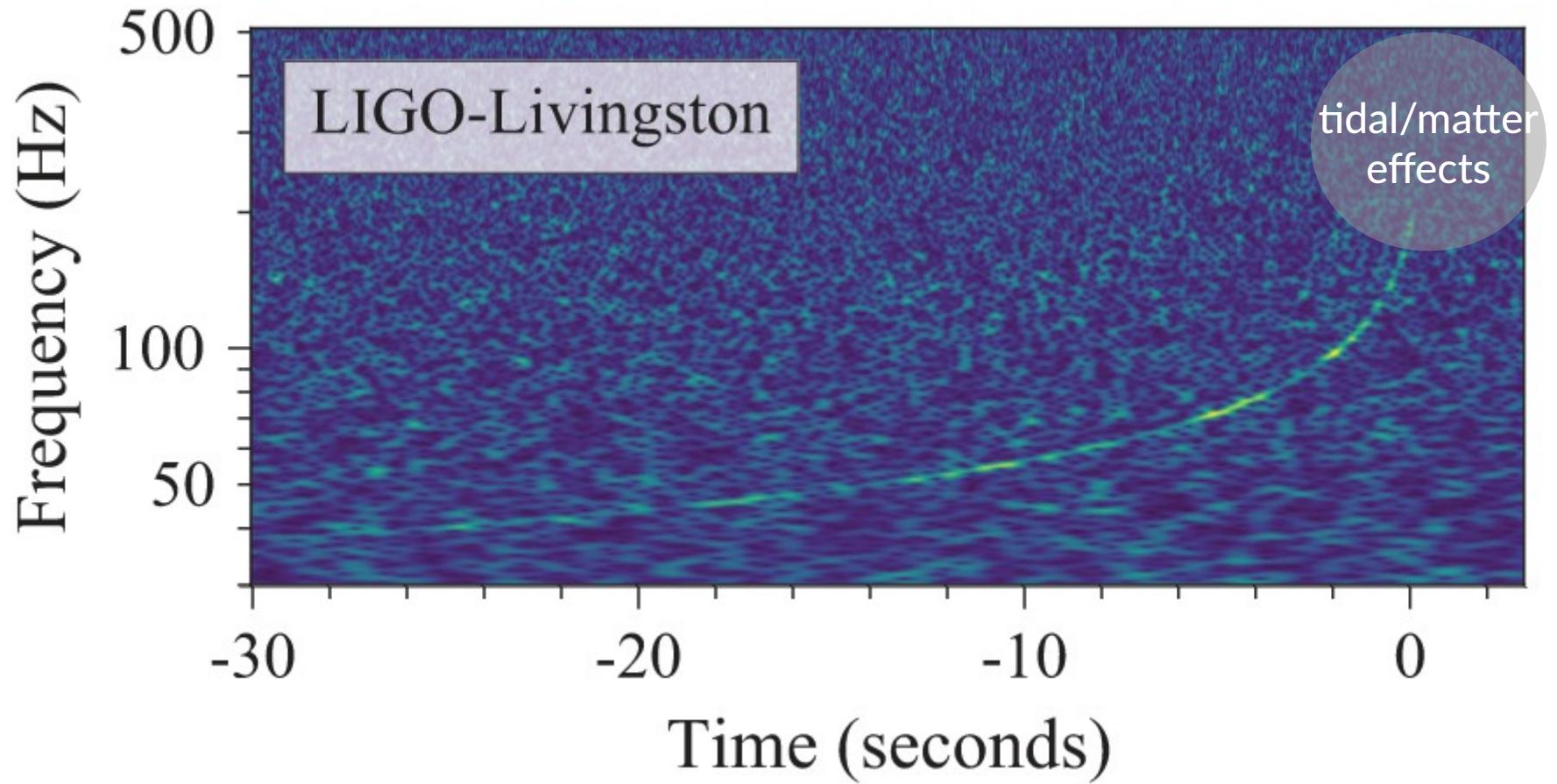
Phase matching: measurement accuracy scales with $1/N_{\text{cycles}}$

$$N_{\text{cycles}} \approx 3000$$

detector-frame chirp mass $\mathcal{M}^{\text{det}} = 1.1977 \text{ M}_\odot \pm 0.07\%$

From signal amplitude, distance/inclination (degenerate)

$$h_+ \propto \frac{1 + \cos^2 \theta_{JN}}{D_L} \quad D_L = 40 \text{ Mpc} \pm 35\%$$



Tidal deformation by the gravity gradient due to companion

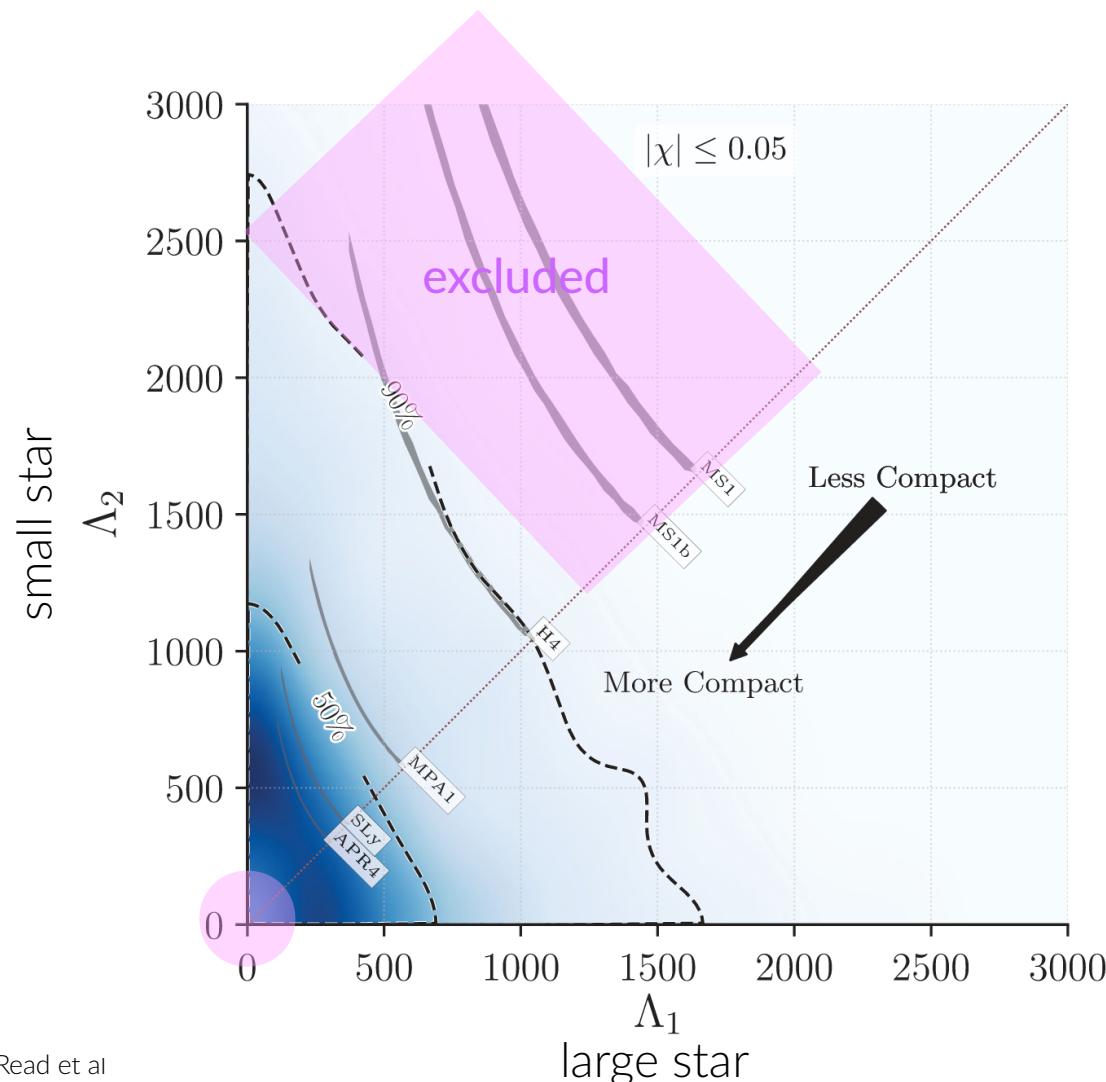
Effect observable in the final tens of GW cycles before merger
 $f_{\text{GW}} > 400 \text{ Hz}$ – Keplerian orbital radius $\sim 60 \text{ km}$ is comparable to NS radius

