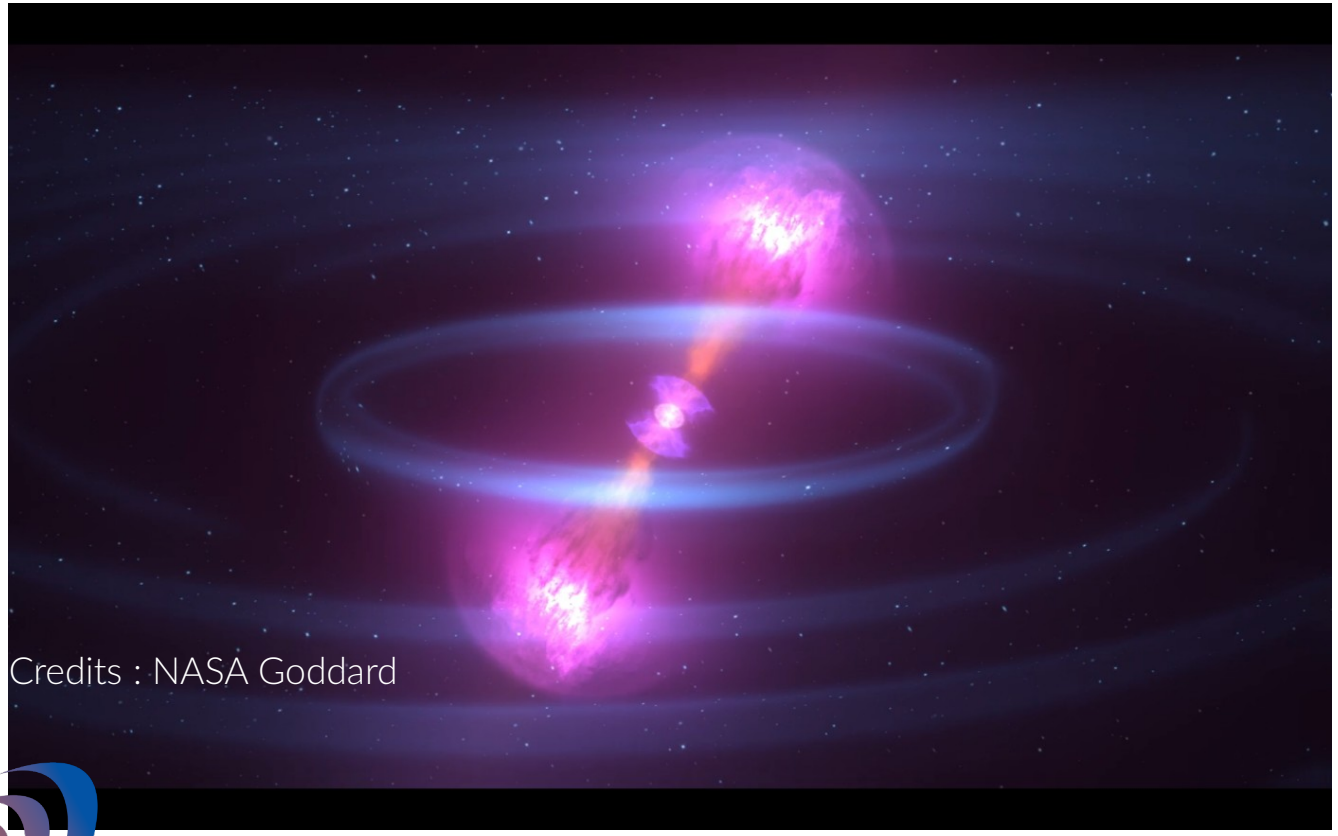
L'avènement de l'astrophysique multi-messager avec les ondes gravitationnelles



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
- Implications en physique, en astrophysique et en cosmologie
- Perspectives

Le Monde
WEEK • END

CULTURE & IDÉES
EUROPE LE SECRET MARCHANDAGE DES NORMES DIESEL

Samedi 13 février 2016 – 72e année – N° 22108 – 4,20 € – France métropolitaine – www.lemonde.fr — Fondateur : Hubert Beuve-Méry — Directeur : Jérôme Fenoglio

Les petits calculs d'un remaniement

▸ François Hollande a choisi un remaniement tactique pour neutraliser les différentes composantes de la majorité avant 2017

▸ L'arrivée de trois ministres écologistes, dont Emmanuelle Cosse, porte un coup sévère au parti de Cécile Duflot

▸ Le retour de l'ancien premier ministre Jean-Marc Ayrault, nommé au Quai d'Orsay, tient à la volonté de rassurer la gauche du PS

▸ Le chef de l'État a choisi l'une de ses proches, Audrey Azoulay, pour remplacer Fleur Pellerin au ministère de la culture

▸ Plus qu'un gouvernement de combat, c'est un gouvernement de contrats qu'a choisi le président

Einstein avait raison

▸ Le physicien avait prédit l'existence des ondes gravitationnelles en 1916, la preuve directe en est aujourd'hui apportée

▸ Cette découverte majeure est à ranger parmi les plus grandes percées de la connaissance

▸ Les trous noirs existent et l'espace-temps est bien un contenant élastique susceptible d'onduler

Pourquoi les banques sont attaquées en Bourse

ÉDITORIAL
UN AIR DE LEHMAN BROTHERS

COMMERCE
LE GRAND BAZAR DU TRAVAIL DU DIMANCHE

CULTURE
LE THÉÂTRE DE L'EUROPE AUX EUROPÉENS

CULTURE & IDÉES
LIVRES POLITIQUES : FAUT-IL ÊTRE LU POUR ÊTRE ÉLU ?

SPORT & FORME
PROFESSION GLADIATEUR

Plan russo-américain pour une trêve en Syrie

▸ Serguei Lavrov et John Kerry s'accordent sur un accès humanitaire aux villes assiégées

MIGRANTS
L'ÉTAT VA RASER LA MOITIÉ DE LA « JUNGLE » DE CALAIS

BACCHANALES MODERNES !
Le nu, l'ivresse et la danse dans l'art français du XIXe siècle

The New York Times

"All the News That's Fit to Print"

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 33. Tonight, a flurry or heavier squall late, low 21. Tomorrow, windy, big, sl, high 23. Weather map, Page A18.

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 him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to [illegible] Mr. Sanders's growing

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

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 and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most fore-

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists

By RICHARD FAUSSET

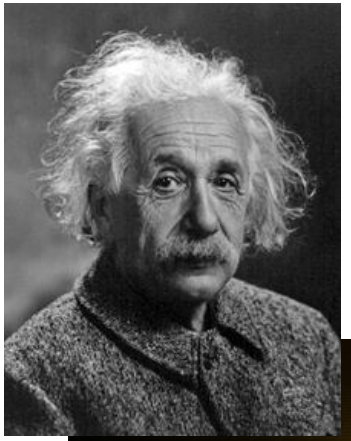
ORANGEBURG, S.C. — When Helen Daley was asked whom she would vote for in the South Carolina [illegible] candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an un-

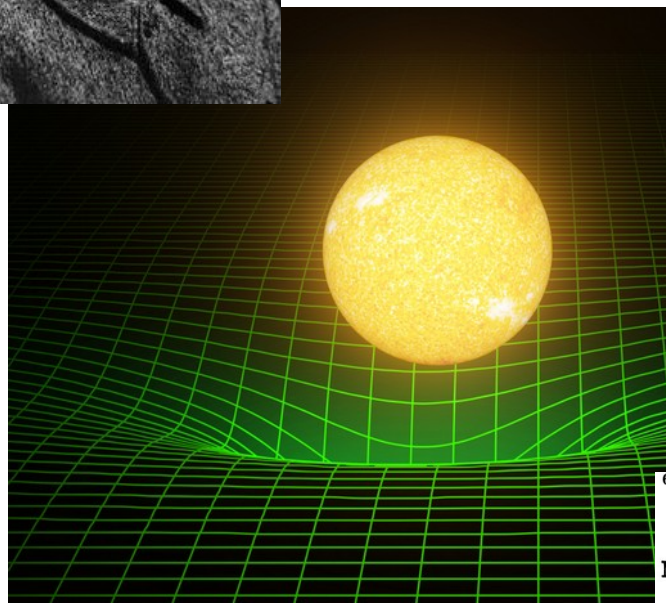
Last Occupier In Rural Oregon Is Coaxed Out

Space-time in general relativity

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

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





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

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

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 $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

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

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 $\mu \neq \nu$.

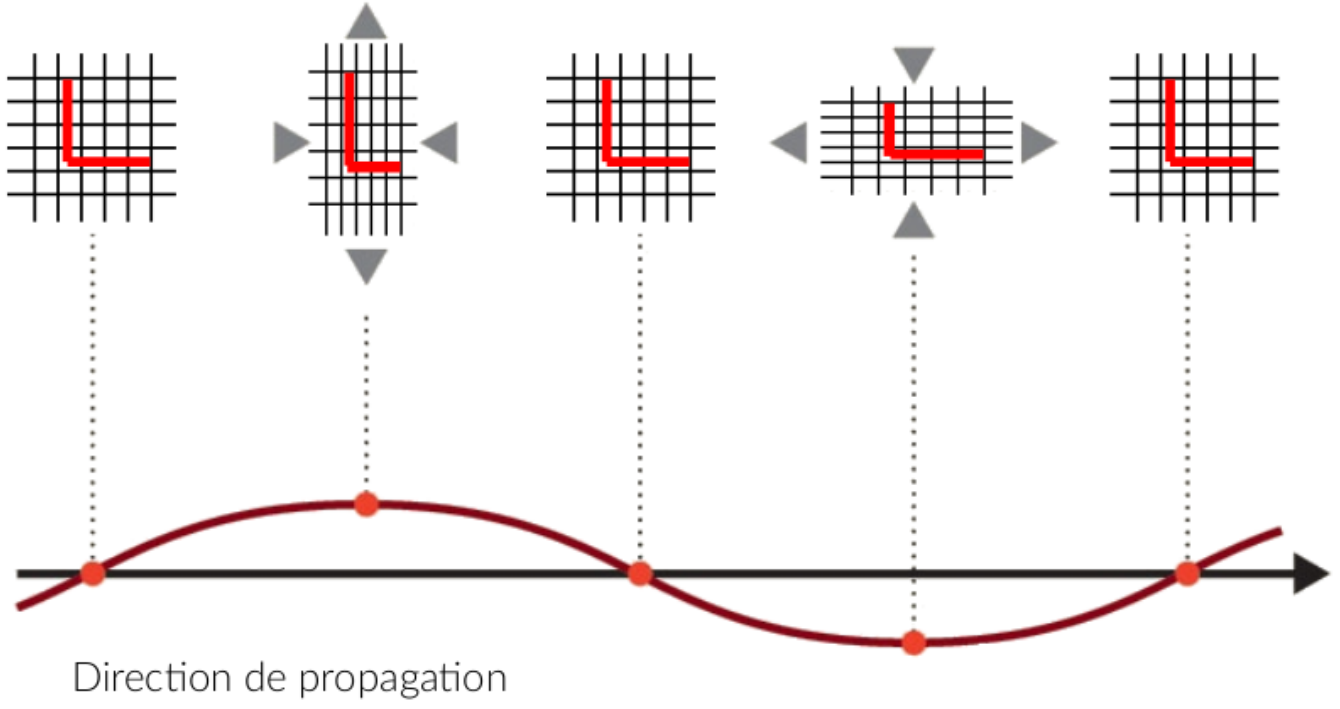
1915

Gravitational waves

Einstein's equations → **wave equation !**
for small perturbations of flat space-time metric

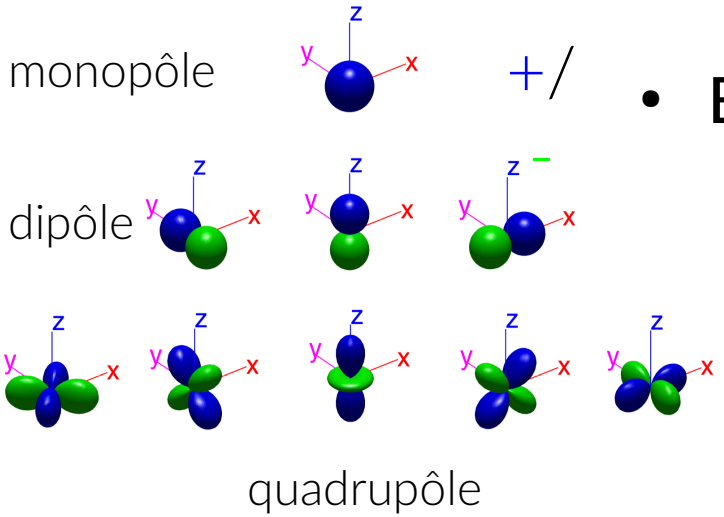
There are **waves of space and time**

Gravitational waves are **transverse**



Gravitational wave amplitude h = no dimension

Sources of gravitational waves



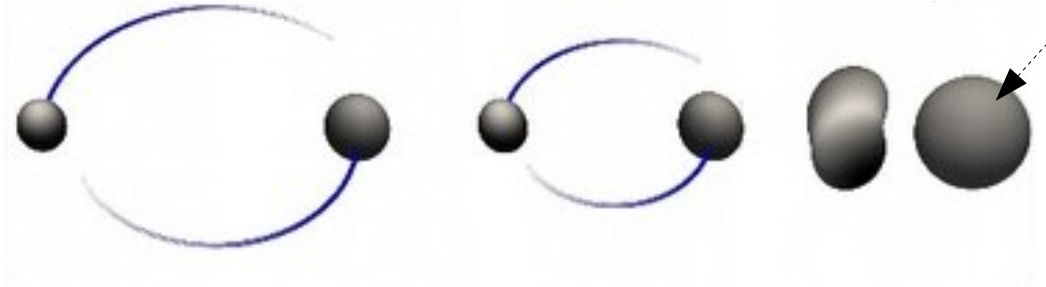
- Electromagnetic waves → **accelerated charges**
  - Variations of the electrostatic dipole

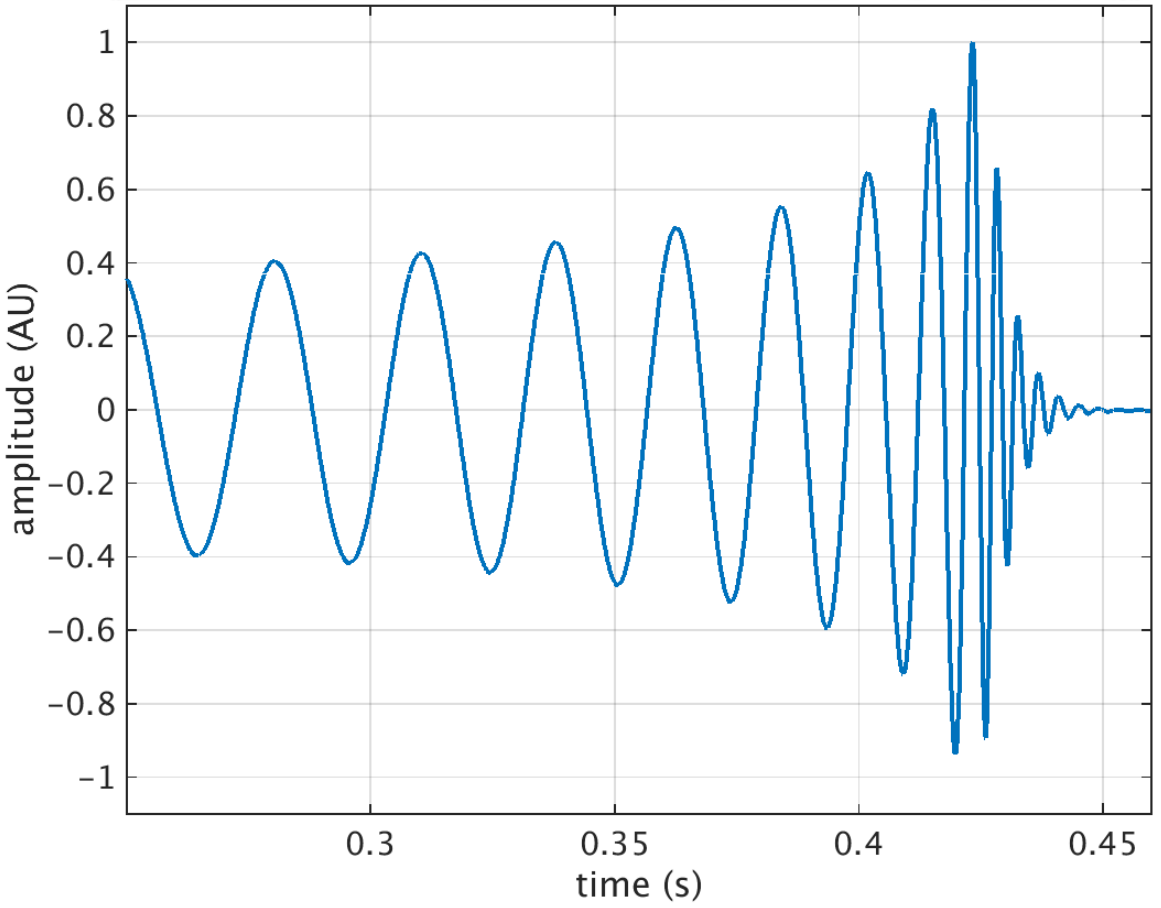
- Gravitational waves → **accelerated masses**
  - Gravitational dipole is constant (momentum is conserved)
  - Variations of **gravitational quadrupole**
  - No emission for spherical objects

