GW observations: from LVK towards the ET

Toulouse, 2025 Apr 07

Archisman Ghosh

Ghent University

GHENT UNIVERSITY

LIGO VIRGO KAGRA

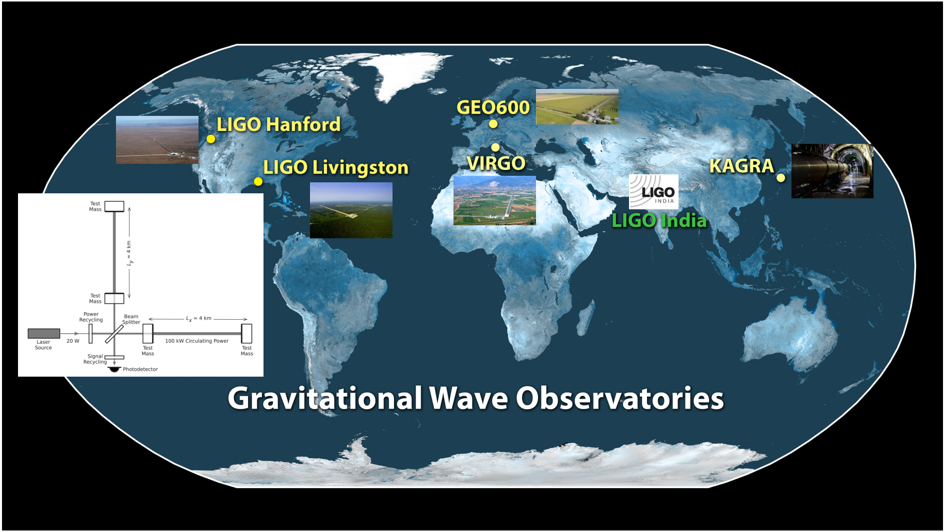
EINSTEIN TELESCOPE

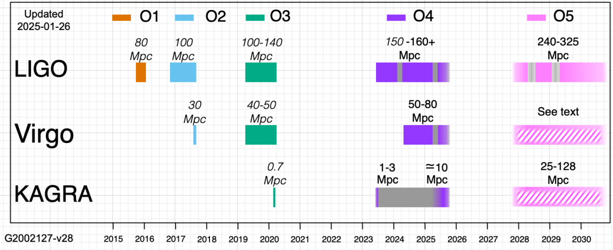
Plan of the talk

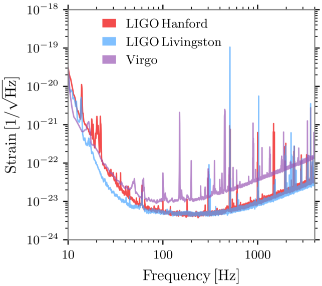
- LVK basics
- Current observational results
- Towards 3G and ET

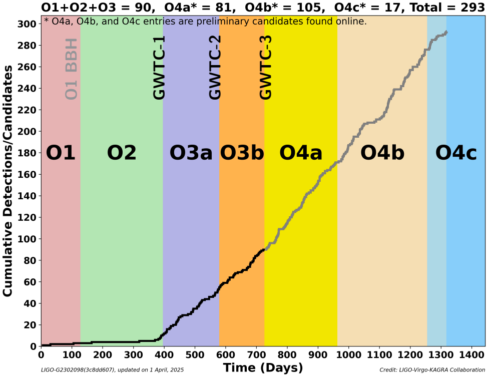
LIGO-Virgo-KAGRA basics

A global network of interferometric GW detectors



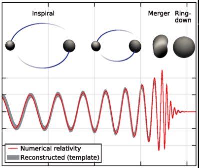




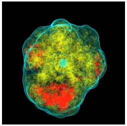


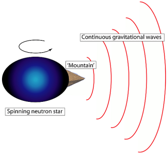
LVK: Abbott+ arXiv:2111.03606

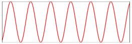
Gravitational-wave sources

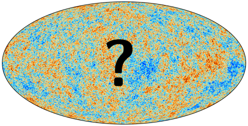


	Modelled	Unmodelled
Transient	Compact binary coalescences NS-NS, NS-BH, BBH	Bursts Supernova explosions
Persistent	Continuous waves Spinning deformed NS	Stochastic background Astrophysical + Cosmological

