# Shedding light on the early Universe with THESEUS


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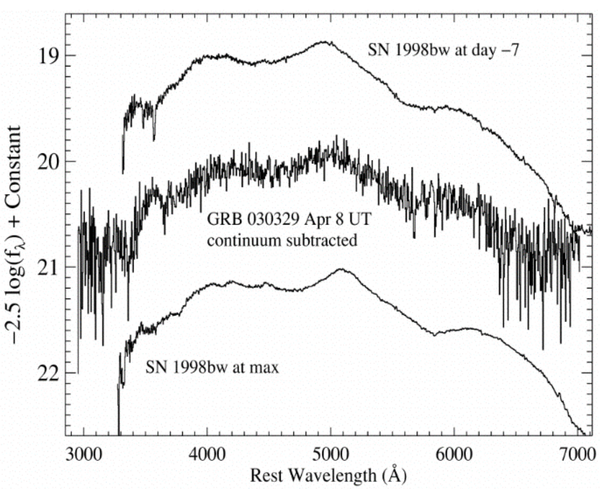
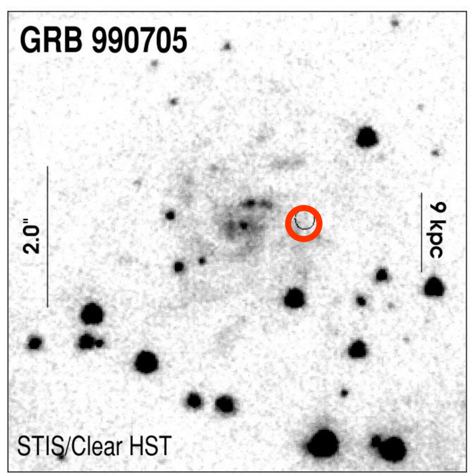
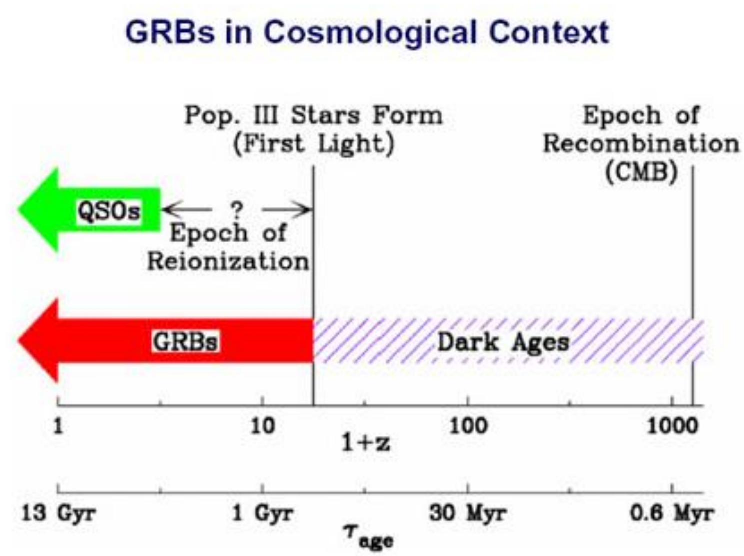
# Gamma-Ray Burst as powerful probes of the early Universe

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~10 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**



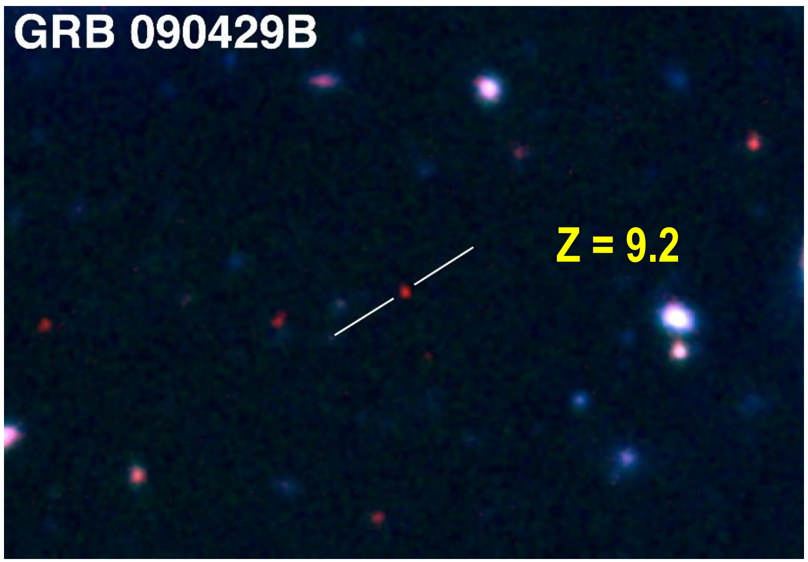



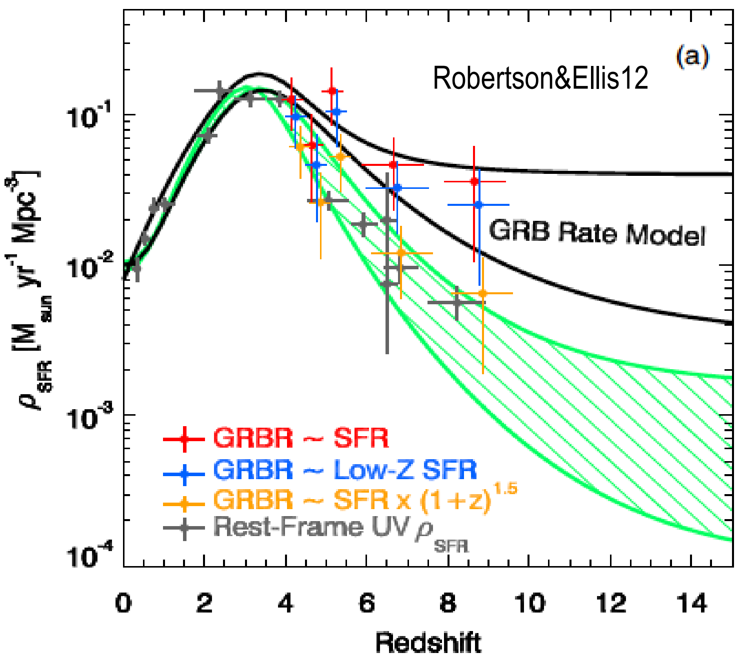




*Lamb and Reichart (2000)*

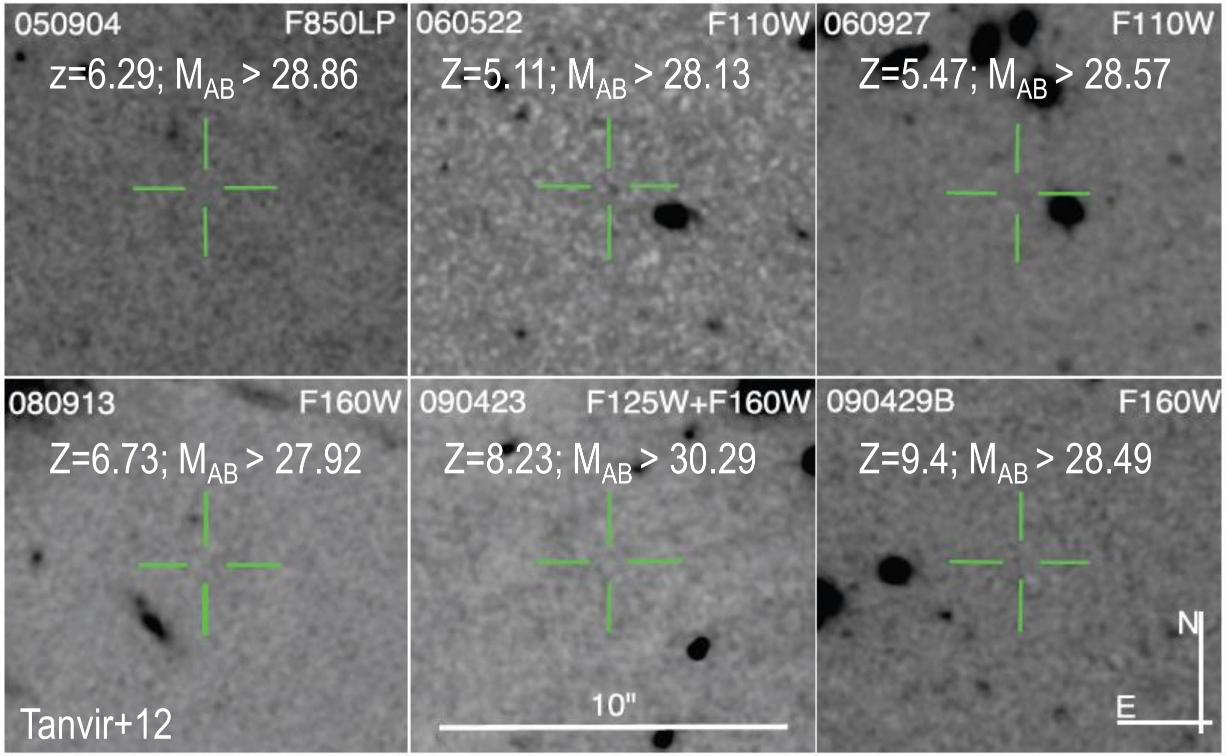
A statistical sample of high–z GRBs can provide fundamental information about:

