Cosmology, multi-messenger astrophysics and fundamental physics with GRBs

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(INAF – OAS Bologna)
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INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

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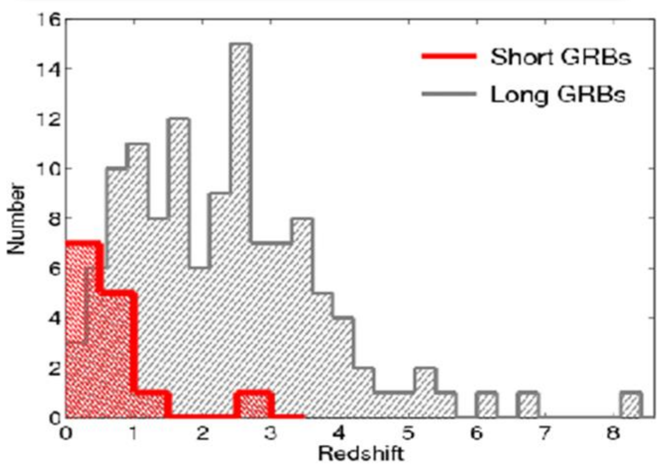
on High Energy Gamma-Ray Astronomy

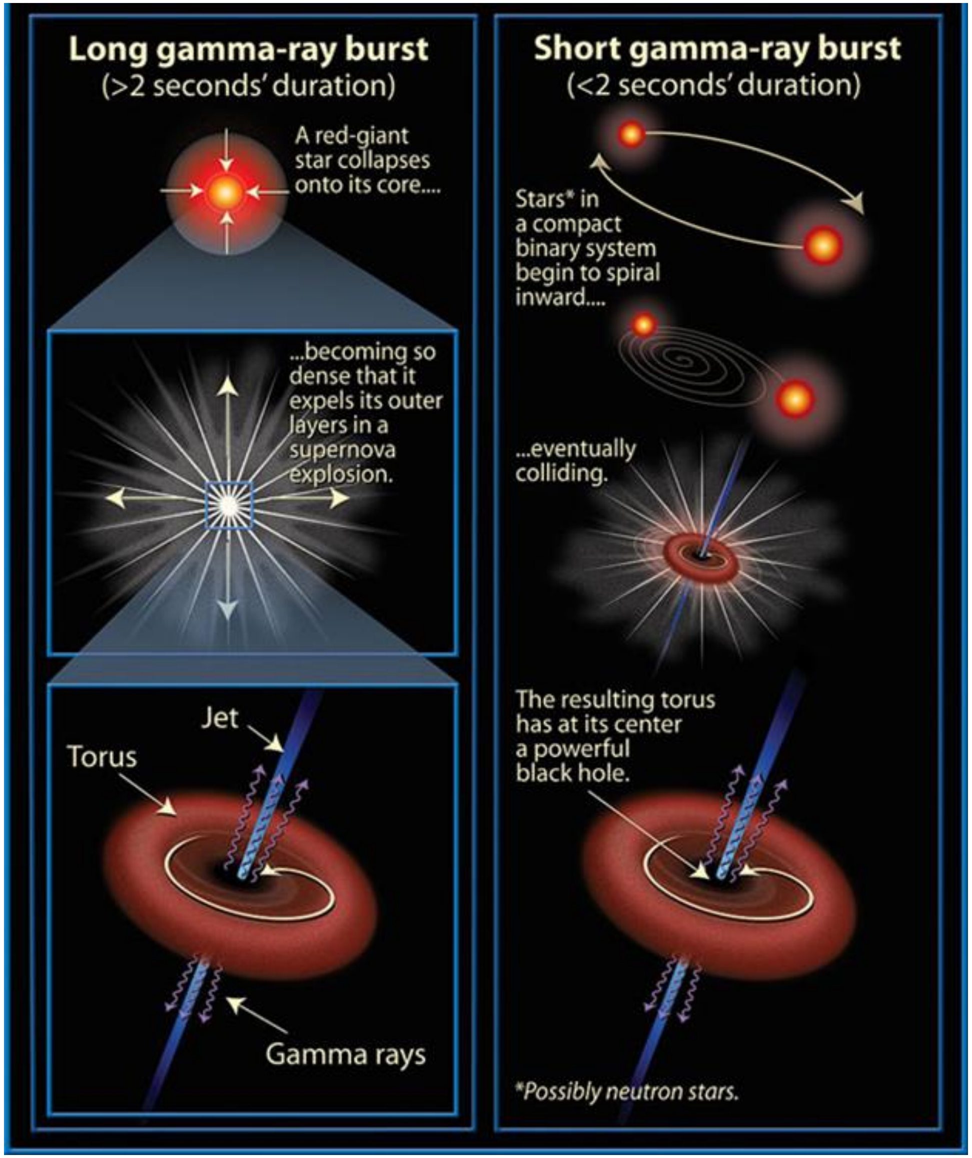
γ 2022
BARCELONA

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**



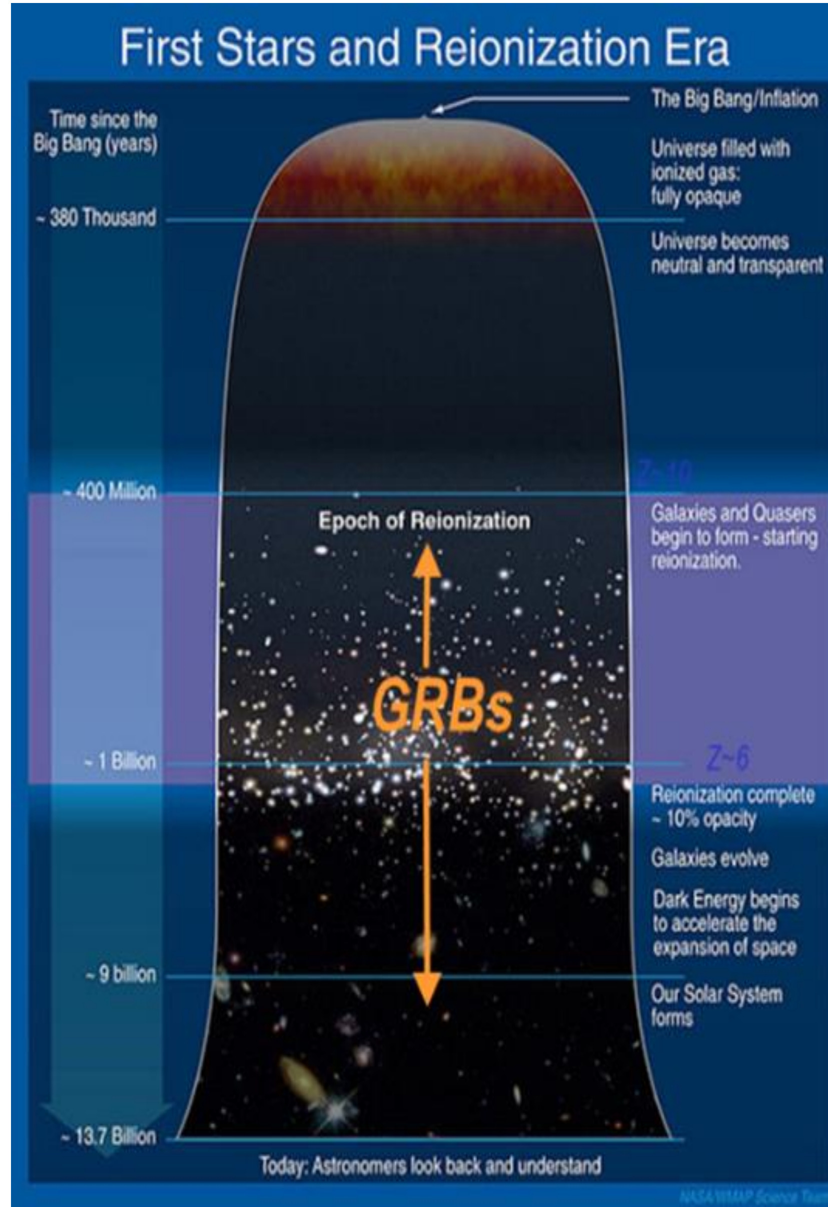


Shedding light on the early Universe with GRBs

- **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

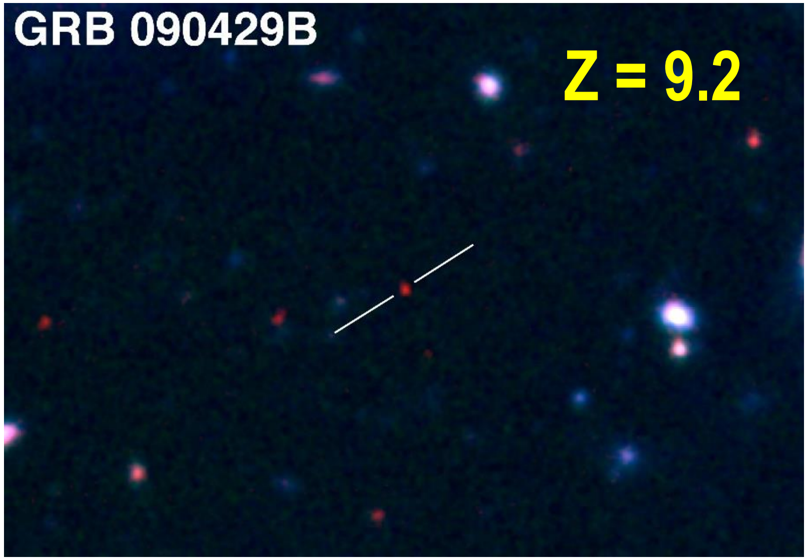


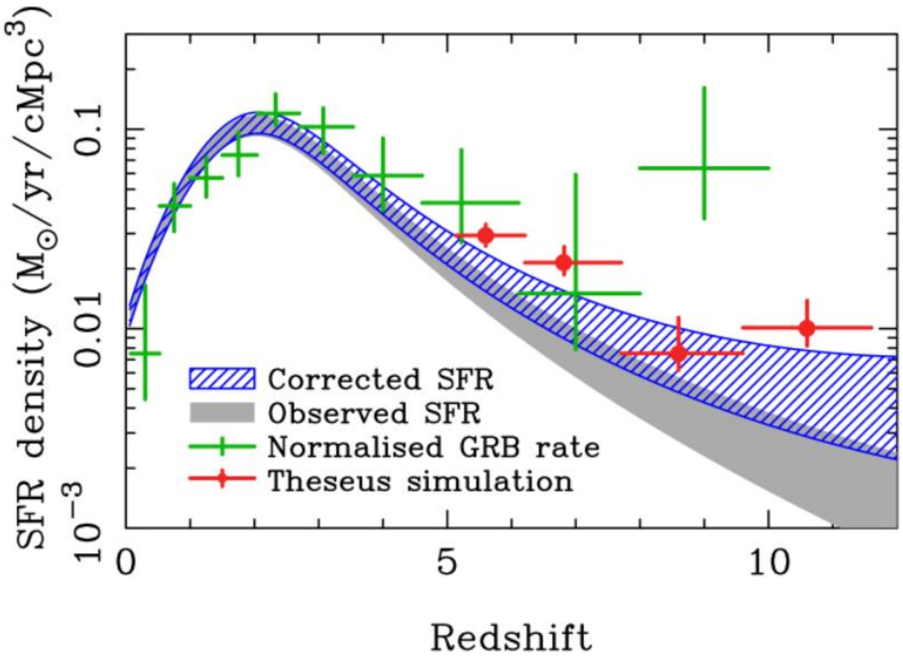
Shedding light on the early Universe with GRBs

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

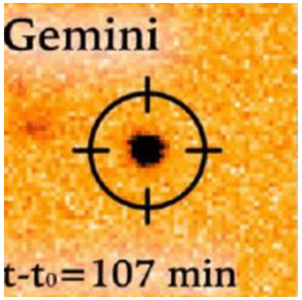
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

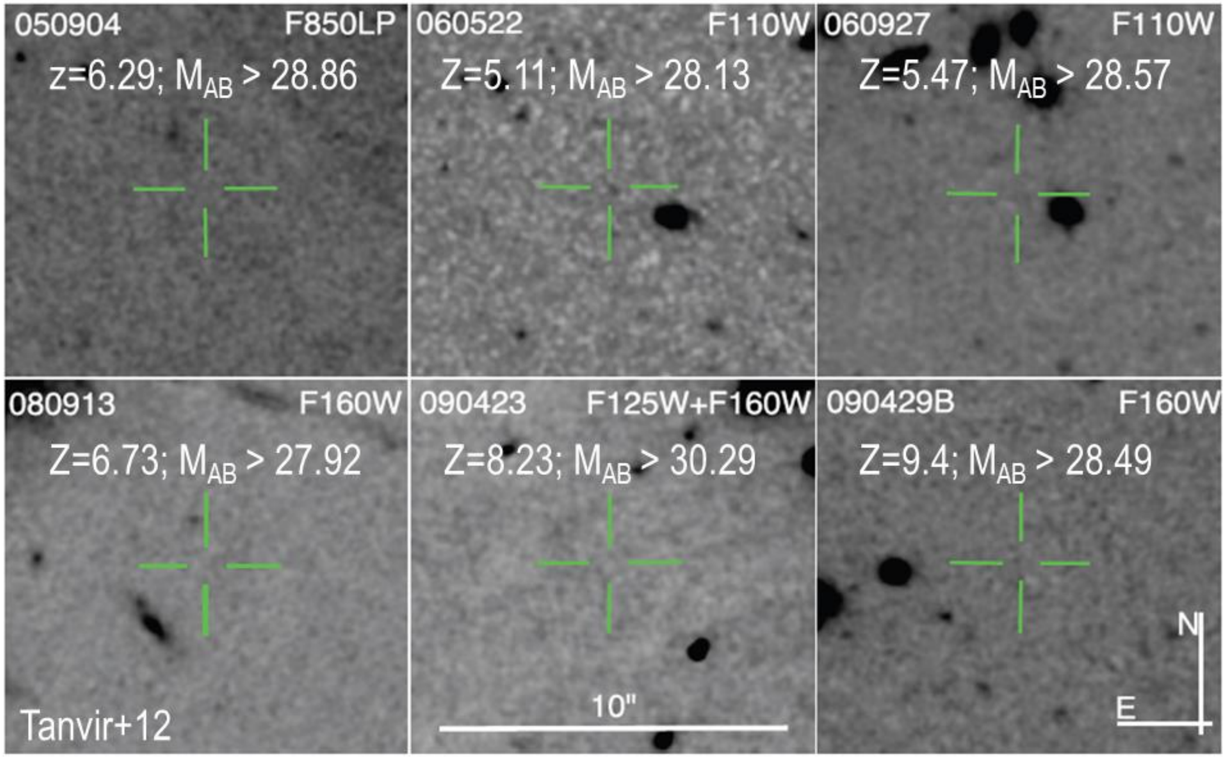
- directly (or indirectly) detect the **first population of stars (pop III)**





- **Detecting and studying primordial invisible galaxies**

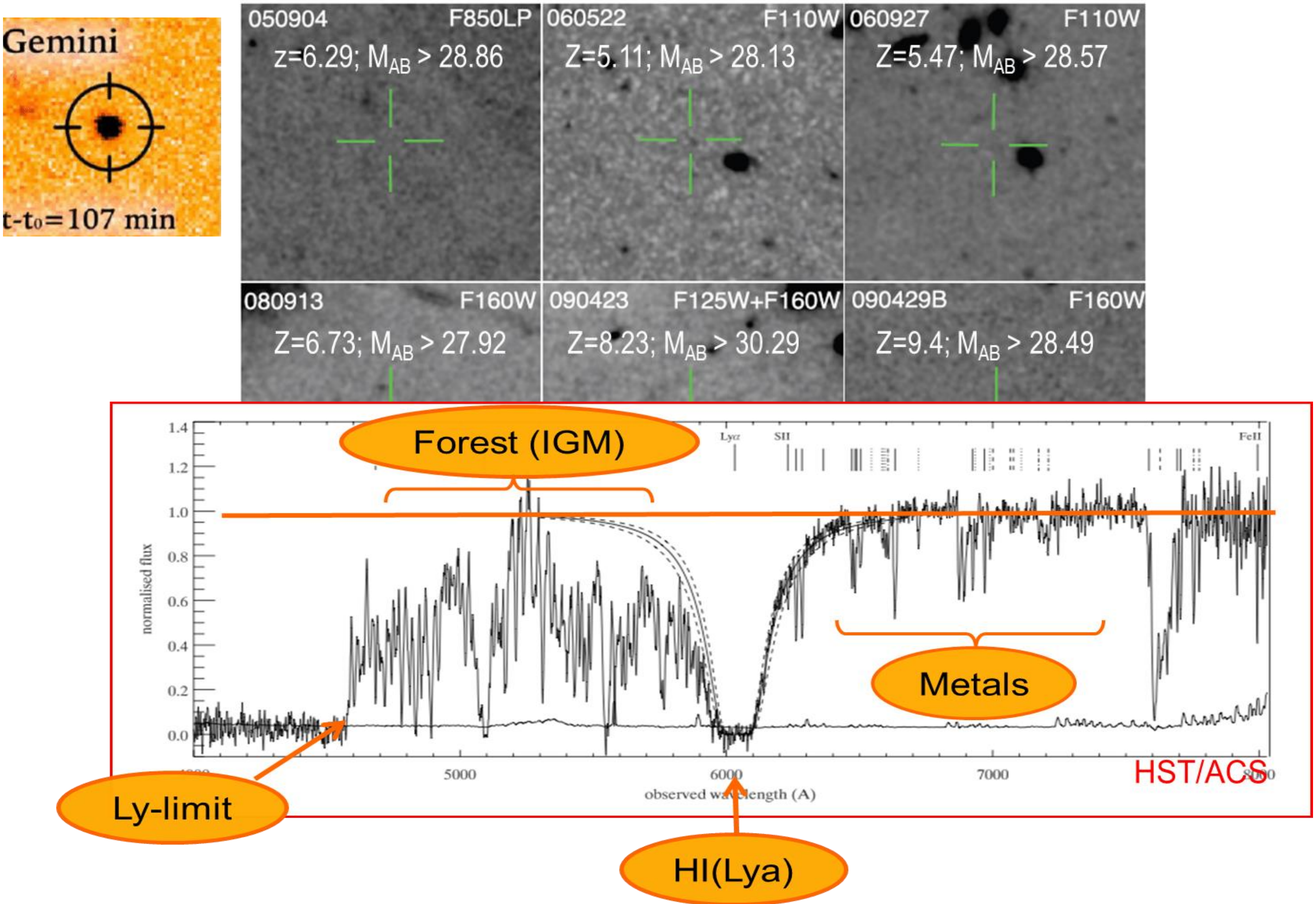




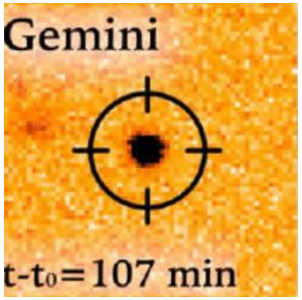
Robertson&Ellis12

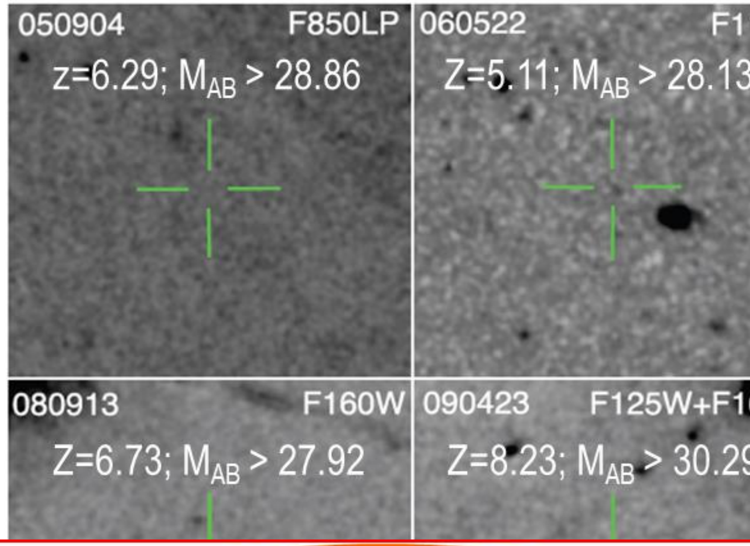
Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