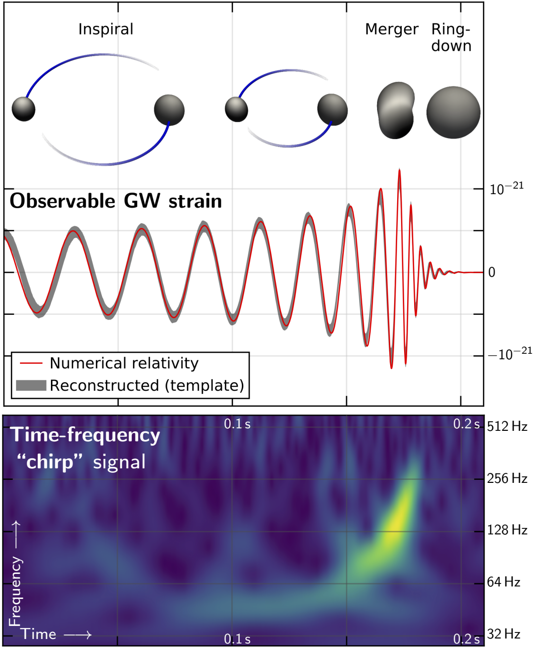




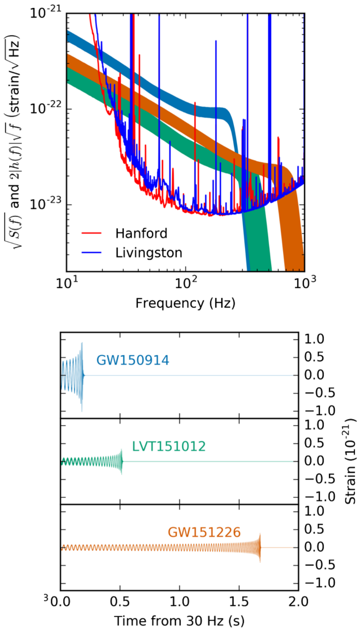




LVC: Abbott+, PRL **116**, 061102 (2016)



LVC: Abbott+, PRX **6**, 041015 (2016)



Data analysis workflow of CBCs

Searches

generate (real-time) triggers

Implications

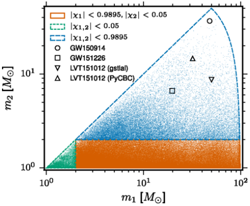
fundamental physics, astrophysics, cosmology

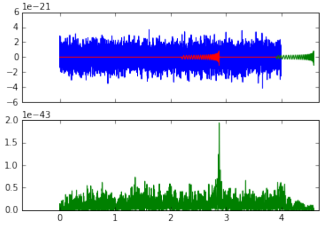
Parameter estimation

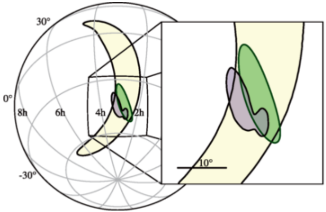
rigorous analysis of data around trigger

Low latency	High latency
quick	accurate
BayesSTAR	LALINFERENCE
RapidPE	BILBY

LVC: Abbott+, PRX **6**, 041015 (2016)



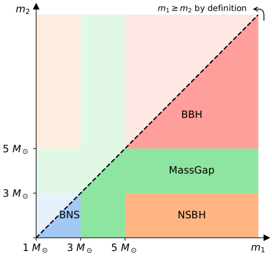




Signal-to-noise ratio

False alarm rate

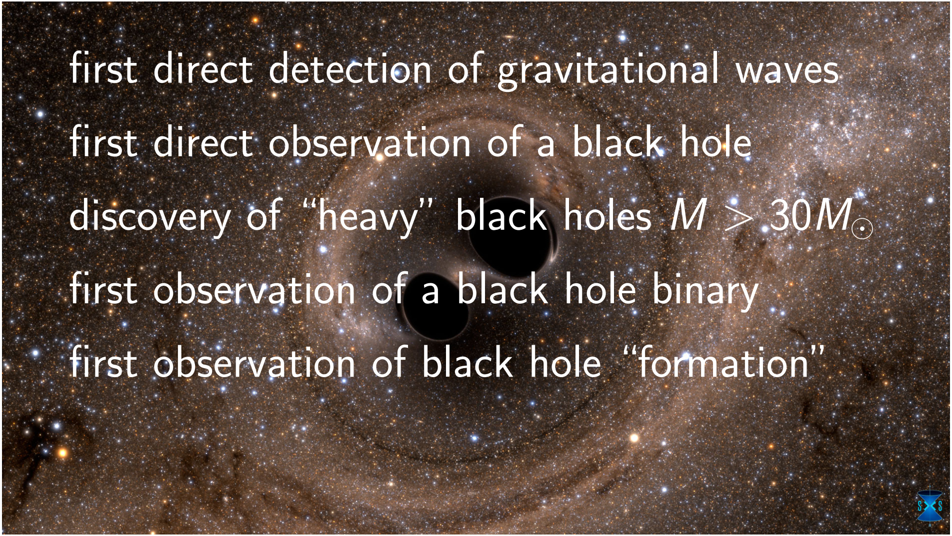
p-astro



Current observational results

GW150914: the discovery of GWs

2017



first direct detection of gravitational waves

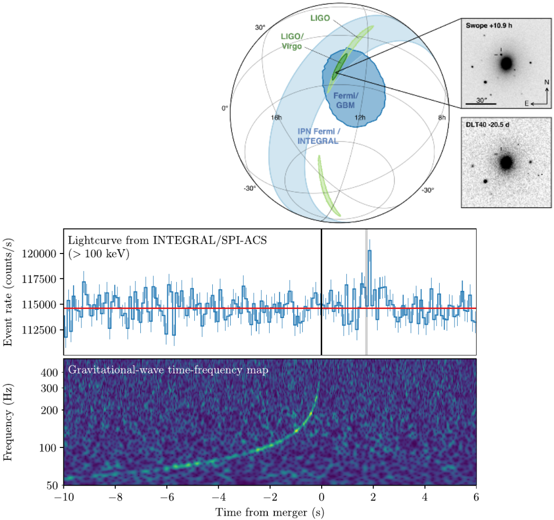
first direct observation of a black hole

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

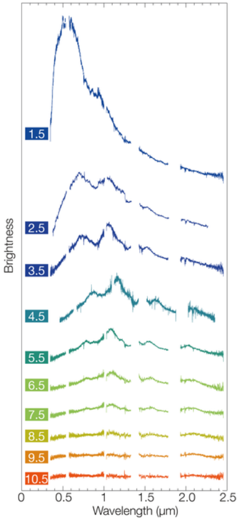
first observation of a black hole binary

first observation of black hole "formation"