source non axi-symetry is required

Black hole binary merger

inspiral merger ringdown





Characteristic waveform signature

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

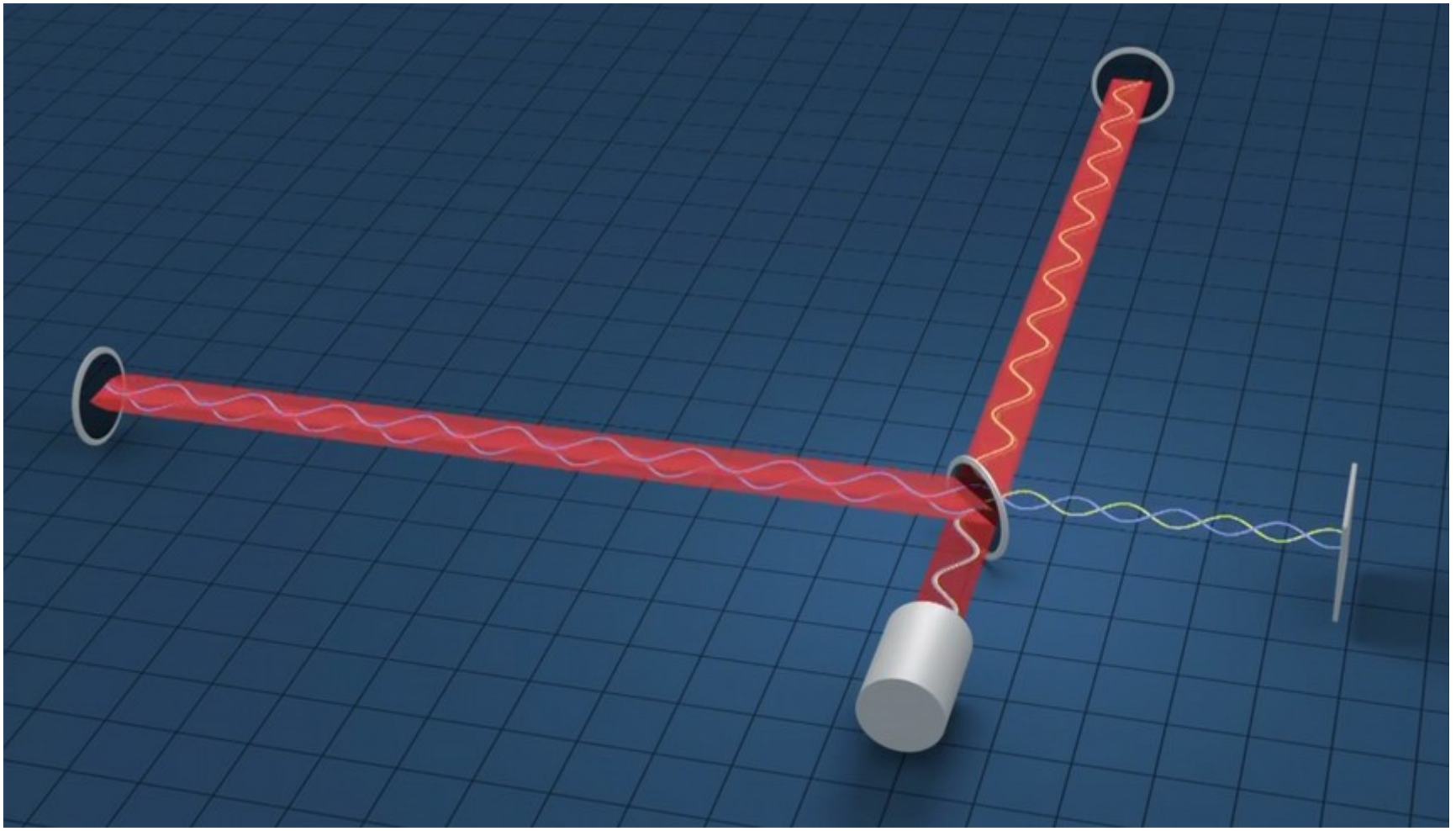
Chirp mass $\mathcal{M}$

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

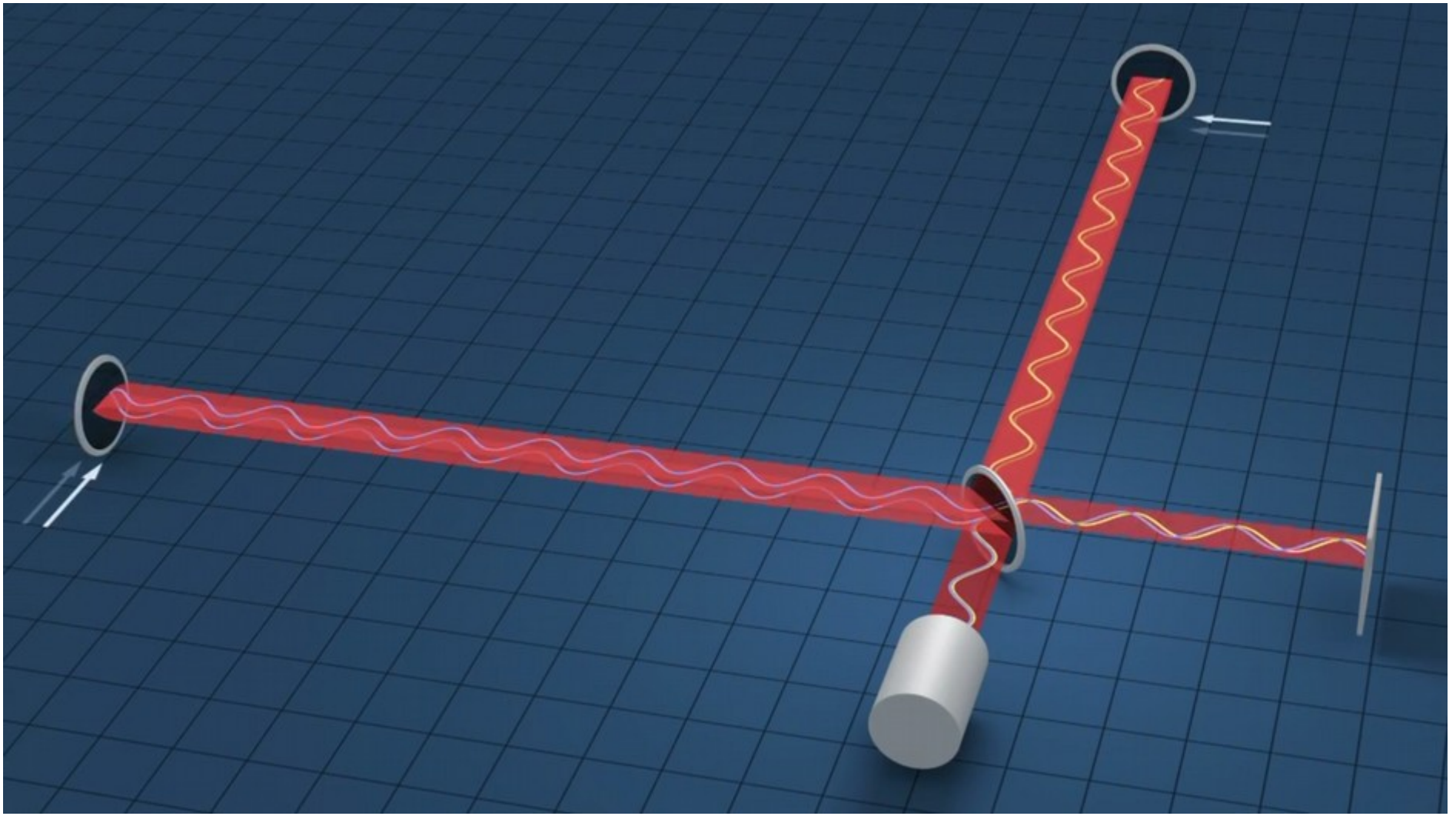
Plan de la présentation

- 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

Michelson interferometer



Michelson interferometer



LIGO (Etats unis)

Virgo (Italie)

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

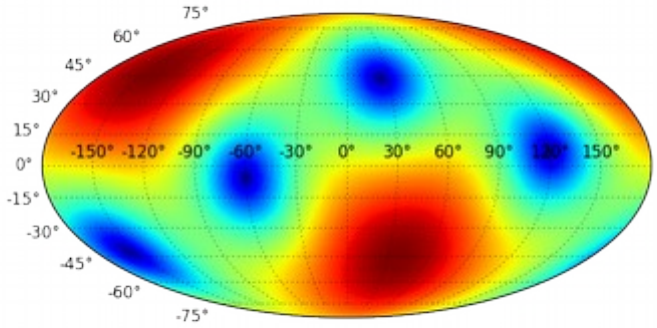
$$\delta\ell \sim 10^{-18} m$$

$$L = 3 \text{ km}$$

Radius of atomic nuclei $10^{-15} m$ (x 1000)

~3000 km
(10 light-ms)

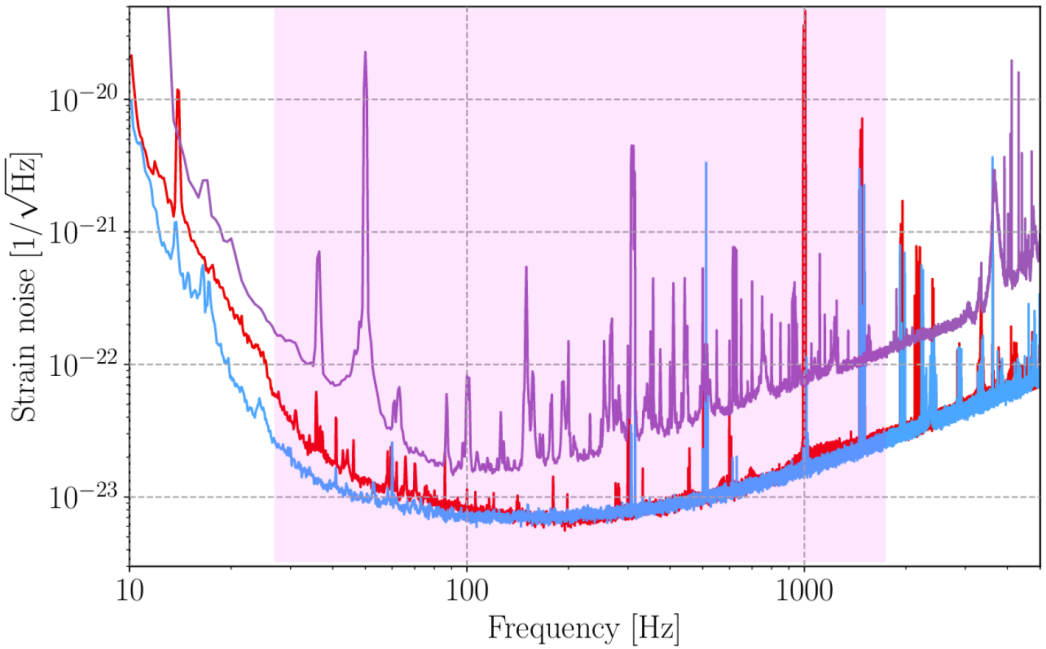
~10000 km
(30 light-ms)



Quasi-omnidirectional

(no pointing)

Sensitivities during O2 (2017)