- **Detecting and studying primordial invisible galaxies**

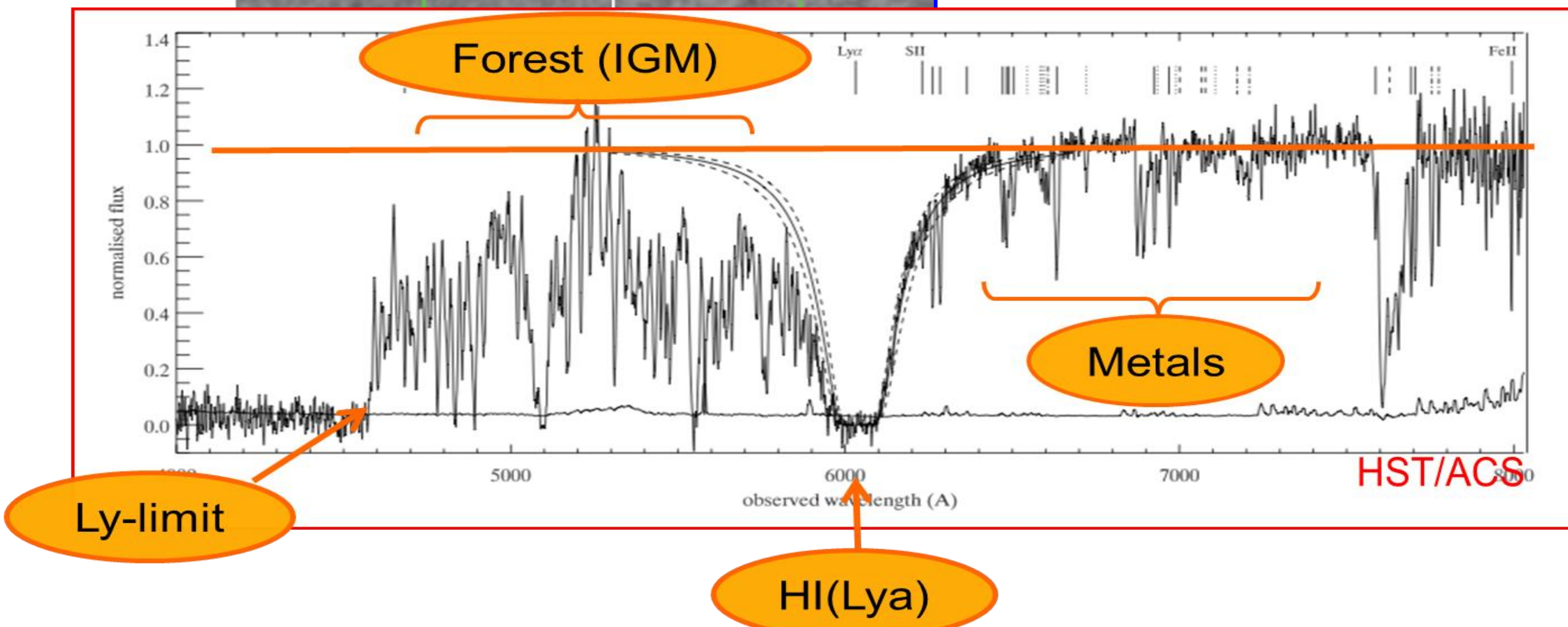


• Detecting and studying primordial invisible galaxies





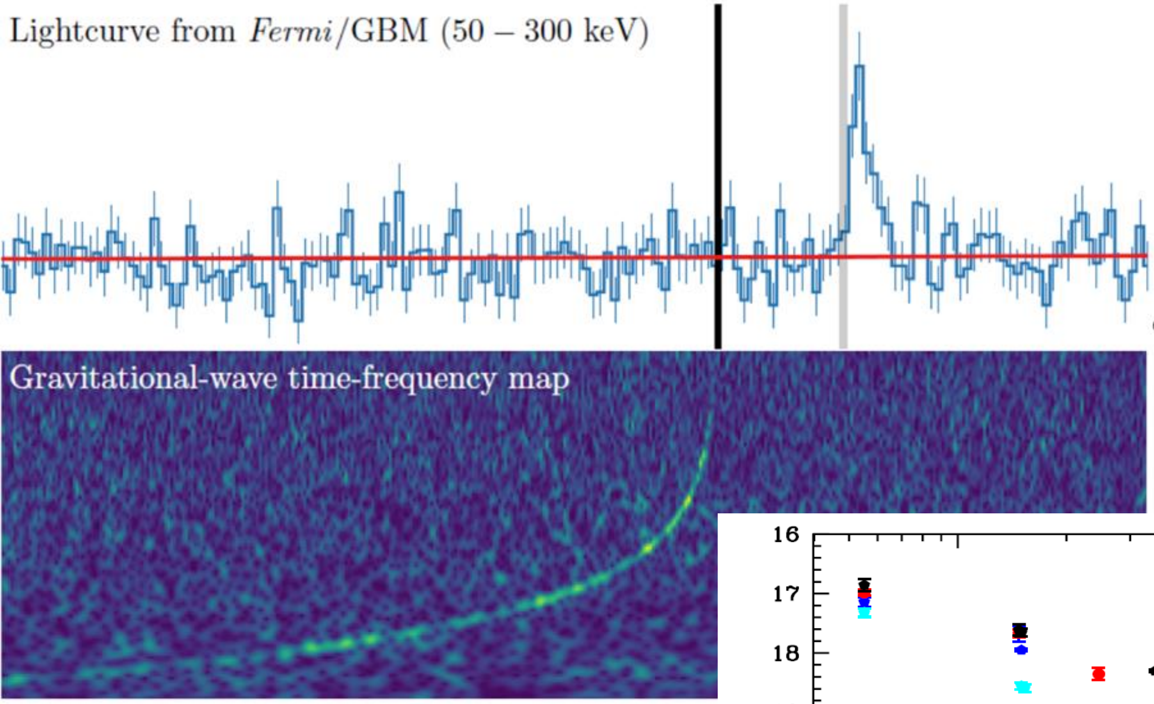
- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

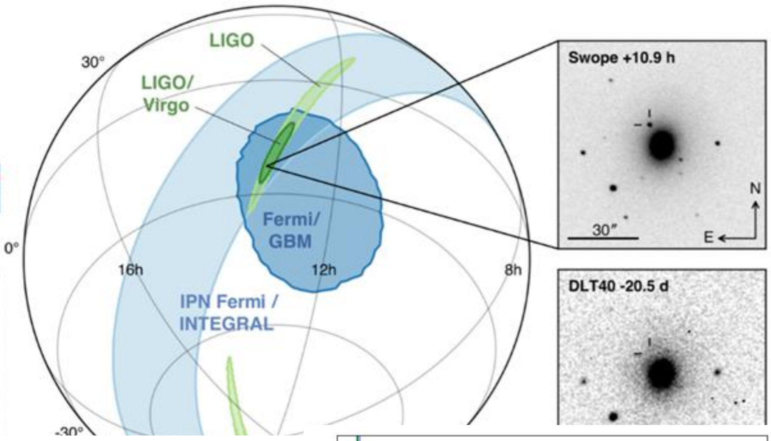


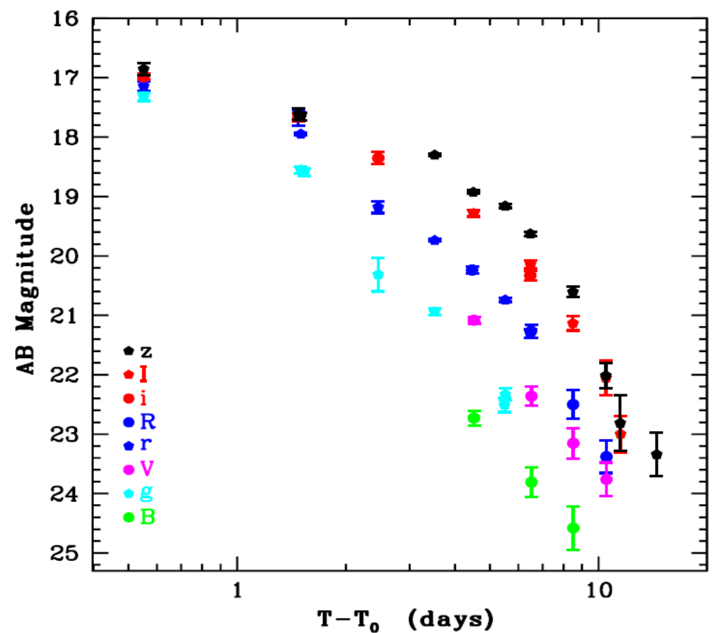
Short GRBs and multi-messenger astrophysics

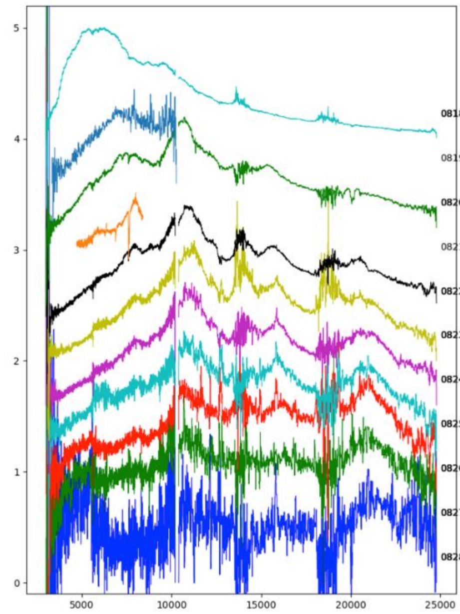
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics









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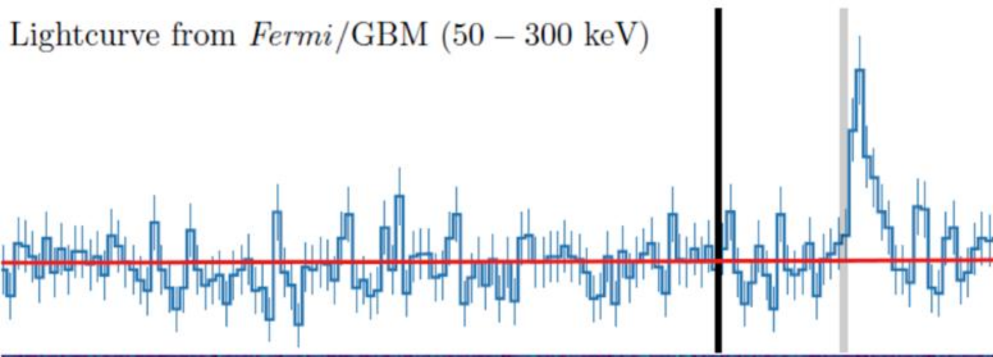
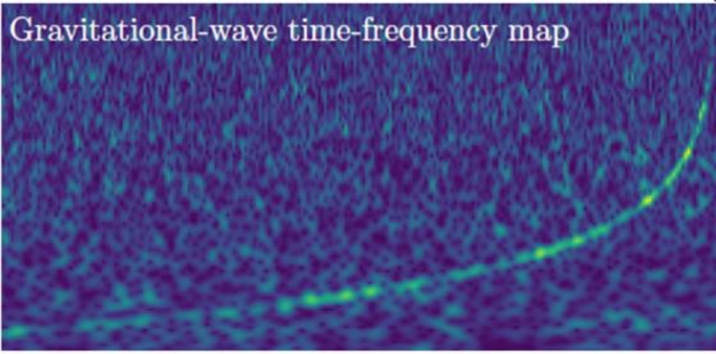
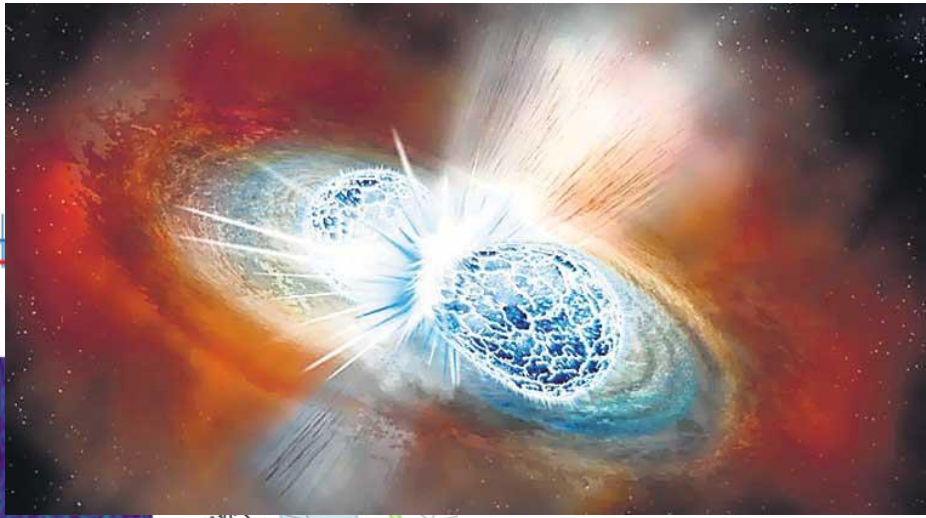
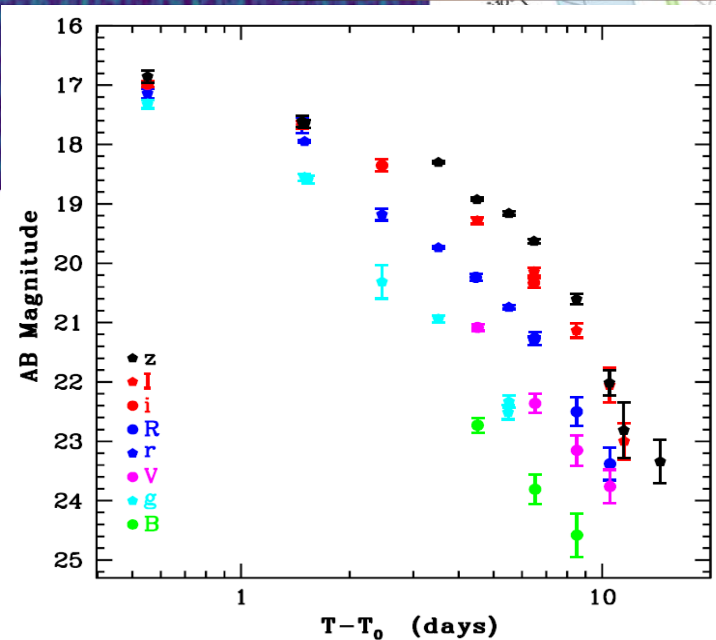
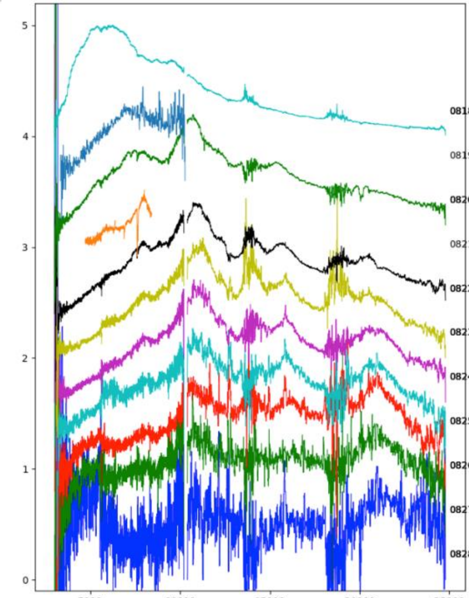






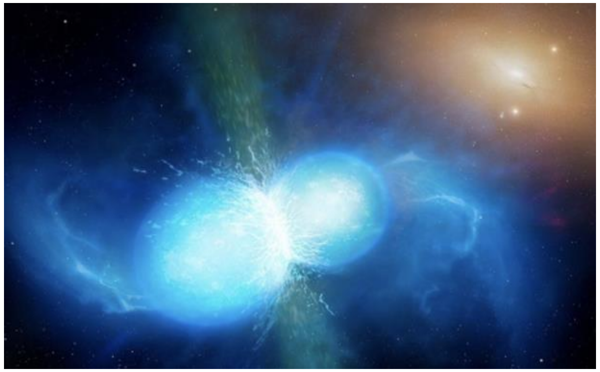




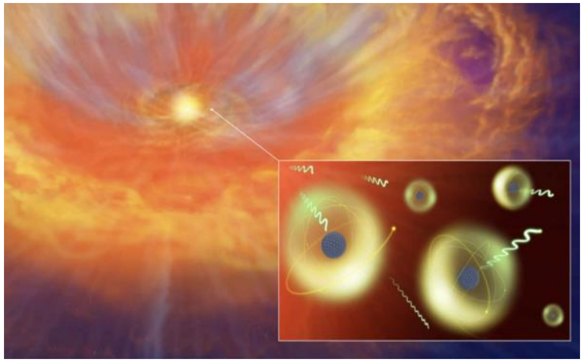
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

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

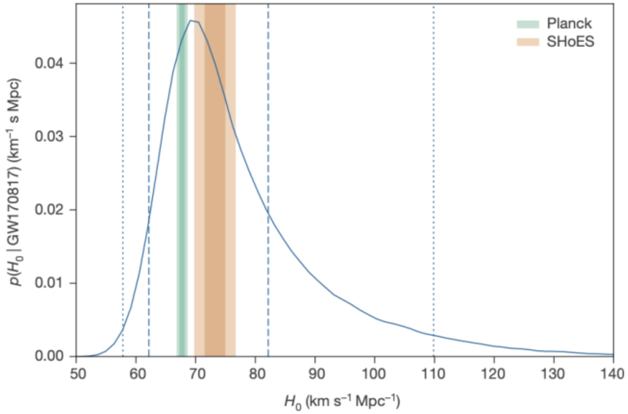
Relativistic jet formation, equation of state, fundamental physics



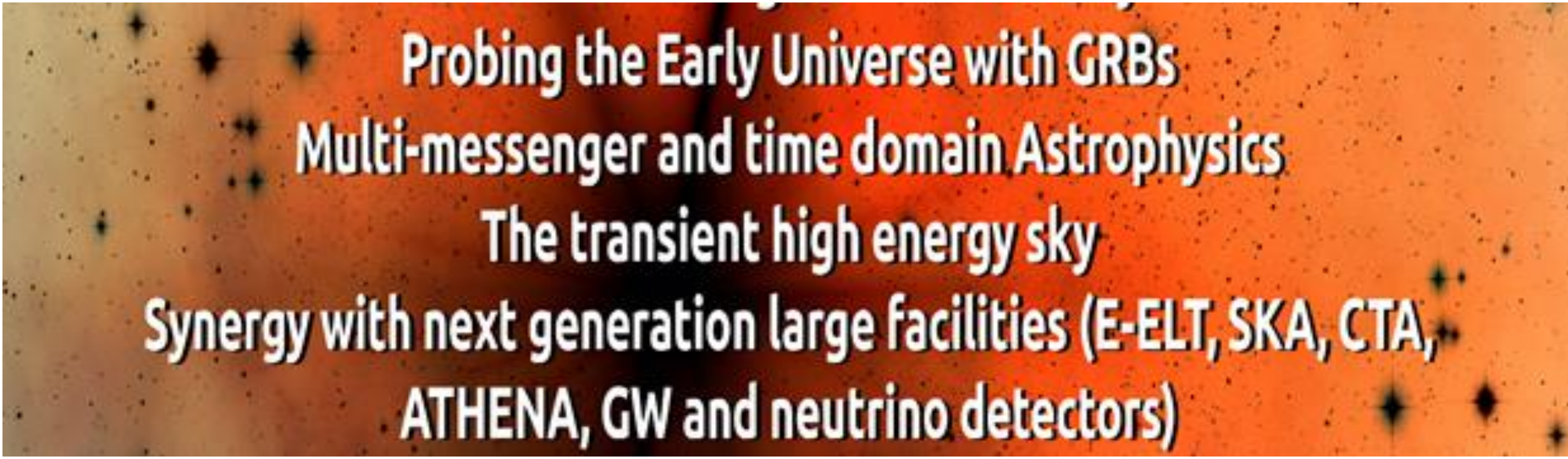
Cosmic sites of r-process nucleosynthesis



New independent route to measure cosmological parameters



Future GRB missions (late'20s and '30s)



- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (idea for NASA probe-class mission)**, 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**