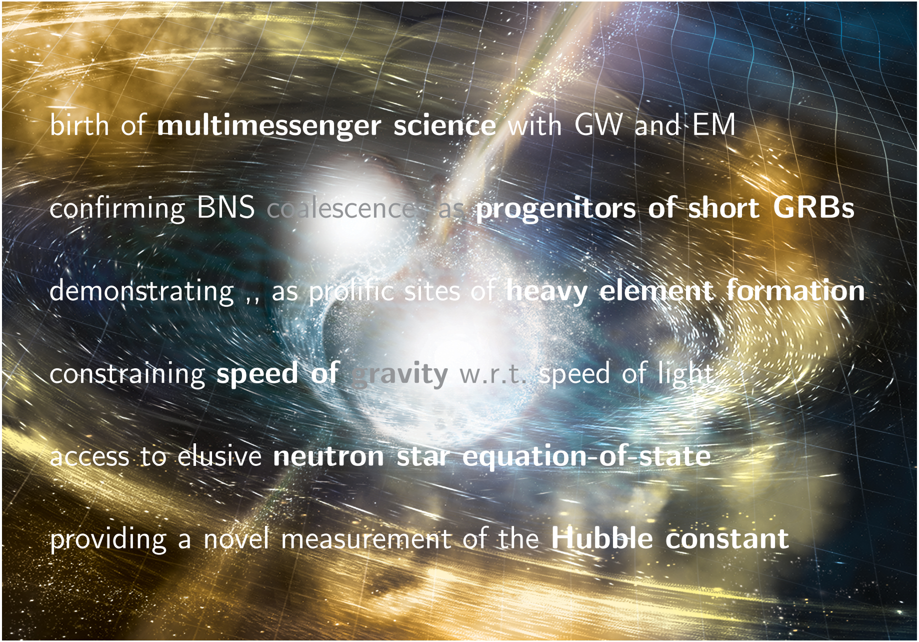
GW170817



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**

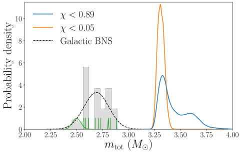
constraining **speed of gravity** w.r.t. speed of light

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)

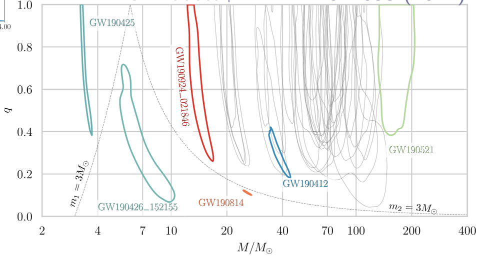


GW190425

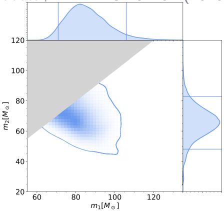
potential BNS

heavy, no counterpart

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



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



GW190521

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

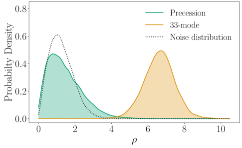
$$m_2 = 66^{+17}_{-8} M_\odot$$

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

GW190814

lighter object in “mass gap” between NS and BH

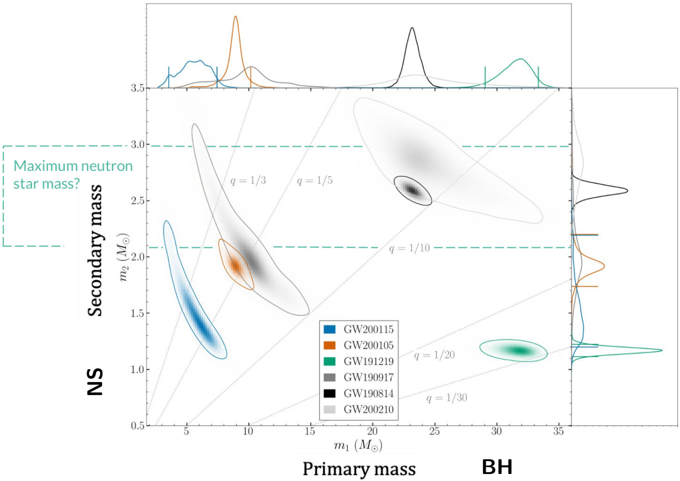
mass ratio > 9 | “higher harmonics” in GW signal



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

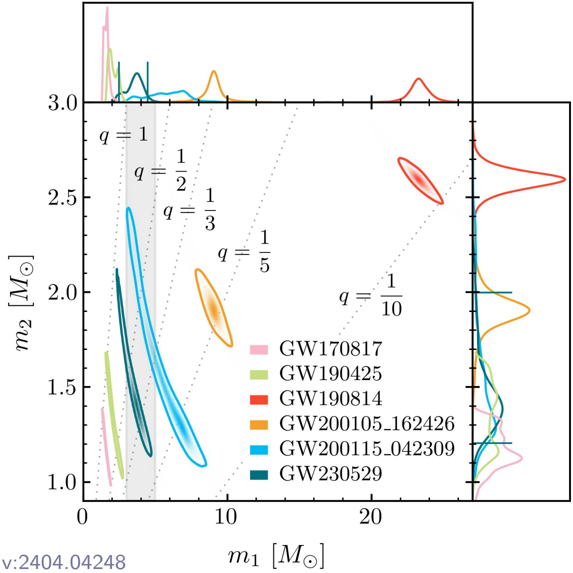
O3b highlights

neutron star – black hole mergers!

