Multi-messenger science with future GRB space missions

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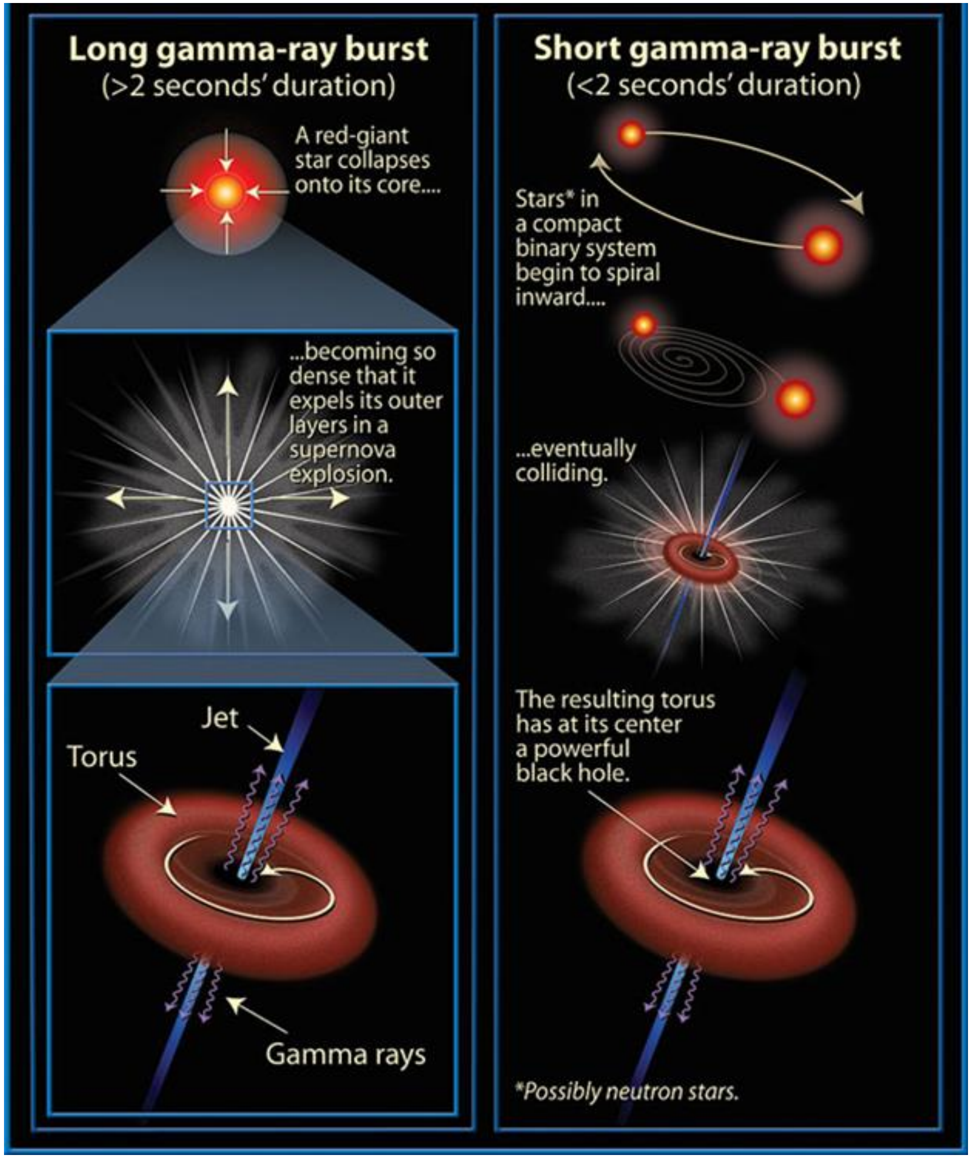
(25 June 2021)

GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

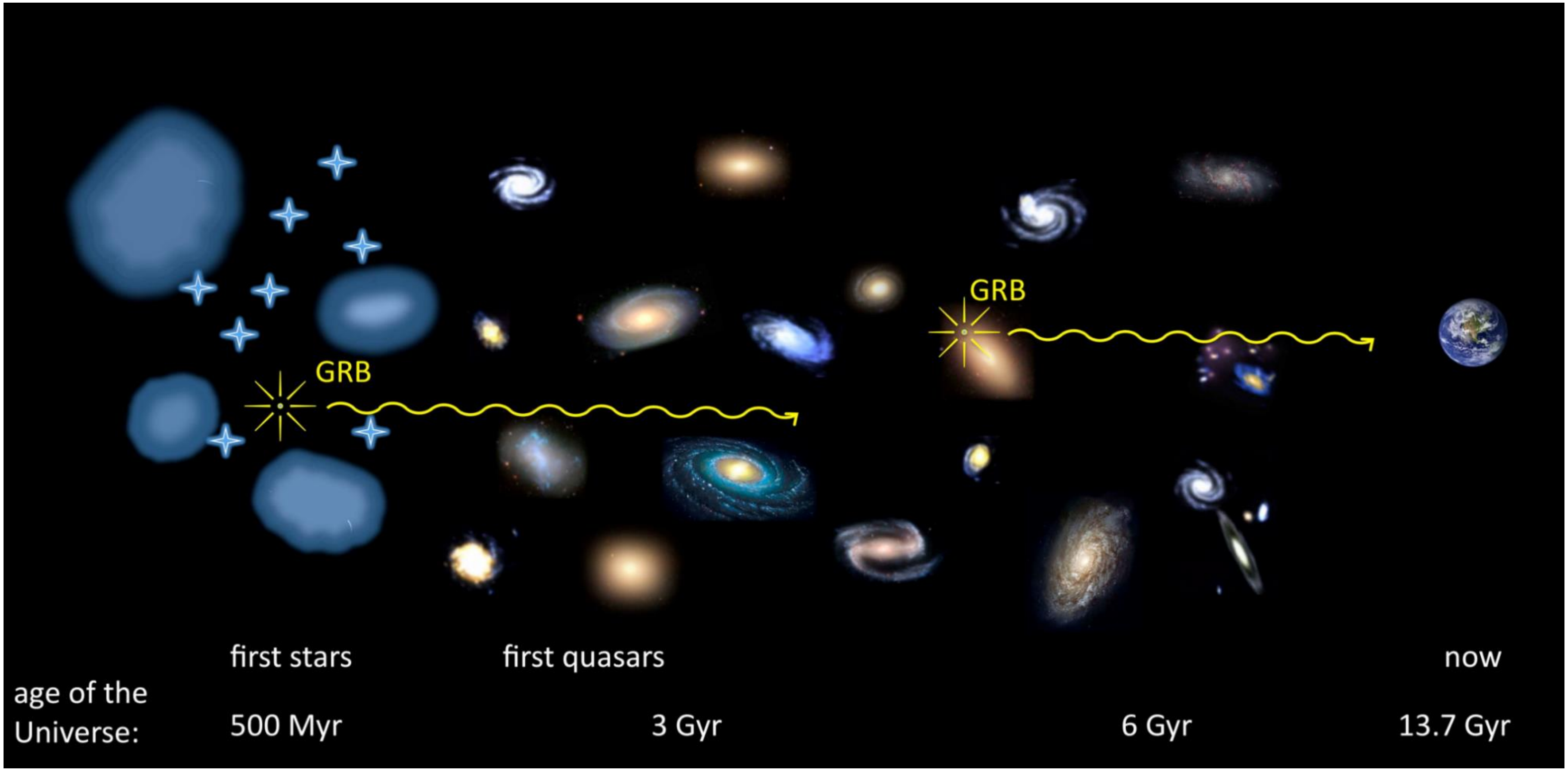
Long GRBs: core collapse of pecular massive stars, **association with SN**

Short GRBs: NS-NS or NS-BH mergers, **association with GW sources**

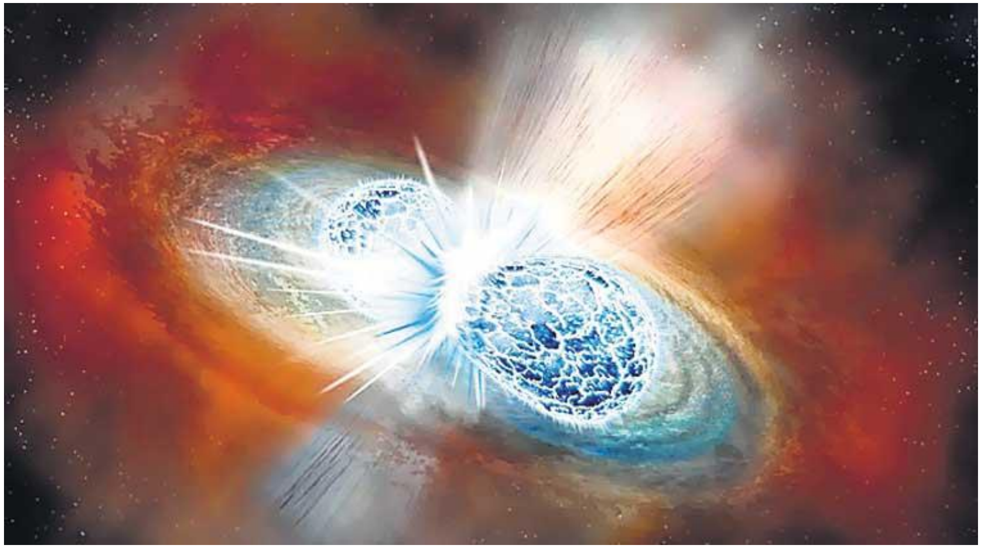


Long GRBs

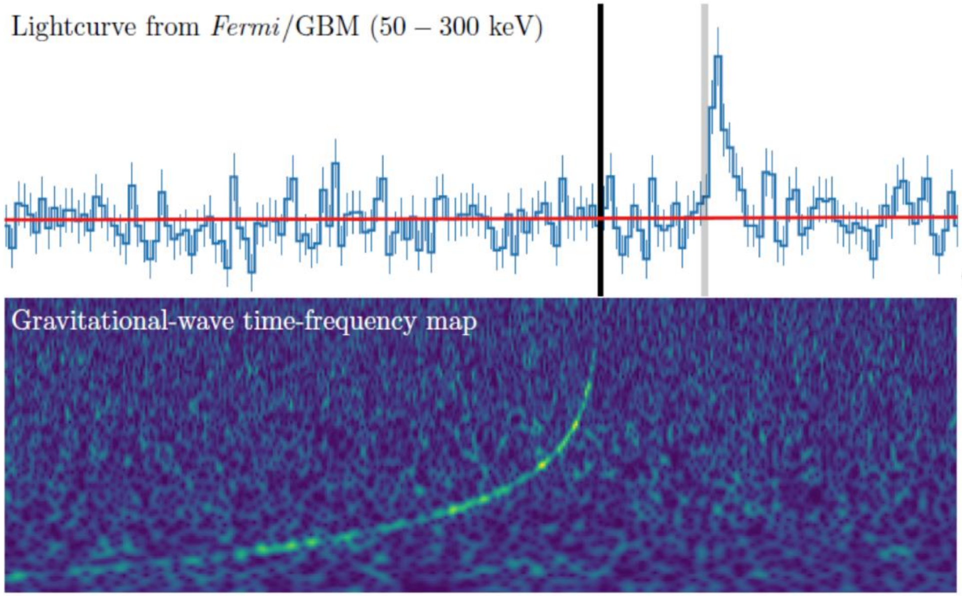
- direct detection and accurate location of exploding stars (and their host galaxies) up to the Cosmic Dawn!!!
- cosmological «beacons»
- standardizable cosmological candles??

