Multi-messenger astrophysics and cosmology with next-generation GRB missions

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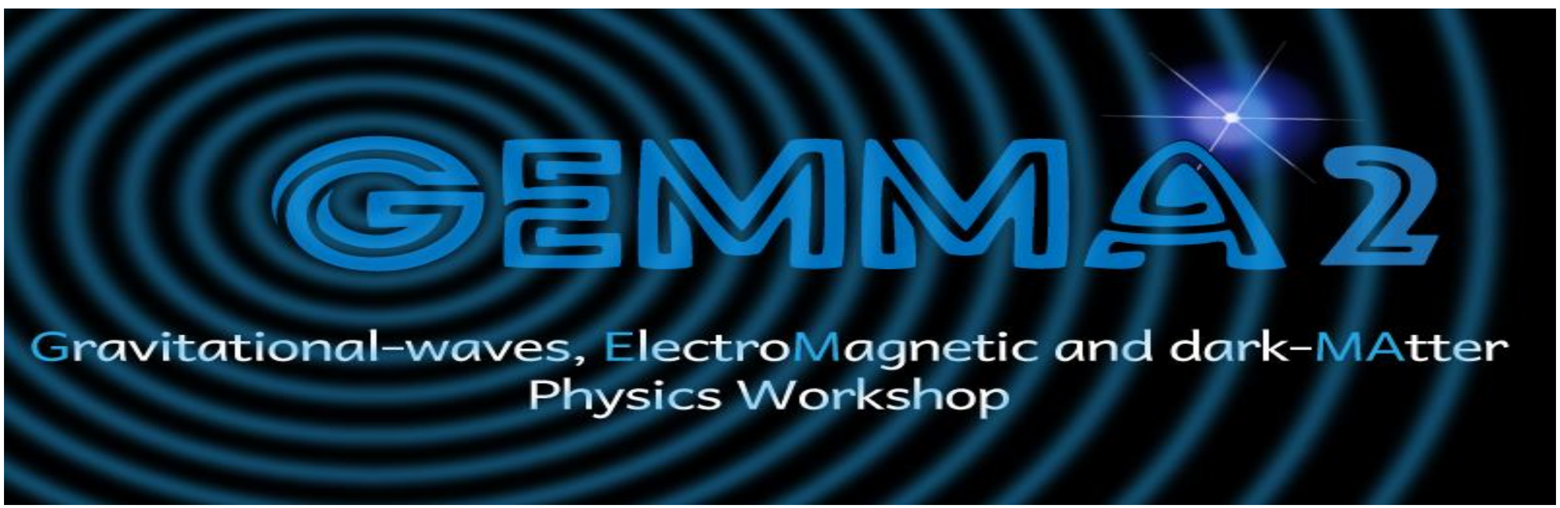
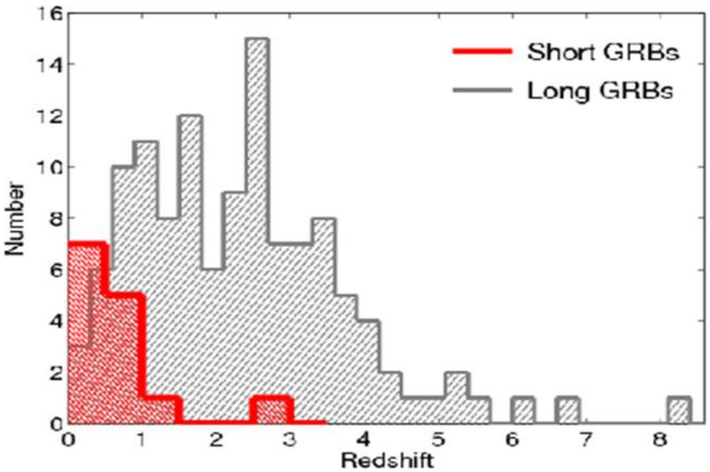
theseus M7
transient high energy sky and early universe surveyor

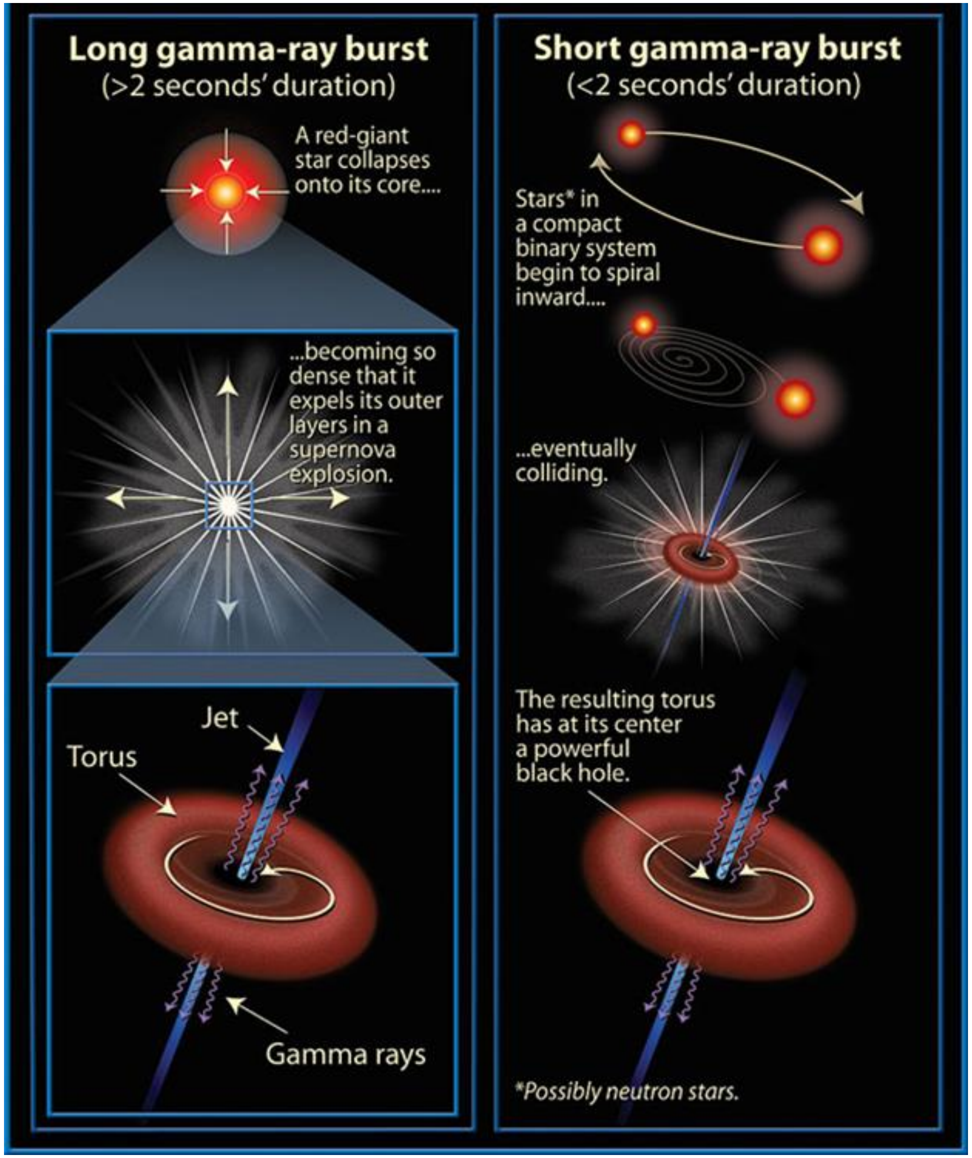


Gamma-Ray Bursts: the most extreme phenomena in the Universe



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

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



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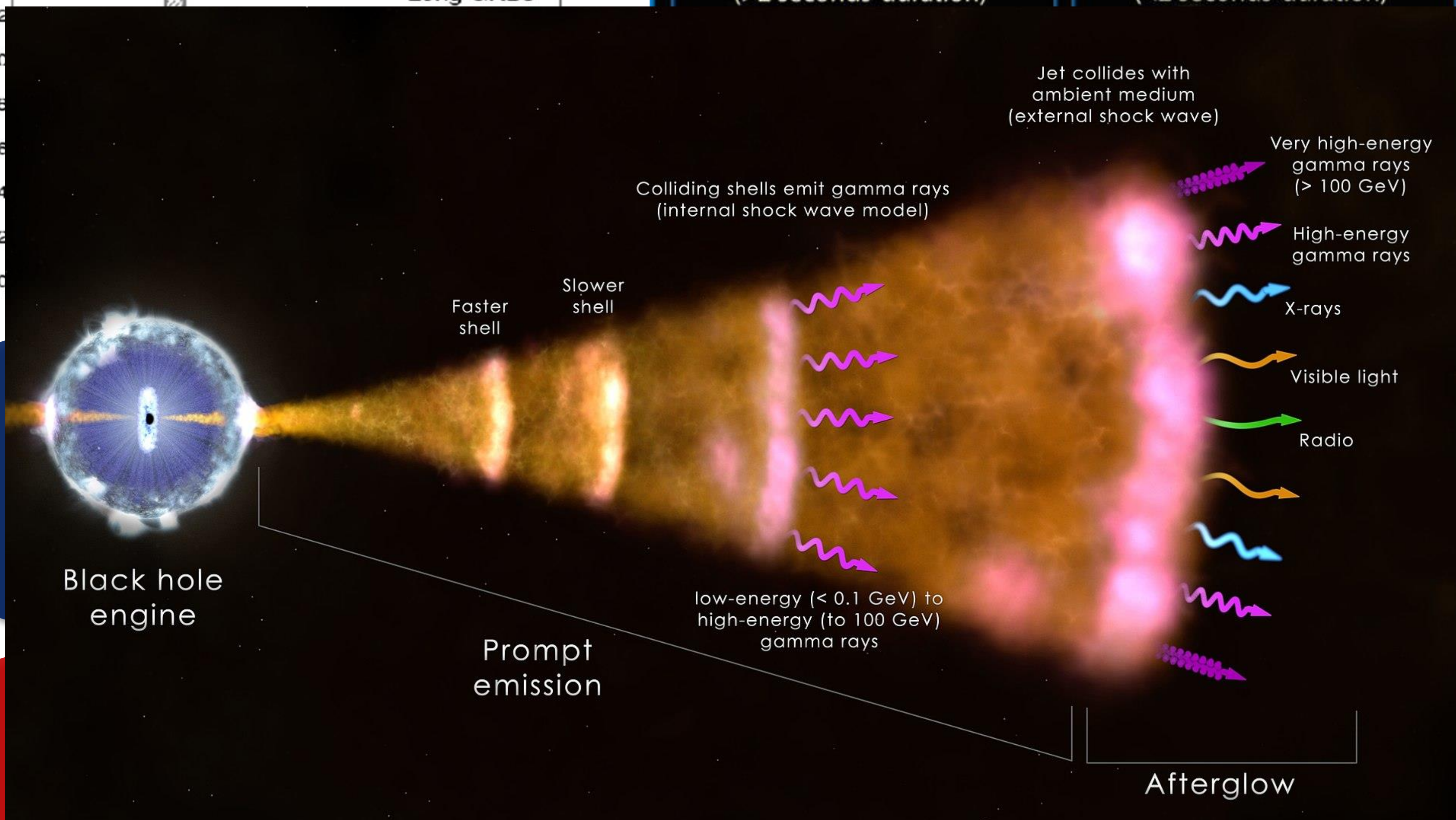


GW sources

The ESA Cosmic Vision Programme

❖ Selected missions

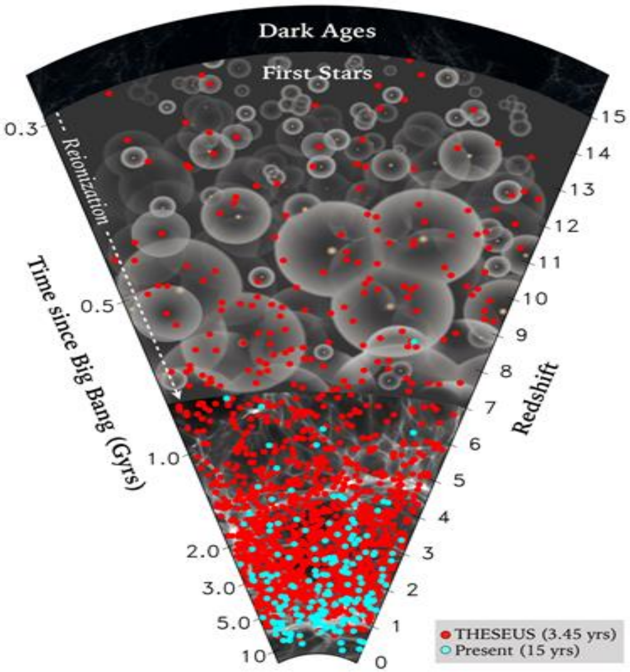
- S1: CHEOPS (exoplanets, 2019)
- M1: Solar Orbiter (solar astrophysics, 2020)
- M2: Euclid (cosmology, 2023)
- L1: JUICE (exploration of Jupiter system, 2023)
- S2 (ESA-CAS): SMILE (solar wind-magneto/ionosphere, 2025)
- M3: PLATO (exoplanets, 2026)
- F1: COMET INTERCEPTOR (solar system origin, 2026)
- M4: ARIEL (exoplanets, 2028)
- F2: ARRAKIHS (cosmology through faint galaxies, 2030)
- M5: ENVISION (exploration of Venus, 2032)
- L2: LISA (gravitational wave observatory, 2035)
- L3: NEWATHENA (X-ray obs., cosmology, MMA, 2037)

The ESA Cosmic Vision Programme

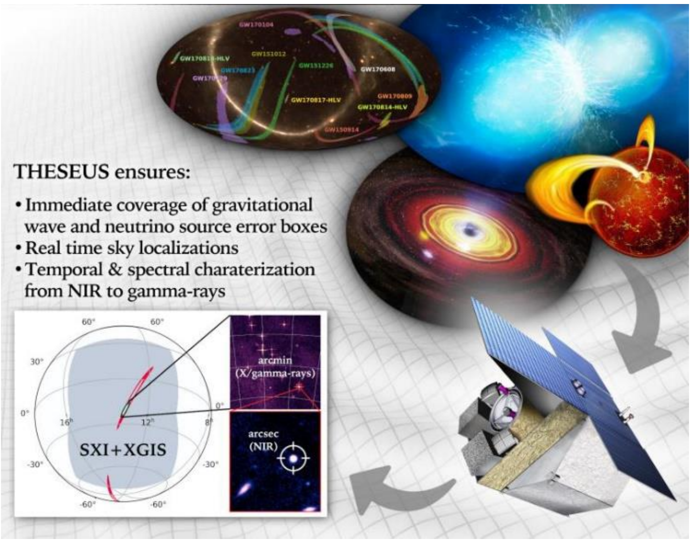
Resonant keywords: cosmology (dark energy, dark matter, re-ionization, structures formation and evolution), **fundamental physics** (relativity, quantum gravity, QCD, gravitational wave universe), **life** (exoplanets formation + evolution + census, solar system exploration)

Next generation GRB missions ('30s)

- Probe the **early Universe (first stars, first galaxies, cosmic reionization)**, by unveiling and exploiting the population of **extremely distant cosmic Gamma - Ray Bursts (GRB)**



- Provide a **fundamental contribution to multi-messenger astrophysics through GRB produced by merging neutron stars** and other X/gamma-ray transient sources

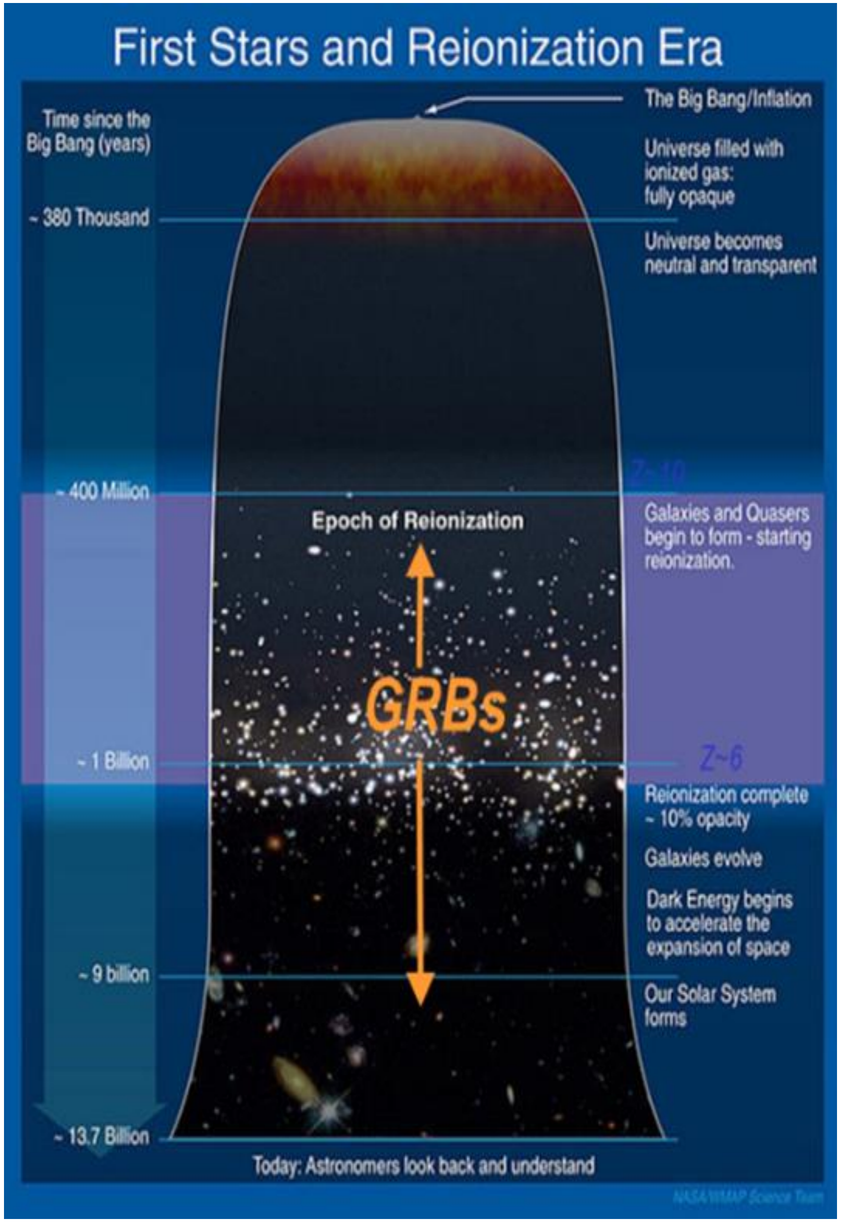


Shedding light on the early Universe with GRBs

- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays

- **Redshift distribution** extending at least to z ~9 and association with exploding massive stars

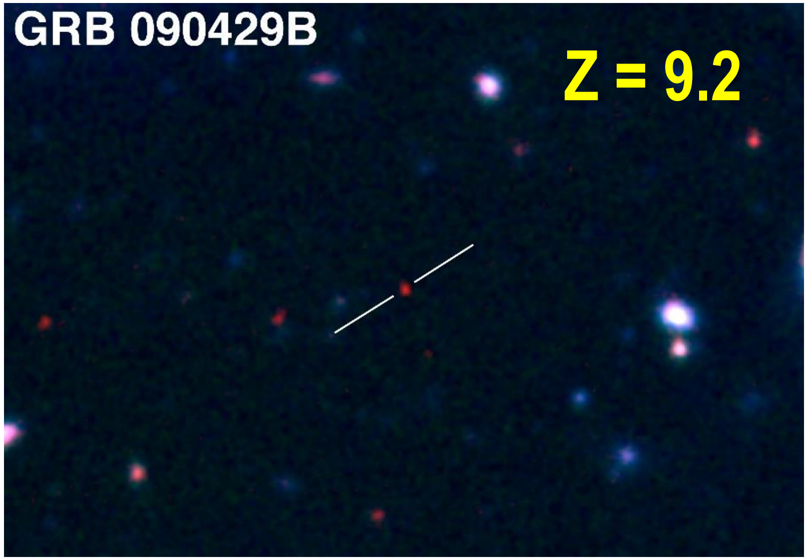
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars

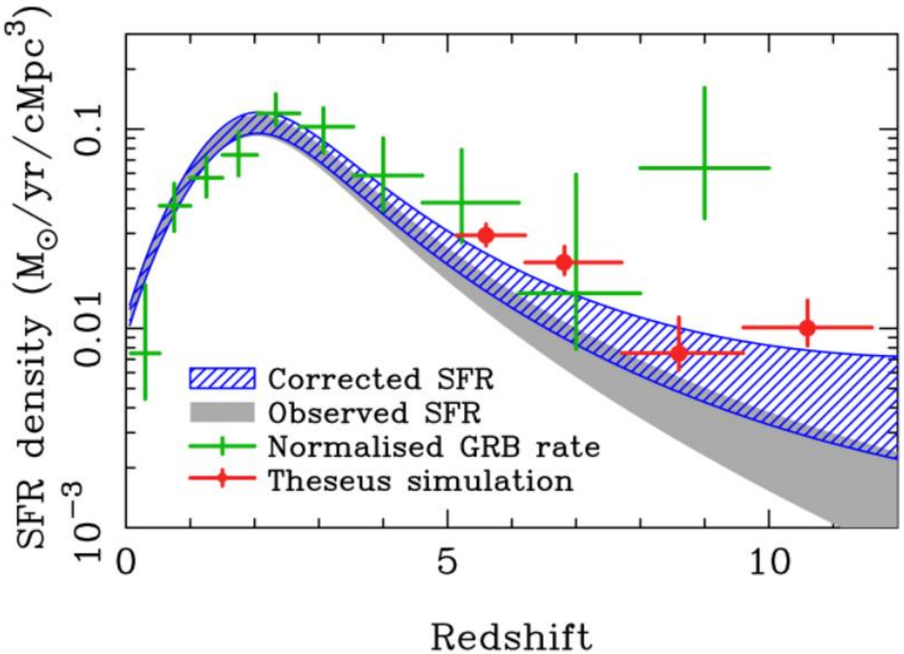


Shedding light on the early Universe with GRBs

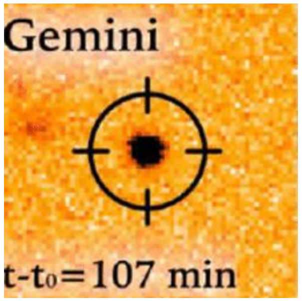
A statistical sample of high–z GRBs can provide fundamental information:

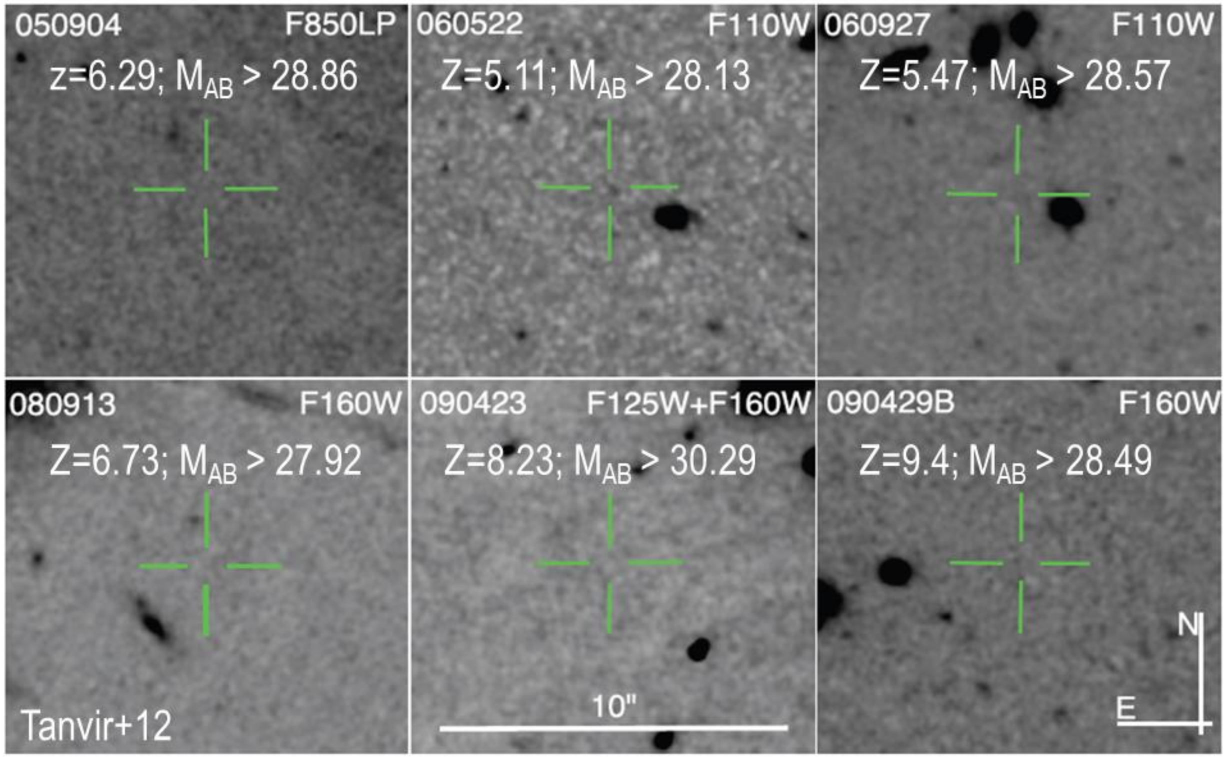
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys
- directly (or indirectly) detect the **first population of stars (pop III)**





Detecting and studying primordial invisible galaxies

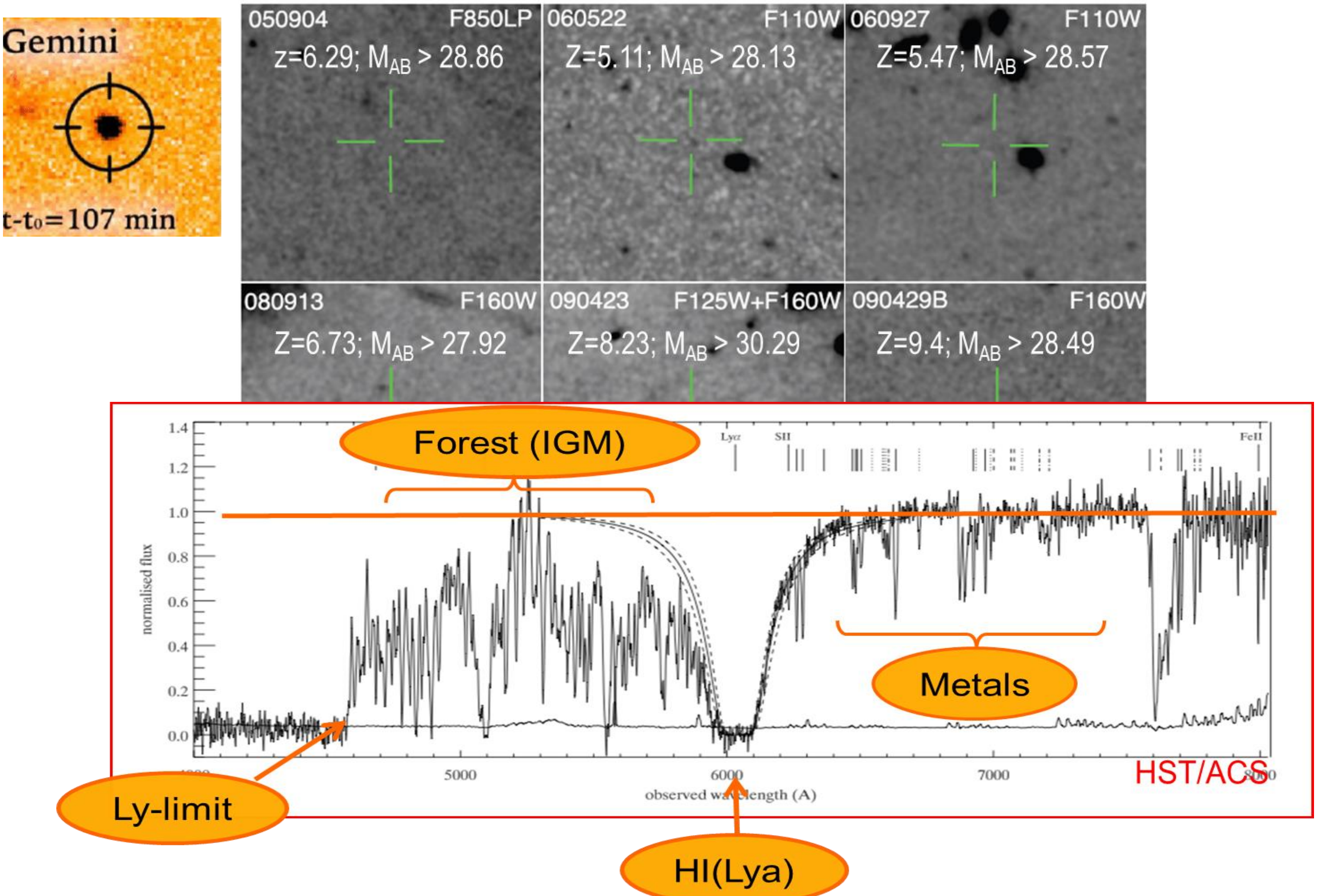




Robertson&Ellis12

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

Detecting and studying primordial invisible galaxies



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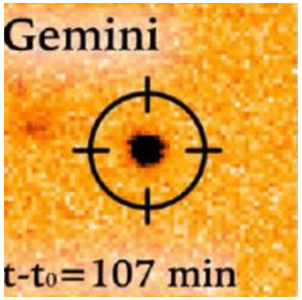
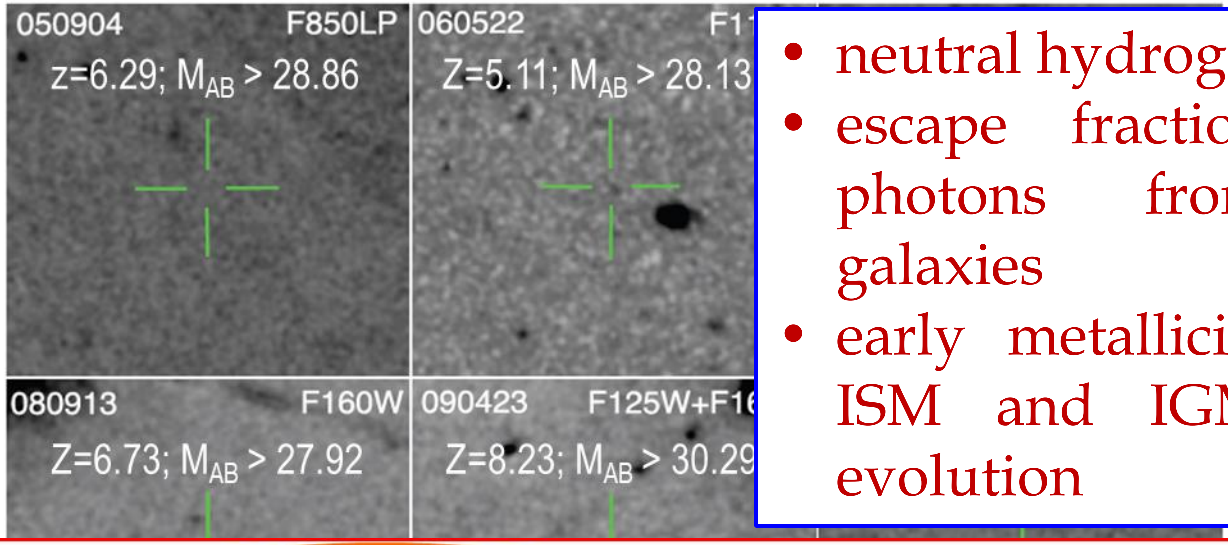
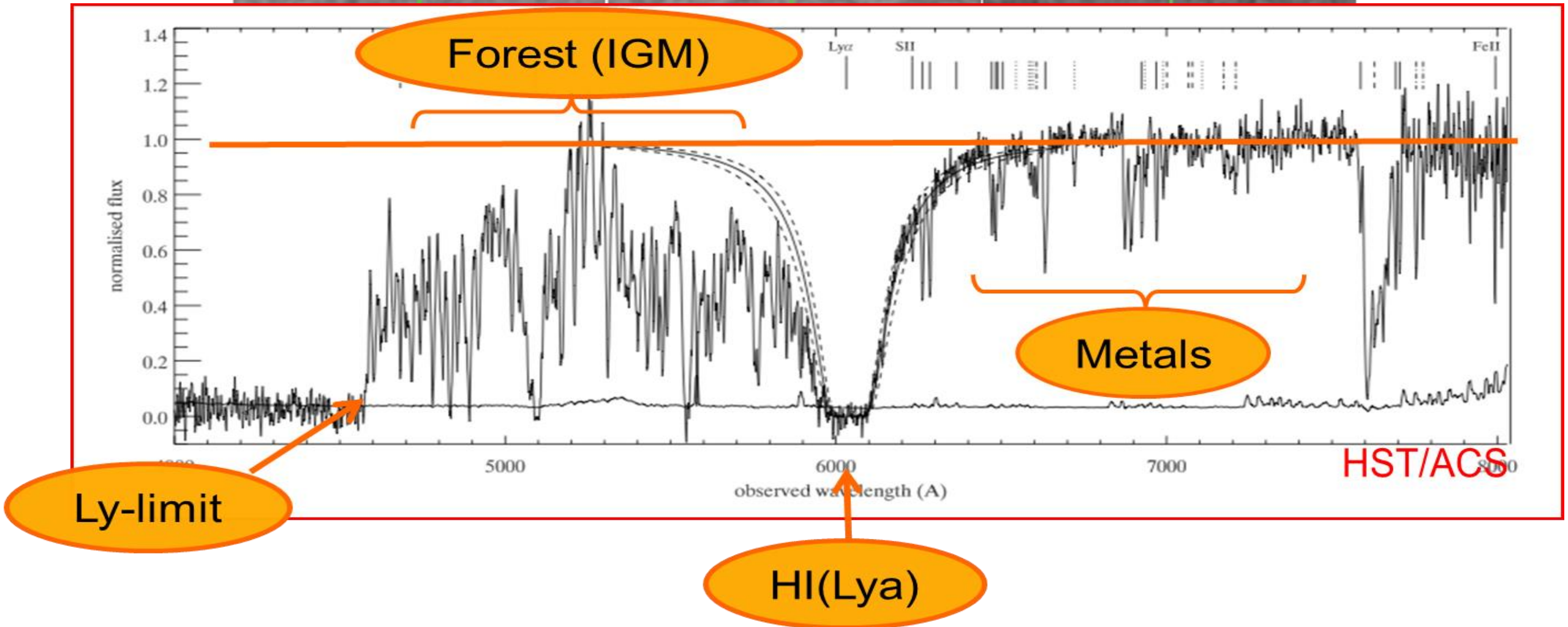




- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution



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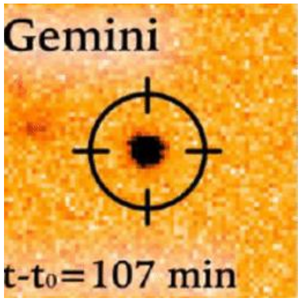
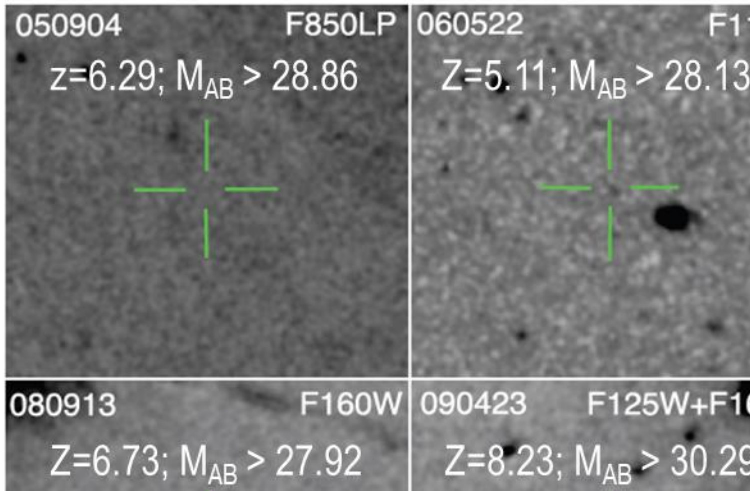
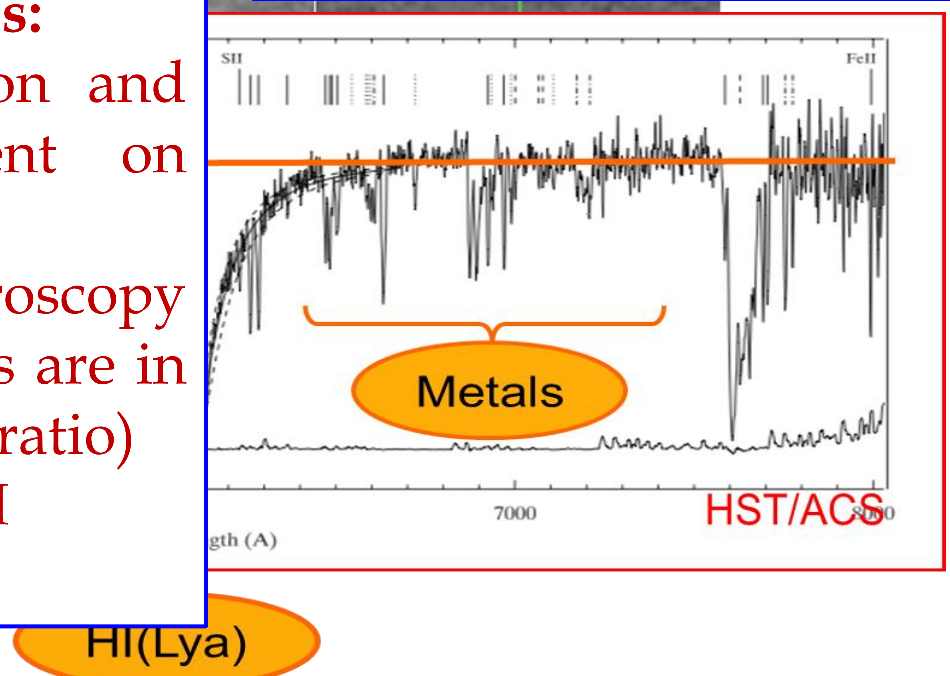




- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

Beyond even JWST capabilities:

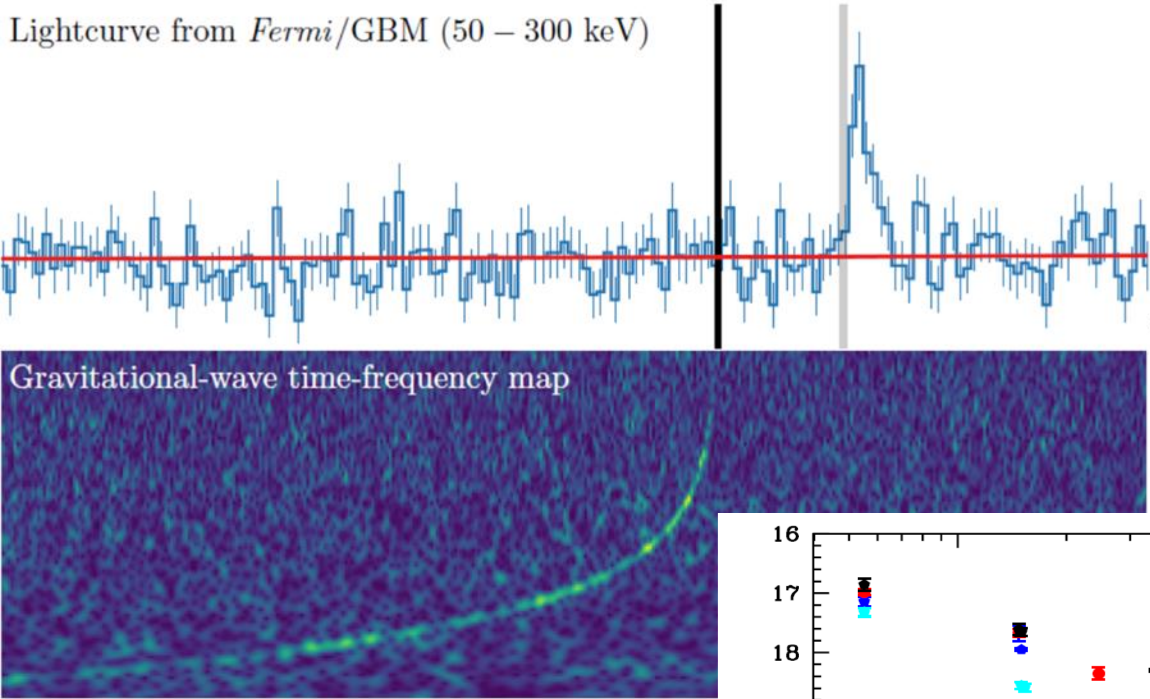
- Primordial galaxies detection and characterization Independent on mass and luminosity
- Allow absorption spectroscopy (needed because most metals are in neutral gas and and for dust ratio)
- Properties of primordial IGM
- Targets for JWST

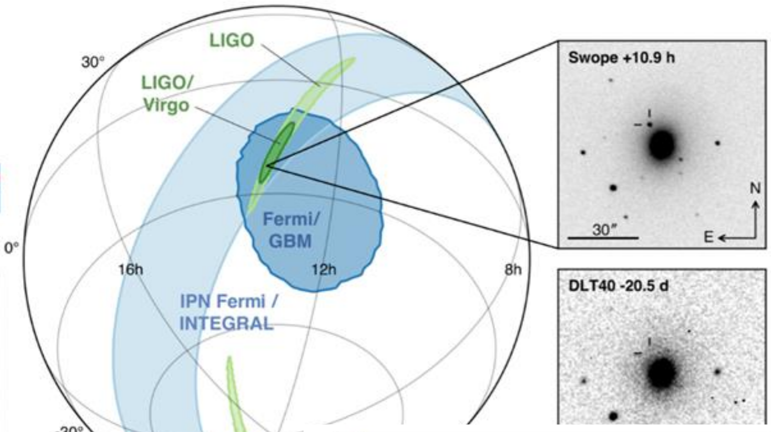


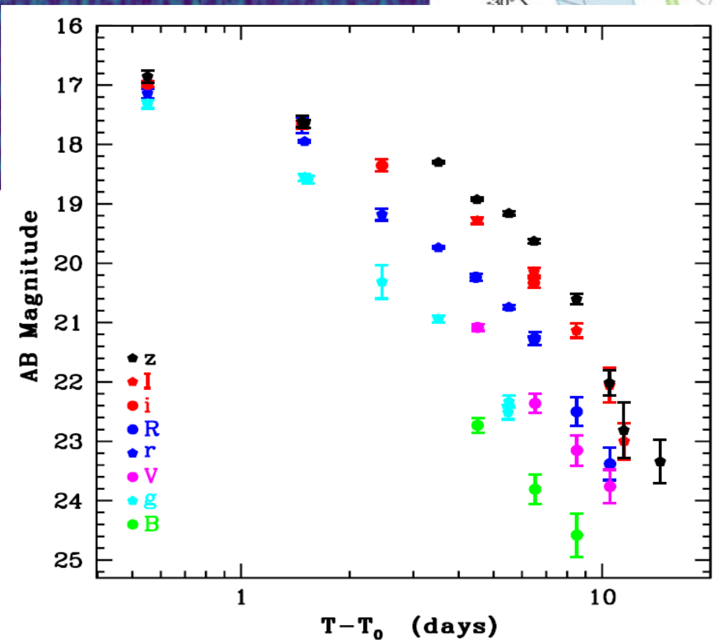
GRBs and multi-messenger astrophysics

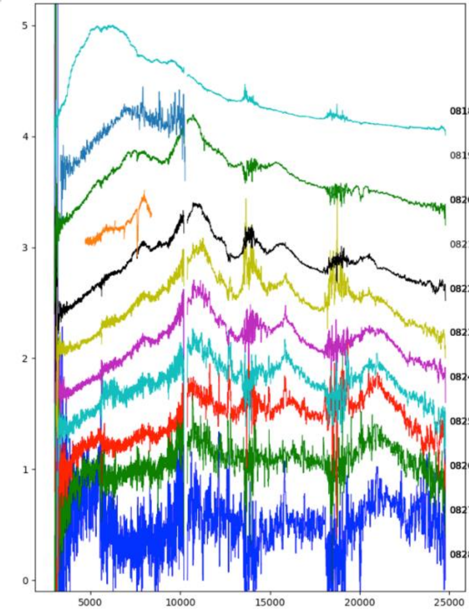
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics