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



- the number density and properties of high-z galaxies

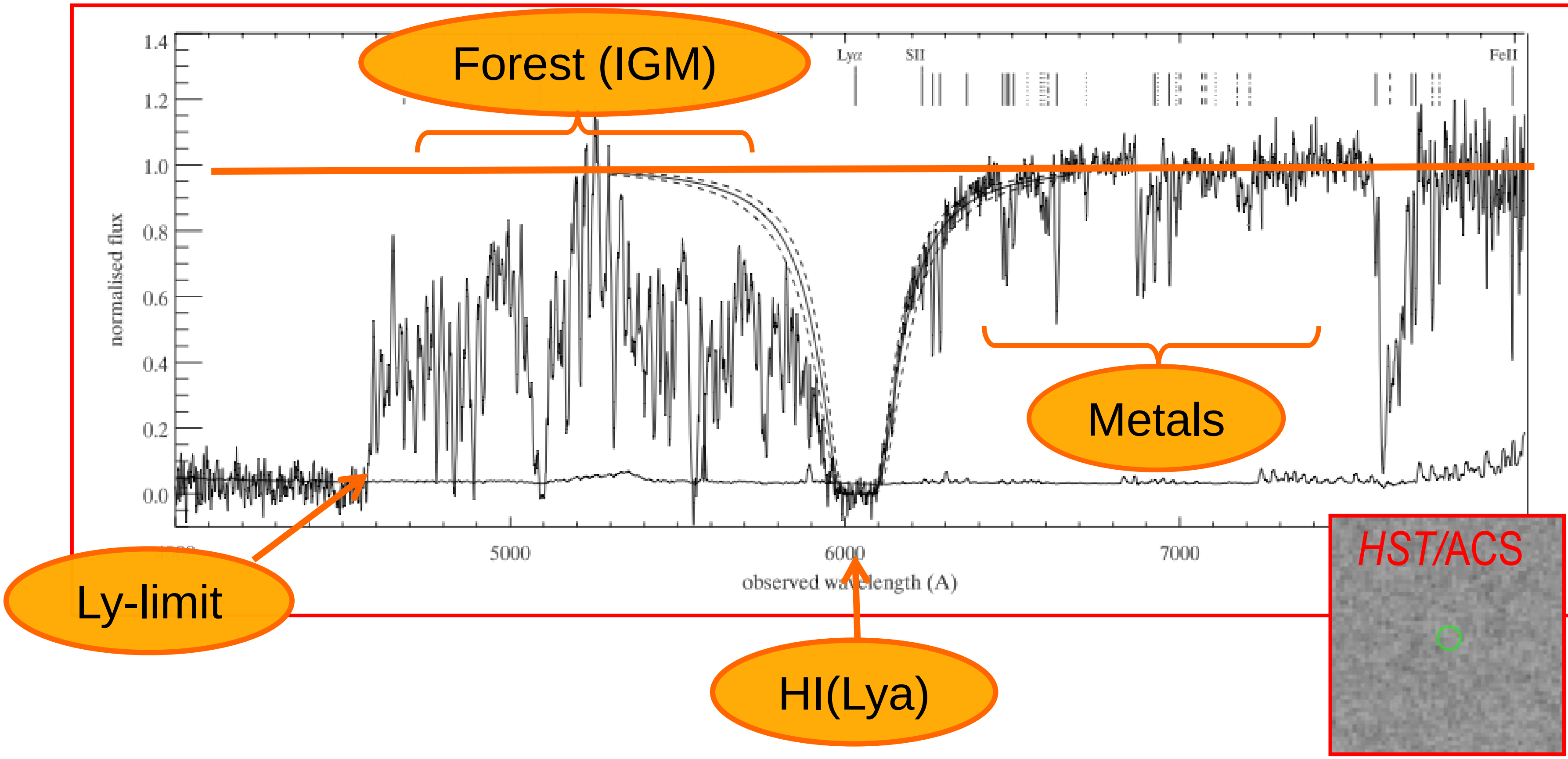



Robertson&Ellis12

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)

# Afterglow spectra contain much information

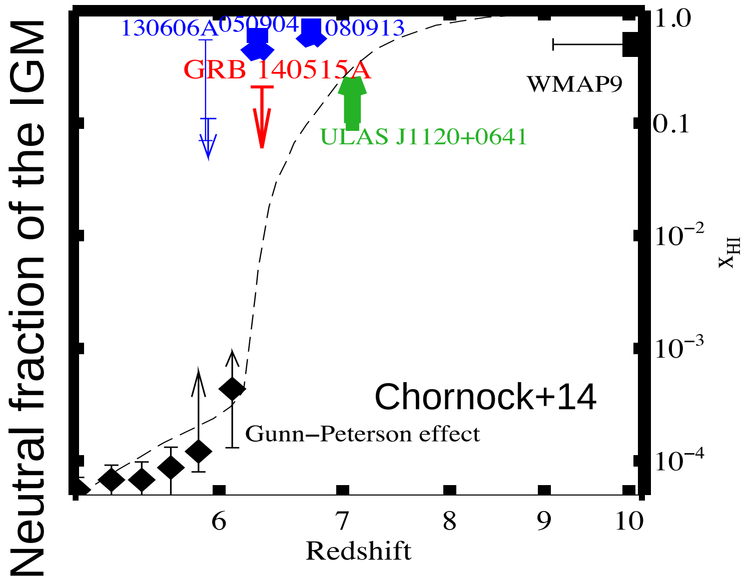
Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but *z*=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).

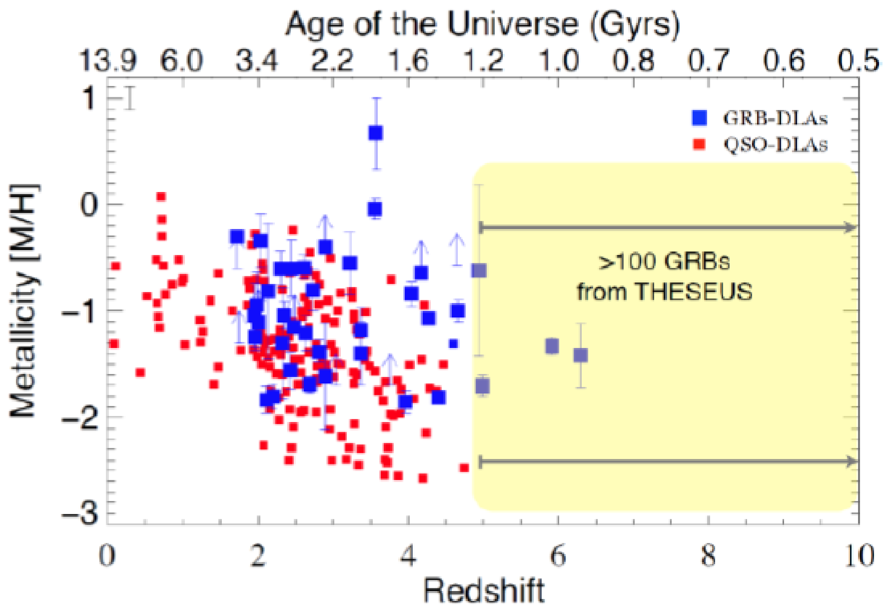


The first, metal–free stars (the so–called **PopIII stars**) can result in powerful GRBs (e.g. Meszaros+10). GRBs offer a powerful route to directly identify such elusive objects (even JWST will not be able to detect them directly) and study the galaxies in which they are hosted.

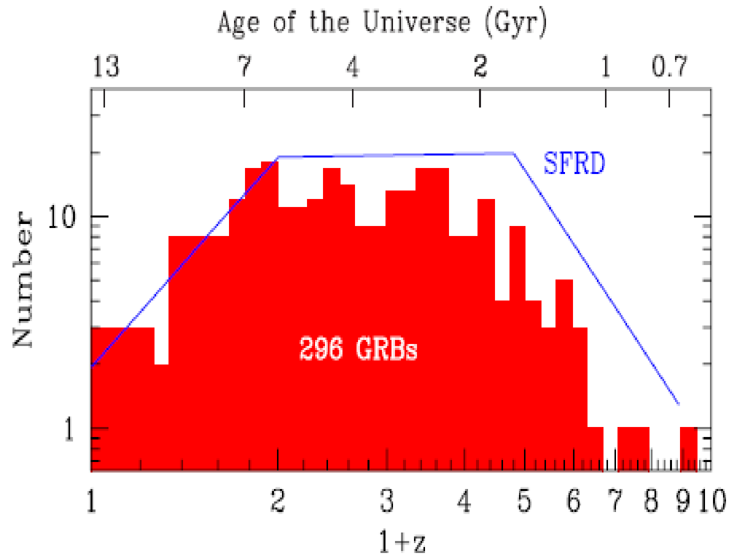
Even indirectly, the role of PopIII stars in **enriching the first galaxies** with metals can be studied by looking at the absorption features of PopII GRBs blowing out in a medium enriched by the first PopIII supernovae (Wang+12).

