The THESEUS space mission concept

Transient High-Energy Sky and Early Universe Surveyor

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Lorenzo Amati
on behalf of the
THESEUS Consortium
(9th October 2024)

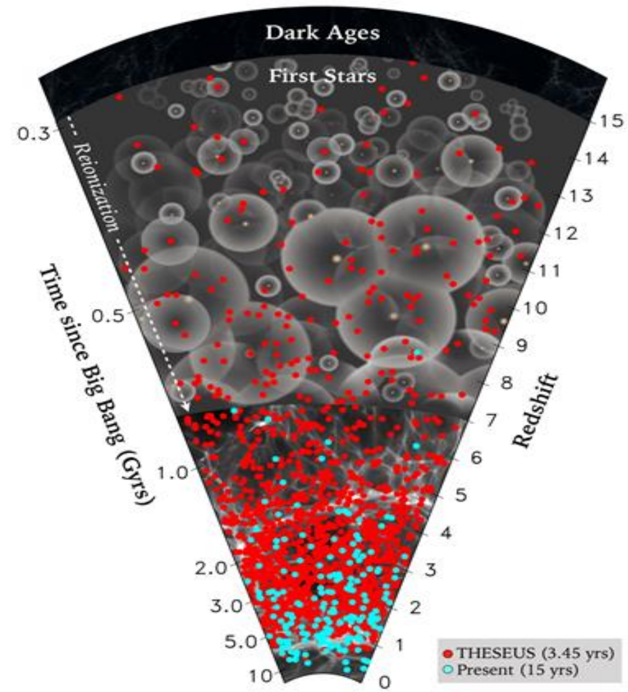
theseus M7
transient high energy sky and early universe surveyor

High Energy Astrophysics and Cosmology in the era of all-sky surveys

THESEUS Science Case

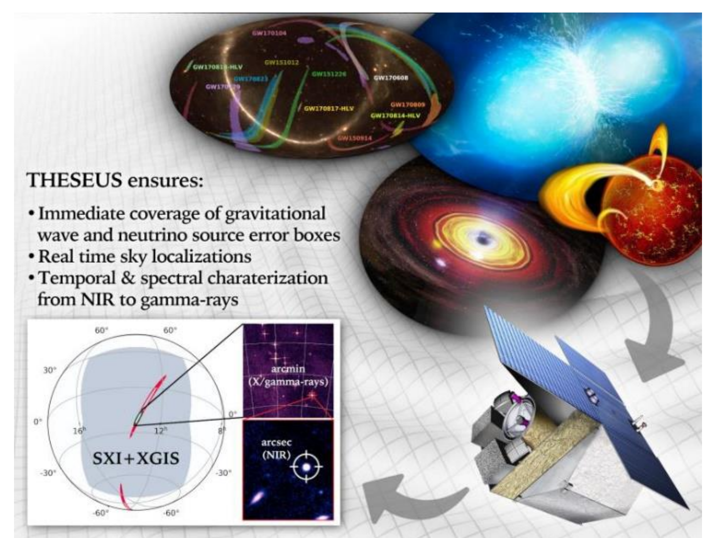
Core Science pillars:

- Probe the **early Universe (first stars, first galaxies, cosmic reionization)**, by unveiling and exploiting the population of high redshift Gamma-Ray Bursts (GRB)
- Provide a **fundamental contribution to multi-messenger time domain astrophysics** through short GRB and other transients

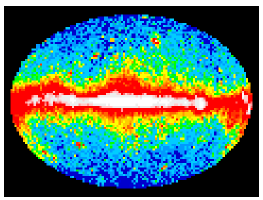


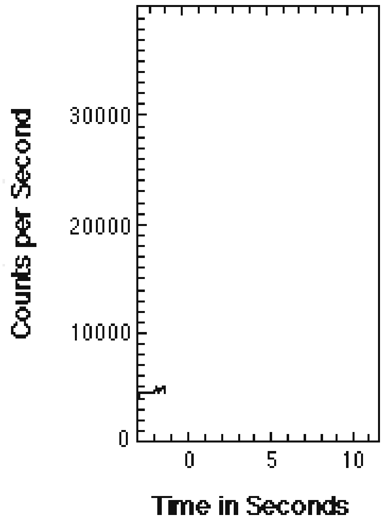
Observatory Science includes:

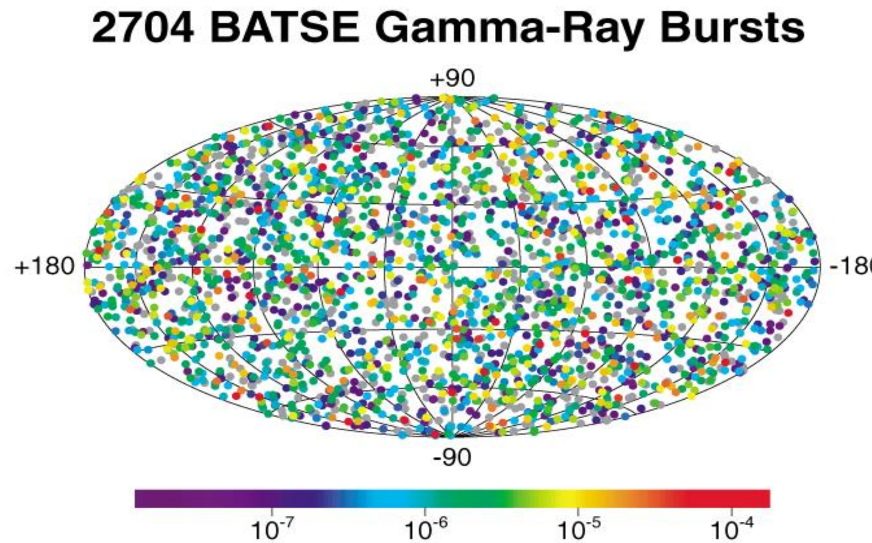
- Study of thousands of faint to bright X-ray sources by exploiting the **simultaneous broad band X-ray and NIR observations**
- Provide a **flexible follow-up observatory** for fast transient events with multi-wavelength ToO capabilities and **GO programmes**

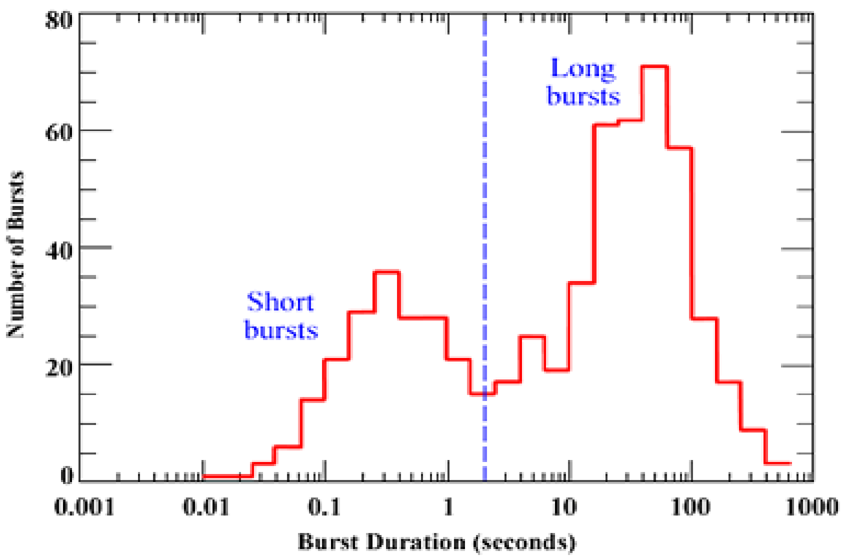


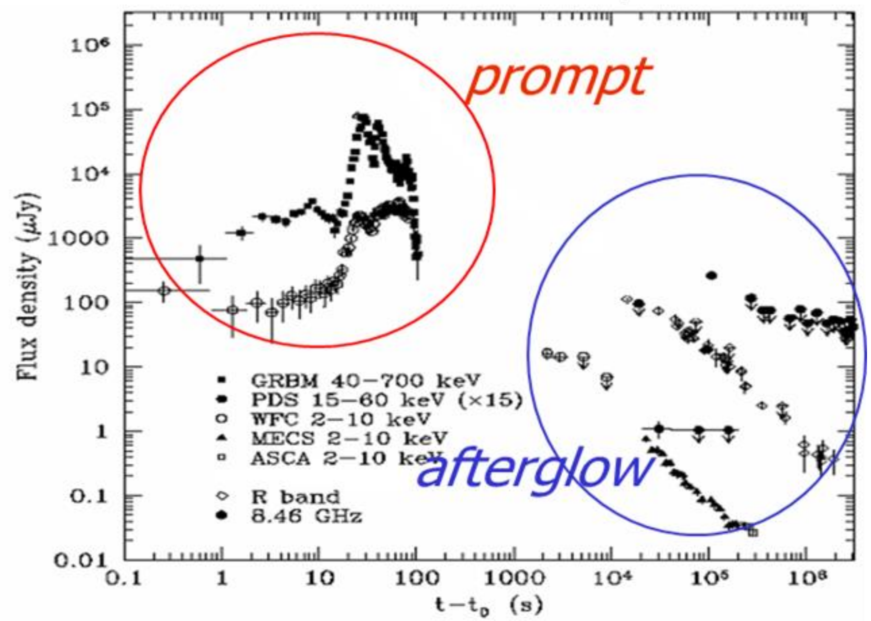
Gamma-Ray Bursts: the most extreme phenomena in the Universe











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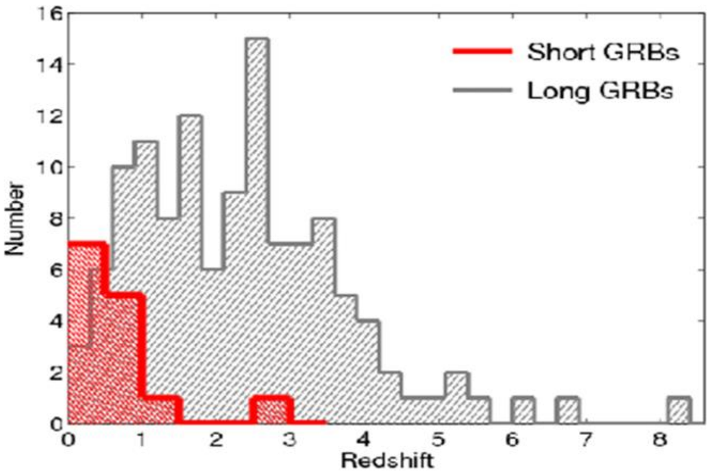
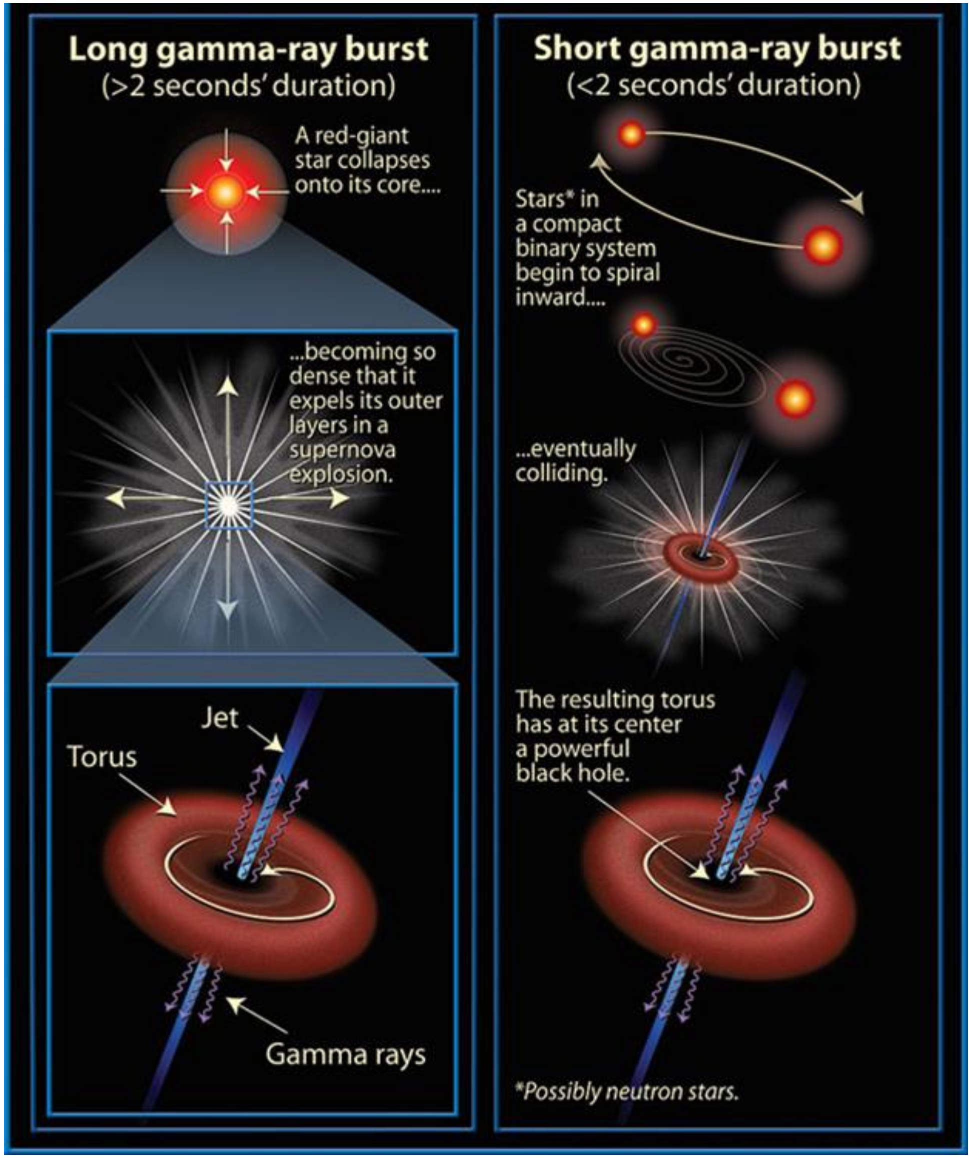
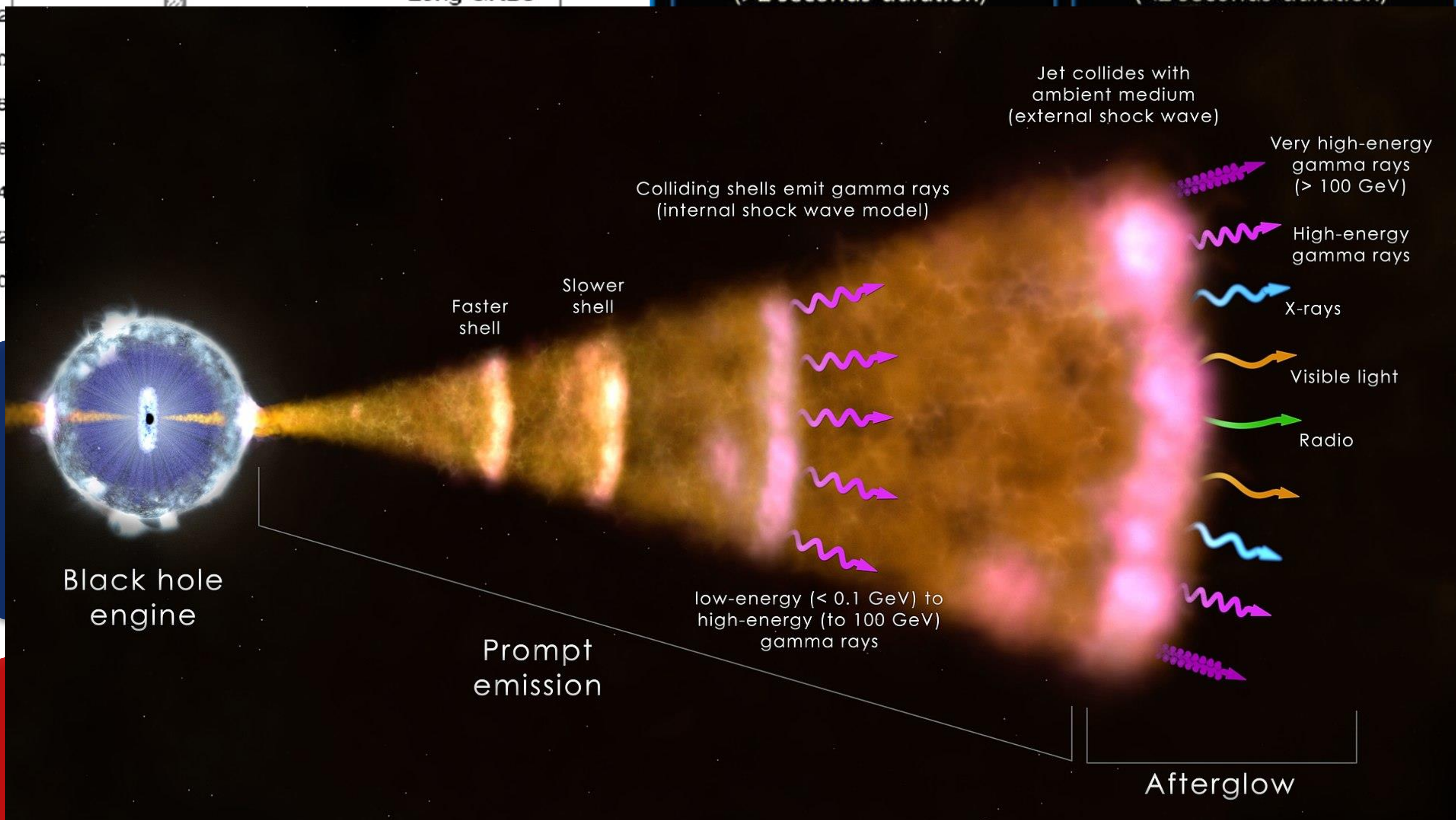


