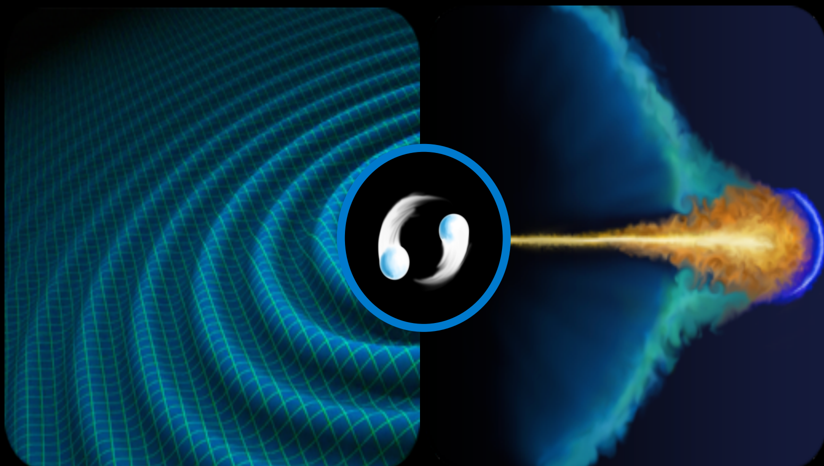
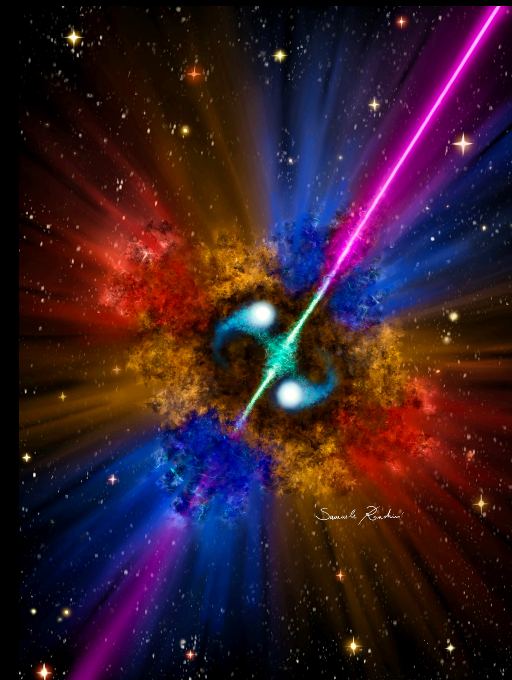
Multi-messenger transients





GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare

GSSI GW team

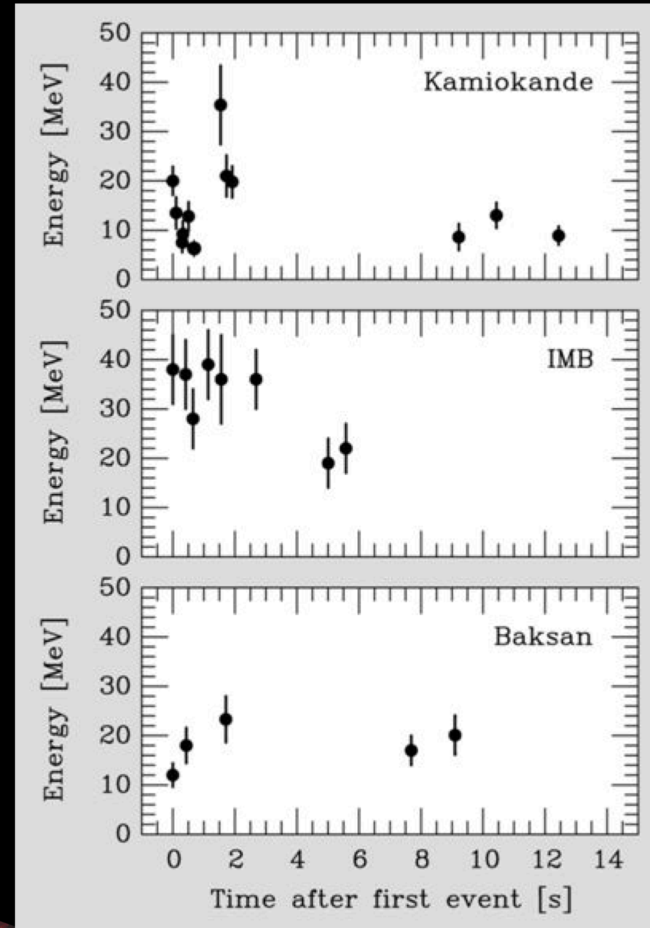
M. Branchesi

Gran Sasso Science Institute

INFN/LNGS and INAF

History of multi-messenger observations

SN1987A

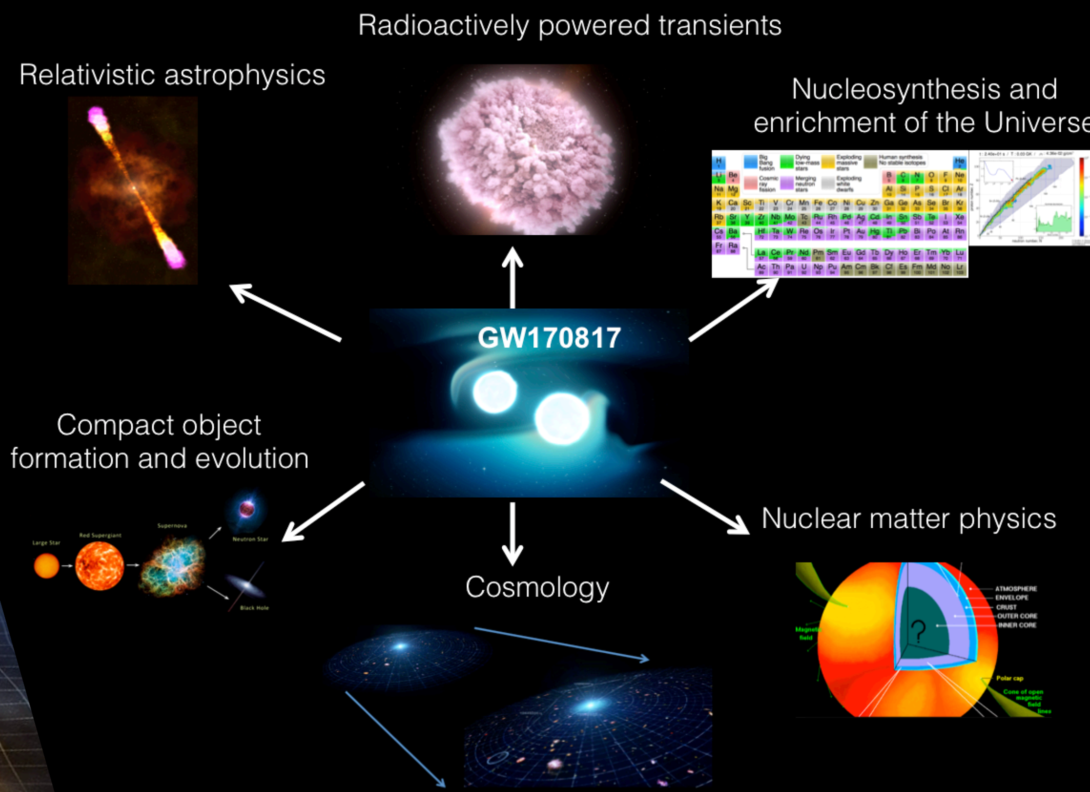


After 30 years..

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

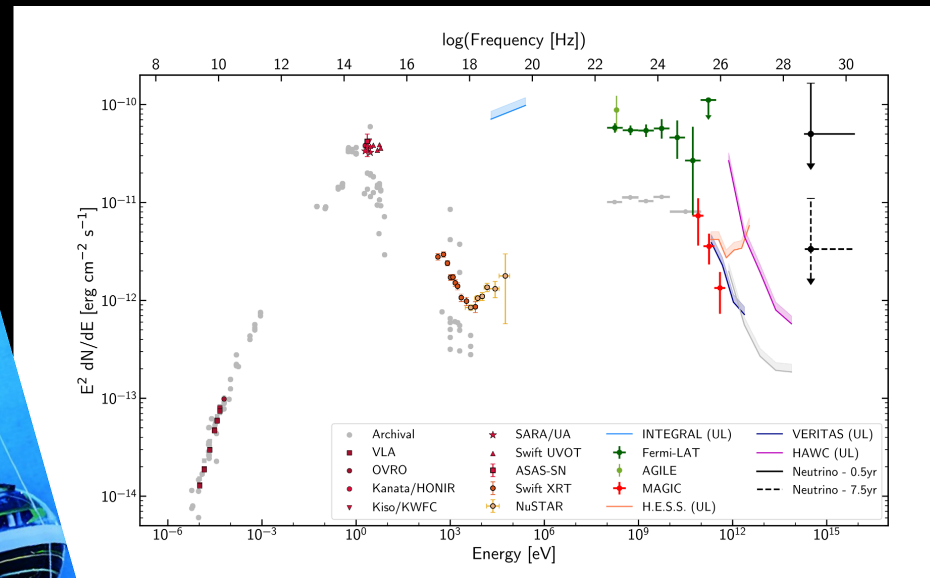
GW170817



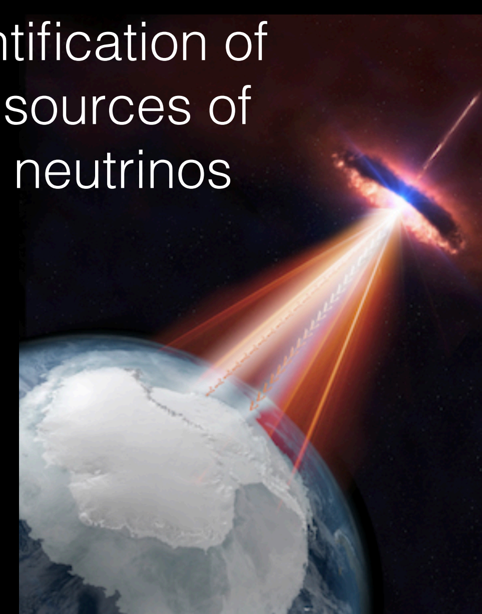
The merger of a binary-neutron-star through gravitational waves and multi-wavelength observations

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

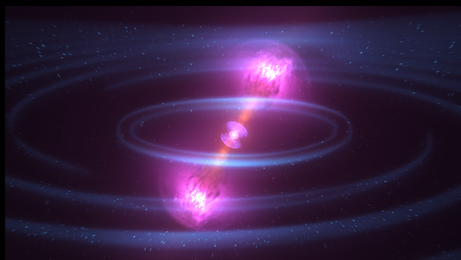


Aarsten et al. 2018, Science, 362

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

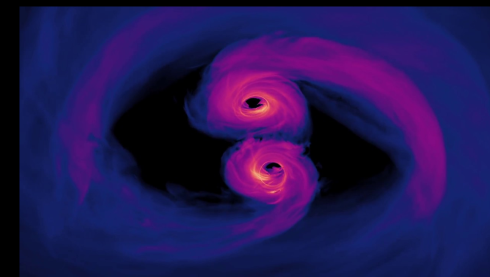
SOME OF THE MOST INTERESTING MULTI-MESSENGER SOURCES

COMPACT OBJECT COALESCENCE
associated with GRBs and KILONOVA



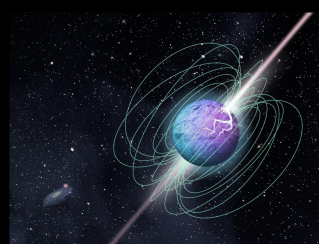
WD-WD and Type Ia SN

MASSIVE-BH MERGER



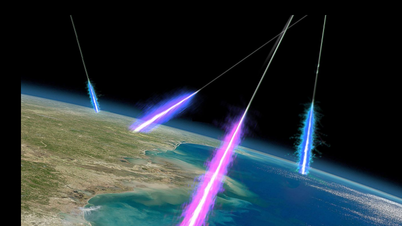
FAST RADIO BURST

MAGNETARS



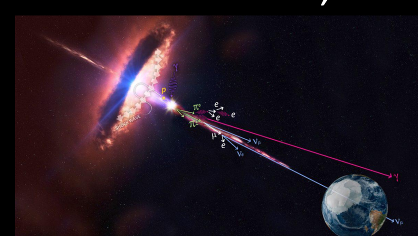
TIDAL DISRUPTION EVENT

SOURCES OF UHCR



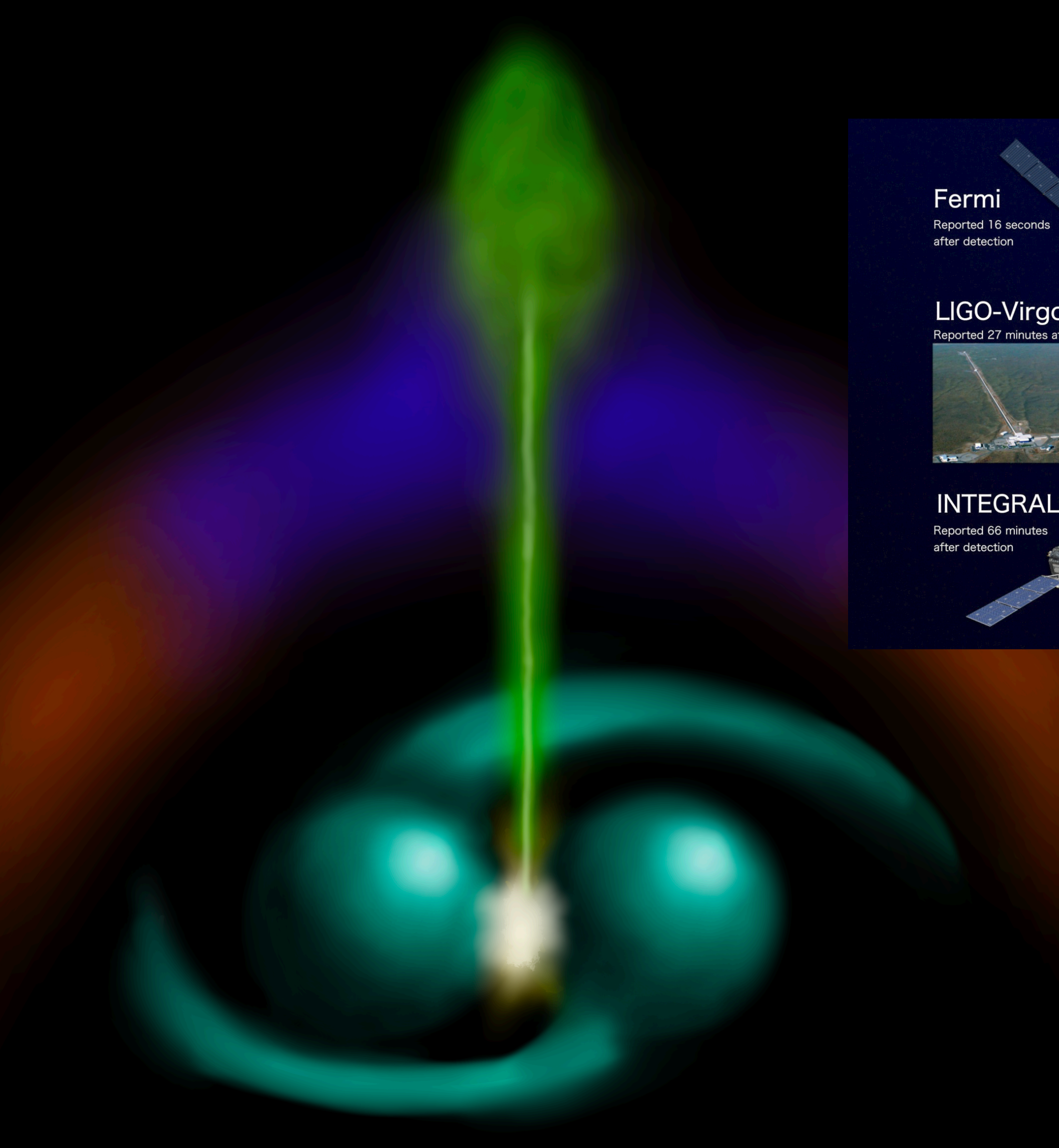
CORE-COLLAPSE SN

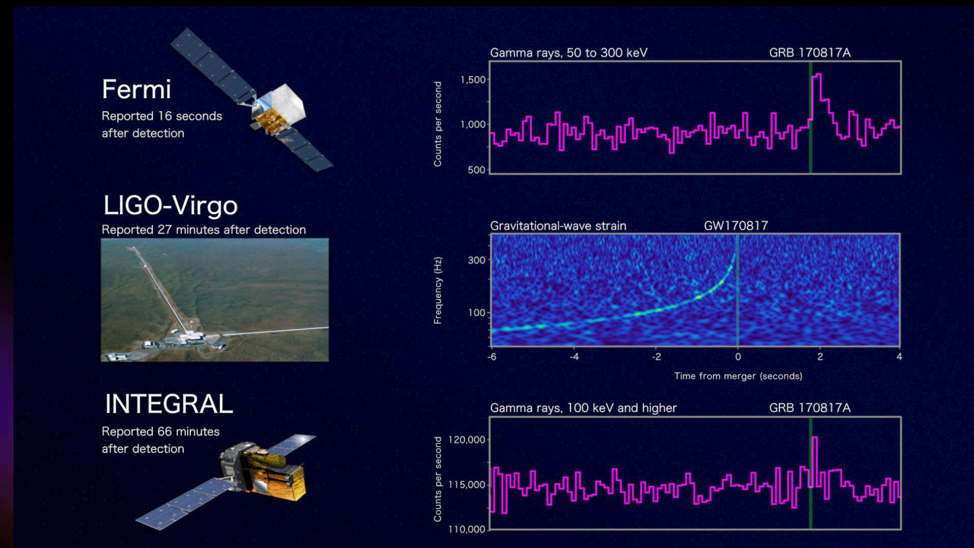
HE NEUSTRINO AGN, STAR
BURST GALAXIES, GRBs



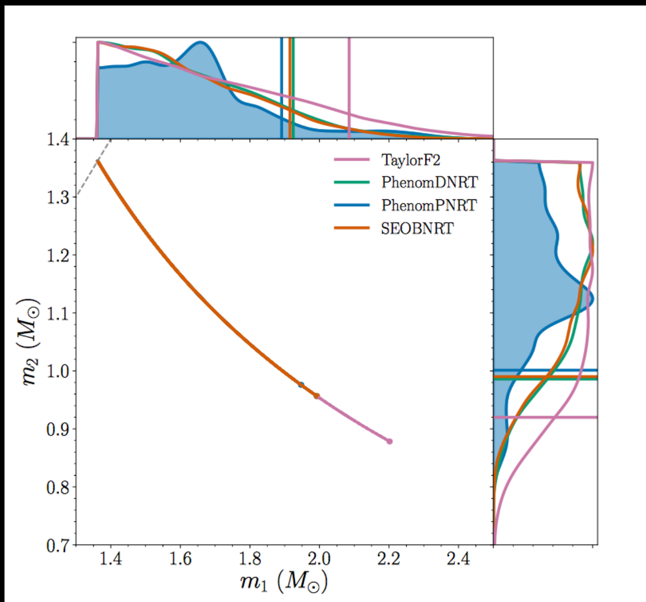
GRAVITATIONAL-WAVES

GW 170817

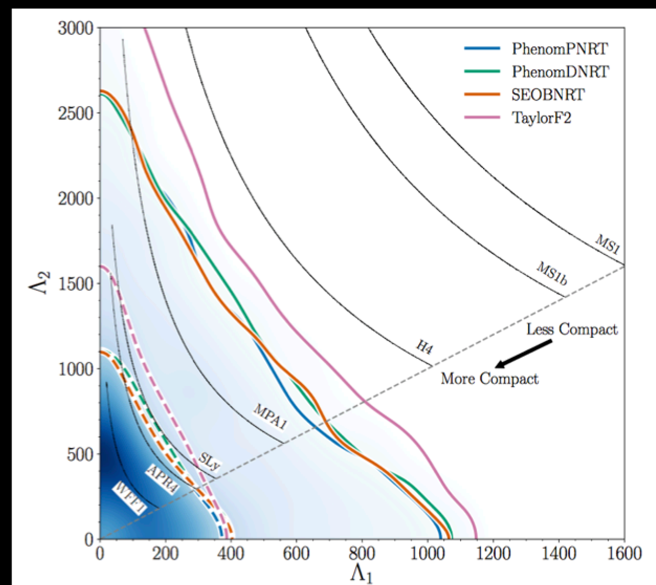


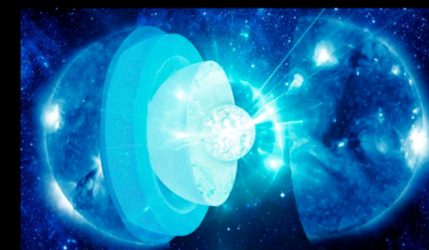

Fermi
Reported 16 seconds after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO-Virgo
Reported 27 minutes after detection
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
INTEGRAL
Reported 66 minutes after detection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

GW 170817



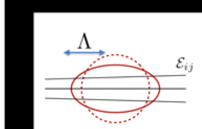
Masses are consistent with the masses of all known neutron stars!

