The great synergy of ET with next-generation GRB observatories

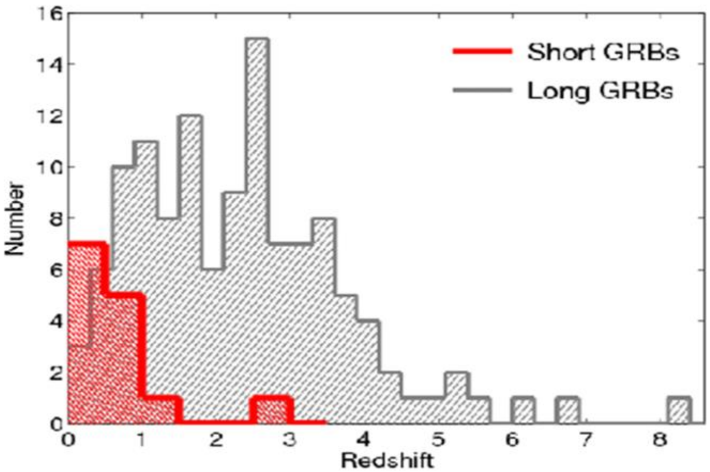
Lorenzo Amati
(INAF – OAS Bologna)

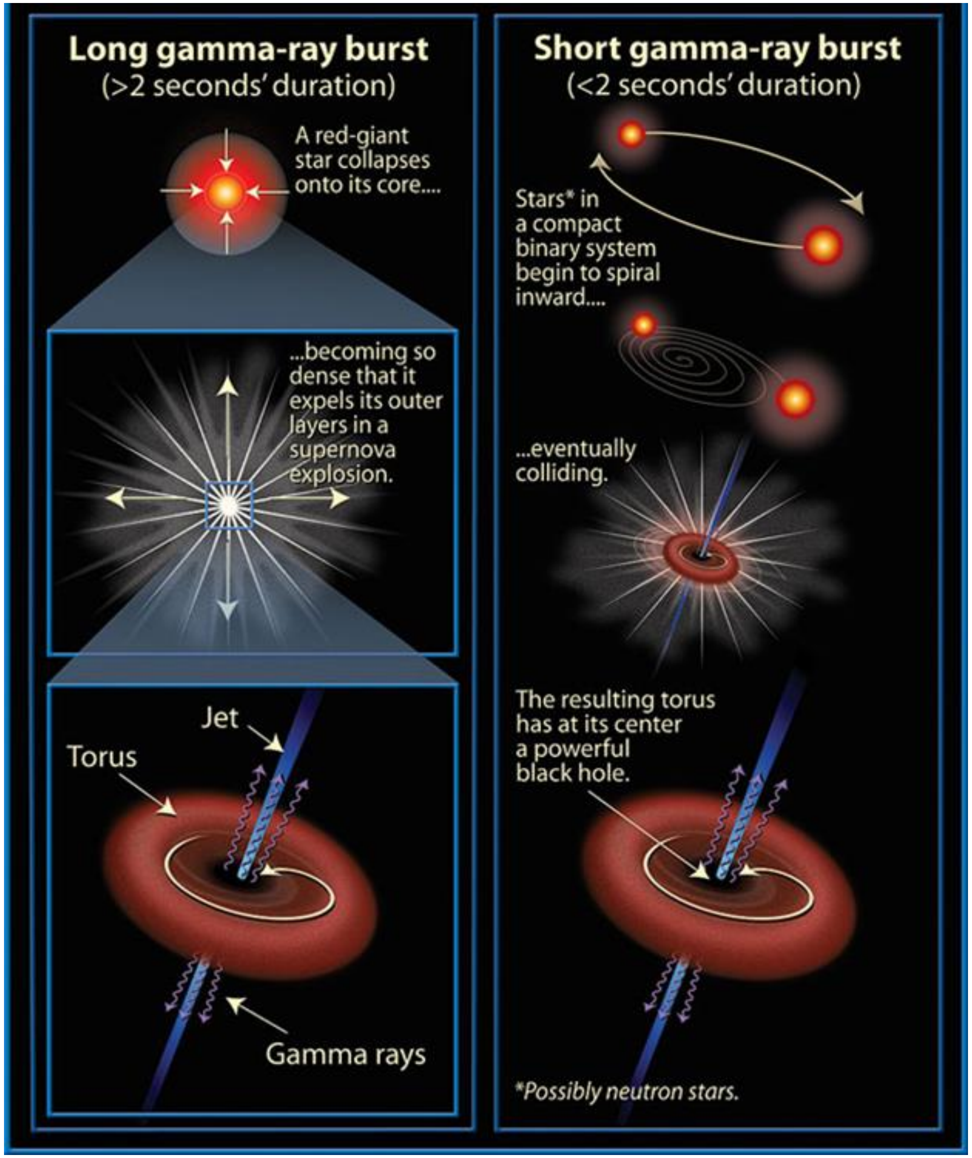
- Targets for JWST

(8th May 2024)

XIV ET Symposium - Maastrich

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

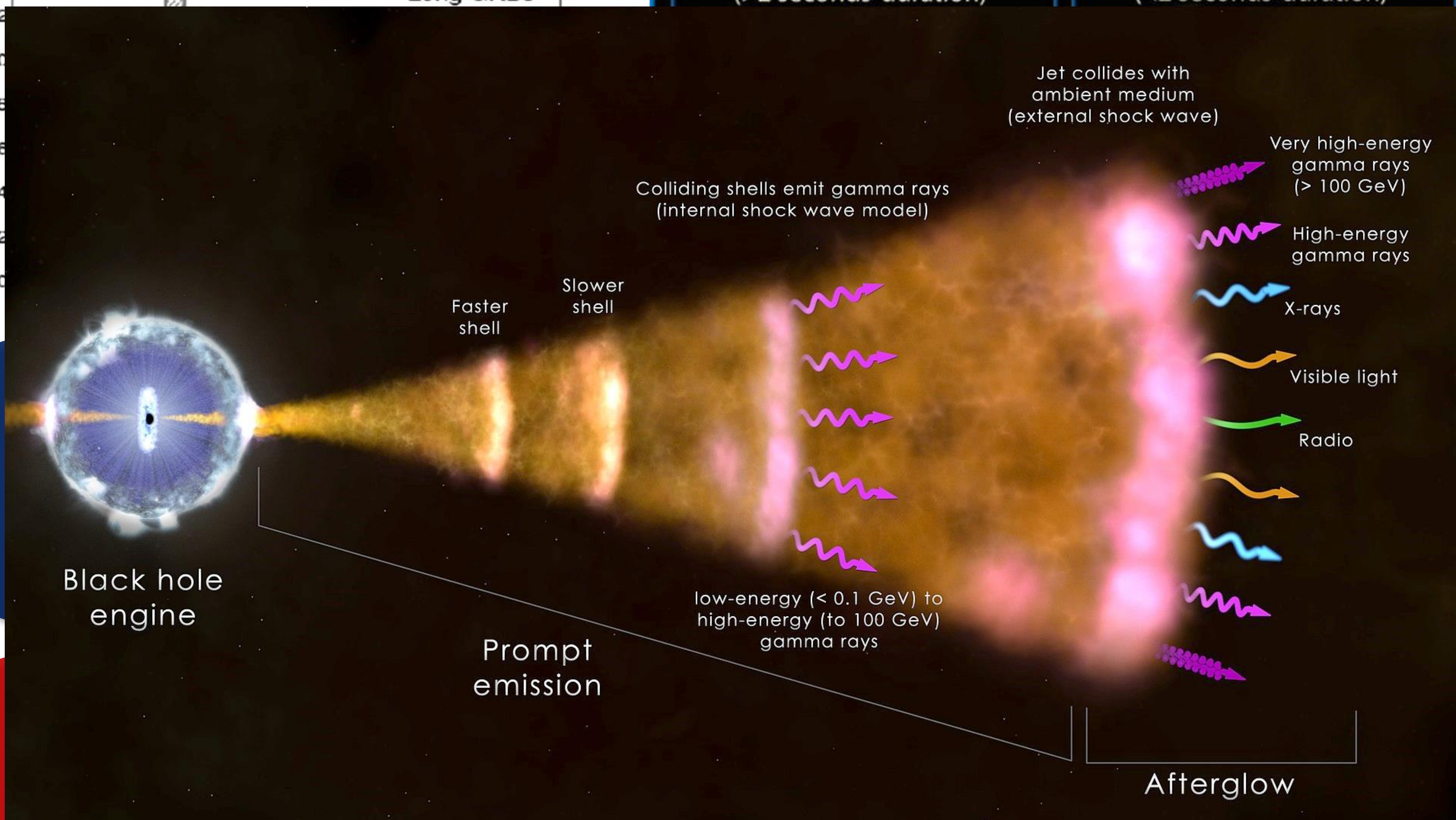




Long GRBs: core collapse of pecular massive stars, **association with SN**

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

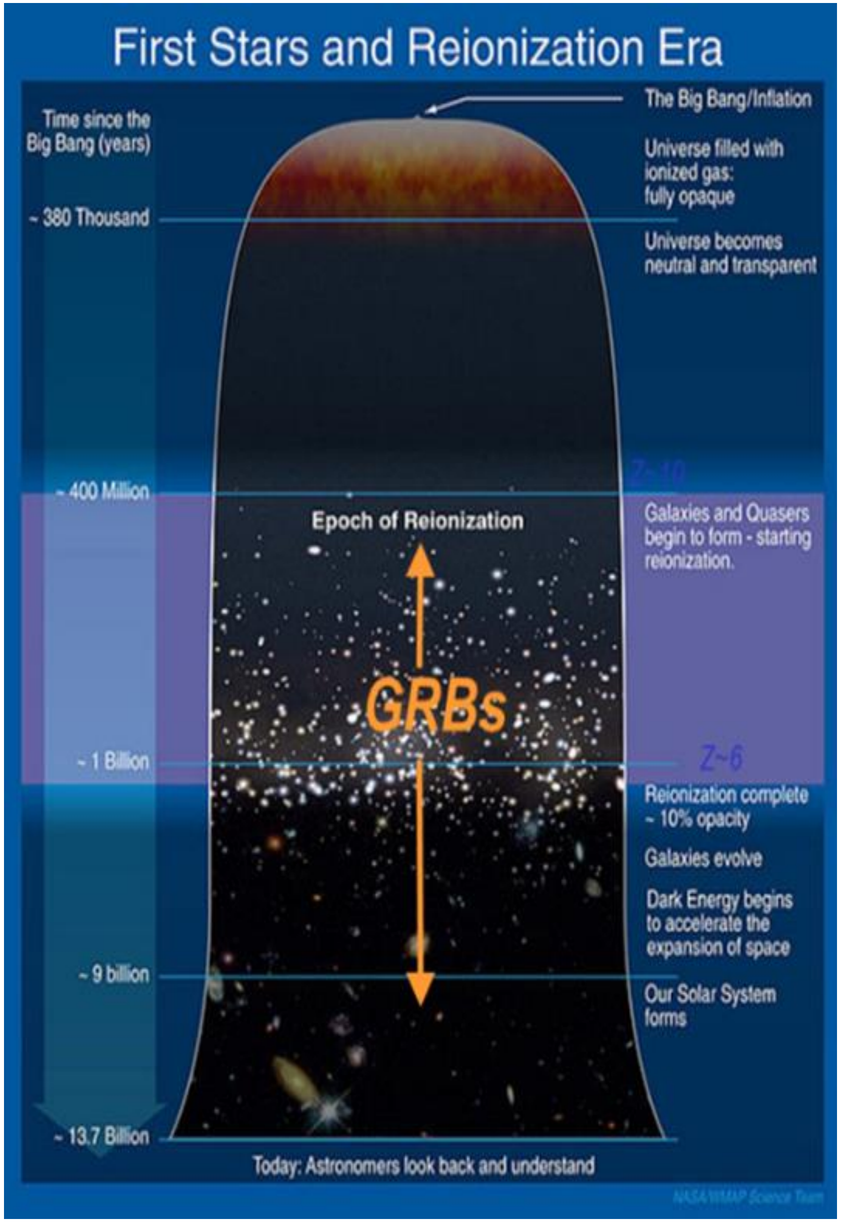
Gamma-Ray Bursts: the most extreme phenomena in the Universe



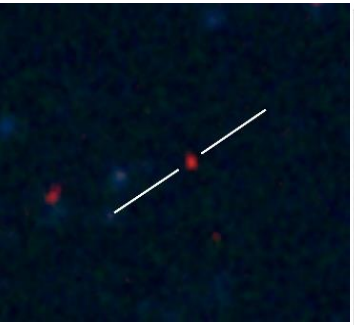
association with GW sources

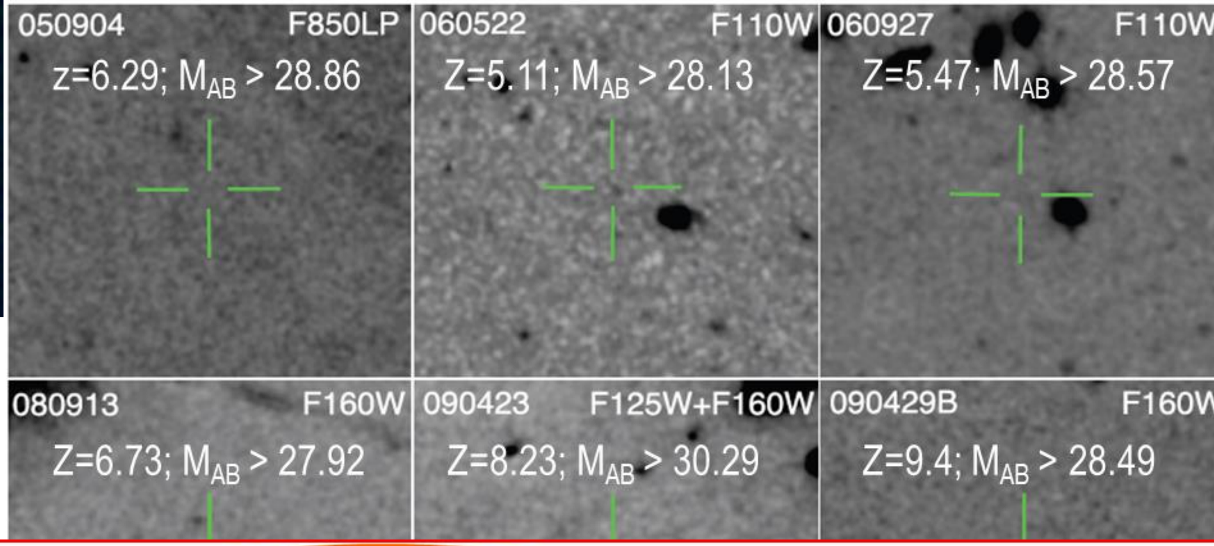
Shedding light on the early Universe with GRBs

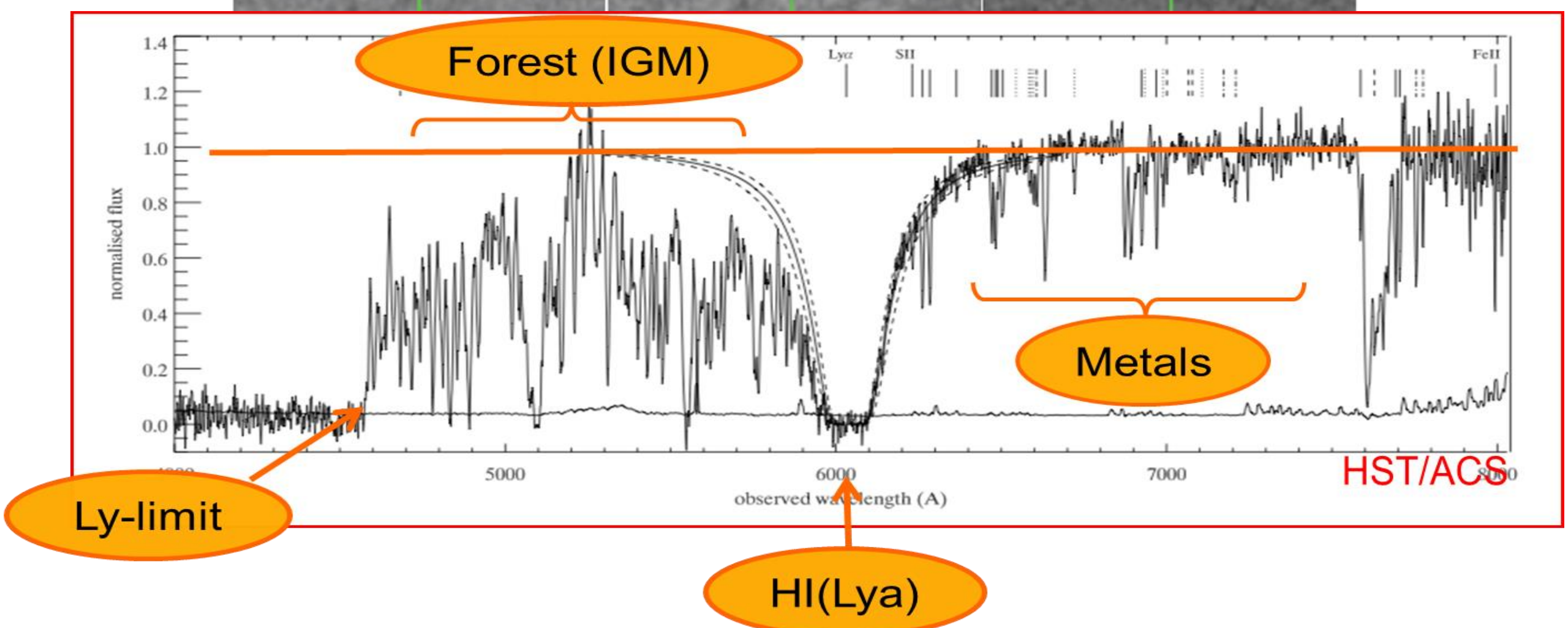
- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays
- **Redshift distribution** extending at least to z ~9 and association with exploding massive stars
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars



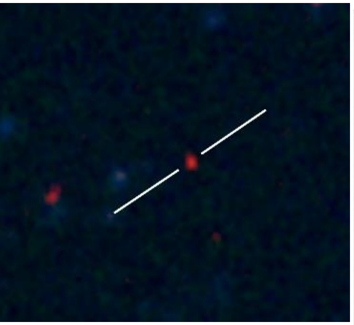
Detecting and studying first stars and primordial invisible galaxies

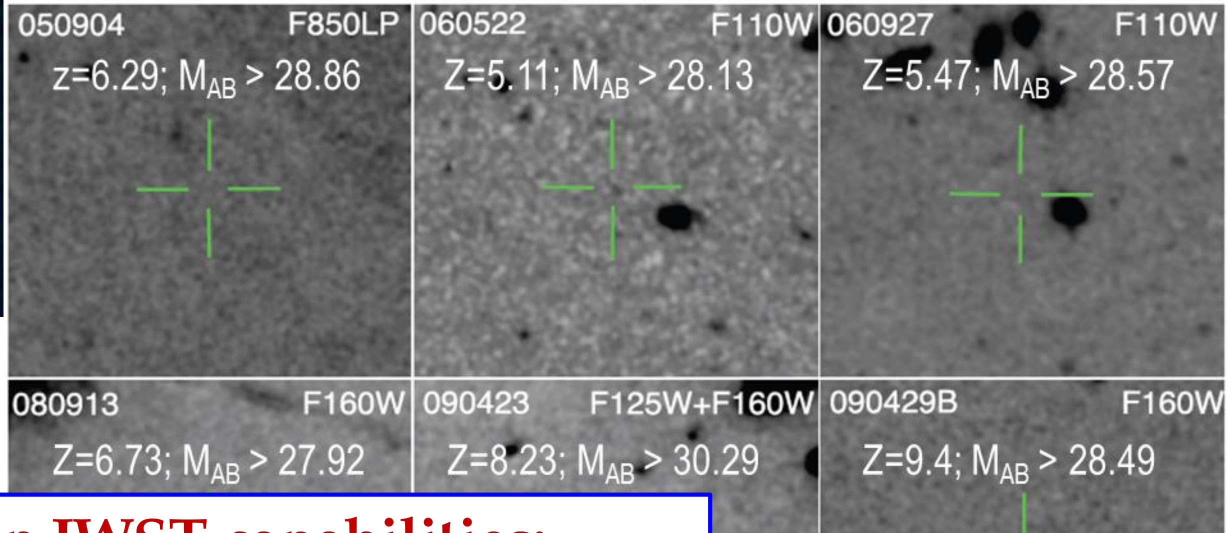






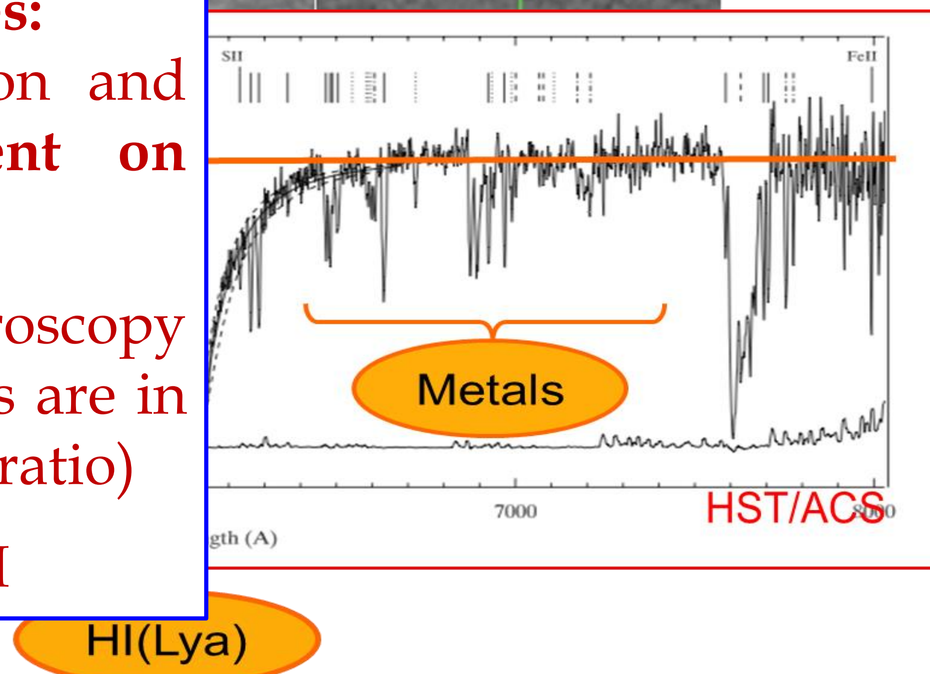
Detecting and studying primordial invisible galaxies