Long GRBs: core collapse of pecular massive stars, **association with SN**

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

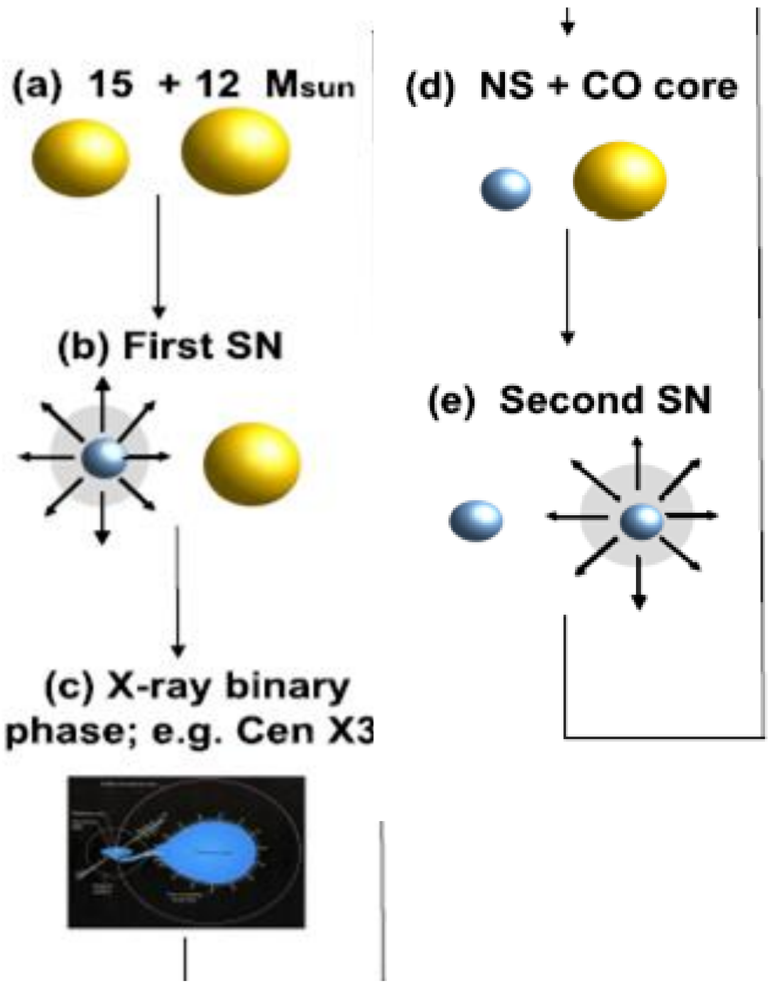


Gamma-Ray Bursts: the most extreme phenomena in the Universe

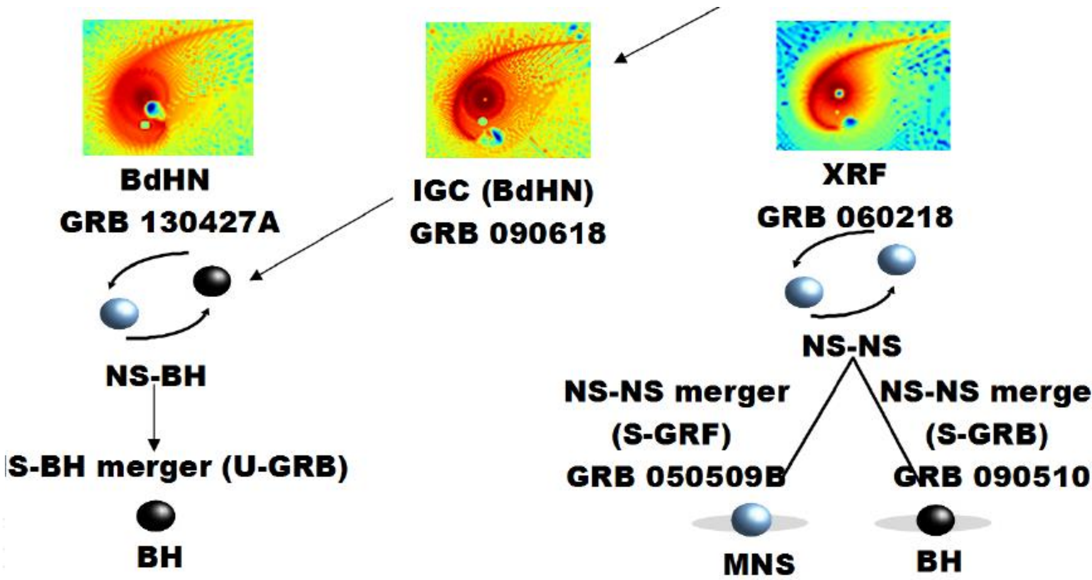


association with
GW sources

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



The binary-driven hypernova model



Bianco et al., ApJ 2024; Aimuratov et al. ApJ 2023; Rueda, et al., ApJ 2022; Ruffini, et al., MNRAS 2021; Moradi, et al., A&A 2021; Rueda, et al., ApJ 2020; Rueda & Ruffini, EPJC 2020; Ruffini, et al., ApJ 2019; Becerra, et al., ApJ 2019; Ruffini, et al., ApJ 2018; Ruffini, et al., ApJ 2018; Becerra, et al., ApJ 2016; Fryer et al., PRL 2015; Fryer, et al., APJL 2014; Rueda & Ruffini, APJL 2012

The ESA Cosmic Vision Programme

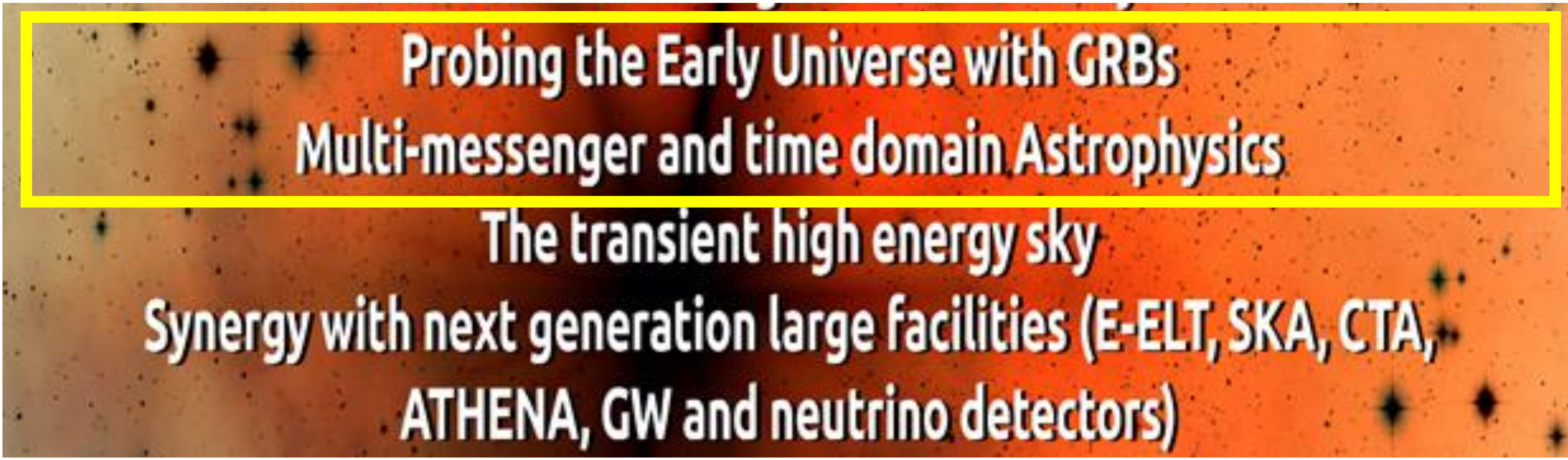
❖ Selected missions

- 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)
- L3: LISA (gravitational wave observatory, 2035)
- L2: 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 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)

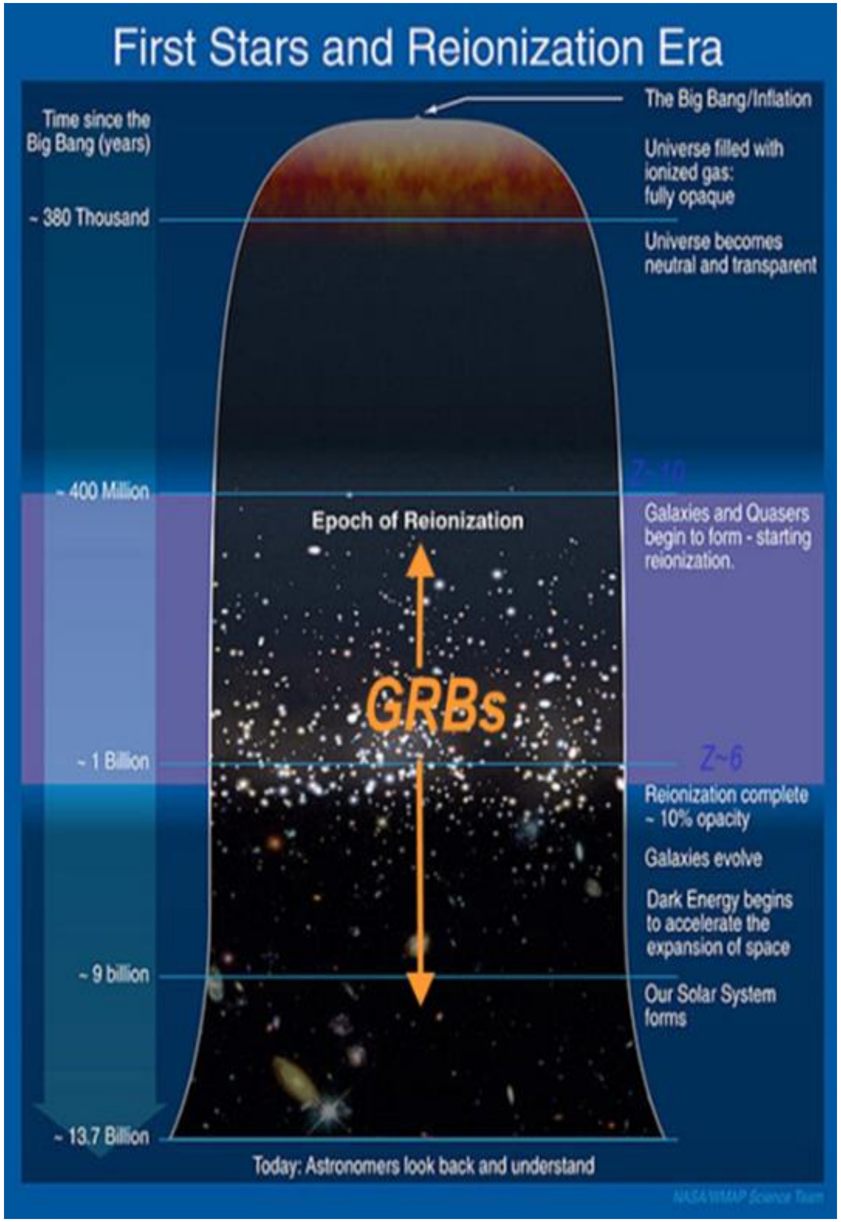
Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)
Articles for SPIE 2020 and Exp..Astr. (all on arXiv)
http://www.isdc.unige.ch/theseus

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

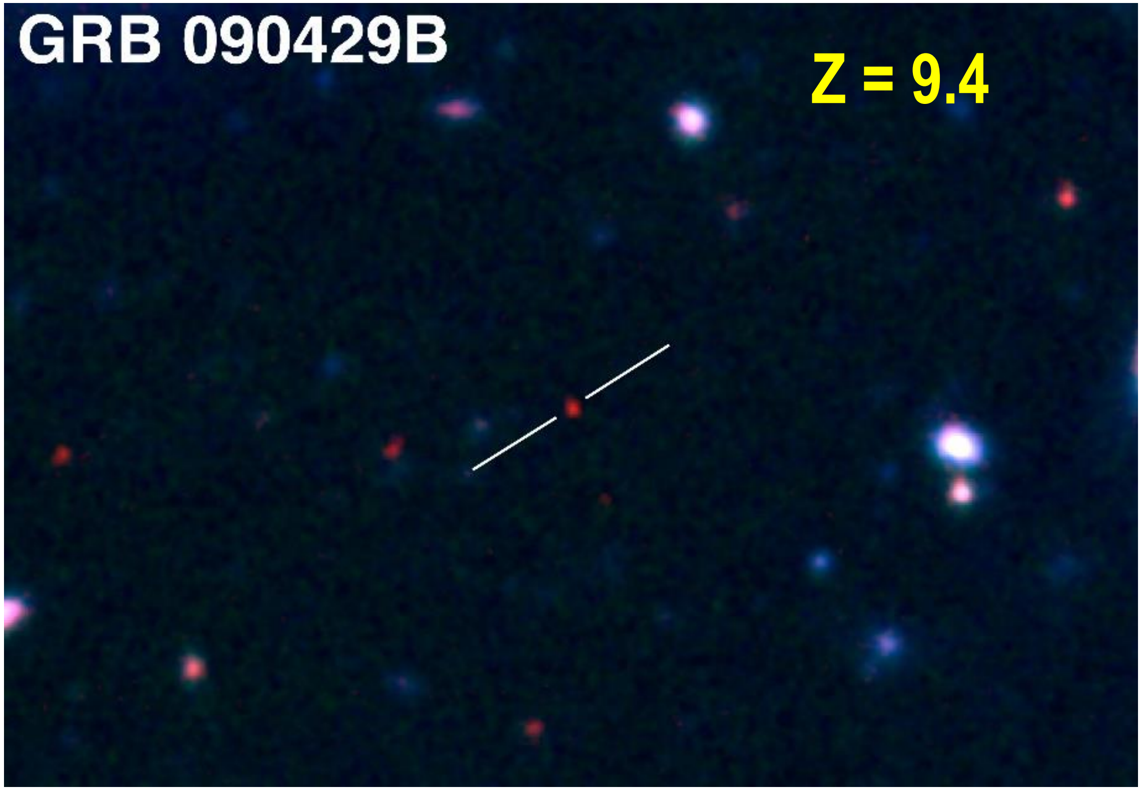
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars



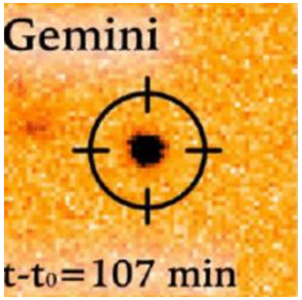
Shedding light on the early Universe with GRBs

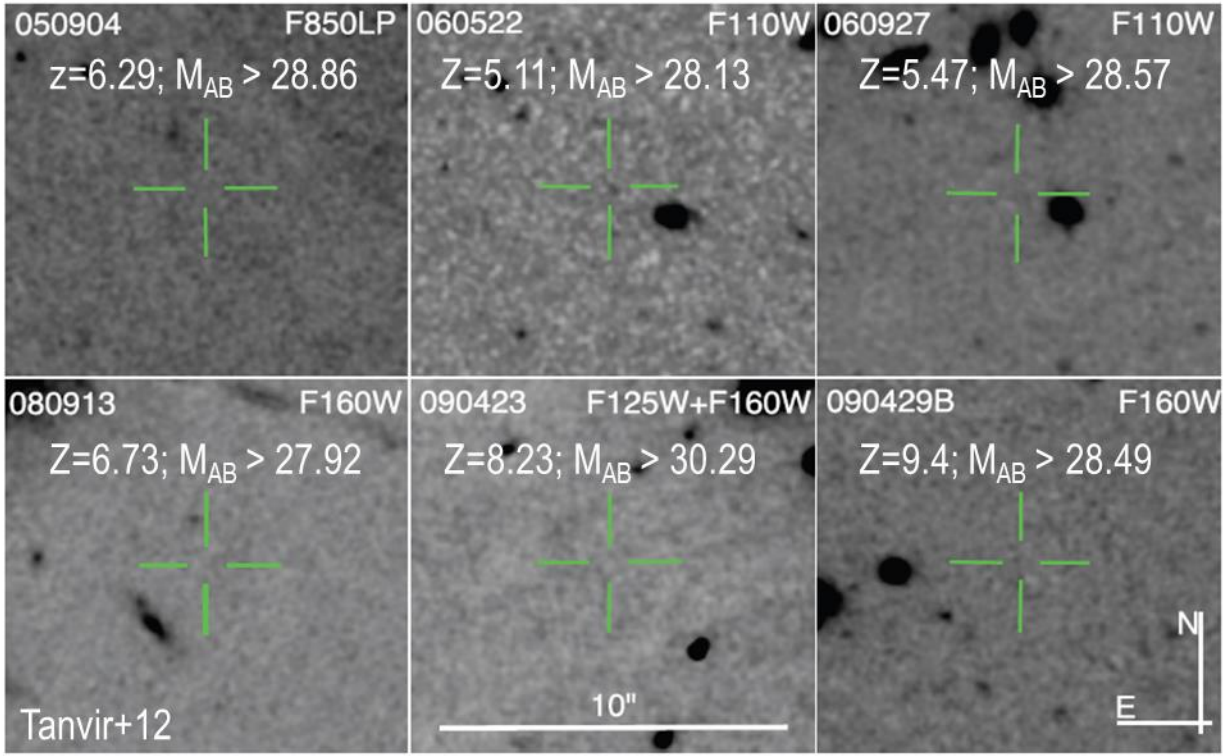
A statistical sample of high–z GRBs can provide fundamental information:

- 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

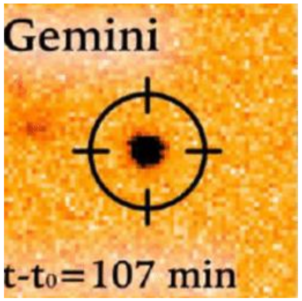


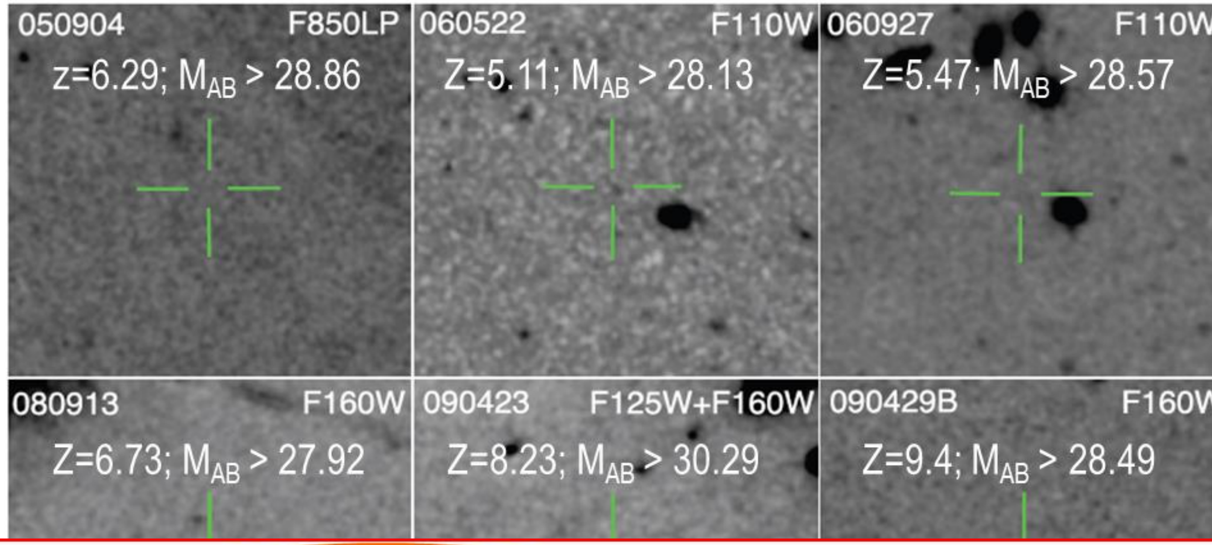


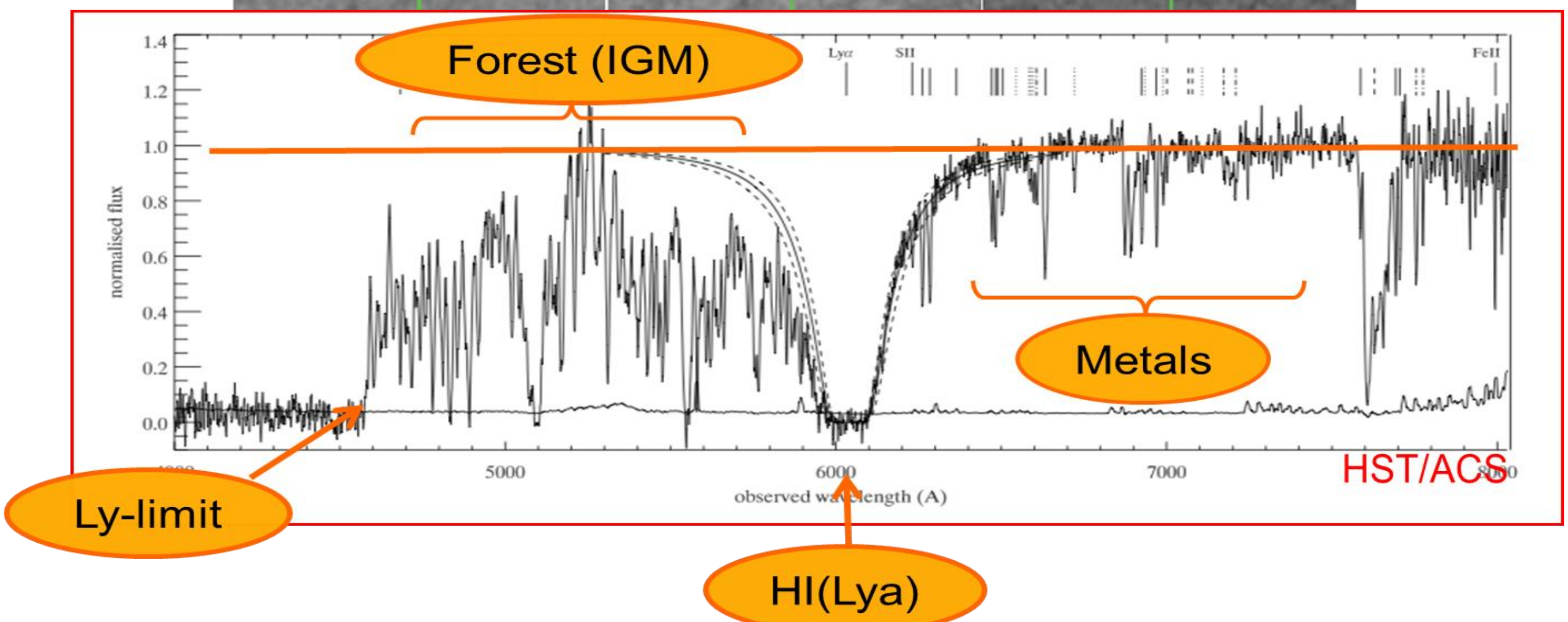
Robertson&Ellis12

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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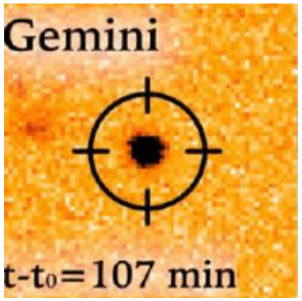
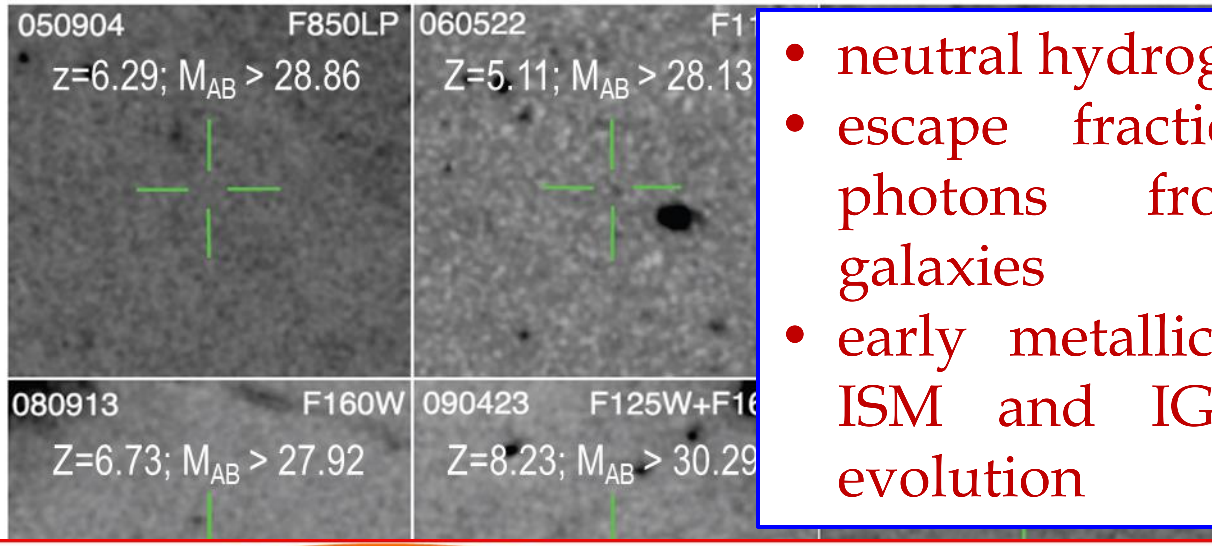
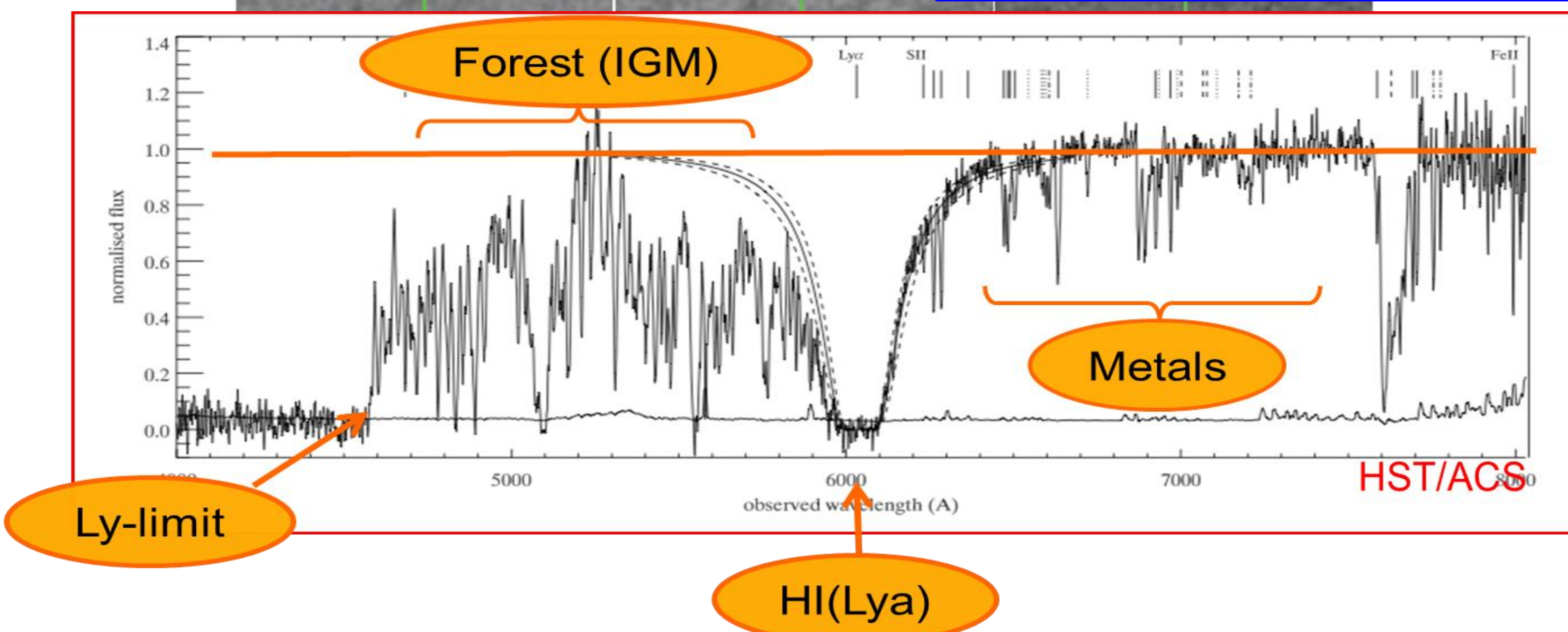




- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution



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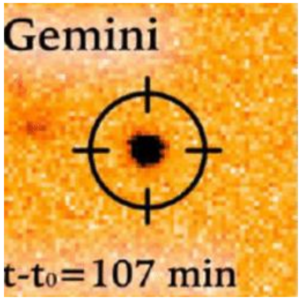