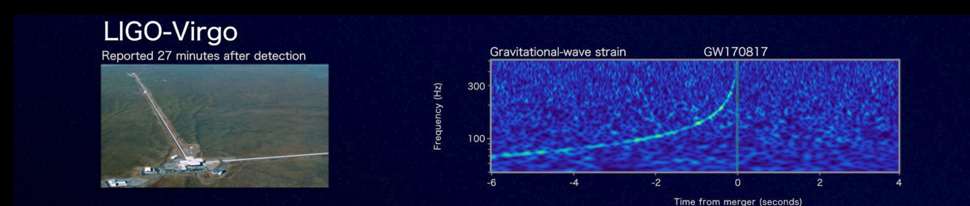




TIDAL DEFORMABILITY

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



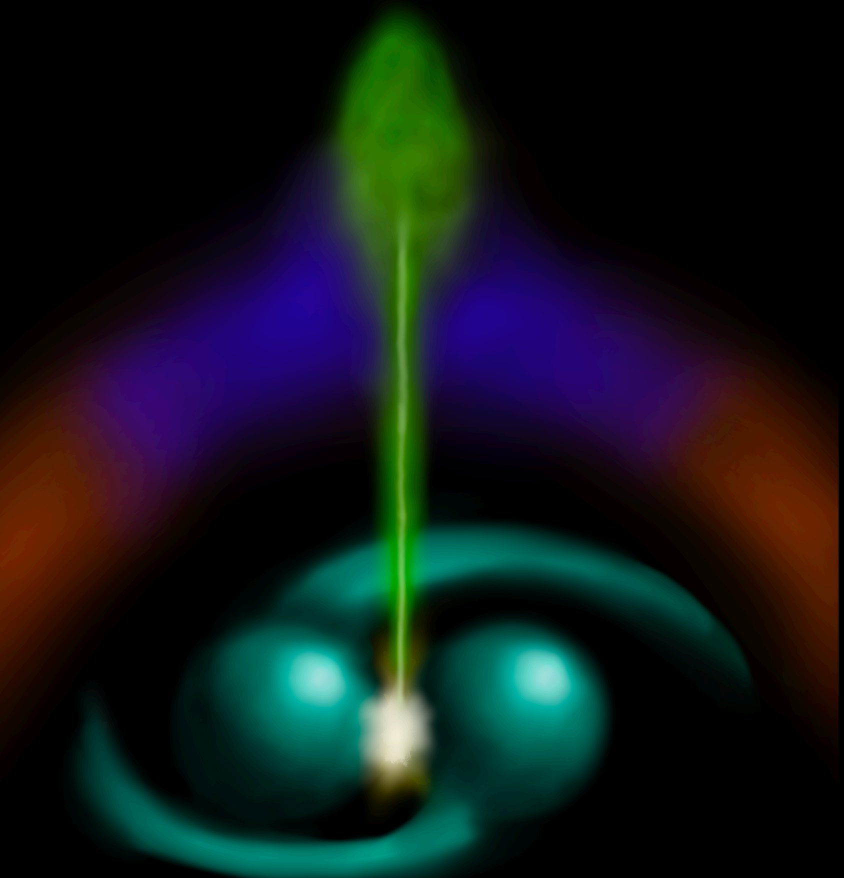


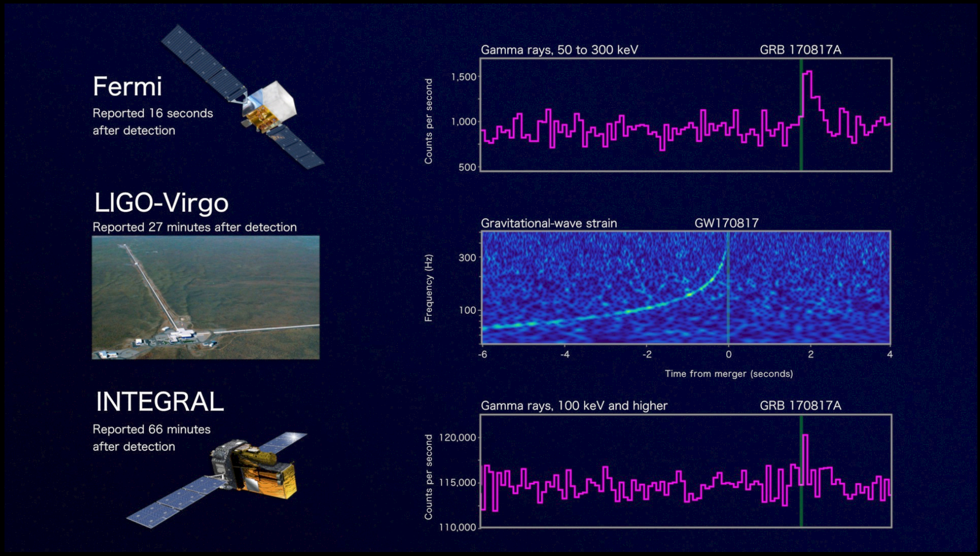
Credits: Ronchini

GW 170817

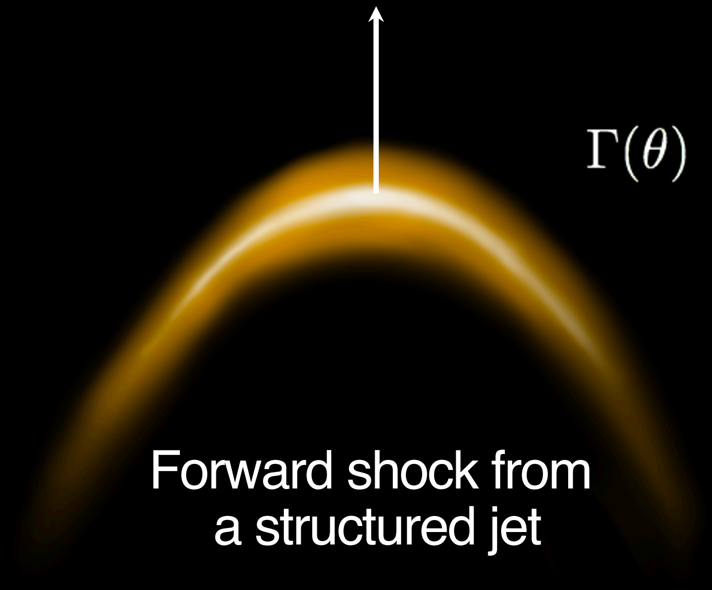
Binary neutron star mergers are progenitor of short GRB

First short GRB observed off-axis

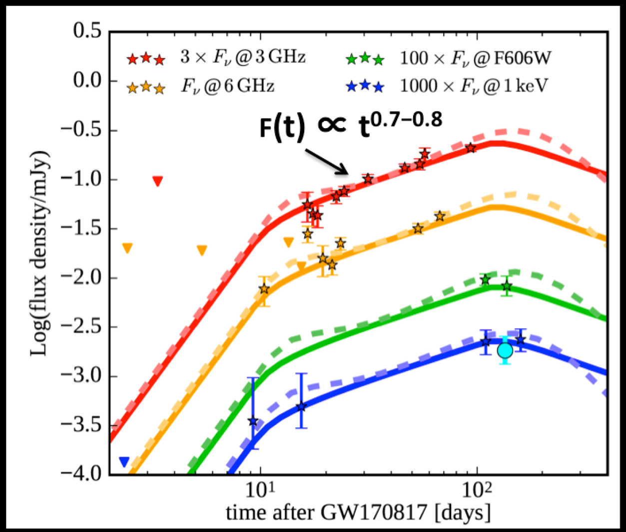




Multi-wavelength afterglow observations

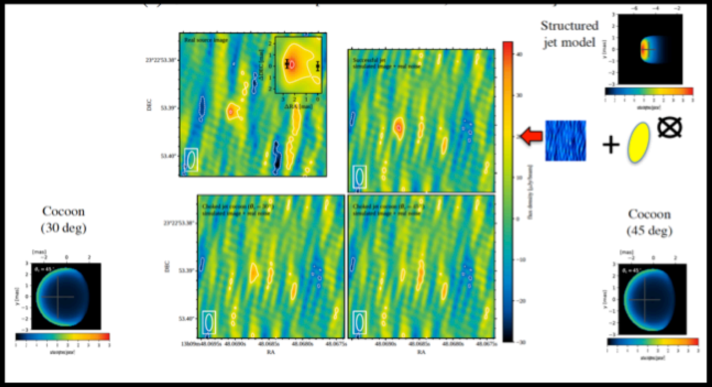


Achromatic flux–rise until ~ 150 days!



D'Avanzo et al. 2017, A&A

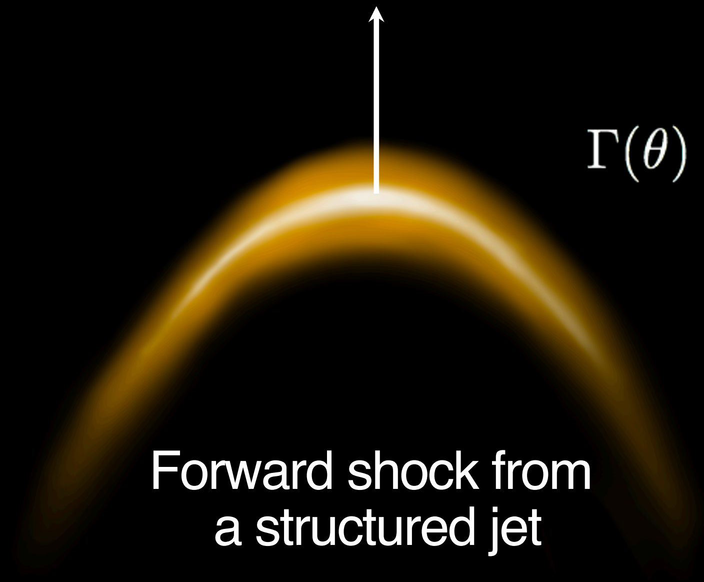
SOURCE SIZE < 2 mas

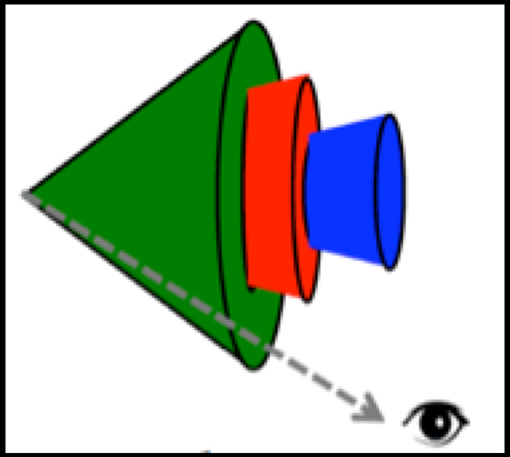


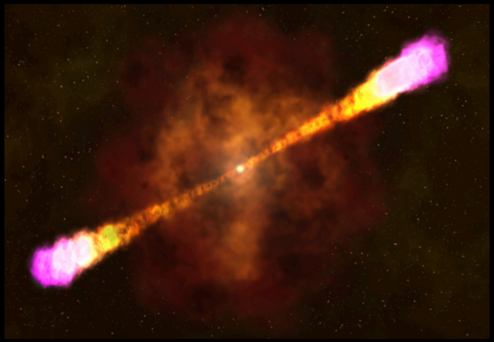
Ghirlanda et al. 2019, Science

See also Mooley, Deller, Gottlieb et al. 2018

Multi-wavelength afterglow observations

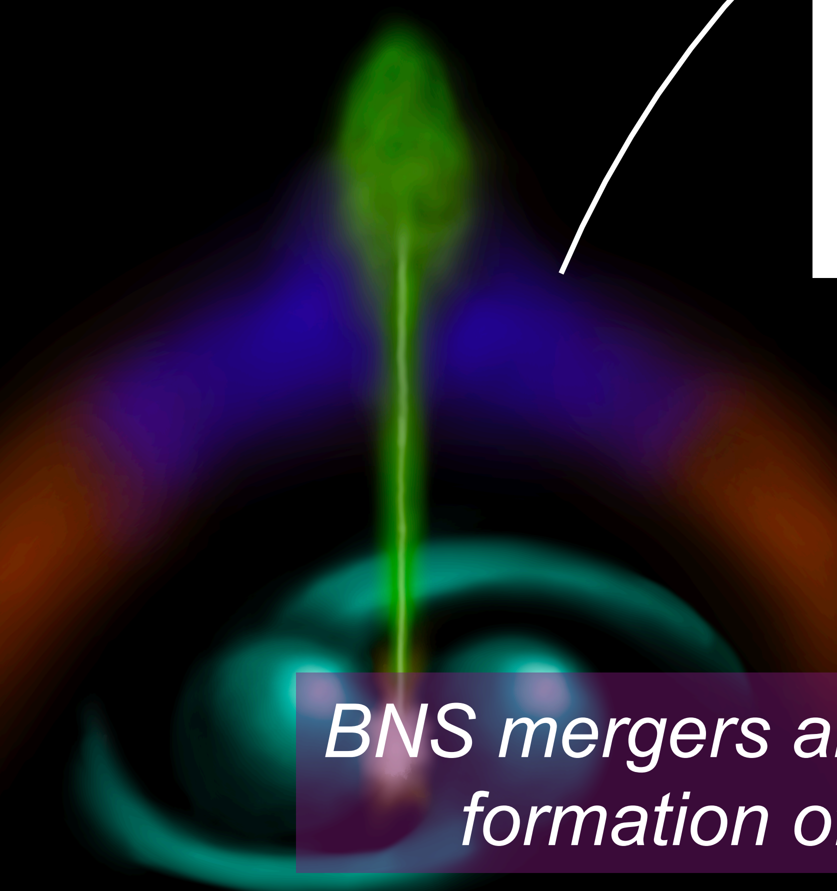


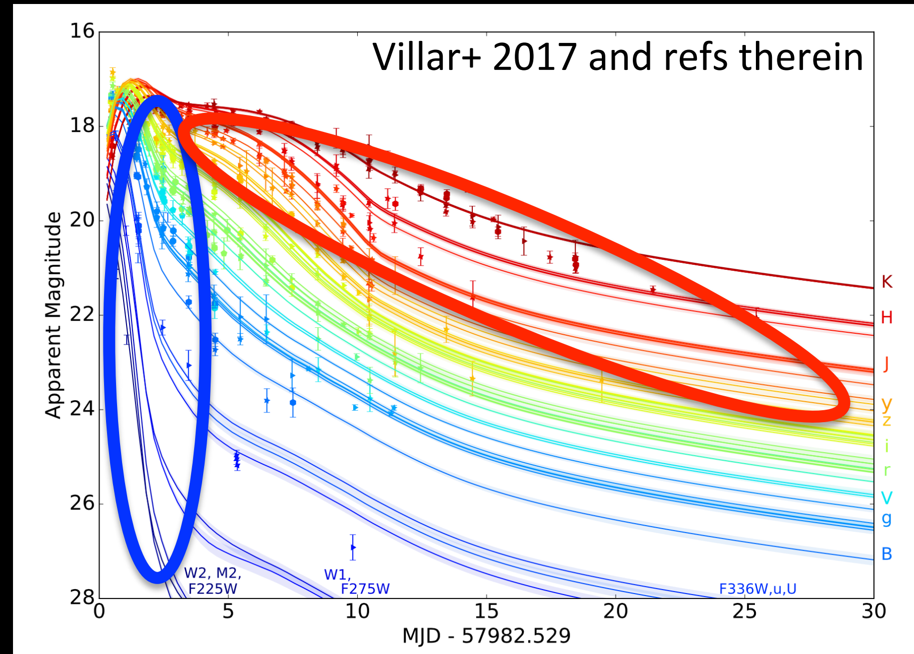




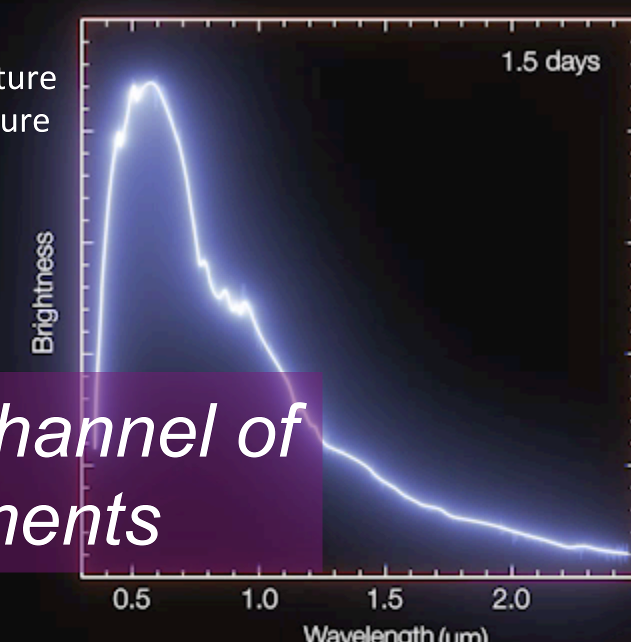
Structured off-axis jet

GW 170817

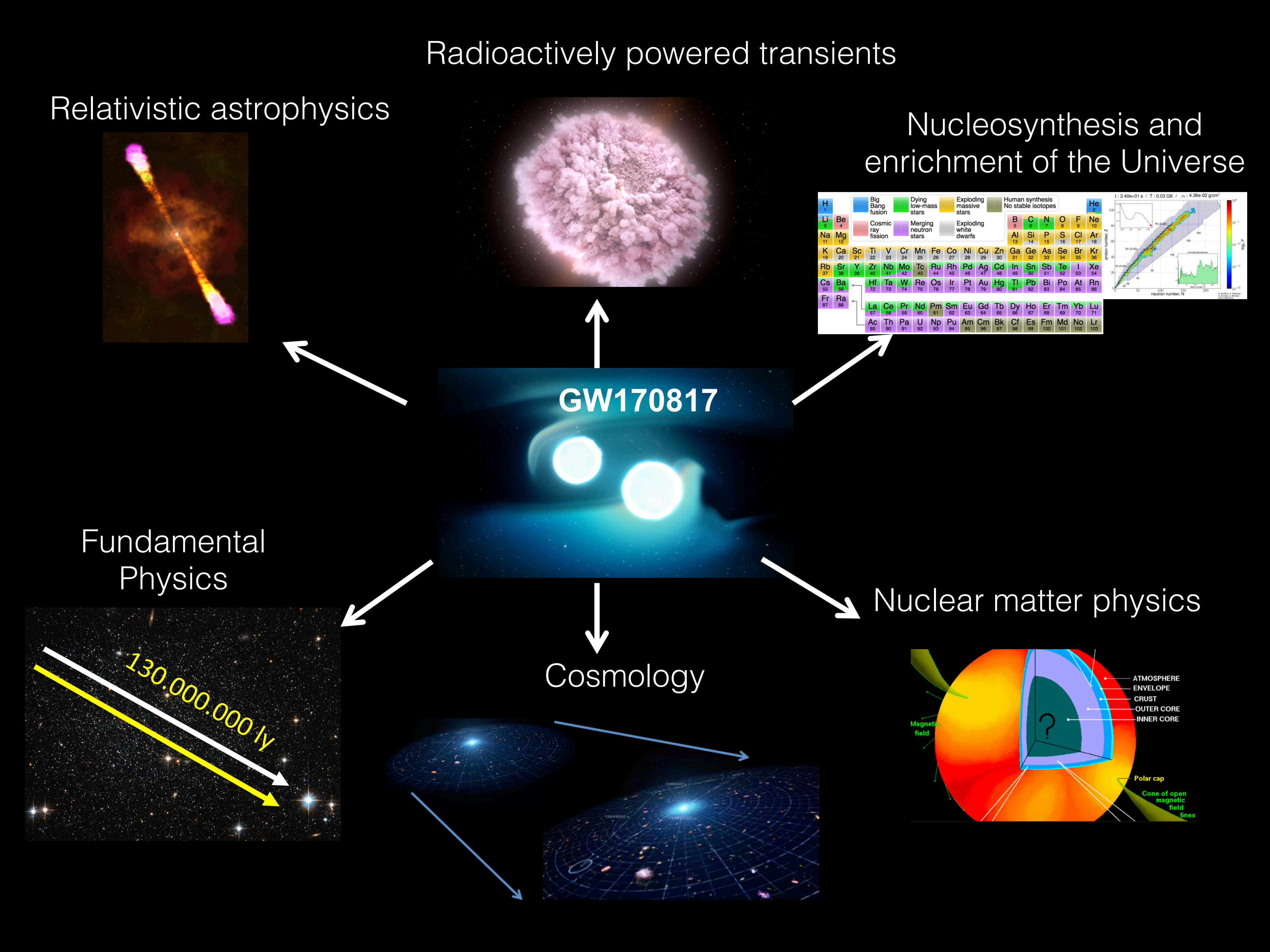




Pian et al. 2017 Nature
Smartt et 2017 Nature

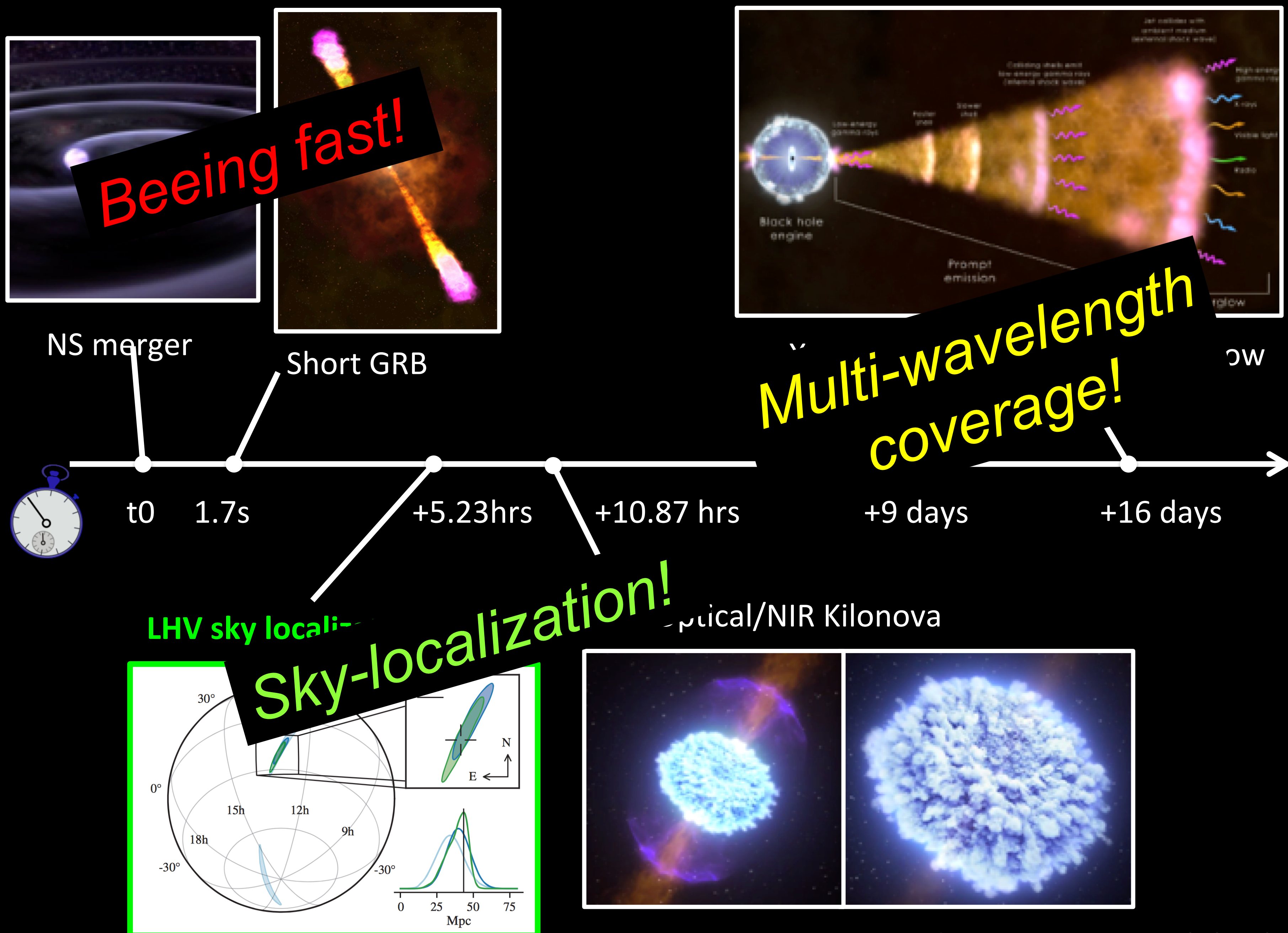


BNS mergers are a major channel of formation of heavy elements



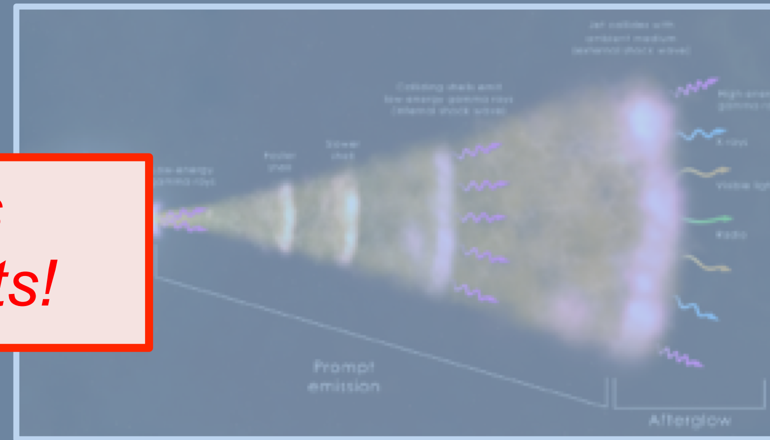
Radioactively powered transients
Relativistic astrophysics
Nucleosynthesis and enrichment of the Universe
Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
GW170817
Fundamental Physics
130.000.000 ly
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*
- *Infrastructure to send rapid alerts!*



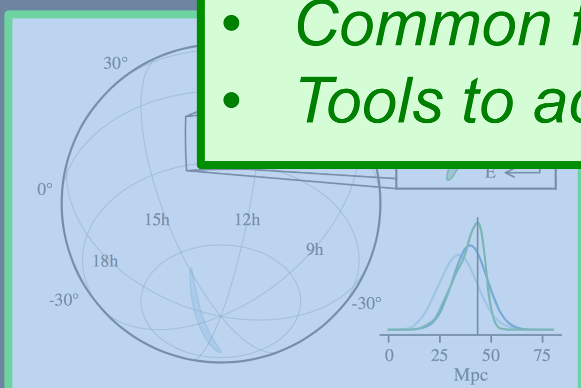
NS merger

Radio afterglow

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

t0 1.7s +5.23hrs +10.87 hrs +9 days +16 days

LHV sky



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

LVC + astronomers, ApJL, 848, L12

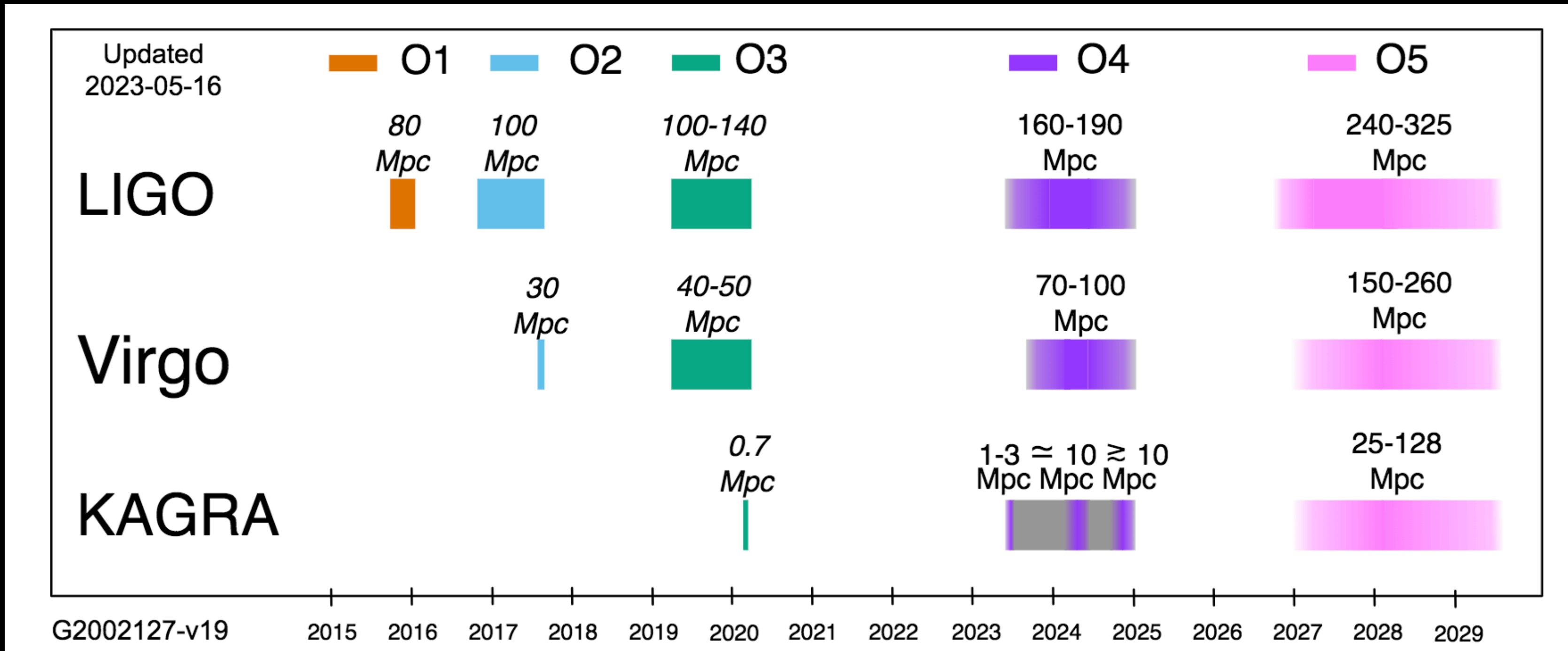
What happened after GW17017?

