

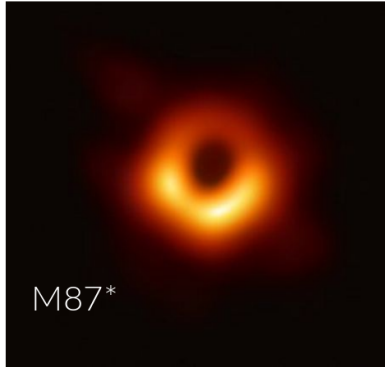
Gravitational wave astronomy today

Eric Chassande-Mottin

AstroParticule et Cosmologie (APC)
CNRS Université Paris Cité



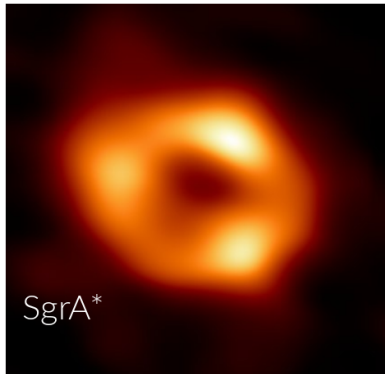
Prelude on black holes



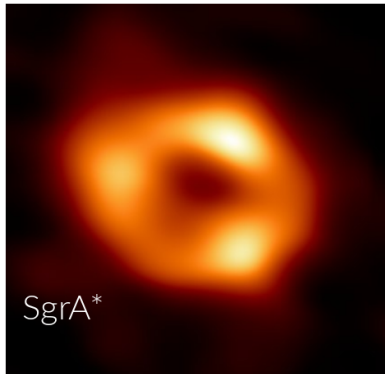
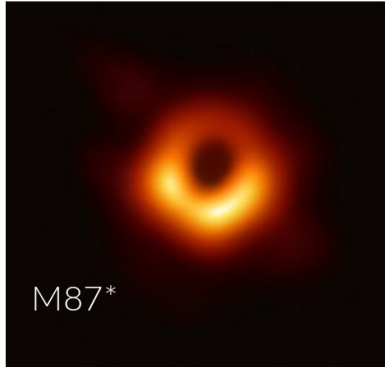
Event Horizon Telescope observes supermassive black holes

$M \sim 10^6 - 10^9 M_{\text{sun}}$

Thank you Shiro!



Prelude on black holes



Event Horizon Telescope observes supermassive black holes

$M \sim 10^6 - 10^9 M_{\text{sun}}$



Muse - Supermassive Black Hole [Link to Youtube](#)

Prelude on black holes

THÈMA
Cygnus X-1 – 21.2 M_{SUN}

LE VAMPIRE ET LA GÉANTE BLEUE

Cygnus X1, c'est la fin d'un couple stellaire : une supergéante bleue lentement dévorée par un trou noir, issu de l'effondrement d'une étoile massive. De leurs échanges, nous ne percevons que des bouffées de rayons X émis par la matière avant d'être avalée par l'astre compact.

LE TROU NOIR
Il n'a pas de surface, et dans un rayon infime, concentre l'équivalent de 15 masses solaires. C'est le vestige d'une étoile supergéante d'au moins 40 masses solaires qui, en quelques dizaines de millions d'années, a perdu beaucoup de masse, dont une partie a probablement été accrétée par l'étoile compagne.

PERTE DE MASSE
L'étoile perd de sa masse sous deux formes : du gaz et un vent de particules. Une quantité constante du premier passe vers le disque d'accrétion, tandis que le vent stellaire, qui souffle dans toutes les directions, est d'intensité variable.

DISQUE D'ACCRETION
Son diamètre est 10 à 15 fois celui du Soleil. Il est très fin et homogène, mais il est pas homogène. Le frottement des particules, qui engendrent des températures de 10 à 15 millions de degrés, est responsable de l'intense émission de rayons X.

COUPLE SERRÉ
La distance entre le trou noir et l'étoile compagne est faible : moins de 20 millions de kilomètres, soit la centième de la distance Terre-Soleil.

DEFORMATION
La puissance gravitationnelle du trou noir déforme l'étoile compagne, qui prend l'aspect d'un œuf dont le bout pointu est dirigé vers le trou noir.

LE TROU NOIR
Toute la matière n'est pas absorbée par le trou noir : 10 % sont expulsés sous forme de jets. Les particules légères (surtout des électrons) sont des lignes de champ magnétique et sont propulsées dans l'espace à une vitesse proche de celle de la lumière.

DISQUE D'ACCRETION
La partie externe du disque est plus froide et tourne plus lentement que son centre.

LIMITES
C'est la dernière orbite stable, celle où la matière tourne encore très régulièrement avant d'approcher l'horizon des événements.

HORIZON DES ÉVÉNEMENTS
C'est le bord du trou noir, là où la matière tombe en chute libre et disparaît dans le trou noir. Il tourne très vite sur lui-même : 800 tours par seconde ! Son rayon est de 50 km.

