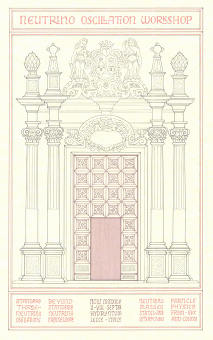
Gravitational Waves: Towards the Einstein Telescope



NOW 2024
Neutrino Oscillation Workshop

Otranto, 2024 Sep 05

Archisman Ghosh
Ghent University

for the **Einstein Telescope Collaboration**

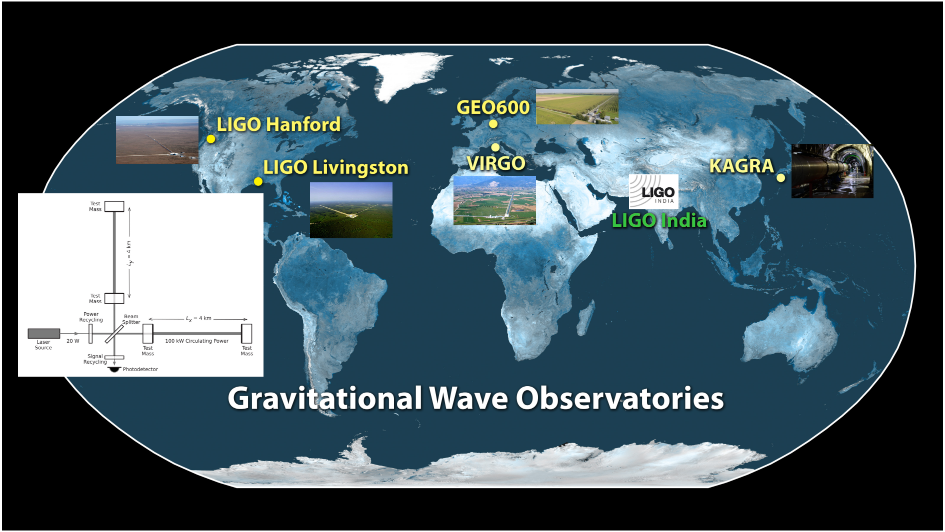
GHENT UNIVERSITY

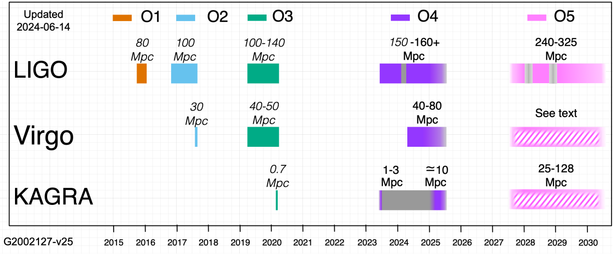
LIGO VIRGO KAGRA

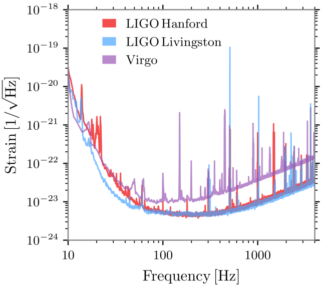
ET EINSTEIN TELESCOPE

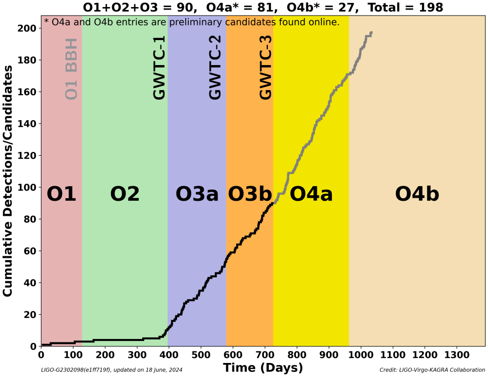
LIGO-Virgo-KAGRA basics

A global network of interferometric GW detectors



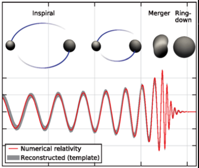




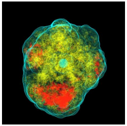


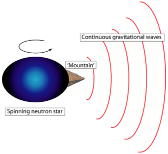
LVK: Abbott+ arXiv:2111.03606

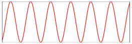
Gravitational-wave sources

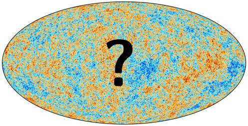


	Modelled	Unmodelled
Transient	Compact binary coalescences NS-NS, NS-BH, BBH	Bursts Supernova explosions
Persistent	Continuous waves Spinning deformed NS	Stochastic background Astrophysical + Cosmological