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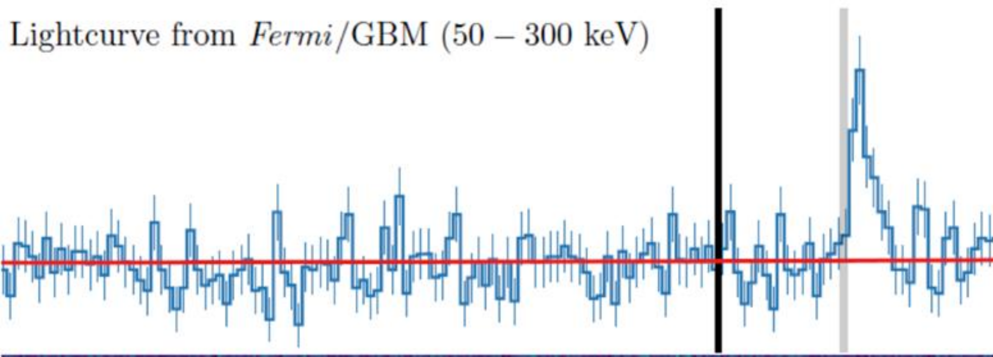
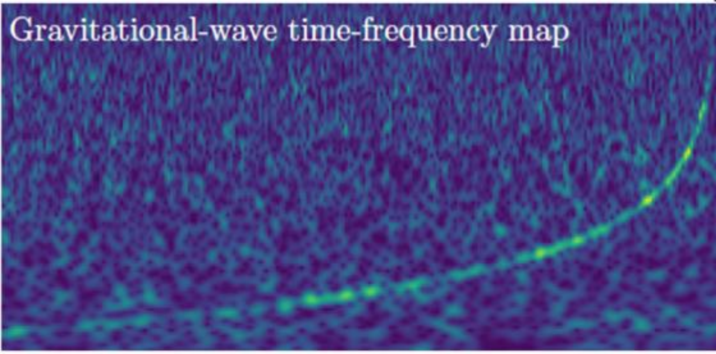
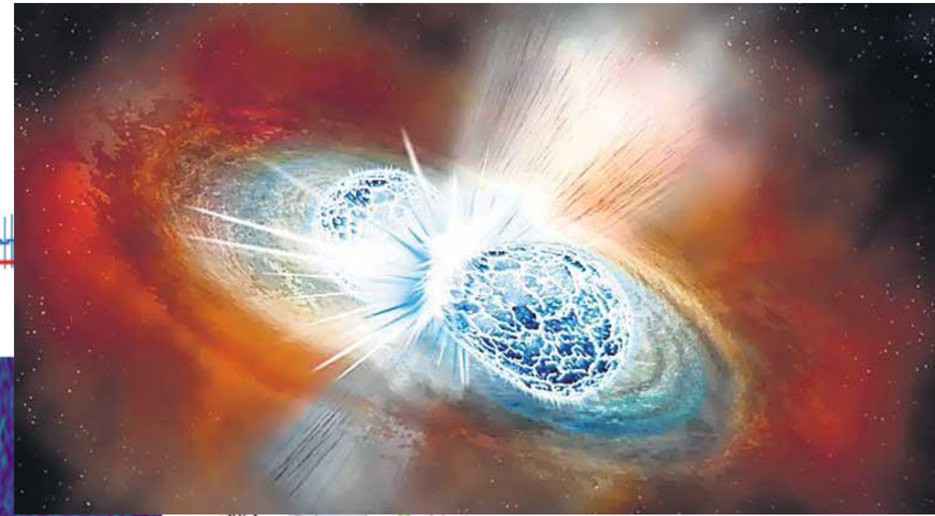
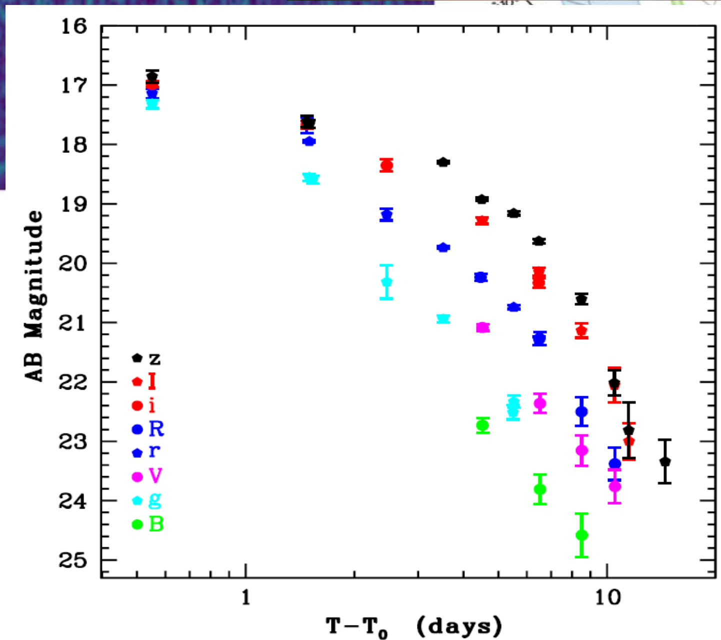
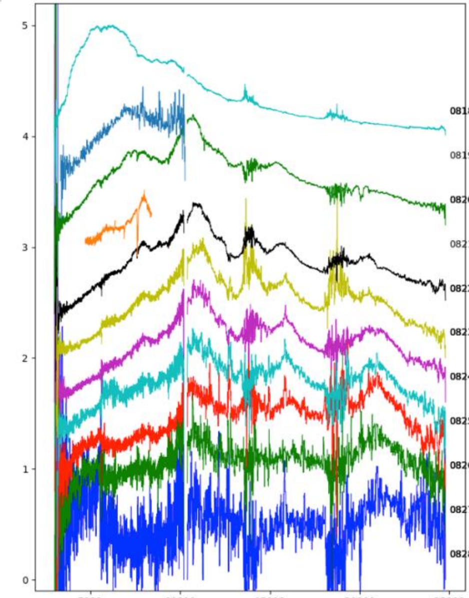




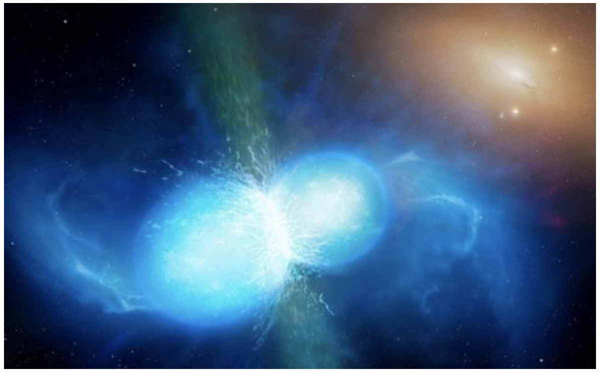




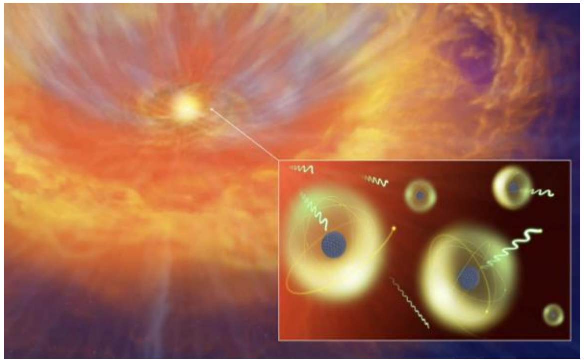


GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

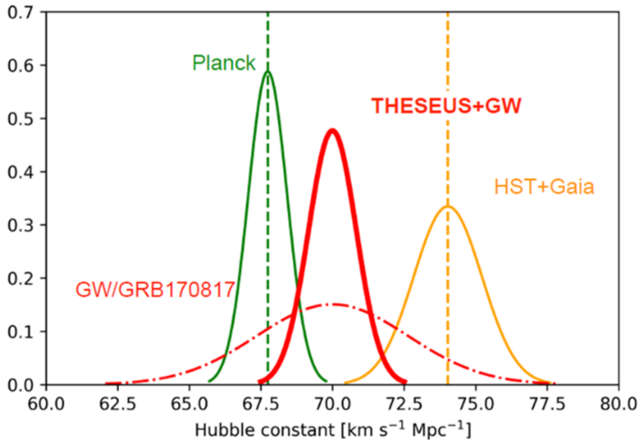
Relativistic jet formation, equation of state, fundamental physics



Cosmic sites of r-process nucleosynthesis



New independent route to measure cosmological parameters



Expected progress in the near future ('20s)

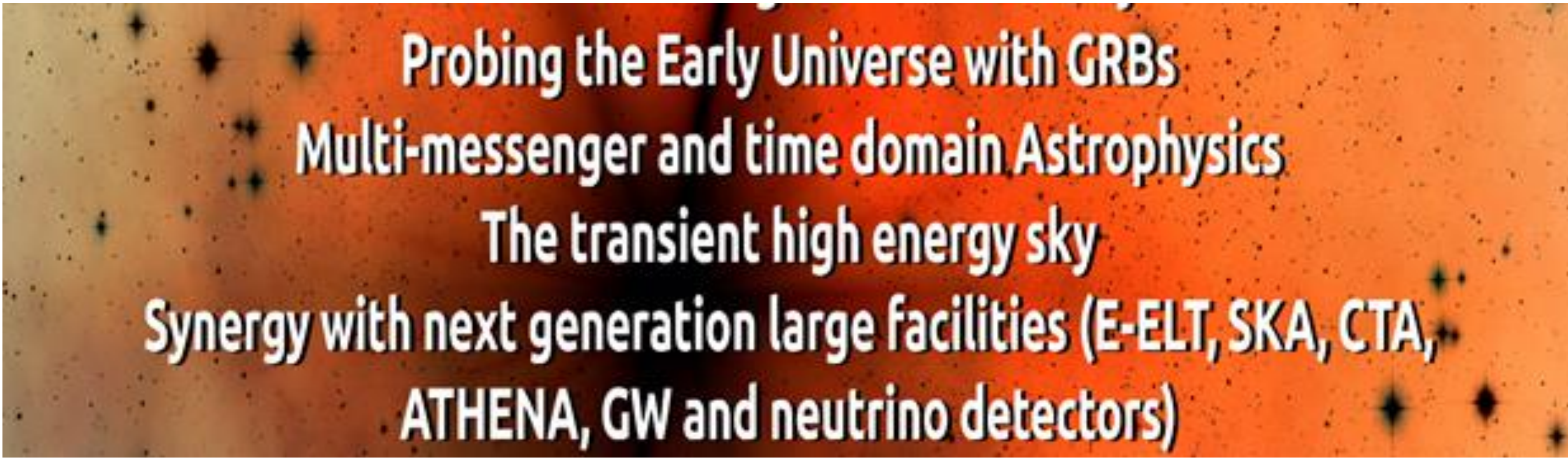
- **Continuing operations of current main GRB / related missions** (Swift, Fermi, Konus-WIND, GECAM, HXMT, MAXI, GRBalpha, …)

- **New / near future GRB / related missions** (EP, SVOM, POLAR-2, COSI, …) and **cubesats networks** (e.g., HERMES)

- **Synergies with new / growing on-ground very large facilities** (late '20s): JWST, ELT, LSST, CTA, SKA, upgraded 2nd generation GW and neutrino detectors

- **Main improvements on GRB physics**, incremental progress in GRB cosmology, little progress in multi-messenger astrophysics **(mostly limited by capabilities of 2G detectors)**

The breakthrough: next generation GRB missions for the ‘30s



- **THESEUS** (under study by ESA as candidate M7 mission), **HiZ-GUNDAM** (JAXA, under study), **Gamow Explorer** (proposal 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** theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- 2018-2021: ESA Phase-A study (2018-2021) as M5 candidate
- 2022: Selected for Phase 0 study (2023) within M7 process
- 2023: Selected for Phase-A study (2024-2026) as M7 candidate
- M7 timeline: Phase-A (2024-2026), adoption 2028, launch 2037

Payload consortium: Italy, Germany, UK, France, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, The Netherlands, Norway, Slovenia, Ireland (+ Hungary?)

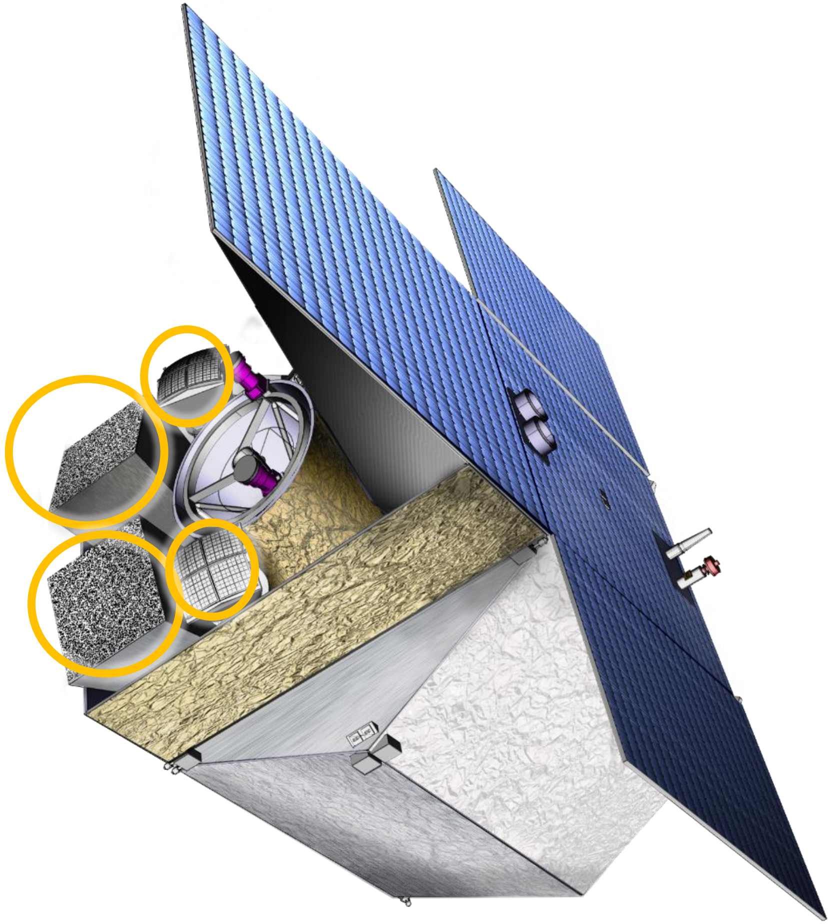
Leads: L. Amati (INAF – OAS Bologna, Italy, lead proposer), A. Santangelo (Un. Tuebingen, D), P. O'Brien (Un. Leicester, UK), D. Gotz (CEA-Paris, France), E. Bozzo (Un. Genève, CH)

Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)
Articles for SPIE 2020 and Exp..Astr. (all on arXiv)
http://www.isdc.unige.ch/theseus

THESEUS Mission Concept

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 from gamma-rays down to soft X-rays, FOV and localization accuracy**



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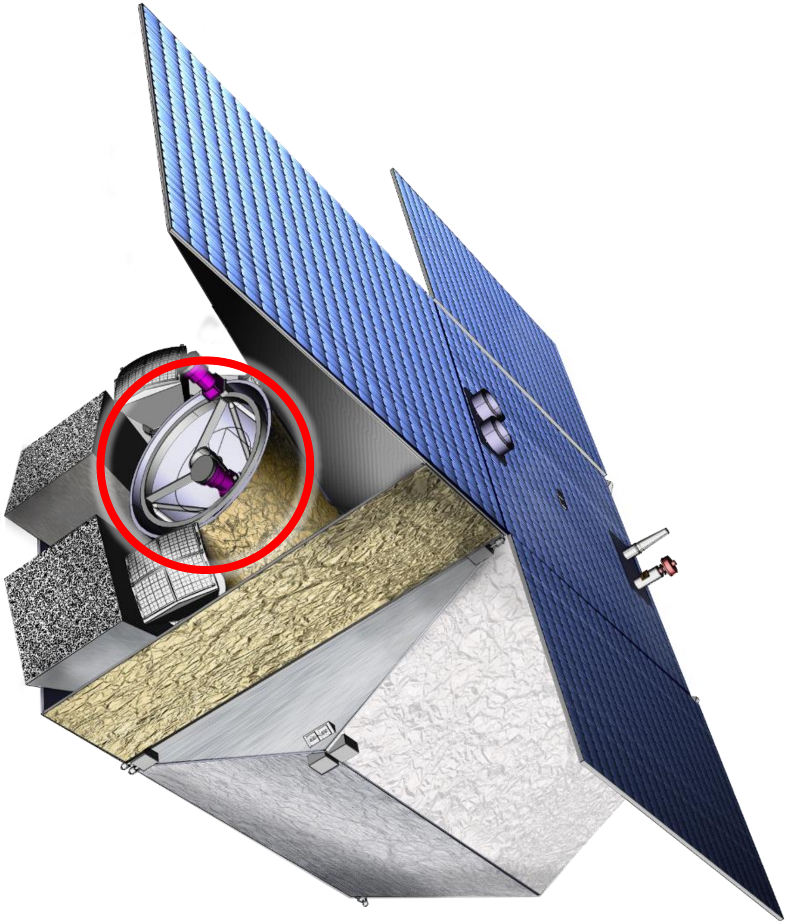
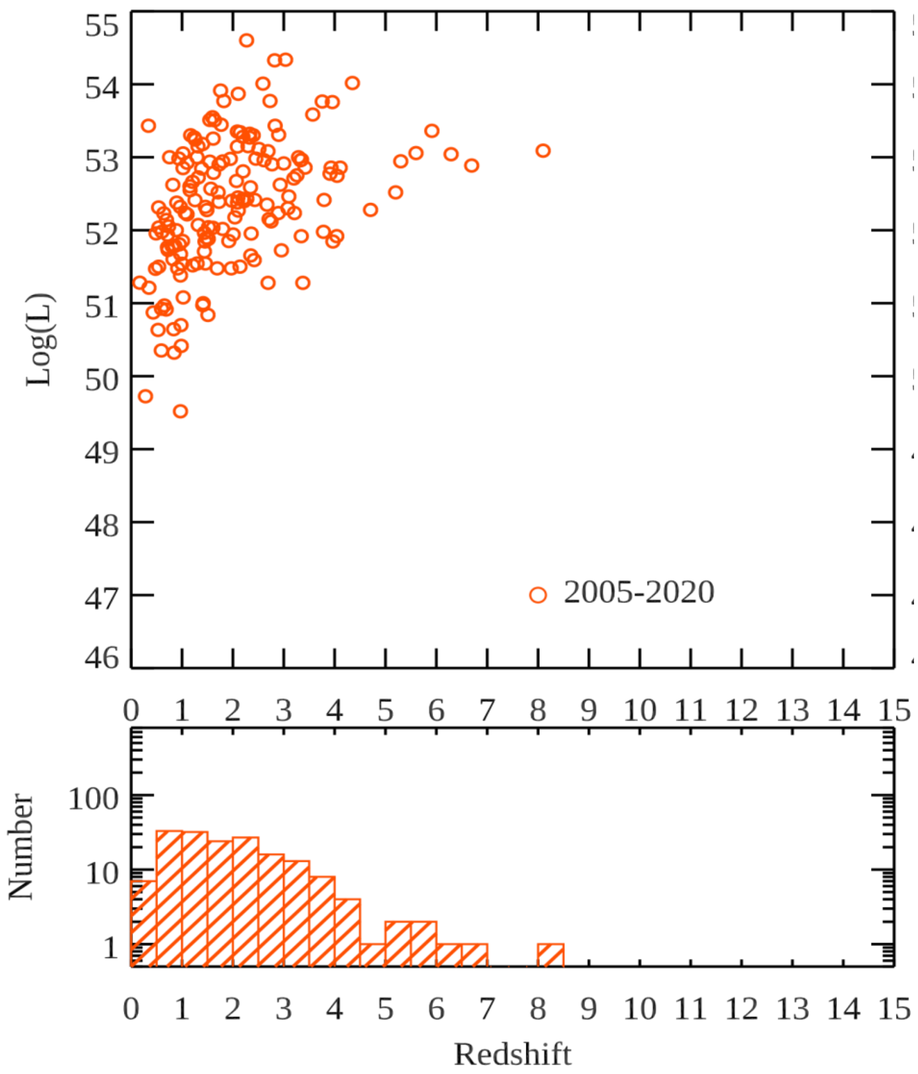
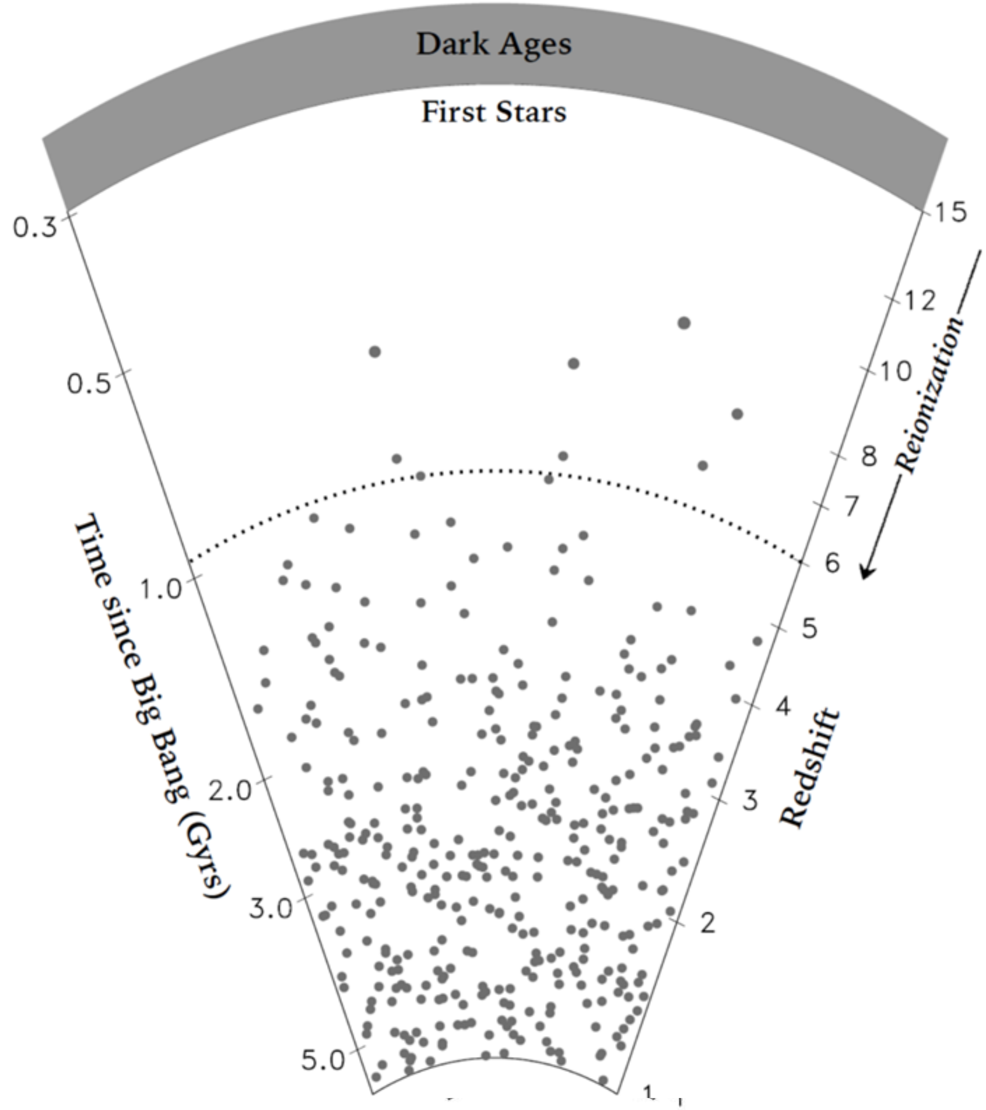
On-board **autonomous fast follow-up in optical/NIR**, arcsec location and **redshift measurement** of detected GRB/transients