Beyond even JWST capabilities:

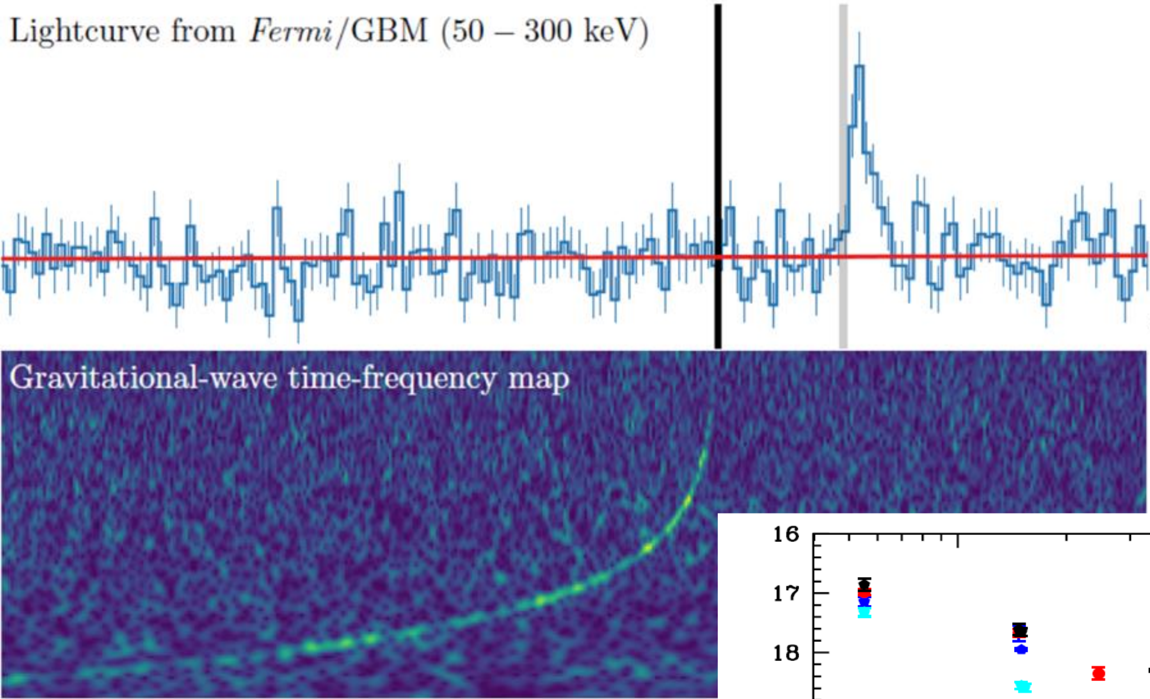
- Primordial galaxies detection and characterization **independent on mass and luminosity**
- Allow absorption spectroscopy (needed because most metals are in neutral gas and and for dust ratio)
- Properties of primordial IGM

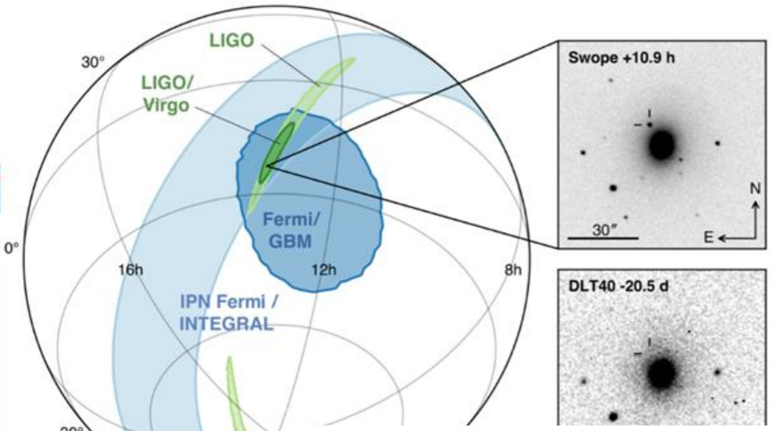


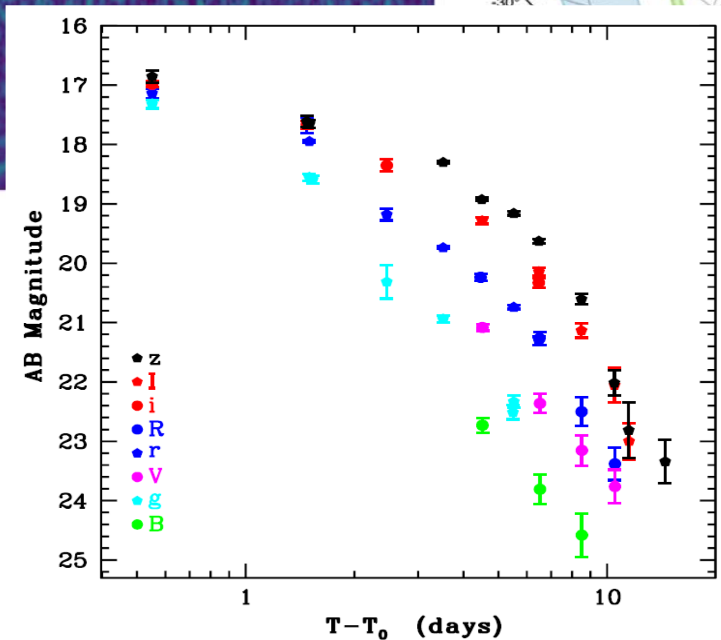
Short GRBs and multi-messenger astrophysics

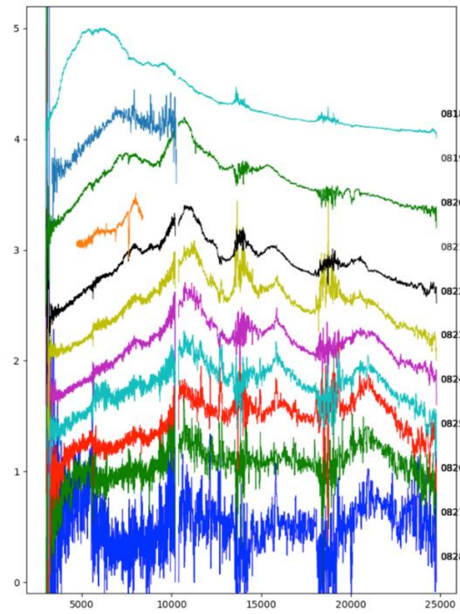
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics



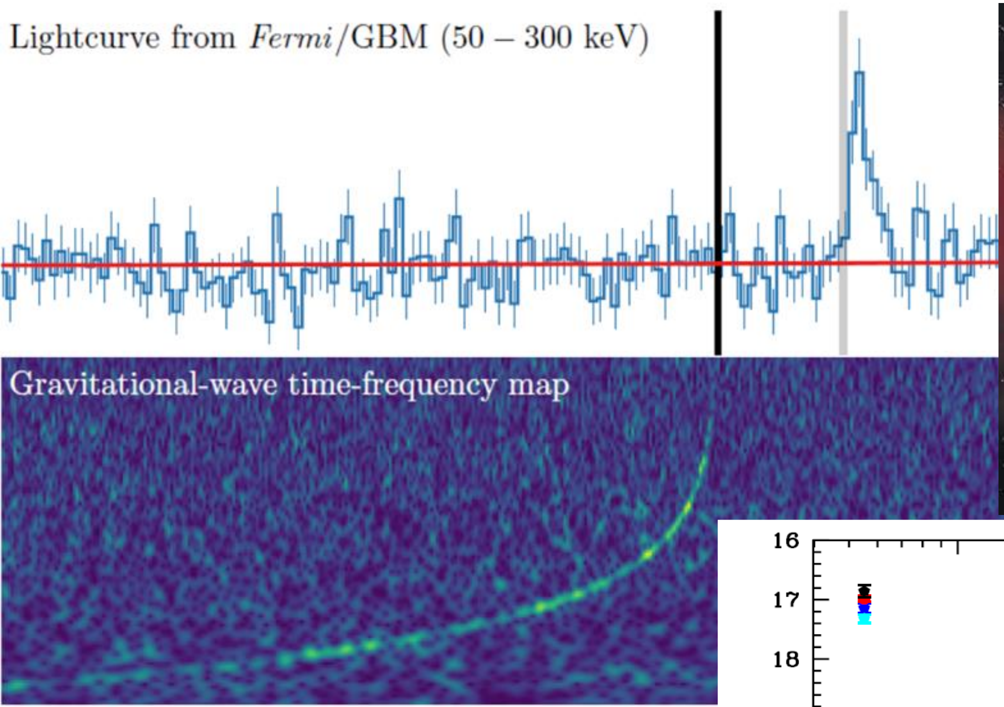


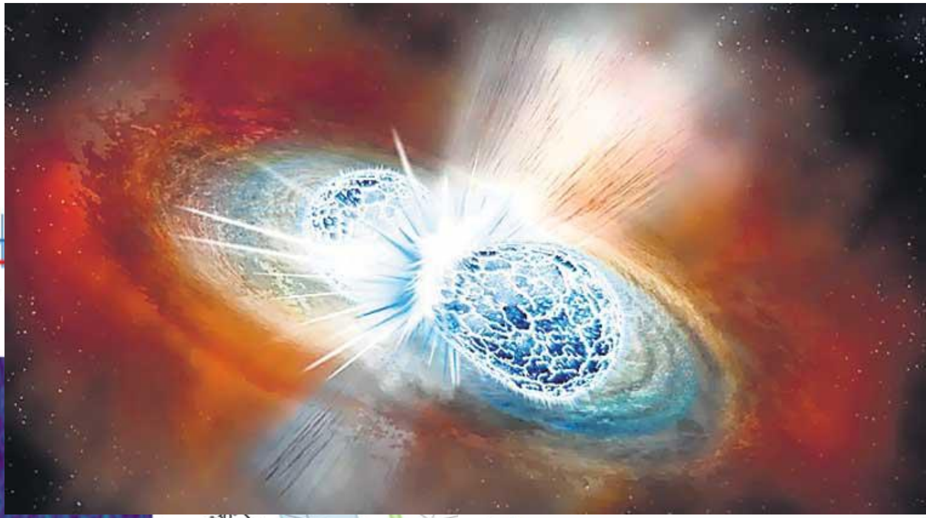


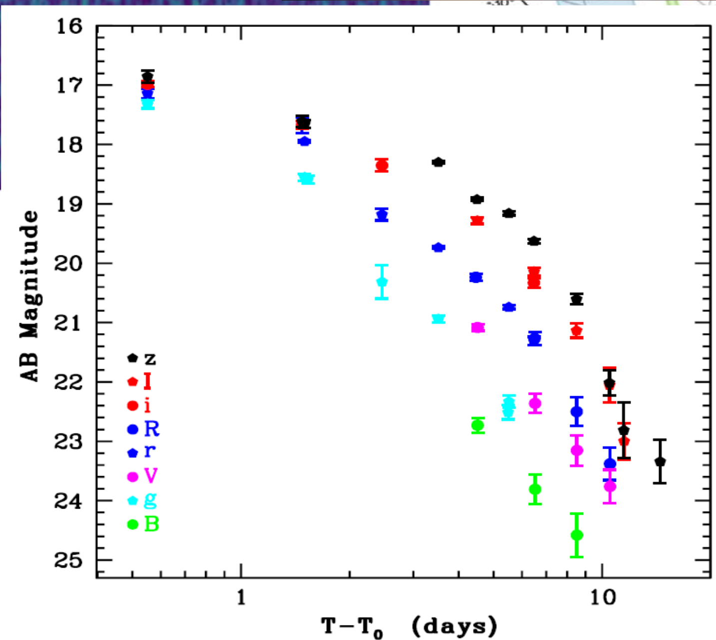


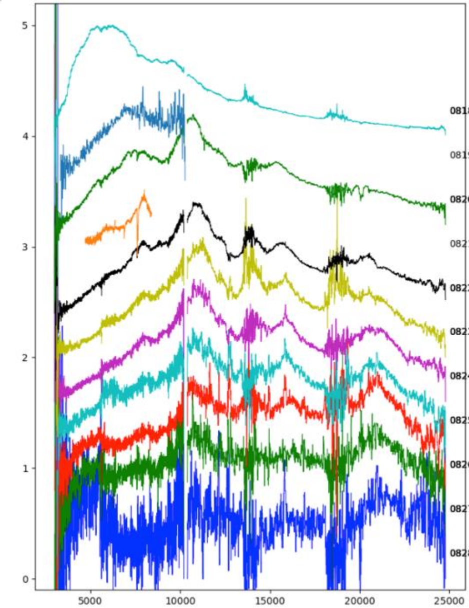
Short GRBs and multi-messenger astrophysics

GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):
the birth of multi-.messenger astrophysics





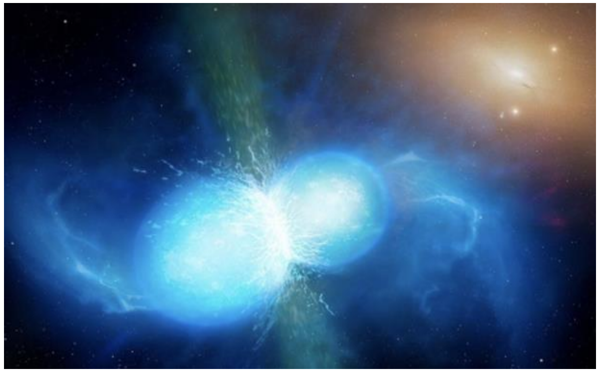




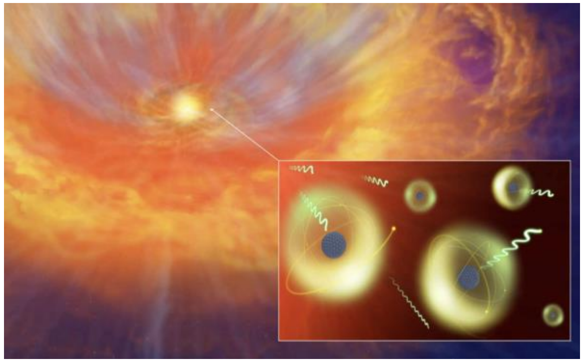
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

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

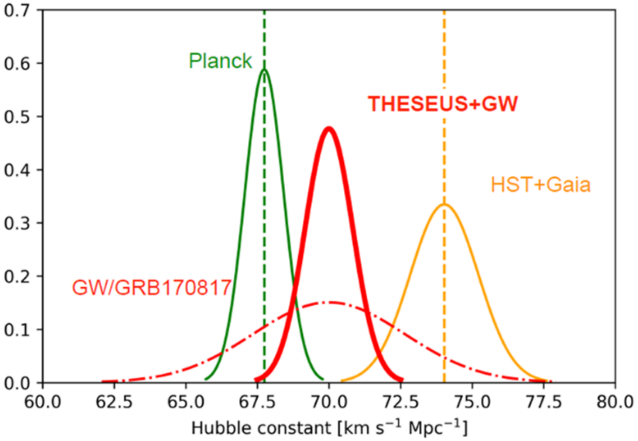
Relativistic jet formation, equation of state, fundamental physics



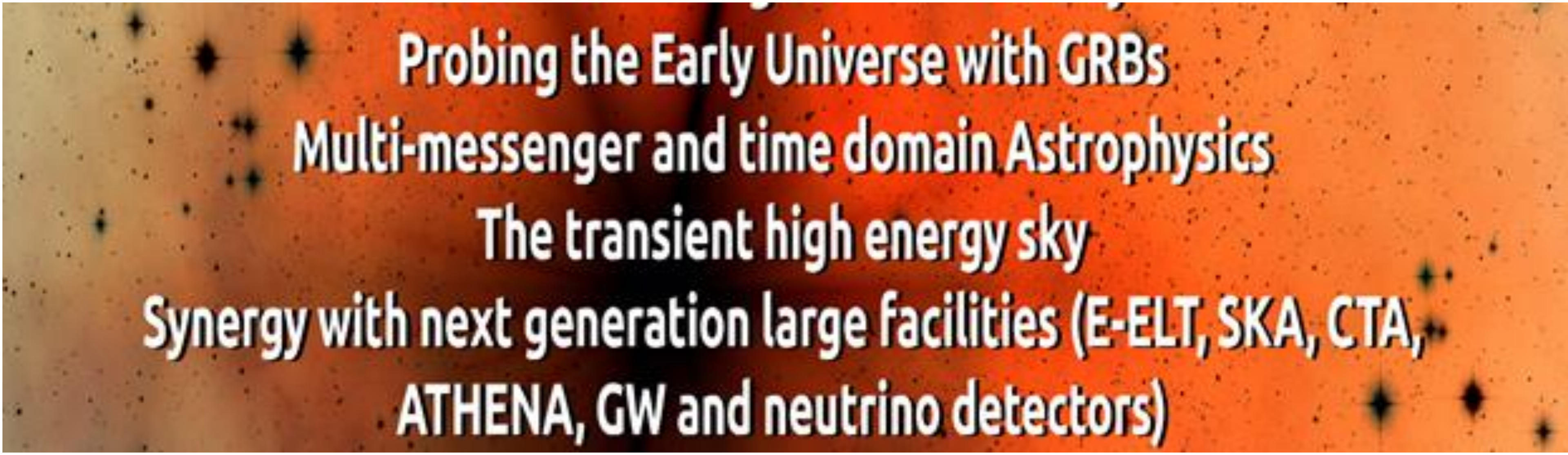
Cosmic sites of r-process nucleosynthesis



New independent route to measure cosmological parameters



Next generation GRB missions (‘30s)



- **THESEUS** (studied for ESA Cosmic Vision / M5), **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

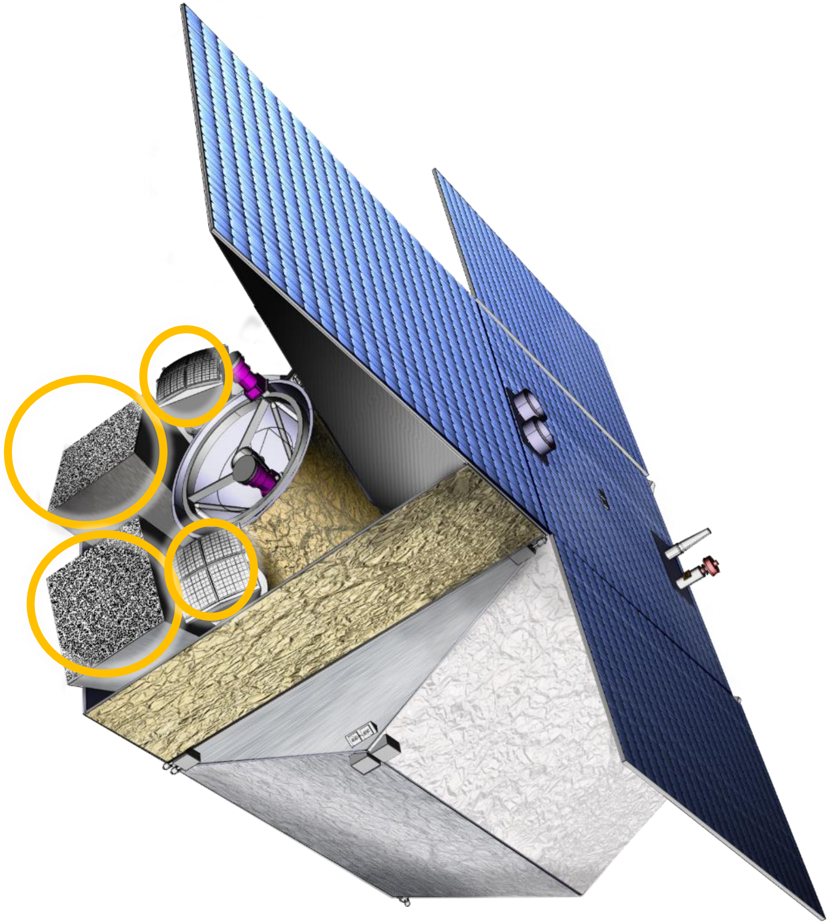
Leads: L. Amati (INAF – OAS Bologna, Italy, lead proposer), A. Santangelo (Un. Tuebingen, D), P. O'Brien (Un. Leicester, UK), D. Gotz (CEA-Paris, France), E. Bozzo (Un. Genève, CH)