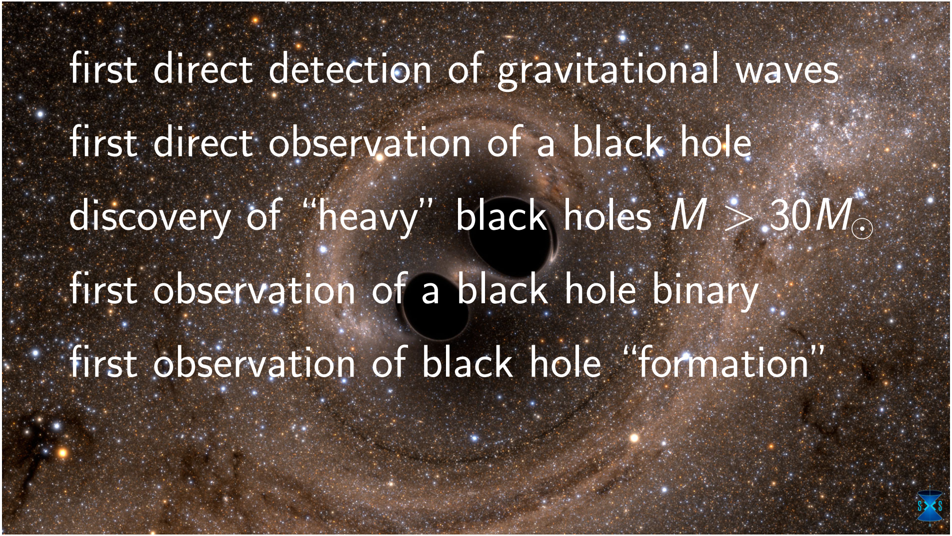




Current observational results

GW150914: the discovery of GWs

2017



first direct detection of gravitational waves

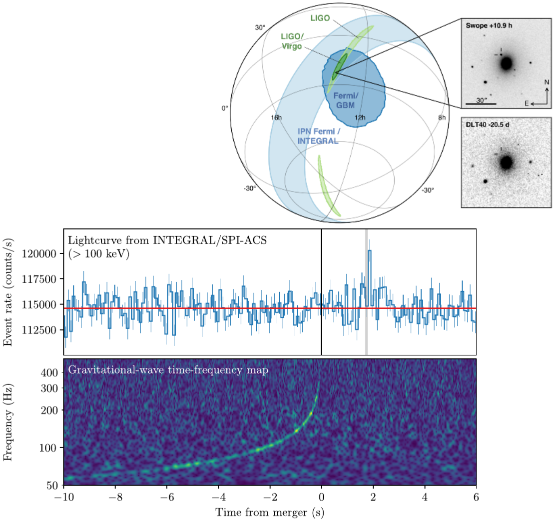
first direct observation of a black hole

discovery of "heavy" black holes $M > 30 M_\odot$

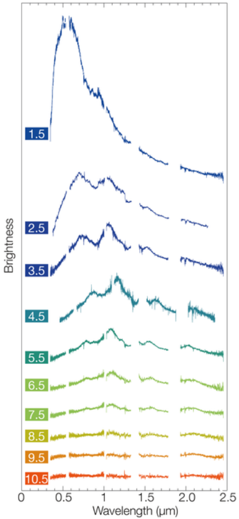
first observation of a black hole binary

first observation of black hole "formation"

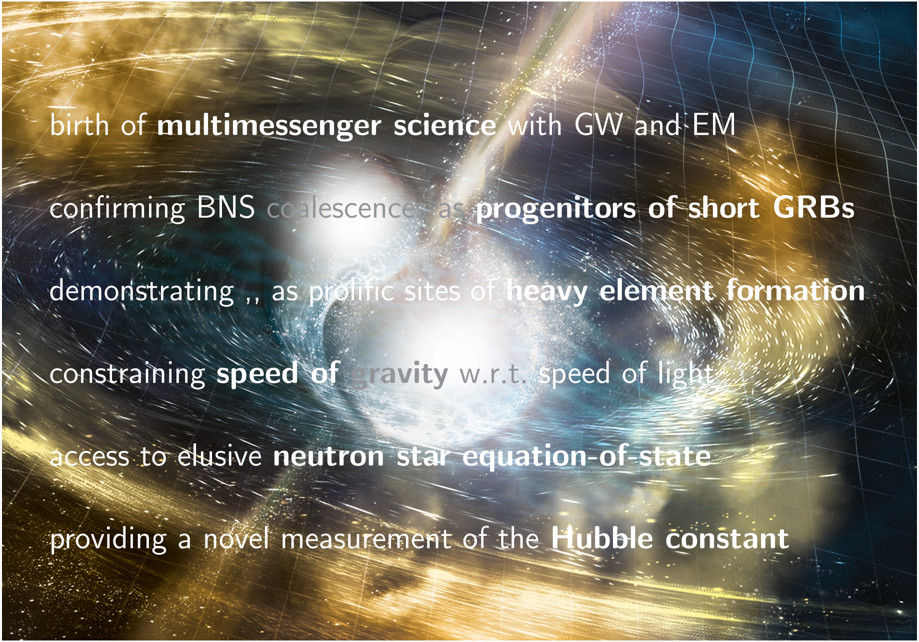
GW170817



Kilonova Pian+ 2017



LVC: Abbott+ Astrophys. J. **848** #2, L13 (2017)