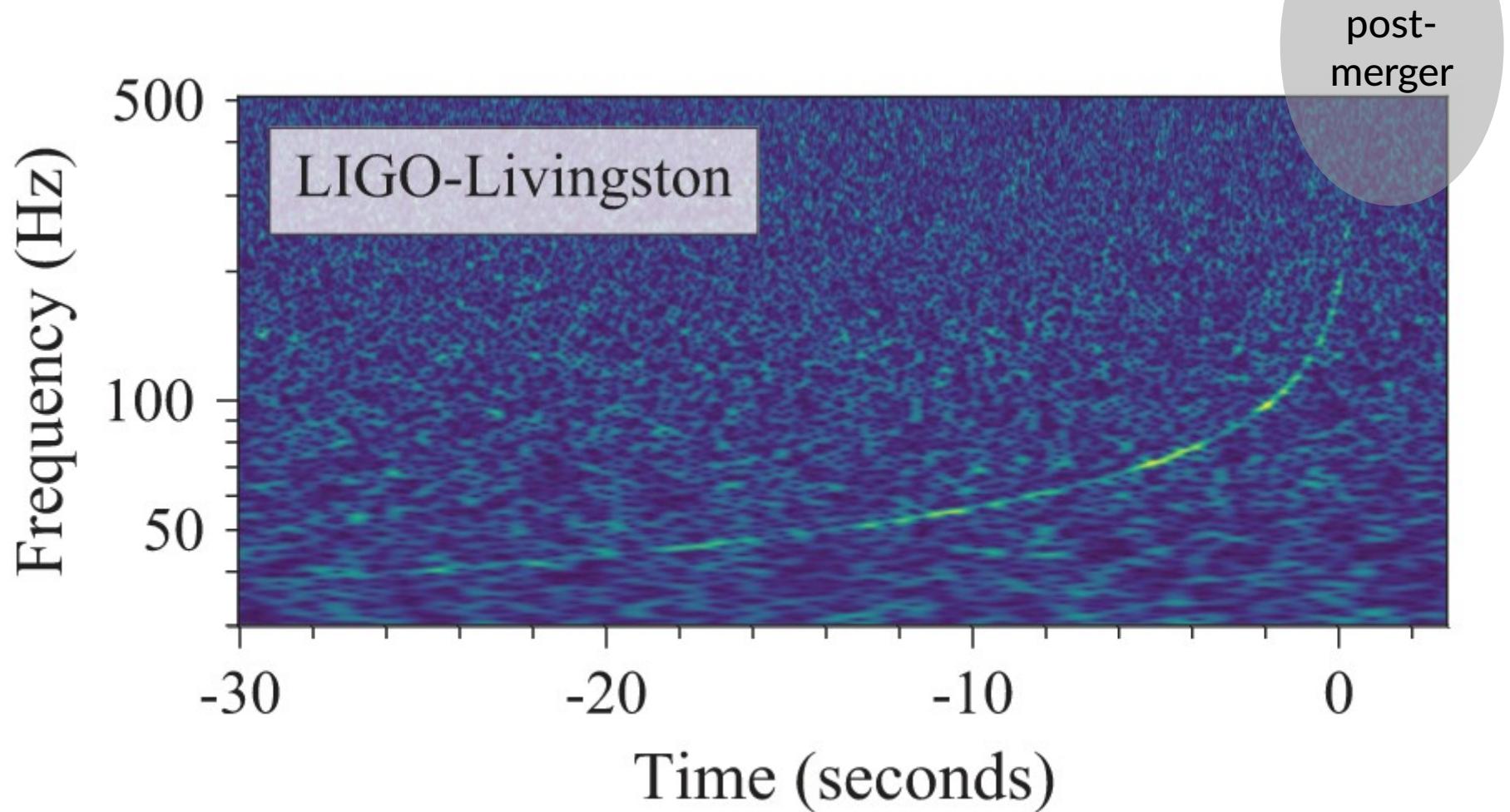
Tidal deformability

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$$

Love number (EoS)

$k_2 = 0$ for BH





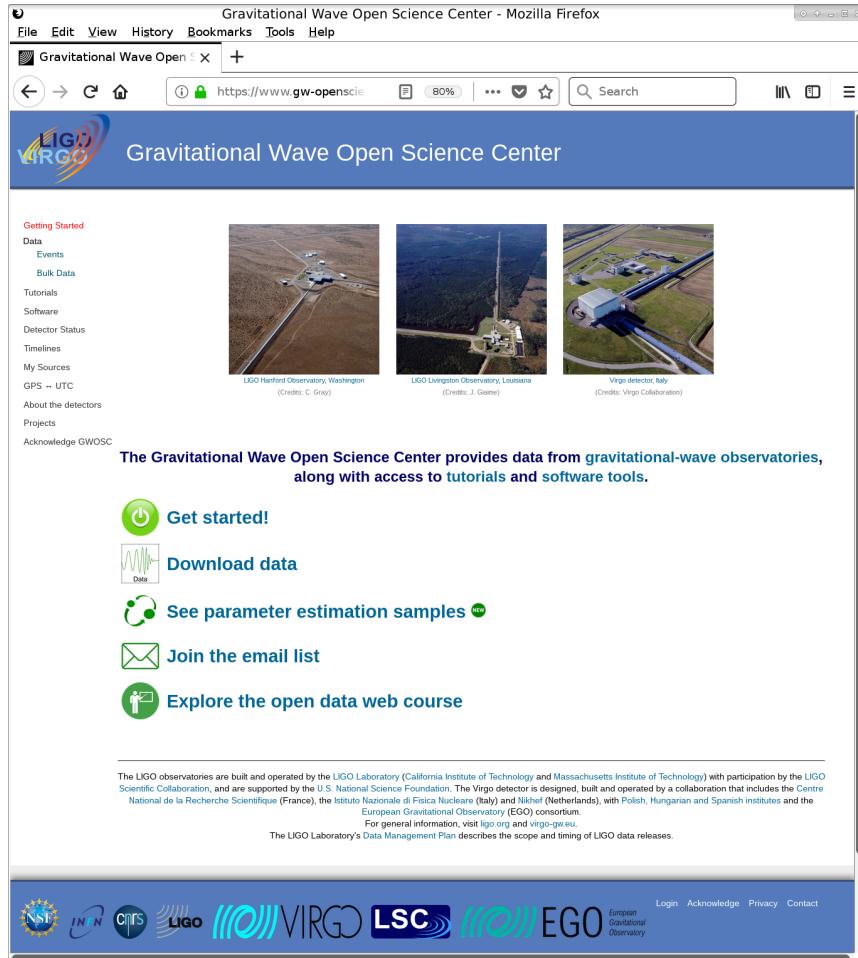
What is the remnant?

prompt collapse to a black hole
hypermassive NS [preferred]
supramassive NS
stable NS

QNM at 6 kHz
livetime ~ 1 s f-mode, 2-4 kHz
livetime $\sim 10\text{--}10^4$ s
magnetar, bar mode or r-mode instability

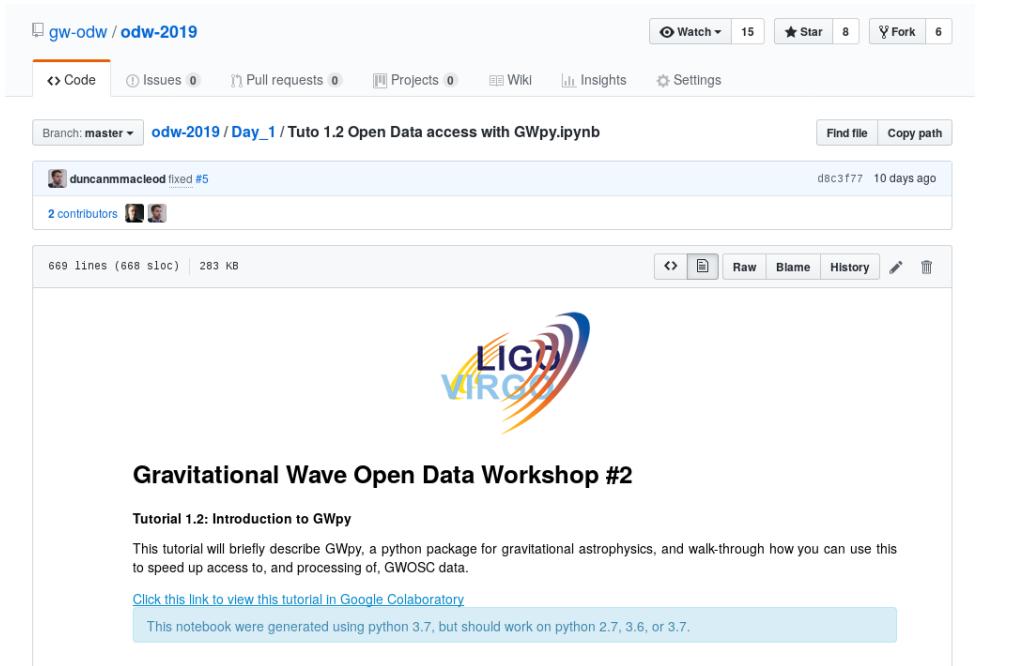
No evidence for a post-merger signal

<https://www.gw-openscience.org> <https://indico.in2p3.fr/2/gw-odw2>



The screenshot shows the homepage of the Gravitational Wave Open Science Center. At the top, there's a navigation bar with links for File, Edit, View, History, Bookmarks, Tools, and Help. Below the bar, a search bar shows the URL <https://www.gw-openscience.org>. The main content area features the LIGO-VIRGO logo and the title "Gravitational Wave Open Science Center". On the left, a sidebar lists various sections: Getting Started, Data, Events, Bulk Data, Tutorials, Software, Detector Status, Timelines, My Sources, GPS -- UTC, About the detectors, Projects, and Acknowledge GWOSC. The central part of the page displays three images of gravitational-wave observatories: LIGO Hanford Observatory, LIGO Livingston Observatory, and the Virgo detector. Below these images, a text block states: "The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to [tutorials](#) and [software tools](#)". A "Get started!" button is followed by five links: "Download data", "See parameter estimation samples", "Join the email list", and "Explore the open data web course". At the bottom, there's a note about the LIGO observatories being built and operated by the LIGO Laboratory and other international partners, along with logos for NSF, INP, CPTI, LIGO, VIRGO, LSC, and EGO.

