MM & GW: challenges & significant results

GS
SI

M. Branchesi
Gran Sasso Science Institute
INFN/INAF/ASI

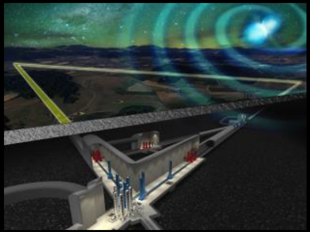
INAF ISTITUTO NAZIONALE DI ASTROFISICA

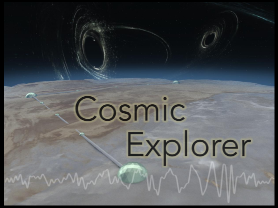
LIGO VIRGO KAGRA

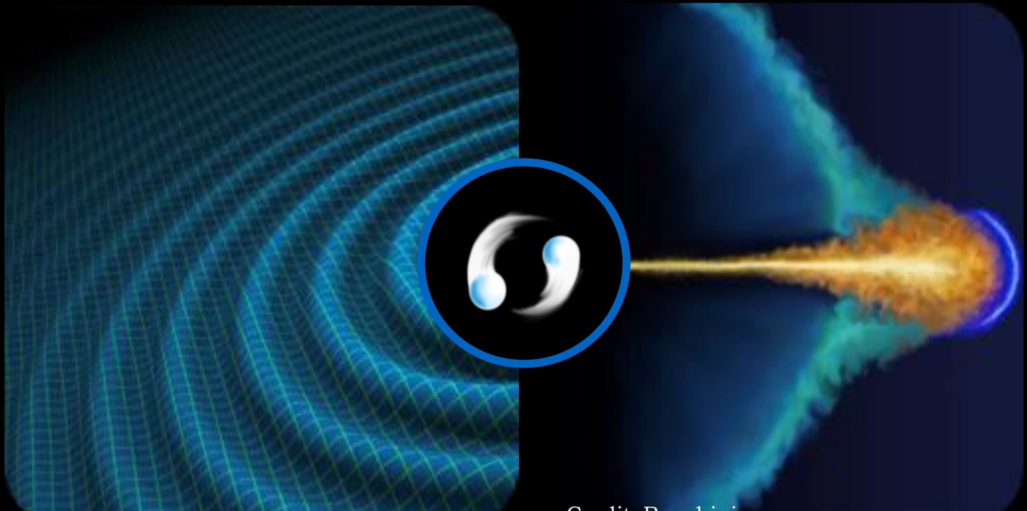
ET EINSTEIN TELESCOPE

ASI

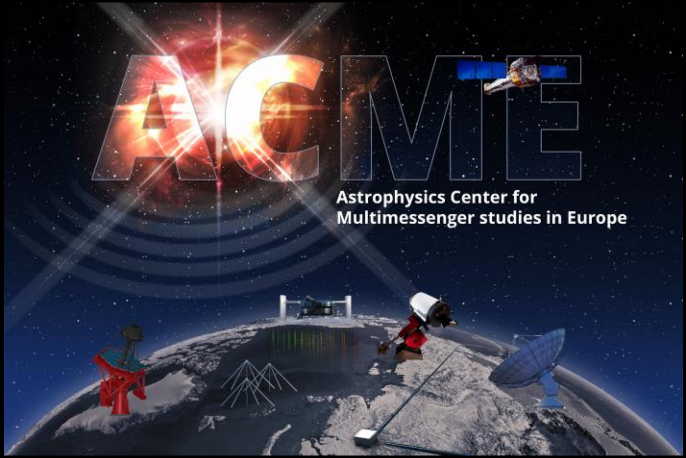
INFN Istituto Nazionale di Fisica Nucleare







Credit: Ronchini



Ground-based gravitational-wave detectors

Credit: LIGO–Virgo

KAGRA, Japan


LIGO, Livingston, LA


LIGO, Hanford, WA


Virgo, Cascina, Italy

Where we are…

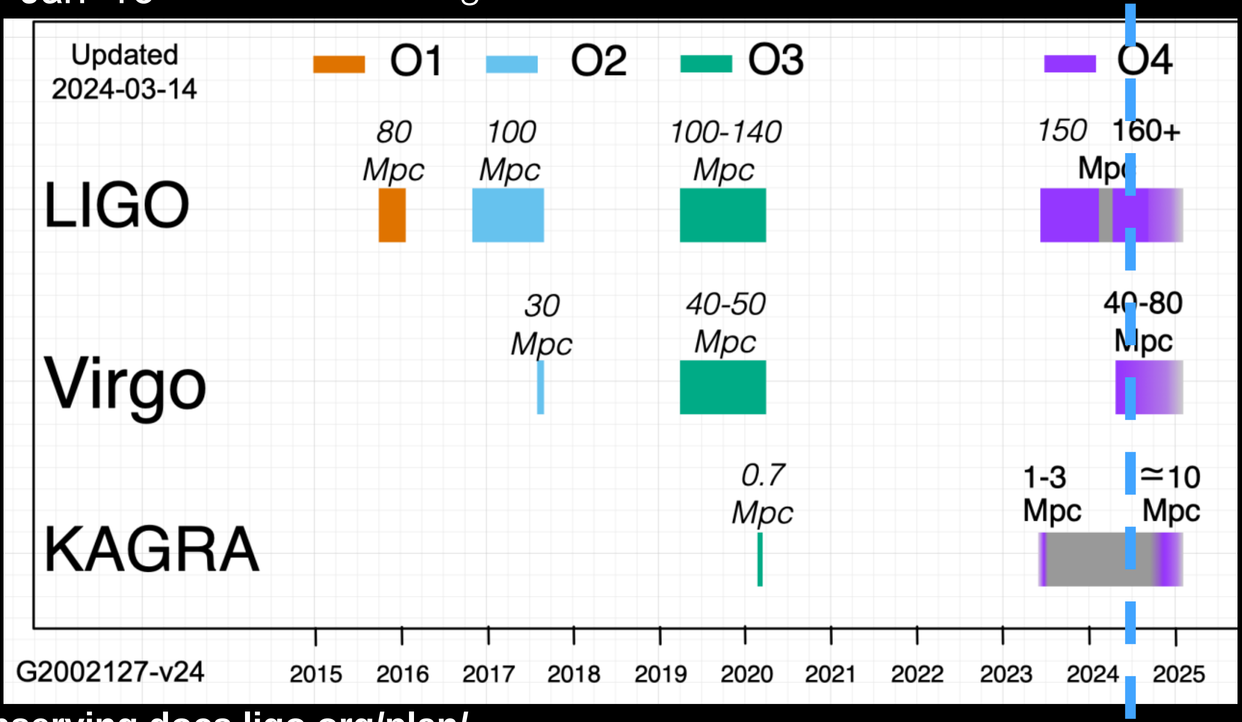
- **O1, O2, O3 completed**
- **O4 ongoing**
  → O4a only LIGO May 2023 - January 2024
  → O4b LIGO and Virgo April 2024 - June 2025

O1
Sep ‘15 - Jan ‘16

O2
Nov ‘16 - Aug ‘17

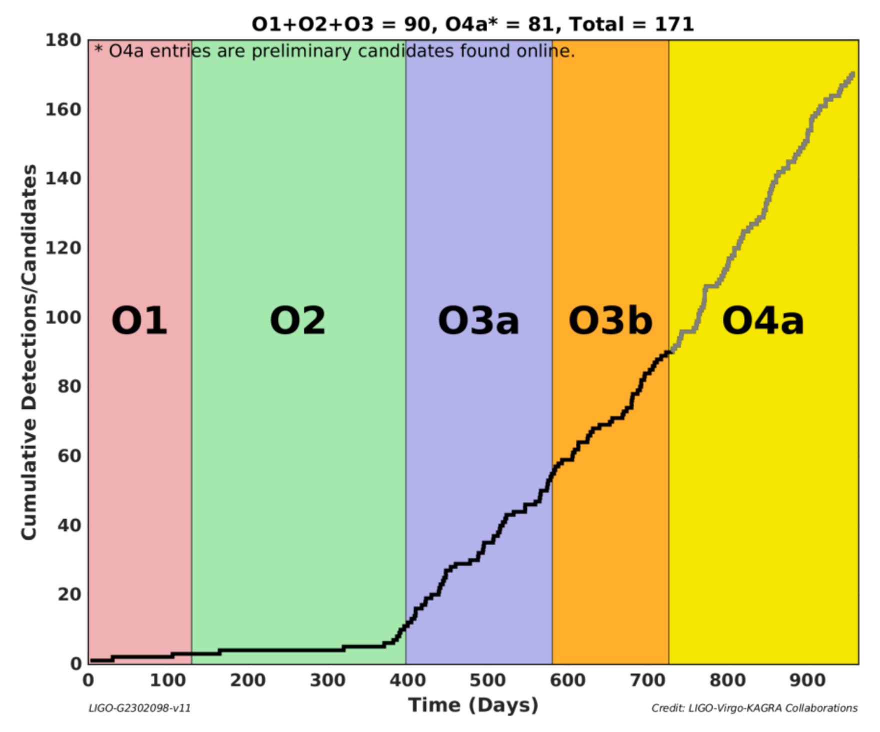
O3
Apr ‘19 - Mar ‘20

O4
May 23 - June ‘25



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

Low-latency pubblic alerts


O1+O2+O3 = 90, O4a* = 81, Total = 171

* O4a entries are preliminary candidates found online.

LIGO-G2302098-v11

Credit: LIGO-Virgo-KAGRA Collaborations

dcc.ligo.org/LIGO-G2302098

O4a 81 + O4b 49 Significant Detection Candidates

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

- **the majority high probability to be BBH**
- **a few candidate consistent with containing a NS**
- **no candidates expected to have significant remnant mass outside of the final compact object**

Low-latency and off-line EM triggered GW search!