birth of **multimessenger science** with GW and EM

confirming BNS coalescences as **progenitors of short GRBs**

demonstrating ,, as prolific sites of **heavy element formation**

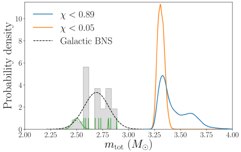
constraining **speed of gravity** w.r.t. speed of light

access to elusive **neutron star equation-of-state**

providing a novel measurement of the **Hubble constant**

O3a highlights

LVC: Abbott+ ApJL 892 #1, L3 (2020)

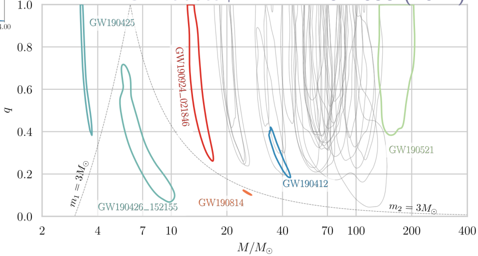


GW190425

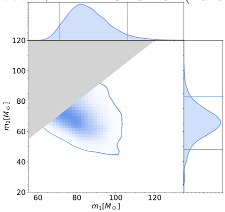
potential BNS

heavy, no counterpart

LVC: Abbott+ PRX **11** 021053 (2021)



LVC: Abbott+ PRL **125** 101102 (2020)



GW190521

$m_1 = 85^{+21}_{-14} M_\odot$

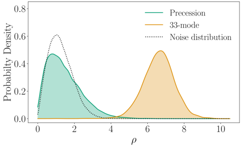
$m_2 = 66^{+17}_{-8} M_\odot$

$M = 142^{+28}_{-16} M_\odot$ (IMBH)

GW190814

lighter object in "mass gap" between NS and BH

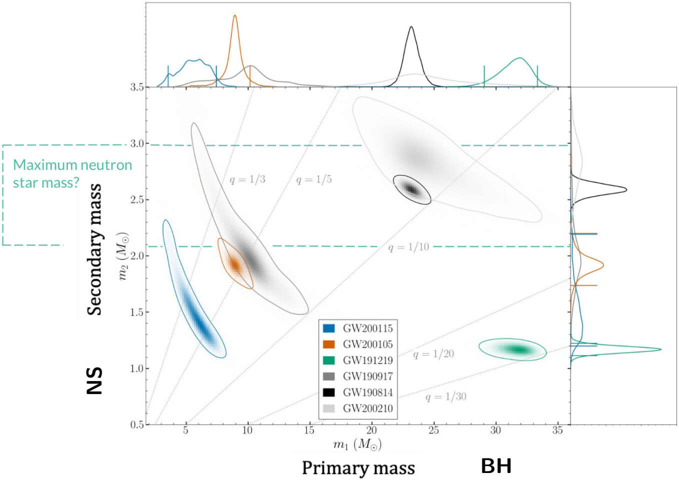
mass ratio > 9 | "higher harmonics" in GW signal



LVC: Abbott+ ApJL 896 #2, L44 (2020)

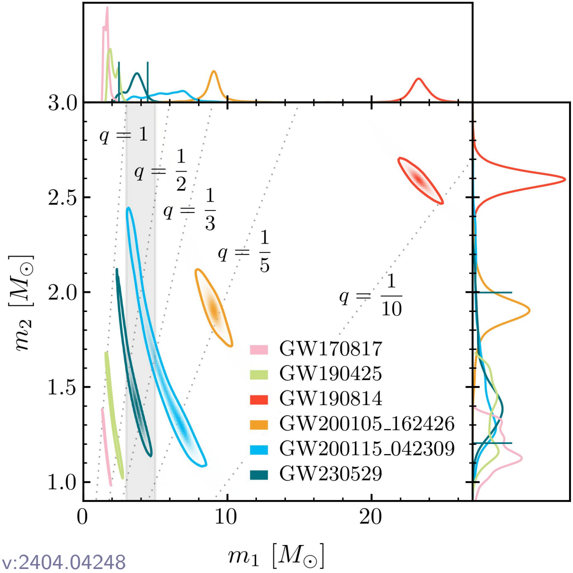
O3b highlights

neutron star – black hole mergers!