More generally, what is **the cosmic chemical evolution** at early times?



# ❑ GRB White paper for ESA/L2-3




➢ The European community played a fundamental role in the enormous progress in the field of the last 15 - 20 years (BeppoSAX, HETE-2, Swift, AGILE, Fermi + enormous efforts in optical IR and radio follow-up)

➢ **Goals**: detect 1000 GRB/year for substantial increase of high-z GRBs (50 at z >9) -> GRBs as probes of Pop III stars, metal enrichment and reionization of the Universe, IGM,SFR evolution up to early Universe ; provide trigger and e.m. counterpart for next generation grav. wave and neutrino detectors; GRB polarisation

➢ **Payload**: different solutions proposed, e.g., multi-BAT or Compton Telescope or Lobster-eye telescope + X-ray telescope +NIR telescope; L2 orbit prefarable

**Table 1:** Scientific requirements for a future GRB mission with assumed 5 yr lifetime.

| Requirement | Goal | Detector ability |
|---|---|---|
| 1. Detect 1000 GRBs/yr | obtain 50 (5) GRBs at $z > 10(20)$ | large FOV, soft response |
| 2. Rapid transmission to ground | allow timely follow-up observations | communication network |
| 3. Rapid localization to few $''$ | opt/NIR identification of 1000 GRBs/yr | slewing X-ray or opt/NIR telescope |
| 4. Provide $z$-indication | allow selection of high-$z$ objects | multi-filter or spectroscopic capability |

# THESEUS

# Transient High Energy Sources and Early Universe Surveyor

**Lead Proposer**: Lorenzo Amati (INAF – IASF Bologna, Italy)

**M4 proposal coordinators**: Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), Alberto Castro-Tirado (IAA, Spain)

**Payload consortium**: Italy, UK, Spain, France, Denmark, Poland, Czech Republic, ESA (+ Hungary, Slovenia, Ireland)

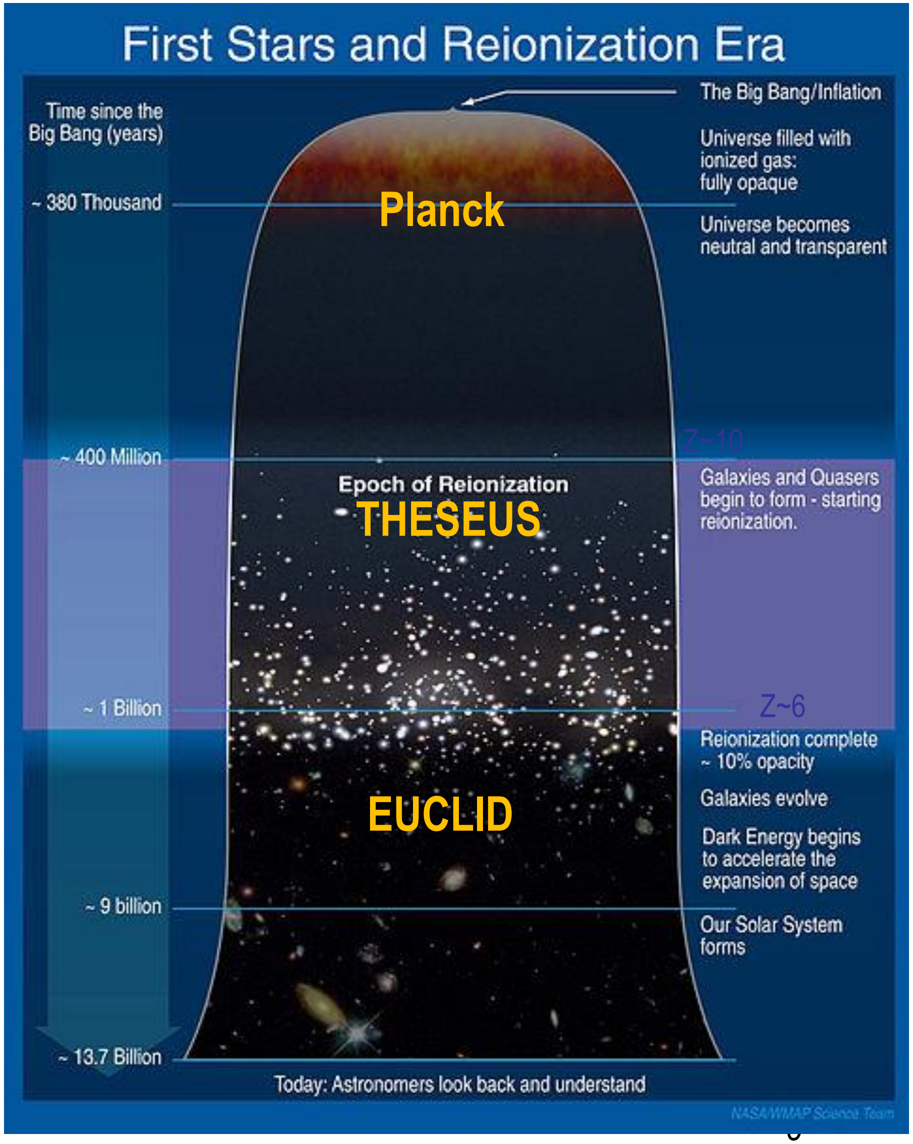
**International partners**: USA (+ interest from Brasil, Japan, Israel, Turkey)

# THESEUS main scientific goal

## Exploring the Early Universe (cosmic dawn and reionization era) by unveiling the Gamma-Ray Burst (GRBs) population in the first billion years

The study of the Universe before and during the epoch of reionization represents one of the major themes for the next generation of space and ground–based observational facilities. Many questions about the first phases of structure formation in the early Universe will still be open in the late 2020s:

- *When and how did first stars/galaxies form?*
- *What are their properties? When and how fast was the Universe enriched with metals?*
- *How did reionization proceed?*



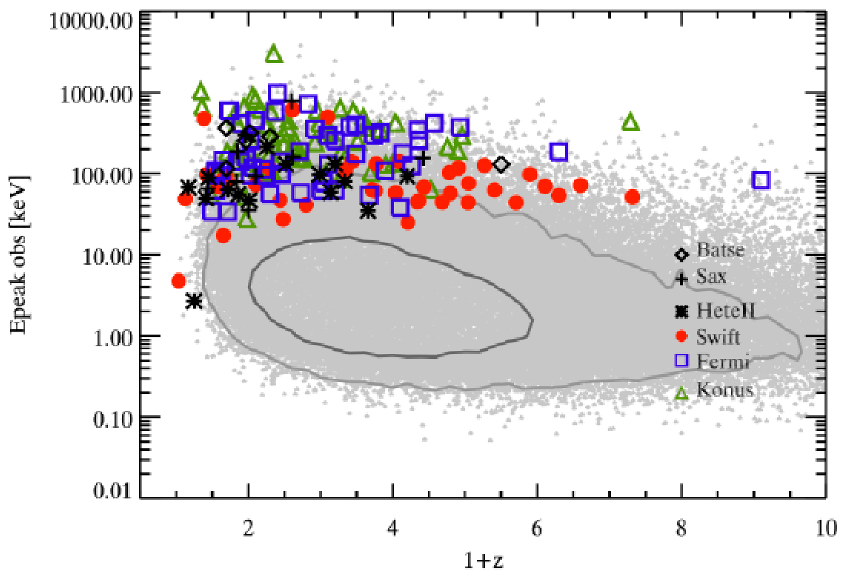
# THESEUS Requirements I

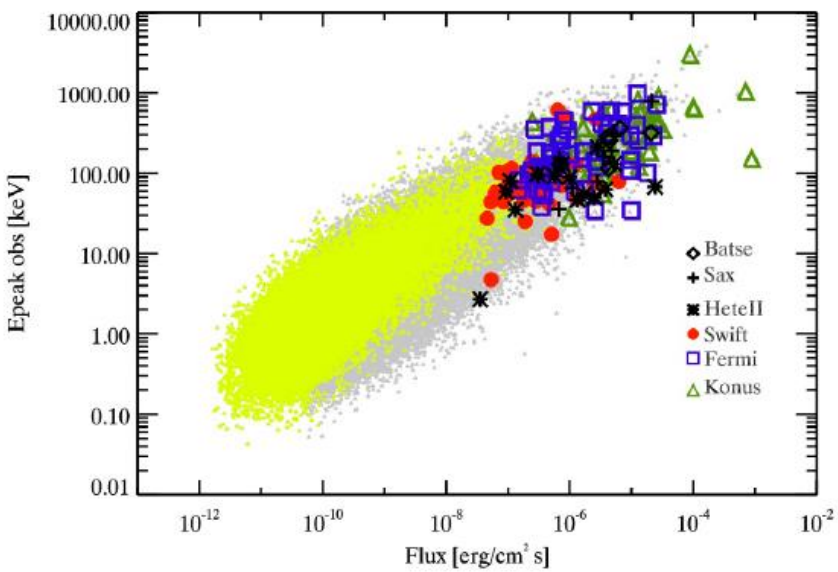
- A full exploration of the early Universe requires the detection of a factor 10 more GRBs (about 80-100) than currently available at z>6