Expected performances: early Universe





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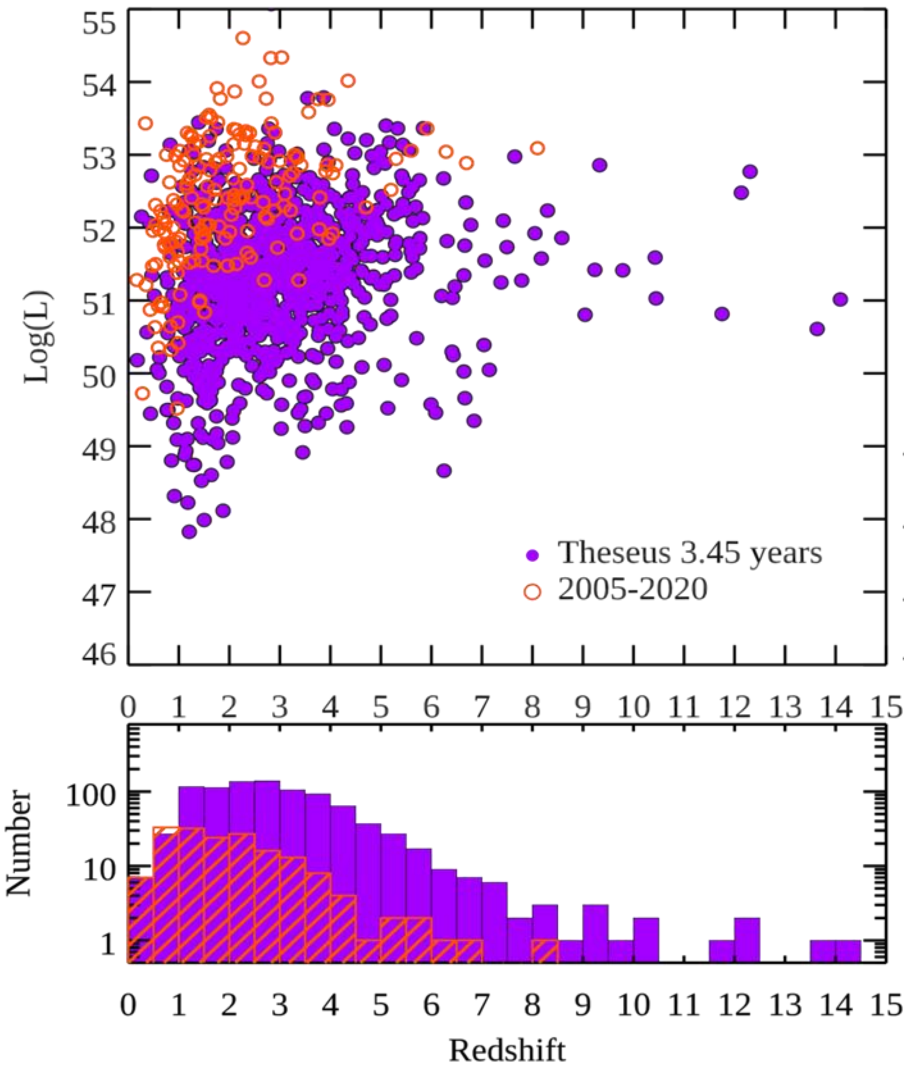

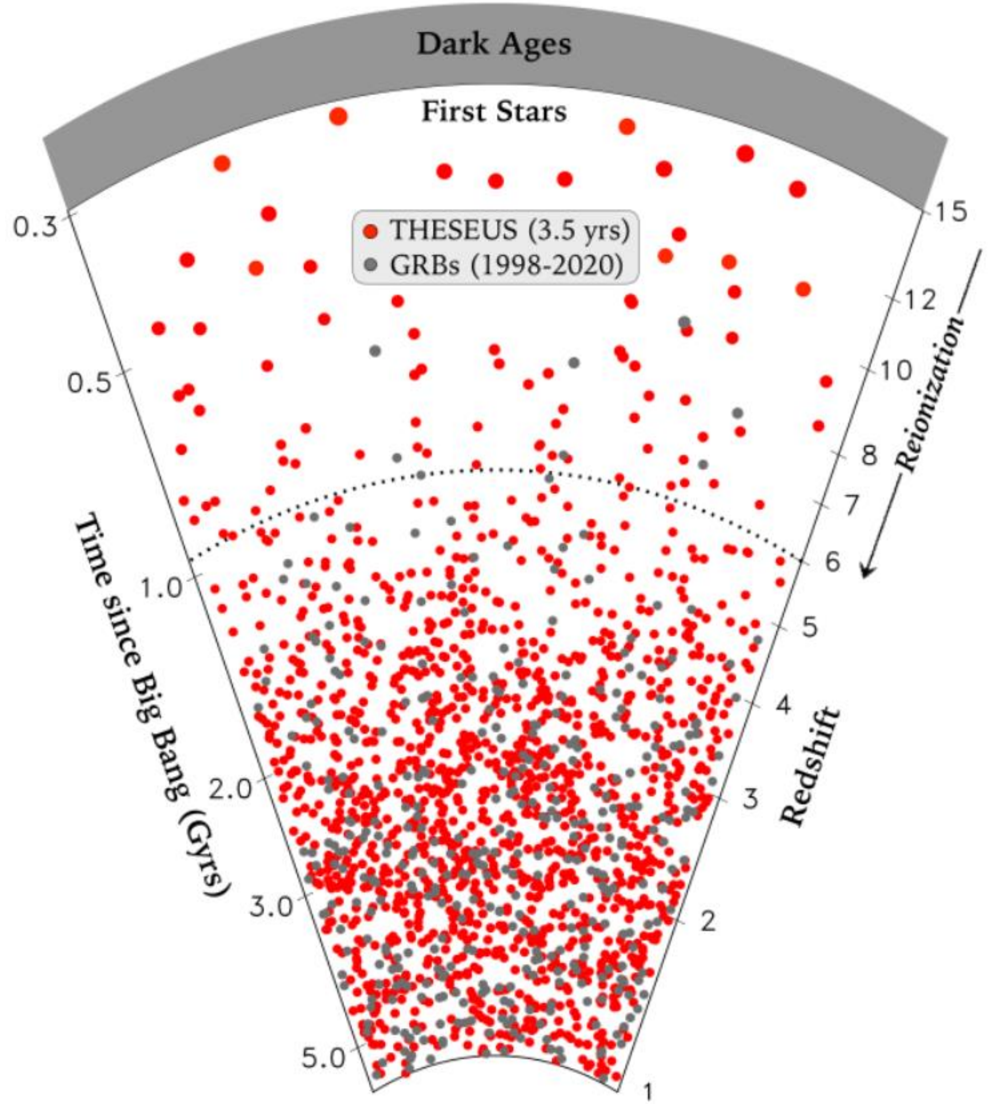

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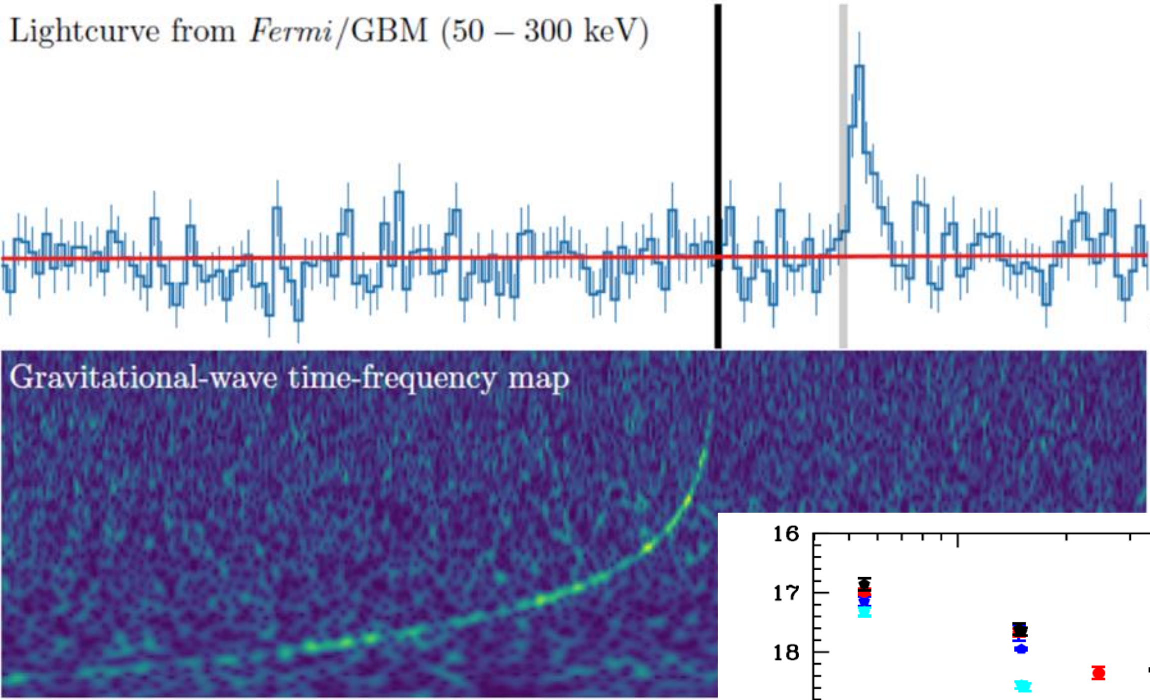
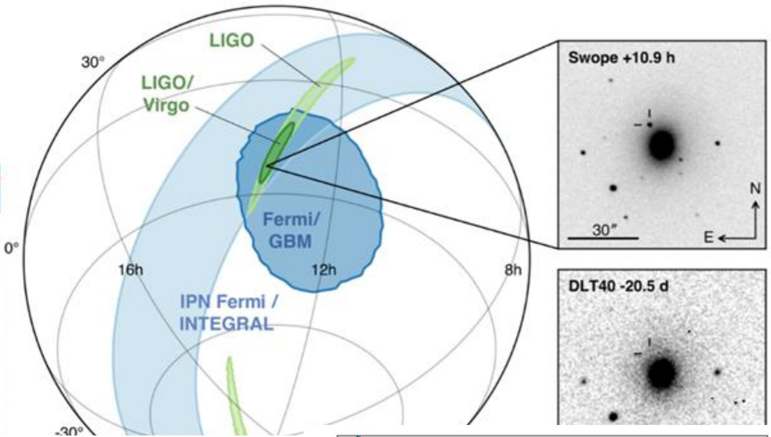
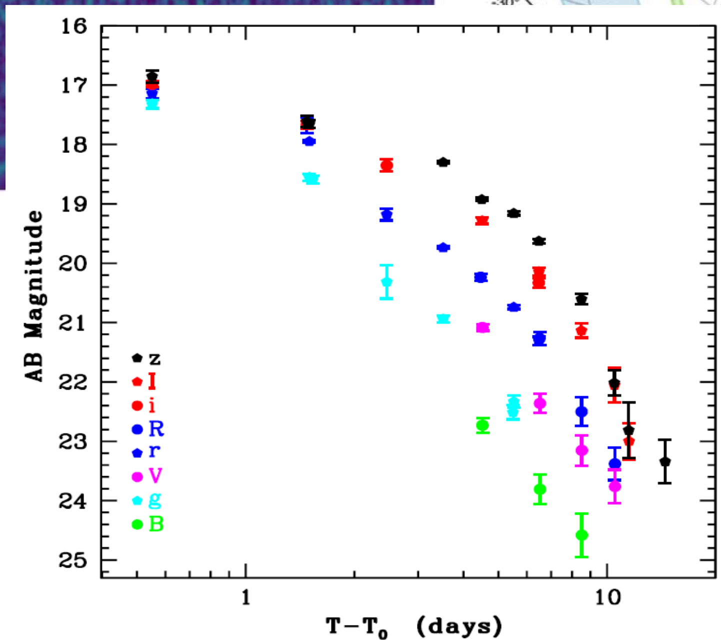
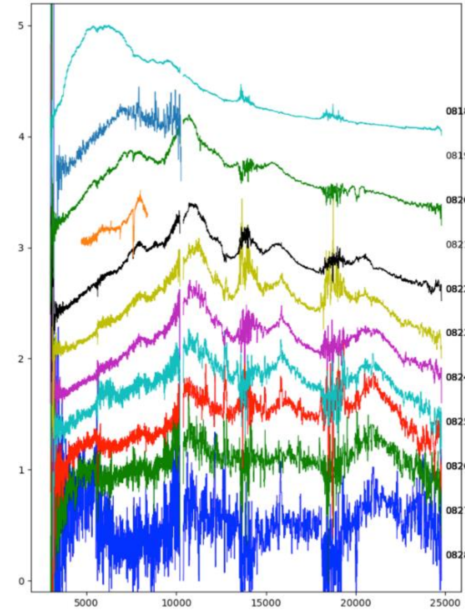






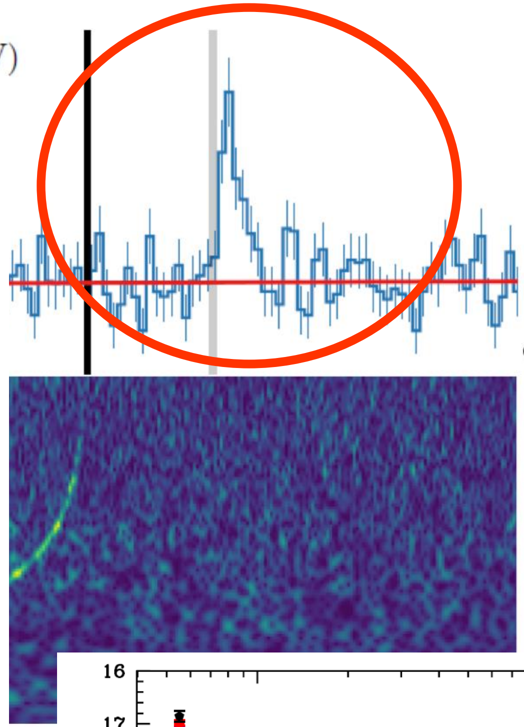


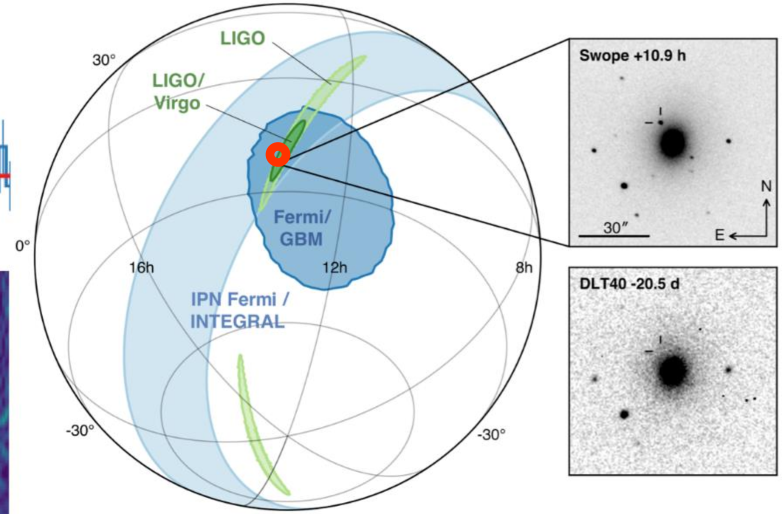
Expected performances: multi-messenger astr.

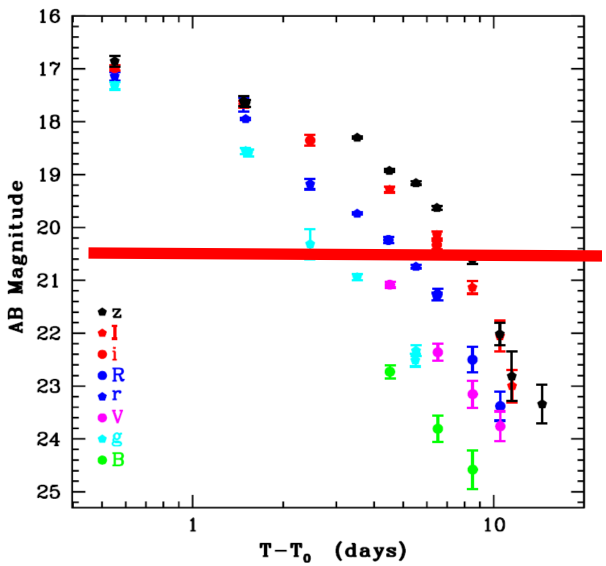
Lightcurve from *Fermi*/GBM (50 – 300 keV)

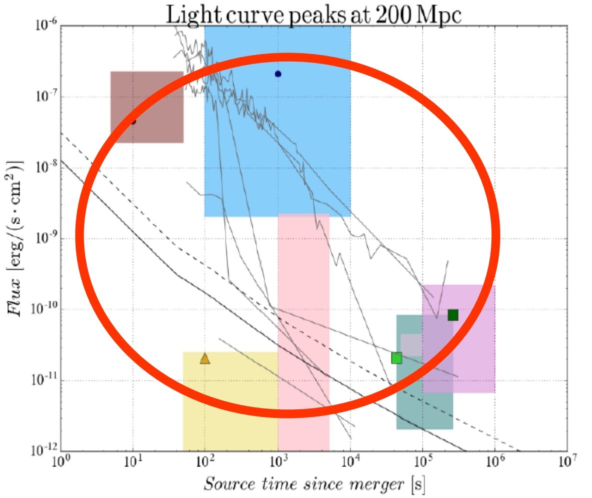
THESEUS:

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



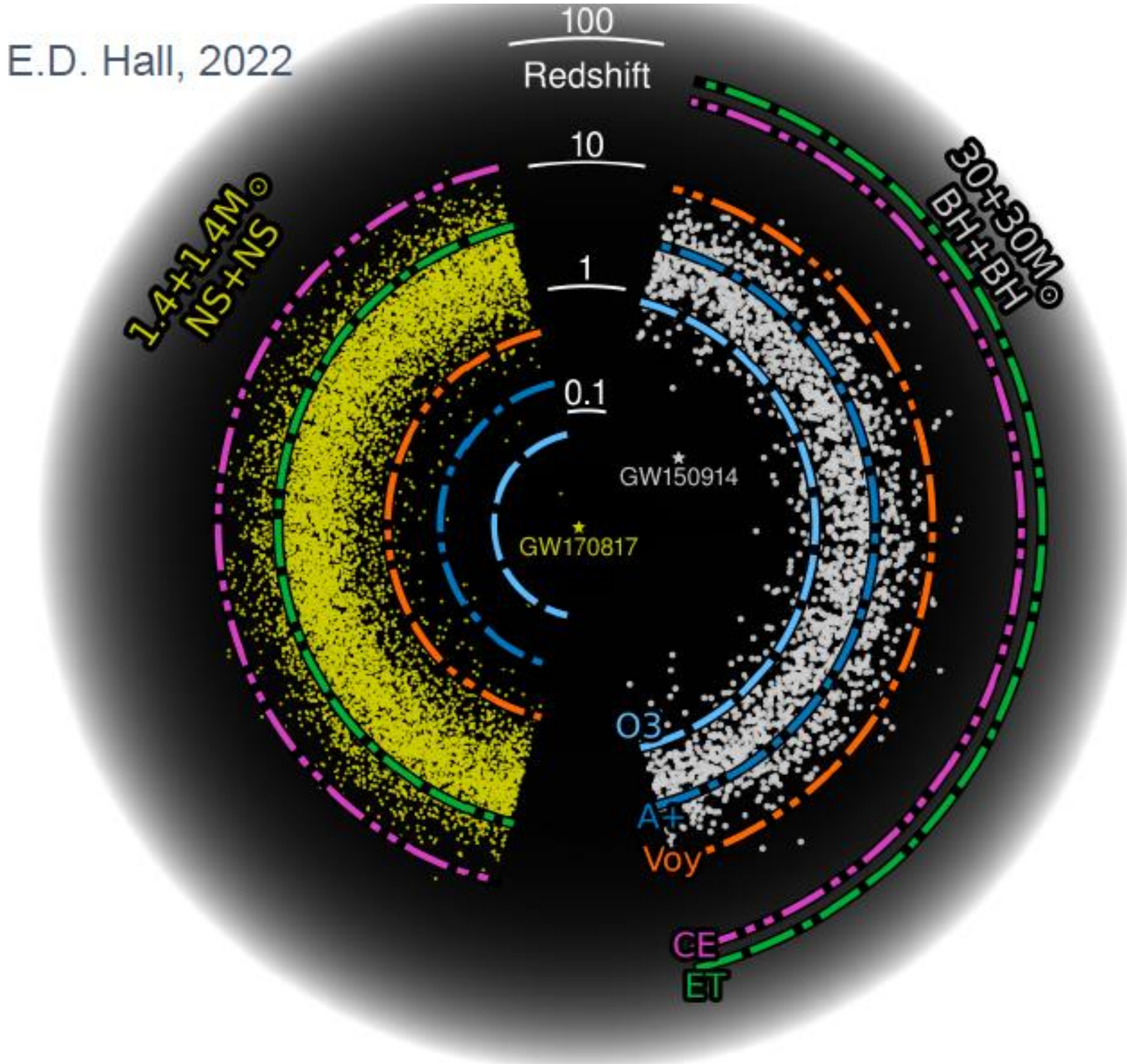






Multi-messenger science with THESEUS

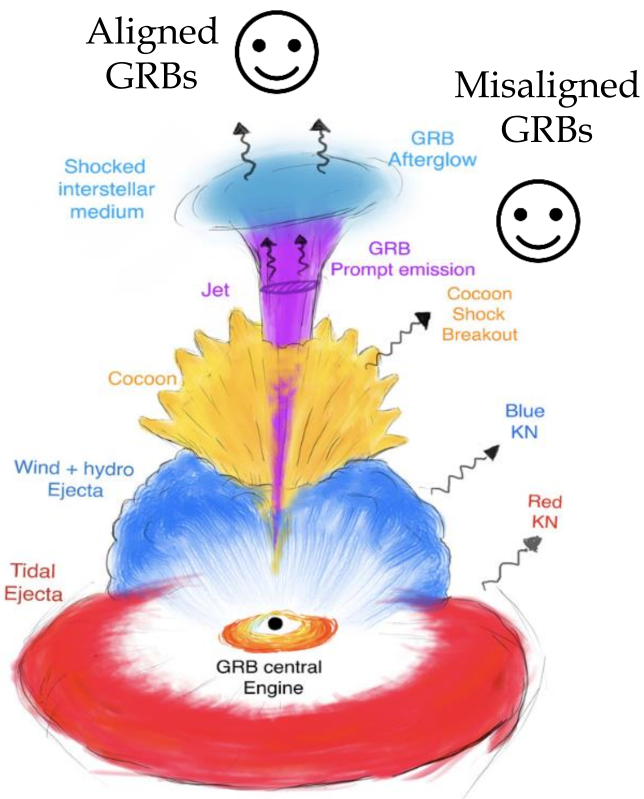
Late ’30s: great synergy with 3G GW detectors (ET, CE)



Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A



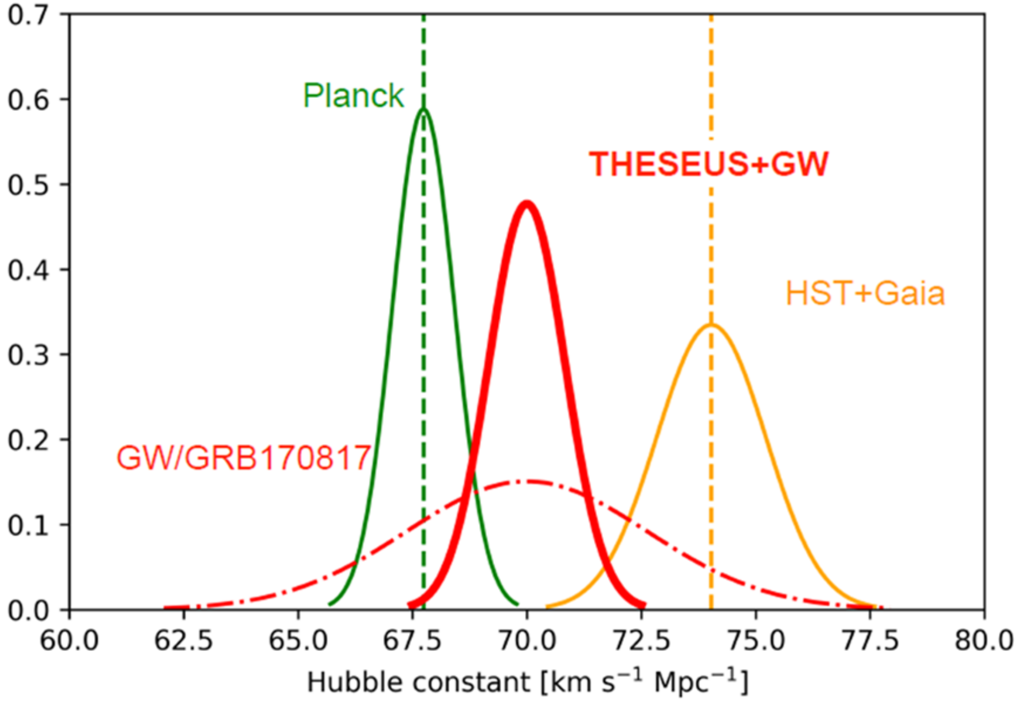
THESEUS + ET in 3 years:

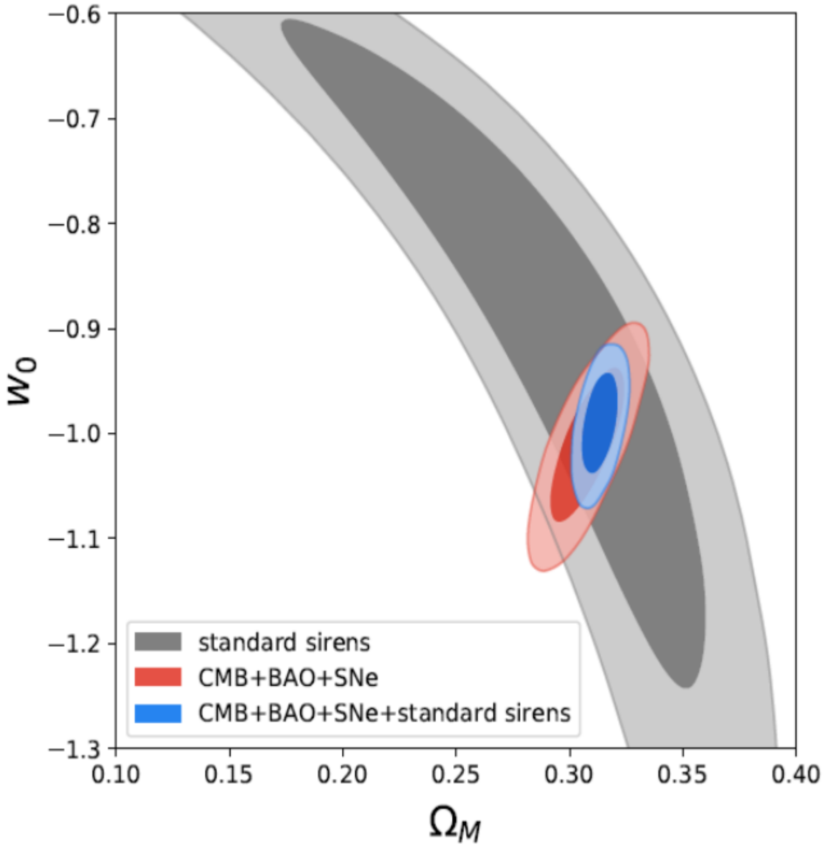
- ~70 aligned+misaligned short GRB
- additional long GRBs from mergers and possible GW-X-ray transients

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 cosmology

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



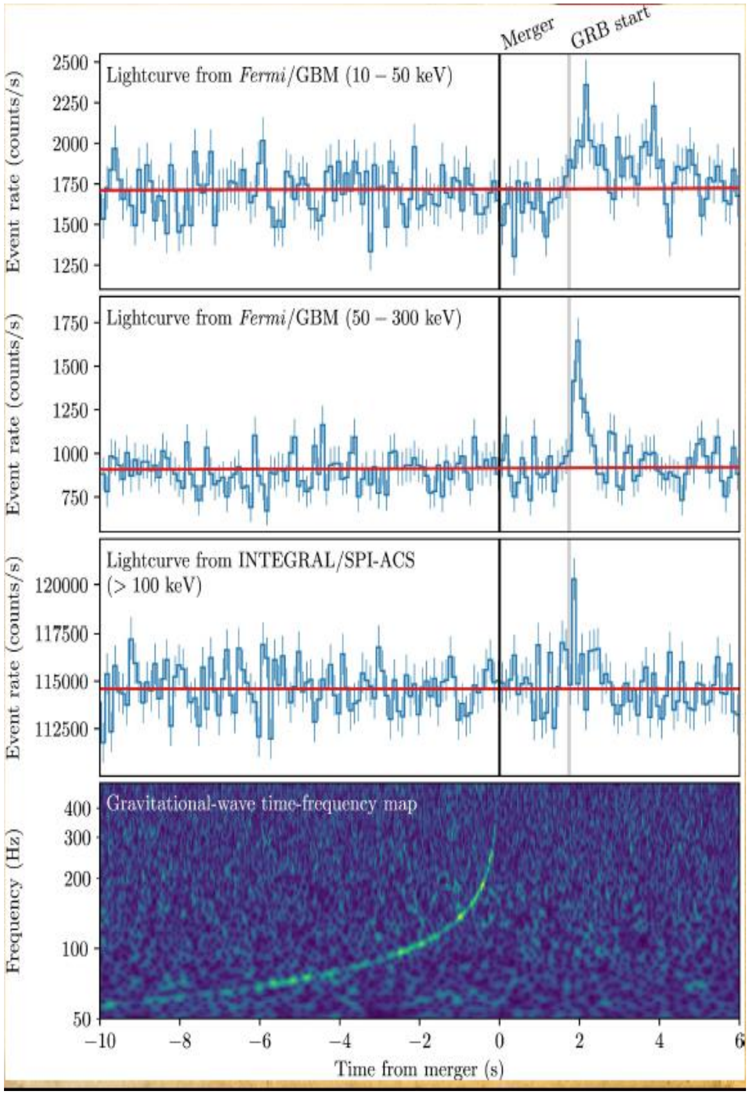


~20 joint GRB+GW events

ET collaboration

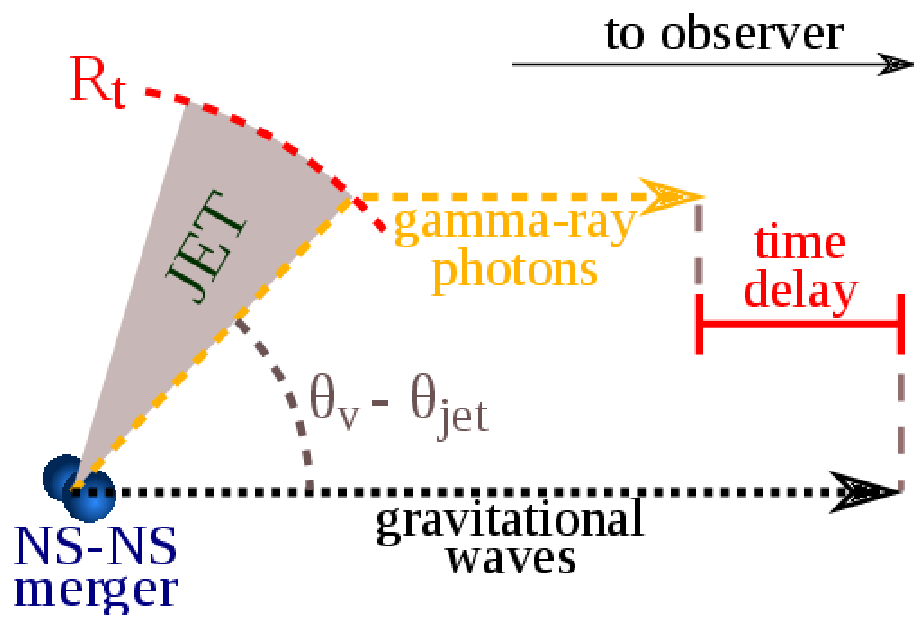
Fundamental physics: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

$|V_{gw}\text{-}C| / C < 10^{-16}$

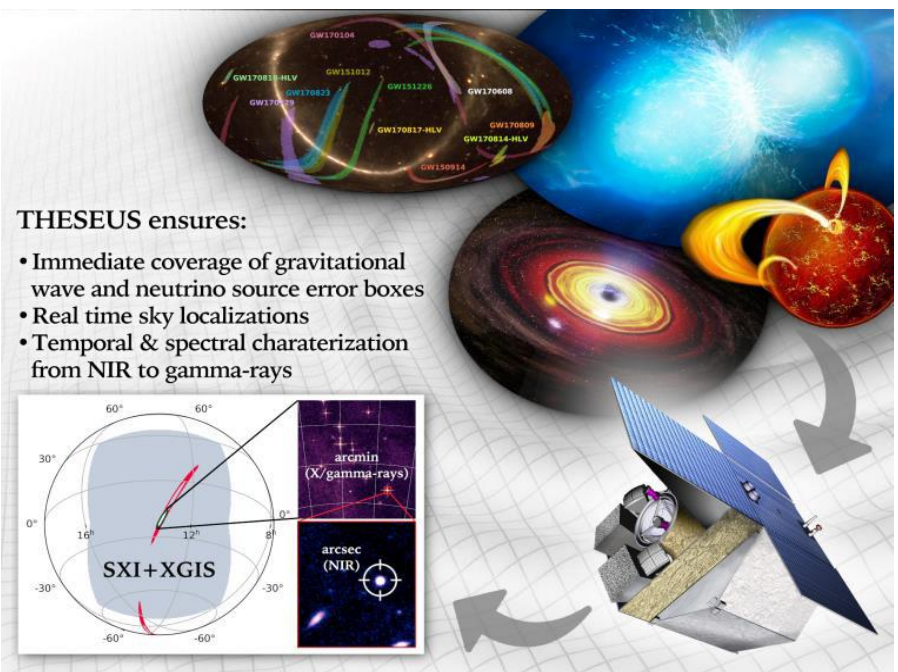


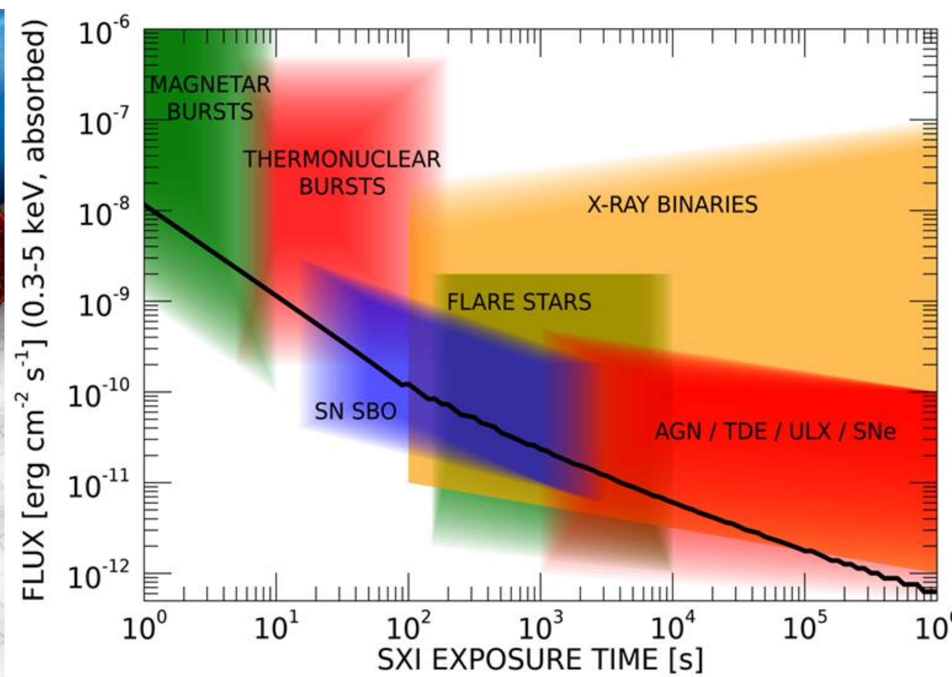
$$\Delta t = (\Delta t_{\mathrm{jet}} + \Delta t_{\mathrm{bo}} + \Delta t_{\mathrm{GRB}})(1+z)$$

$$\Delta t_{\mathrm{GRB}} \simeq (1 - \beta \cos\theta) \frac{R_{\mathrm{GRB}}}{c} \simeq \frac{R_{\mathrm{GRB}}}{\Gamma^2 c}$$

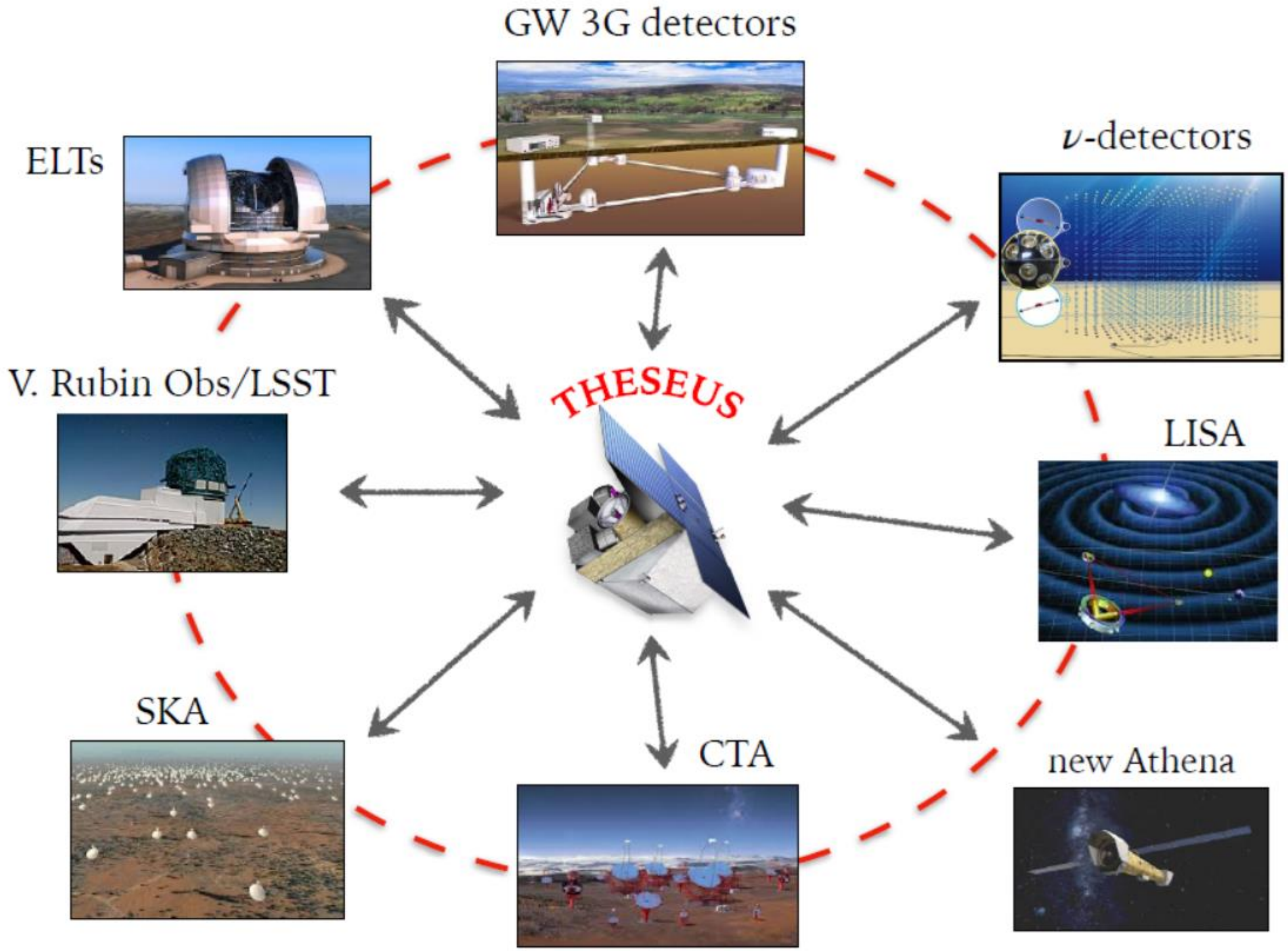
Exploring the transient sky

- **GRBs extreme emission physics**, central engine, sub-classes & progenitors, **cosmological parameters & fundamental physics**
- Study of **many classes of X-ray sources** by exploiting the **simultaneous broad band X-ray and NIR observations**
- Provide a **flexible follow-up observatory** for fast transient events with **multi-wavelength ToO capabilities** and **guest-observer programmes**





THESEUS: crucial synergies in the late '30s



The «**M7**» **timeline** will allow to **widely broaden the mission scientific impact** by taking advantage of the **perfectly matched synergies** with major facilities coming fully operative in the 2030s **(e.g., 3G GW detectors)**

In summary

- GRBs are a key phenomenon for **cosmology**, **multi-messenger astrophysics** and **fundamental physics**

- **Next generation GRB missions like THESEUS**, under study by ESA (M7 Phase-A) **aim to ully exploit these potentialities**, providing a substantial contribution to extreme GRB physics and time-domain astronomy

- The '30s timeline will allow an **unprecedented great synergy with future very large observing** facilities in the e.m. and multi messenger domains, **enhancing their scientific return and fully exploiting investments put in them**.

