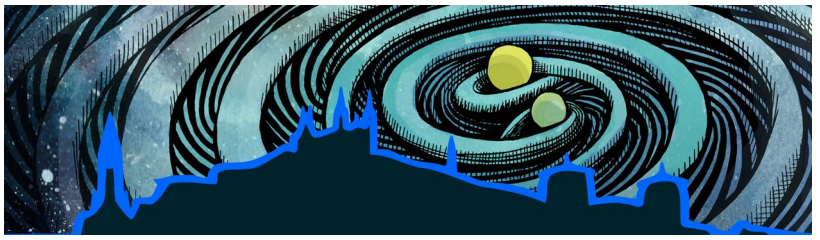
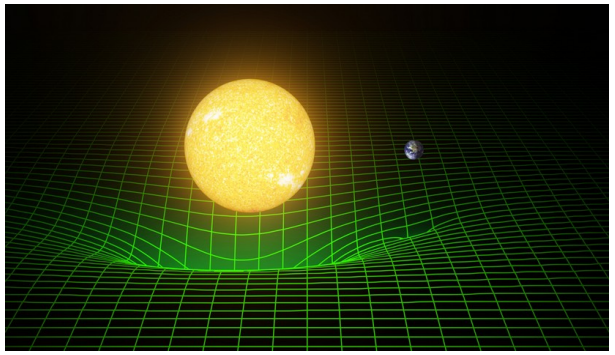
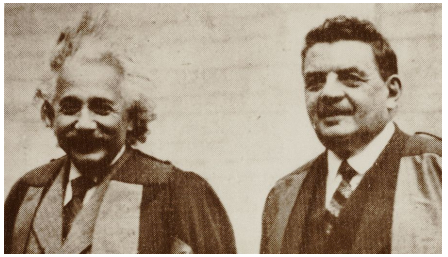
Résultats marquants des trois premières périodes d'observation de LIGO-Virgo

Eric Chassande-Mottin
AstroParticule et Cosmologie (APC)
CNRS Université Paris Cité







1915

Edouard Herriot

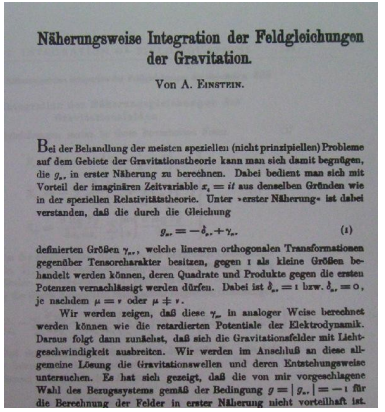
L’espace-temps est dynamique et déformable

La gravité provient de la courbure de l’espace-temps

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

géométrie (métrique)

matière énergie



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 $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist.

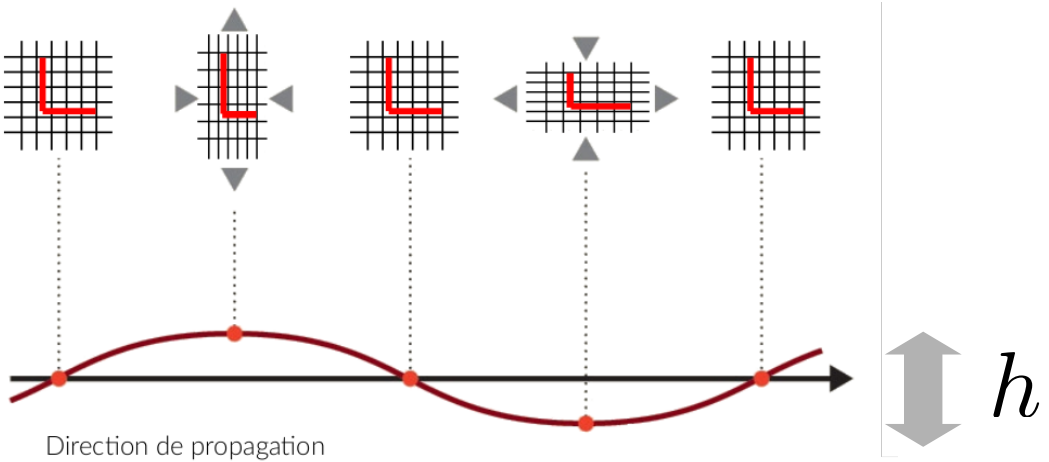
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Box \bar{h}_{ab} = 0$$

équation d'onde

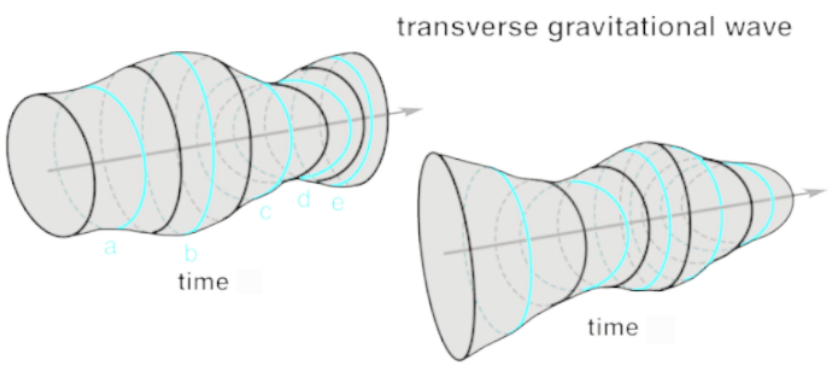
Petite perturbation
de la métrique

$$g_{ab} = \eta_{ab} + h_{ab}$$



h

onde transverse – 2 polarisations

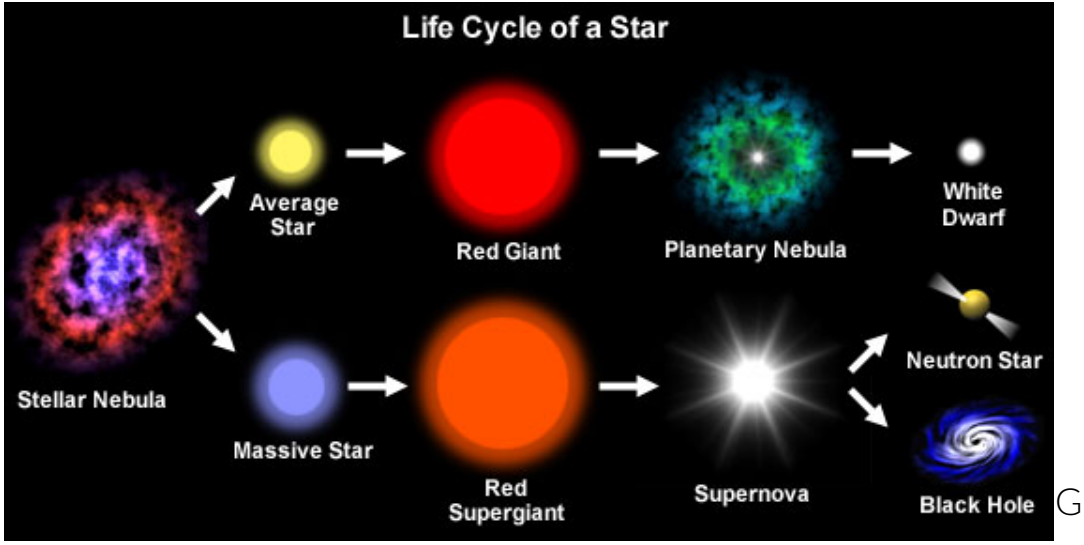


charges accélérées → ondes électromagnétiques

masses accélérées → ondes gravitationnelles

- Pas émission pour les objets sphériques
- Requiert un certain degré de non-axisymétrie

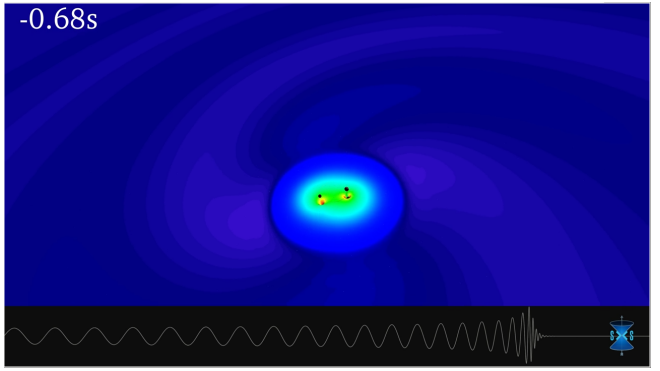
Grandes masses, vitesses relativistes → **Objets astrophysiques compacts**



