Status of the GW field and perspectives with current and future GW detectors

M. Branchesi

Gran Sasso Science Institute

INFN/INAF/ASI

GSSI

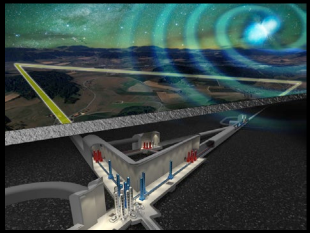
ASI

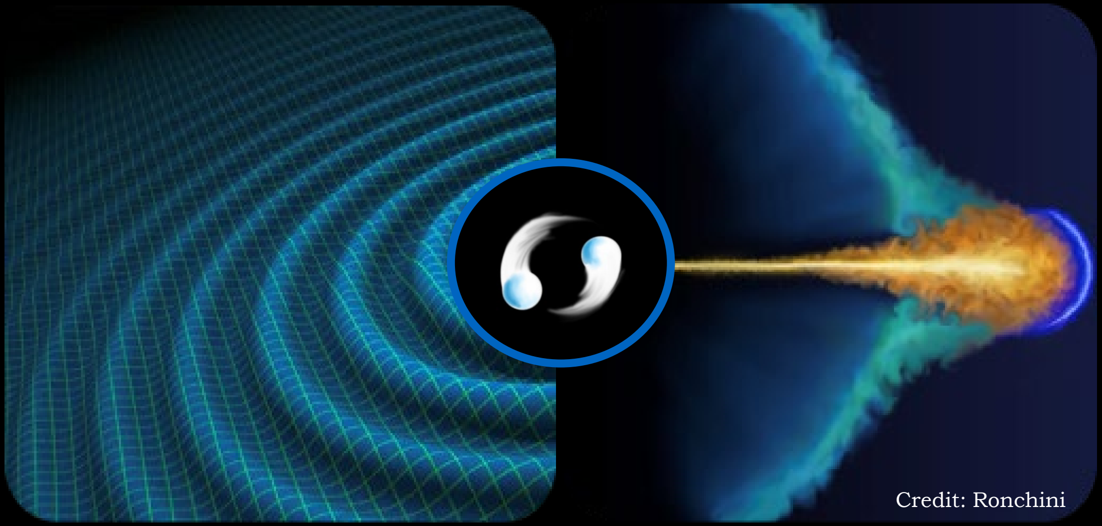
INFN Istituto Nazionale di Fisica Nucleare

INAF ISTITUTO NAZIONALE DI ASTROFISICA

LIGO VIRGO KAGRA

ET EINSTEIN TELESCOPE





Credit: Ronchini

Ground-based gravitational-wave detectors

LIGO VIRGO KAGRA

Earth

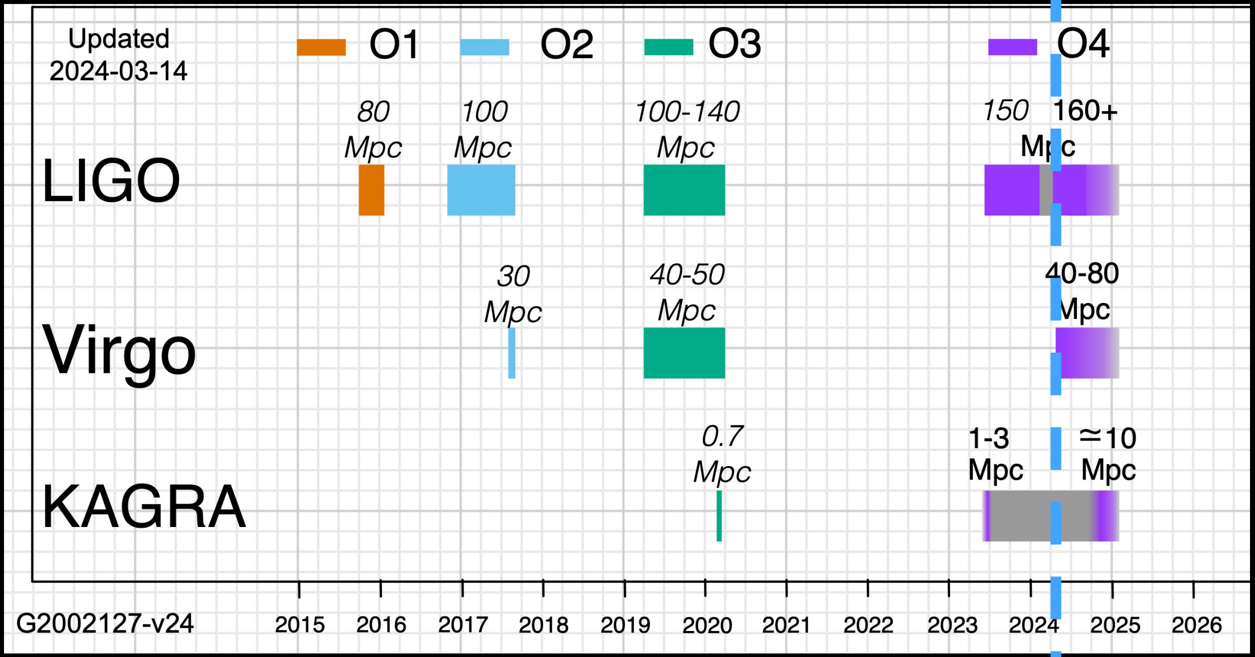
Credit: LIGO–Virgo

KAGRA, Japan

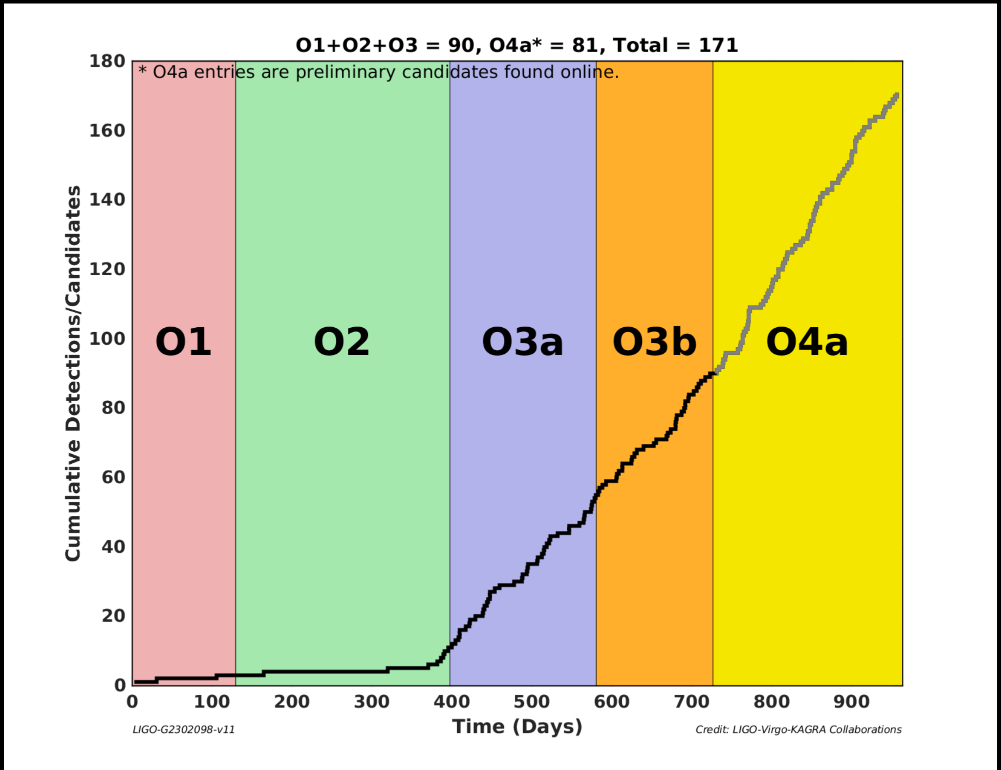
Where we are…

- **O1, O2, O3 completed**
- **O4 ongoing**
  → O4a only LIGO May 2023 - January 2024
  → O4b LIGO and Virgo April 2024 - February 2025

O1	O2	O3	O4
Sep ‘15 - Jan ‘16	Nov ‘16 - Aug ‘17	Apr ‘19 - Mar ‘20	May 23 - Feb ‘25



http://observing.docs.ligo.org/plan/



dcc.ligo.org/LIGO-G2302098

LIGO VIRGO KAGRA

Low-latency pubblic alerts

O4a 81 Significant Detection Candidates

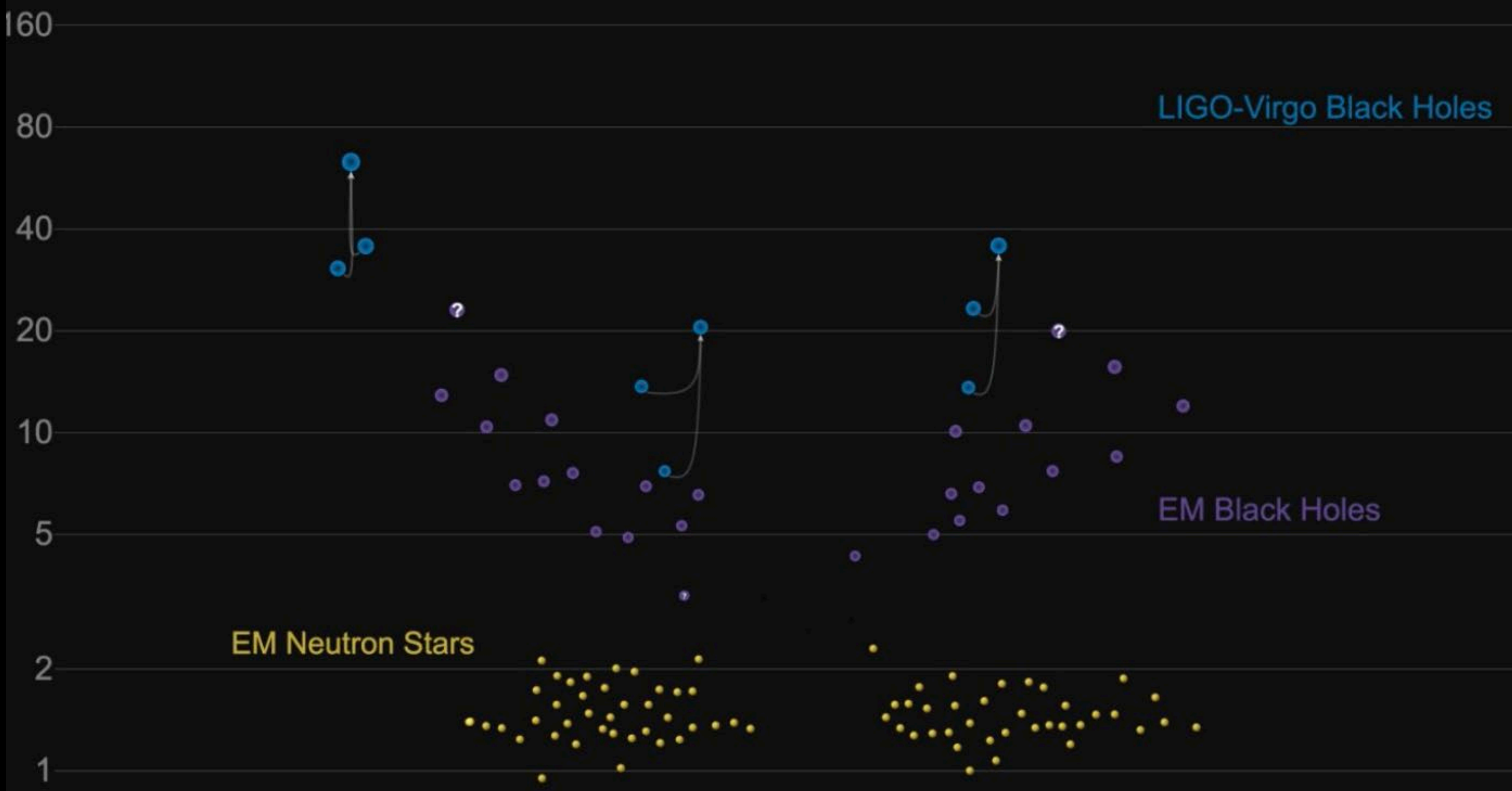
(FAR one per 6 months for compact binary merger targets)

GraceDB

- **the majority high probability to be BBH**
- **~1 - 2 candidate consistent with containing a NS**
- **~2 - 3 candidates consistent with an object in the lower mass gap**
- **no candidates expected to have significant remnant mass outside of the final compact object**

Masses in the Stellar Graveyard

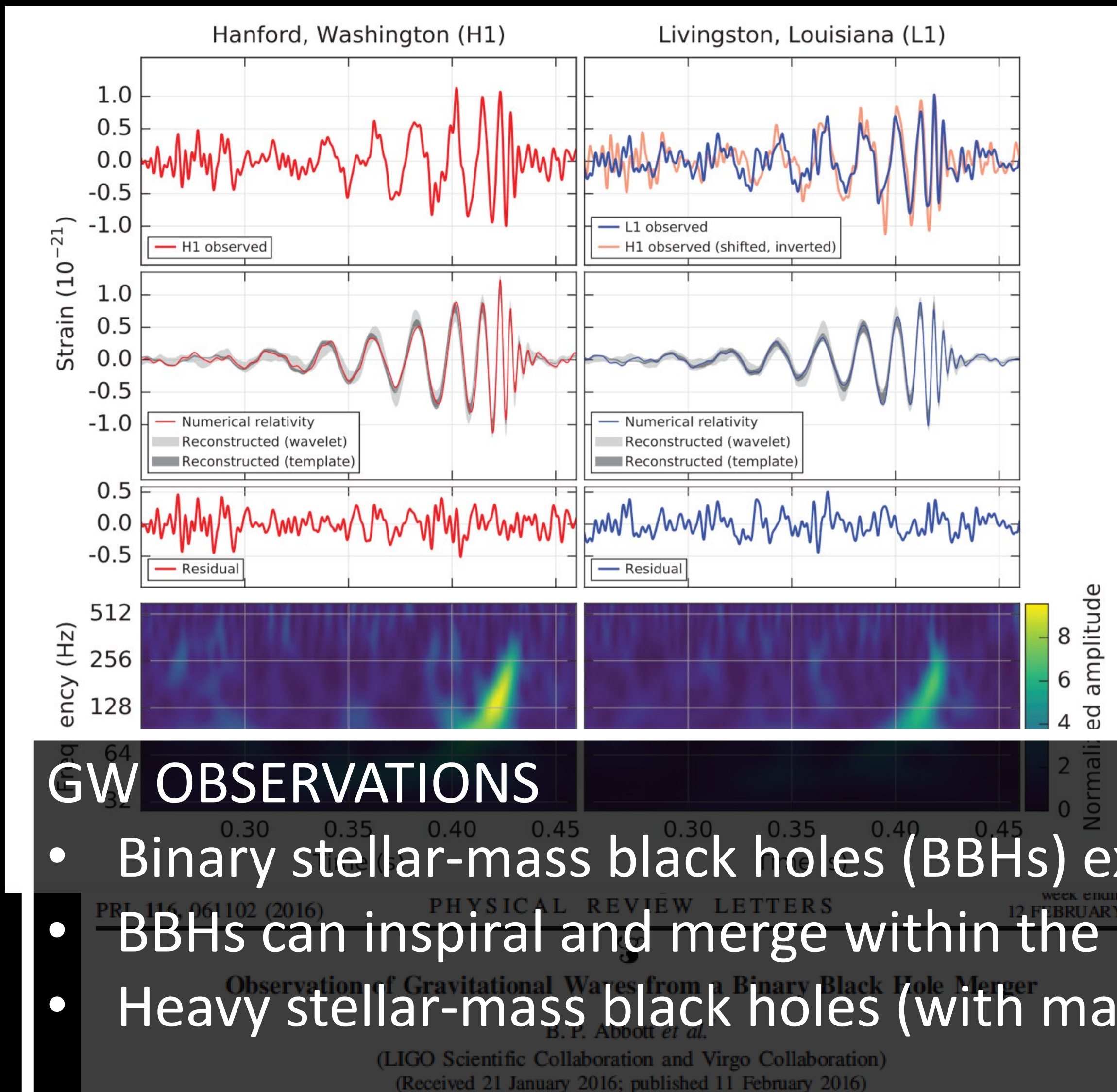
in Solar Masses



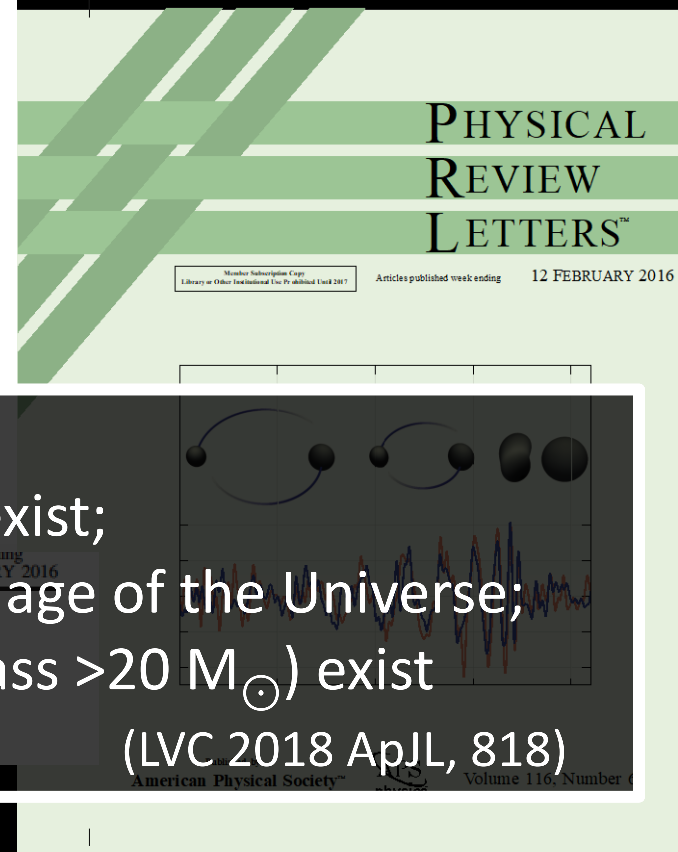
O1

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Observations of gravitational waves from a binary black- hole merger