- Such requirements are beyond the capabilities of current and future planned missions (e.g., SVOM)

- As supported by intensive simulation efforts (e.g. Ghirlanda+15 MNRAS) a high detection rate of high redshift GRBs required a *soft* **and** *sensitive* (down to $10^{-9}$ erg/cm$^2$/s) *wide field* high-energy trigger, with precise and reliable localization techniques (< 2 arc min)

# Hunting high-z GRBs



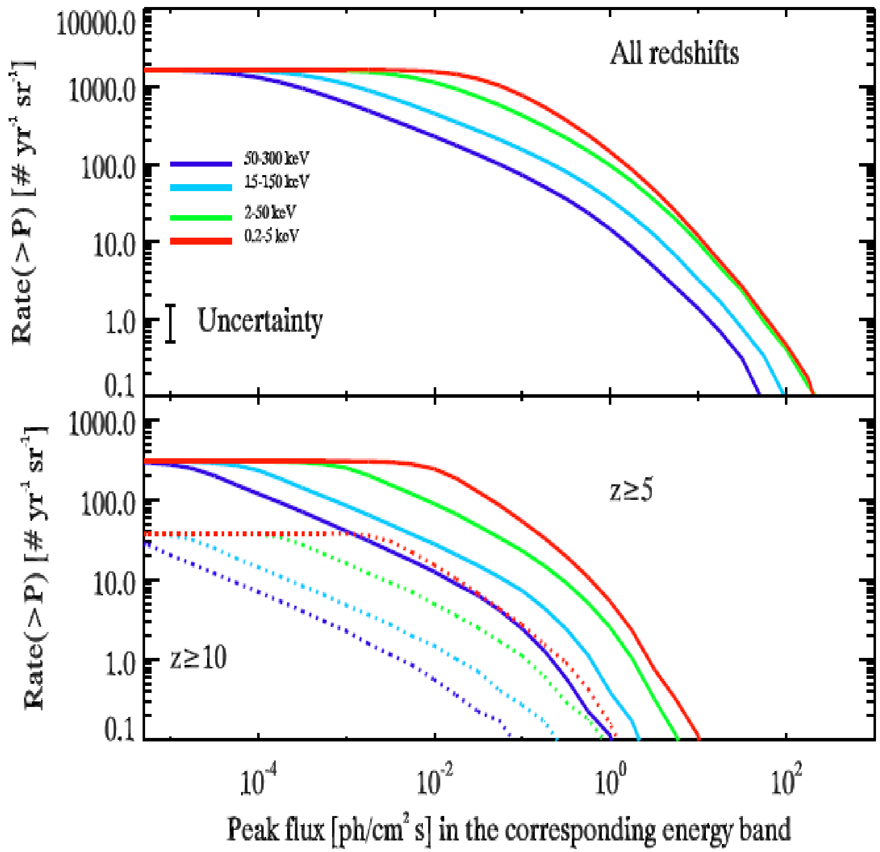




**Figure 3.** Cumulative peak flux distributions representing the rate, i.e. the number of GRBs yr$^{-1}$ sr², with peak flux $\geqslant P$. Different energy ranges where the peak flux $P$ is computed are shown with different colors (as shown in the legend). The typical uncertainty on the predicted rates (for any energy range) is shown by the vertical bar (see §5). *Top panel*: entire population of simulated GRBs. *Bottom panel*: population of high redshift GRBs: $z \geqslant 5(10)$ shown by the solid (dotted) line. For the soft energy band 0.2–5 keV (shown by the red line) a typical $N_H = 2 \times 10^{21}$ cm$^{-2}$ has been assumed to account for the absorption.

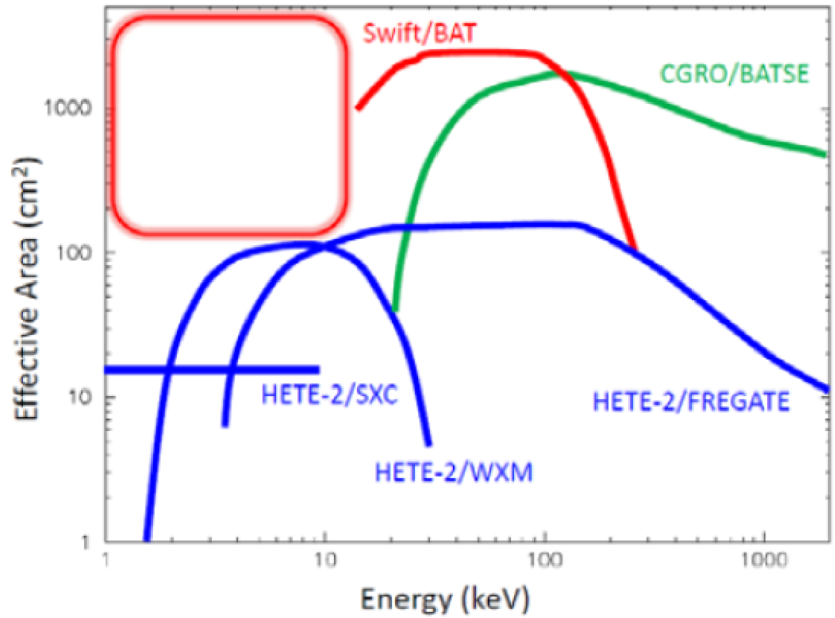
e.g., Ghirlanda et al. 2015

# THESEUS Requirements II

- In order to efficiently classify and filter the triggers (no previous experience had such a sensitivity in soft X-rays on a wide FOV), a broad band spectral coverage is needed at high energies (in addition the GRB phenomenon will be better characterized)

- In order to *identify, classify and study* the high-z GRB counterparts, an near-infrared (due to cosmological Ly-alpha suppression) telescope is needed on board. It will provide accurate positions, GRB redshifts, and GRB afterglows *spectra* (R~1000).

- An agile and autonomous platform (Swift-like) is required in order to point at the GRB position quickly, as well as a prompt downlink of GRB trigger, position and redshift




| | Energy Band | FOV | Energy resolution | Peak eff. area | Source location | Operation |
|---|---|---|---|---|---|---|
| CGRO/BATSE | 20–2000 keV | open | 10 keV (100 keV) | ~1700 $cm^2$ | >1.7 deg | ended |
| Swift | 15–150 keV | 1.4 sr | 7 keV (60 keV) | ~2000 $cm^2$ | 1–4 arcmin | active |
| Fermi/GBM | 8 keV – 40 MeV | open | 10 keV (100 keV) | 126 $cm^2$ | >3 deg | active |
| Konus–WIND | 20 keV – 15 MeV | open | 10 keV at 100 keV | 120 $cm^2$ | – | active |
| BeppoSAX/WFC | 2–28 keV | 0.25 sr | 1.2 keV (6 keV) | 140$cm^2$ | 1 arcmin | ended |
| HETE-2/WXM | 2–25 keV | 0.8 sr | 1.7 keV (6 keV) | 350$cm^2$ | 1–3 arcmin | ended |
| THESEUS | 0.3–20000 keV | 1 - 1.4 sr | 300 eV (6 keV) | 1500 $cm^2$ | 0.5–1 arcmin | 2025–2028 ? |
| SVOM | 4 keV – 5 MeV | 1.5 sr | 2 keV (60 keV) | 1000 $cm^2$ | 2–10 arcmin | 2018-2022 ? |
| UFFO–p | 5–100 keV | 1.5 sr | 2 keV (60 keV) | 191 $cm^2$ | 5–10 arcmin | 2014–2018 ? |
| CALET/GBM | 7 keV – 20 MeV | 3 sr | 5 keV (60 keV) | 68 $cm^2$ | – | 2014–2018 ? |

**+ Infrared telescope and fast slewing !!!**

Table 2: Characteristics c
GRB–dedicated instrume
capable of measuring GRB prompt emission down to 2 keV (BeppoSAX/WFC and HETE–2/WXM), and next future GRB experiments under development or advanced study (SVOM, Lomonosov/UFFO–p, CALET/GBM).