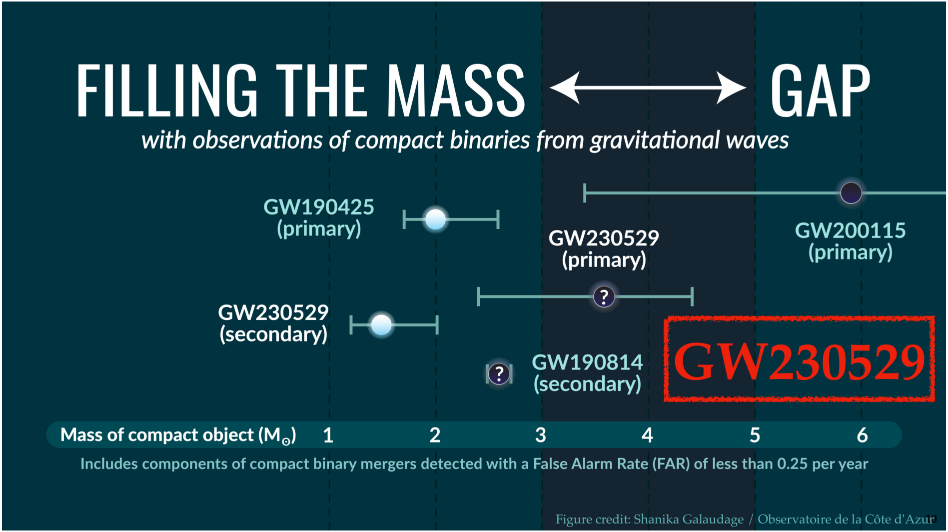


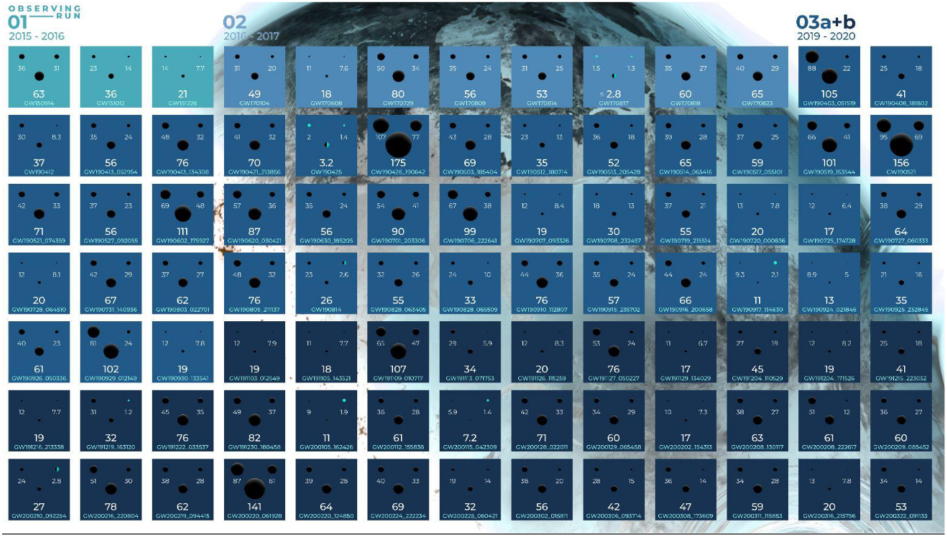
LVK: Abbott+ ApJL **915** #1 L5 (2021); LVK: Abbott+ arXiv:2111.03606; LIGO-G2102416

O4a: GW230529

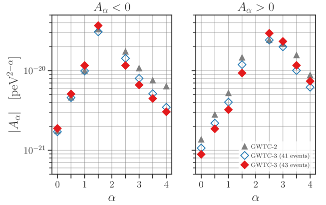


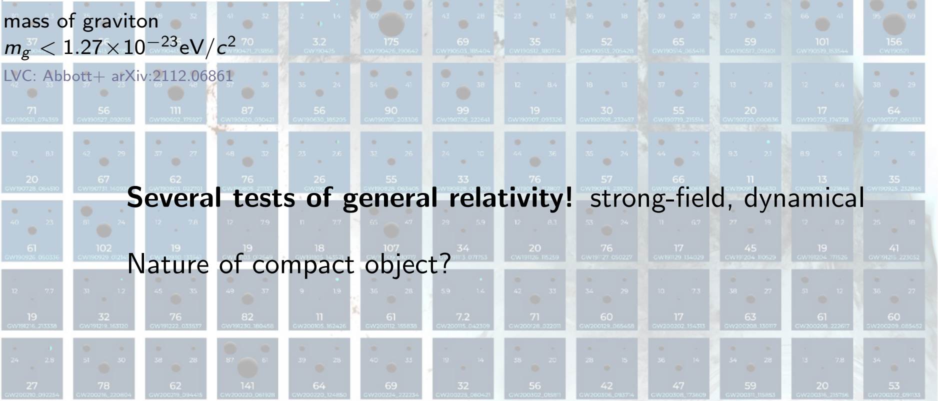
LVK: Abbott+ arXiv:2404.04248


FILLING THE MASS GAP
with observations of compact binaries from gravitational waves
GW190425 (primary)
GW230529 (primary)
GW200115 (primary)
GW230529 (secondary)
GW190814 (secondary)
GW230529
Mass of compact object ($M_\odot$) 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


OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020

Fundamental physics





mass of graviton

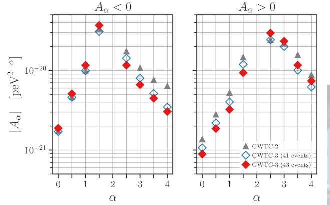
$m_g < 1.27\times10^{-23}\text{eV}/c^2$

LVC: Abbott+ arXiv:2112.06861

Several tests of general relativity! strong-field, dynamical

Nature of compact object?