GW150914



GW OBSERVATIONS

- Binary stellar-mass black holes (BBHs) exist;
- BBHs can inspiral and merge within the age of the Universe;
- Heavy stellar-mass black holes (with mass >20 $M_{\odot}$) exist

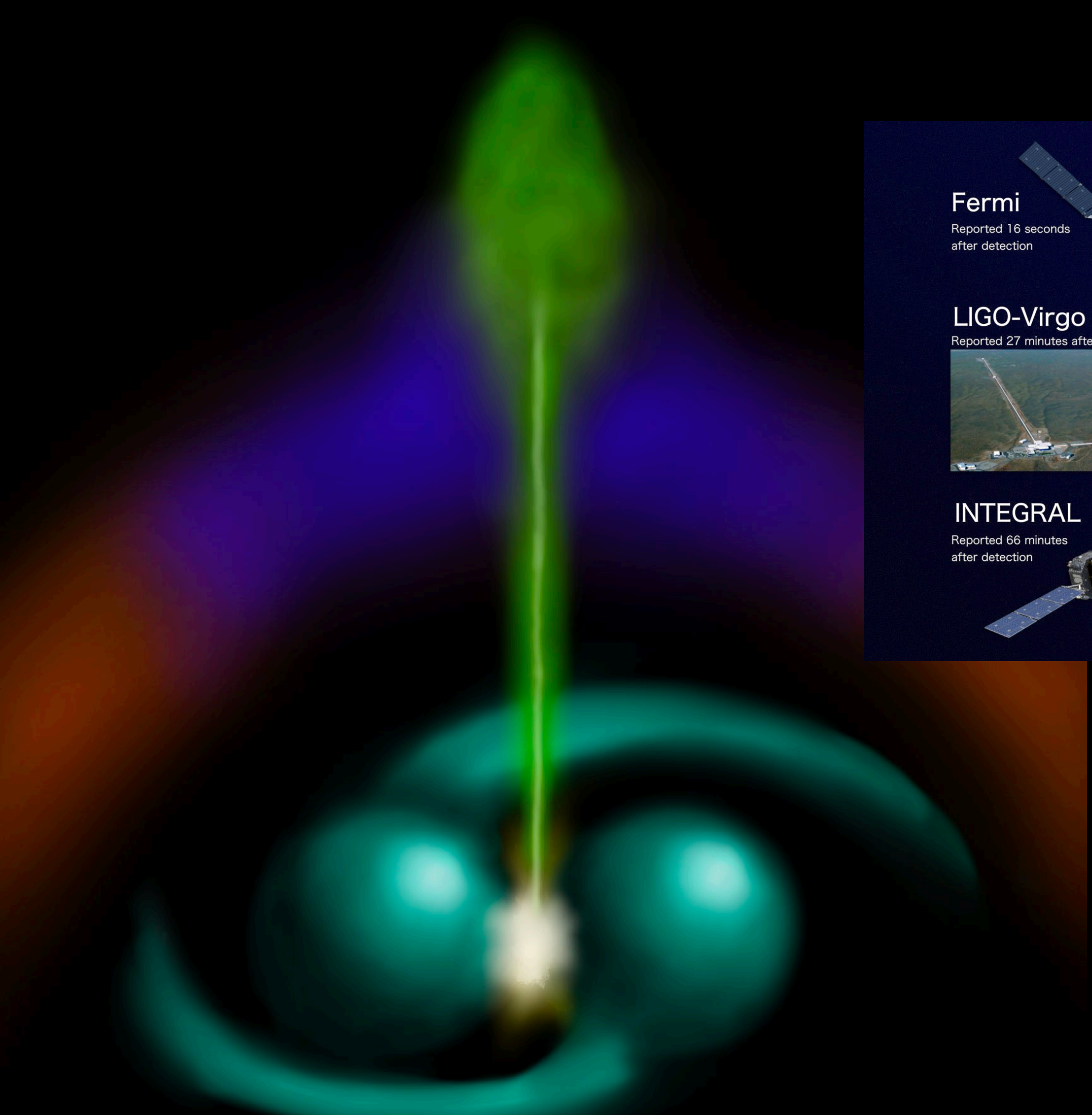
(LVC 2018 ApJL, 818)

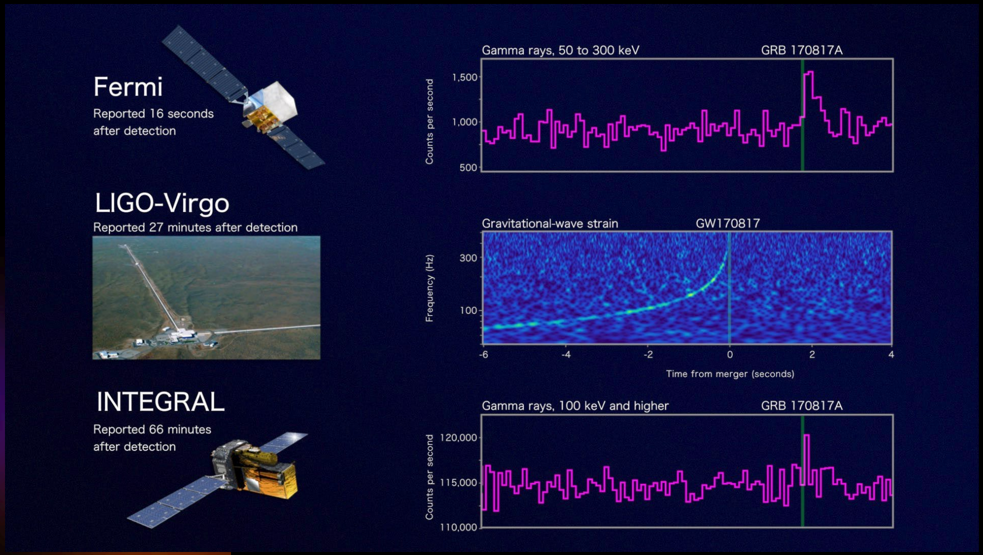
Masses in the Stellar Graveyard

in Solar Masses

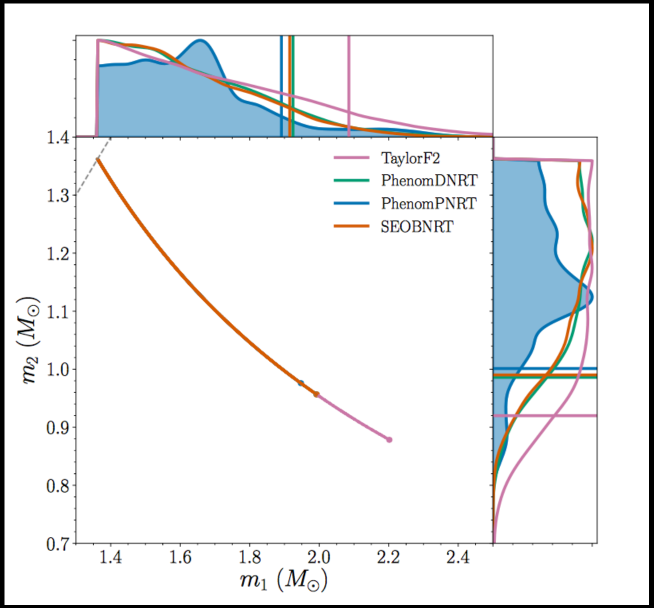
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW 170817

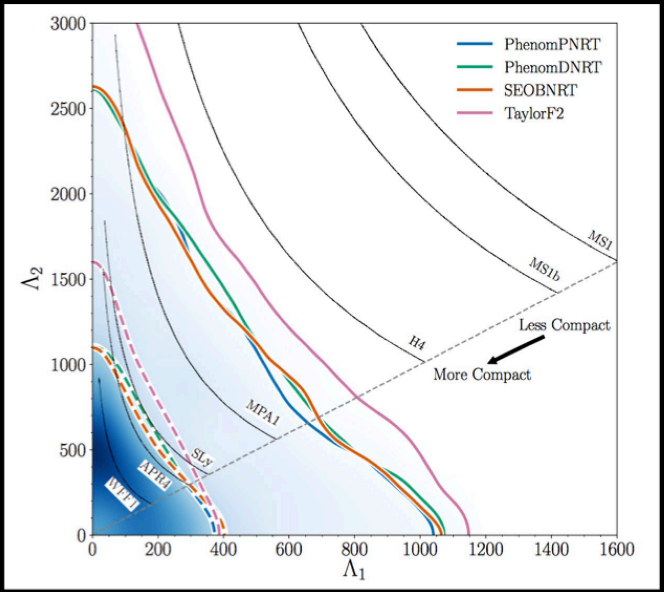


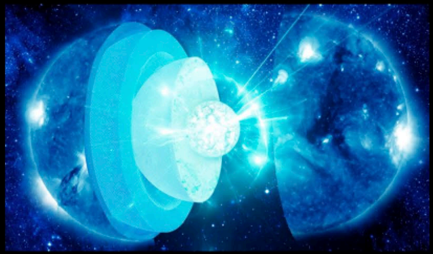

Fermi
Reported 16 seconds after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO-Virgo
Reported 27 minutes after detection
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
INTEGRAL
Reported 66 minutes after detection
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000

GW 170817



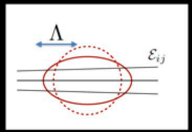
Masses are consistent with the masses of all known neutron stars!

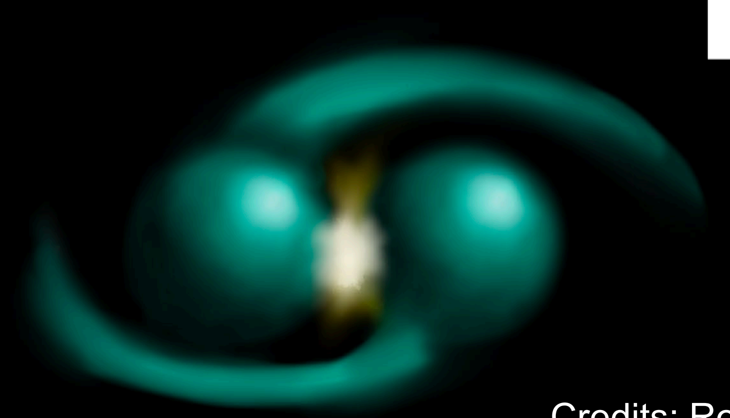


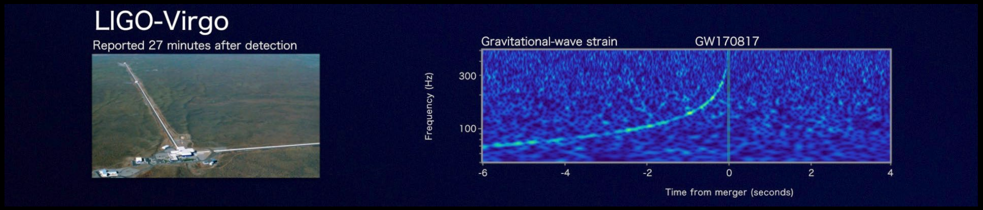


TIDAL DEFORMABILITY

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$





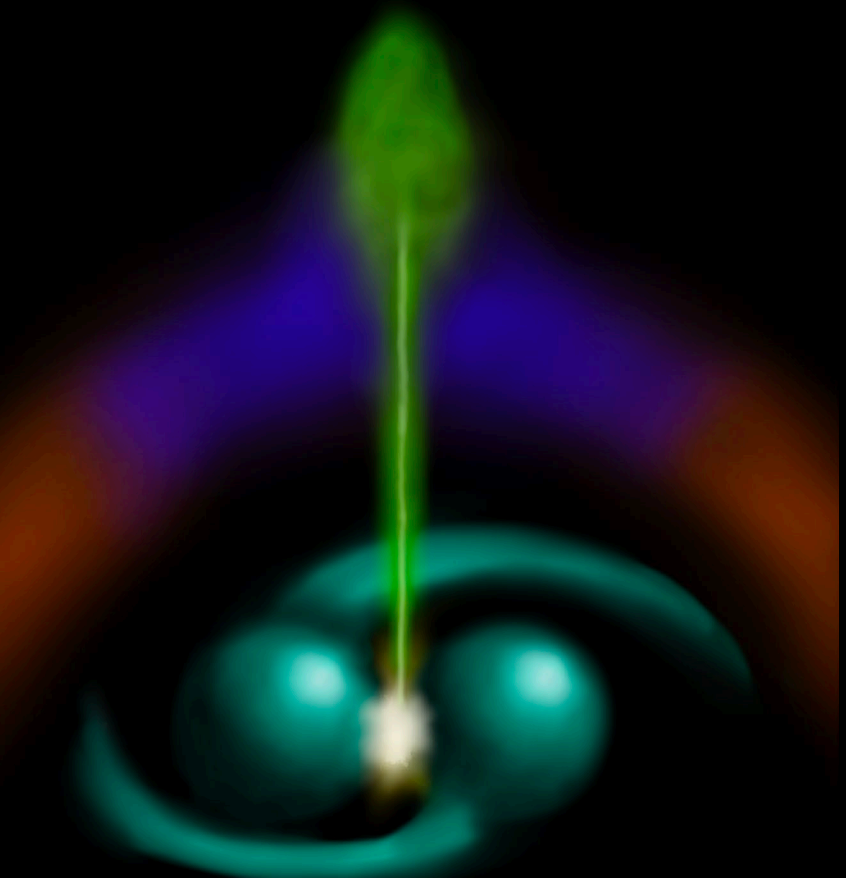


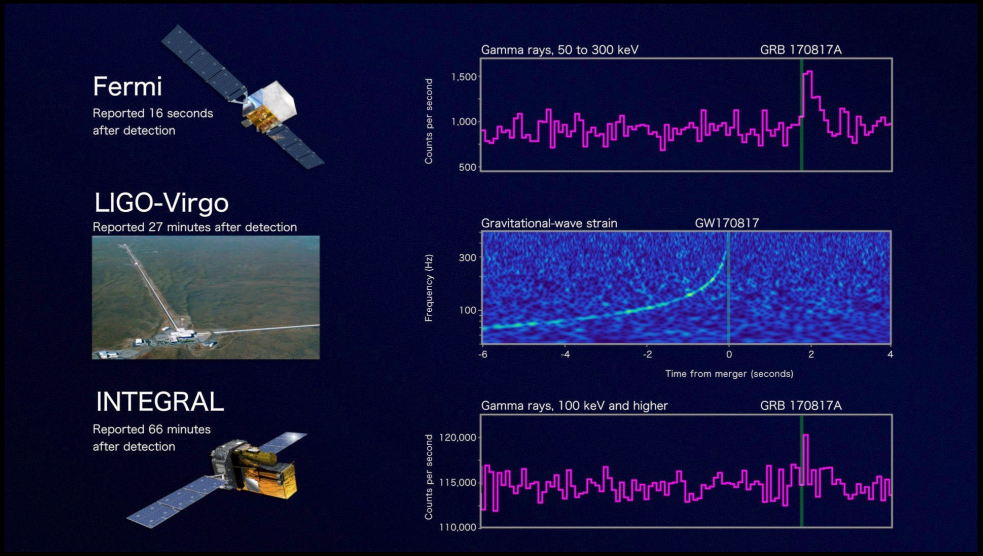
Credits: Ronchini

GW 170817

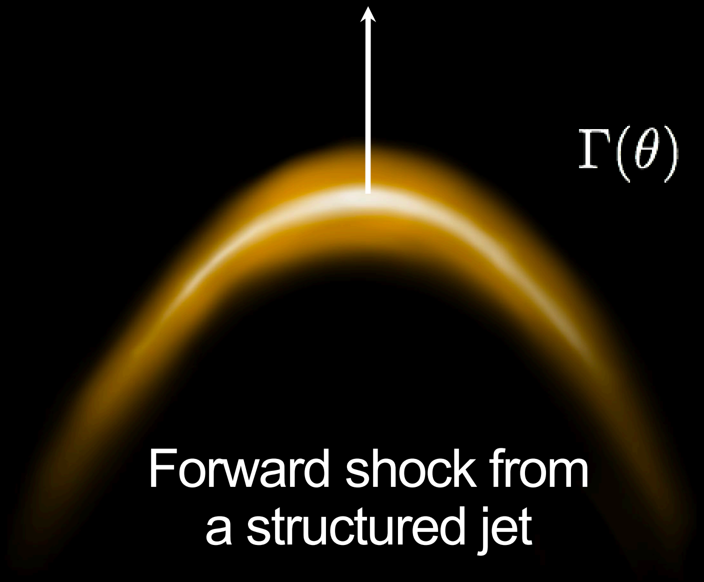
Binary neutron star mergers are progenitor of short GRB