# THESEUS payload

- **Soft X-ray Imager (SXI):** a set of « Lobster-Eye » X-ray (0.3 - 6 keV) telescopes covering a total FOV of 1 sr field with 0.5 – 1 arcmin source location accuracy, provided by a **UK** led consortium

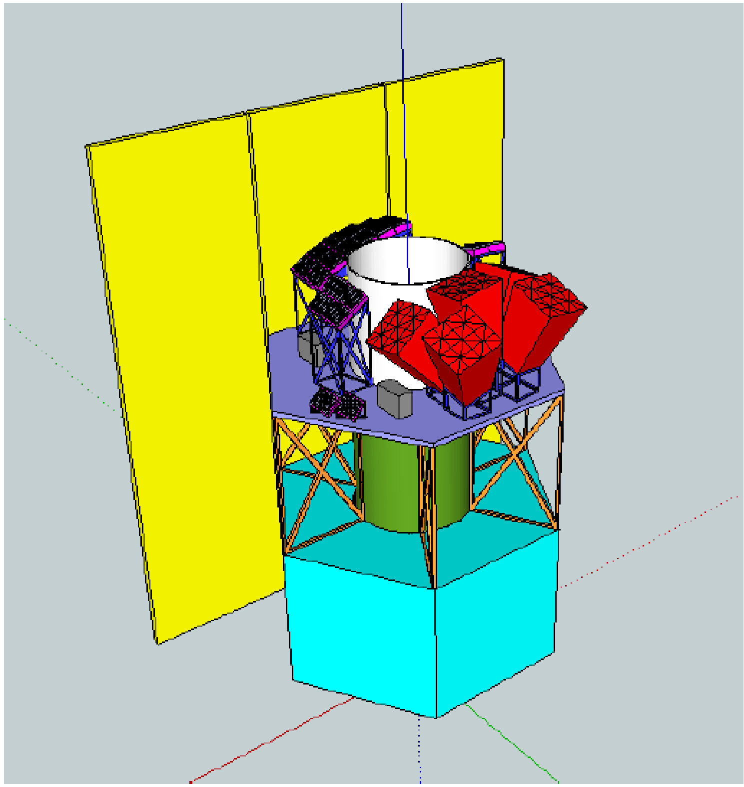
- **InfraRed Telescope (IRT):** a 70 cm class near-infrared (up to 2 microns) telescope (IRT) with imaging and moderate spectral capabilities provided by a **Spain (M4) / France (M5)** led consortium

- **X/Gamma-ray Spectrometer (XGS)**: non-imaging spectrometer (XGS) based on SDD+CsI, covering the same FOV than the Lobster telescope extending its energy band up to 20 MeV. This instrument will be provided by an **Italian** led consortium

# Payload accomodation and budgets

| PAYLOAD MODULE | | | | |
|---|---|---|---|---|
| ***SXI*** | 90.0 | 20% | 18.0 | 108.0 |
| ***XGS*** | 70.5 | 20% | 14.1 | 84.6 |
| ***IRT*** | 112.6 | 20% | 22.5 | 135.1 |
| ***PDHU+PSU + harness*** | 18.0 | 20% | 3.6 | 21.6 |
| Total P/L Module Mass | 283.1 | | 56.6 | 349.3 |

| | |
|---|---|
| Total Service Module Mass (kg) | 481.1 |
| Total Payload Module Mass (kg) | 349.3 |
| System level margin (20%) | 166.1 |
| Dry Mass at launch (kg) | 996.5 |
| Propellant | 16.0 |
| Launcher adapter | 77.0 |
| Total mass at launch (kg) | 1089.5 |



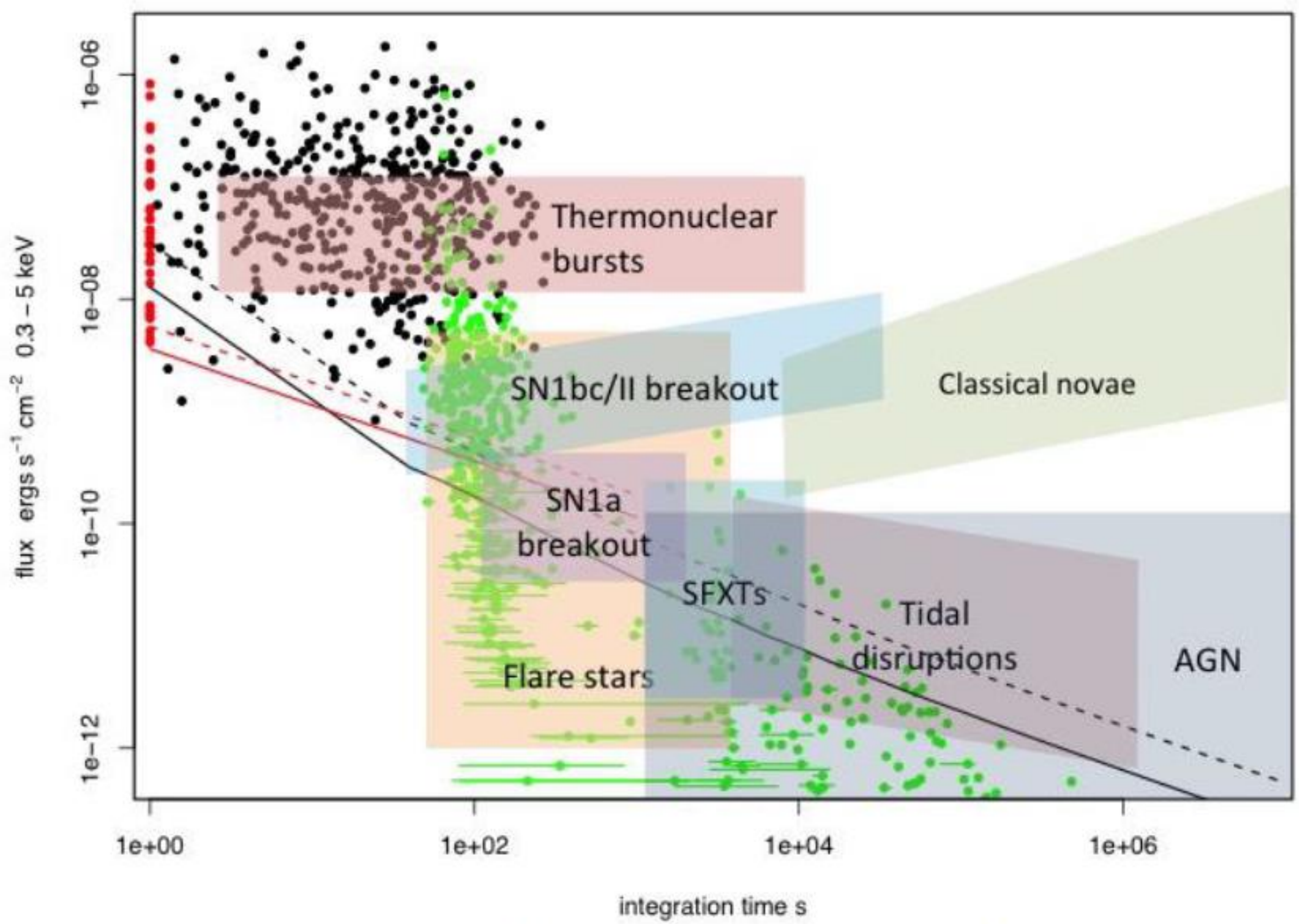



*Figure 2.4: Sensitivity of the SXI (black curves) and XGS (red) vs. integration time. The solid curves assume a source column density of 5×10$^{20}$ cm$^{-2}$ (i.e. well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 10$^{22}$ cm$^{-2}$ (significant intrinsic absorption). The black dots are the peak fluxes for Swift BAT GRBs plotted against T90/2. The flux in the soft band 0.3-10 keV was estimated using the T90 BAT spectral fit including the absorption from the XRT spectral fit. The red dots are those GRBs for which T90/2 is less than 1 second. The green dots are the initial fluxes and times since trigger at the start of the Swift XRT GRB light-curves. The horizontal lines indicate the duration of the first time bin in the XRT light-curve. The various shaded regions illustrate variability and flux regions for different types of transients and variable sources.*