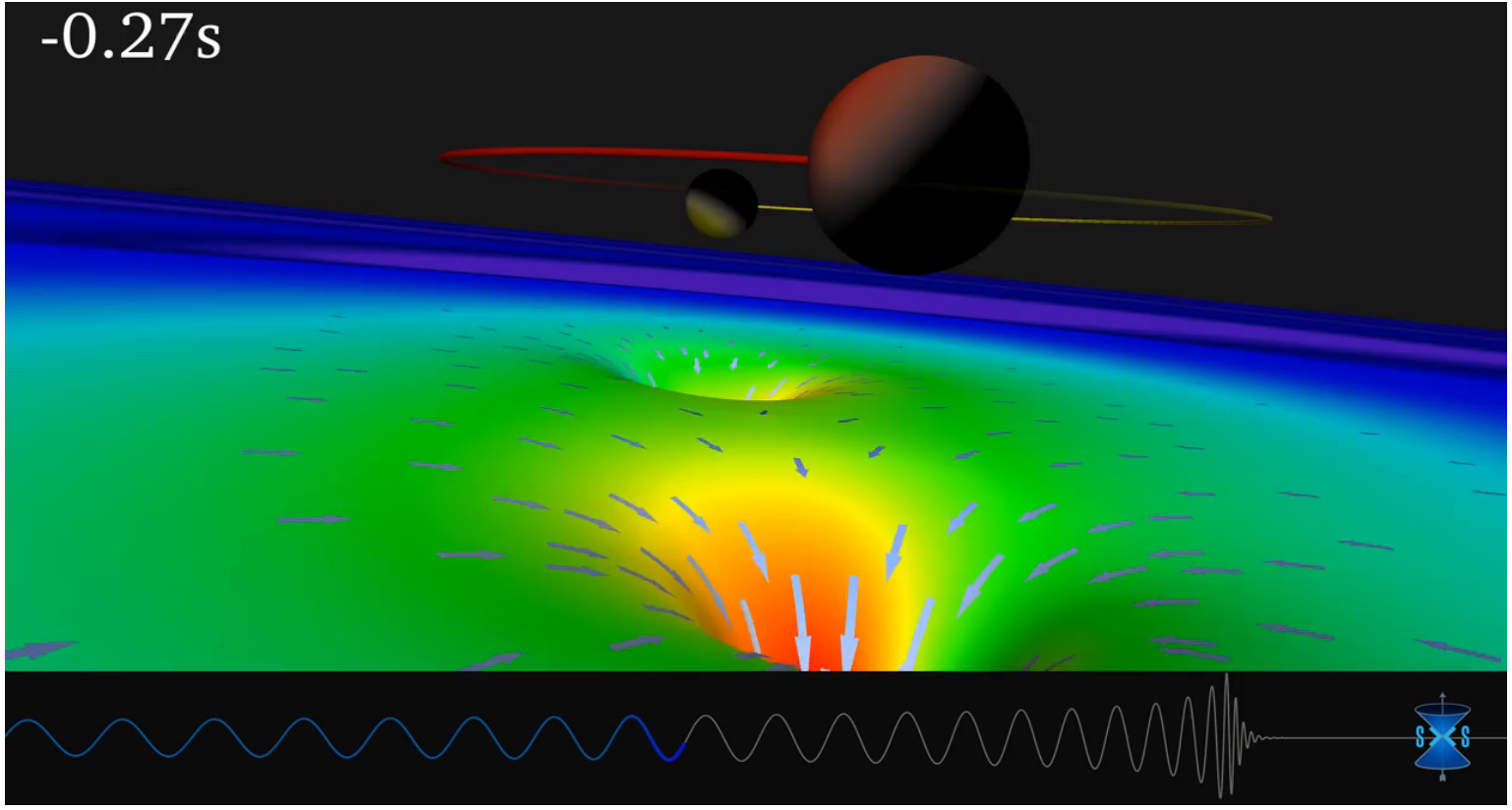
Naines blanches

Etoiles à neutrons

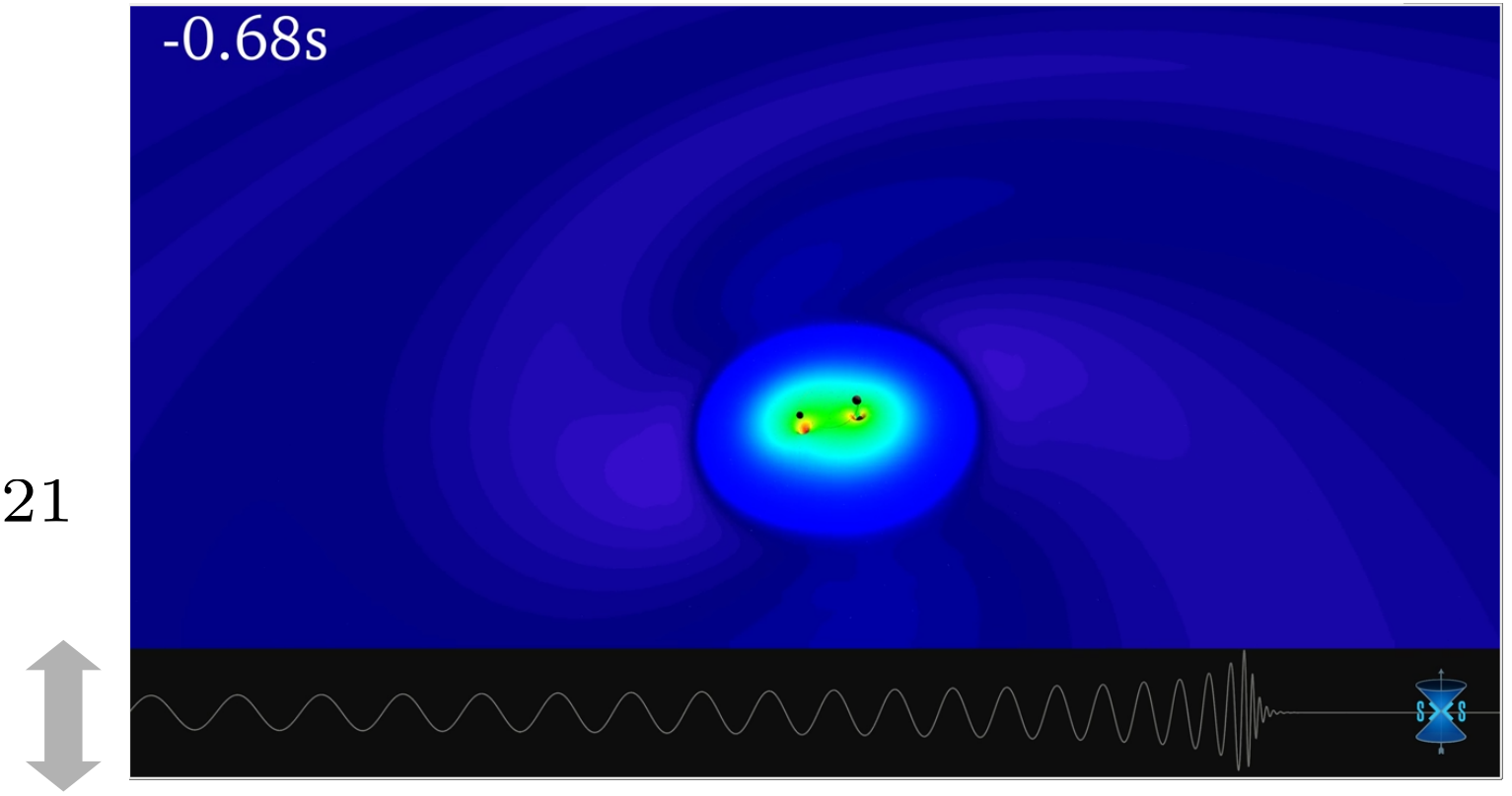
Trous noirs



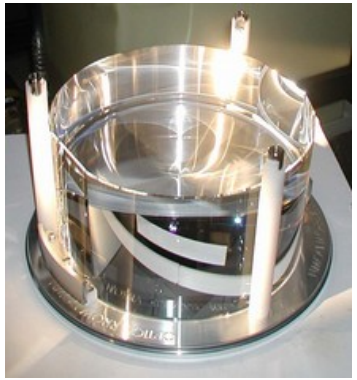
G à Lyon


-0.27s

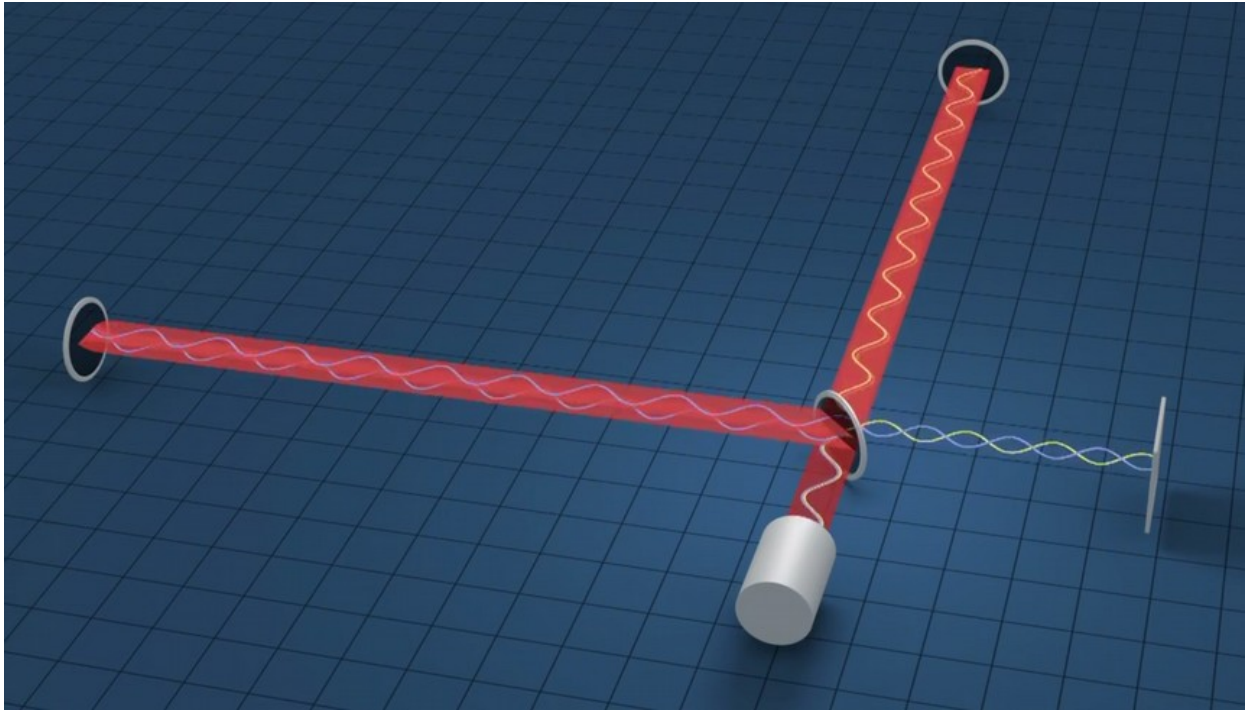
$$h_{\mathrm{typ}} \sim 10^{-21}$$



Principe de détection : Interféromètre de Michelson



Cf Laurent Pinard




LIGO (US)


Virgo (Italy)

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

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

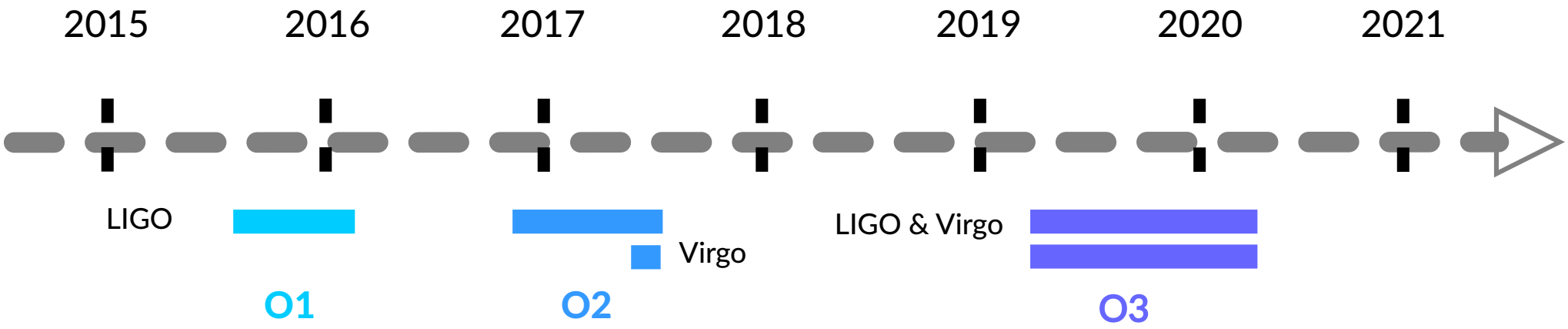
$$L = O(1)\mathrm{km}$$

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


LIGO Handford H1


LIGO Livingston L1


Virgo V1


2015
2016
2017
2018
2019
2020
2021
LIGO
Virgo
LIGO & Virgo
O1
O2
O3

	Known waveform	Unknown waveform
Transient Short duration	**Coalescing Binary Systems** Neutron Stars, Black Holes	**'Bursts'** asymmetric core collapse supernovae cosmic strings ???
Permanent Long duration	**Continuous Sources** Spinning neutron stars crustal deformations, accretion	*Astrophysical or* **Cosmic GW background** stochastic, incoherent background