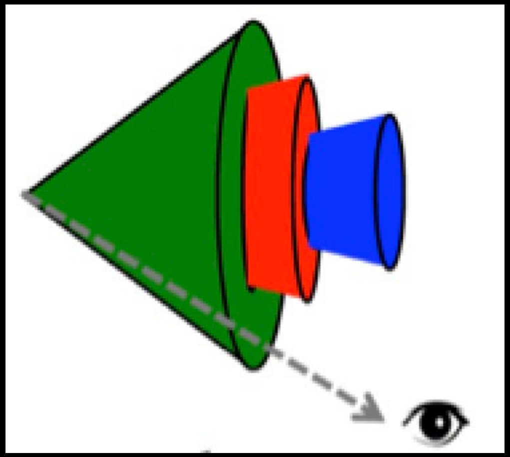
First short GRB observed off-axis

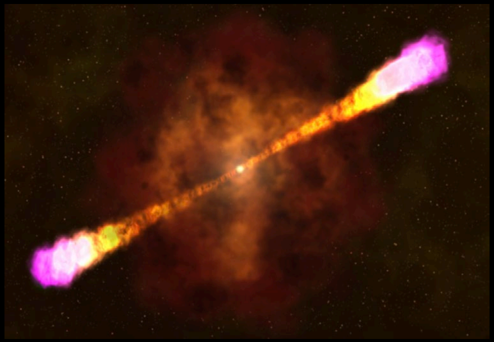




Multi-wavelength afterglow observations

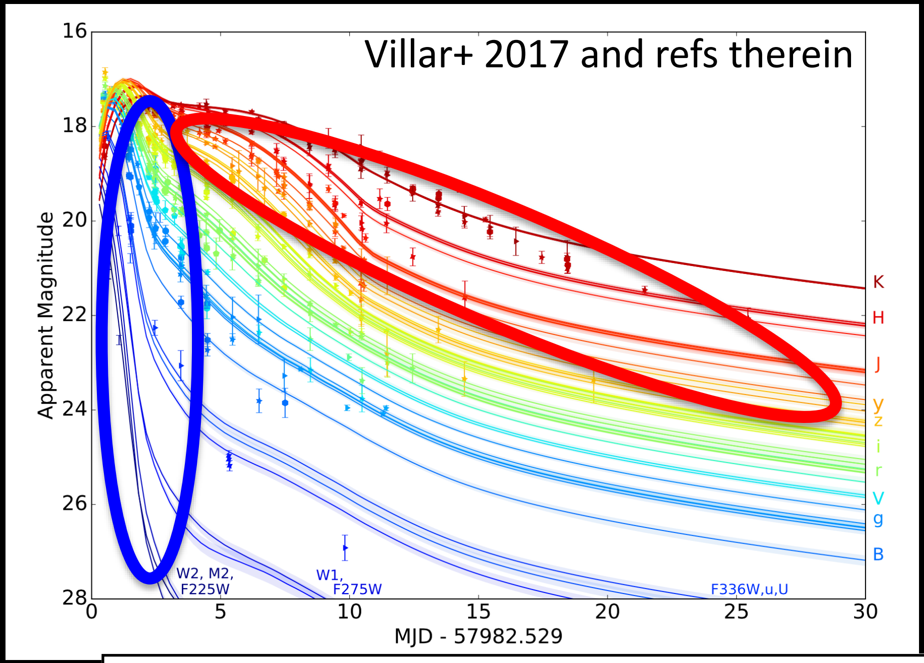


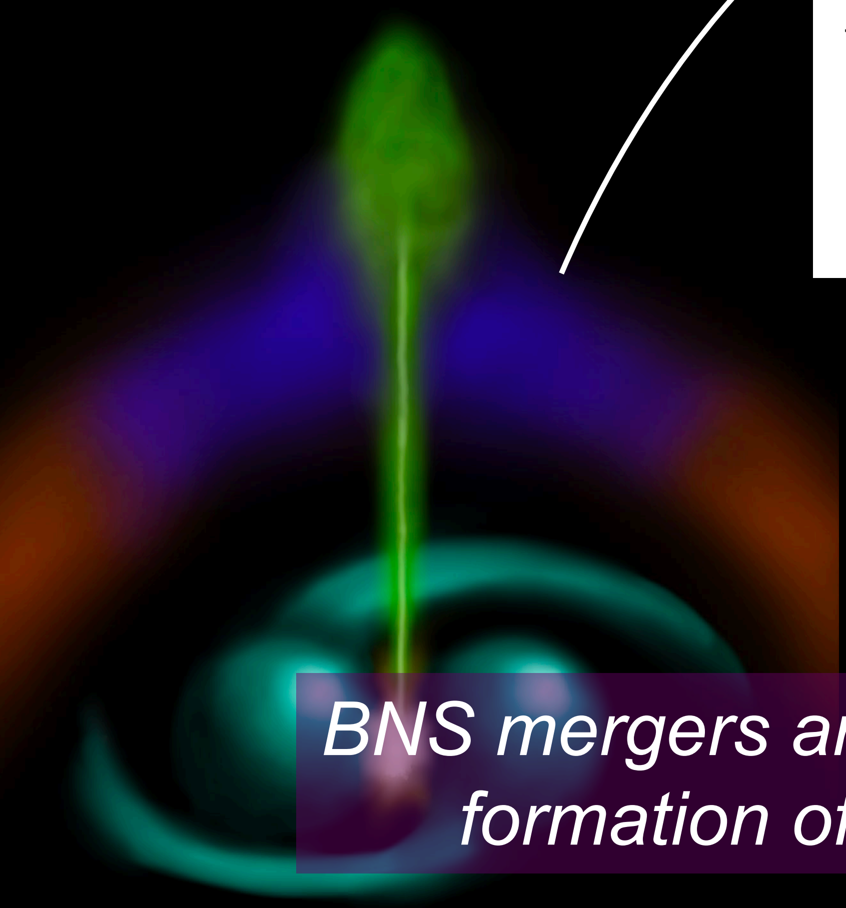




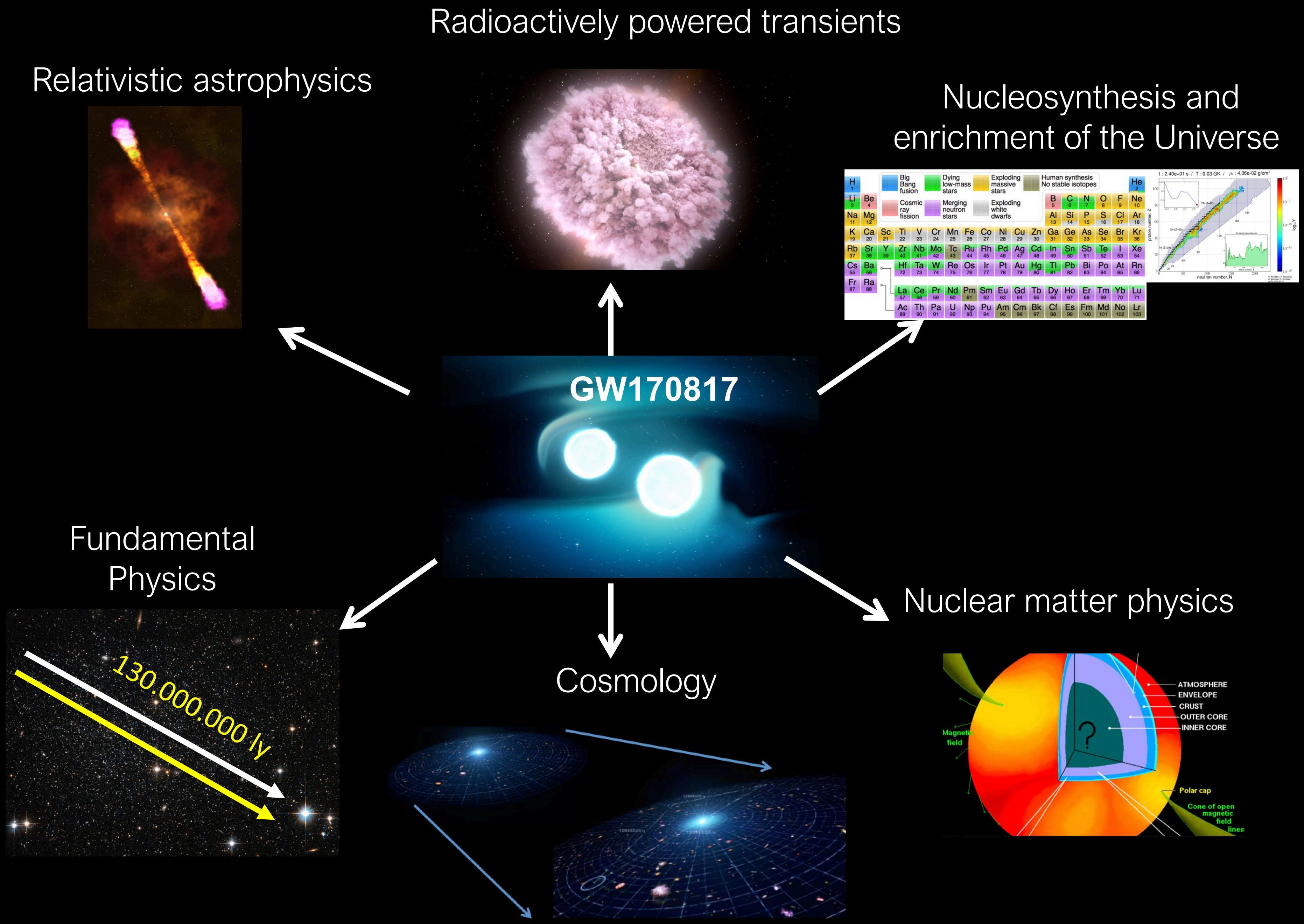
Structured off-axis jet

GW 170817



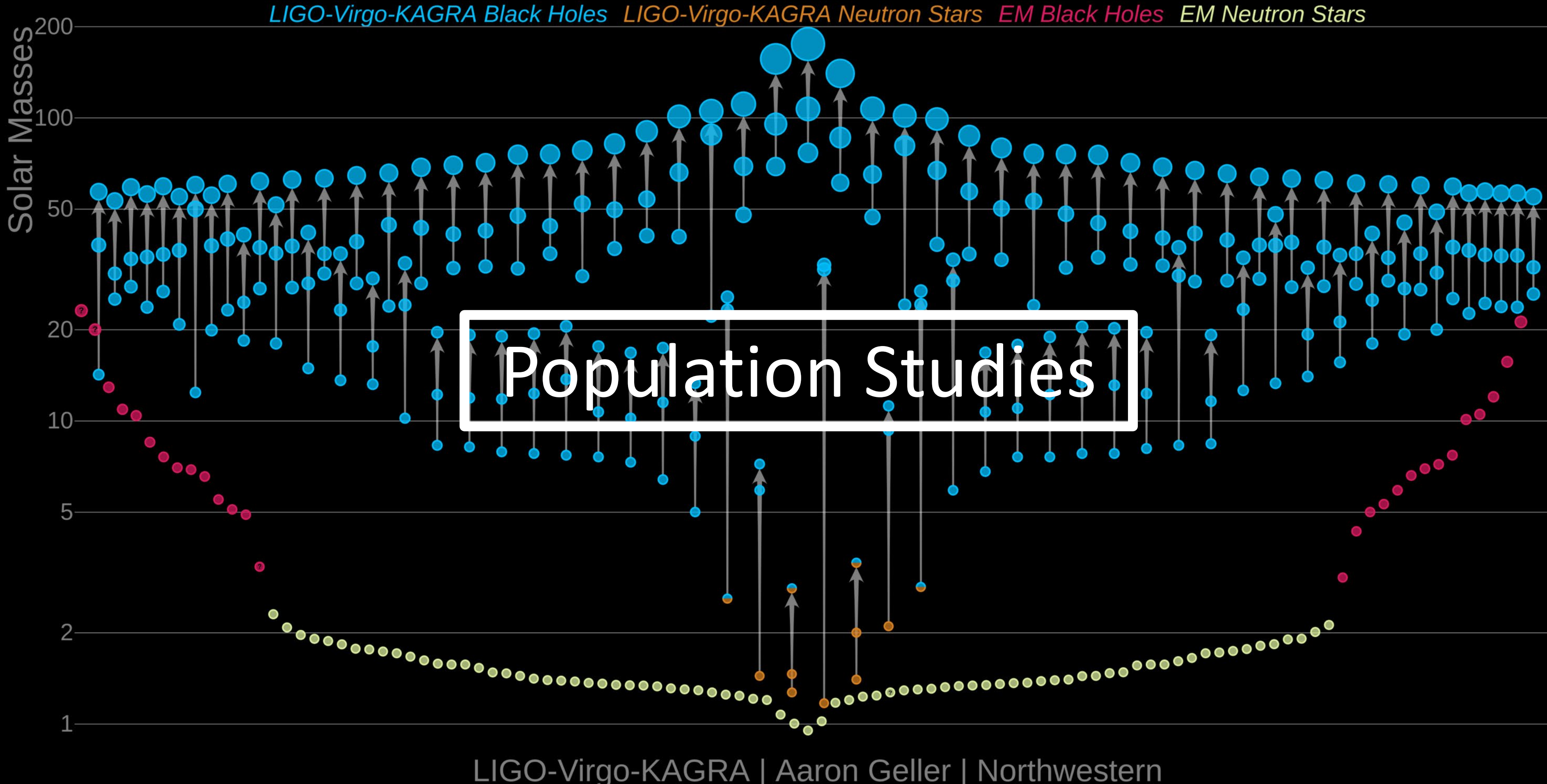


BNS mergers are
formation of h


Radioactively powered transients
Relativistic astrophysics
Nucleosynthesis and enrichment of the Universe
GW170817
Fundamental Physics
130.000.000 ly
Cosmology
Nuclear matter physics
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Polar cap
Cone of open magnetic field lines
Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs