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**

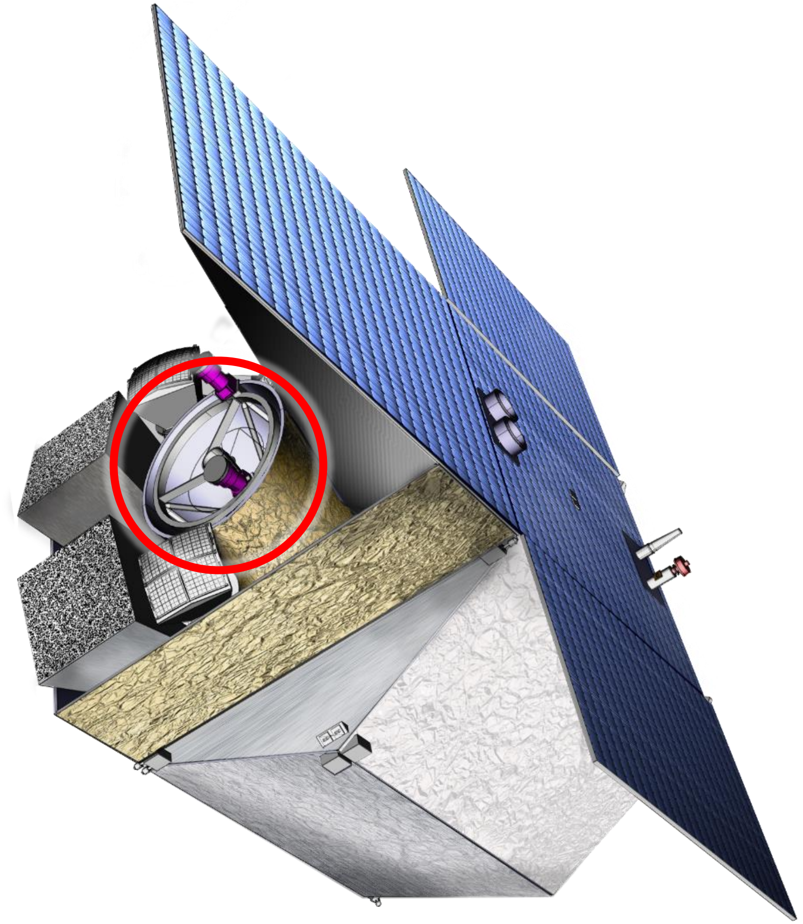


THESEUS Mission Concept

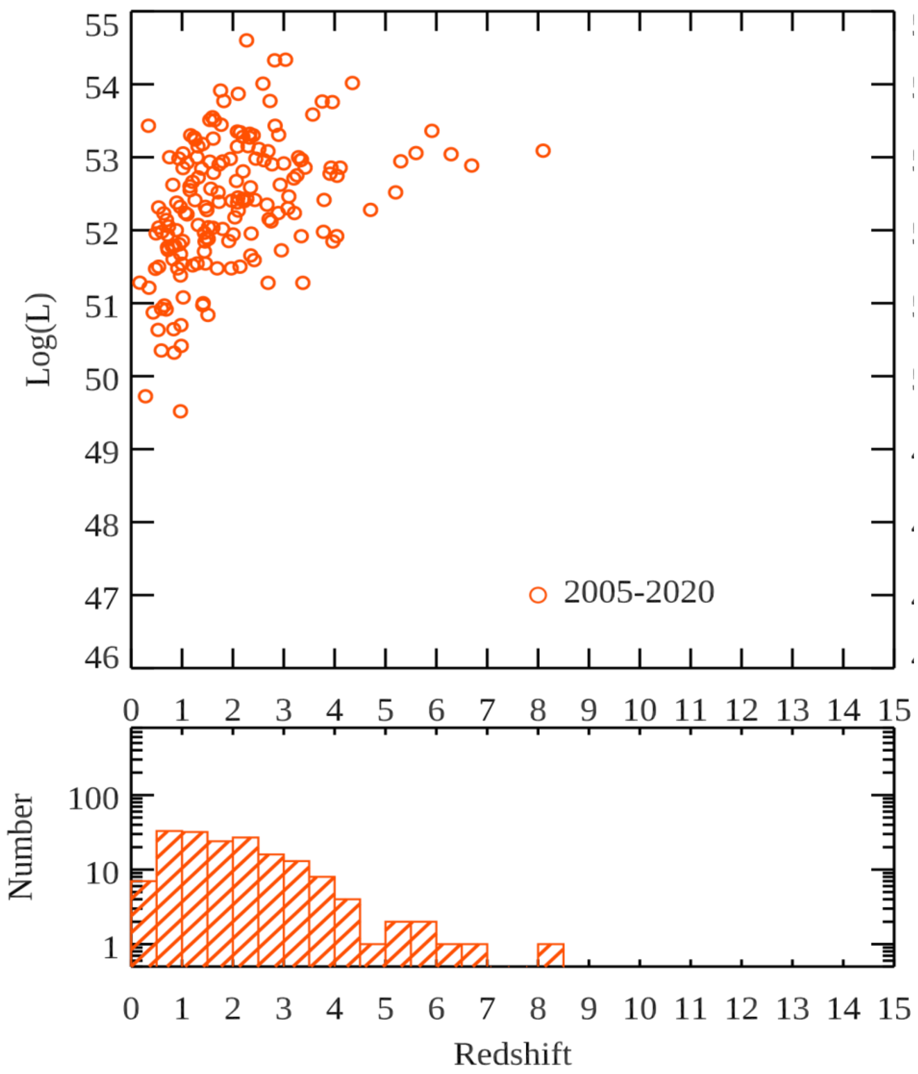
THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

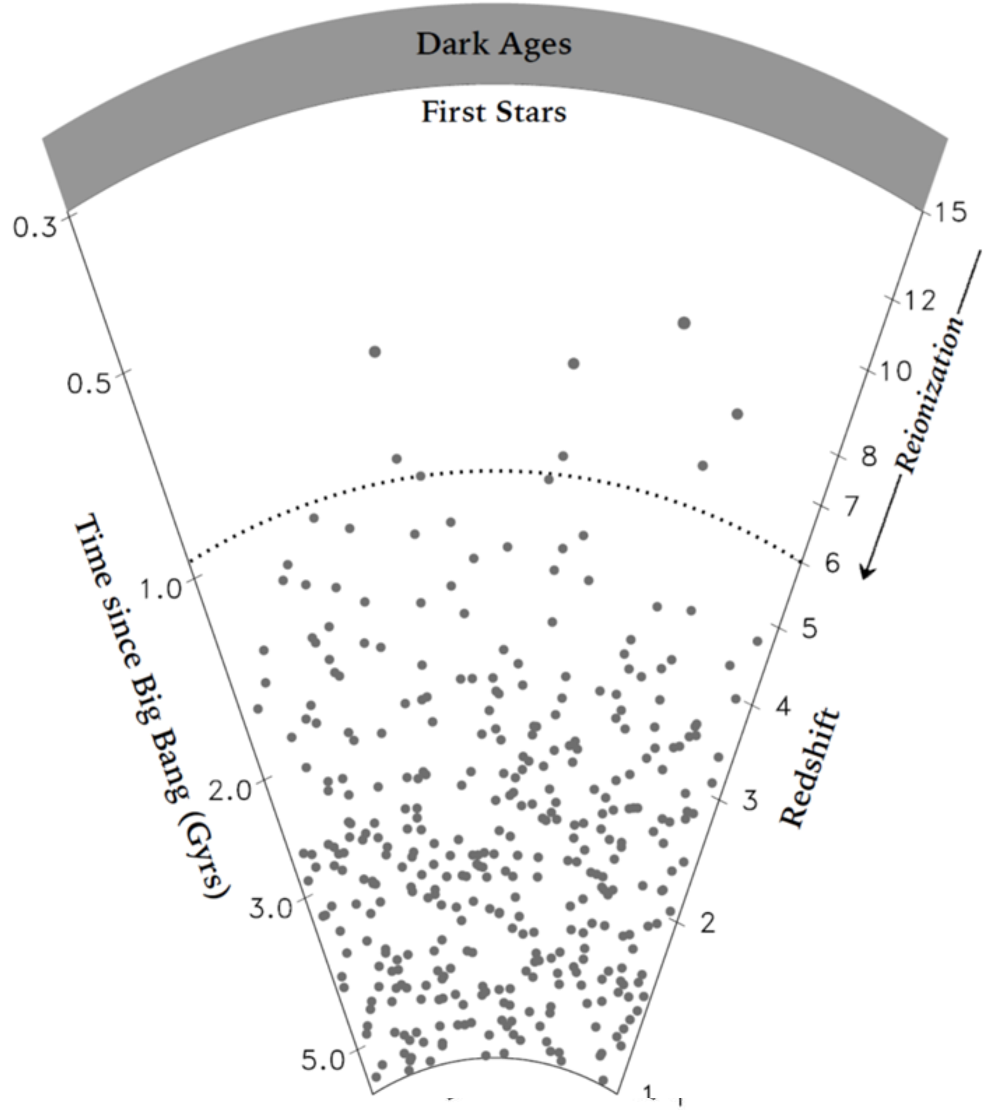
Set of innovative wide-field monitors with **unprecedented combination of broad energy range from gamma-rays down to soft X-rays**, **FOV and localization accuracy**

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

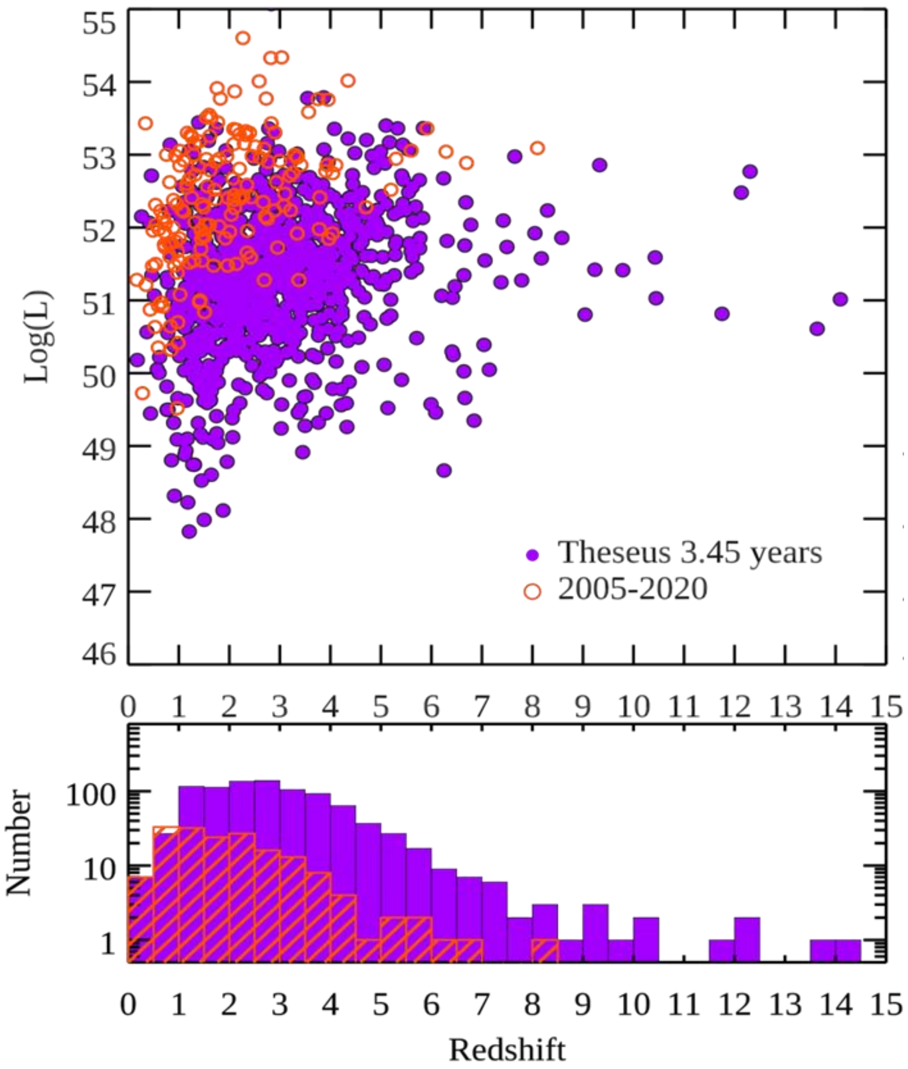


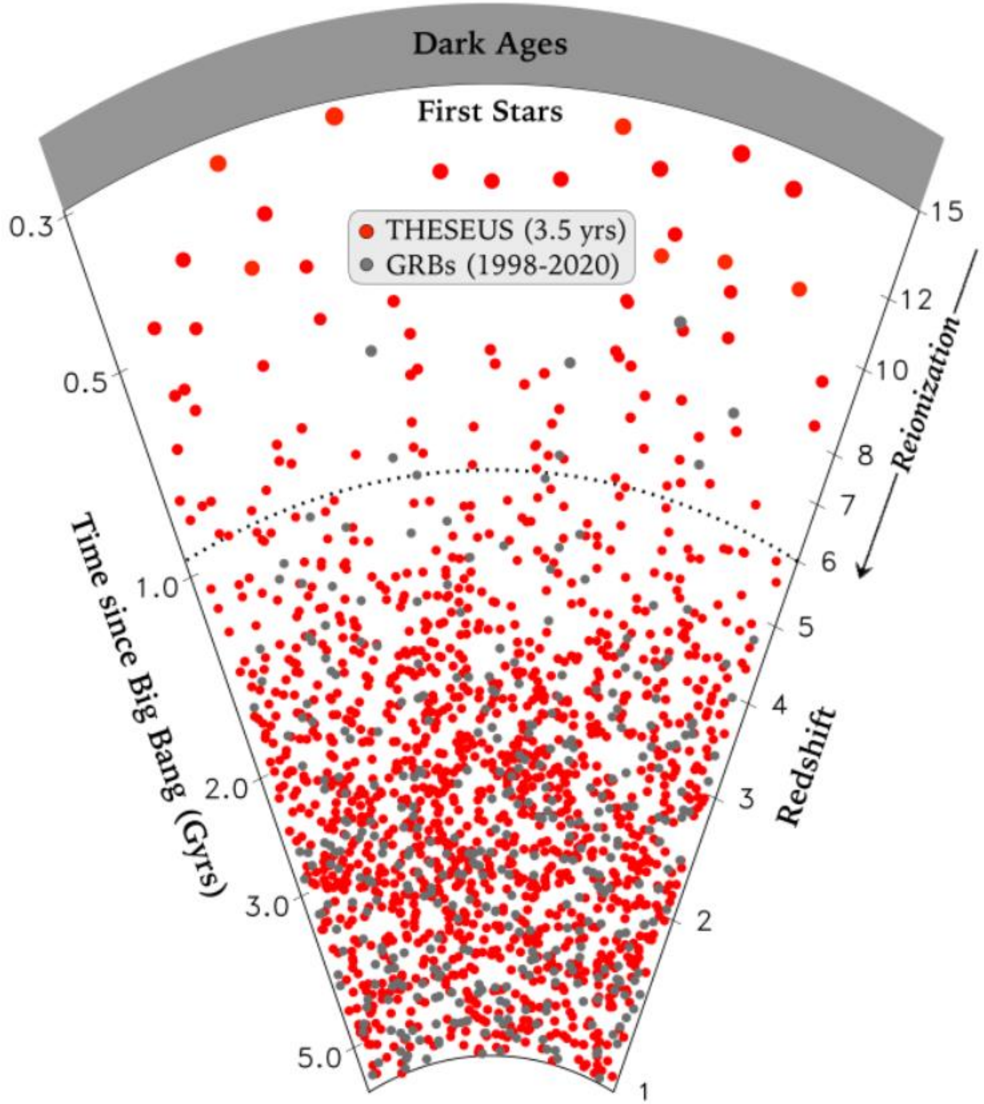
Expected performances: early Universe





Expected performances: early Universe

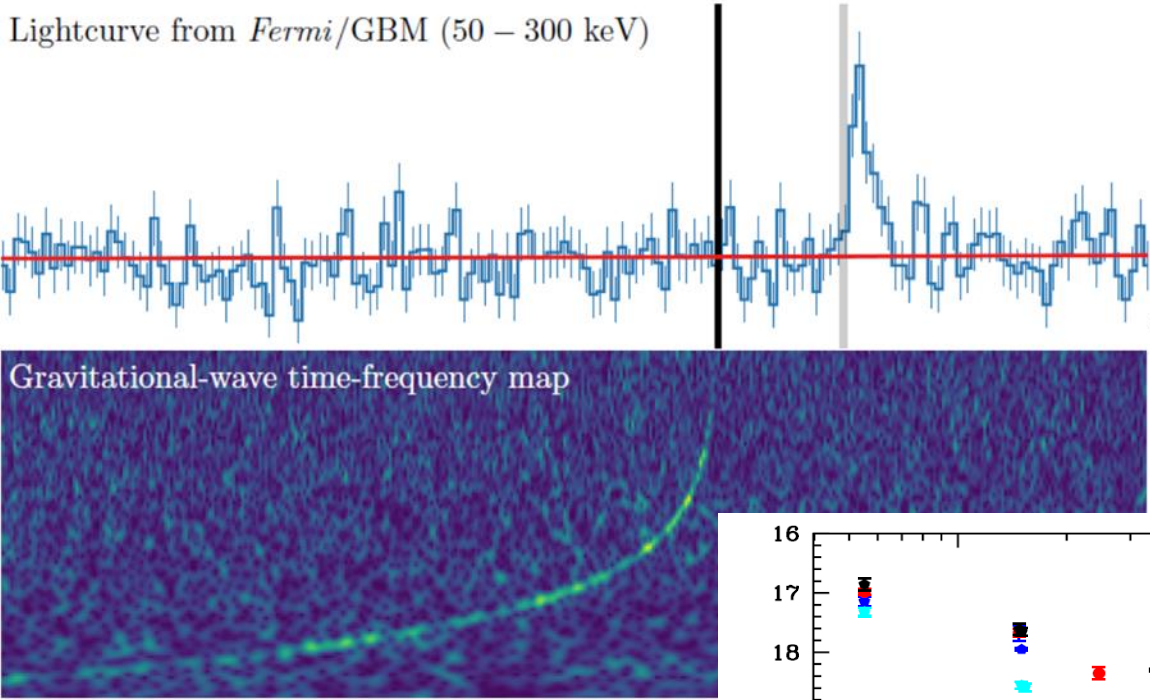


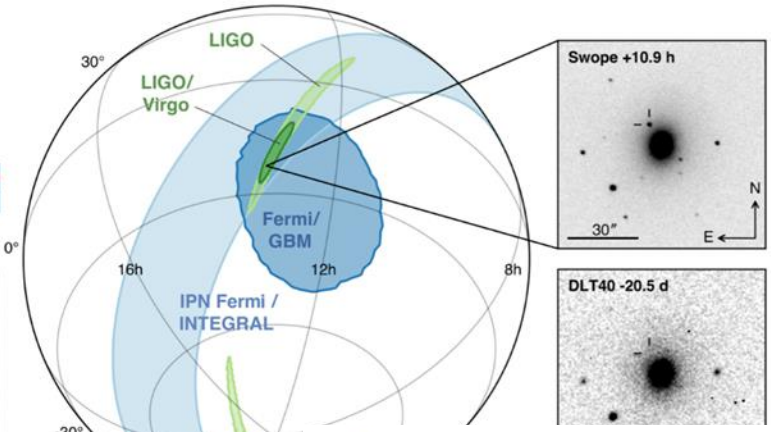


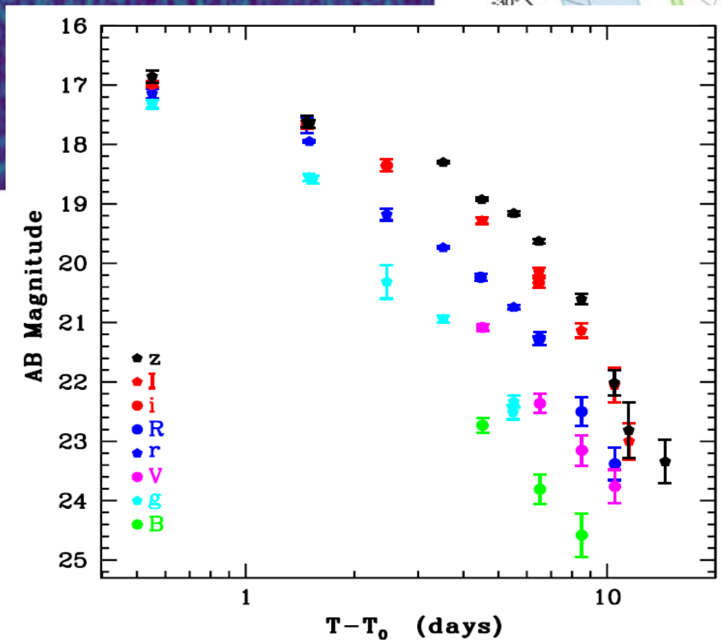
Expected performances: multi-messenger astr.