GW search using time and position of EM transients

GRBs

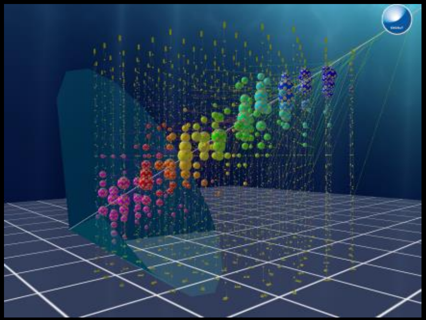
Magnetars

LIGO
VIRGO
KAGRA

FRBs

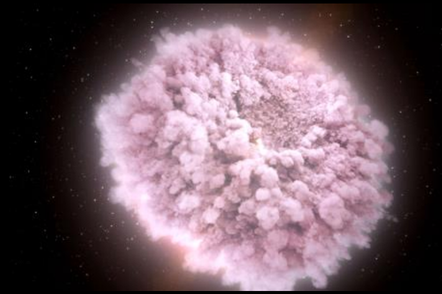
SNe

Neutrinos

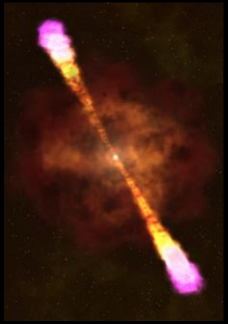


Multi-messenger astronomy with gravitational-waves

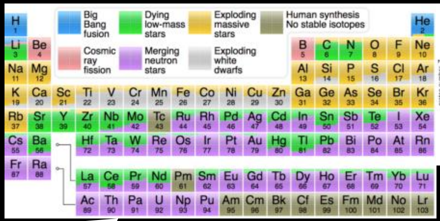
Radioactively powered transients



Relativistic astrophysics

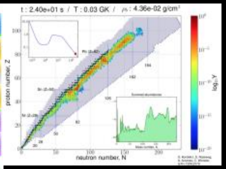


Nucleosynthesis and enrichment of the Universe

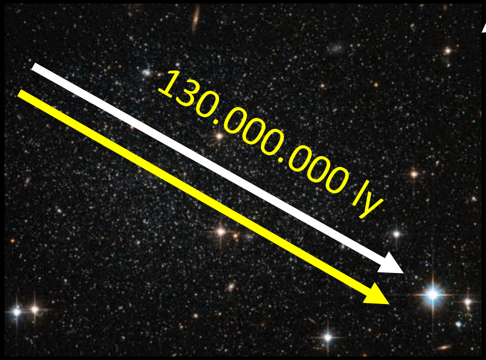


🟦 Big Bang fusion
🟩 Dying low-mass stars
🟨 Exploding massive stars
▨ Human synthesis No stable isotopes
🟥 Cosmic ray fission
🟪 Merging neutron stars
⬜ Exploding white dwarfs

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56		Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88																
			La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
			Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