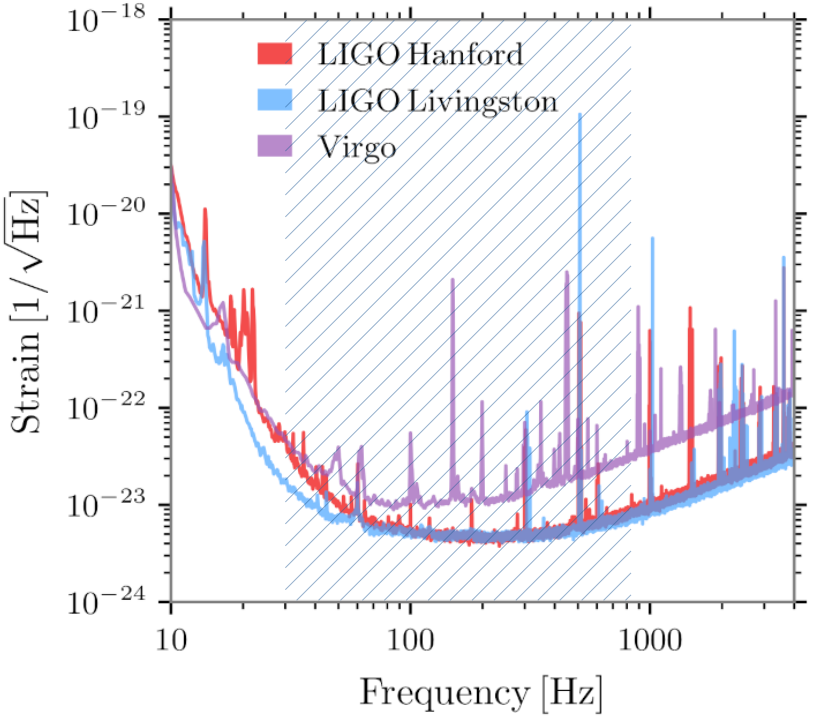
Core science

Compact stars (neutron stars or black holes)

Fundamental physics (test of GR)

Cosmology

Sensitivities during O3
2019-2020



Distance range to
binary neutron stars
(averaged over sky position and inclination)

L1: 135 Mpc

H1: 115 Mpc

V1: 50 Mpc

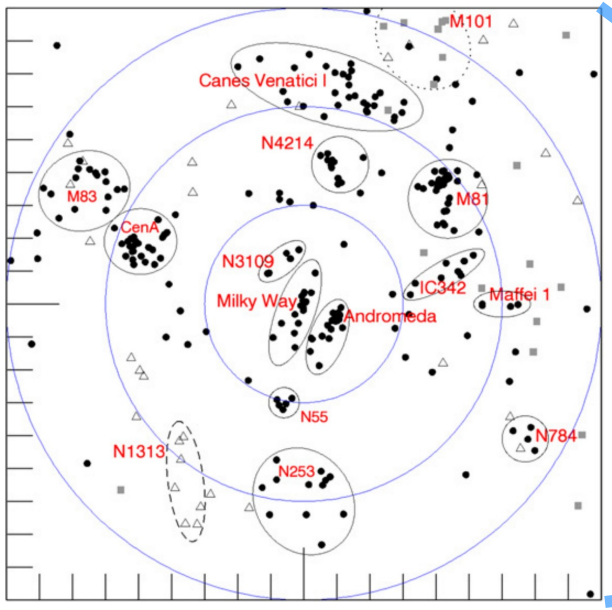
Distance reach for **binary black hole** mergers extends **much further away**.

1 parsec = 3.26 ly
= 31 x 10^{12} km

24 nov 2022

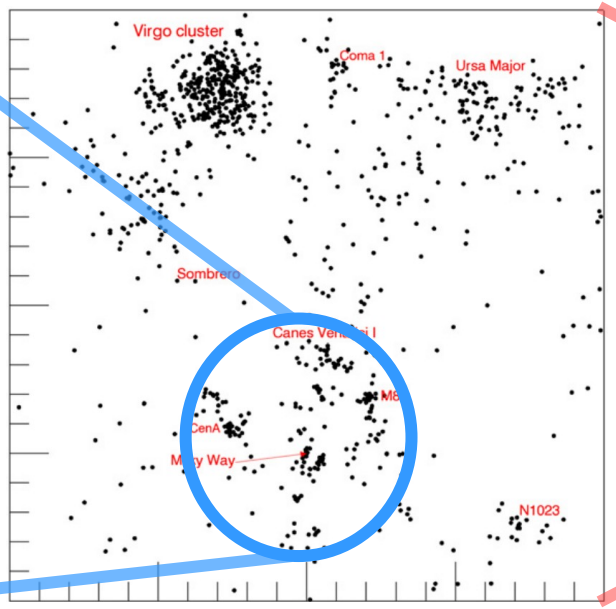
How far is this?

Local group



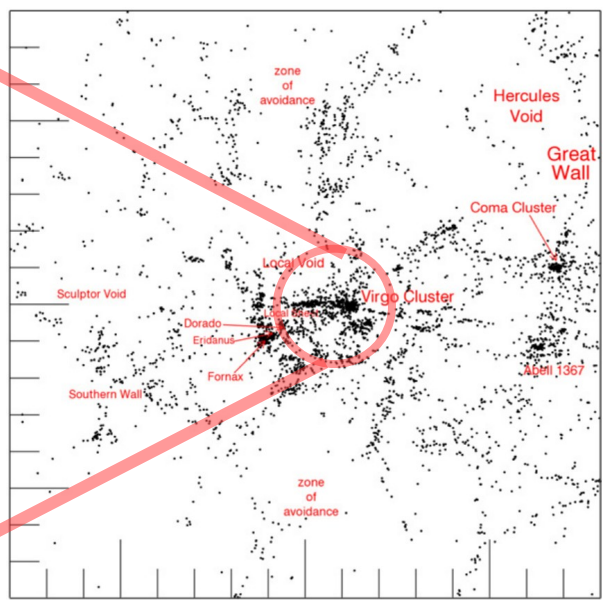
~12 Mpc
~ 10 galaxies

To Virgo cluster



~27 Mpc
~ 100 galaxies

Laniakea Supercluster

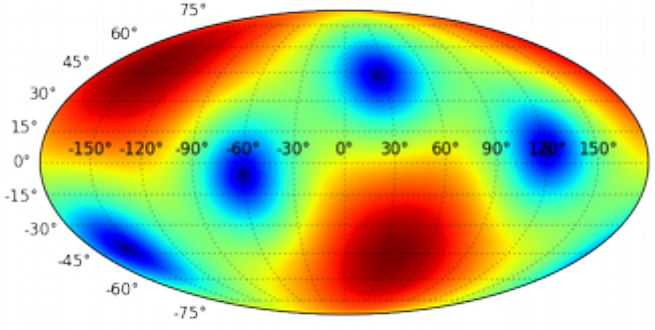


~215 Mpc
~ 50 000 galaxies

From Courtois et al, ApJ 146 3 2013

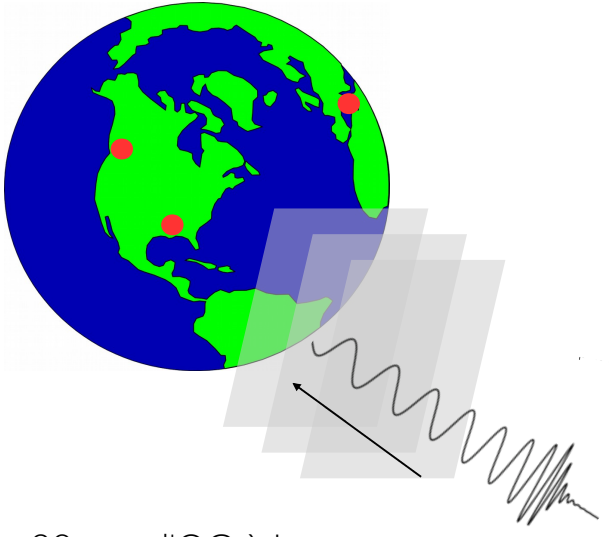
~3000 km
(10 light-ms)

~10000 km
(30 light-ms)



Quasi-omnidirectionel

(pas de pointage)



Localisation de la source

10–100 deg²

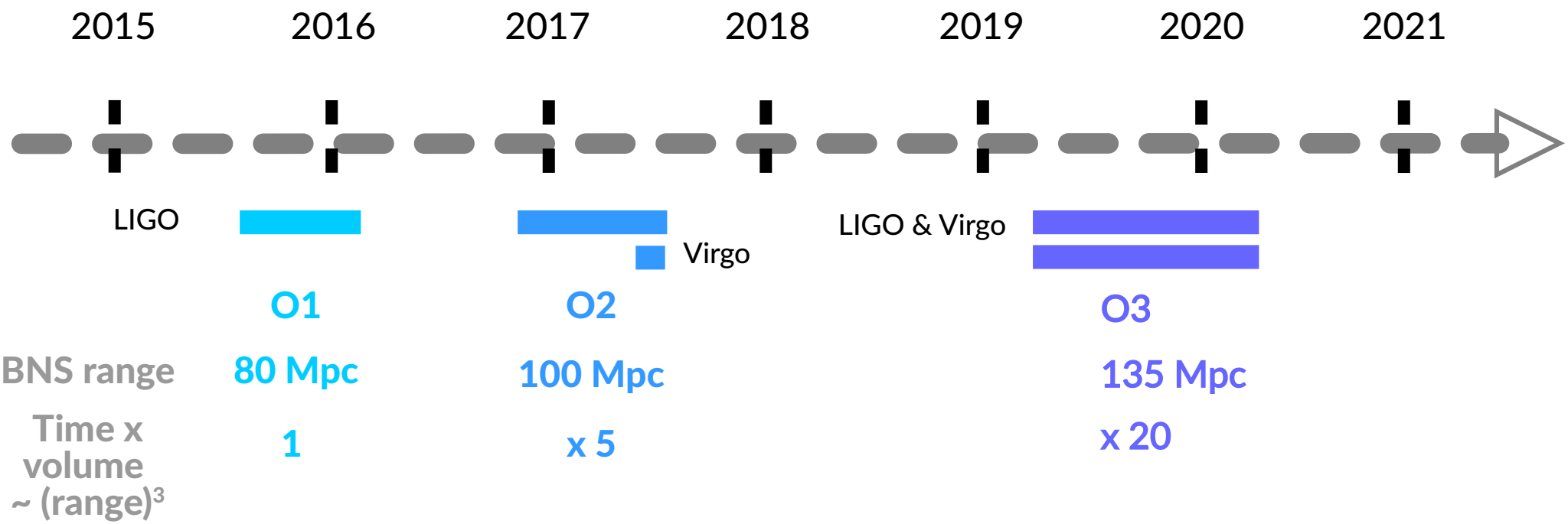
Par comparaison :

0.2 deg²

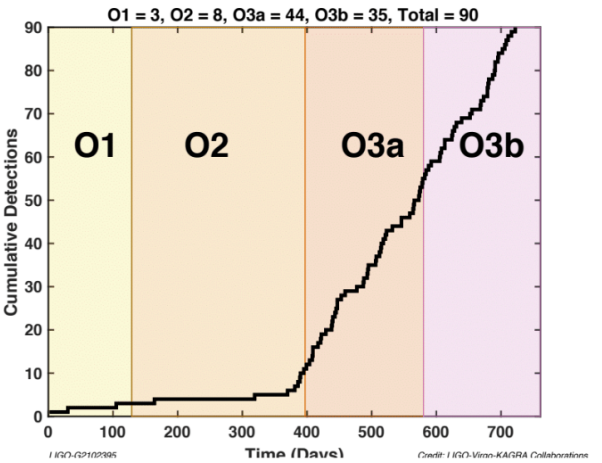

LIGO Handford H1


LIGO Livingston L1


Virgo V1


2015
2016
2017
2018
2019
2020
2021
LIGO
Virgo
LIGO & Virgo
O1
O2
O3
BNS range
80 Mpc
100 Mpc
135 Mpc
Time x volume ~ (range)3
1
x 5
x 20





