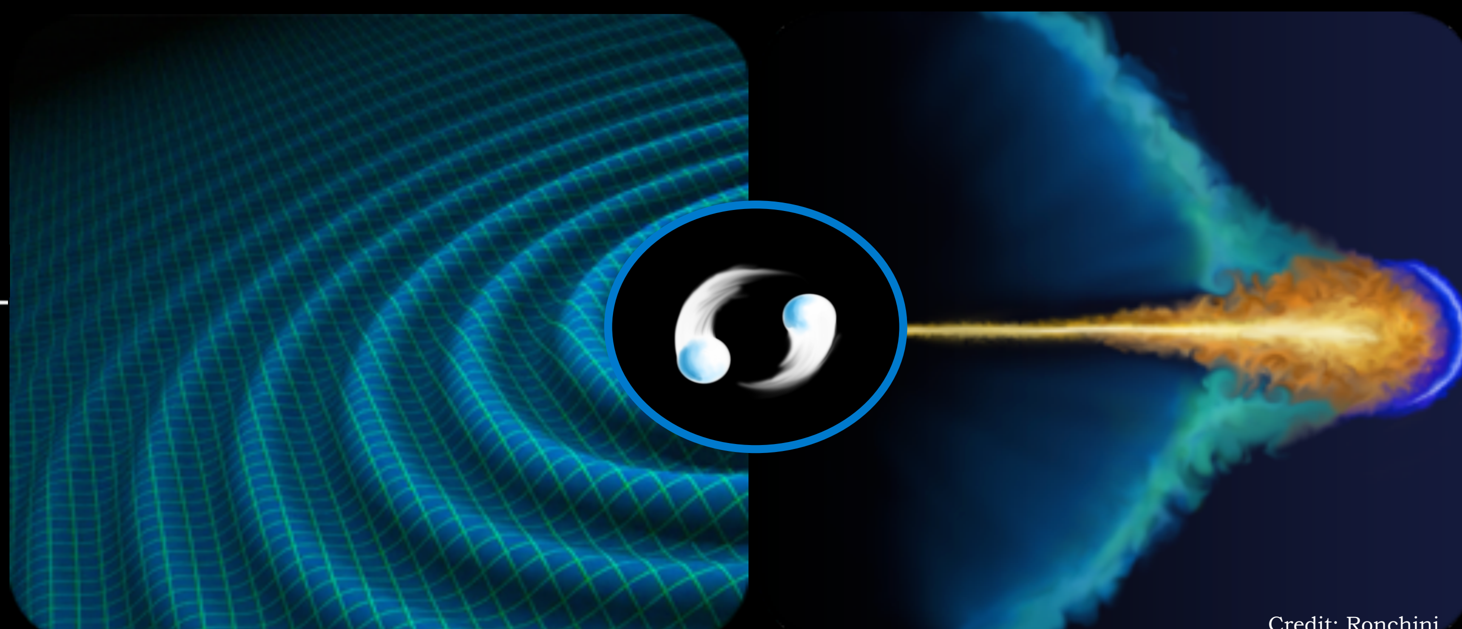
Multi-messenger Astronomy

Multi-Messenger Astrophysics
at EGO 10-12 October 2022

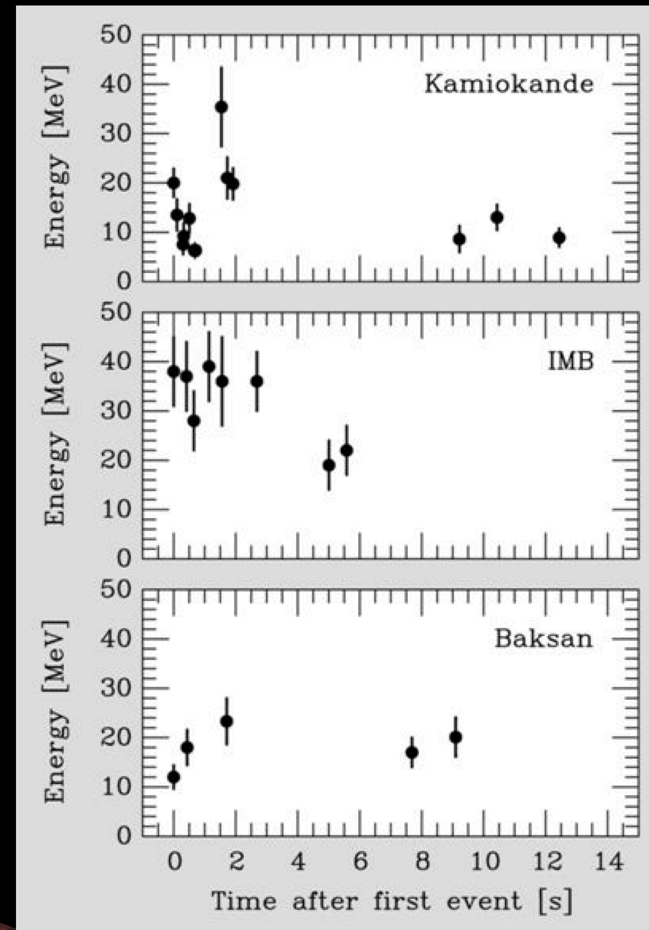
M. Branchesi
Gran Sasso Science Institute
INFN/LNGS and INAF

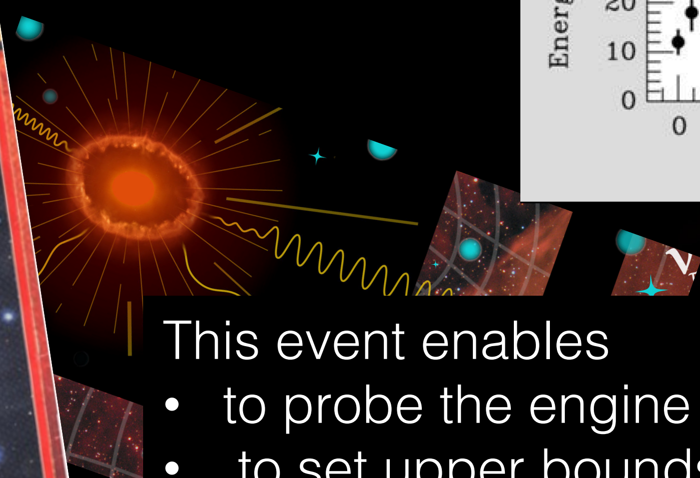
GSSI GW team



History of multi-messenger observations

SN1987A



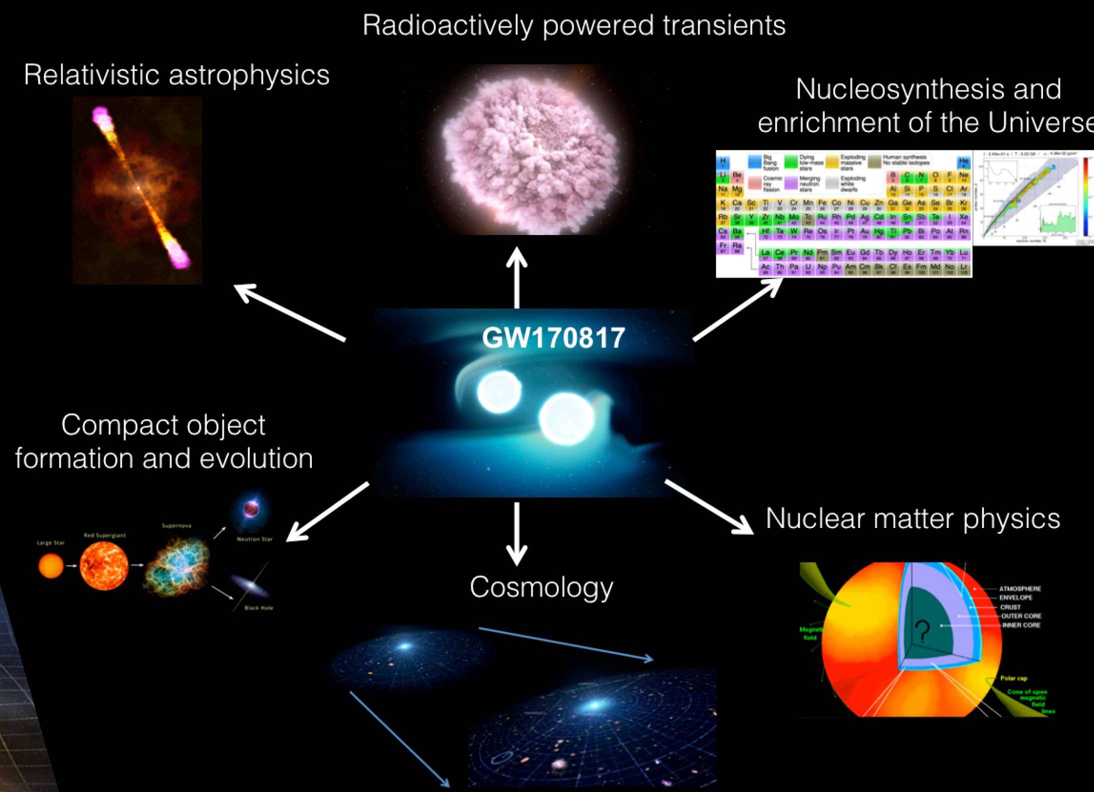


After 30 years..

This event enables

- to probe the engine of core-collapse SN
- to set upper bounds on the neutrino mass, charge, and number of flavours
- to perform unique tests of gravity

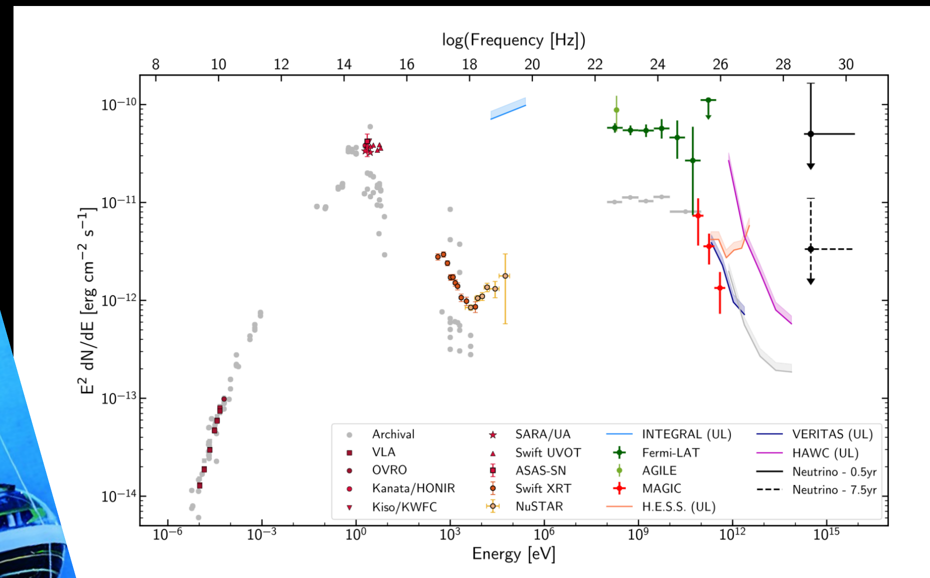
GW170817



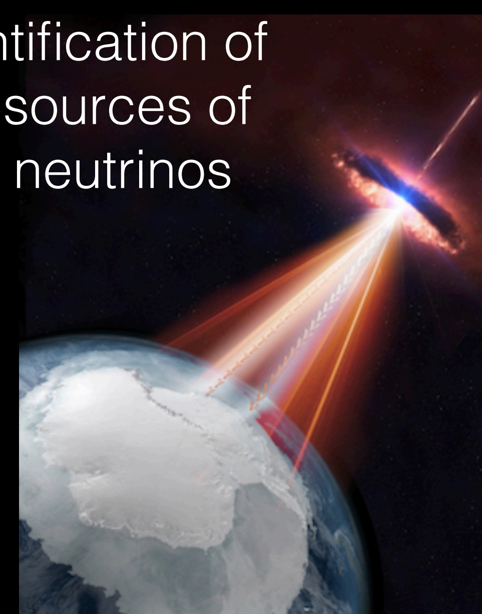
The merger of a binary-neutron-star through gravitational waves and multi-wavelength observations

Abbot et al. 2017, PRL, 119
Abbott et al. 2017 ApJL,848

Possible association of high-energy neutrinos with the blazar TXS 0506+056



first direct identification of astrophysical sources of extragalactic neutrinos

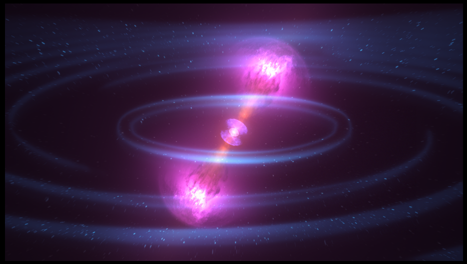


Aarsten et al. 2018, Science, 362

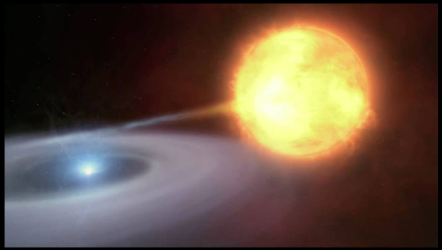
These events demonstrated the potential of multi-messenger observations to provide key insight into the physics of the most energetic events such as SN, GRBs, AGN

SOME OF THE MOST INTERESTING MULTI-MESSENGER SOURCES

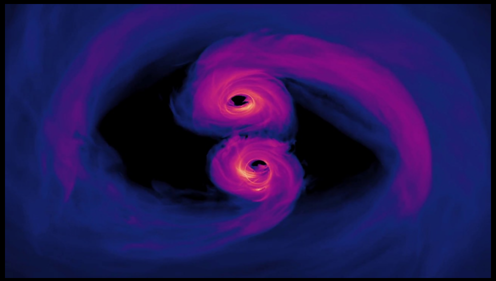
COMPACT OBJECT COALESCENCE associated with GRBs and KILONOVA



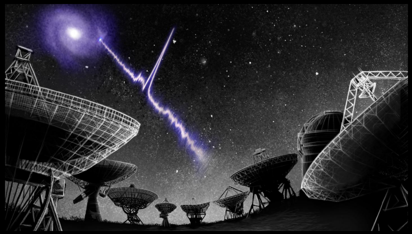
WD-WD and Type Ia SN



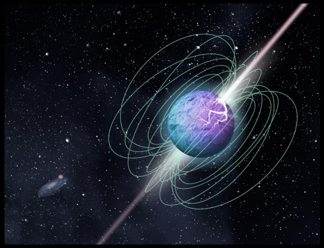
MASSIVE-BH MERGER



FAST RADIO BURST

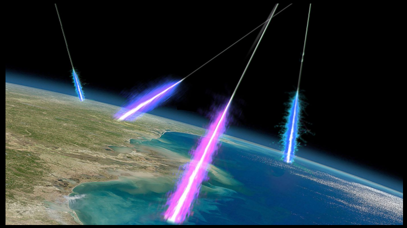


MAGNETARS

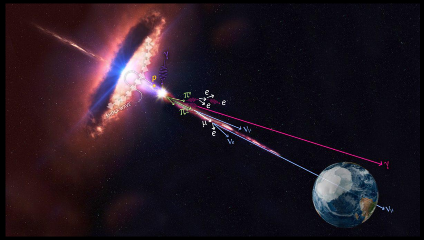


TIDAL DISRUPTION EVENT

SOURCES OF UHCR



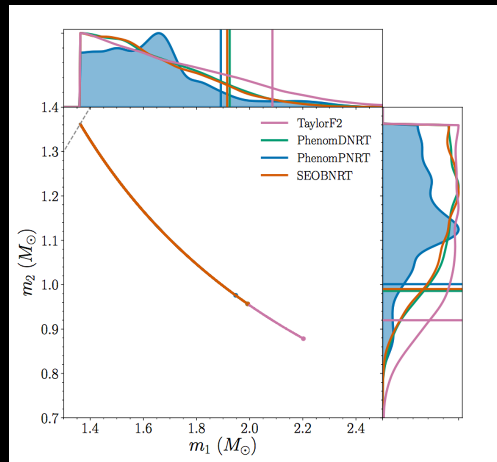
HE NEUSTRINO AGN, STAR BURST GALAXIES, GRBs



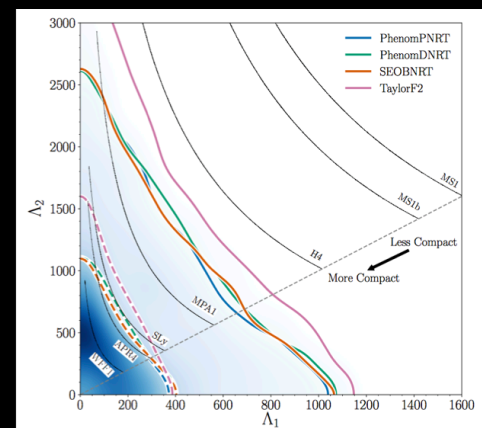
CORE-COLLAPSE SN

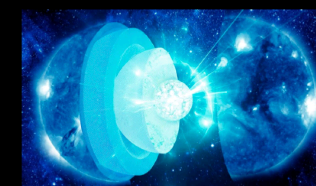
GW 170817

GW 170817



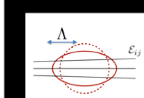
Masses are consistent with the masses of all known neutron stars!