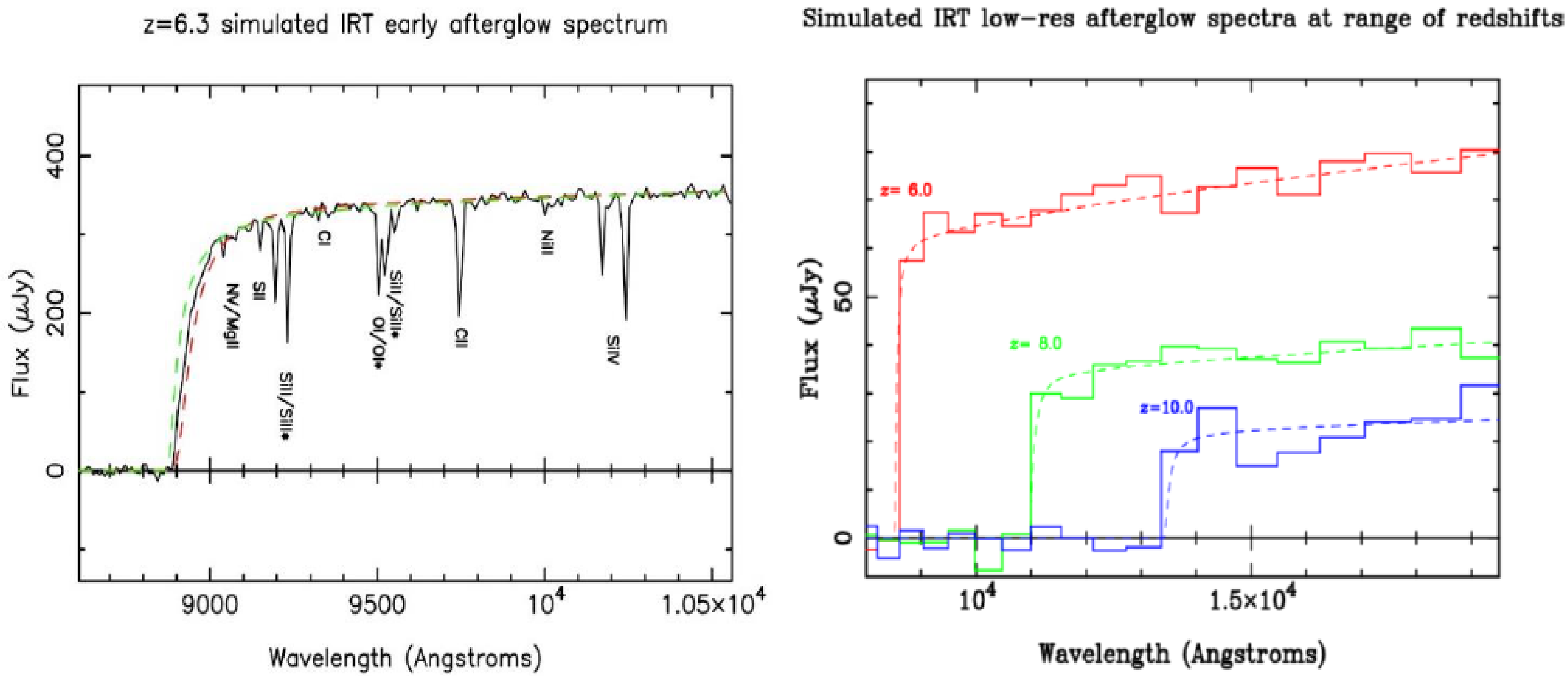



*Figure 2.6 – Left: a simulated IRT high resolution (R=1000) spectrum for a GRB at z=6.3 observed at 1 hour post trigger assuming a GRB similar to GRB 050903. The black spectrum has host log(NH)=21 and neutral fraction Fx=0.5 (and metallicity 0.1solar). The two models are: Red: log(NH)=21.3, Fx=0 Green: log(NH)=20.3, Fx=1. The IRT spectra are capable for such GRBs to constrain parameters in addition to providing an accurate redshift. Right: simulated IRT low resolution (R=20) spectra as a function of redshift for a GRB at the limiting magnitude AB mag 20.8 at z=10, and by assuming a 20 minute exposure.The underlying (noise-free) model spectra in each case are shown as smooth, dashed lines. Even for difficult cases the low-res spectroscopy should provide redshifts to a few percent precision or better. For many applications this is fine - e.g. star formation rate evolution.*

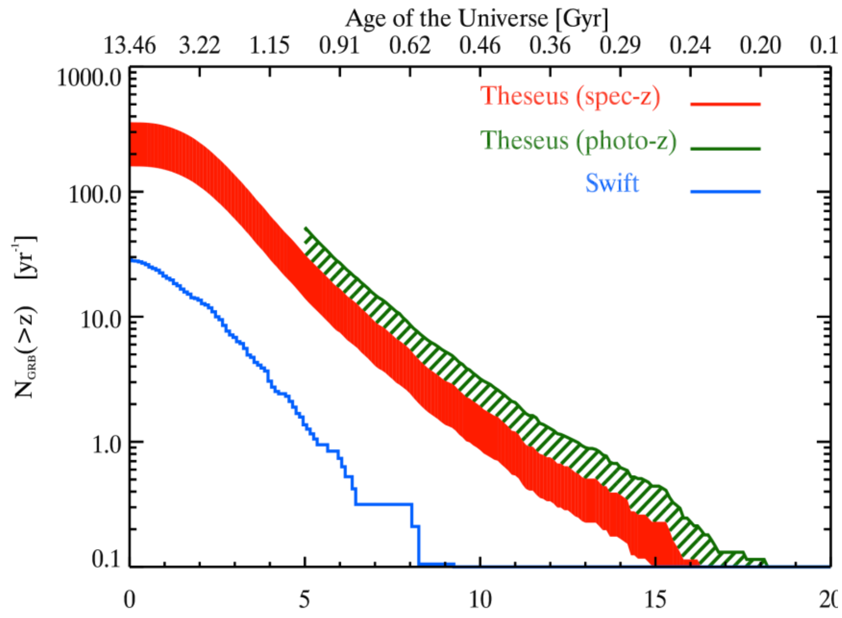
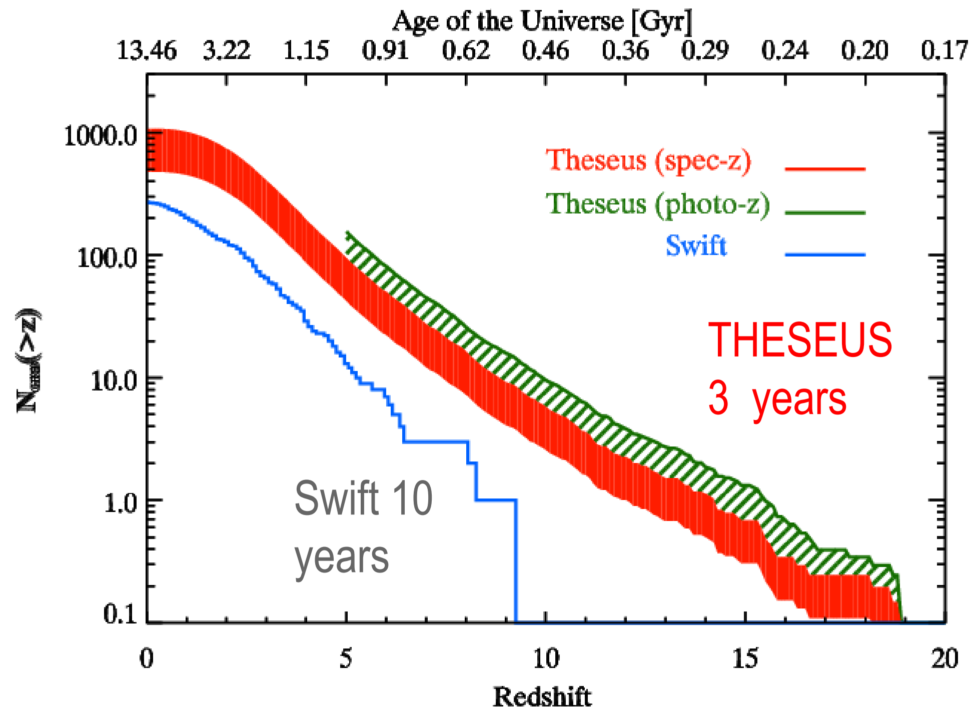



Figure 1. Rate of redshift measurement by Theseus. The solid filled (red) region repres
the rate of bursts as a function of redshift (cumulative distribution as in Fig.1) that wil




| | Theseus rate = # yr$^{-1}$ | | | |
|---|---|---|---|---|
| | All | z>5 | z>8 | z>10 |
| Detections | 310 – 700 | 23 – 52 | 4 – 9 | 1.5 – 3 |
| Photometric z | | 23 – 52 | 4 – 9 | 1.5 – 3 |
| Spectroscopic z | 160 – 360 | 14 – 30 | 2 – 6 | 1 – 2 |

**Ghirlanda + Salvaterra**

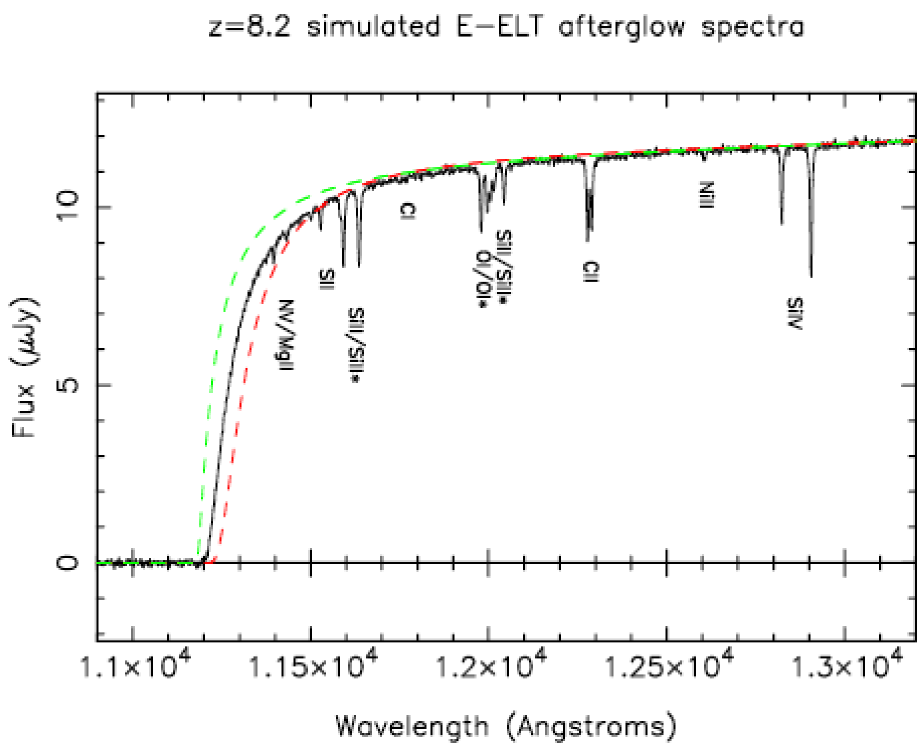



*Fig. 1.4: simulated E-ELT 30 min spectrum of a faint GRB afterglow observed after ~1 day. The S/N provides exquisite abundance determinations while fitting the Ly-a damping wing simultaneously fixes the IGM neutral fraction and the host HI column density, as illustrated by the two extreme models, a pure 100% neutral IGM (green,) and best-fit host absorption with a fully ionized IGM*