2015 2016 2017 2018 2019 2020 2021

LIGO

O1
3 detections

GW150914

O2
8 detections
GWTC-1

GW170814
GW170817

Virgo

LIGO & Virgo

O3

O3a
39 detections
GWTC-2

44 detections
GWTC-2.1

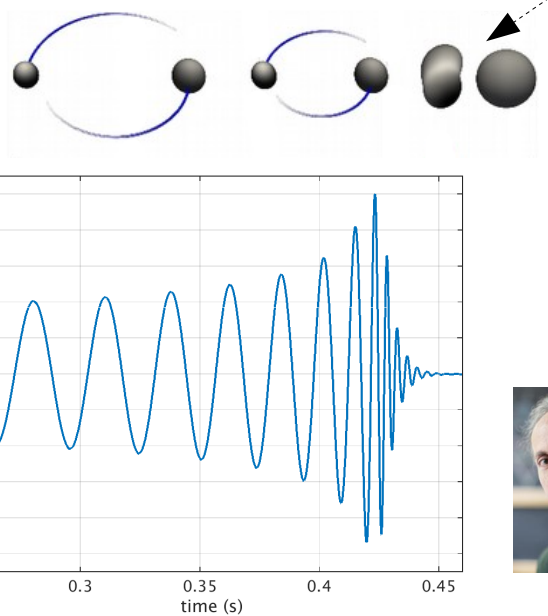
O3b
35 detections
GWTC-3

http://arxiv.org/abs/2010.14527
http://arxiv.org/abs/2108.01045
http://arxiv.org/abs/2111.03606

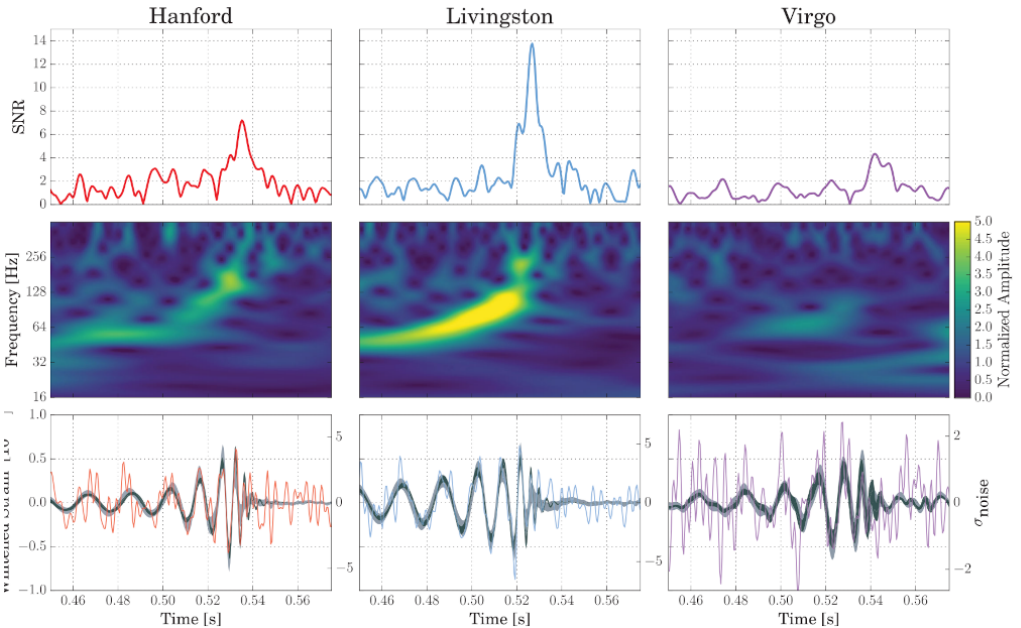
Aug 14 2017

Signature caractéristique de la fusion de deux trous noirs

spirale fusion désexcitation



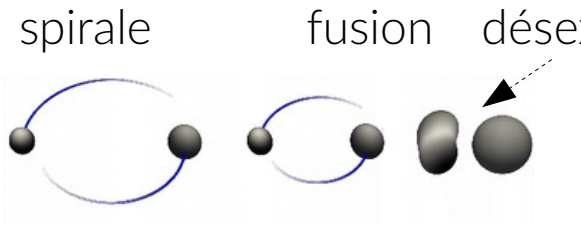
GW170814

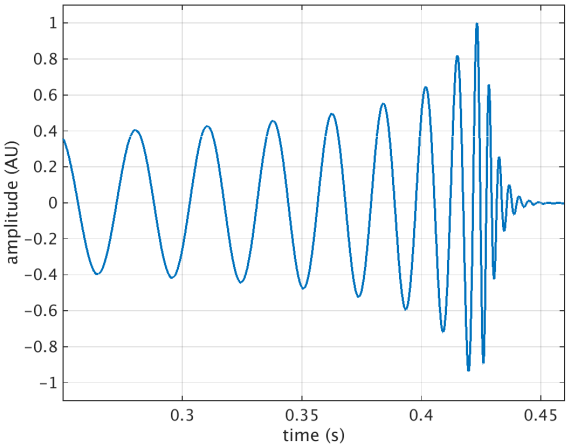


Are polarization states pure tensor?

Aug 14 2017

Signature caractéristique de la fusion de deux trous noirs





GW170814

15 paramètres

(masses, spins, et géométrie : position + orientation)