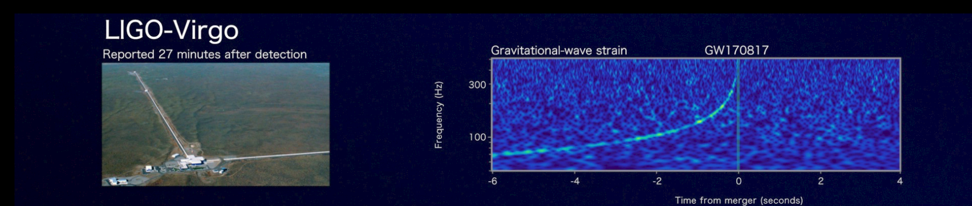




TIDAL DEFORMABILITY

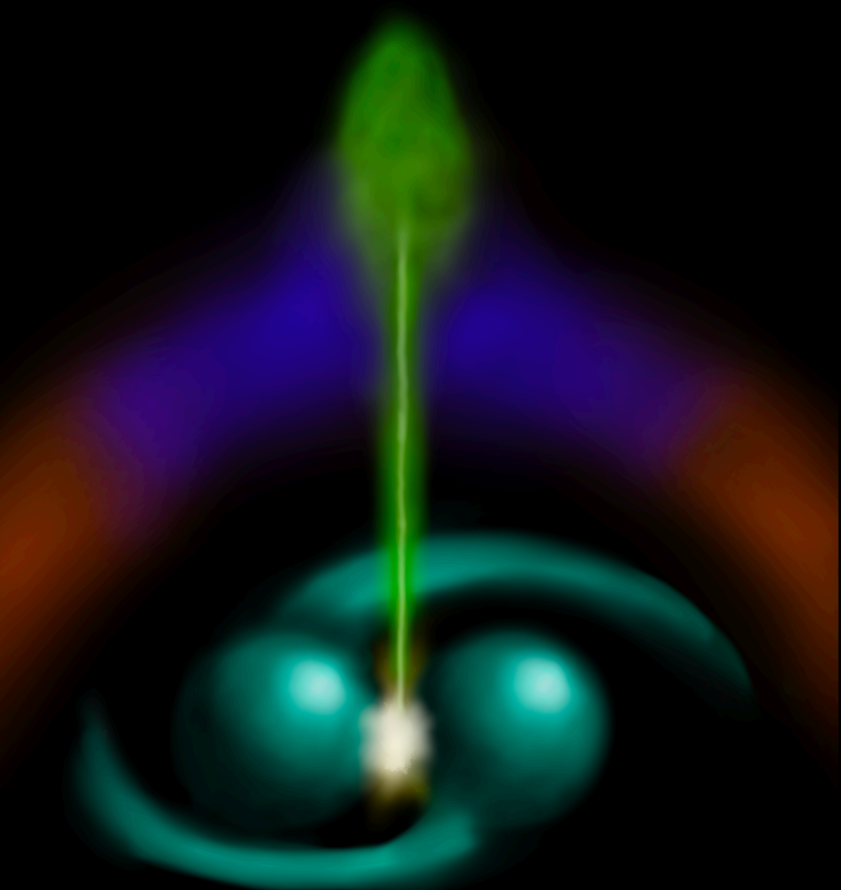
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

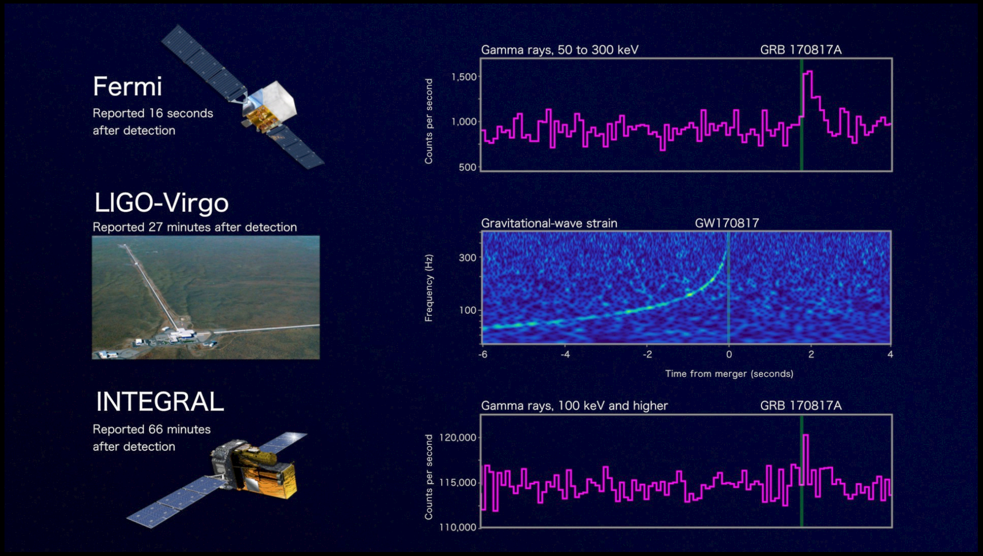




Credits: Ronchini

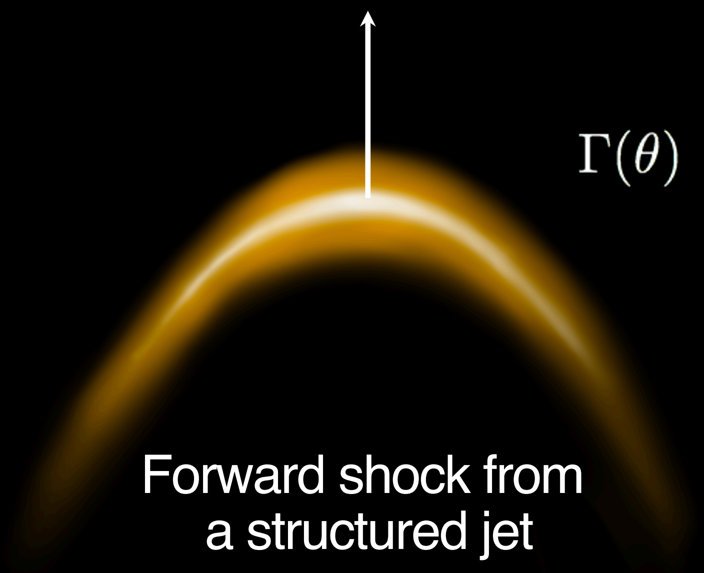
GW 170817

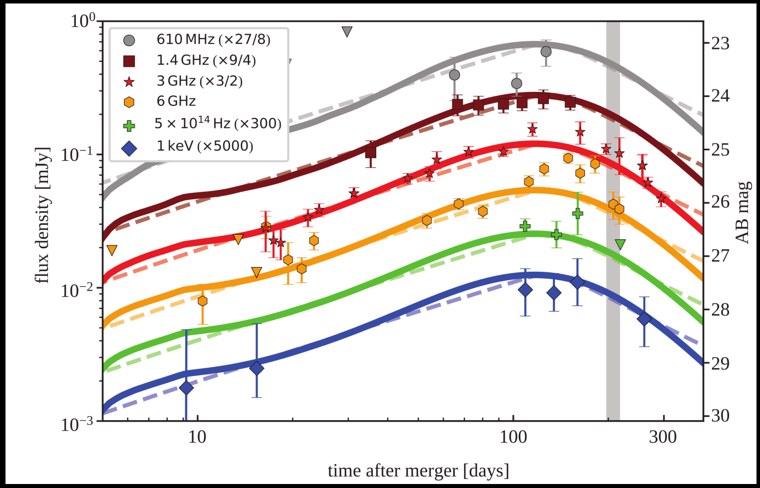


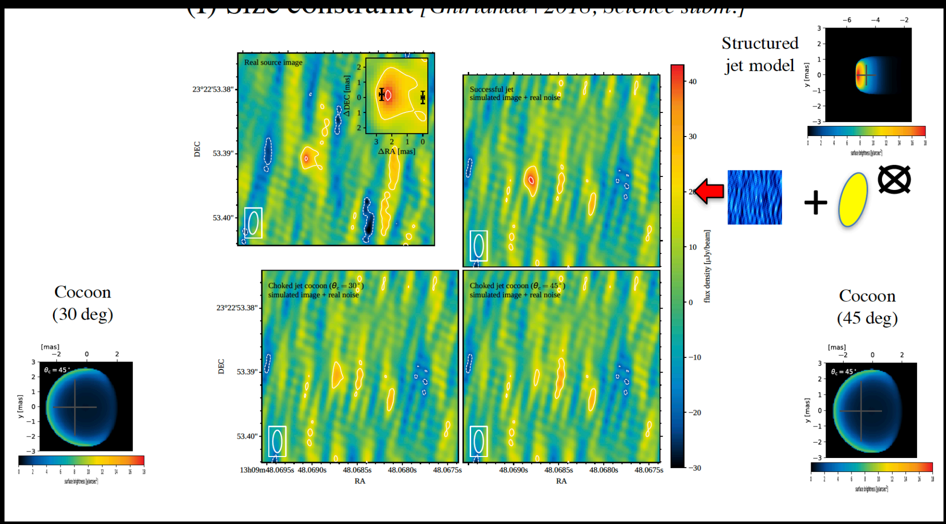


Fermi
Reported 16 seconds after detection
LIGO-Virgo
Reported 27 minutes after detection
INTEGRAL
Reported 66 minutes after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)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