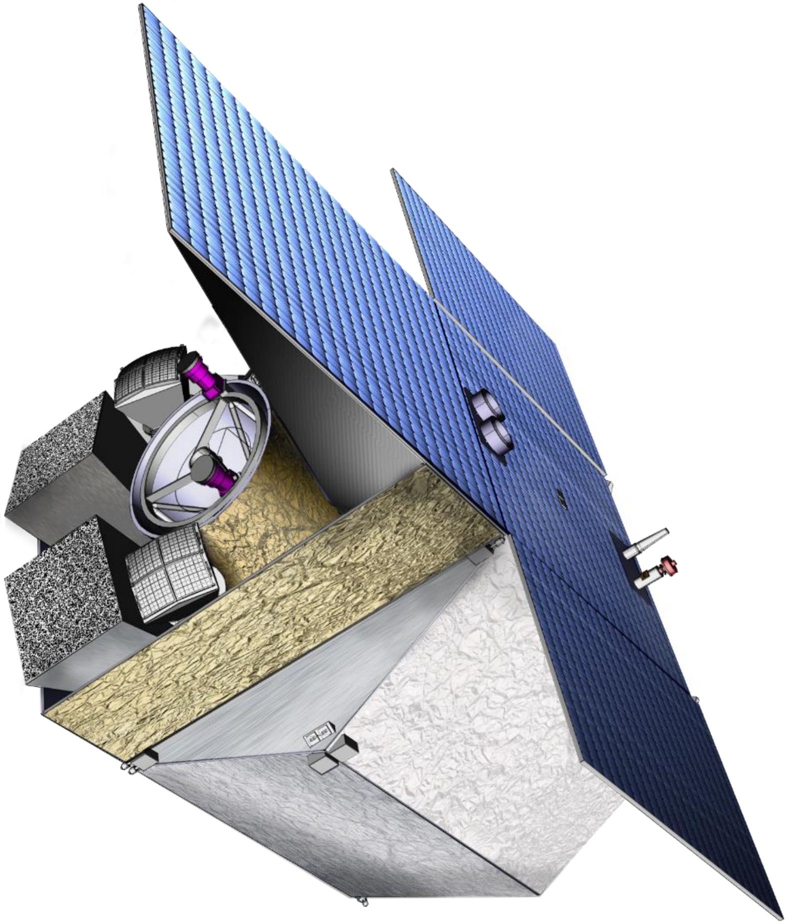
Future GRB missions: the case of THESEUS

(led by Italy; ESA/M5 Phase-A study, re-proposed for M7)

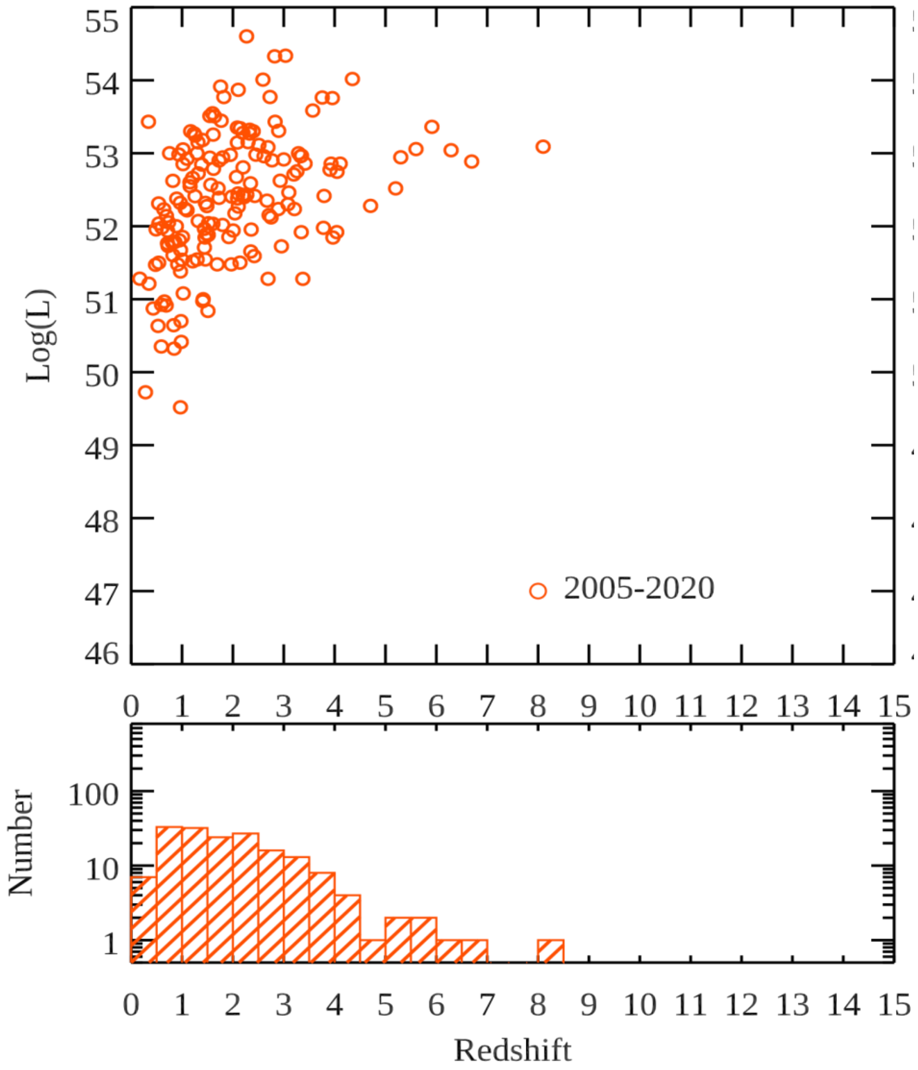
THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

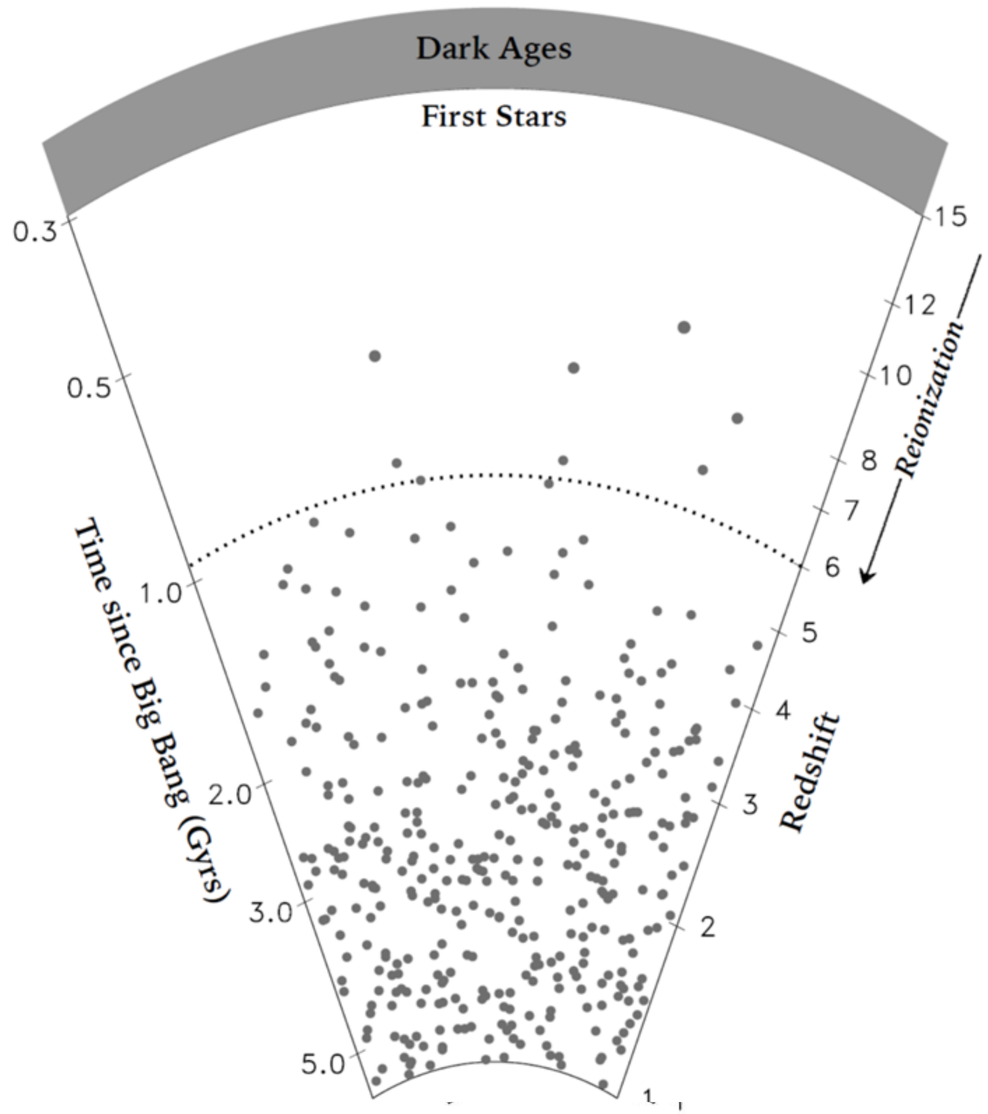
Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**

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

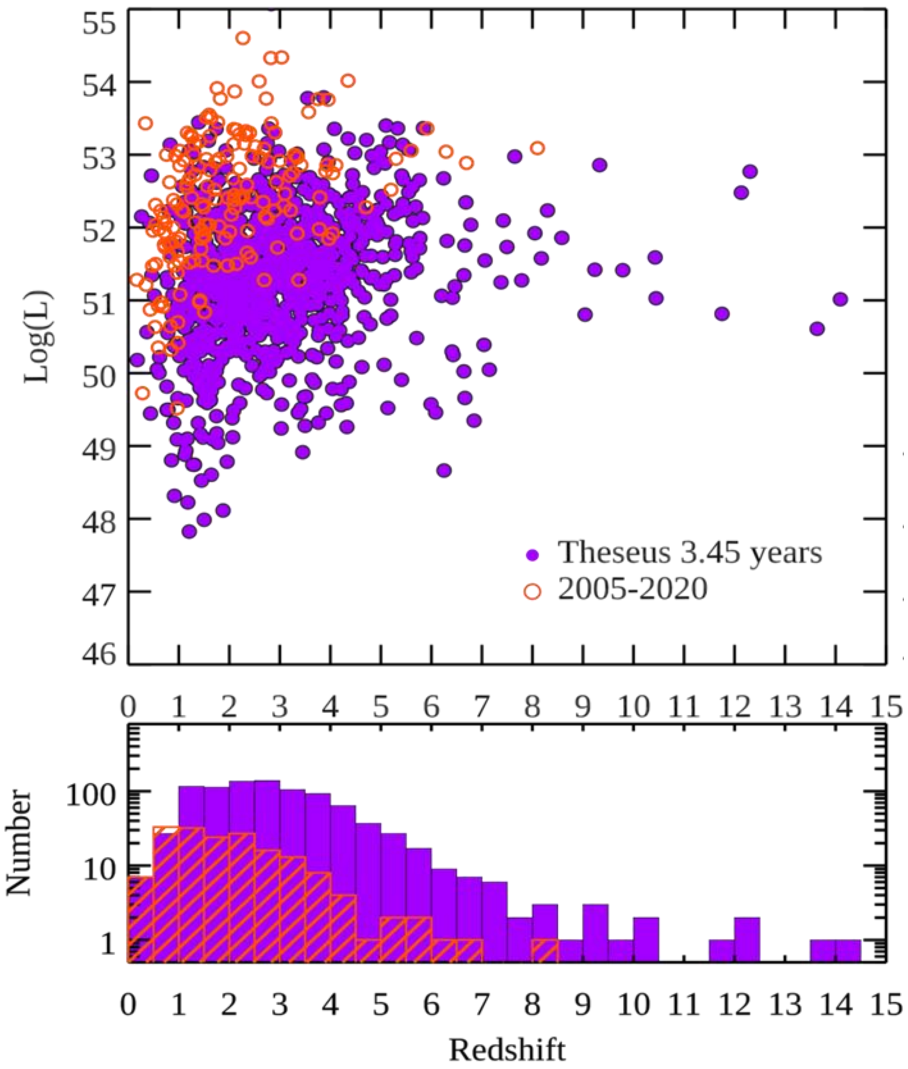


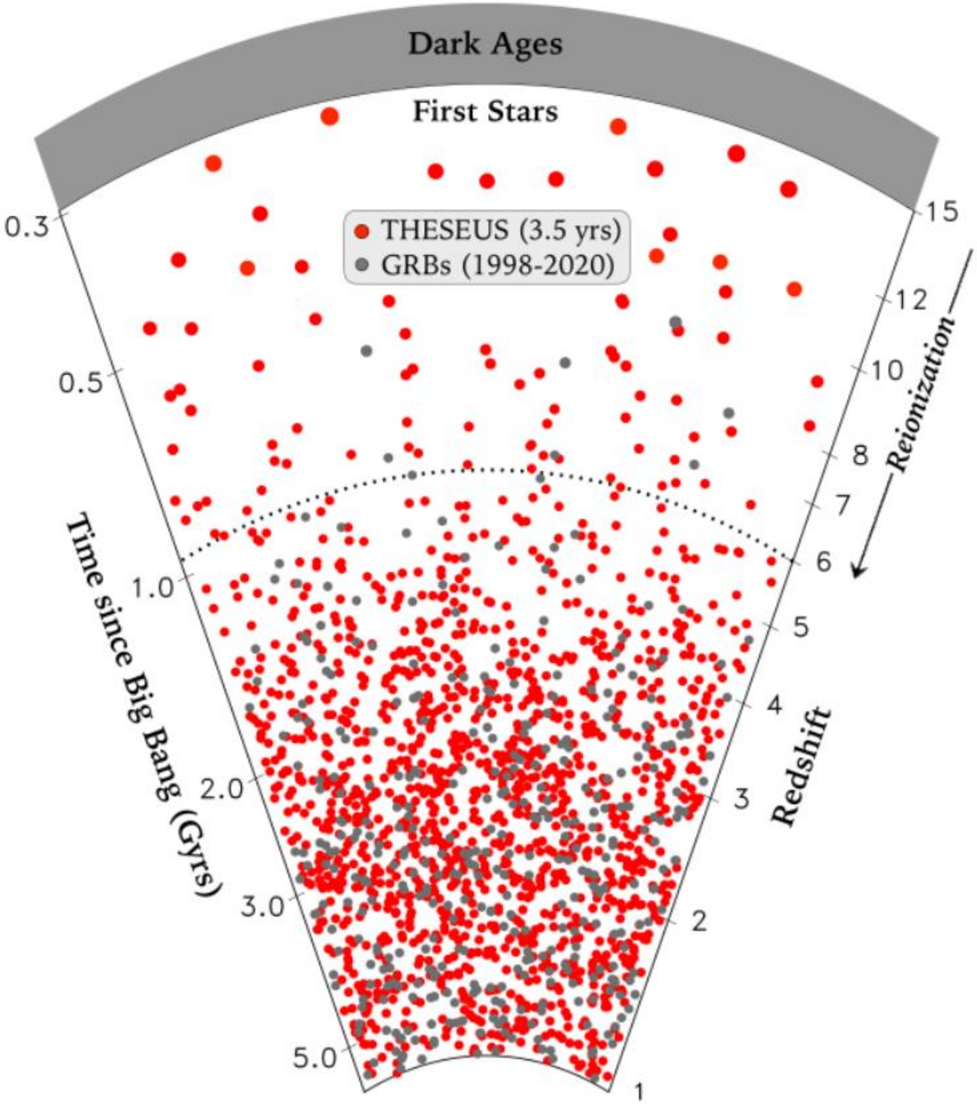
Shedding light on the early Universe with GRBs





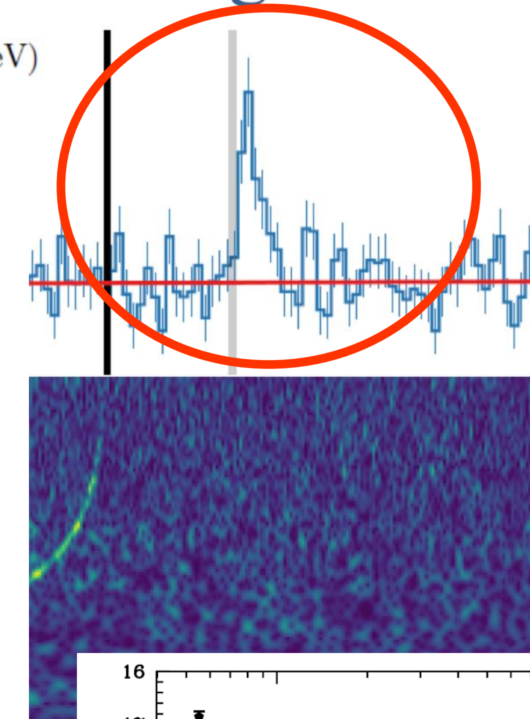
Shedding light on the early Universe with GRBs





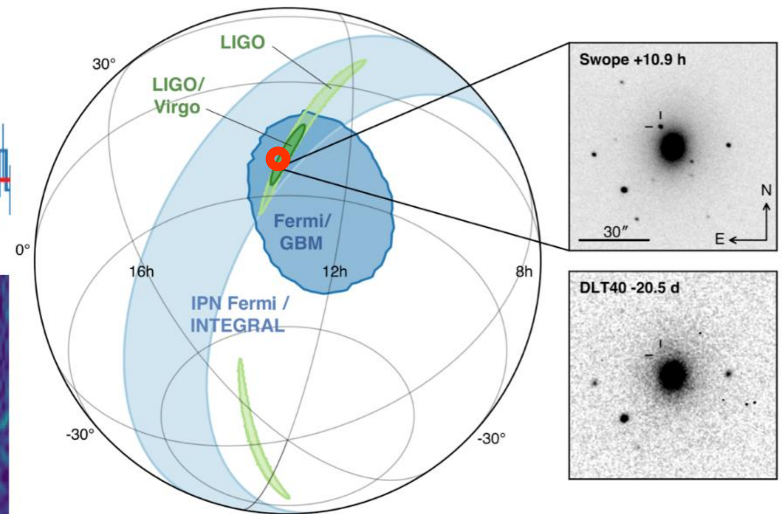
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

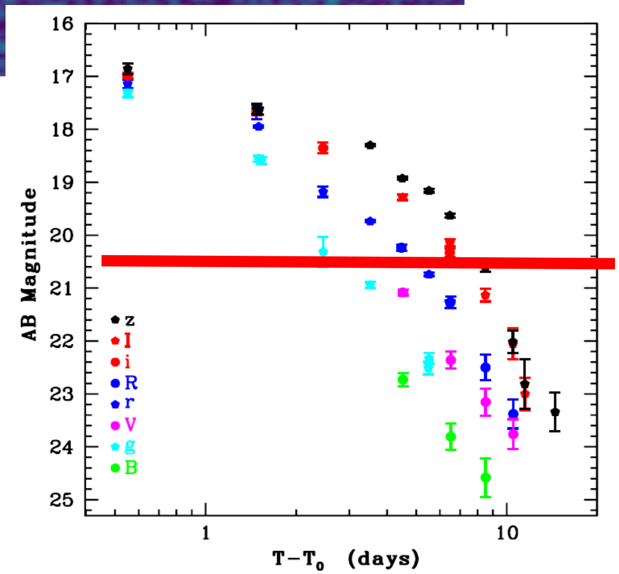
Lightcurve from *Fermi*/GBM (50 – 300 keV)

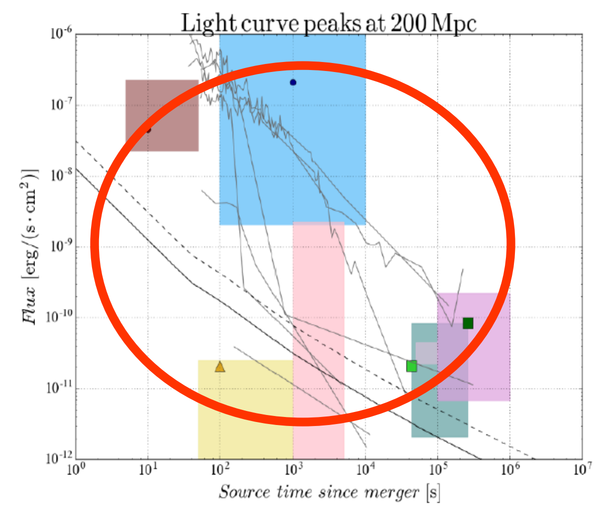


THESEUS:

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

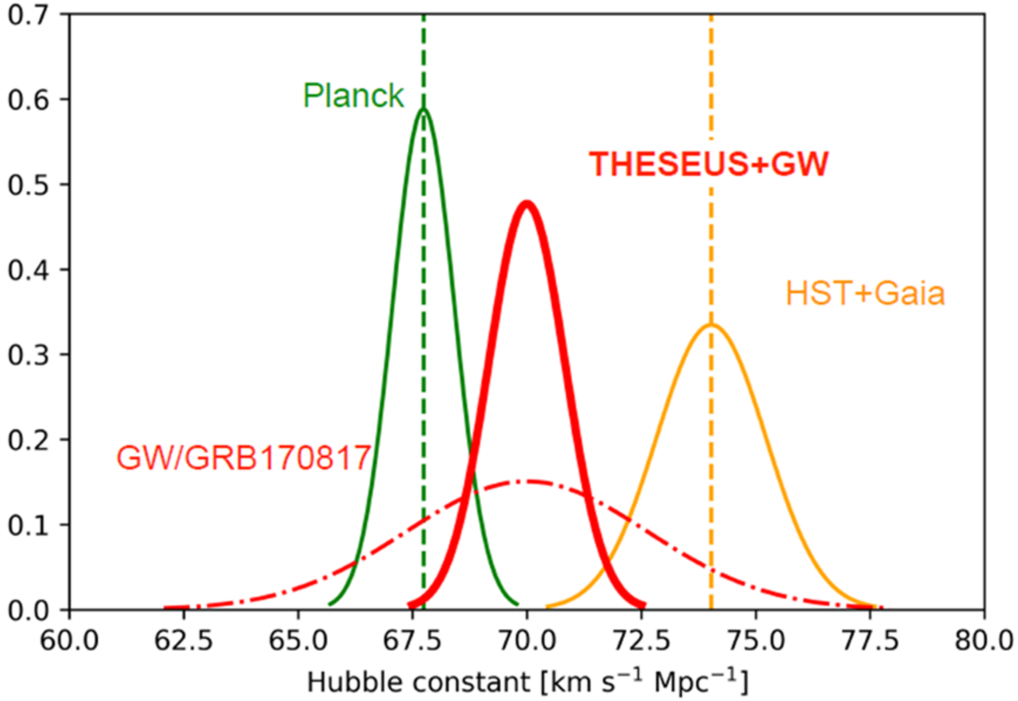


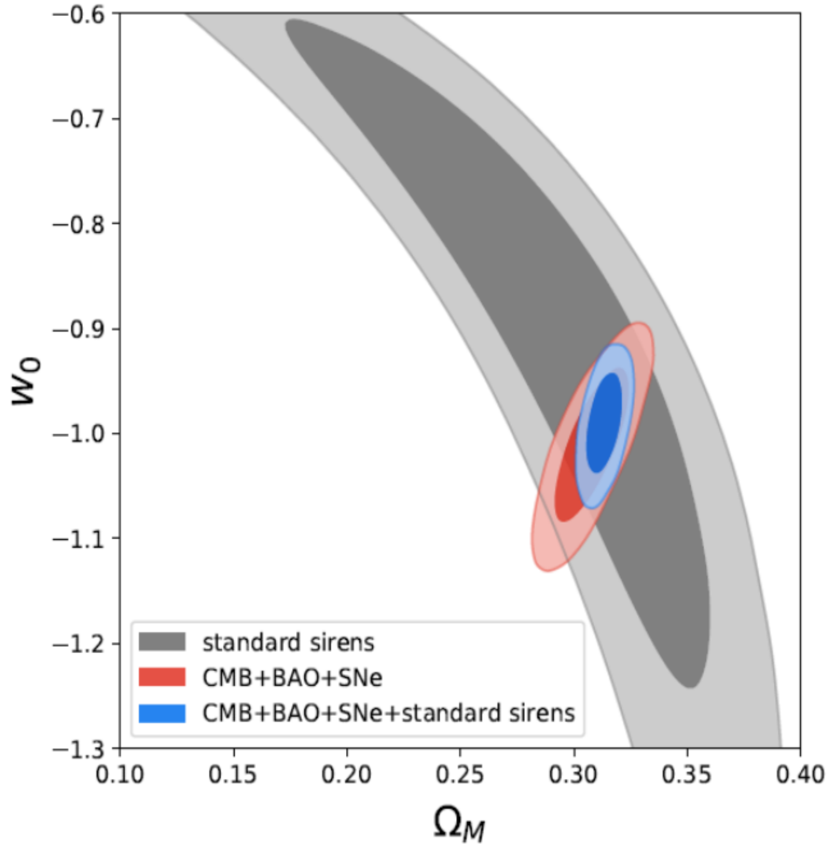




Multi-messenger cosmology through GRBs

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME





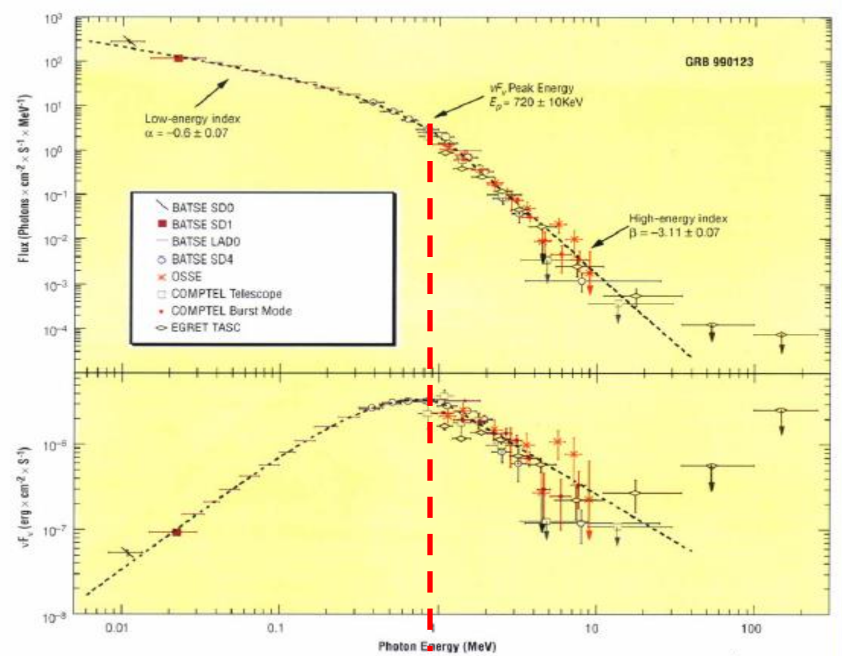
~20 joint GRB+GW events

Measuring cosmological parameters with GRBs

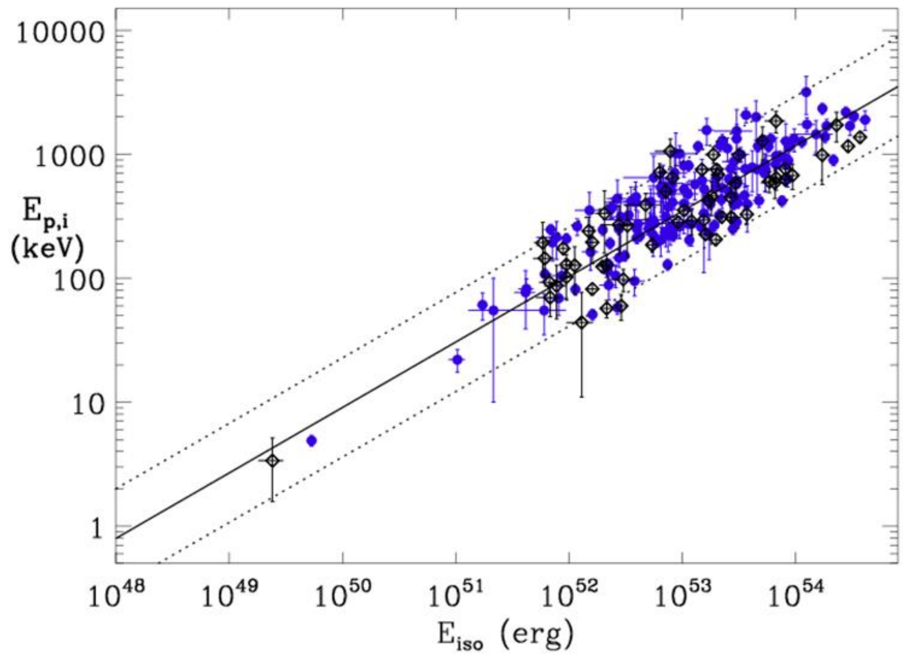
- GRB nFn spectra typically show a peak at a characteristic photon energy E_p
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

$$E_{p,i} = E_p \times (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$



Ep

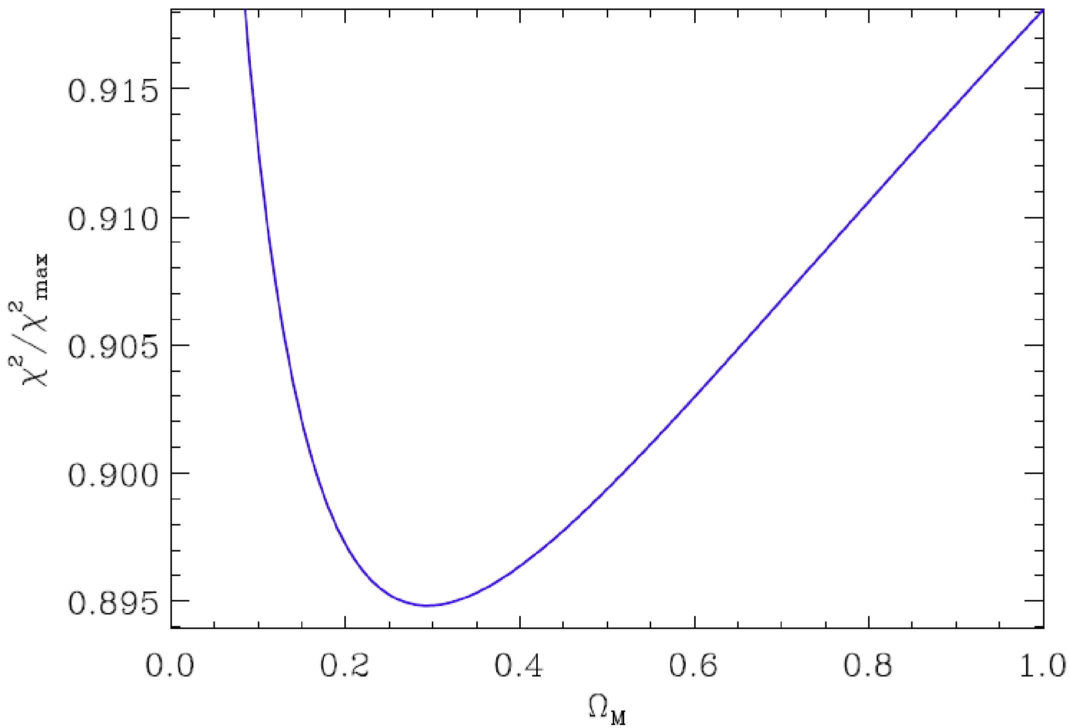


Amati et al. (2002,2006,2008, 2013)

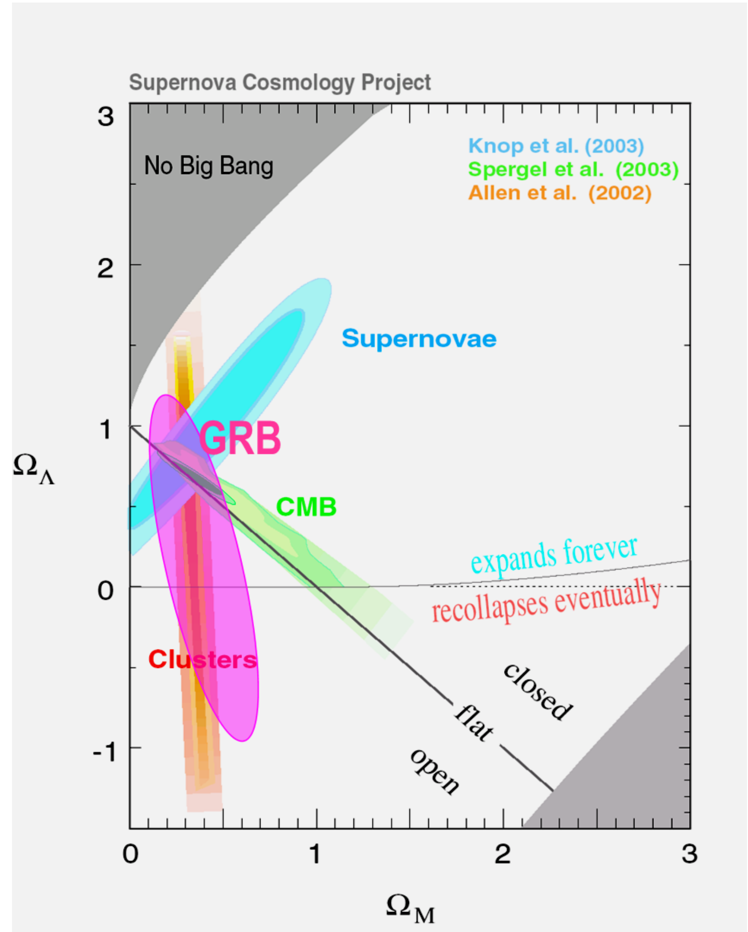
Measuring cosmological parameters with GRBs

- a fraction of the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation is indeed due to the cosmological parameters used to compute E_{iso}

- **Evidence, independent on other cosmological probes, that, if we are in a flat ΛCDM universe , Ω_M is lower than 1 and around 0.3**

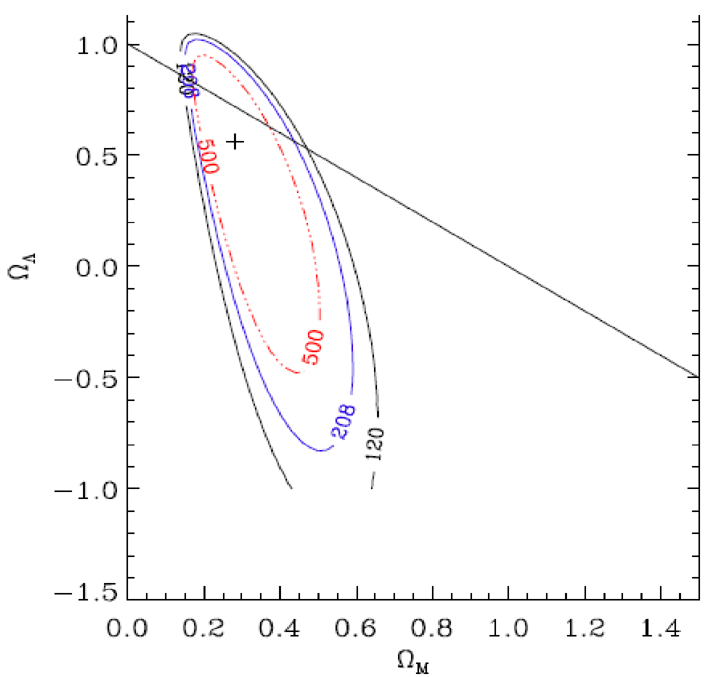


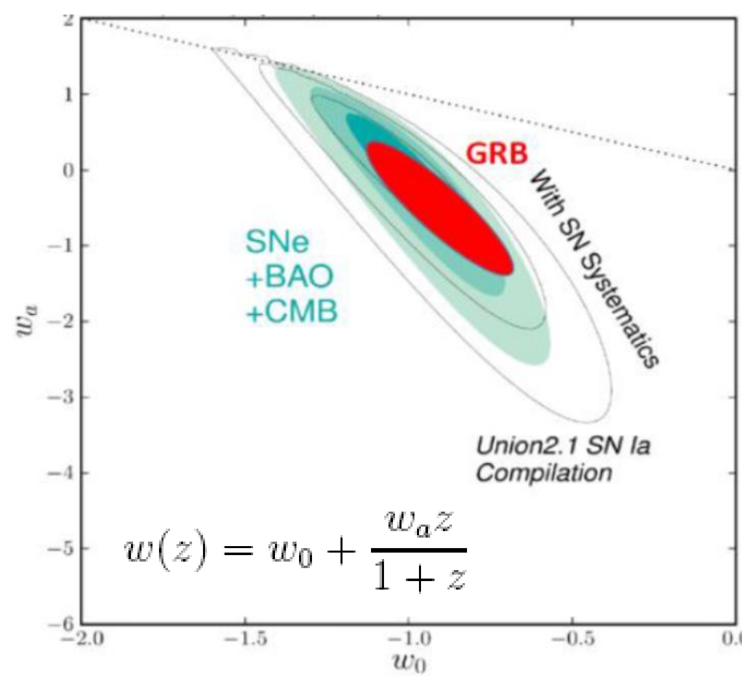
Amati et al. 2008, Amati & Della Valle 2013



- Future GRB experiments (e.g., SVOM, HERMES, THESEUS, …) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

Number of GRBs	Ω_m (flat)	w_0 (flat, Ω_m=0.3,w_a=0.5)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
208 (real) GRBs (this work)	$0.26^{+0.23}_{-0.12}$	$-1.2^{+0.4}_{-1.1}$
500 (208 real + 292 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
208 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
500 (208 real + 292 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$





Fundamental physics with GRBs: testing LI / QG

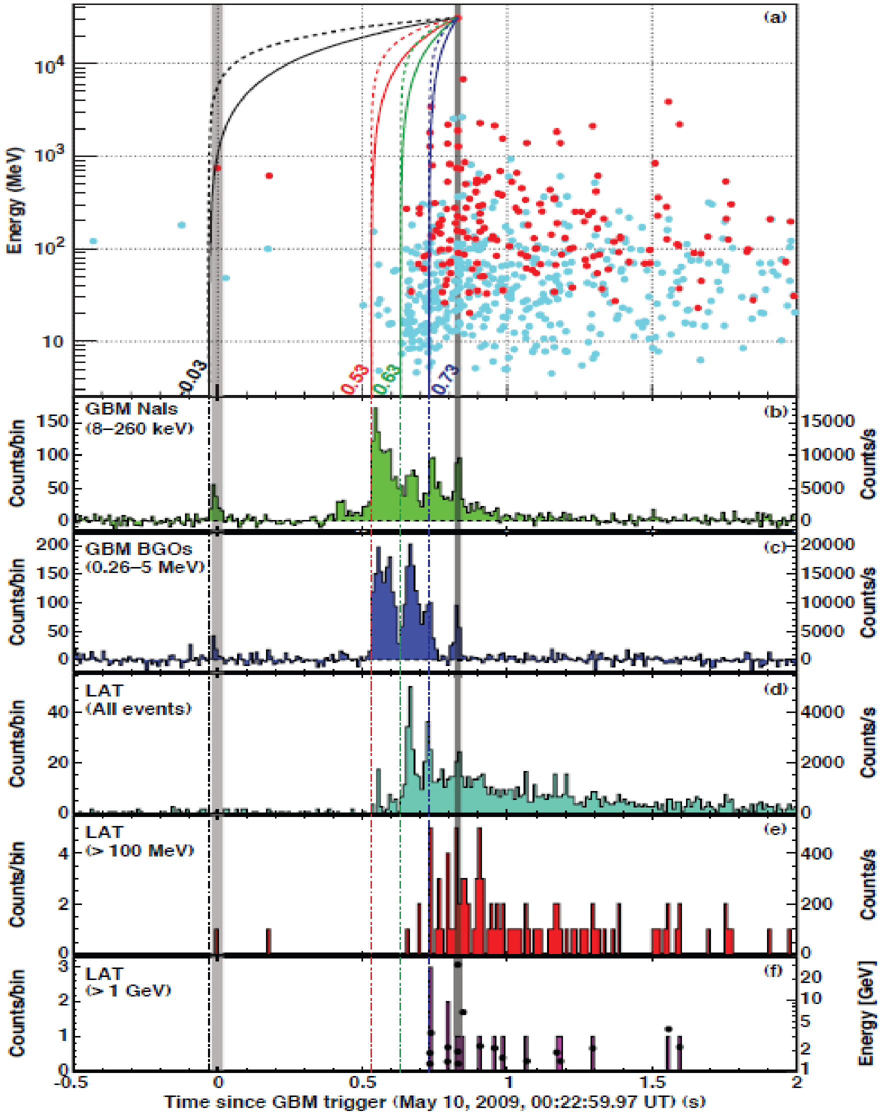
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

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



In summary

- GRBs are a key phenomenon for cosmology (ealry Universe, cosmological parameters), multi-messenger astrophysics (GW, neutrinos) and fundamental physics

- Next generation GRB missions, like THESEUS, developed by a large European collaboration and already studied by ESA (M5 Phase A) will fully exploit these potentialities and will provide us with unprecedented clues to GRB physics and sub-classes.