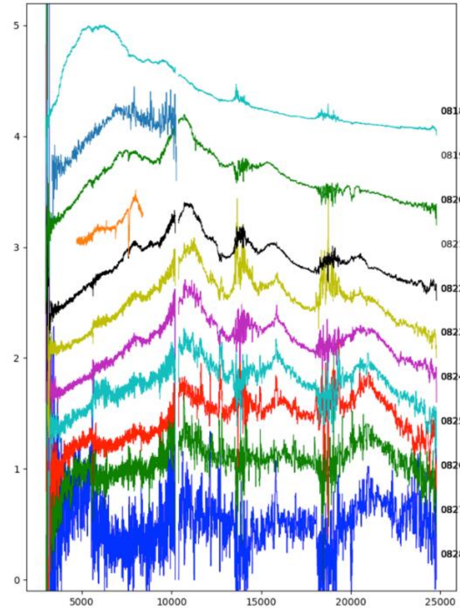
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics



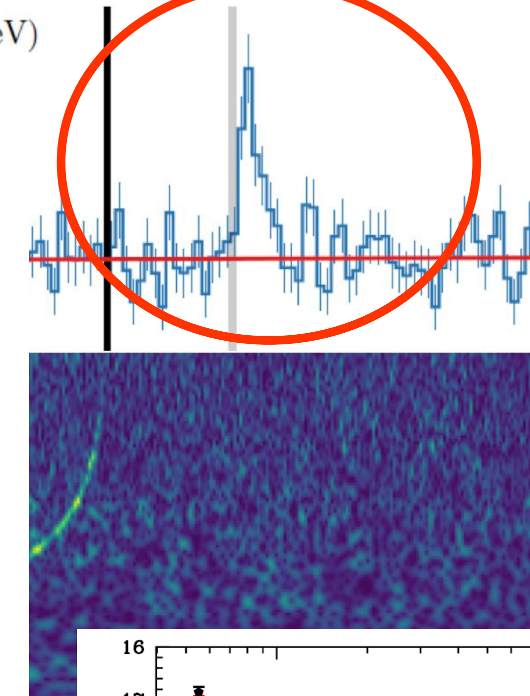






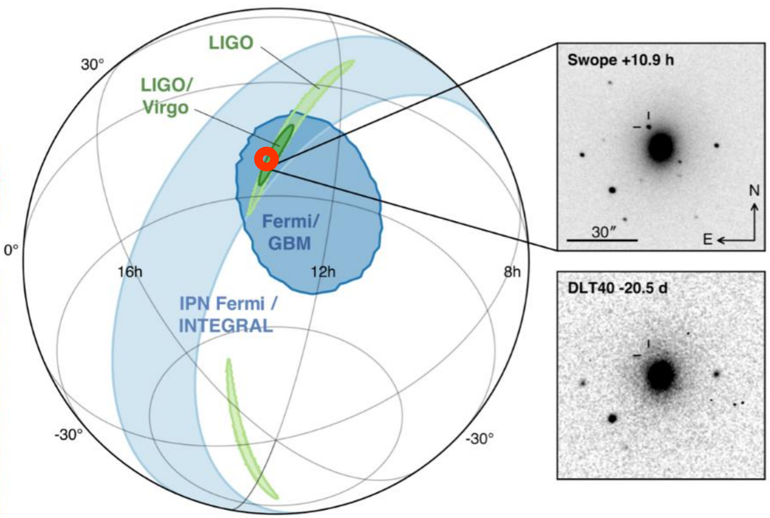
Expected performances: multi-messenger astr.

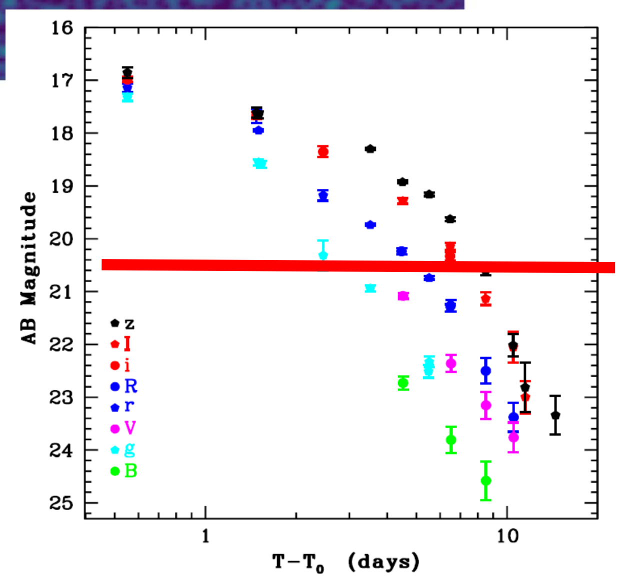
Lightcurve from *Fermi*/GBM (50 – 300 keV)

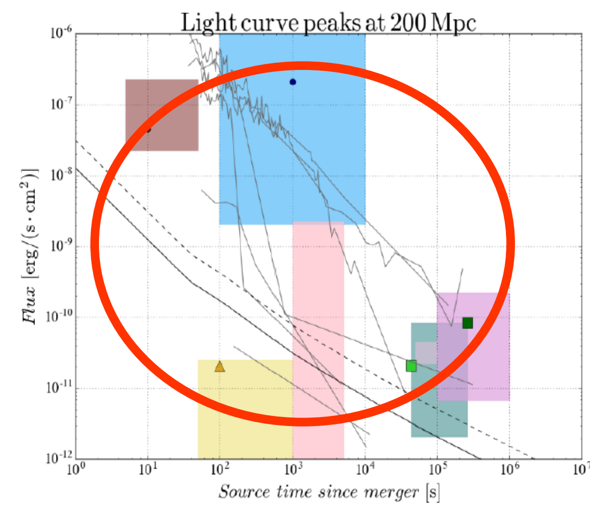


THESEUS:

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

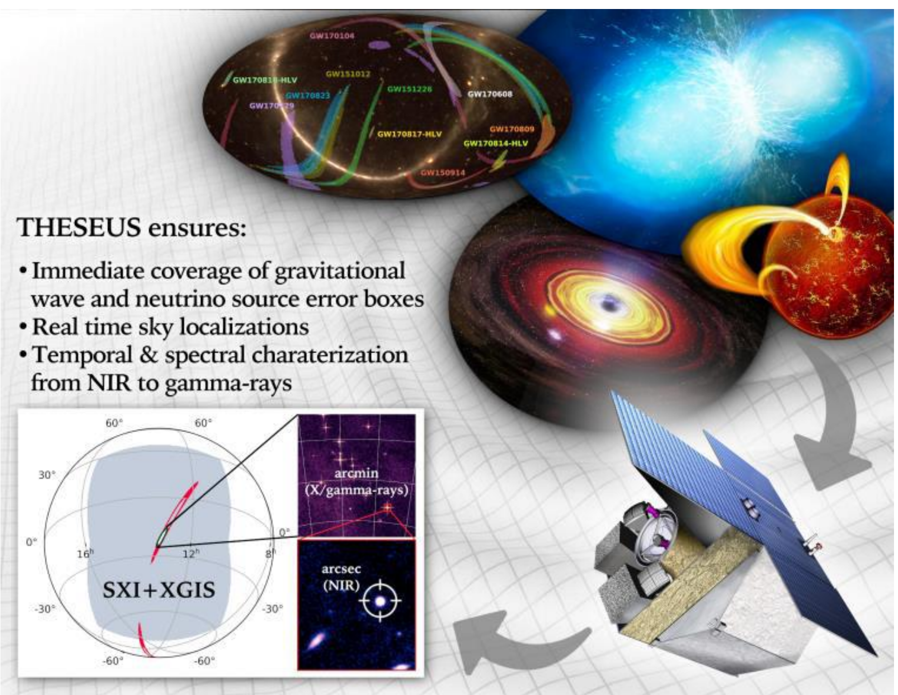


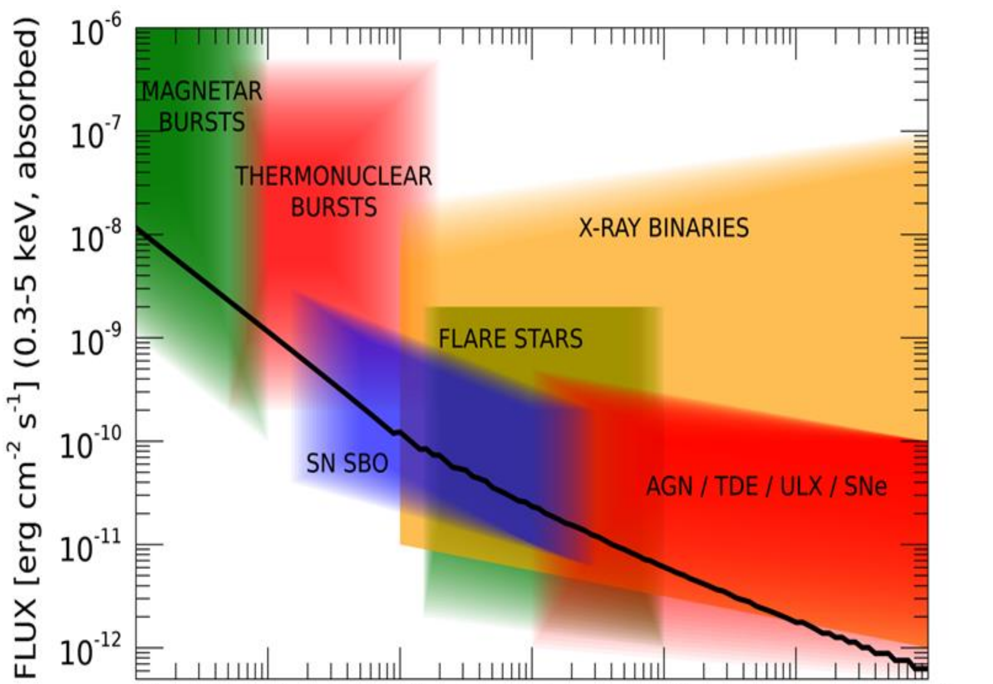




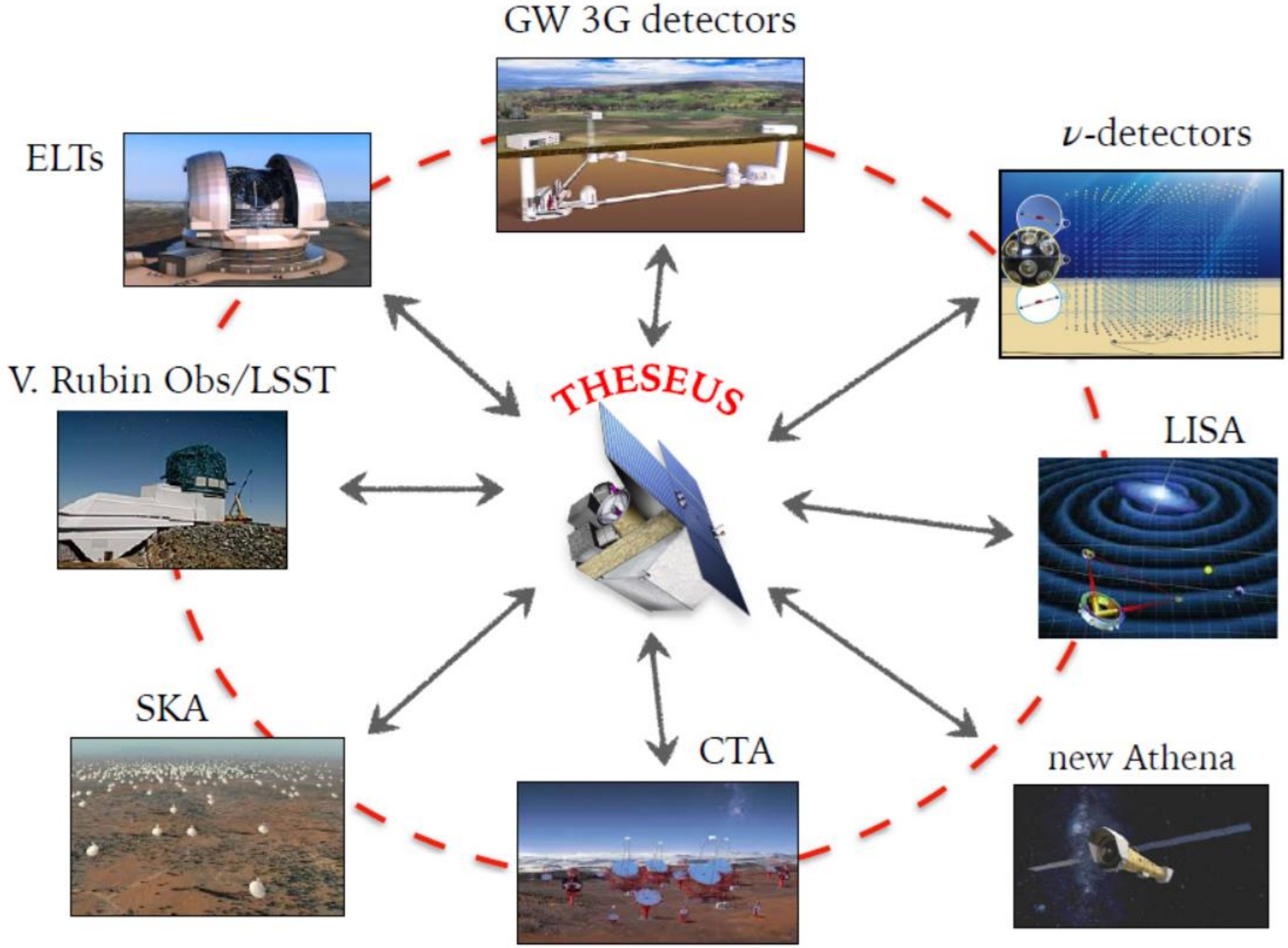
Exploring the transient sky

- 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



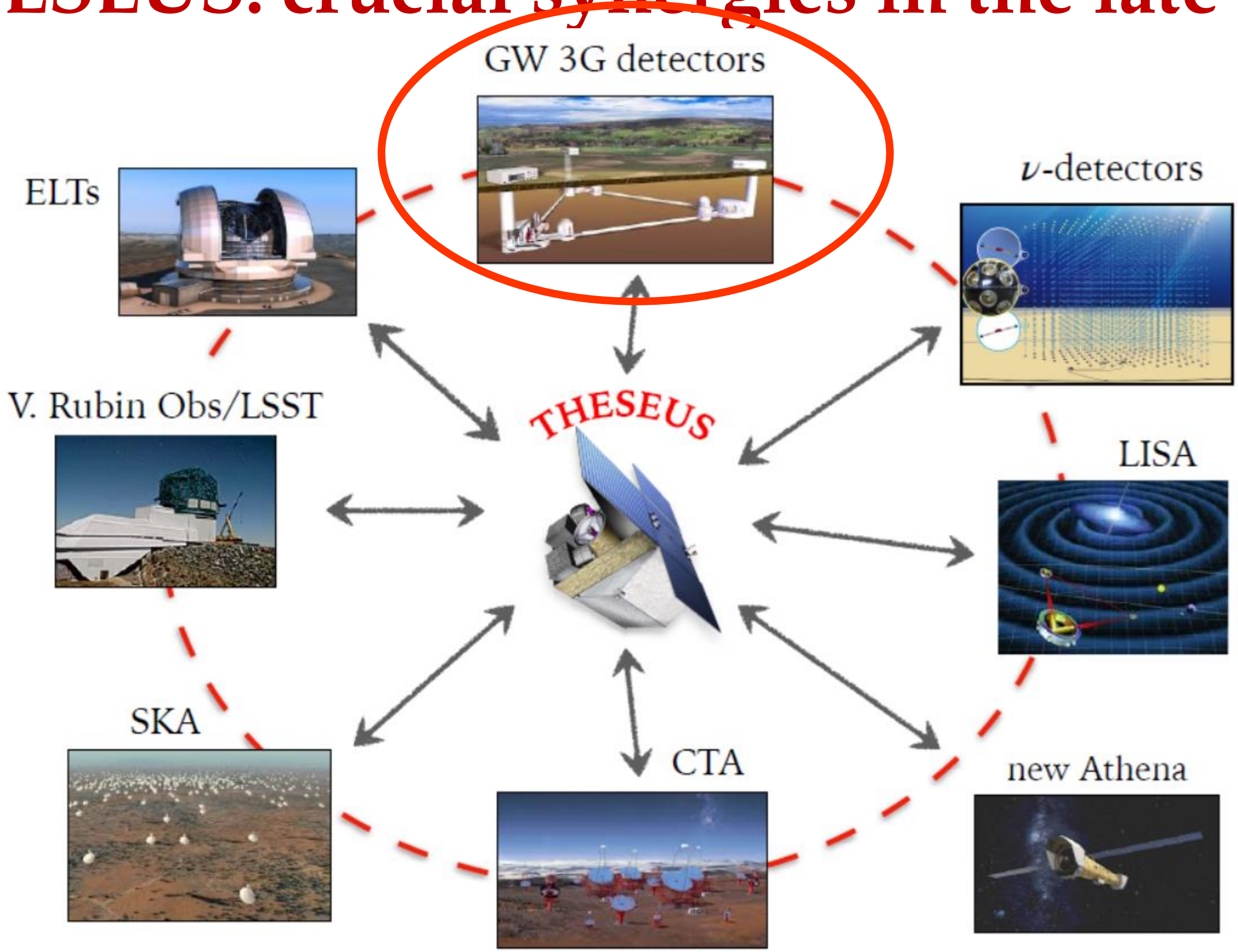


THESEUS: crucial synergies in the late '30s



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)**

THESEUS: crucial synergies in the late '30s

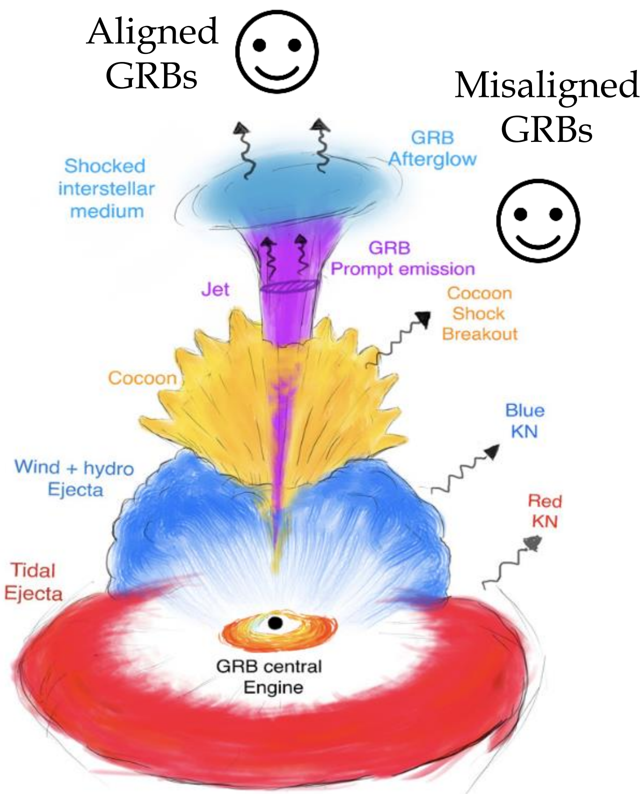


The «**M7**» **timeline** will allow to **widely broaden the mission scientific impact** by taking advantage of the **perfectly matched synergies** with major facilities coming fully operative in the 2030s **(e.g., 3G GW detectors)**