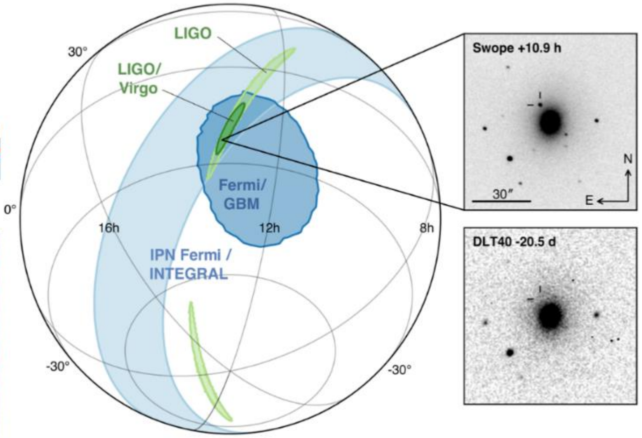


Short GRBs: e.m. counterparts of gravitational-waves sources



LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

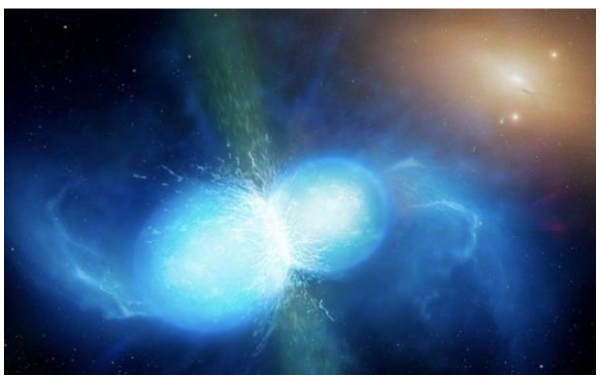




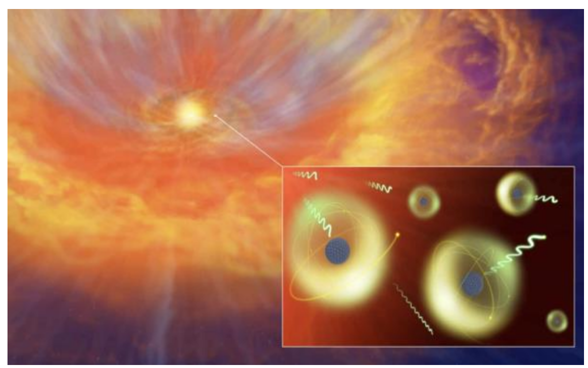
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

GW170817 + SHORT GRB 170817A + KN AT2017GFO
THE BIRTH OF MULTI-MESSENGER ASTROPHYSICS

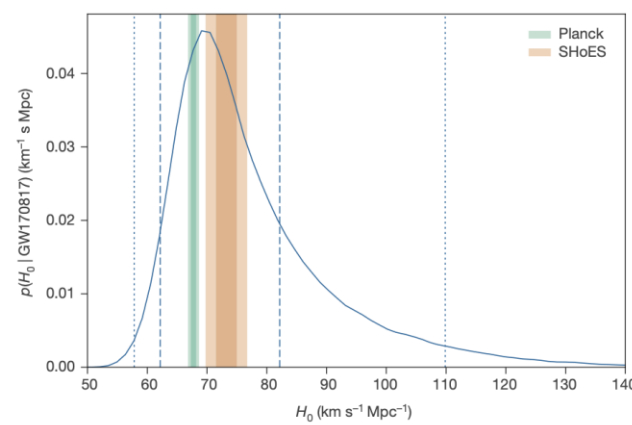
Relativistic jet formation, equation of state, fundamental physics



Cosmic sites of r-process nucleosynthesis

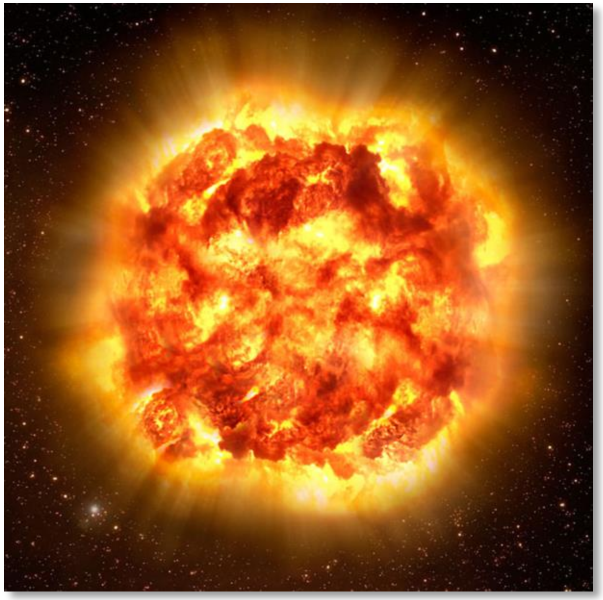


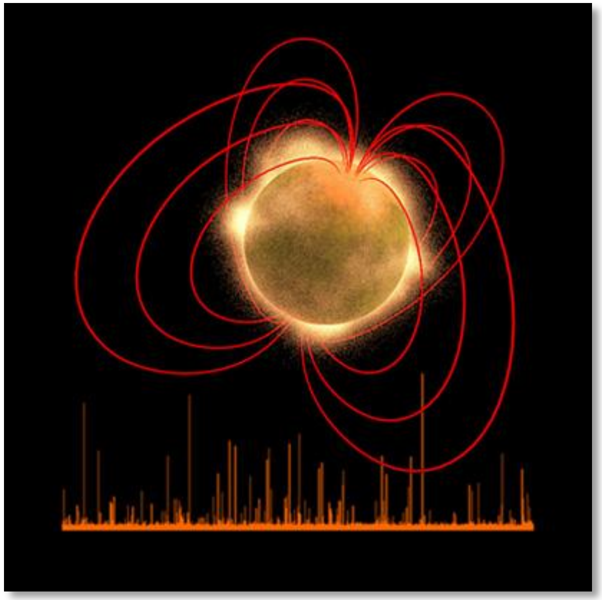
New independent route to measure cosmological parameters



GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

- **Short GRBs**
- Core-collapse stars
- Soft Gamma-ray Repeaters
- Unexpected transients…





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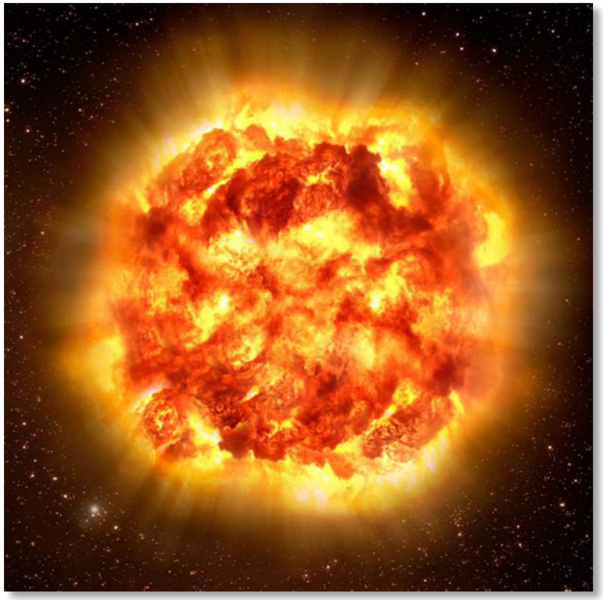
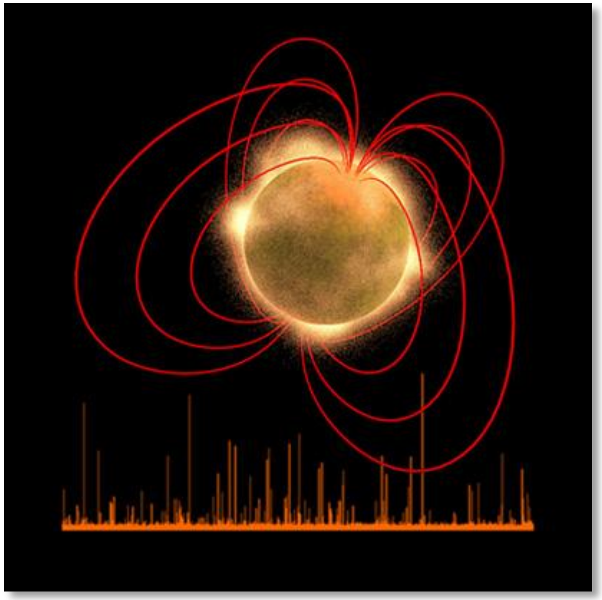

Future GRB missions: objectives

- ***Physic of prompt emission*, internal engine, progenitors** (es., sub-luminous, ultra-long, XRFs, NS vs. BH, jet structure and magnetization) *-> extend sensitive mesurements to soft X-rays (< 10 keV), improved polarization and timing, …*

- ***Early afterglow emission****: -> internal engine, improve on multi-wavelength measurements*

- ***GRB cosmology:*** *use of long GRBs for early Universe (SFR, first stars and galaxies, cosmic re-ionization) and as possible «standardizable» candels*

- **GRBs and multi-messenger astrophysics:** short GRBs as a key e.m. phenomenon for GW and neutrino astrophysics

- **GRBs and fundamental physics**: extreme physics, BH and NS properties, test of quantum-gravity /LI, etc.