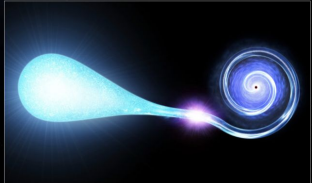
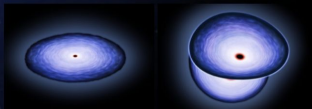
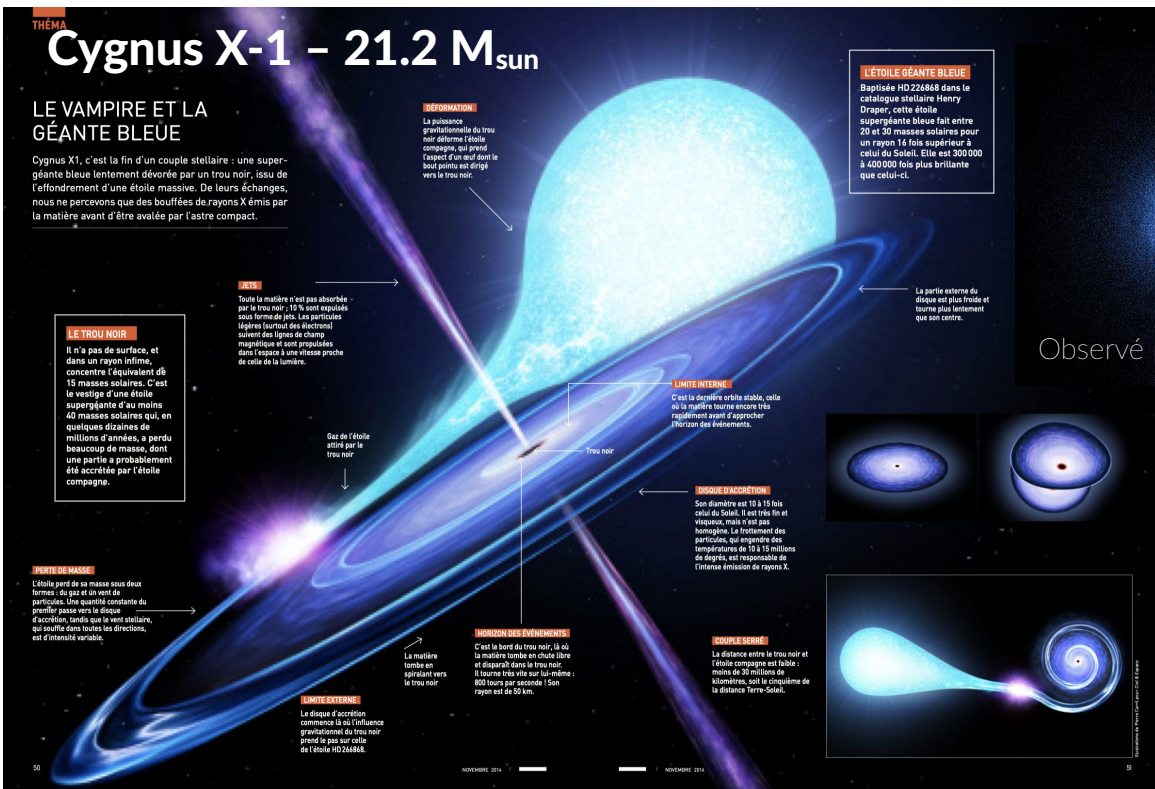
LIMITES
Le disque d'accrétion commence là où l'influence gravitationnelle du trou noir prend le pas sur celle de l'étoile HD 226868.

L'ÉTOILE GÉANTE BLEUE
Baptisée HD 226868 dans le catalogue stellaire Henry Draper, cette étoile supergéante bleue fait entre 20 et 30 masses solaires pour un rayon 16 fois supérieur à celui du Soleil. Elle est 200 000 à 400 000 fois plus brillante que celui-ci.

Gaz de l'étoile attiré par le trou noir

Trou noir

Observé par Chandra



Prelude on black holes

Gaia BH 3 – 32.7 M_{sun}

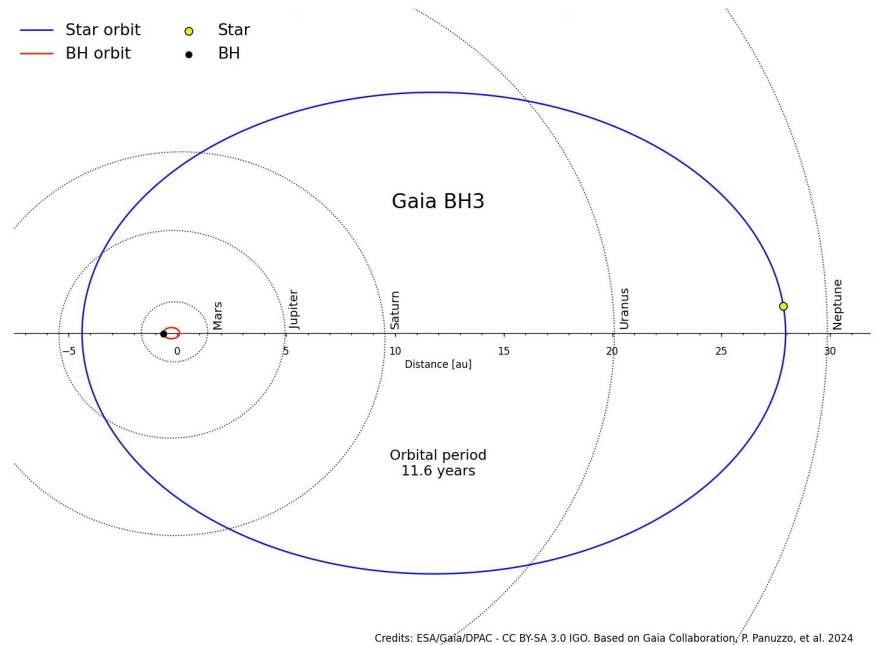
Astronomy & Astrophysics manuscript no. main
April 22, 2024