LIGO, Virgo and KAGRA O1+O2+O3 runs

90 GW CANDIDATE EVENTS!

LVK arXiv:2111.03606

O4 LIGO, Virgo and KAGRA run



- O4: 18 months of active observing time, started end of May
- So far, only LIGOs

GraceDB

Low-latency pubblic alerts:

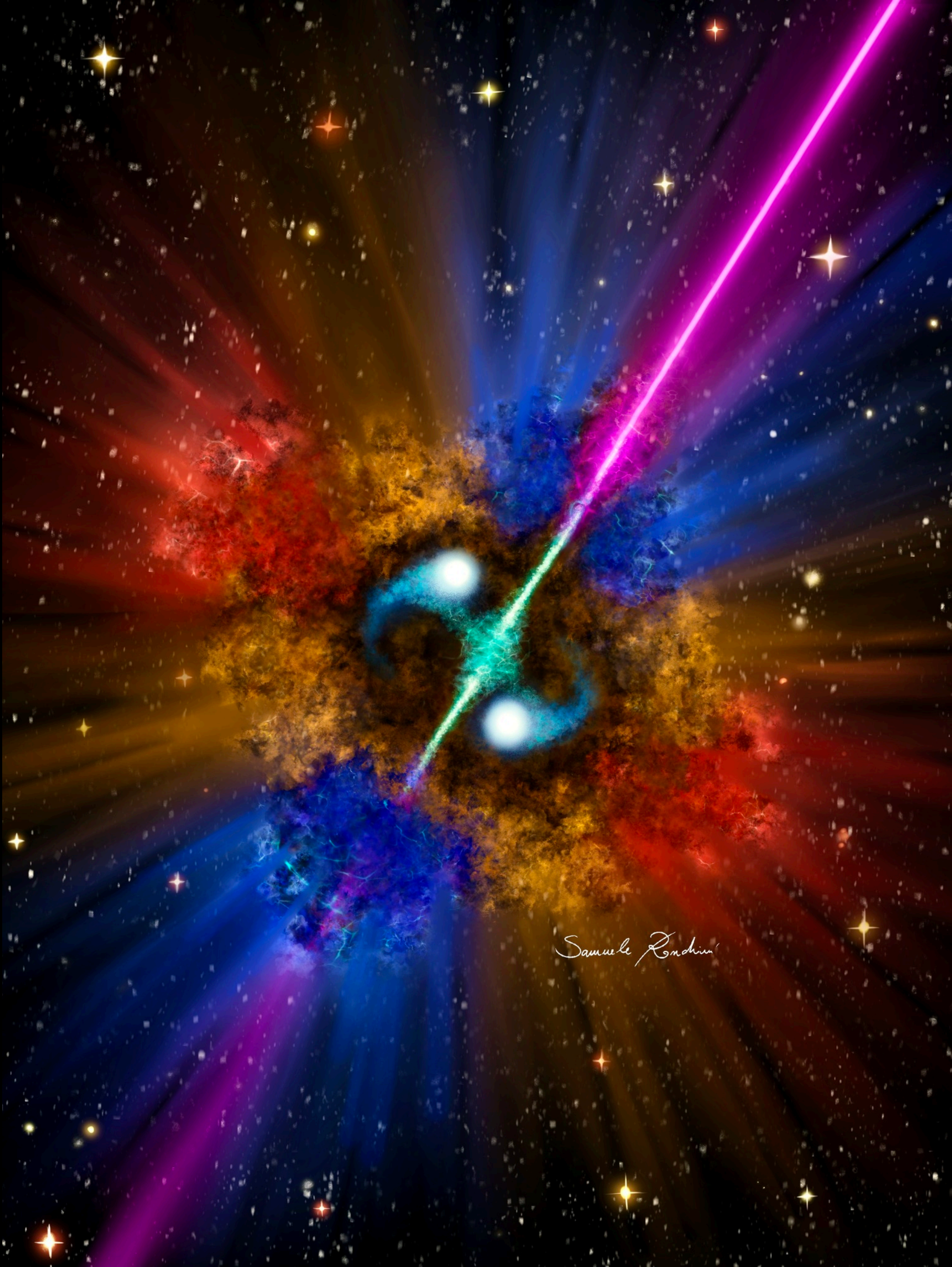
67 Significant Detection Candidates

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

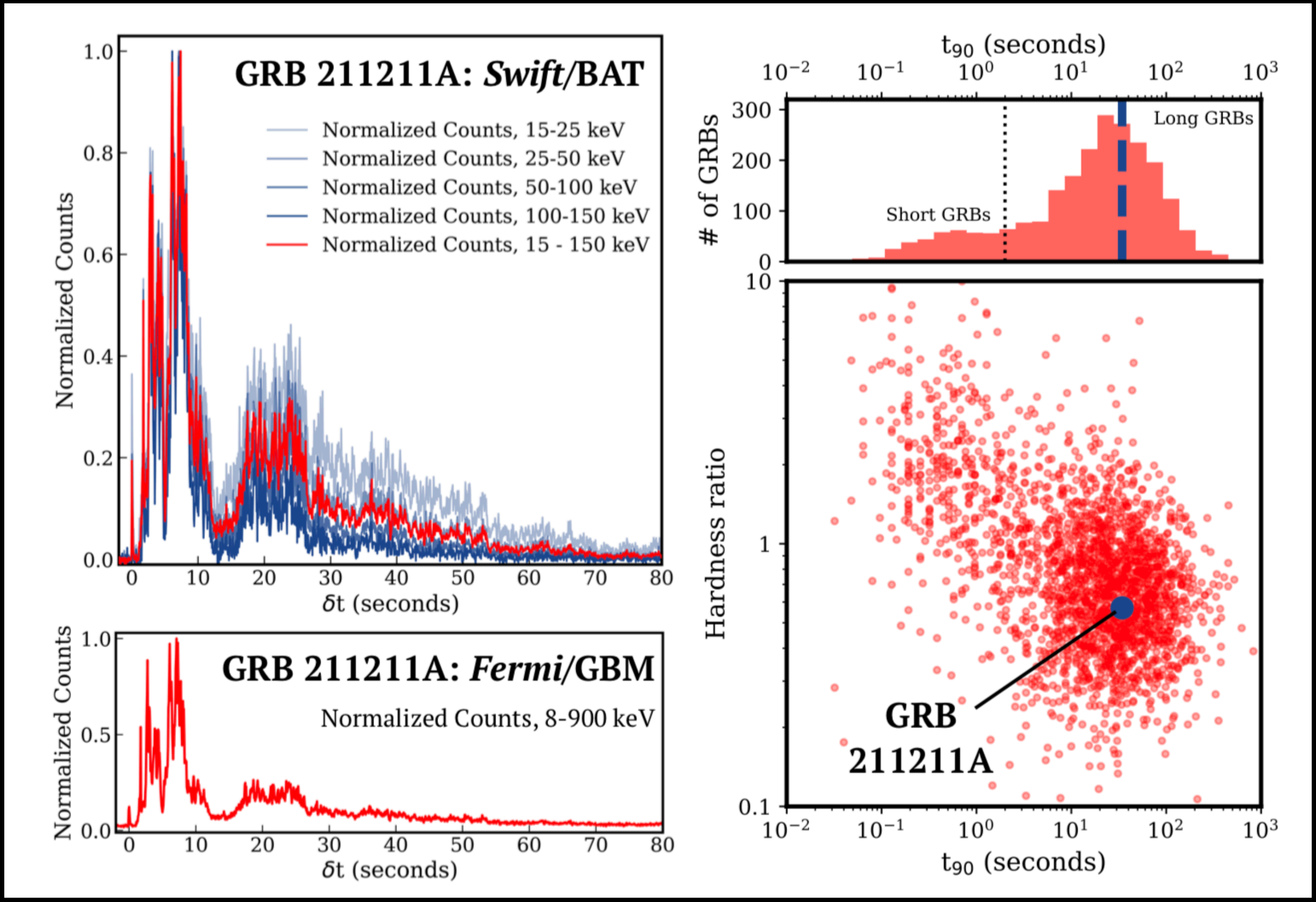
The majority high probability to be BBH, no BNS

BNS mergers are there!

GRB 211211A



GRB 211211A: long GRB/KILONOVA

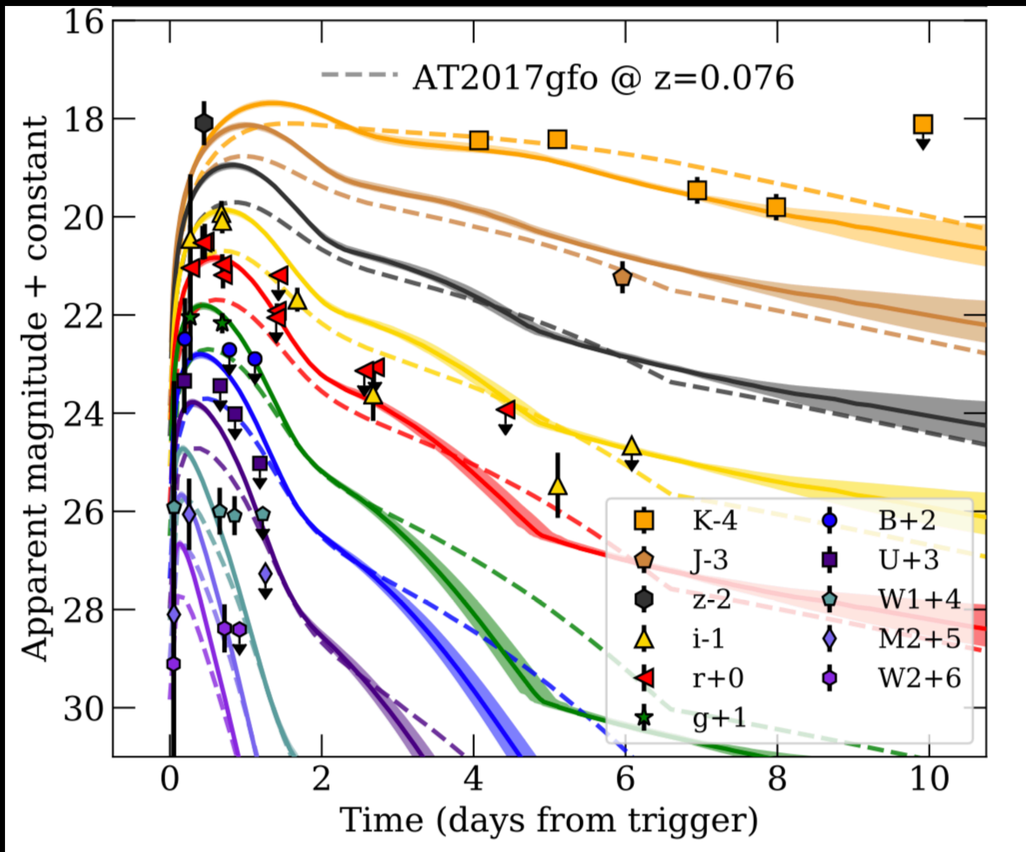


Minute-duration GRB, prompt and bright spikes last more than 12 s

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

Rastinejad, J. C. et al. 2022 Nature

GRB 211211A: long GRB/KILONOVA



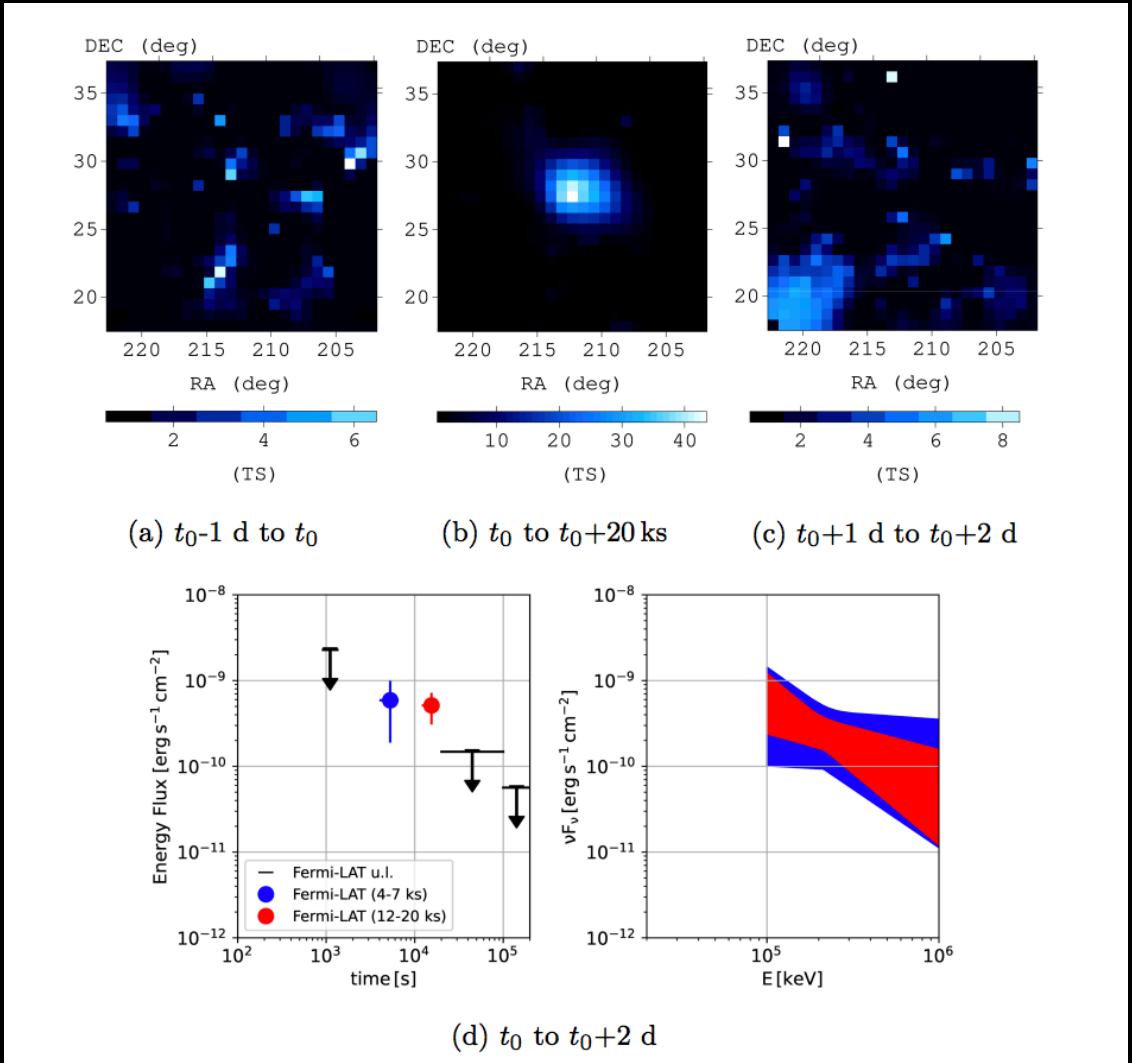
Rastinejad, J. C. et al. 2022 Nature

GW170817-like events are within reach

A percentage of long GRB population arise from mergers

See alsoTroja et al. 2022 Nature, Xiao, S. et al. 2022 Nature

GRB 211211A: GeV emission

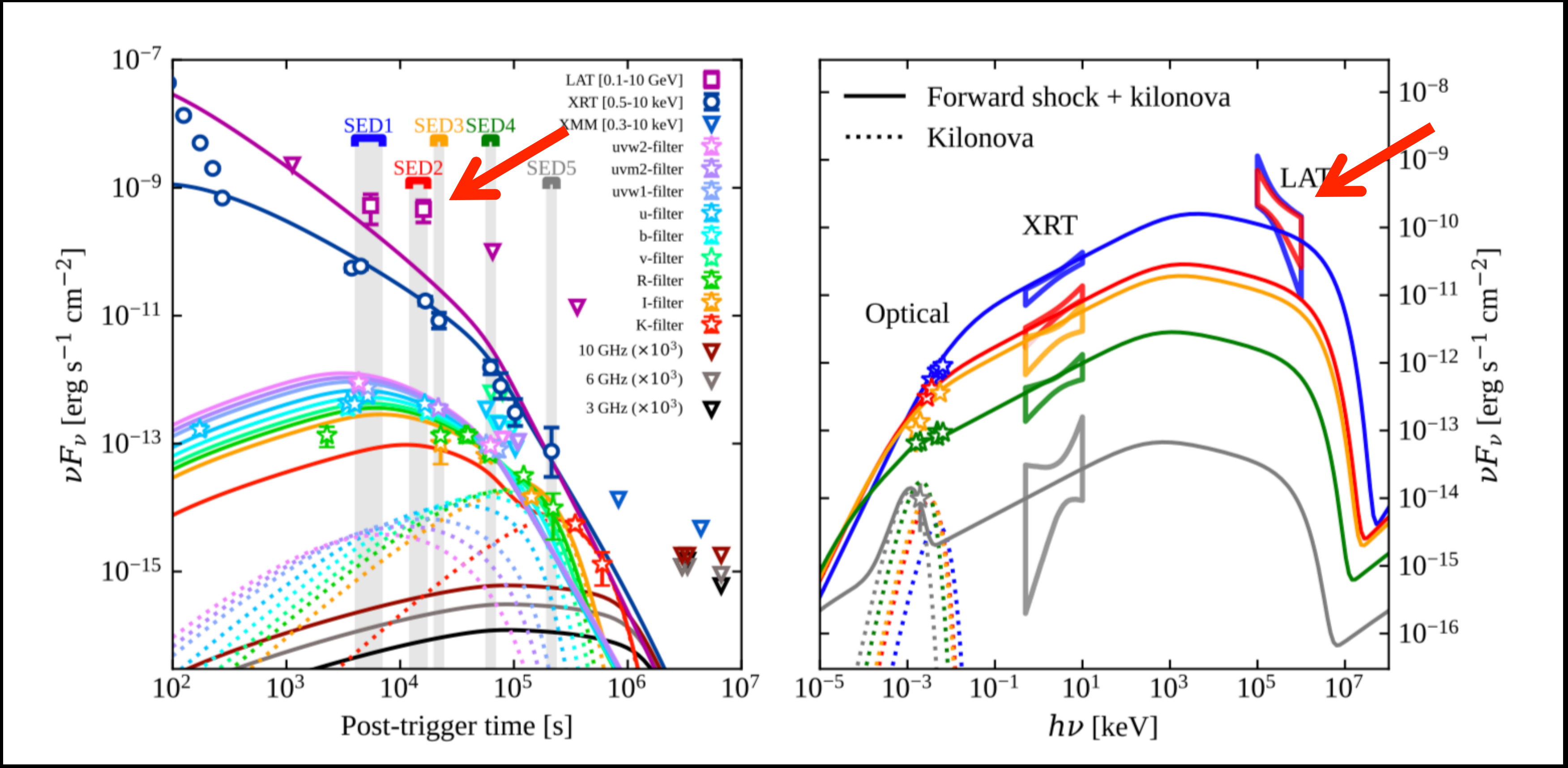


Discovery of a significant (>5σ) transient-like emission by Fermi/LAT

Photon energies 0.1-1 GeV

Mei et al. 2022, Nature

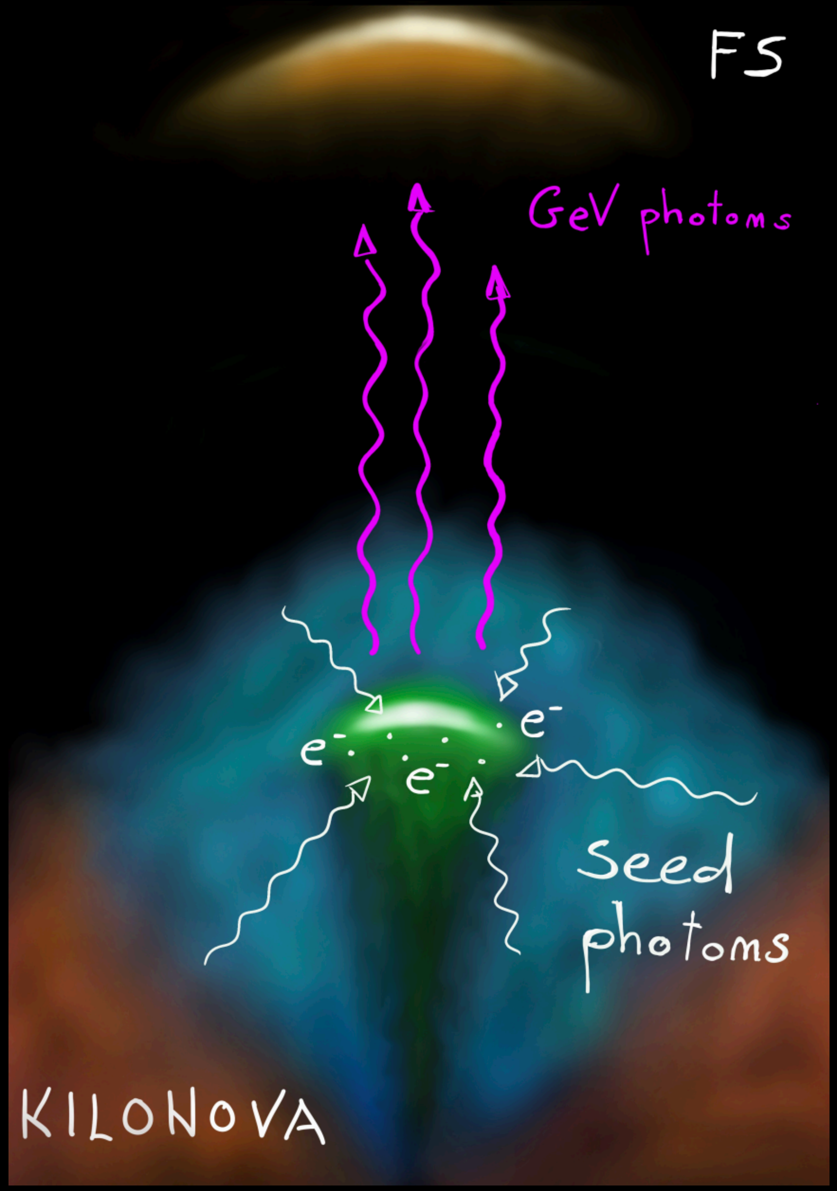
GRB 211211A: GeV excess



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, Nature

GEV emission from a compact binary merger



External Inverse Compton

kilonova → seed photons for the EIC

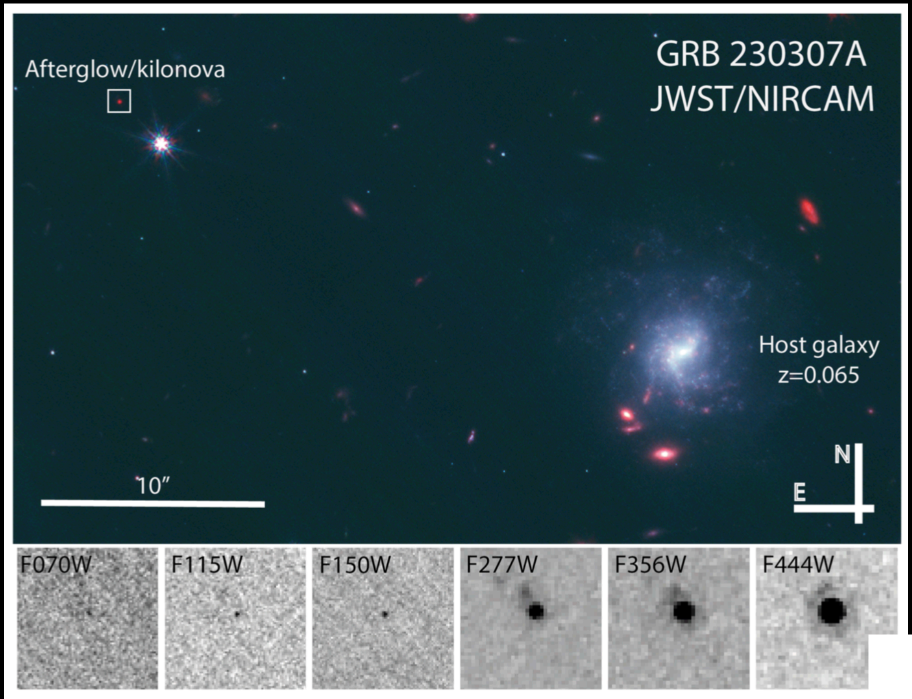
electrons nearby the kilonova photosphere at $t = 10^4$ s