O1+O2+O3

Masses in the Stellar Graveyard

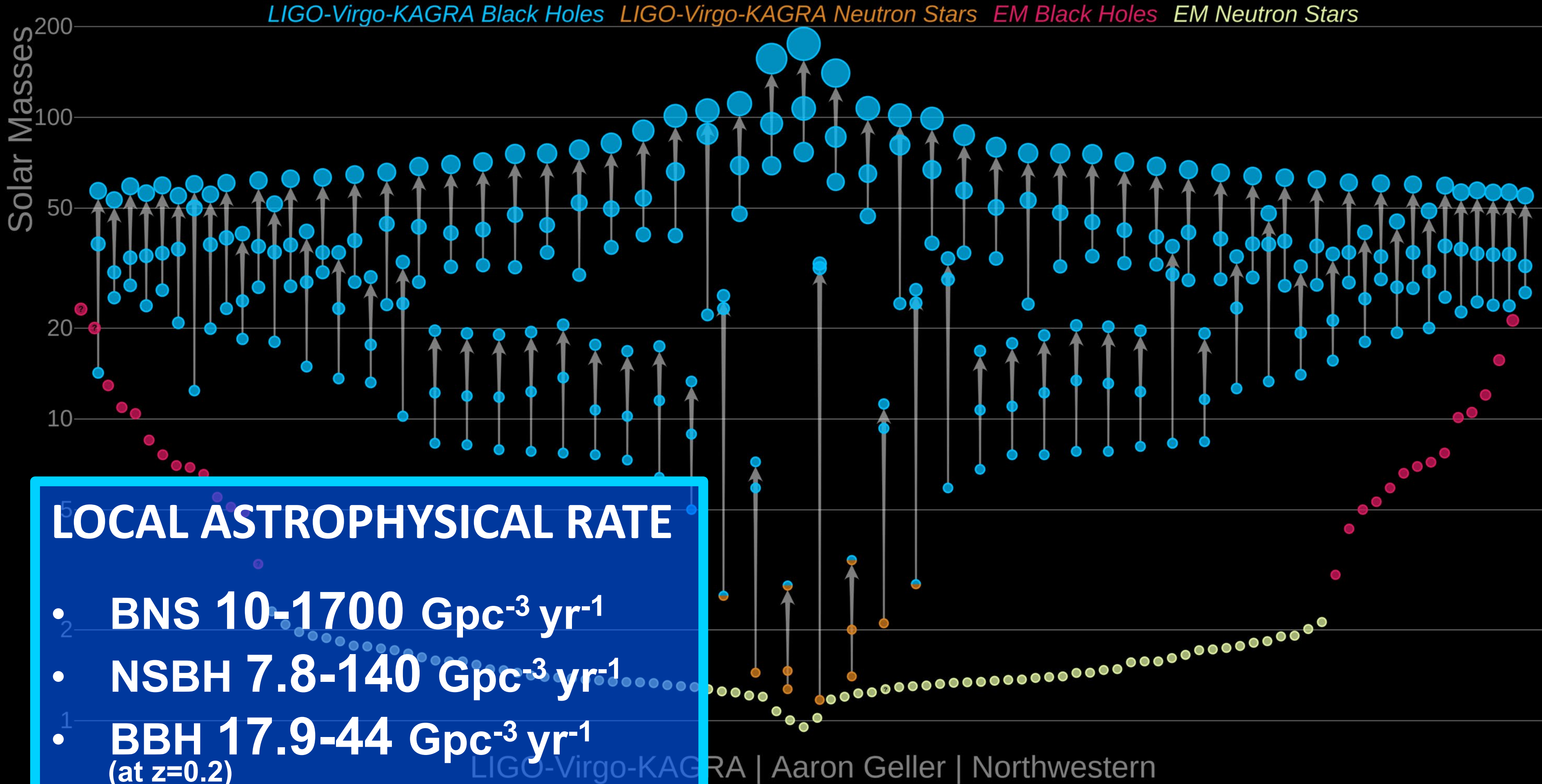


90 GW EVENTS!

LVK Physical Review X, 2023, 041039

O1+O2+O3

Masses in the Stellar Graveyard

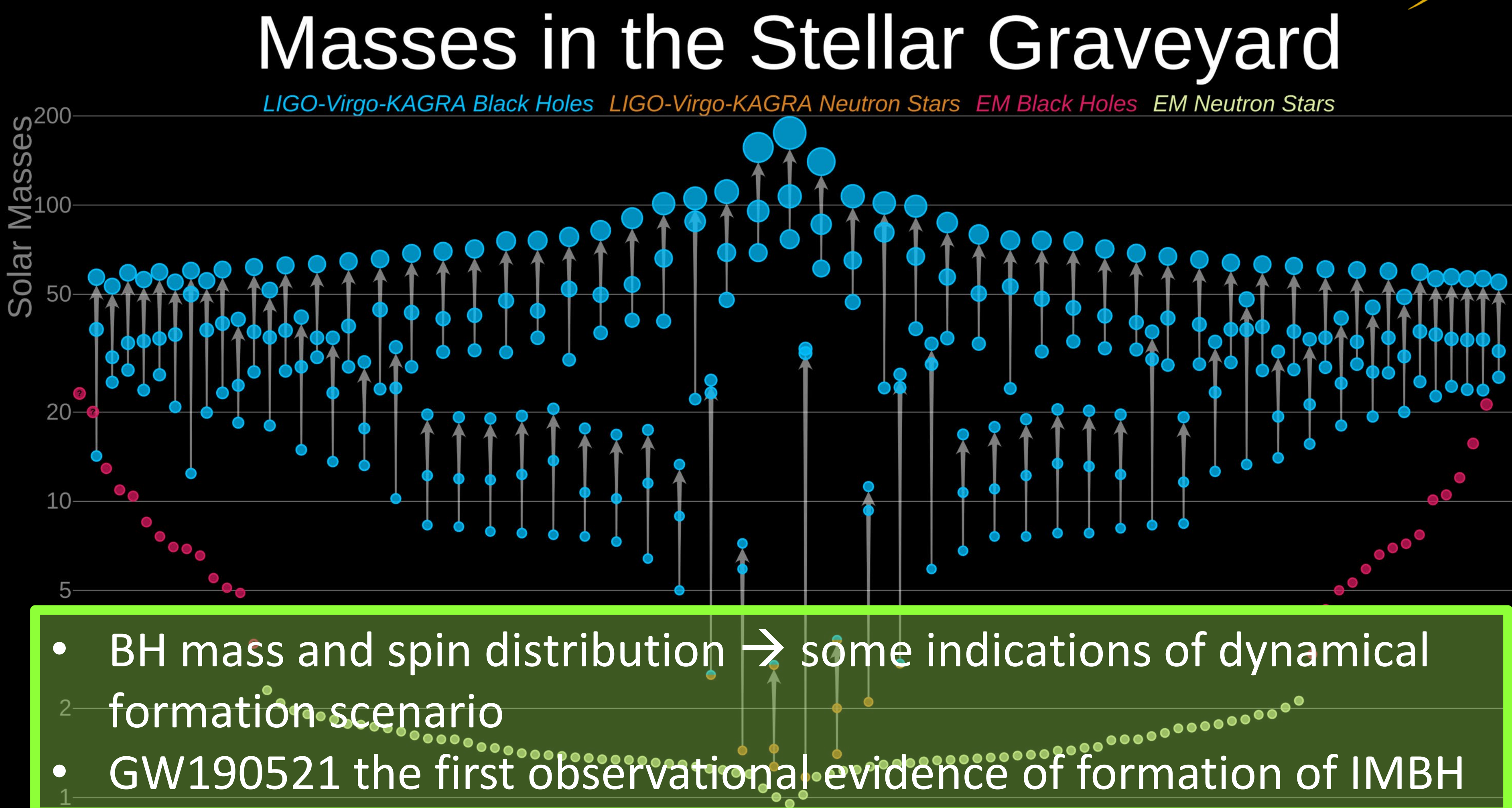


LOCAL ASTROPHYSICAL RATE

- **BNS 10-1700 Gpc^{-3} yr^{-1}**
- **NSBH 7.8-140 Gpc^{-3} yr^{-1}**
- **BBH 17.9-44 Gpc^{-3} yr^{-1}**
  (at z=0.2)

LVK Physical Review X, 2023, 13, 011048

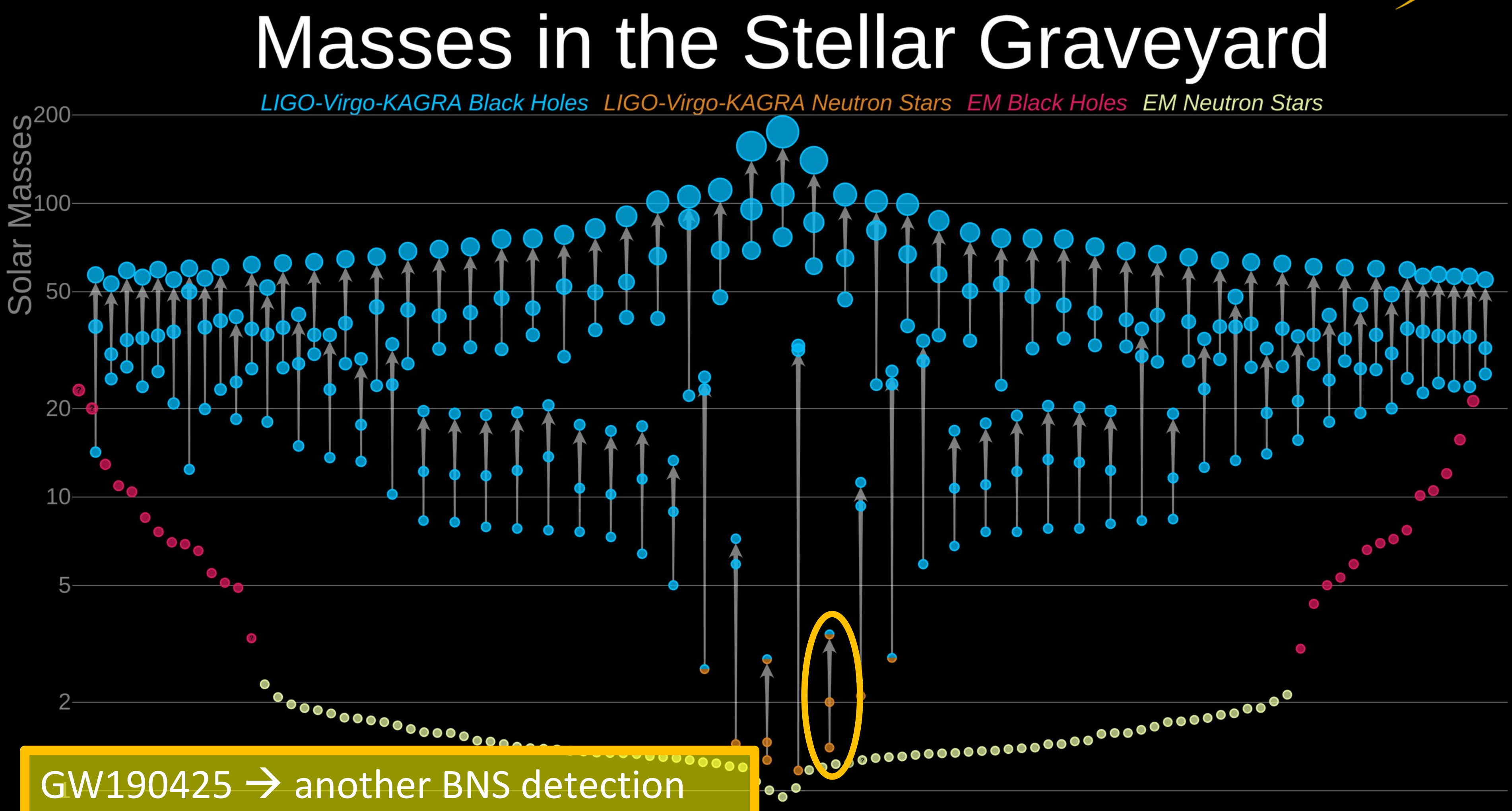
Some of the interesting results in O3



- BH mass and spin distribution → some indications of dynamical formation scenario
- GW190521 the first observational evidence of formation of IMBH

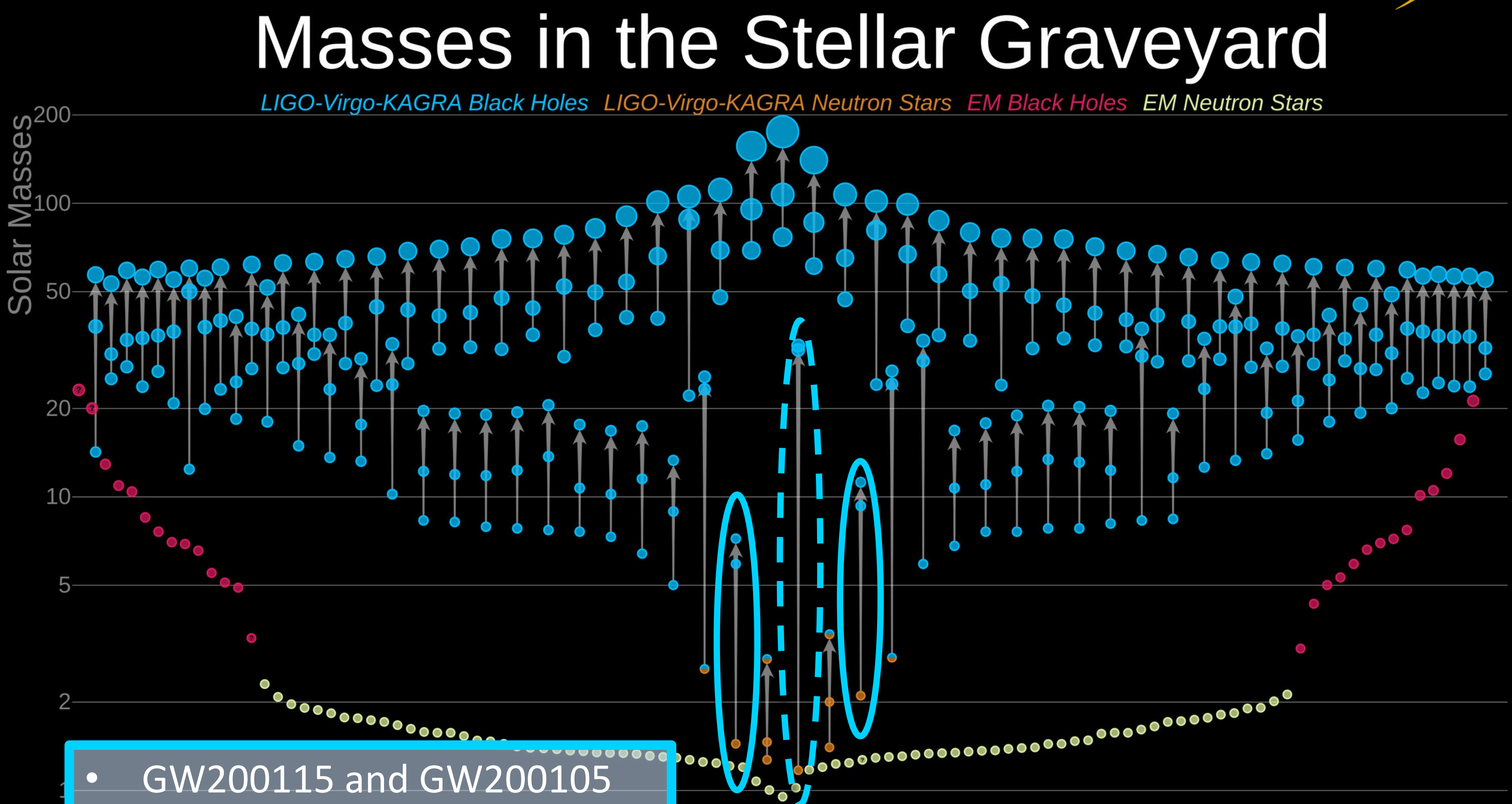
LVK Physical Review X, 2023, 13, 011048
LVK 2020, APJL, 900

Some of the interesting results in O3



GW190425 → another BNS detection
Total mass larger than any known BNS
(5σ from mean of Galactic BNS)