- **Synergy with mw and mm large facilities**: large FOV + accurate source location

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Future GRB missions: synergies

- **Many next generation large observatories of the near** future (e.g., SKA, CTA, ATHENA, LSST, ELT, TMT, JWST) have GRB-related science in their core-science programmes

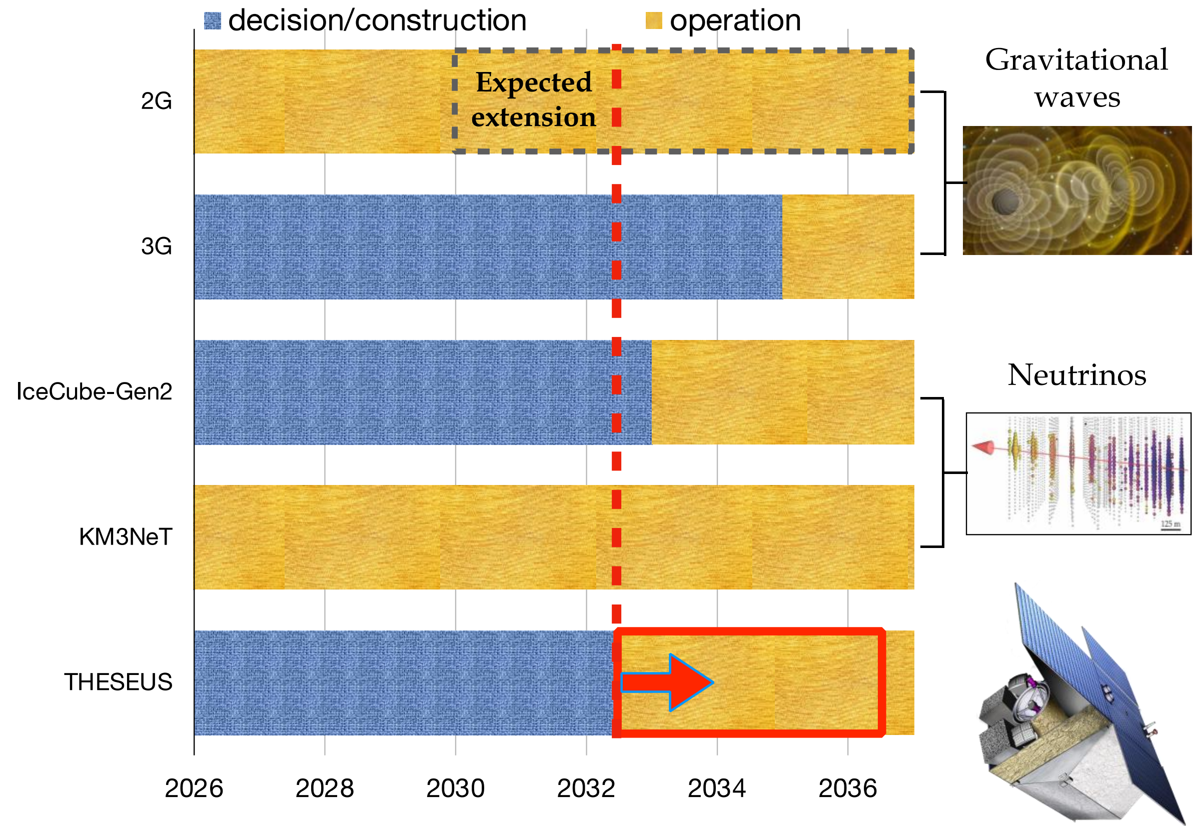
- **GRBs as key phenomenon for multi-messenger astrophysics** (GW, neutrinos): synergy with, e.g., advanced LIGO/VIRGO KAGRA, I-LIGO and, in perspective, 3G detectors (ET, CE) and possibly LISA.

- **NOTE:** further investigation of GRB impact on emergence and survivaility of life in the Universe may be of strong interst

Future GRB missions: synergies

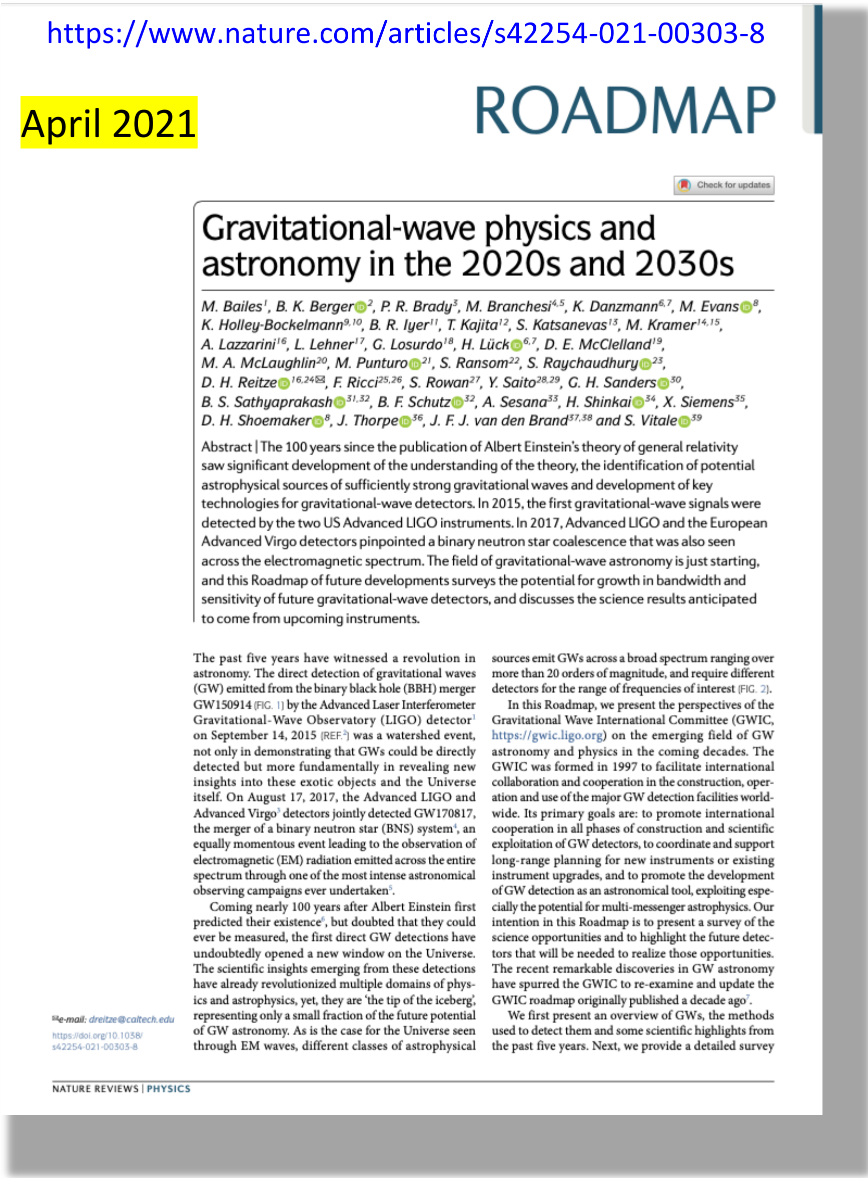
ENTERING THE GOLDEN ERA OF MULTI-MESSENGER ASTROPHYSICS

Synergy with future GW and neutrino facilities will enable transformational investigations of multi-messenger sources



https://www.nature.com/articles/s42254-021-00303-8

April 2021



ROADMAP

Check for updates

Gravitational-wave physics and astronomy in the 2020s and 2030s

M. Bailes[1], B. K. Berger[2], P. R. Brady[3], M. Branchesi[4,5], K. Danzmann[6,7], M. Evans[8], K. Holley-Bockelmann[9,10], B. R. Iyer[11], T. Kajita[12], S. Katsanevas[13], M. Kramer[14,15], A. Lazzarini[16], L. Lehner[17], G. Losurdo[18], H. Lück[6,7], D. E. McClelland[19], M. A. McLaughlin[20], M. Punturo[21], S. Ransom[22], S. Raychaudhury[23], D. H. Reitze[16,24✉], F. Ricci[25,26], S. Rowan[27], Y. Saito[28,29], G. H. Sanders[30], B. S. Sathyaprakash[31,32], B. F. Schutz[32], A. Sesana[33], H. Shinkai[34], X. Siemens[35], D. H. Shoemaker[8], J. Thorpe[36], J. F. J. van den Brand[37,38] and S. Vitale[39]

Abstract | The 100 years since the publication of Albert Einstein's theory of general relativity saw significant development of the understanding of the theory, the identification of potential astrophysical sources of sufficiently strong gravitational waves and development of key technologies for gravitational-wave detectors. In 2015, the first gravitational-wave signals were detected by the two US Advanced LIGO instruments. In 2017, Advanced LIGO and the European Advanced Virgo detectors pinpointed a binary neutron star coalescence that was also seen across the electromagnetic spectrum. The field of gravitational-wave astronomy is just starting, and this Roadmap of future developments surveys the potential for growth in bandwidth and sensitivity of future gravitational-wave detectors, and discusses the science results anticipated to come from upcoming instruments.

The past five years have witnessed a revolution in astronomy. The direct detection of gravitational waves (GW) emitted from the binary black hole (BBH) merger GW150914 (FIG. 1) by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detector[1] on September 14, 2015 (REF.[2]) was a watershed event, not only in demonstrating that GWs could be directly detected but more fundamentally in revealing new insights into these exotic objects and the Universe itself. On August 17, 2017, the Advanced LIGO and Advanced Virgo[3] detectors jointly detected GW170817, the merger of a binary neutron star (BNS) system[4], an equally momentous event leading to the observation of electromagnetic (EM) radiation emitted across the entire spectrum through one of the most intense astronomical observing campaigns ever undertaken[5].

Coming nearly 100 years after Albert Einstein first predicted their existence[6], but doubted that they could ever be measured, the first direct GW detections have undoubtedly opened a new window on the Universe. The scientific insights emerging from these detections have already revolutionized multiple domains of physics and astrophysics, yet, they are 'the tip of the iceberg', representing only a small fraction of the future potential of GW astronomy. As is the case for the Universe seen through EM waves, different classes of astrophysical sources emit GWs across a broad spectrum ranging over more than 20 orders of magnitude, and require different detectors for the range of frequencies of interest (FIG. 2).