presence of a late-time low-power jet

New counterpart for GW signals
to probe jet-neutron rich ejecta interaction

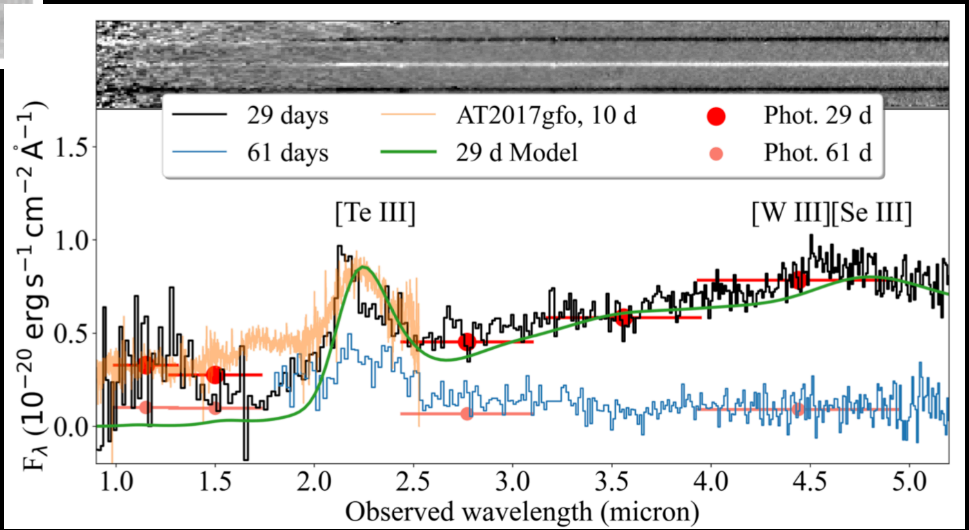
Mei et al. 2022, Nature

GRB 230307A...another long-GRB associated with compact object mergers!



JWST mid-IR imaging and spectroscopy 29 and 61 days after the burst

Levan et al.2023, Nature

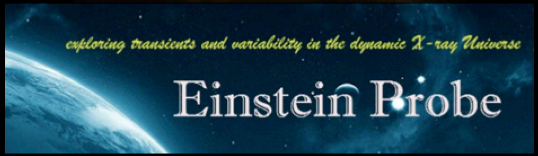


- Tellurium emission line
- Mid-IR source due to the production of lanthanides

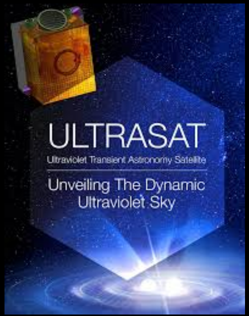
production of lanthanides

After GW170817 NO FIRM EM COUNTERPARTS: detection rate, type of systems, large sky-localization and fainter counterparts to be searched…

SVOM



NEW OBSERVATORIES

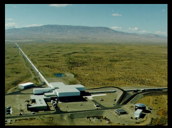


Rubin Observatory

LIGO INDIA

NETWORK OF GW DETECTORS

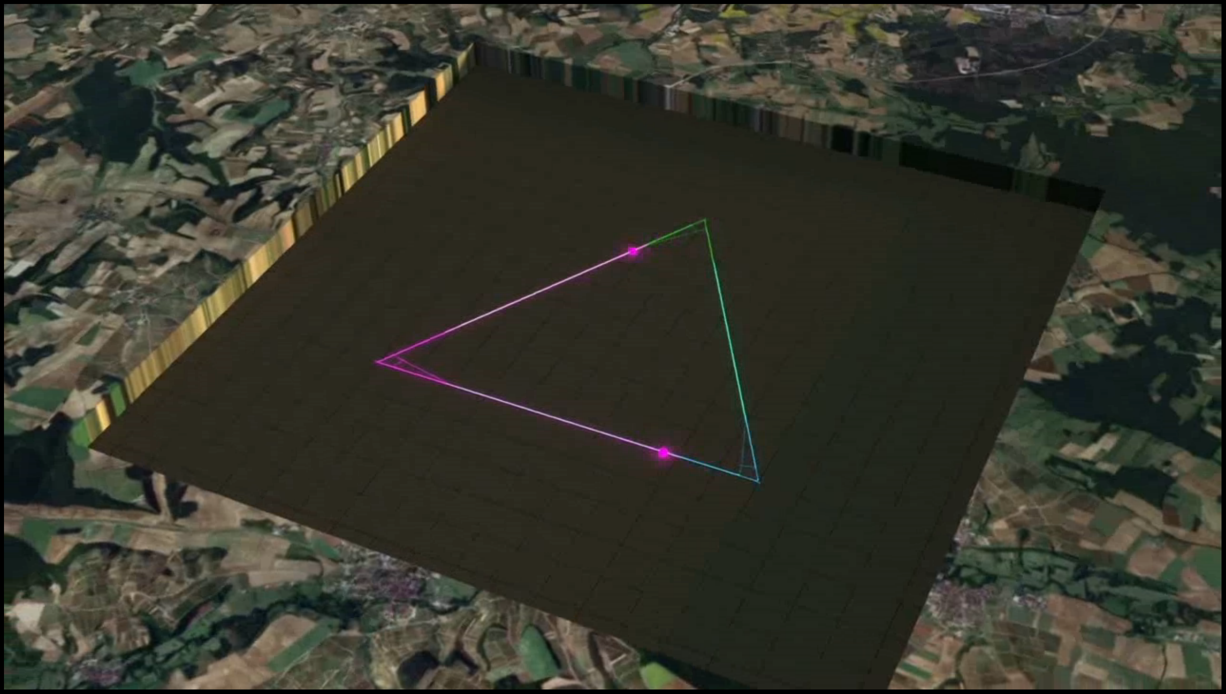
SKA SQUARE KILOMETRE ARRAY



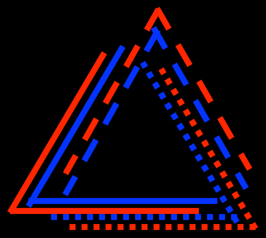
Next generation GW astronomy and multi-wavelenght follow-up

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



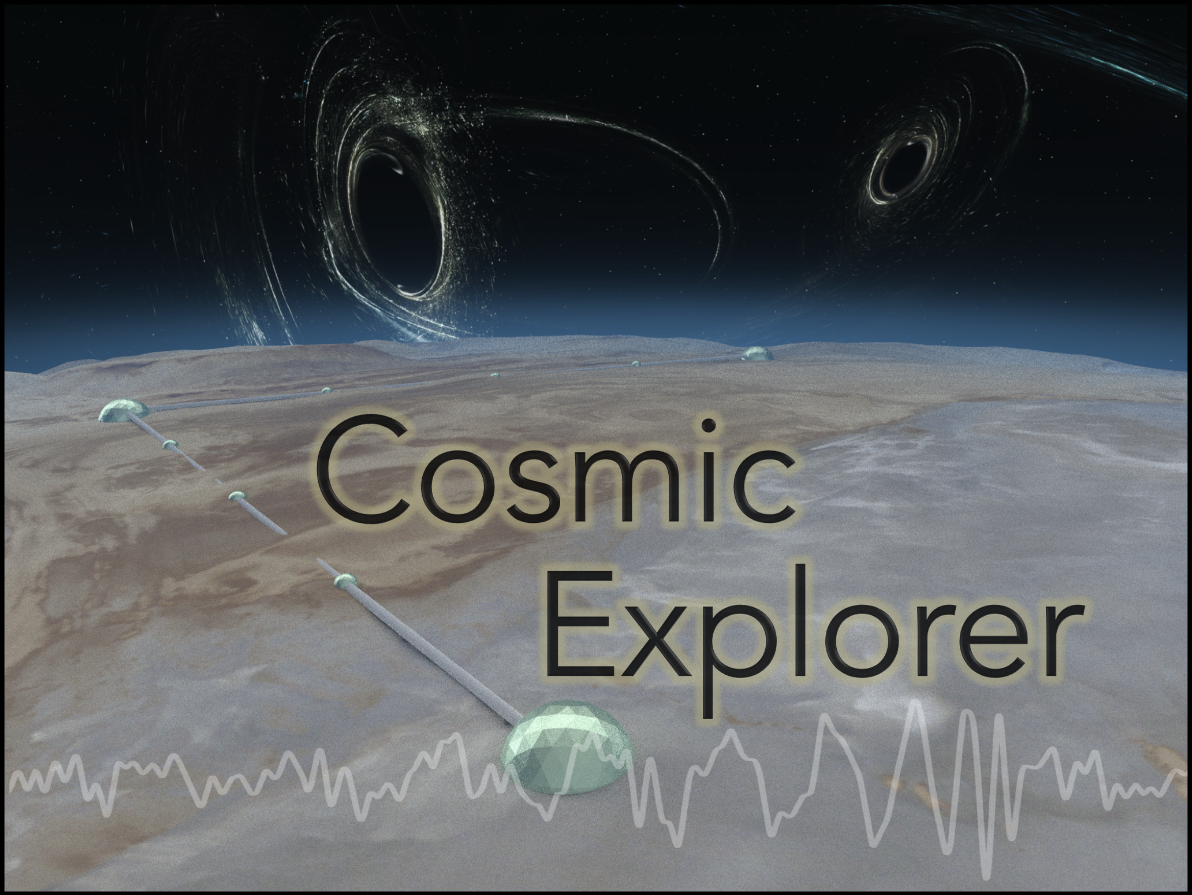
Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...



INCLUDED IN ESFRI ROADMAP in 2021

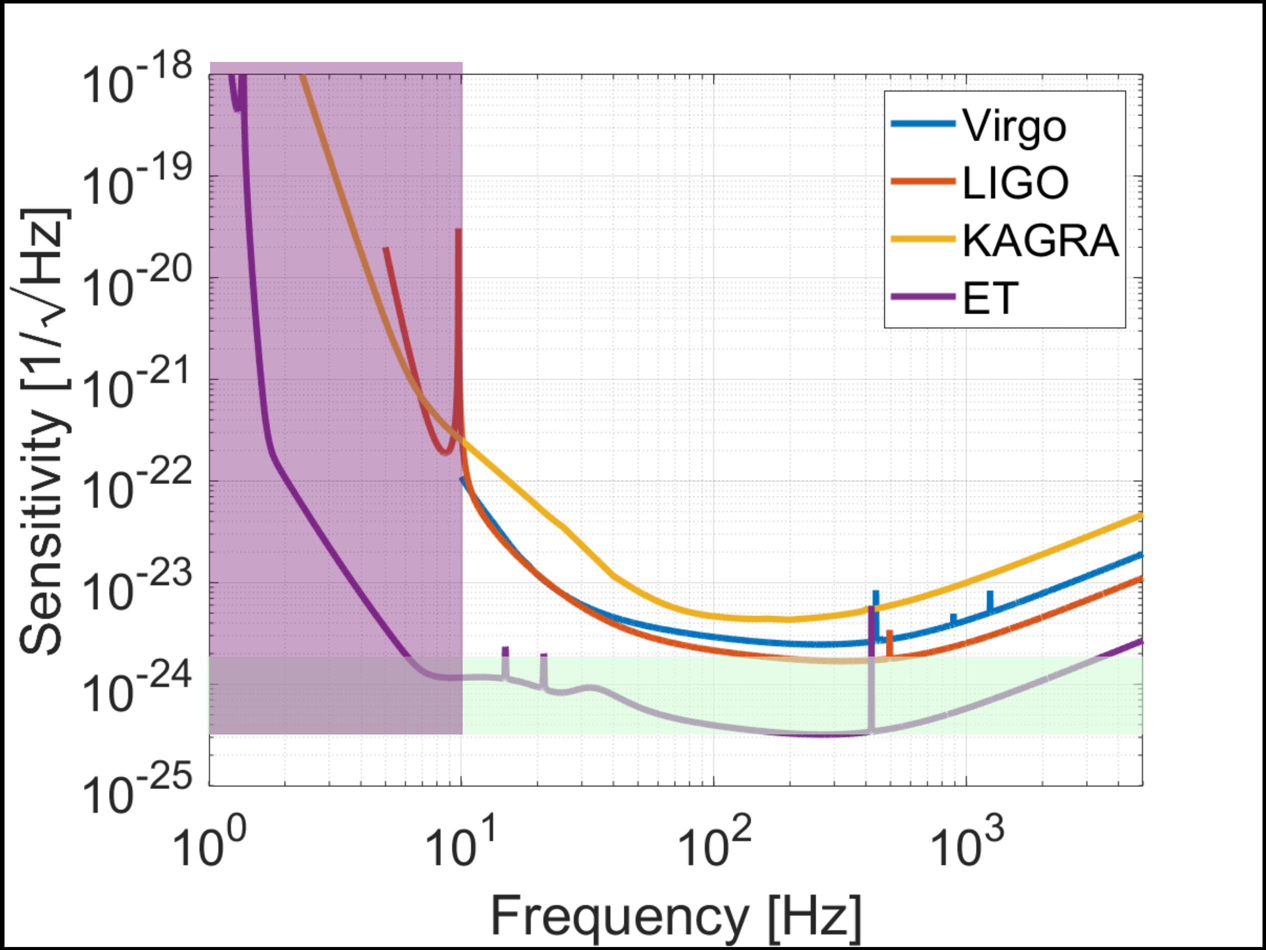
ET collaboration more than 1500 scientists!

3G effort worldwide



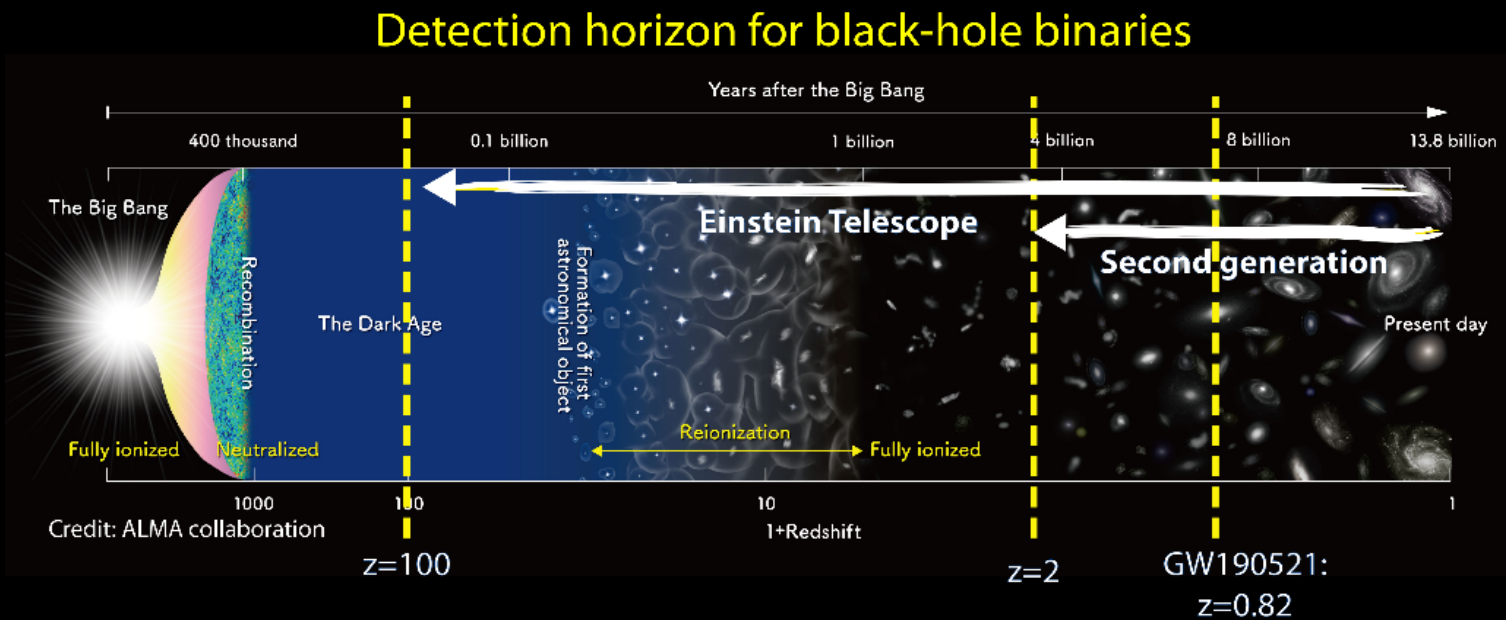
Cosmic Explorer: L shaped detectors, two sites
(40km, 20 km [option])

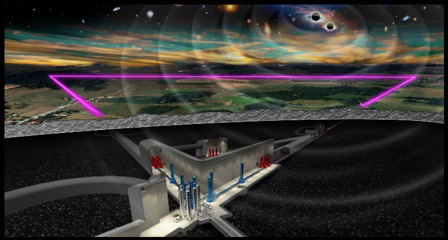
EXPECTED SENSITIVITY



The ET sensitivity will make it possible:

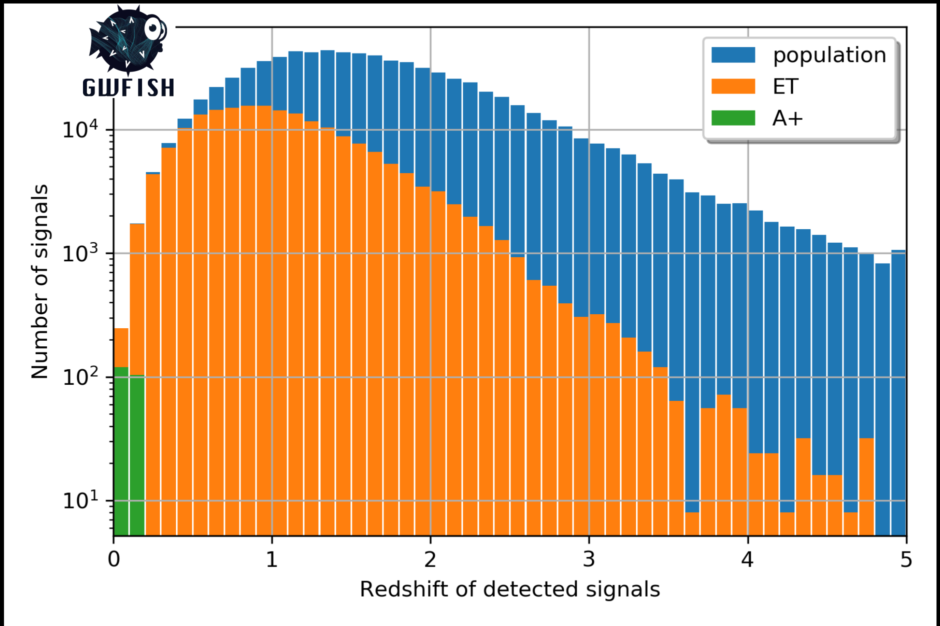
- Large distances back to the EARLY UNIVERSE



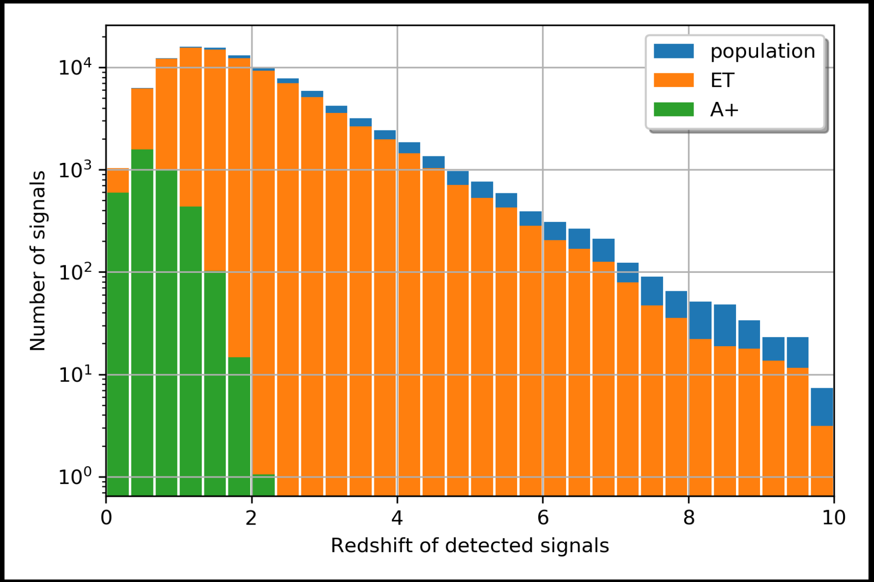


COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS



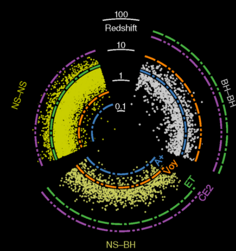
Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