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LETTER TO THE EDITOR

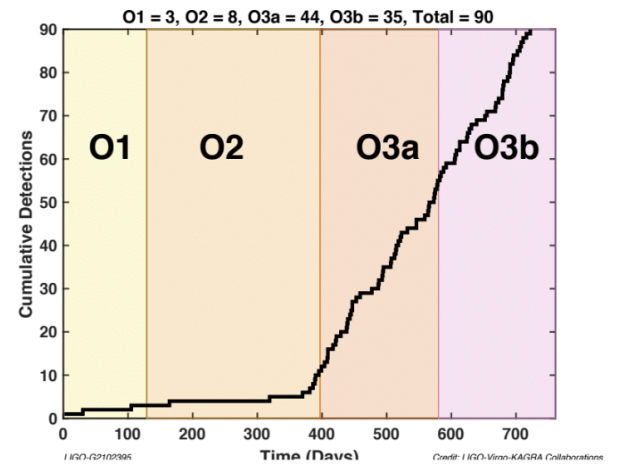
Discovery of a dormant 33 solar-mass black hole in pre-release Gaia astrometry[★]

Gaia Collaboration: P. Panuzzo^{1,*,} T. Mazeh^{2,} F. Arenou^{3,} B. Holl^{4,5,6,} E. Caffau^{7,} A. Jorissen^{8,} C. Babusiaux^{9,} P. Gavras^{10,} J. Sahlmann^{11,} U. Bastian^{12,} L. Wyrzykowski^{13,} L. Eyer^{14,} N. Leclerc^{15,} N. Bauchet^{16,} A. Bombrun^{17,} N. Mowlavi^{18,} G.M. Seabroke^{19,} D. Teysier^{20,} E. Balbinot^{21,22,} A. Helmi^{23,} A.G.A. Brown^{24,} A. Vallenari^{25,} T. Prusti^{26,} J.H.J. de Bruijne^{27,} A. Barbier^{28,} M. Biermann^{29,} O.L. Creevey^{30,} C. Ducourant^{31,} D.W. Evans^{32,} R. Guerra^{33,} A. Hutton^{34,} C. Jordi^{35,36,} S.A. Klioner^{37,} U. Lammers^{38,} L. Lindegren^{39,} X. Lur^{40,41,42,} F. Mignard^{43,} C. Nicolas^{44,} S. Randich^{45,} P. Sartoretti^{46,} R. Smiljanic^{47,} P. Tanga^{48,} N.A. Walton^{49,} C. Aerts^{50,51,52,} C.A.L. Bailer-Jones^{53,} M. Cropper^{54,} R. Drimmel^{55,} F. Jansen^{56,} D. Katz^{57,} M.G. Lattanzi^{58,59,} C. Soubiran^{60,} F. Thévenin^{61,} F. van Leeuwen^{62,} R. Andrae^{63,} M. Aillard^{64,} J. Bakker^{65,} R. Blomme^{66,} J. Castañeda^{67,68,69,} F. De Angeli^{70,} C. Fabricius^{71,72,73,} M. Fouesneau^{74,} Y. Frémat^{75,} L. Galluccio^{76,} A. Guerrier^{77,} U. Heiter^{78,} E. Masana^{79,80,81,} R. Messineo^{82,} K. Nienartowicz^{83,84,} F. Pailler^{85,} F. Riegle^{86,} W. Roux^{87,} R. Sordo^{88,} G. Gracia-Abri^{89,} J. Portell^{90,91,92,} M. Altmann^{93,94,} K. Benson^{95,} J. Berthier^{96,} P.W. Burgess^{97,} D. Busonero^{98,} G. Busso^{99,} C. Cacciari^{100,} H. Cánovas^{101,} J.M. Carrasco^{102,103,104,} B. Carry^{105,} A. Cellino^{106,} N. Cheek^{107,} G. Clementini^{108,} Y. Damerdjij^{109,110,} M. Davidson^{111,} P. de Teodoro^{112,} L. Delchambre^{113,}