Some of the interesting results in O3

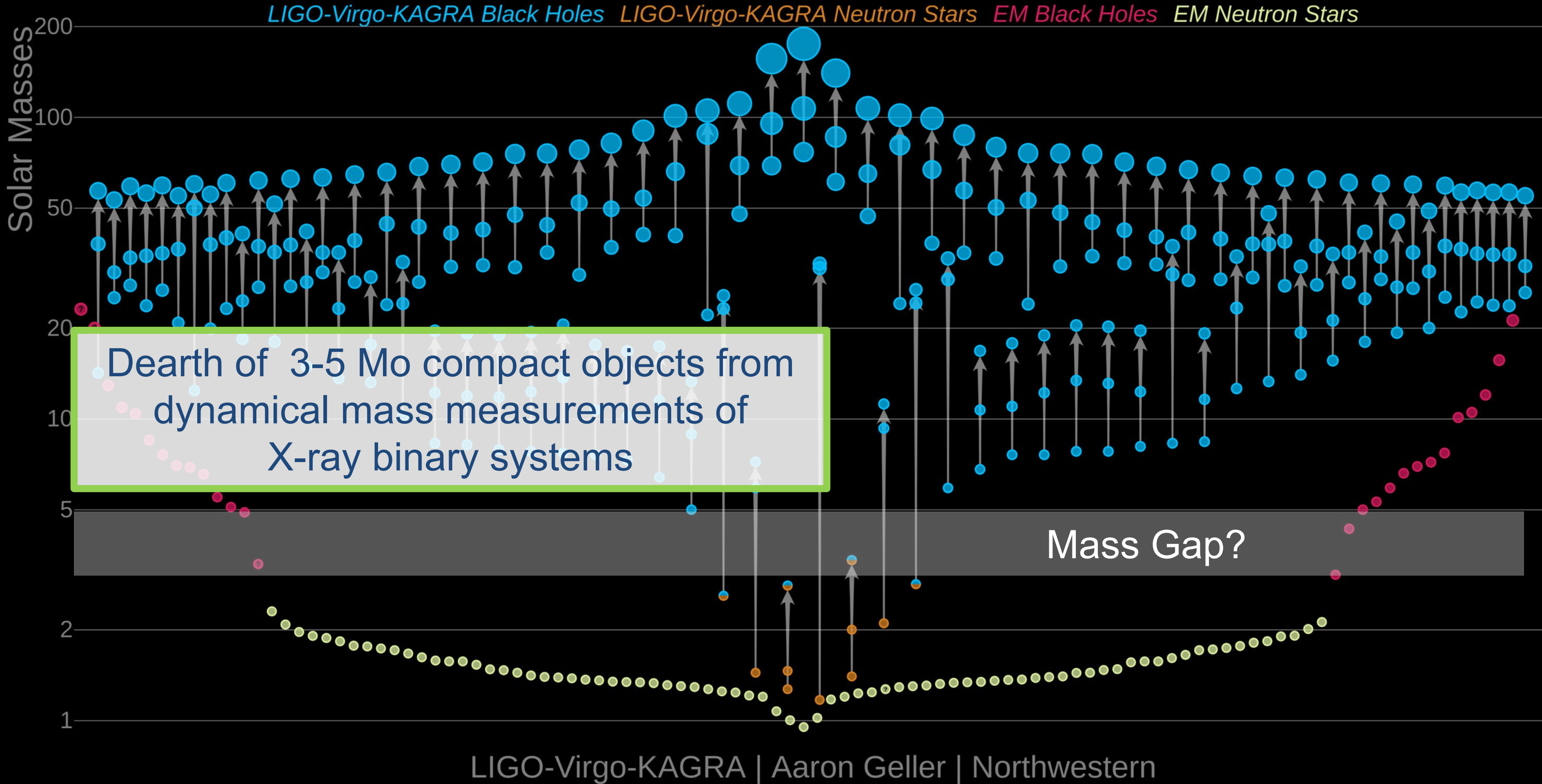


- GW200115 and GW200105 → first observations of NSBH
- GW191219 candidate NSBH

Abbott et al. 2021, ApJL 915
LVK Physical Review X, 2023, 13, 011048

First result from O4

Masses in the Stellar Graveyard



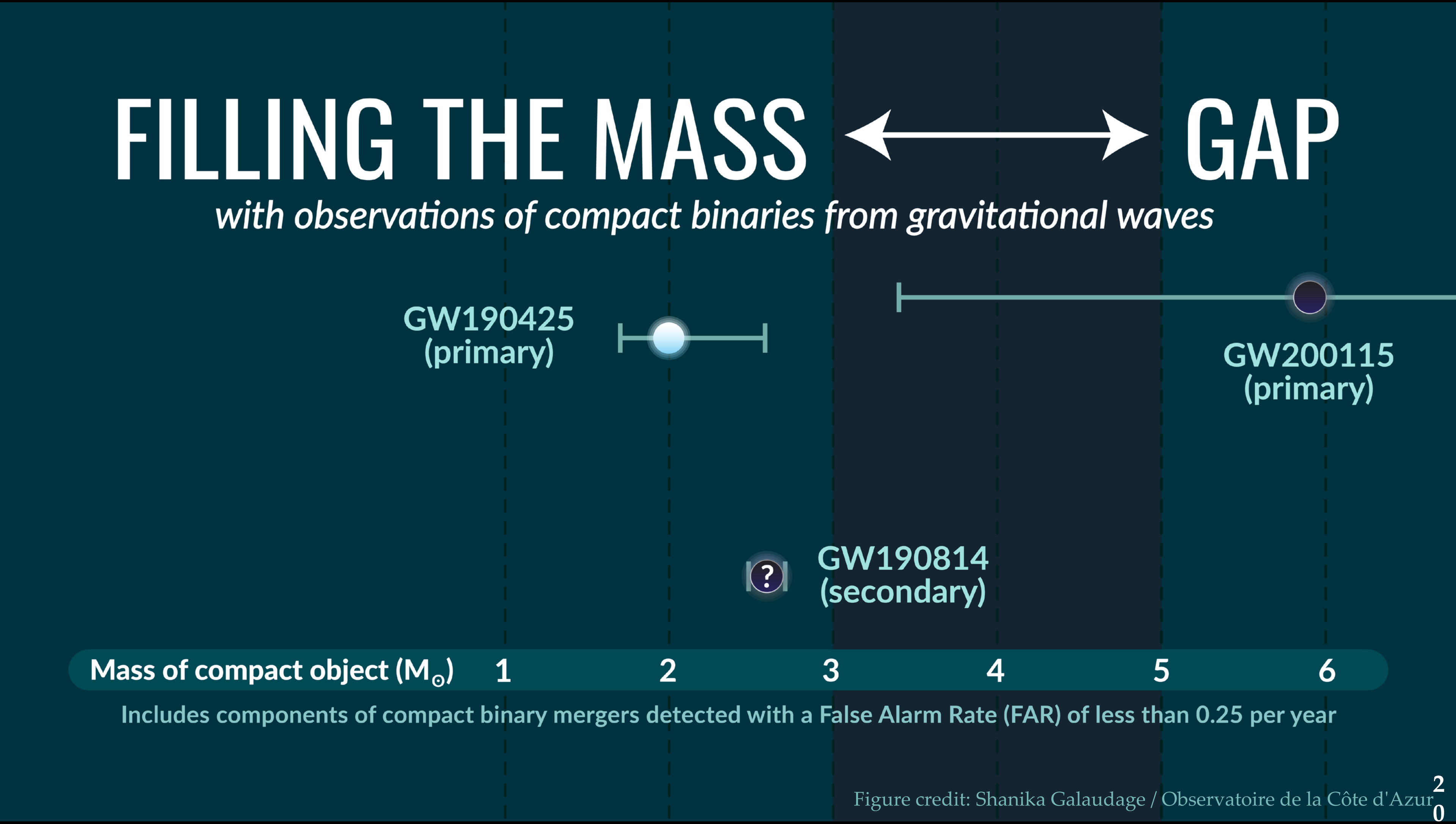
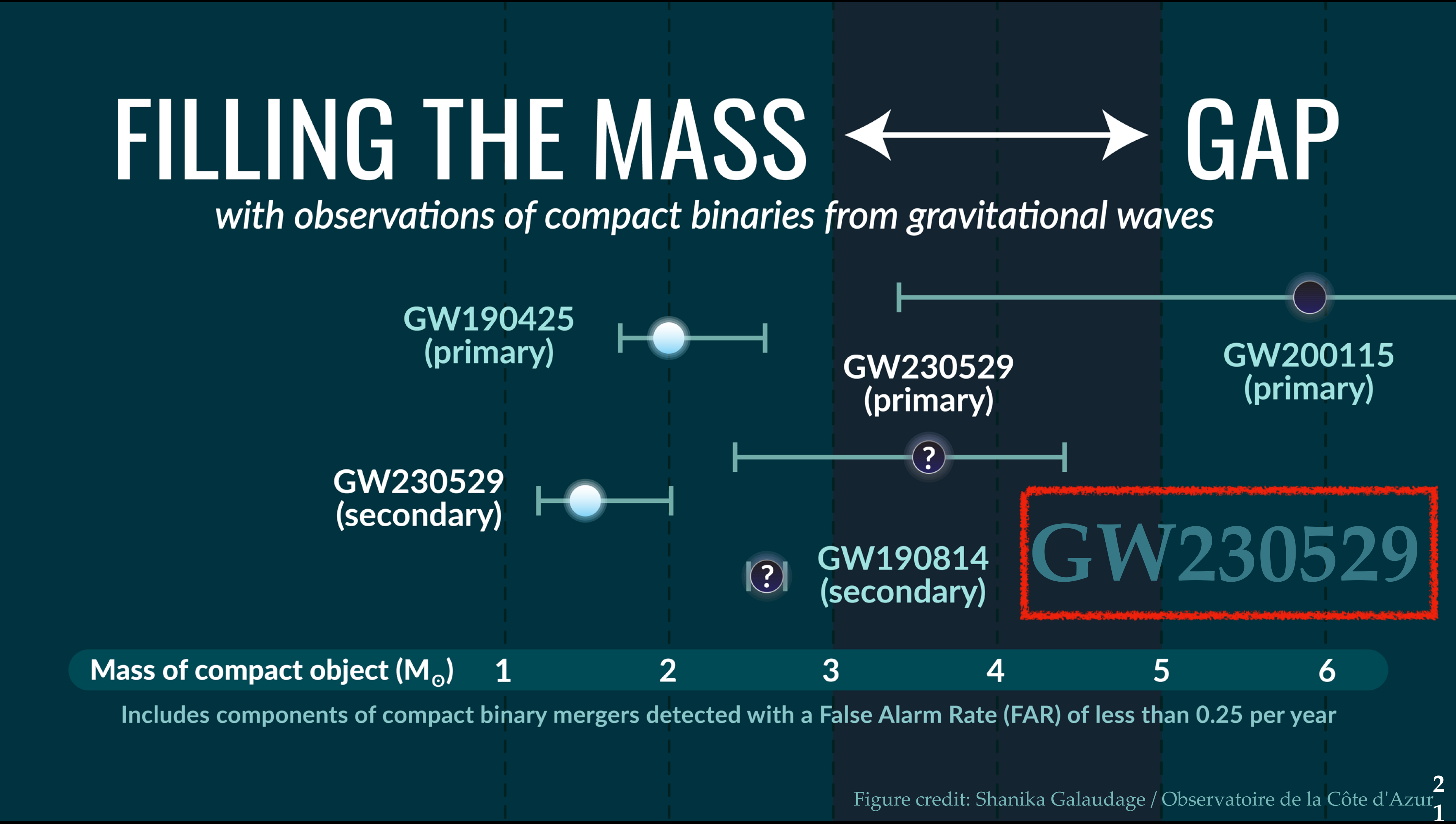


Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur

LVK arXiv 2404.04248

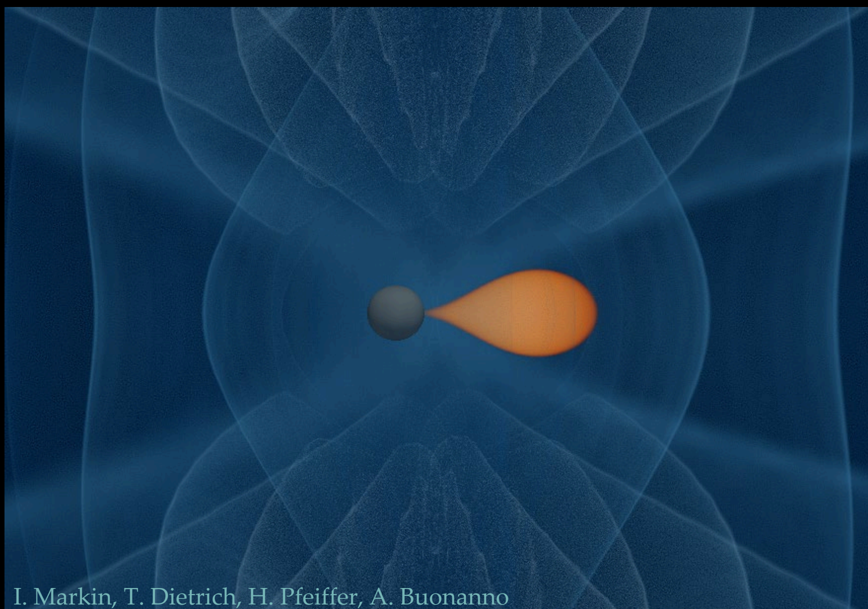


GW230529 provides best evidence of compact objects existing in the lower mass gap

GW230529

LVK arXiv 2404.04248

- Likely a neutron star merging with a mass-gap compact object
- the primary component of the source has a mass less than 5 $M_{\odot}$ at 99% credibility

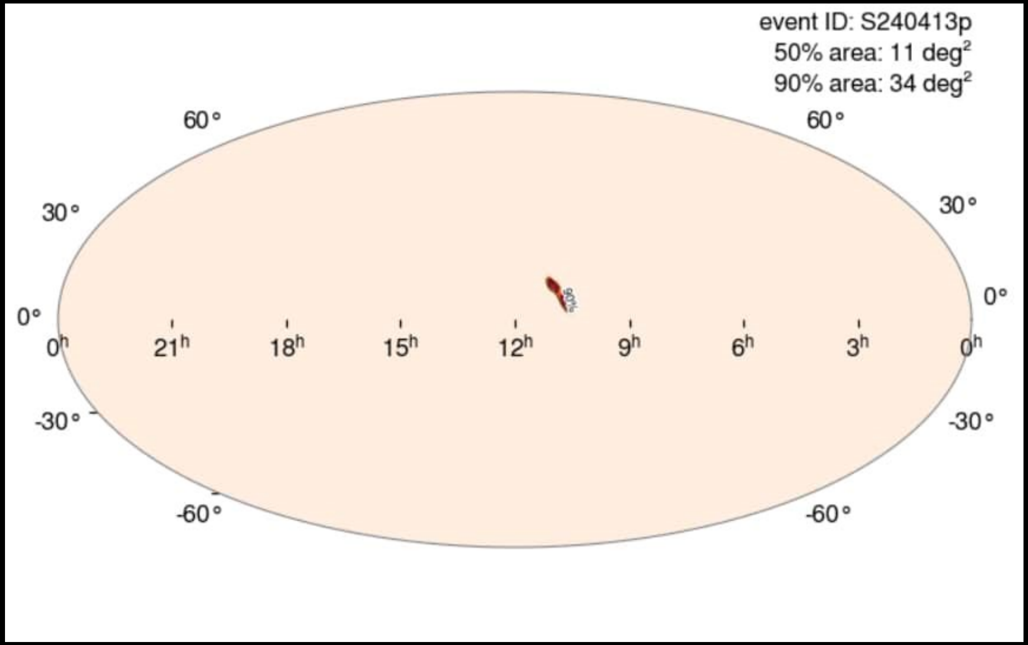


Primary mass $m_1/M_{\odot}$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_{\odot}$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_{\odot}$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_{\odot}$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_{\odot}$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

- updated local NSBH merger rate: $\mathbf{30-200}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- most probable detected NSBH to have undergone tidal disruption (increased symmetry in its component masses)
- no EM couterpart: poor sky-localization

O4b started on April 10

- Virgo join O4 with a BNS sensitivity of 60 Mpc
- First «triple detection (HLV)» on Friday 13
- BBH (or possibly, NSBH) with an EXCELLENT sky localization



NO multi-messenger event after GW17017

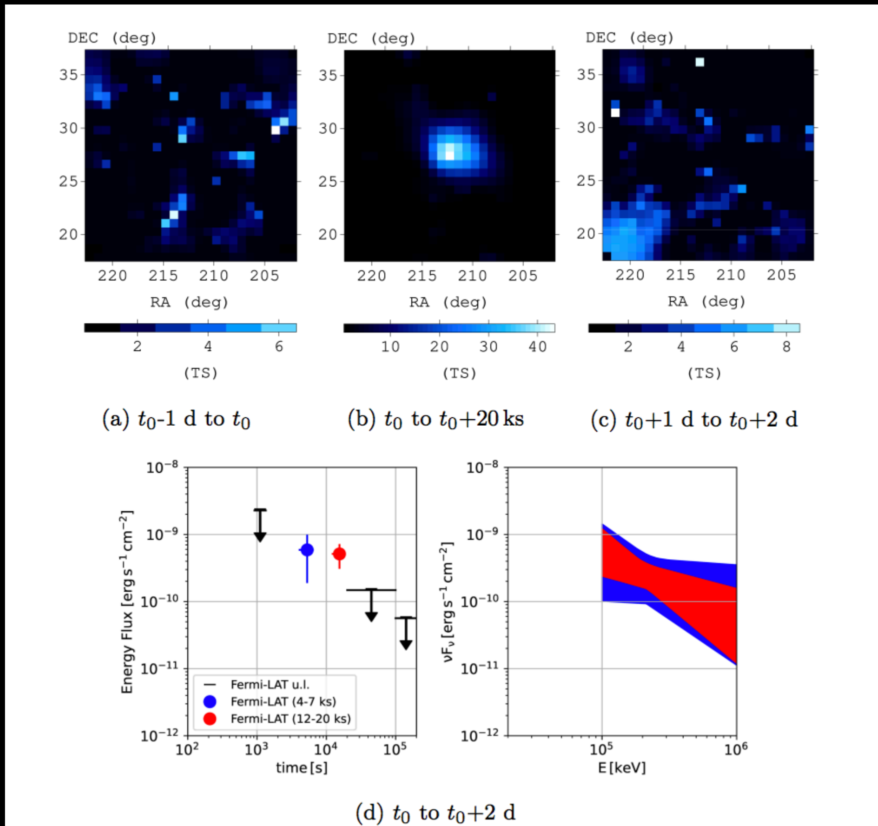
BNS mergers are there!

- *Expected a few to a few tens of MM detections per year with the current GW detectors up to z = 0.2*

- Two long GRBs with kilonova emission, GRB 211211A and GRB 230307A within the current GW detector reach!

Rastinejad et al. 2022 Nature, Mei et al. 2022 Nature, Troja et al. 2022 Nature, Levan et al.2023 Nature

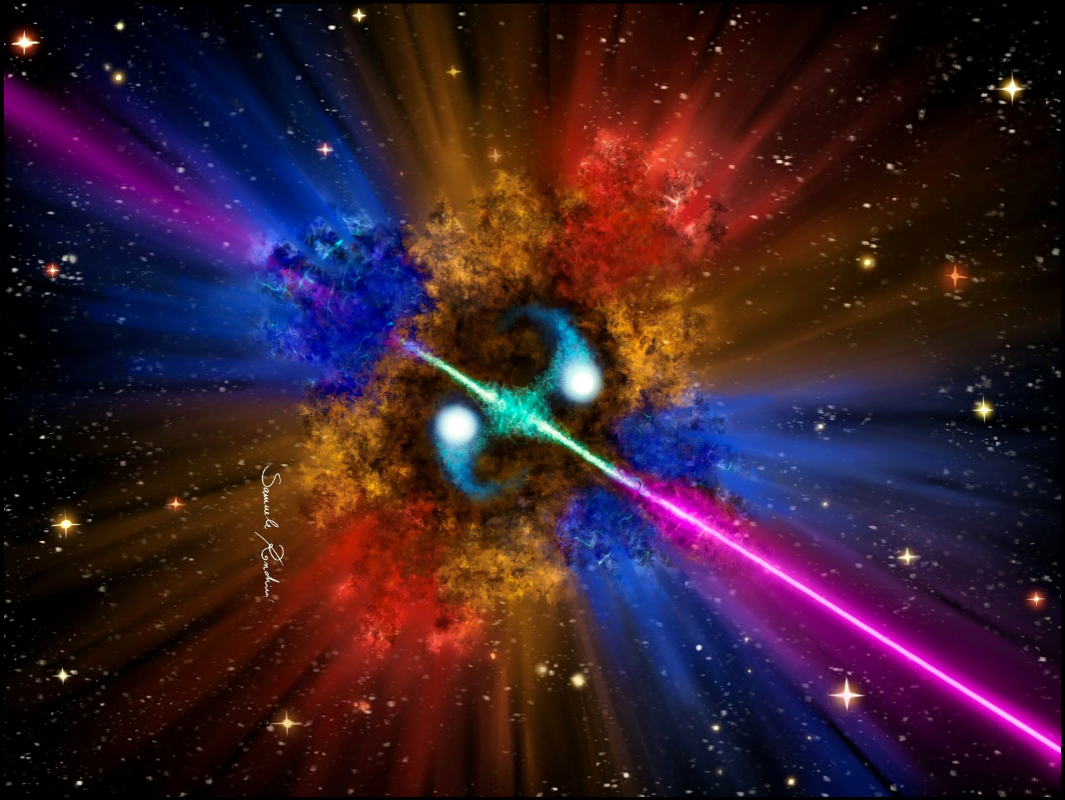
GRB 211211A: GeV counterpart by Fermi-LAT



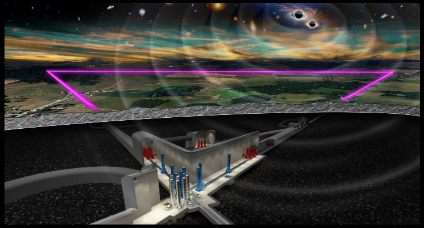
Mei et al. 2022, Nature

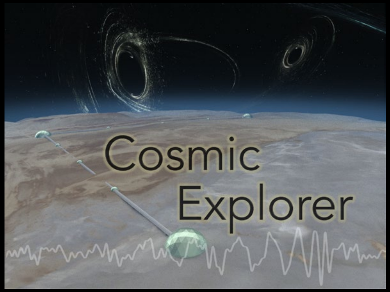
in EXCESS with respect to standard afterglow

Seeds photons emitted from the kilonova ejecta scattered via inverse Compton by electrons in a low-power jet launched at late times



In the era of next GW detector
MM detections will be routine!