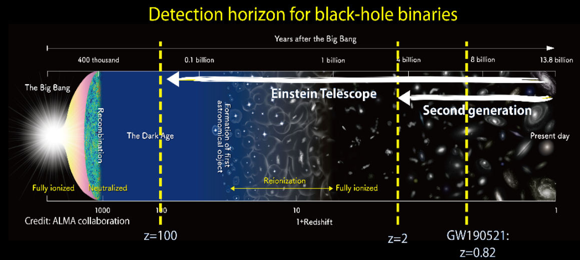
10^5 BNS detections per year
10^5 BBH detections per year

GWFish Harms et al. 2022, Astronomy and Computinng

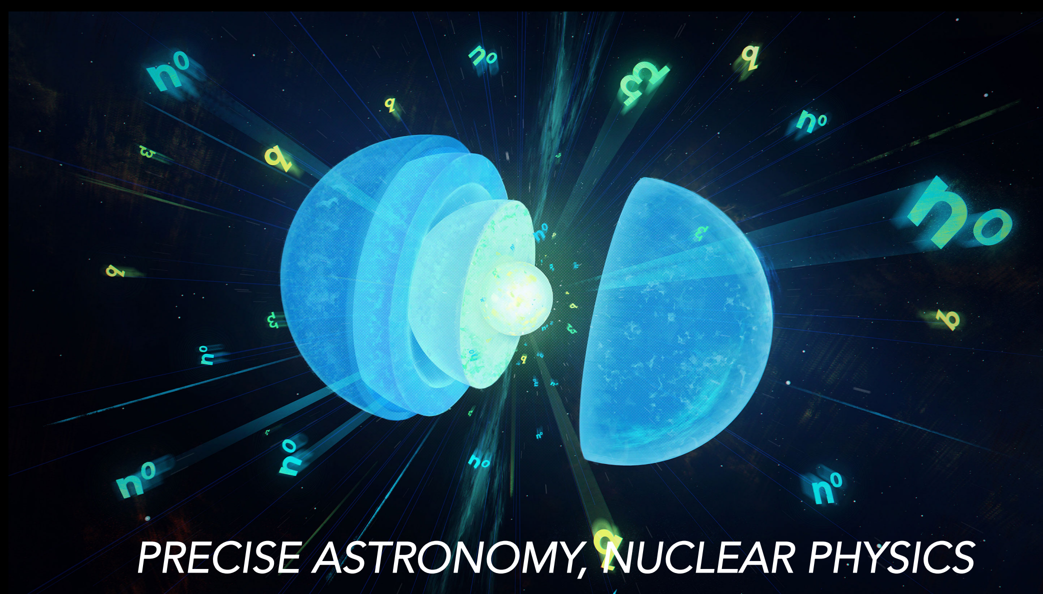
The ET sensitivity will make it possible:

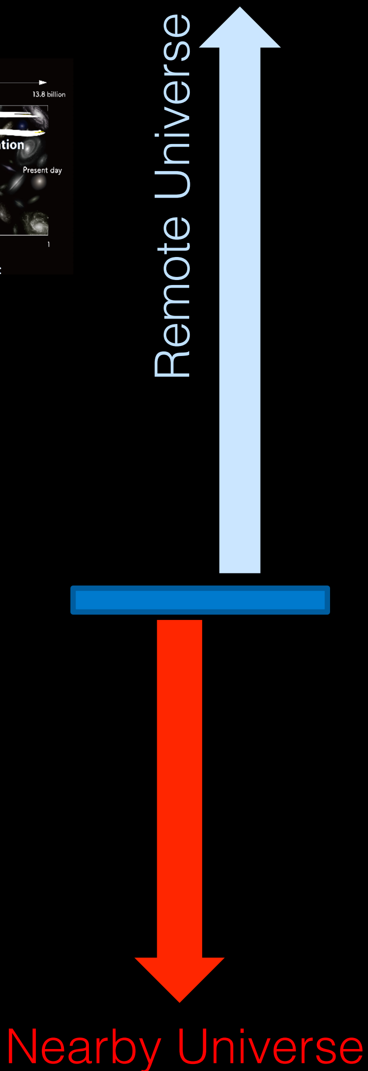
- EARLY UNIVERSE
- POPULATION





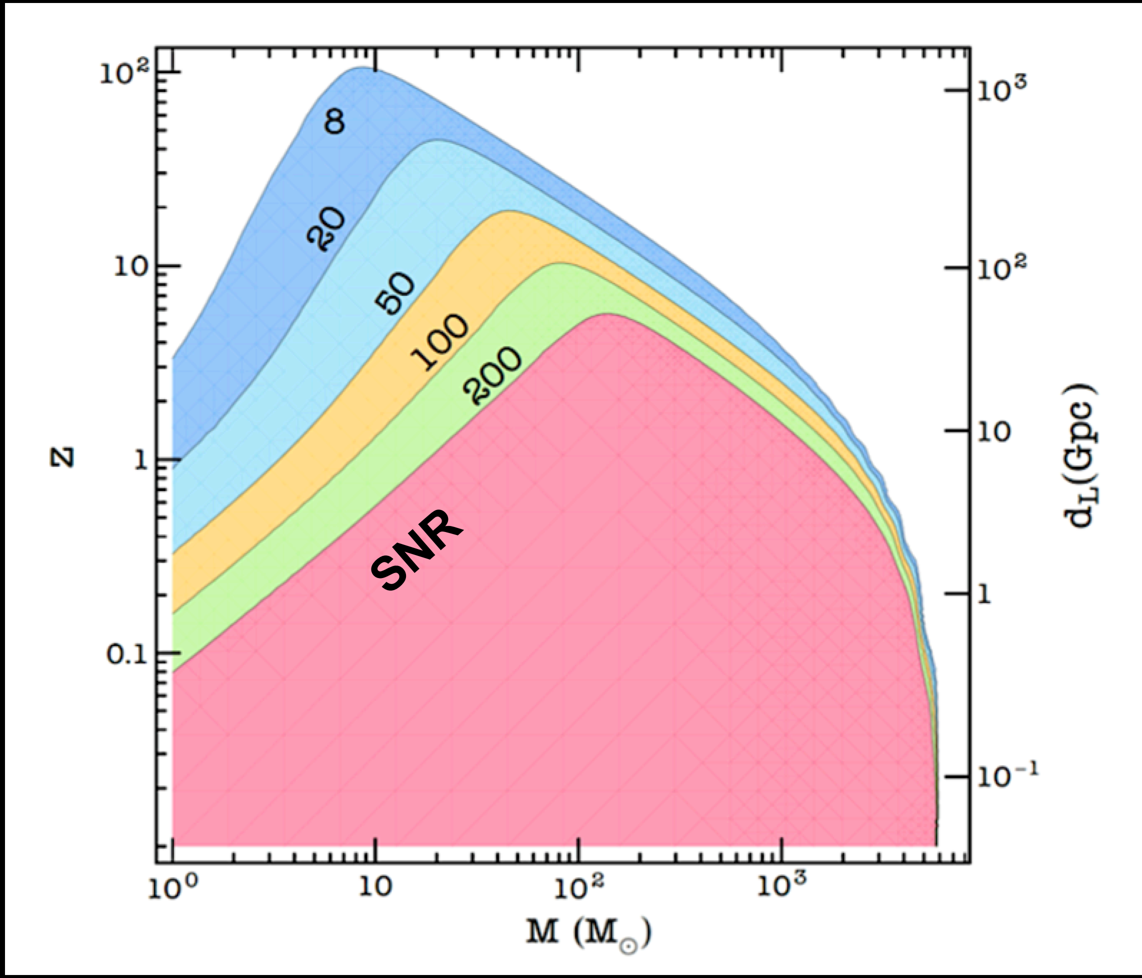
- PRECISE GW ASTRONOMY: exceptional parameter estimation accuracy for very high SNR events

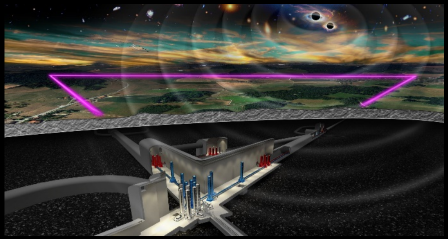




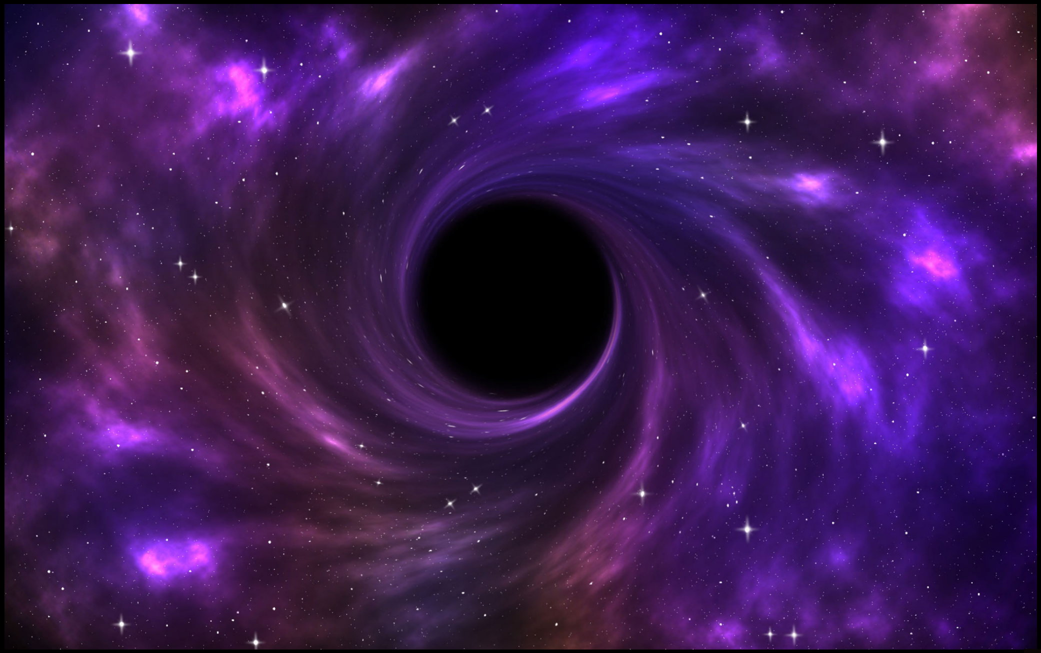
The ET wide frequency band will make it possible:

- Access UNEXPLORED MASS up to 10^3 Mo



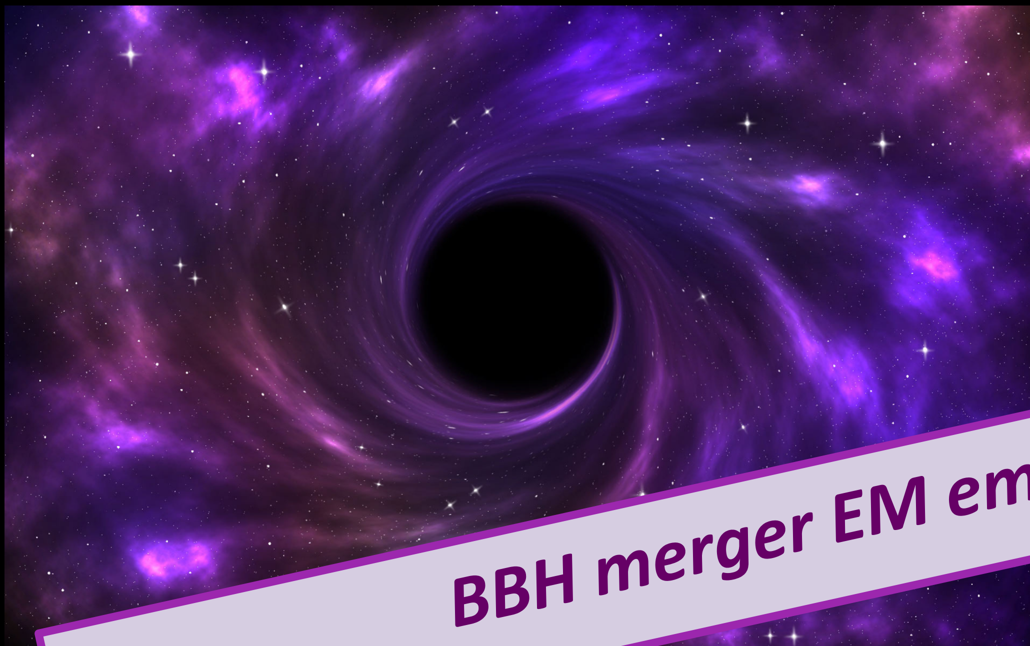


BLACK HOLES WITH MASSES OF 100-10000 Mo



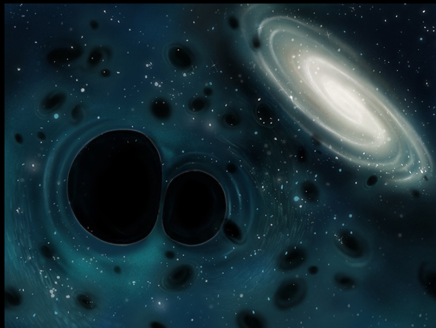
Seeds of Massive BH?

BLACK HOLES WITH MASSES OF 100-10000 Mo



BBH merger EM emission?

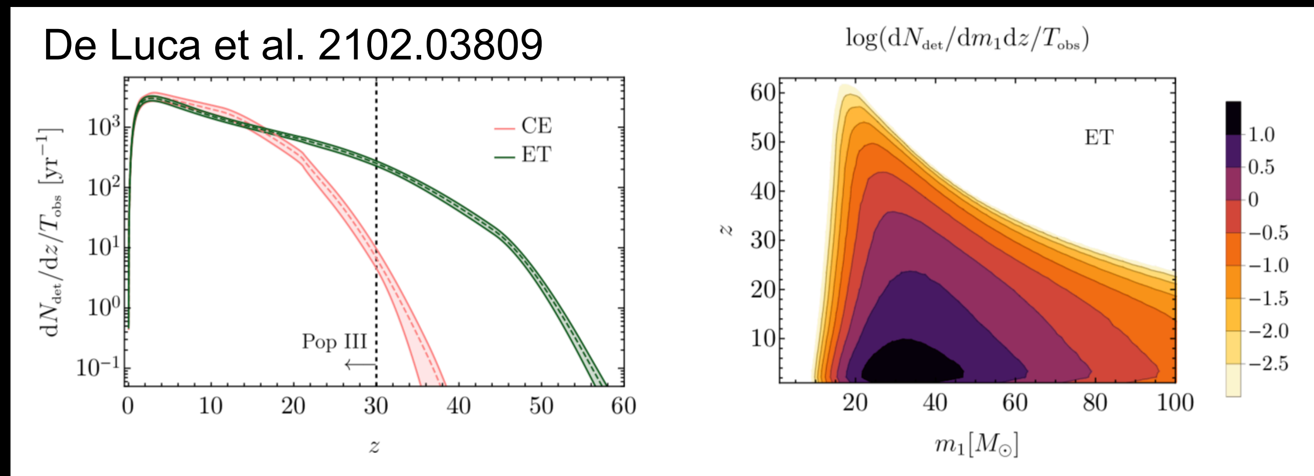
Seeds of Massive BH?



PRIMORDIAL BLACK-HOLES

Disentangle astrophysical PoPIII from primordial BHs

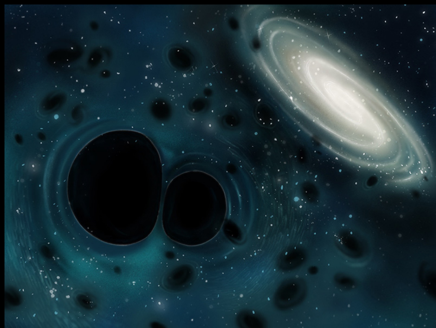
Any BBH merger at z>30 primordial



- Difference between ET and CE due to the better ET sensitivity at low frequencies
- Note: accurate measurement of z is also needed !

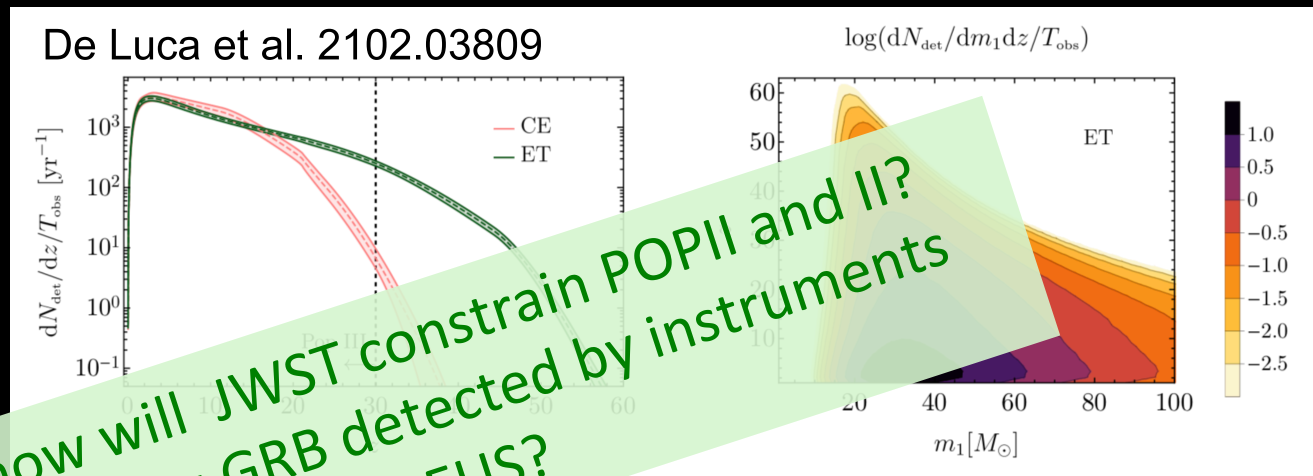
See NG et al. 2022.ApJL
NG et al. 2023, PRD

Recent population synthesis work on POPIII and POPII BBH mergers
(see Costa et al. MNRAS 2023, Santoliquido et al.2023 MNRAS)



PRIMORDIAL BLACK-HOLES

Disentangle astrophysical PoPIII from primordial BHs



Any BBH merger at z>30 primordial

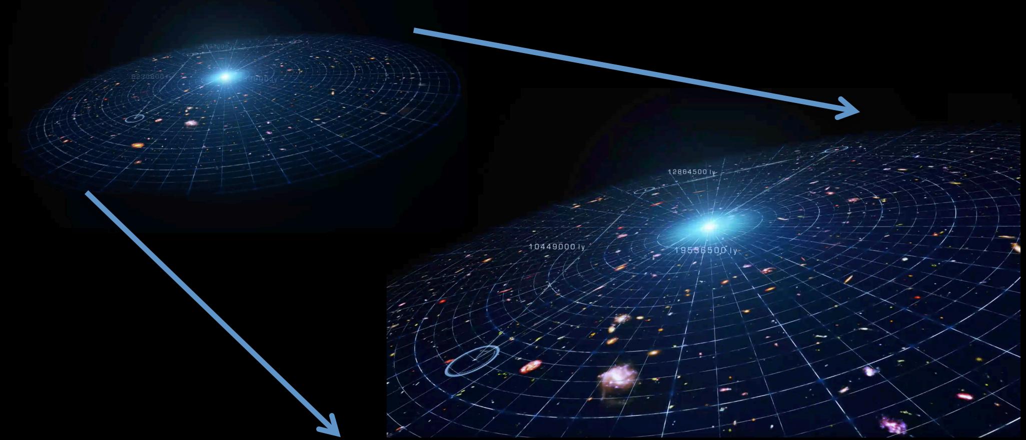
- Difference between ET and CE due to the better ET sensitivity at low frequencies
- Note: accurate measurement of z is also needed !

Multi-probe: how will JWST constrain POPII and II?
What info from high-z GRB detected by instruments such as THESEUS?

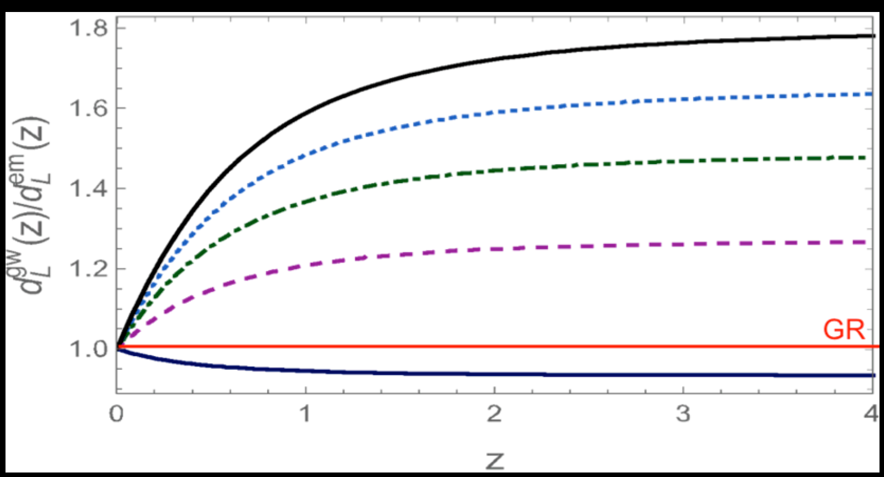
See NG et al. 2022.ApJL
NG et al. 2023, PRD

Recent population synthesis work on POPIII and POPII BBH mergers
(see Costa et al. MNRAS 2023, Santoliquido et al.2023 MNRAS)

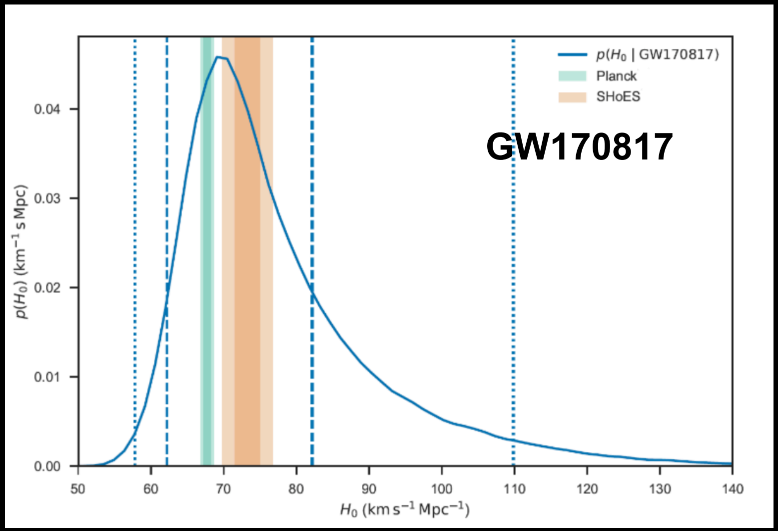
UNIVERSE EXPANSION, DARK ENERGY, MODIFIED GRAVITY AT COSMOLOGICAL SCALE



Modified GW propagation

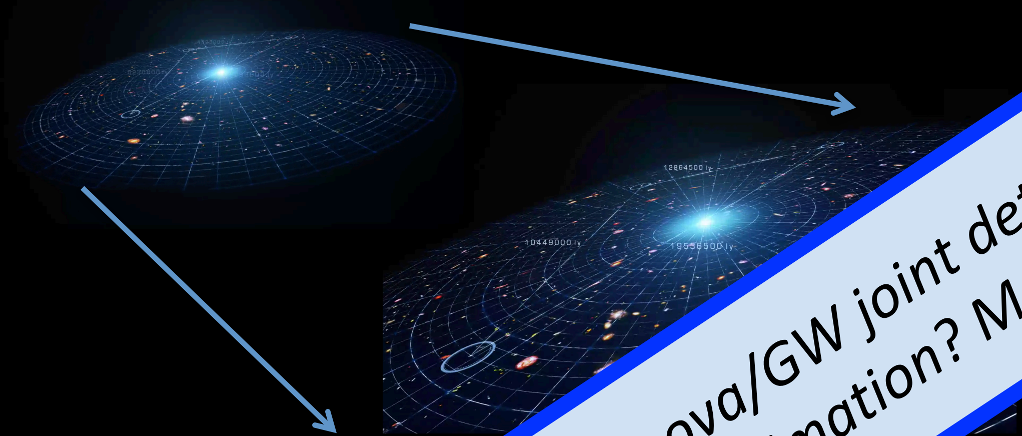


Belgacem et al. JCAP 2019



Abbott et al. Nature 2017

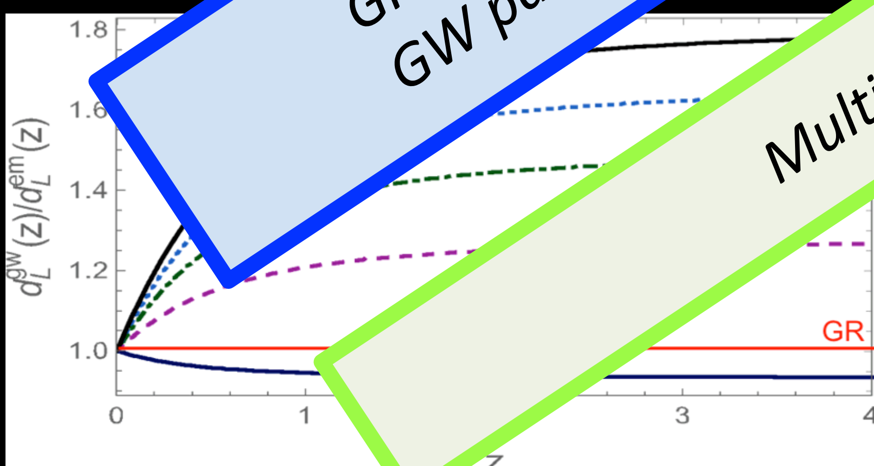
UNIVERSE EXPANSION, DARK ENERGY, MODIFIED GRAVITY AT COSMOLOGICAL SCALE



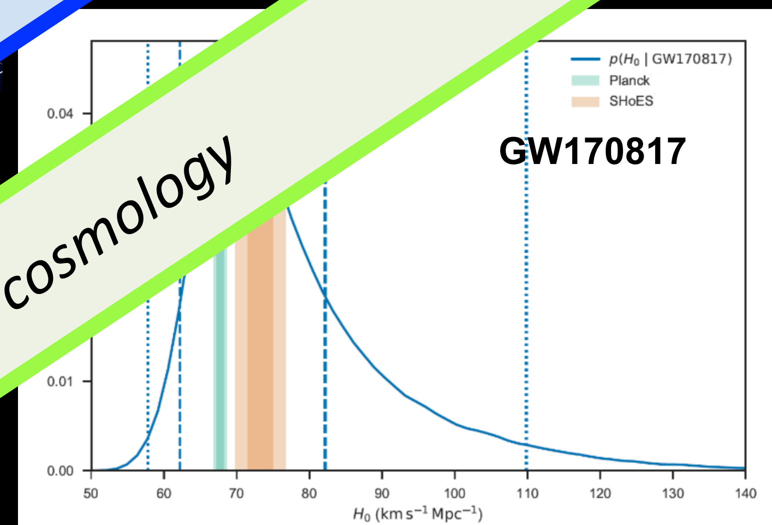
GRB/GW? Kilonova/GW joint detections?
GW parameter estimation? Maximum z?