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

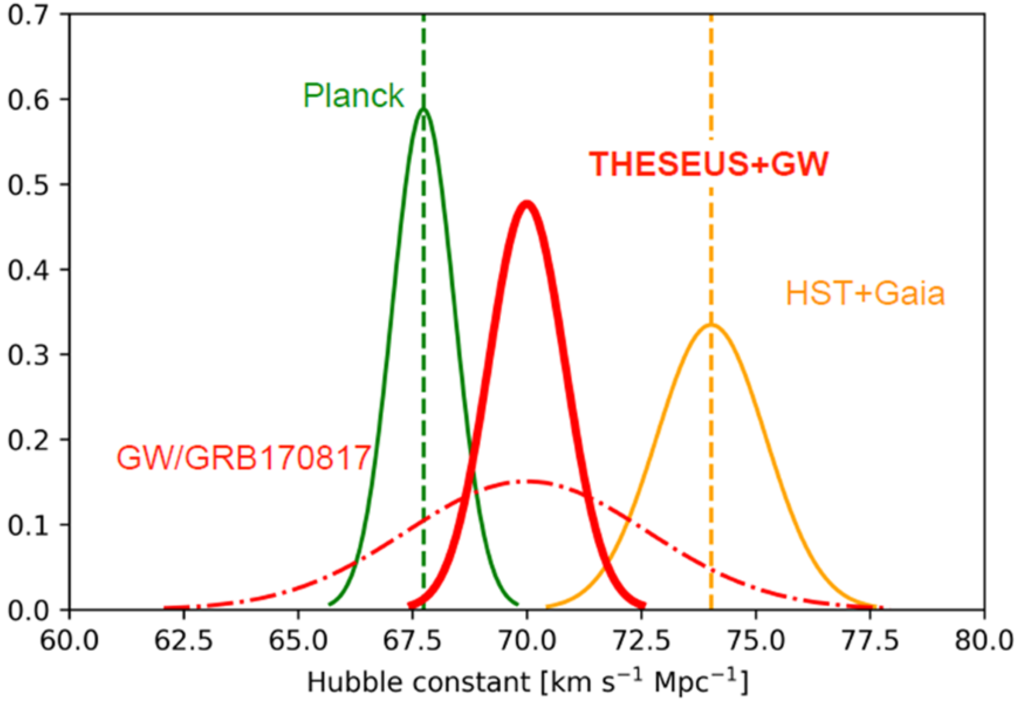
Multi-messenger science with THESEUS

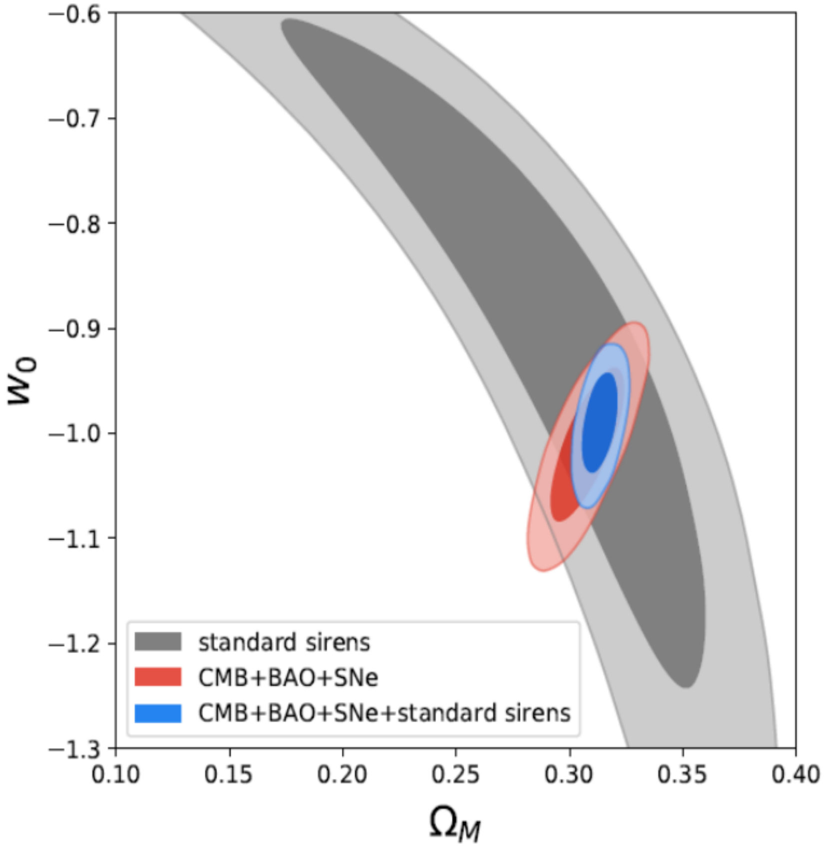
THESEUS & 3G SCIENCE

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

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME





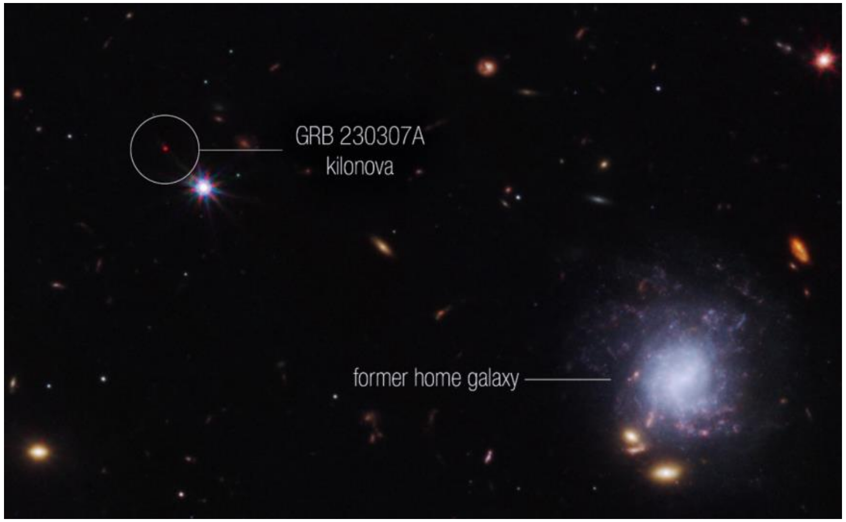
~20 joint GRB+GW events

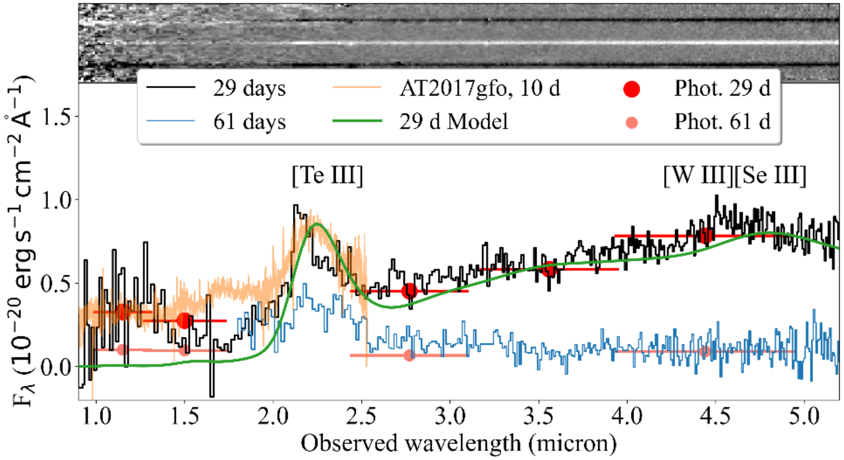
ET collaboration

Long-GRBs from compact binary mergers

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

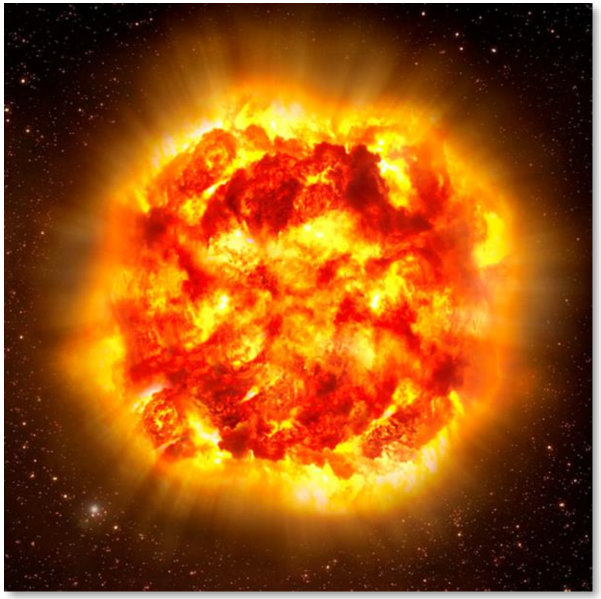
- GRB 211211A at d~350 Mpc (Rastinejad et al. 2022)
- GRB 230307A at d~280 Mpc (Levan et al. 2023 in press)
- **Conclude: enhanced rate of binary mergers simultaneously detected by ET and THESEUS**

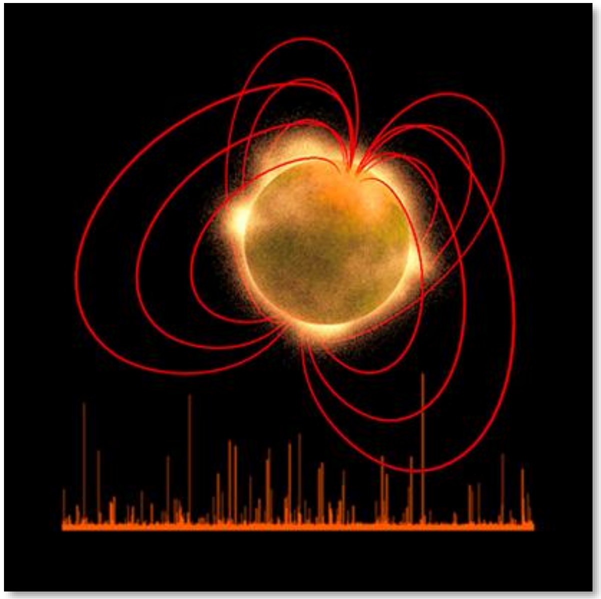




Multi-messenger science with THESEUS

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





In summary

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

- **THESEUS**, a mission concept developed by a large European collaboration led by Italy and under study by ESA (M7 Phase-A) **will fully exploit these potentialities**, providing a substantial contribution to extreme GRB physics and time-domain astronomy

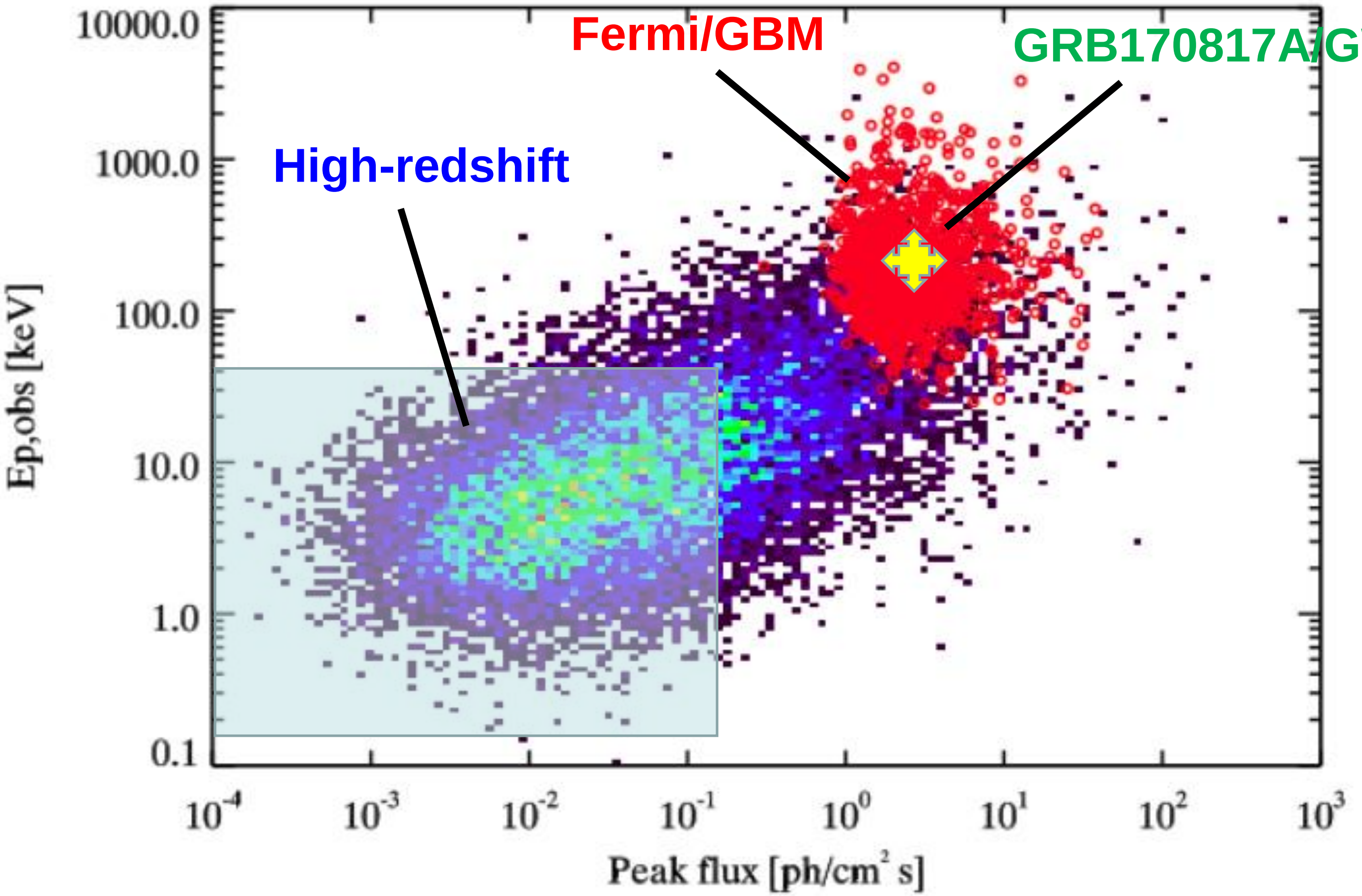
- The "M7" timeline will allow an **unprecedented great synergy with future very large observing** facilities in the e.m. and multi messenger domains, **enhancing their scientific return and fully exploiting the European leadership and investments put in them**.

- **The very strong synergy with Einstein Telescope** will provide a breakthough in multi-messenger astrophysics and allow to fully exploit the large investment by Italy and Europe in the project

- **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/

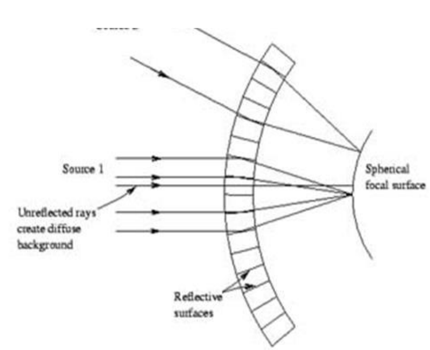
Back-up slides

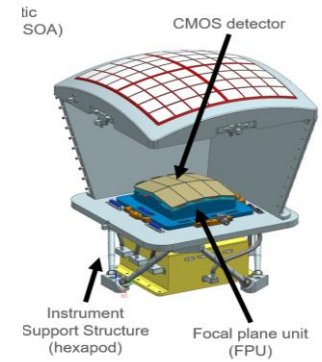
THESEUS will have a combination of instrumentation and mission profile allowing the detection of all types of GRBs (long, short/hard, weak/soft, high-redshift) and provide accurate location and redshift measurement for a large fraction of them



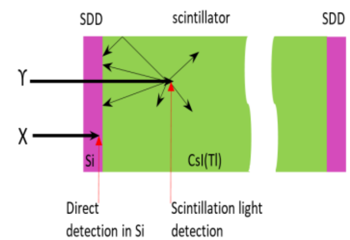
THESEUS Mission Concept

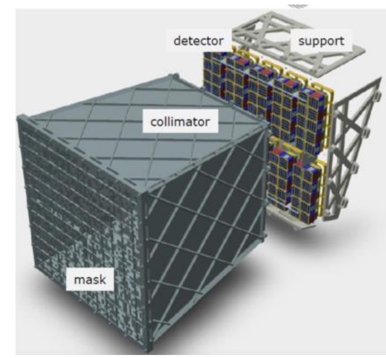
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′



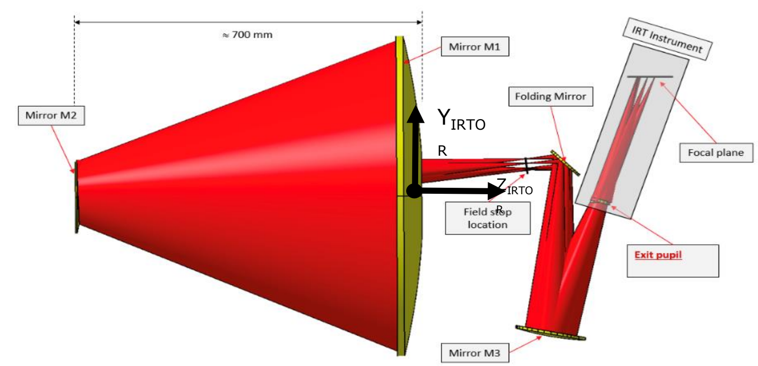


- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy





- **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

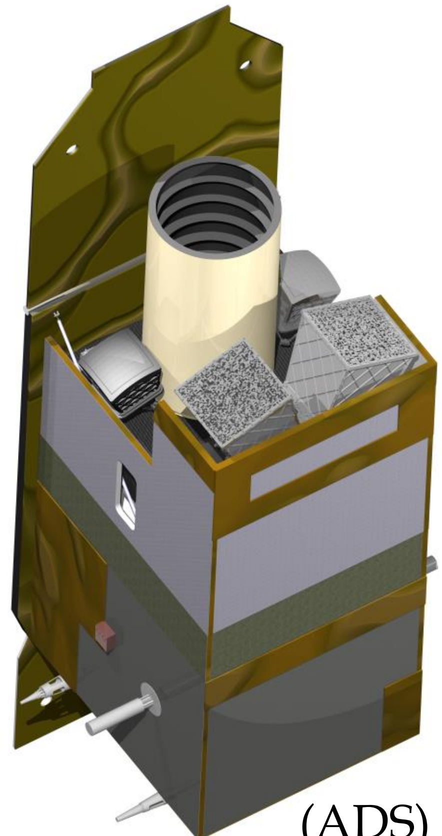


THESEUS Mission Concept

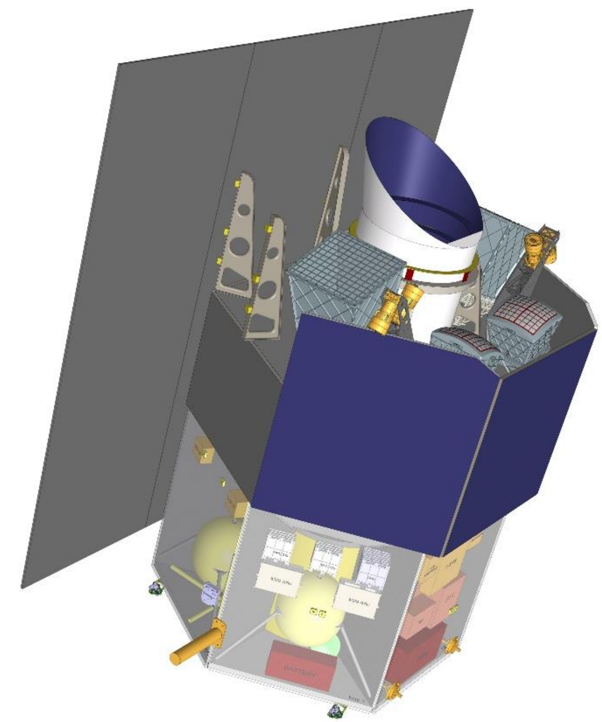
- **Fast slewing capability** (>10°/min), granting prompt NIR follow-up of GRBs and transients

- **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**

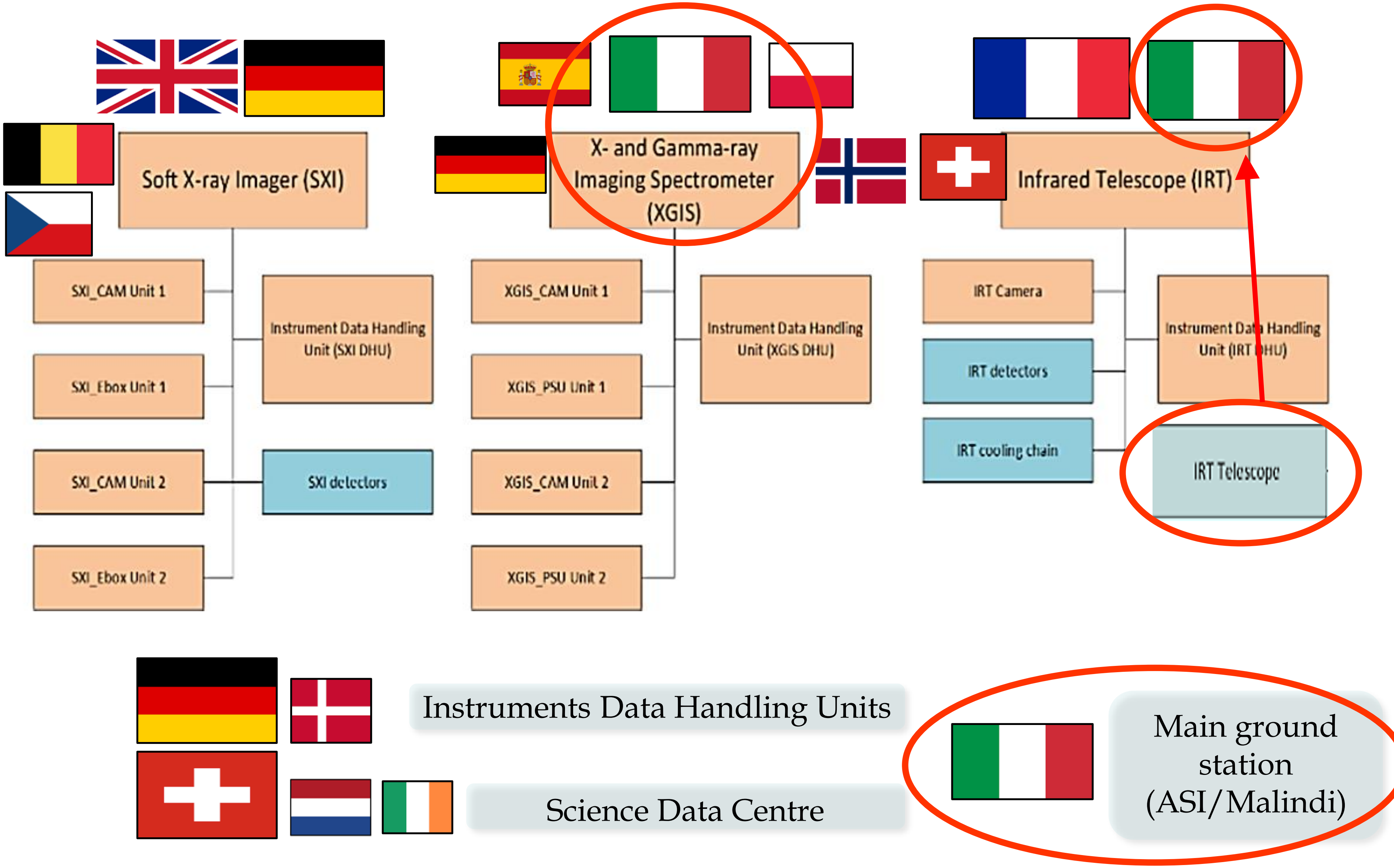


(ADS)