BNS range

H1: 60 Mpc

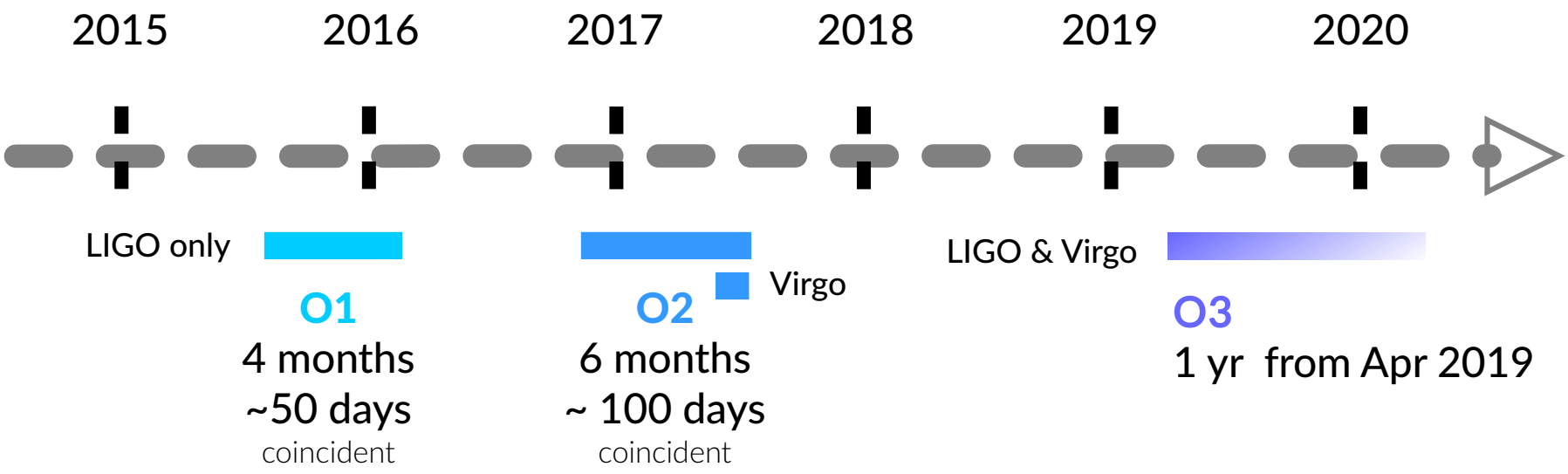
L1: 80 Mpc

V1: 25 Mpc

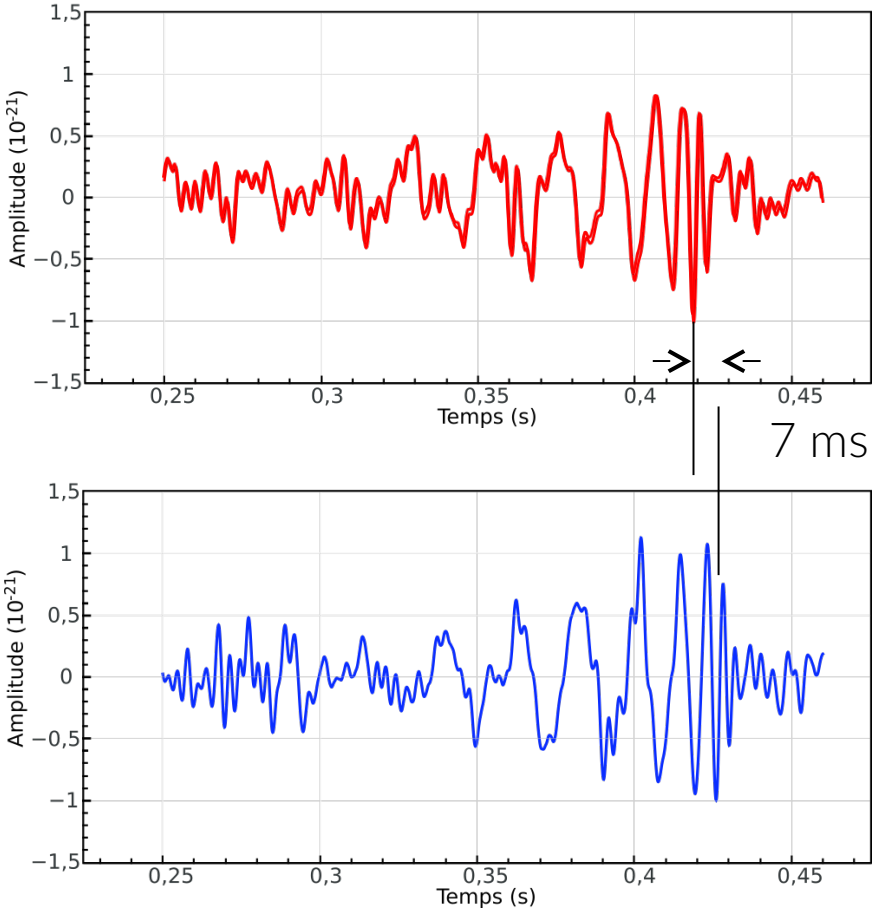

LIGO Handford H1


LIGO Livingston L1

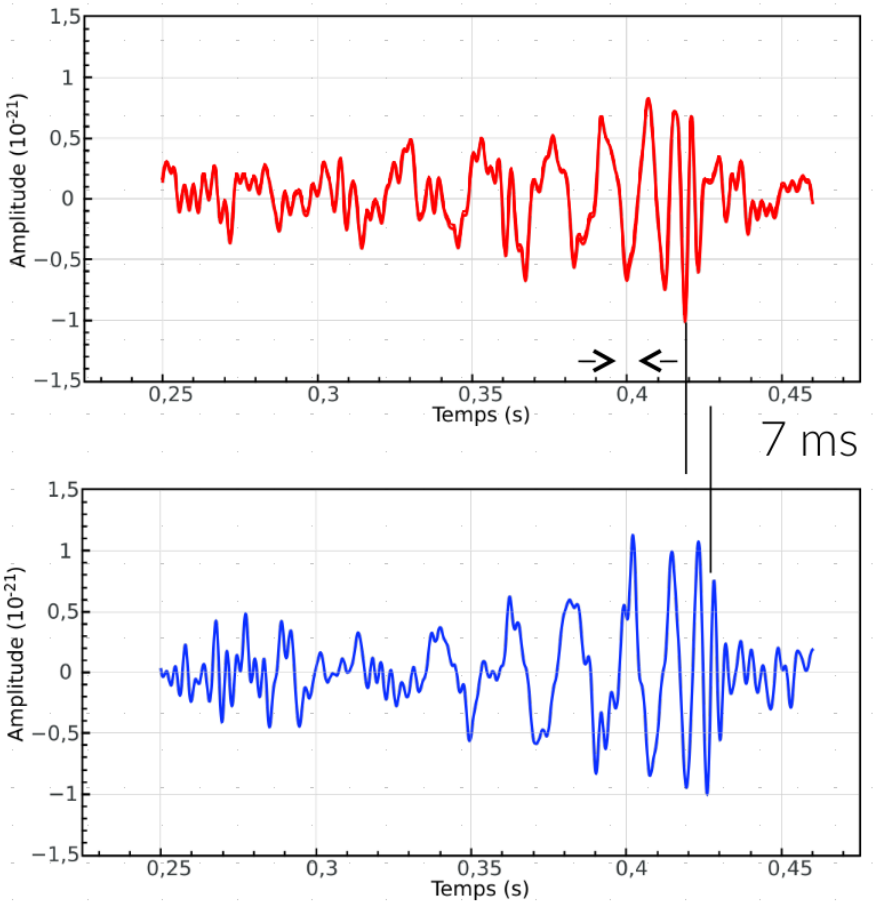

Virgo V1

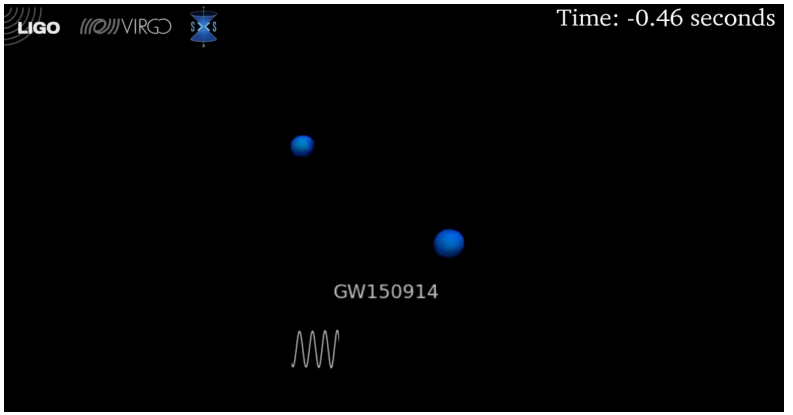

2015
2016
2017
2018
2019
2020
LIGO only
O1
4 months
~50 days
coincident
O2
6 months
~ 100 days
coincident
Virgo
LIGO & Virgo
O3
1 yr from Apr 2019

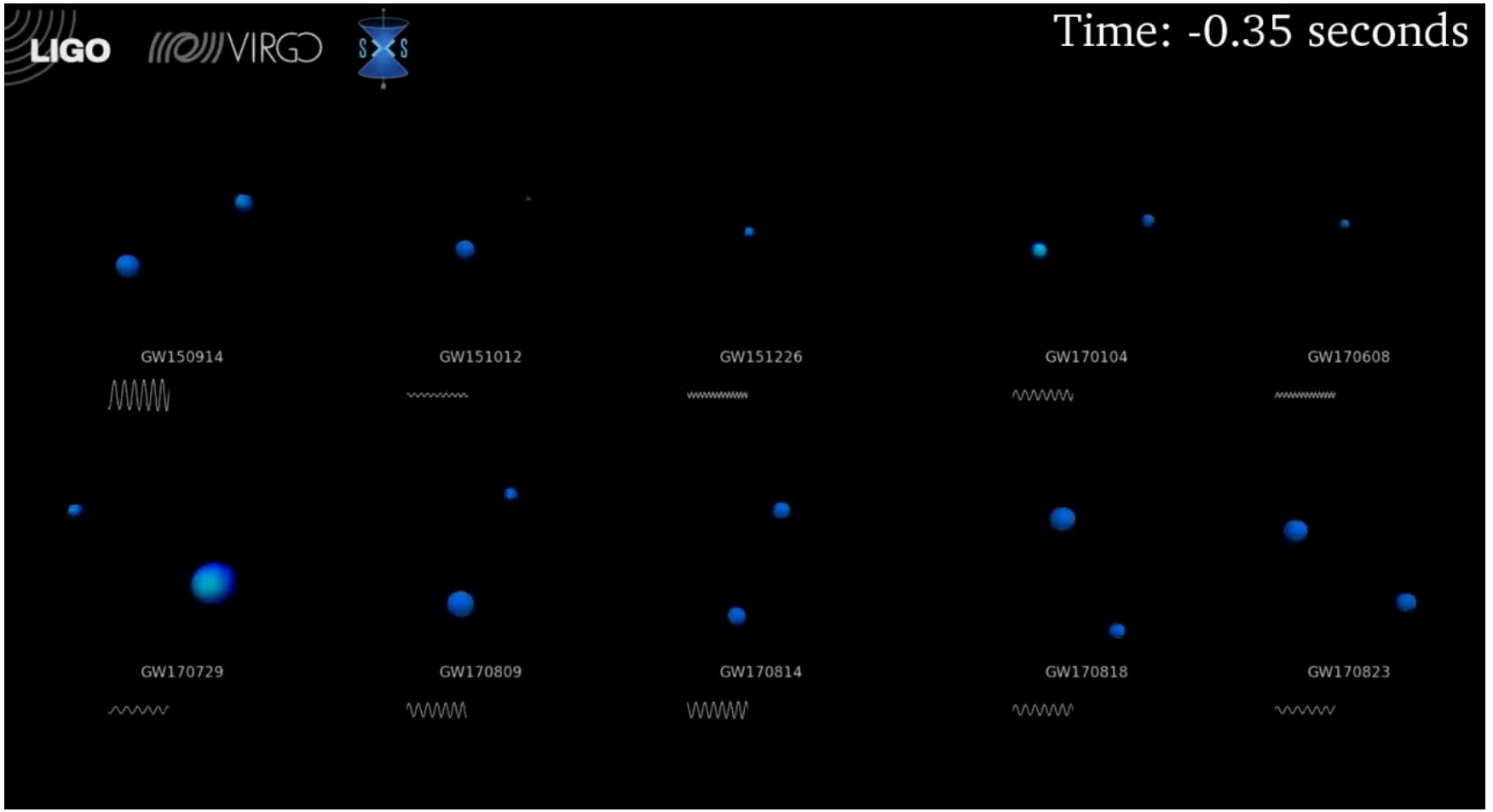
Sep 14, 2015


1,5
1
0,5
0
−0,5
−1
−1,5
Amplitude (10-21)
0,25
0,3
0,35
0,4
0,45
Temps (s)
7 ms
1,5
1
0,5
0
−0,5
−1
−1,5
Amplitude (10-21)
0,25
0,3
0,35
0,4
0,45
Temps (s)

Sep 14, 2015

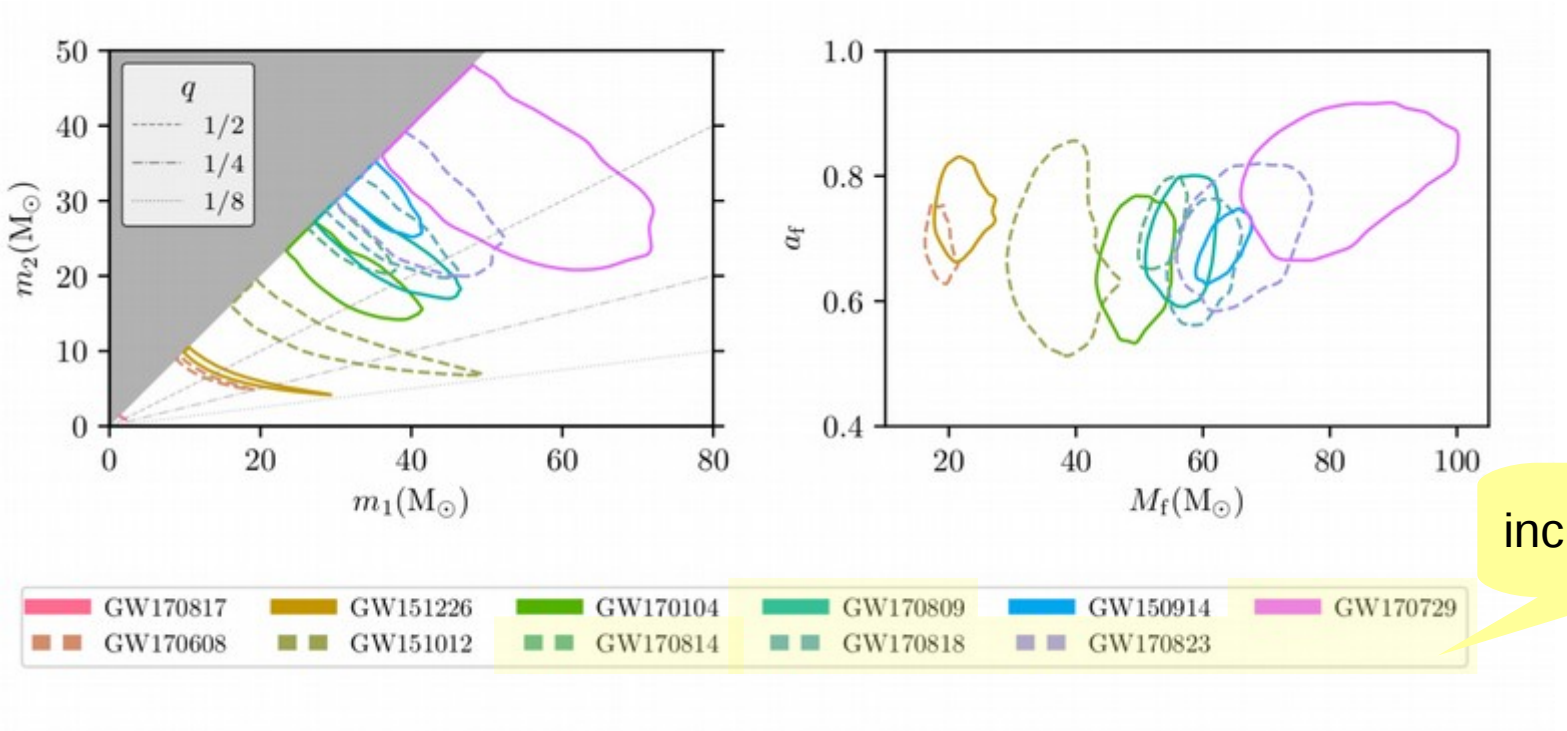

1,5
1
0,5
0
−0,5
−1
−1,5
Amplitude (10-21)
0,25
0,3
0,35
0,4
0,45
Temps (s)
7 ms
1,5
1
0,5
0
−0,5
−1
−1,5
Amplitude (10-21)
0,25
0,3
0,35
0,4
0,45
Temps (s)


LIGO
VIRGO
Time: -0.46 seconds
GW150914


LIGO
VIRGO
Time: -0.35 seconds
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

Catalog GWTC#1

- 10 binary black hole mergers



including Virgo

- population of objects hidden to conventional astronomy

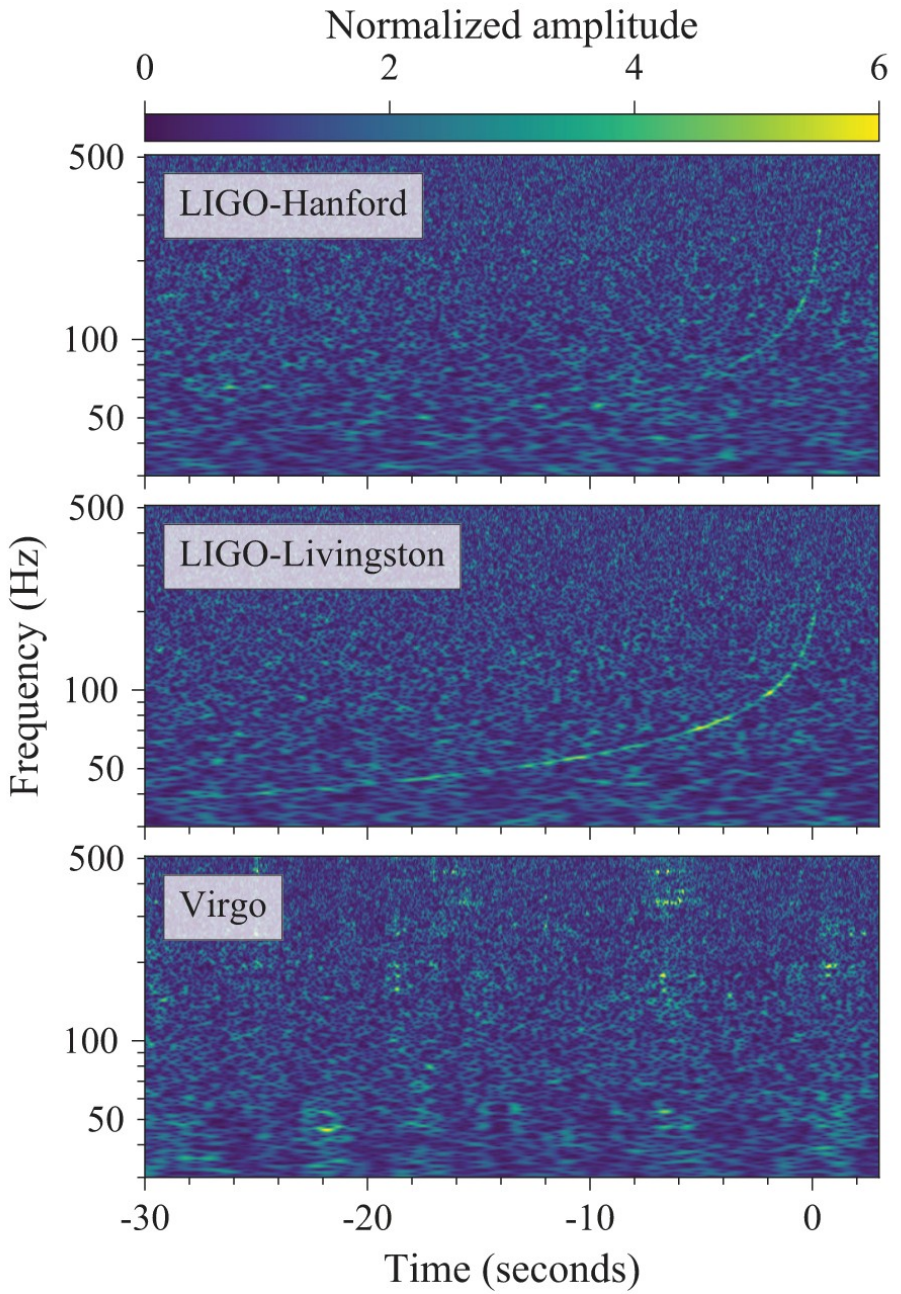
arXiv:1811.12907, https://www.gw-openscience.org/catalogs/