In this Roadmap, we present the perspectives of the Gravitational Wave International Committee (GWIC, https://gwic.ligo.org) on the emerging field of GW astronomy and physics in the coming decades. The GWIC was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major GW detection facilities worldwide. Its primary goals are: to promote international cooperation in all phases of construction and scientific exploitation of GW detectors, to coordinate and support long-range planning for new instruments or existing instrument upgrades, and to promote the development of GW detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics. Our intention in this Roadmap is to present a survey of the science opportunities and to highlight the future detectors that will be needed to realize those opportunities. The recent remarkable discoveries in GW astronomy have spurred the GWIC to re-examine and update the GWIC roadmap originally published a decade ago[7].

We first present an overview of GWs, the methods used to detect them and some scientific highlights from the past five years. Next, we provide a detailed survey

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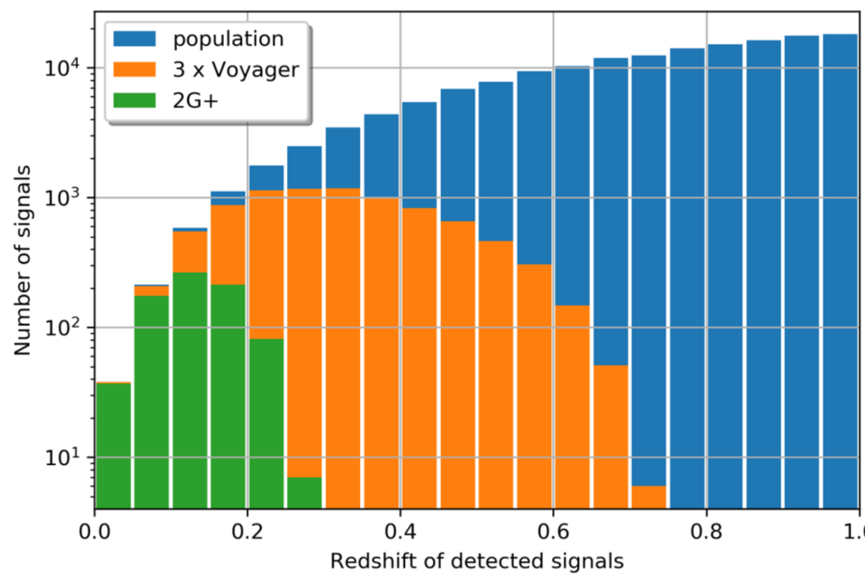
https://doi.org/10.1038/s42254-021-00303-8

GWIC Roadmap and Letter of Endorsement from EGO/virgo clearly mention further upgrades of 2G to bridge in the 3G era

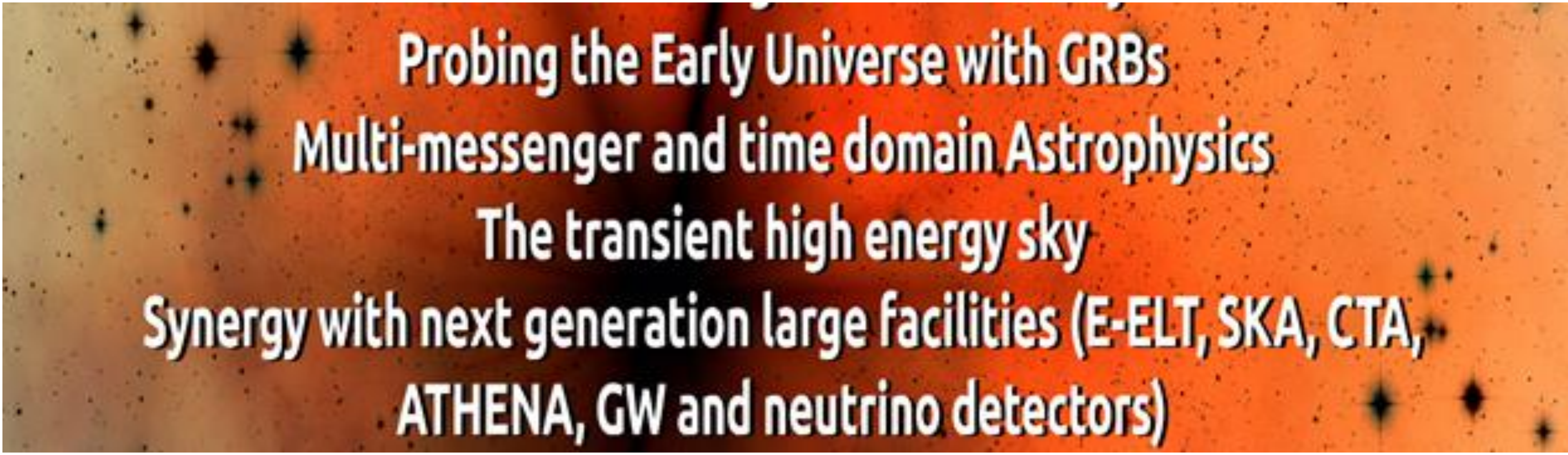


NS-NS merger detection efficiency with 2G and 2G++ will sensibly improve at z>0.1 with 2G++

Future missions (early / mid '20s)

- **SVOM (2022-):** prompt emission down to 5 keV and up to MeVs, prompt follow-up with small X-ray and O/UV telescopes, dedicated on-ground telescopes
- **Einstein Probe (2022-):** very good sensitivity, arcmin location accuracy, operating only in the very soft X-ray energy band (0.3 - 5 keV), 1.4 sr FOV, follow-up in X-rays
- **GECAM (2020)**: all-sky FOV, 6 keV – few MeVs, source location a few degrees; **POLAR-2 (2024?):** improved polarimetry of prompt emission;
- **HERMES and other nano-satellite programs (2022-):** small detectors, energy band > 10 keV, potentially very good location accuracy for mid-bright GRBs, very good timing, depends on follow-up from ground
- **eXTP (2025?)** China-Europe, monitoring in 2-50 keV on 4-5 sr, X-ray followp-up with deep spectroscopy and polarimetric sensitivity

Future missions (late‘20s and ‘30s)

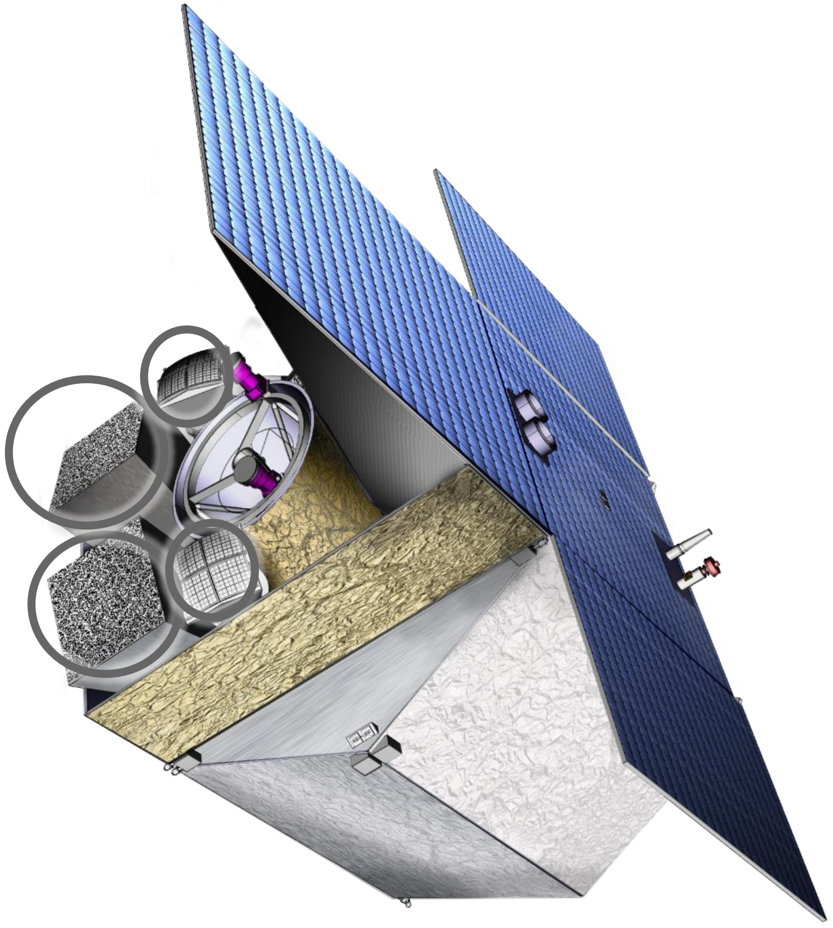


- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (under study for NASA decadal survey**), Gamow Explorer** (under study for NASA MIDEX**): prompt emission down to soft X-rays, source location accuracy of few arcmin**, **prompt follow-up with NIR telescope**, **on-board REDSHIFT**

