Transient High Energy Sky and Early Universe Surveyor (THESEUS)

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on behalf of the THESEUS consortium

IX CONGRESSO NAZIONALE OGGETTI COMPATTI

Monte Porzio Catone 22-25 Settembre 2015

THESEUS

Transient High Energy Sources and Early Universe Surveyor

Lead Proposer: <u>Lorenzo Amati</u> (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, Denmark, Poland, Czech Republic, ESA (+ France, Hungary, Slovenia, Ireland)

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

THESEUS aims at vastly increasing the discovery space of the high energy transient phenomena over the entire cosmic history.

The primary scientific goals are linked to the Early Universe ESA Cosmic Vision theme:

How Did the Universe Originate and What is it Made of?

4.1 Early Universe

4.2 The Universe taking shape

4.3 The evolving violent Universe

GRBs within Cosmic Vision

- 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)

- In 2012, two European proposals for ESA Call for Small mission dedicated to GRBs and all-sky monitoring: **GAME** (led by Italy, SDD-based cameras + CZT-based camera + scintillator based detectors) and **A-STAR** (led by UK, lobster-eye telescopes + CdTe detectors)

- The **White Paper on GRBs** as probes of the early Universe submitted in response to ESA Call for science theme for next L2/L3 missions (Amati, Tanvir, et al., arXiv:1306.5259) was very well considered by ESA

- ATHENA (ESA/L2, 2028): very high spectral resolution spectroscopic observations of high redshift gamma-ray bursts (GRBs) to study metal enrichment in the early Universe

- **ESA/M4: THESEUS** (Early Universe through high-redshift GRBs + GRB physics, sub-classes, etc.), LOFT (M3 assessment study, GRBs as part of observatory science), GAMMA-LIGHT, XIPE, …

Italian leadership and contribution to THESEUS: motivation and heritage

- **BeppoSAX (Italy, +NL contribution)** : X-ray afterglow emission -> optical counterparts and host galaxies -> cosmological distance scale, GRB-SN connection, X-ray flashes, Ep- Eiso ("Amati") correlation -> cosmological parameters and dark energy

- HETE-2 (USA; Italian contribution): deeper investigation of X-ray flashes

- Swift (USA, Italian contribution): early afterglow phenomenology, sub-energetic GRBs, ultra-long GRBs, soft long tail of short GRBs

- AGILE (Italy): timing of prompt emission + X-ray detections

- Fermi (USA, Italian contribution): high energy emission, additional spectral features -> crucial tests for emission physics, engine (+ testing quantum gravity ?)

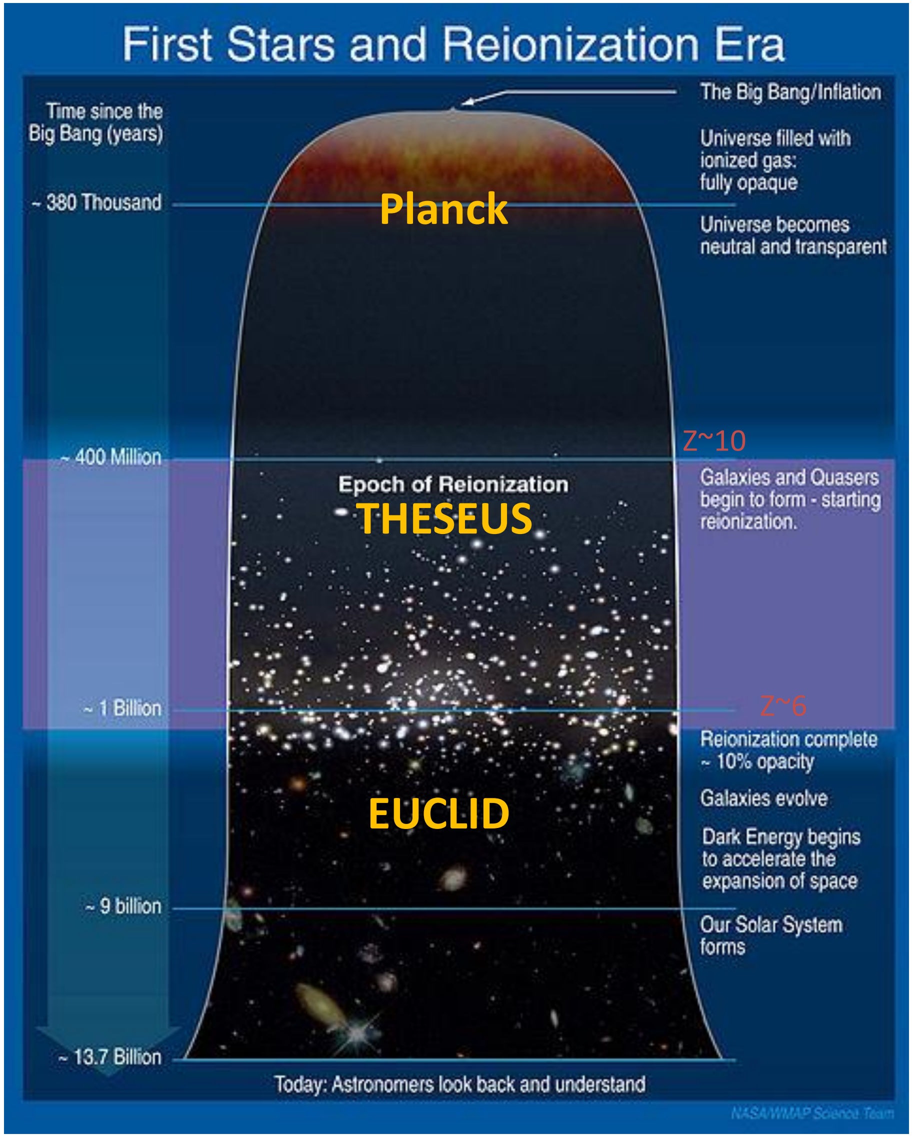
- Piship of large optical /NIR follow-up programmes (TNG, VLT, etc.)