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

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

Aug 17, 2017



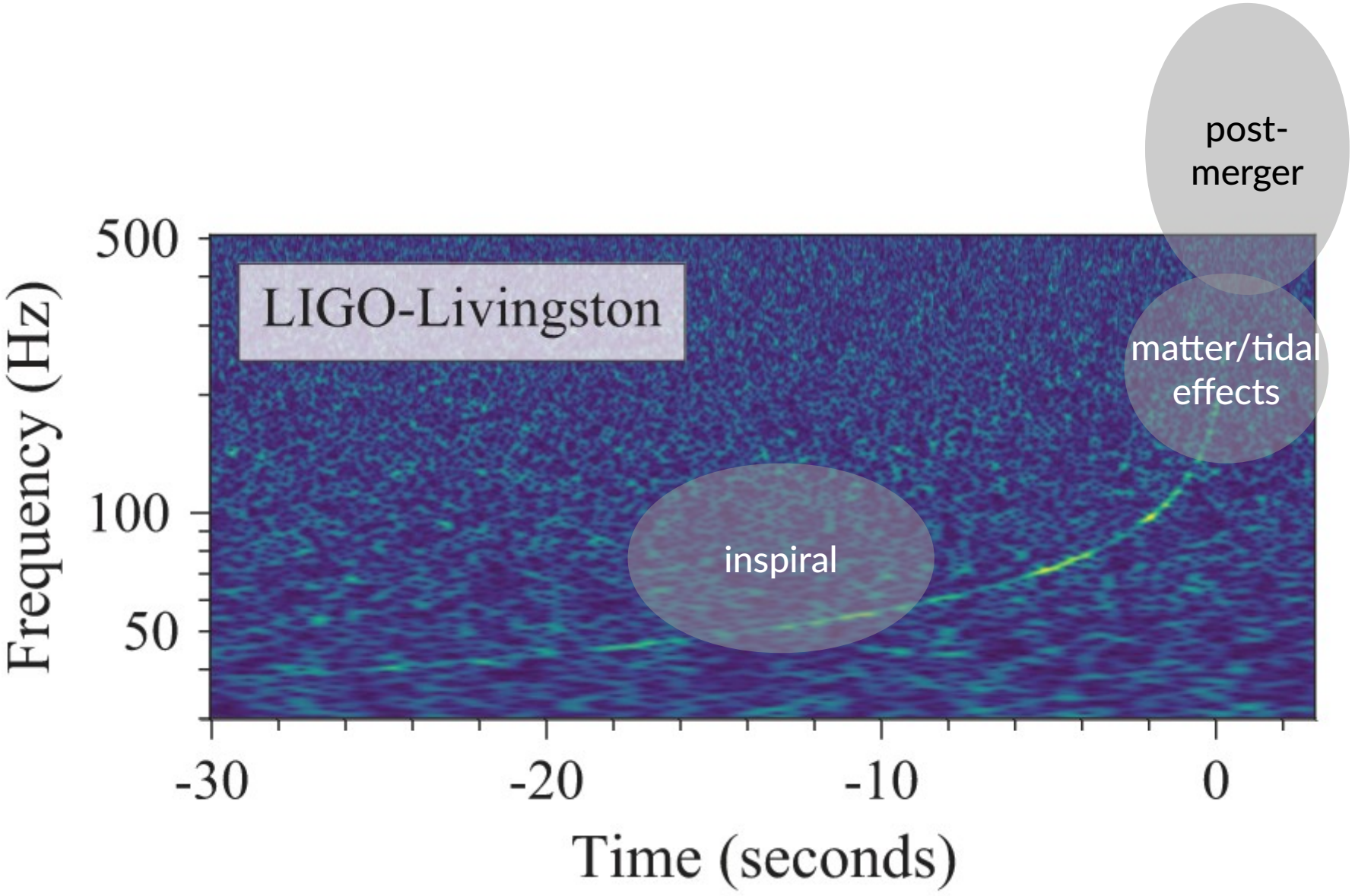
$$\tau \propto \mathcal{M}_{\rm det}^{-5/3}$$ chirp mass

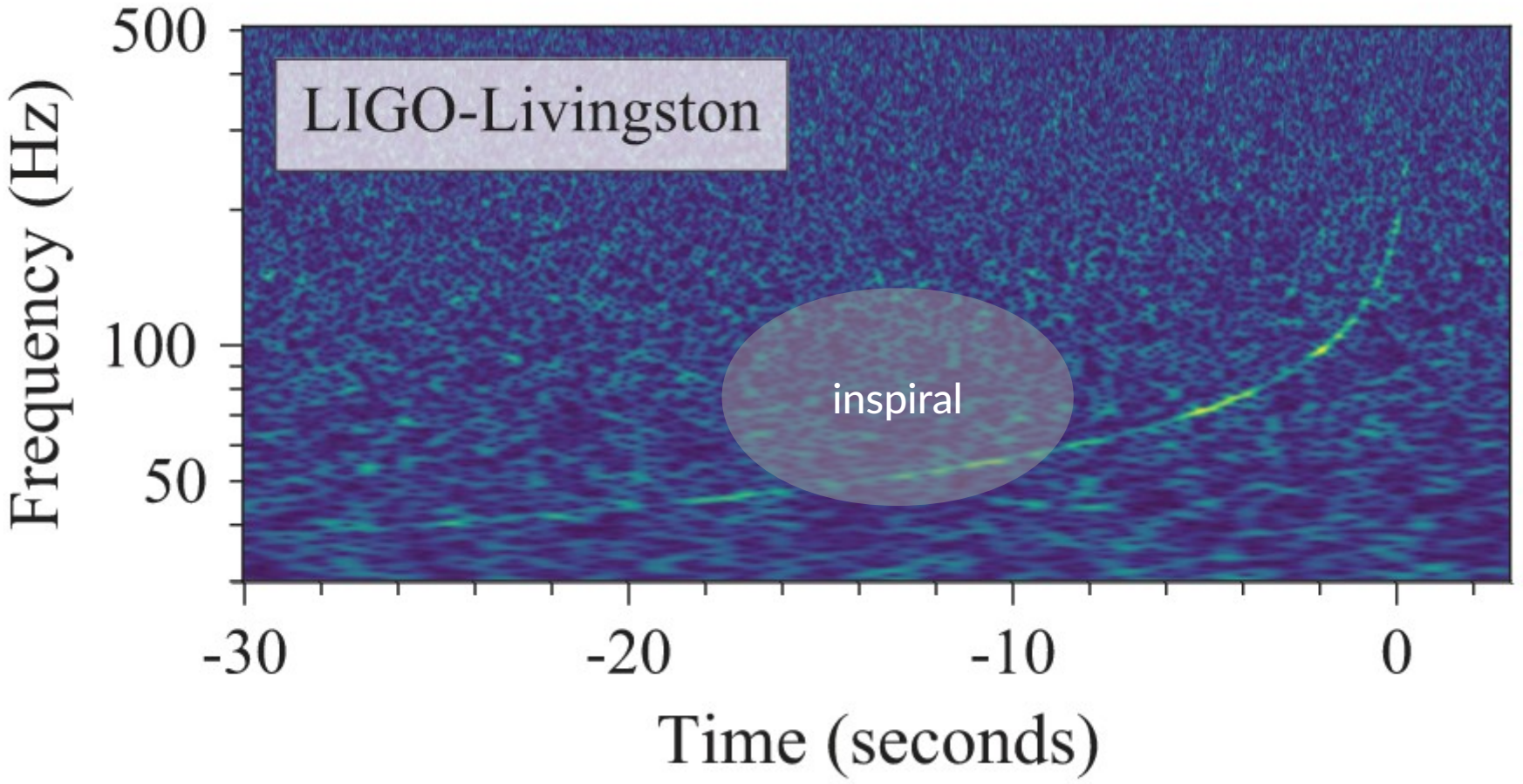
$$\tau \lesssim 1\,{\rm s} \quad \text{for BBH}$$

GW170817 $\tau \sim 100\,{\rm s}$

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

A lot of science with one signal





From signal phase, chirp mass estimate

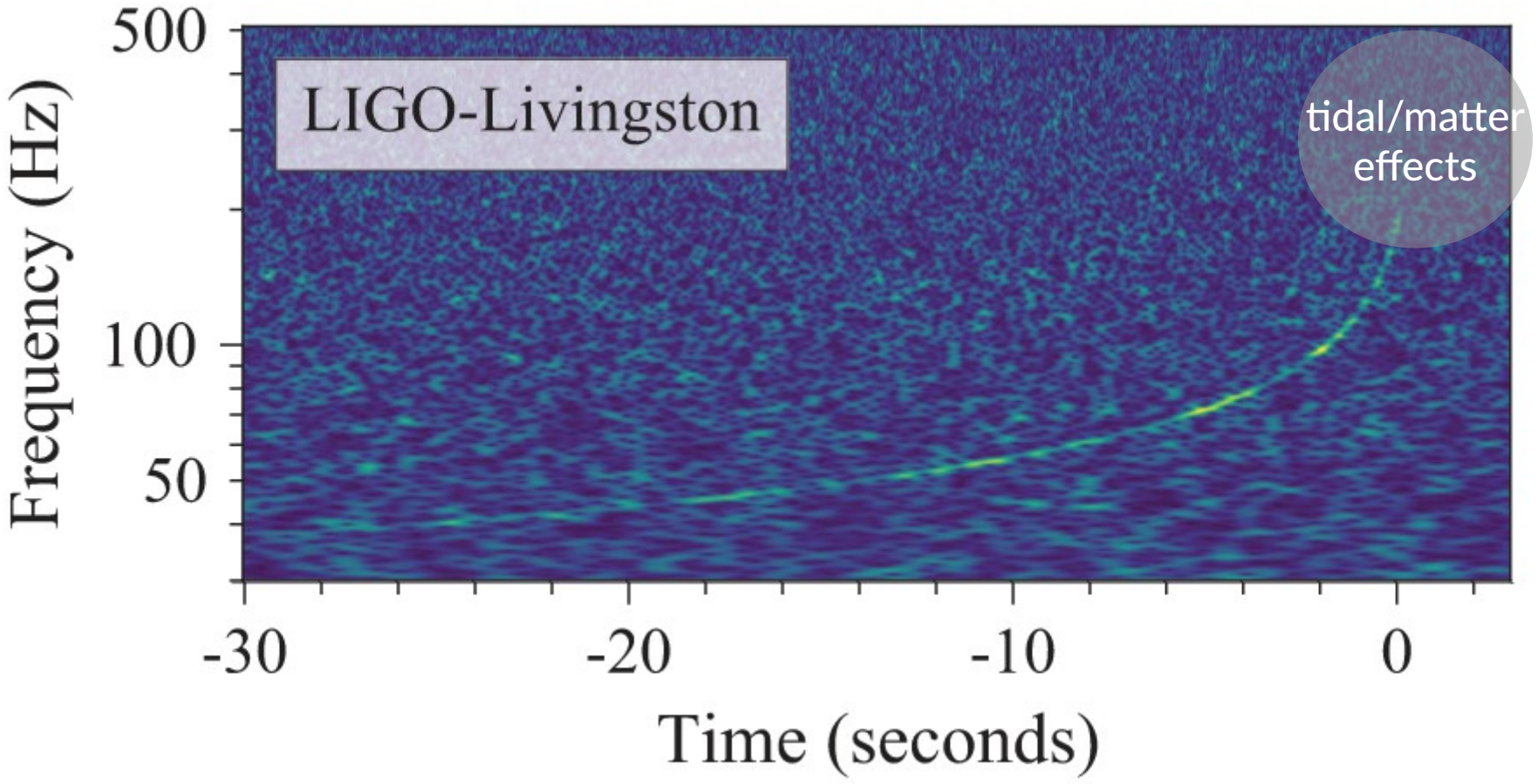
Phase matching: measurement accuracy scales with $1/N_{cycles}$

$N_{cycles} \approx 3000$

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

From signal amplitude, distance/inclination (degenerate)

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



Tidal deformation by the gravity gradient due to companion

Effect observable in the final tens of GW cycles before merger

f_{GW} > 400 Hz – Keplerian orbital radius ~ 60 km is comparable to NS radius

Tidal deformability

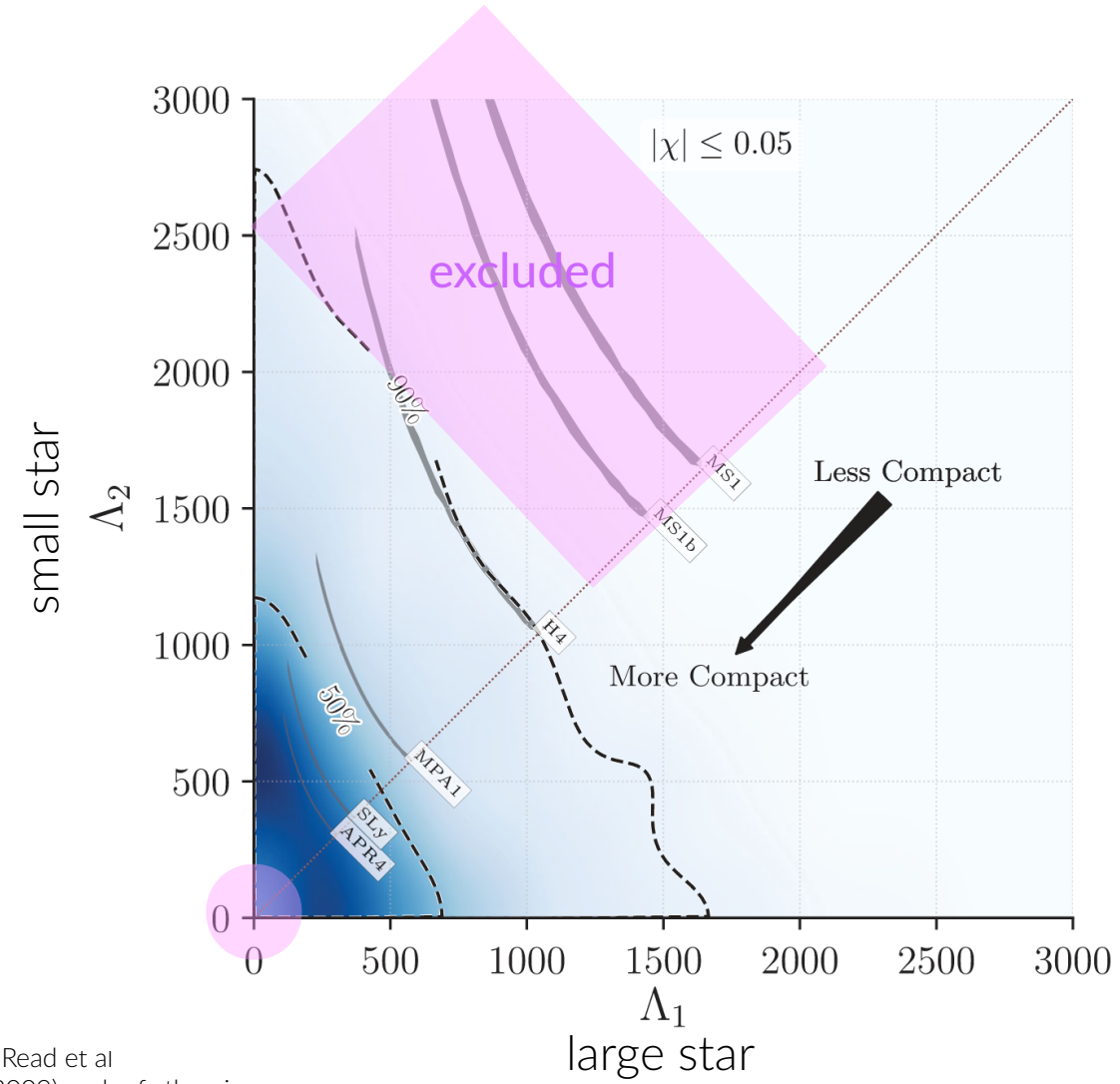
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$$

NS radius (EoS)