19 Apr 2024

<https://arxiv.org/abs/2404.10486>



2015

2016

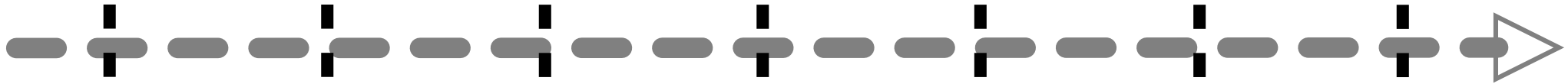
2017

2018

2019

2020

2021



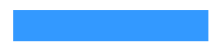
LIGO



O1

3 detections

GW150914



O2

8 detections
GWTC-1

GW170817



Virgo

LIGO & Virgo



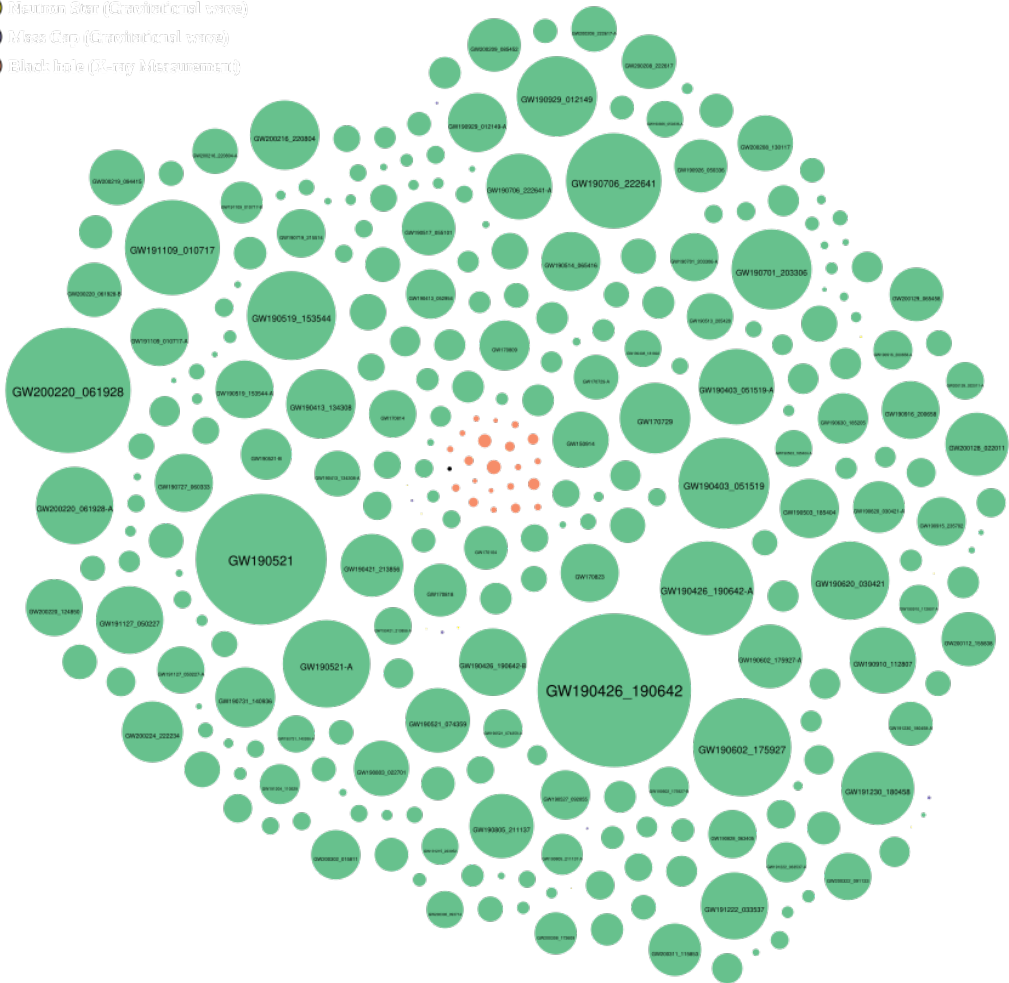
O3

O3a
39 detections
GWTC-2

44 detections
GWTC-2.1

O3b
35 detections
GWTC-3

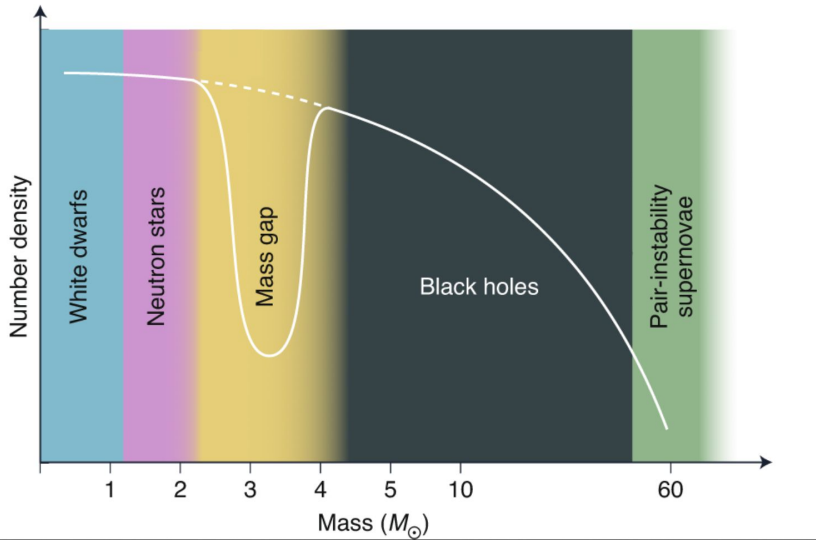
- Black hole (Gravitational wave)
- Neutron Star (Gravitational wave)
- Mass Gap (Gravitational wave)
- Black hole (Binary Measurement)