$$m_1 = 30.5^{-3.0}_{+5.7} M_\odot$$
$$m_2 = 25.3^{-4.2}_{+2.8} M_\odot$$

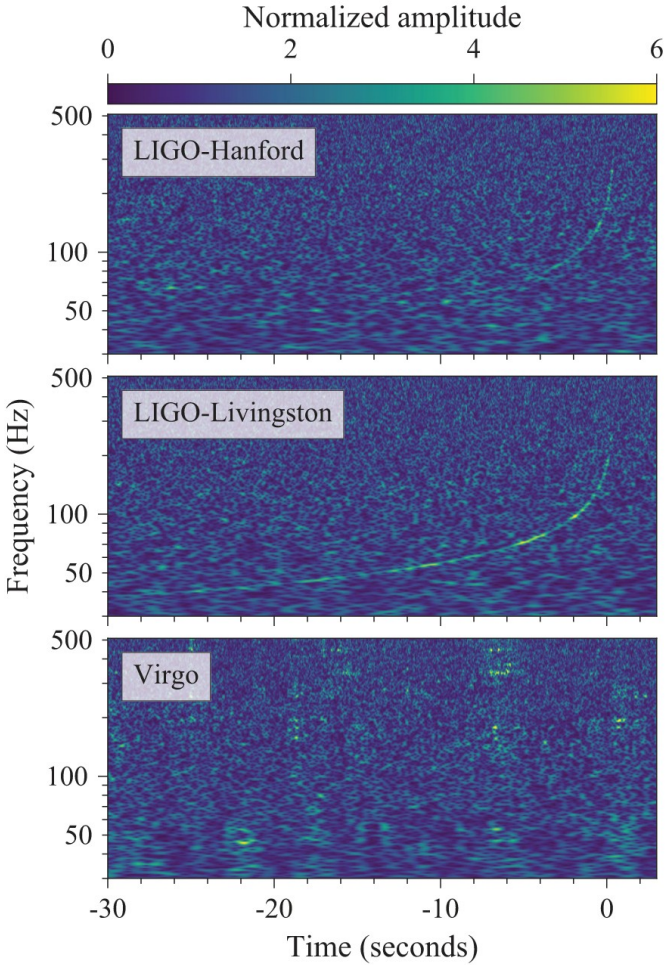
} avec la phase

$$D_L = 540^{-210}_{+130}\ \mathrm{Mpc}$$

} avec l'amplitude

soit 1.8 milliard d'années lumière

Aug 17, 2017



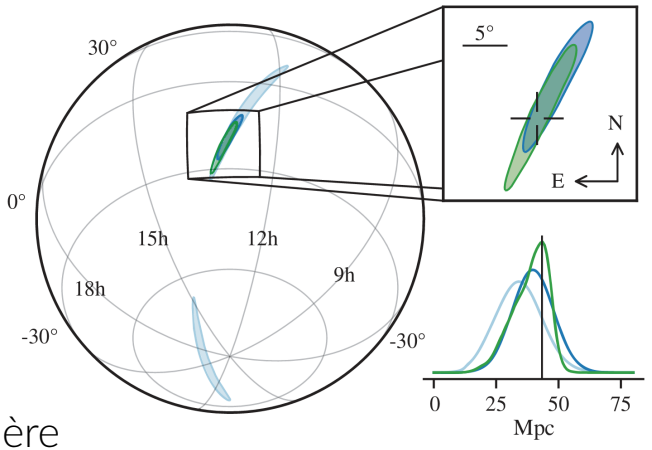
GW170817

$$m_1 = 1.46^{+0.12}_{-0.10} M_\odot$$

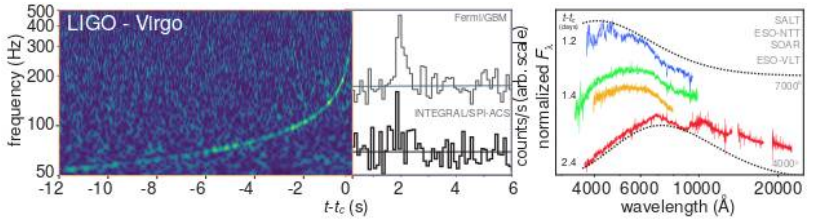
$$m_2 = 1.27^{+0.09}_{-0.09} M_\odot$$

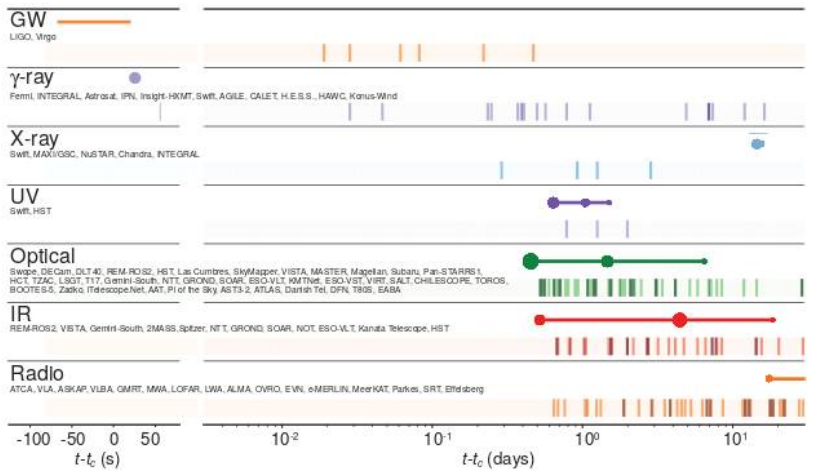
$$D_L = 40^{+7}_{-15}\ \mathrm{Mpc}$$

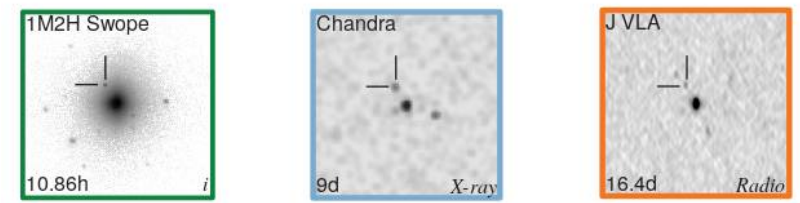
soit 130 millions d'années lumière

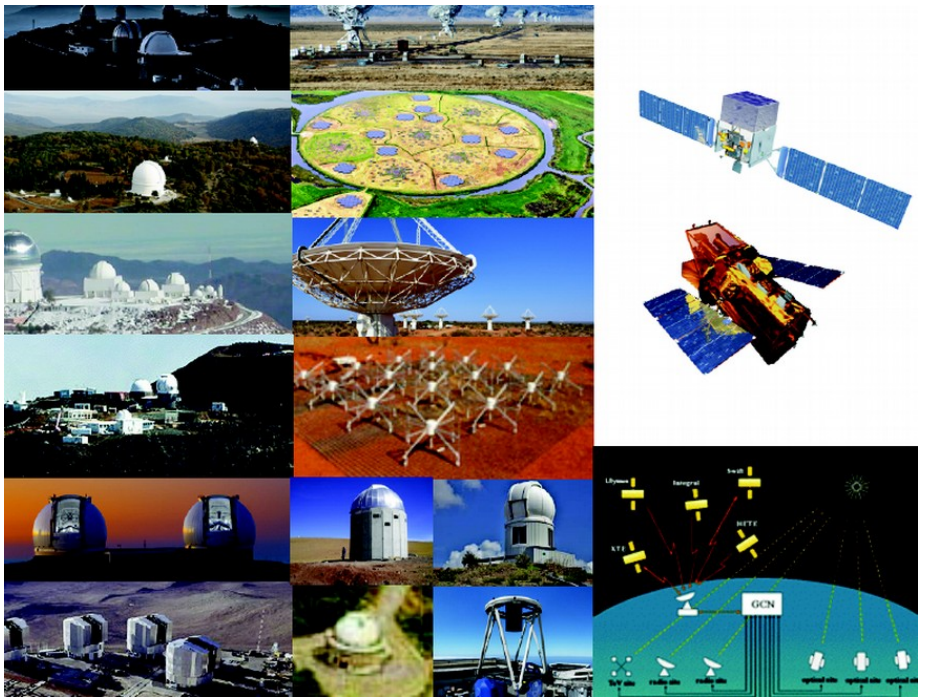


GW170817 : Astrophysique multimessager !





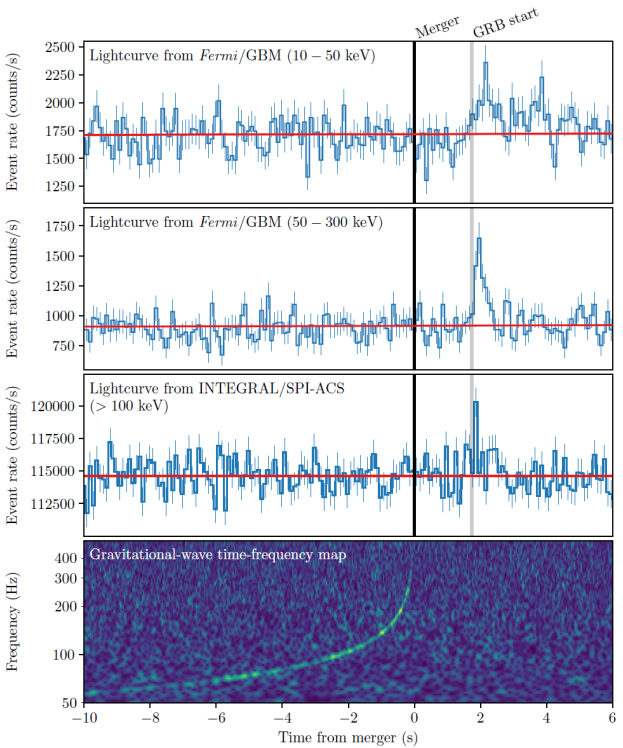




30 ans d'OG à Lyon

Gamma-rays

T0+1.7 s



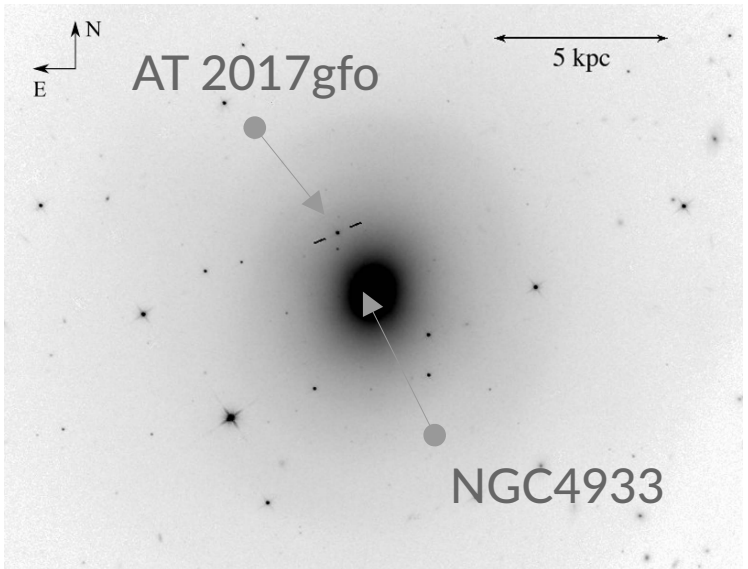
Association with gamma-ray bursts
Jet of relativistic plasma?

Speed of gravity: $|c/c_g - 1| < 5 \times 10^{-16}$
alt. gravity scalar-tensor theories

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

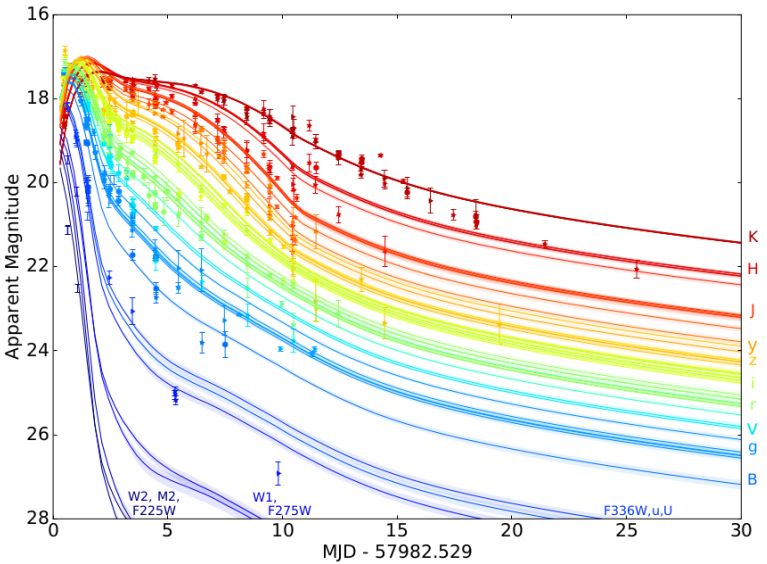
30 ans d'OG

Near infrared, visible and UV



HST/WFC3-IR F110W t_c+4.79d

T0+~1d "Kilonova " – Thermal optical transient fed by the radioactive decay of instable nuclei formed by rapid neutron capture

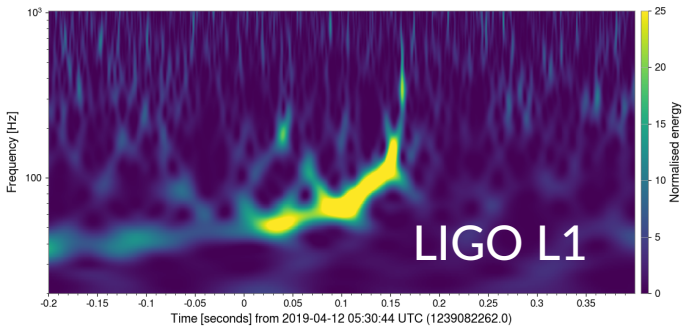


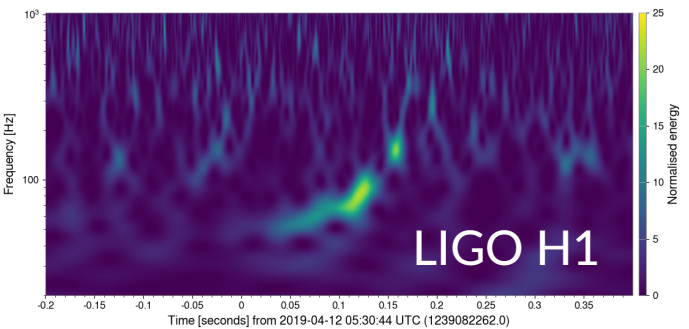
V. Ashley Villar et al, arXiv:1710.11576

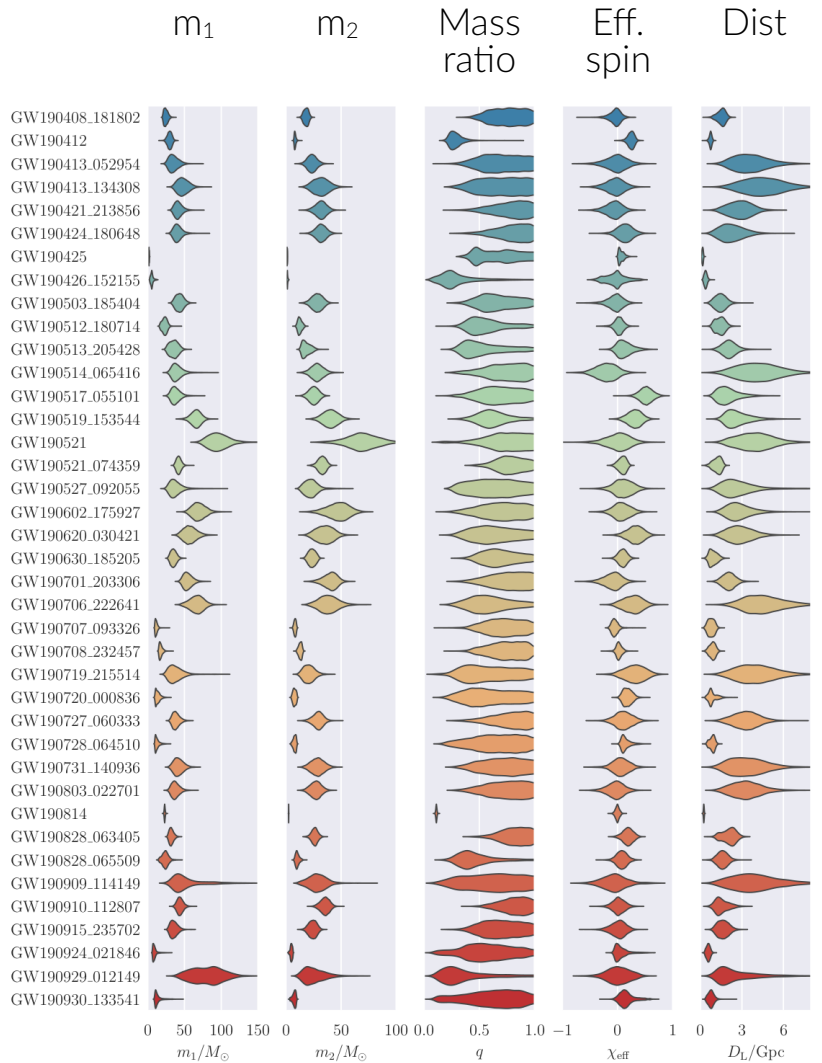
What did we detect?