- THESEUS is a unique occasion for fully exploiting the European leadership in time-domain and multi-messenger astrophysics and in related key-enabling technologies

- THESEUS observations will impact on several fields of astrophysics, cosmology and fundamental physics and will enhance importantly the scientific return of next generation multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

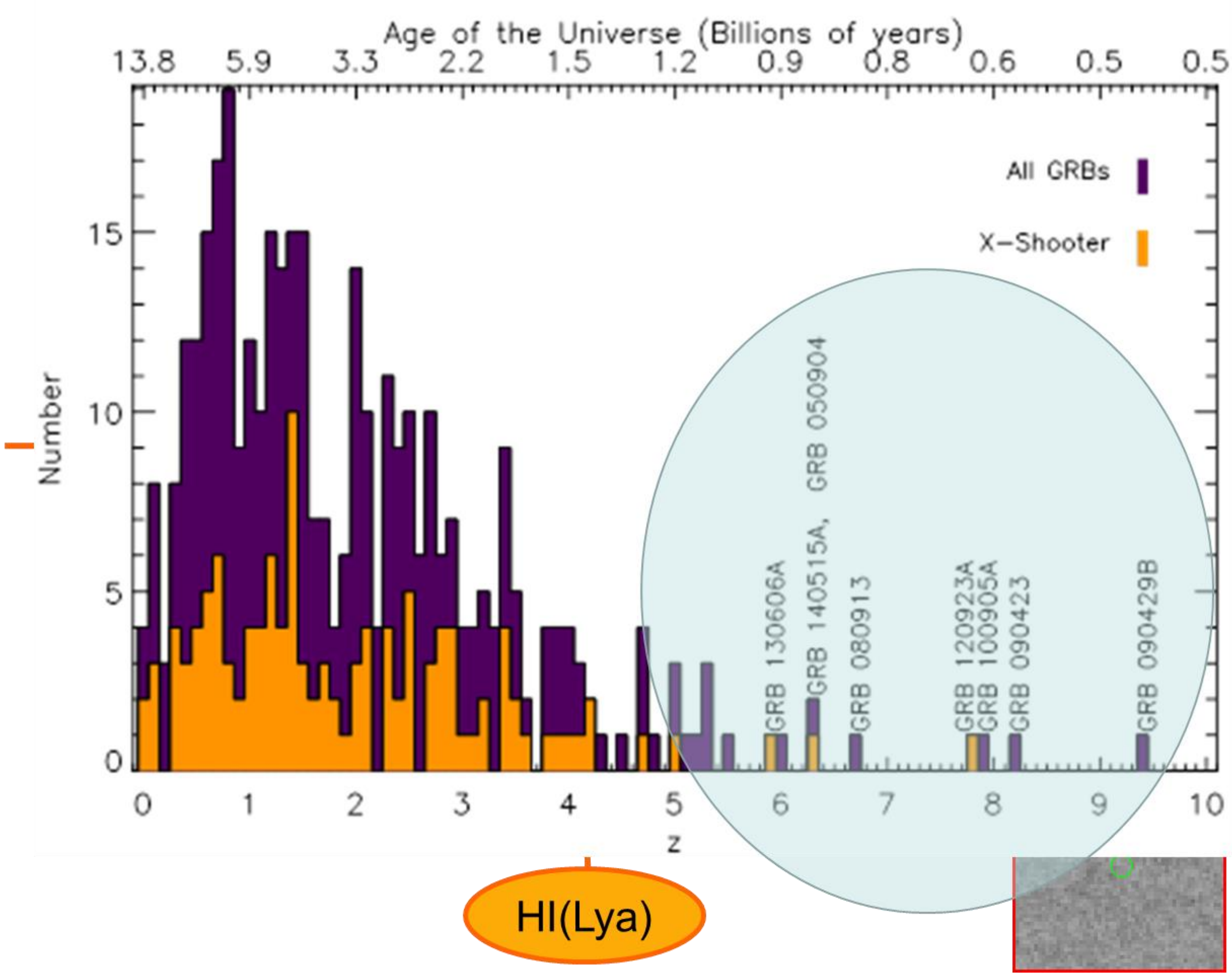
- **THESEUS ESA/M5 Phase A study successful -> reproposed for M7 (2037)**

SPIE articles on instruments, Adv.Sp.Res. & Exp.Astr. articles on science

http://www.isdc.unige.ch/theseus/

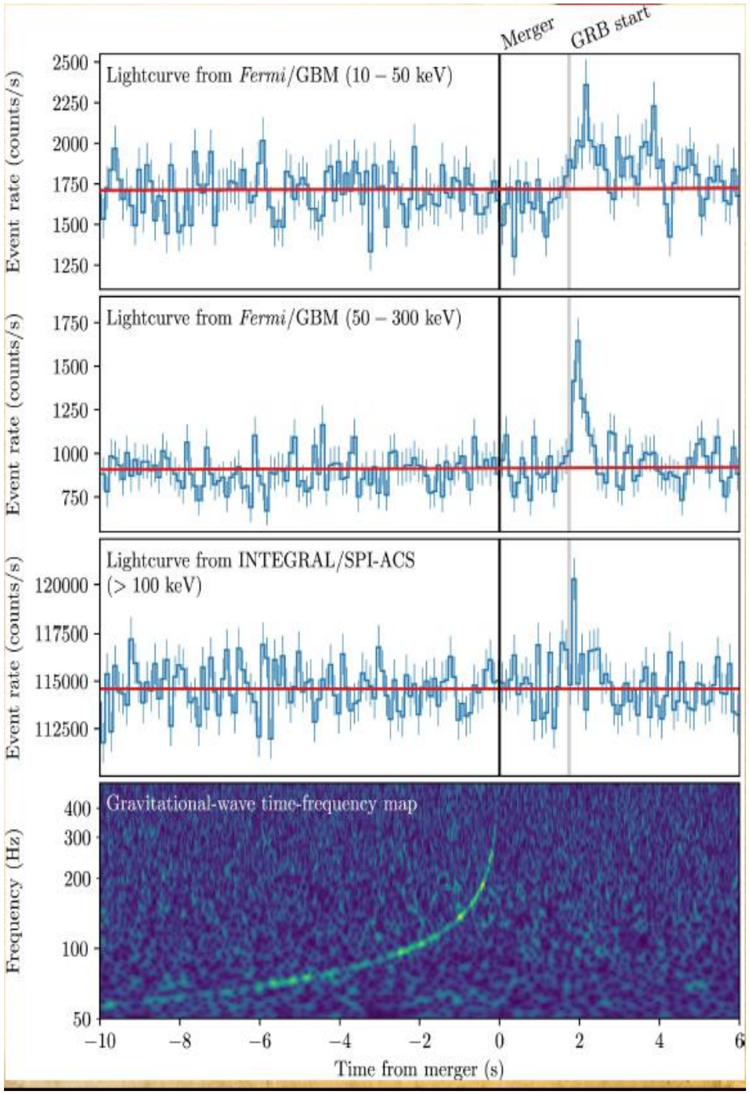
Back-up slides

- **Detecting and studying primordial invisible galaxies**



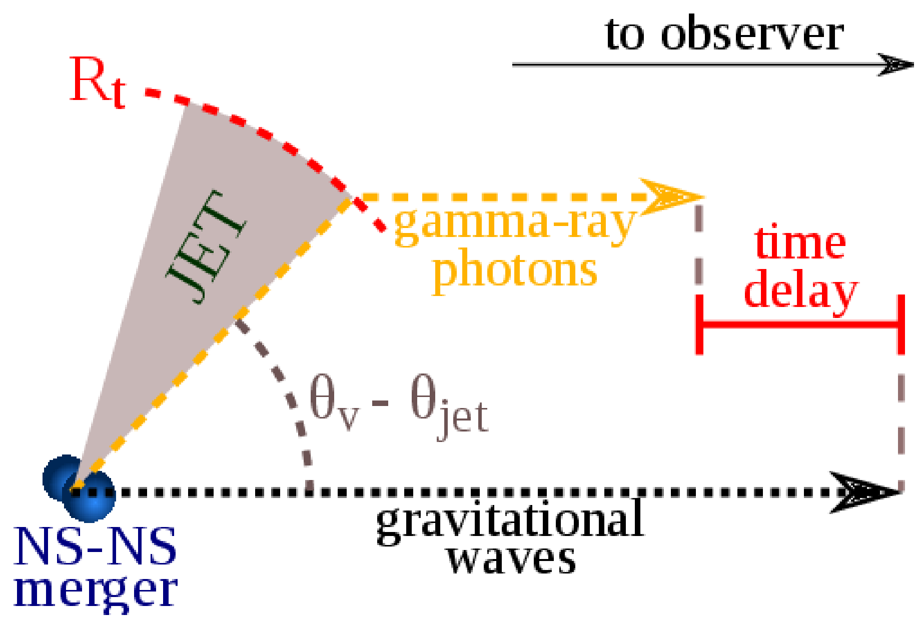
Fundamental physics with GRBs: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

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



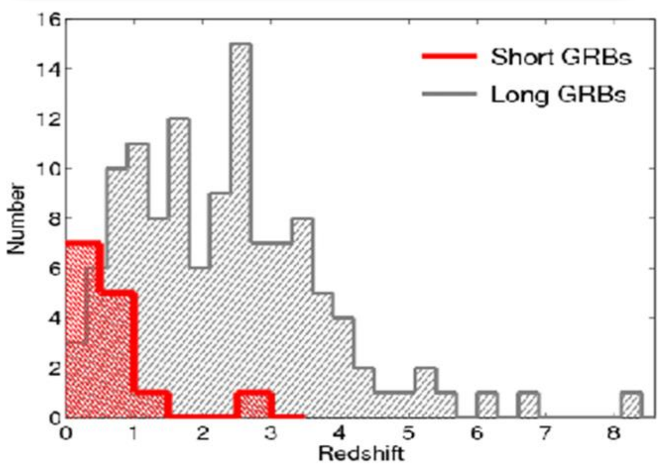
$$\Delta t = (\Delta t_{\rm jet} + \Delta t_{\rm bo} + \Delta t_{\rm GRB})(1+z)$$

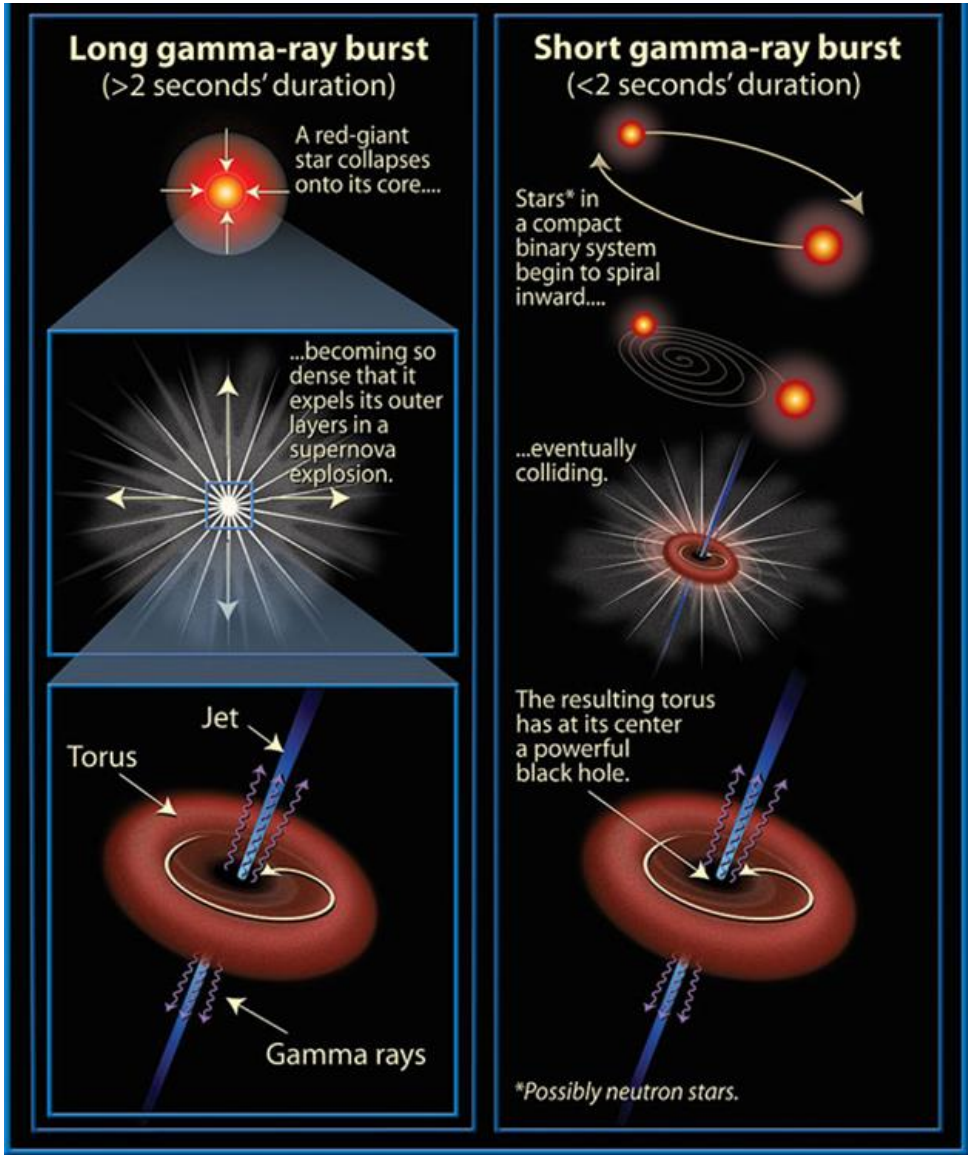
$$\Delta t_{\rm GRB} \simeq (1 - \beta \cos\theta)\frac{R_{\rm GRB}}{c} \simeq \frac{R_{\rm GRB}}{\Gamma^2 c}$$

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**





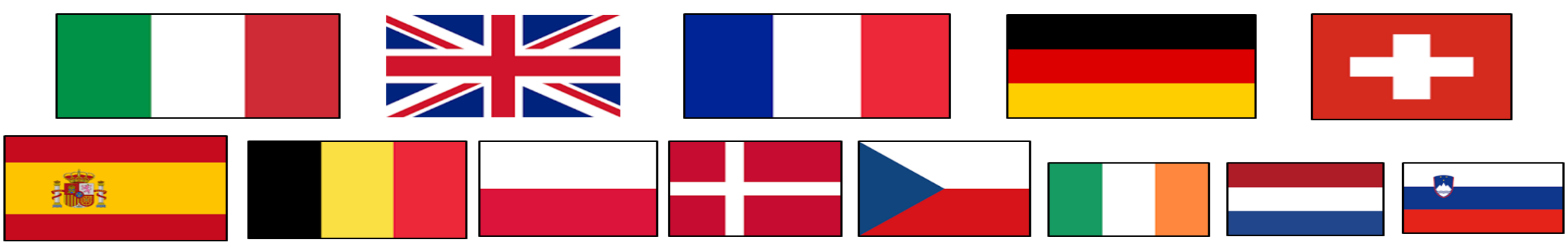
Future missions: the case of THESEUS

Transient High Energy Sky and Early Universe Surveyor

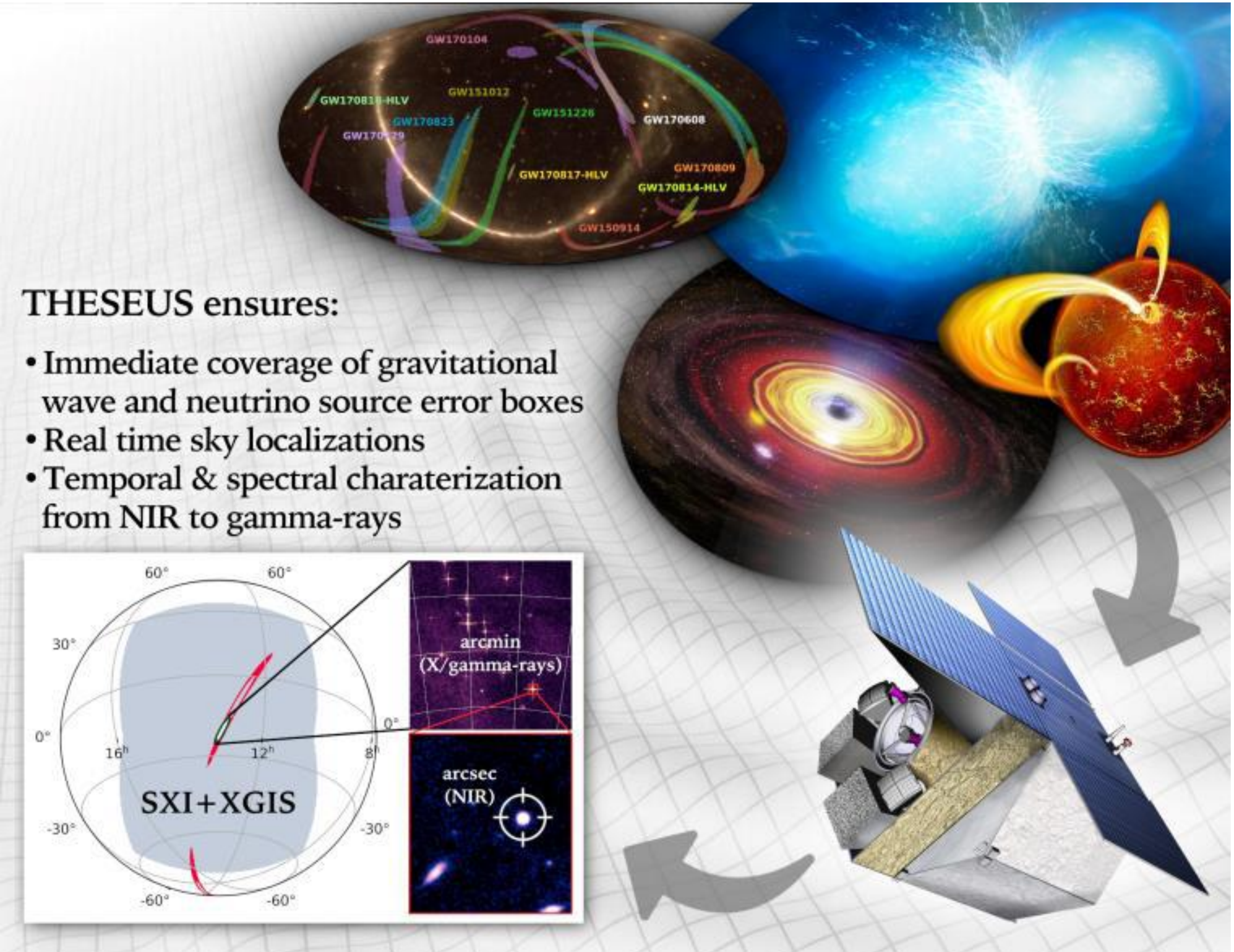
Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), A. Santangelo (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA



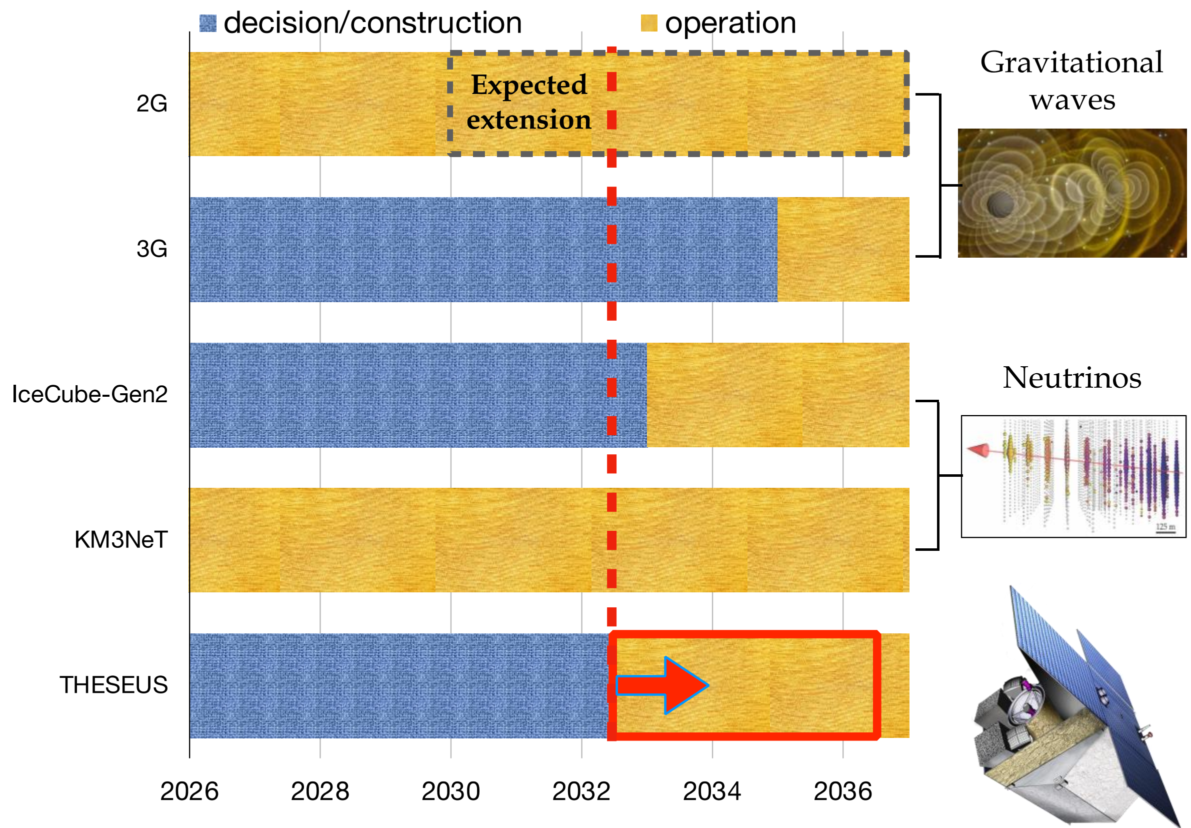
Exploring the multi-messenger transient sky