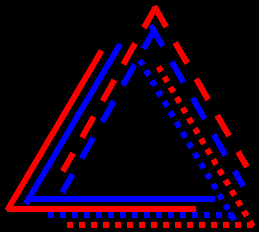
Next generation GW astronomy and multi-wavelenght follow-up

See GWIC roadmap; Bailes et al. 2021, Nature Reviews Physics; Maggiore et al 2020, JCAP; Evans et al. 2021 arXiv:2109.09882; Branchesi et al. 2023, JCAP

ET: the European 3G GW observatory concept

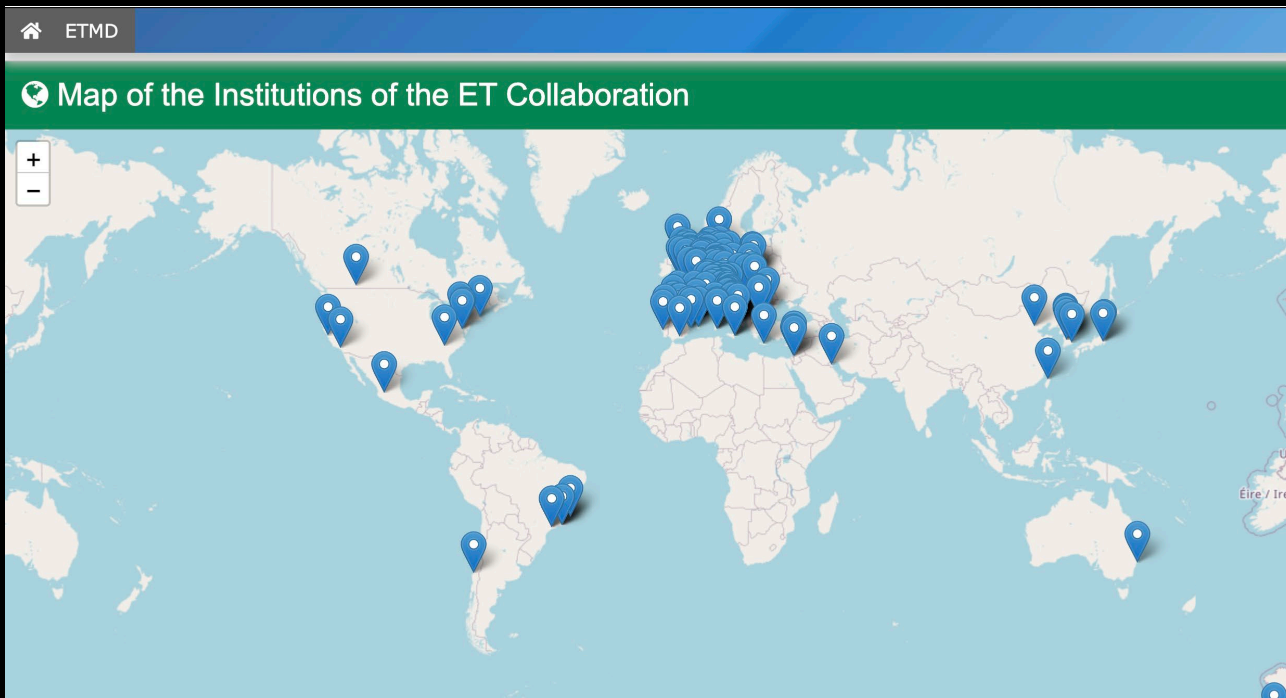
EINSTEIN TELESCOPE

Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...



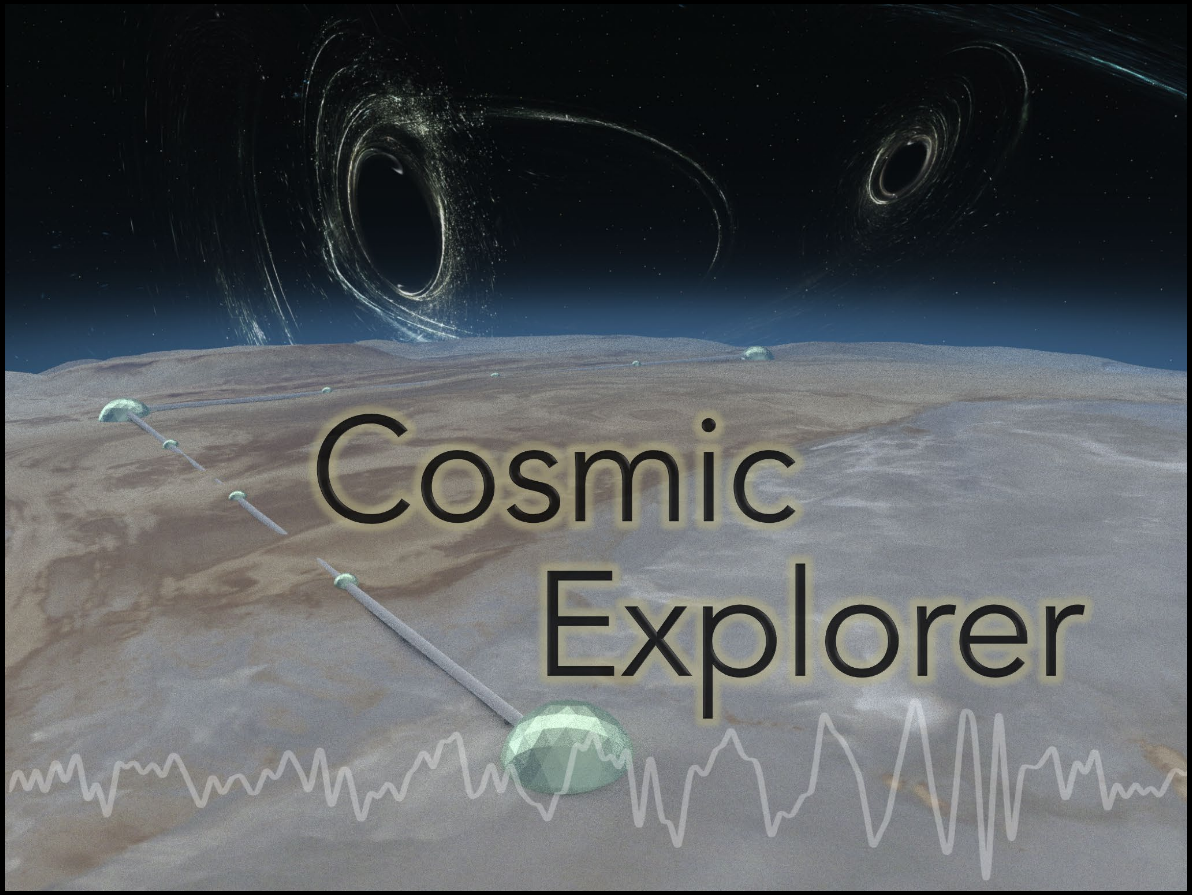
INCLUDED IN ESFRI ROADMAP in 2021

ET collaboration



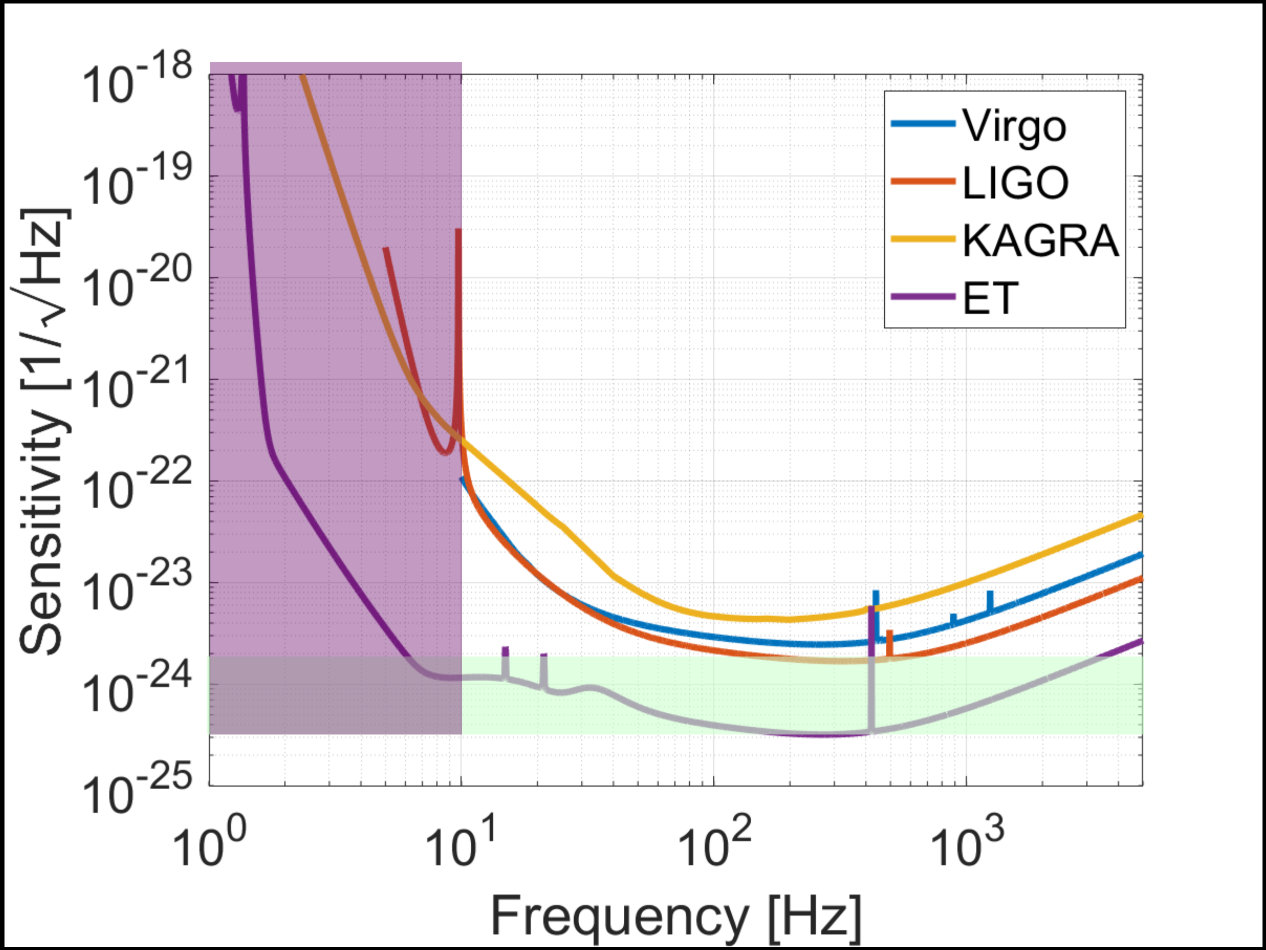
Currently **1631 members** representing **237** Institutions in **28** different countries

Next generation GW effort worldwide



Cosmic Explorer: L shaped detectors, two sites
(40km, 20 km [option])

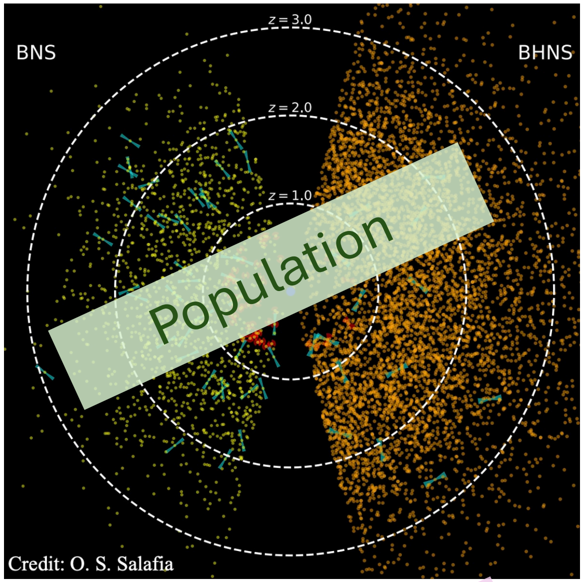
EXPECTED SENSITIVITY

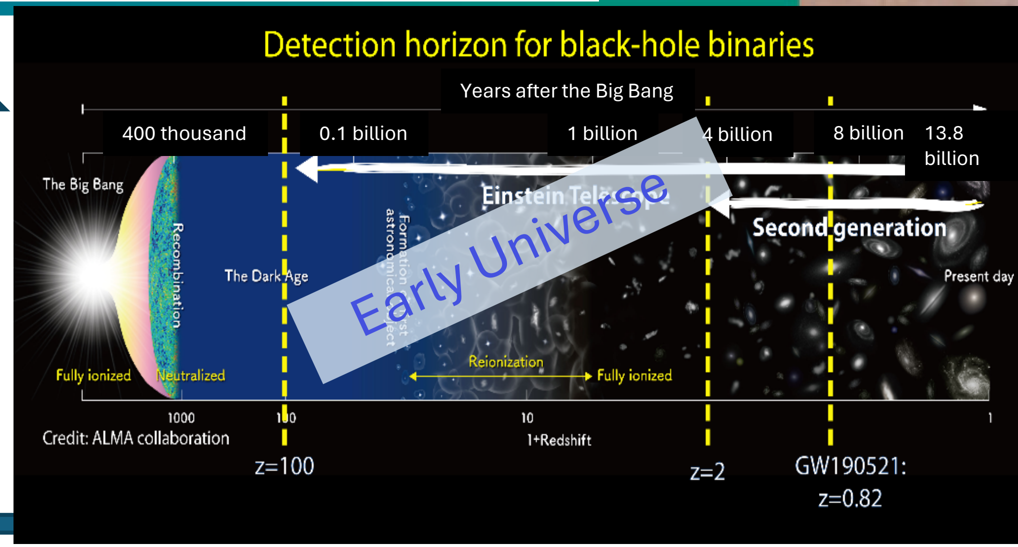


ESFRI

ET Science in a nutshell

EINSTEIN TELESCOPE

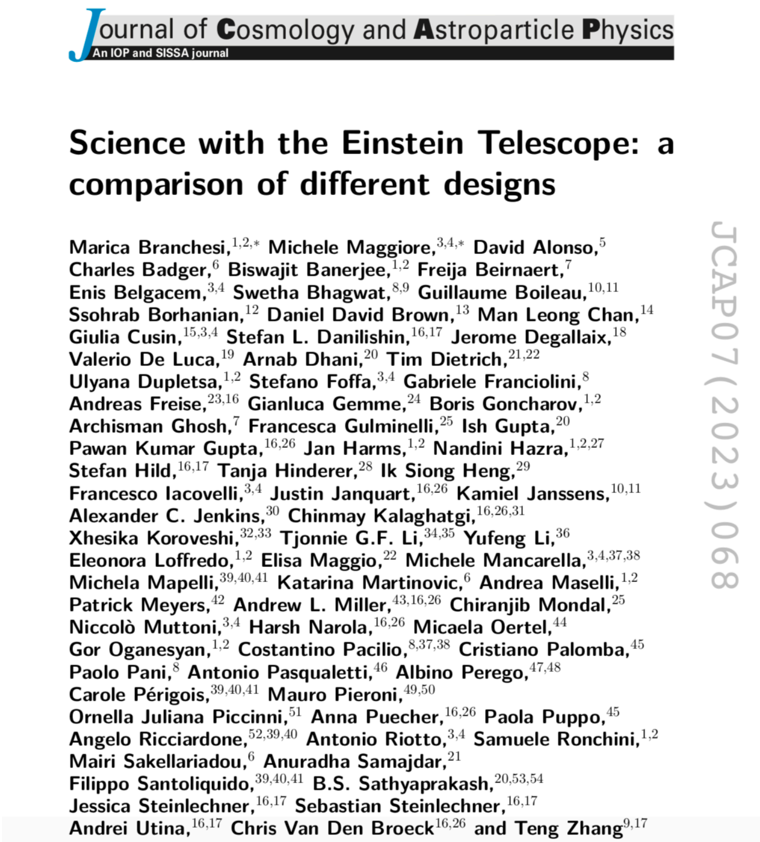




Combination of

- distances and masses explored
- number of detections
- detections with very high SNR

wealth of data expected to ***revolutionize astrophysics, nuclear physics, cosmology and fundamental physics***



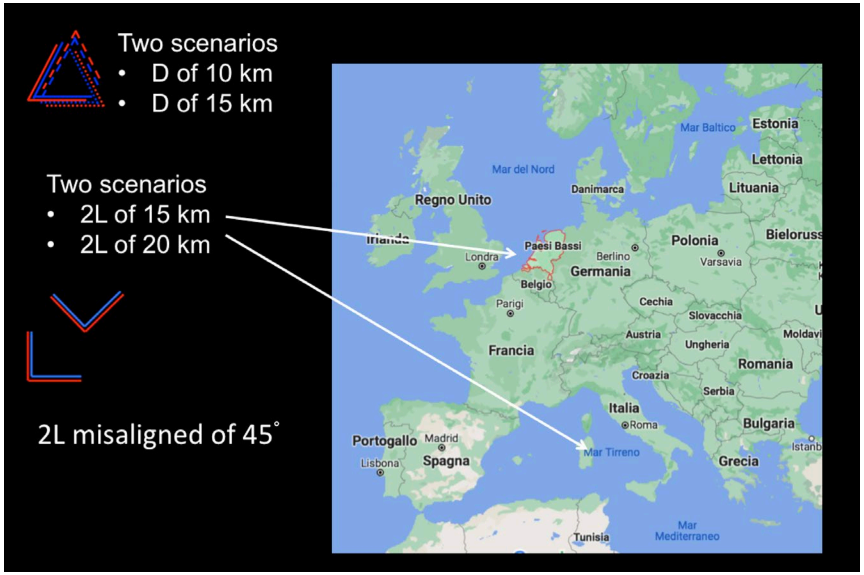
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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]

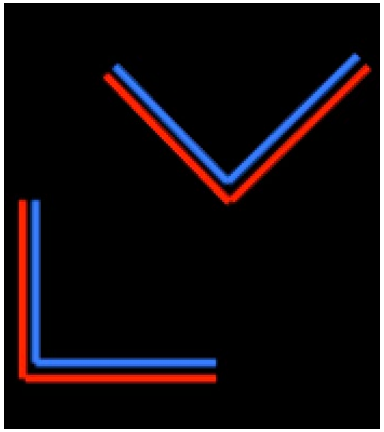
JCAP07(2023)068

ET design: 2L vs Triangle science case



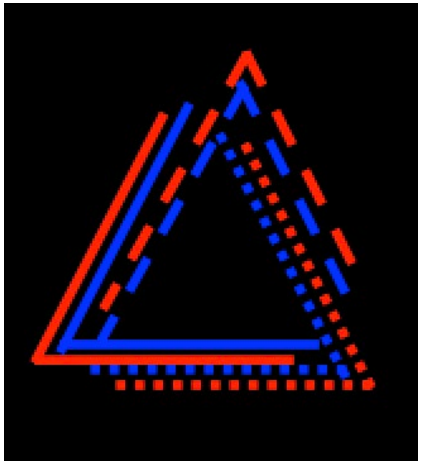
- New updated Science Case Paper for ET
- Detailed comparison among different configurations and designs through simple metrics and specific science cases

ET design: 2L vs Triangle science case



- the 15 km 2L misaligned is superior on almost all the metrics with respect to triangle 10 km

- for compact binary coalescences, the 15 km 2L misaligned enable an **improvement factors of order 2-3** on the **number of even**ts which pass given cuts on SNR and on the **accuracy of parameter** reconstruction