Lecture videos, Jupyter notebooks, challenge data set available online – Run on Google Colab cloud



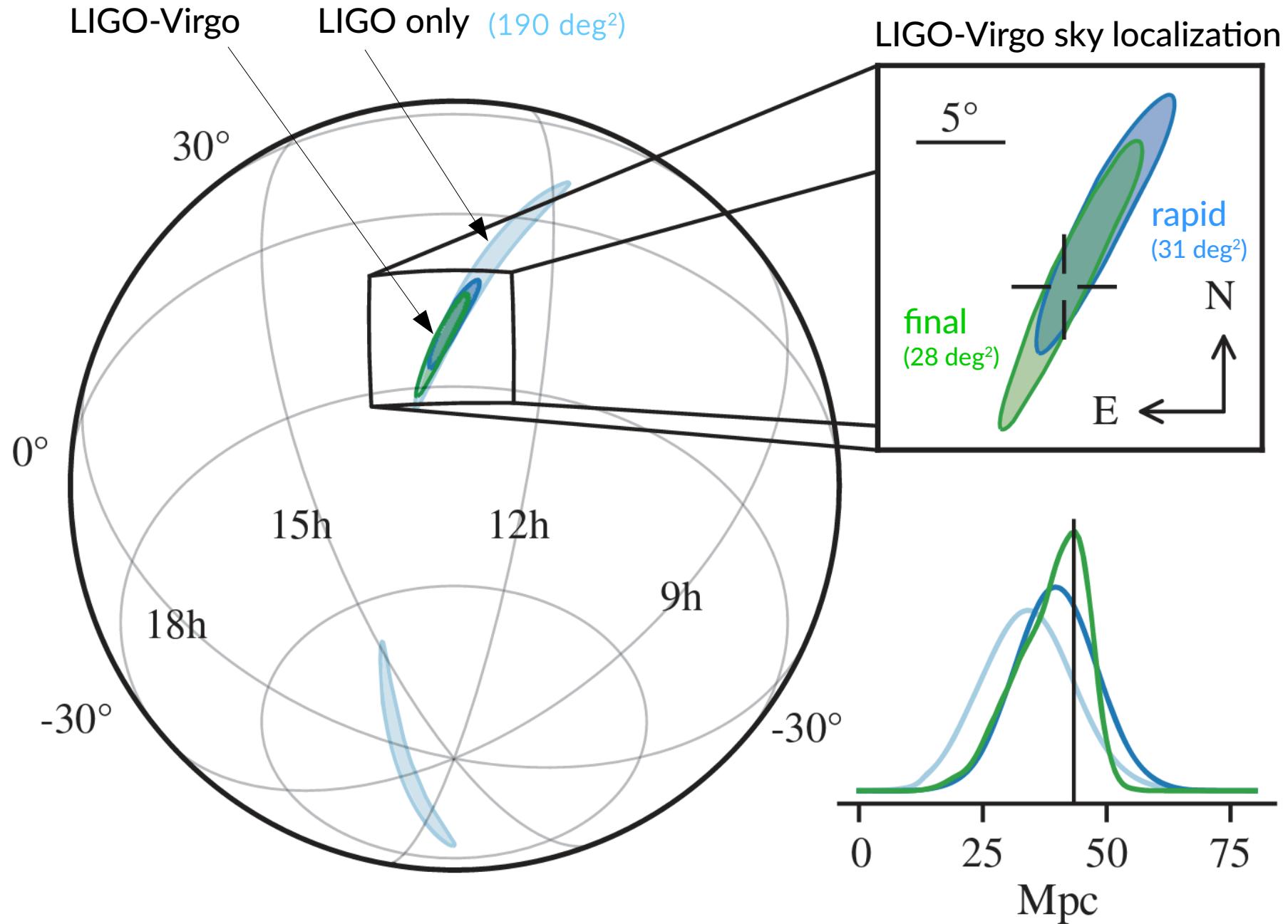
The screenshot shows a GitHub repository page for "gw-odw / odw-2019". The repository has 15 stars and 6 forks. The master branch contains a file named "odw-2019 / Day_1 / Tuto 1.2 Open Data access with GWpy.ipynb". The file was last updated 10 days ago by user duncanmacleod. It has 2 contributors. The file size is 283 KB and contains 669 lines (668 sloc). Below the file, there's a large LIGO-VIRGO logo. The repository description is "Gravitational Wave Open Data Workshop #2". It includes a section for "Tutorial 1.2: Introduction to GWpy" which describes the package for gravitational astrophysics and how to use it to speed up access to and processing of GWOSC data. A link to view the tutorial in Google Colaboratory is provided, along with a note that the notebook was generated using Python 3.7 but should work on 2.7, 3.6, or 3.7.

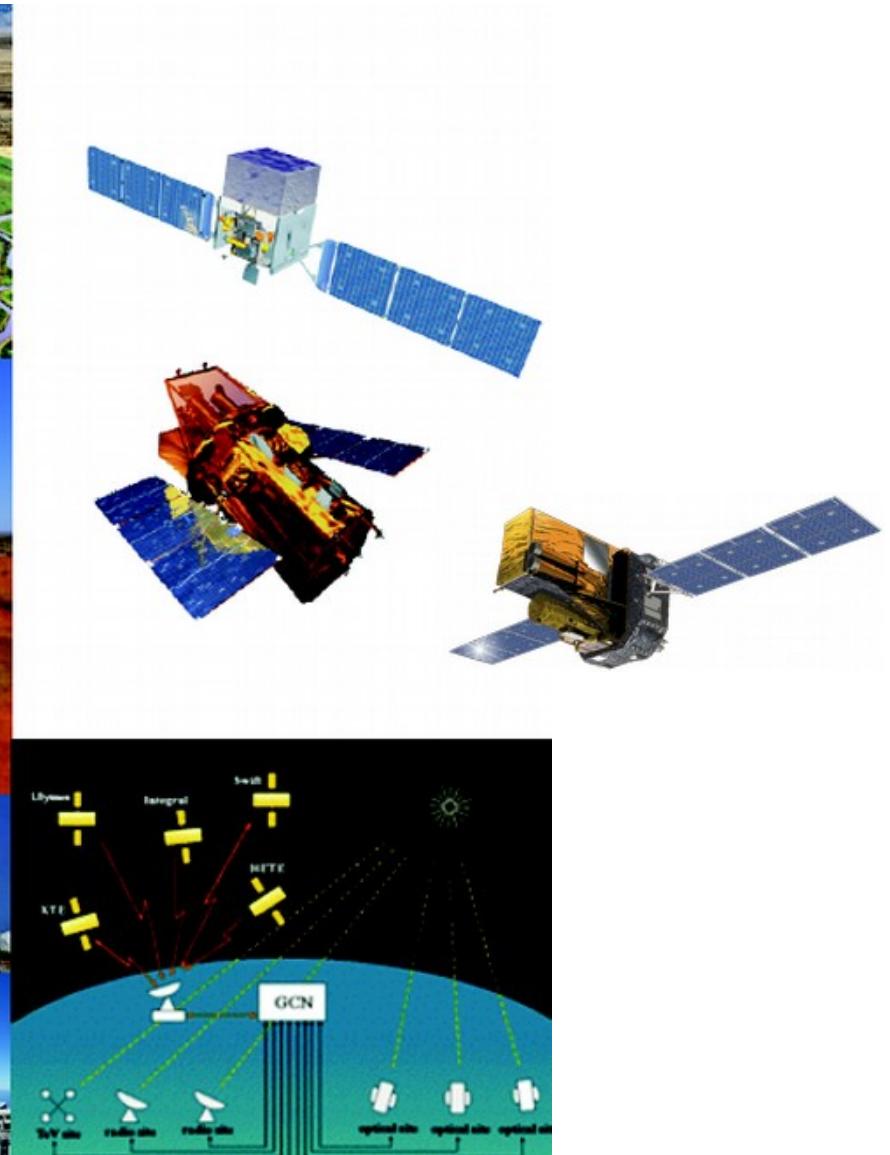
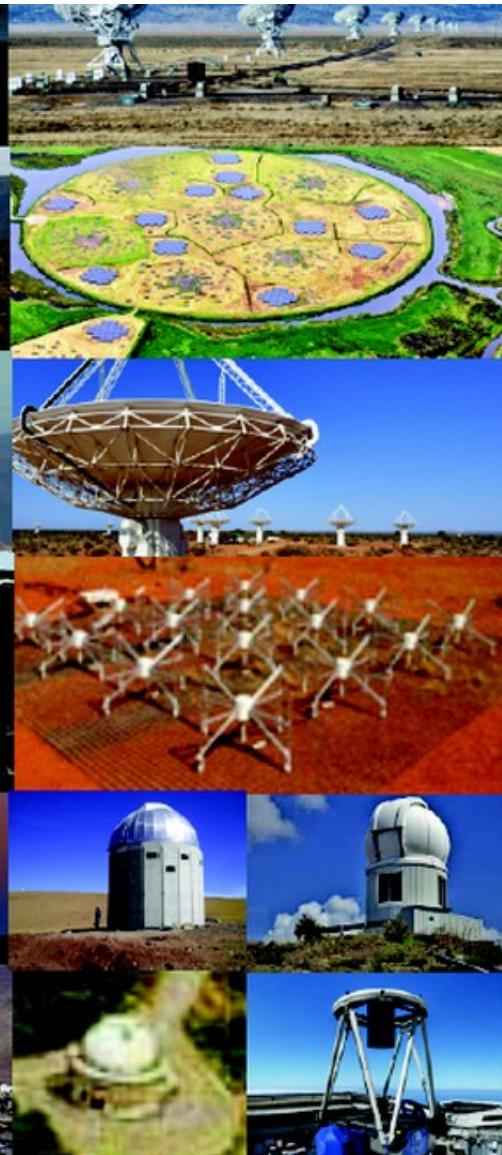
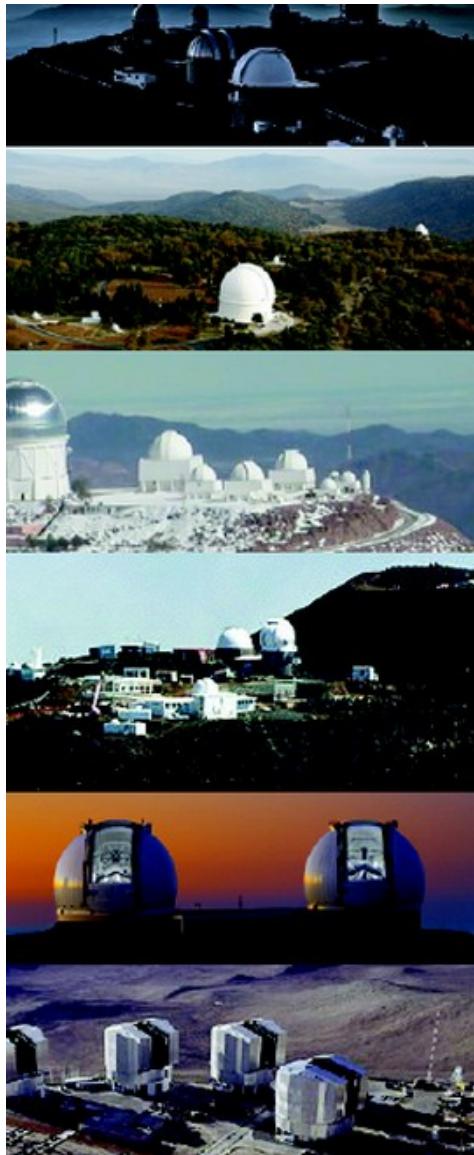