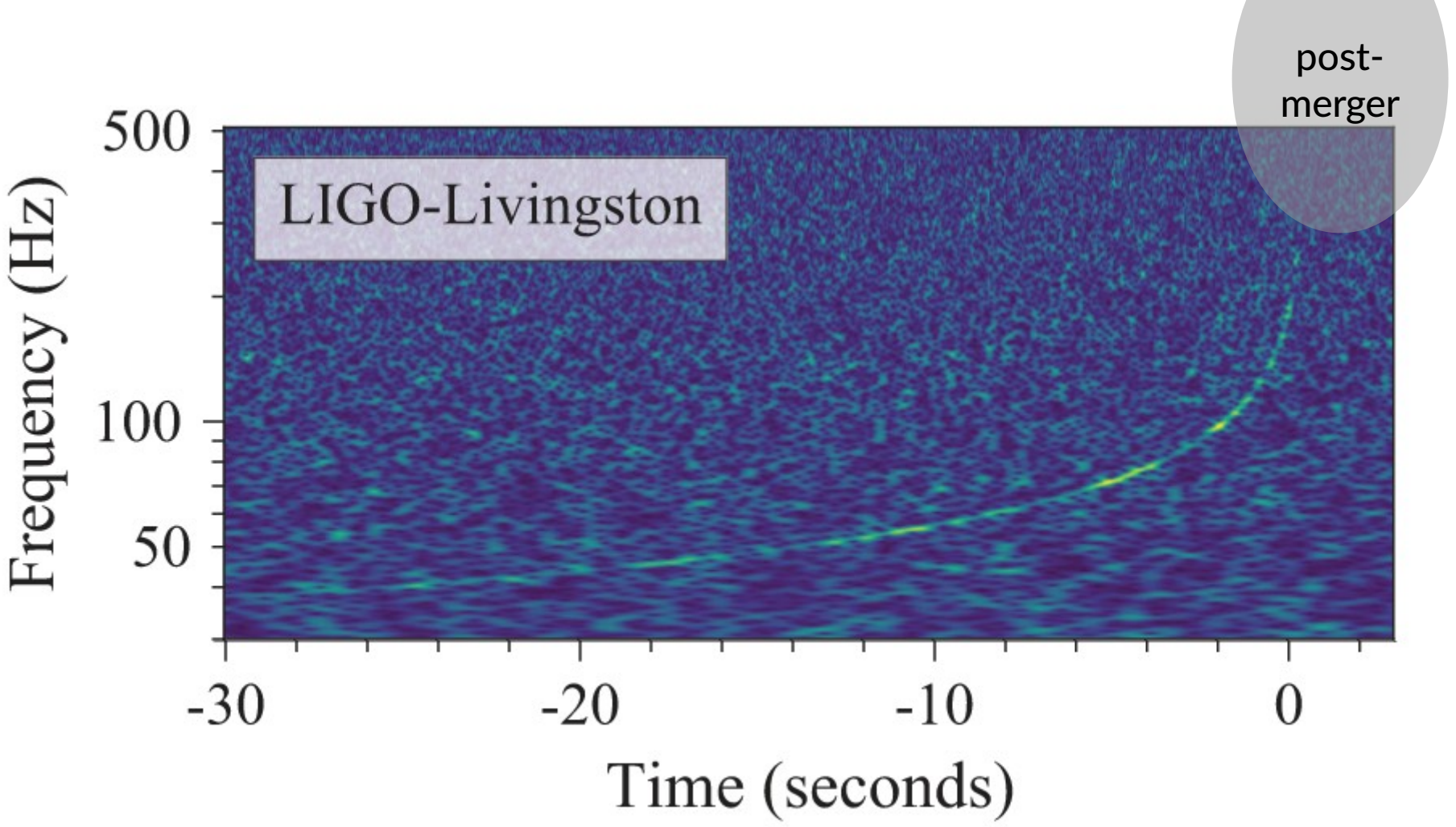
Love number (EoS)

mass

$k_2 = 0$ for BH



Selection of EoS from J. S. Read et al
Phys. Rev. D79, 124032 (2009) and refs therein



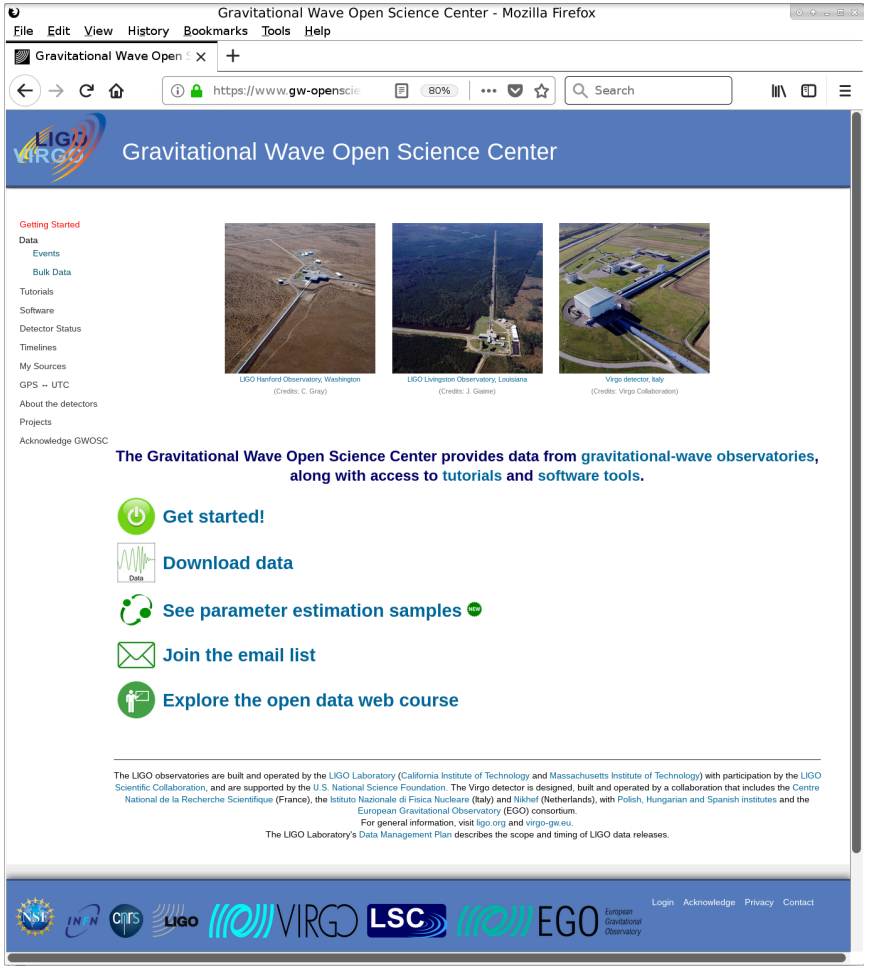
What is the remnant?

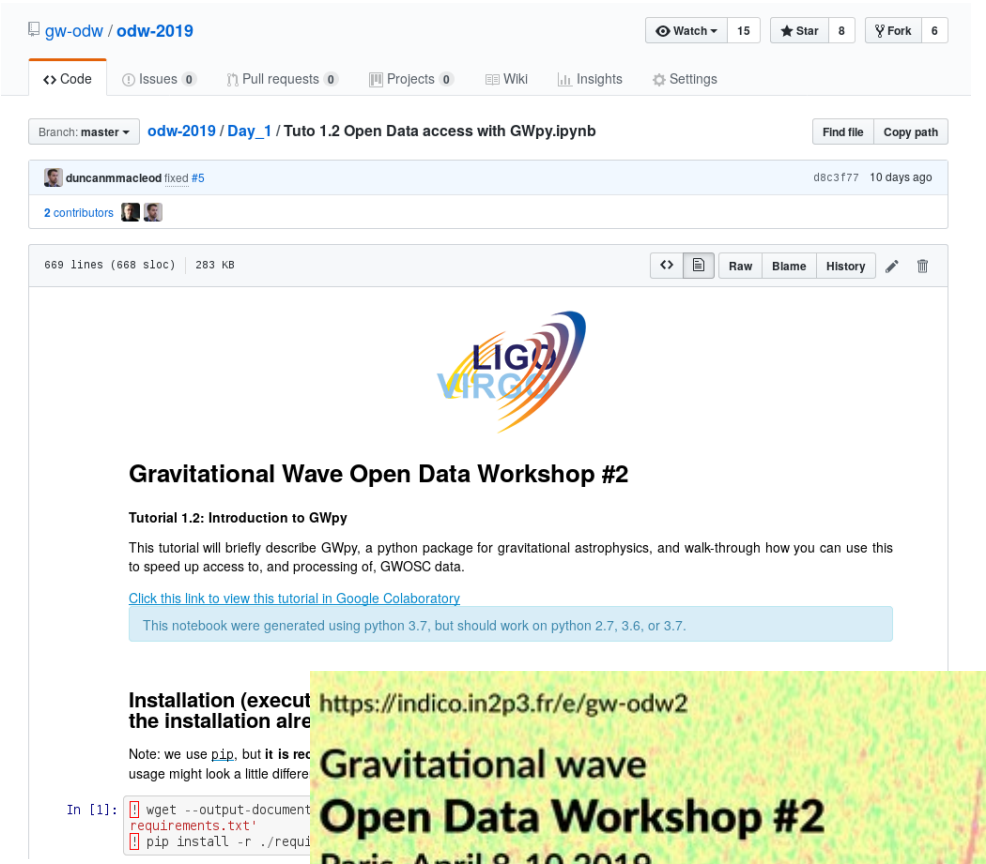
prompt collapse to a black hole	QNM at 6 kHz
hypermassive NS [preferred]	livetime ~ 1 s f-mode, 2-4 kHz
supramassive NS	livetime ~ $10–10^4$ s
stable NS	magnetar, bar mode or r-mode instability

No evidence for a post-merger signal

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

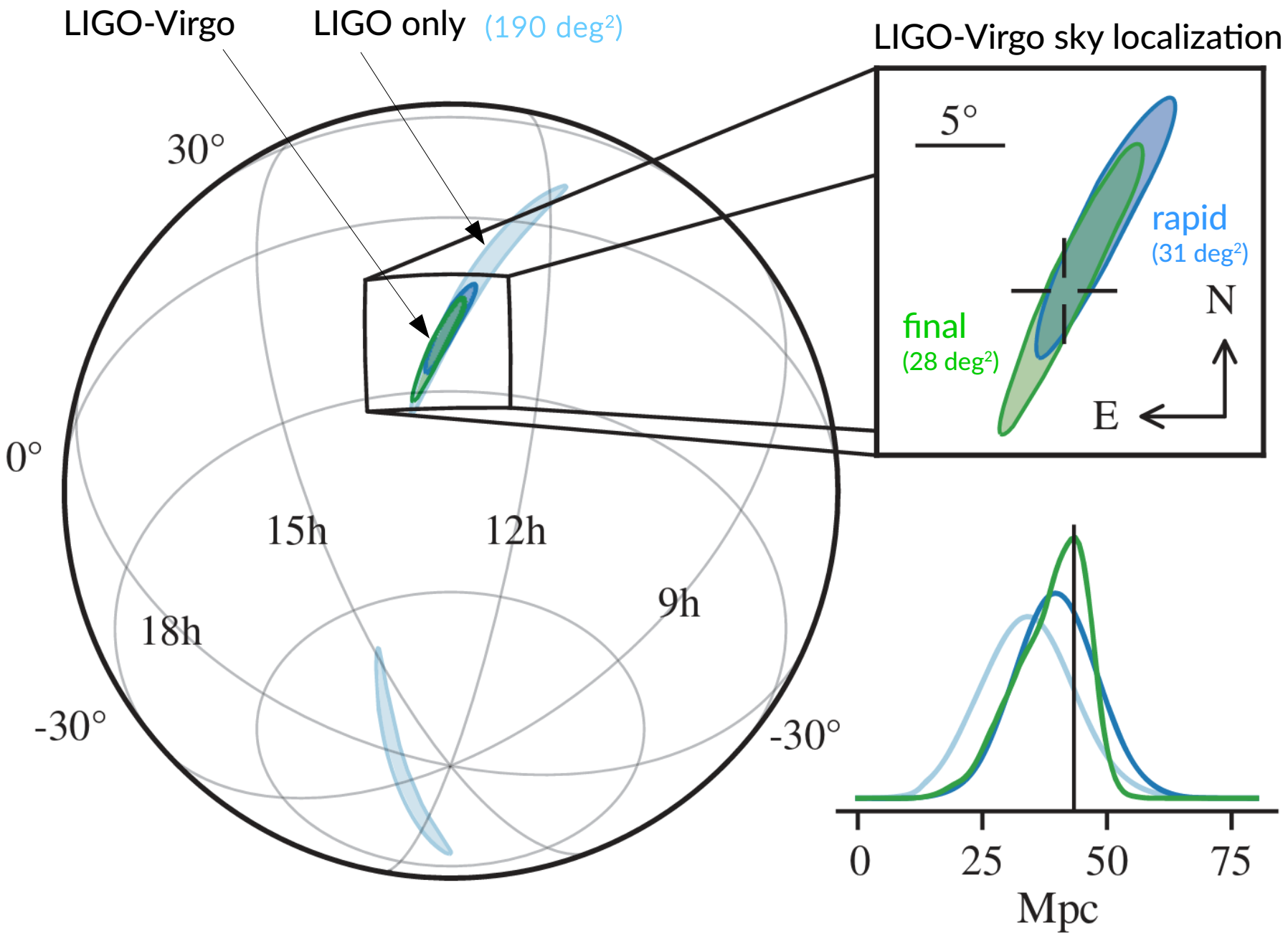
Lecture videos, Jupyter notebooks, challenge data set available online – Run on Google Colab cloud



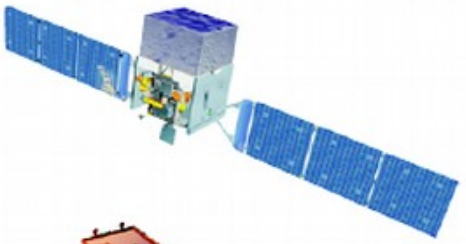


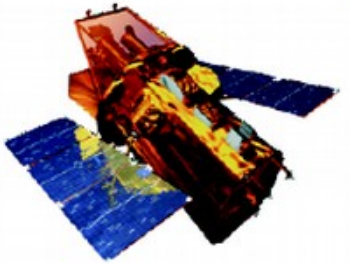
Plan de la présentation

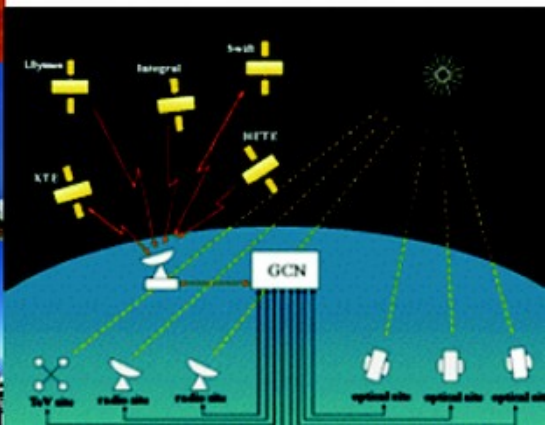
- Introduction sur les ondes gravitationnelles
- Détecteurs et observations jusqu'ici
- **GW170817 et l'astronomie multi-messager**
- Implications en physique, en astrophysique et en cosmologie
- Perspectives