Fundamental physics



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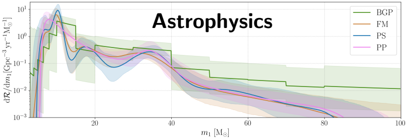
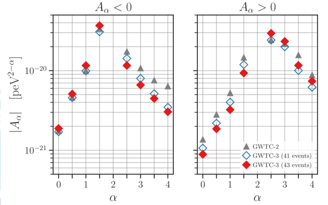


LVC: Abbott+ arXiv: 2111.03634

Fundamental physics

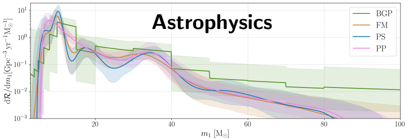


mass of graviton

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

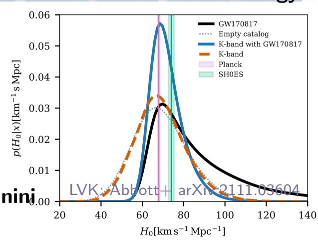
LVC: Abbott+ arXiv:2112.06861

Astrophysics



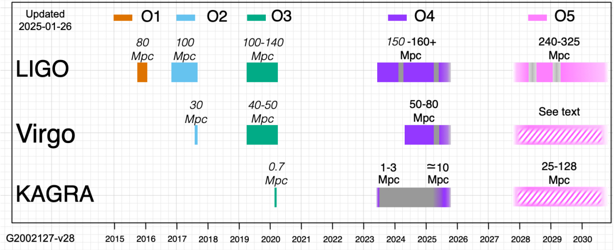
LVC: Abbott+ arXiv: 2111.03634

Cosmology

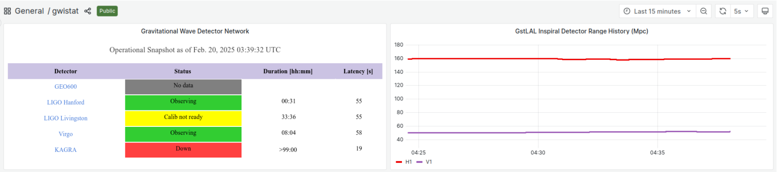


LVK: Abbott+ arXiv:2111.03604

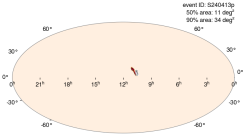
Talks by: **Chris Van Den Broeck, Michela Mapelli, Nicola Tamanini**

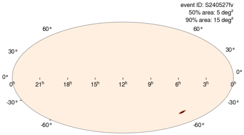


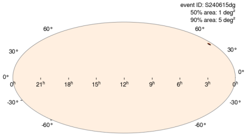
O4a: 2023 May 24 – 2024 Jan 16
O4b: 2024 Apr 10 – 2025 Jan 28
O4c: 2025 Jan 28 – 2025 Oct 07

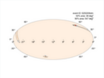


https://gracedb.ligo.org/: **203** significant detection candidates in O4







S250206dm	NSBH (55%), BNS (37%), Terrestrial (8%)	Yes	Feb. 6, 2025 21:25:30 UTC	GCN Circular Query Notices | VOE		1 per 25.01 years

What will we see next?

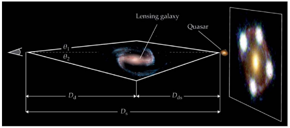
Exotic physics around black holes

neutron stars

GW **lensing**

Strong lensing: search for lensed pairs, time delays

Weak lensing: cross-correlations



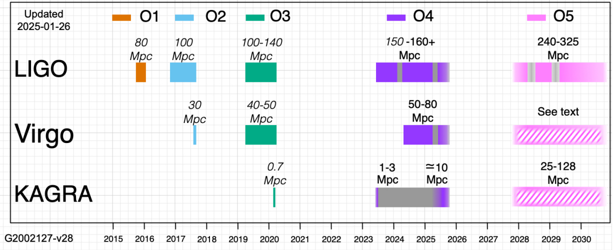
Dark matter with GW

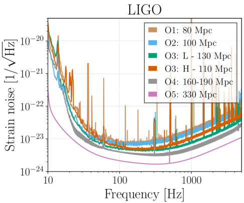
Primordial BHs | ultralight bosonic DM

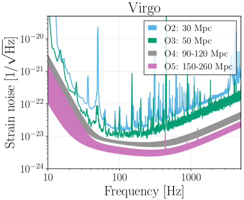
Multimessenger observation with **neutrinos**

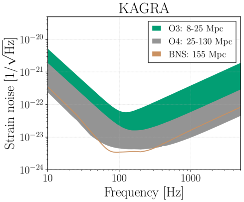
Supernova | **Stochastic** GW background