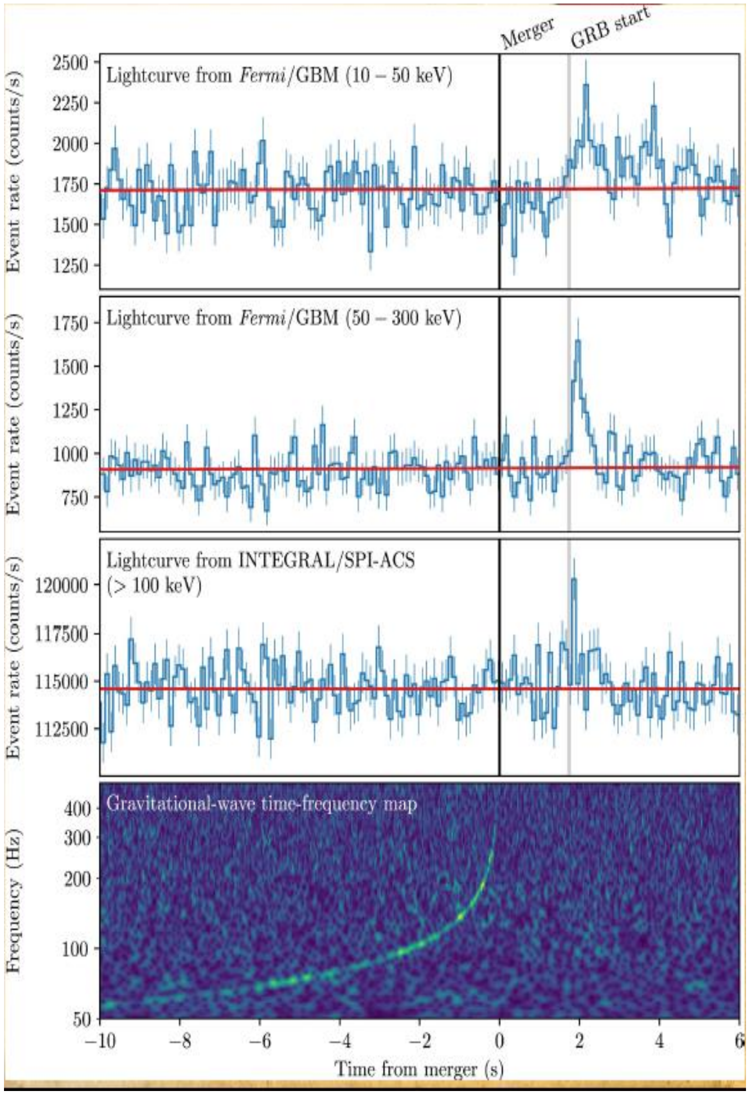


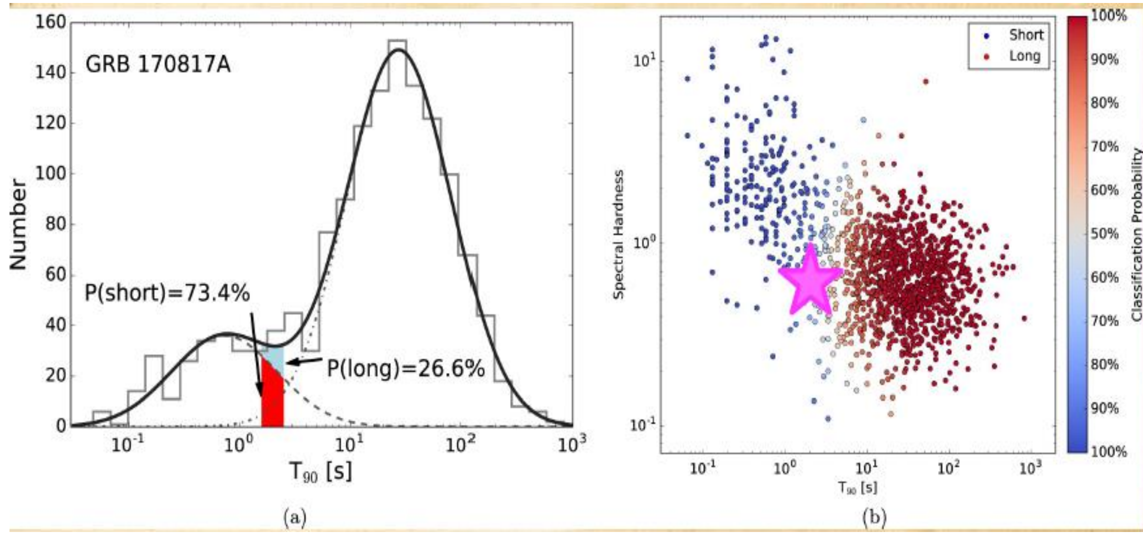
(THALES)

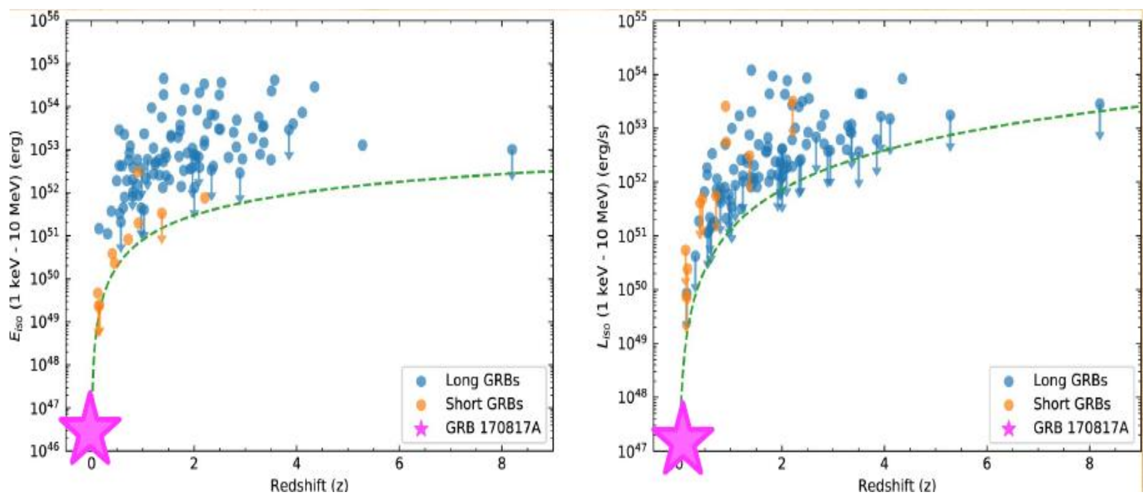
THESEUS payload procurement scheme M7



• GRB170817A/GW170817: a "peculiar" short GRB

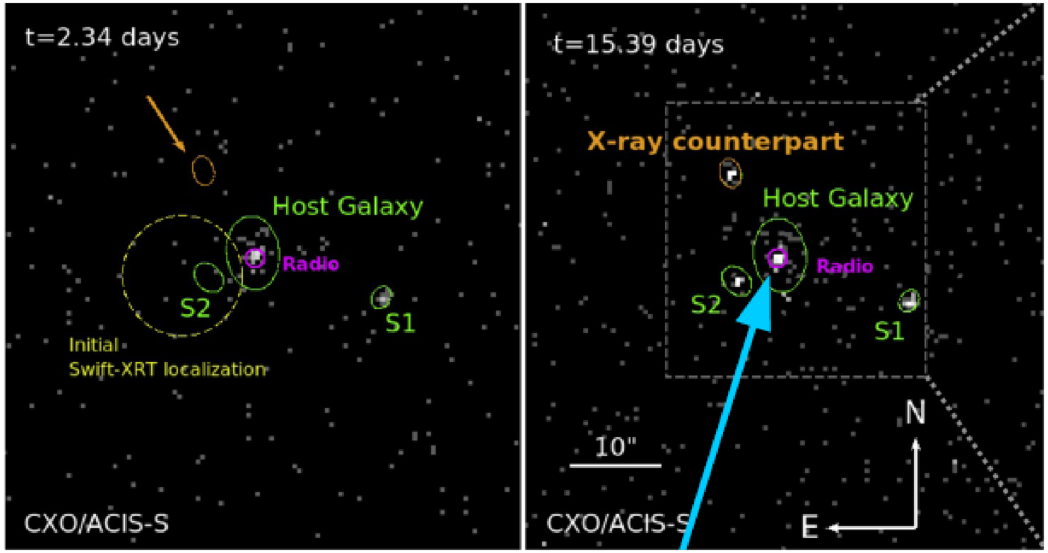


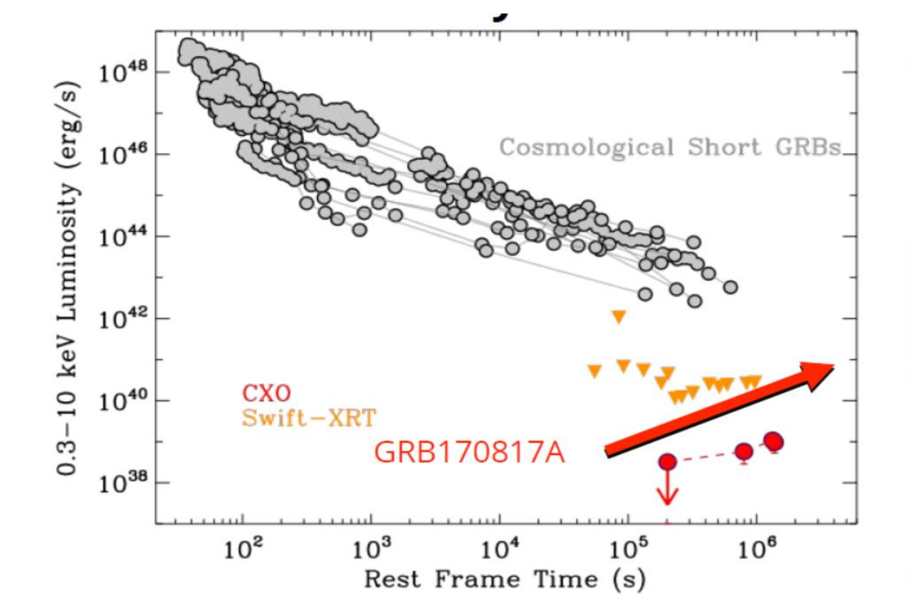


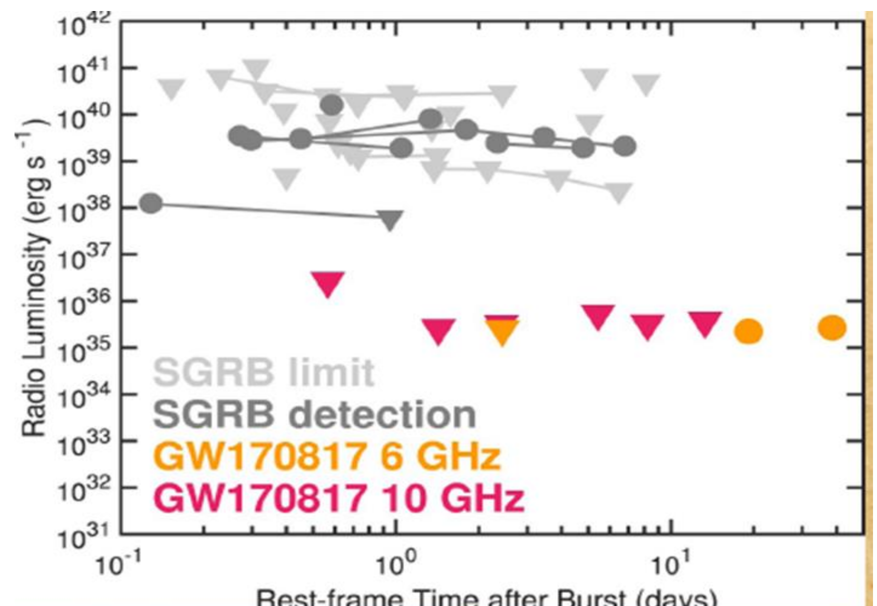


$E_{iso} = (5.3 \pm 1.0)\times10^{46}$ erg $\quad$ $L_{iso} = (1.2 \pm 0.6)\times10^{47}$ erg/s

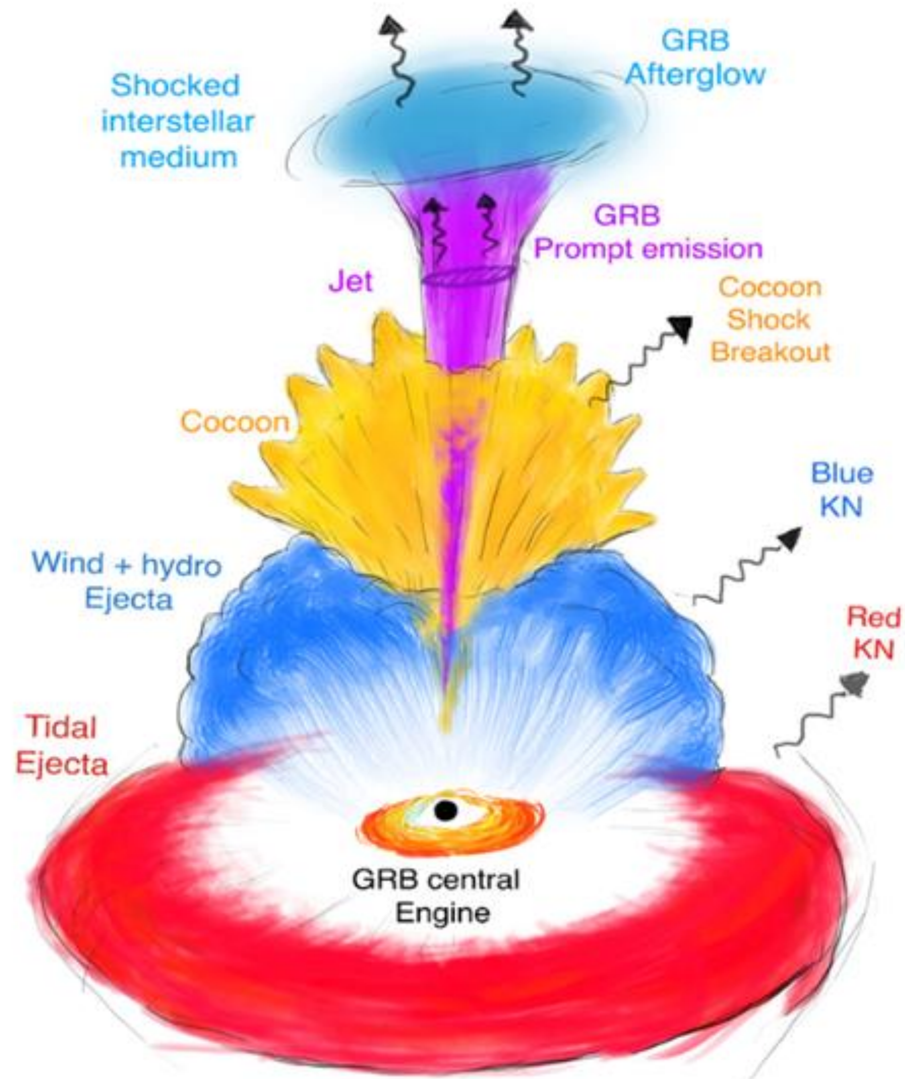
• **GRB170817A/GW170817: an underluminous and "late peaking" afterglow**

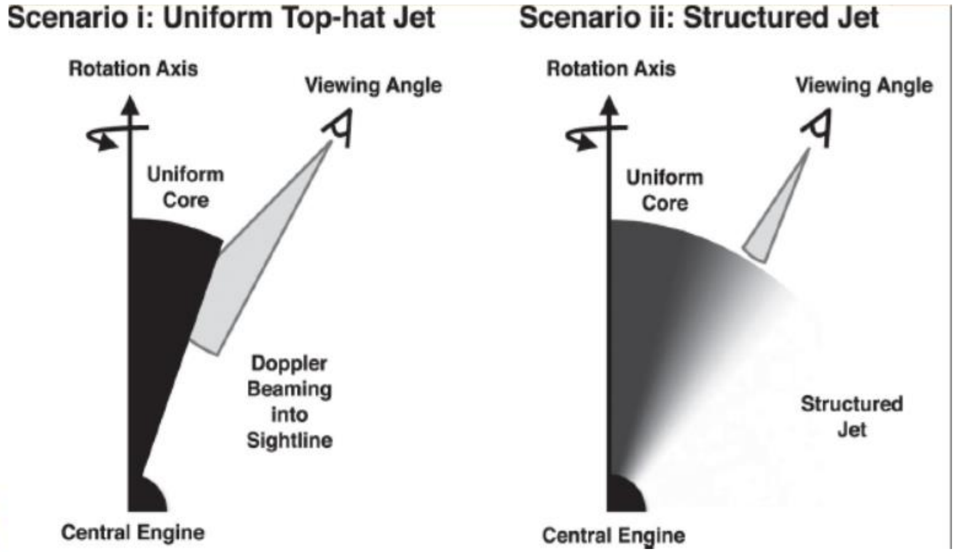






• GRB170817A/GW170817: an off-axis nerby GRB





$$t_{pk} \approx 2.1 \left(\frac{E_{k,iso,52}}{n}\right)^{1/3} \left(\frac{\theta_{obs}-\theta_j}{10^\circ}\right)^{8/3} d$$

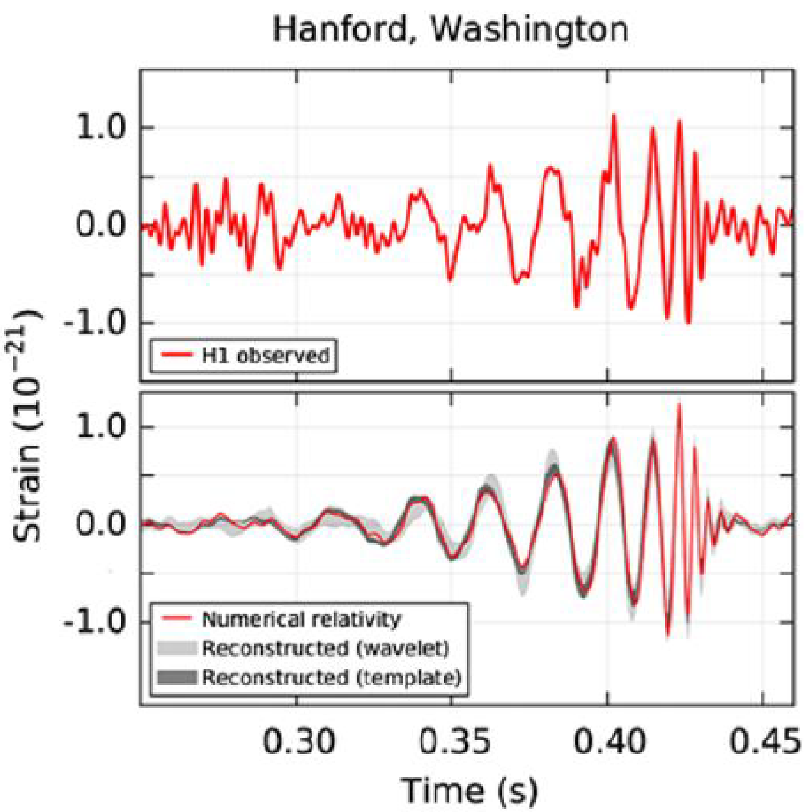
For t_{pk} ~ 15-70 d

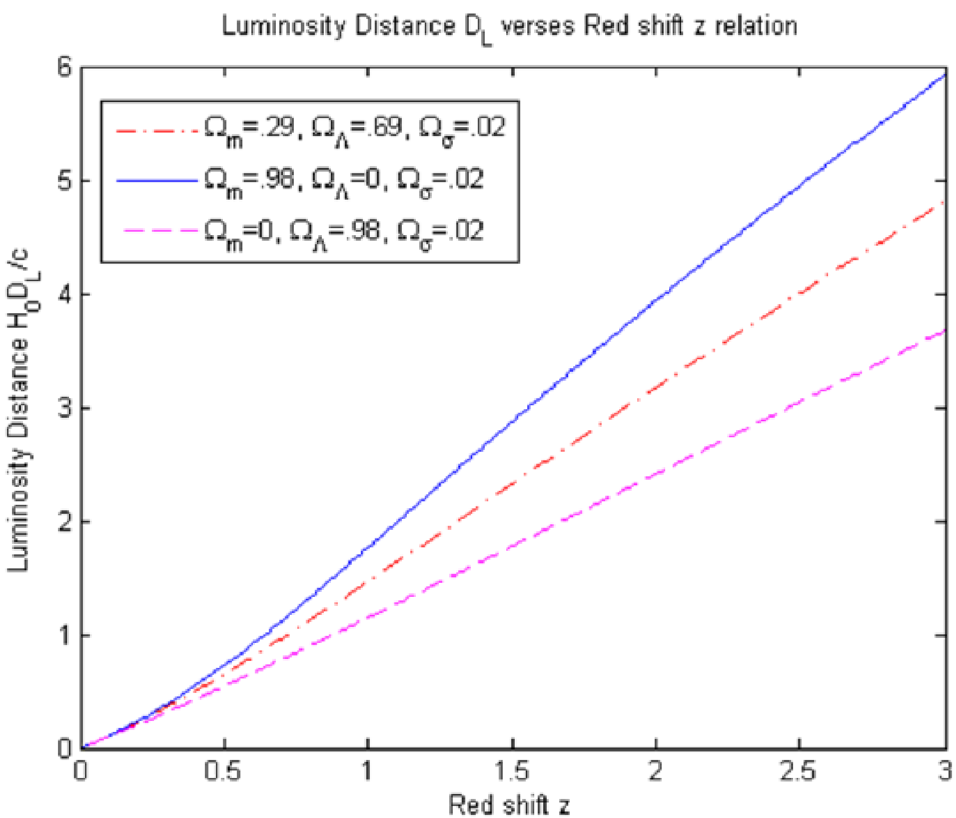
For typical parameters inferred from SGRBs (θ_j ~5-15 deg):