**N. Tanvir**

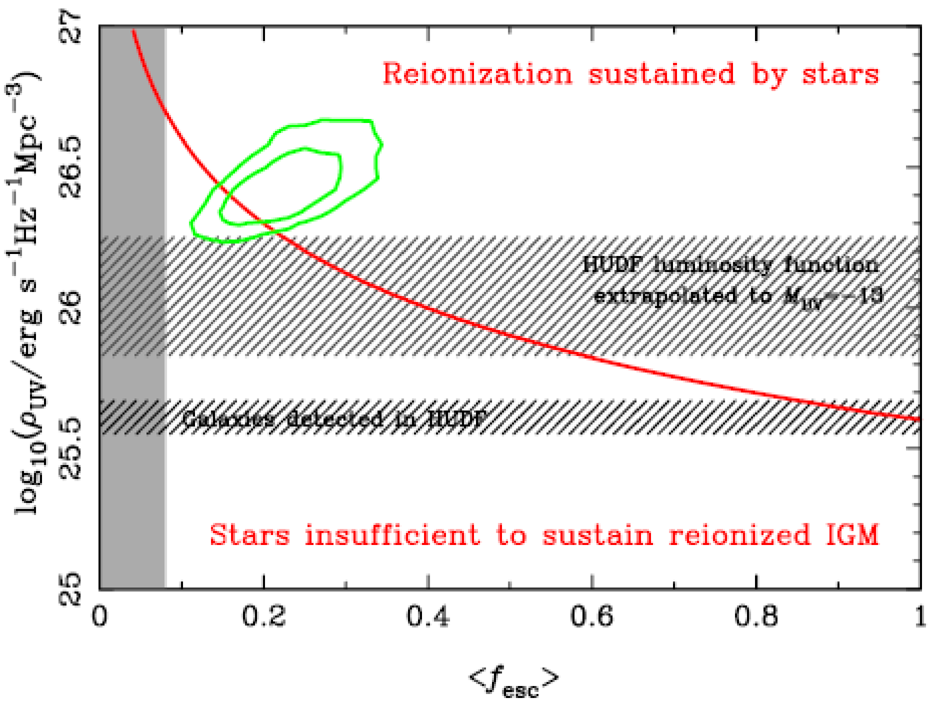
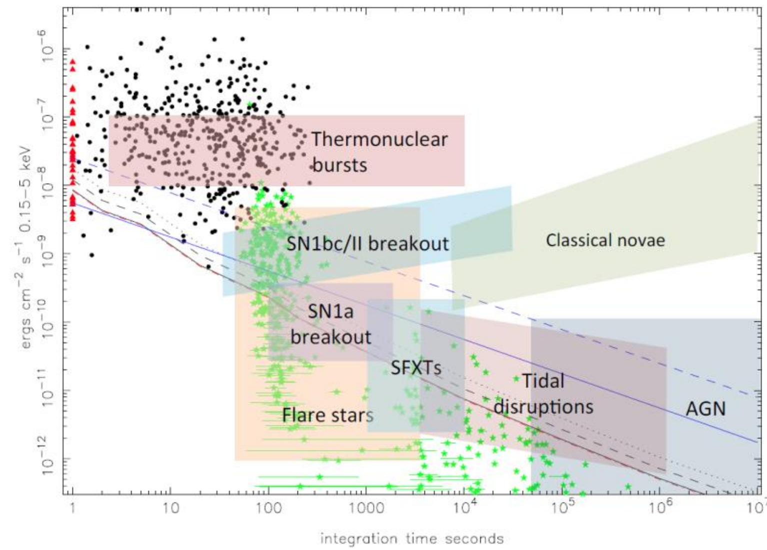



*Fig. 1.3: The UV luminosity density from stars at z~8 and average escape fraction $\langle f_{esc} \rangle$ are insufficient to sustain reionization unless the galaxy luminosity function steepens to magnitudes fainter than $M_{UV}$=-13 (grey hatched region), and/or $\langle f_{esc} \rangle$ is much higher than that typically found at z~3 (grey shaded region). Even in the late 2020s, $\langle f_{esc} \rangle$ at these redshifts will be largely unconstrained by direct observations. The green contours show the 1- 2-σ expectations for a sample of 30 GRBs at z~8 for which deep spectroscopy provides the host neutral column and deep imaging constrains the fraction of star formation occurring in hosts below the JWST limit (Robertson et al. 2013 ApJ 768 71). The input parameters were* $\log_{10}(\rho_{UV})$=26.44 *and $\langle f_{esc} \rangle$=0.23, close to the (red) borderline for reionization by stars*

**N. Tanvir**

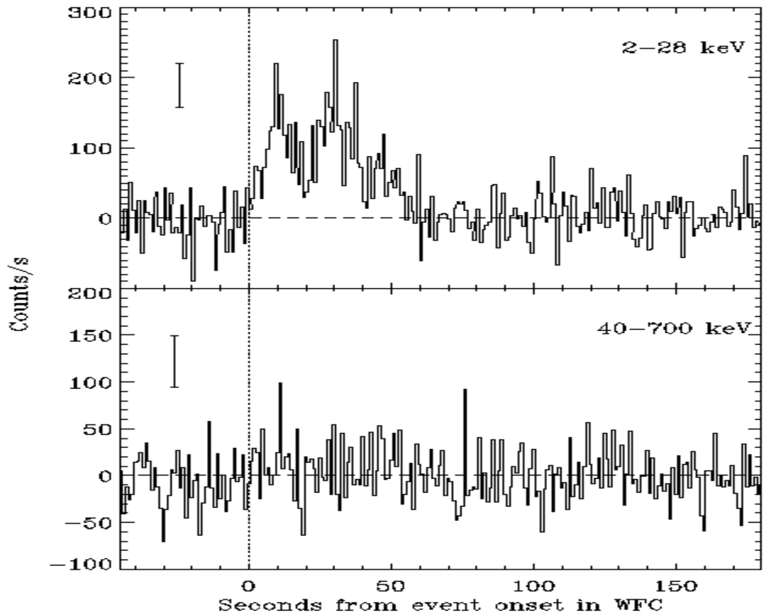
# Additional science: performing an unprecedented deep survey of the soft X-ray transient Universe in order to:

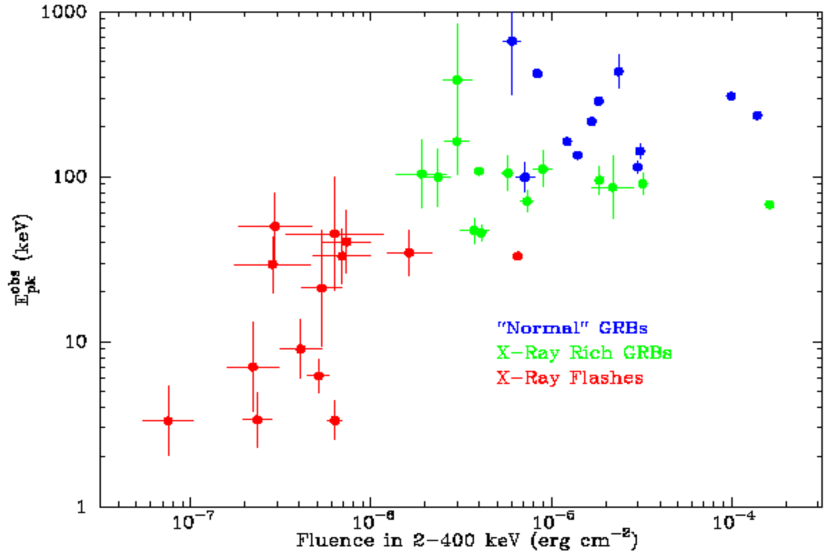
- Fill the present gap in the discovery space of **new classes of transients events**, thus providing unexpected phenomena and discoveries;
- Provide a **fundamental step forward in the comprehension of the physics** of various classes of Galactic and extra-Galactic transients, like, e.g.: tidal disruption events TDE, magnetars/SGRs, SN shock break-out, Soft X-ray Transients SFXTS, thermonuclear bursts from accreting neutron stars, Novae, dwarf novae, stellar flares, AGNs / Blazars);
- **Provide real time trigger and accurate (~1 arcmin within a few s) high-energy transients for follow-up with next generation optical, IR, radio, X-rays, TeV or neutrino telescopes and identify electromagnetic counterpart of detections by next generation gravitational wave detectors.**