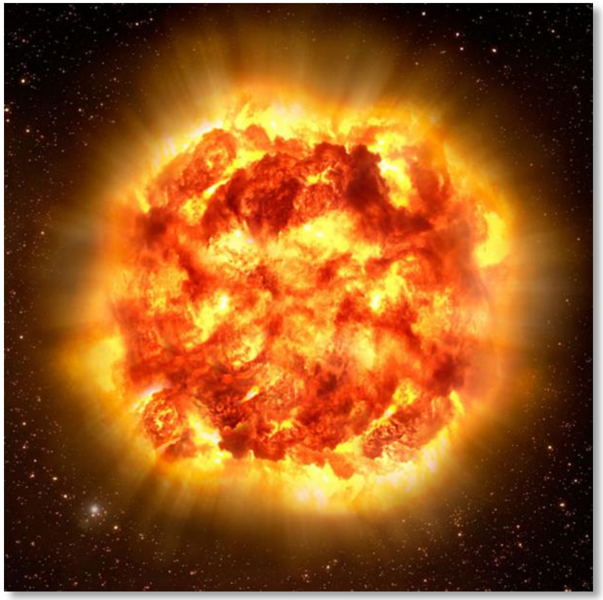
- **The very strong synergy with Einstein Telescope and possibly cosmic explorer** will provide a breakthough in multi-messenger astrophysics

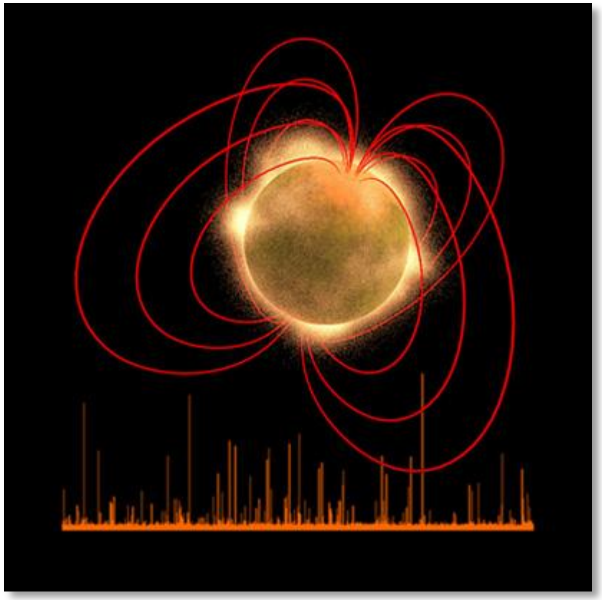
- **THESEUS: ESA/M5 Phase A study and selected for M7 Phase A (->2037)**
  SPIE articles on instruments, Adv.Sp.Res. & Exp.Astr. articles on science
  http://www.isdc.unige.ch/theseus/

Back-up slides

Multi-messenger science with THESEUS

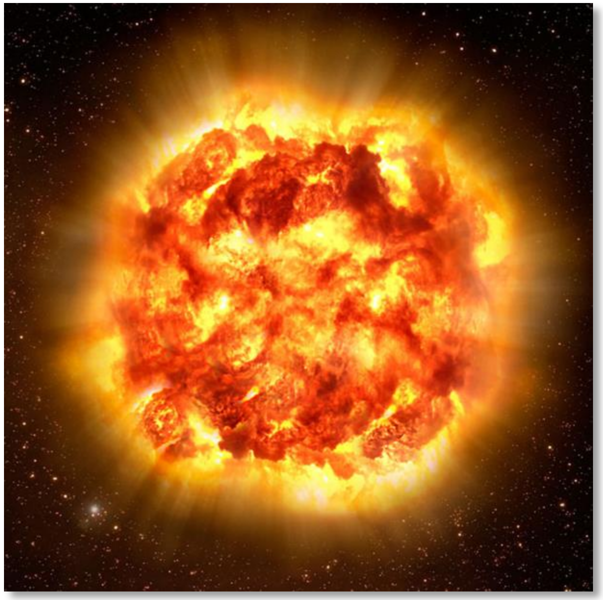
- **Short GRBs**
- Core-collapse stars
- Soft Gamma-ray Repeaters
- Unexpected transients…

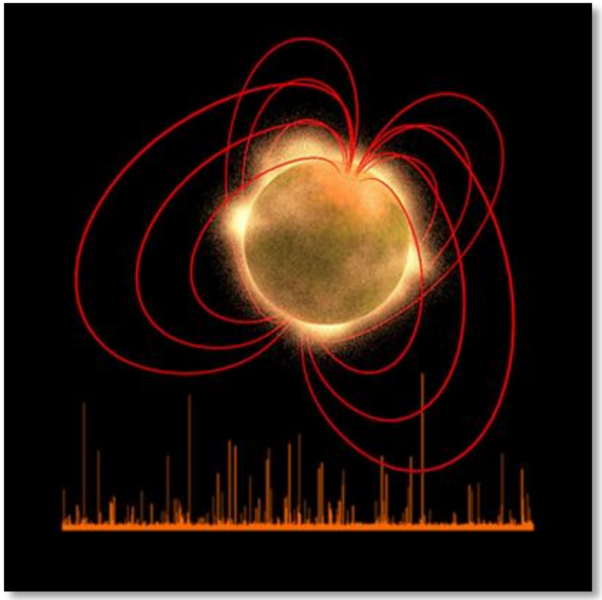




Multi-messenger science with THESEUS

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

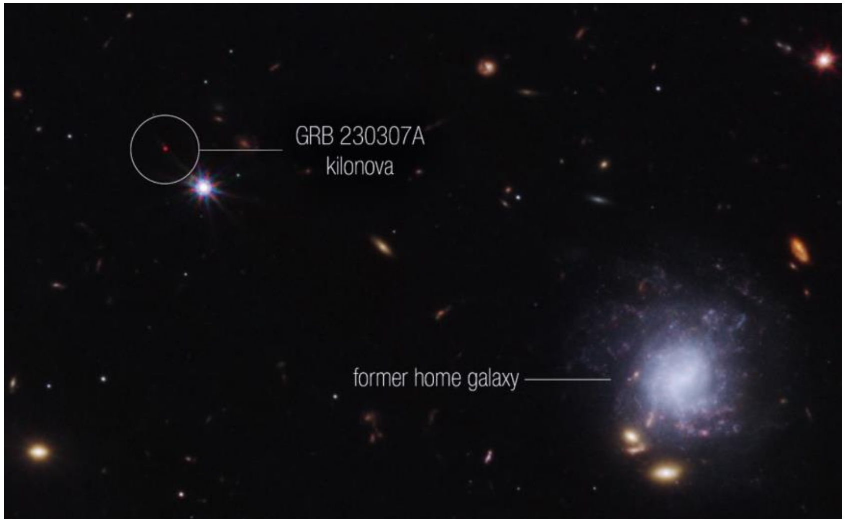


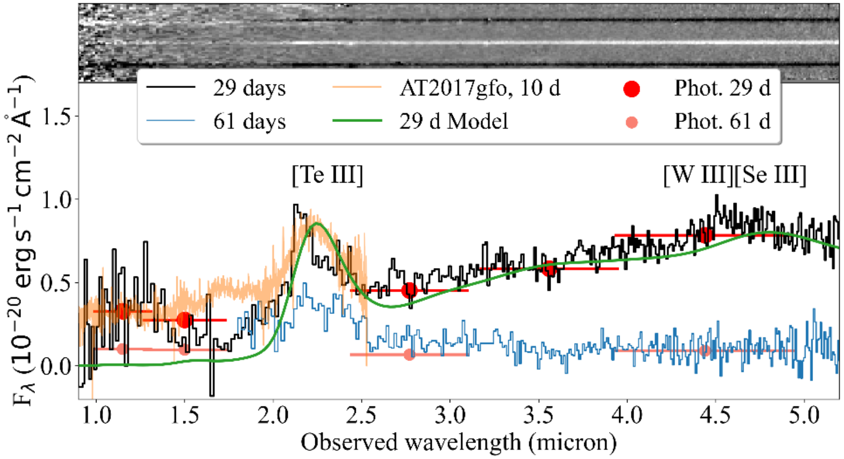


Long-GRBs from compact binary mergers

Recently revealed population of apparently long-duration GRBs accompanied by kilonova events, indicating a NS binary merger progenitor.

- GRB 211211A at d~350 Mpc (Rastinejad et al. 2022)
- GRB 230307A at d~280 Mpc (Levan et al. 2023 in press)
- **Conclude: enhanced rate of binary mergers simultaneously detected by ET and THESEUS**





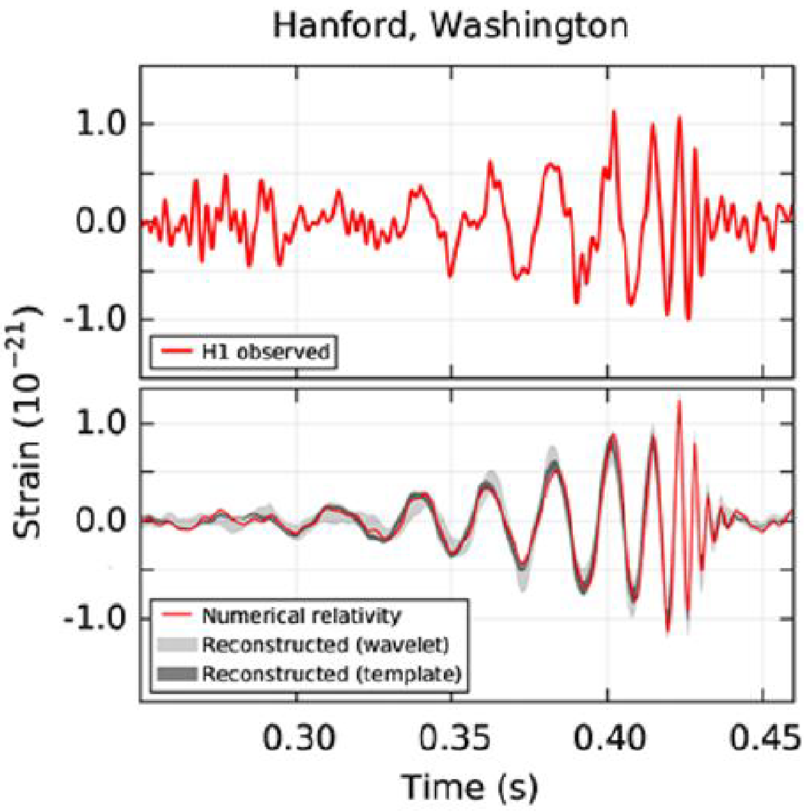
Multi-messenger science with THESEUS

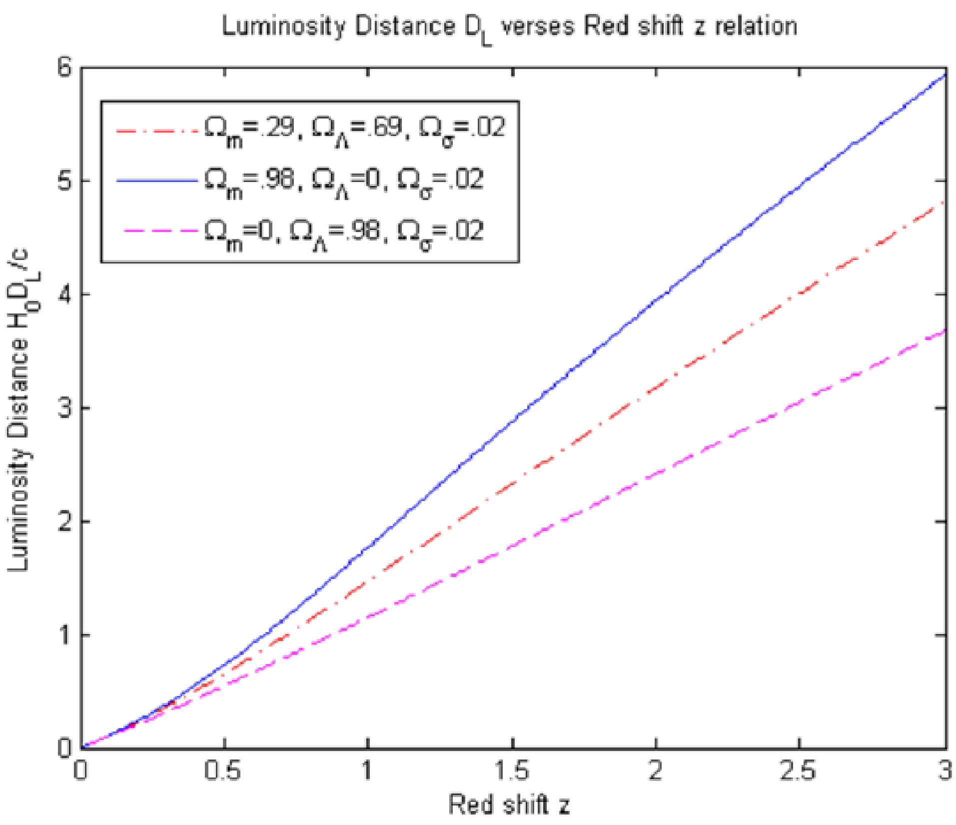
THESEUS & 3G SCIENCE

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**

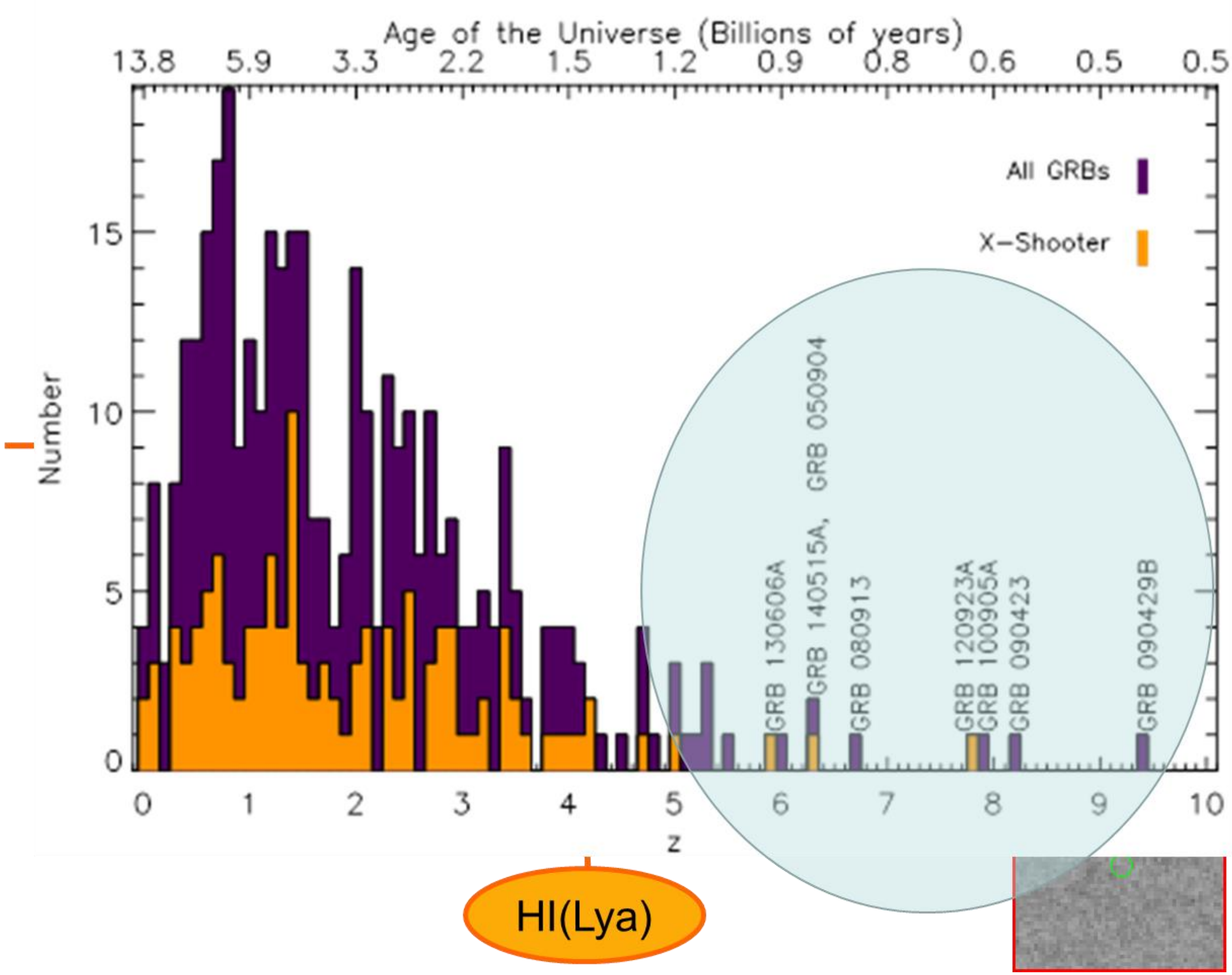
Multi-messenger cosmology with GRBs

- Modelization of GW signal provide **cosmology independent estinmate of source distance**
- Detection and localization of associated GRB **leads to redshift estimate**



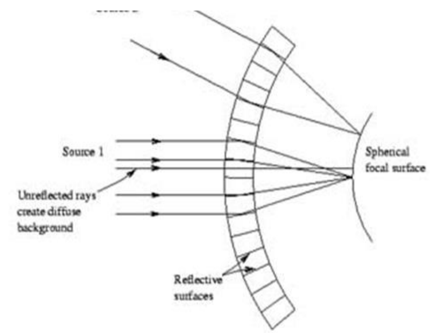


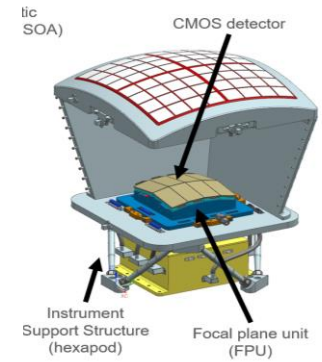
Shedding light on the early Universe with GRBs



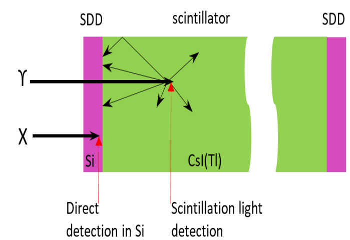
THESEUS Mission Concept

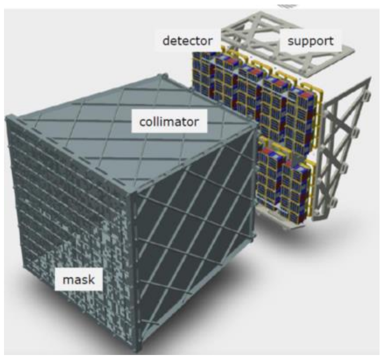
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′



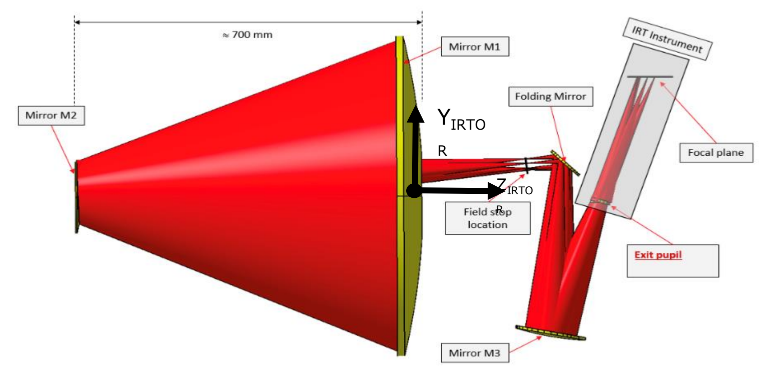


- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy

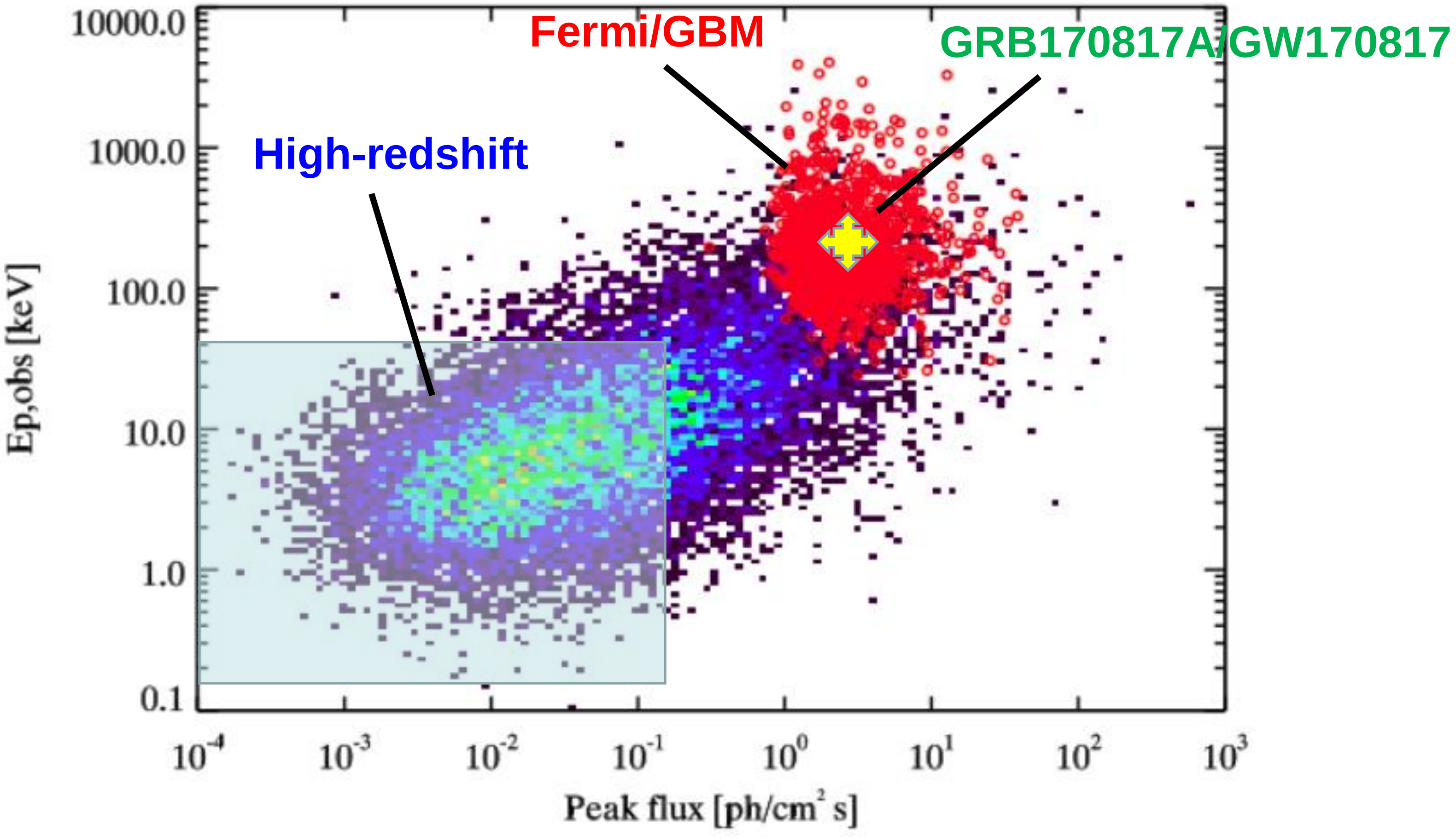




- **InfraRed Telescope (IRT):** a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 15′x15′ FOV, with both imaging and moderate resolution spectroscopy capabilities



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

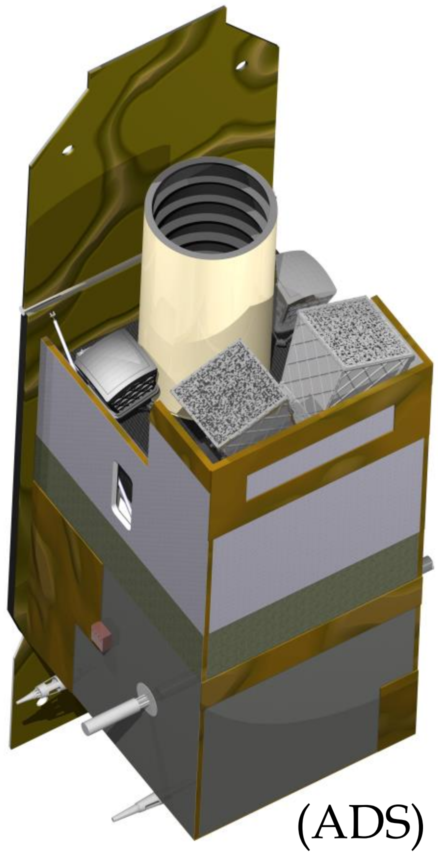


THESEUS Mission Concept

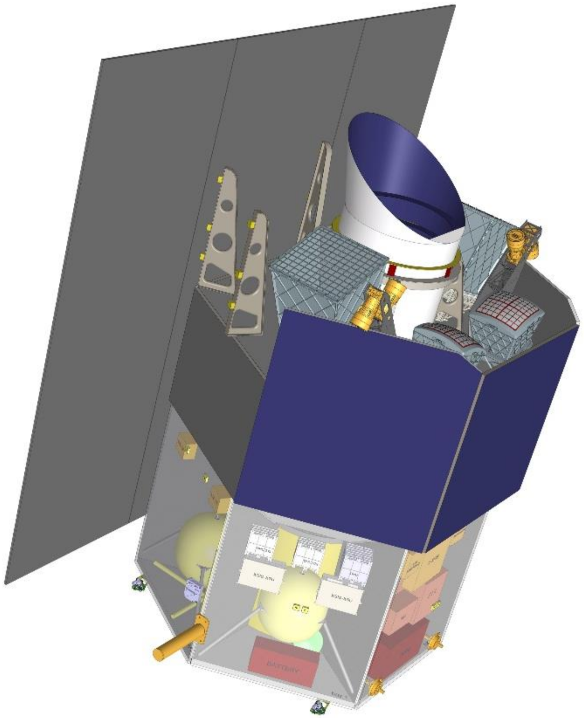
- **Fast slewing capability** (>10°/min), granting prompt NIR follow-up of GRBs and transients