θ_{obs} ~20-40 deg

Multi-messenger cosmology with GRBs

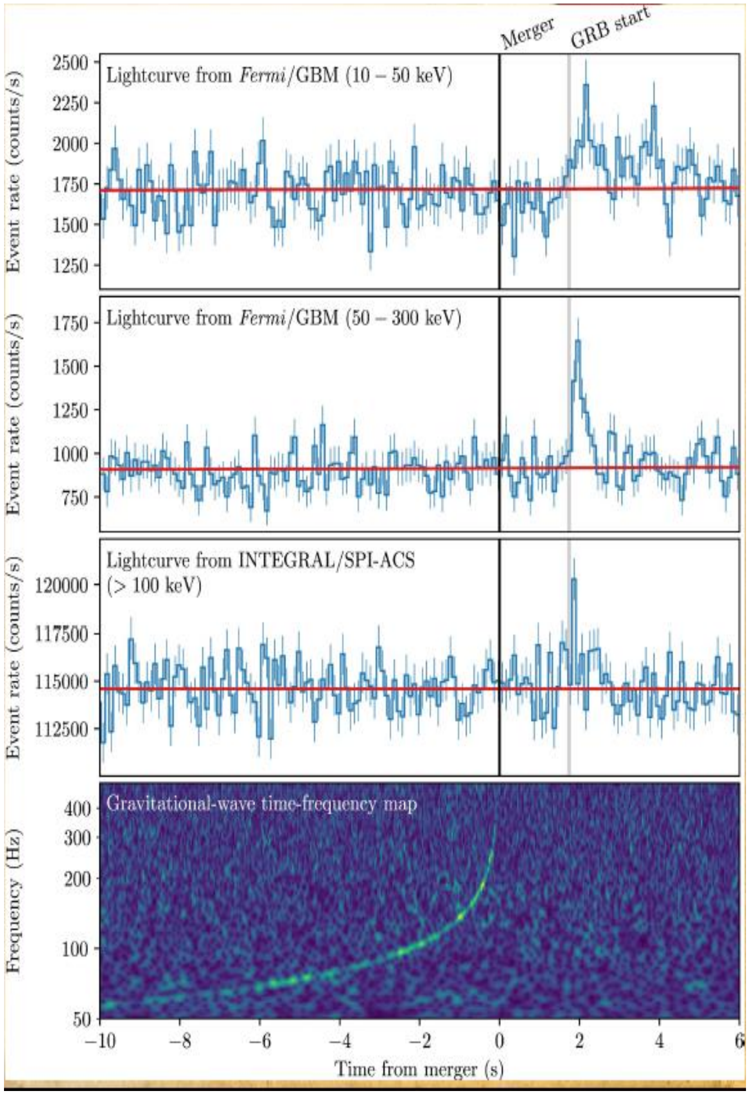
- Modelization of GW signal provide **cosmology independent estinmate of source distance**
- Detection and localization of associated GRB **leads to redshift estimate**





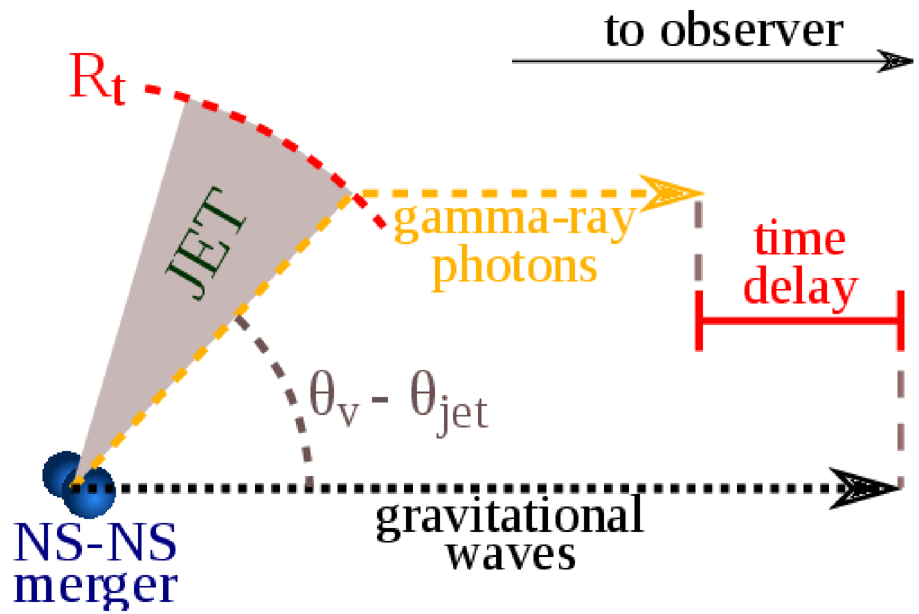
Fundamental physics: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

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



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

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

Fundamental physics: testing LI / QG

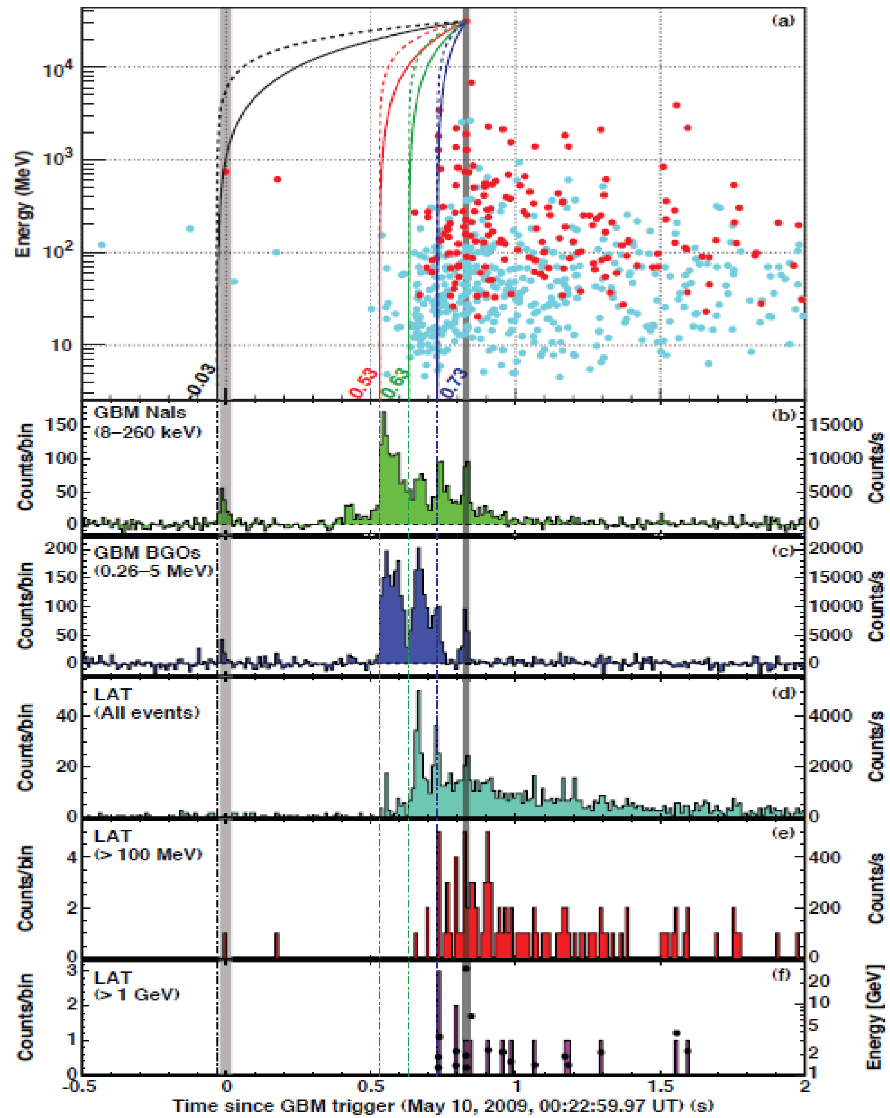
- Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

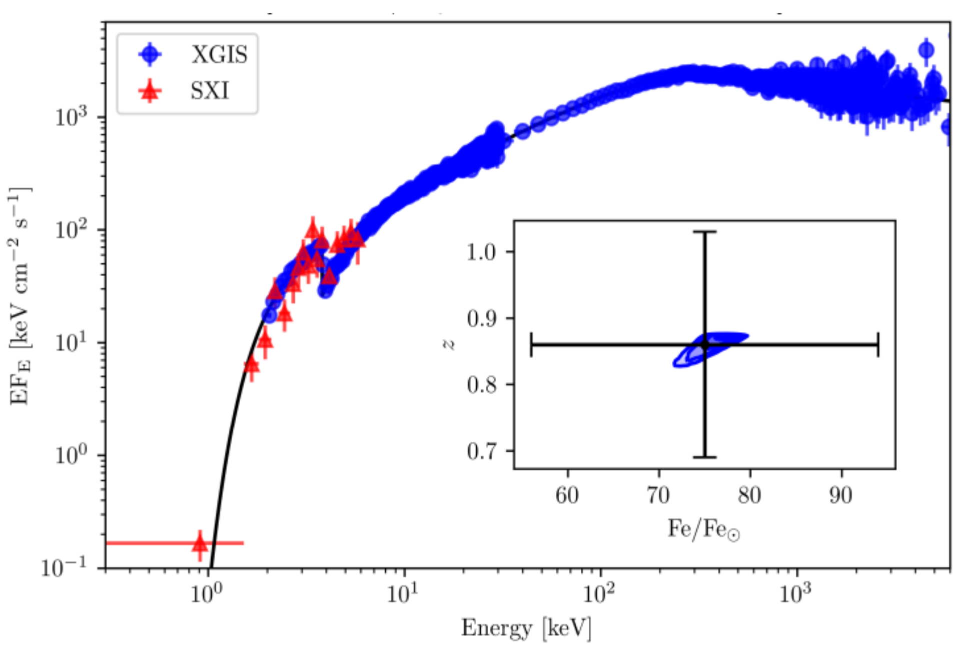
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

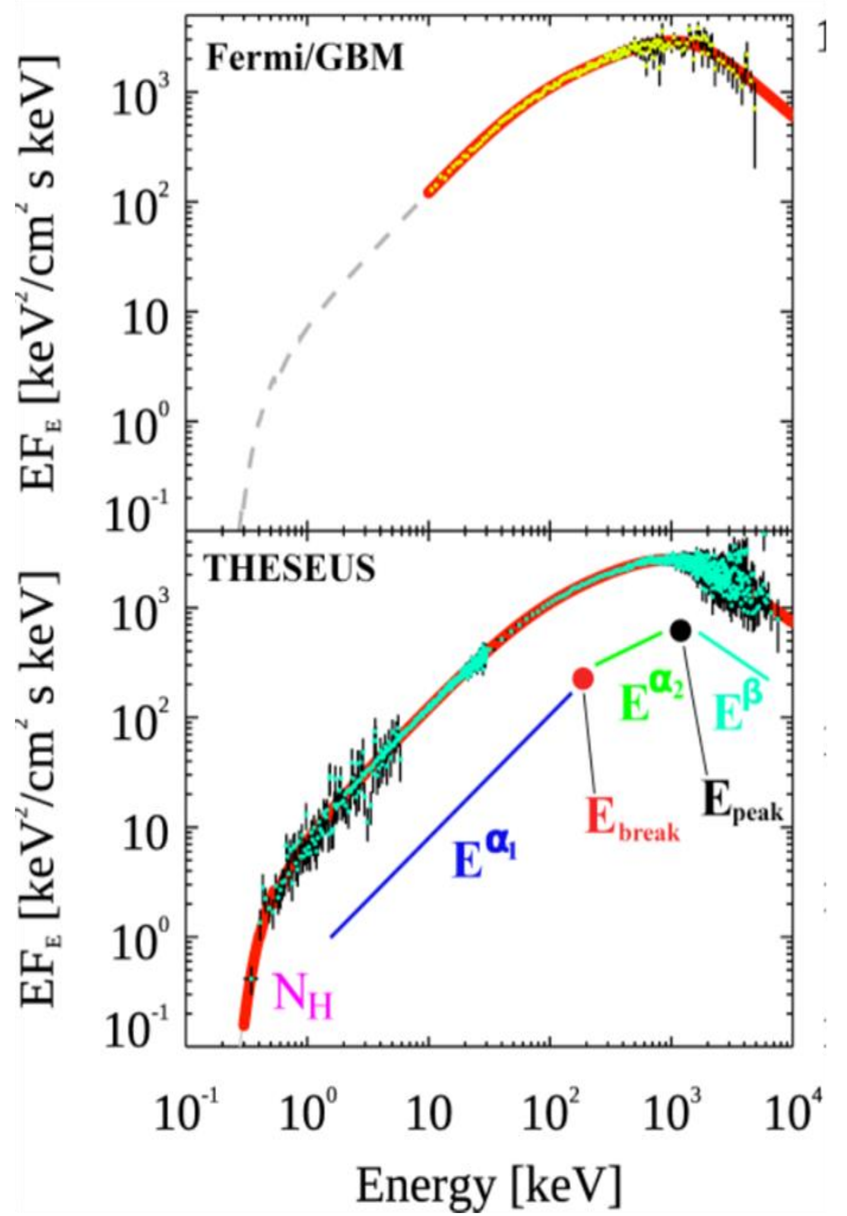
$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
−30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start 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



GRBs extreme and fundamental physics

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



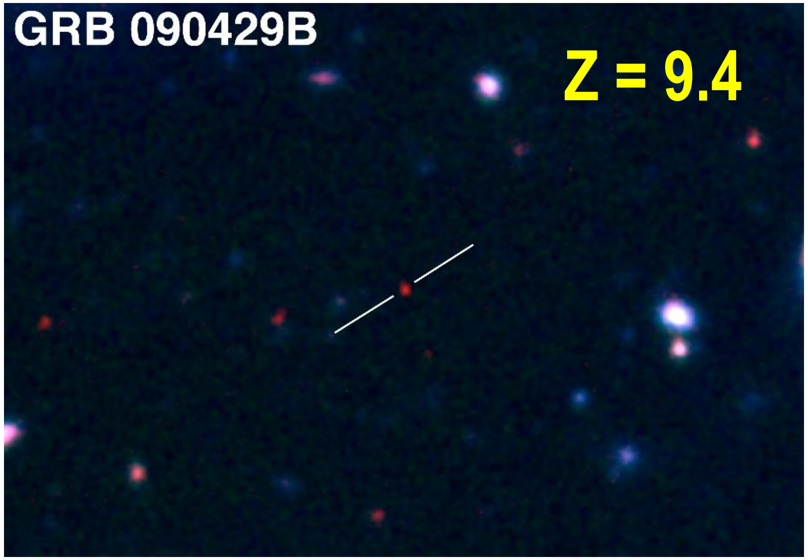


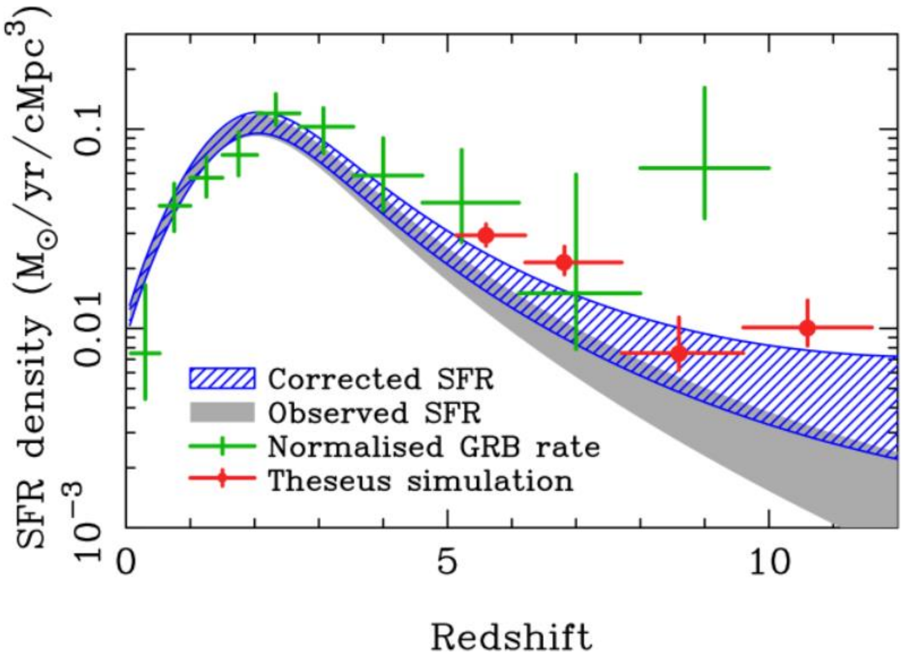
Shedding light on the early Universe with GRBs

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

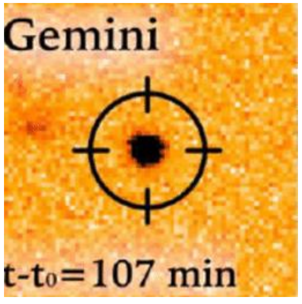
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

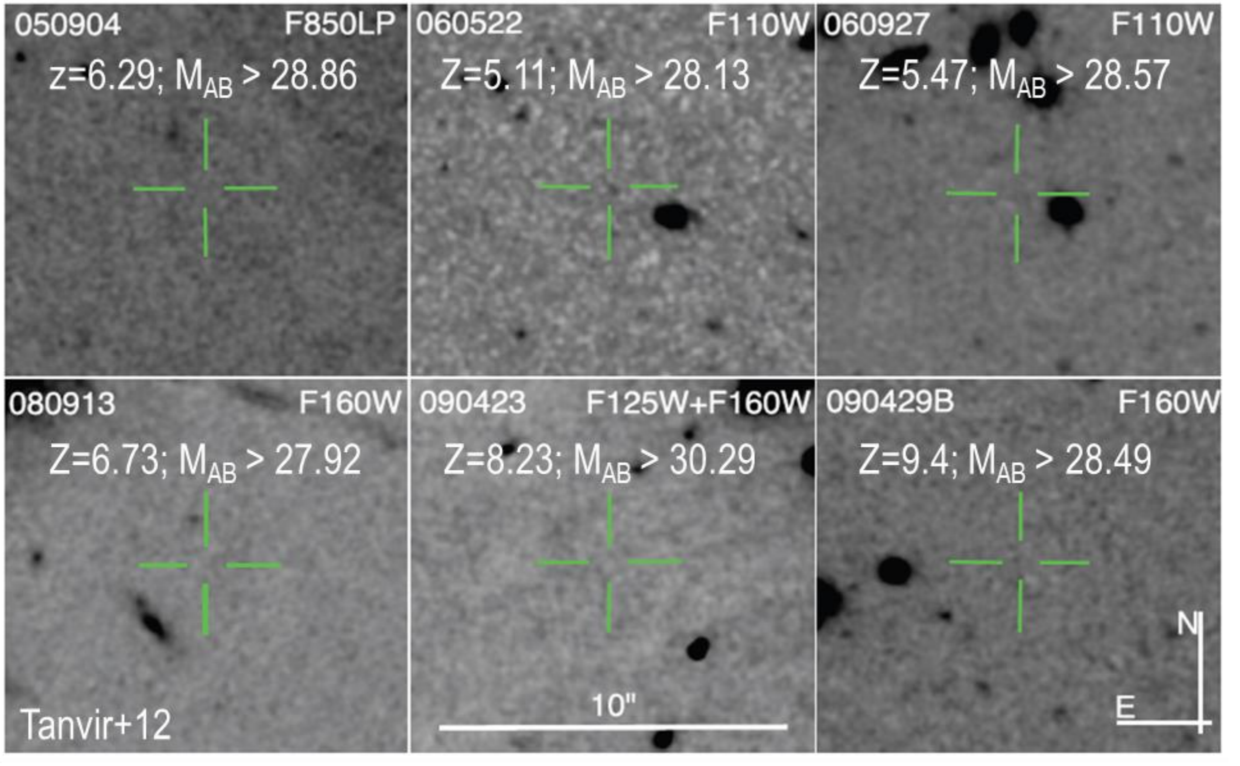
- directly (or indirectly) detect the **first population of stars (pop III)**