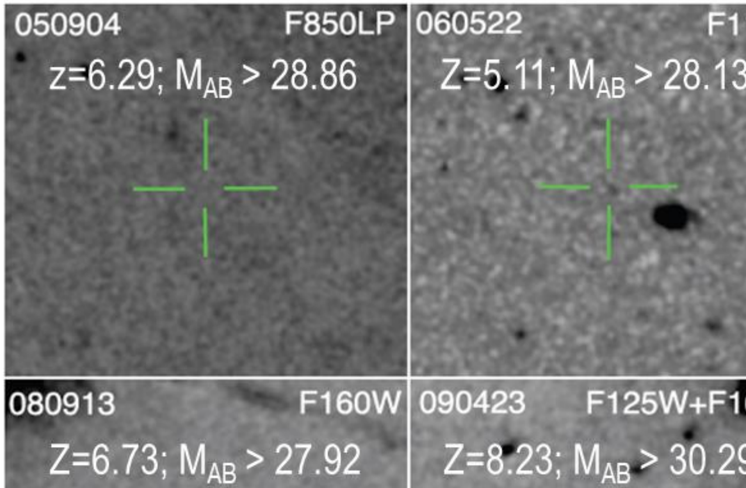

- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
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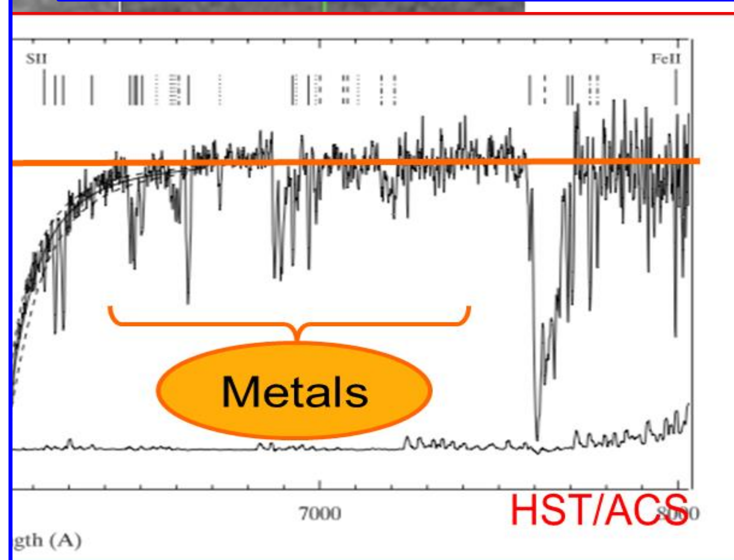
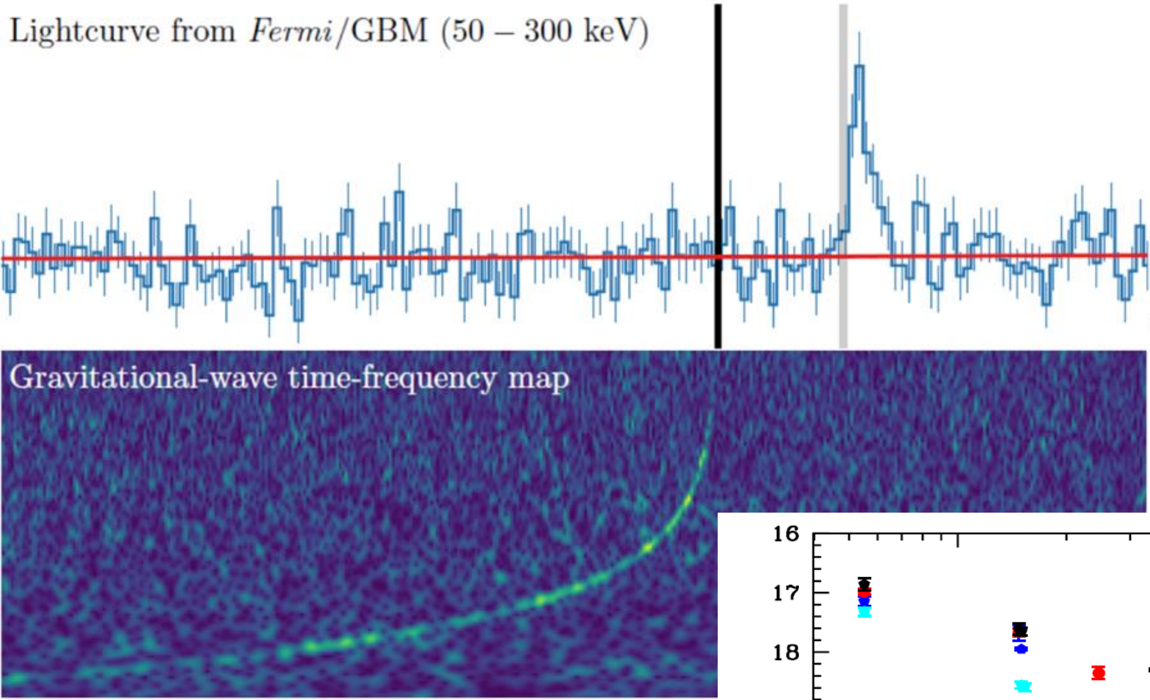
Beyond even JWST capabilities:

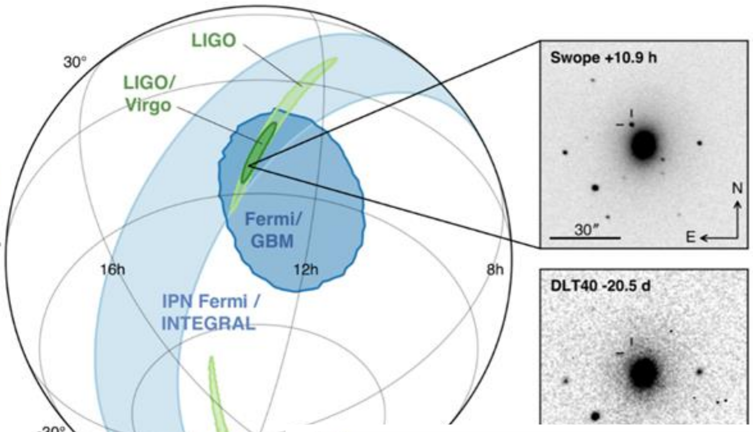
- Primordial galaxies detection and characterization Independent on mass and luminosity
- Allow absorption spectroscopy (needed because most metals are in neutral gas and and for dust ratio)
- Properties of primordial IGM
- Targets for JWST

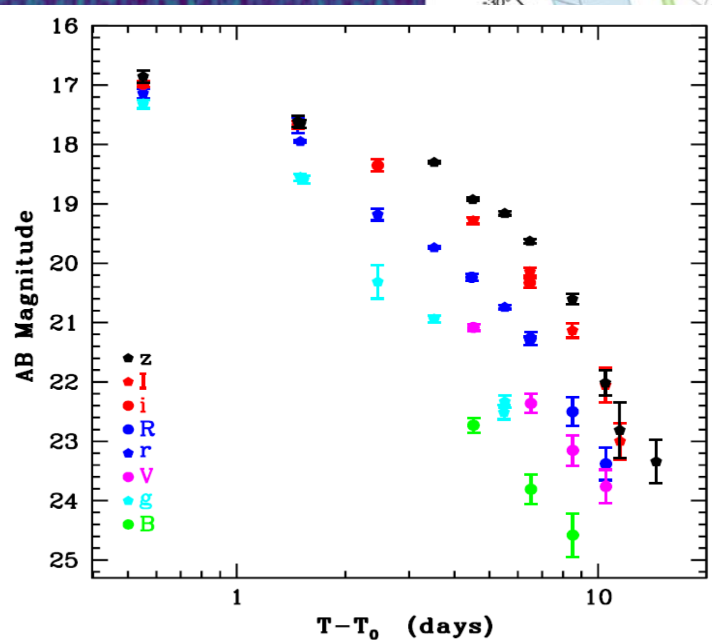


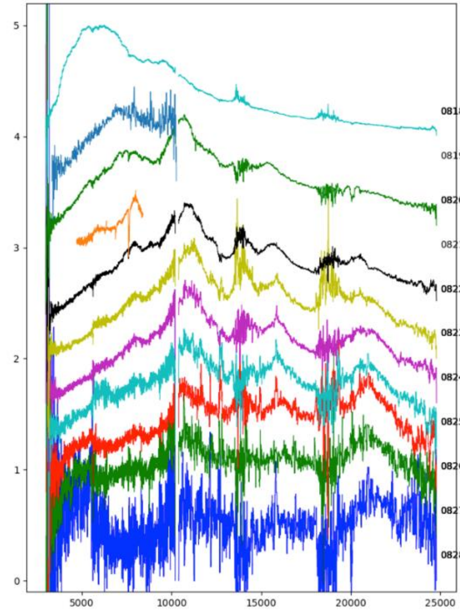
Short GRBs and multi-messenger astrophysics

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









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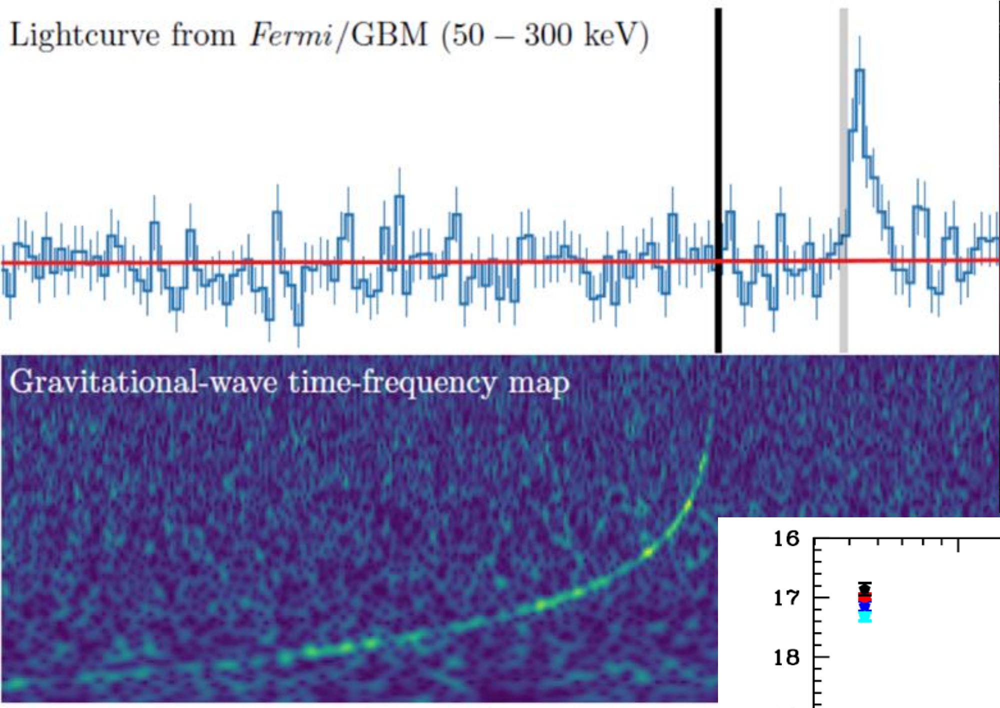
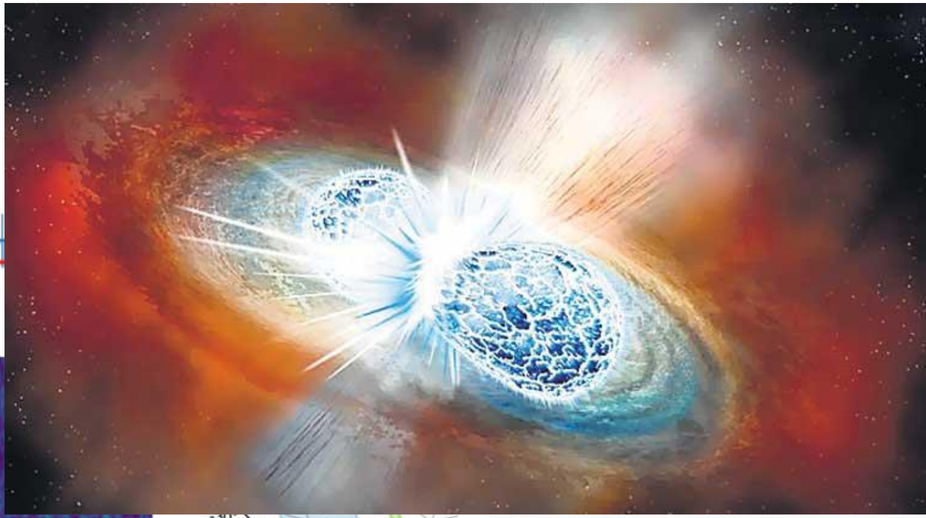
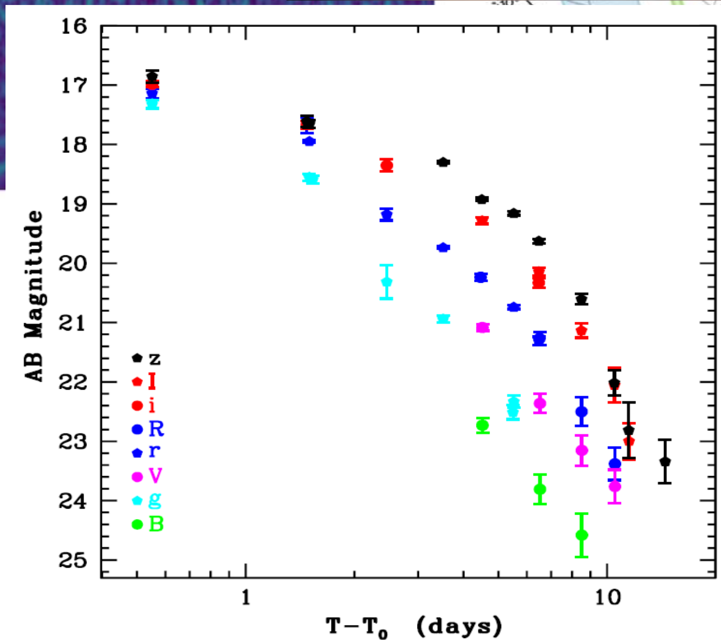
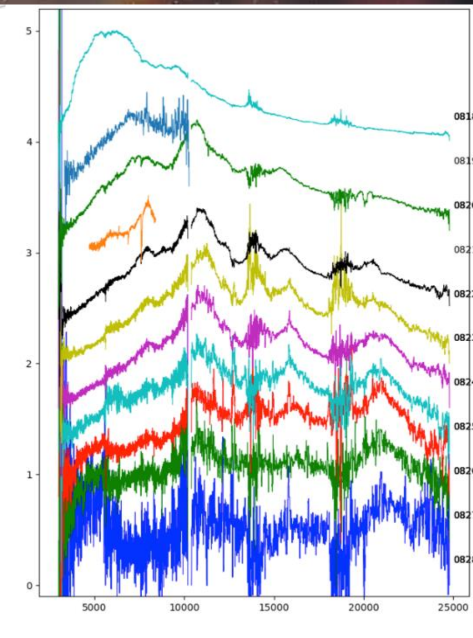