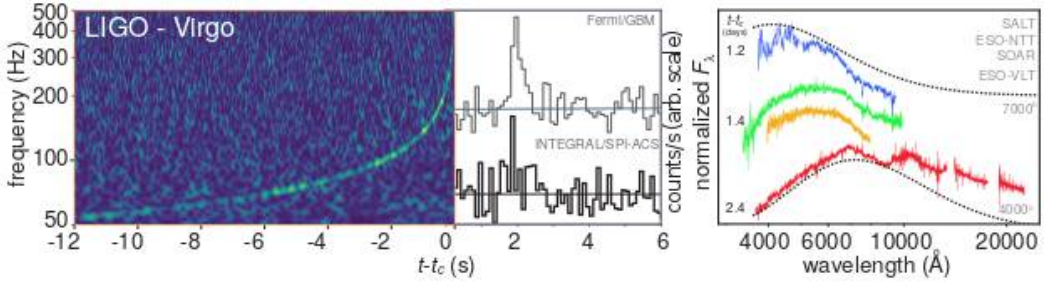
Cf présentation Orion Sauter

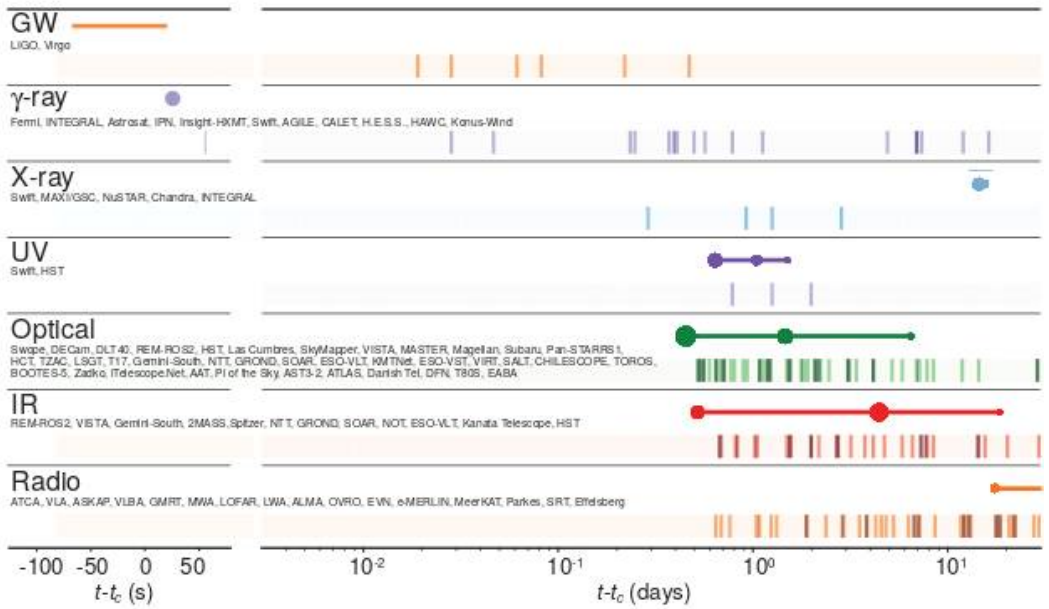


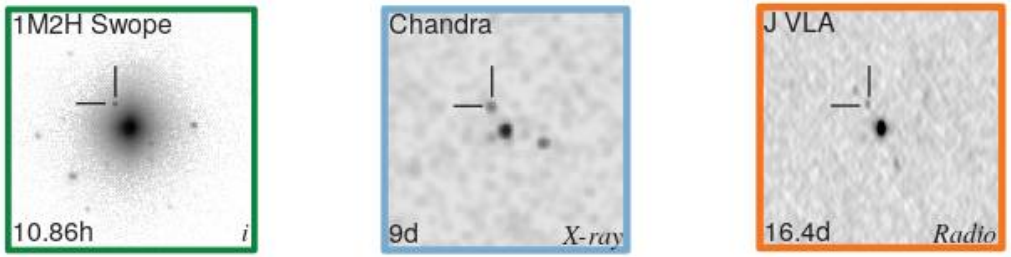



Swift
HETE
XTE
GCN

GW170817 follow-up



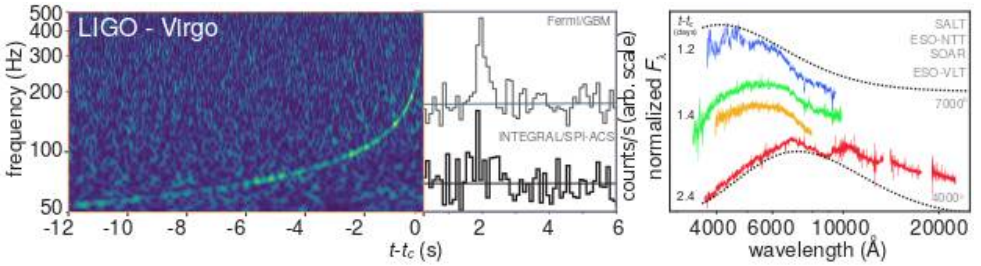


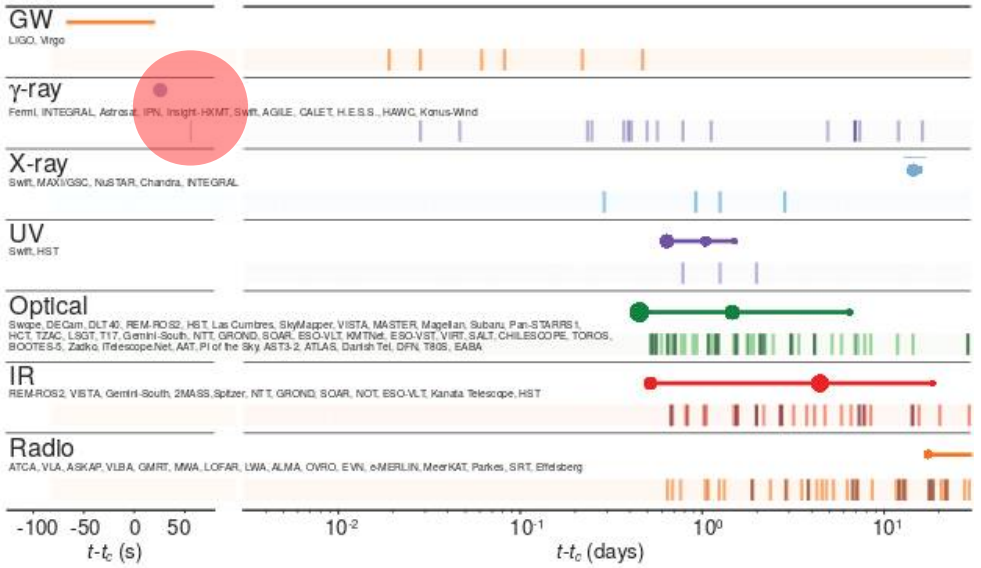


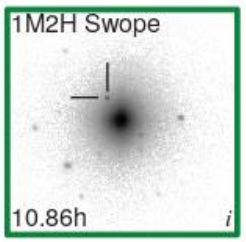
(first month shown)
… continued …

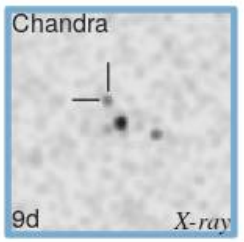
Voir aussi la présentation de Julien Souchard (neutrinos et rayons cosmiques)

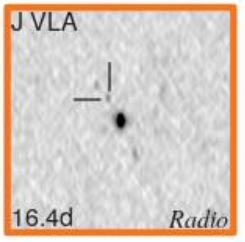
Three time scales: seconds









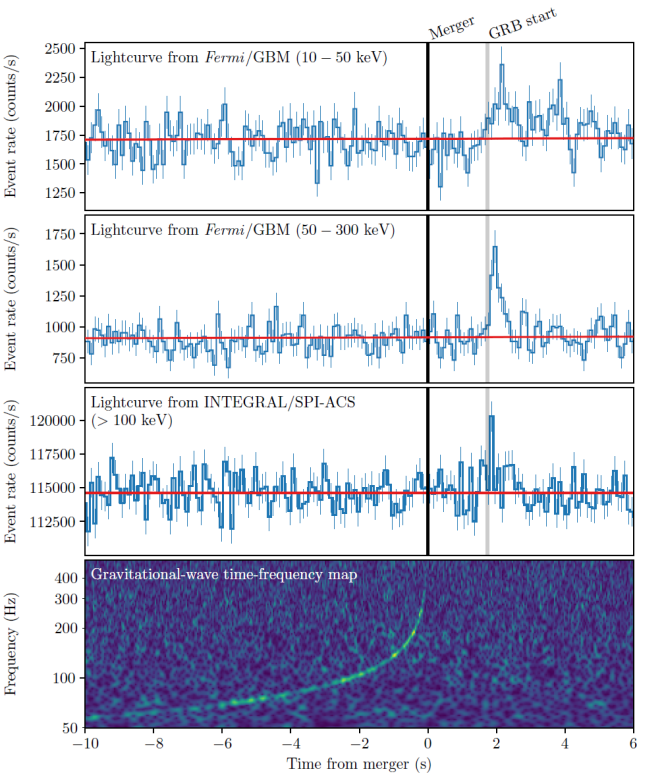


T0+1.7 s : gamma-ray burst

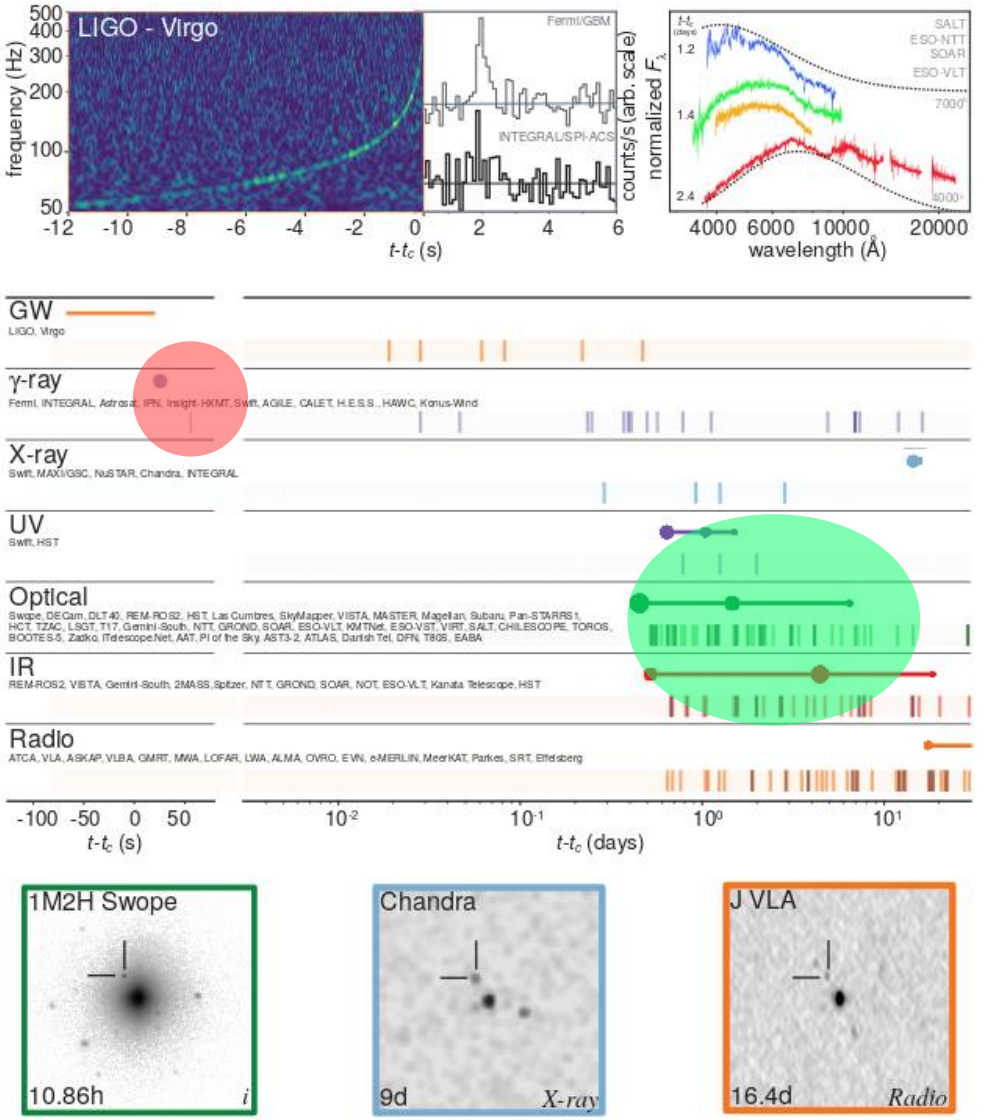
Short duration, ~ 2 sec

E_{iso} ~ 1.2 x 10^{46} erg (assuming D_L = 40 Mpc)

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



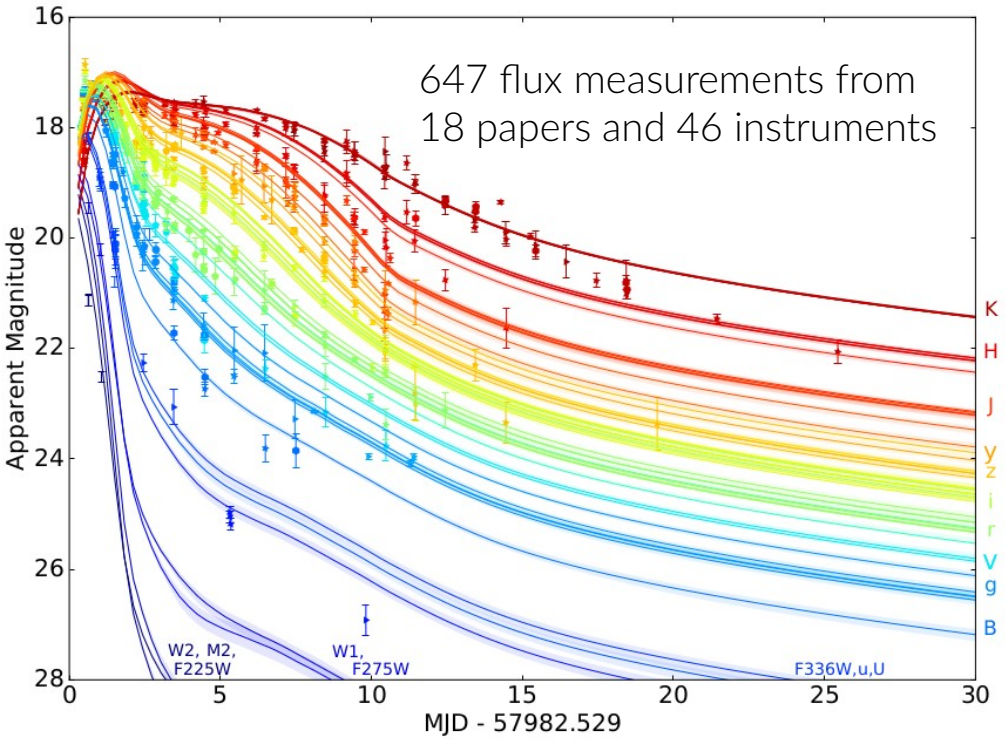
Three time scales: hours/day



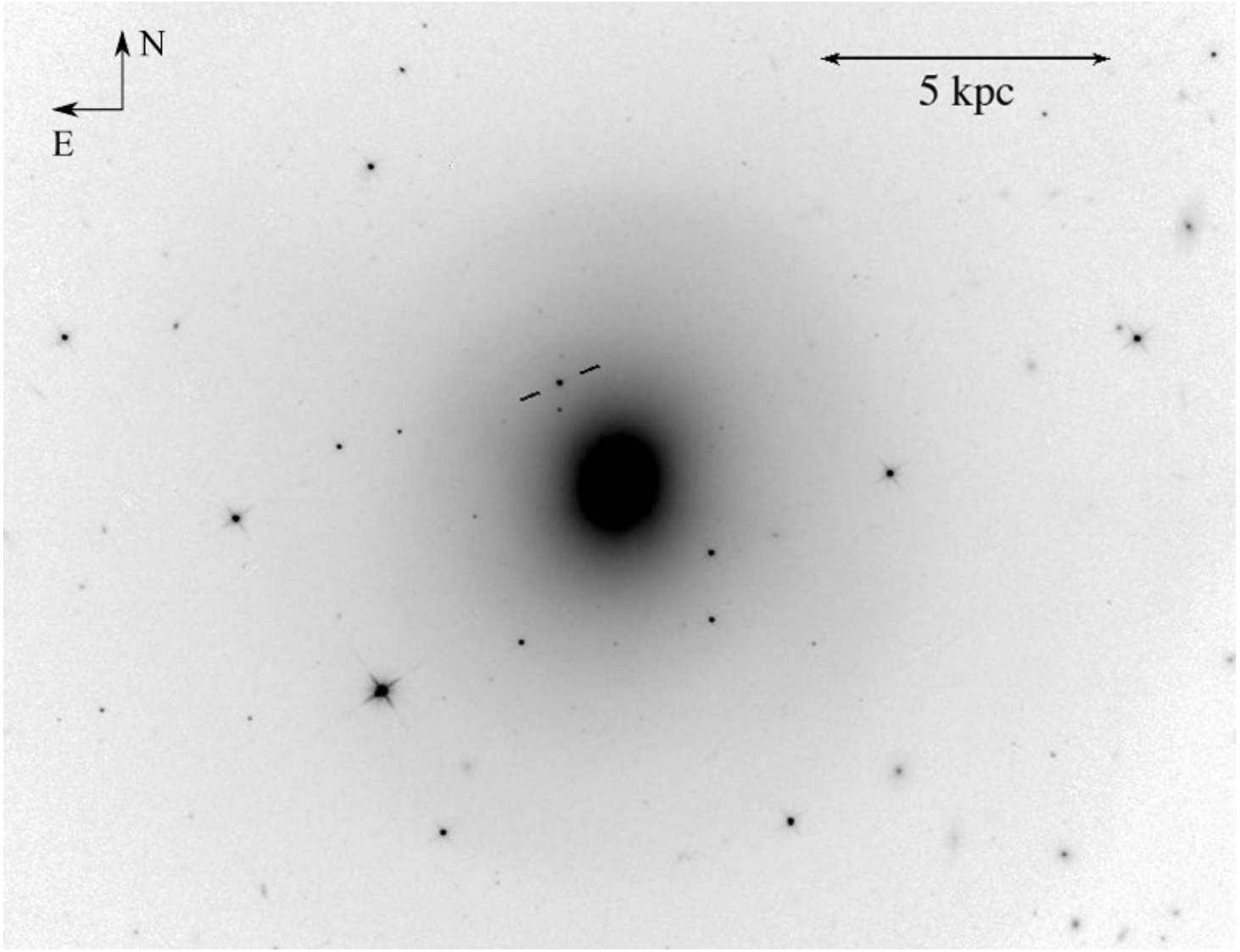
T0+~1 d : UV, optical and IR

Host galaxy identification

"**Kilonova**": radioactive-decay (r-process) powered emission from the merger ejecta