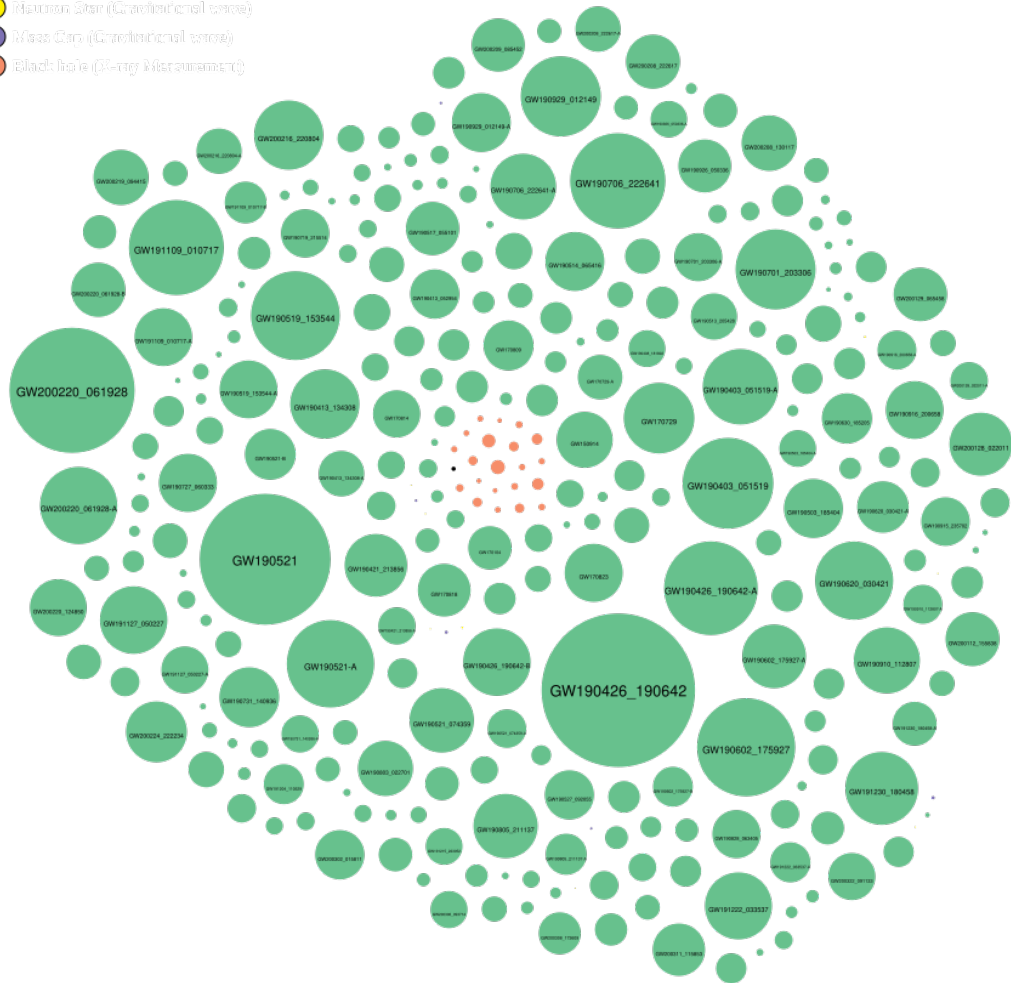
How abundant are stellar mass black holes in the Universe?

How their mass is distributed?

How do black holes form?



- Black Hole (Gravitational wave)
- Neutron Star (Gravitational wave)
- Mass Gap (Gravitational wave)
- Black Hole (Binary Misplacement)

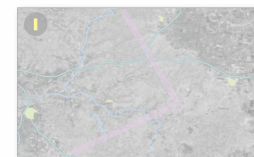
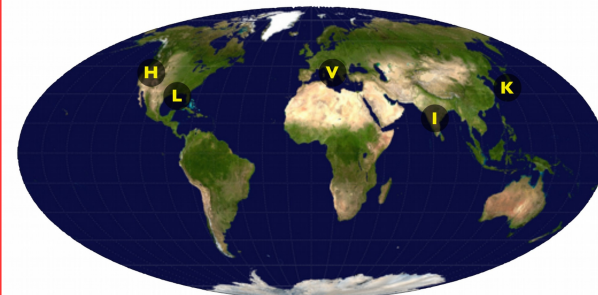
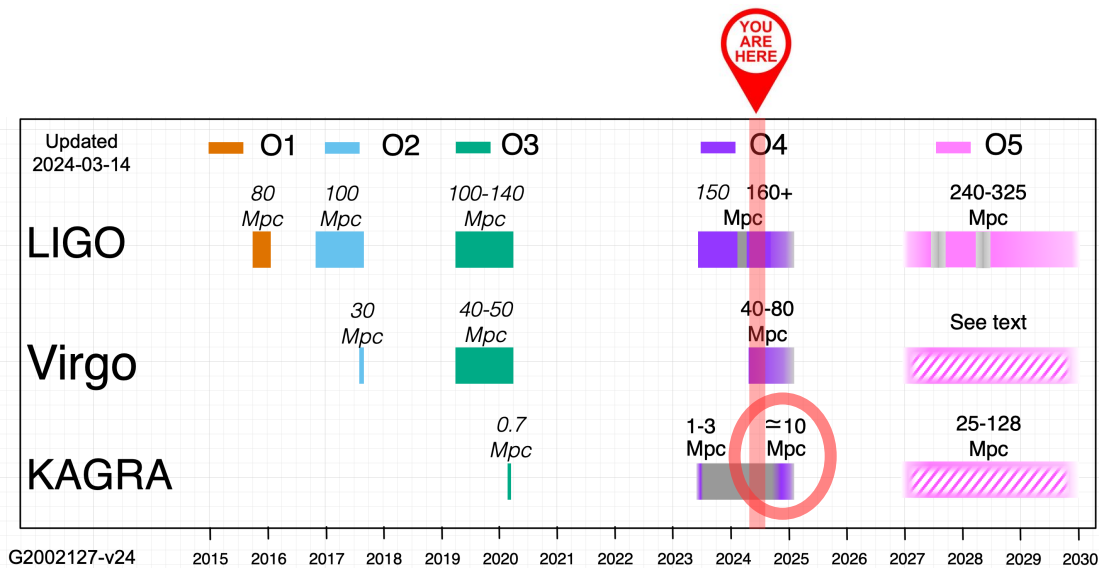