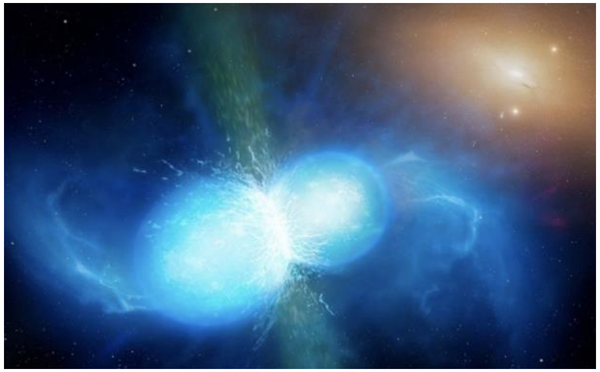




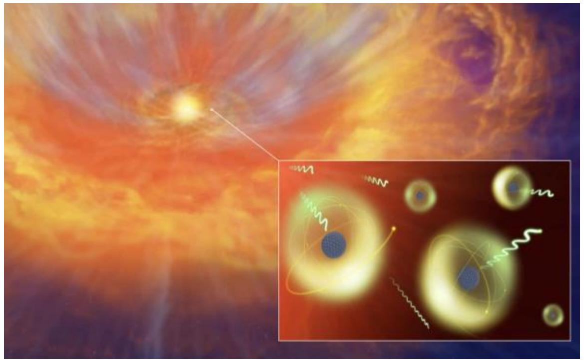
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

GW170817 + SHORT GRB 170817A + KN AT2017GFO

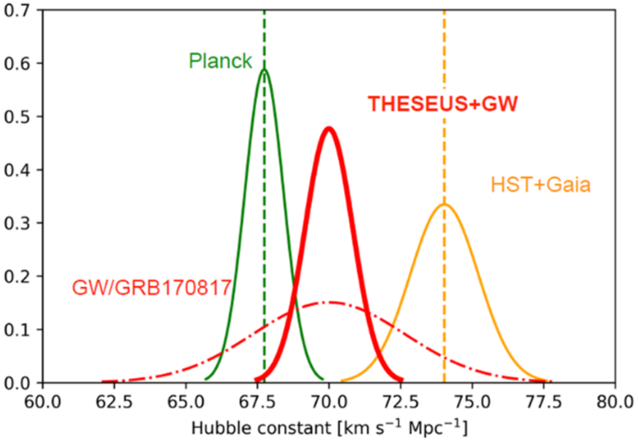
Relativistic jet formation, equation of state, fundamental physics



Cosmic sites of r-process nucleosynthesis



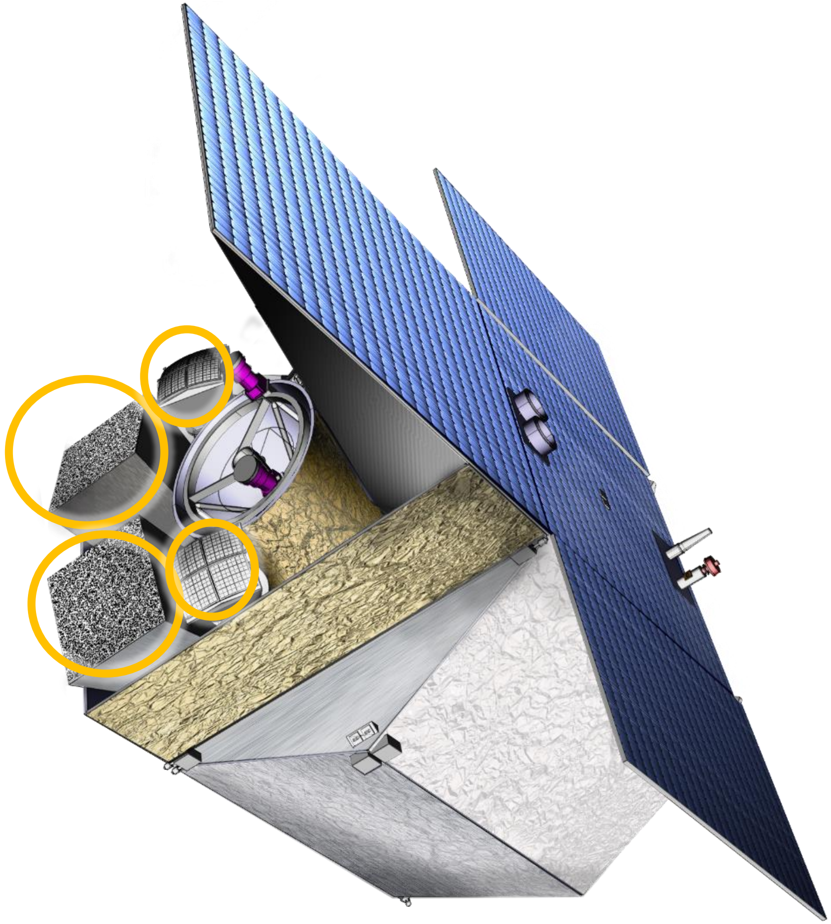
New independent route to measure cosmological parameters



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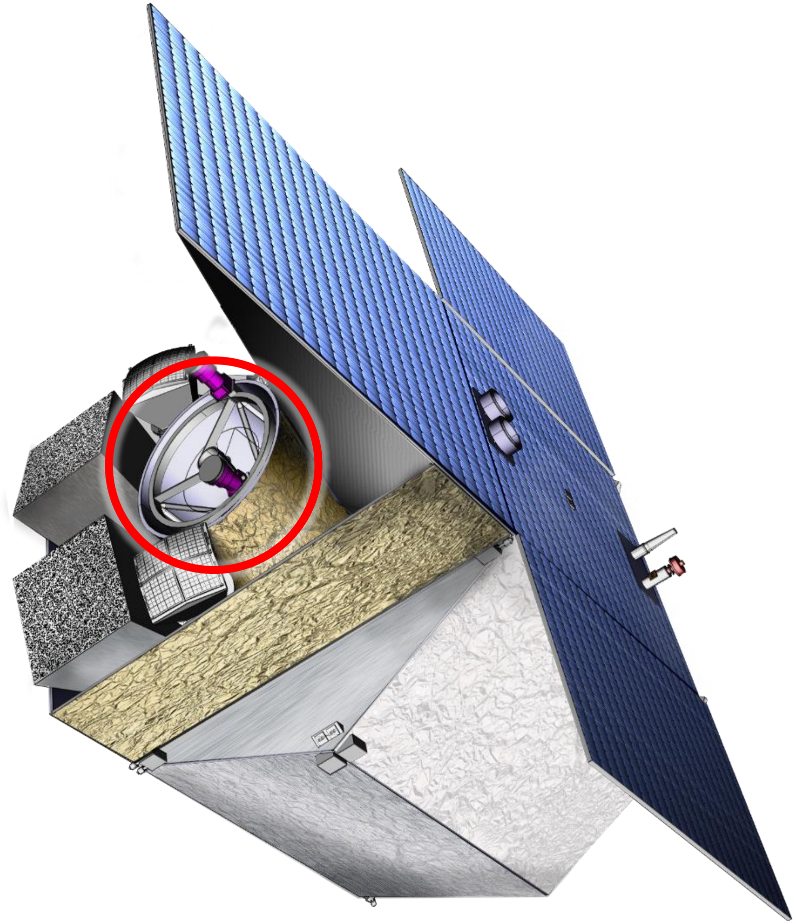
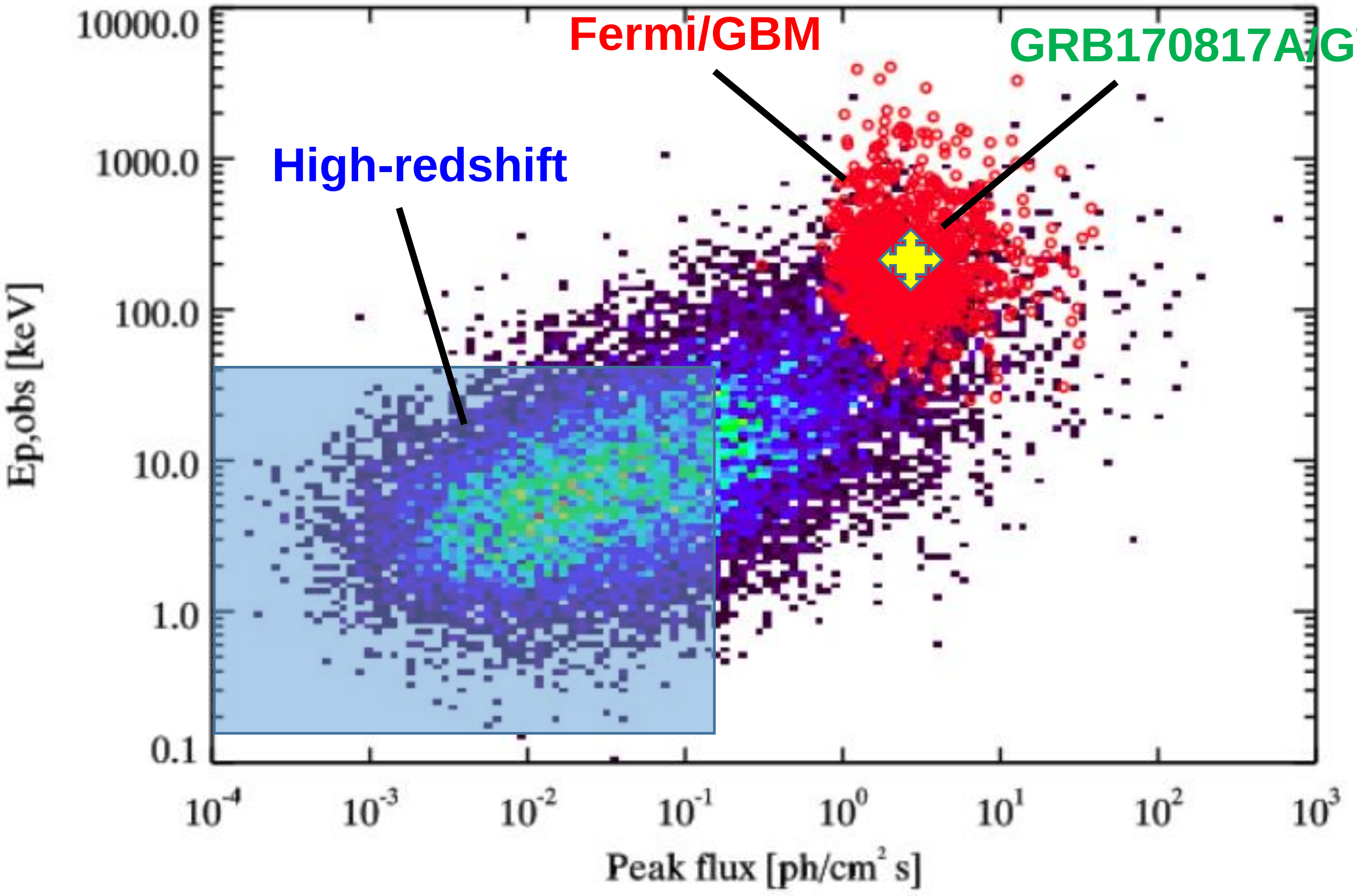
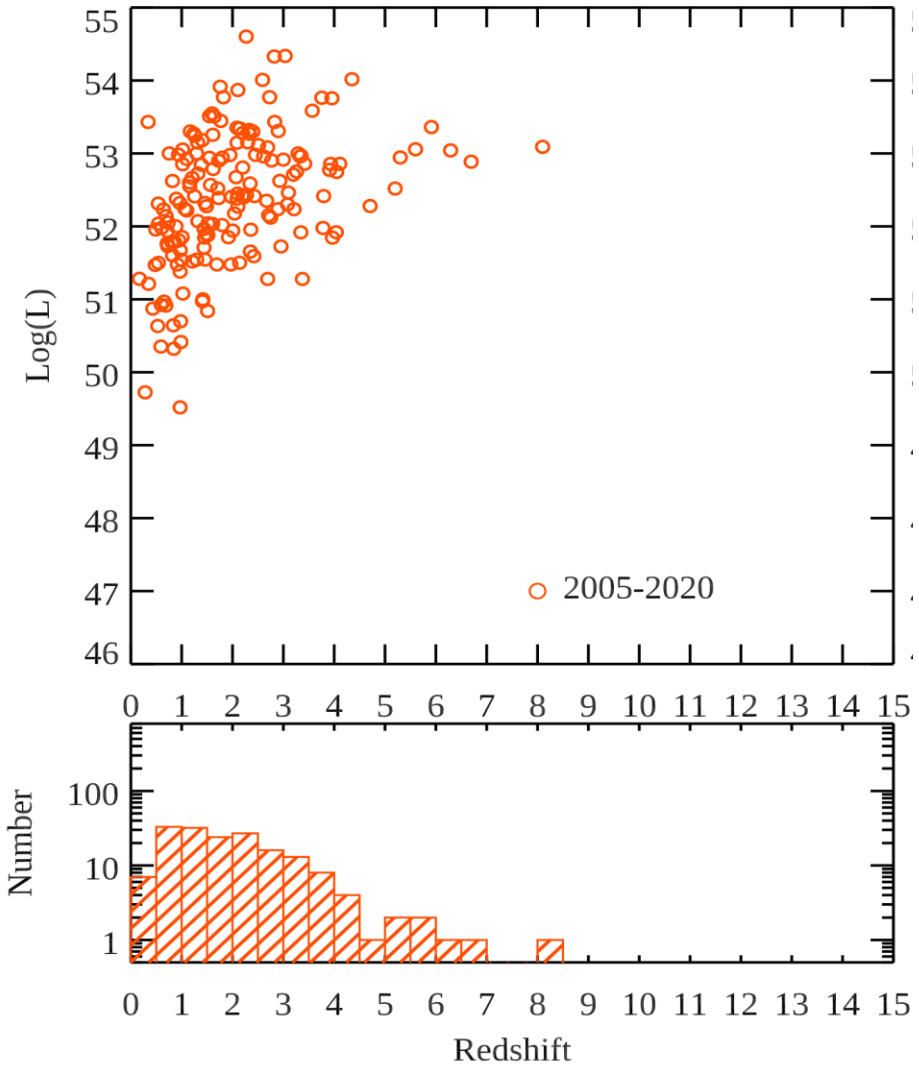
On-board **autonomous fast follow-up in optical/NIR**, arcsec location and **redshift measurement** of detected GRB/transients