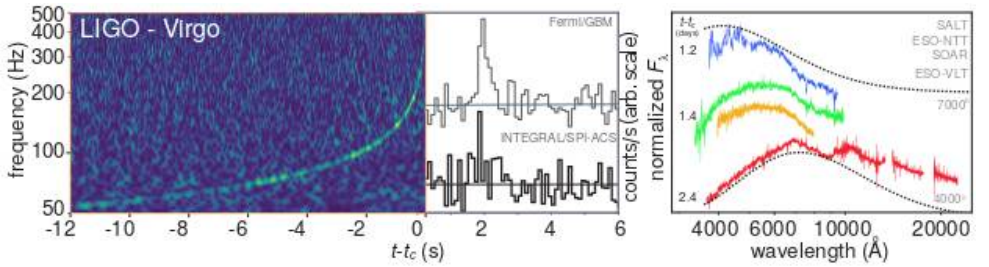
V. Ashley Villar et al, arXiv:1710.11576

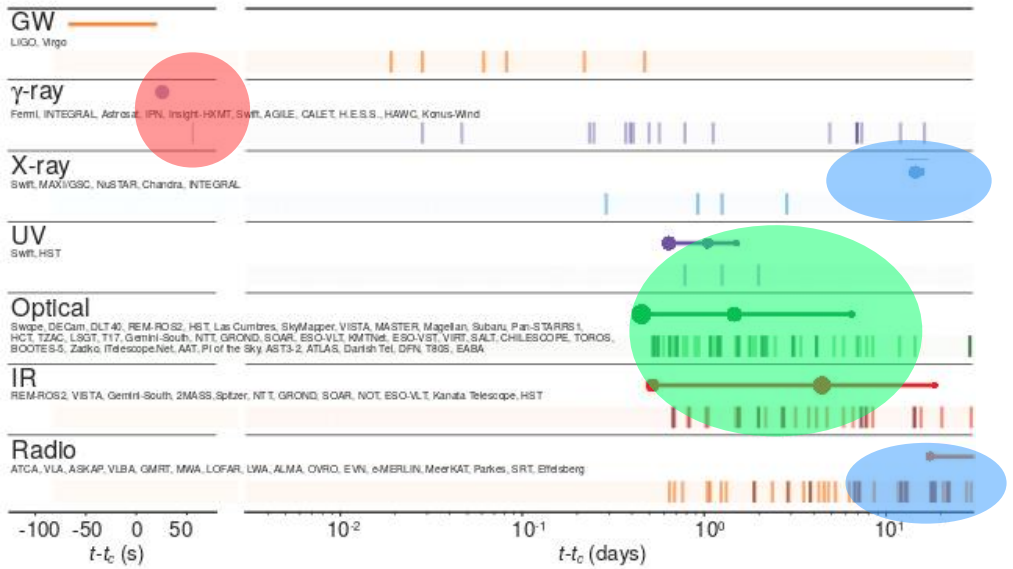


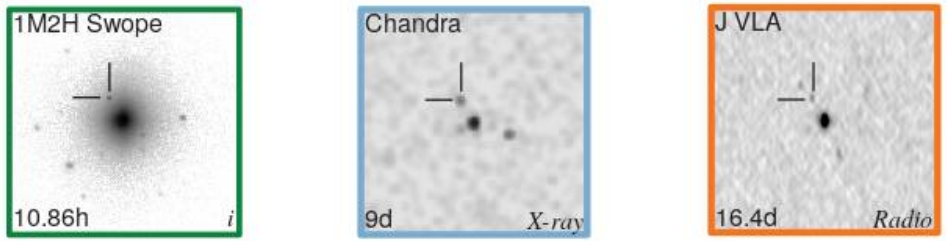
HST/WFC3-IR F110W t_c+4.79d

Tanvir et al, ApJL 848:L27 2017

Three time scales: weeks/months



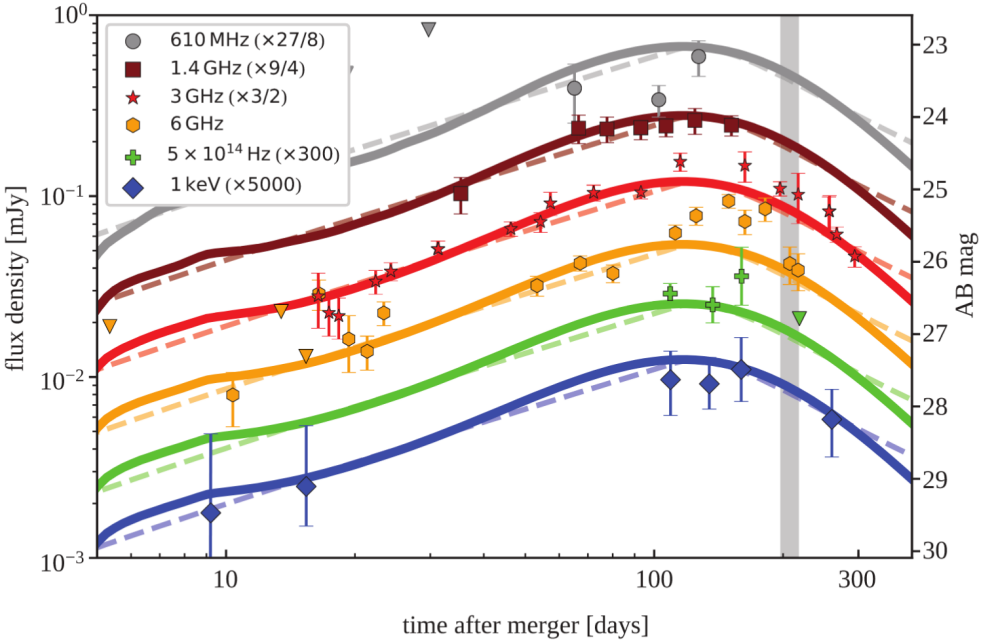




X-ray T0+9 d, radio T0+16 d

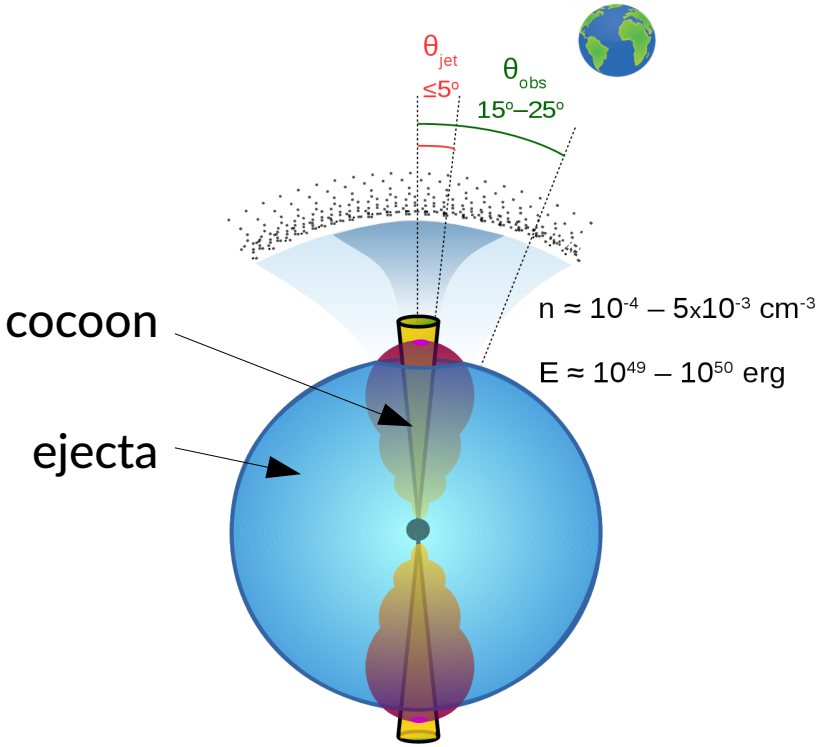
Peak in X-ray & radio (100 μJy) at T0+~150 d

and optical (m=26.5) at T0+110 d

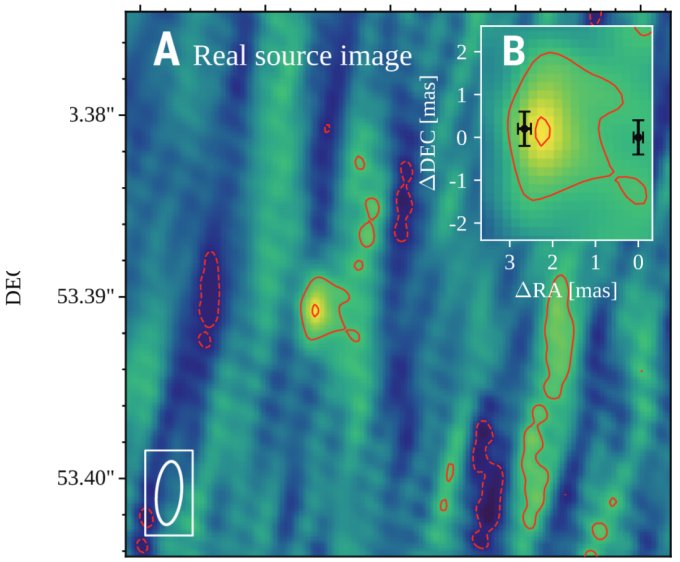


Ghirlanda et al. ArXiv:1808.00469

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 $\Gamma \sim 4$, $\theta_{jet} \sim 4°$

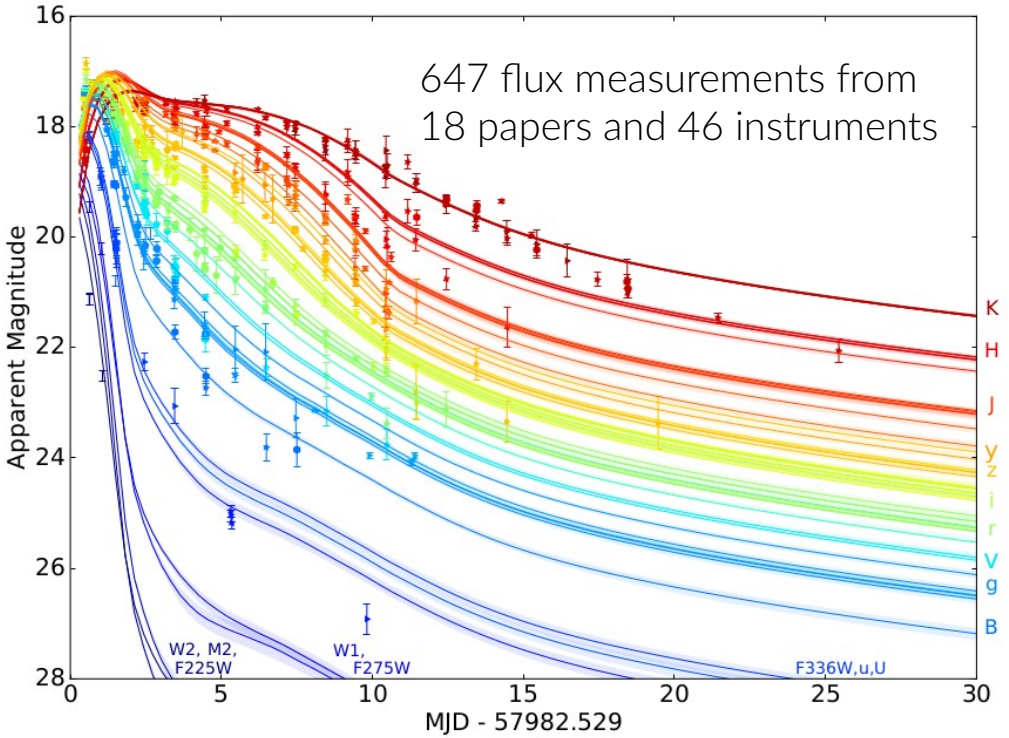


Mooley et al, ArXiv:1806.09693
Ghirlanda et al. ArXiv:1808.00469

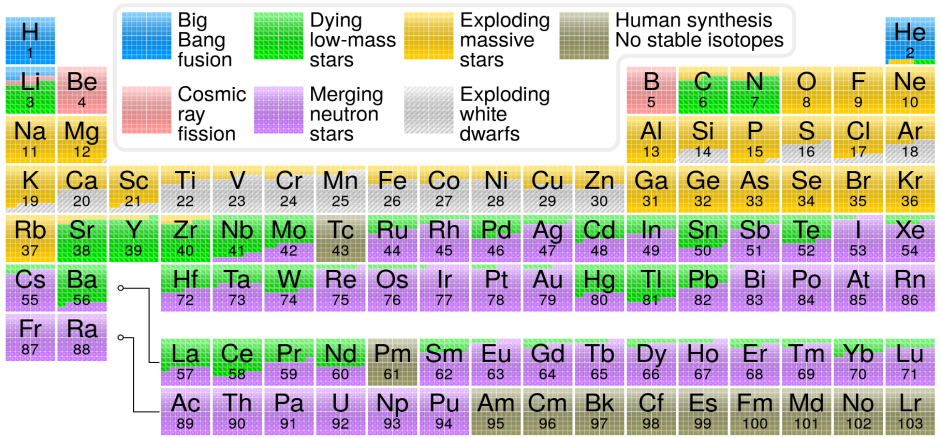
Plan de la présentation

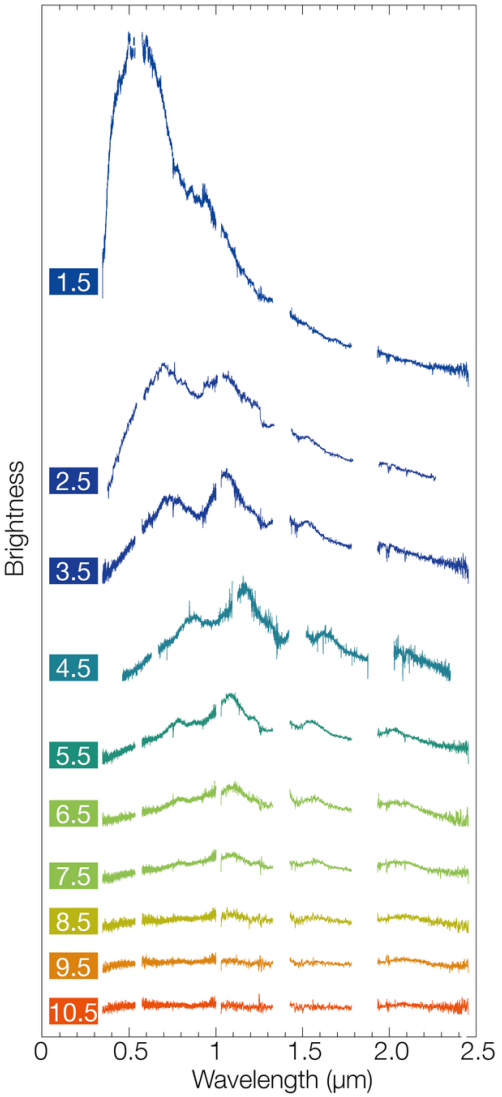
- Introduction sur les ondes gravitationnelles
- Détecteurs et observations jusqu'ici
- GW170817 et l'astronomie multi-messager
- **Implications en physique, en astrophysique et en cosmologie**
- Perspectives