Muse - Starlight [Link to Youtube](#)

Chorus

*“Our hopes and expectations
Black holes and revelations”*

Science run O4

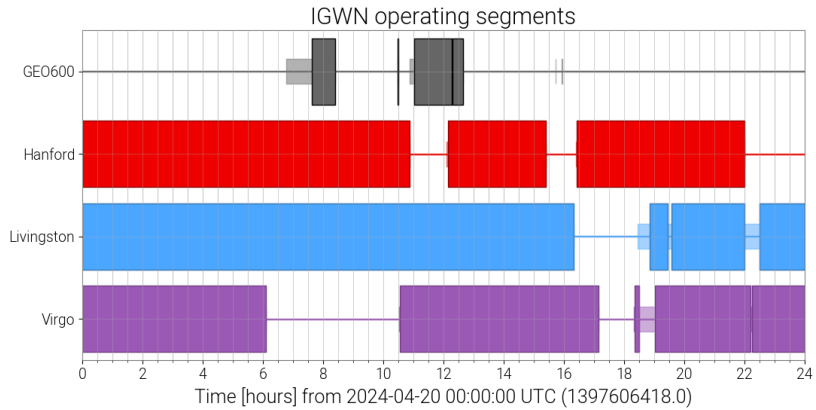


Update:

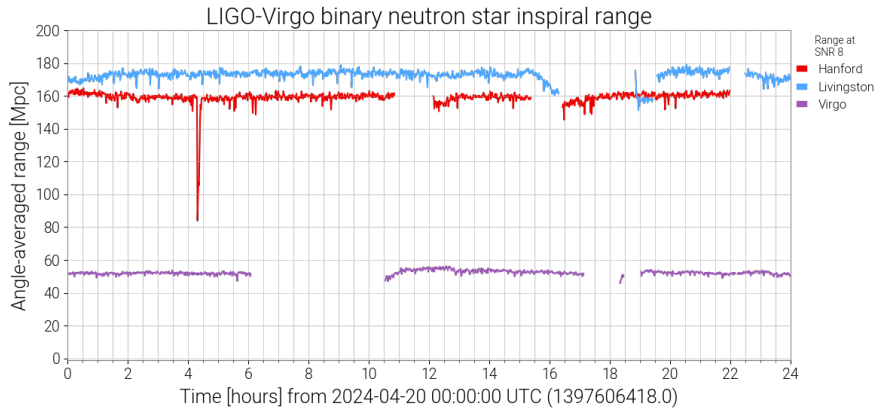
O4b will end on Jun 9 2025

O5 expected to start in Jun 2027

https://gwosc.org/detector_status



Good duty cycle > 80 %



Stable range ~ 55 Mpc

<https://gracedb.ligo.org>

GraceDB Public Alerts ▾ Latest Search Documentation Login

Please log in to view full database contents.

Latest as of 22 April 2024 14:41:20 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:

Tap on entry for detailed information

UID	Labels	FAR (Hz)	Created ▾
S240422bw	DQOK LOW_SIGNIF_LOCKED EM_READY EMBRIGHT_READY PASTRO_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT	1.596e-05	2024-04-22 10:46:20 UTC
S240422bn	DQOK LOW_SIGNIF_LOCKED EM_READY PASTRO_READY EMBRIGHT_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT	9.766e-06	2024-04-22 09:18:05 UTC
S240421ei	EM_COINC EM_READY LOW_SIGNIF_PRELIM_SENT LOW_SIGNIF_LOCKED PASTRO_READY EMBRIGHT_READY DQOK SKYMAP_READY	3.800e-06	2024-04-21 23:53:05 UTC

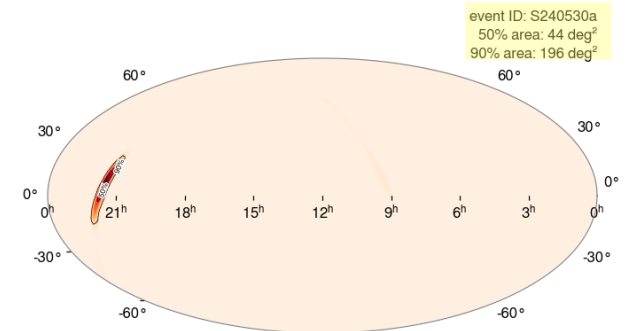
First preliminary alert with 20 to 60 sec latency

Significant detection candidates : 105
→ 3 significant alerts/week of operation

Low Significance Detection Candidates: ~2000

O4b: Virgo data used for localization

Example : SNR > 2.5 for V1



<https://gracedb.ligo.org/superevents/S240530a/view/>

<https://gracedb.ligo.org>

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Please log in to view full database contents.