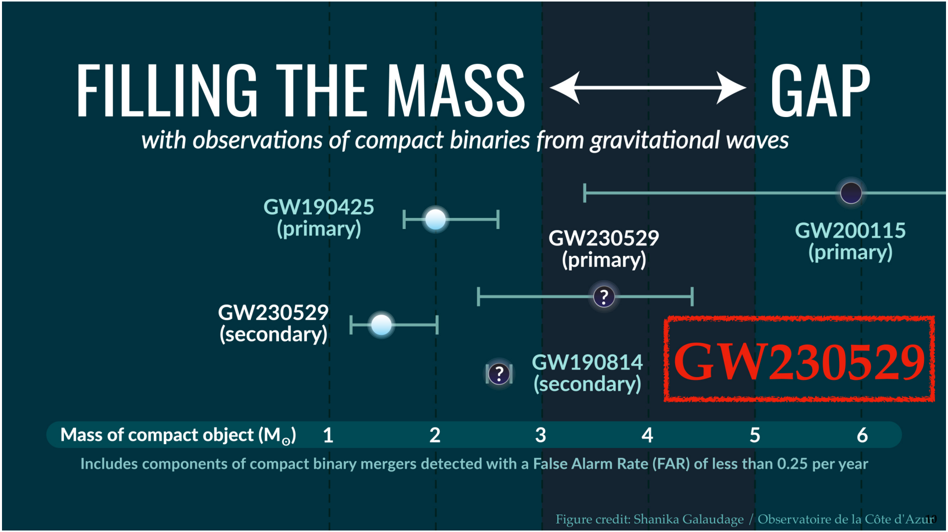


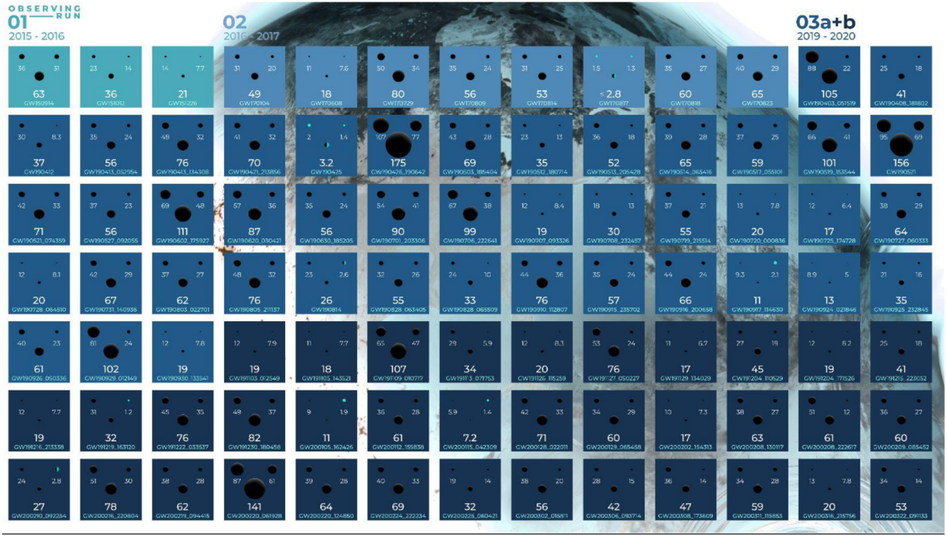
LVK: Abbott+ ApJL **915** #1 L5 (2021); LVK: Abbott+ arXiv:2111.03606; LIGO-G2102416

O4a: GW230529

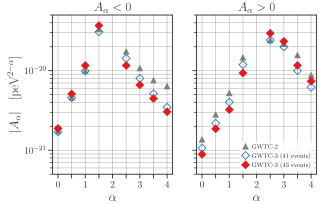


LVK: Abbott+ arXiv:2404.04248


FILLING THE MASS GAP
with observations of compact binaries from gravitational waves
GW190425 (primary)
GW200115 (primary)
GW230529 (primary)
GW230529 (secondary)
GW190814 (secondary)
GW230529
Mass of compact object (M⊙) 1 2 3 4 5 6
Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year
Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur
10


OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133

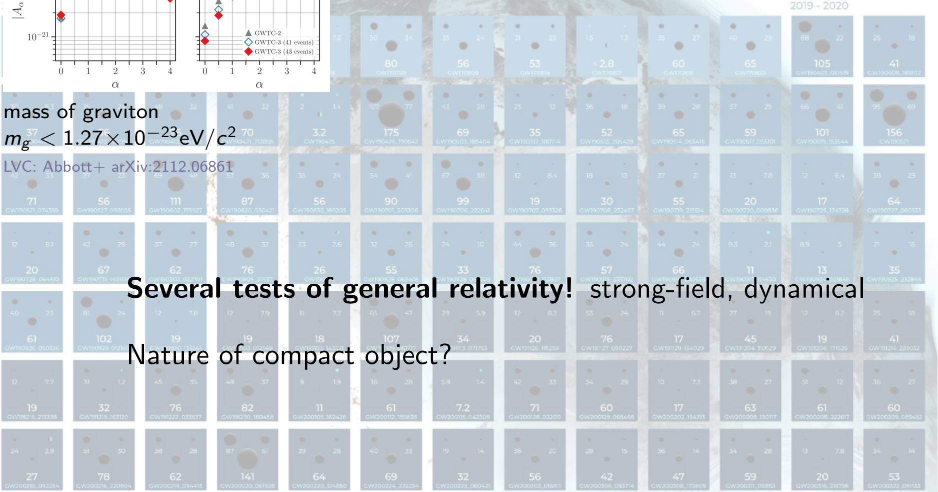
Fundamental physics



mass of graviton

$m_g < 1.27 \times 10^{-23} \mathrm{eV}/c^2$

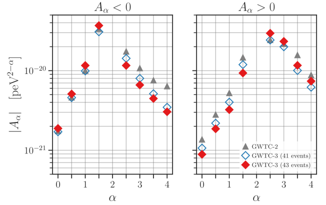
LVC: Abbott+ arXiv:2112.06861



Several tests of general relativity! strong-field, dynamical

Nature of compact object?

Fundamental physics



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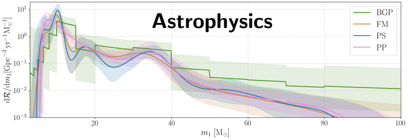
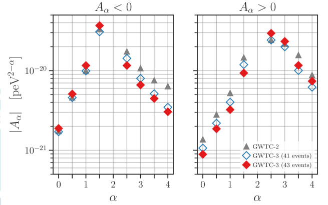


LVC: Abbott+ arXiv: 2111.03634

Fundamental physics



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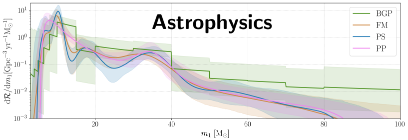
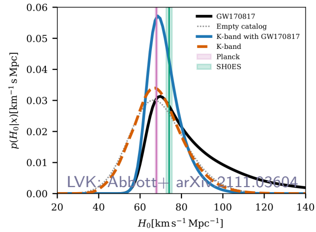
LVC: Abbott+ arXiv:2112.06861



LVC: Abbott+ arXiv: 2111.03634

Cosmology



LVK: Abbott+ arXiv:2111.03604

LETTER

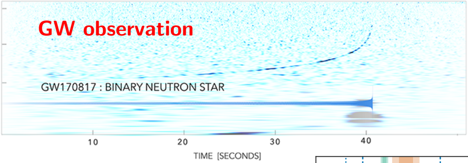
doi:10.1038/nature24471

A gravitational-wave standard siren measurement of the Hubble constant

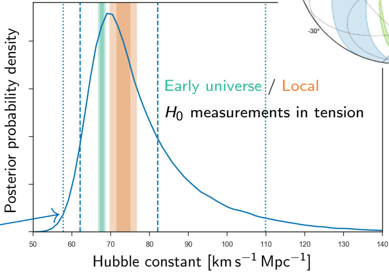
self-calibrated distance indicator

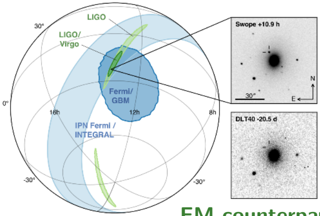
The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