The screenshot shows the website for the "Gravitational wave Open Data Workshop #2" held in Paris, April 8-10, 2019. The background features a green and yellow abstract pattern. The title "Gravitational wave Open Data Workshop #2" is prominently displayed, along with the date "Paris, April 8-10 2019". Below the title, it says "AstroParticule & Cosmologie" and "Paris Diderot University". A text box states: "Three-day workshop to learn how to access and analyze LIGO and Virgo data". At the bottom, there's a link to "http://www.gw-openscience.org" and logos for LIGO, LSC, VIRGO, EGO, CNRS, INP, and PNHE.

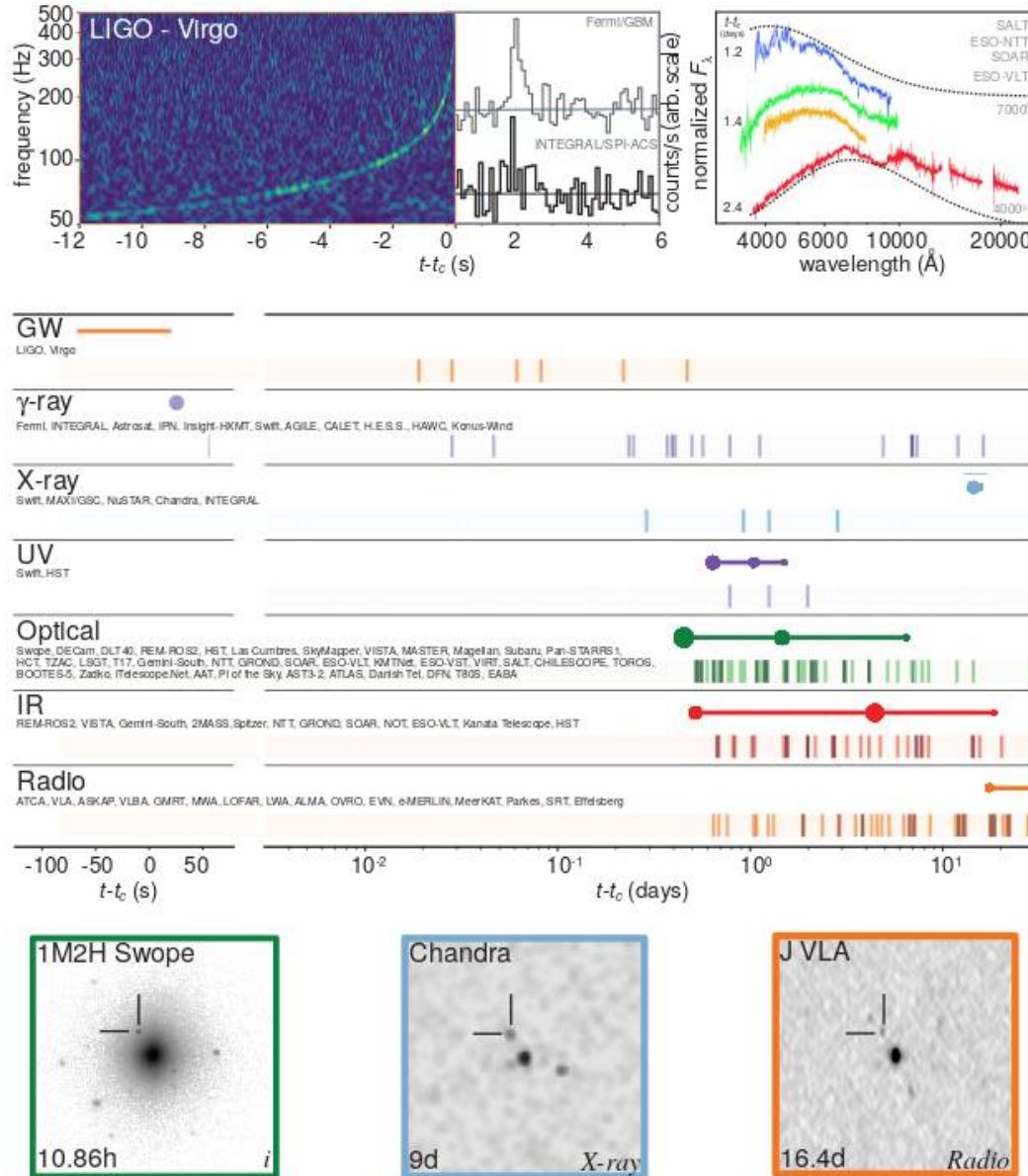
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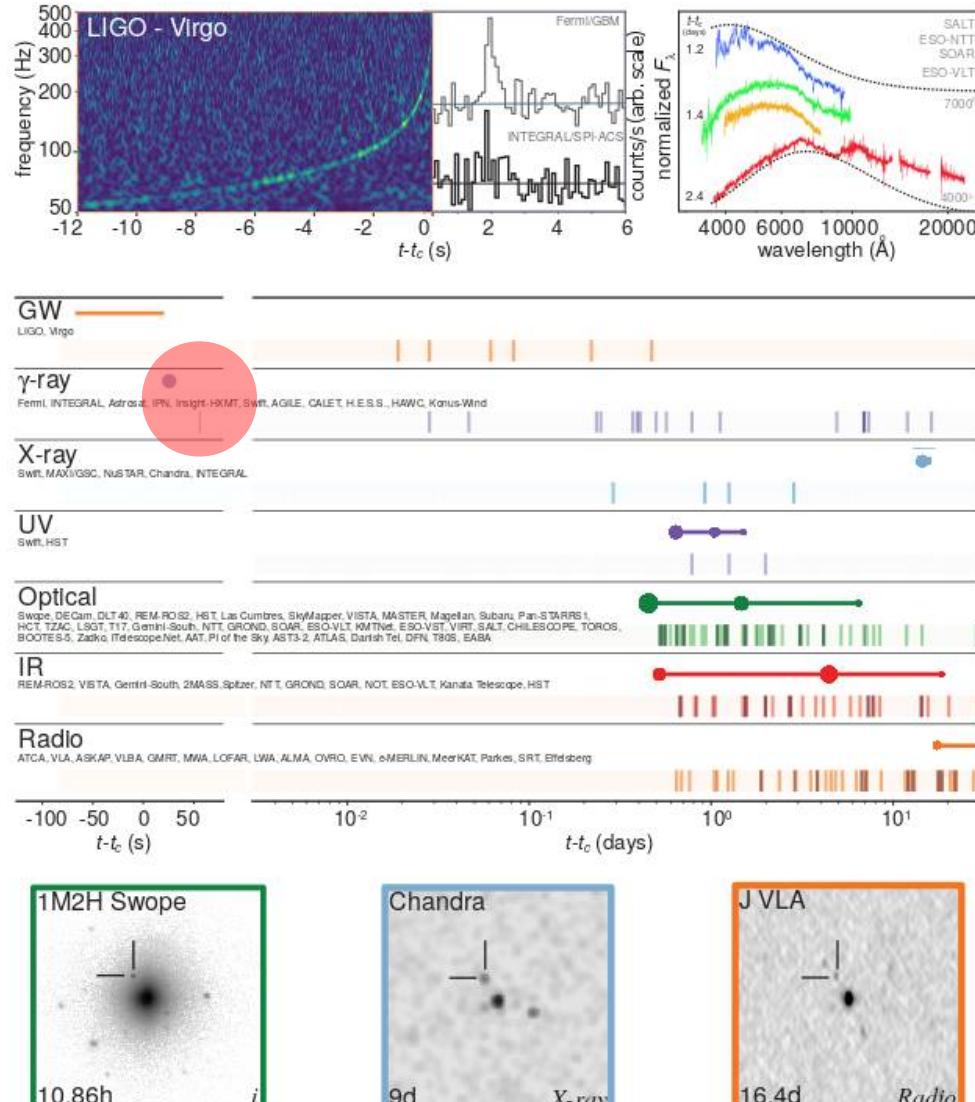
GW170817 follow-up



(first month shown)
... continued ...