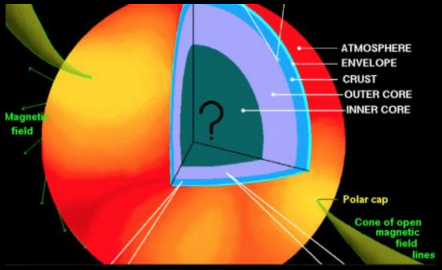


Fundamental Physics

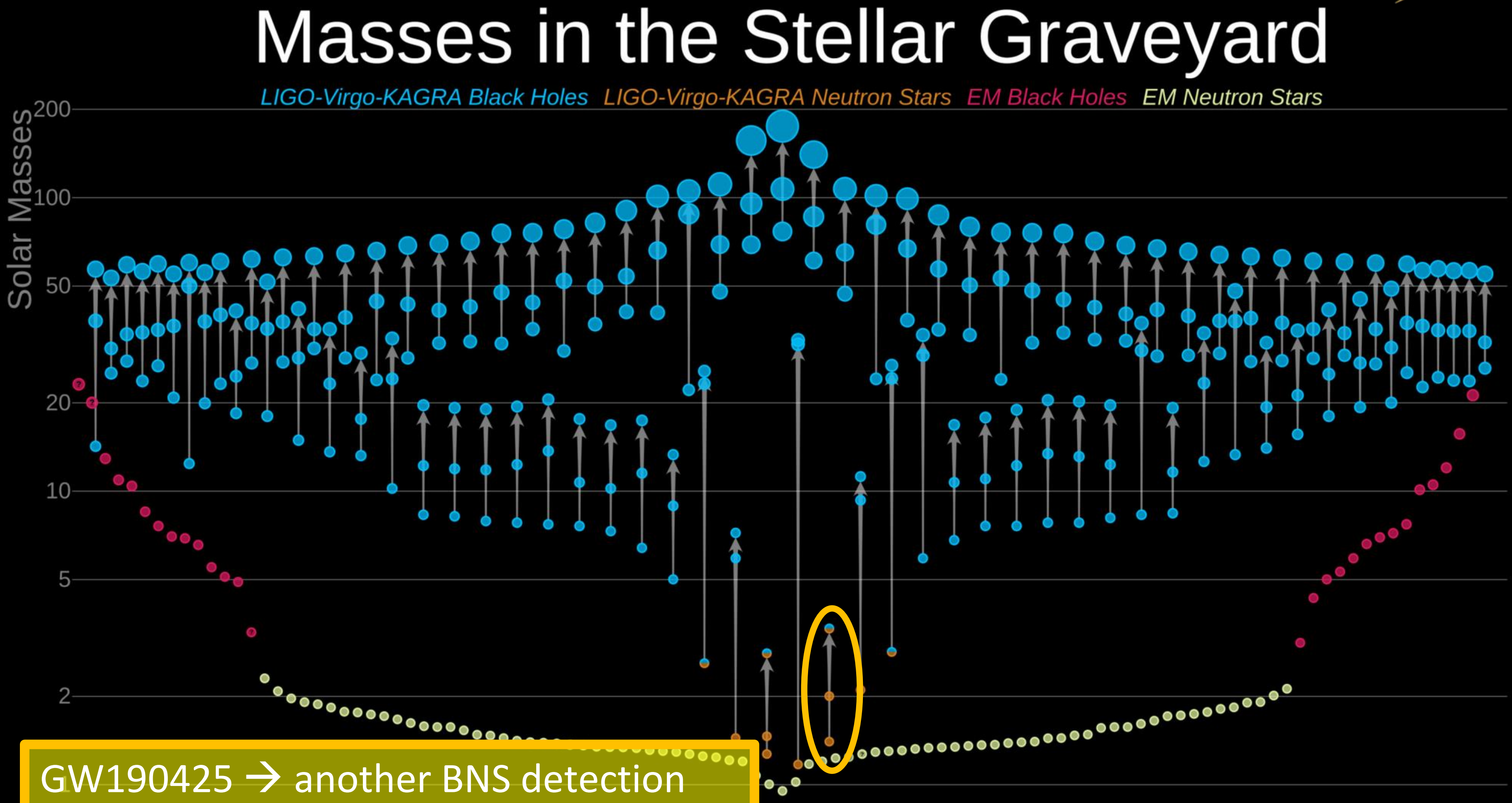


Cosmology

Nuclear matter physics

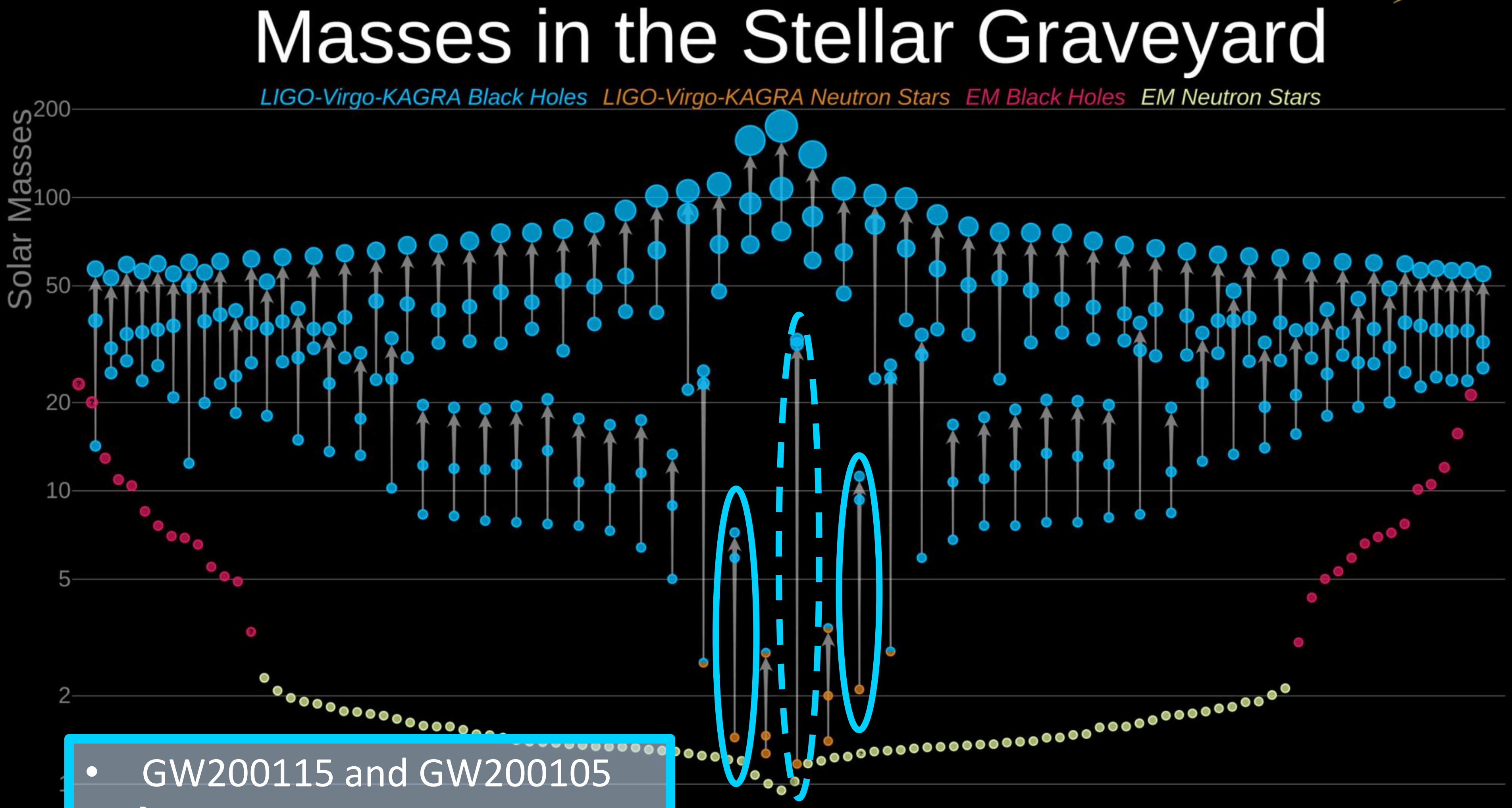


Another BNS in O3



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

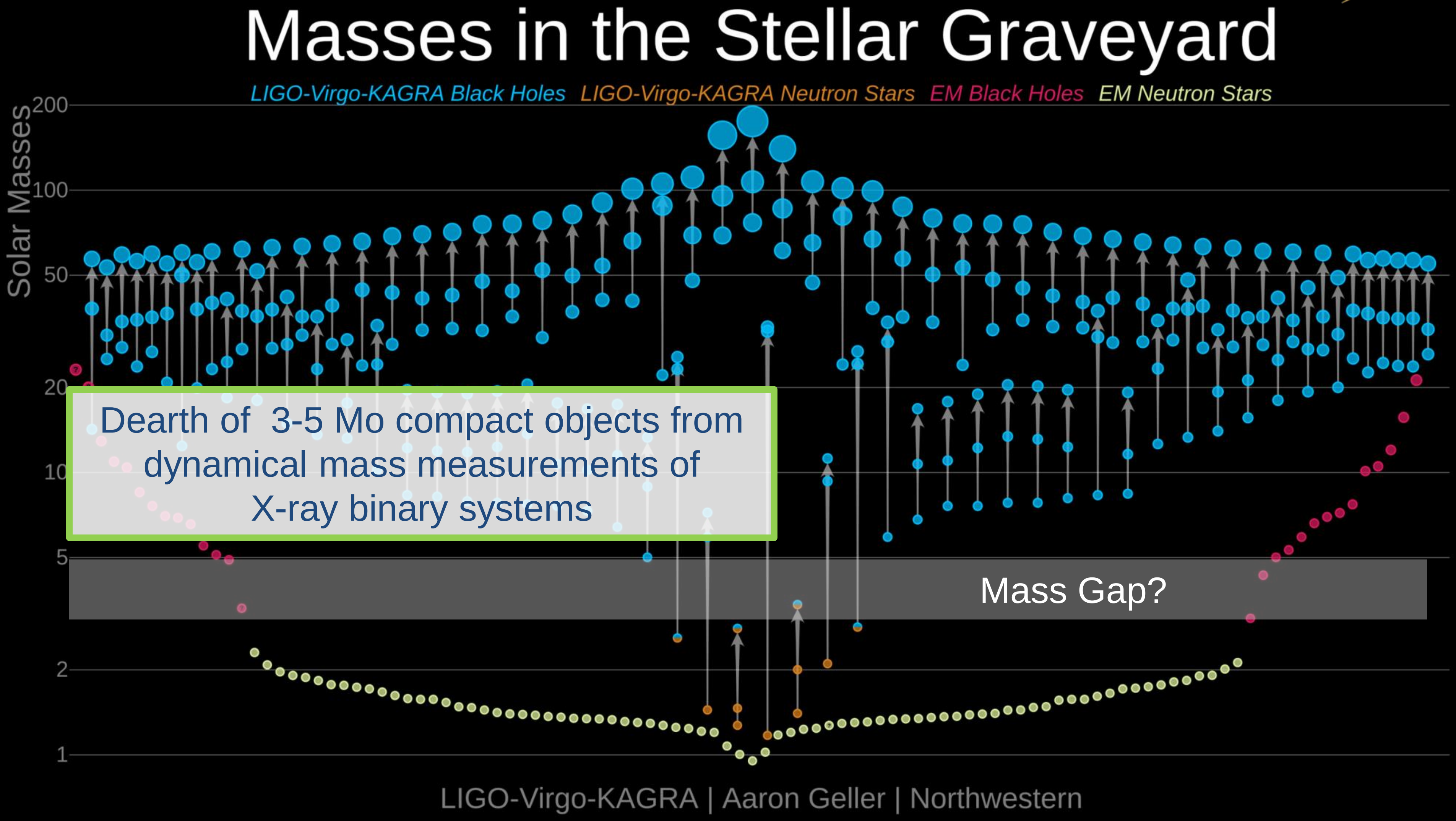
Some of the interesting results in O3



- 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

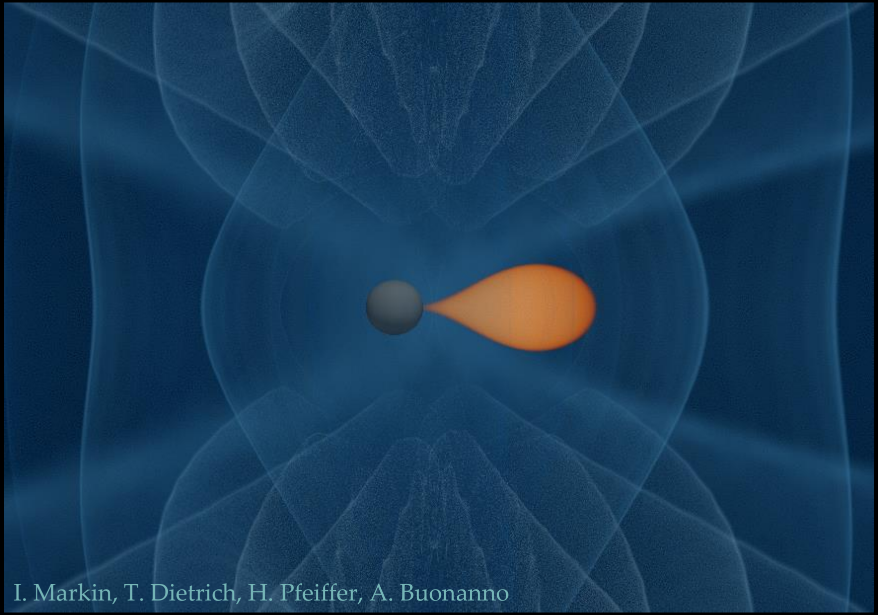


Dearth of 3-5 Mo compact objects from dynamical mass measurements of X-ray binary systems

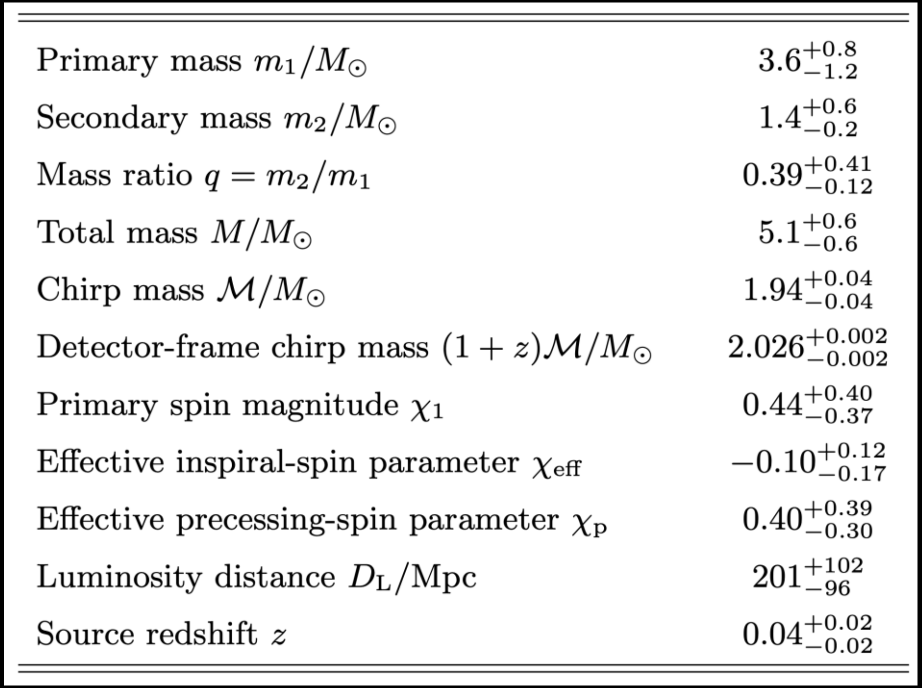
GW230529

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



I. Markin, T. Dietrich, H. Pfeiffer, A. Buonanno



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

NO multi-messenger GW event after GW17017

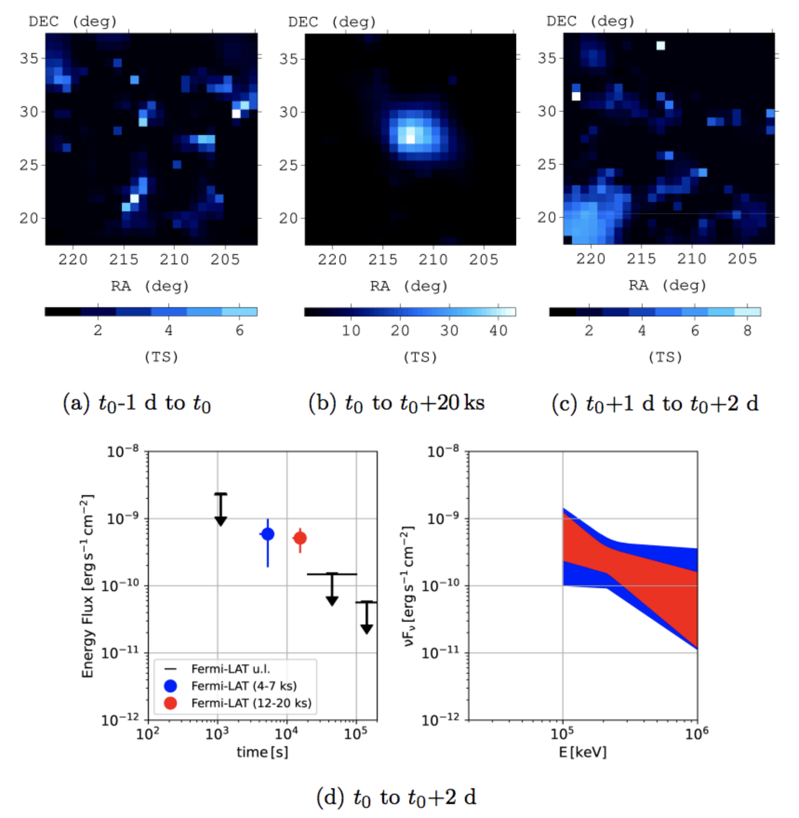
BNS mergers are there!