Multi-probe cosmology

Modified GW

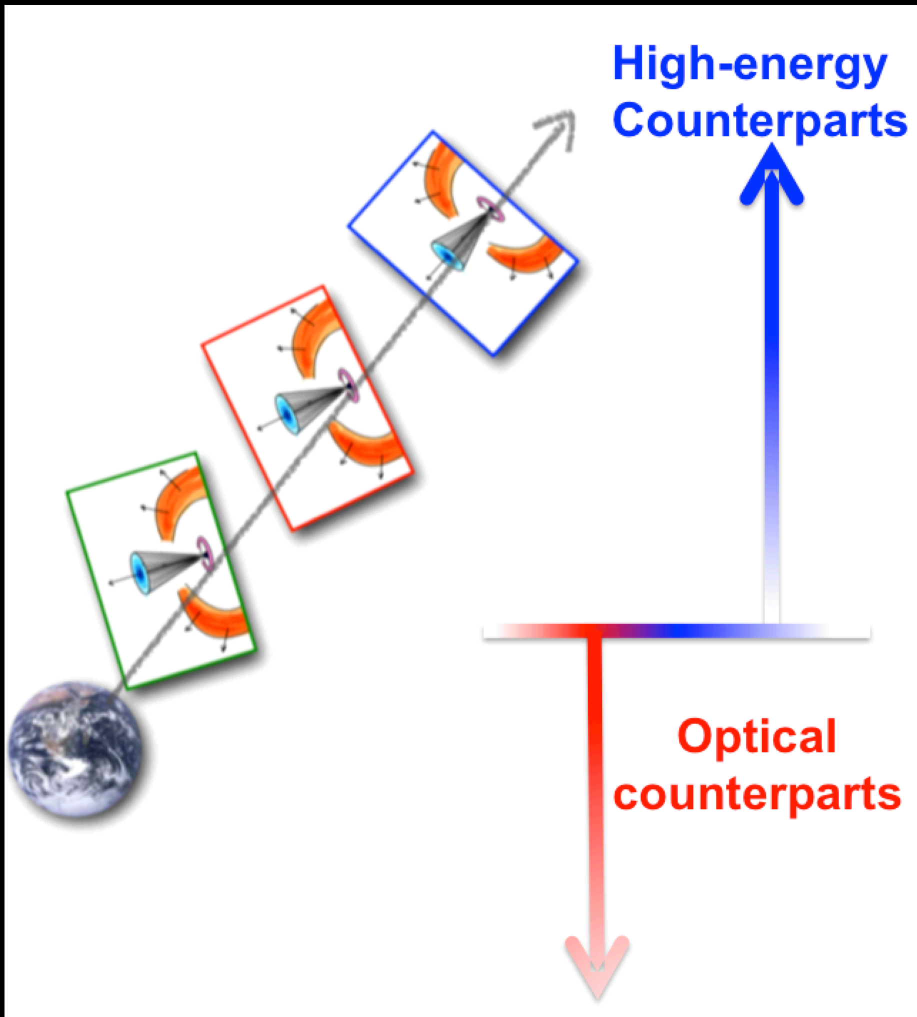


Belgacem et al. JCAP 2019



Abbott et al. Nature 2017

Multi-messenger in the ET era



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

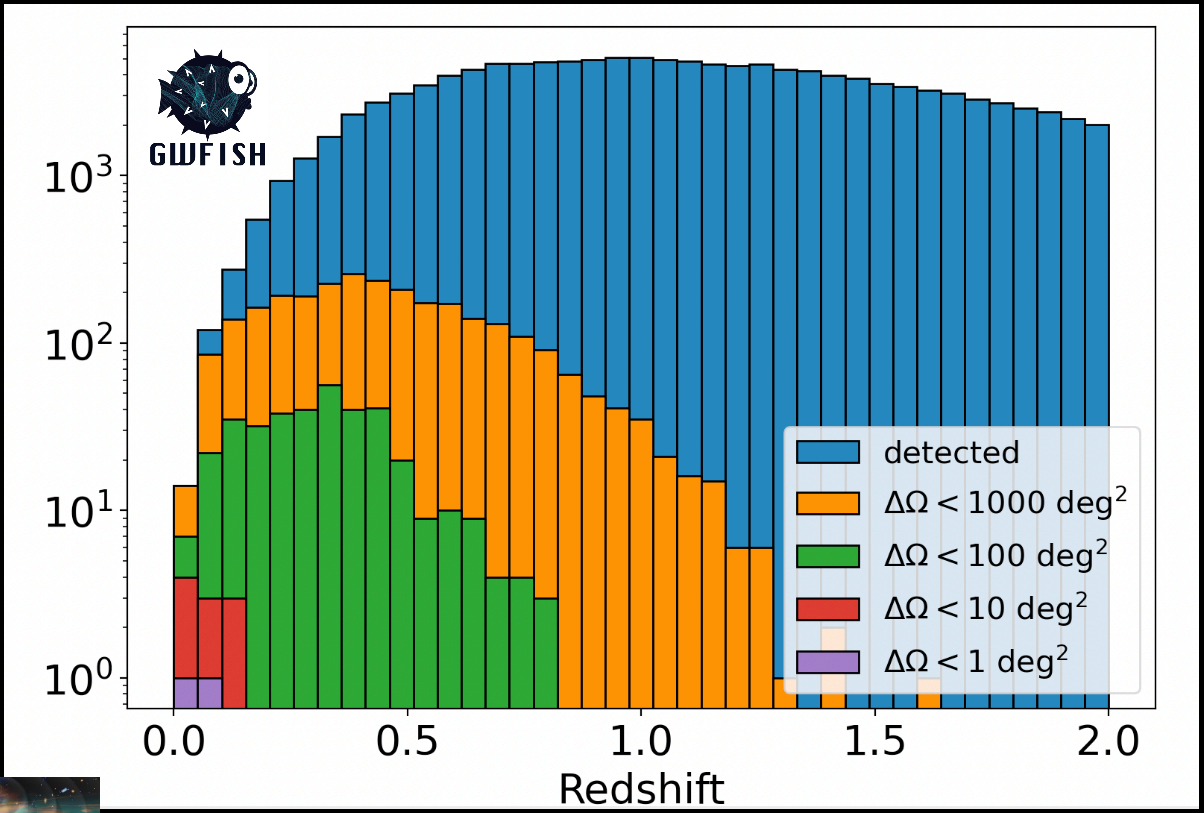
Credit: Ronchini

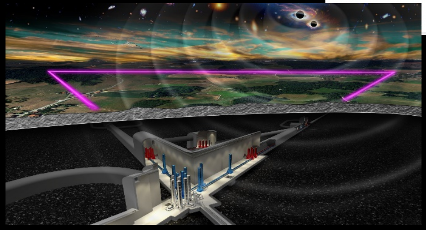
KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE

Hundred of MM events per year!

Image credit: NASA Goddard Space Flight Center

ET sky-localization capabilities

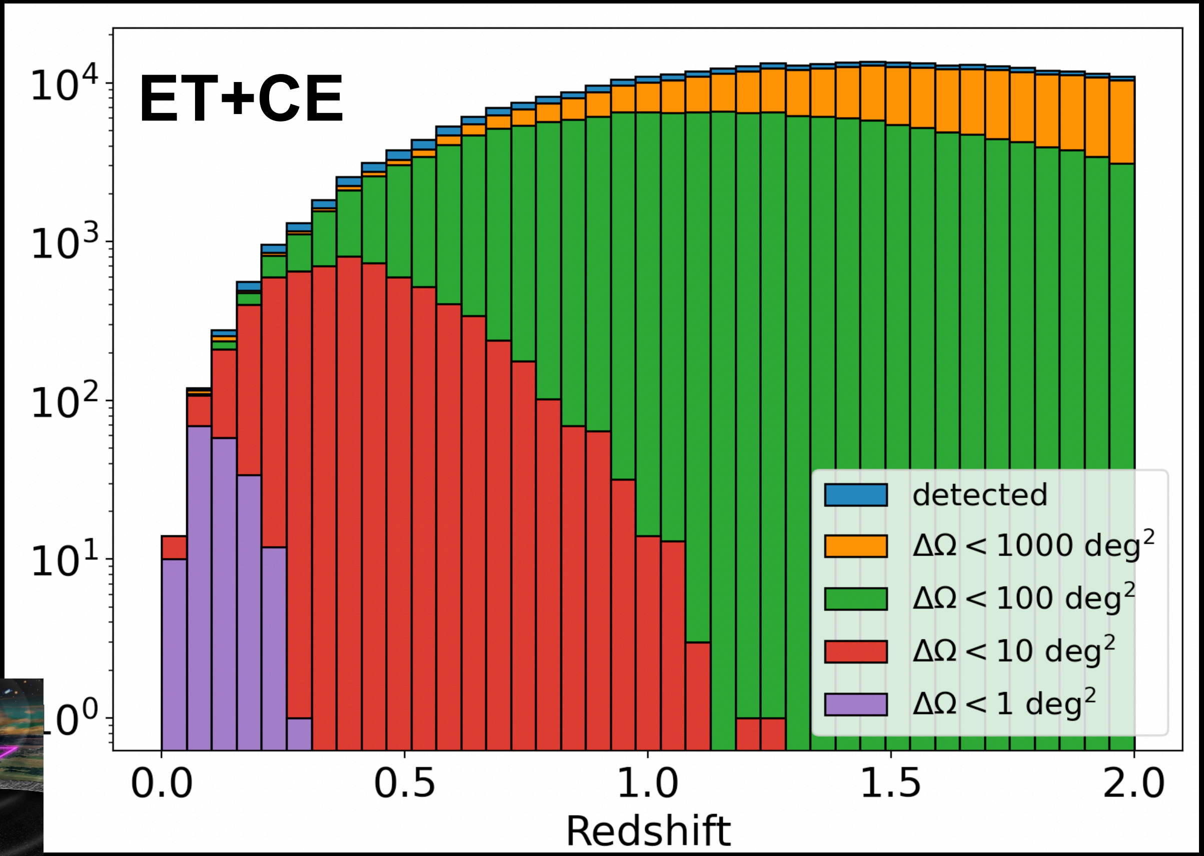


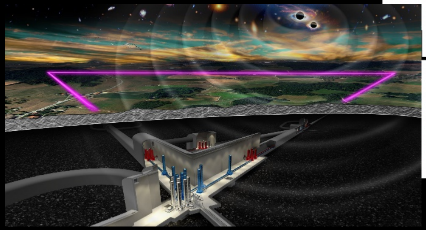


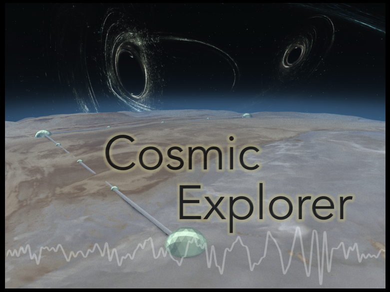
ET low frequency sensitivity make it possibile
To localize BNS!

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

Network sky-localization capabilities



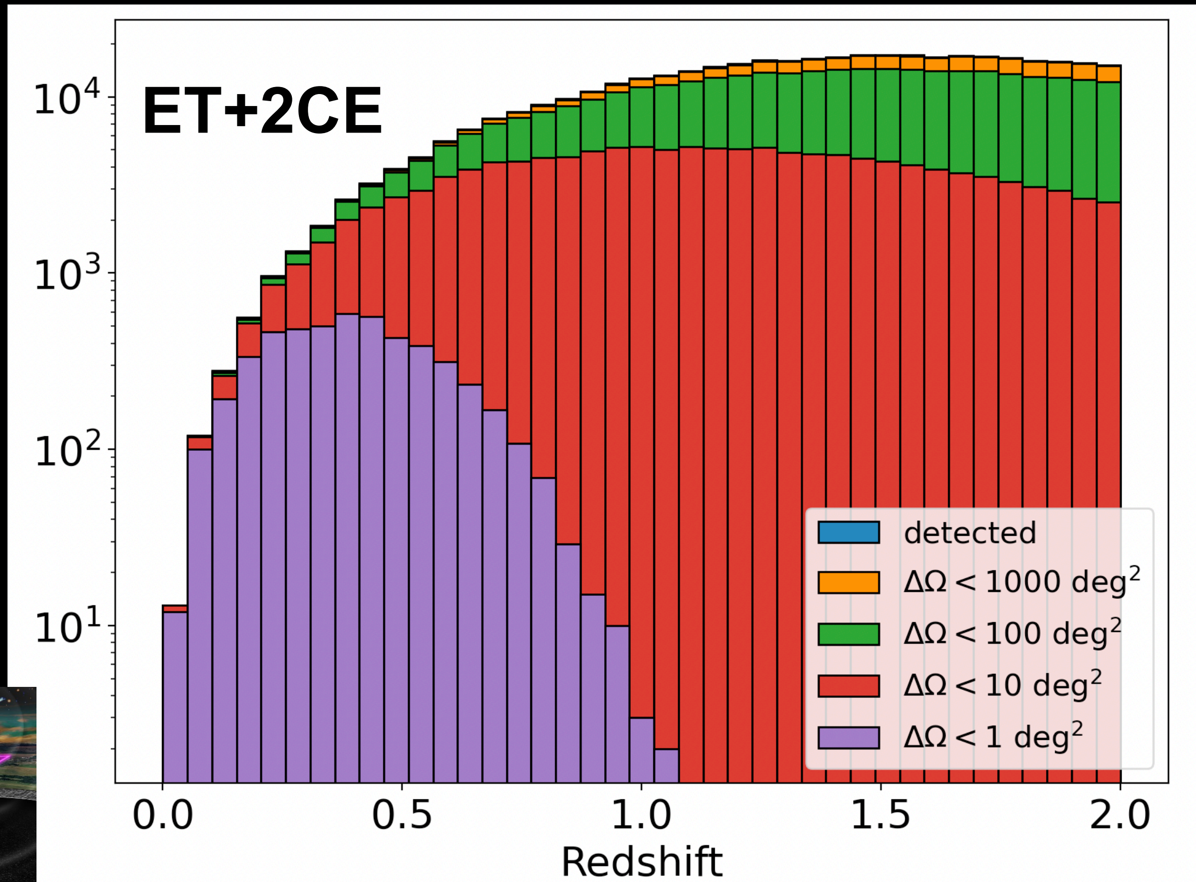


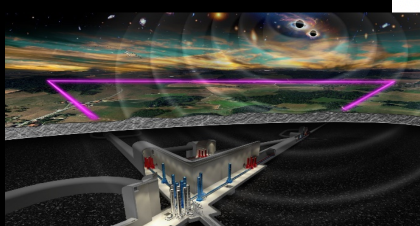


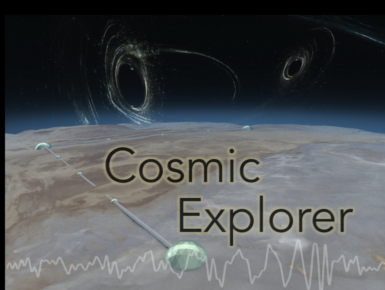
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Dupletsa et al. 2022, Ronchini et al. 2022

Network sky-localization capabilities







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

Dupletsa et al. 2023

Prioritization of triggers required

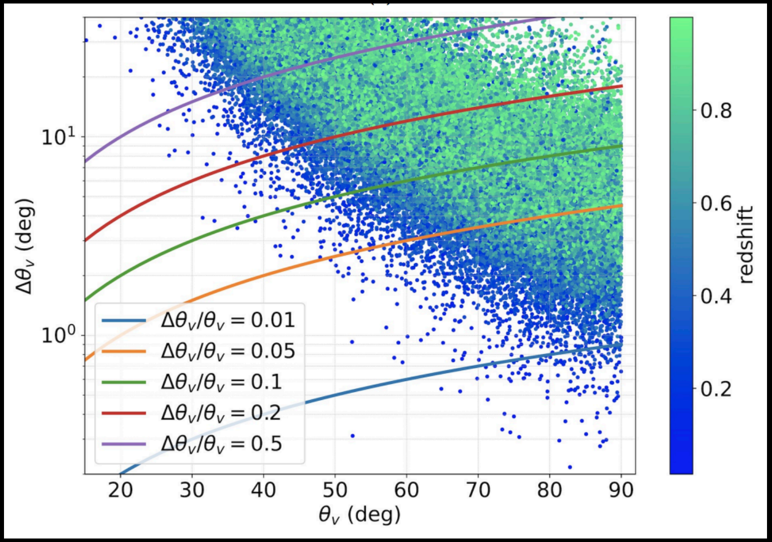
Sky-localization

	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

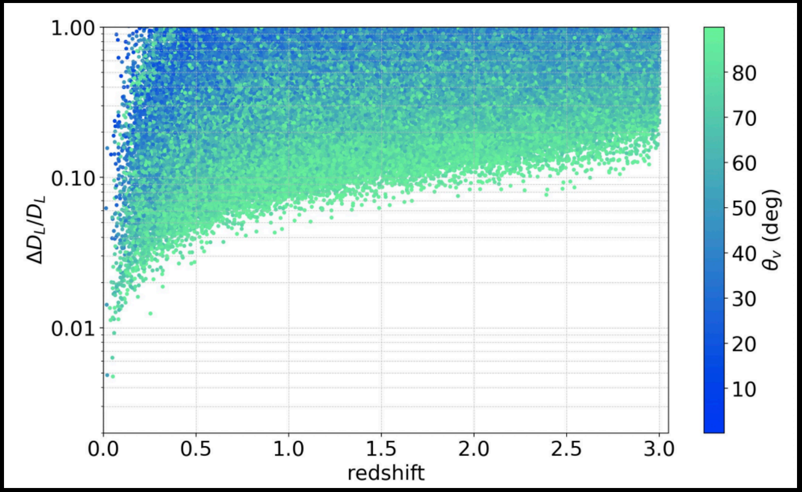
Too large numbers of triggers well localized to be followed-up

Send in low-latency source parameters and continuous updates

Viewing angle



Distance



Ronchini et al. A&A 2022

- *Real-time search: overlapping signals, low-frequencies*
- *A few tens of alerts per hour*
- *Pre-merger alerts*

- *Select triggers to be followed*
- *Send in low-latency all source parameters and continuous updates, dyanmical database*
- *GW detectors as external trigger user*

- *What EM oservatories for the search?*
- *What resources to characterize the transients?*

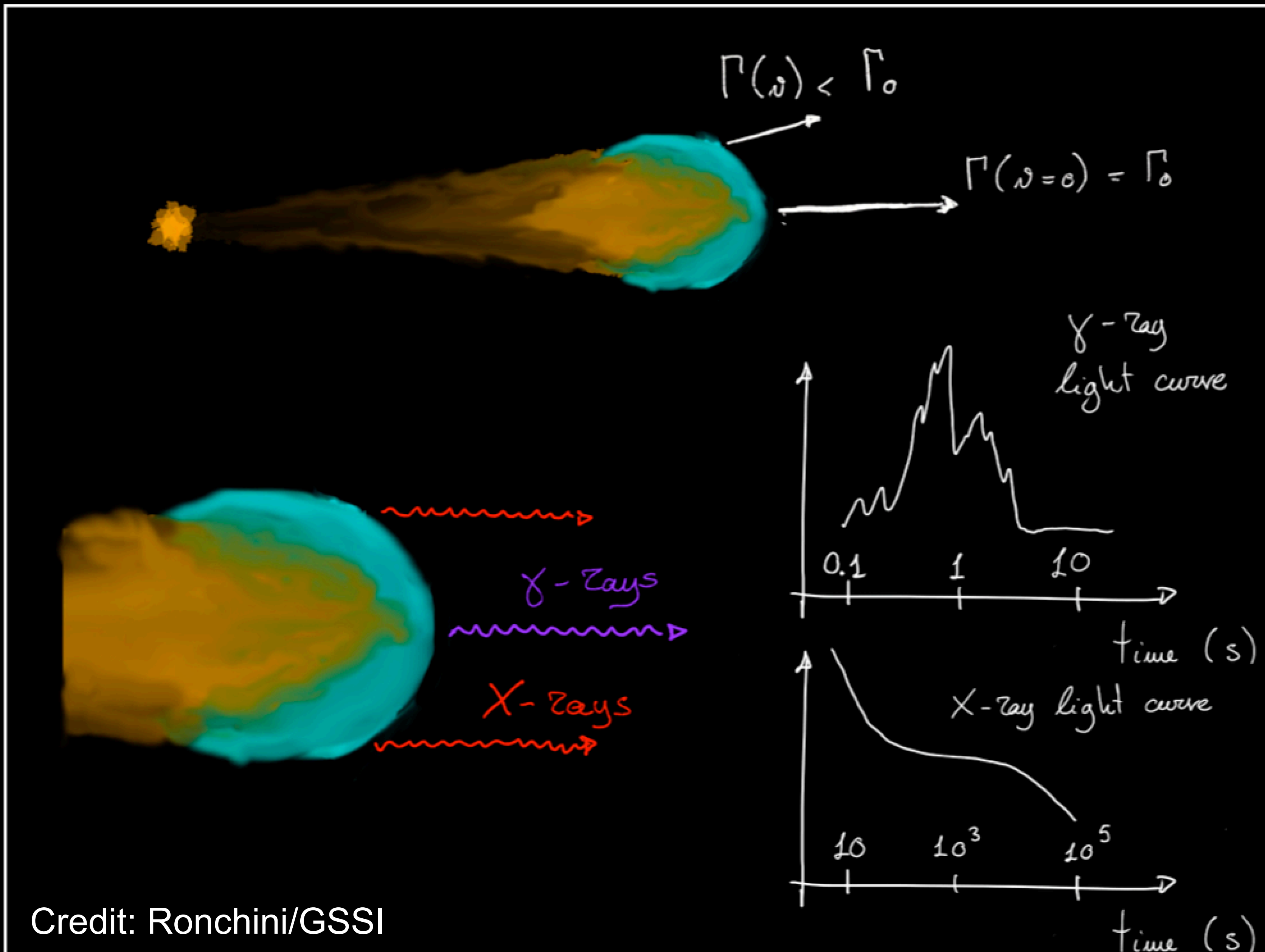
- *Brokers, common platform*
- *Common format*
- *Tools to access archive and data*