Future missions: the case of THESEUS

THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**



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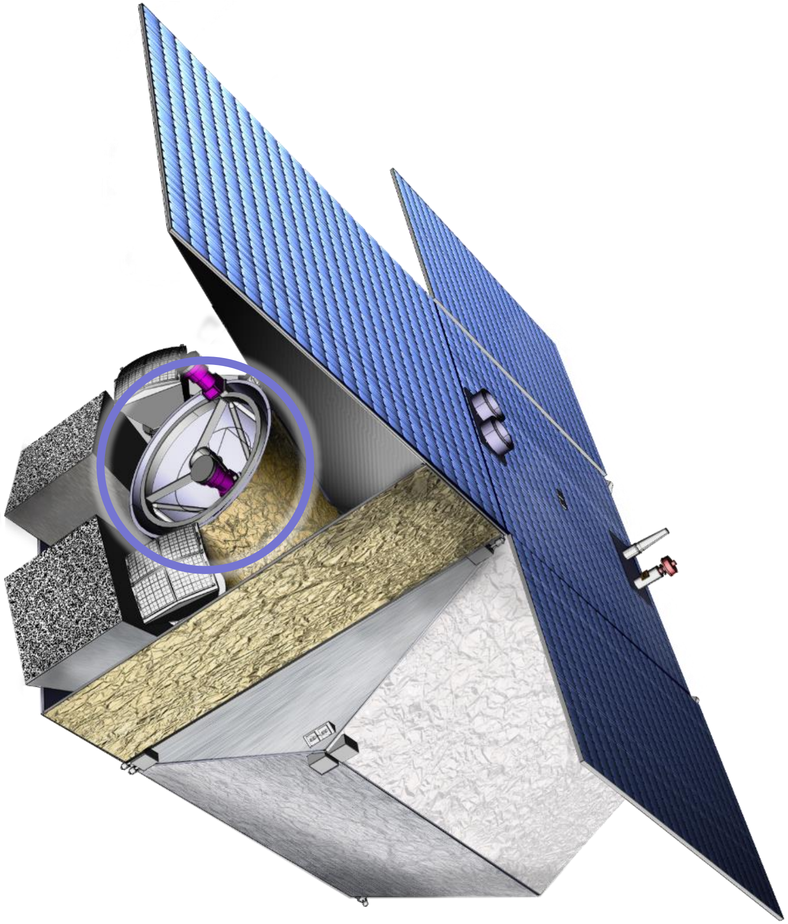
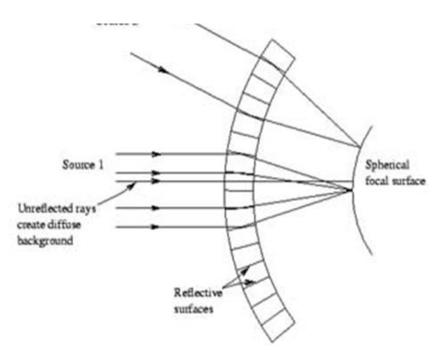
Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**

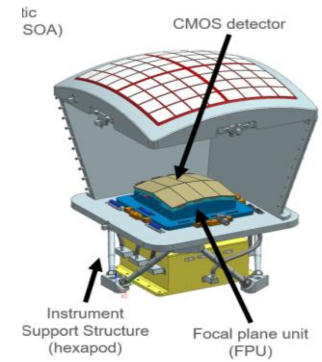
On-board **autonomous fast follow-up** in optical/NIR, arcsec location and **redshift measurement** of detected GRB/transients



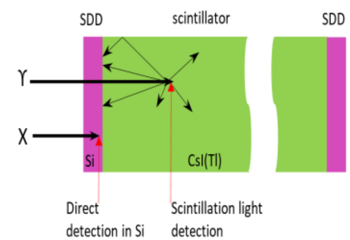
Future missions: the case of THESEUS

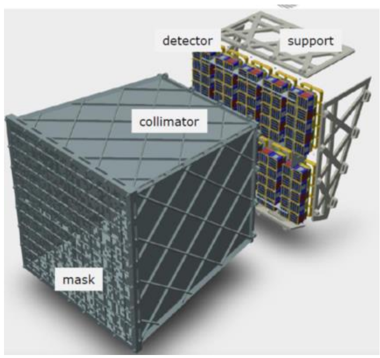
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′



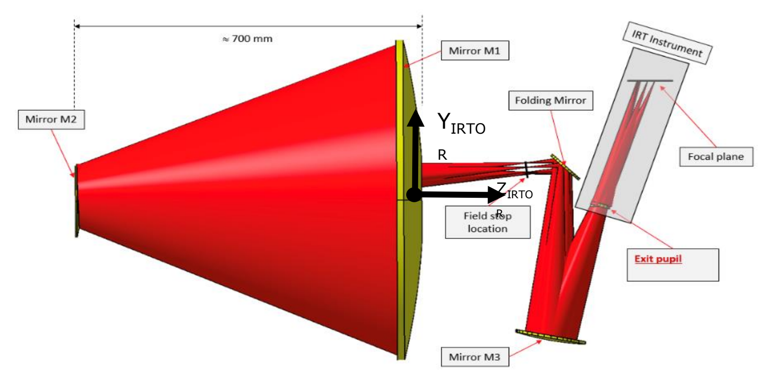


- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy

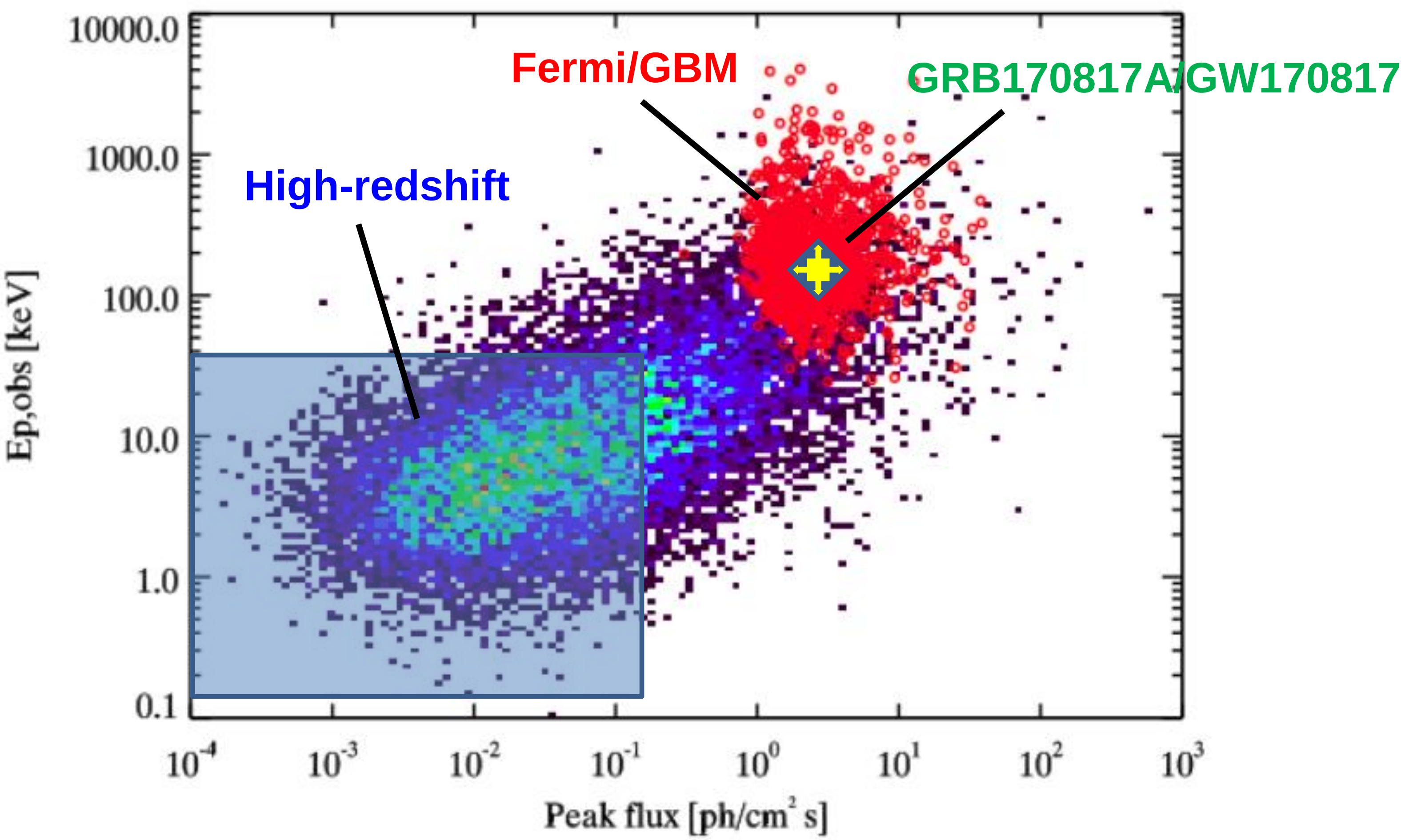




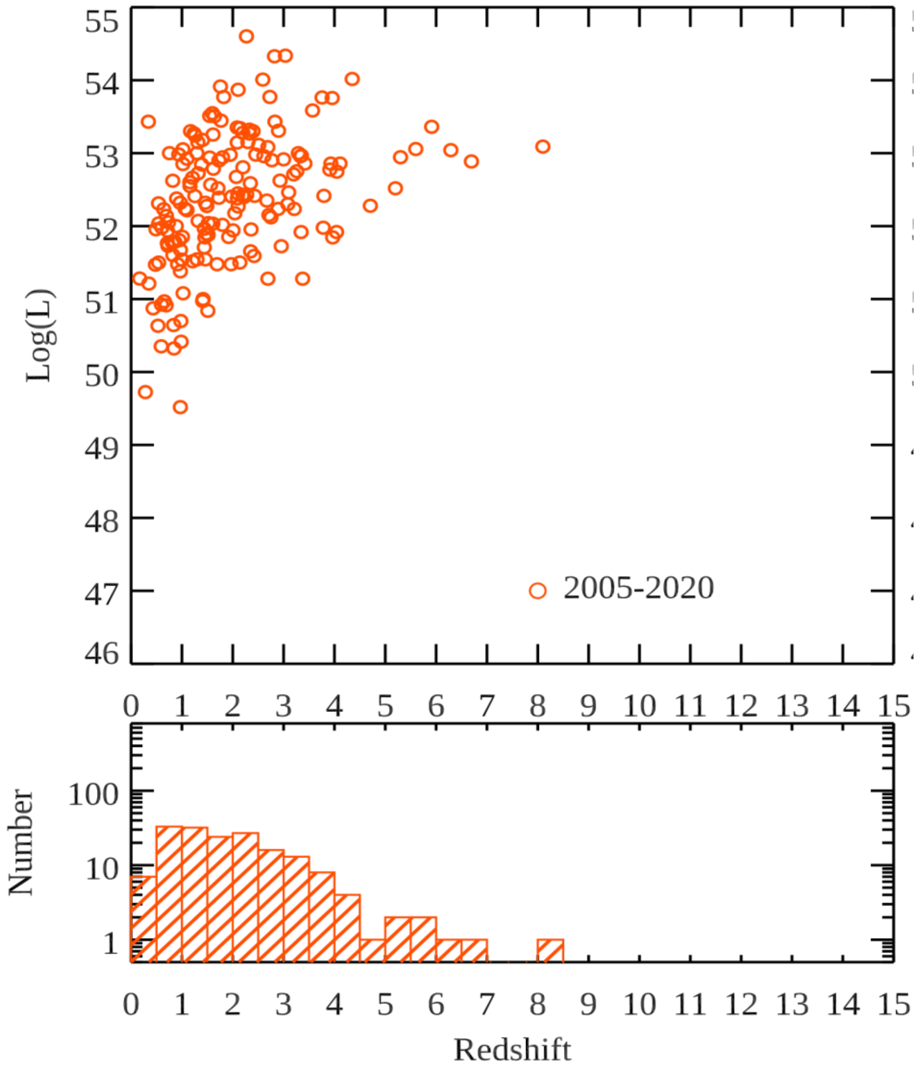
- **InfraRed Telescope (IRT):** a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 15′x15′ FOV, with both imaging and moderate resolution spectroscopy capabilities