Expected a few hundred of BNS detections per year with the current GW detectors (at design sensitivity) 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

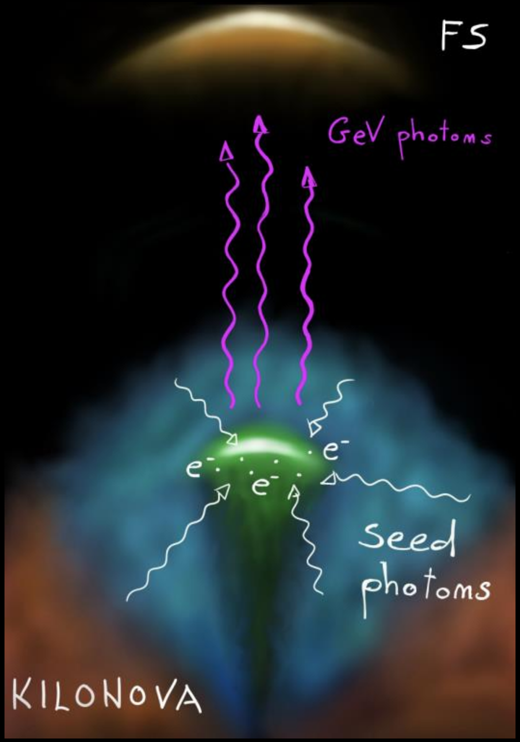


(a) t_0-1 d to t_0 (b) t_0 to t_0+20 ks (c) t_0+1 d to t_0+2 d

(d) t_0 to t_0+2 d

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

NO FIRM EM COUNTERPARTS: detection rate, type of systems, large sky-localization and fainter counterparts to be searched…

Euclid

Nancy Roman

SVOM

HERMES SP

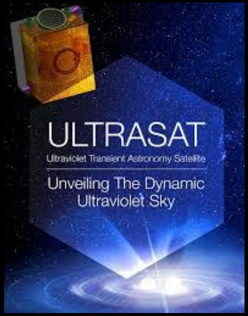
GECAM

exploring transients and variability in the dynamic X-ray Universe

Einstein Probe

NEW OBSERVATORIES

James Webb Space Telescope



ULTRASAT

Ultraviolet Transient Astronomy Satellite

Unveiling The Dynamic Ultraviolet Sky

Rubin Observatory

LIGO INDIA

NETWORK OF GW DETECTORS

SKA SQUARE KILOMETRE ARRAY

ELT

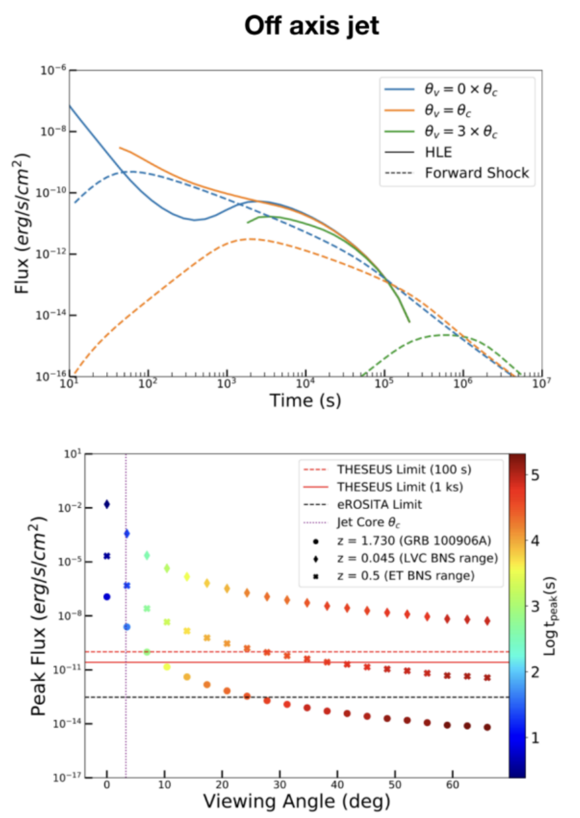
Einstein Probe

- Wide-FoV sensitive instrument in X-ray
- New window in X-ray transients
- Large observational resources to the follow-up of the EP (e.g. ESO facilities by STARGATE)

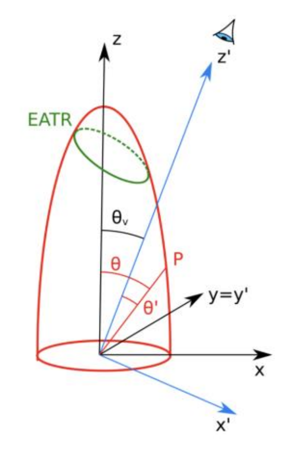
Increased chance to detect off-axis systems

Triggered GW search on XRT

Ierardi, Chopra, Oganesyan, Ascenzi, Banerjee, Patricelli, Branchesi, Jonker, Levan et al.



Ascenzi et al. 2020



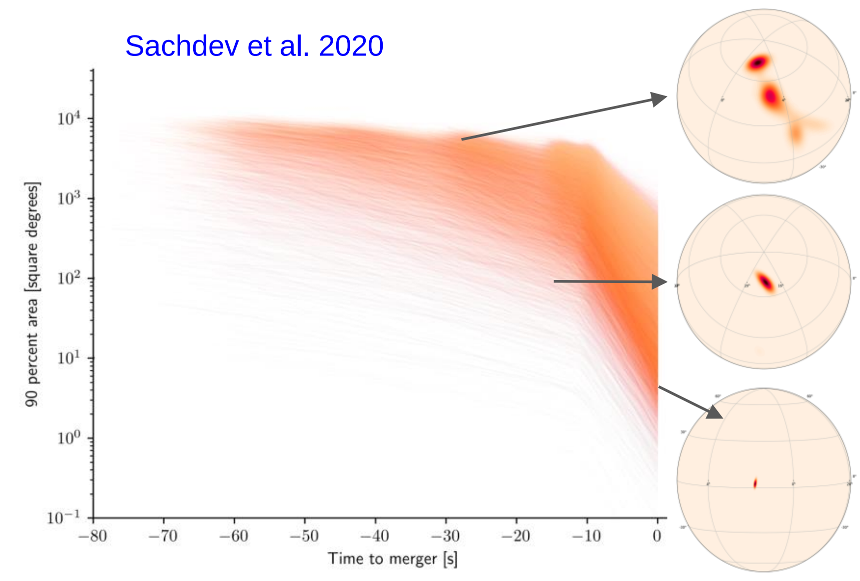
Early-warning in O5

GW instruments:

- **O5 LIGO-Virgo-Kagra**

EM instruments, large field of view

- ASTRI, CTA, LHAASO, ULTRASAT, X-ray satellites (EP, SVOM)



Ongoing efforts:

- Modification of BAYESTAR to provide the viewing angle in low-latency (Jacopo Tissino, Leo Singer)
- Designing observational strategy of Cherenkov telescopes with MAGIC. Scanning GBM localizations to trace VHE transient in the localization area (PI: Banerjee). To serve as a template for scanning the LVK localization area.

Pic credit: J. Tissino

CHALLENGES and OPPORTUNITIES

CURRENT GW DETECTORS

- A number of MM/GW are potentially detectable with current observatories
- Innovative EM observatories are starting observations
- Early warning
- **VirgoNext and A# around 2030**

CHALLENGES

- Smaller BNS rate, fainter sources to be detected, relatively poor sky-localization

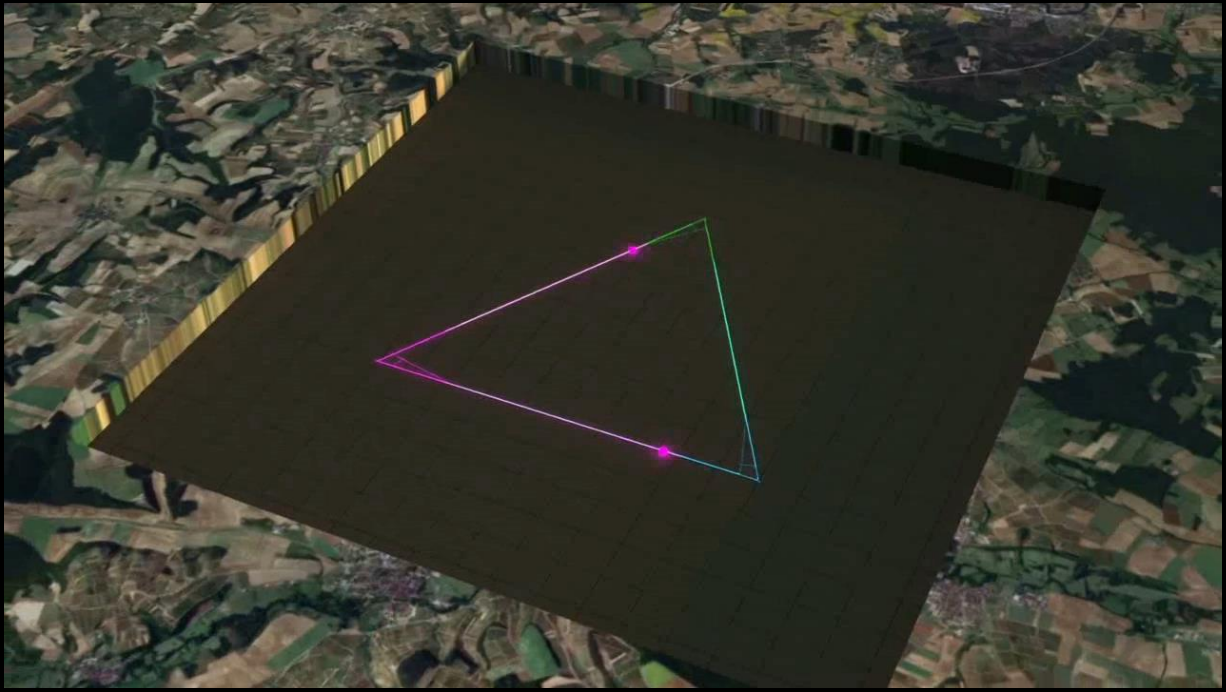
ACME

- Help to enlarge the MM users, training young reserachers
- Help the MM communities to optimize observational strategies, instrument operations, data analysis, modelling
- Coordinate observations
- Being a FORUM for the MM European Community

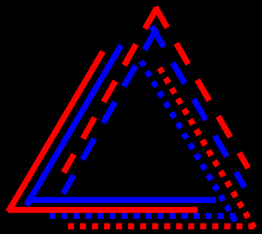
Next generation GW astronomy and multi-wavelenght follow-up