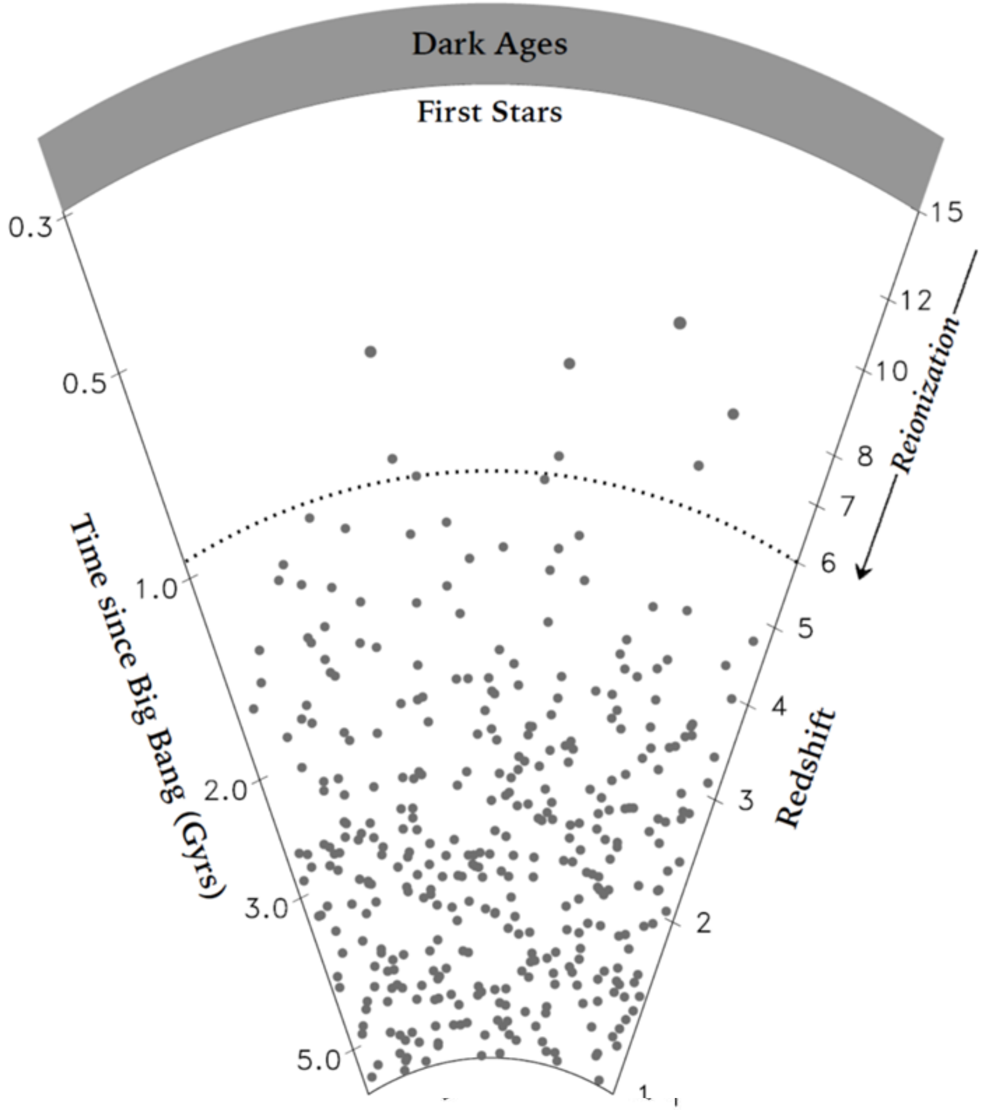


THESEUS will have a combination of instrumentation and mission profile allowing the detection of all types of GRBs (long, short/hard, weak/soft, high-redshift) and provide accurate location and redshift measurement for a large fraction of them



Expected performances: early Universe





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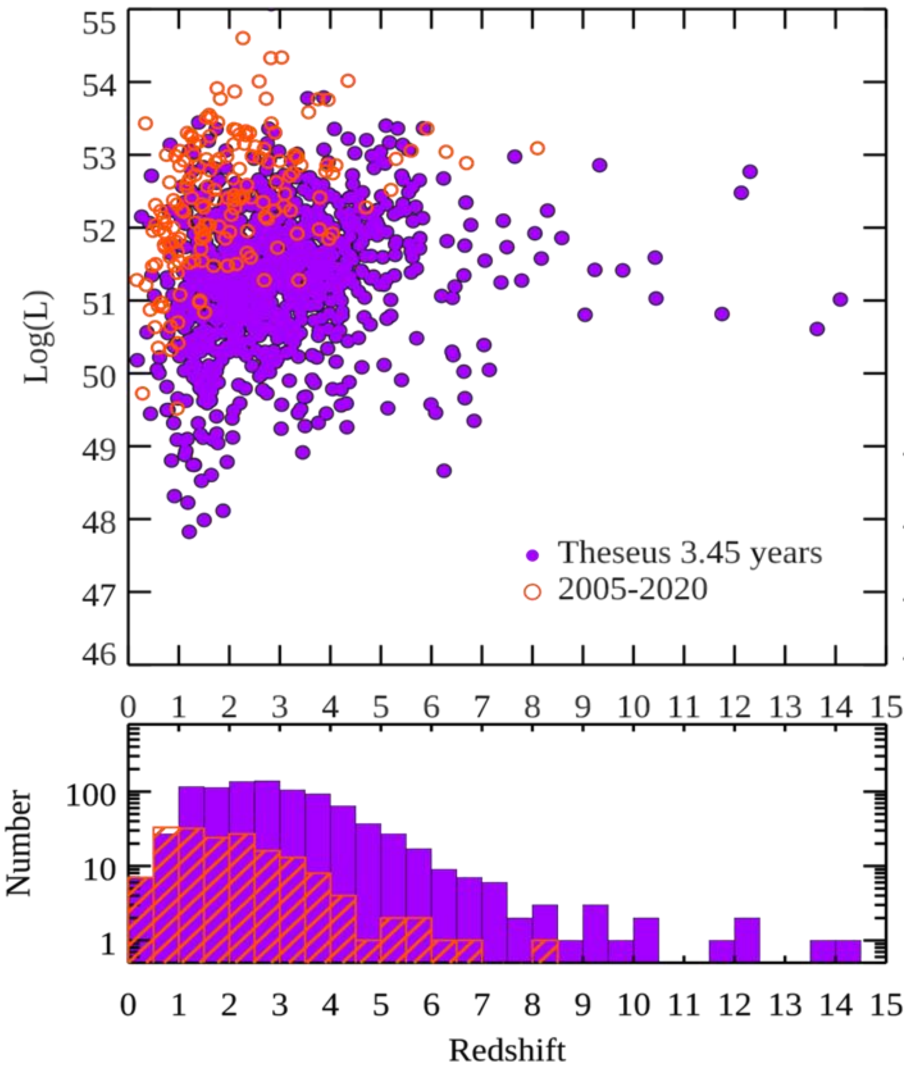
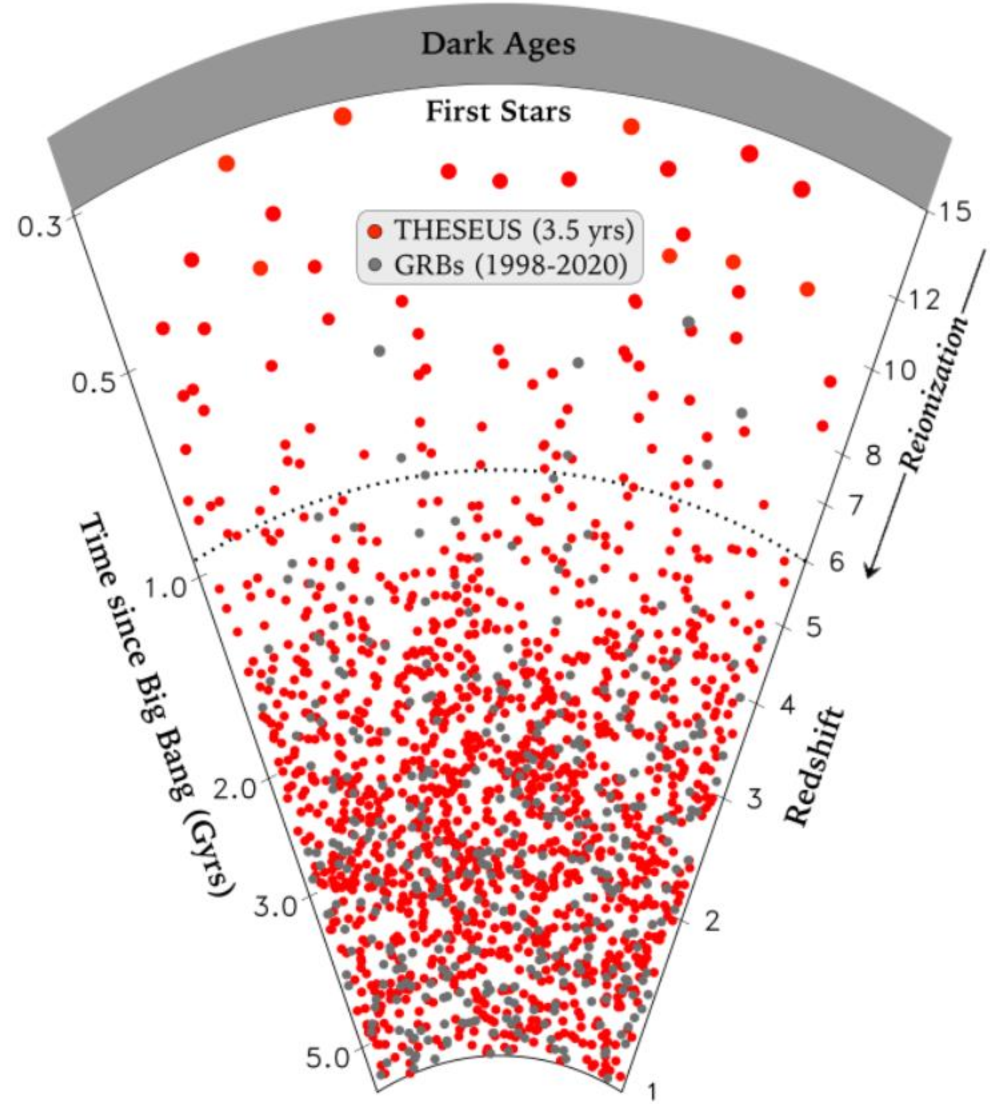
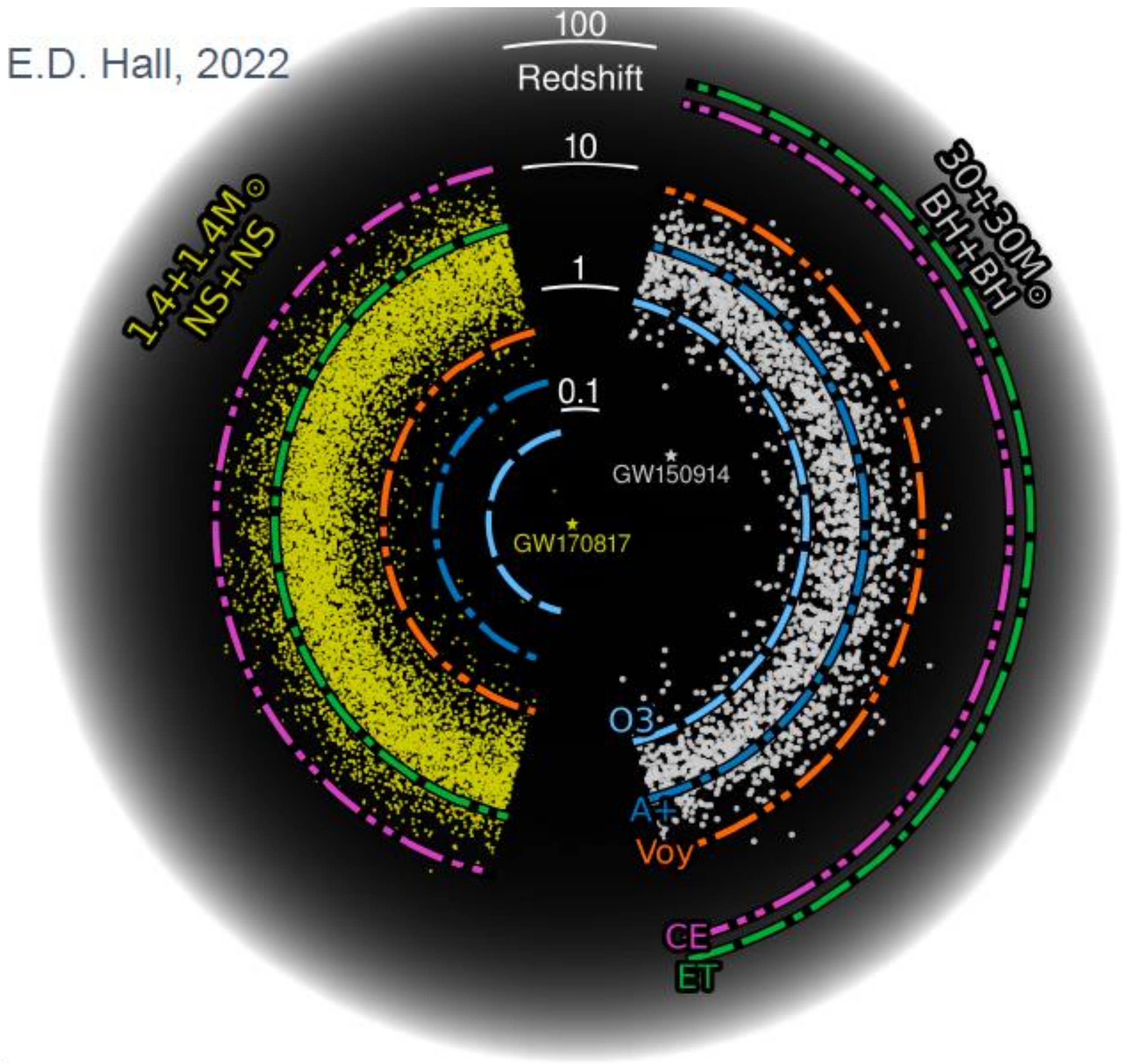




Multi-messenger science with THESEUS

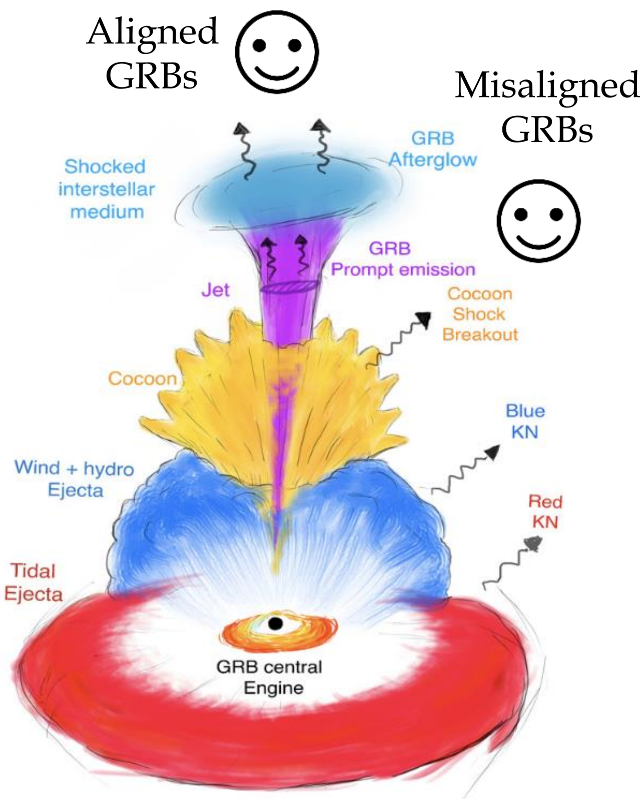
M7 timeline: great synergy with 3G GW detectors (ET, CE)



Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A



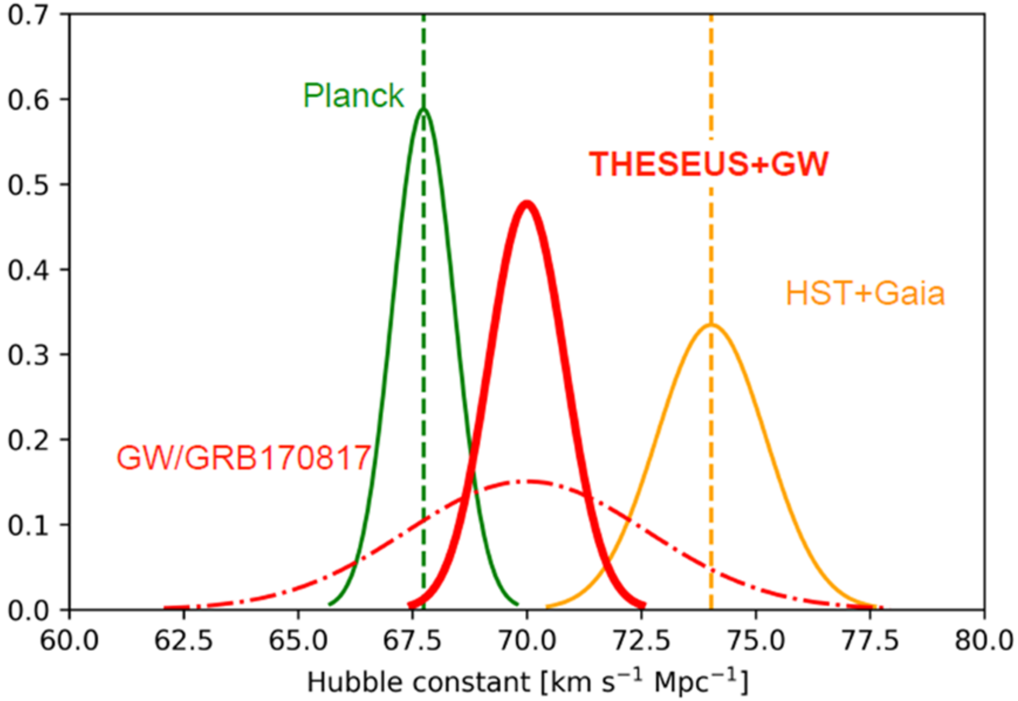
THESEUS + ET in 3 years:

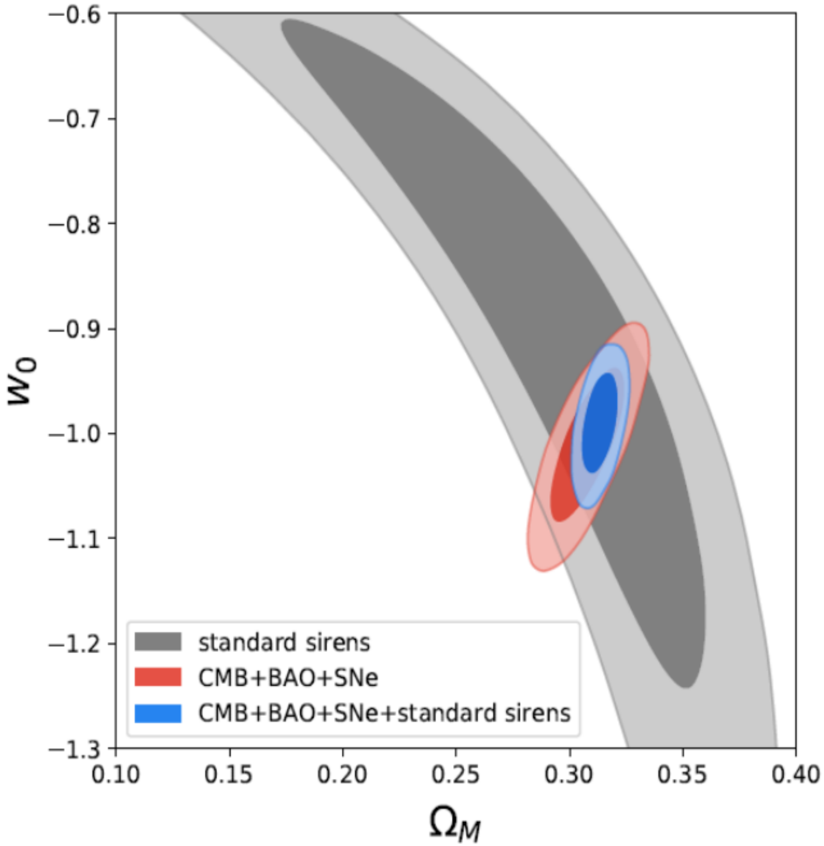
- ~70 aligned+misaligned short GRB
- additional long GRBs from mergers and possible GW-X-ray transients

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



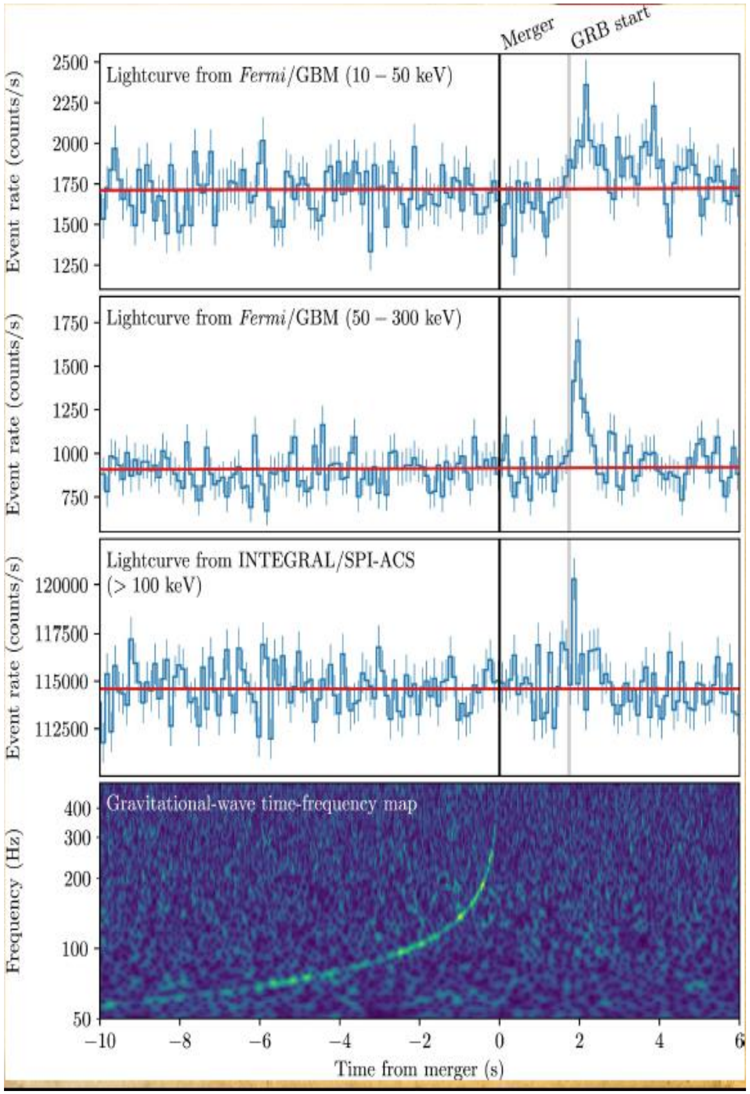


~20 joint GRB+GW events

ET collaboration

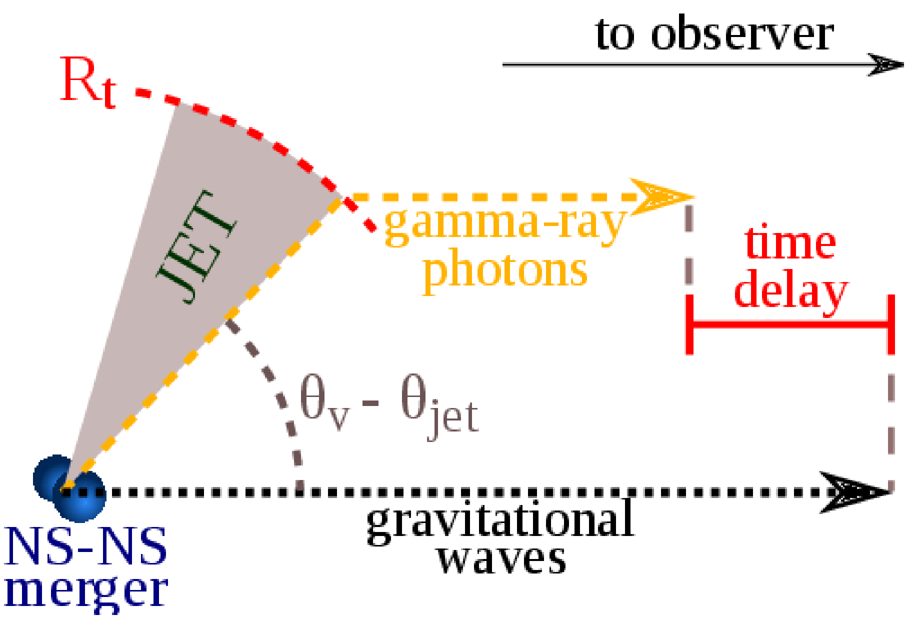
Fundamental physics: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

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

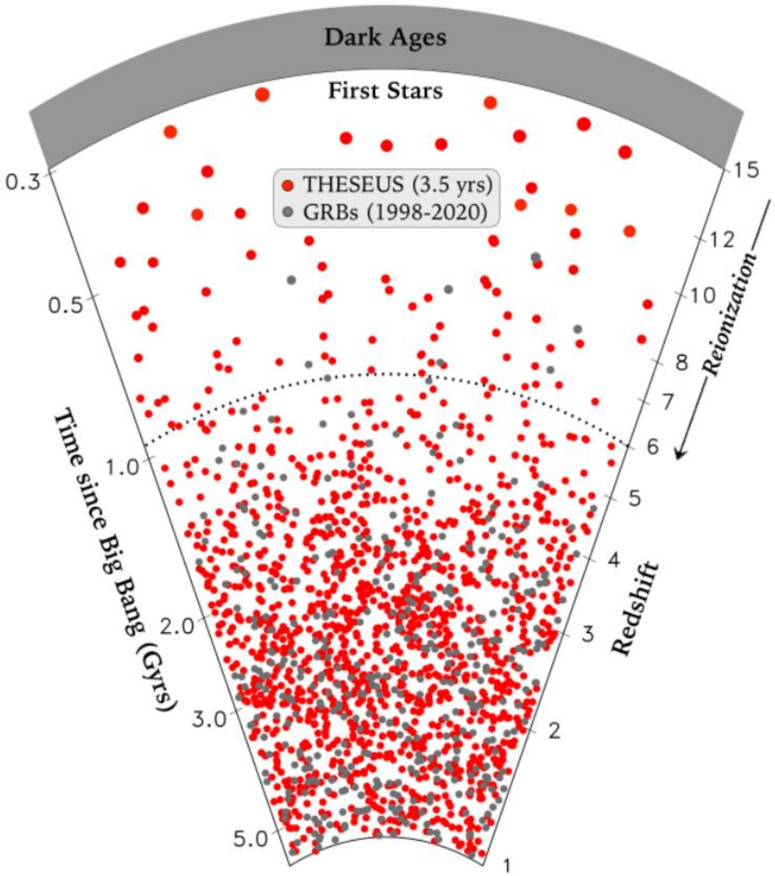


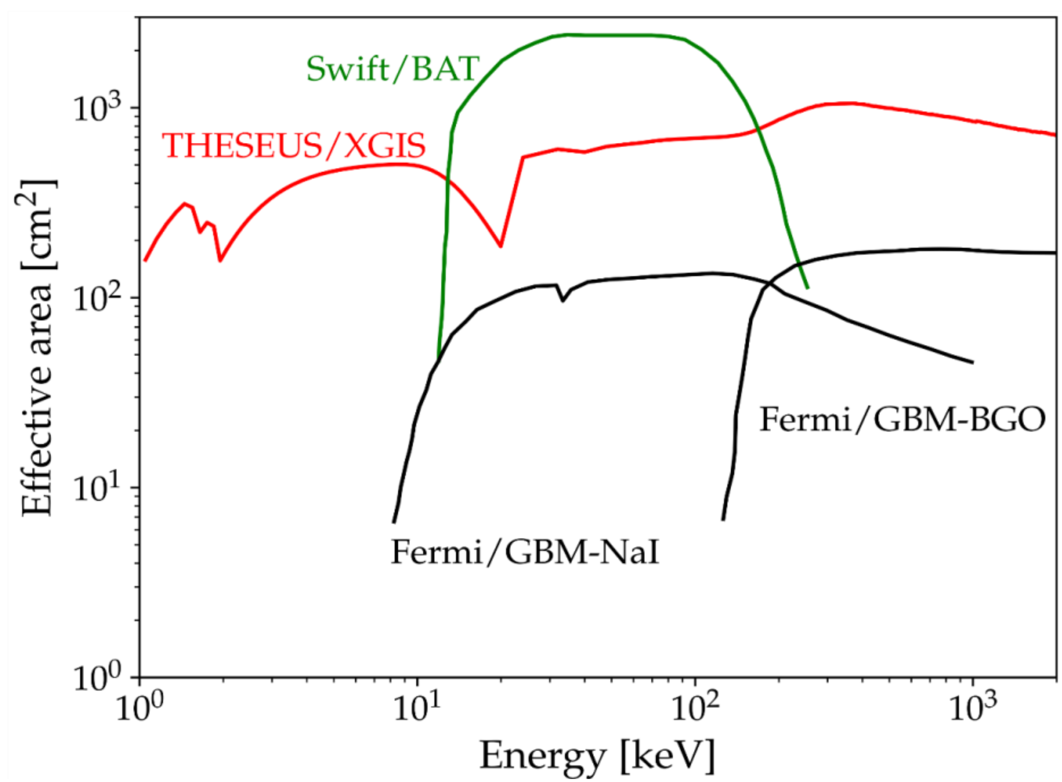
$$\Delta t = (\Delta t_{\rm jet} + \Delta t_{\rm bo} + \Delta t_{\rm GRB})(1+z)$$

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

GRBs extreme and fundamental physics

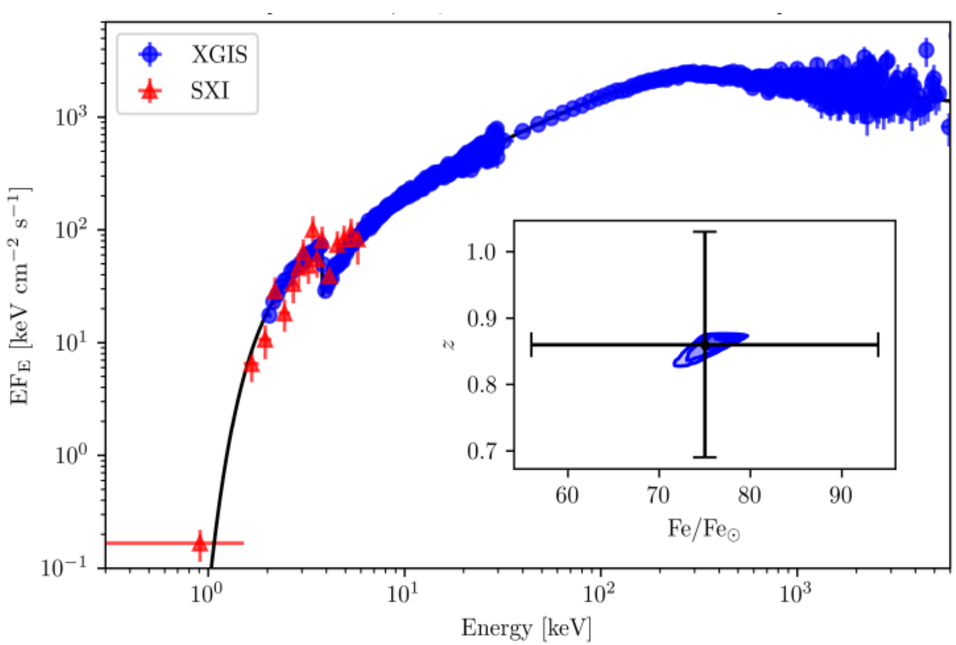
- THESEUS will measure the prompt and early afterglow emission of thousand GRBs over an unprecedented huge energy band (0.3 keV – 10 MeV) with great sensitivity, timing and spectroscopic capabilities, plus NR afterglow and redshift measurement