Future GRB missions: synergies

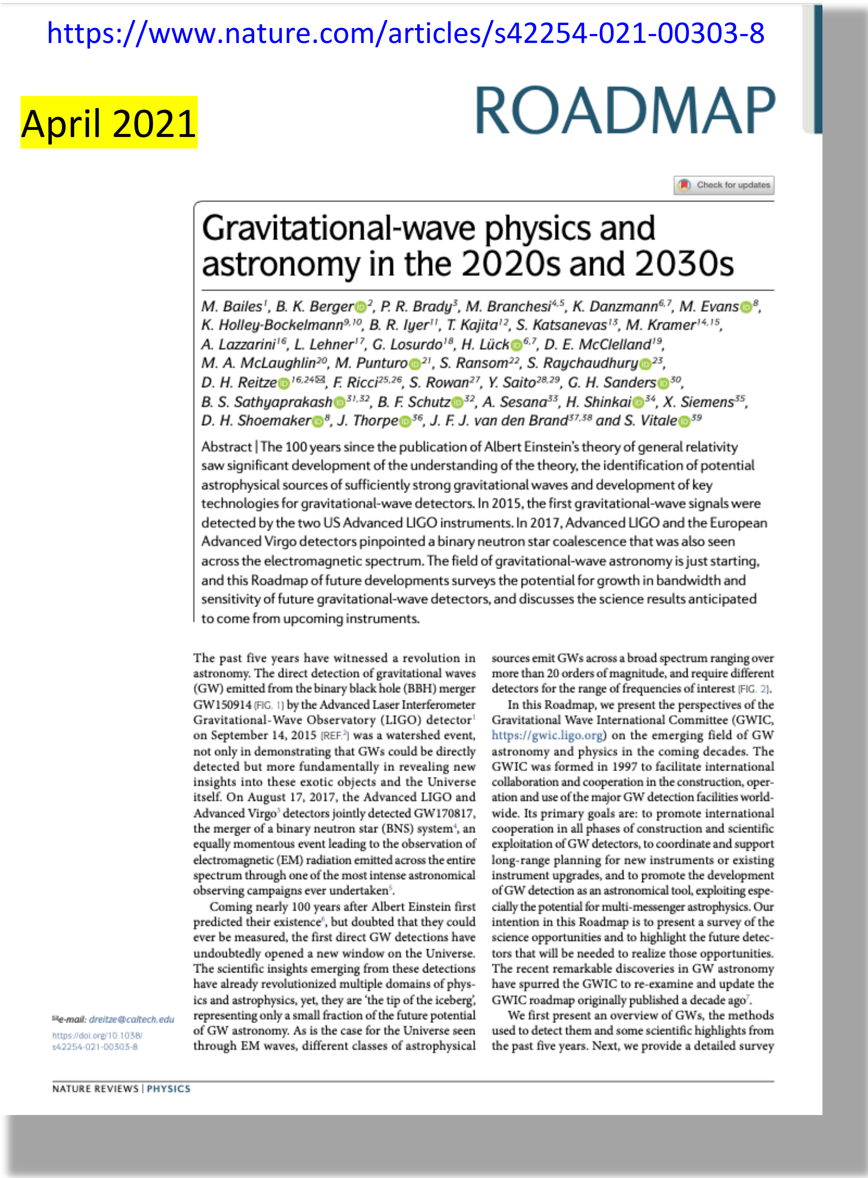
ENTERING THE GOLDEN ERA OF MULTI-MESSENGER ASTROPHYSICS

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

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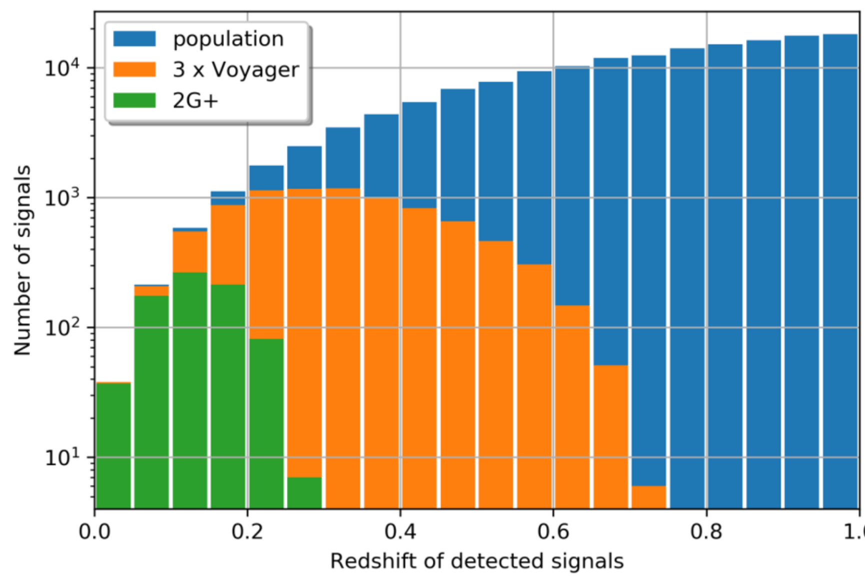
GWIC Roadmap and Letter of Endorsement from EGO/virgo clearly mention further upgrades of 2G to bridge in the 3G era

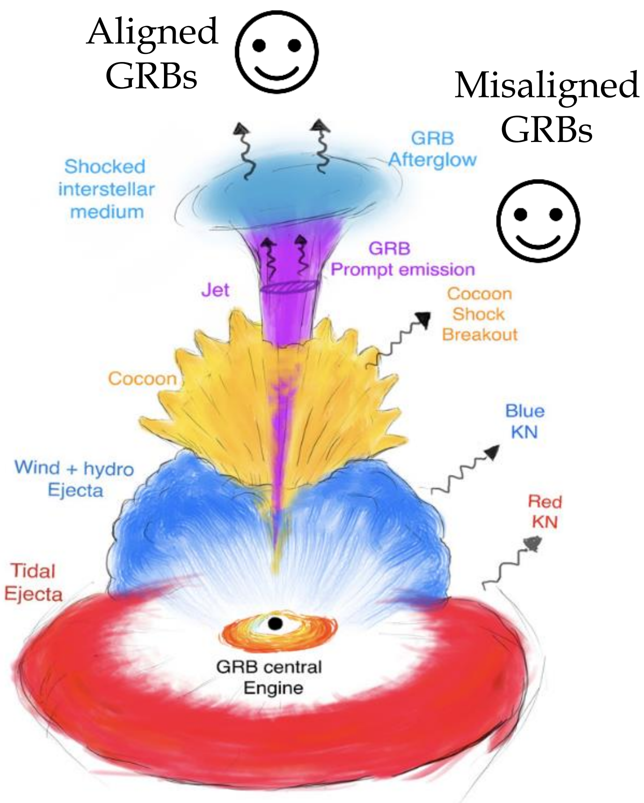


NS-NS merger detection efficiency with 2G and 2G++ will sensibly improve at z>0.1 with 2G++

Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A



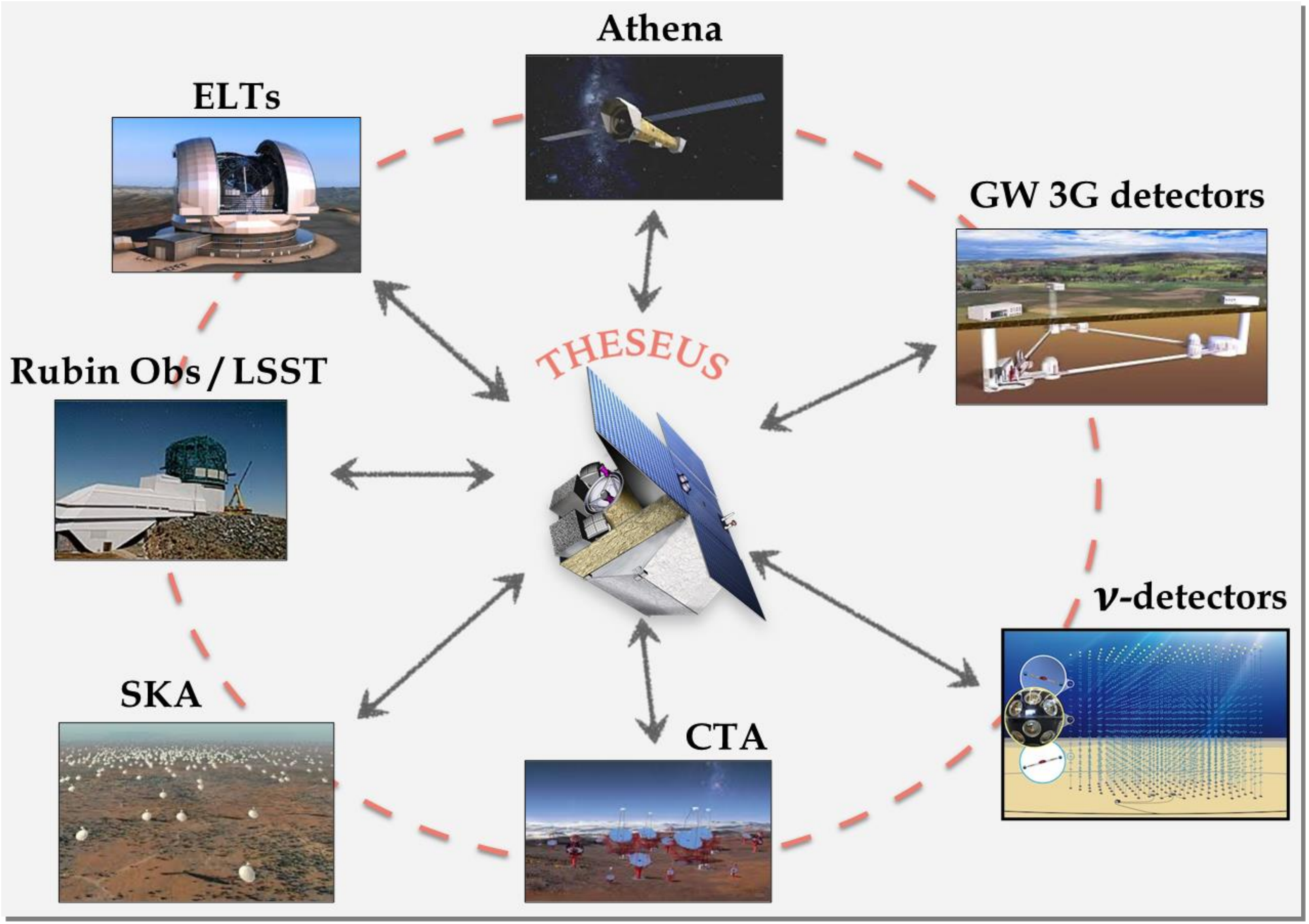
Expected rates:

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-wavelength/messenger synergies



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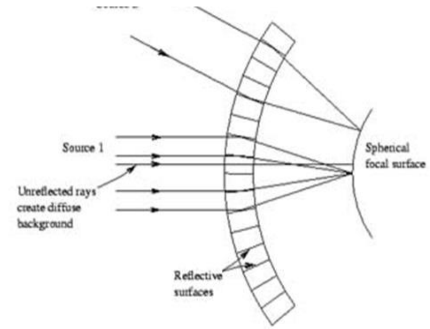
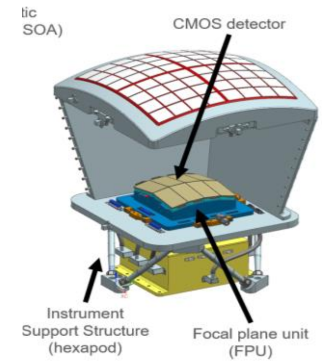
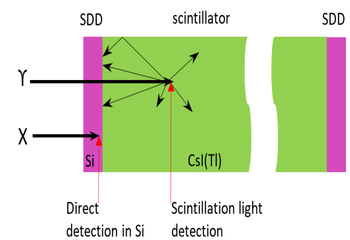
Future missions: the case of THESEUS

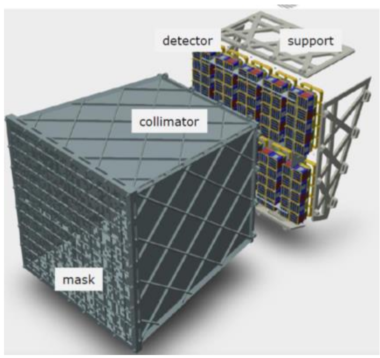
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′ 



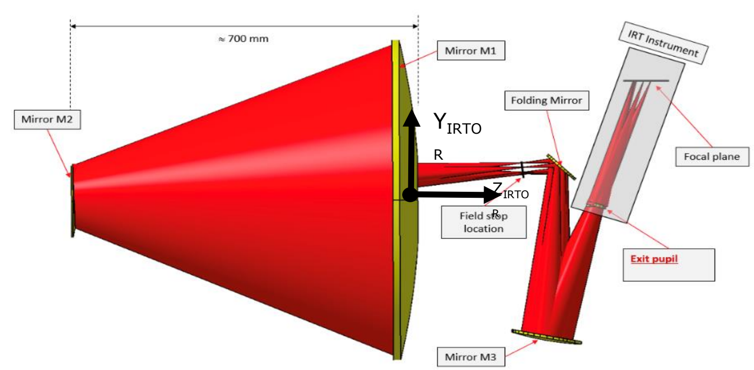


- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy 





- **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 



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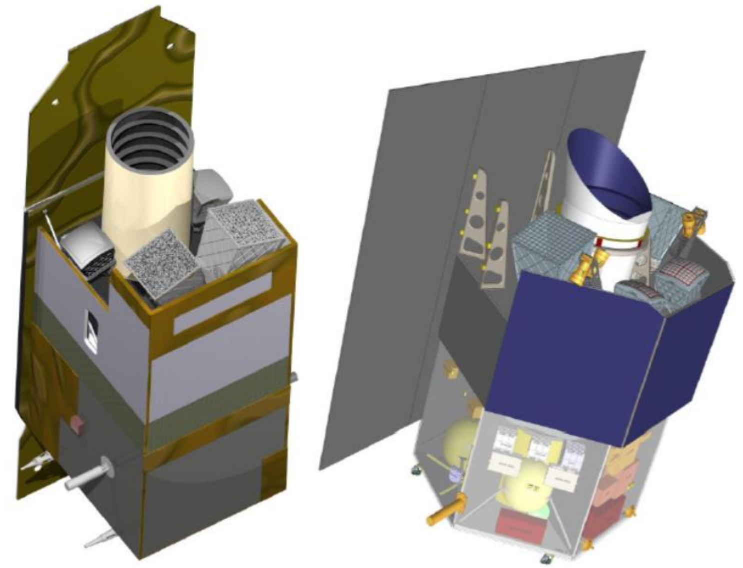


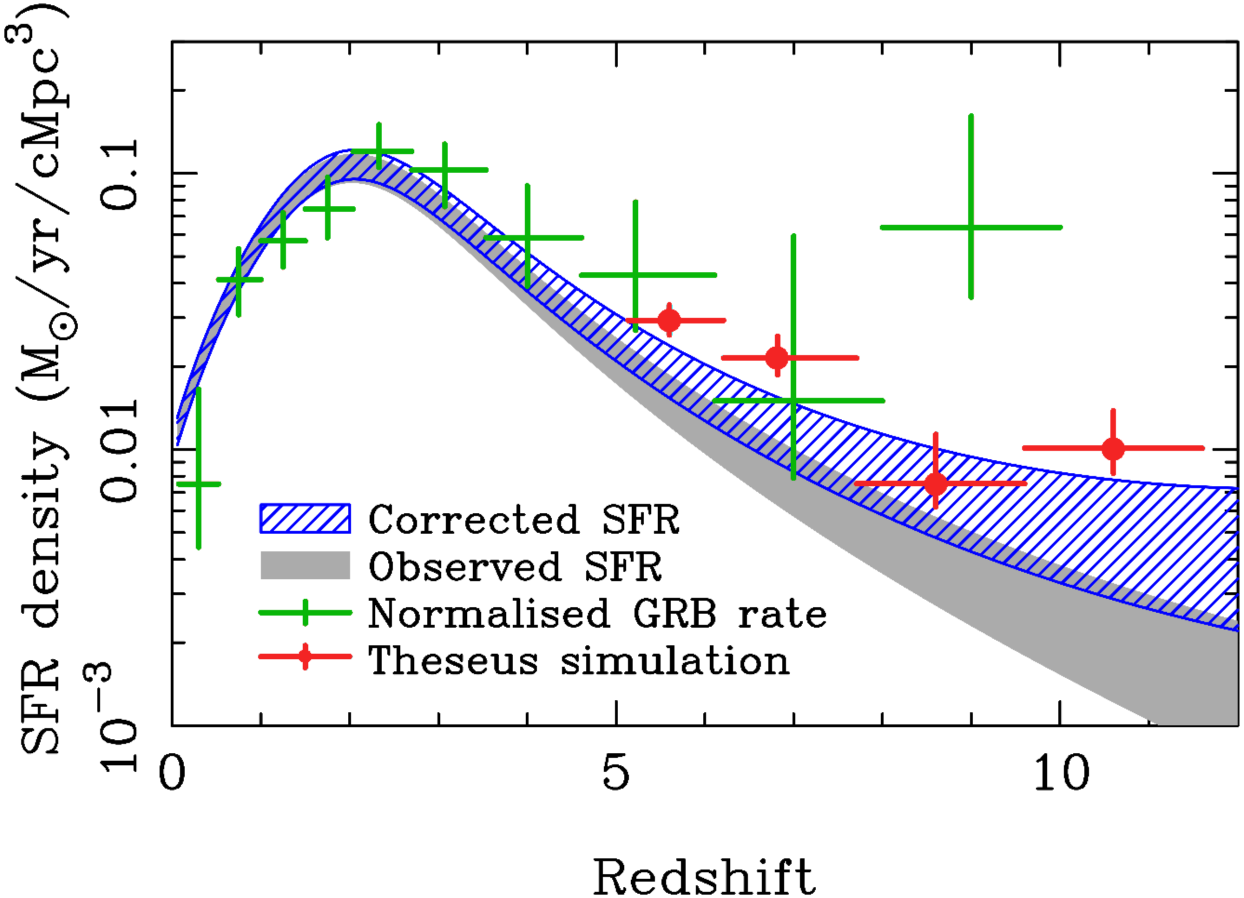
Figure 5-4 - Schematic view of the spacecraft design for the Phase A ADS (left) and TAS (right) Studies.