GW observation



distance, d_L



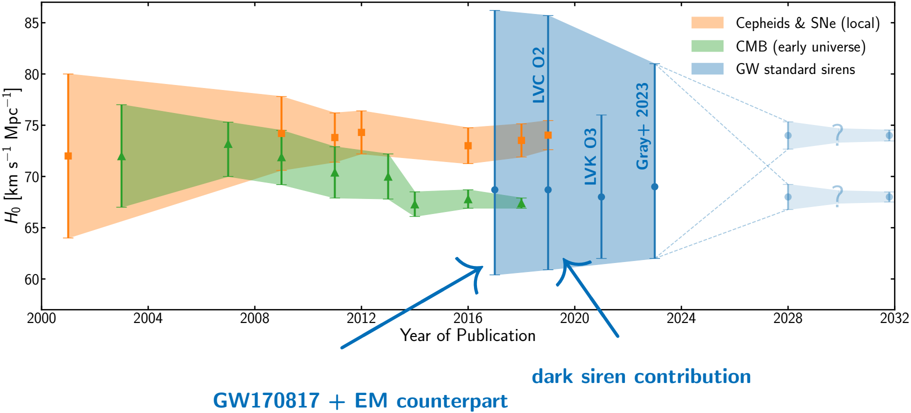


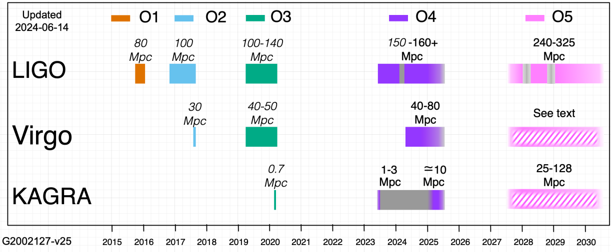
EM counterpart

redshift, z

First GW standard siren measurement of H_0

Gravitational-waves to resolve the H_0 tension?





O4a: 2023 May 24 – 2024 Jan 16
O4b: 2024 Apr 10 – 2025 Jun 09

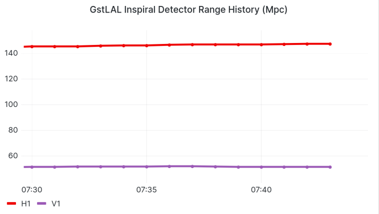
gwistat

Last 15 minutes · 5s

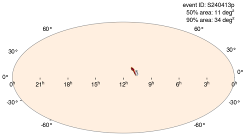
Gravitational Wave Detector Network

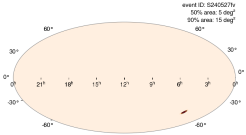
Operational Snapshot as of Sept. 5, 2024 05:44:39 UTC

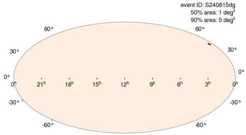
Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Low power	00:00	49
LIGO Hanford	Observing	00:32	25
LIGO Livingston	Calib not ready	03:35	58
Virgo	Observing	10:11	22
KAGRA	Down	>99:00	8



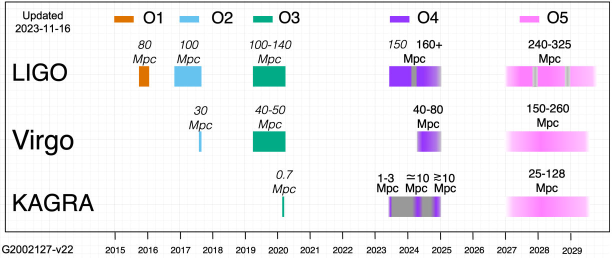
https://gracedb.ligo.org/: **124** significant detection candidates in O4