Towards 3G and the Einstein Telescope







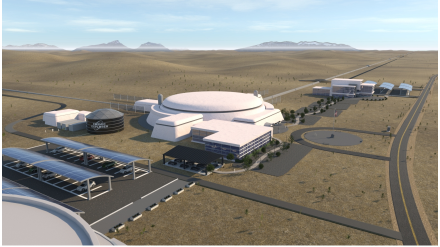


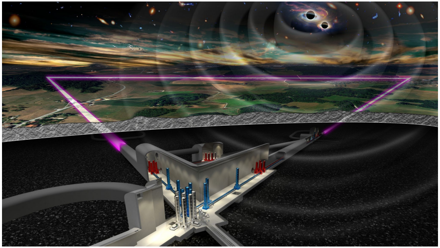
LIGO-P1200087

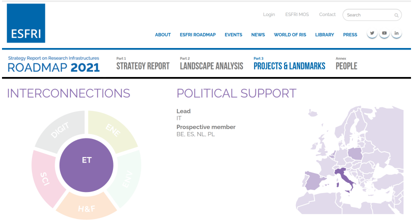
O5 / A+ $\longrightarrow$ A$^\sharp$ / V_nEXT upgrades

Einstein Telescope, Cosmic Explorer, LISA

3G ground-based detectors: ET and CE







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

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

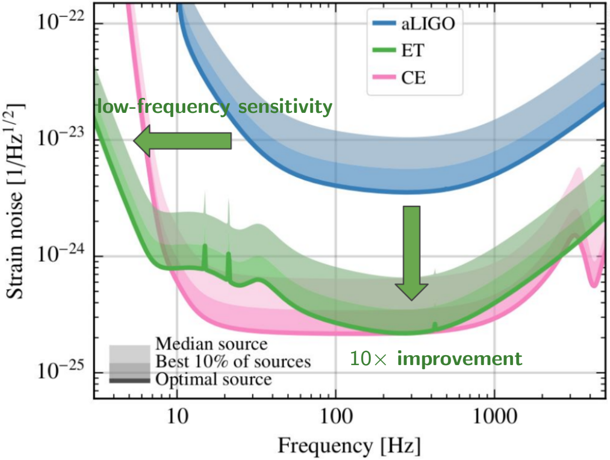
Cosmology

Multimessenger Obs

Population Studies

Forum on future EM and neutrino experiments?

3G ground-based detectors: ET and CE



Particularly for ET:

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

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

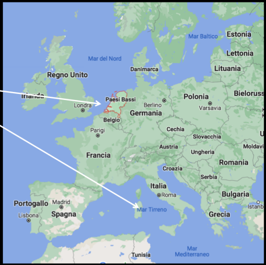
Marica Branchesi,[1,2,*] Michele Maggiore,[3,4,*] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Enis Belgacem,[3,4] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19] Arnab Dhani,[20] Tim Dietrich,[21,22] Ulyana Dupletsa,[1,2] Stefano Foffa,[3,4] Gabriele Franciolini,[8] Andreas Freise,[23,16] Gianluca Gemme,[24] Boris Goncharov,[1,2] Archisman Ghosh,[7] Francesca Gulminelli,[25] Ish Gupta,[20] Pawan Kumar Gupta,[16,26] Jan Harms,[1,2] Nandini Hazra,[1,2,27] Stefan Hild,[16,17] Tanja Hinderer,[28] Ik Siong Heng,[29] Francesco Iacovelli,[3,4] Justin Janquart,[16,26] Kamiel Janssens,[10,11] Alexander C. Jenkins,[30] Chinmay Kalaghatgi,[16,26,31] Xhesika Koroveshi,[32,33] Tjonnie G.F. Li,[34,35] Yufeng Li,[36] Eleonora Loffredo,[1,2] Elisa Maggio,[22] Michele Mancarella,[3,4,37,38] Michela Mapelli,[39,40,41] Katarina Martinovic,[6] Andrea Maselli,[1,2] Patrick Meyers,[42] Andrew L. Miller,[43,16,26] Chiranjib Mondal,[25] Niccolò Muttoni,[3,4] Harsh Narola,[16,26] Micaela Oertel,[44] Gor Oganesyan,[1,2] Costantino Pacilio,[8,37,38] Cristiano Palomba,[45] Paolo Pani,[8] Antonio Pasqualetti,[46] Albino Perego,[47,48] Carole Périgois,[39,40,41] Mauro Pieroni,[49,50] Ornella Juliana Piccinni,[51] Anna Puecher,[16,26] Paola Puppo,[45] Angelo Ricciardone,[52,39,40] Antonio Riotto,[3,4] Samuele Ronchini,[1,2] Mairi Sakellariadou,[6] Anuradha Samajdar,[21] Filippo Santoliquido,[39,40,41] B.S. Sathyaprakash,[20,53,54] Jessica Steinlechner,[16,17] Sebastian Steinlechner,[16,17] 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,

CBC localization
new sources!