90 confident detections

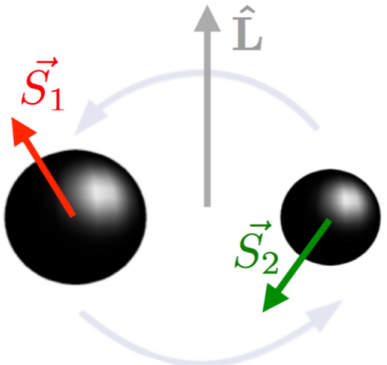
A large population of “heavy” **binary black holes,** so far unobserved







GWTC 2 & 3



https://arxiv.org/abs/2010.14527

What did we detect?

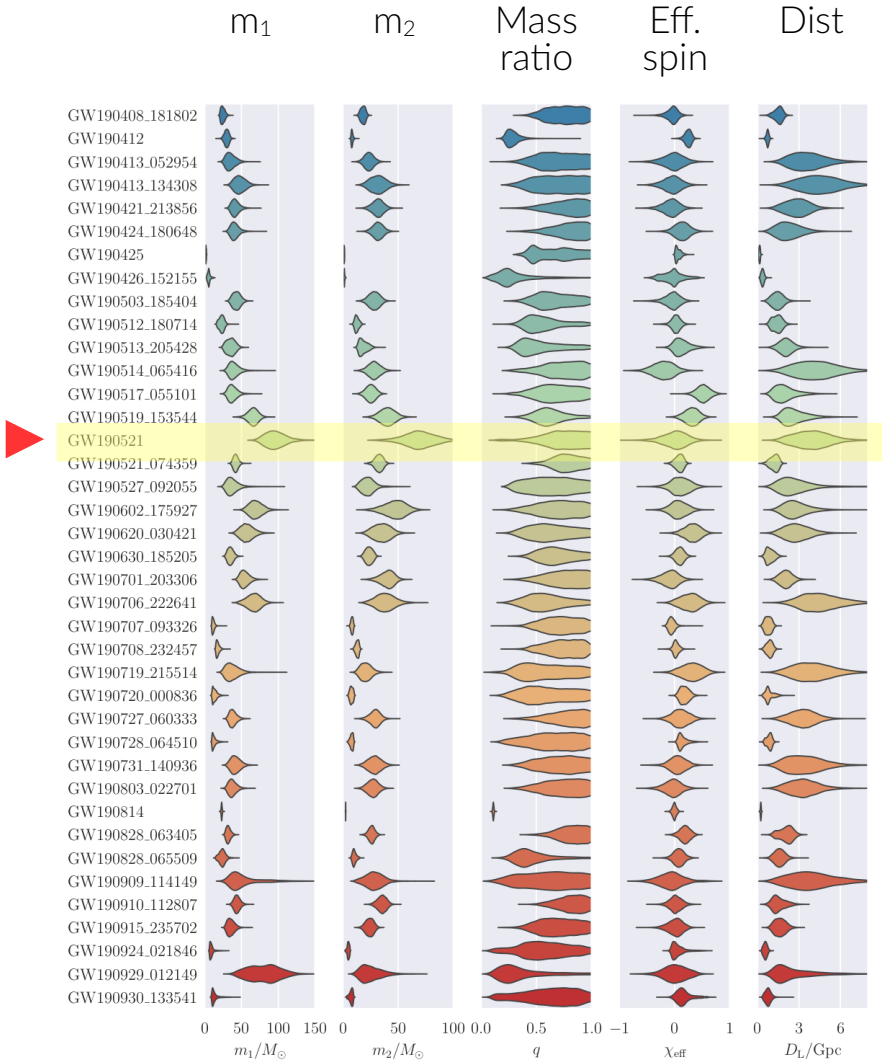
GWTC 2

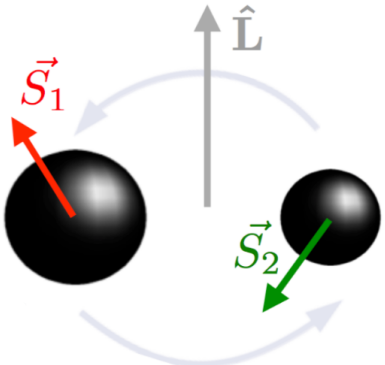
A large population of “heavy” **binary black holes,** so far unobserved

m_1 = 71–106 $M_\odot$
m_2 = 49–84 $M_\odot$

Incompatible with the current understanding of black hole formation from massive stars

Expect high mass gap ~(65-135 $M_\odot$) from pulsational pair instability





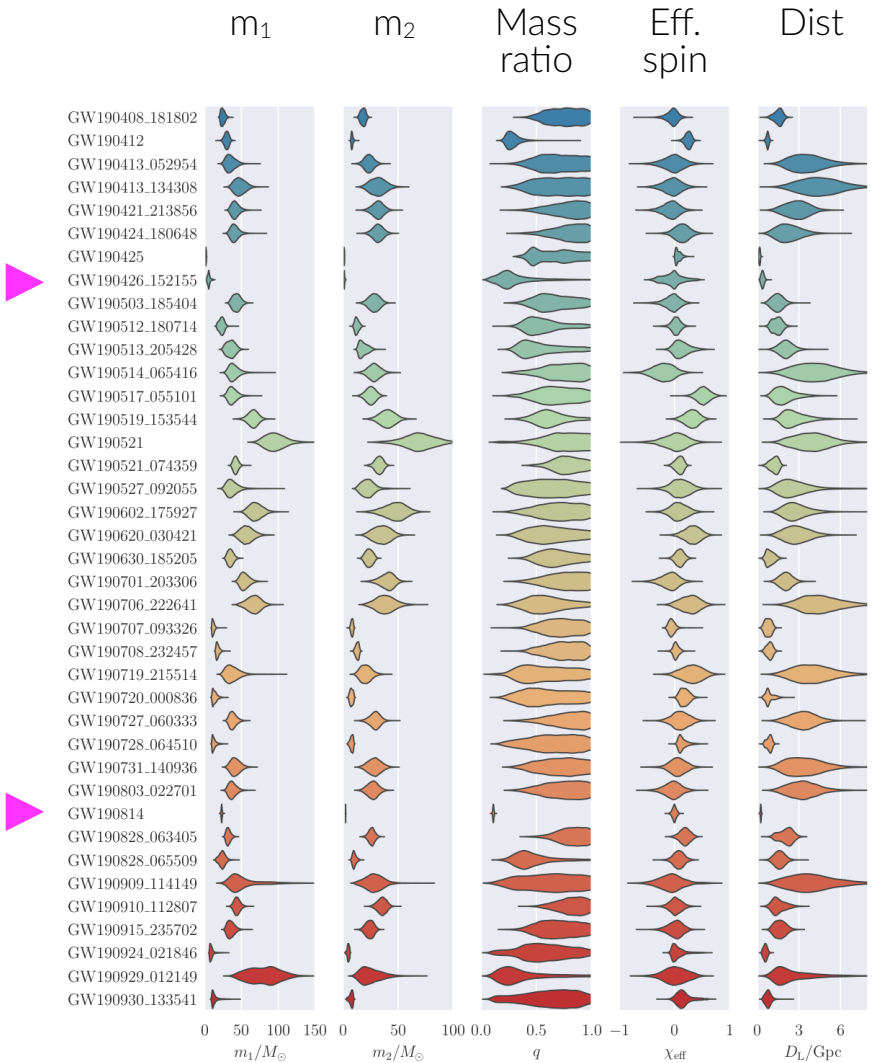
https://arxiv.org/abs/2010.14527

What did we detect?

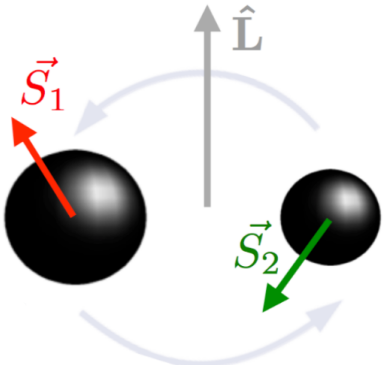
Other types of binary systems

- Binary neutron stars
- Possible mixed black hole and neutron star binaries

Black holes from stellar core collapses are expected to be > 3 M_{sun}



GWTC 2



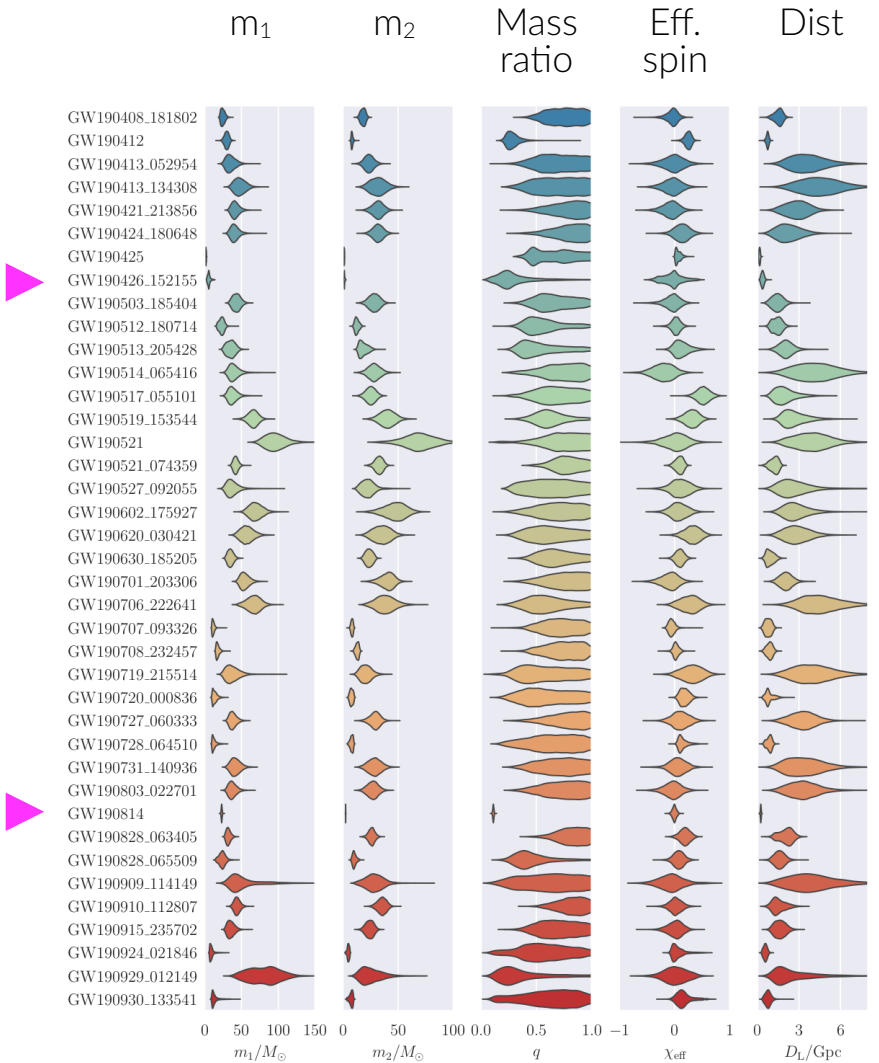
https://arxiv.org/abs/2010.14527

What did we detect?