GW 170817



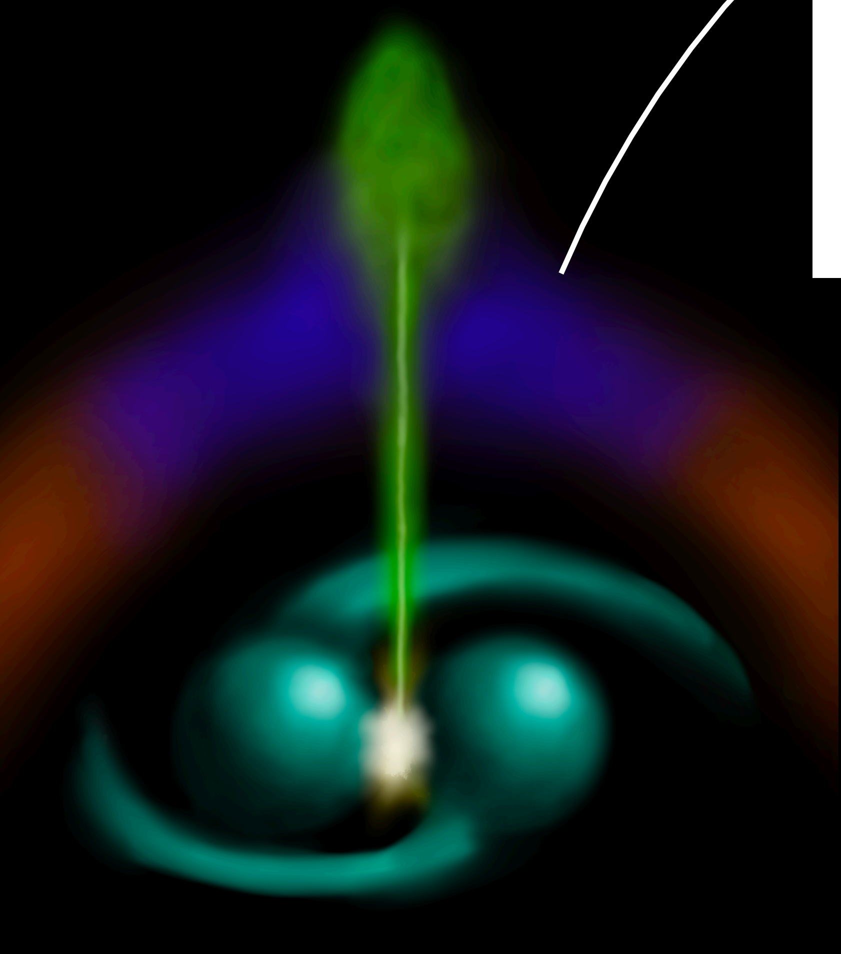


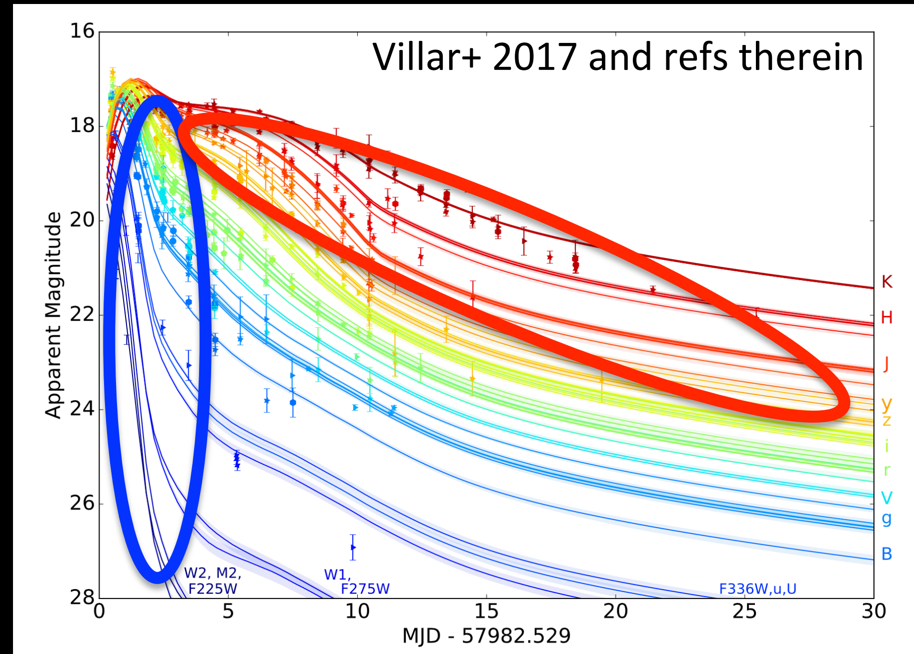


From Ghirlanda et al. 2019

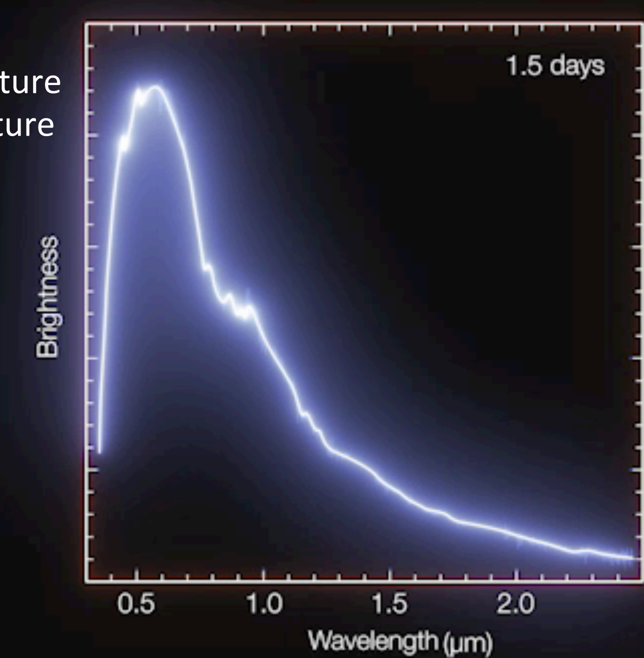
Credits: Ronchini

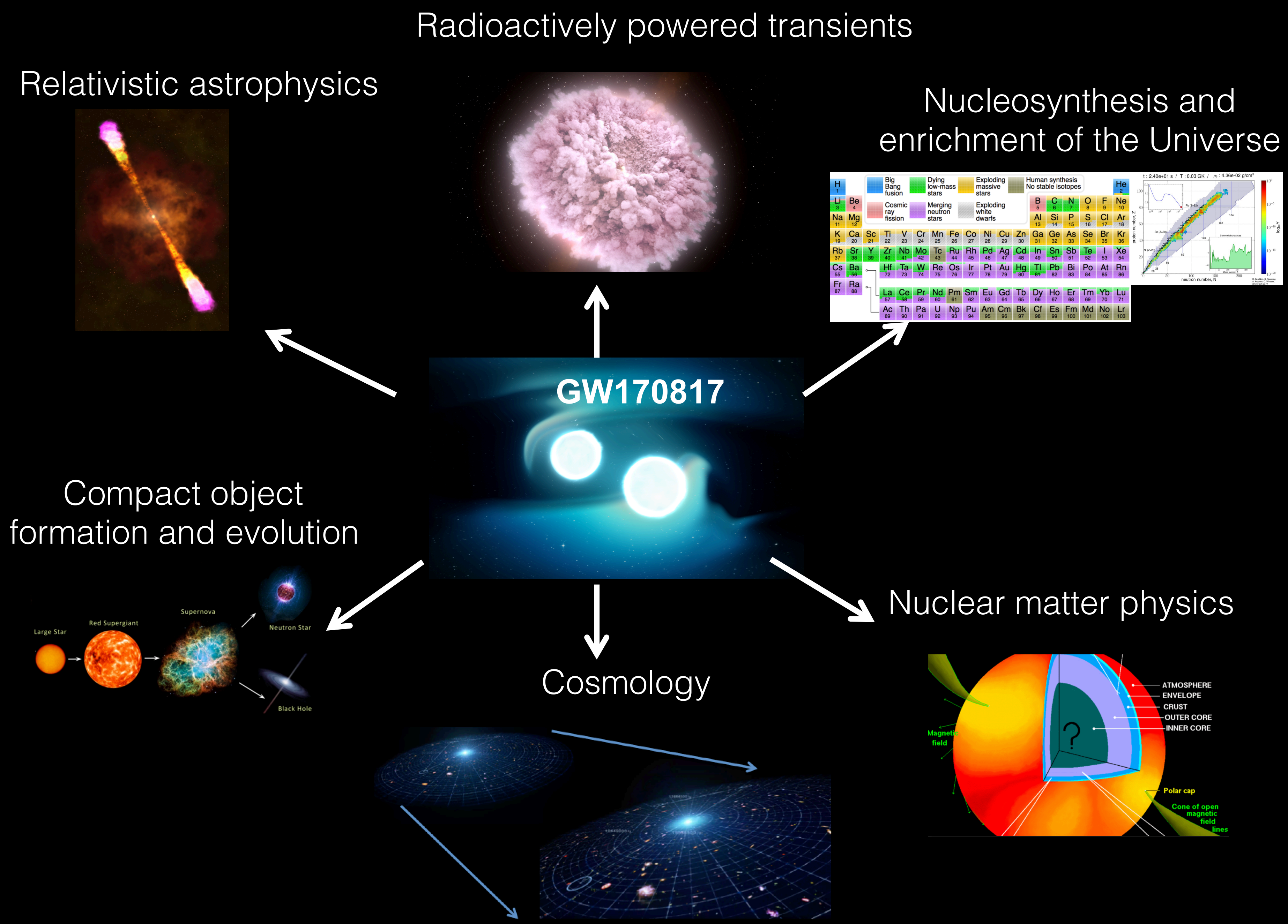
GW 170817



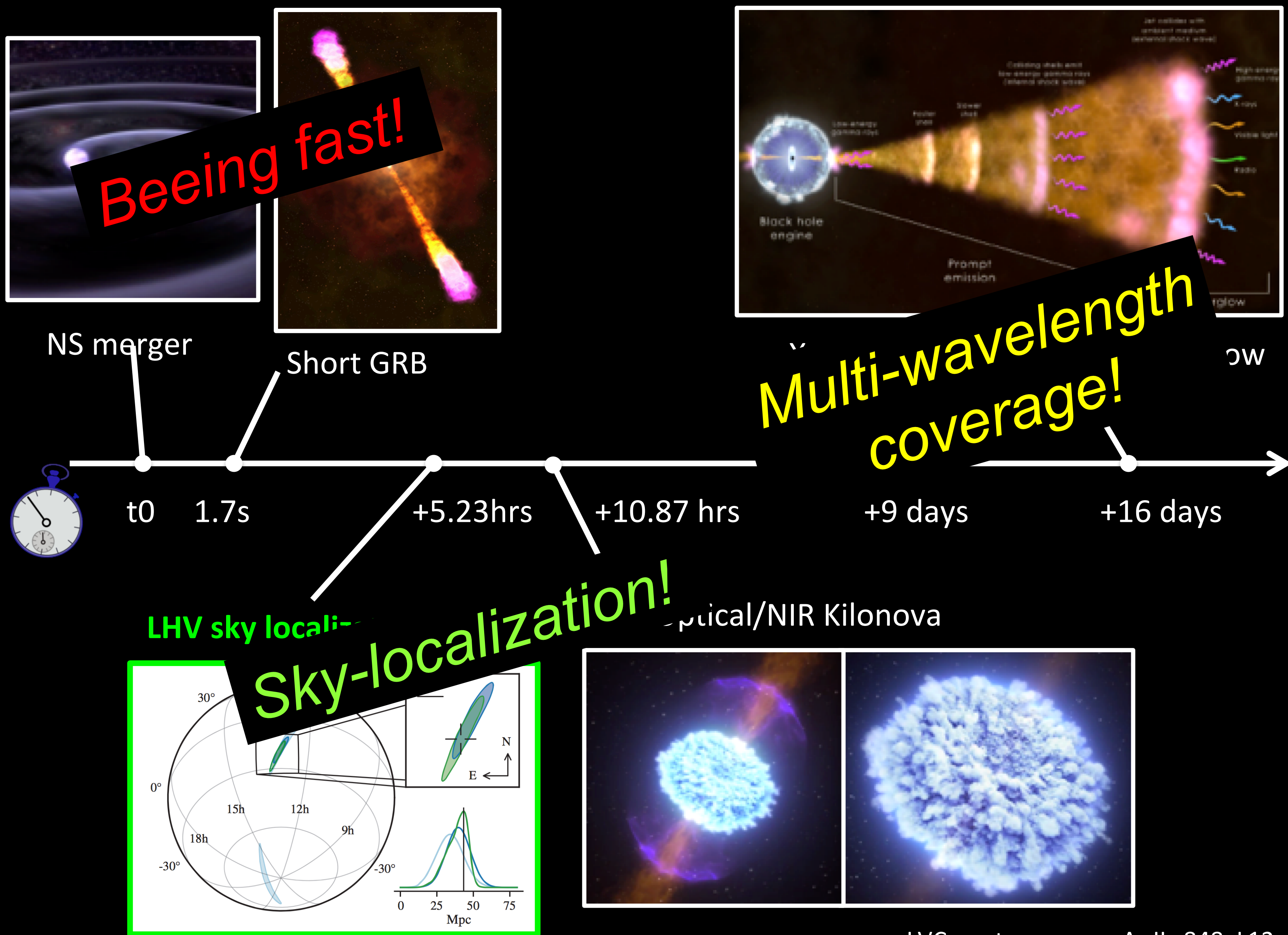


Pian et al. 2017 Nature
Smartt et 2017 Nature

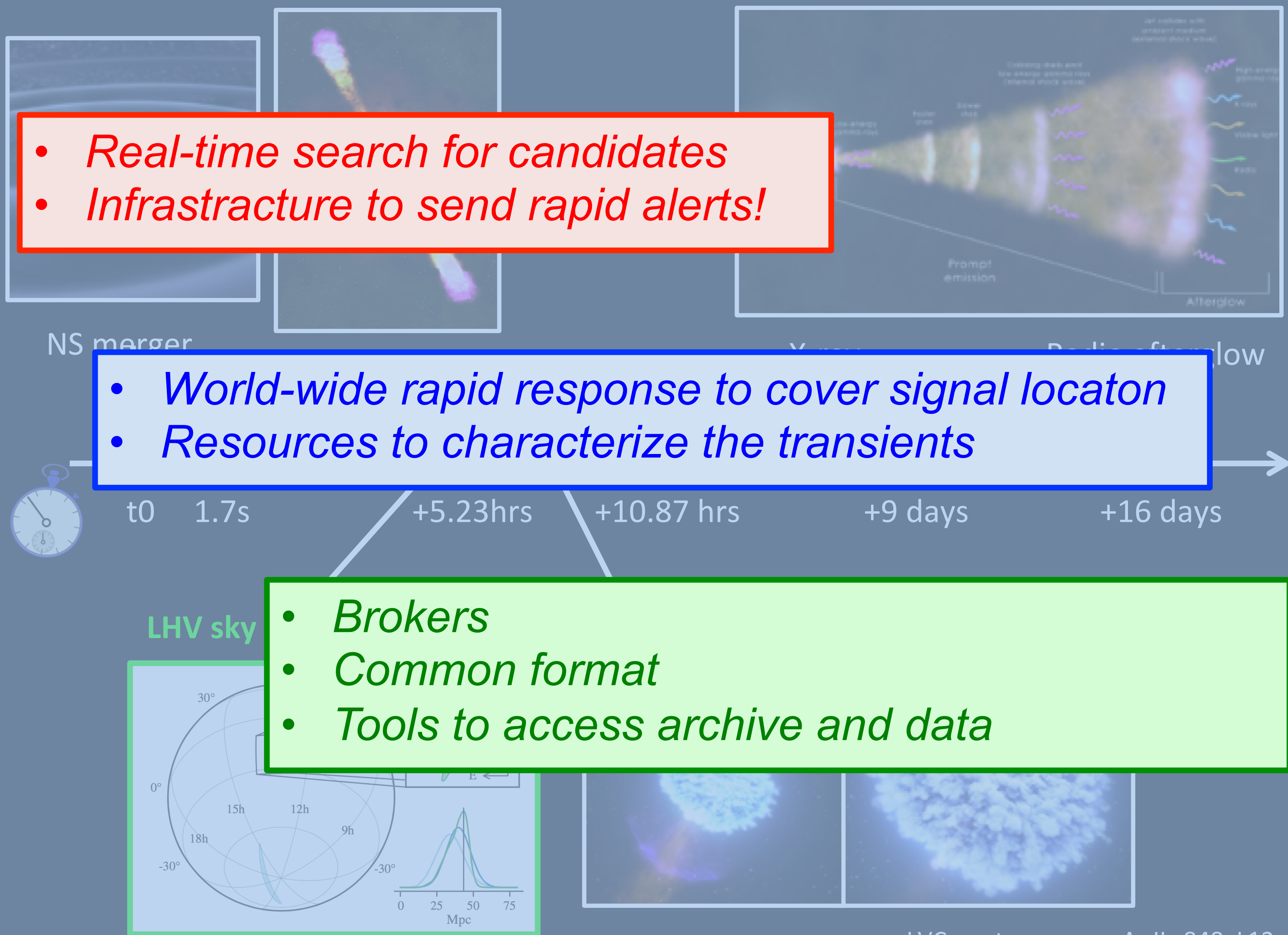



Radioactively powered transients
Relativistic astrophysics
Nucleosynthesis and enrichment of the Universe
Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
GW170817
Compact object formation and evolution
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
Cosmology
Nuclear matter physics
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines

How was that possible?



LVC + astronomers, ApJL, 848, L12



- *Real-time search for candidates*
- *Infrastracture to send rapid alerts!*

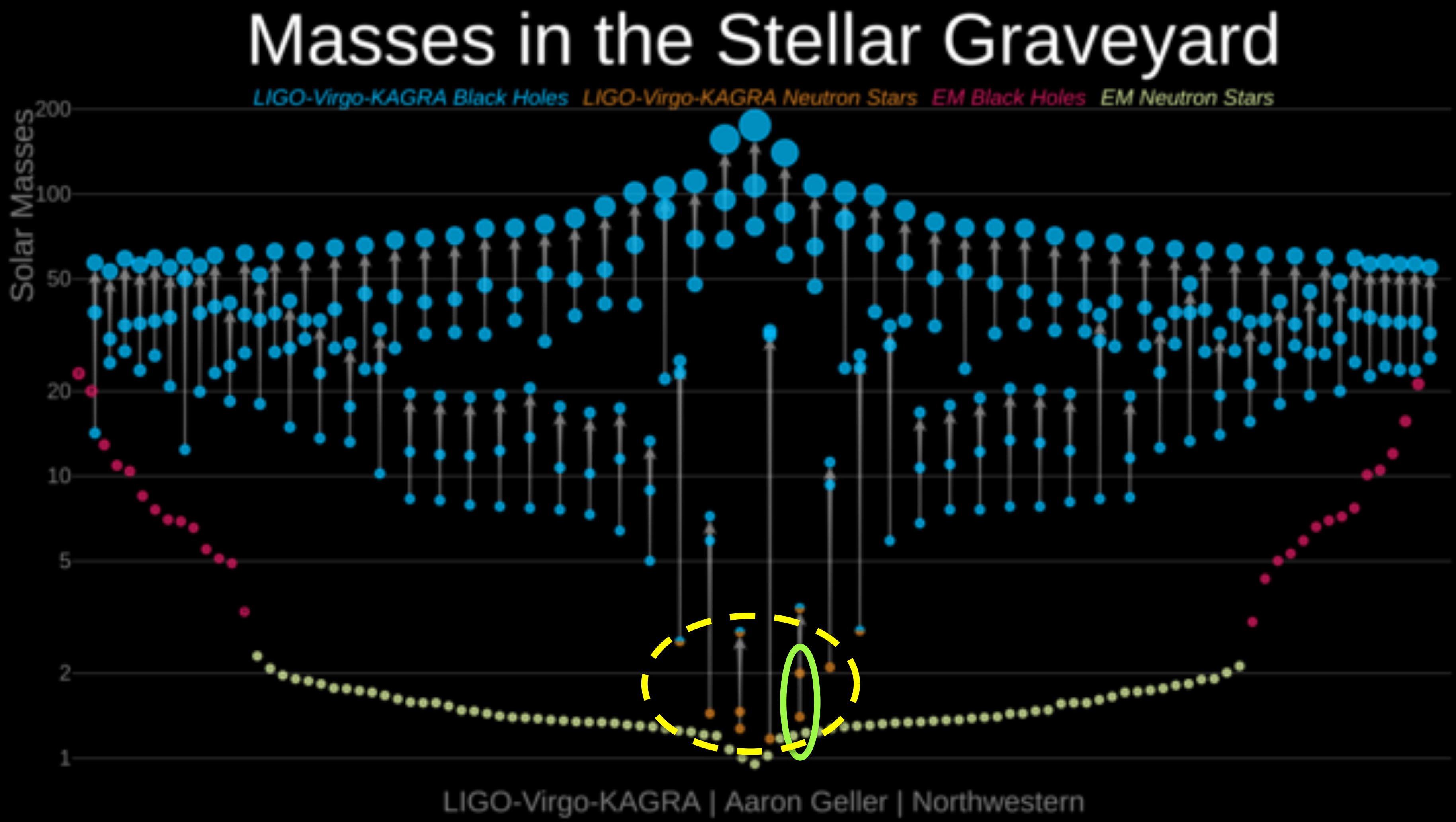
- *World-wide rapid response to cover signal locaton*
- *Resources to characterize the transients*

- *Brokers*
- *Common format*
- *Tools to access archive and data*

LVC + astronomers, ApJL, 848, L12

What happened after GW17017?