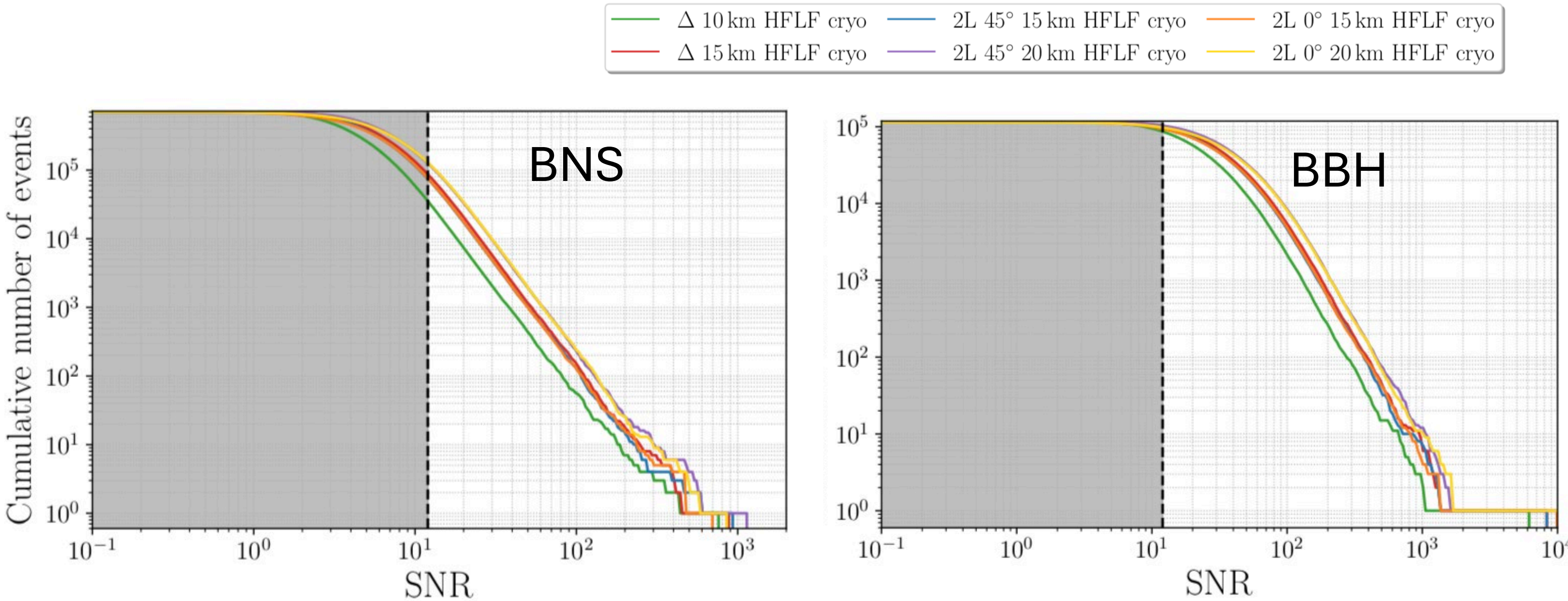


ET Blue-book (work in progress):

- the blue book will enlarge the scientific cases and include covering several assumptions and models to provide a global overview of the science
- Ready in Autumn

Multi-messenger in the ET era:
a few numbers

A few ET numbers

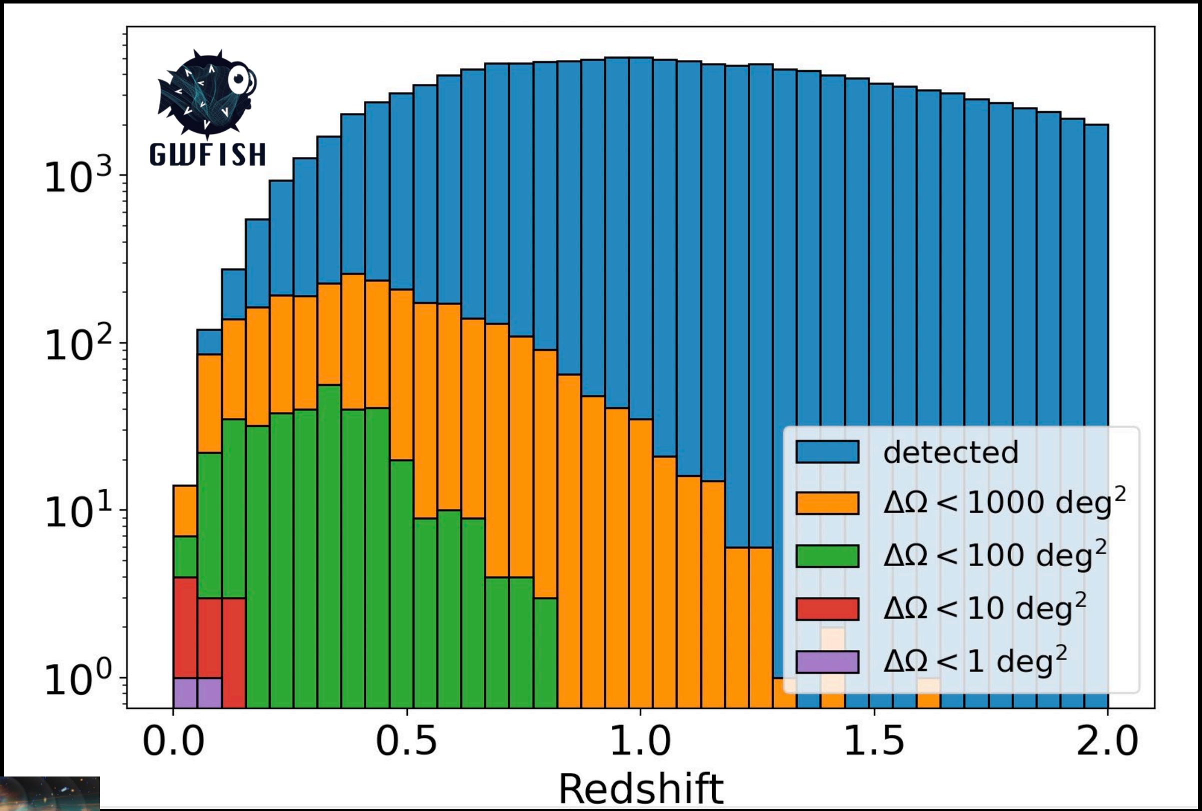


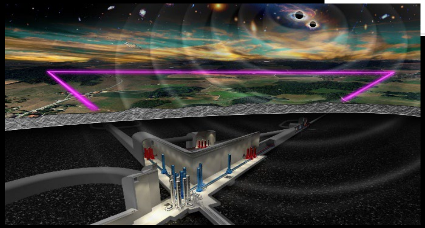
10^5 BNS alerts per year
10^5 BBH alerts per year

→ A few tens of alerts per hour
Overlapping signals

Branchesi, Maggiore et al 2023, JCAP

ET sky-localization capabilities

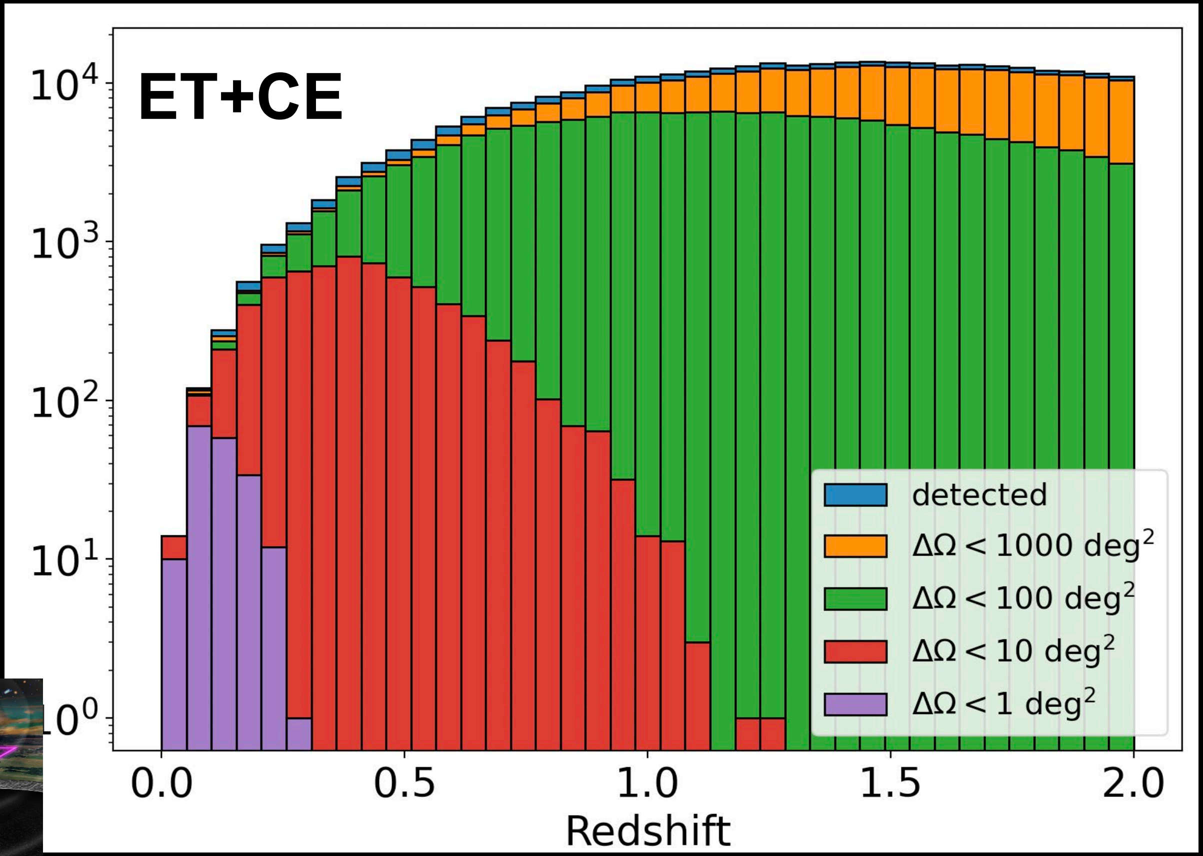


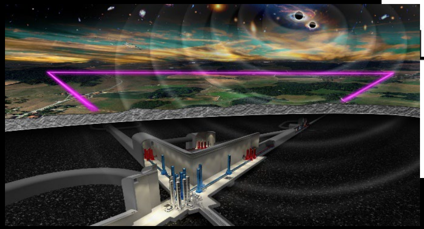


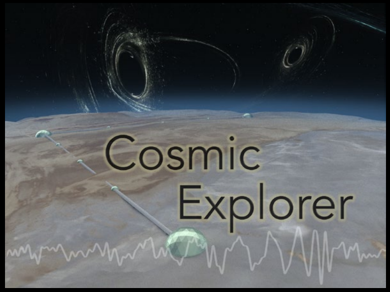
ET low frequency sensitivity make it possibile
To localize BNS!

- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

Network sky-localization capabilities

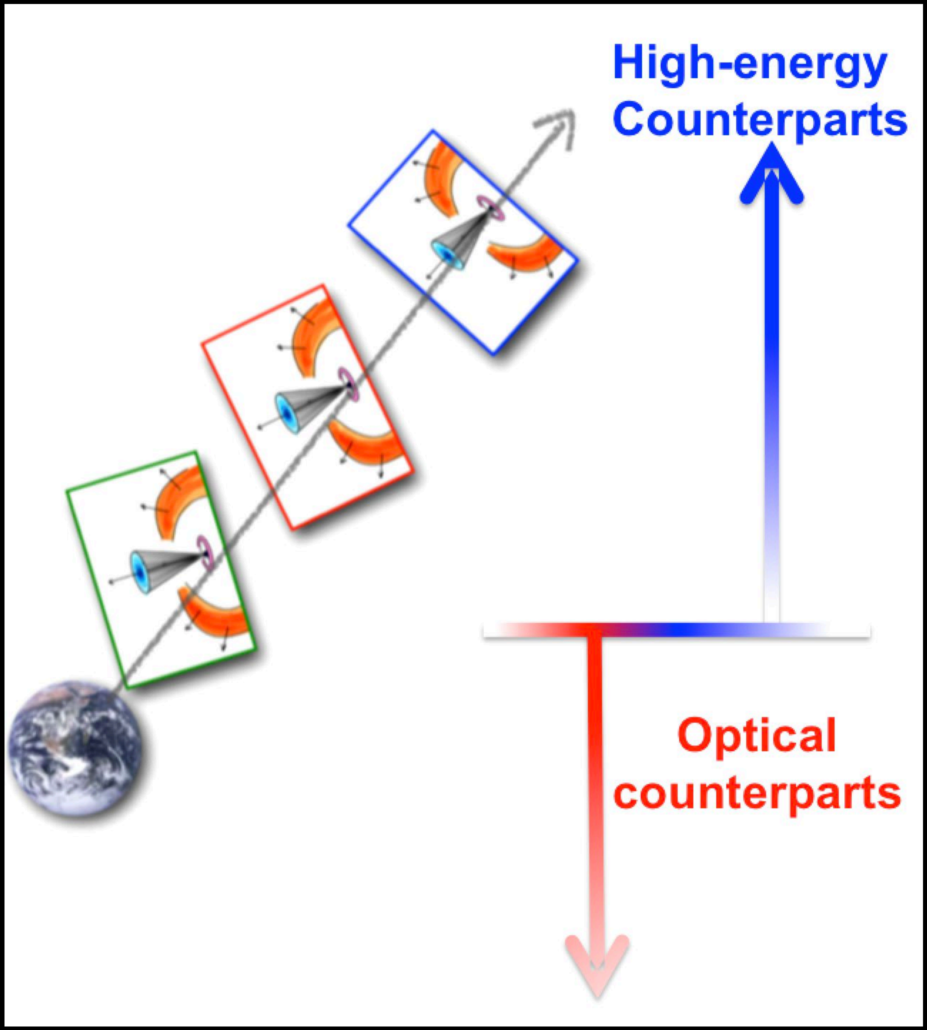






- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

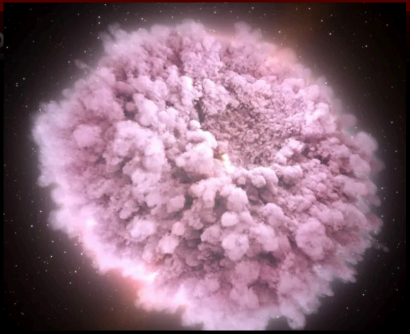
Dupletsa et al. 2023, Ronchini et al. 2022



RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS,
COSMOLOGY and MODIFIED GRAVITY

Credit: Ronchini

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE



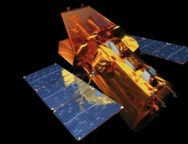
Hundred of MM events per year!

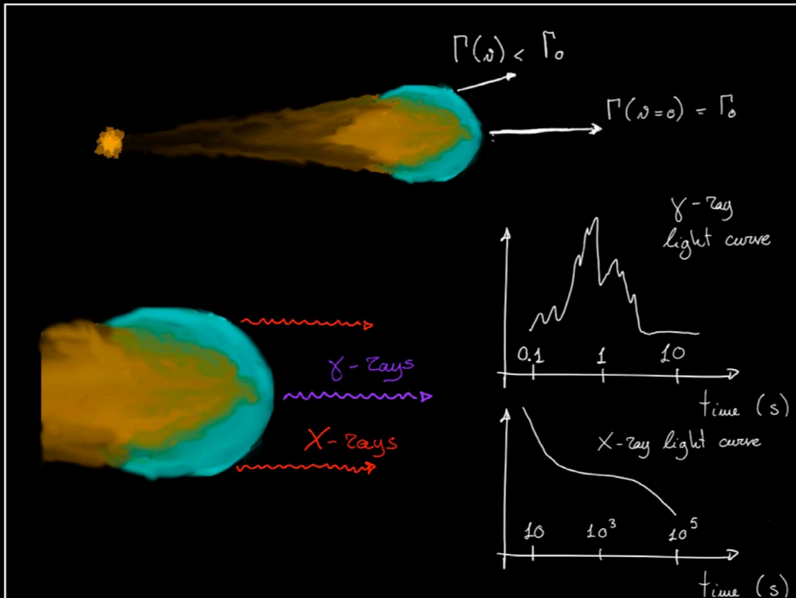
Image credit: NASA Goddard Space Flight Center

HIGH-ENERGY

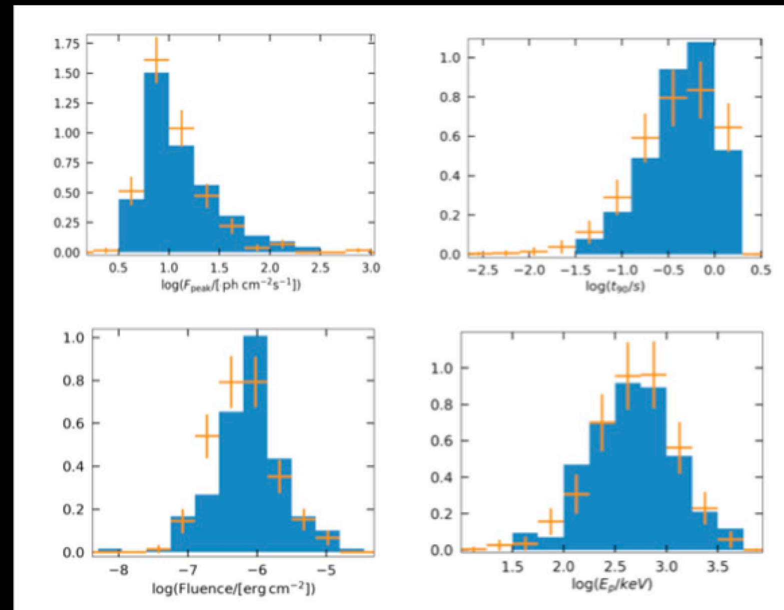
RELATIVISTIC JET PHYSICS, GRB EMISSION MECHANISMS, COSMOLOGY and MODIFIED GRAVITY