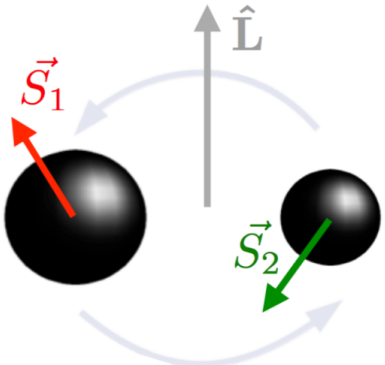
Other types of binary systems

- Binary neutron stars
- Possible mixed black hole and neutron star binaries

Black holes from stellar core collapses are expected to be > 3 M_{sun}



GWTC 2



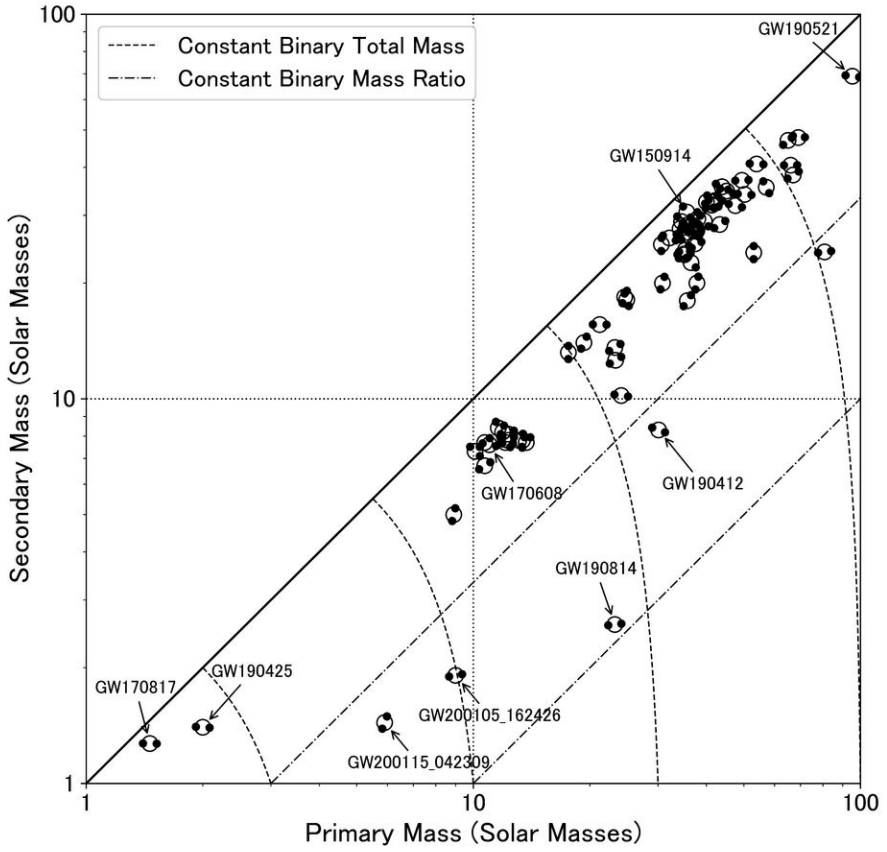
https://arxiv.org/abs/2010.14527

What did we detect?

A large population of "heavy" **binary black holes,** so far unobserved

Raises many questions

How do they form?
In what environment?



Credit: LVK / IGFAE / T Dent
arXiv:2108.01045
arXiv:2111.03606

What did we detect?

A large population of "heavy" **binary black holes,** so far unobserved

Formation scenarios:

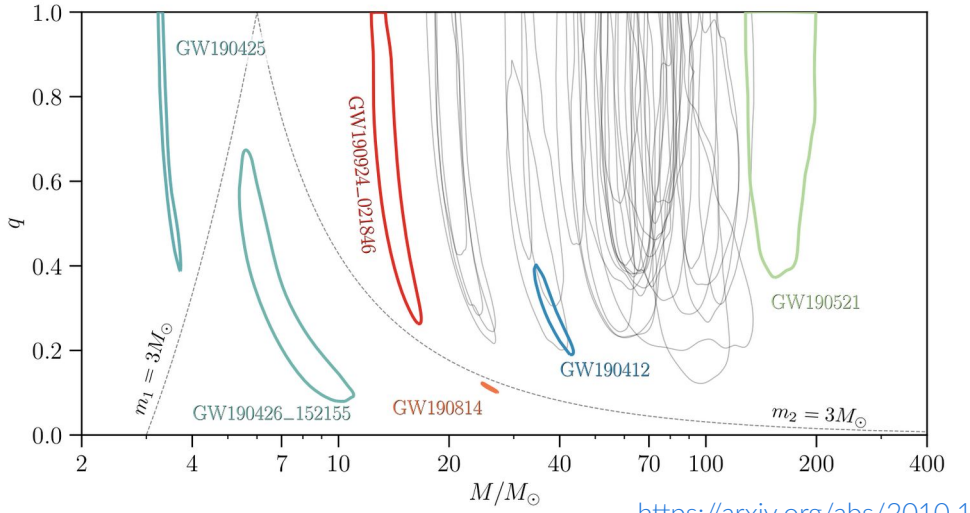
Formation in isolated binaries

Dynamical formation in dense environments (globular clusters or galactic nuclei)

Others ?

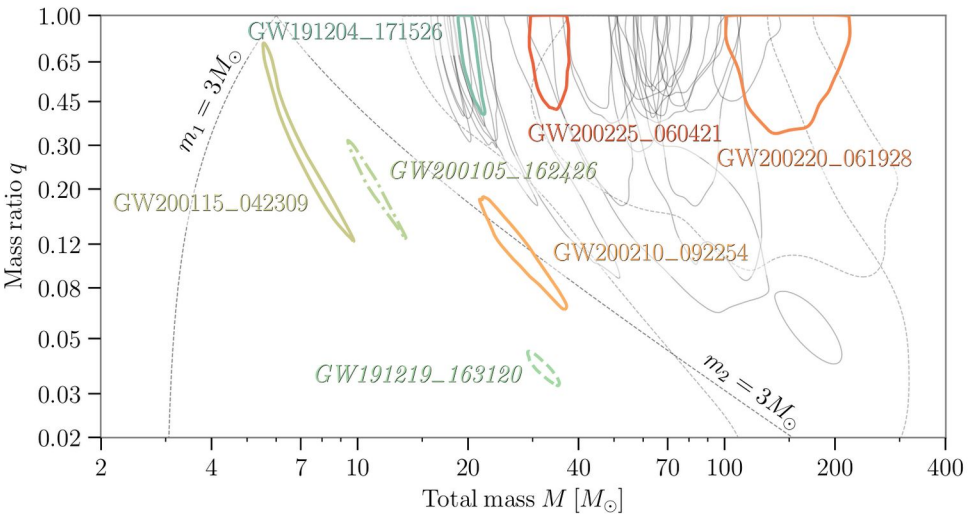
A mix of populations ?

GWTC-2



https://arxiv.org/abs/2010.14527

GWTC-3



http://arxiv.org/abs/2111.03606

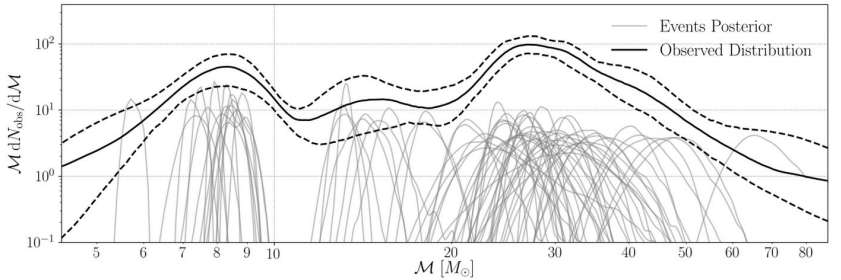
What did we detect?

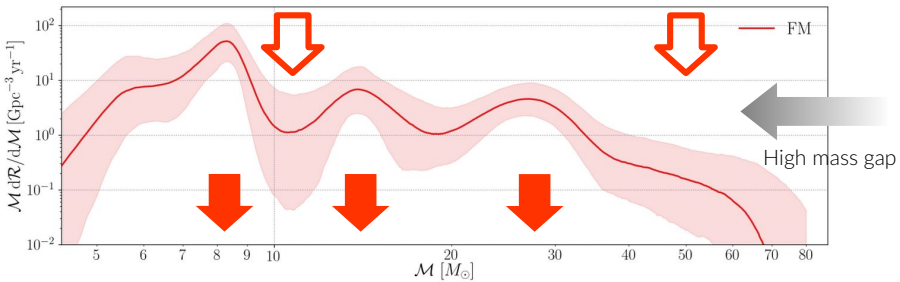
Clusters and deficiencies in the mass distribution