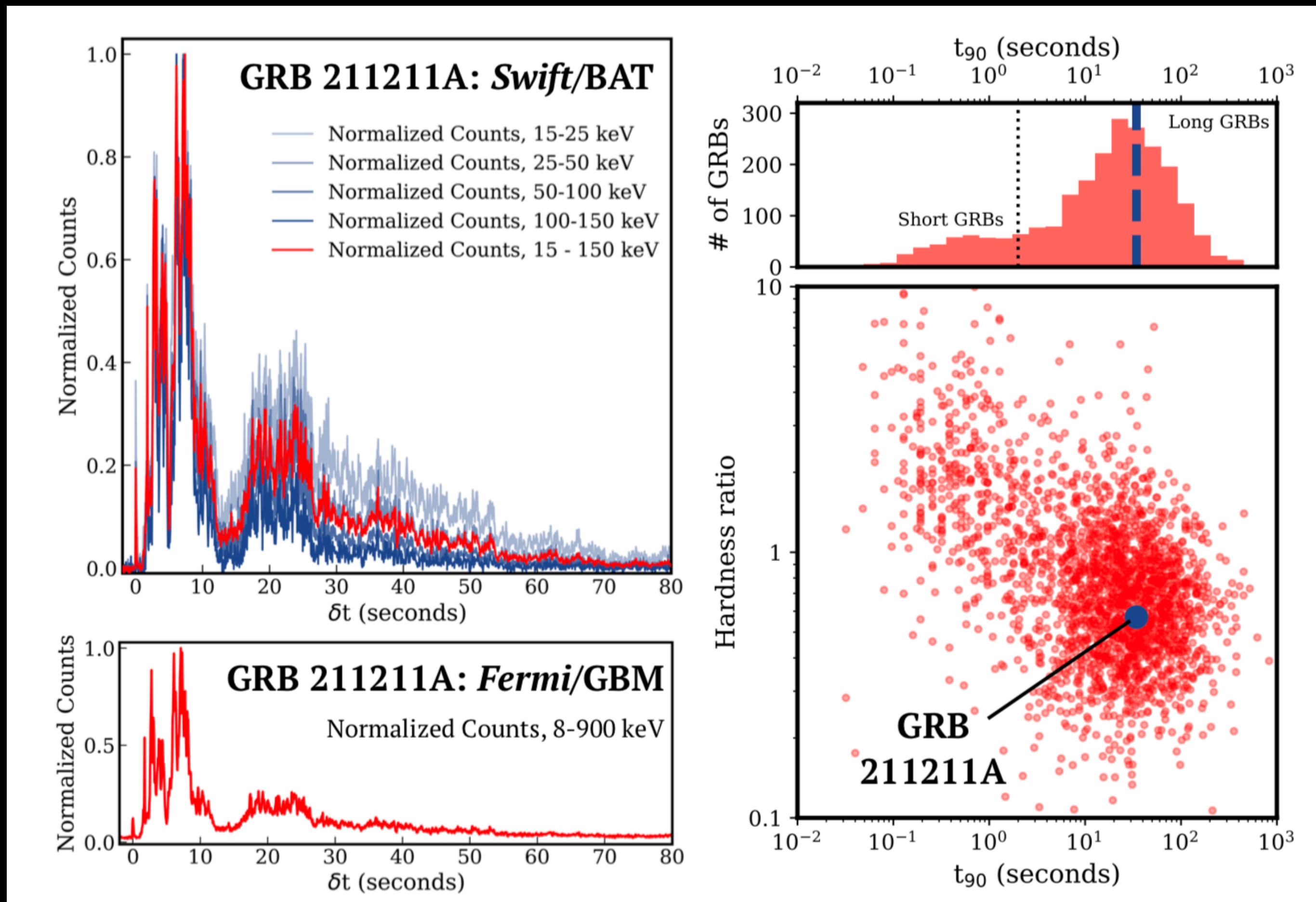
LIGO, Virgo and KAGRA O1+O2+O3 runs



90 GW CANDIDATE EVENTS!

LVK arXiv:2111.03606

GRB 211211A: long GRB/KILONOVA

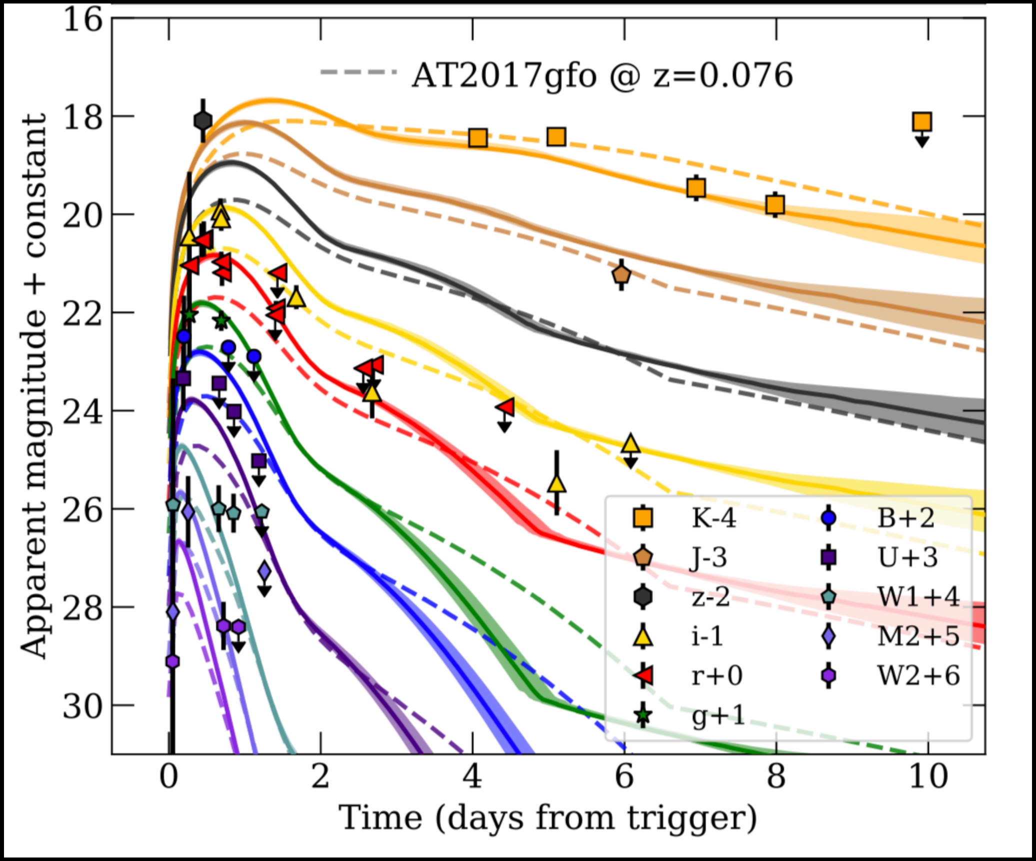


Minute-duration GRB, prompt and bright spikes last more than 12 s

Nearby GRB at 350 Mpc and 7.9 kpc from the galaxy center

Rastinejad, J. C. et al. arXiv:2204.10864

GRB 211211A: long GRB/KILONOVA



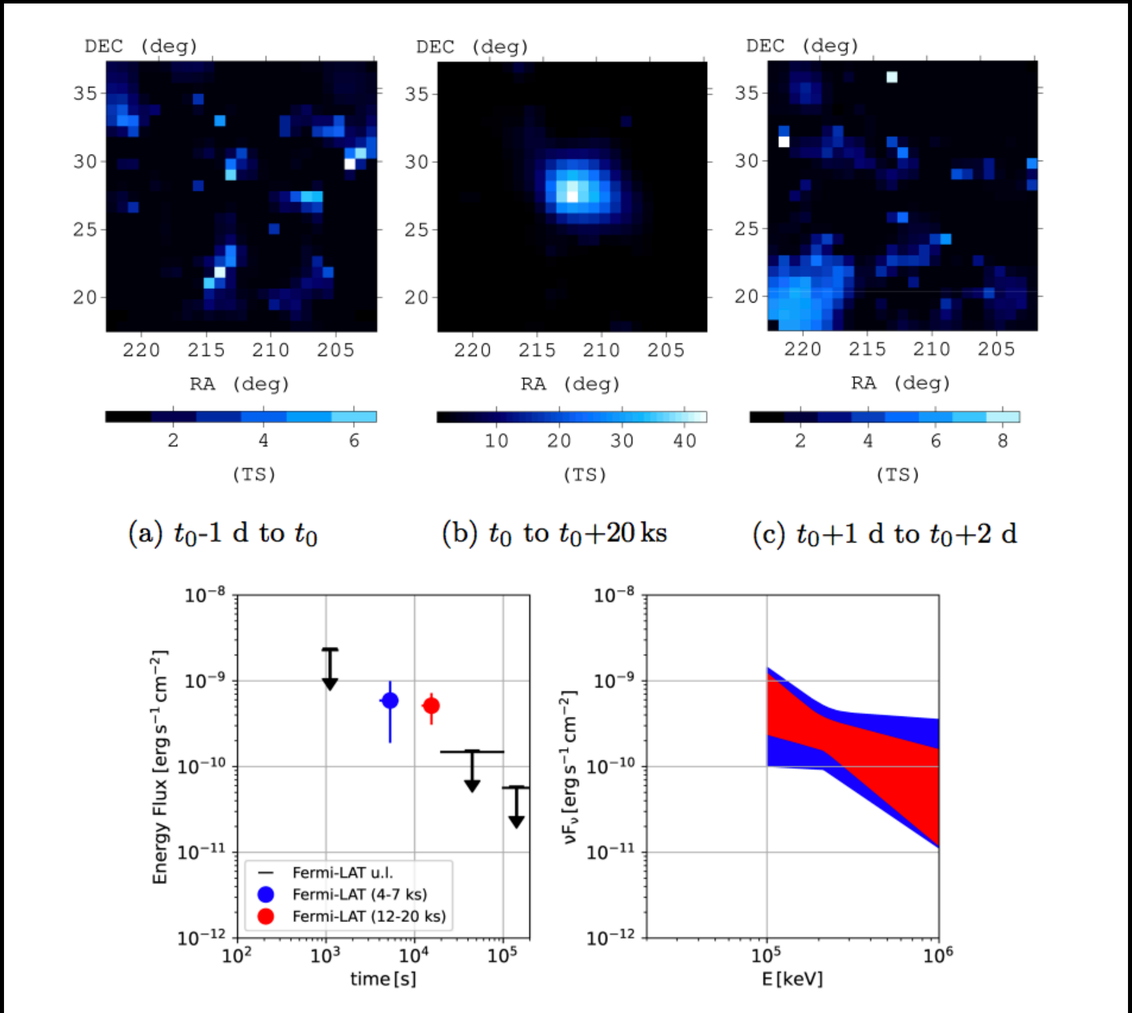
Rastinejad, J. C. et al. arXiv:2204.10864

10% of the local long GRB population could arise from mergers

GW170817-like events are within reach

See also Xiao, S. et al. and Troja et al. arXiv:2209.03363

GRB 211211A: GeV emission



(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

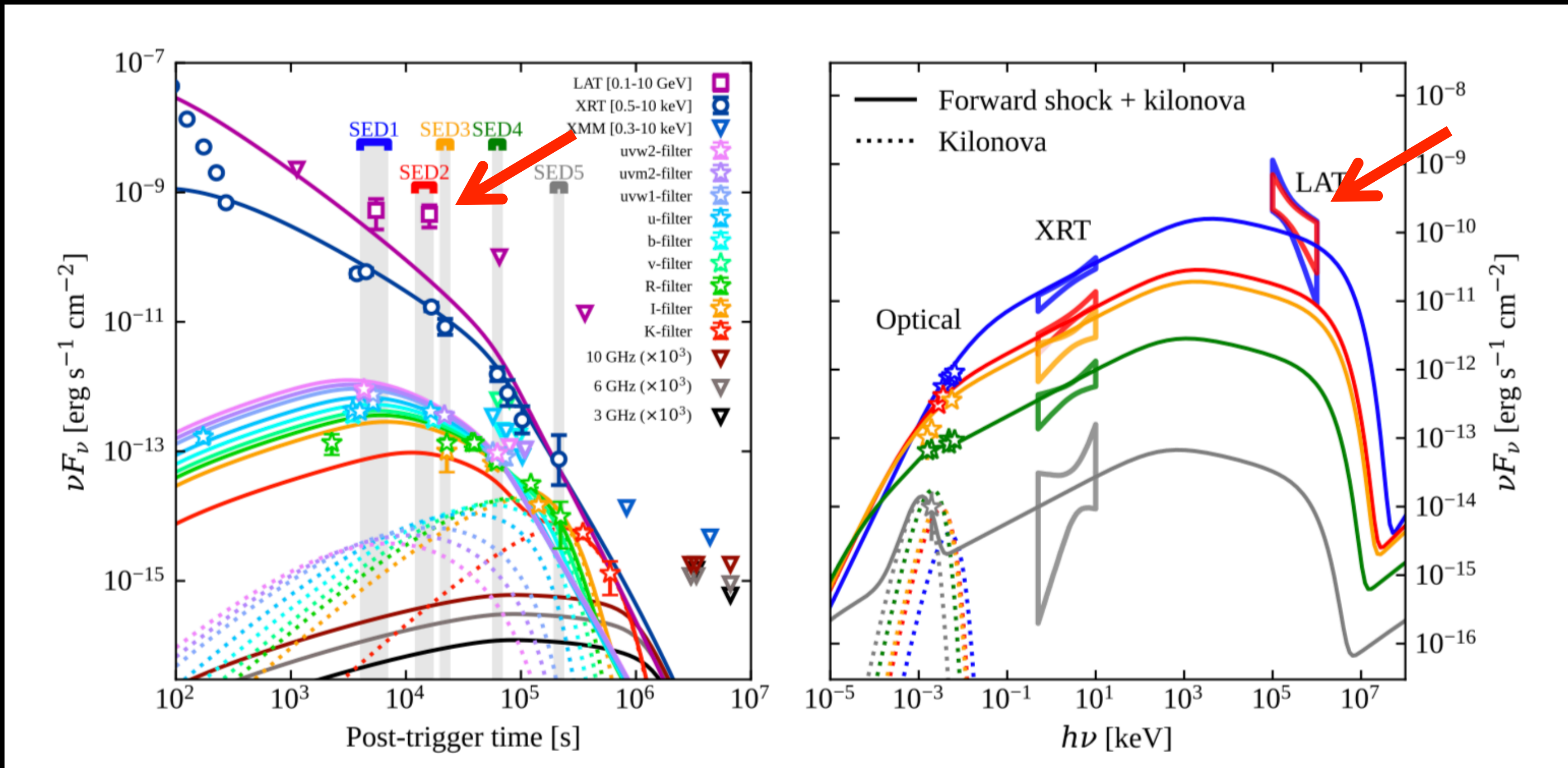
(d) t_0 to t_0+2 d

Discovery of a significant (>5σ) transient-like emission by Fermi/LAT

Photon energies 0.1-1 GeV

Mei et al. 2022, arXiv:2205.08566

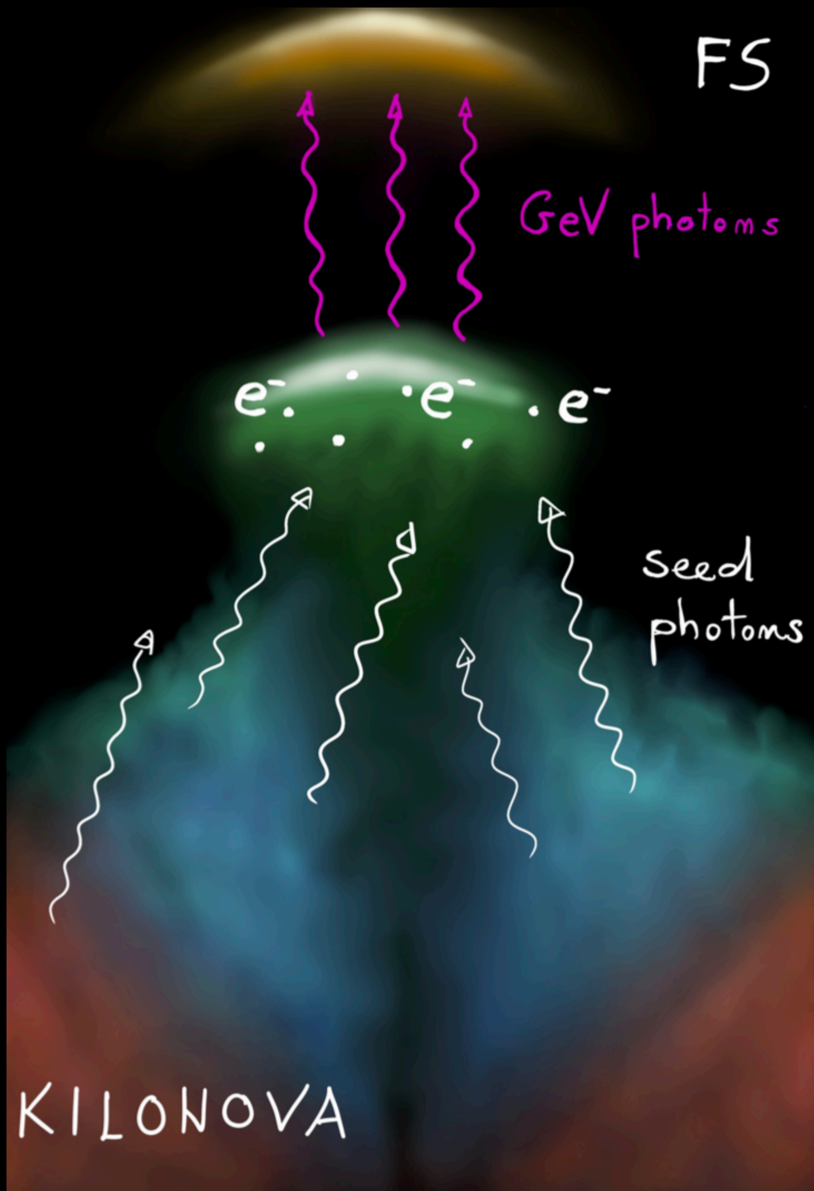
GRB 211211A: GeV excess



The GeV emision is in EXCESS with respect to synchrotron emission from standard forward shock of the relativisic jet explaining the afterglow emission in the other bands