Voir aussi la présentation de Julien Souchard (neutrinos et rayons cosmiques)

Three time scales: seconds

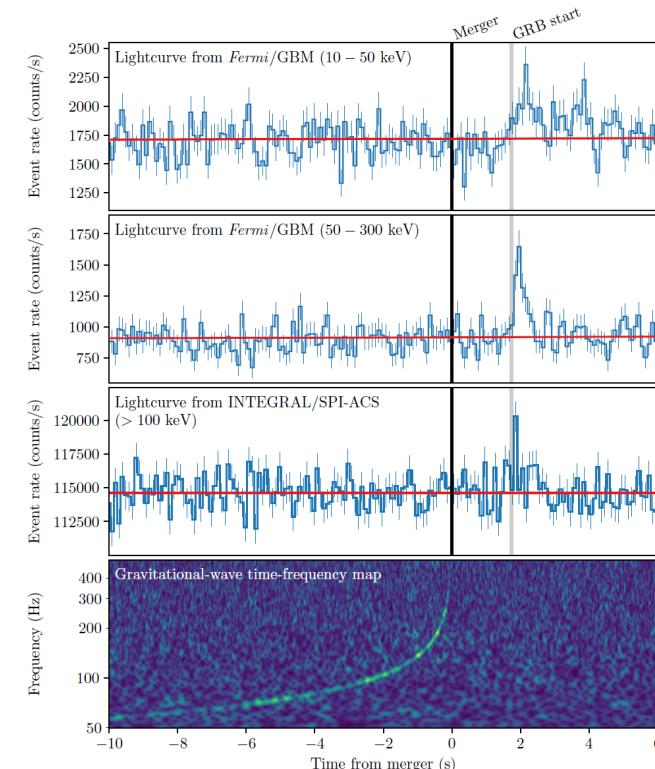


T0+1.7 s : gamma-ray burst

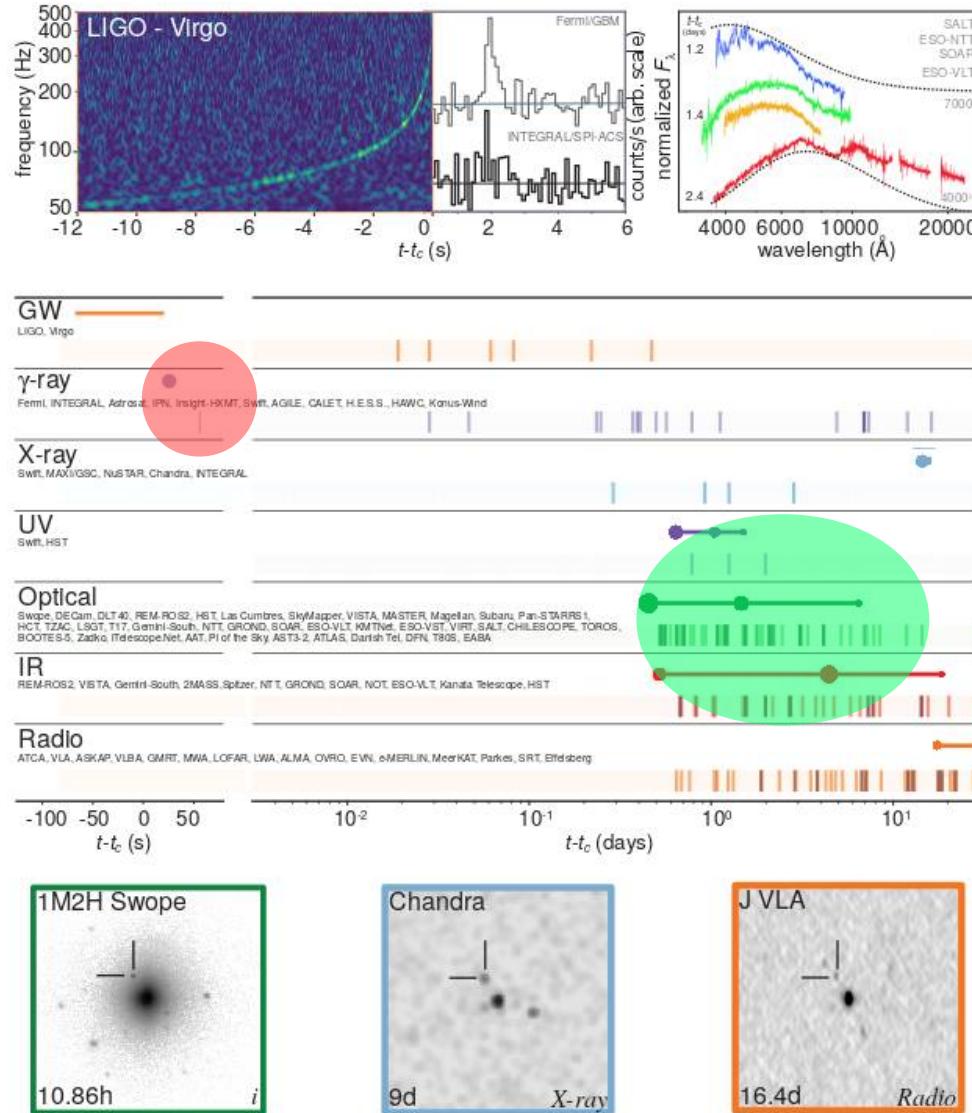
Short duration, ~ 2 sec

$E_{\text{iso}} \sim 1.2 \times 10^{46} \text{ erg}$ (assuming $D_L = 40 \text{ Mpc}$)

Atypical GRB: several orders of mag less energetic, softer spectrum



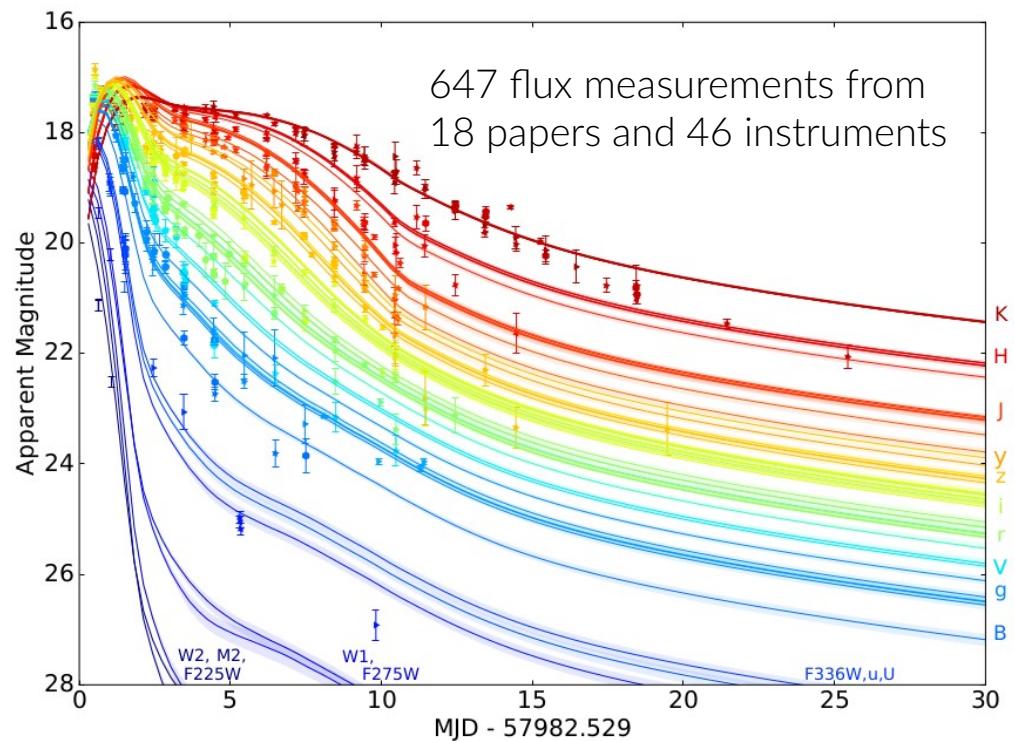
Three time scales: hours/day

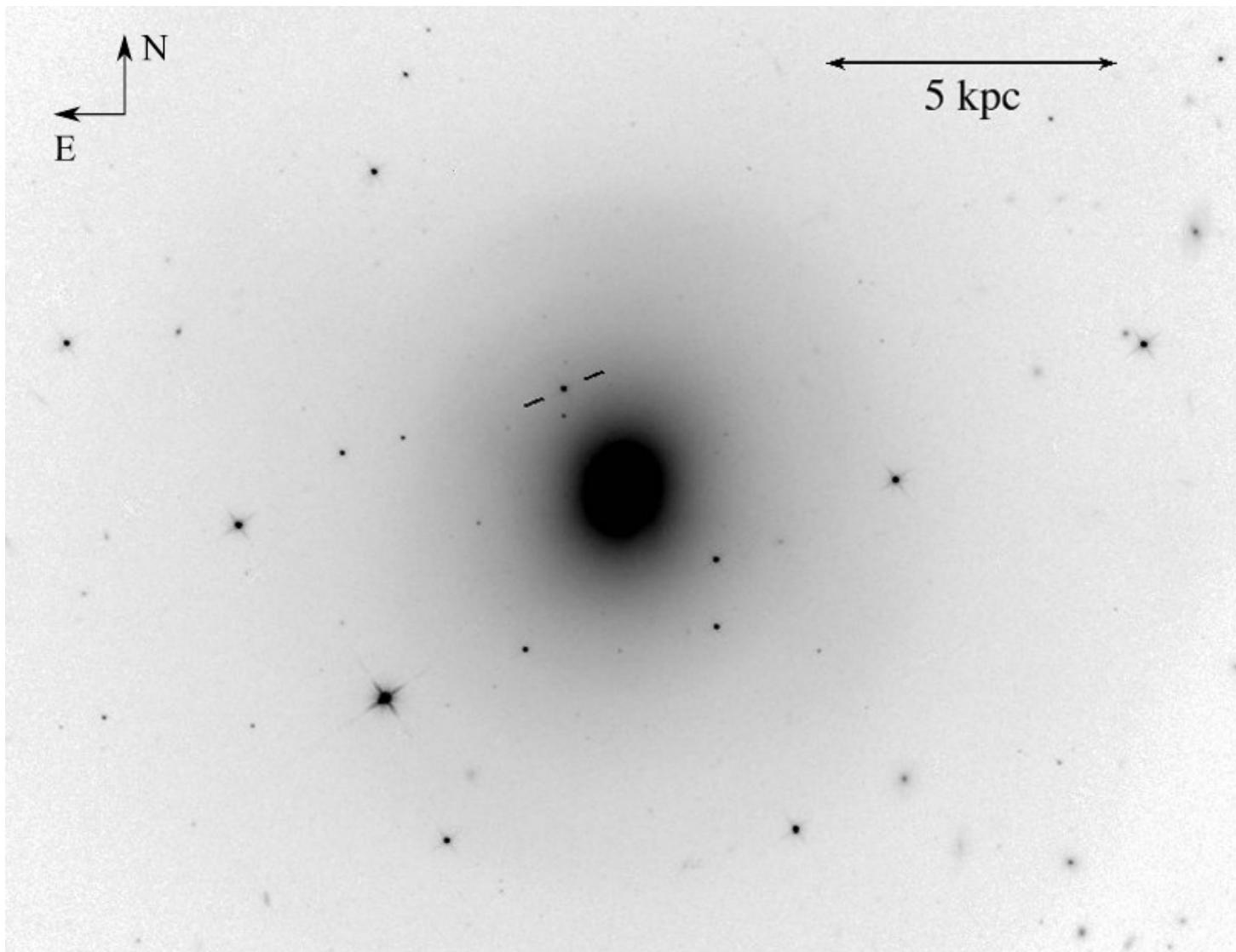


T0+~1 d : UV, optical and IR

Host galaxy identification

“Kilonova”: radioactive-decay (r-process) powered emission from the merger ejecta