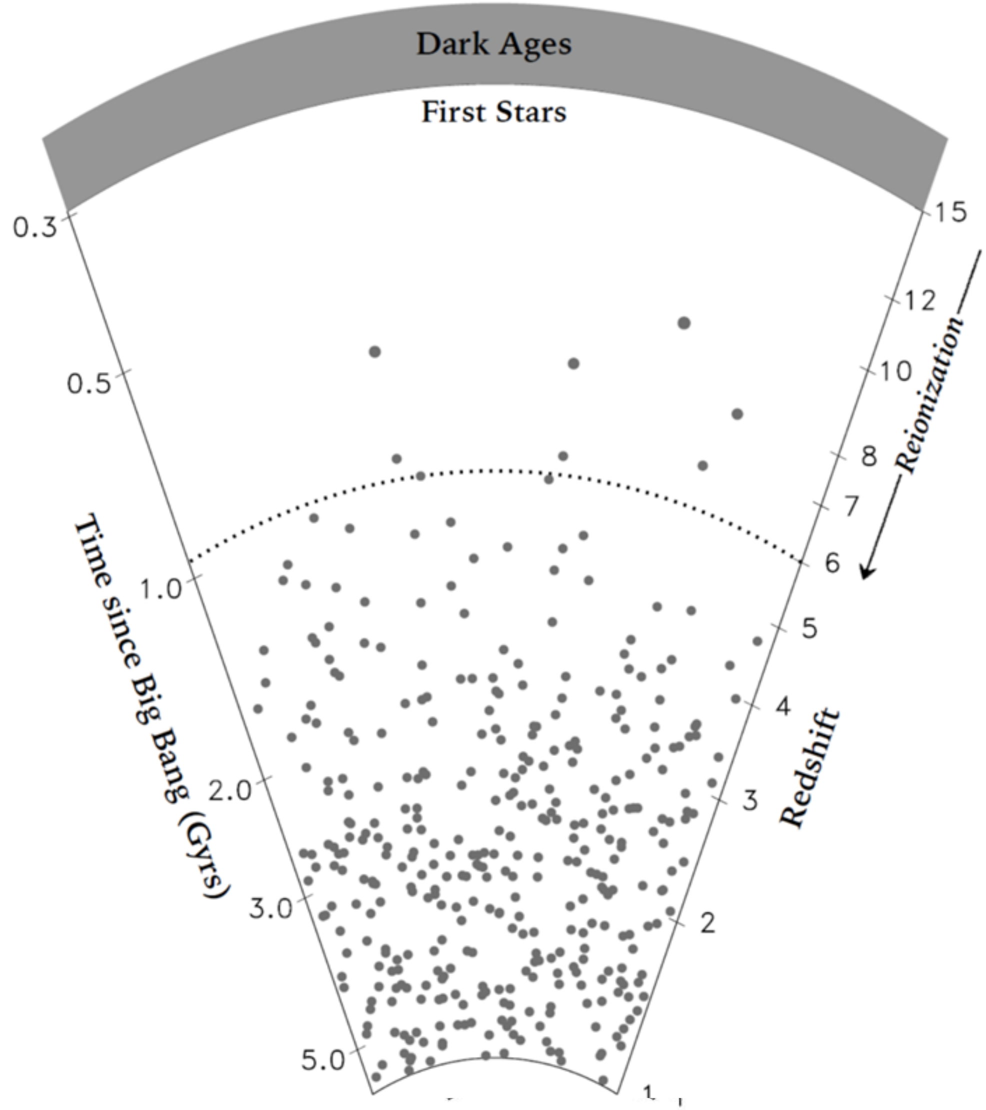


THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), providing accurate location and redshift for a large fraction of them