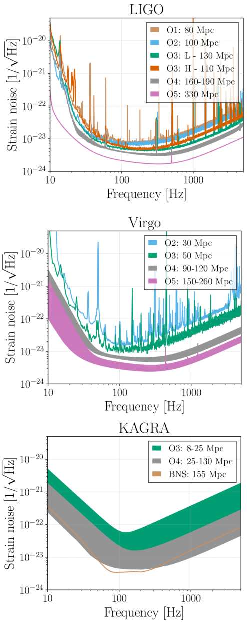






Towards 3G and the Einstein Telescope



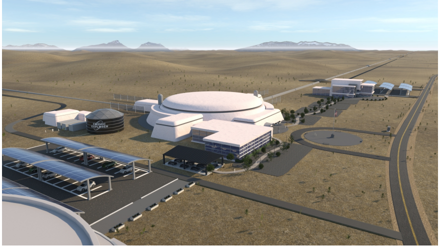


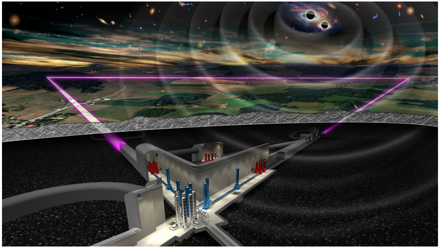
LIGO-P1200087

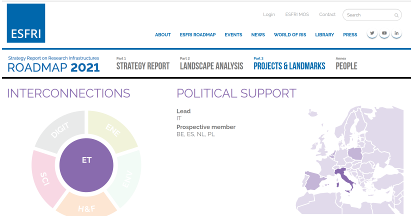
O5 / A+ ⟶ A$^\sharp$ / V_nEXT upgrades

Einstein Telescope, Cosmic Explorer, LISA

3G ground-based detectors: ET and CE

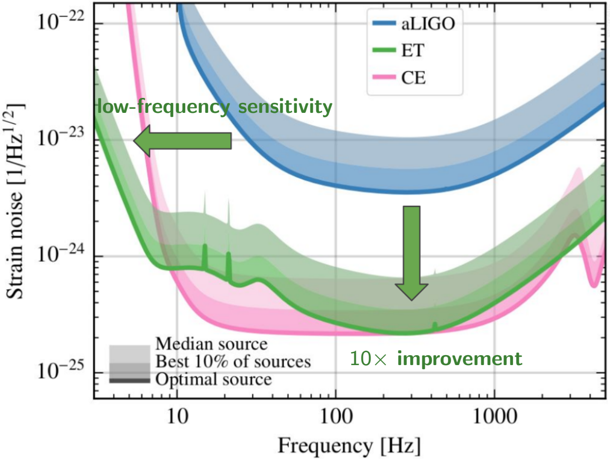






Sos-Enattos, Sardinia | Euregio Meuse-Rhine (EMR)

3G ground-based detectors: ET and CE



Particularly for ET:

longer arms ($\gtrsim 10\,\text{km}$)
underground
active subtraction
"xylophone" (HF-LF)
cryogenic
glass $\longrightarrow$ silicon
laser wavelength?
coating material?
quantum technology

Sos-Enattos, Sardinia | Euregio Meuse-Rhine (EMR)

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

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Mairi Sakellariadou,[6] Anuradha Samajdar,[21]
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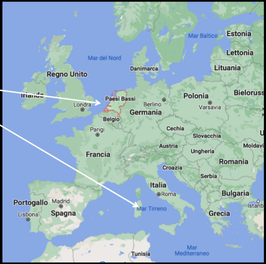
Andrei Utina,[16,17] Chris Van Den Broeck[16,26] and Teng Zhang[9,17]

JCAP07(2023)068

Two scenarios
- D of 10 km
- D of 15 km

Two scenarios
- 2L of 15 km
- 2L of 20 km



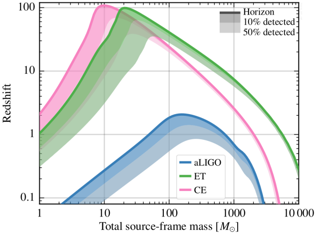
2L misaligned of 45°

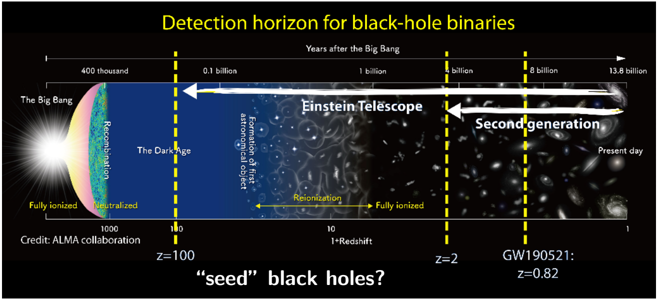
Branchesi, Maggiore et al. 2023,

Contents

3G ground-based detectors: ET and CE

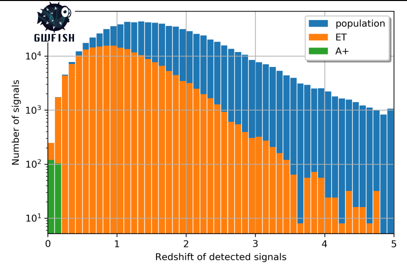
arXiv:1903.09260; courtesy: Evan Hall, Salvatore Vitale



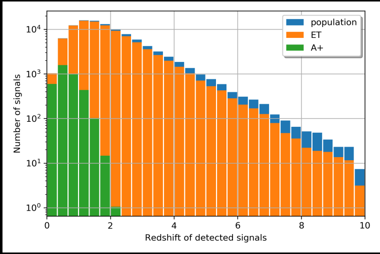


COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS



Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year

10^5 BBH detections per year

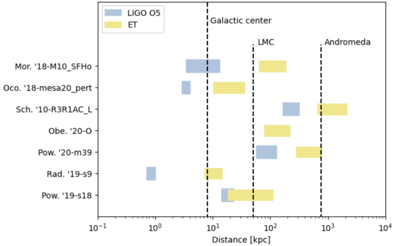
Other sources

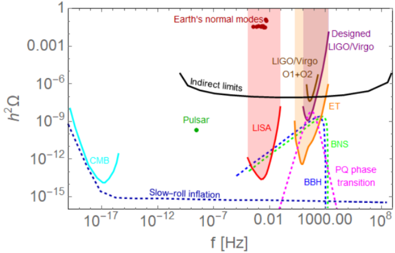
Supernovae?