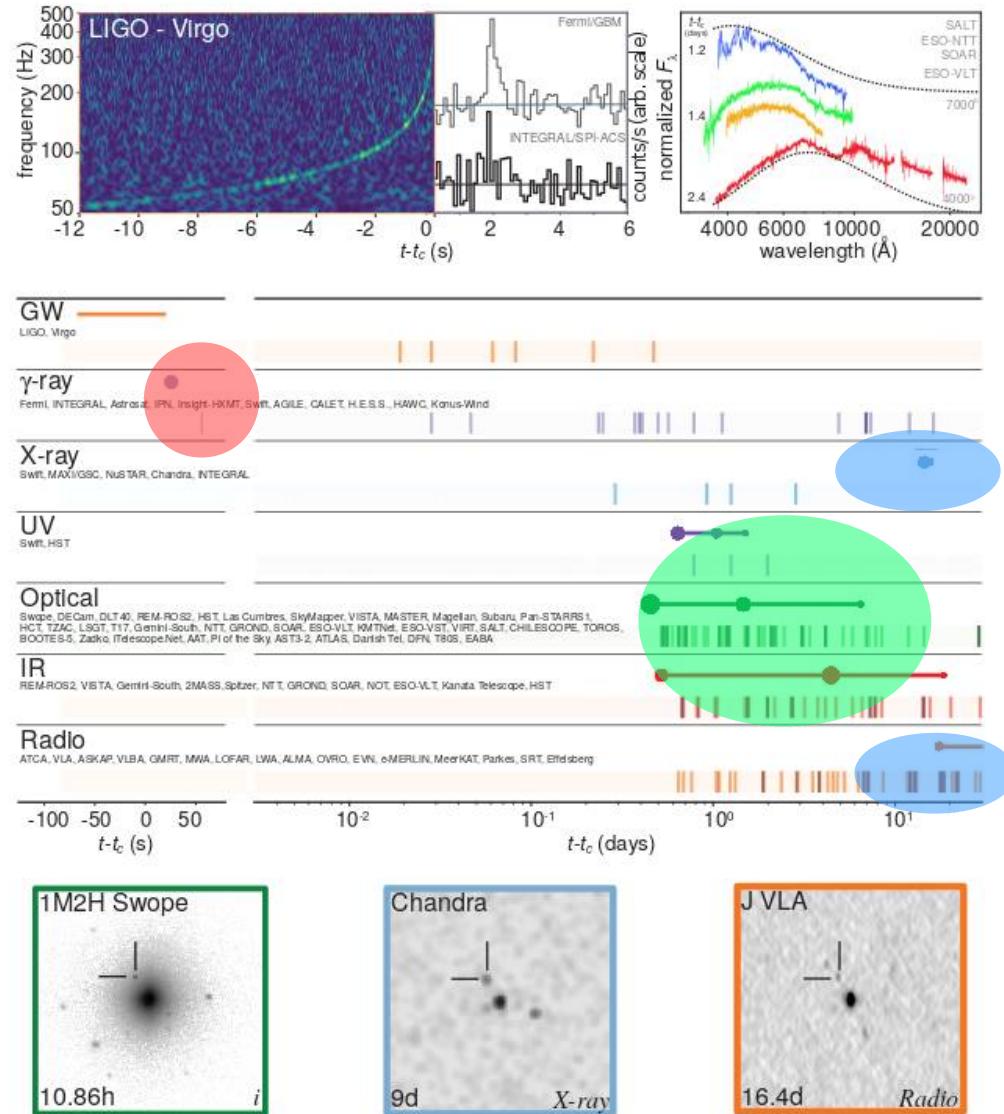




HST/WFC3-IR F110W $t_c + 4.79$ d

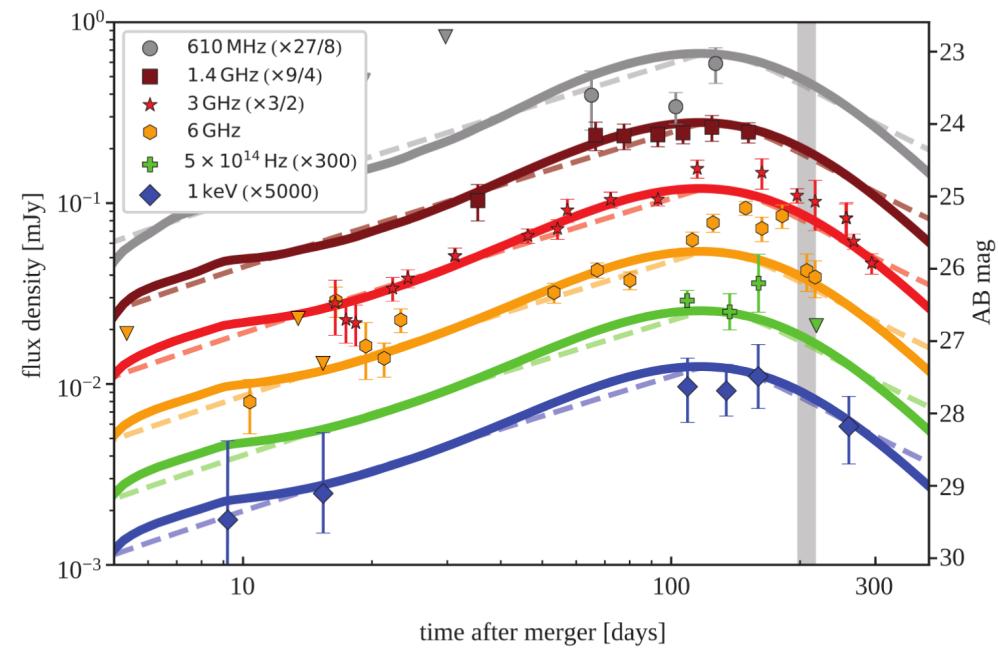
Tanvir et al, ApJL 848:L27 2017

Three time scales: weeks/months

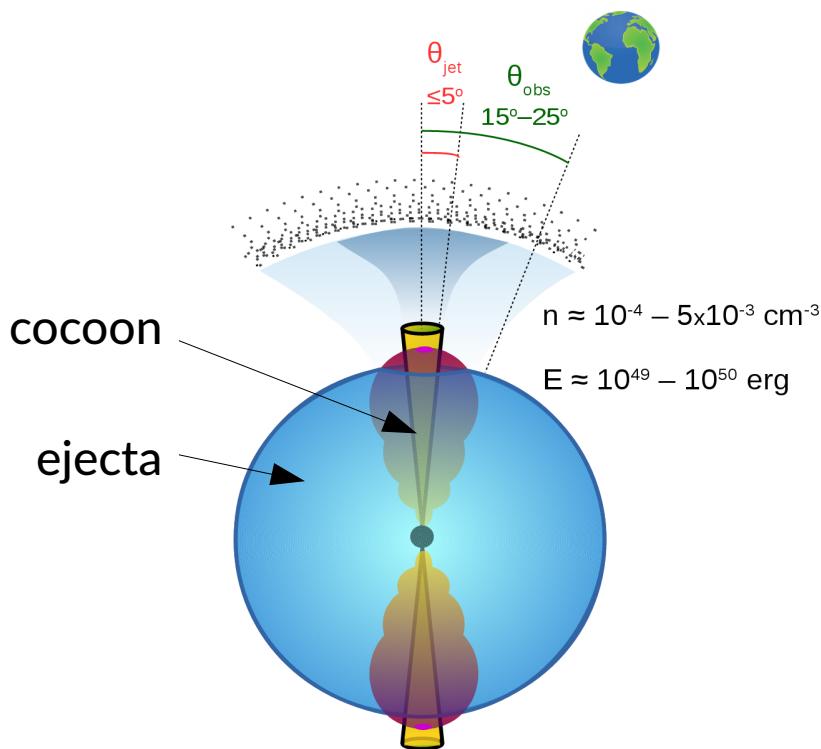


X-ray T0+9 d, radio T0+16 d

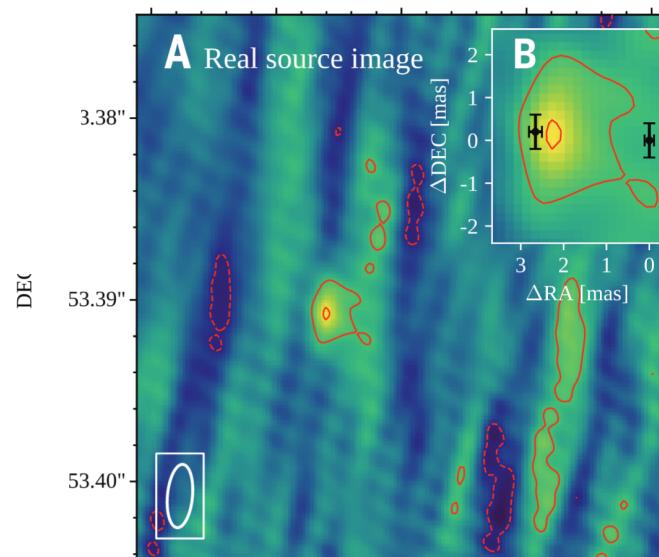
Peak in X-ray & radio (100 μJy) at T0+~150 d
and optical ($m=26.5$) at T0+110 d