Implications (1): nucleosynthesis



V. Ashley Villar et al, arXiv:1710.11576

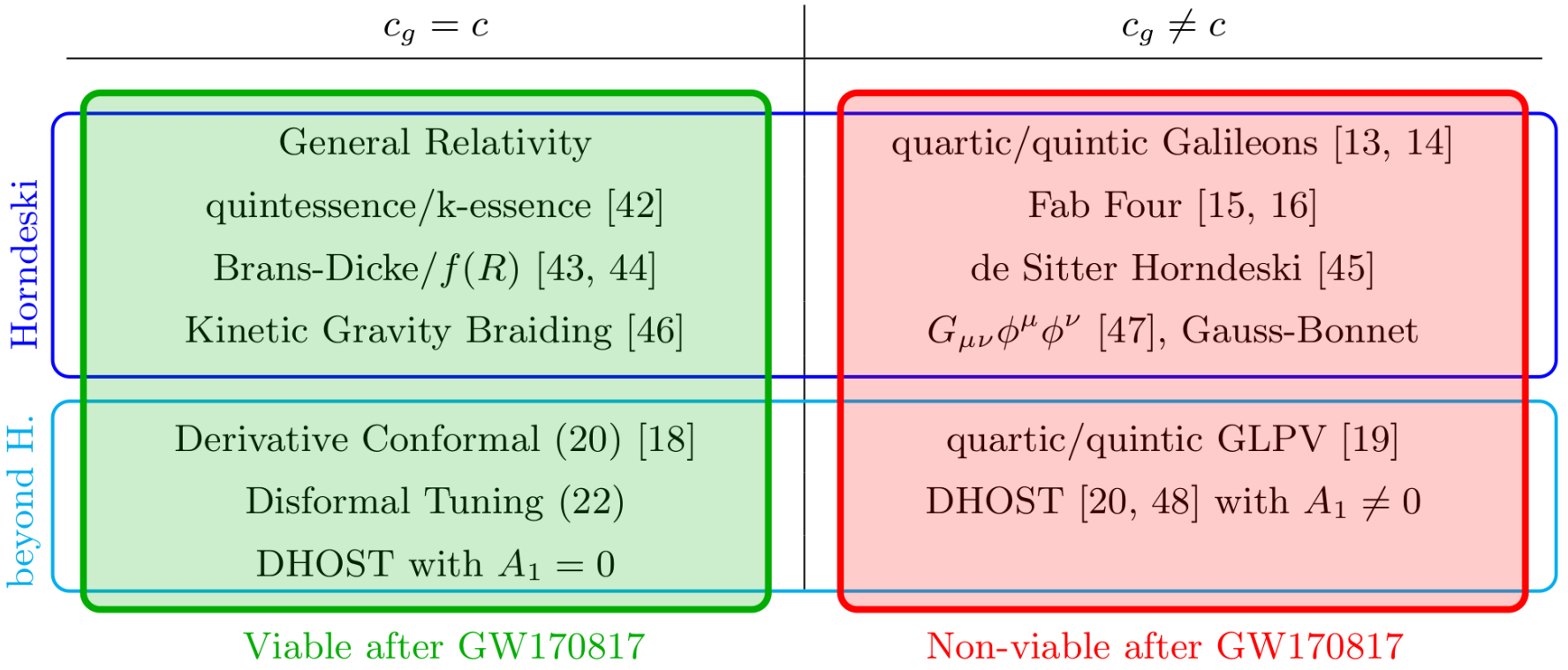




Cf présentation David Lunney

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



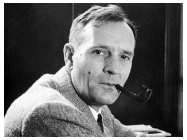
https://arxiv.org/abs/1710.05901
https://arxiv.org/abs/1710.05877

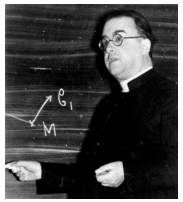
Implications (3): Cosmology

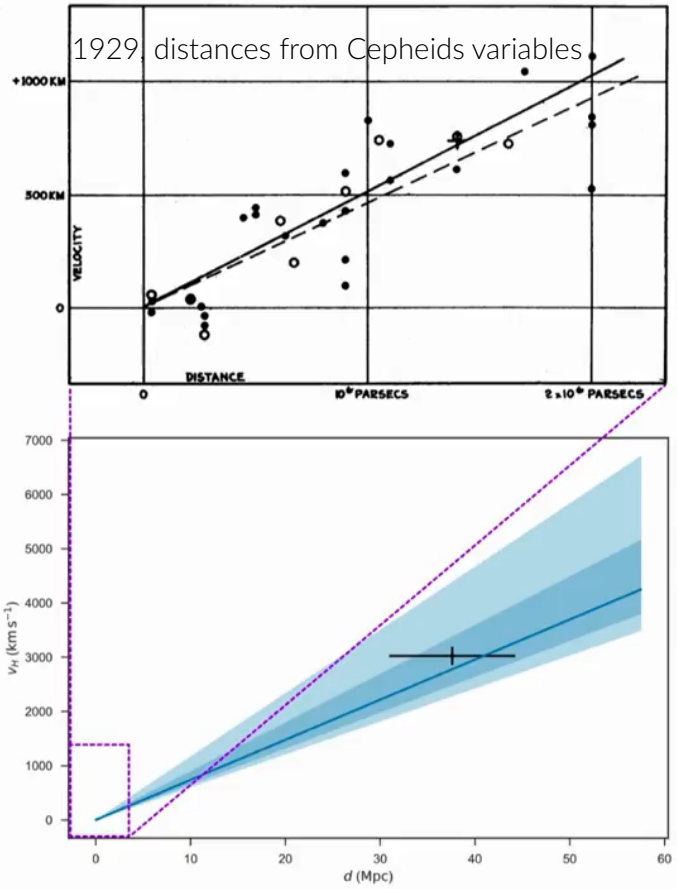
Hubble Lemaître law $v_H = cz = H_0 D_L$

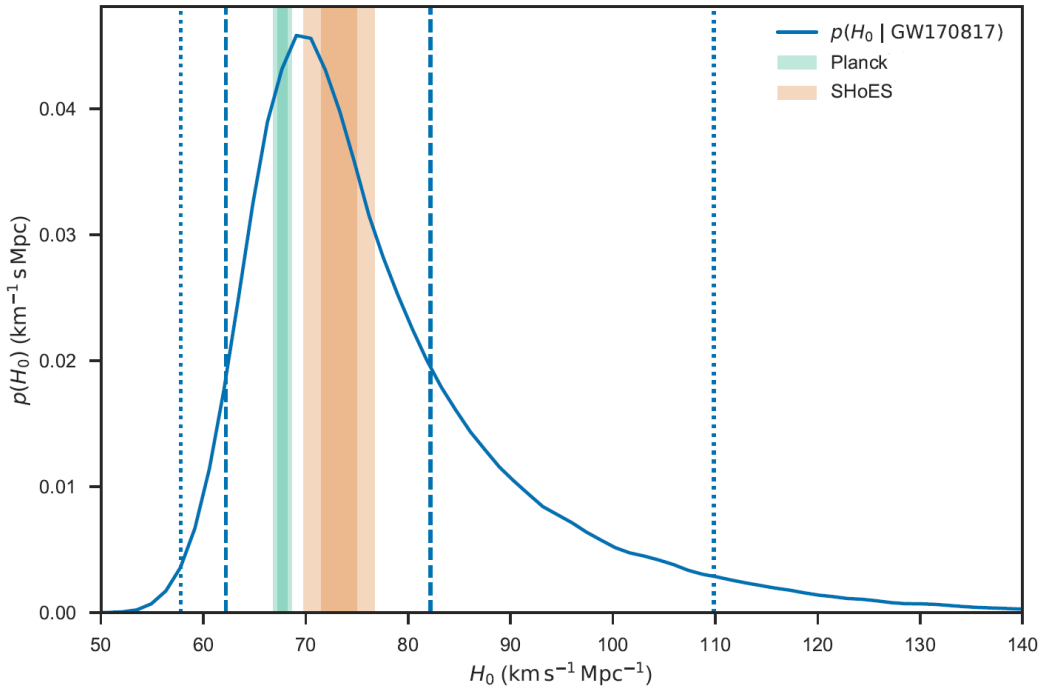
from host galaxy identif.

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

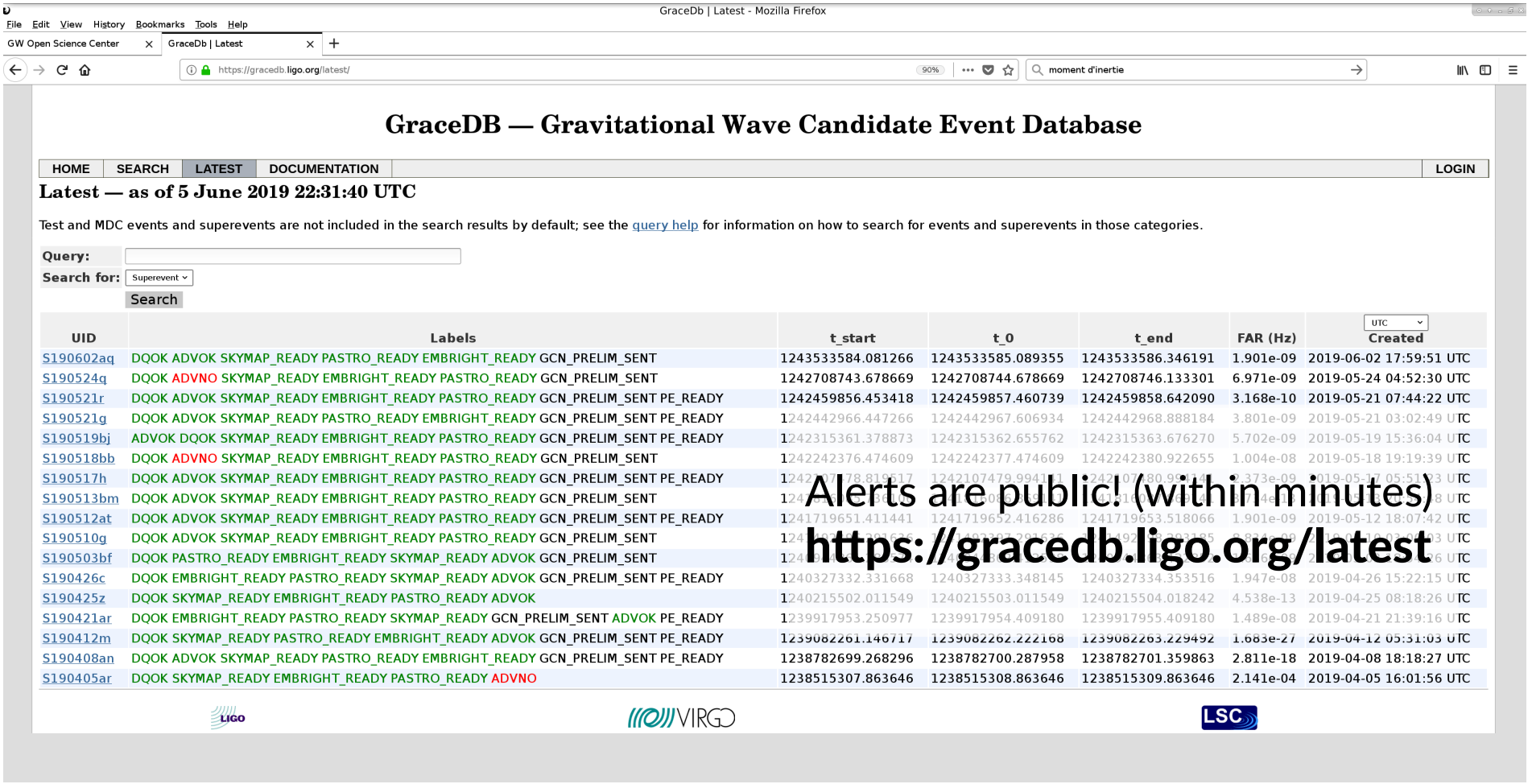
LIGO at ~120 Mpc (L1) and 100 Mpc (H1)
Virgo at ~50 Mpc (x ~2 wrt O2) ~90 % duty cycle

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	

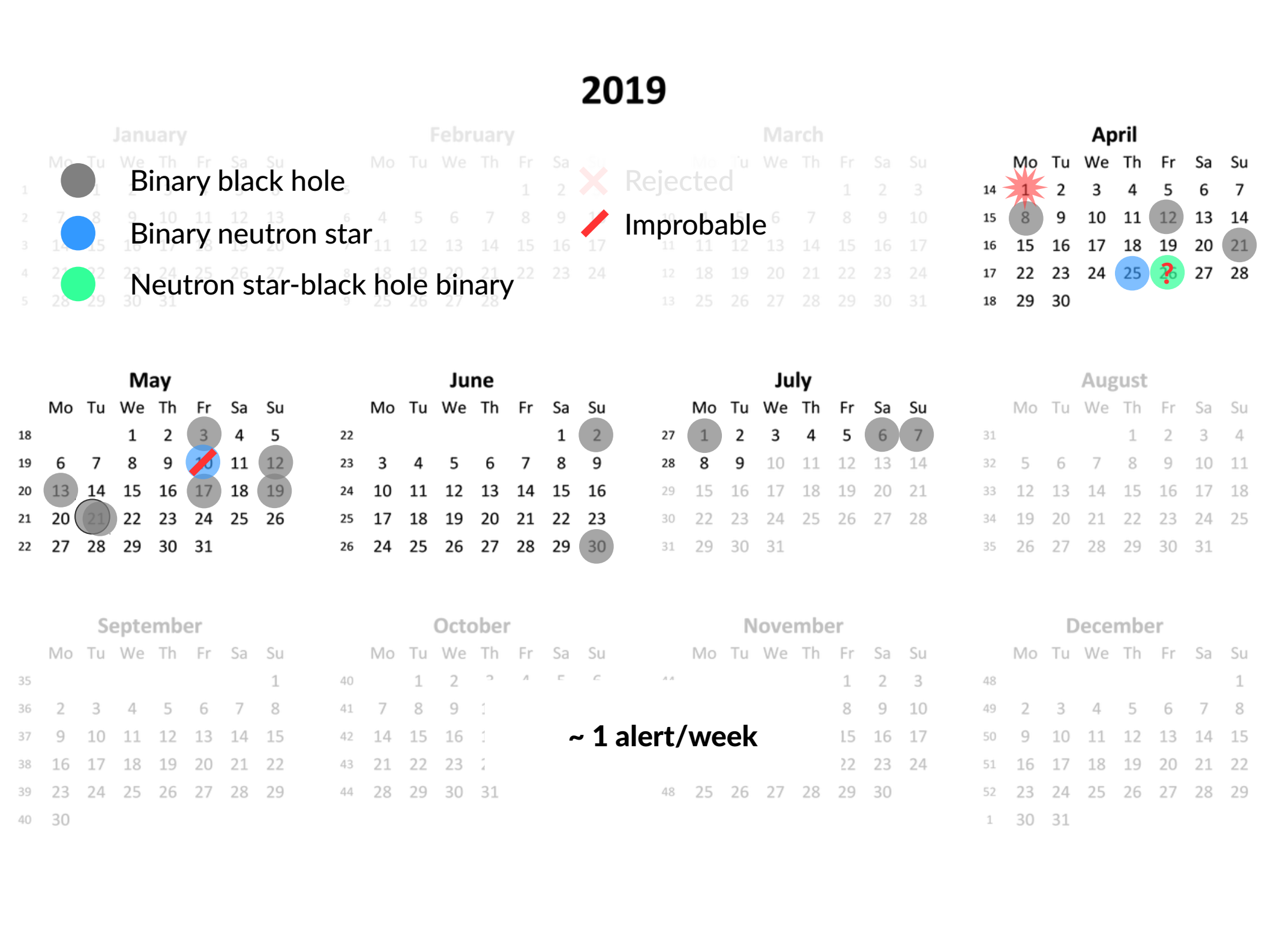
Detector status summary pages — LVC links



Alerts are public! (within minutes)

https://gracedb.ligo.org/latest

2019


Binary black hole
Binary neutron star
Neutron star-black hole binary
Rejected
Improbable
April
Mo Tu We Th Fr Sa Su
14 1 2 3 4 5 6 7
15 8 9 10 11 12 13 14
16 15 16 17 18 19 20 21
17 22 23 24 25 26 27 28
18 29 30
?
May
Mo Tu We Th Fr Sa Su
18 1 2 3 4 5
19 6 7 8 9 10 11 12
20 13 14 15 16 17 18 19
21 20 21 22 23 24 25 26
22 27 28 29 30 31
June
Mo Tu We Th Fr Sa Su
22 1 2
23 3 4 5 6 7 8 9
24 10 11 12 13 14 15 16
25 17 18 19 20 21 22 23
26 24 25 26 27 28 29 30
July
Mo Tu We Th Fr Sa Su
27 1 2 3 4 5 6 7
28 8 9 10 11 12 13 14
29 15 16 17 18 19 20 21
30 22 23 24 25 26 27 28
31 29 30 31
~ 1 alert/week

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**