Mei et al. 2022, arXiv:2205.08566

GEV emission from a compact binary merger



External Inverse Compton

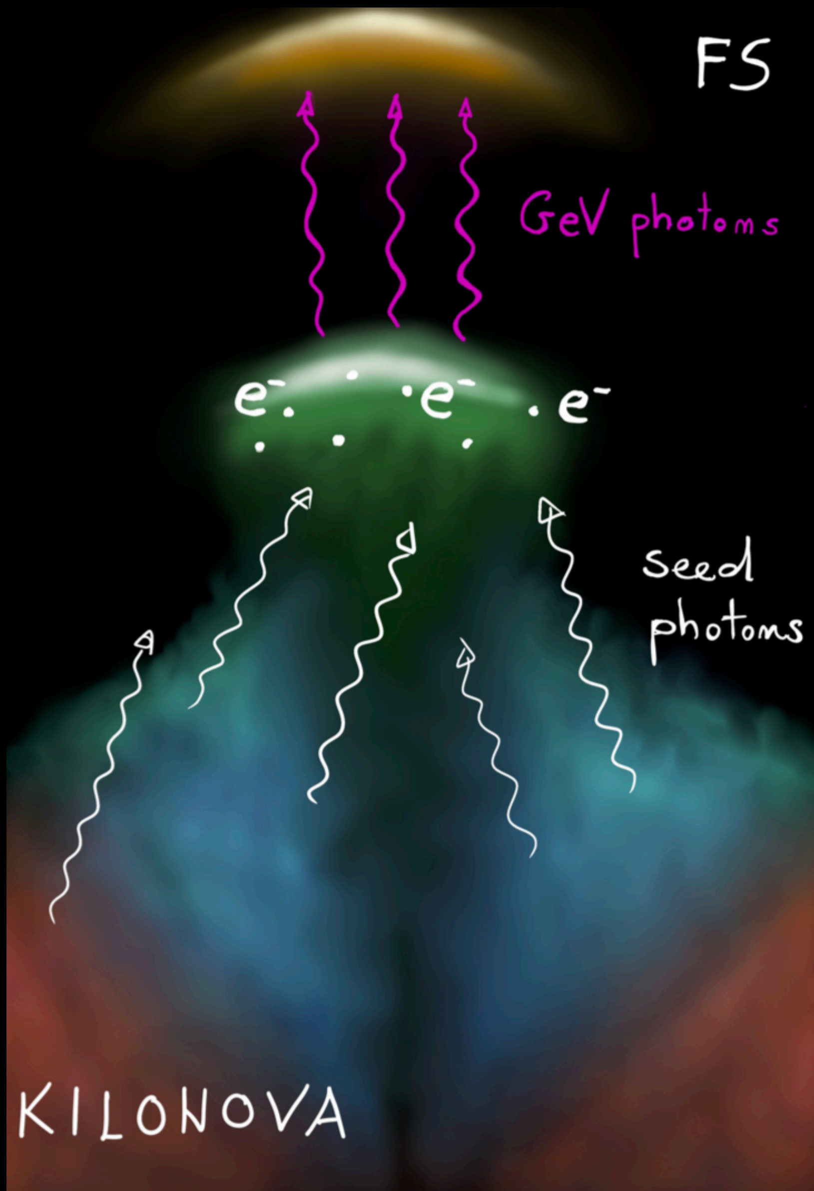
kilonova → seed photons for the EIC

electrons nearby the kilonova photosphere at $t = 10^4$ s

presence of a long-lived low power jet

Mei et al. 2022, arXiv:2205.08566

GEV emission from a compact binary merger



External Inverse Compton

kilonova → seed photons for the EIC

electrons nearby the kilonova photosphere at $t = 10^4$ s

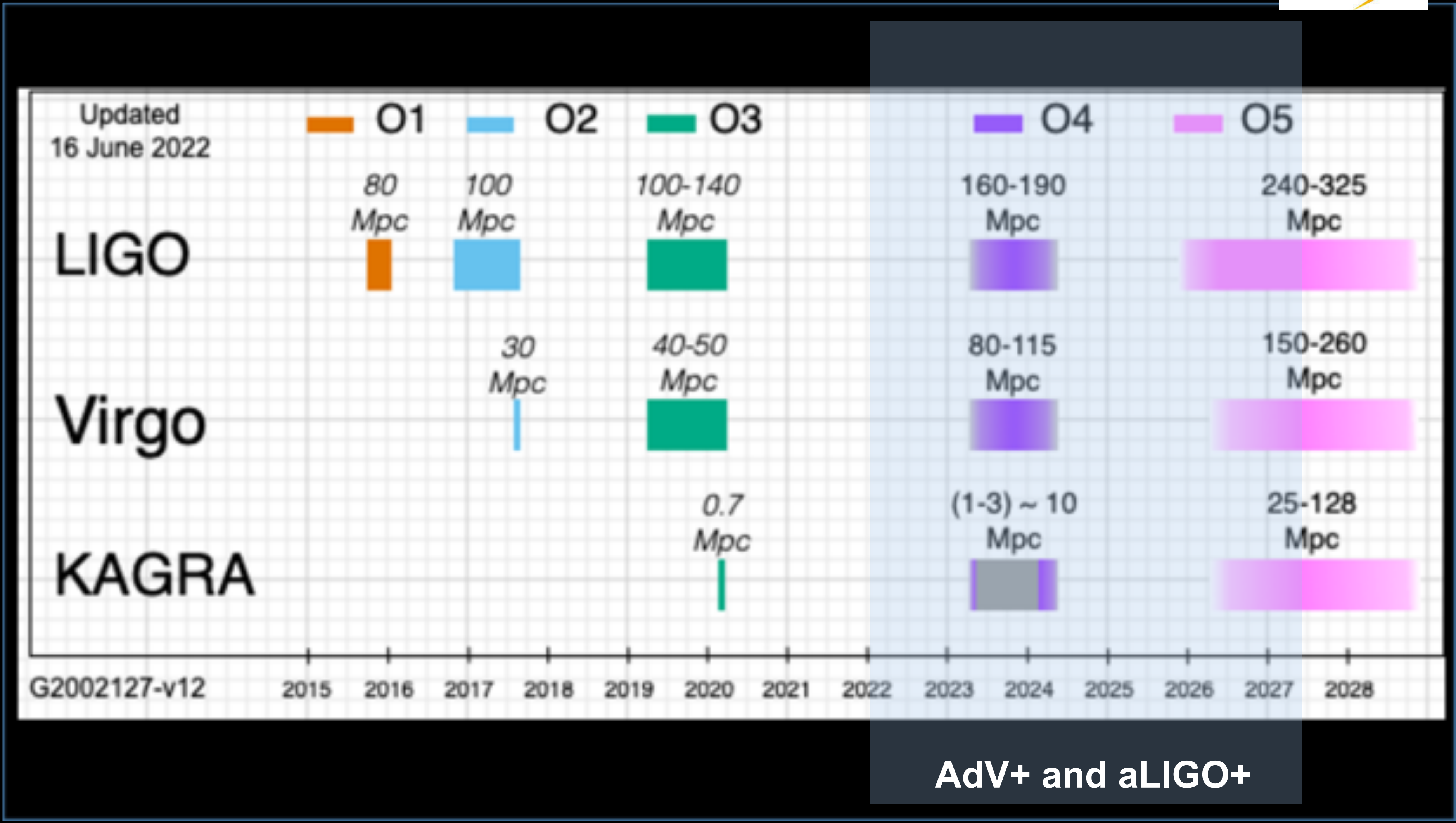
presence of a long-lived low power jet

New counterpart for GW signals

Mei et al. 2022, arXiv:2205.08566

Next observing runs

Observing run timeline and BNS range evolution



Abbott et al. 2020, LRR

O4 volume ~ 3*O3 volume
O5 volume ~10*O3 volume

O4 EXPECTATIONS

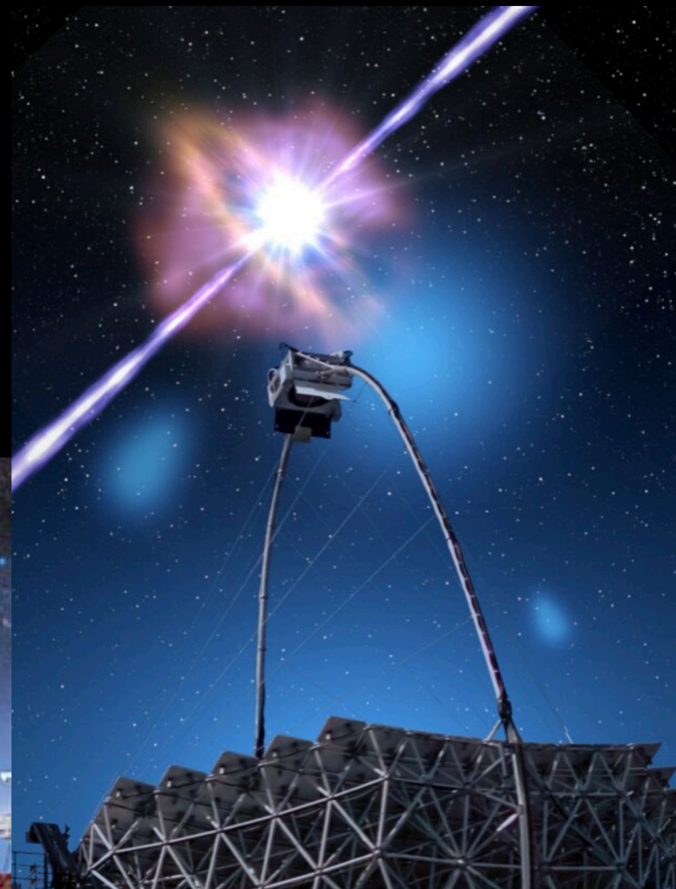
LIGO, VIRGO, AND KAGRA OBSERVING RUN PLANS

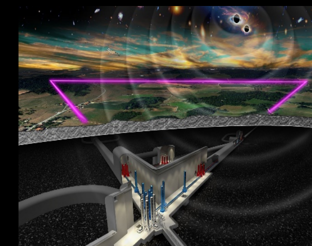
- LIGO, Virgo and KAGRA will start observations on March 2023
- Kagra: 1 Mpc with a plan to improve to 3-25 Mpc during O4
- We do expect a factor 3 in the number of events: we should reasonably expect (O3 79 GW events) to have: ~ 240 GW events. That is almost 1 detection per day, **about 5-10 BNS detections**
- Sky-localizations similar to O3, median value for BNS a few hundreds of sq. degrees

Credits: De Pietri


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
cta
cherenkov telescope array
Rubin Observatory
LIGO INDIA
LOFAR
SKA
SQUARE KILOMETRE ARRAY
ELT
NETWORK OF GW DETECTORS
KM3NeT
NEUTRINO DETECTORS
GEN2

CTA and GW DETECTOR synergies





LIGO INDIA

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

Rubin Observatory LSST

It revolutionizes time domain astrophysics!

BROKERS
Alerce, AMPEL,
ANTARES,
BABAMUL
Fink, Lasair,
Pitt-Google

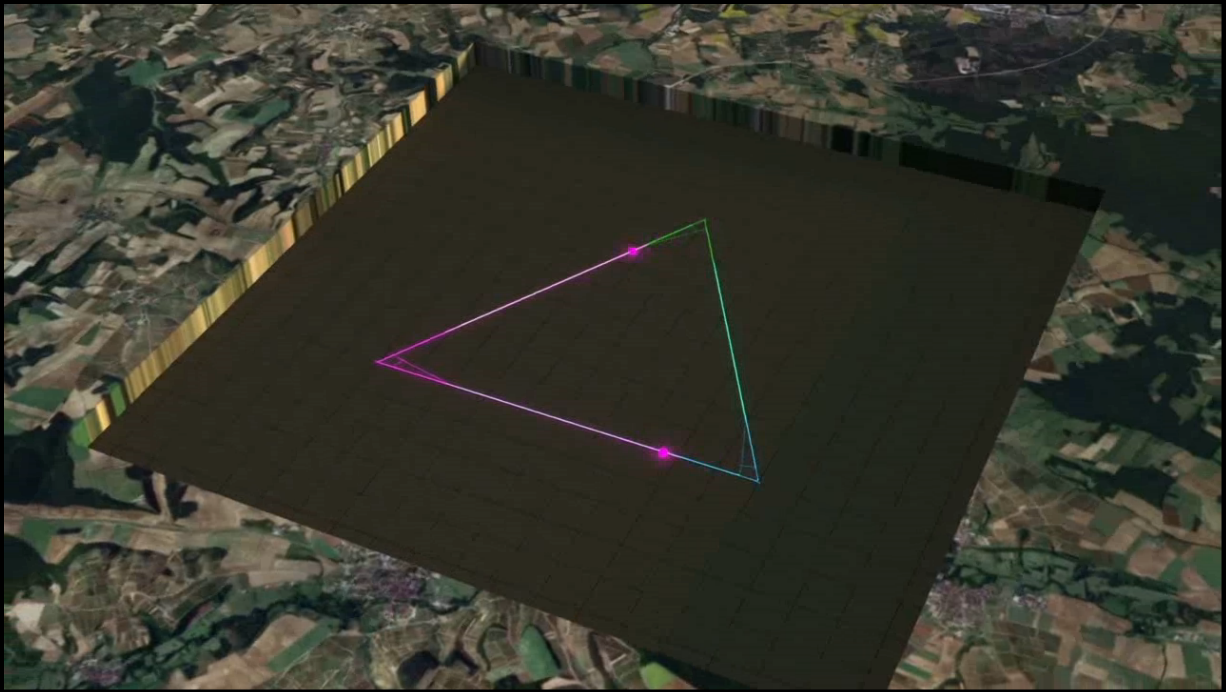
LSST will detect and send out alerts
up to 10.000.000 transients per night

Square Kilometer Array!

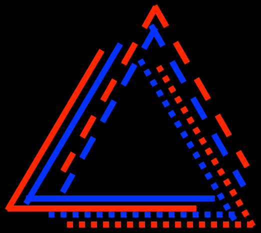
A big data instrument!