Detecting and studying primordial invisible galaxies

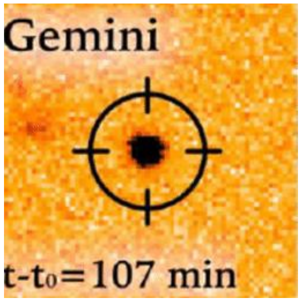


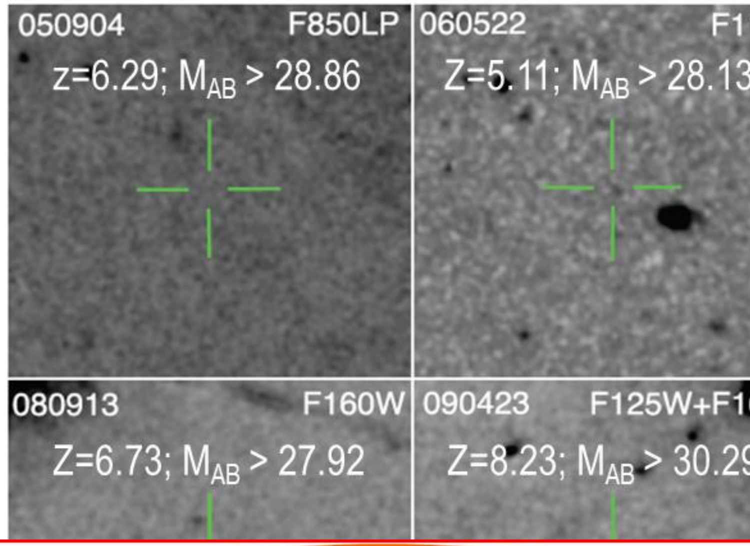


Robertson&Ellis12

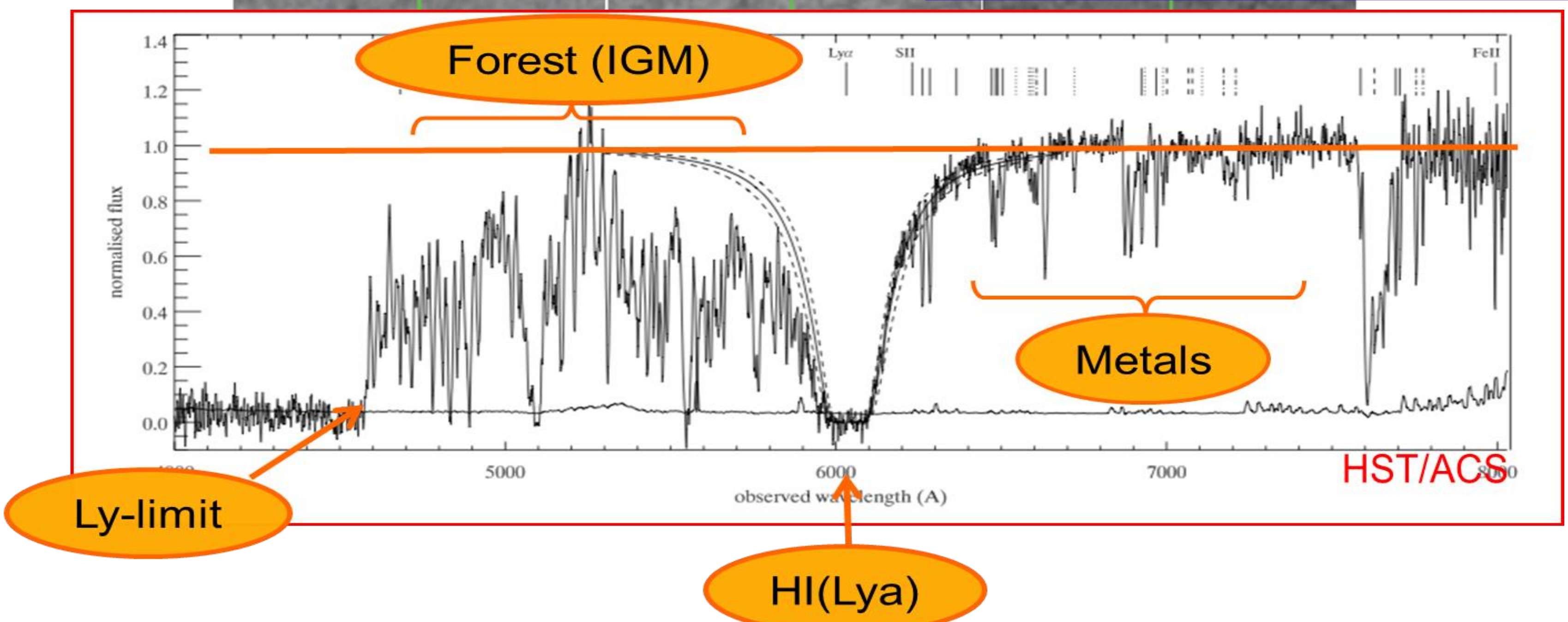
Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

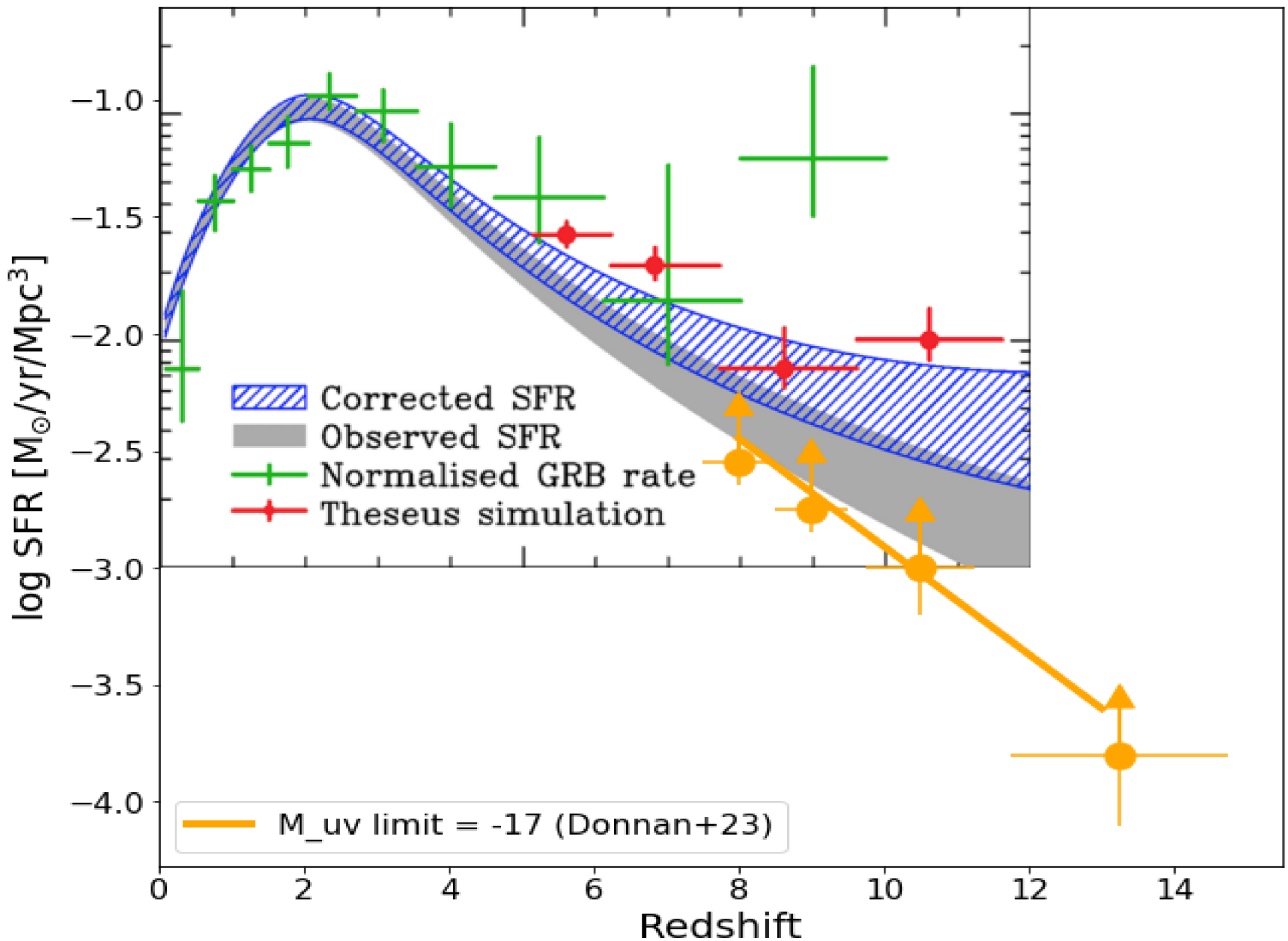
Detecting and studying primordial invisible galaxies





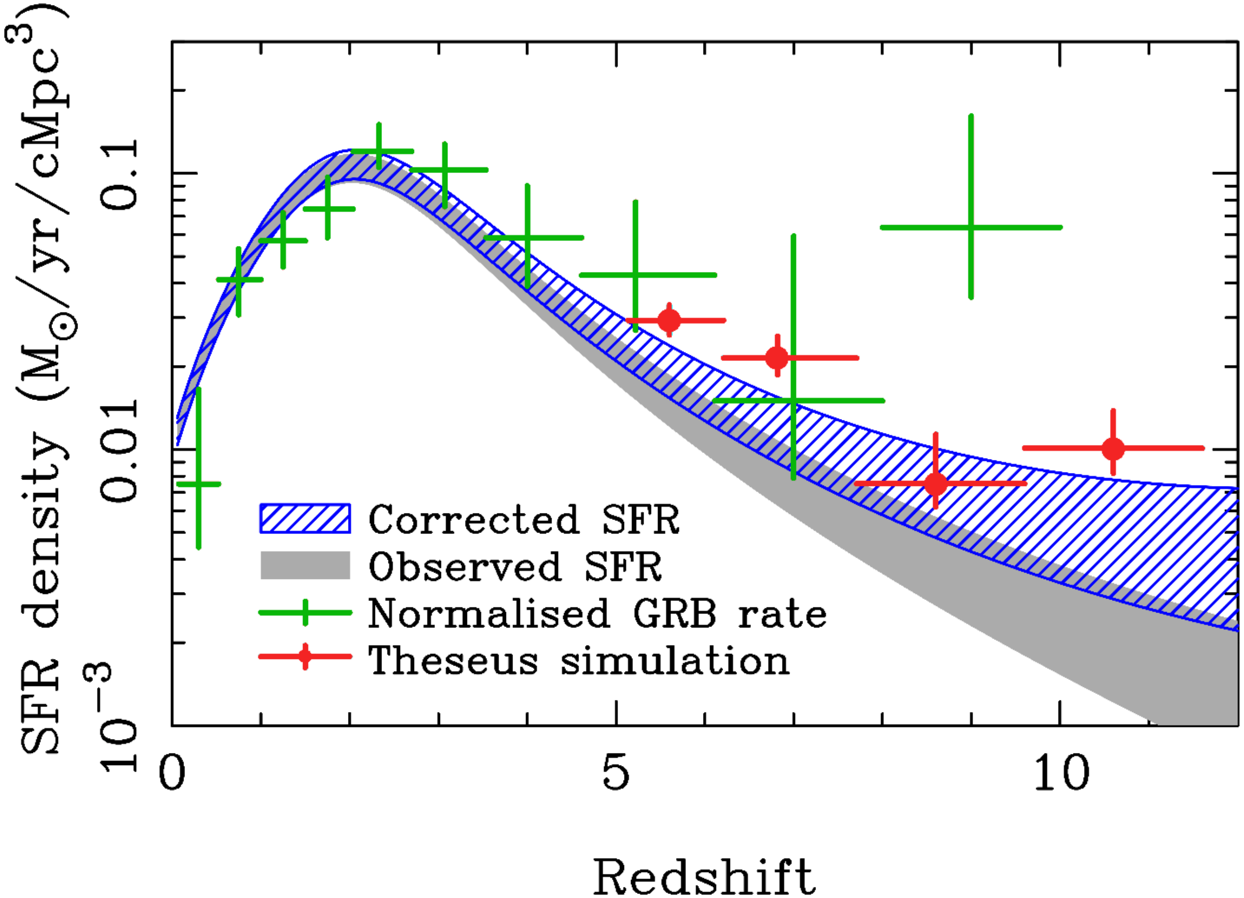
- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution





log SFR [M⊙/yr/Mpc³]
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
0
2
4
6
8
10
12
14
Redshift
Corrected SFR
Observed SFR
Normalised GRB rate
Theseus simulation
M_uv limit = -17 (Donnan+23)

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

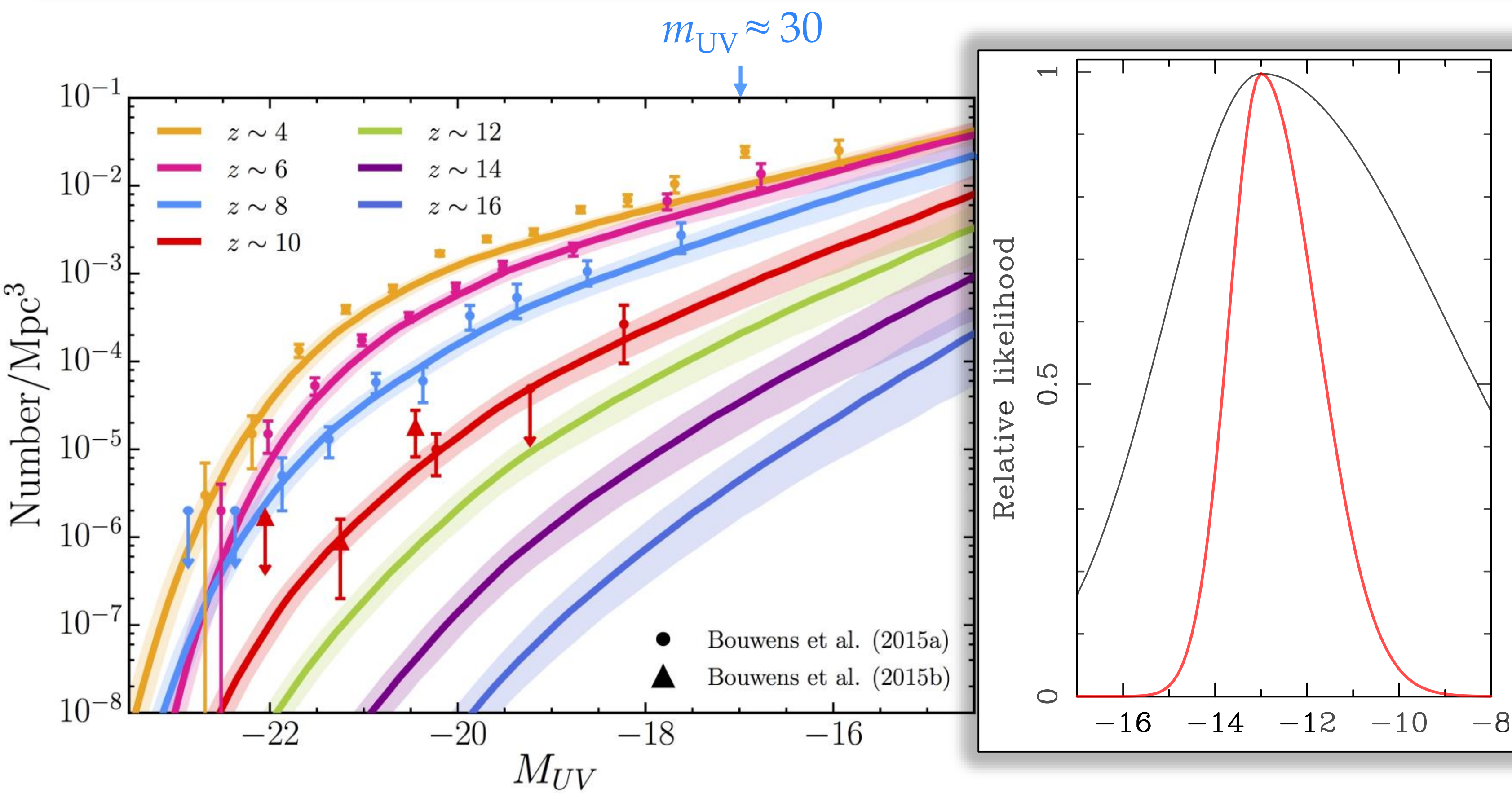


A sample of **>40 high–z GRBs** will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

THESEUS Consortium 2021

• Detecting and studying primordial invisible galaxies

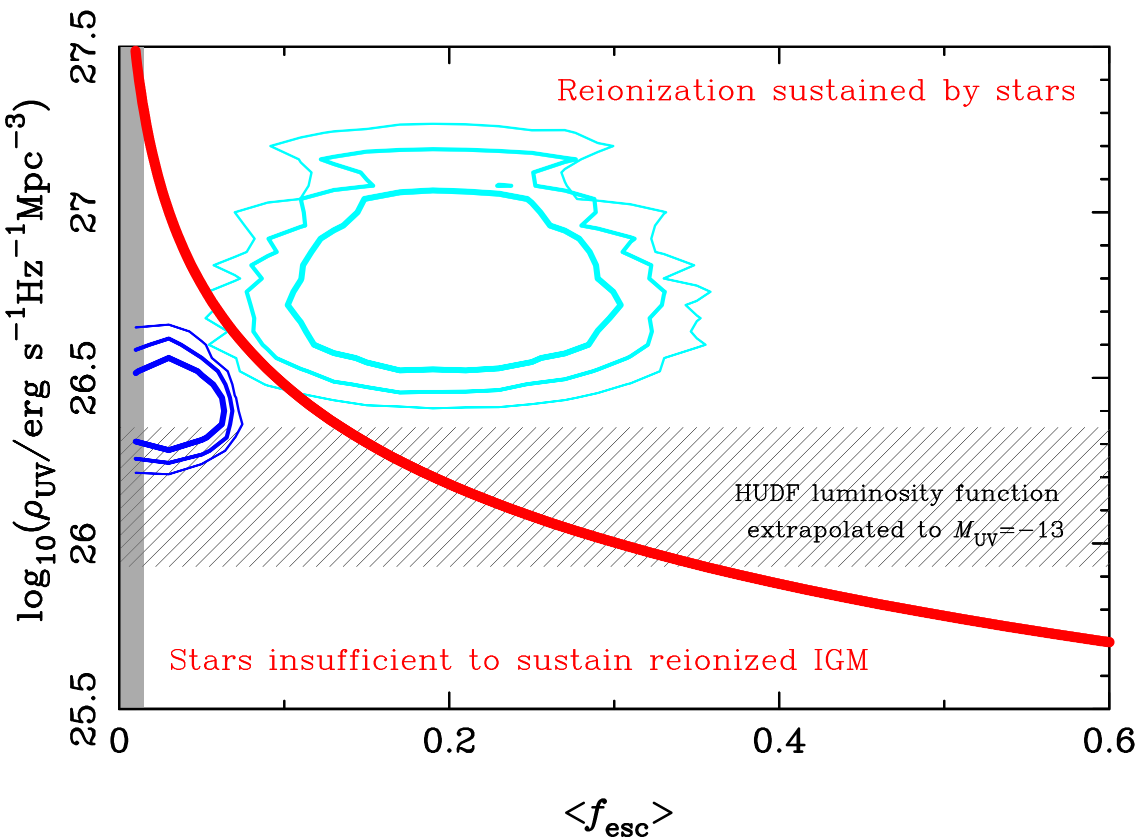
The proportion of GRB hosts below a given detection limit provides an estimate of the fraction of star formation "hidden" in such faint galaxies



Bright ⟷ Faint

THESEUS Consortium 2021

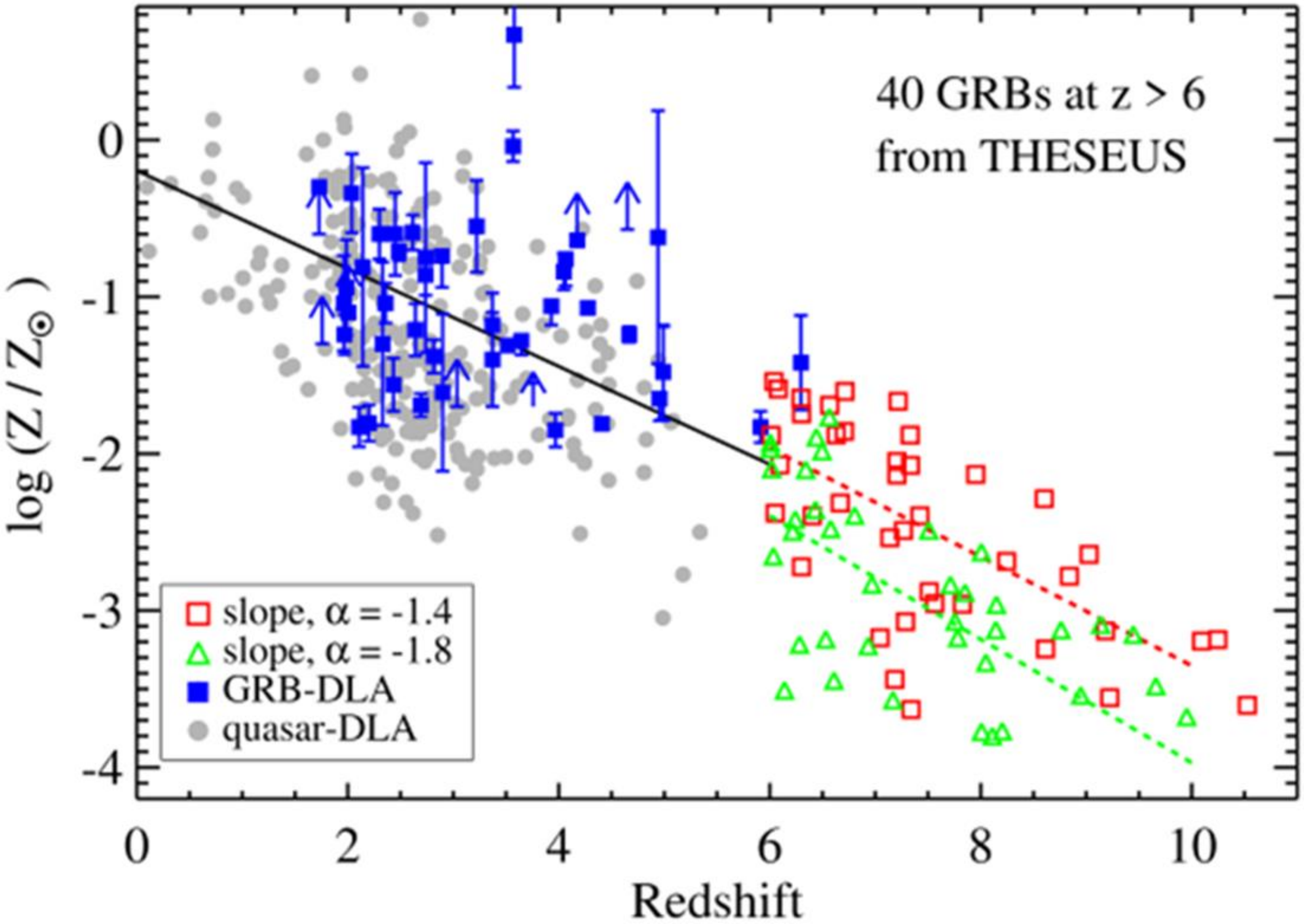
• Shedding light on cosmic reionization



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