- **Low-Earth Orbit (LEO),** with about 4° inclination and 550-640 km altitude, granting low and stable BKG for the monitors

- The weight (about 2.3 tons) and dimensions are suitable for **launch with VEGA-E**

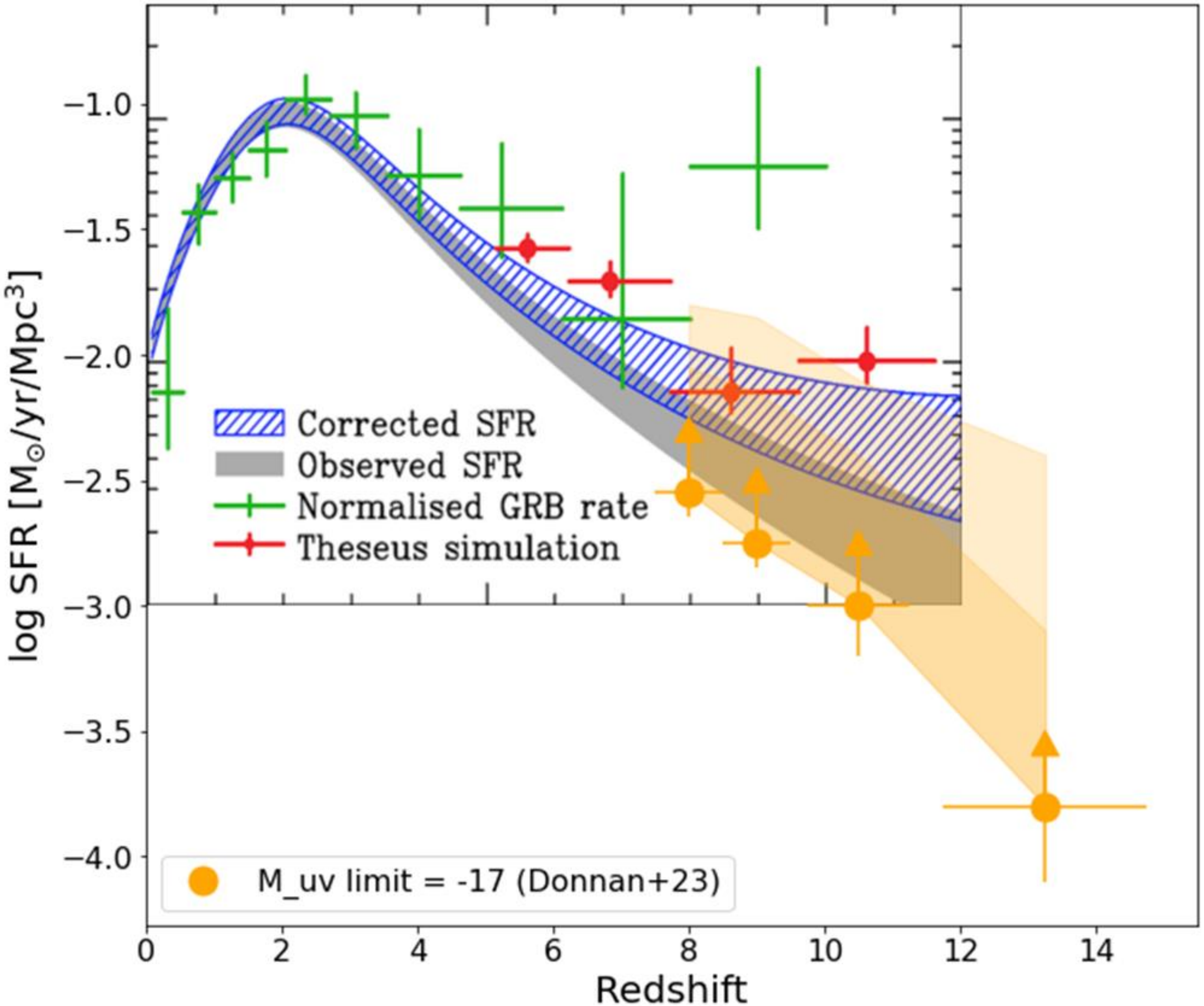


(ADS)

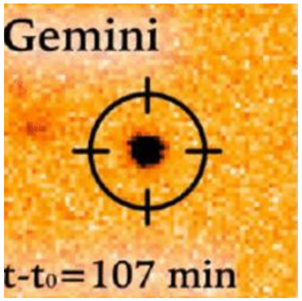


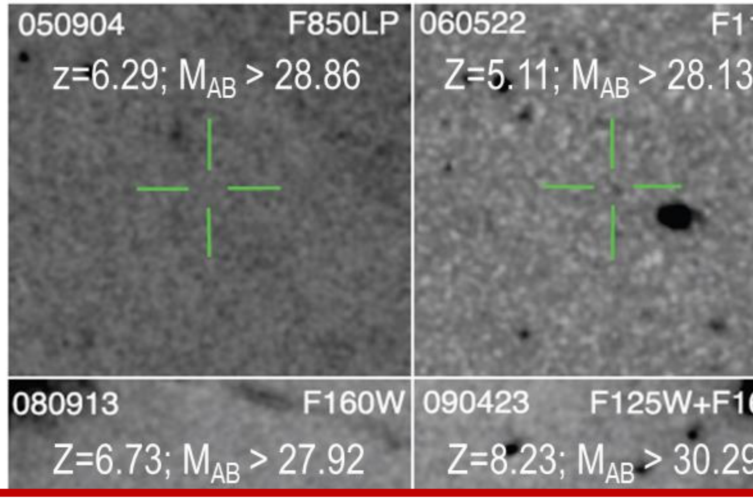
(THALES)

SFR(z) from JWST observations: lower limits consistent with previous estimates



Detecting and studying primordial invisible galaxies



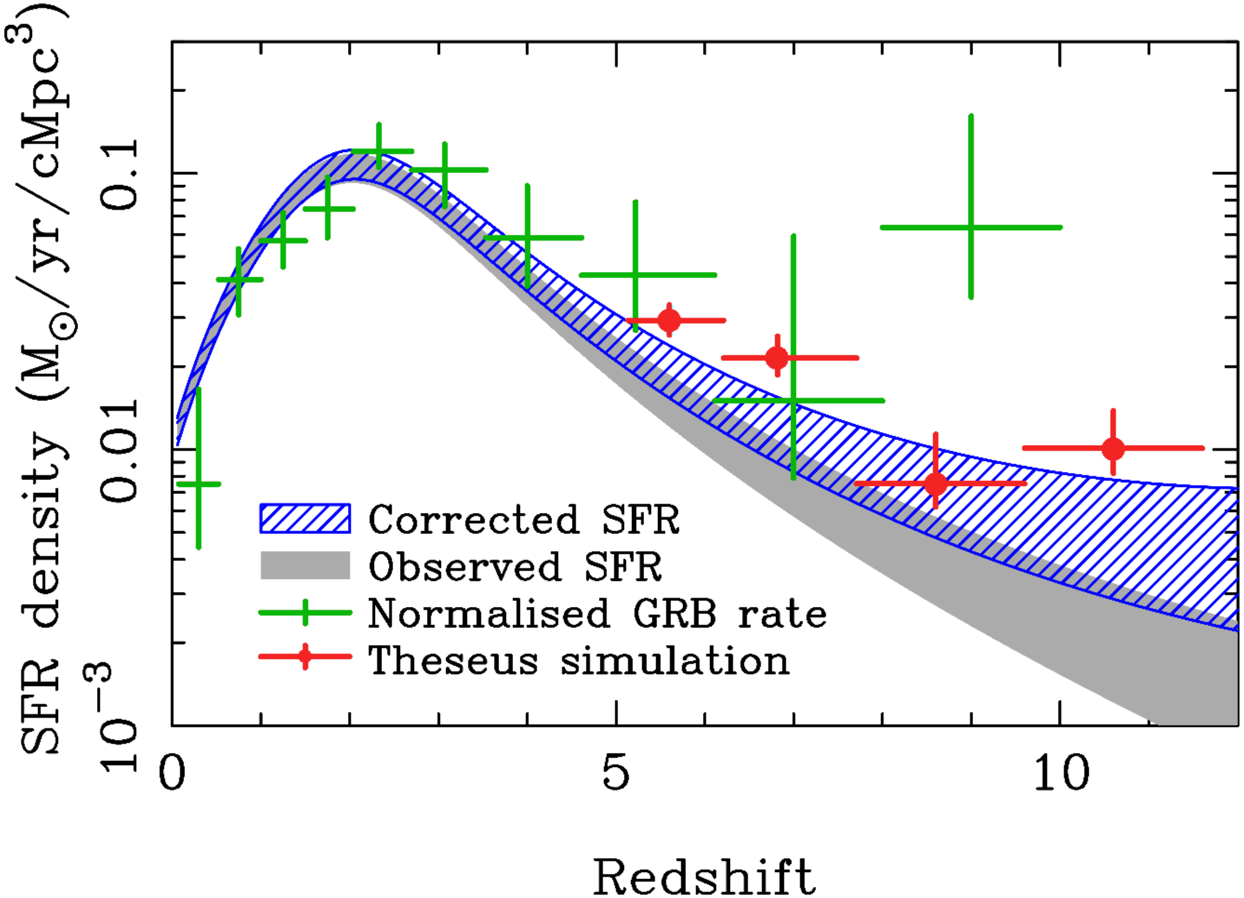


- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- chemical abundances in the ISM and IGM and its evolution

JWST early results on primordial galaxies

- lower limits only to total SFR(z), consistent with previous estimates and our assumptions
- raised further interest: e.g., possible excess of high-luminosity galaxies

- **Independent measure of cosmic SFR at high-z (possibly including pop-III stars)**

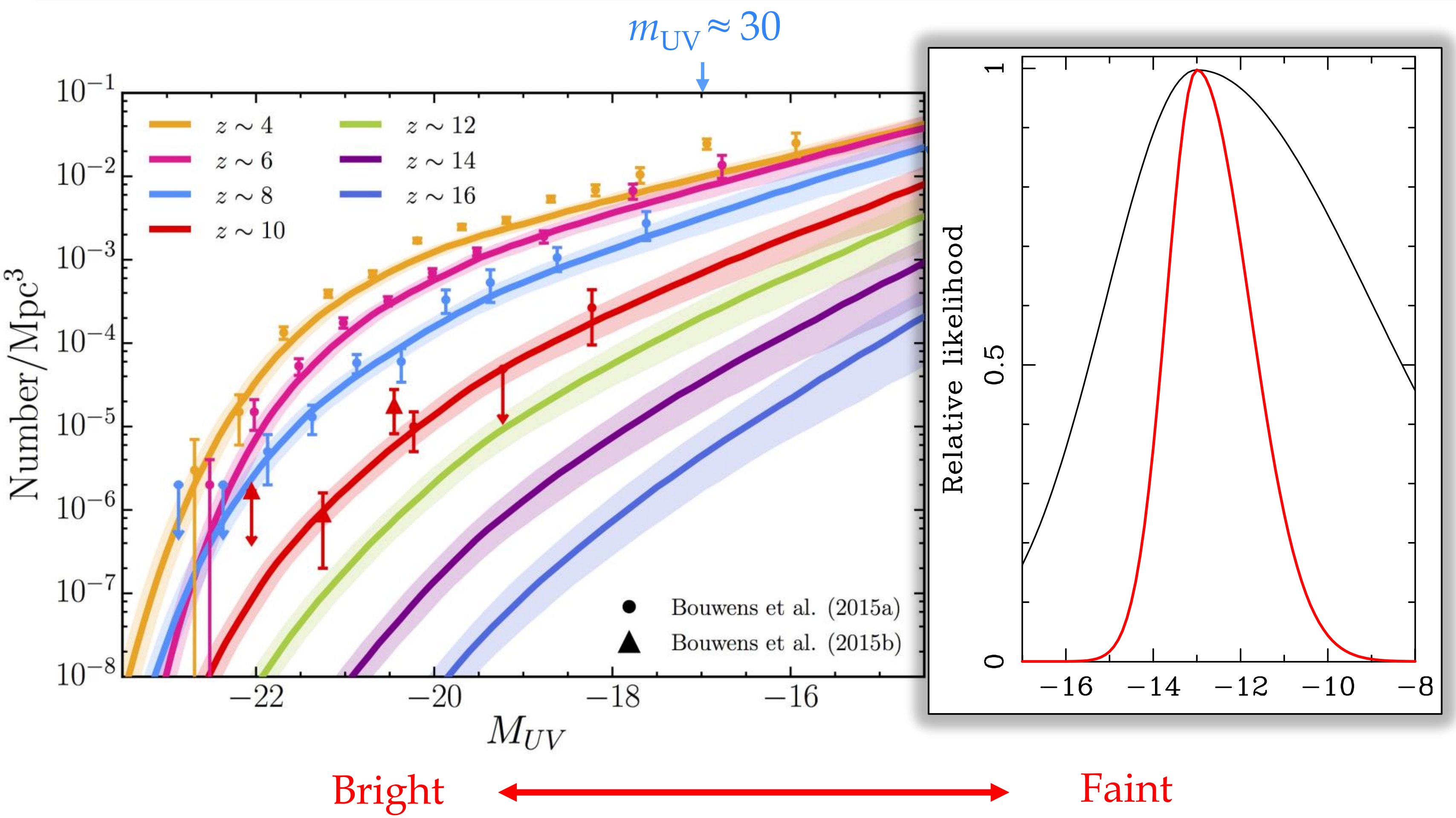


A sample of **>40 high–z GRBs** will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

THESEUS Consortium 2021

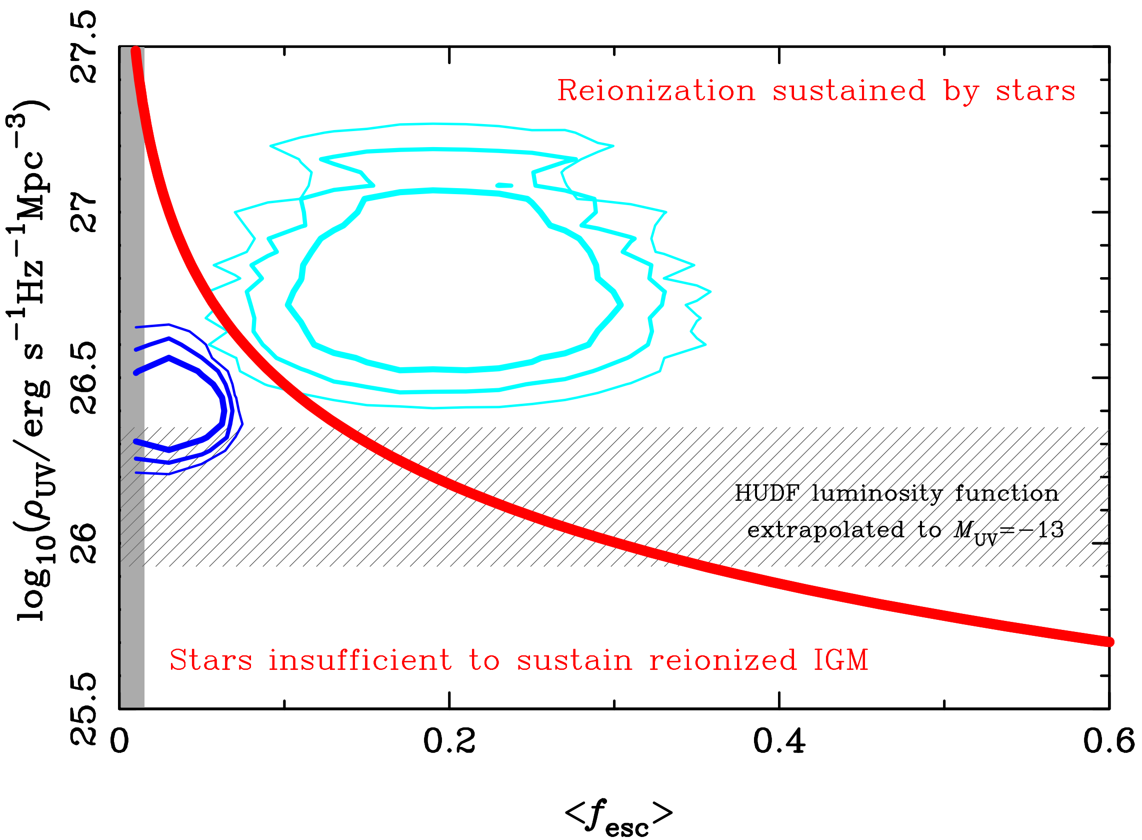
• Detecting and studying primordial invisible galaxies

The proportion of GRB hosts below a given detection limit provides an estimate of the fraction of star formation "hidden" in such faint galaxies



THESEUS Consortium 2021

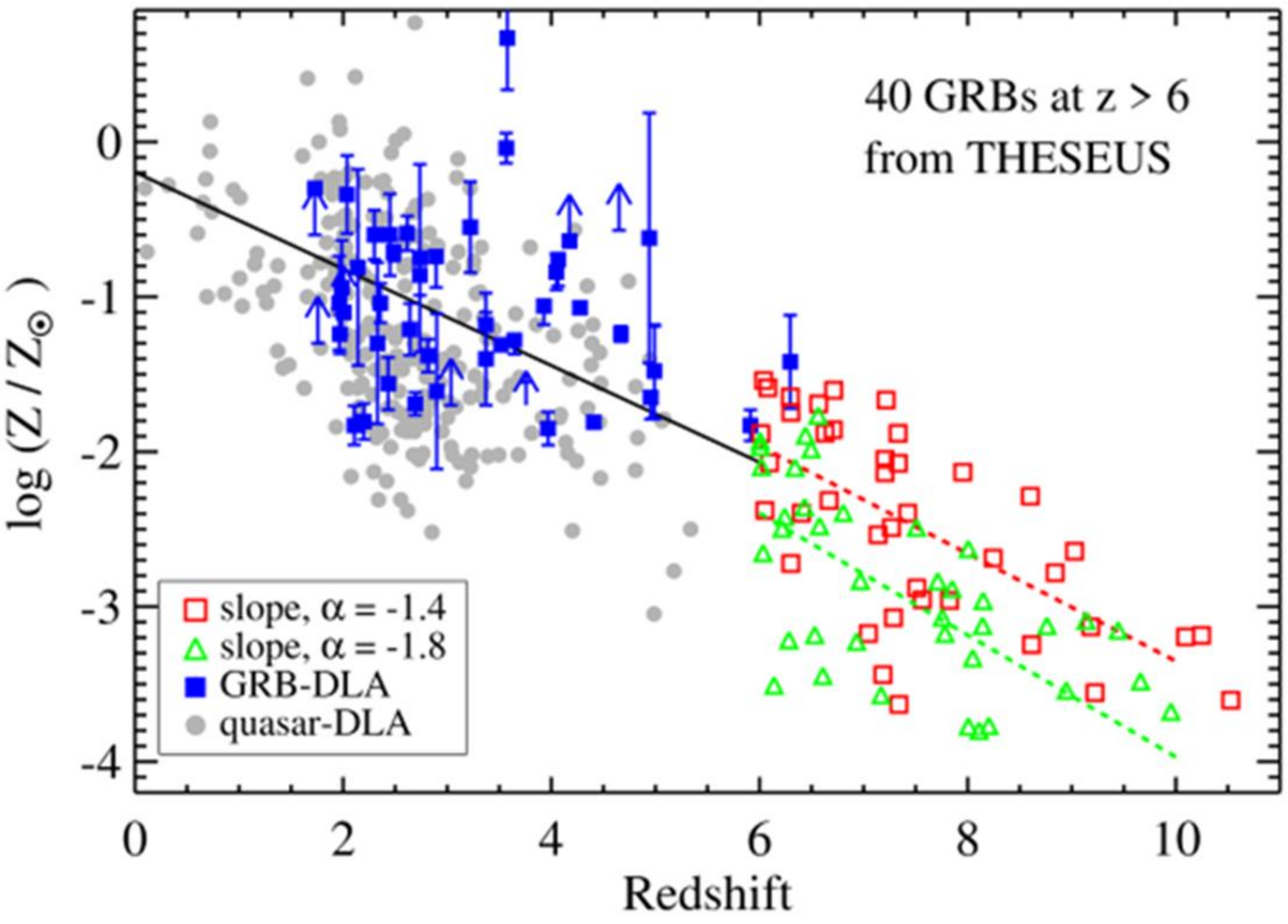
• Shedding light on cosmic reionization



Combination of massive star formation rate and ionizing escape fraction will establish whether stellar radiation was sufficient to reionize the universe, and indicate the galaxy populations responsible