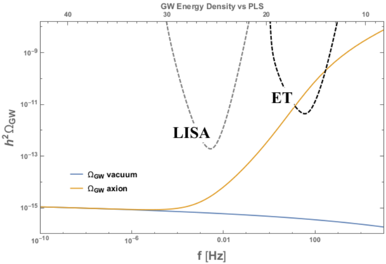
Isolated NS?

GW background?

Something exotic??







Data analysis challenges

- $\mathcal{O}(10^6)$ compact binary detections $\Rightarrow$ big data!

- Very long signals $\Rightarrow$ need new data analysis methods!

- Overlapping signals.

ET Collaboration

Site Characterization

electronic Infastructure

Waveforms

Common Tools

Stellar Collapse | NS

Data Analysis Platform

Nuclear Physics

Instrument Science

Observational Science

Fundamental Physics

Synergies w/ GW

Cosmology

Multimessenger Obs

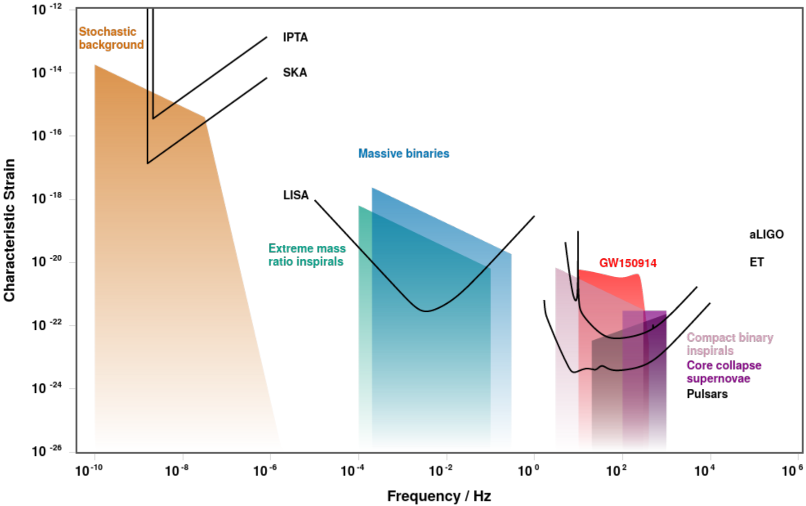
Population Studies

Forum on future EM and neutrino experiments?

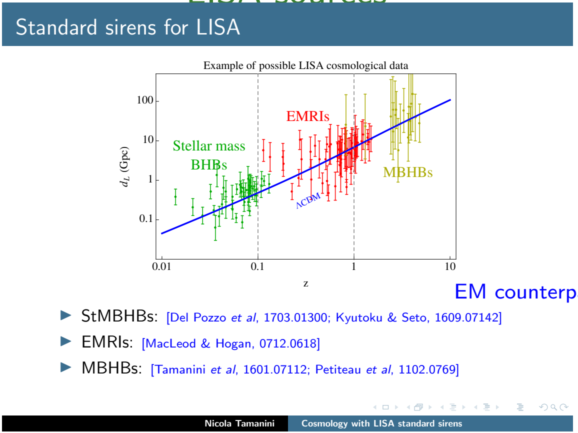
EXTRA SLIDES

GWs in other bands

Moore, Cole, & Berry, http://gwplotter.com/

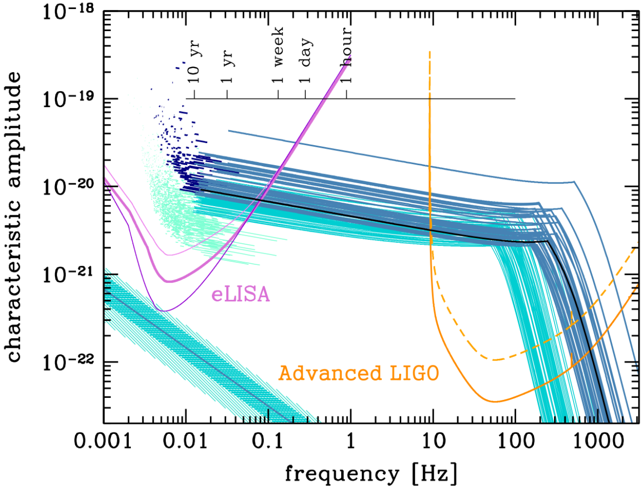


LISA sources



- **StMBHBs:** Del Pozzo *et al.* (2017); Kyutoku & Seto (2016)
- **EMRIs:** MacLeod & Hogan (2007)
- **MBHBs:** Tamanini *et al.* (2016); Petiteau *et al.* (2011)

Multiband GW astronomy



Sesana 2016