Shedding light on the early Universe with GRBs





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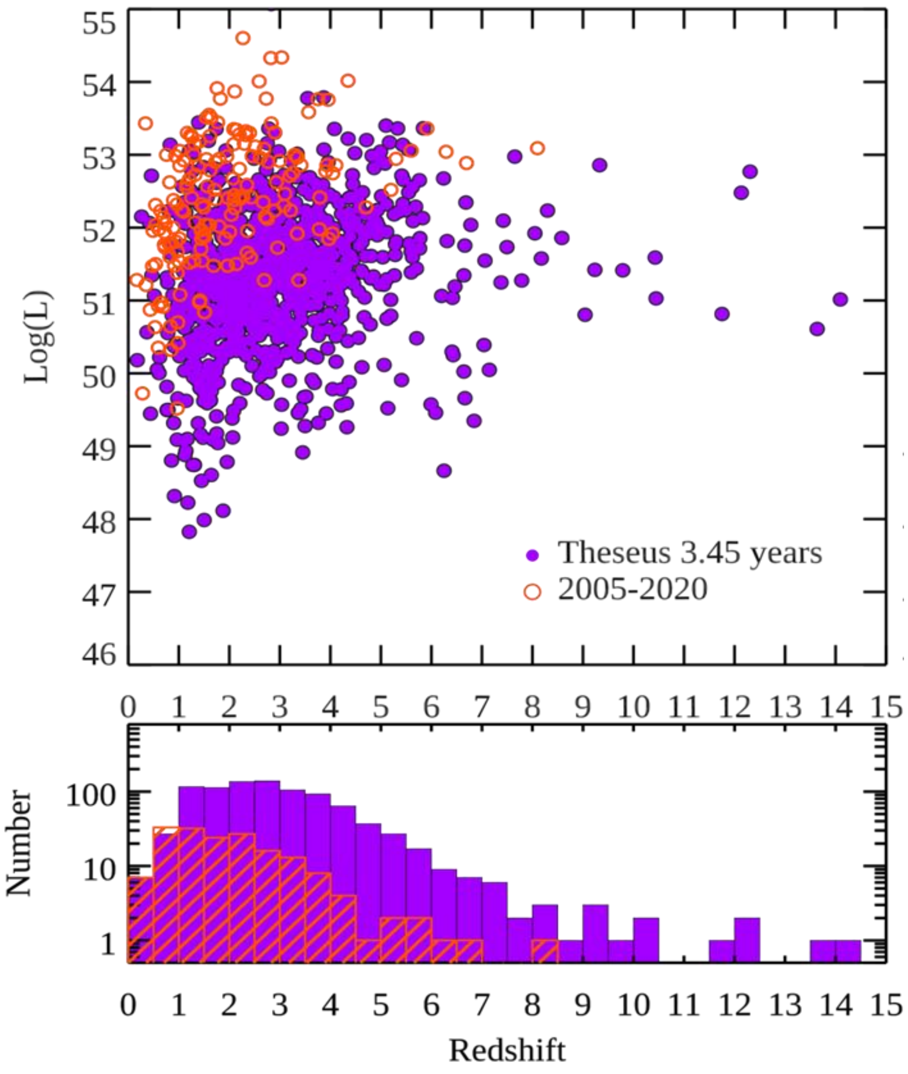
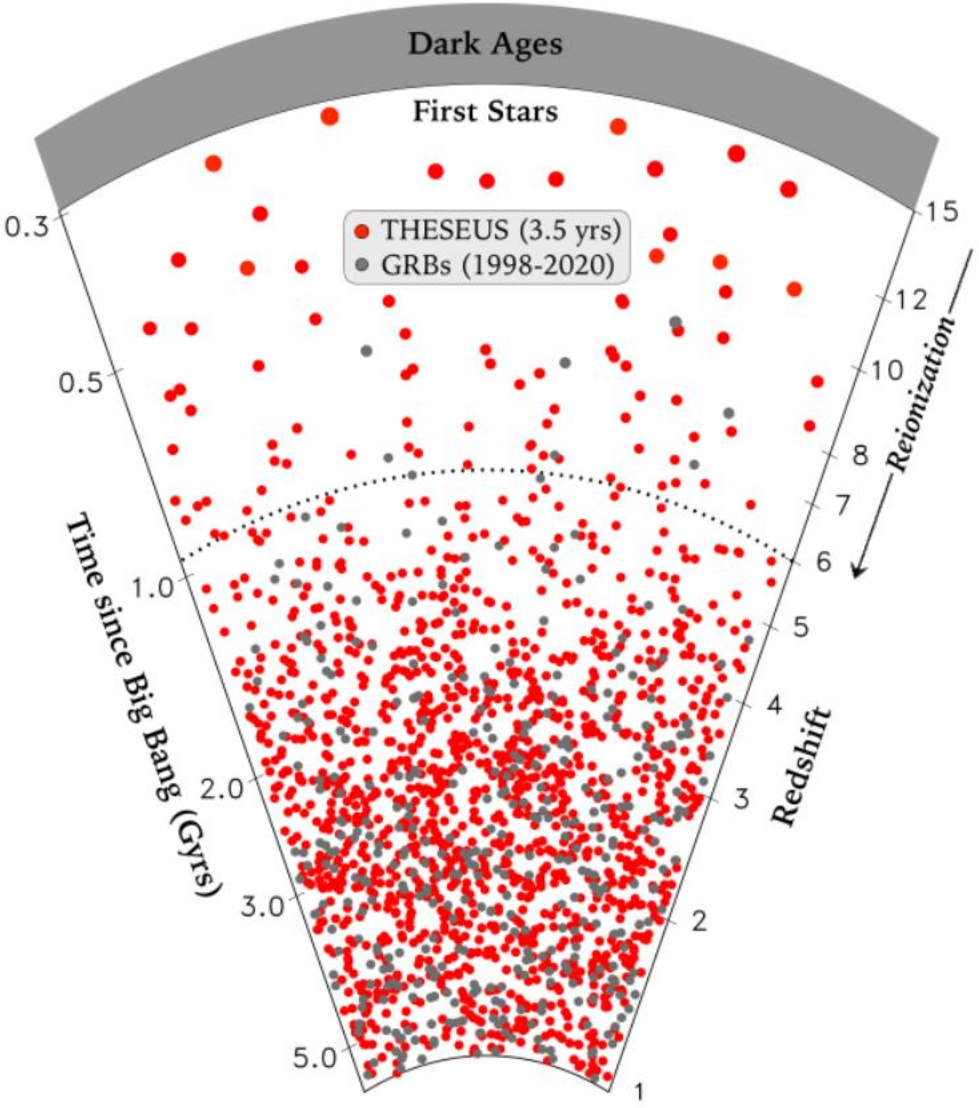
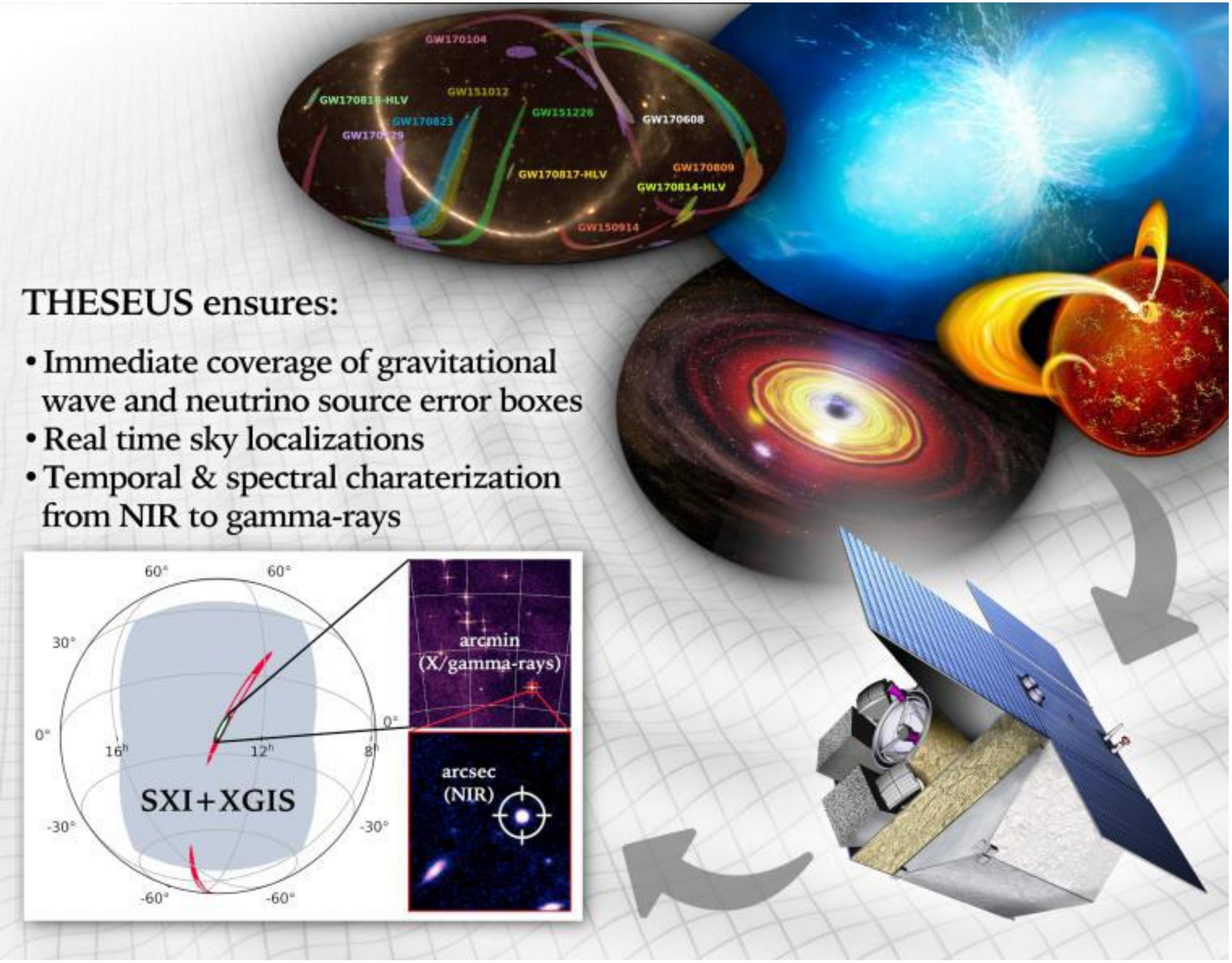
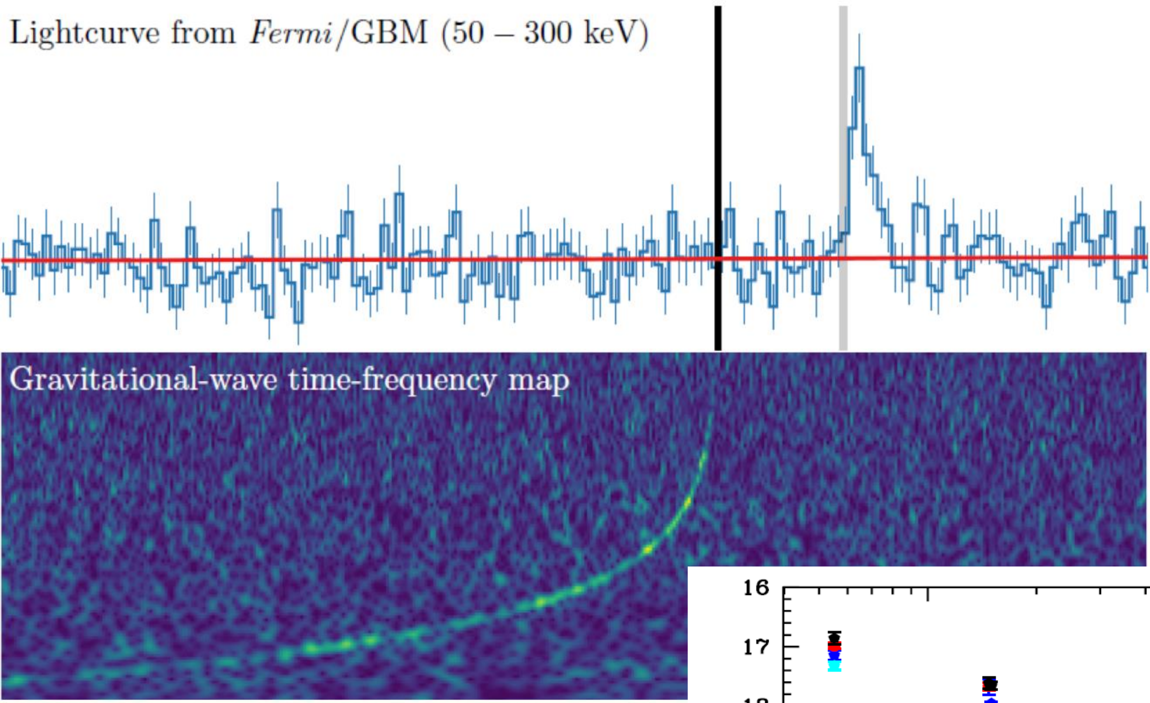


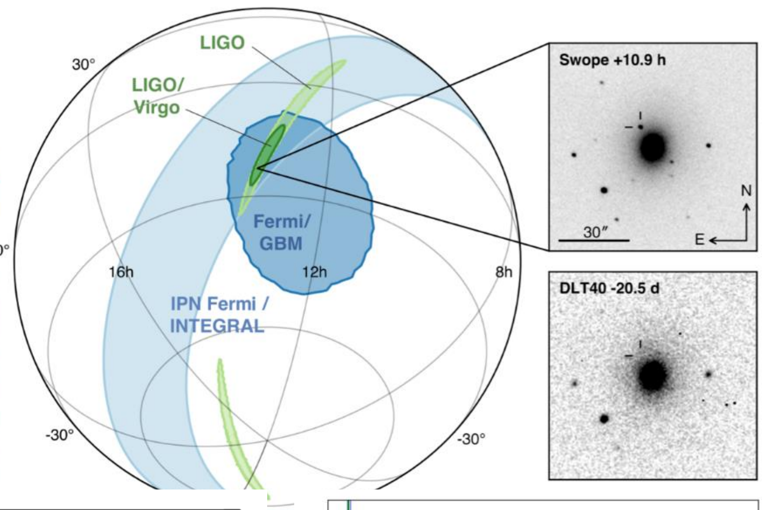


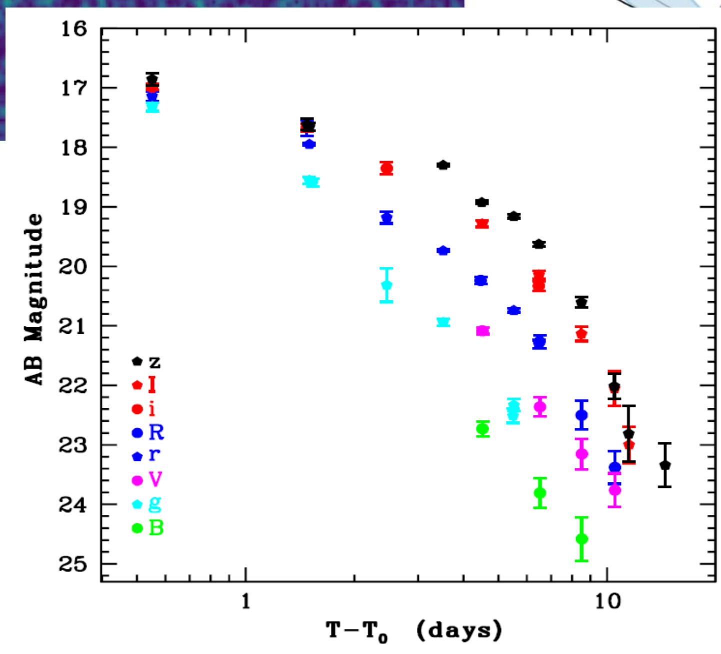
Exploring the multi-messenger transient sky