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



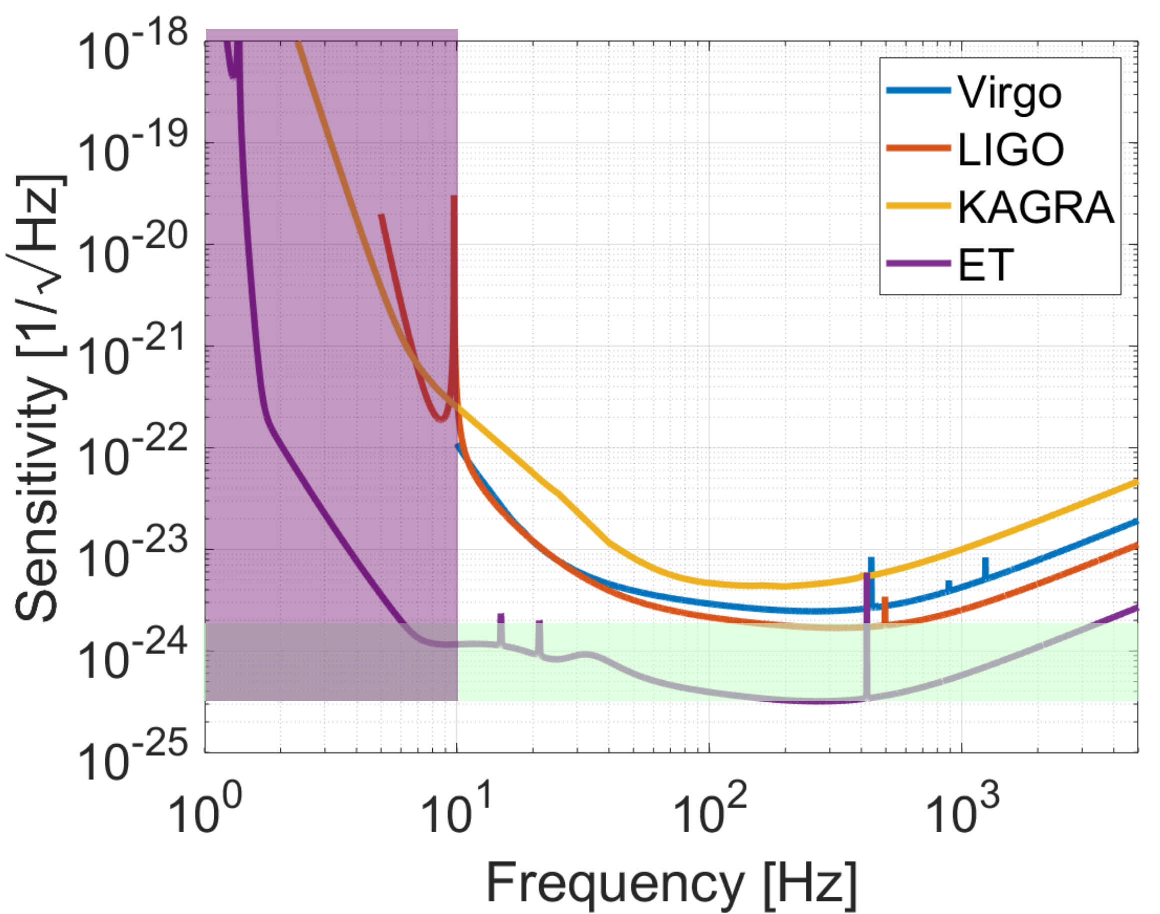
Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...



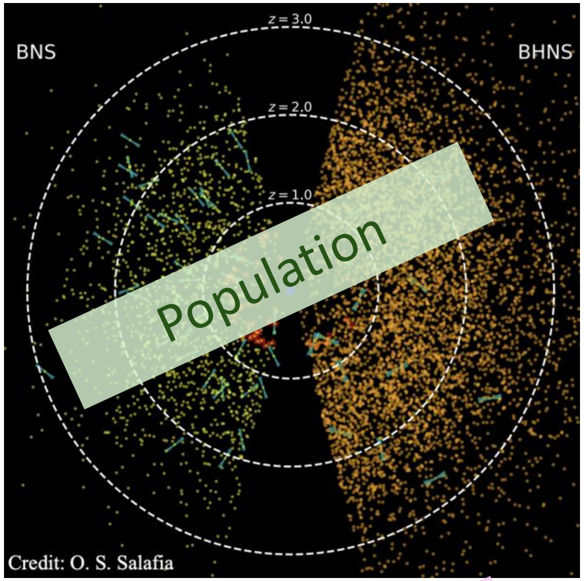
INCLUDED IN ESFRI ROADMAP in 2021

ET collaboration more than 1600 scientists!

EXPECTED SENSITIVITY



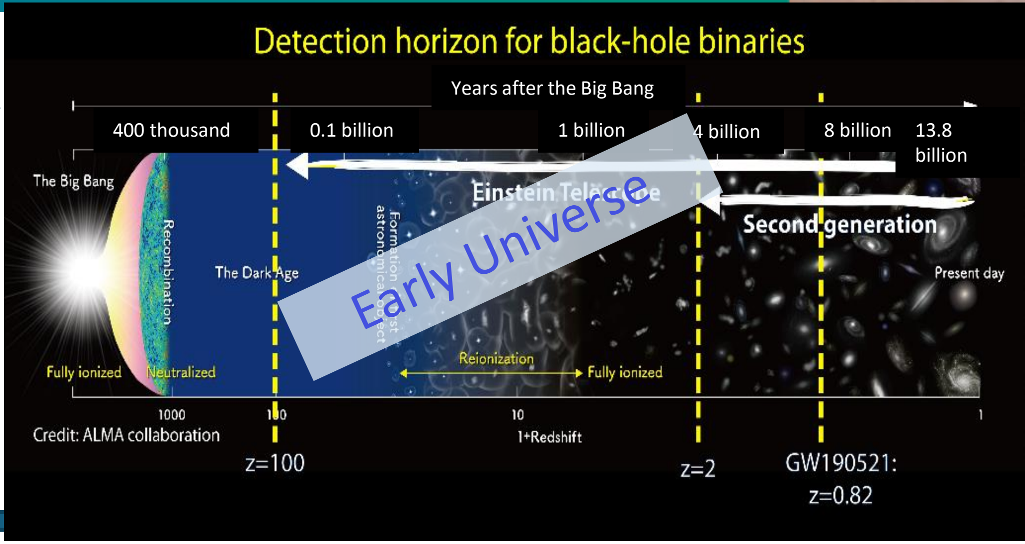
ET Science in a nutshell



Credit: O. S. Salafia

Remote Universe

Closer Universe

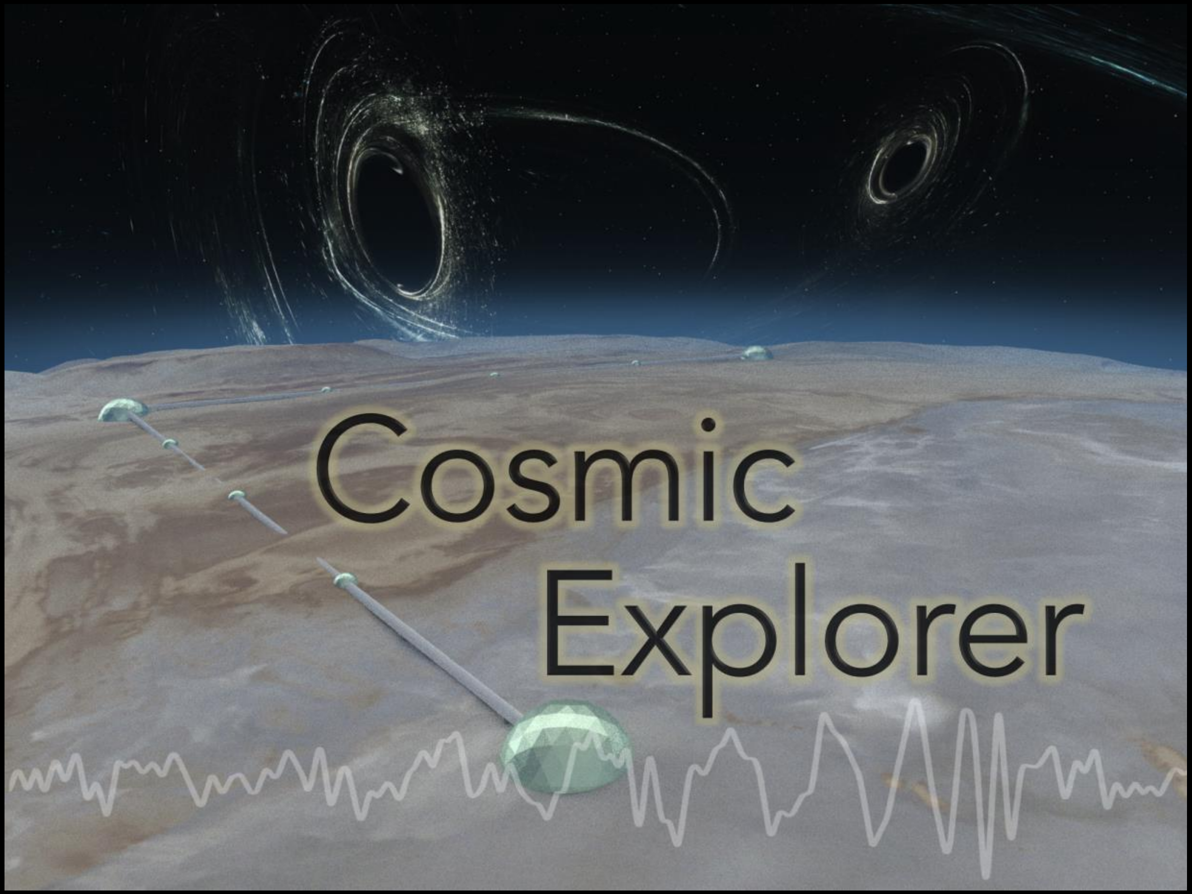


Credit: ALMA collaboration

Combination of:

- Larger distances and broader masses explored
- Increased number of detections
- Detections with very high SNR

Next generation GW effort worldwide

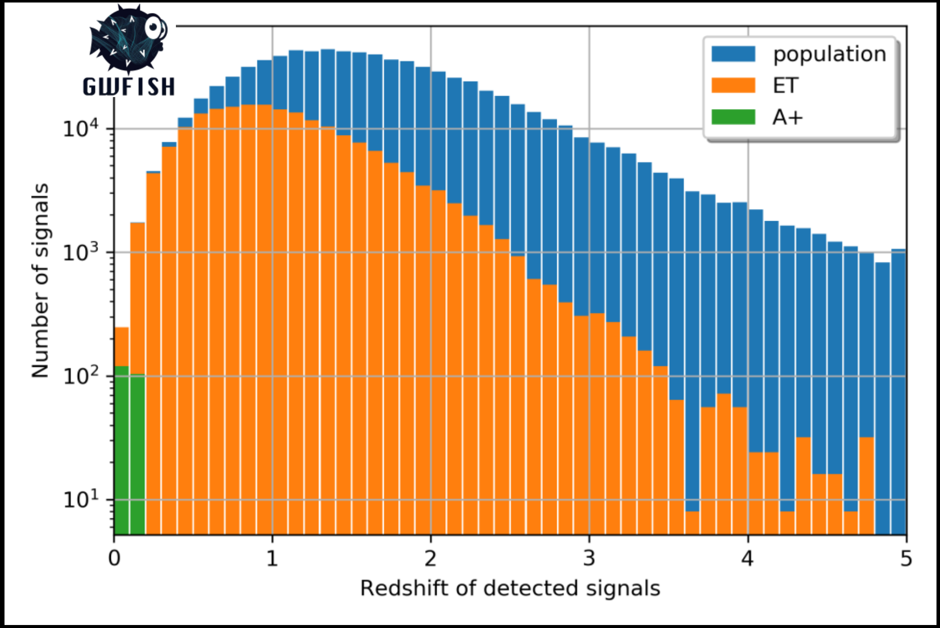


Cosmic Explorer: L shaped detectors, two sites
(40km, 20 km [option])