Prompt and afterglow emission from a structured jet



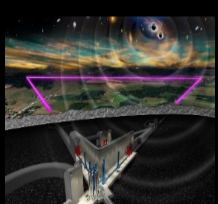


BNS population calibrated using
Fermi and Swift short GRBs



Almost all detected short GRB will have a GW counterpart
around 70% ET and 95% ET+CE

Depending on the satellites, we will have
tens to hunreds of detections per year



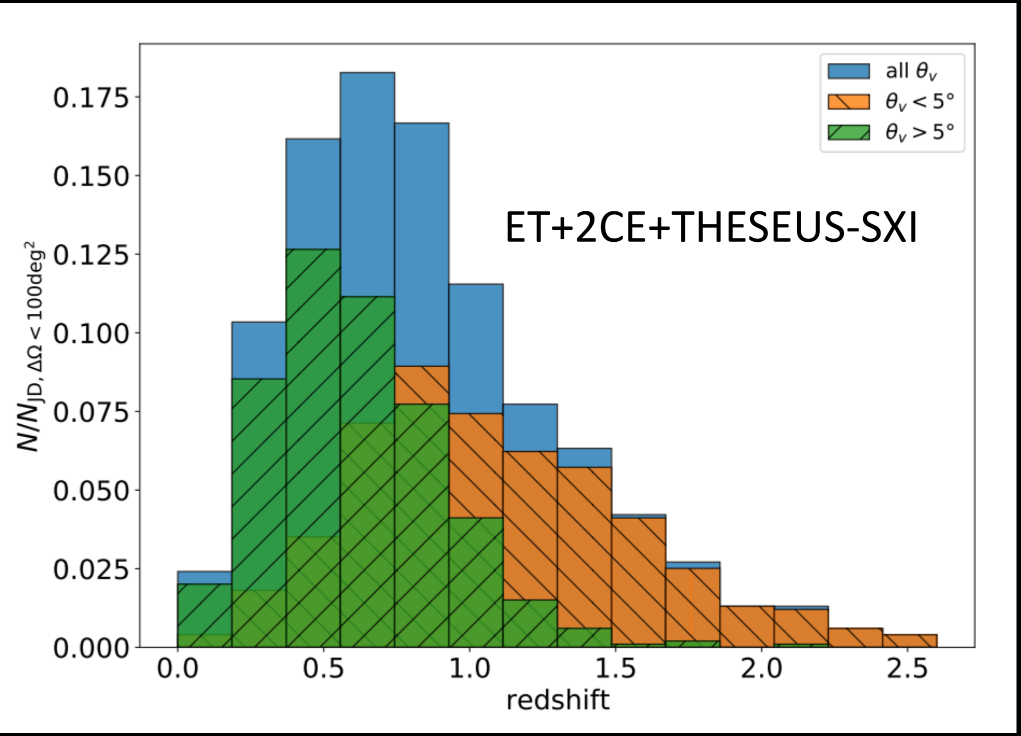
Crucial instruments able to localize at arcmin-arcsec
level to drive the ground-based follow-up!

Ronchini, MB et al. A&A 2022

Joint detection GW+X-ray afterglow per year

WFX-ray monitors

Redshift distribution of joint X-ray+GW detections observed in pointing mode



Joint GW+Xray detections

WFX-ray telescopes

- significant increase of joint detections: tens-hundreds per year
- enable to study jet structure
- trigger ground-based follow-up and more sensitive instrument such as ATHENA

Ronchini, MB, Oganesyan, et al. A&A 2022

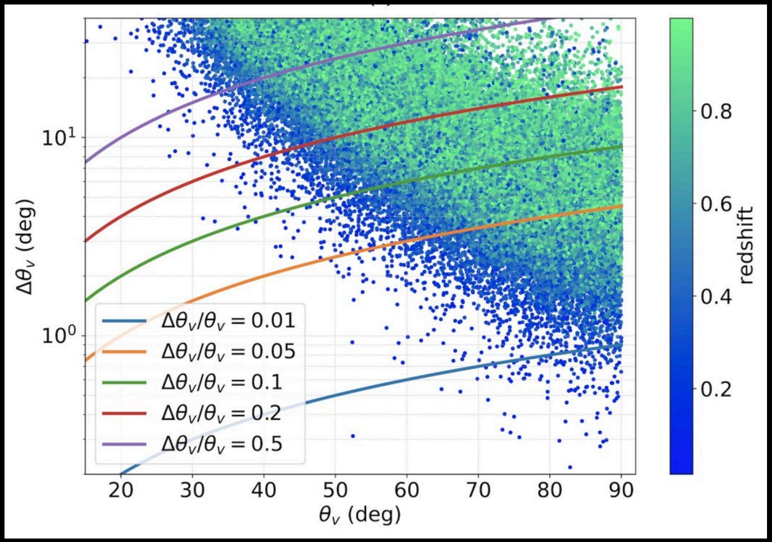
Prioritization of triggers required

Sky-localization

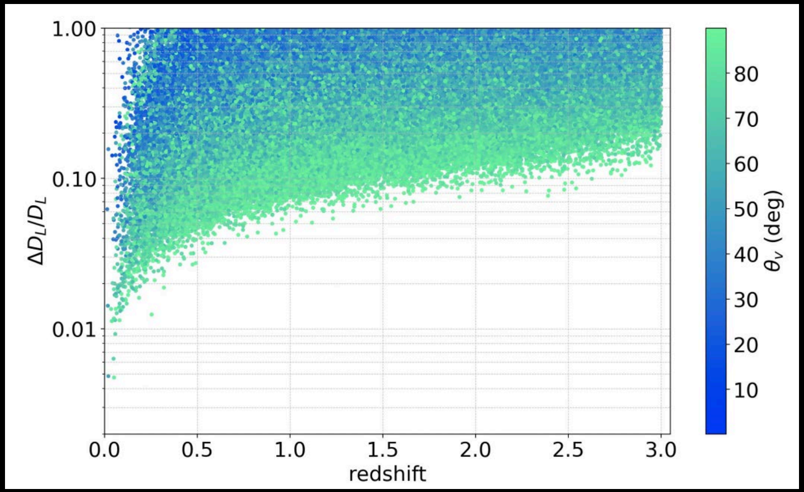
	ET	ET+CE	ET+2CE
$N_{\rm det}$	143970	458801	592565
$N_{\rm det}(\Delta\Omega < 1\ {\rm deg}^2)$	2	184	5009
$N_{\rm det}(\Delta\Omega < 10\ {\rm deg}^2)$	10	6797	154167
$N_{\rm det}(\Delta\Omega < 100\ {\rm deg}^2)$	370	192468	493819
$N_{\rm det}(\Delta\Omega < 1000\ {\rm deg}^2)$	2791	428484	585317

Too large numbers of triggers well localized to be followed-up

Viewing angle

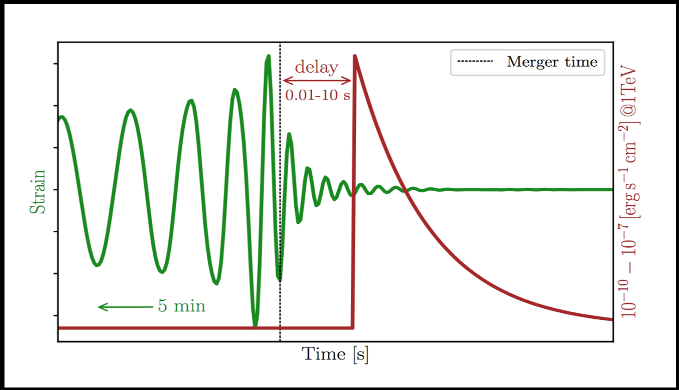


Distance



Ronchini et al. A&A 2022

Pre-merger detections



ET alone

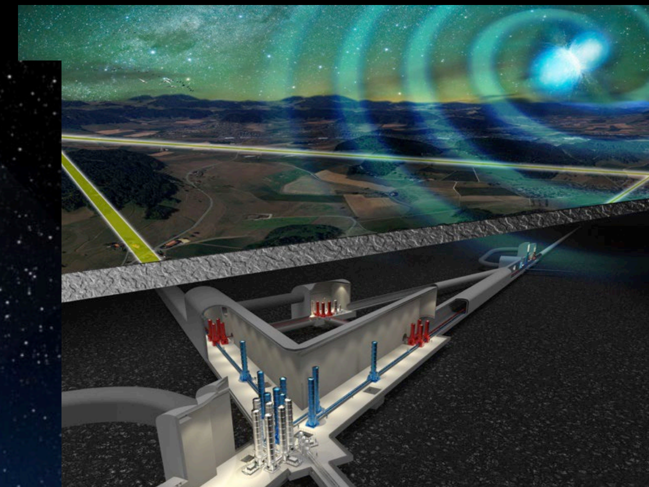
Branchesi, Maggiore et al. 2023, JCAP

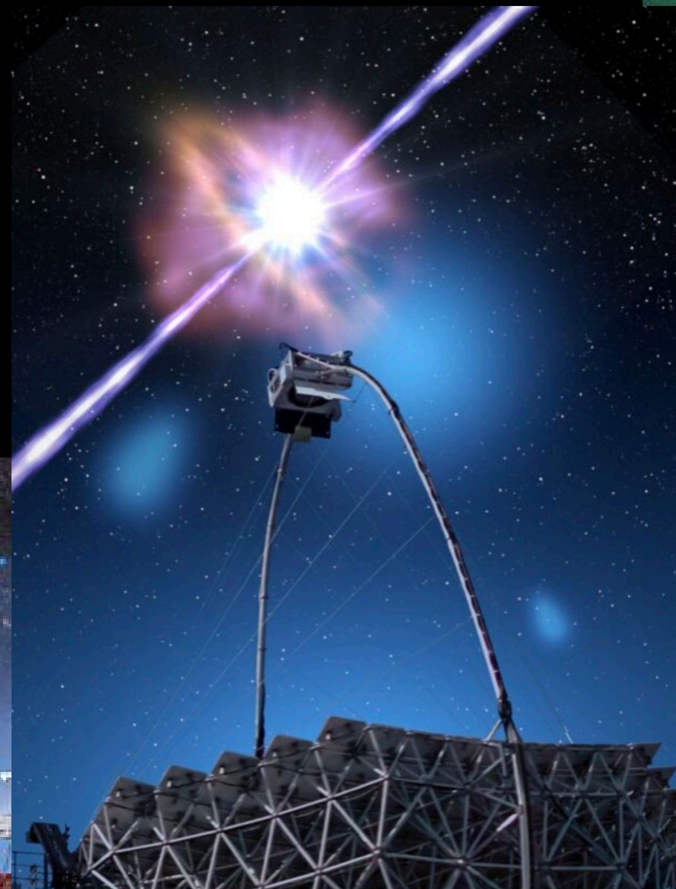
Configuration	$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs 30 min	All orientation BNSs 10 min	All orientation BNSs 1 min	BNSs with $\Theta_v < 15°$ 30 min	BNSs with $\Theta_v < 15°$ 10 min	BNSs with $\Theta_v < 15°$ 1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	132
	All detected	905	4343	23597	81	393	2312
2L 15 km misaligned	10	0	1	8	0	0	0
	100	20	54	169	2	7	26
	1000	194	565	1399	23	73	199
	All detected	2172	9598	39499	198	863	3432

Five minutes before the merger, a **factor 10 higher number of well-localizaed events** when ET operates in a network of next generation GW detectors

See Banerjee et al. 2023, A&A

CTA and GW DETECTOR synergies

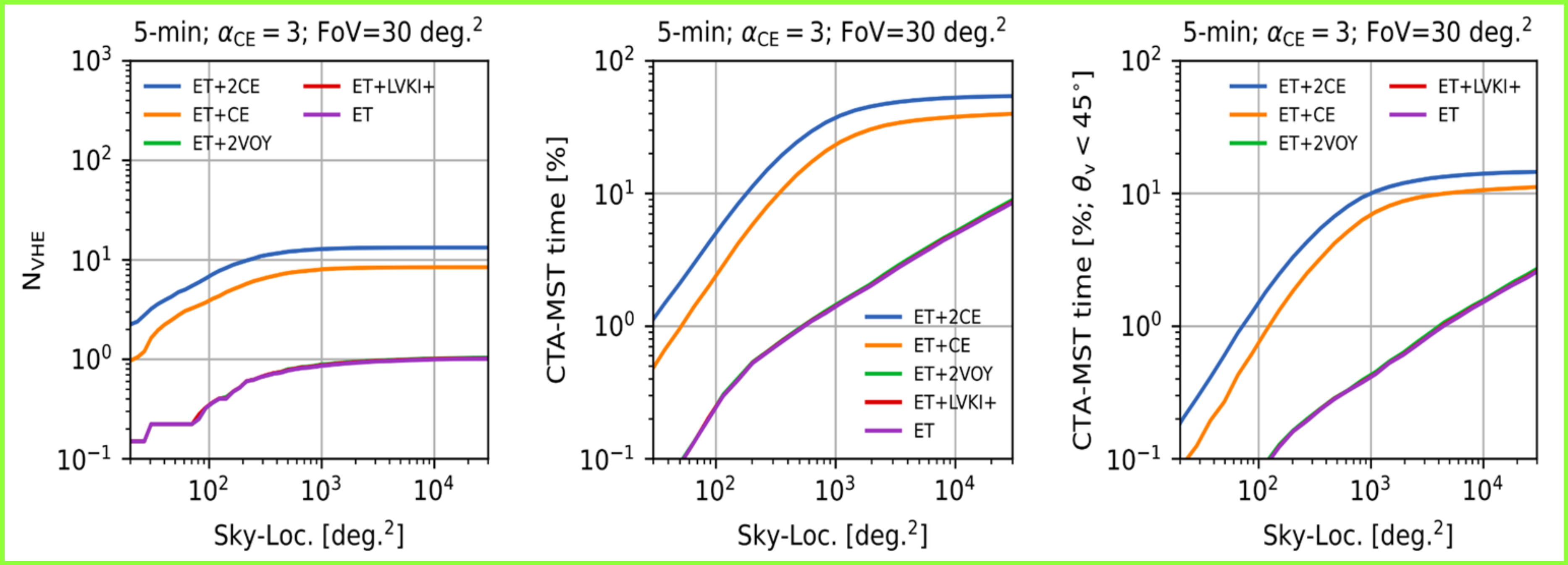




GRB 190114C (MAGIC)
GRB 180720B(HESS)
Afterglow VHE emission!

LHAASO experiment detected the gamma ray burst GRB 221009A up to energies > 10 TeV

Observation strategy: MST



ET+CE: ten VHE counterparts can potentially be detected using 10% of the CTA time

Banerjee, Oganesyan, Branchesi et al 2023, A&A

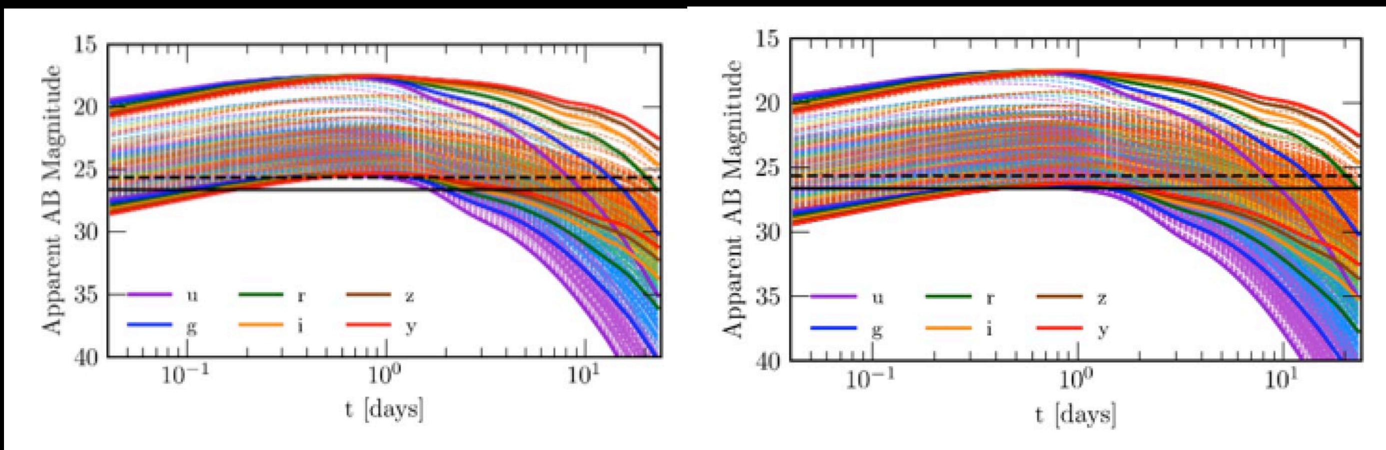
THERMAL EMISSION - KILONOVAE

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and COSMOLOGY

PHYISCS and COSMOLOGY

GW/KILONOVAE

BNSs detected with a sky-localization < 40 deg²



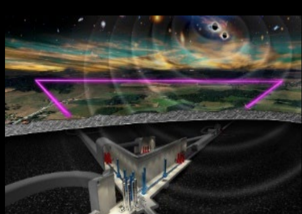
(a) Δ 10 km HFLF cryo

(c) 2L 15 km HFLF cryo

Two filter (g and i) observations repeated the first and second night after the merger and an exposure time for each pointing of 600 s

Branchesi, Maggiore et al. 2023, JCAP

- **Sevaral tens per year** of joint detections of VRO and ET
- **Several hundreds** when ET operates in network of detectors (also current generation ones)



Loffredo, Hazra, Dupletsa et al. in prep
Bisero et al in prep
Colombo et al. In prep

VERA C. RUBIN OBSERVATORY

Some of the next generation multi-messenger observatories

A REVOLUTION IN OUR KNOWLEDGE OF THE EARLY UNIVERSE,
BH and NS TRANNSIENT PHENOMENA ALONG THE COSMIC HISTORY…