Main scientific goals

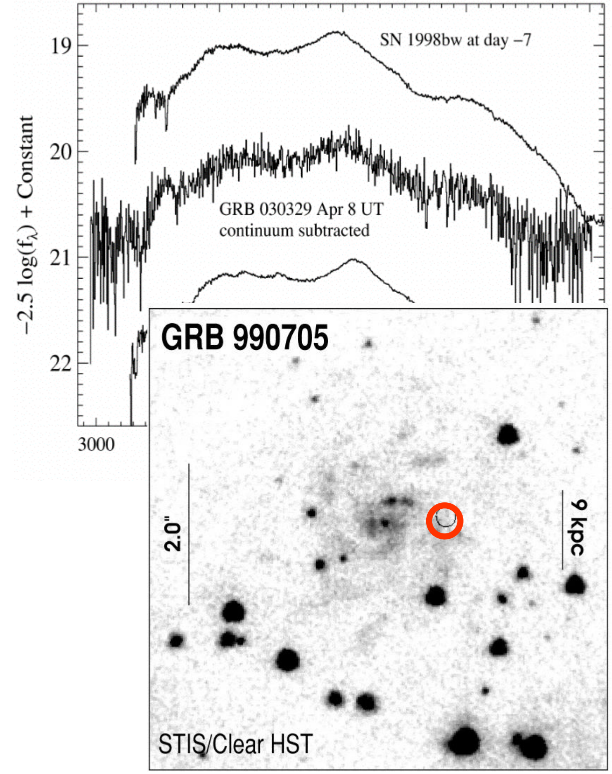
a) **Exploring the Early Universe (cosmic dawn and reionization era) by unveiling the Gamma-Ray Burst (GRBs) population in the first billion years**

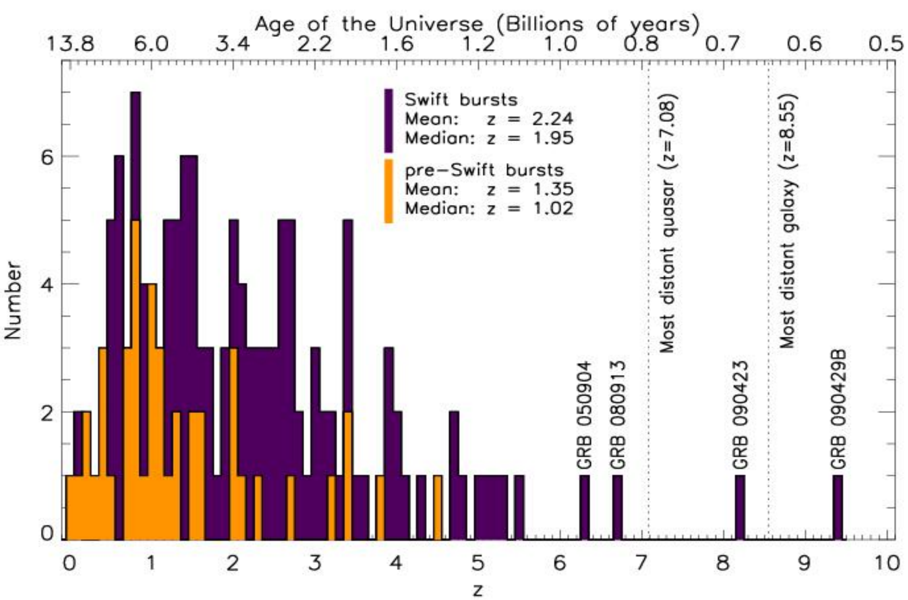
The study of the Universe before and during the epoch of reionization represents one of the major themes for the next generation of space and ground–based observational facilities. Many questions about the first phases of structure formation in the early Universe will still be open in the late 2020s:

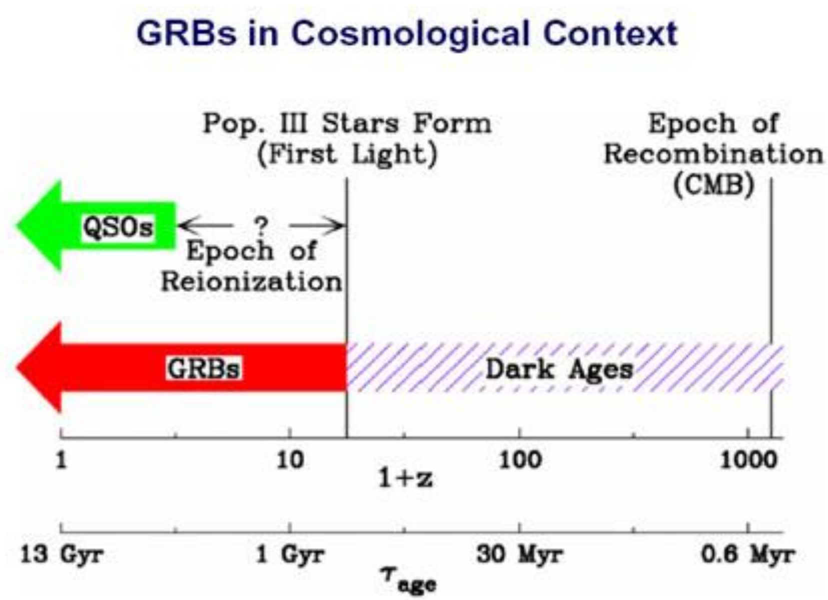
- *When and how did first stars/galaxies form?*
- *What are their properties? When and how fast was the Universe enriched with metals?*
- *How did reionization proceed?*