Late time radio VLBI observations



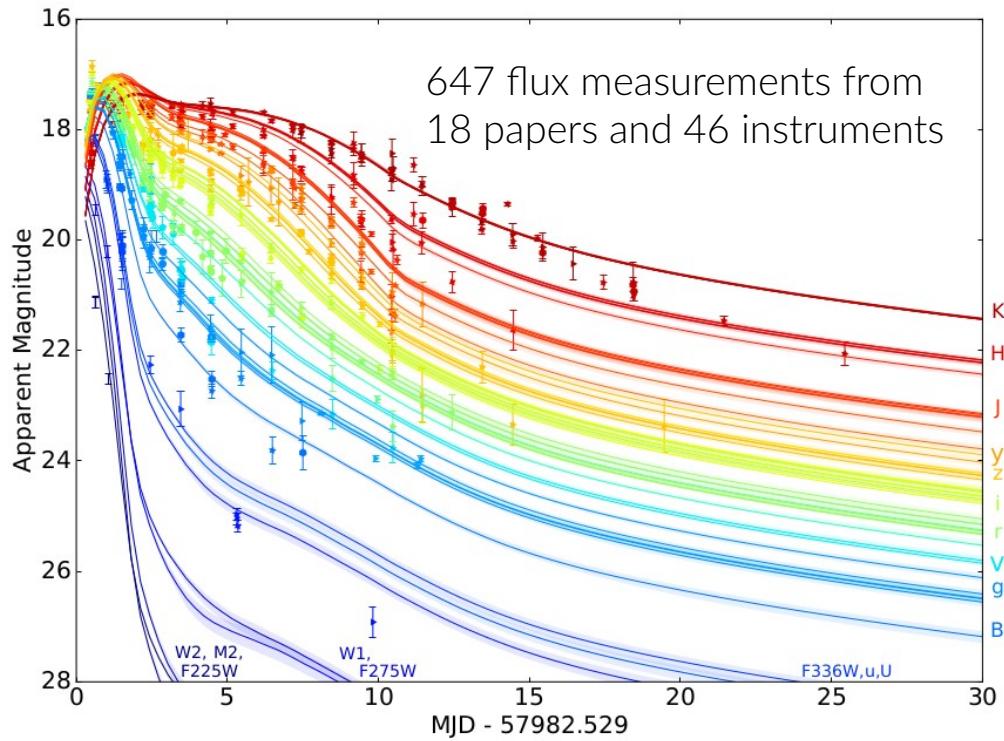
- Mooley et al & Ghirlanda et al
T0+ ~ 200 days
 - Very-long based interf [10 000 km]
> 32 radiotelescopes [worldwide]
 ~ 2 mas resolution
- Moving collimated jet observed
 - midly relativistic jet $\Gamma \sim 4$, $\theta_{\text{jet}} \sim 4^\circ$



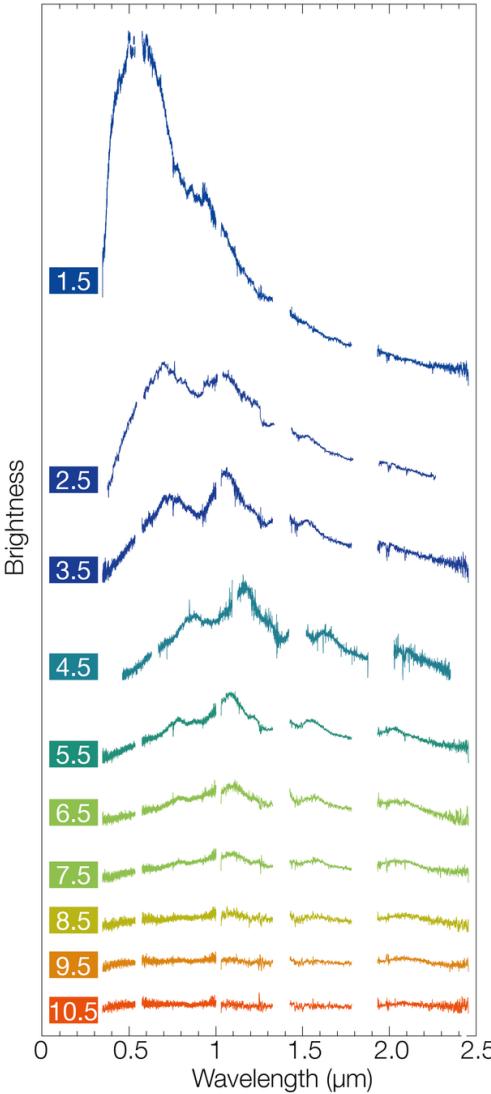
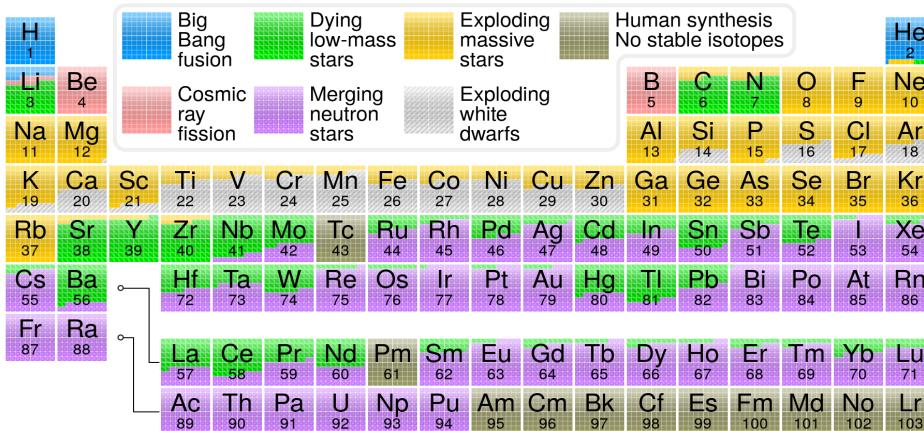
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- Perspectives

Implications (1): nucleosynthesis



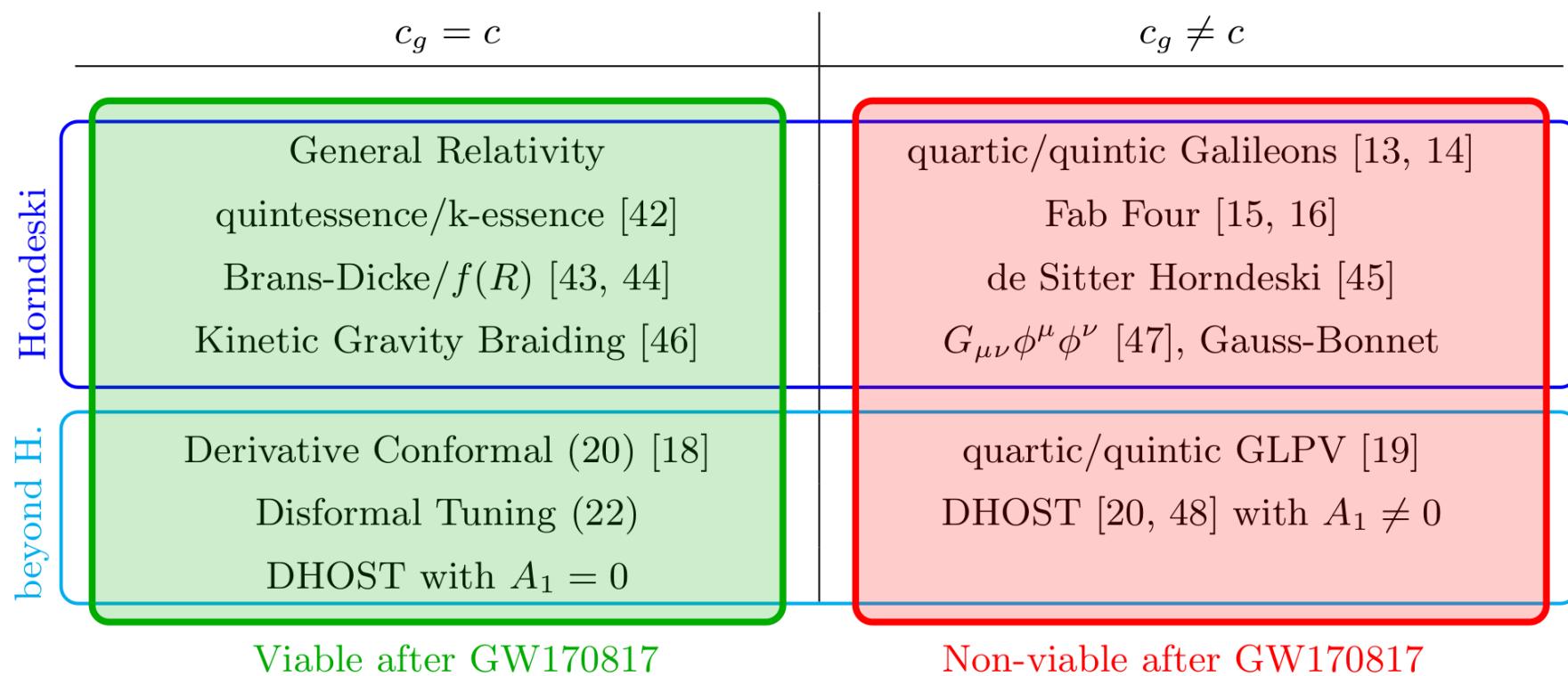
V. Ashley Villar et al, arXiv:1710.11576