Next generation GW astronomy and multi-wavelenght follow-up

ET: the European 3G GW observatory concept

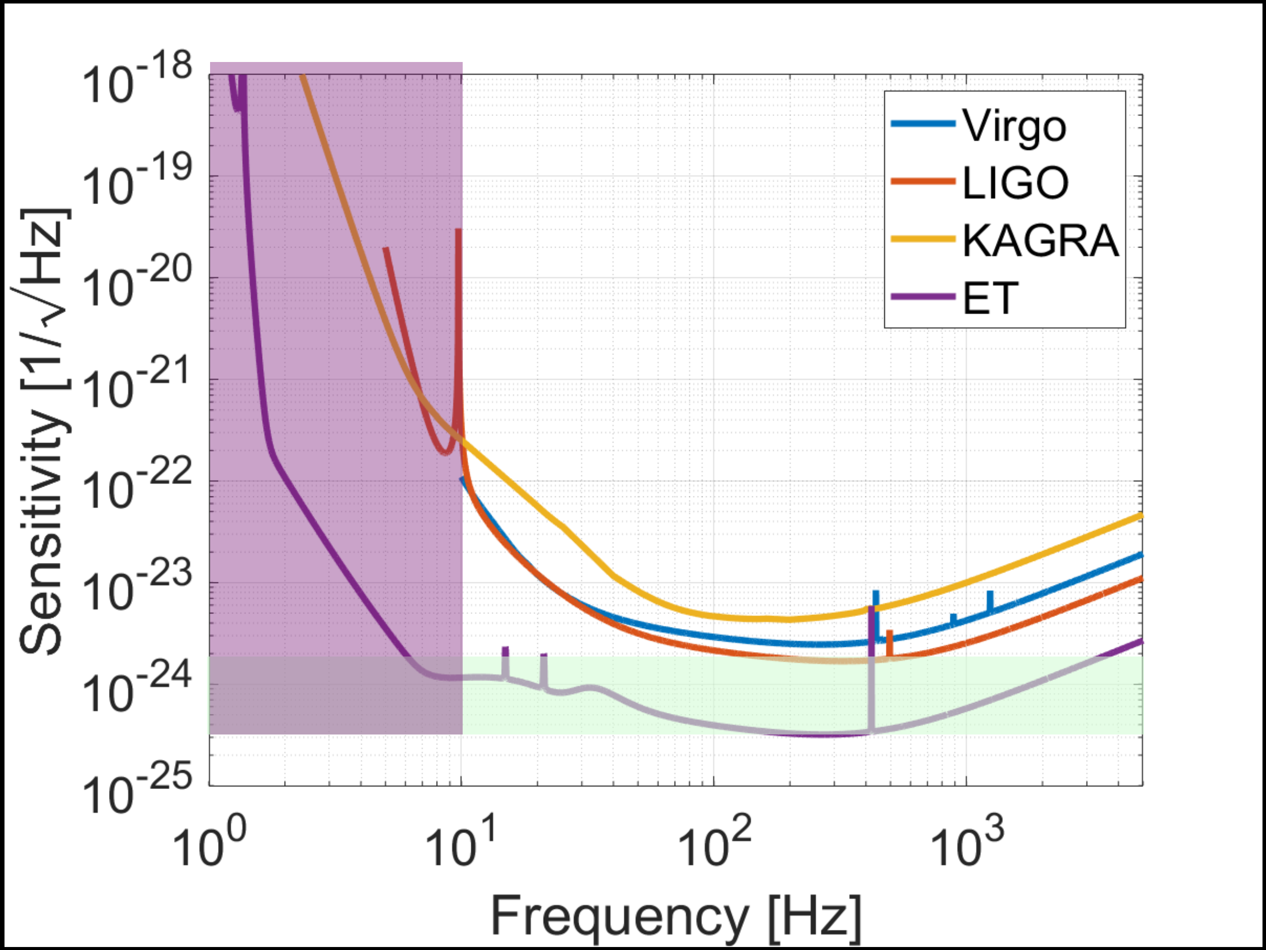


Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...



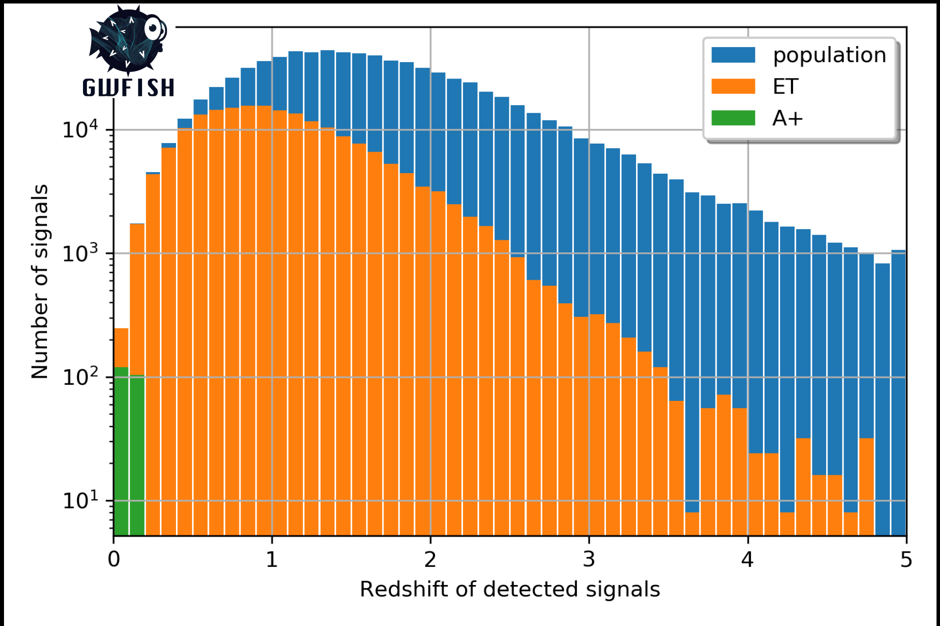
INCLUDED IN ESFRI ROADMAP in 2021

EXPECTED SENSITIVITY

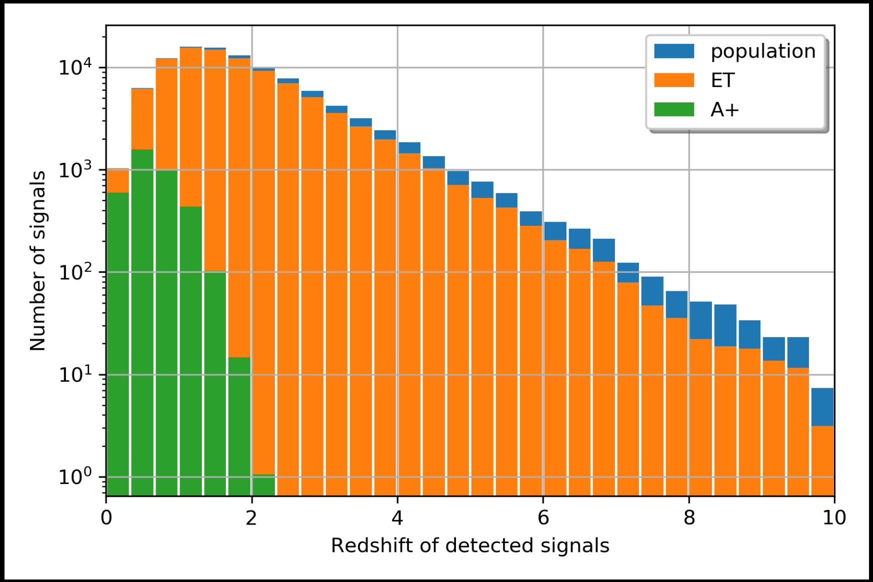


COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS

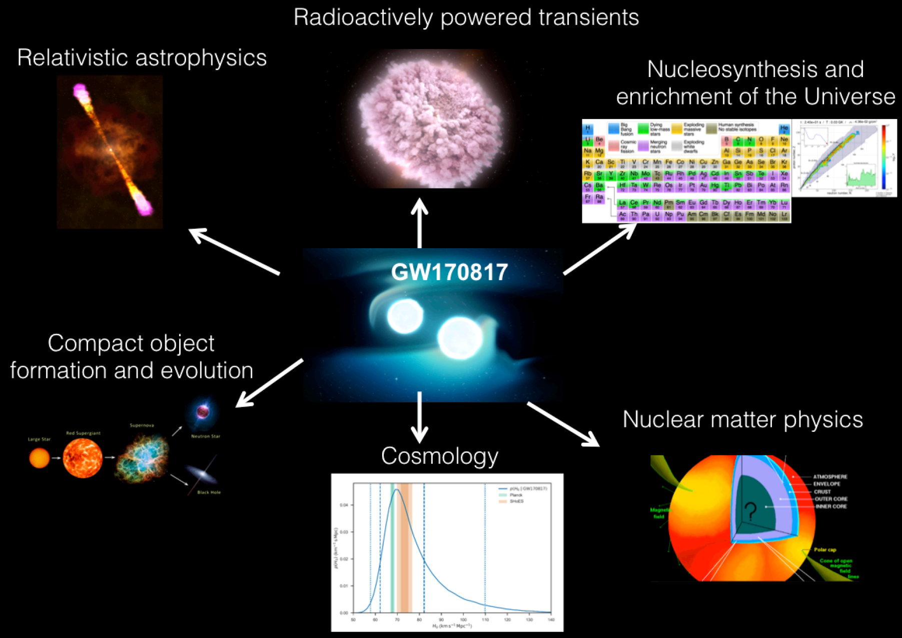


Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year
10^5 BBH detections per year

Harms et al. arXiv:2205.02499

Multi-messenger in the ET era



Kilonova/GW - EOS constraints

Kilonova/GW - Nucleosynthesis

GRBs – BNS/NSBH merger up to high z

Relativistic jet properties

Jet-less/jet GRBs

GRB/stable NS remnant

Link to Star Formation History

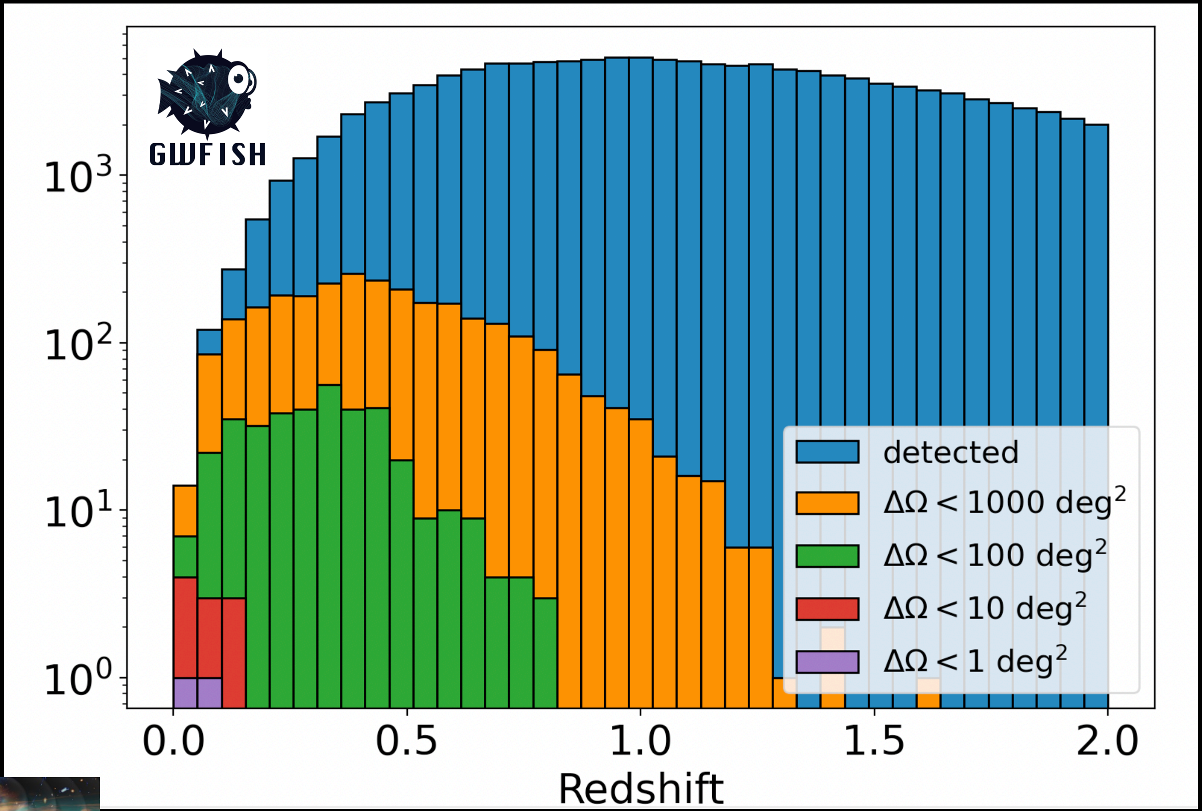
Emission mechanism

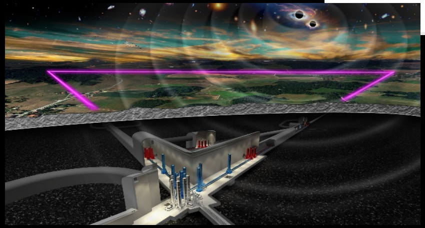
Cosmology

- Large increase of detection rate
  - population of BNS/NSBH
  - detections along the cosmic history
- Better parameter estimation

- Higher chance to detect other sources and counterparts: core-collapse SN, new-born neutron stars, magnetars, FRBs, neutrinos

ET sky-localization capabilities

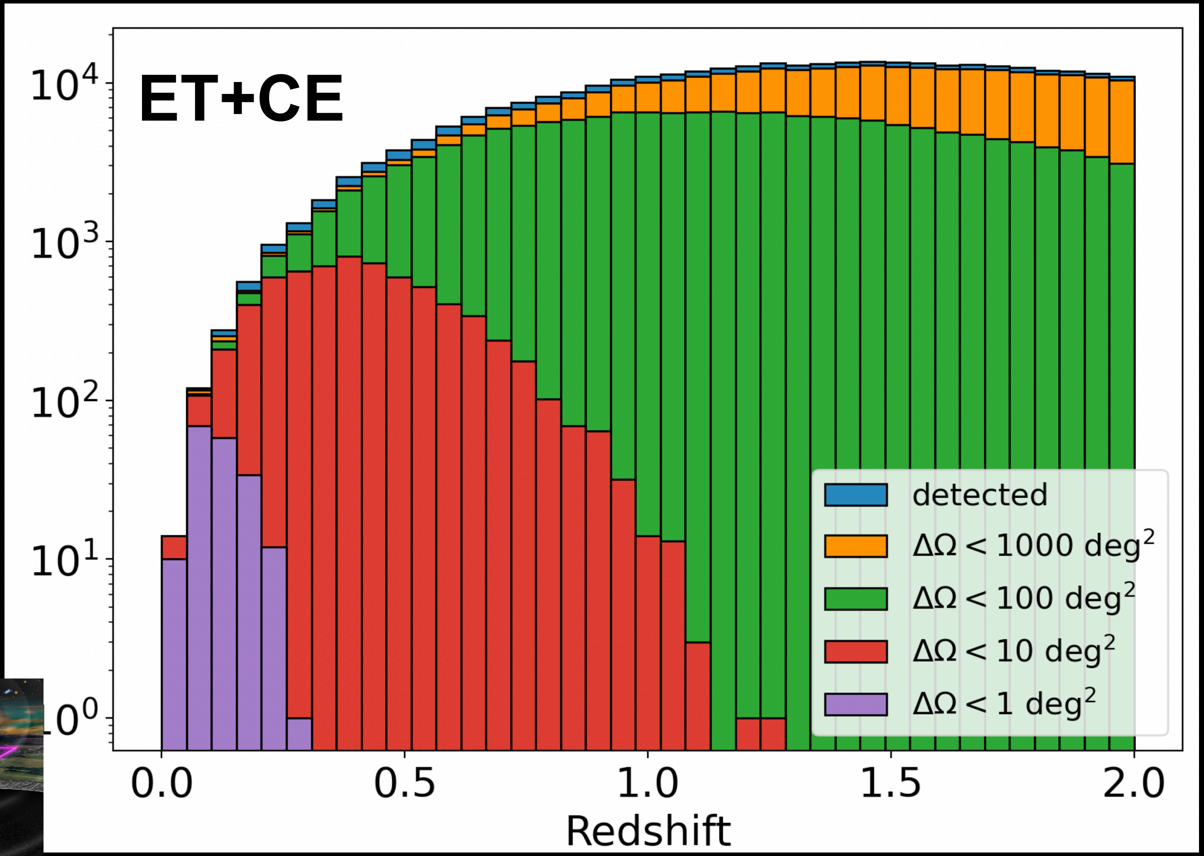


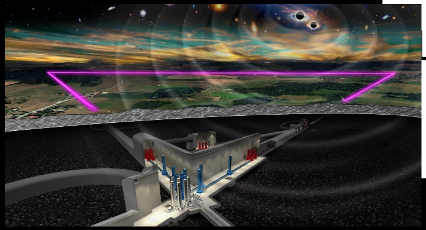


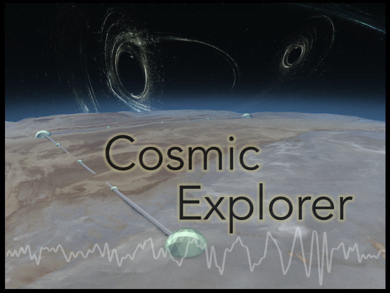
ET low frequency sensitivity make it possibile
To localize BNS!