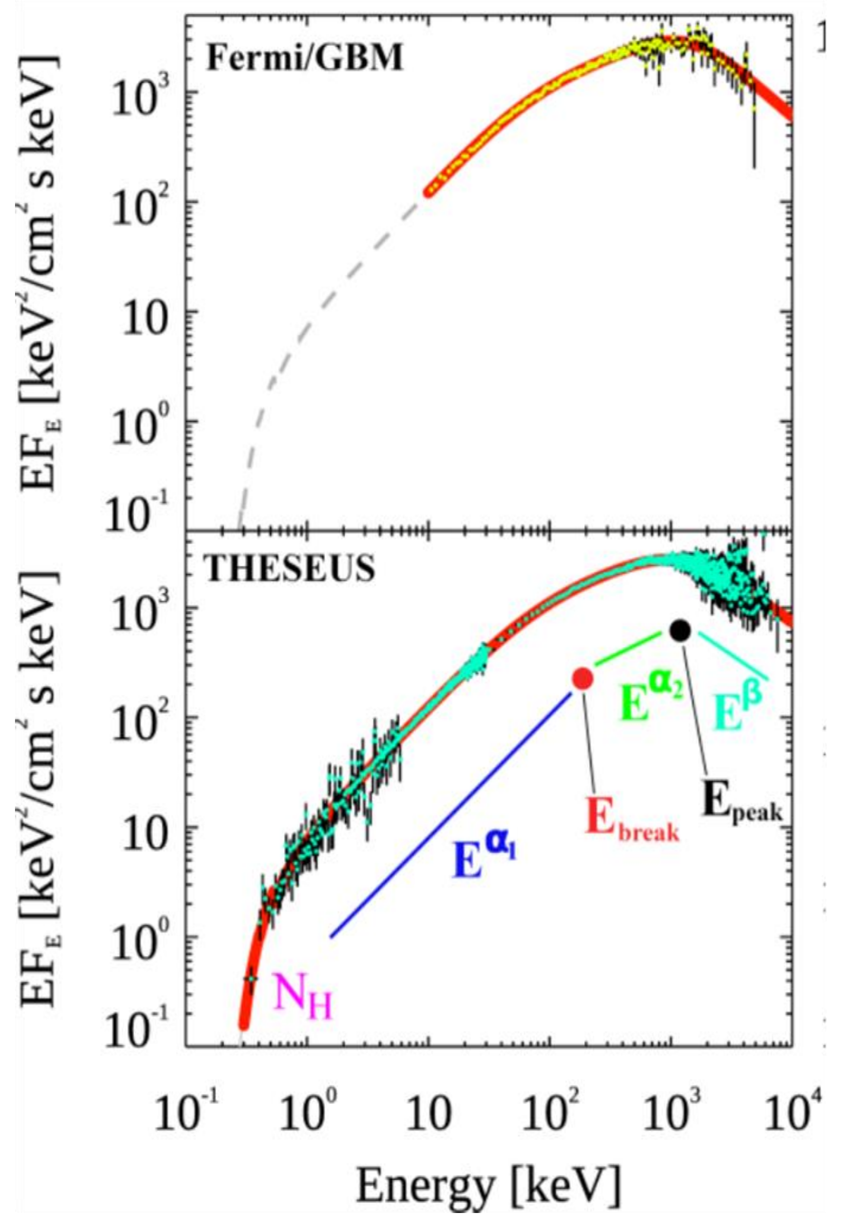




GRBs extreme and fundamental physics

- ❑ Extreme prompt emission physics & jet structure
- ❑ Central engine, sub-classes & progenitors,
- ❑ Cosmological parameters & fundamental physics





Fundamental physics: testing LI / QG

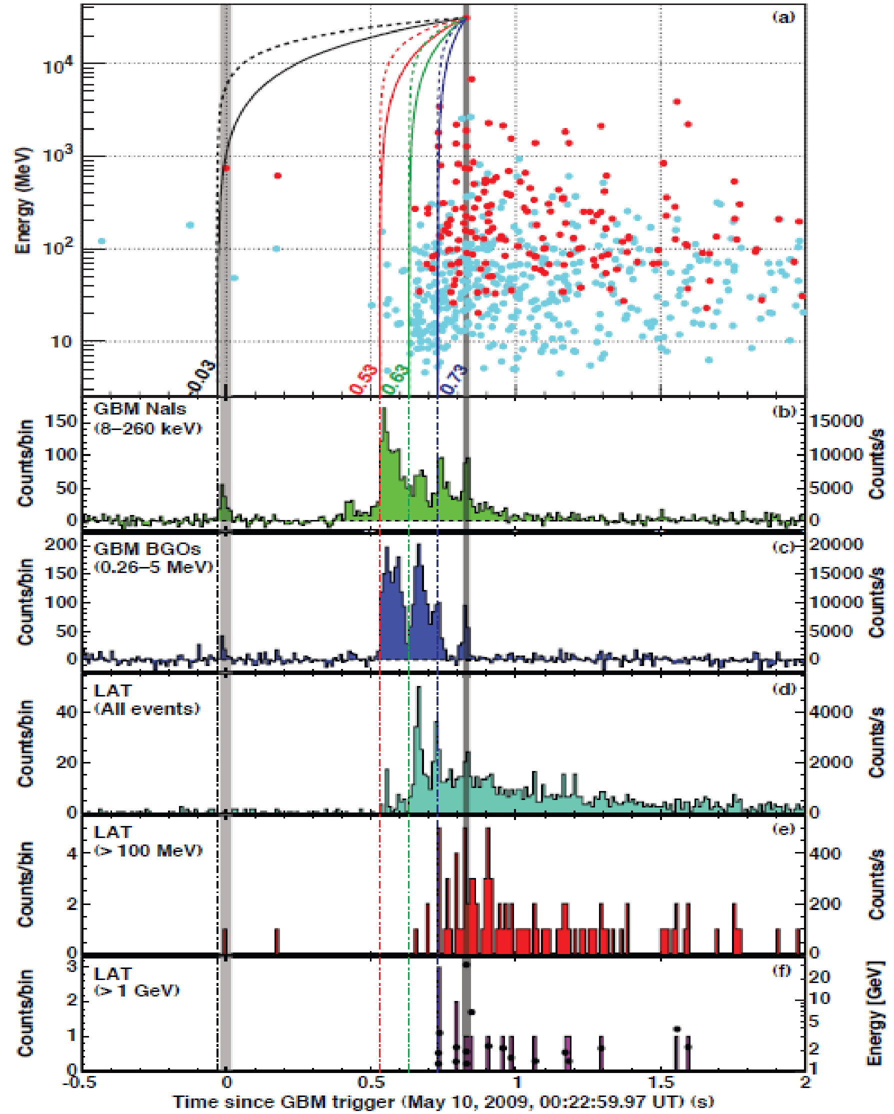
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

$$v_{\rm ph} = \frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c \left[1 - s_n \frac{n+1}{2} \left(\frac{E_{\rm ph}}{M_{{\rm QG},n} c^2} \right)^n \right]$$

$$\Delta t = s_n \frac{(1+n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n} c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

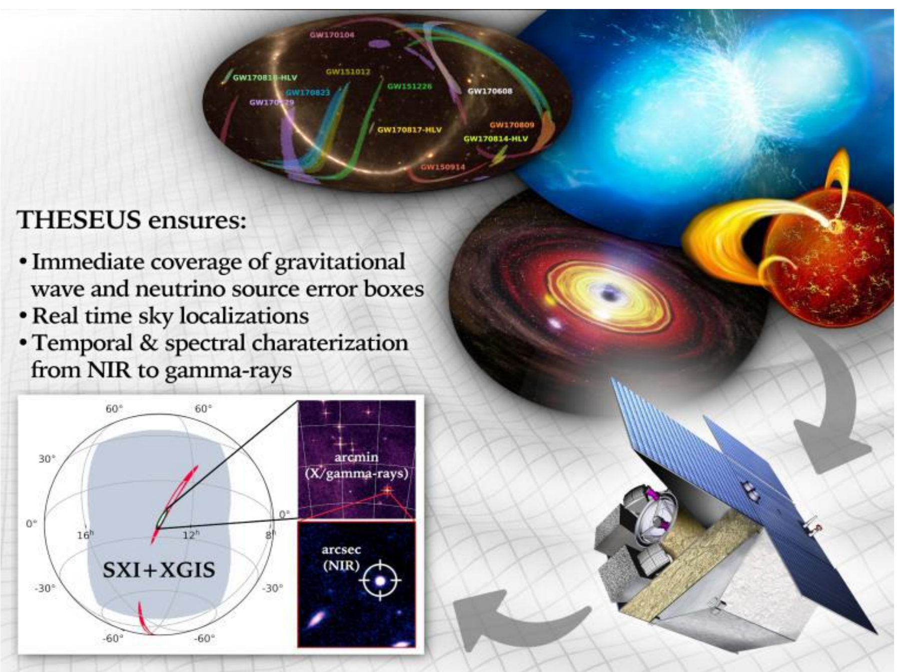
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

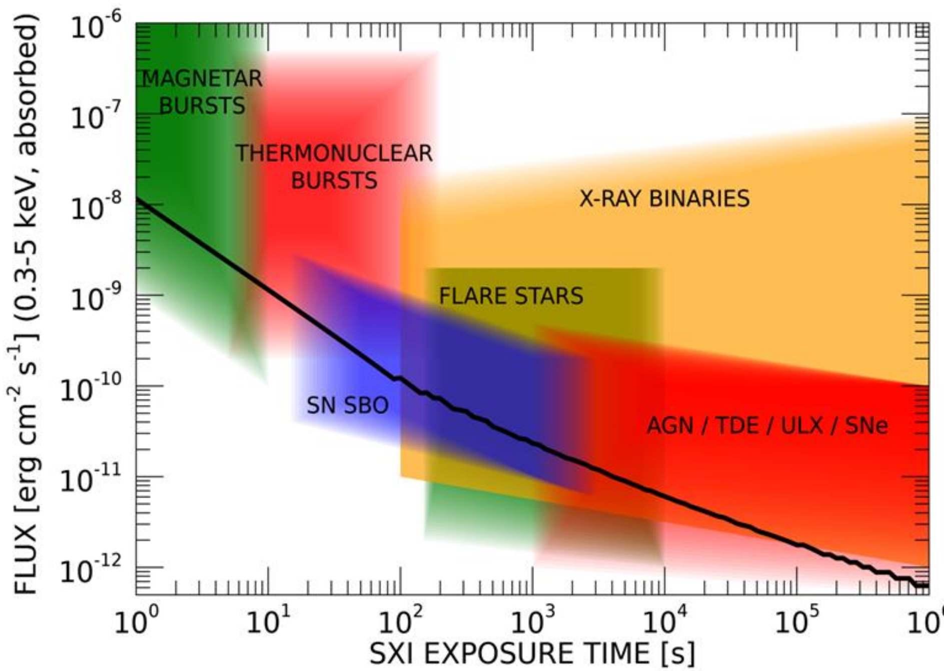
$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
−30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	±1	> 102
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	±1	> 1.33
$\left\lvert\frac{\Delta t}{\Delta E}\right\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22



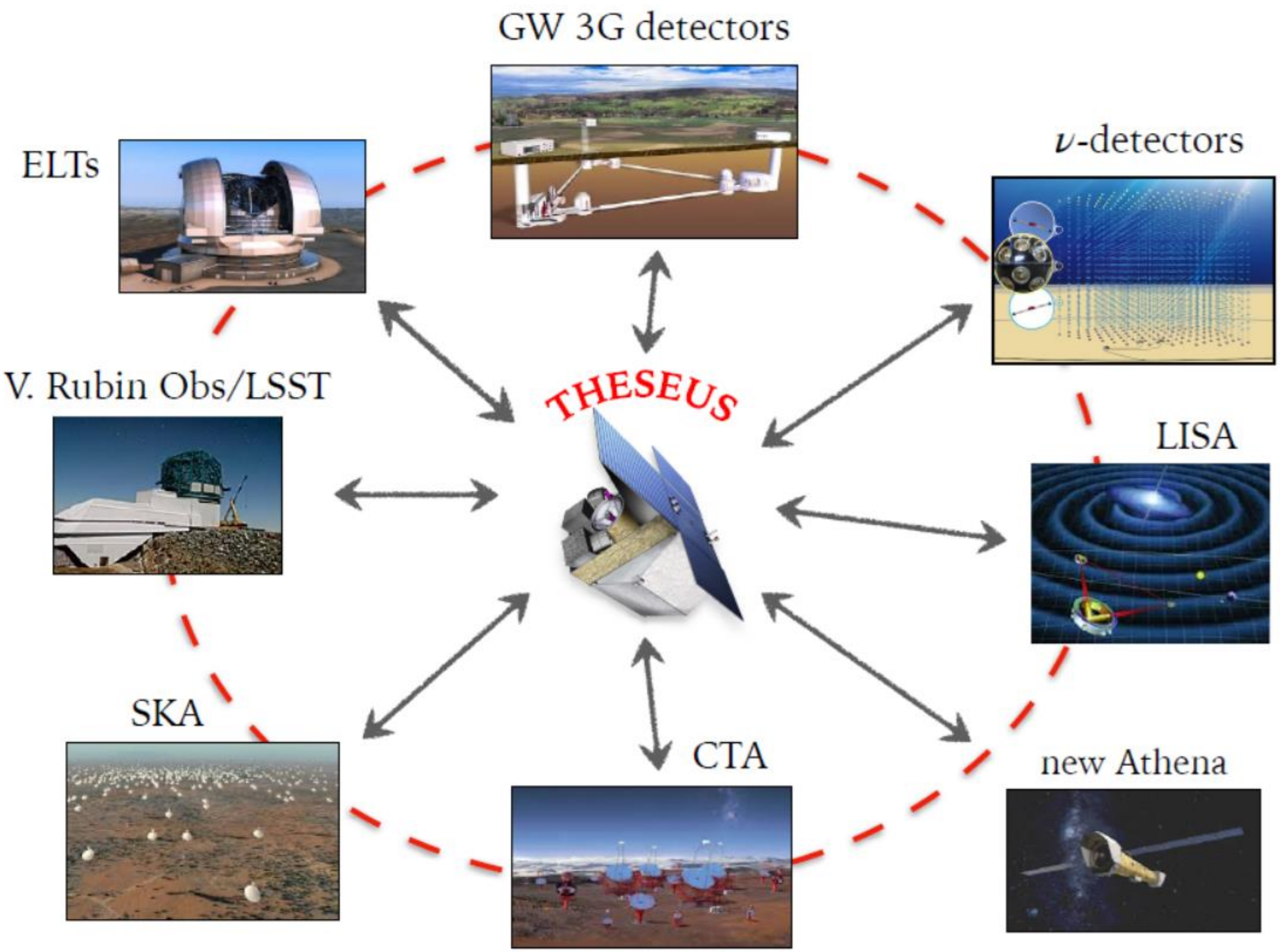
Exploring the transient sky

- **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**, developed by a large European collaboration, studied (M5 Phase A) and re-selected (M7 Phase-0) by ESA **will fully exploit these potentialities and also provide unprecedented clues to GRB physics and a substantial contribution to time-domain astronomy**

- The "M7" 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 the European leadership and investments put in them**.

- Because of the wide scope of its science goals, the great synergies and timeline and a **guest-observer programme**, **THESEUS scientific return will involve an unprecedented wide scientific community.**

- **THESEUS: ESA/M5 Phase A study and selected for M7 Phase 0 (->2037)**
  SPIE articles on instruments, Adv.Sp.Res. & Exp.Astr. articles on science
  http://www.isdc.unige.ch/theseus/