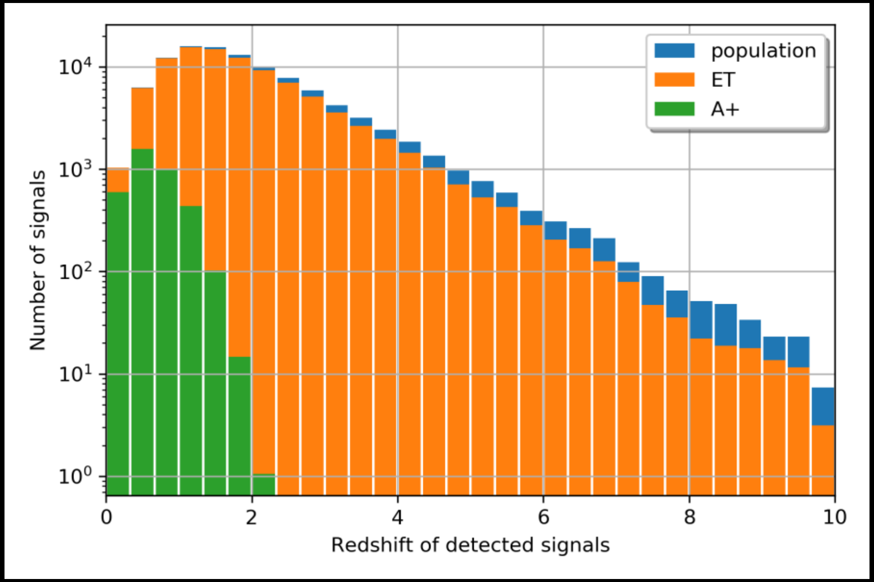
Multi-messenger in the ET era: a few numbers

COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS

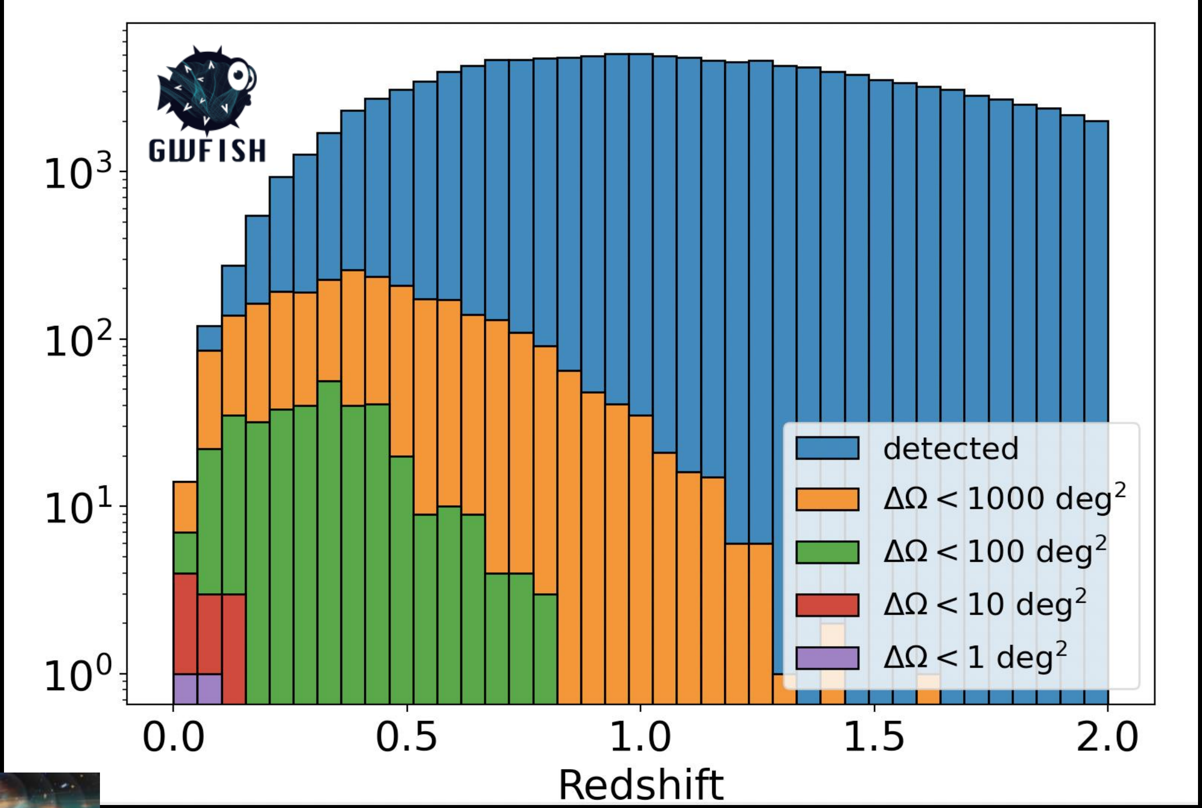


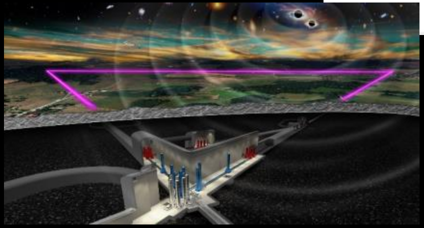
Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year

10^5 BBH detections per year

ET sky-localization capabilities

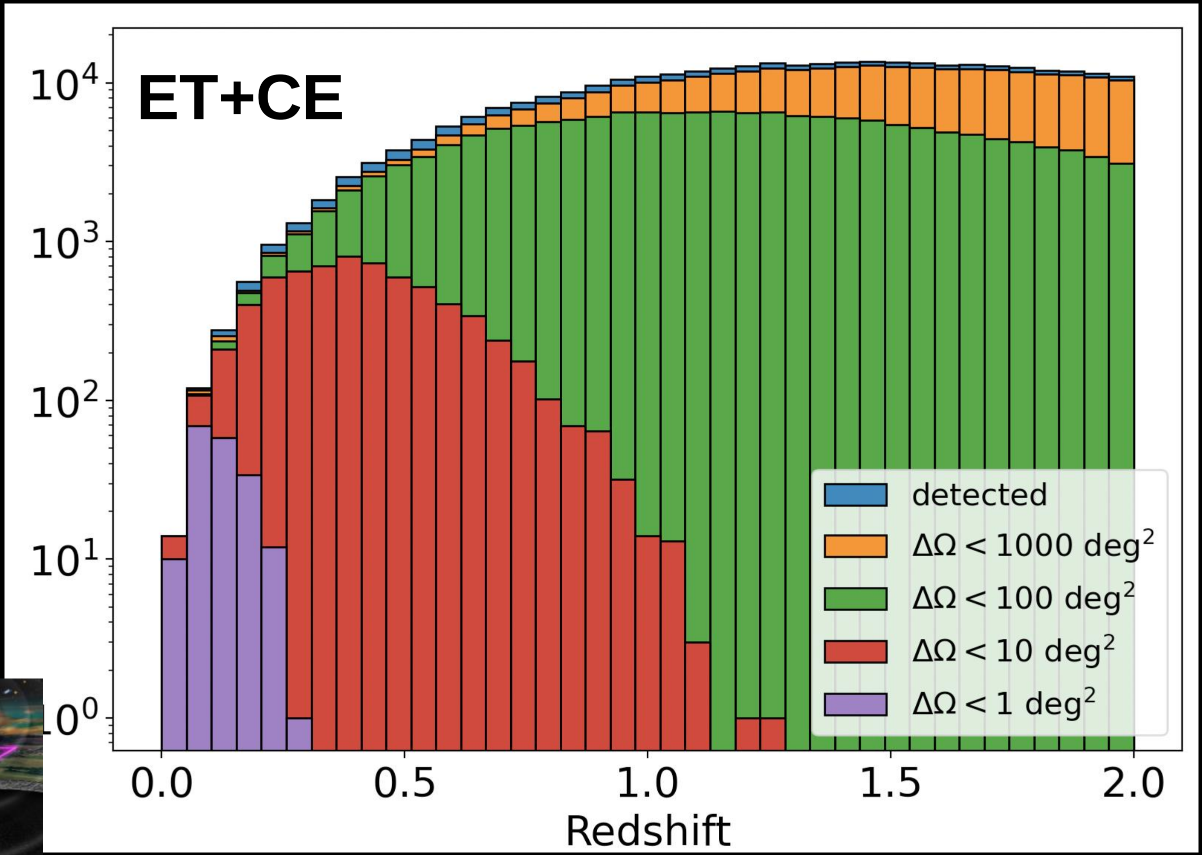


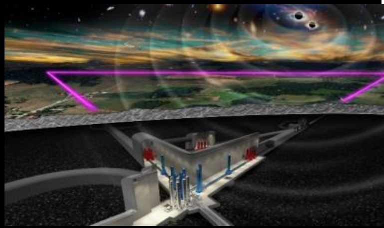


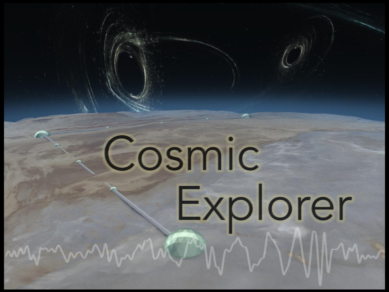
ET low frequency sensitivity make it possibile
To localize BNS!