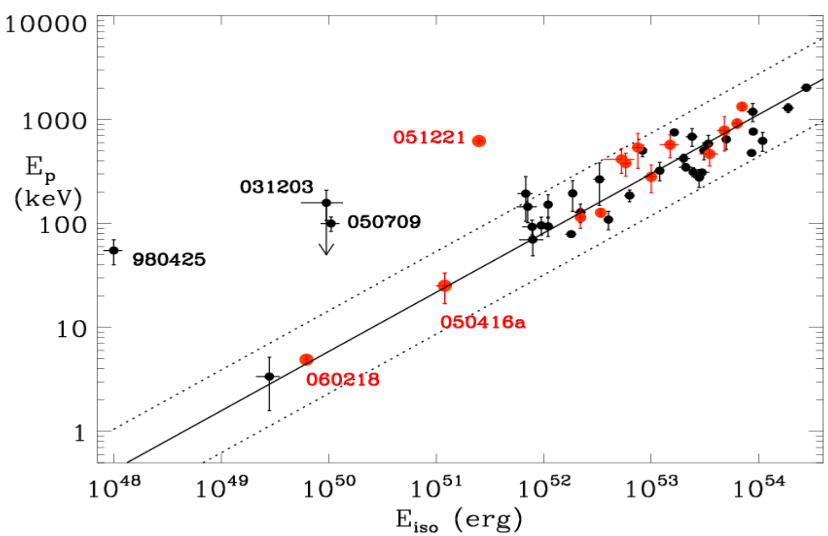


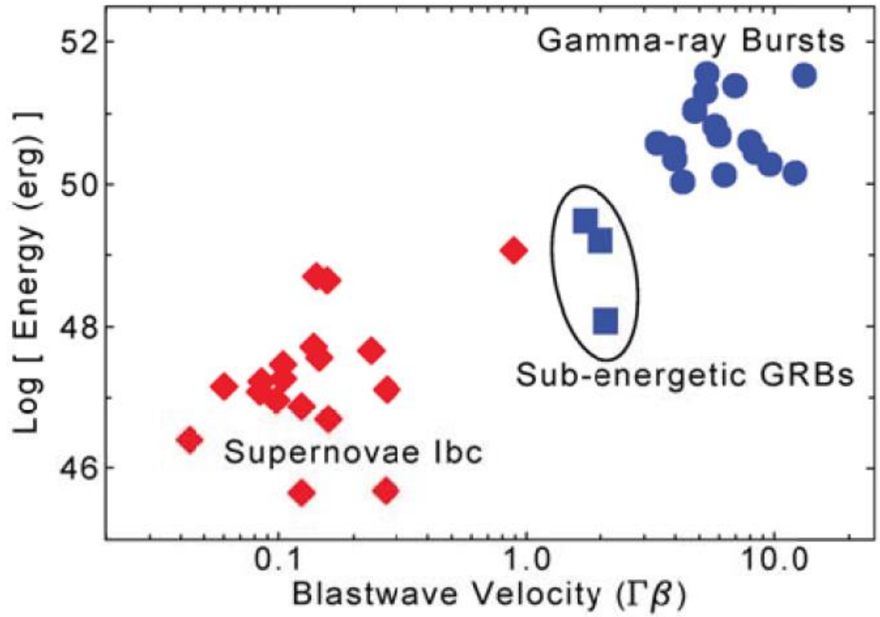

| Transient type | SXI Rate |
|---|---|
| GW sources | 0.03-33 $yr^{-1}$ |
| Magnetars | 40 $day^{-1}$ |
| SN shock breakout | 4 $yr^{-1}$ |
| TDE | 50 $yr^{-1}$ |
| AGN+Blazars | 350 $day^{-1}$ |
| Thermonuclear bursts | 35 $day^{-1}$ |
| Novae | 250 $yr^{-1}$ |
| Dwarf novae | 30 $day^{-1}$ |
| SFXTs | 1000 $yr^{-1}$ |
| Stellar flares | 400 $yr^{-1}$ |
| Stellar super flares | 200 $yr^{-1}$ |

# e.g.: X-Ray flashes and subluminous GRBs



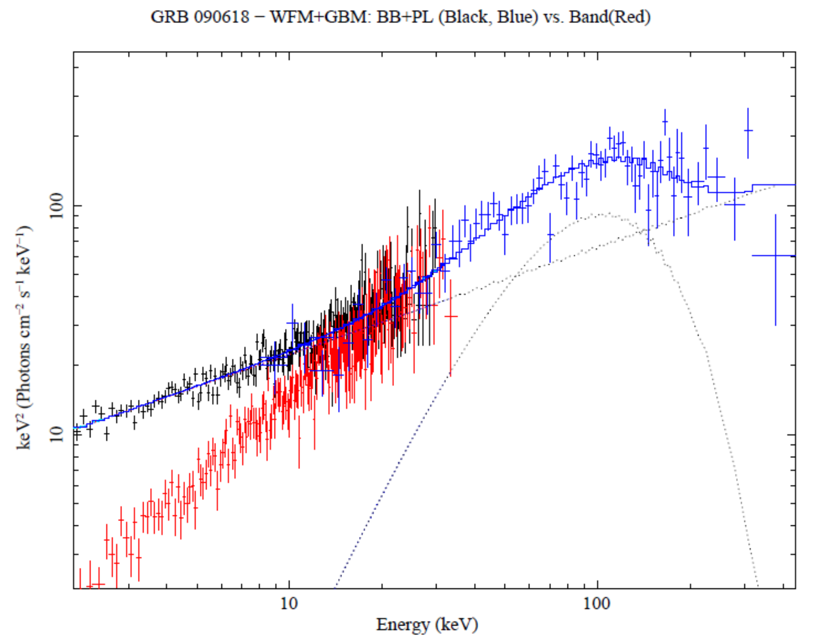
# e.g., Physics of GRBs and properties of circum-burst material

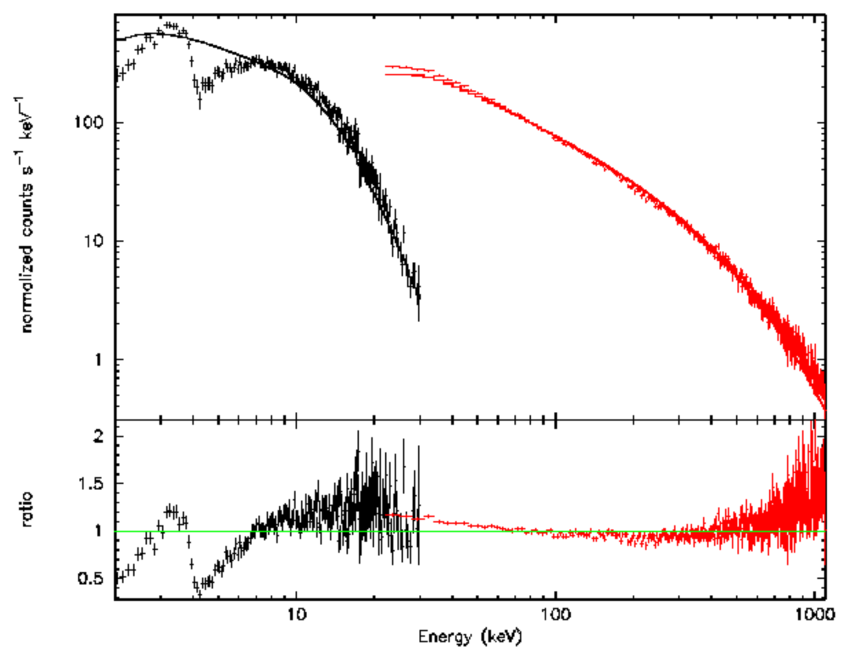
- It is recognized that the GRB phenomenon can be understood only going back to the study of the Prompt Emission

- **A very broad energy band down to soft X-rays is needed.**

- Measurements down to a few keV were provided in the past by BeppoSAX, but a higher sensitivity and energy resolution is urgently needed.

- Present GRB experiments are limited to prompt emission > ~10 keV; future (SVOM, CALET/GBM,UFFO,LOBSTER) > ~ 5 - 8 keV



# Conclusions

- Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~10 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**

- The high experience and level of the European GRB community (science, observations and technology) strongly pushes for an ESA-led GRB oriented mission: **THESEUS will fully exploit GRBs as powerful and unique tools to investigate the early universe and will provide us with unprecedented clues to GRB physics and sub-classes.**

- **THESEUS will be submitted to the ESA/M5 Call in spring 2016:** contributions are very welcome from everybody willing to help; about 200 researcher worldwide already provided their support to THESEUS) (contact: amati@iasfbo.inaf.it**;** support: *http://goo.gl/forms/PFUfgjqNxG*