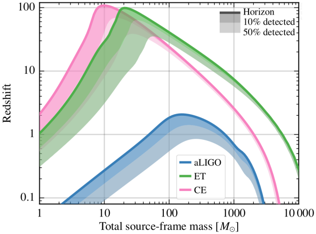
correlated noise
"null stream"

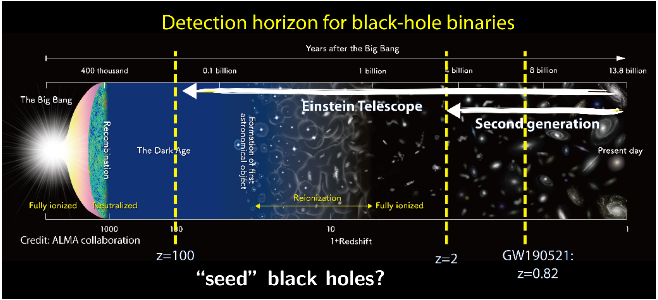
Contents

+Summary and Appendix

3G ground-based detectors: ET and CE

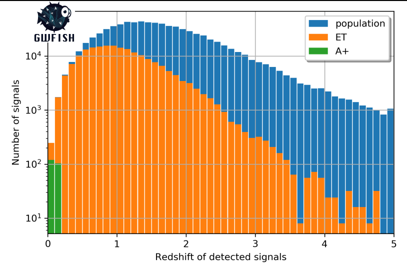
arXiv:1903.09260; courtesy: Evan Hall, Salvatore Vitale



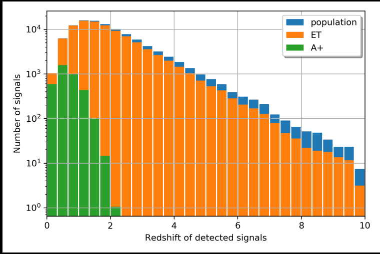


COMPACT OBJECT BINARY POPULATIONS

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

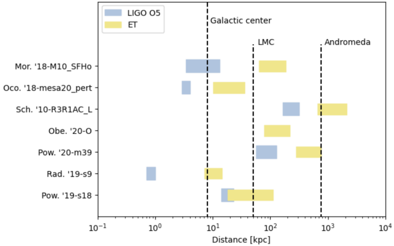
Other sources

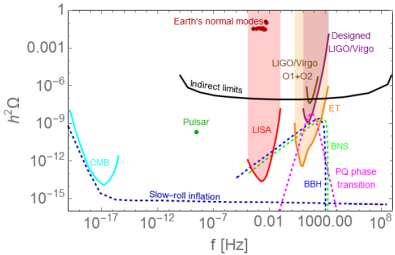
Supernovae?

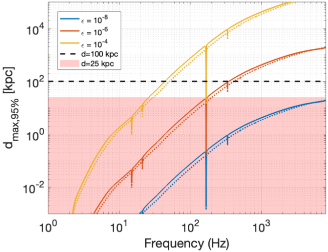
Isolated NS?

GW background?

Something exotic??







What can ET uniquely do?

- Black hole spectroscopy
- GW memory
- Early-universe physics
- Large scale structure of the universe — angular resolution
- Gravitational lensing of GWs
- Evolution of compact binary population with redshift
- Seed black holes?
- Early warning for BNS mergers
- Multiband GW astronomy
- Neutron star equation-of-state and postmerger

Modelling challenges and detector unknowns

- Will we have accurate enough waveform models?

- What can we assume about the detector?

  Calibration, glitches, duty cycle, ...

Data analysis challenges

- $\mathcal{O}(10^6)$ compact binary detections $\Rightarrow$ big data!
- Very long signals $\Rightarrow$ need new data analysis methods!
- Data gaps interrupting signals.
- Overlapping signals.
- Little signal-free stretches of data $\Rightarrow$ PSD estimation?
- Correlated noise at low frequencies: magnetic, seismic, Newtonian

Recent, ongoing work ...

- Speeding up CBC PE for long signals: relative binning, multibanding, factorization of the parameter space, machine learning based approaches [huge body of work]
- Overlapping signals [Samajdar+ 2021; Janquart+ 2023]
- Utilization of the null stream [Goncharov+ 2022]
- Correlated noise [Janssens+ 2022, Janssens+ 2023]
- Likelihood with correlated noise [Cireddu+ 2024, Wong+ 2025]
- Glitch mitigation using the null stream [Narola+ 2024]
- Calibration using a detector network [Sathyaprakash, Schutz]

arXiv > gr-qc > arXiv:2503.12263

Search...

Help | Adva

General Relativity and Quantum Cosmology

[Submitted on 15 Mar 2025]

The Science of the Einstein Telescope

Adrian Abac, Raul Abramo, Simone Albanesi, Angelica Albertini, Alessandro Agapito, Michalis Agathos, Conrado Albertus, Nils Andersson, Tomás Andrade, Igor Andreoni, Federico Angeloni, Marco Antonelli, John Antoniadis, Fabio Antonini, Manuel Arca Sedda, M. Celeste Artale, Stefano Ascenzi, Pierre Auclair, Matteo Bachetti, Charles Badger, Biswajit Banerjee, David Barba-González, Dániel Barta, Nicola Bartolo, Andreas Bauswein, Andrea Begnoni, Freija Beirnaert, Michał Bejger, Enis Belgacem, Nicola Bellomo, Laura Bernard, Maria Grazia Bernardini, Sebastiano Bernuzzi, Christopher P. L. Berry, Emanuele Berti, Gianfranco Bertone, Dario Bettoni, Miguel Bezares, Swetha Bhagwat, Sofia Bisero, Marie Anne Bizouard, Jose J. Blanco-Pillado, Simone Blasi, Alice Bonino, Alice Borghese, Nicola Borghi, Ssohrab Borhanian, Elisa Bortolas, Maria Teresa Botticella, Marica Branchesi, Matteo Breschi, Richard Brito, Enzo Brocato, Floor S. Broekgaarden, Tomasz Bulik, Alessandra Buonanno, Fiorella Burgio, Adam Burrows, Gianluca Calcagni, Sofia Canevarolo, Enrico Cappellaro, Giulia Capurri, Carmelita Carbone, Roberto Casadio, Ramiro Cayuso, Pablo Cerdá-Durán, Prasanta Char, Sylvain Chaty, Tommaso Chiarusi, Martyna Chruslinska, Francesco Cireddu, Philippa Cole, Alberto Colombo, Monica Colpi, Geoffrey Compère, Carlo Contaldi, Maxence Corman, Francesco Crescimbeni, Sergio Cristallo, Elena Cuoco, Giulia Cusin, Tito Dal Canton, Gergely Dálya, Paolo D'Avanzo, Nazanin Davari, Valerio De Luca, Viola De Renzis, Massimo Della Valle, Walter Del Pozzo, Federico De Santi, Alessio Ludovico De Santis, Tim Dietrich, Ema Dimastrogiovanni, Guillem Domenech, Daniela Doneva, Marco Drago, Ulyana Dupletsa, Hannah Duval, Irina Dvorkin, Nancy Elias-Rosa et al. (385 additional authors not shown)