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

Network sky-localization capabilities



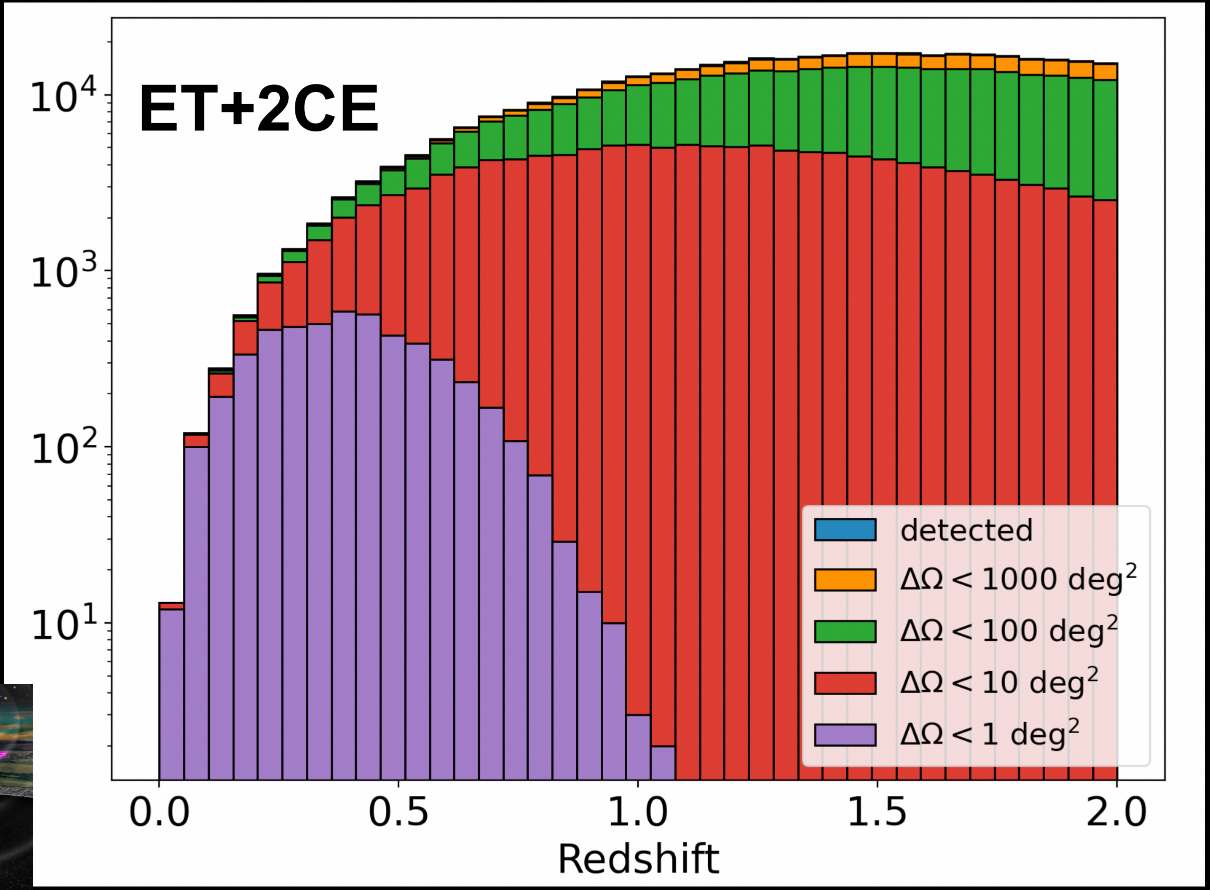


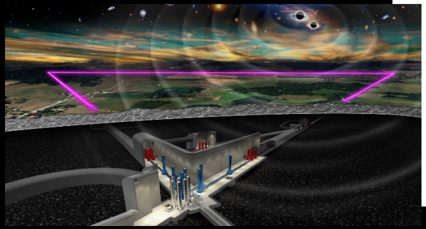


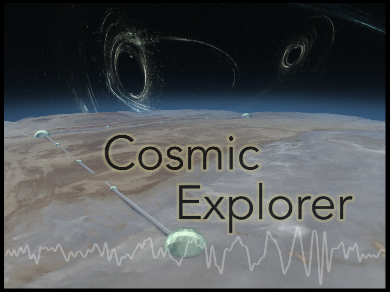
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Harms et al. arXiv:2205.02499, Ronchini et al. arXiv:2204.01746

Network sky-localization capabilities

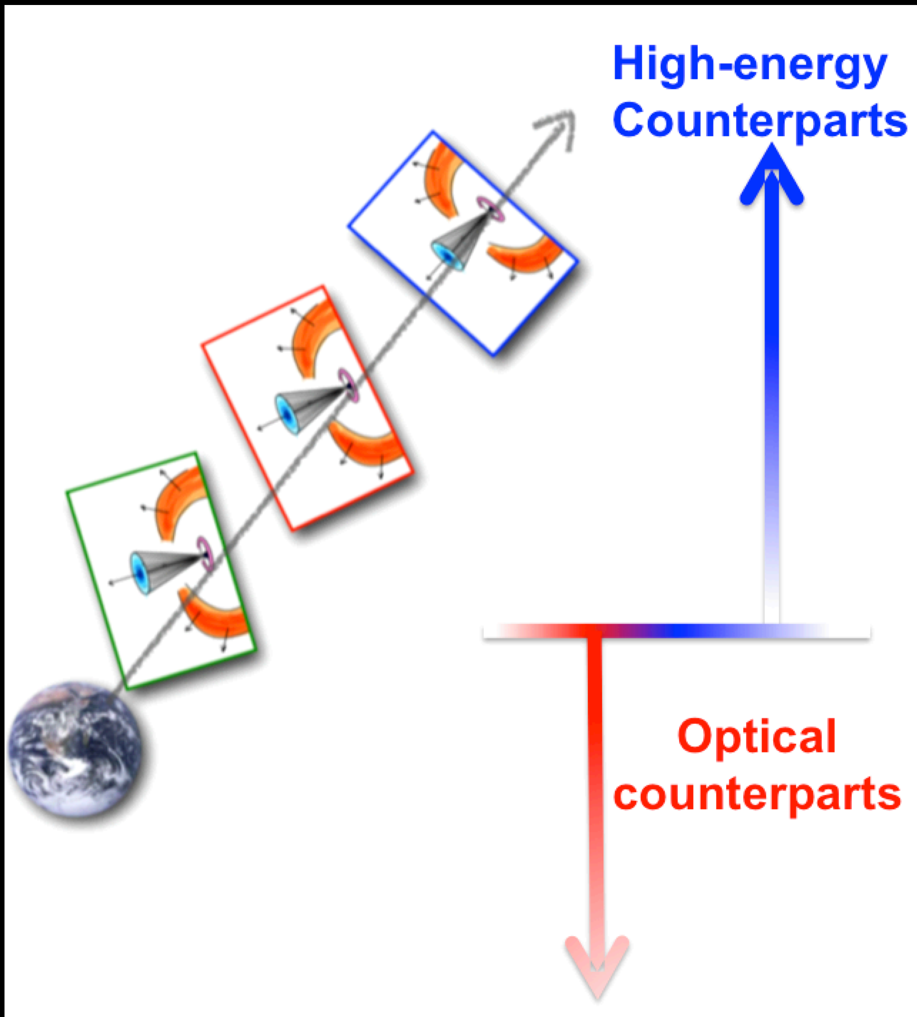






- O(1000) detections per year with sky-localization (90% c.r.) < 1 sq. deg

Harms et al. arXiv:2205.02499, Ronchini et al. arXiv:2204.01746



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

Credit: Ronchini

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE

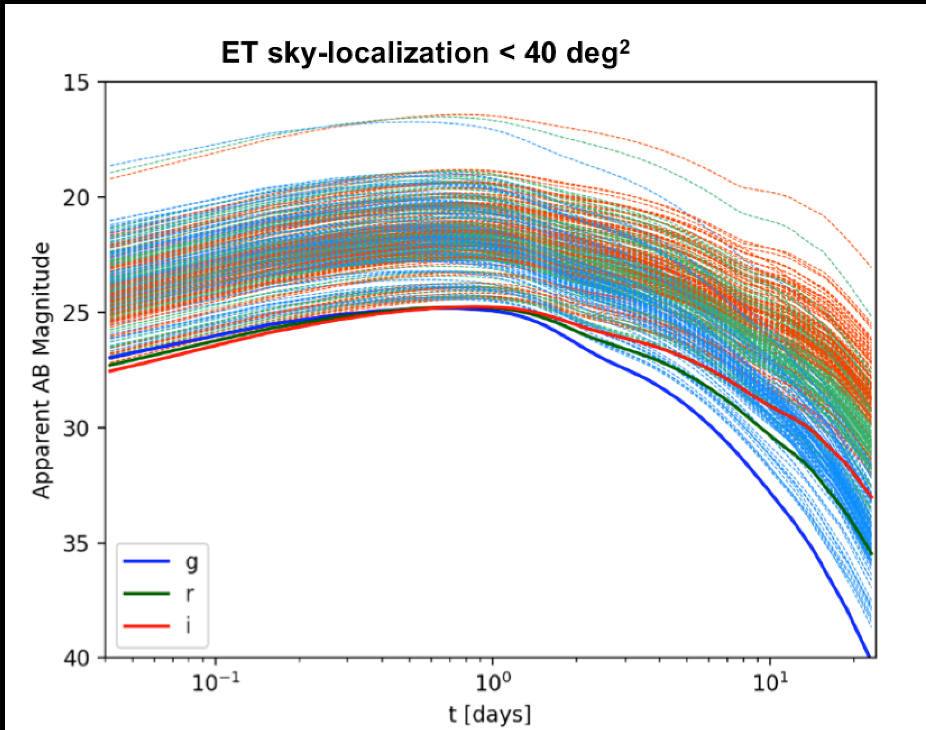
Hundred of MM events per year!

Image credit: NASA Goddard Space Flight Center

THERMAL EMISSION - KILONOVAE

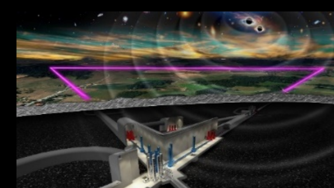
KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

ET+Vera Rubin synergy



VERA RUBIN OBSERVATORY ToO:

- three epochs of 600s observations in two filters
- detection efficiency is larger than 99% up to z=0.3



VERA C. RUBIN OBSERVATORY

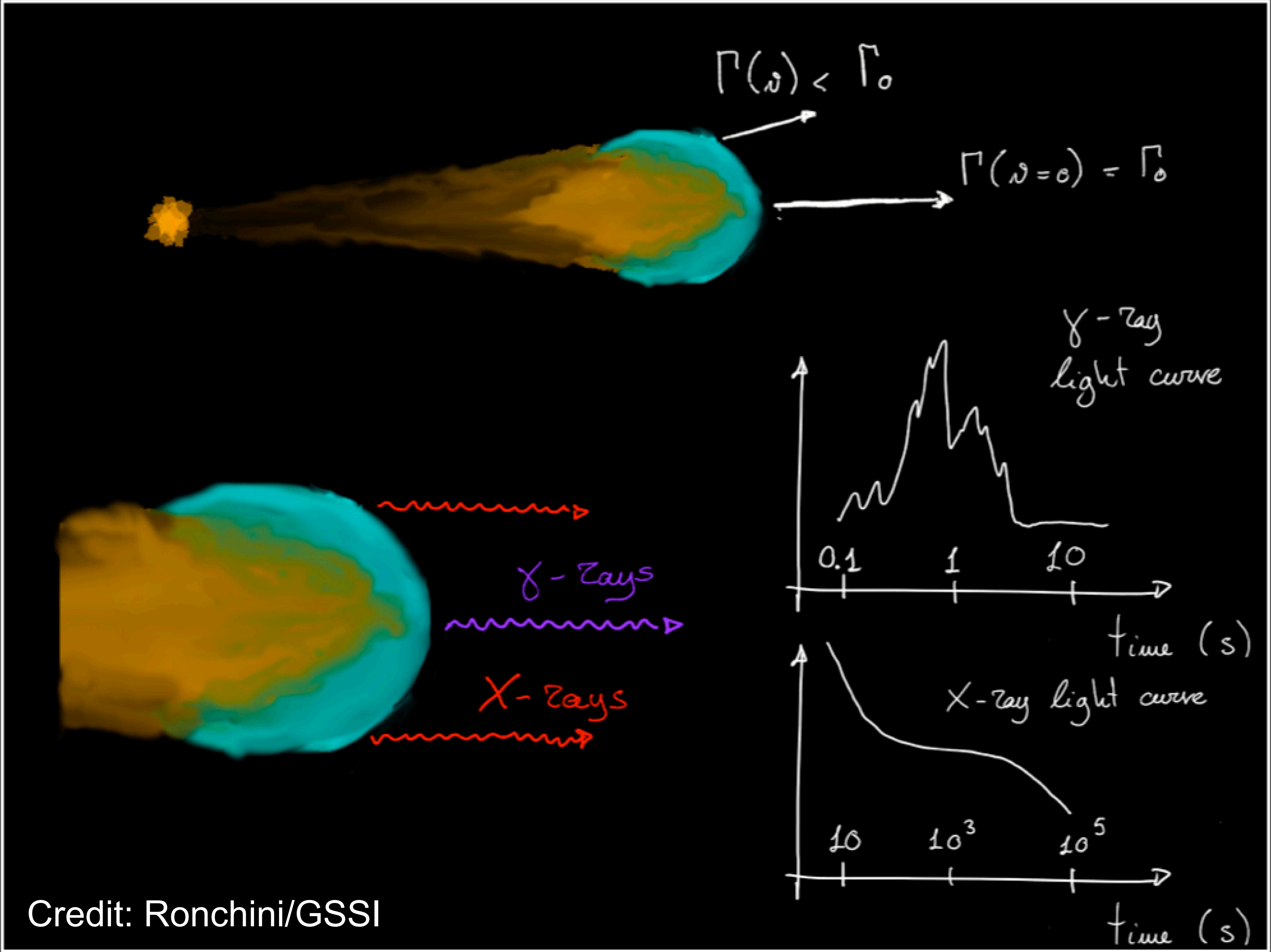
Around 40 joint ET/VRO per year with less than 10% of VRO telescope time

COSMOLOGY: Hubble constant measurement from GW standard sirens with percent precision!