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

Network sky-localization capabilities

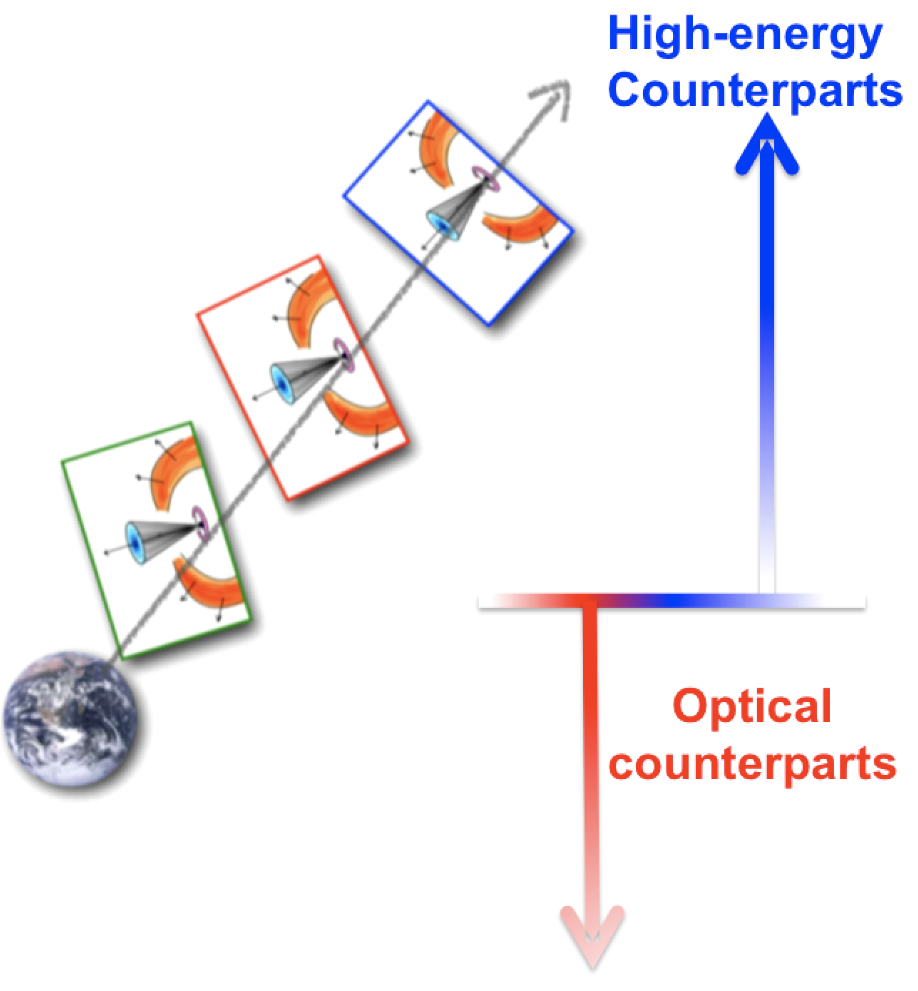






- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Dupletsa et al. 2023, Ronchini et al. 2022



High-energy Counterparts

Optical counterparts

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

Credit: Ronchini

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE

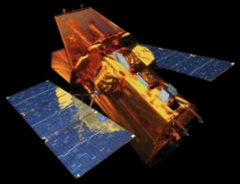
Image credit: NASA Goddard Space Flight Center

HIGH-ENERGY

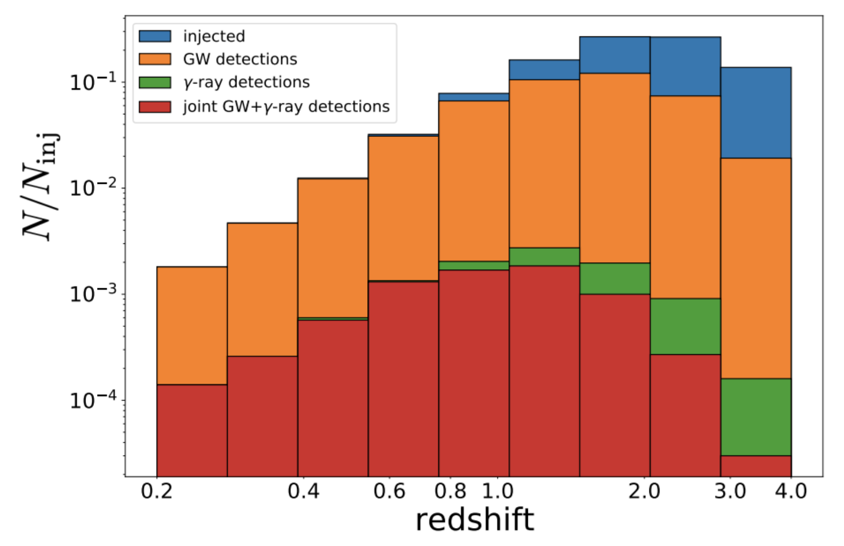
RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS,
COSMOLOGY and MODIFIED GRAVITY

GW + γ-ray joint detections per year

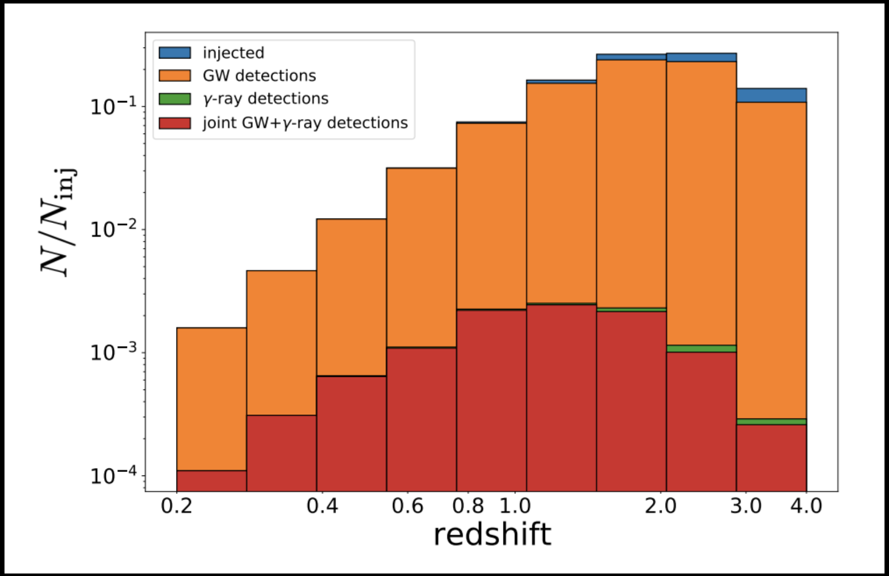
SURVEY MODE



Fermi-GBM+ET



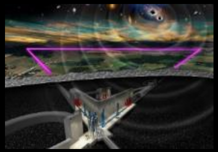
Fermi-GBM+(ET+CE)

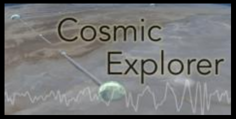


Almost all detected short GRB will have a GW counterpart

Depending on the satellites, we will have
tens (e.g. THESEUS) to hunreds (e.g HERMES) of detections per year

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

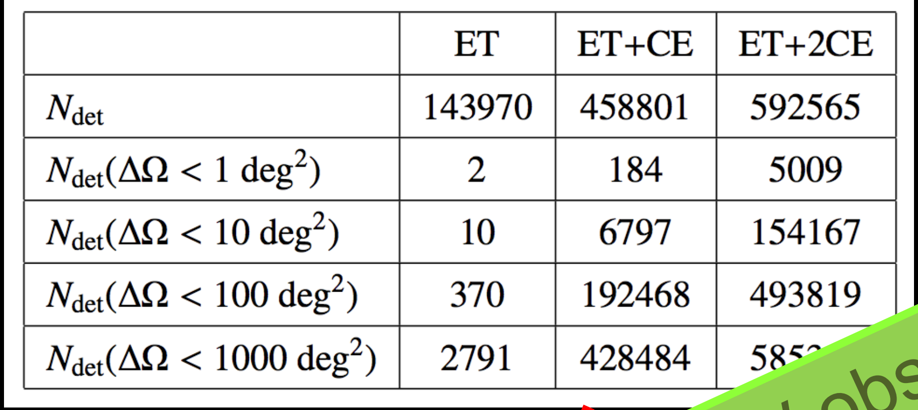




Ronchini, MB, Oganesyan, et al. 2022

Prioritization of triggers required

Sky-localization



	ET	ET+CE	ET+2CE
N_{det}	143970	458801	592565
$N_{\mathrm{det}}(\Delta\Omega < 1\ \mathrm{deg}^2)$	2	184	5009
$N_{\mathrm{det}}(\Delta\Omega < 10\ \mathrm{deg}^2)$	10	6797	154167
$N_{\mathrm{det}}(\Delta\Omega < 100\ \mathrm{deg}^2)$	370	192468	493819
$N_{\mathrm{det}}(\Delta\Omega < 1000\ \mathrm{deg}^2)$	2791	428484	585

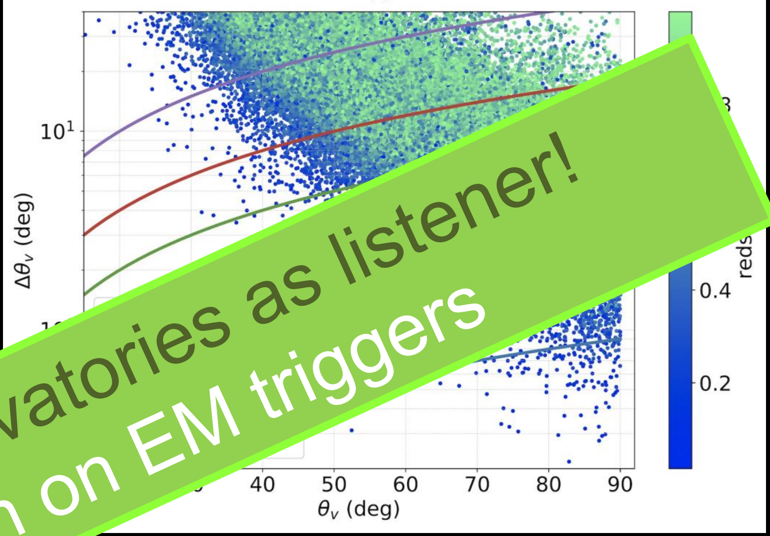
Too lar

tri to

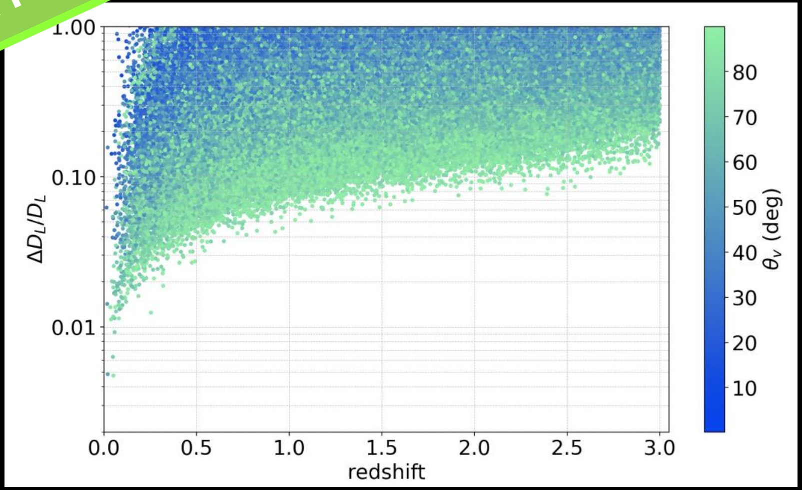
up

d in low-latency source parameters and continuous updates

Viewing angle



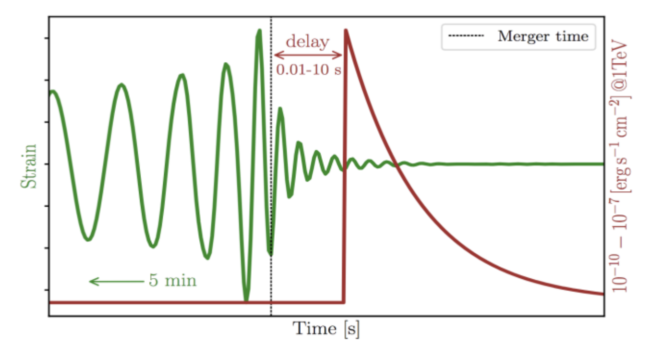
Distance



Start to think to GW observatories as listener!