ASTRO-COLIBRI

HIGH-ENERGY

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

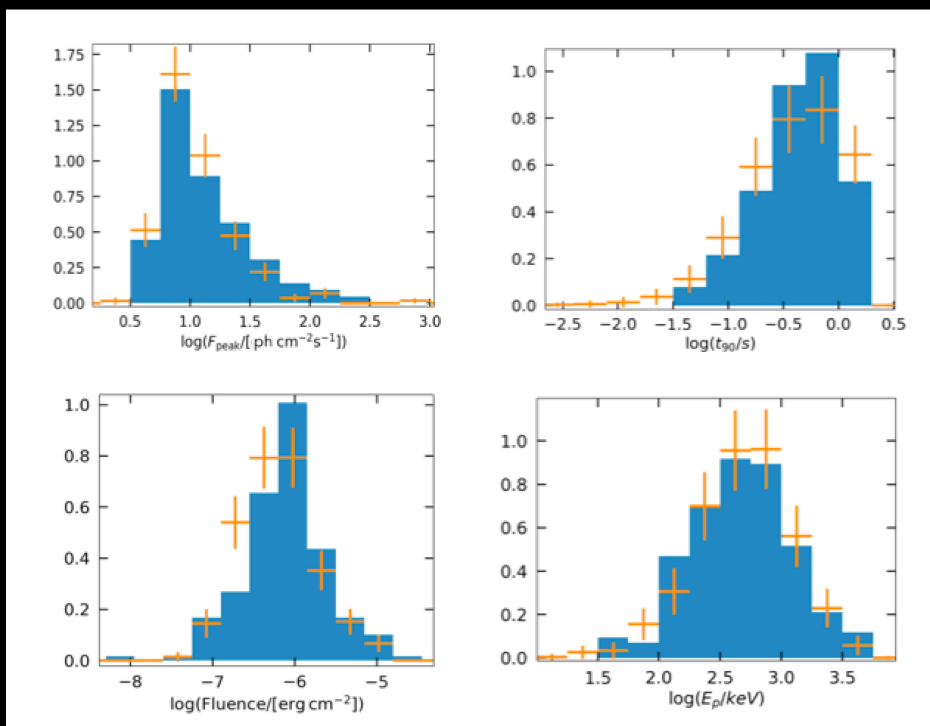
Prompt and afterglow emission from a structured jet



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



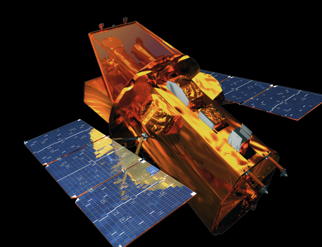
GRB data from Ghirlanda 2016

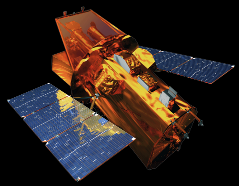
$$0.26^{+0.34}_{-0.14}$$

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

Rate of SGRB observed by Fermi

From population synthesis

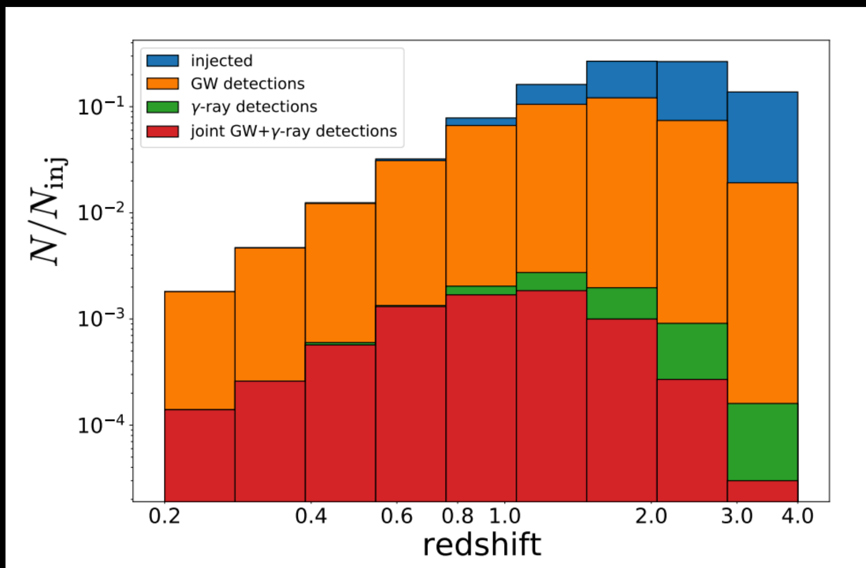




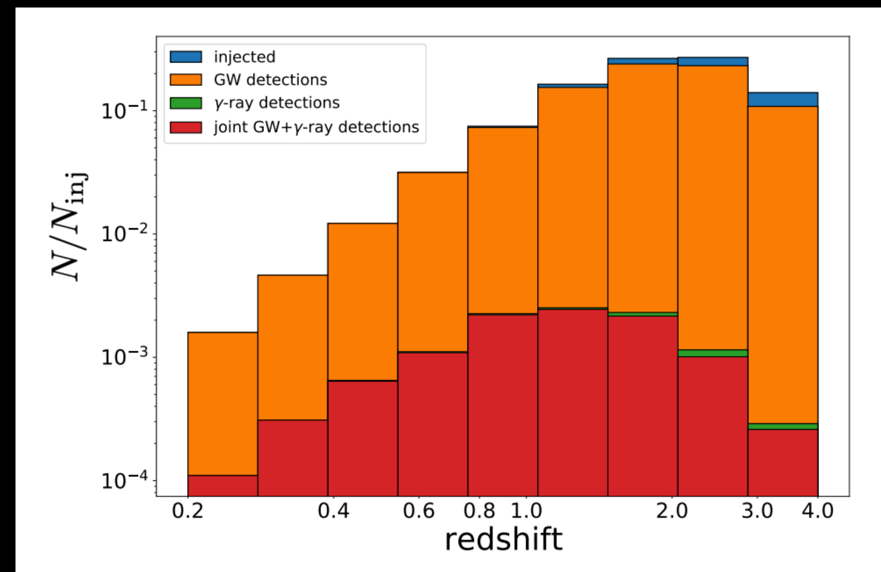
GW + γ-ray joint detections per year

SURVEY MODE

Fermi-GBM+ET

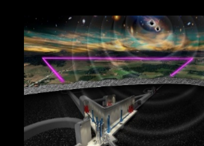


Fermi-GBM+(ET+CE)

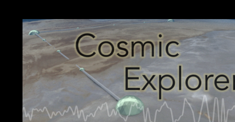


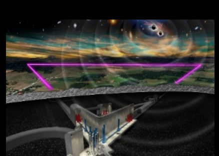
Almost all detected short GRB will have a GW counterpart

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



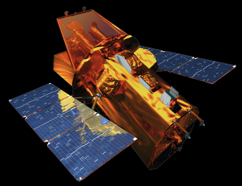
Crucial instruments able to localize at arcmin-arcsec level to drive the ground-based follow-up!

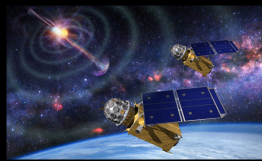




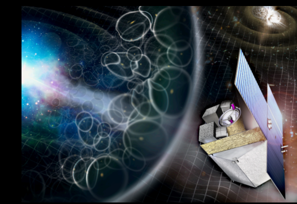
Ronchini et al. **A&A 2022**

GW + γ-ray joint detections per year

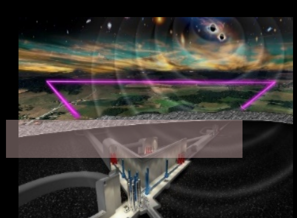


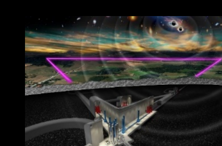


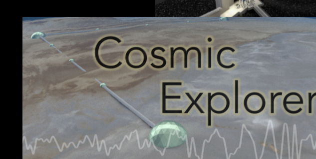
SURVEY MODE



INSTRUMENT	band MeV	$F_{\rm lim}$ erg cm^{-2} s^{-1}	FOV/4π	loc. acc.	Joint ET +γ-ray	N_{JD}/N_γ	Joint (ET+CE) +γ-ray	N_{JD}/N_γ
Fermi-GBM	0.01 - 25	0.5(*)	0.75	5 deg (^{a})	33^{+14}_{-11}	$68^{+13}_{-18}\%$	47^{+14}_{-14}	$95^{+5}_{-7}\%$
Swift-BAT	0.015 - 0.15	2×10^{-8}	0.11	1-3 arcmin	10^{+3}_{-3}	$62^{+11}_{-14}\%$	13^{+5}_{-4}	$94^{+6}_{-7}\%$
GECAM	0.006 - 5	2×10^{-8}	1.0	1 deg	121^{+84}_{-48}	$57^{+8}_{-10}\%$	205^{+145}_{-72}	$92^{+4}_{-5}\%$
SVOM-ECLAIRs	0.004 - 0.250	1.792(*)	0.16	< 10 arcmin	3^{+1}_{-1}	$69^{+10}_{-9}\%$	4^{+1}_{-1}	$95^{+5}_{-4}\%$
SVOM-GRM	0.03 - 5	0.23(*)	0.16	~ 5 deg	9^{+4}_{-3}	$59^{+6}_{-6}\%$	14^{+6}_{-4}	$92^{+3}_{-3}\%$
THESEUS-XGIS	0.002 - 10	3×10^{-8}	0.16	< 15 arcmin	10^{+5}_{-4}	$63^{+13}_{-13}\%$	15^{+6}_{-4}	$94^{+6}_{-7}\%$
HERMES	0.05 - 0.3	0.2(*)	1.0	1 deg	84^{+42}_{-30}	$61^{+10}_{-11}\%$	139^{+54}_{-36}	$94^{+6}_{-6}\%$
TAP-GTM	0.01 - 1	1(*)	1.0	20 deg	60^{+24}_{-24}	$67^{+13}_{-14}\%$	84^{+30}_{-24}	$95^{+5}_{-6}\%$



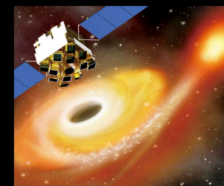


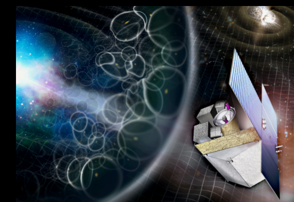


Ronchini, MB, Oganesyan, et al. 2022, A&A

Joint detection GW+X-ray afterglow per year

	FOV (sr)	loc. accuracy (arcmin)
EP	1.1	5
Gamow	0.4	1-2
THESEUS-SXI	0.5	1-2
TAP-WFI	0.4	1





SURVEY MODE:

- a few tens of detections per year

POINTING MODE

following BNS mergers / yr detected
with **GW sky localization < 100 deg^2** with detectable X-ray emission

- a few tens for ET alone and a few hundreds per year for ET+CE

BUT necessary

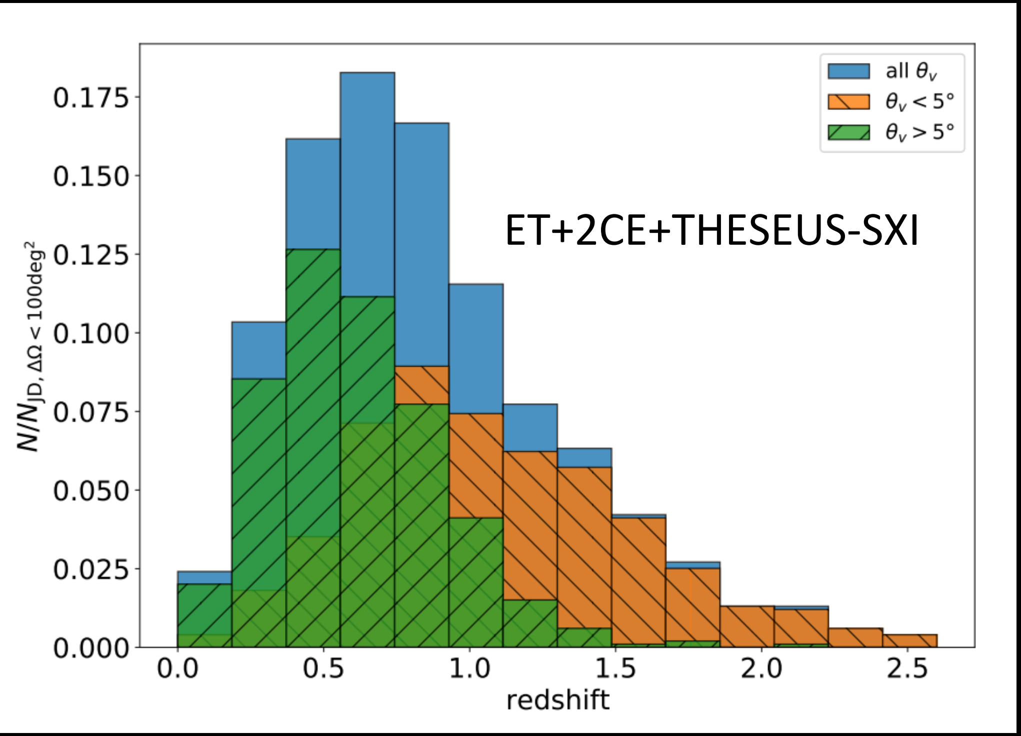
- fast response to GW alerts and re-pointing
- prioritizationof the alerts to be followed

Ronchini et al. 2022 A&A

Joint detection GW+X-ray afterglow per year

WFX-ray monitors

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



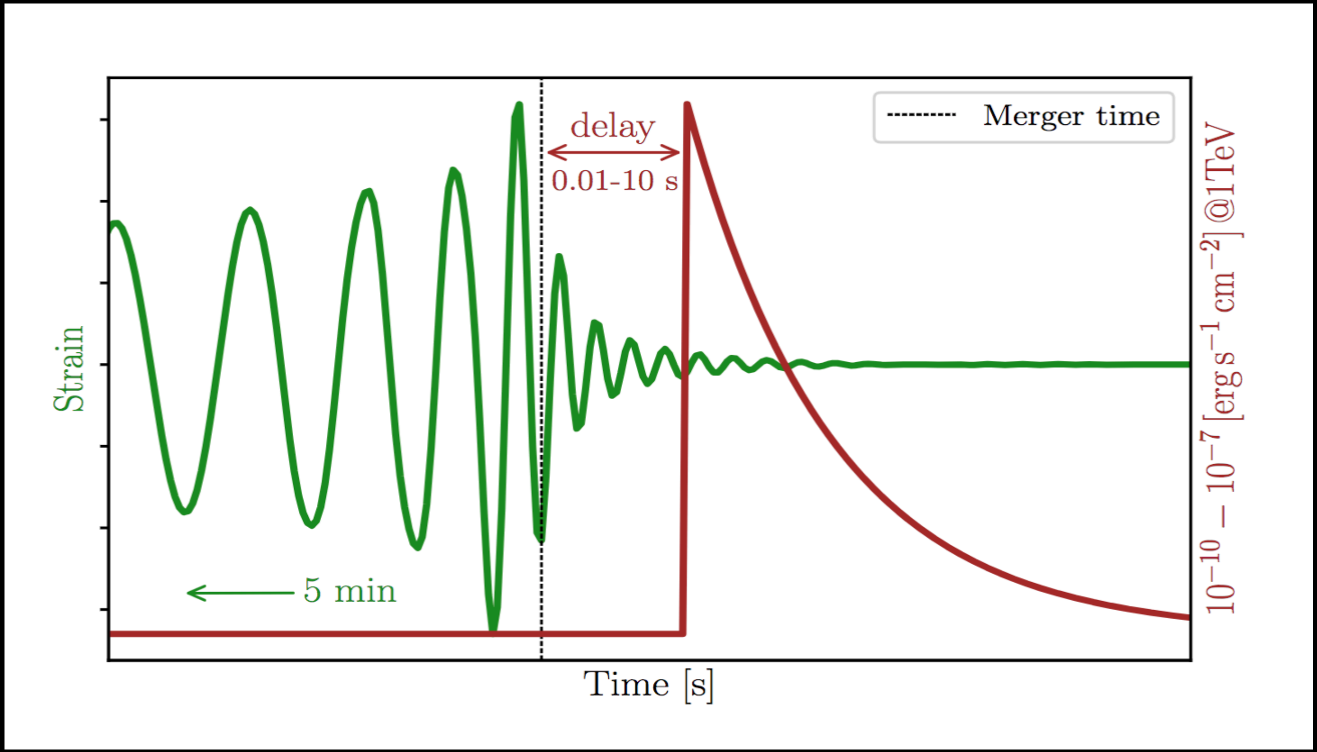
Joint GW+Xray detections

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

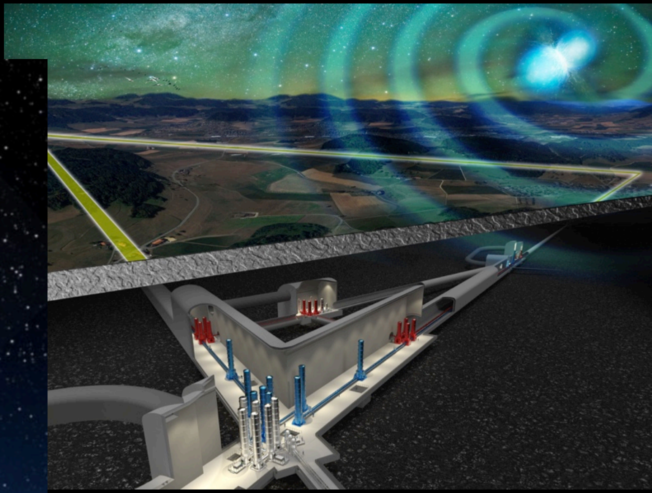
Pre-merger detections

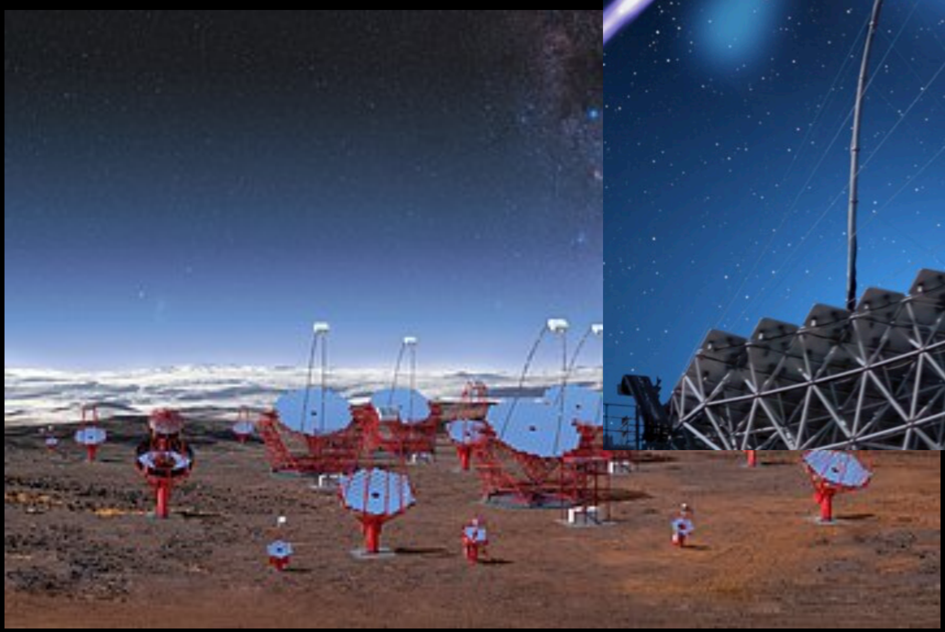


Critical to detect the prompt/early multi-wavelength emission

- to probe the central engine of GRBs, particularly to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms (e.g. VHE prompt CTA/ET synergy)
- to probe the structure of the outer sub-relativistic ejecta, early UV emission (e.g. ULTRASAT/UVEX/DORADO synergy)

CTA and GW DETECTOR synergies

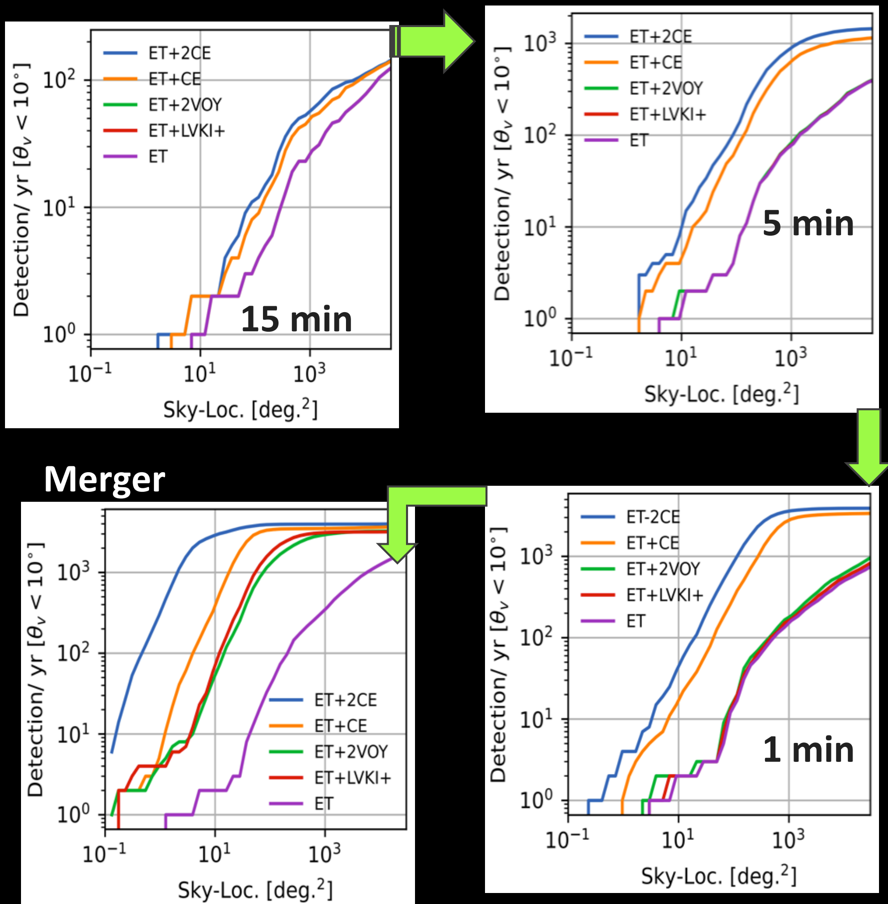




GRB 190114C (MAGIC)
GRB 180720B(HESS)
Afterglow VHE emission!