HIGH-ENERGY

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

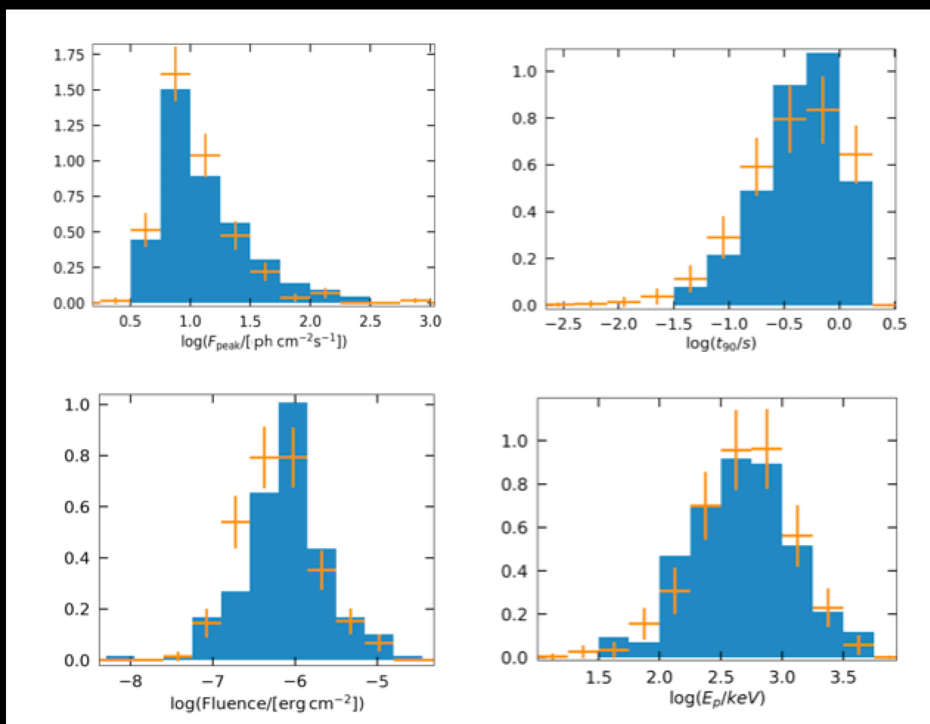
Prompt and afterglow emission from a structured jet



Credit: Ronchini/GSSI

Model calibration using the properties of observed short GRB samples

- Starting with the BNS population
- Comparison with statistical properties of Fermi GBM sGRBB sample
  Optimal parameters estimated via MCMC



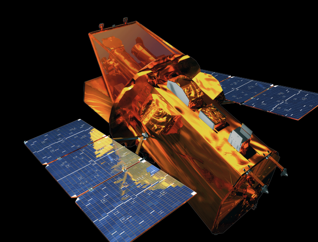
GRB data from Ghirlanda 2016

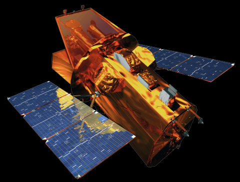
$$0.26^{+0.34}_{-0.14}$$

$$\mathcal{R}_{SGRB} = f_{(NS-NS)\to jet} \times \mathcal{R}_{(NS-NS)}$$

Rate of SGRB observed by Fermi

From population synthesis

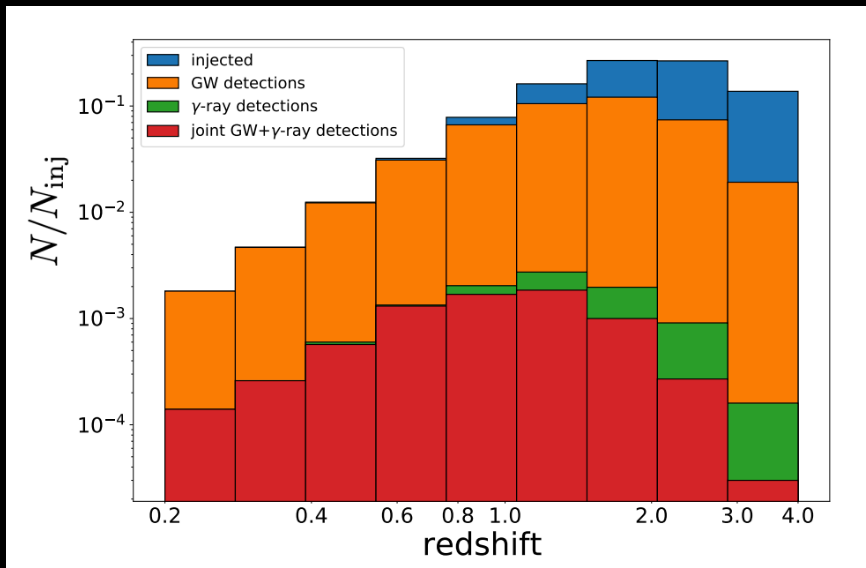




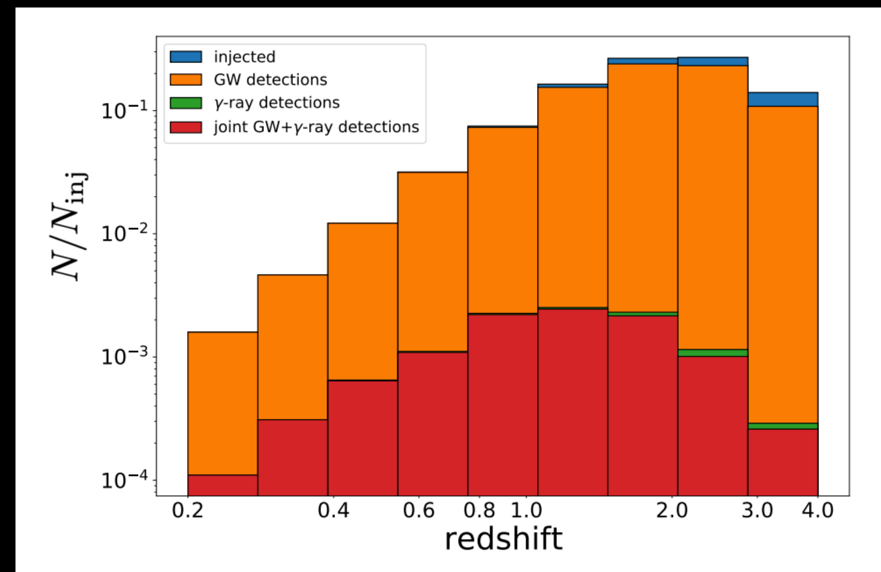
GW + γ-ray joint detections per year

SURVEY MODE

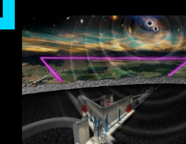
Fermi-GBM+ET



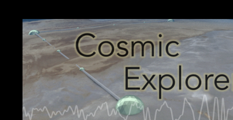
Fermi-GBM+(ET+CE)

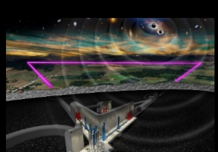


Almost all detected short GRB will have a GW counterpart



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



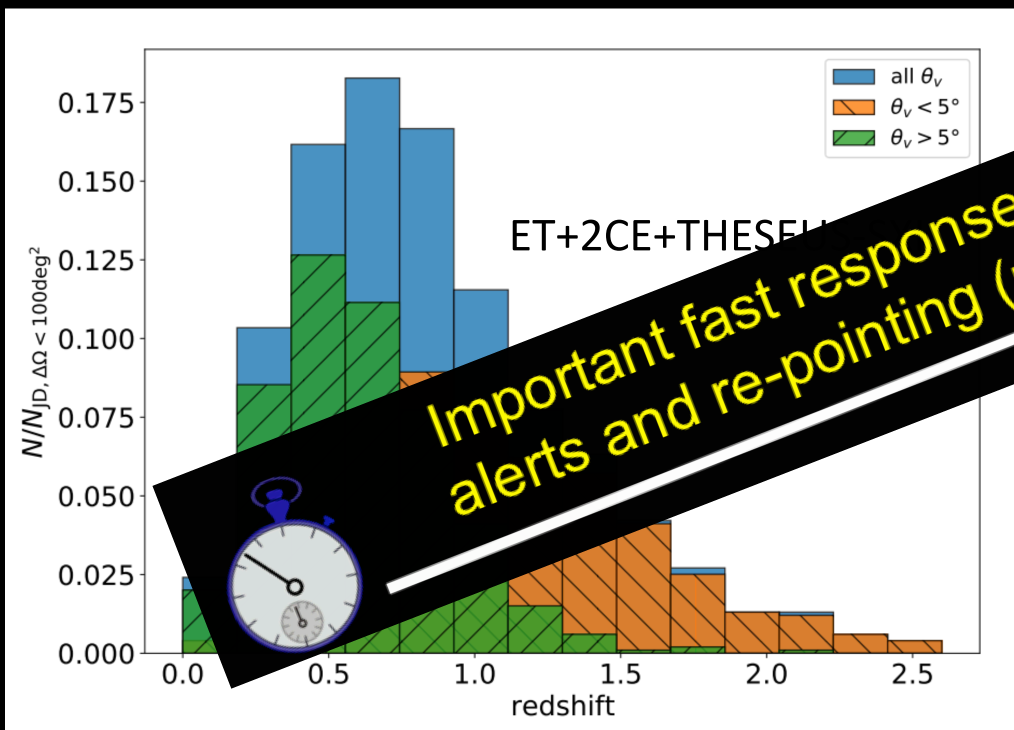


Ronchini, **MB, Oganesyan**, et al. **2022 A&A**

Joint detection GW+X-ray afterglow per year

The importance of WFX-ray monitors

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



Joint GW+Xray detections
with sky-localization < 100 sq. degrees

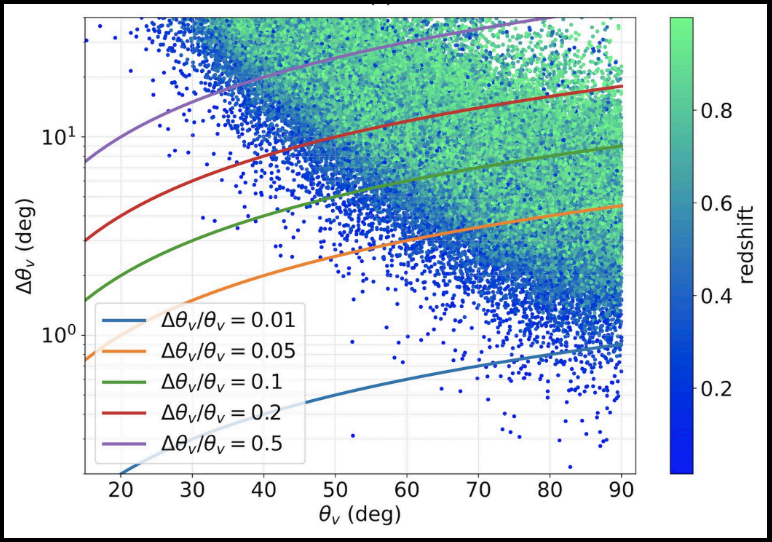
Important fast response to GW alerts and re-pointing (minutes)!

WF… …opes

- …ease of joint …ions (tens-hundreds per year)
- enable to study jet structure
- trigger ground-based follow-up and more sensitive instrument such as ATHENA

Prioritization of triggers required

Viewing angle

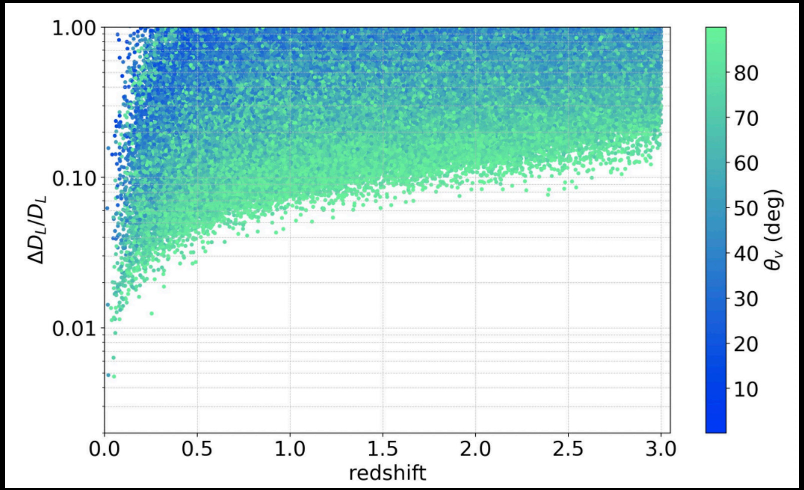


Sky-localization

	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

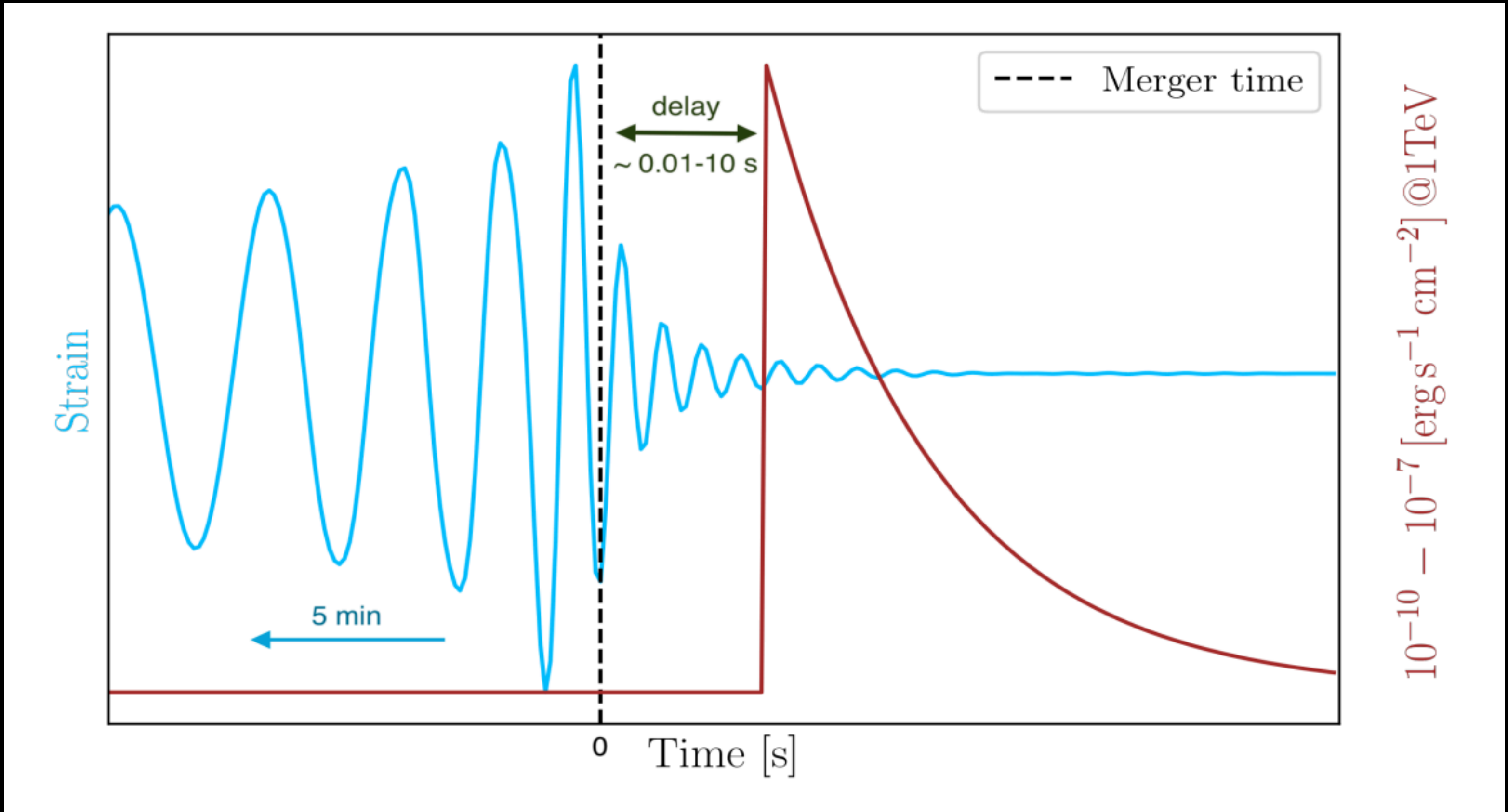
Too large numbers of triggers well localized to be followed-up

Distance



Ronchini, MB, Oganesyan, et al. arXiv:2204.01746

Detection of VHE prompt emission from BNS?



USE OF EARLY WARNING ALERTS FROM ET!

Banerjee et al. 2022, in prep.

SKY-LOCALIZATION PRE-MERGERS

BNS Events per year up to z=1.5

Detector	Ω [deg.^{2}]	All orientation BNSs 15 min	5 min	1 min	0 min
ET	10	4 [0, 4]	5 [0, 9]	8 [0, 11]	14 [1, 27]
	30	16 [0, 22]	25 [2, 40]	42 [3, 72]	81 [6, 157]
	100	63 [4, 117]	130 [8, 255]	208 [16, 435]	436 [33, 919]
	1000	445 [26, 1024]	948 [61, 2225]	1511 [89, 3429]	3130 [194, 7021]
ET+CE	1	n.d.	4 [0, 3]	3 [0, 11]	177 [9, 400]
	10	12 [0, 13]	51 [2, 112]	185 [10, 430]	6656 [366, 14836]
	30	37 [1, 66]	253 [15, 587]	915 [47, 2107]	36782 [2022, 78357]
	100	168 [11, 369]	1325 [73, 3034]	5075 [263, 11255]	123303 [6422, 250439]
	1000	1229 [69, 2862]	15497 [896, 34487]	69423 [3703, 144222]	194834 [10065, 388038]

Banerjee et al. 2022, in prep.

A REVOLUTION IN OUR KNOWLEDGE OF THE EARLY UNIVERSE, FUNDAMENTAL PHYSICS AND ASTROPHYSICS…

Thanks!

GSSI GW team

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B. E. Loffredo, N. Hazra et al.

AHEAD 2020
HIGH ENERGY ASTROPHYSICS

MUR
Ministero dell'Università e della Ricerca

PRIN 2020 grant 2020KB33TP
PRIN 2017 grant 20179ZF5KS