- Low Earth Orbit (< 5°, ~600 km)
- Autonomously rapid slewing bus
- 4-years nominal

Future missions (early / mid '20s)

- **SVOM (2022/23-):** 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 (2022/23-):** 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
- **POLAR-2 (2025?):** improved polarimetry of prompt emission;
- **HERMES and other nano-satellite programs (2022/23-):** 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

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



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

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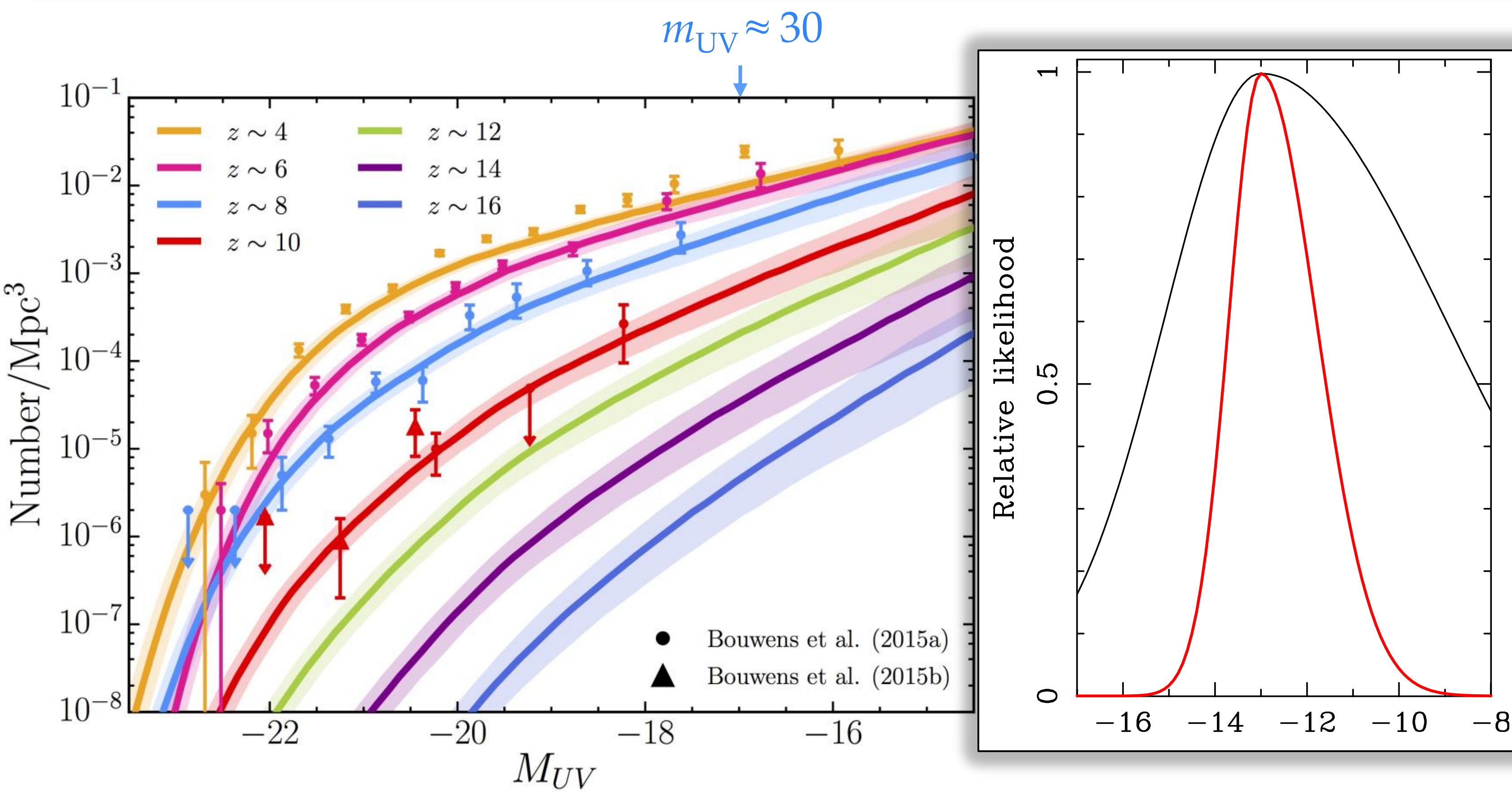
• Detecting and studying primordial invisible galaxies

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

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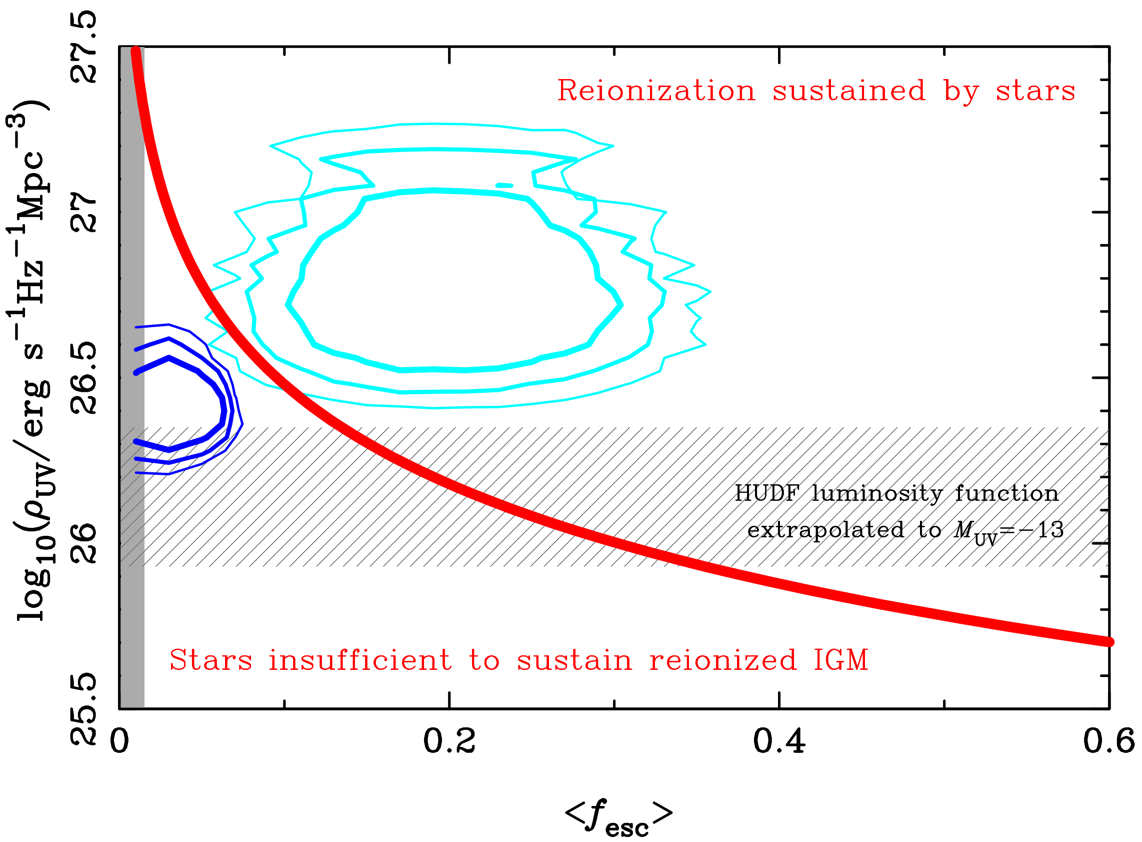
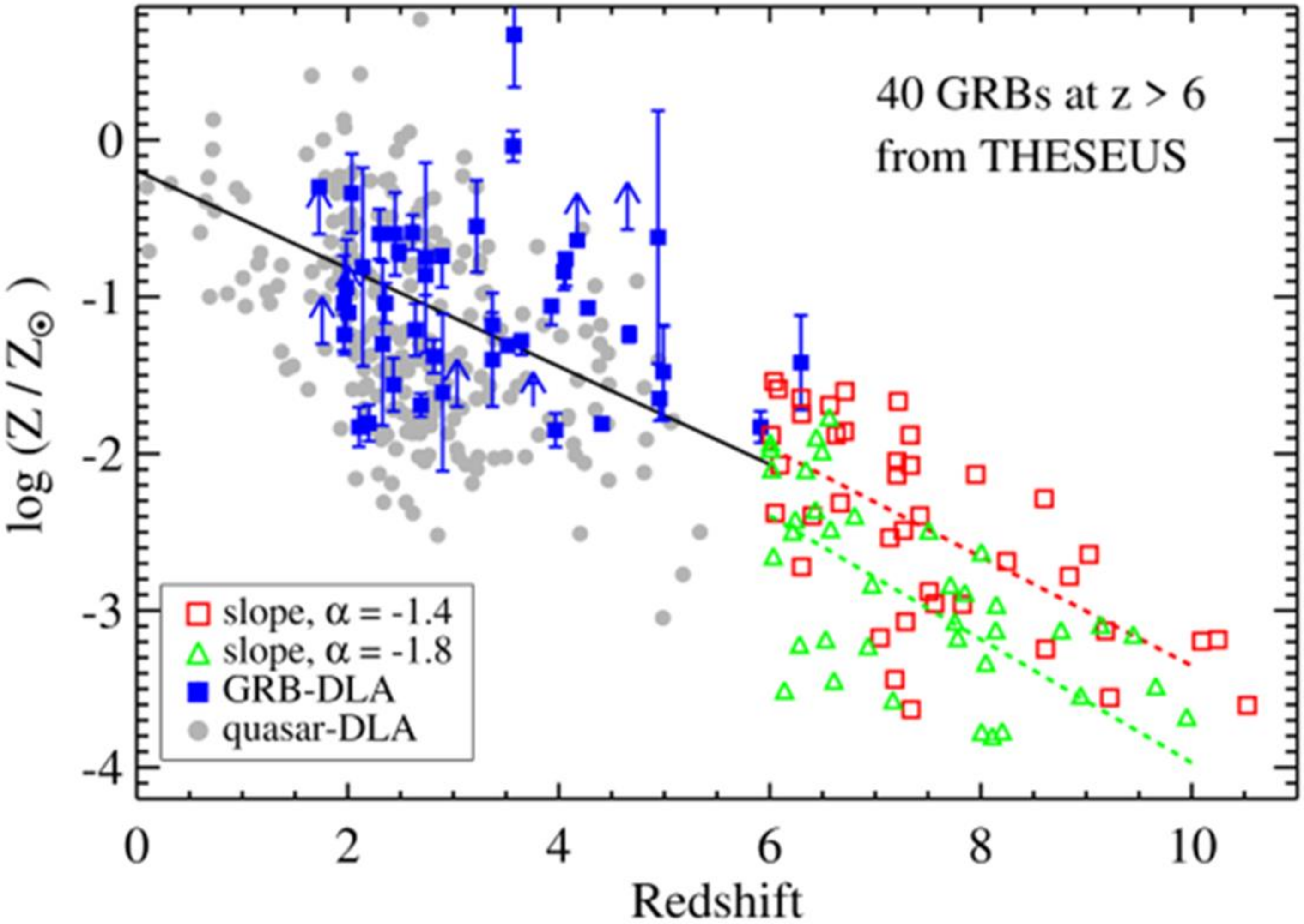
- **Shedding light on cosmic reionization**



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**



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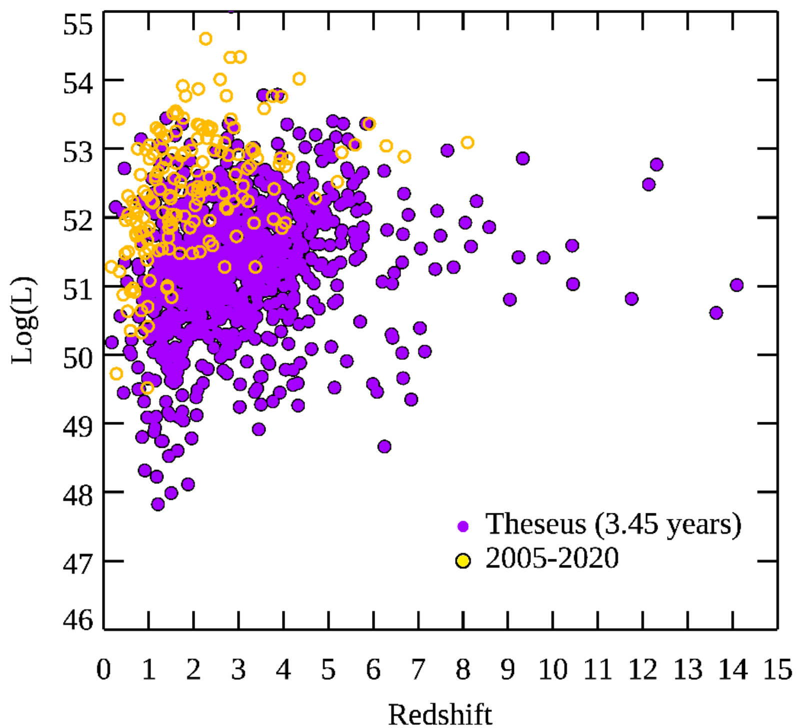
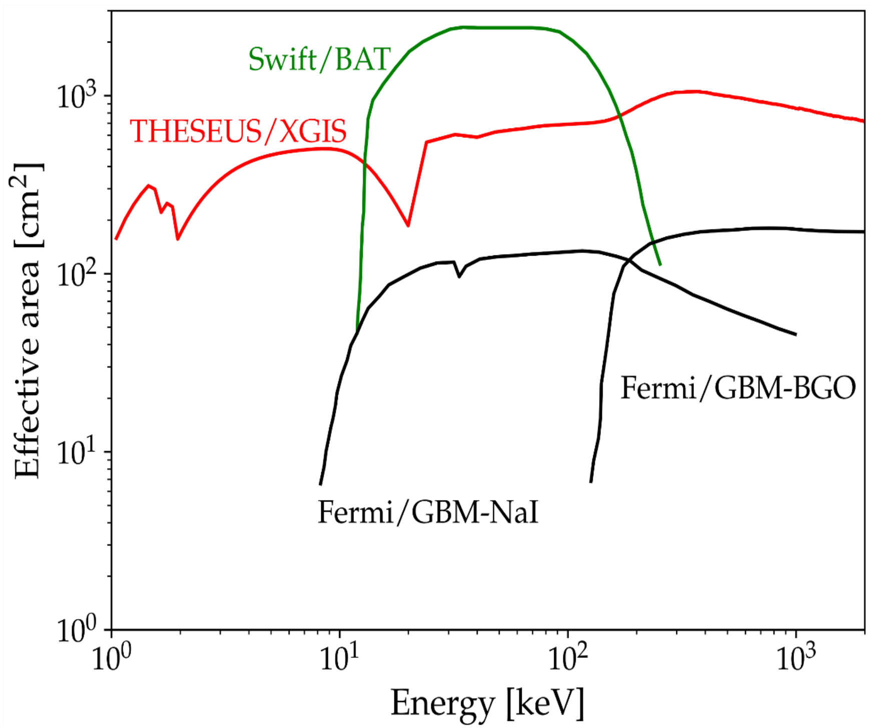
THESEUS capabilities for GRB SCIENCE

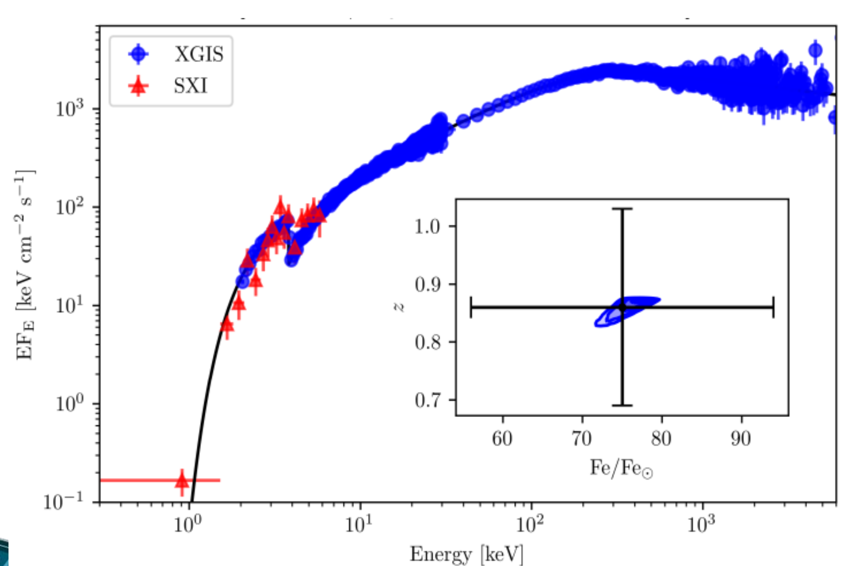
THESEUS will provide an unprecedented sample of many hundreds of GRBs with redshift, wide band X/gamma-ray spectroscopic and few ms timing characterization, NIR

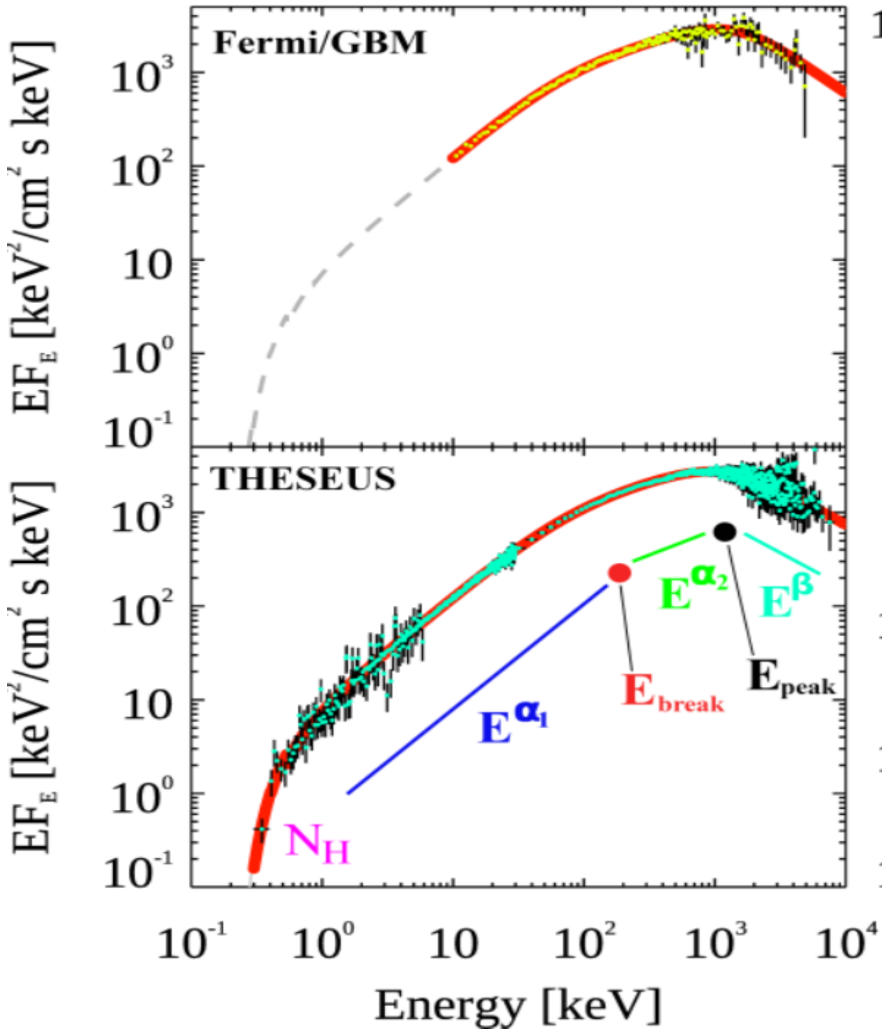




THESESEUS capabilities for GRB SCIENCE

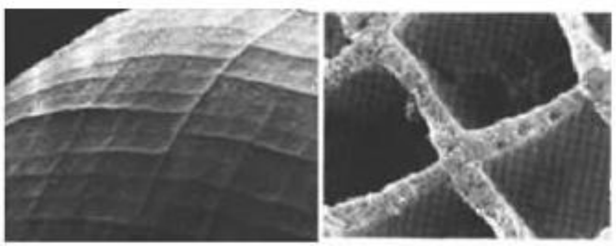
Extreme prompt emission physics, jet structure, central engine, circum-burst environment -> progenitors, weak/soft "local" GRBs, cosmological parameters, fundamental physics



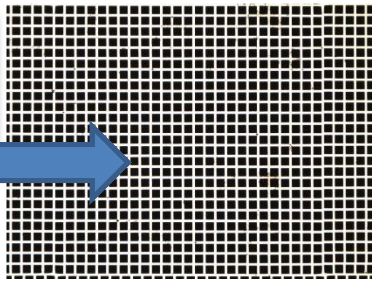


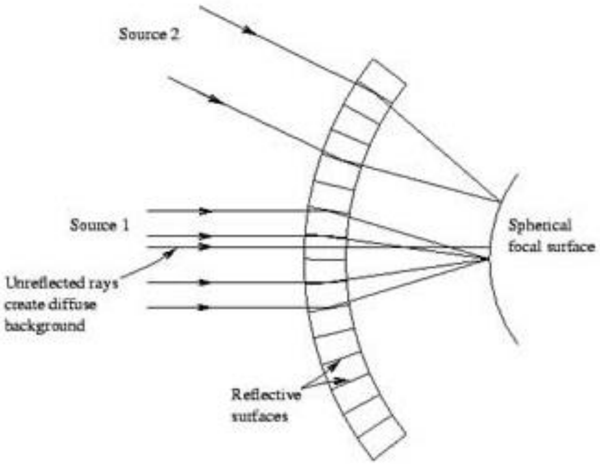
The Soft X-Ray Imager (SXI)