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

Sky-localization capability:

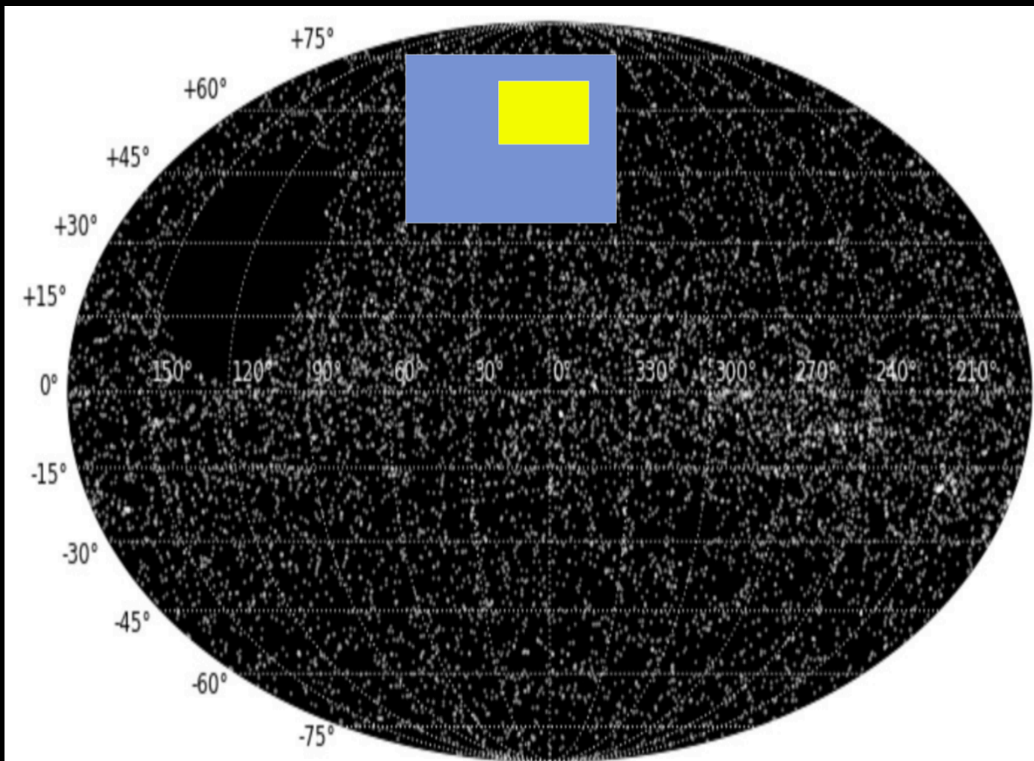


Detector	Ω [deg^2]	All orientations			
		15 min	5 min	1 min	0 min
ET + CE	100	442	1325	5075	123303
ET	100	90	130	208	436

Detector	Ω [deg^2]	Viewing angle (<10^0)			
		15 min	5 min	1 min	0 min
ET + CE	100	21	71	314	3376
ET	100	3	6	13	40

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

Observation strategy:

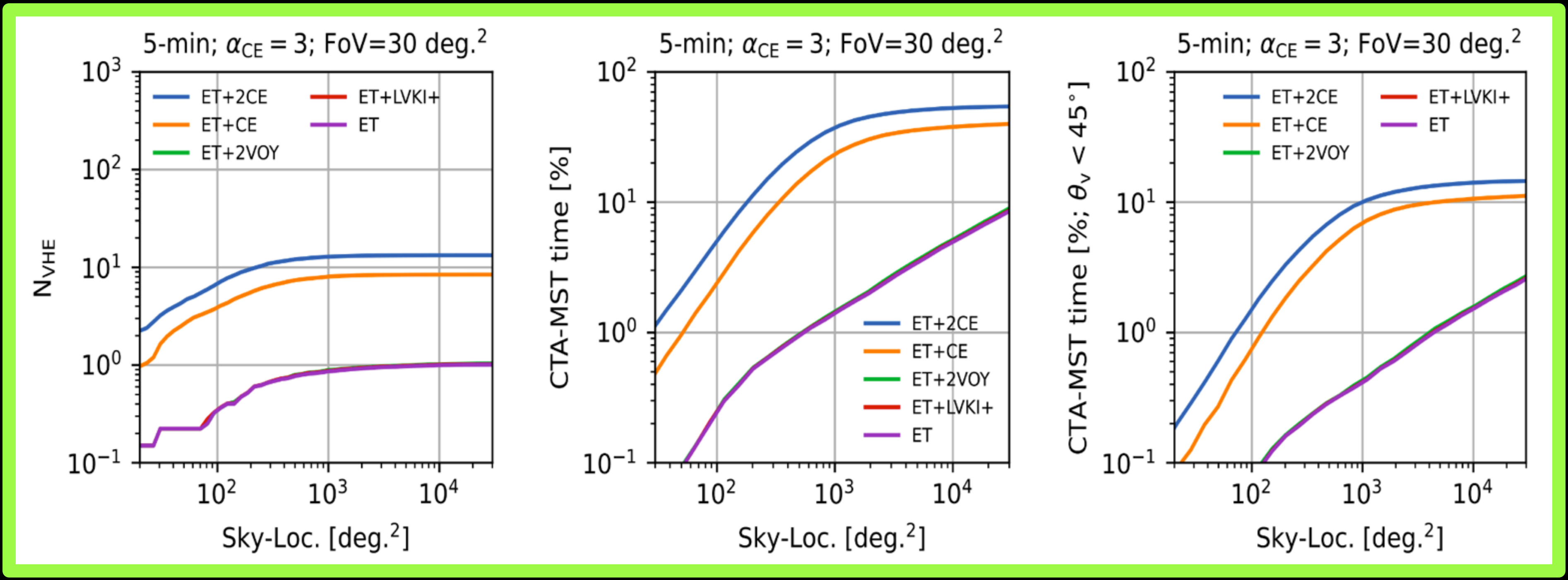


Follow-up pre-merger alerts with CTA

- Follow-up well localized sources (< FoV)
- Single shot observation
- Mosaic strategy
- Divergent pointing

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

Observation strategy: MST



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

Banerjee, Oganesyan, Branchesi et al 2022, A&A

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

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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]
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JCAP07(2023)068

New updated Science Paper for ET

Branchesi, Maggiore et al. 2023, JCAP

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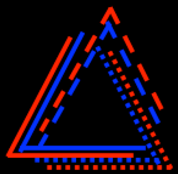
+Summary and Appendix

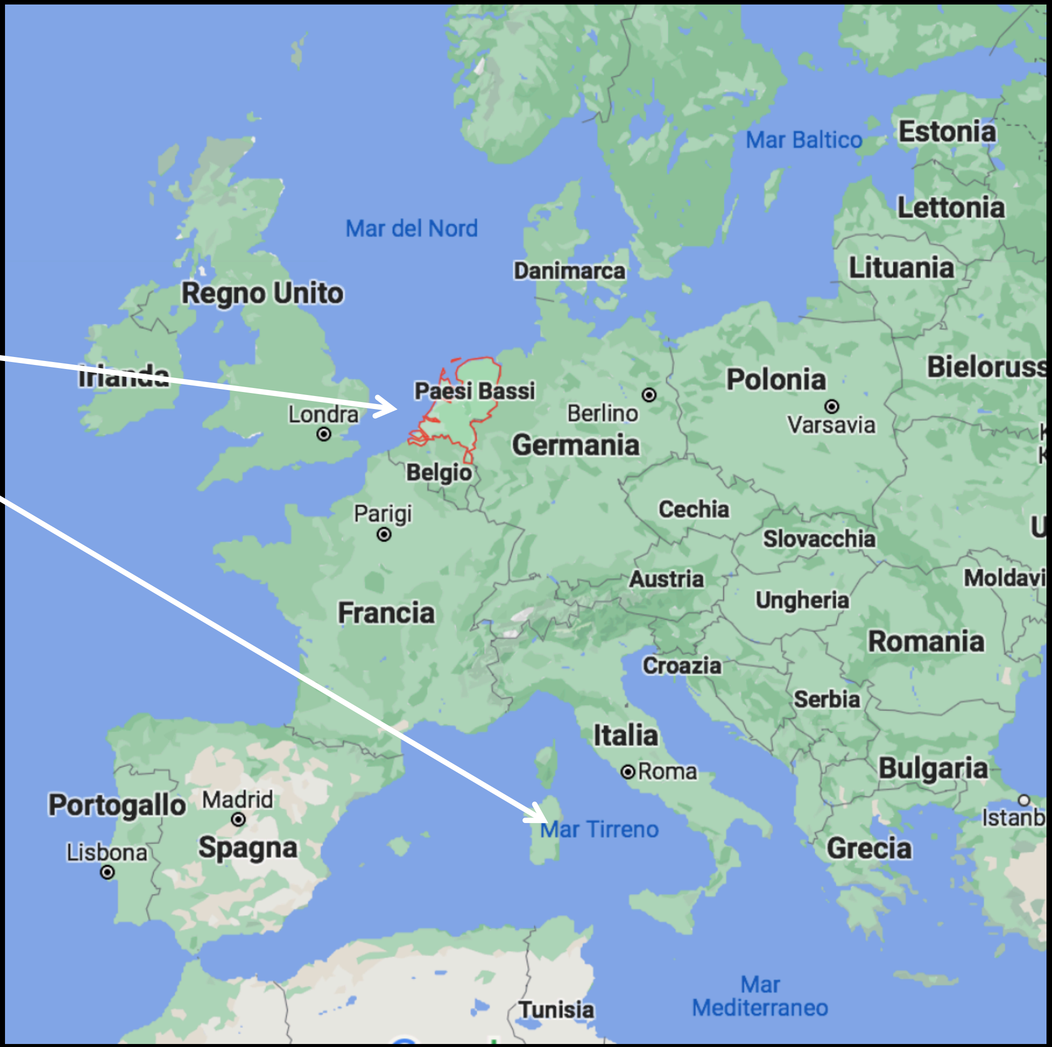
MM science with different designs of ET



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

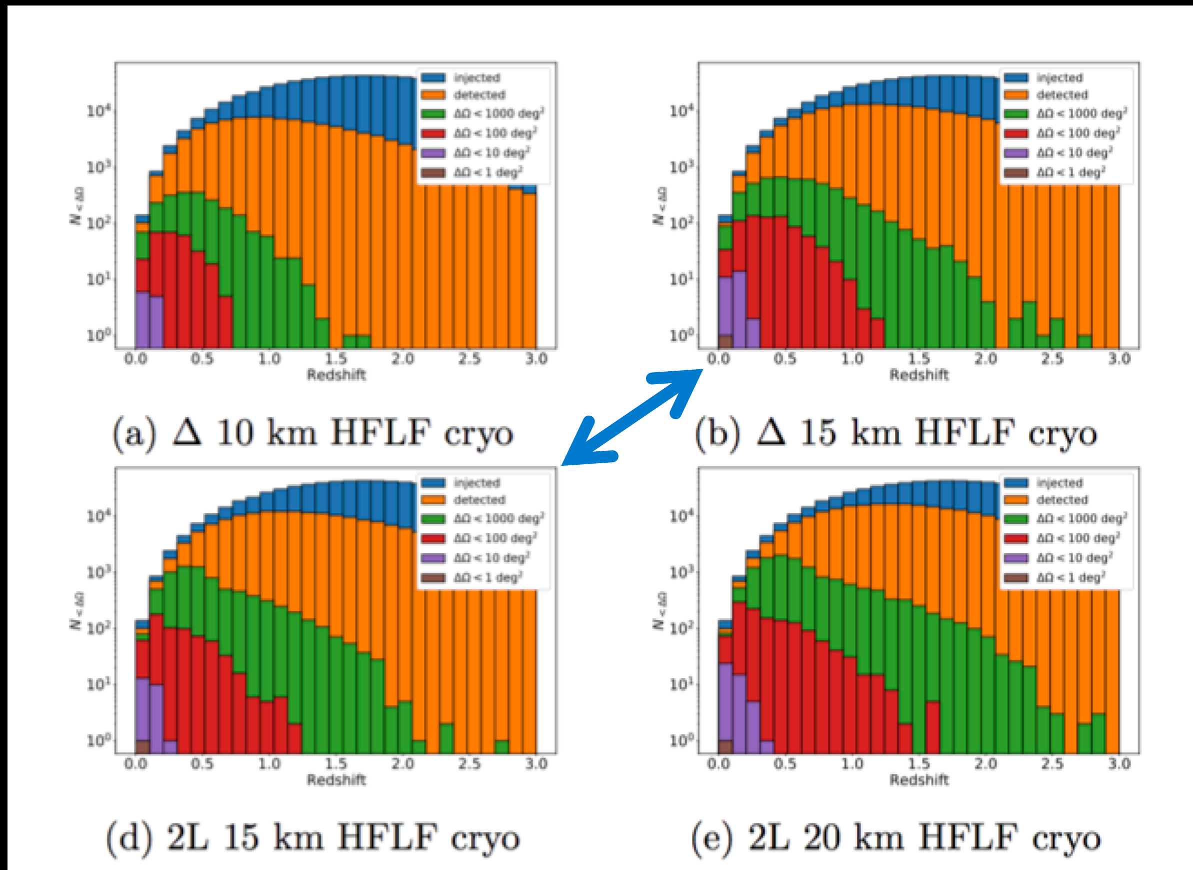
Two scenarios
- 2L of 15 km
- 2L of 20 km

2L misaligned of 45°



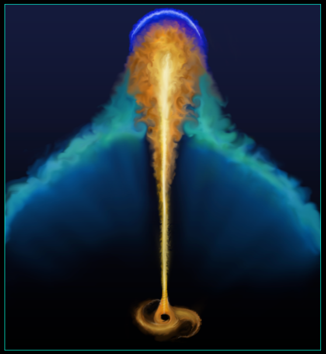
Branchesi, Maggiore et al. 2023

GW Sky-Localization



2L with 15 km

- comparable to 15 km triangle
- better than10 km triangle



2L-15km-45° better than 10 km triangle
(and comparable to 15 km triangle)

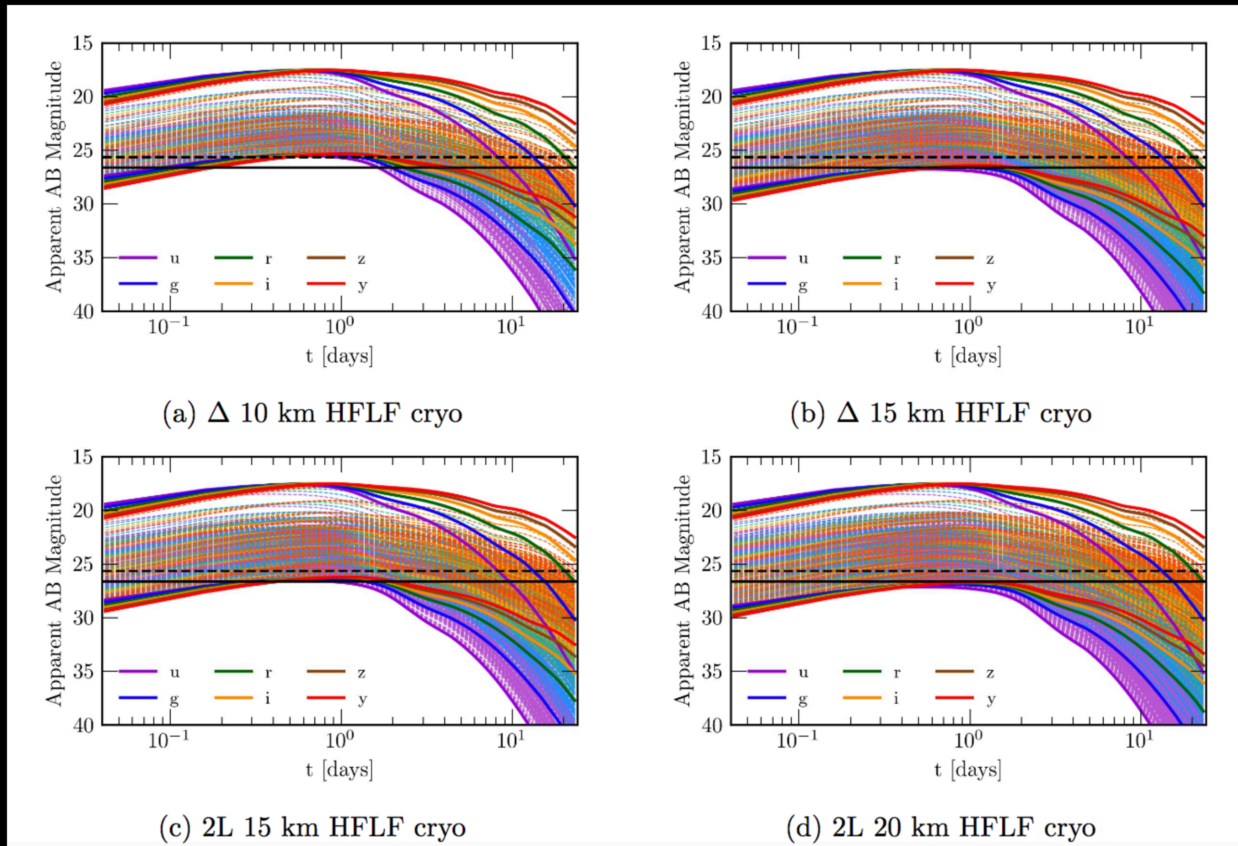
- larger number of well-localized events up to a larger redshift
- number of short GRBs with an associated GW signal increases by about 30%, and the number of expected kilonovae counterparts increases by a factor of 2

THERMAL EMISSION - KILONOVAE

KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

IMPACT on GW/KILONOVAE science

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

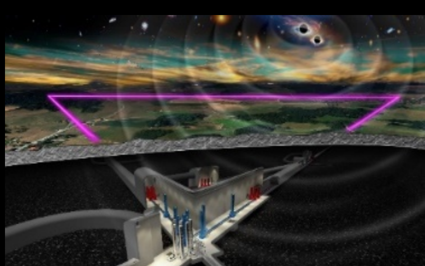


(a) Δ 10 km HFLF cryo

(b) Δ 15 km HFLF cryo

(c) 2L 15 km HFLF cryo

(d) 2L 20 km HFLF cryo

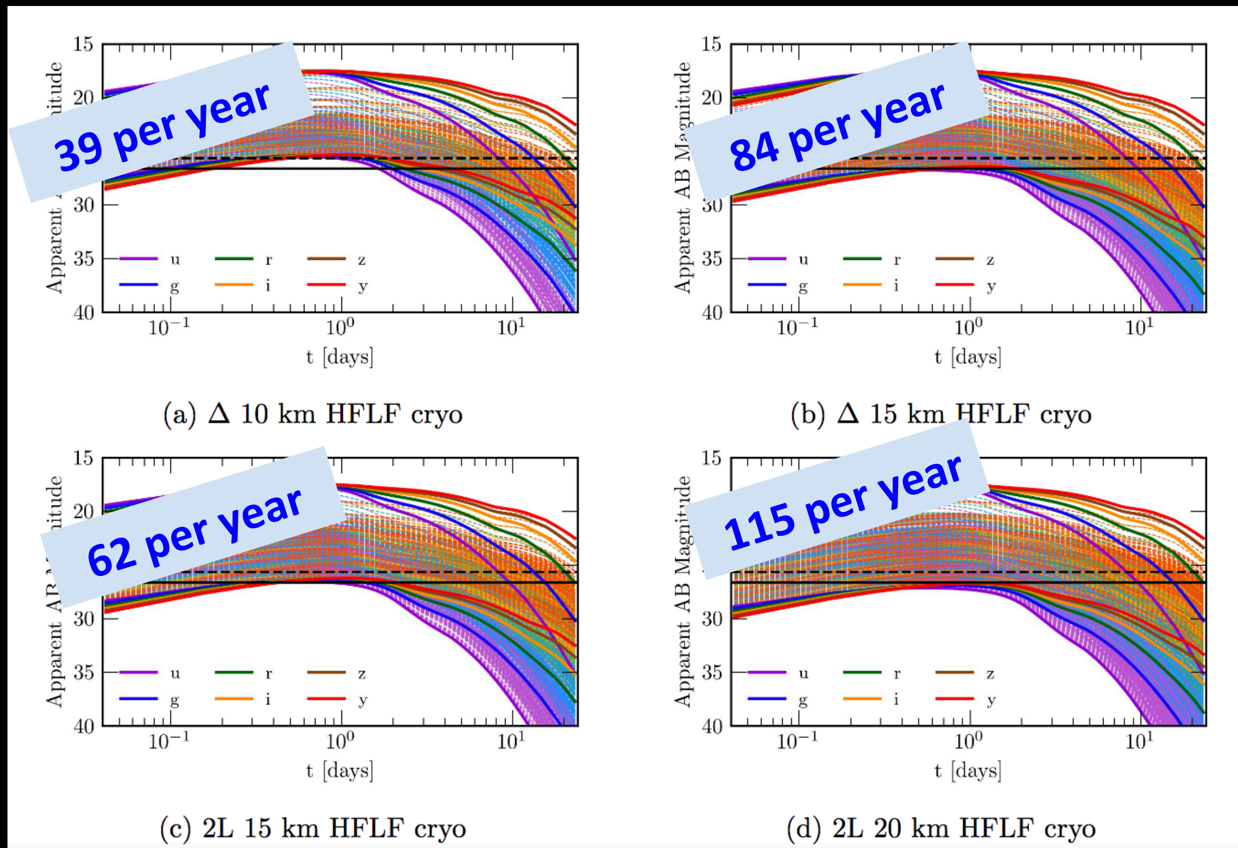


Two filter (g and i) observations repeated the first and second night after the merger and an exposure time for each pointing of 600 s

VERA C. RUBIN OBSERVATORY

IMPACT on GW/KILONOVAE science

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



(a) Δ 10 km HFLF cryo

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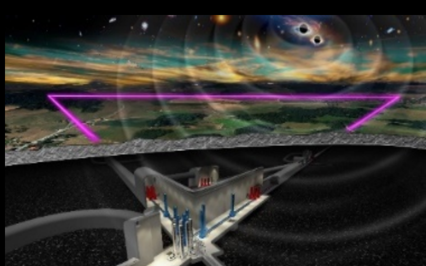

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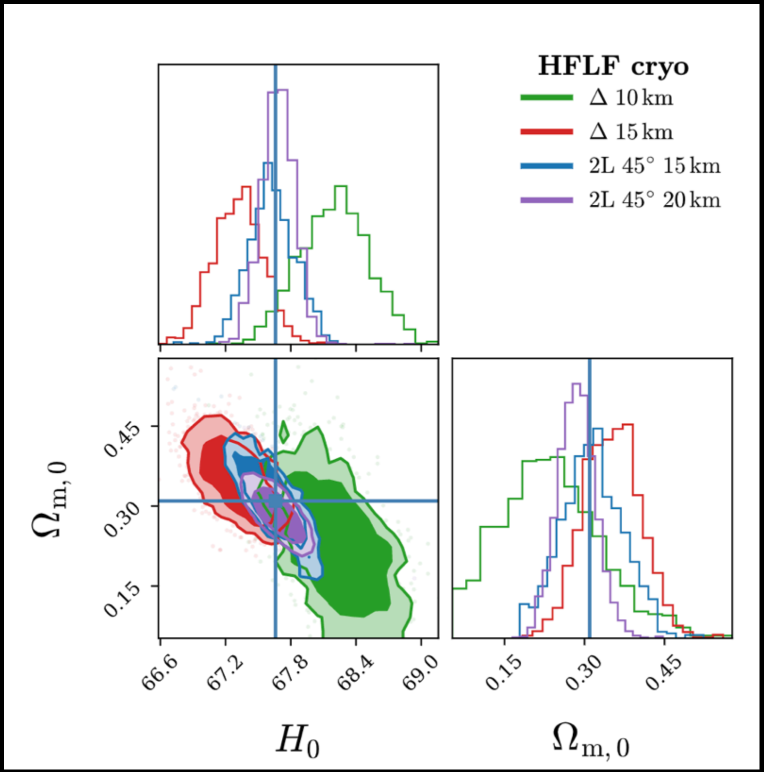
VERA C. RUBIN OBSERVATORY

Cosmology

Joint GW-kilonova detections, ET+VRO



HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

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

- Results depend on the BNS merger rate normalization

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