Latest as of 22 April 2024 14:41:20 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:

Tap on entry for detailed information

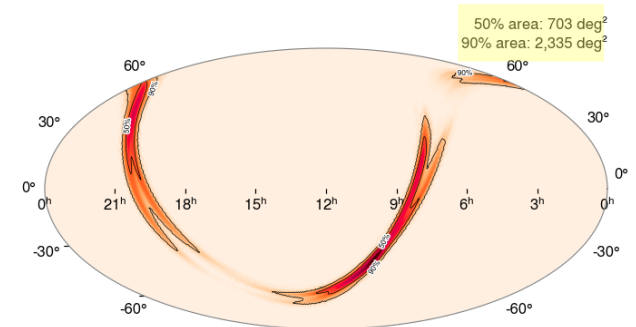
UID	Labels	FAR (Hz)	Created
S240422bw	DQOK LOW_SIGNIF_LOCKED EM_READY EMBRIGHT_READY PASTRO_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT	1.596e-05	2024-04-22 10:46:20 UTC
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S240421ei	EM_COINC EM_READY LOW_SIGNIF_PRELIM_SENT LOW_SIGNIF_LOCKED PASTRO_READY EMBRIGHT_READY DQOK SKYMAP_READY	3.800e-06	2024-04-21 23:53:05 UTC

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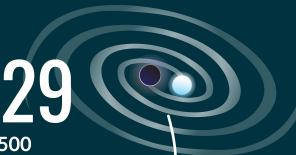
Low Significance Detection Candidates: ~2000

To be compared with an H1 L1 event



<https://gracedb.ligo.org/superevents/S231206ca/view/>

Get to know
GW230529
 Full name GW230529_181500



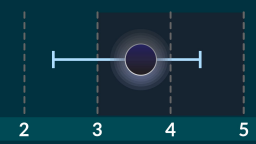
Discovered on 29 May 2023 at 18h15 UTC

most likely a merger between a Neutron Star & Black Hole (NSBH)

~1.4 M_{\odot} ~3.6 M_{\odot}

Most symmetric NSBH event so far more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

Primary object in lower mass gap further supports that this region is not empty



Mass (M_{\odot}) 2 3 4 5

~ 650 million light years away


Detectors

- Offline OR not operational
- Online BUT not used for analysis*
- Online AND used for analysis

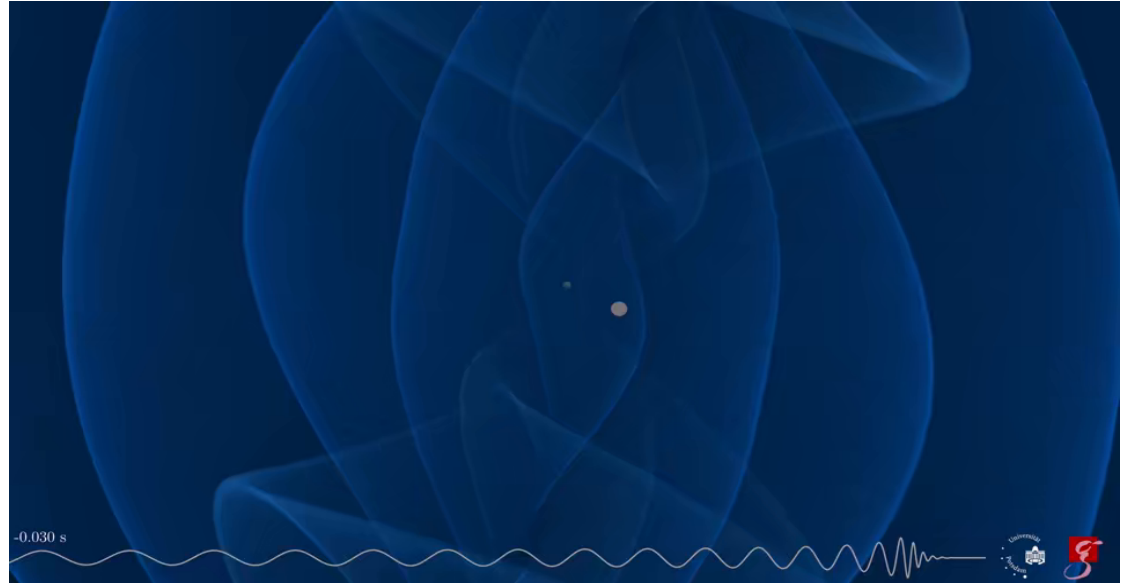
H L V K

* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

@astronerdika
 LVK COLLABORATION



GW230529



Credits: I. Markin (Potsdam University), T. Dietrich (Potsdam University and Max Planck Institute for Gravitational Physics), H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics)

Observatories: Swift Fermi HAWC IceCube AMON Integral GECAM FlaapLUC LVC Catalogs Other

📅 2024-04-07 📅 04-07 04-08 04-09 04-10 04-11 04-12 04-13 04-14 04-15 04-16 04-17 04-18 04-19 04-20 04-21 04-22 📅 2024-04-22

S240421ar
Gravitational wave

RA/Dec: 159.17°/49.70°
2024-04-21 05:29:35

retracted
Gravitational wave

RA/Dec: 270.26°/-29.14°
2024-04-20 04:22:45

S240413p
Gravitational wave

RA/Dec: 165.72°/11.64°
2024-04-13 02:20:19

S240421ar
Gravitational wave

Cone search

Custom cone search

name: S240421ar

RA [deg]: 159.17° Dec [deg]: 49.70°

RA: 10h36m40s Dec: 49d42m8.61s

classification: BBH: 0.41 / Noise: 0.59

Detailed info about selected source:

VoEvent: [XML](#) VoEvent: [JSON](#) History: [#0](#) [#1](#) [#2](#) [#3](#)

name: S240421ar

Detection time: 2024-04-21 05:29:35

RA [deg]: 159.17° Dec [deg]: 49.70°

RA: 10h36m40s Dec: 49d42m8.61s

classification: BBH: 0.41 / Noise: 0.59

The astrophysical event S240421ar was observed on April 21, 2024, at 05:29:35 UTC, by the Laser Interferometer Gravitational-Wave Observatory (LVC). Located at right ascension 159.17 degrees and declination 49.70 degrees, the source is positioned in the constellation Leo Minor. With a false alarm rate of approximately 1.14 per year, the event's significance is considered moderate. The observatory detected this event using the CWB pipeline, primarily from instrument readings H1 and L1.