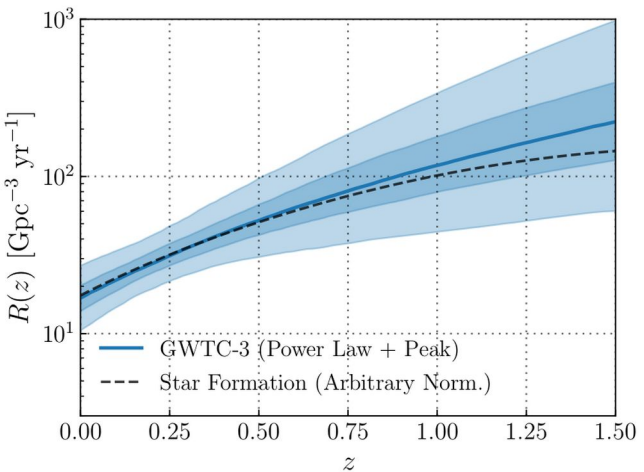
BBH merger rate at z = 0.2

17—45 $Gpc^{-3}\ yr^{-1}$

Increase with redshift z

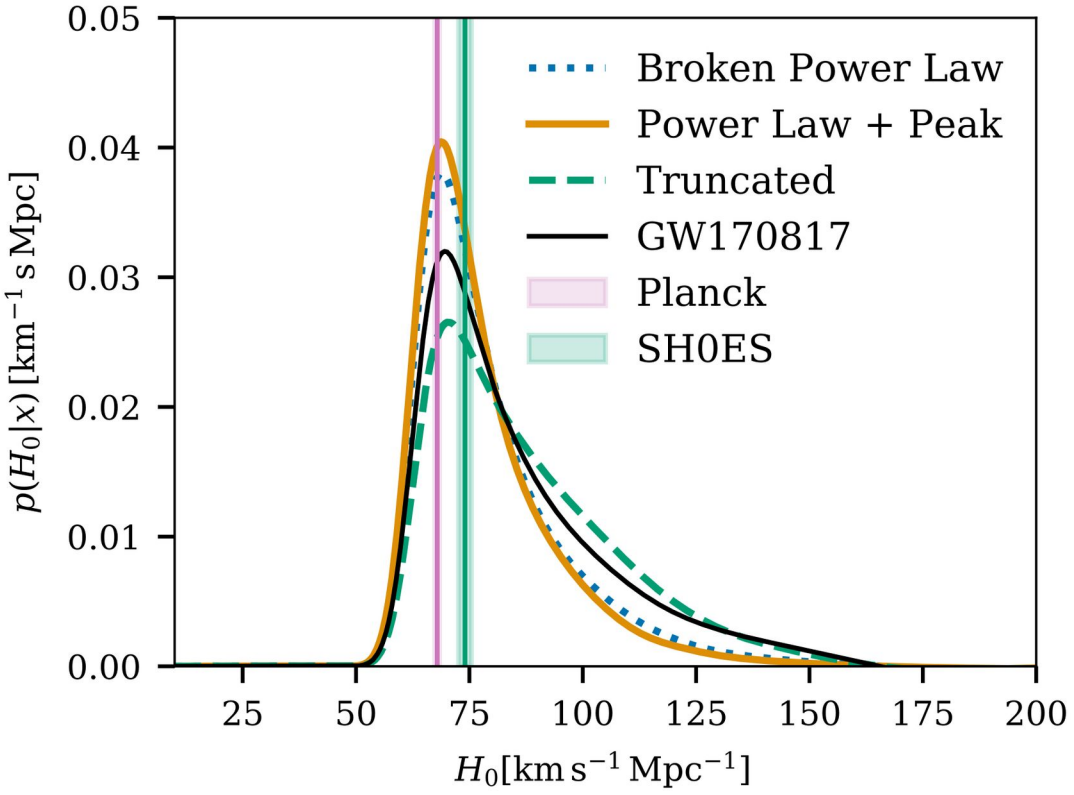






arXiv:2111.03606

Gravitational-wave cosmology



Bright sirens (GW170817)

Lumin. distance from GW data

Redshift from electromagnetic counterpart (or galaxy catalog)

→ Hubble constant

Dark sirens (BBH)

$$m^{(d)} = (1 + z)m^{(s)}$$

Joint fit of cosmological parameters and mass population models

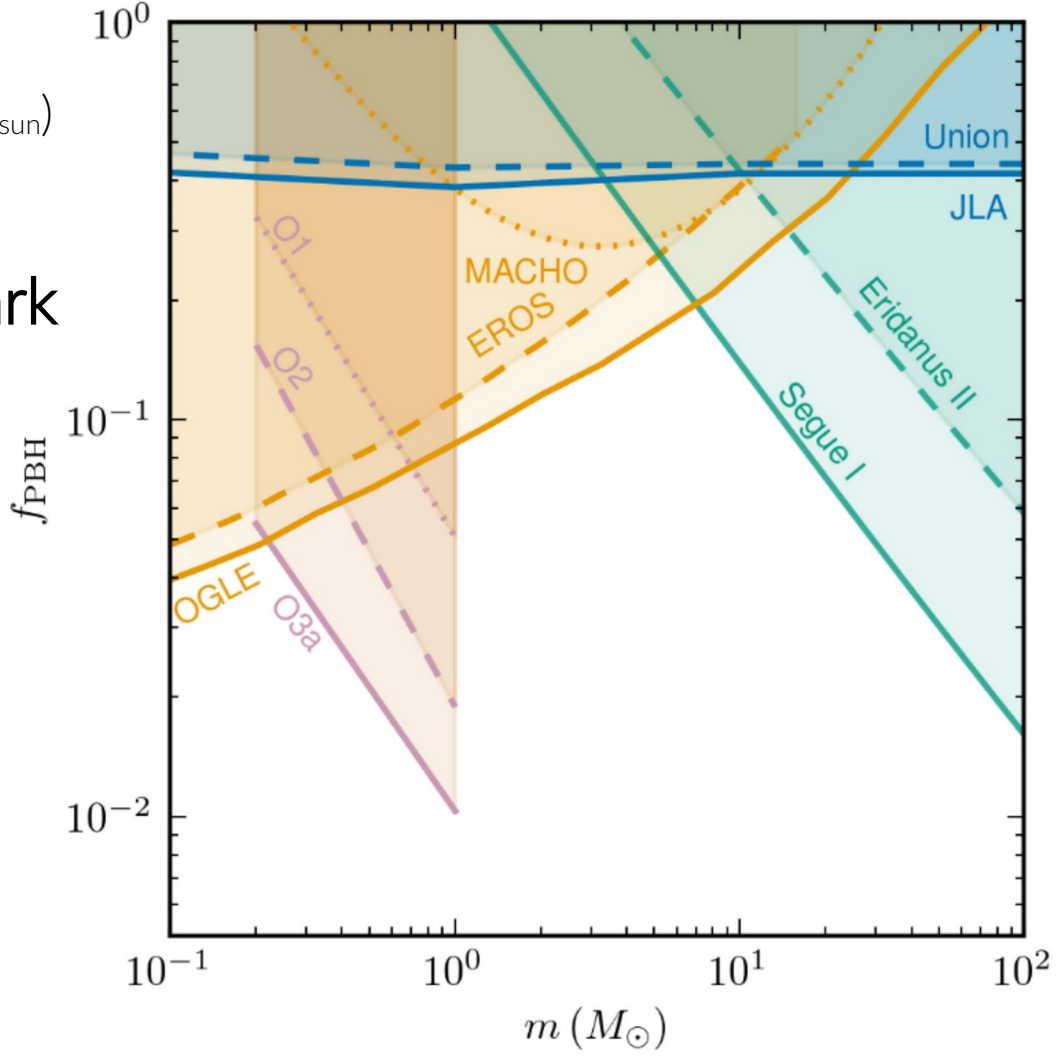
arXiv:2111.03604

What did we ***not*** detect?

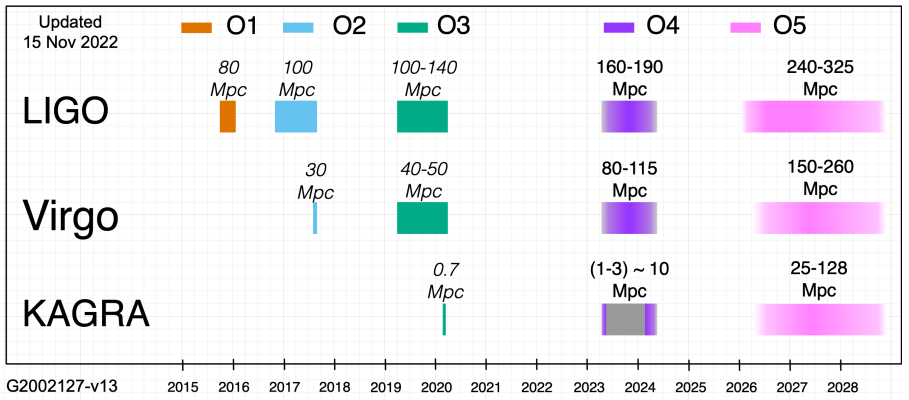
Search for sub-solar mass binaries (0.2–1M_{sun})

3 different pipelines → No detection

Constraints on the fraction of dark matter in primordial black holes



What's next? *"Avant le déluge"*



→ 2028 Prochaines campagnes

- O4 (2023) : 100aine de sources
- O5 (2026) : x 5 plus

~2030 Stratégie pour l'**après O5**

~2035 **3ème gén :** Einstein tel & Cosmic Explorer

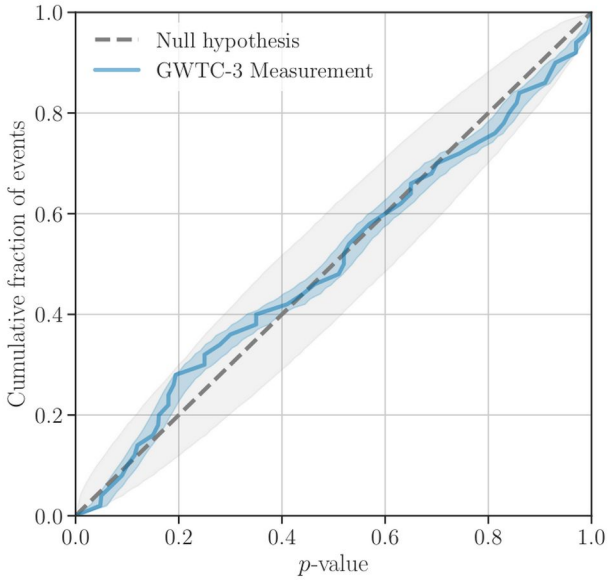
Cf David Shoemaker

https://observing.docs.ligo.org/plan/
arXiv:1304.0670

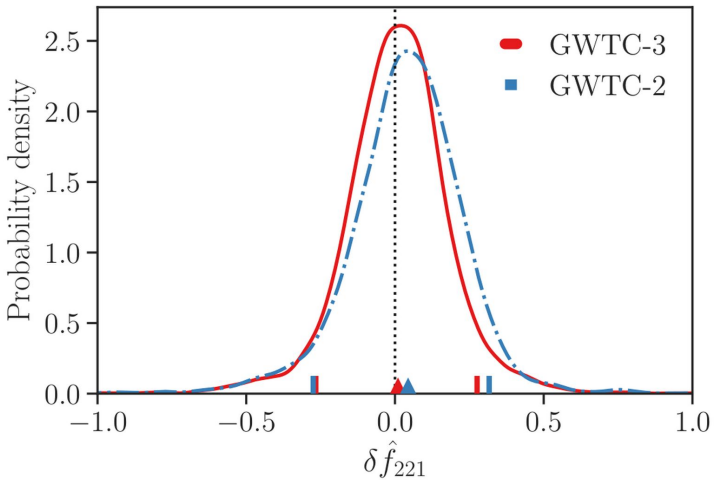
Conclusions

- Une nouvelle astronomie !
  - Une population de trous noirs jusqu'ici inconnue
  - Multimessager : fusion de deux étoiles à neutrons et contreparties
- Nombreuses implications en cascade
  - Physique nucléaire : équation d'état de la matière dense
  - Cosmologie : mesure de la constante de Hubble
  - Nucléosynthèse cosmique : abondances des éléments lourds
  - Gravité quantique ? Dimensions supplémentaires?
- Un futur prometteur
  - Une décennie d'observation à venir
  - Un riche programme scientifique
  - Les équipes lyonnaises très bien positionnées pour les 30 prochaines années !

24 nov 2022



LVK Collaboration, arXiv 2112.06861 [gr-qc]



Tests of General Relativity from GW

- Range of effects tested
  - Waveform consistency (residual)
  - Internal consistency of the waveform parts
  - GW generation (post-Newton)
  - GW propagation (dispersion)
  - Polarization
  - Remnant properties (ringdown, echoes)
- No statistically significant deviation observed