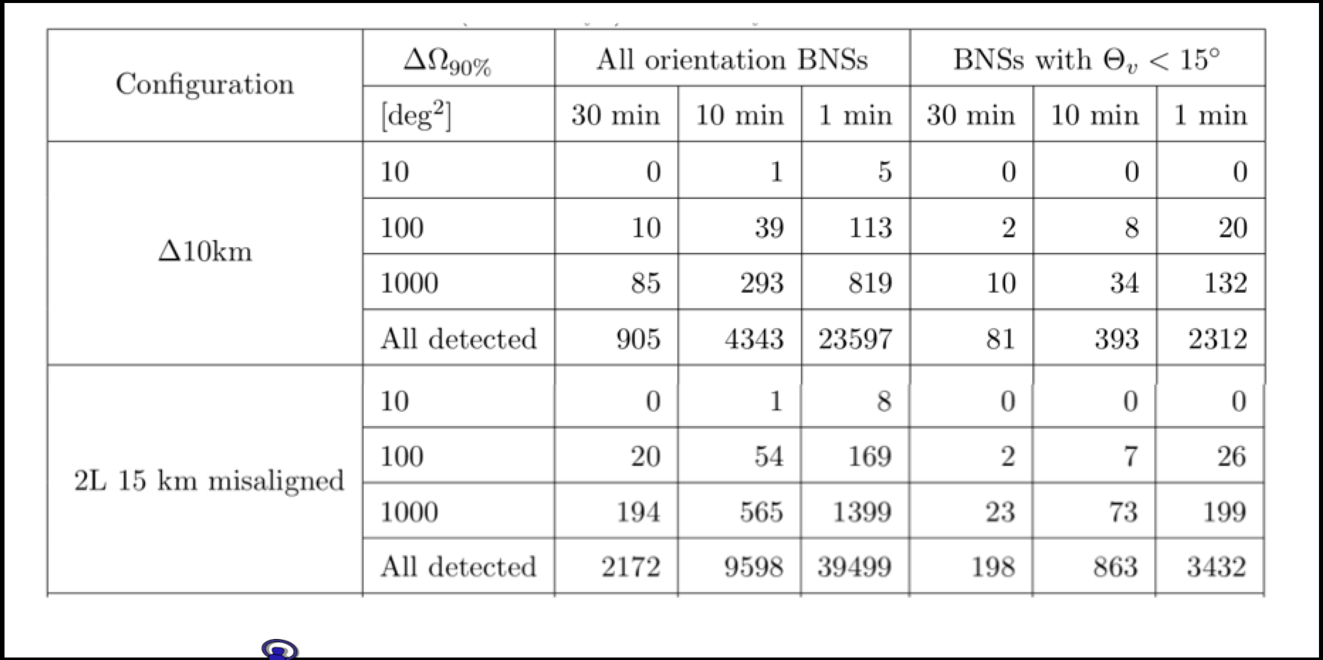
Parameter estimation on EM triggers

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

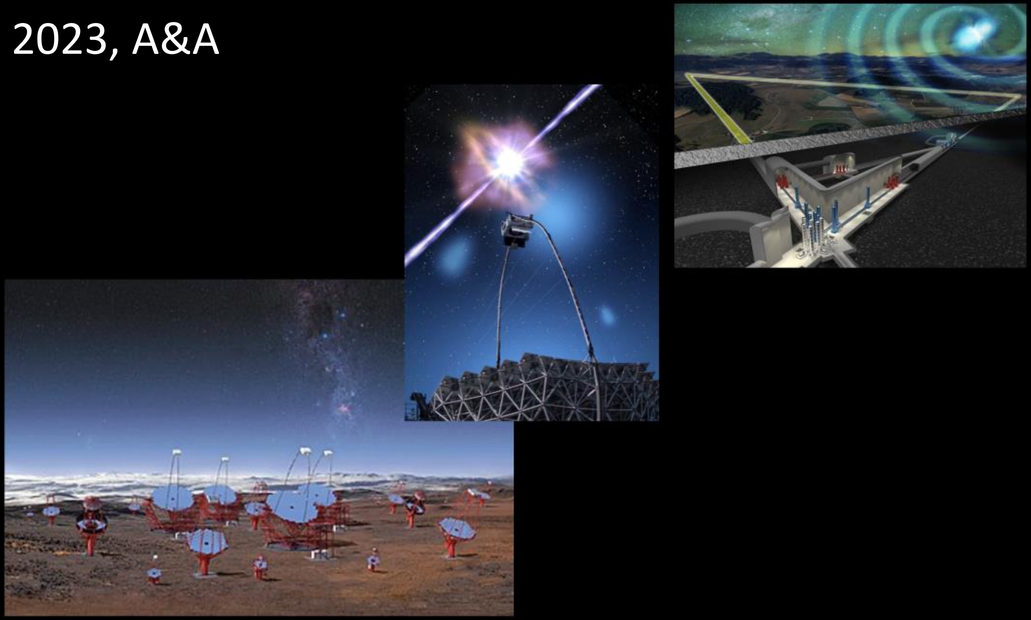
See Banerjee et al. 2023, A&A

CTA and GW DETECTOR synergies

Analyzing different observational strategies:

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

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

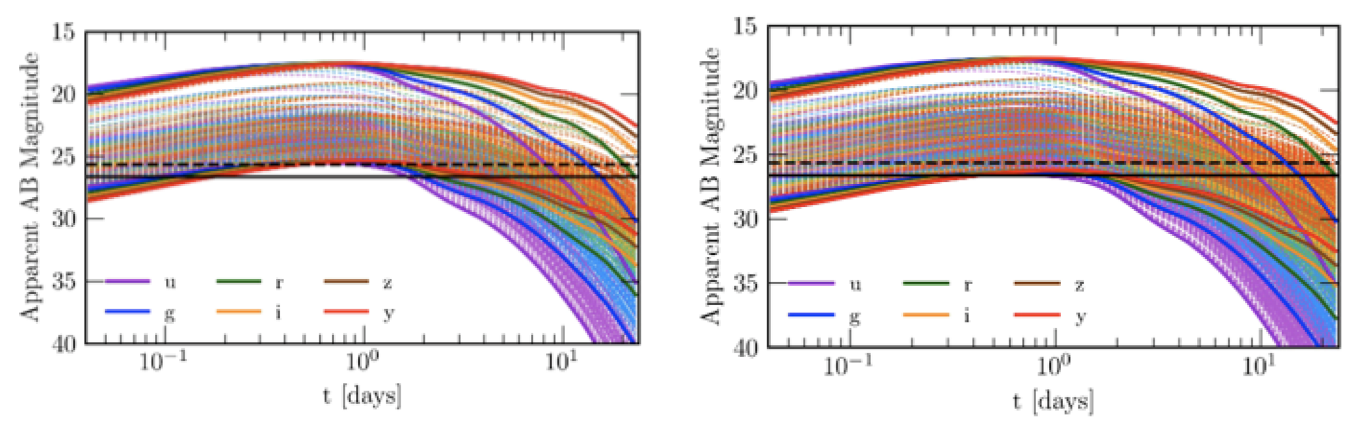


THERMAL EMISSION - KILONOVAE

KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

GW/KILONOVAE

BNSs detected with a sky-localization < 40 deg^2



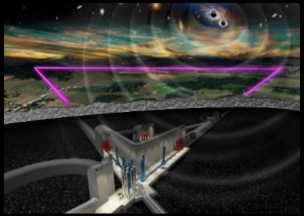
(a) Δ 10 km HFLF cryo

(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 -limited by Rubin efficiency)



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

VERA C. RUBIN
OBSERVATORY

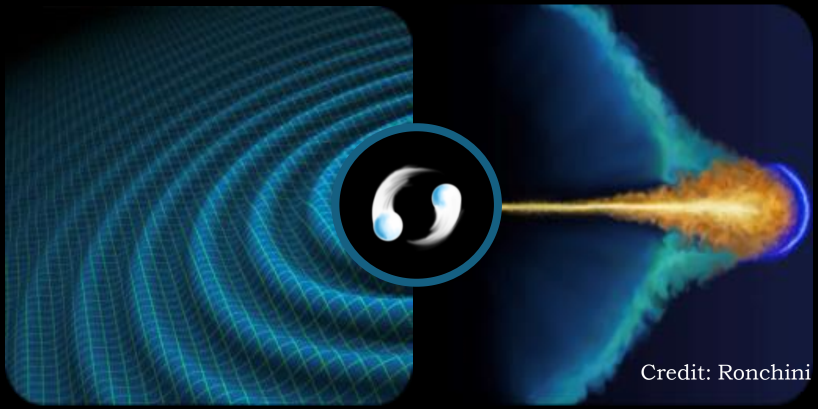
SUMMARY

CURRENT GW DETECTORS

- A number of MM/GW are potentially detectable with current observatories
- **ACME a large opportunity to maximize the science results fromMM observations for the European community**

Large investments of Europe on innovative next generation facilities:

- **Einstein Telesco**pe together with CTA, SKA, ELT, KM3NET
- **ACME can help to evaluate prospects and optimize their design and operation**



Credit: Ronchini