Cf présentation David Lunney

Implications (2): modified gravity

- Coincidence with GRB170817A within 1.7 s
- Very stringent constraints on the speed of gravity $|c/c_g - 1| < 5 \times 10^{-16}$
- Incompatible with a large set of alt. gravity scalar-tensor theories brought forward to explain dark energy

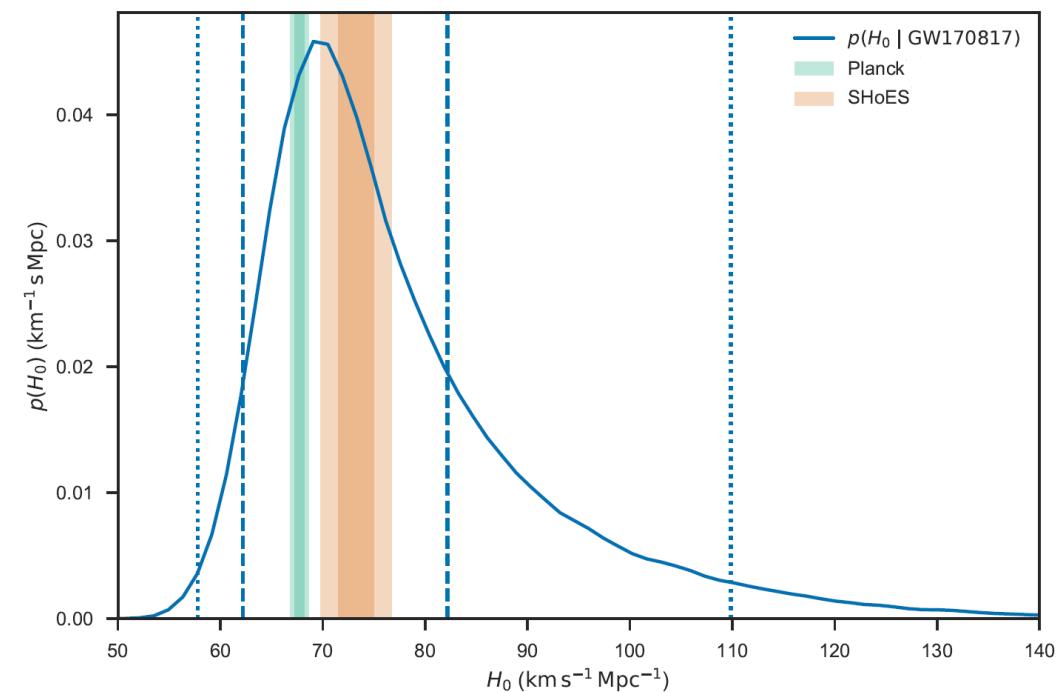
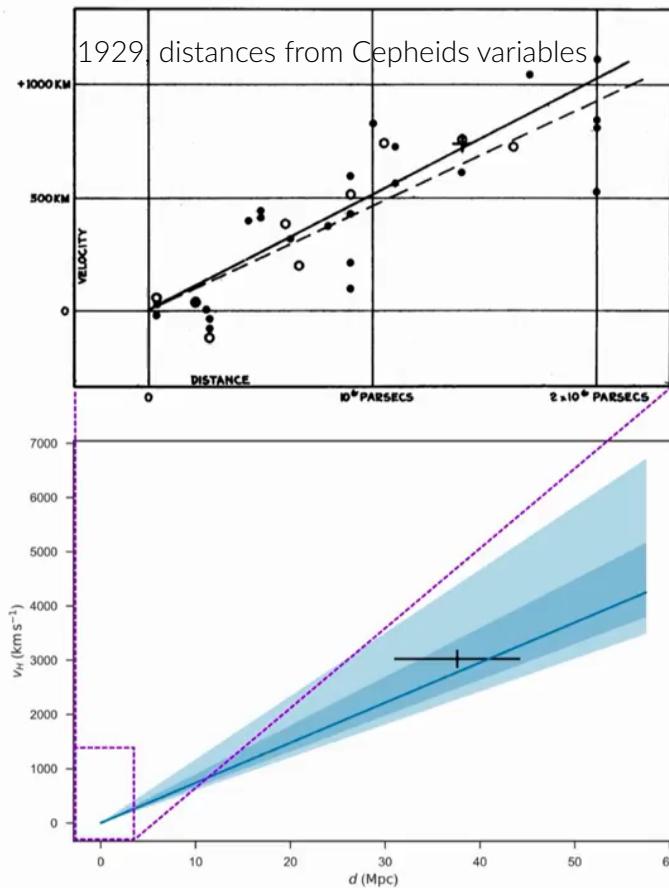


Implications (3): Cosmology

Hubble Lemaître law $v_H = cz = H_0 D_L$

from host galaxy identif.

from GW signal amplitude
[no “cosmological ladder”!]



Plan de la présentation

- Introduction sur les ondes gravitationnelles
- DéTECTEURS et observations jusqu'ici
- GW170817 et l'astronomie multi-messager
- Implications en physique, en astrophysique et en cosmologie
- **Perspectives**

Science run O3

LIGO at ~120 Mpc (L1) and 100 Mpc (H1)
Virgo at ~50 Mpc (x ~2 wrt O2) ~90 % duty cycle

Gravitational Wave Detector Network

Operational Snapshot as of Jul 08, 17:33 UTC

Detector	Status	Duration
GEO 600	Observing	0:02
LIGO Hanford	Observing	22:23
LIGO Livingston	Observing	14:14
Virgo	Science	2:21
KAGRA	Future addition	

[Detector status summary pages](#)

[IVC links](#)

GraceDb | Latest - Mozilla Firefox

File Edit View History Bookmarks Tools Help

GW Open Science Center GraceDb | Latest

https://gracedb.ligo.org/latest/ 90% moment d'inertie

GraceDB — Gravitational Wave Candidate Event Database

HOME SEARCH LATEST DOCUMENTATION LOGIN

Latest — as of 5 June 2019 22:31:40 UTC

Test and MDC events and superevents are not included in the search results by default; see the [query help](#) for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC	Created
S190602aq	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51	UTC
S190524q	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30	UTC
S190521r	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22	UTC
S190521g	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49	UTC
S190519bj	ADVOK DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04	UTC
S190518bb	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39	UTC
S190517h	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242107478.819517	1242107479.994111	1242107480.997114	3.373e-09	2019-05-17 05:51:13	UTC
S190513bm	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241551000.381000	1241551001.41510000	1241551002.41710000	7.744e-10	2019-05-13 18:08:48	UTC
S190512at	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42	UTC
S190510g	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241000000.201626	1241000001.202125	1241000002.202125	8.804e-09	2019-05-10 00:02:03	UTC
S190503bf	DQOK PASTRO_READY EMBRIGHT_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT	1240192000.200164	1240192001.200164	1240192002.200164	1.000e-08	2019-05-03 23:59:56	UTC
S190426c	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT PE_READY	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15	UTC
S190425z	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26	UTC
S190421ar	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT ADVOK PE_READY	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16	UTC
S190412m	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03	UTC
S190408an	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27	UTC
S190405ar	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVNO	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56	UTC

Alerts are public! (within minutes)
<https://gracedb.ligo.org/latest>

LIGO VIRGO LSC

2019

January

Mo	Tu	We	Th	Fr	Sa	Su
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

Binary black hole



Binary neutron star



Neutron star-black hole binary

February

Mo	Tu	We	Th	Fr	Sa	Su
					1	2
6	7	8	9	10	11	12
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

Rejected

Improbable

March

Mo	Tu	We	Th	Fr	Sa	Su
					1	2
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

April

Mo	Tu	We	Th	Fr	Sa	Su
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				
31						

May

Mo	Tu	We	Th	Fr	Sa	Su
18	19	20	21	22	23	24
25	26	27	28	29	30	31

June

Mo	Tu	We	Th	Fr	Sa	Su
22	23	24	25	26	27	28
29	30	31				
31						

July

Mo	Tu	We	Th	Fr	Sa	Su
27	28	29	30	31		
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

August

Mo	Tu	We	Th	Fr	Sa	Su
31					1	2
32	33	34	35	36	37	38
39	40	41	42	43	44	45
46	47	48	49	50	51	52
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September

Mo	Tu	We	Th	Fr	Sa	Su
35	36	37	38	39	40	41
42	43	44	45	46	47	48
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October

Mo	Tu	We	Th	Fr	Sa	Su
40	41	42	43	44	45	46
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Future prospects

- O3 will last till Apr 2020 ; 9 more months to go!
 - 55 binary black holes?
 - Few binary neutron stars [with EM counterpart?]
 - Neutron star-black-hole binary?
- Advanced Virgo+ [approved]
 - Phase I design completed, under review
 - x 1.5–2 better sensitivity; ~1 alert **every day**
 - Joint science run with LIGO and KAGRA (Japan) **end 2021**
- 3rd detector generation ramping up
 - Einstein Telescope, another x 10 better sensitivity
 - Binary black hole mergers in the whole Universe ($z > 15$)

Concluding remarks

- Multi-messenger astronomy in its infancy
 - Many breakthroughs with only one event!
- GW observable universe is expanding very fast
 - Sensitivities x 2 every two years; x 8 in volume
 - More detectors around the globe soon (Japan, India)
- Major facilities for electromagnetic follow-up in the next 10 years
 - CTA; SVOM; LSST and JWST; SKA
- Very promising science program with large discovery potential