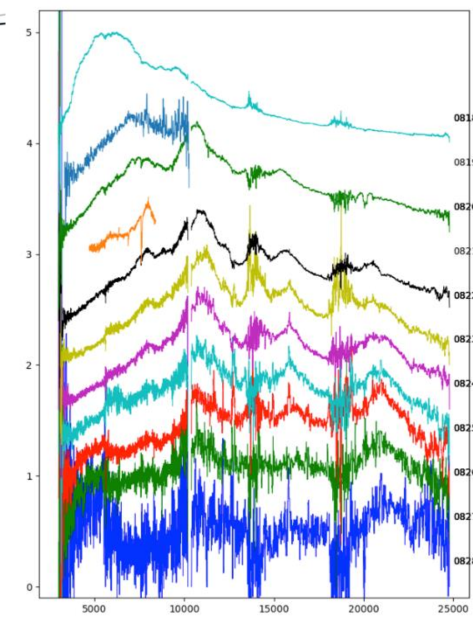


LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars









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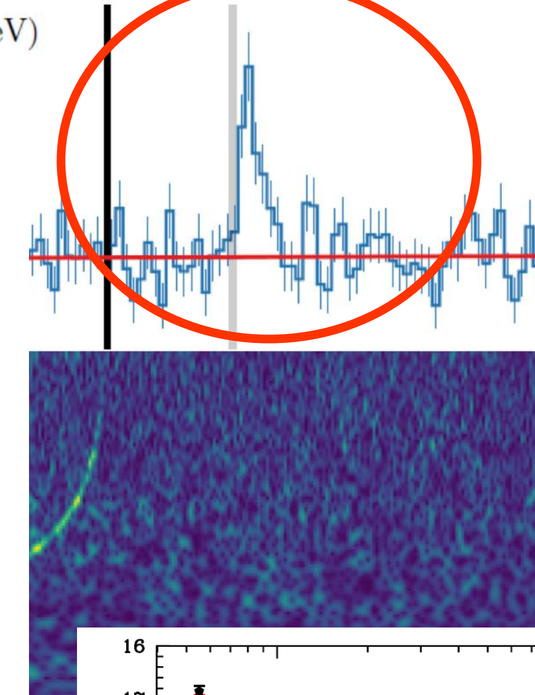
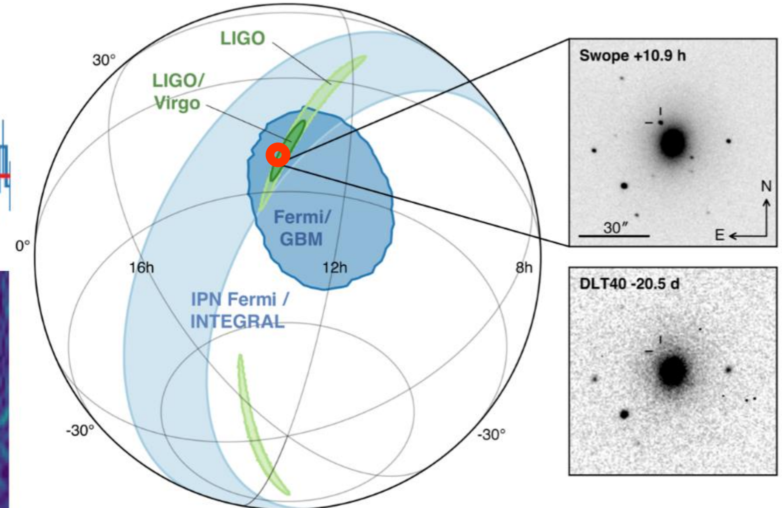
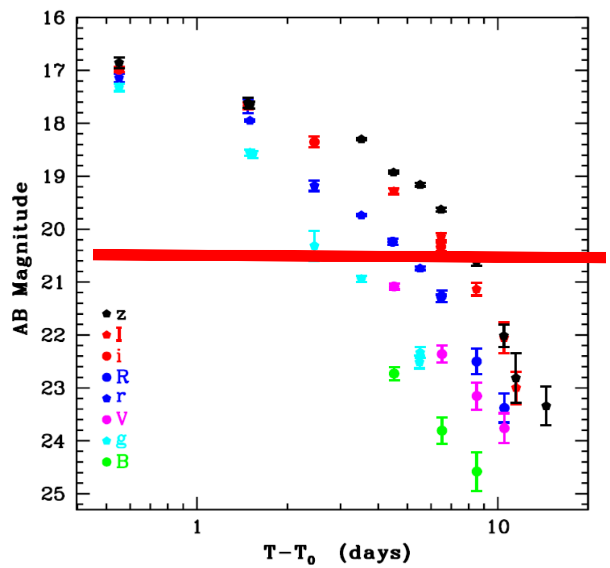
Lightcurve from *Fermi*/GBM (50 – 300 keV)

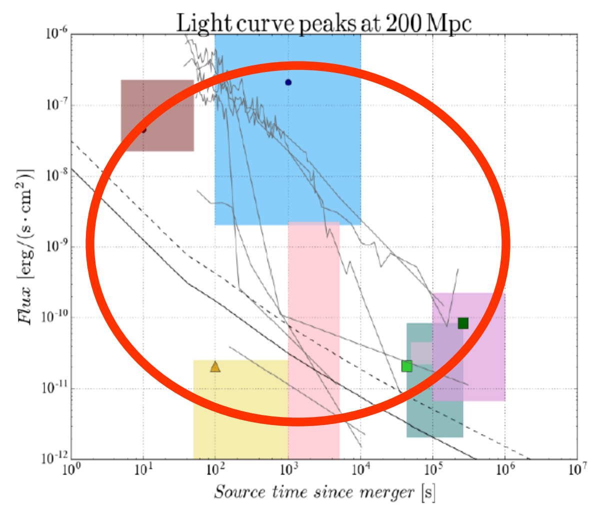


THESEUS:

- ✓ short GRB detection over large FOV with arcmin localization
- ✓ Kilonova detection, arcsec localization and characterization
- ✓ Possible detection of weaker isotropic X-ray emission



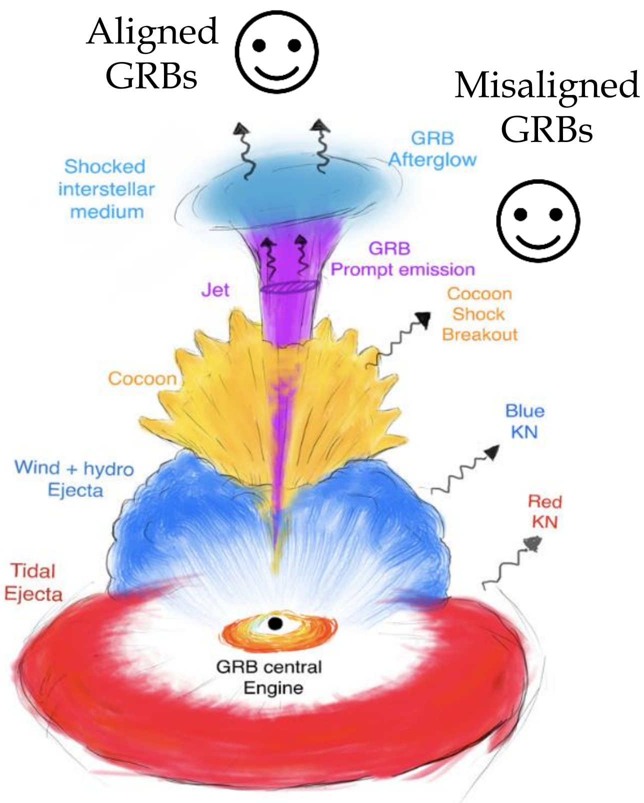




Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A



Expected rates:

THESEUS + 2G++:

- ~10 yr aligned+misaligned collimated short GRBs
- ~50/yr isotropic X-ray transients from possible NS-NS merger remnant

Low redshifts events: detailed study of kilonovae, jet structure, remnant nature

Multi-messenger science with THESEUS

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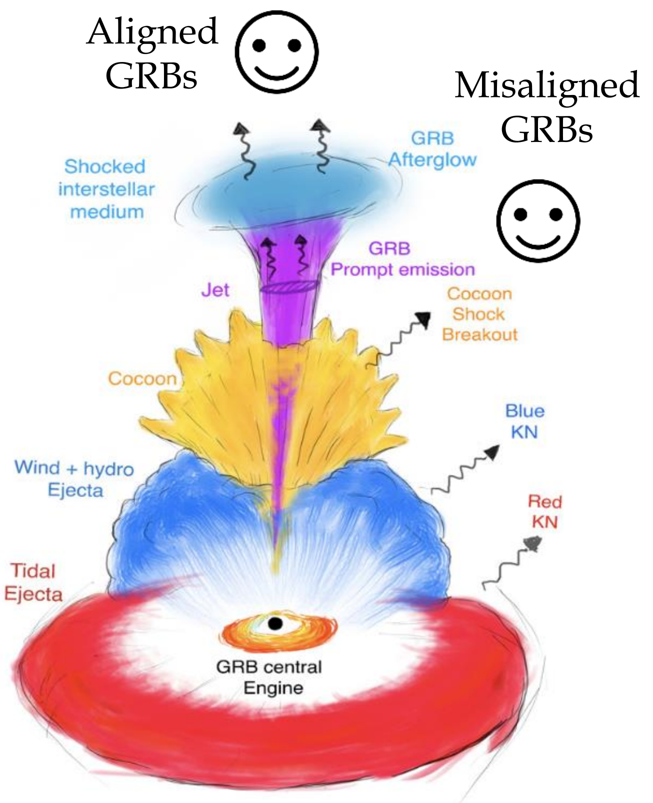
Lessons from GRB170817A



Expected rates:

THESEUS + 3G:

- ~50 aligned+misaligned short GRBs
- ~200 X-ray transients

Higher redshift events – X/γ is likely only route to EM detection: larger statistical studies including source evolution, probe of dark energy and test modified gravity on cosmological scales

Multi-messenger science with next generation GRB missions

Main topics	THESEUS role	What will we learn?
Physics of compact binaries	short GRB+GW detection and localization	**relativistic jet formation mechanism/efficiency, remnant nature, NS EoS**
Relativistic plasma	accurate sky coordinates of GW events associated with misaligned afterglows	**Jet propagation, jet structure and its universality, NSBH vs NSNS**
Physics of kilonova	accurate sky coordinates of GW events	**Role of NS-NS/NSBH in r-process element nucleosynthesis**
Fundamental physics	Identify counterparts for events at z>0.3	**Tests of modified gravity theories**
Cosmology	accurate sky coordinates of GW events allowing redshift measurement	**Independent H_0 measure**