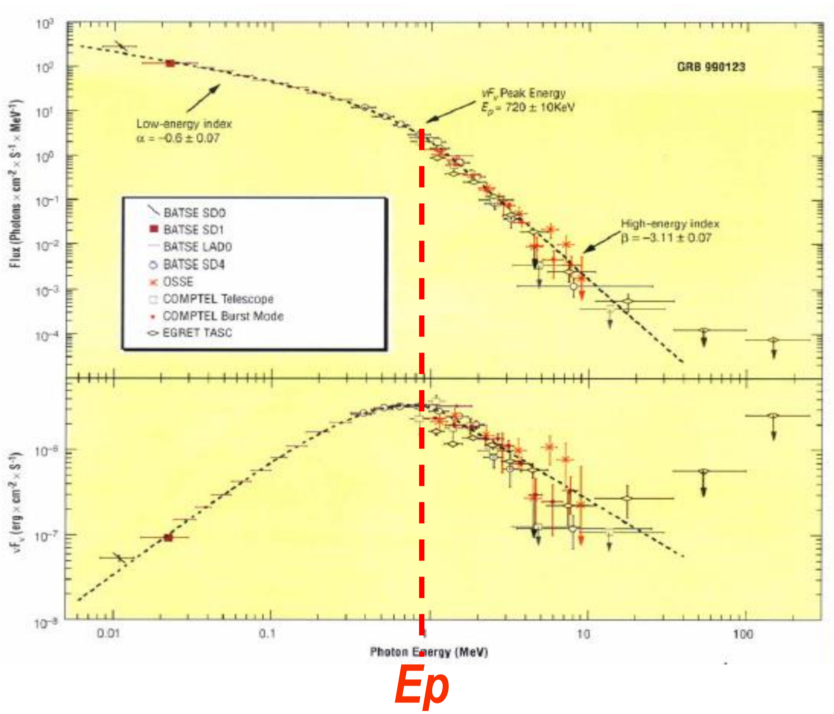
THESEUS Consortium 2021

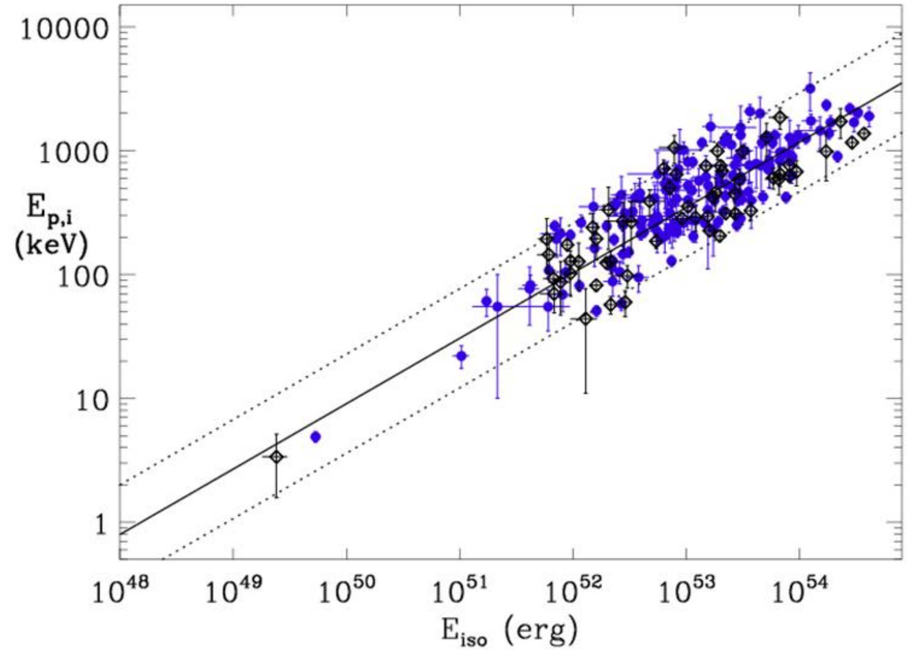
• **Cosmic chemical evolution at high-z**

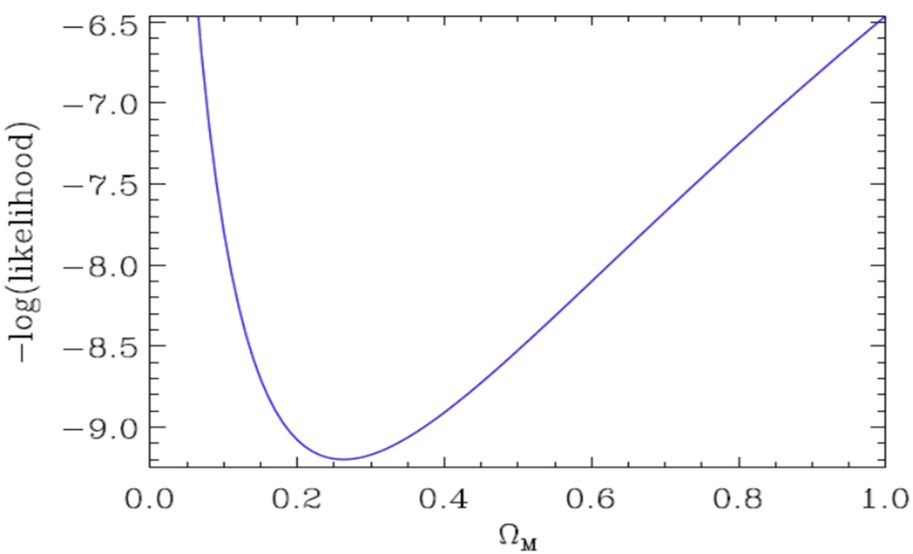


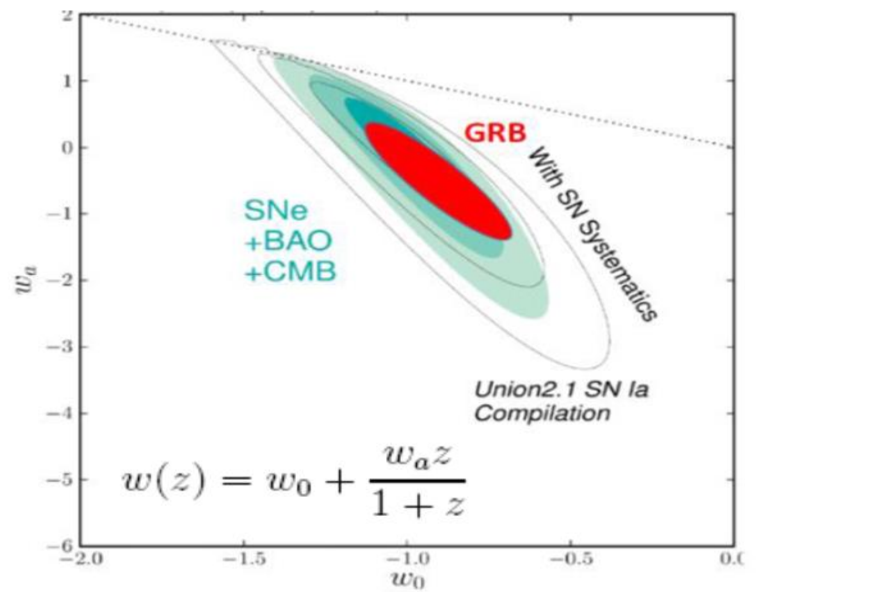
THESEUS Consortium 2021

Measuring cosmological parameters



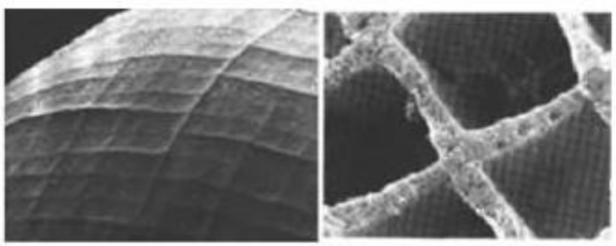




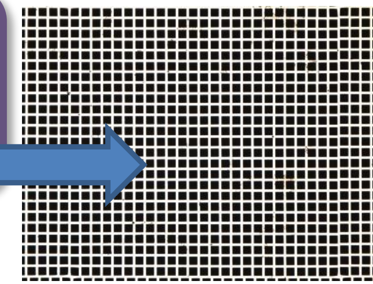


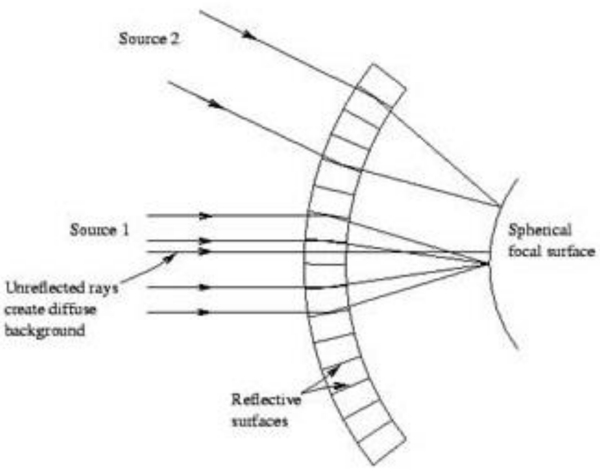
The Soft X-Ray Imager (SXI)

Two sensitive "lobster-eye" X-ray telescopes (0.3 - 5 keV); total FOV of 0.5sr (>1000 × conventional X-ray telescopes); 100ms photon timing; source location accuracy <2′



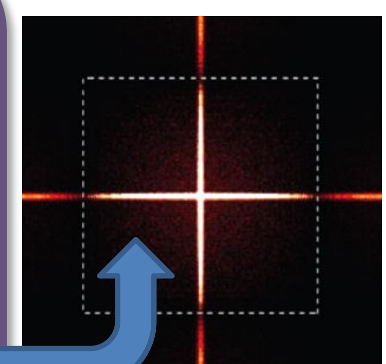
Mimic a lobster-eye using curved, square-pore MPOs





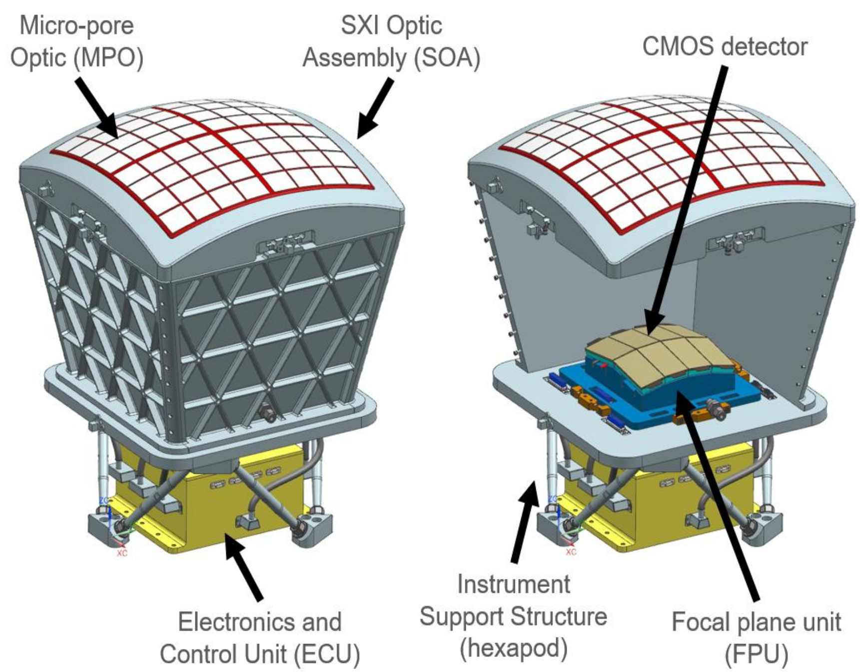
No single optical axis: get a wide field of view plus focusing with constant effective area

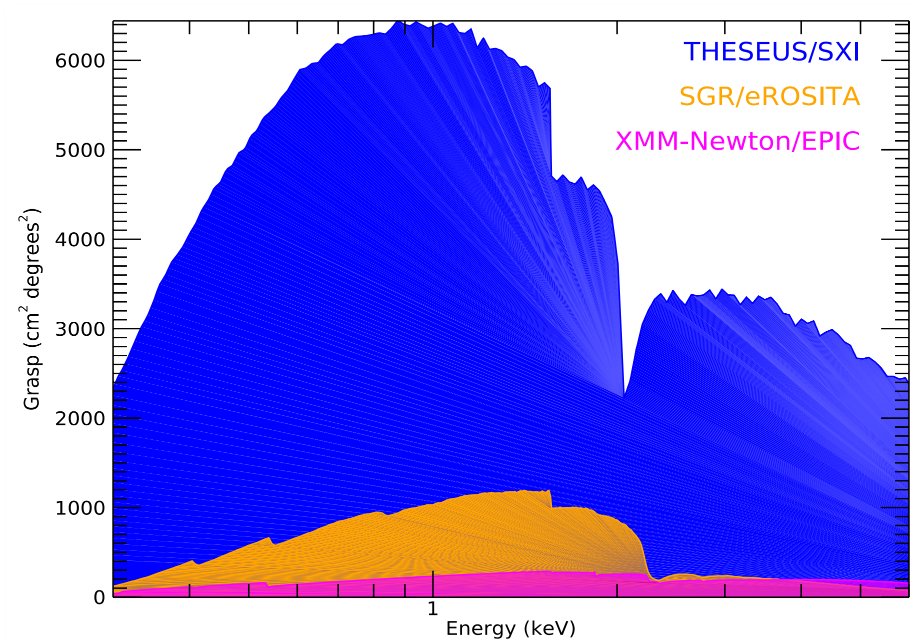
Spot (double reflection)
Lines (single reflections)



The Soft X-Ray Imager (SXI)

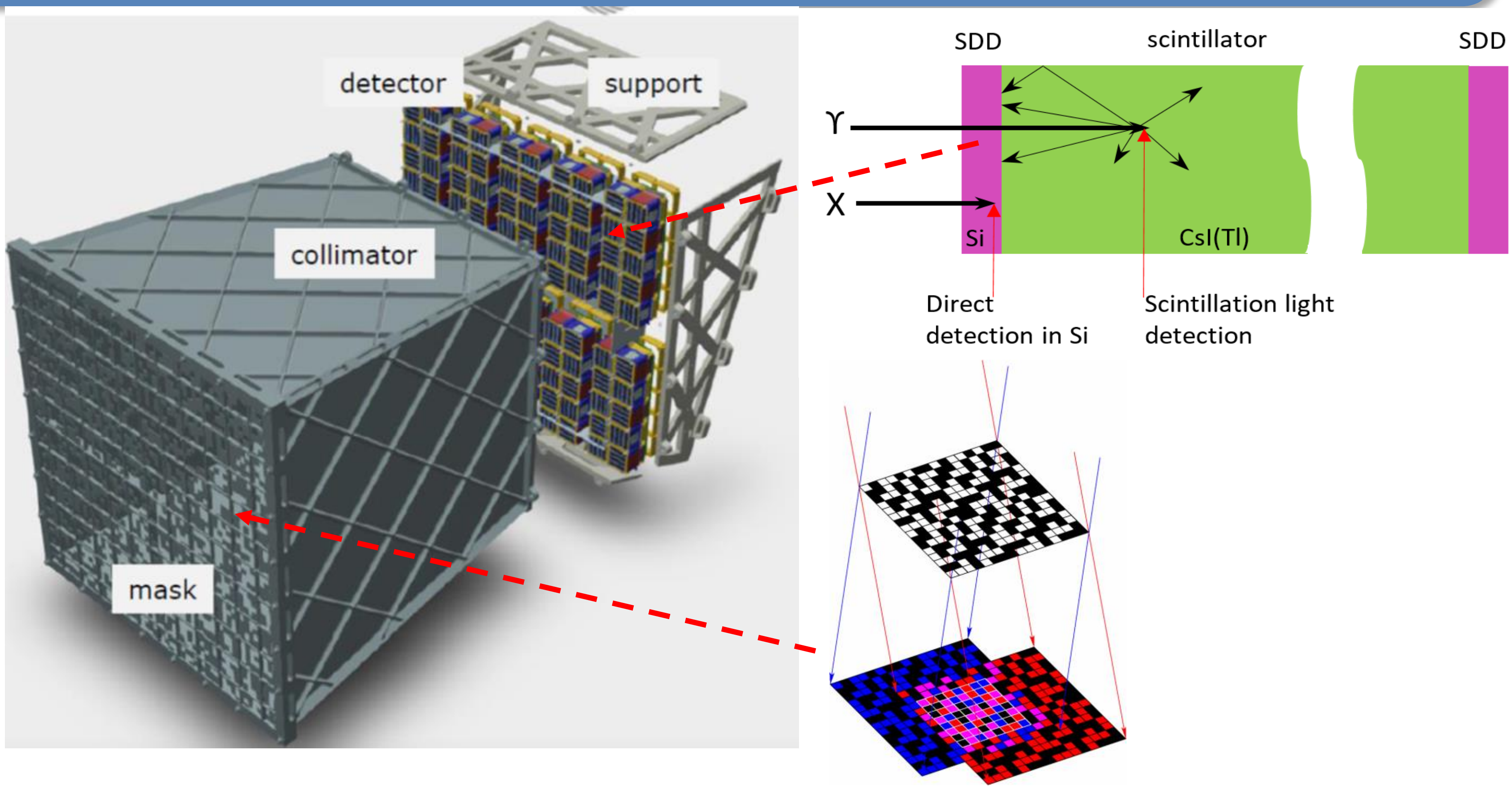
SXI will show a unique combination of FOV and effective area (GRASP), enabling simulatneous detection and localization of many transients in parallel.





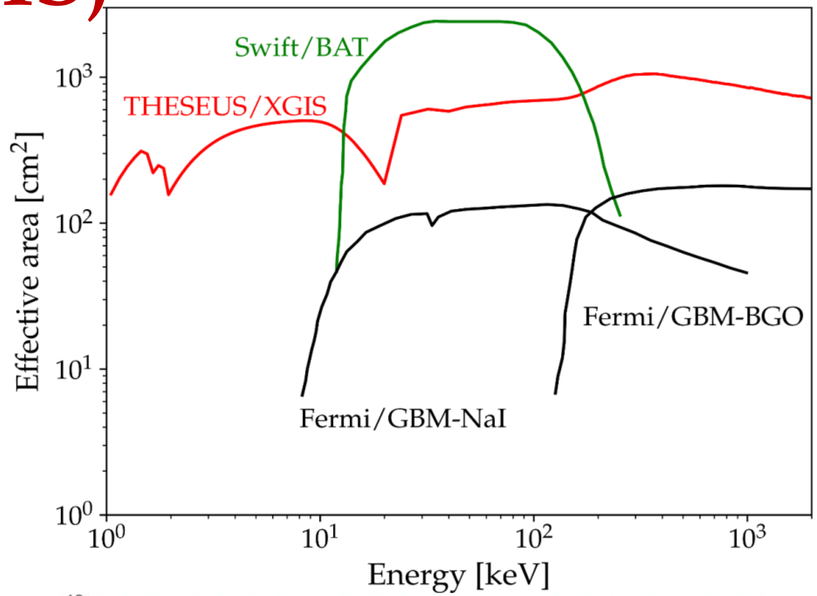
The X-Gamma Ray Imaging Spectrometer (XGIS)

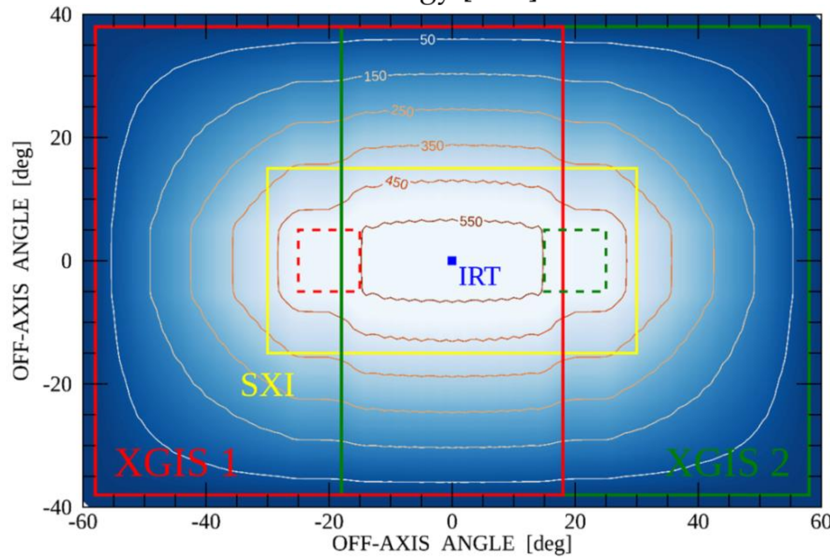
Two coded-mask X-gamma ray cameras using innovative coupling between Silicon drift detectors (2-30 keV) and CsI crystal scintillator bars (20 keV–10 MeV)



The X-Gamma Ray Imaging Spectrometer (XGIS)

- Unprecedented energy band (2 keV – 10 MeV)
- Large effective area down to 2 keV
- FOV >2 sr overlapping the SXI one
- GRB location accuracy <15′ in 2-150 keV
- Excellent timing (< a few μs)

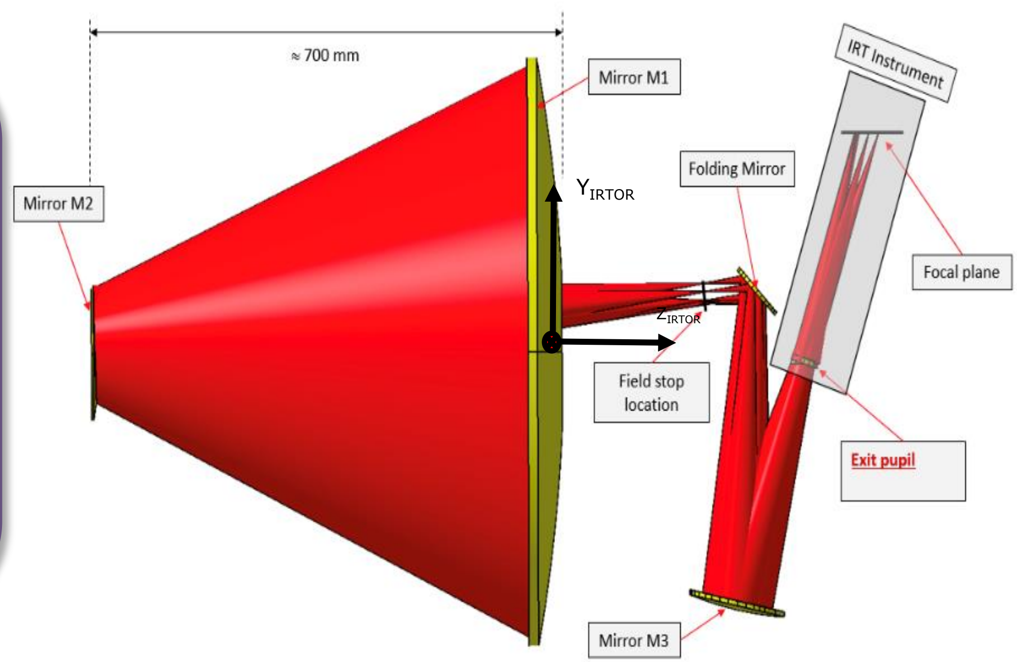




The Infra-Red Telescope (IRT)

A 0.7 m class telescope with an off-axis Korsch optical design allowing for a large field of view (15′x15′) with imaging and moderate (R~400) spectroscopic capabilities

Teledyne H2RG sensitive in 0.7-1.8 microns
Expected sensitivity per filter (over 150 s): 20.9 (I), 20.7 (Z), 20.4 (Y), 21.1 (J), 21.1(H).
Spectral sensitivity limit (over 1800 s), about 17.5 (H) over the 0.8-1.6 microns



The Infra-Red Telescope (IRT)

On-board photometric redshift for >90% detected GRB afterglows

On-board sensitive absorption spectrosocpy for medium-bright events