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′



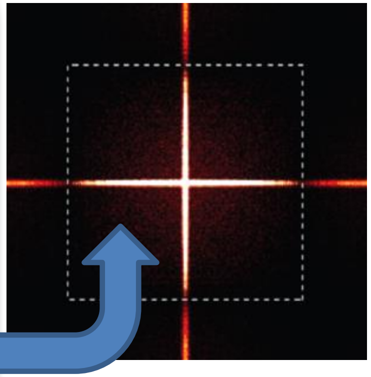
Mimic a lobster-eye using curved, square-pore MPOs





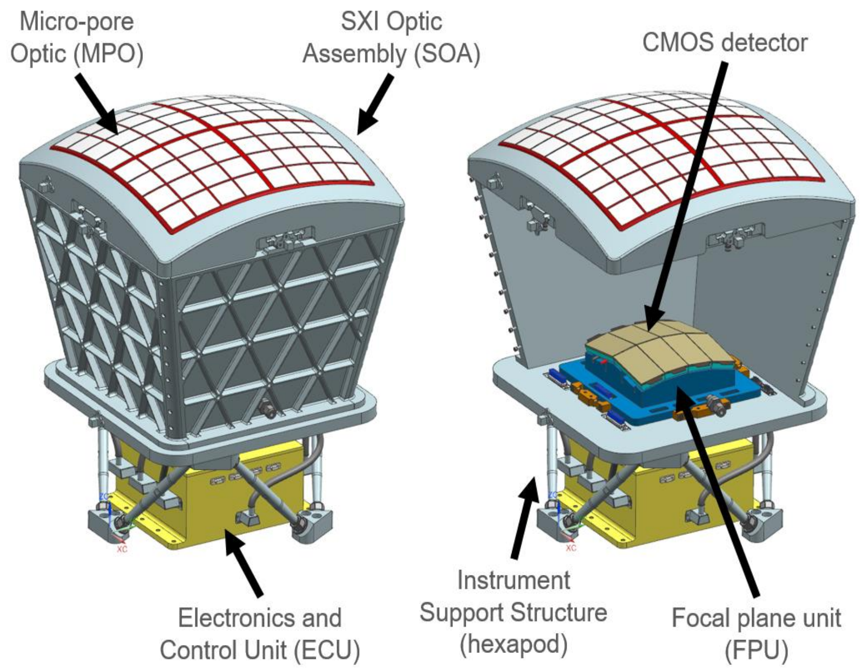
No single optical axis: get a wide field of view plus focusing with constant effective area

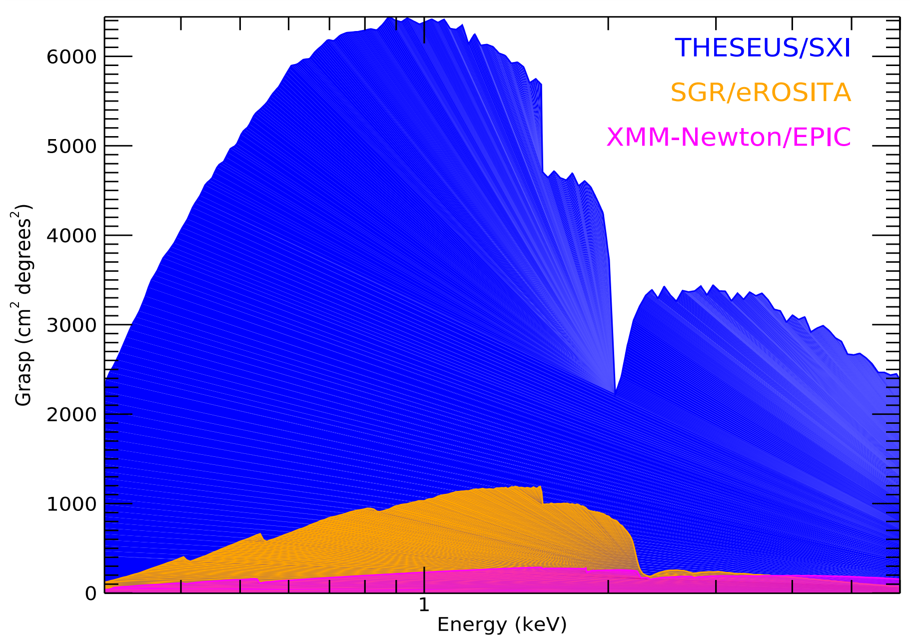
Spot (double reflection)
Lines (single reflections)



The Soft X-Ray Imager (SXI)

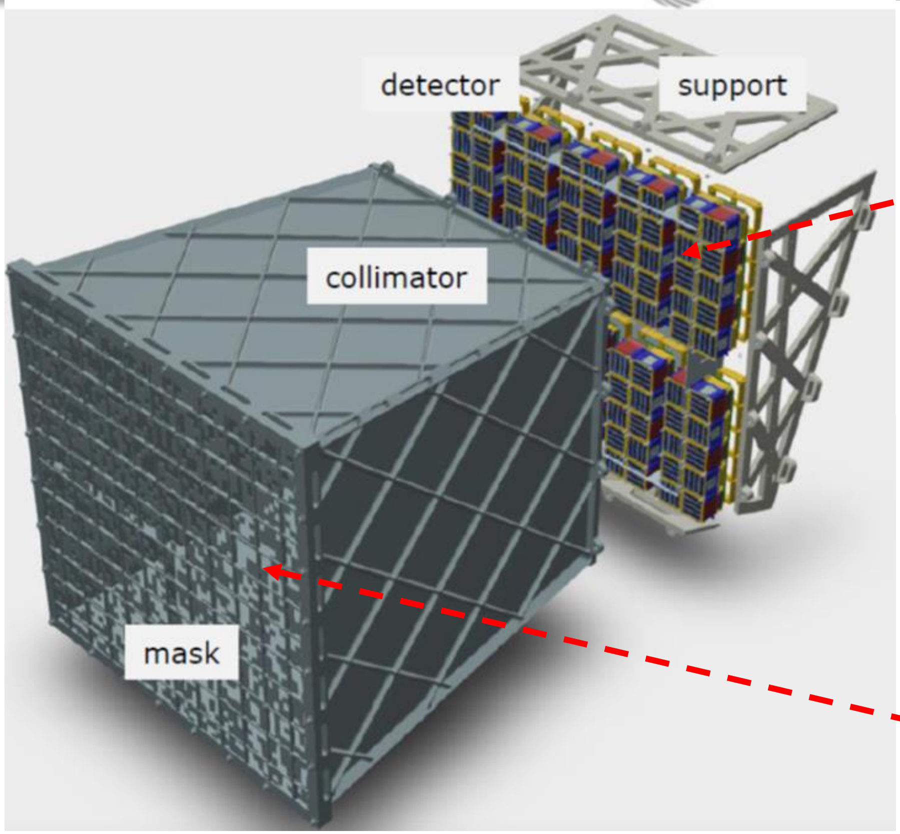
SXI will show a unique combination of FOV and effective area (GRASP), enabling simulatneous detection and localization of many transients in parallel.

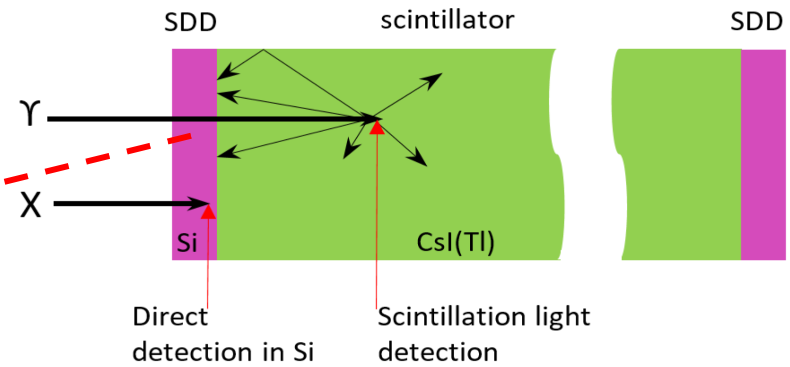


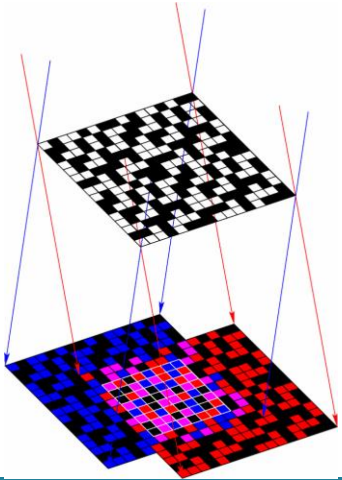


The X-Gamma Ray Imaging Spectrometer (XGIS)

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)

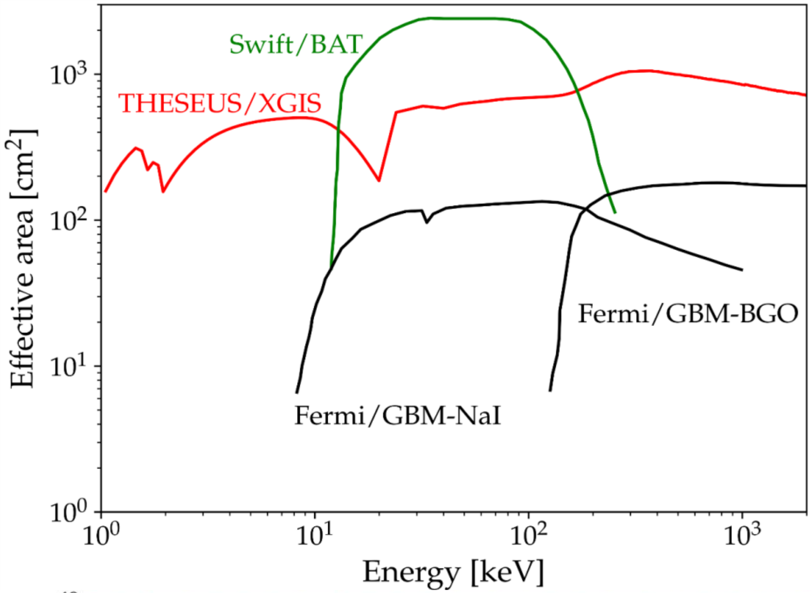


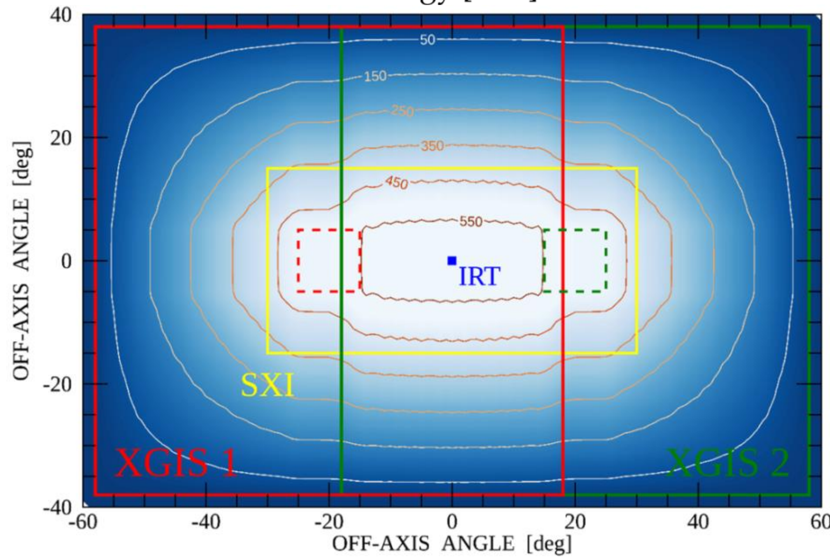




The X-Gamma Ray Imaging Spectrometer (XGIS)

- 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)





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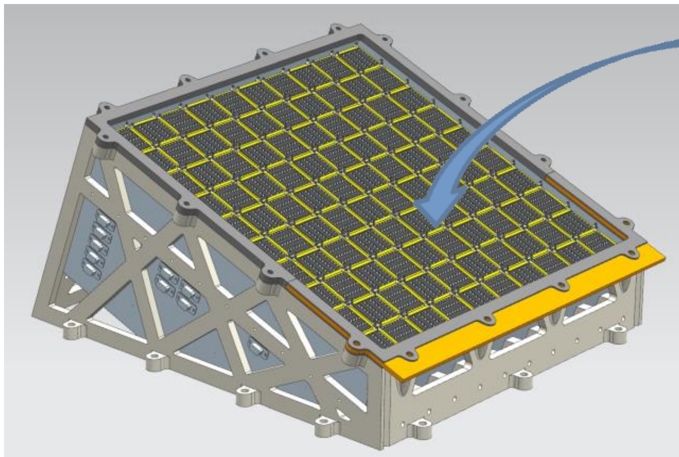
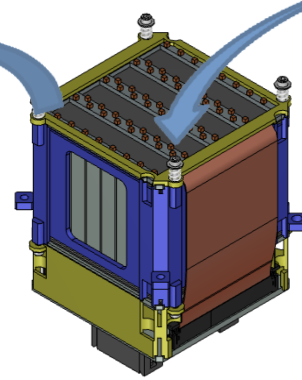
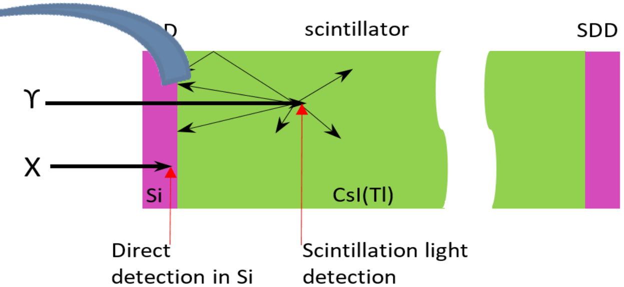
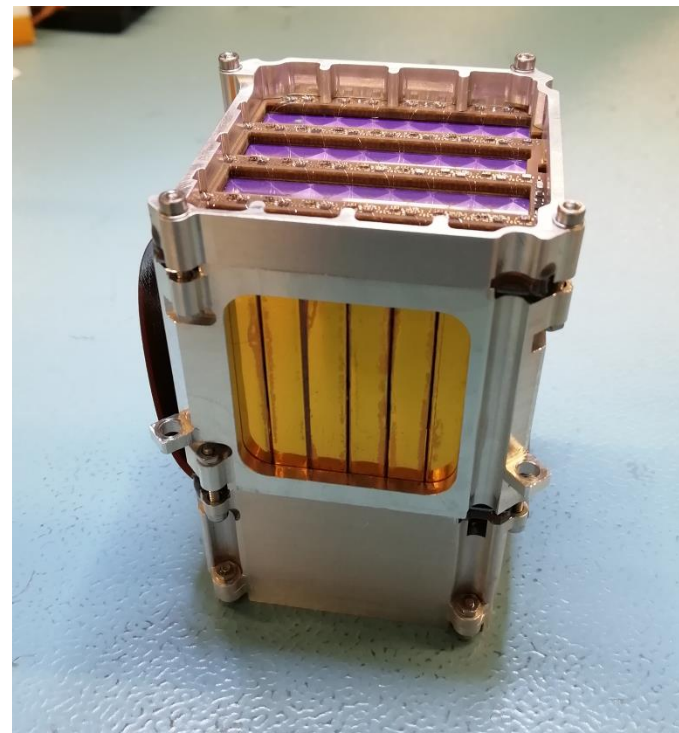






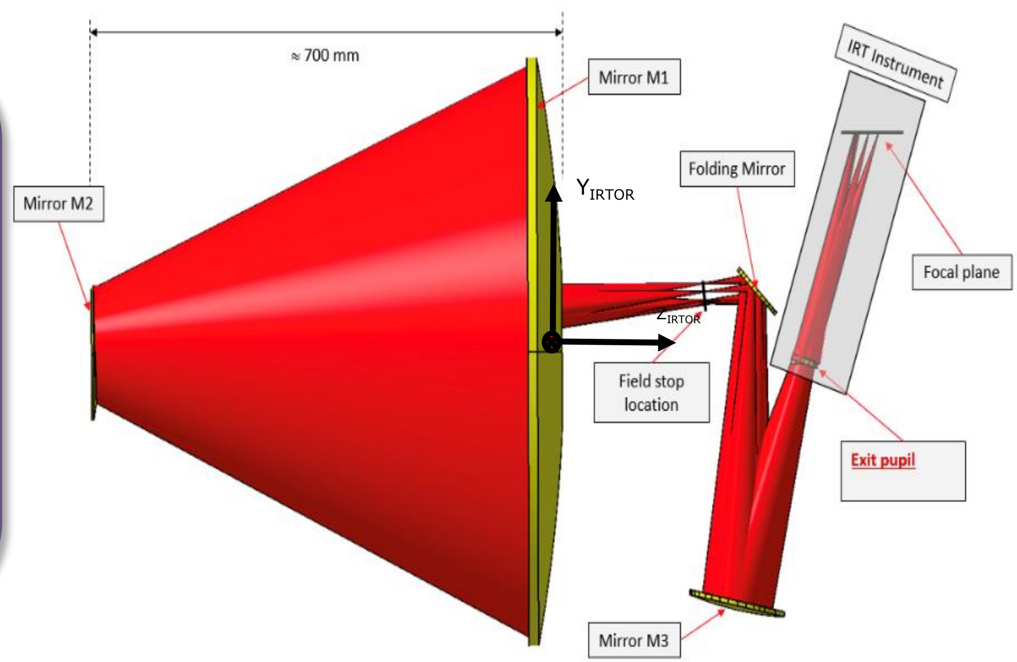
XGIS Phase A study: detection module prototype (ESA-OHB-ESA –INAF/OAS +ASI-INAF partners)



The Infra-Red Telescope (IRT)

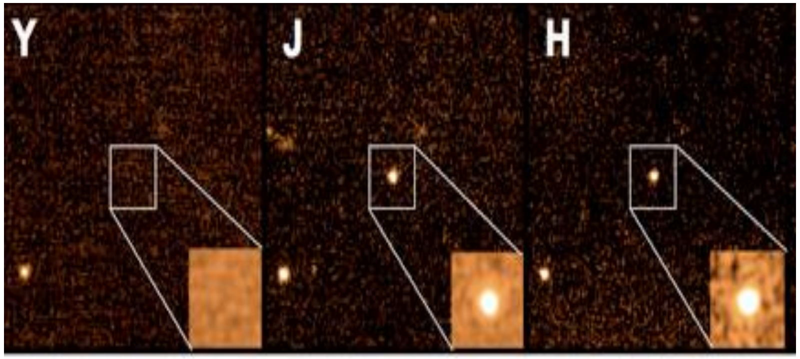
A 0.7 m class telescope with an off-axis Korsch optical design allowing for a large field of view (15′x15′) with imaging and moderate (R~400) spectroscopic capabilities

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

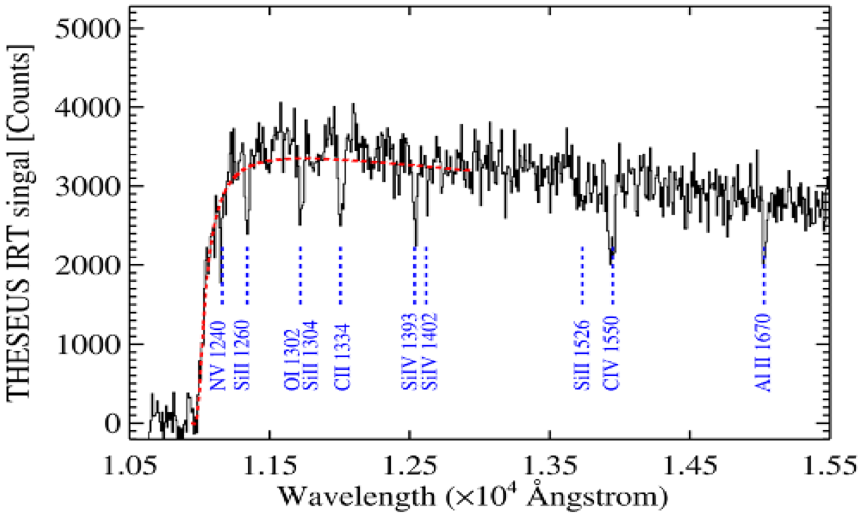


The Infra-Red Telescope (IRT)

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



On-board sensitive absorption spectrosocpy for medium-bright events



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