Preliminary analysis indicates that this event is likely due to a binary black hole (BBH) system, with a confidence level of 41%. The probability of the event being a binary neutron star (BNS), neutron star-black hole (NSBH), or mass gap event is currently zero. The gravitational wave noise is estimated at 59%. The source has a low extinction of 0.016, suggesting relatively clear visibility. The event is situated at a comfortable sun distance of 106.41 degrees.

Learn more about GWs: [link](#)

Discuss this event in our forum: [🗨️](#)

External information:

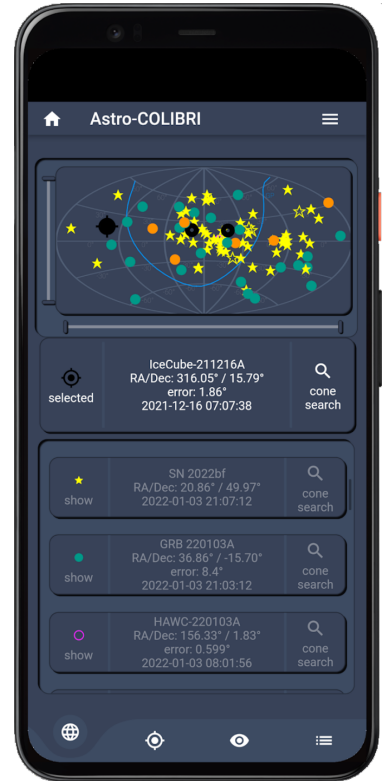
[GracDB](#) Information on the gravitational wave event

[TreasureMap](#) Follow-ups of GW events

[ALADIN](#) Displays event in an interactive sky atlas

[ESASky](#) Displays event in an interactive sky atlas

[TNS](#) Transients



Conclusions (1)

One more year of O4 till June 2025

- LIGO L1 = 180 Mpc, LIGO H1 = 160 Mpc, Virgo = 55 Mpc
- 200 more detector sources eventually ?
- Mostly BBH (but not only)
- Much better view of the BH mass distribution
- 4-detector data with LVK end of the year?
- First signs of precessing binaries (next slide)

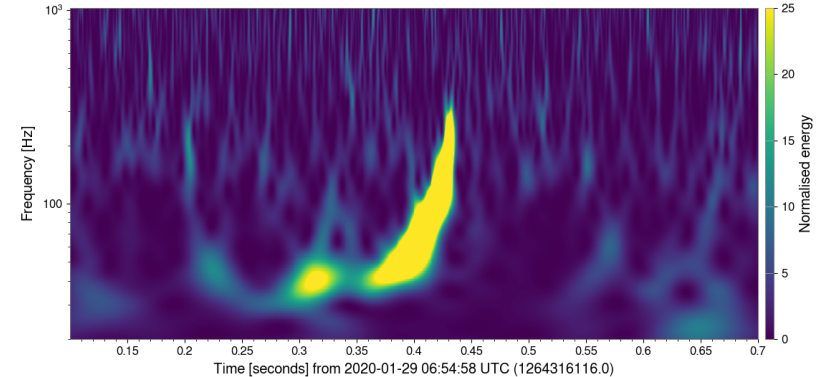
Conclusions (2)

Precession

GW200129 -- [link](#)

Hannam et al, General-relativistic precession in a black-hole binary, *Nature* 610 (2022) 7933, 652-655
<https://arxiv.org/abs/2112.11300>

“Here we report the measurement of strong-field precession in the LIGO–Virgo–Kagra gravitational-wave signal GW200129. The binary’s orbit **precesses at a rate ten orders of magnitude faster than previous weak-field measurements** from binary pulsars. We also find that the primary black hole is probably highly spinning.”



Primary mass, $m_1 (M_\odot)$	39^{+6}_{-7}
Secondary mass, $m_2 (M_\odot)$	22^{+8}_{-4}
Total mass, $M = m_1 + m_2 (M_\odot)$	62^{+3}_{-3}
Mass ratio, $q = m_2/m_1$	$0.6^{+0.4}_{-0.2}$
Primary spin, a_1/m_1	$0.9^{+0.1}_{-0.5}$
Primary spin tilt angle, θ_{LS_1} (rad)	$1.4^{+0.4}_{-0.5}$
Secondary spin, a_2/m_2	(undetermined)
Binary inclination, θ_{jN} (rad)	$0.5^{+0.3}_{-0.3}$
Luminosity distance, D_L (Mpc)	1000^{+200}_{-200}
Redshift, z	$0.21^{+0.03}_{-0.04}$

Table 1 Properties of the binary-black-hole source of GW200129. Source parameter measurements from our analysis of GW200129, with uncertainties at the 90% credible interval. The posterior distributions for both the secondary spin magnitude and tilt angle θ_{LS_2} are essentially flat, and for this reason we have indicated the secondary spin as “undetermined”. This is expected for a signal of GW200129’s strength, as explained in the main text. A naive application of our 90% credible-interval calculation gives $a_2/m_2 \in [0.05, 0.95]$ and $\cos(\theta_{LS_2}) \in [-0.93, 0.85]$, i.e., an arbitrary 90% stretch of the range of possible values.