Einstein Telescope (ET) is the European project for a gravitational-wave (GW) observatory of third-generation. In this paper we present a comprehensive discussion of its science objectives, providing state-of-the-art predictions for the capabilities of ET in both geometries currently under consideration, a single-site triangular configuration or two L-shaped detectors. We discuss the impact that ET will have on domains as broad and diverse as fundamental physics, cosmology, early Universe, astrophysics of compact objects, physics of matter in extreme conditions, and dynamics of stellar collapse. We discuss how the study of extreme astrophysical events will be enhanced by multi-messenger observations. We highlight the ET synergies with ground-based and space-borne GW observatories, including multi-band investigations of the same sources, improved parameter estimation, and complementary information on astrophysical or cosmological mechanisms obtained combining observations from different frequency bands. We present advancements in waveform modeling dedicated to third-generation observatories, along with open tools developed within the ET Collaboration for assessing the scientific potentials of different detector configurations. We finally discuss the data analysis challenges posed by third-generation observatories, which will enable access to large populations of sources and provide unprecedented precision.

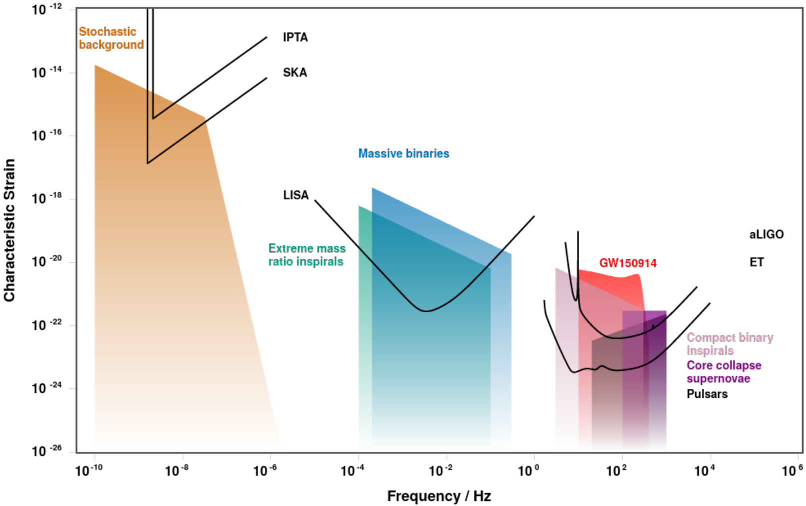
Comments: 880 pages, 203 figures

Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE); Instrumentation and Methods for Astrophysics (astro-ph.IM); Nuclear Theory (nucl-th)

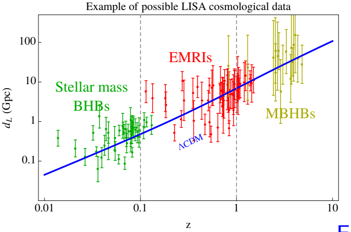
EXTRA SLIDES

GWs in other bands

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



LISA sources

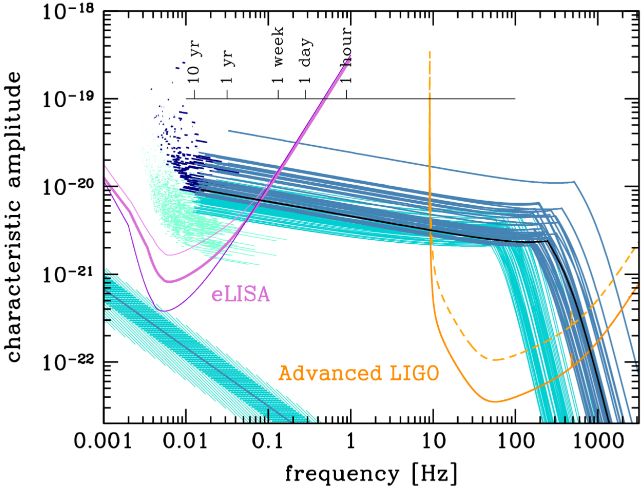


EM counterparts!

- StMBHBs: [Del Pozzo *et al*, 1703.01300; Kyutoku & Seto, 1609.07142]
- EMRIs: [MacLeod & Hogan, 0712.0618]
- MBHBs: [Tamanini *et al*, 1601.07112; Petiteau *et al*, 1102.0769]

- 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