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**

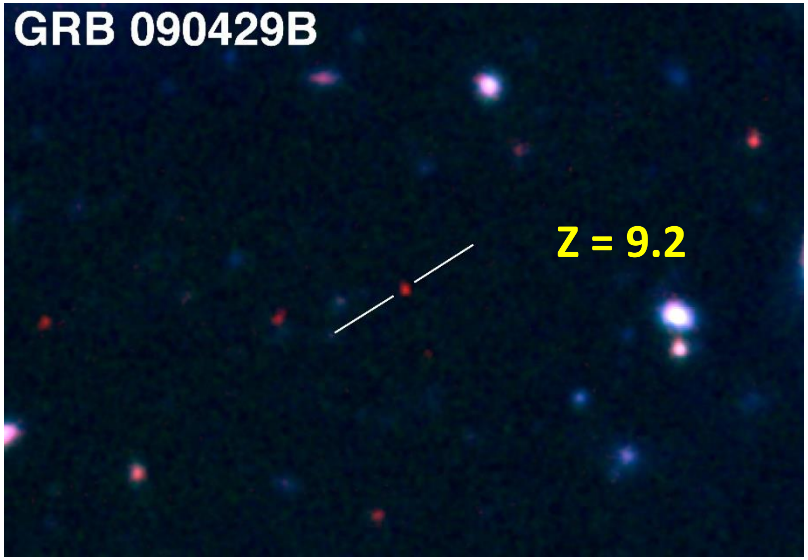


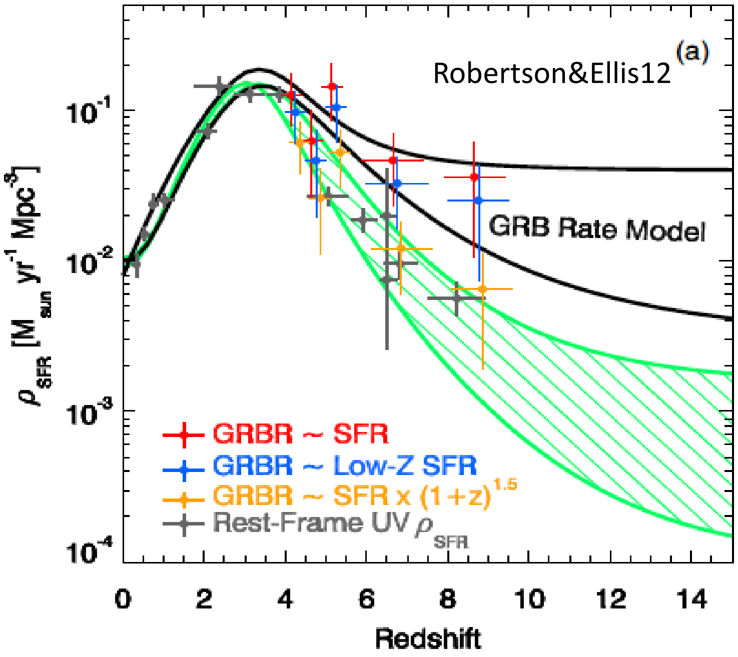




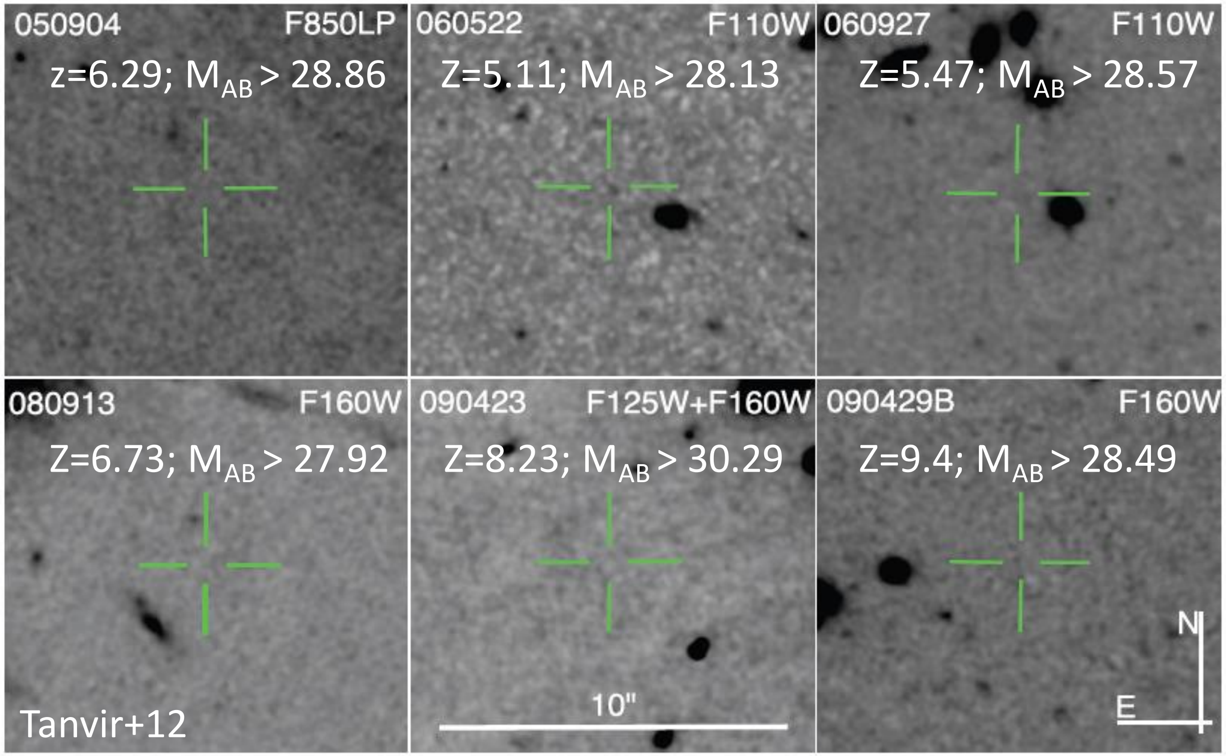
A statistical sample of high–z GRBs can provide fundamental information about:

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





- the number density and properties of low-mass galaxies

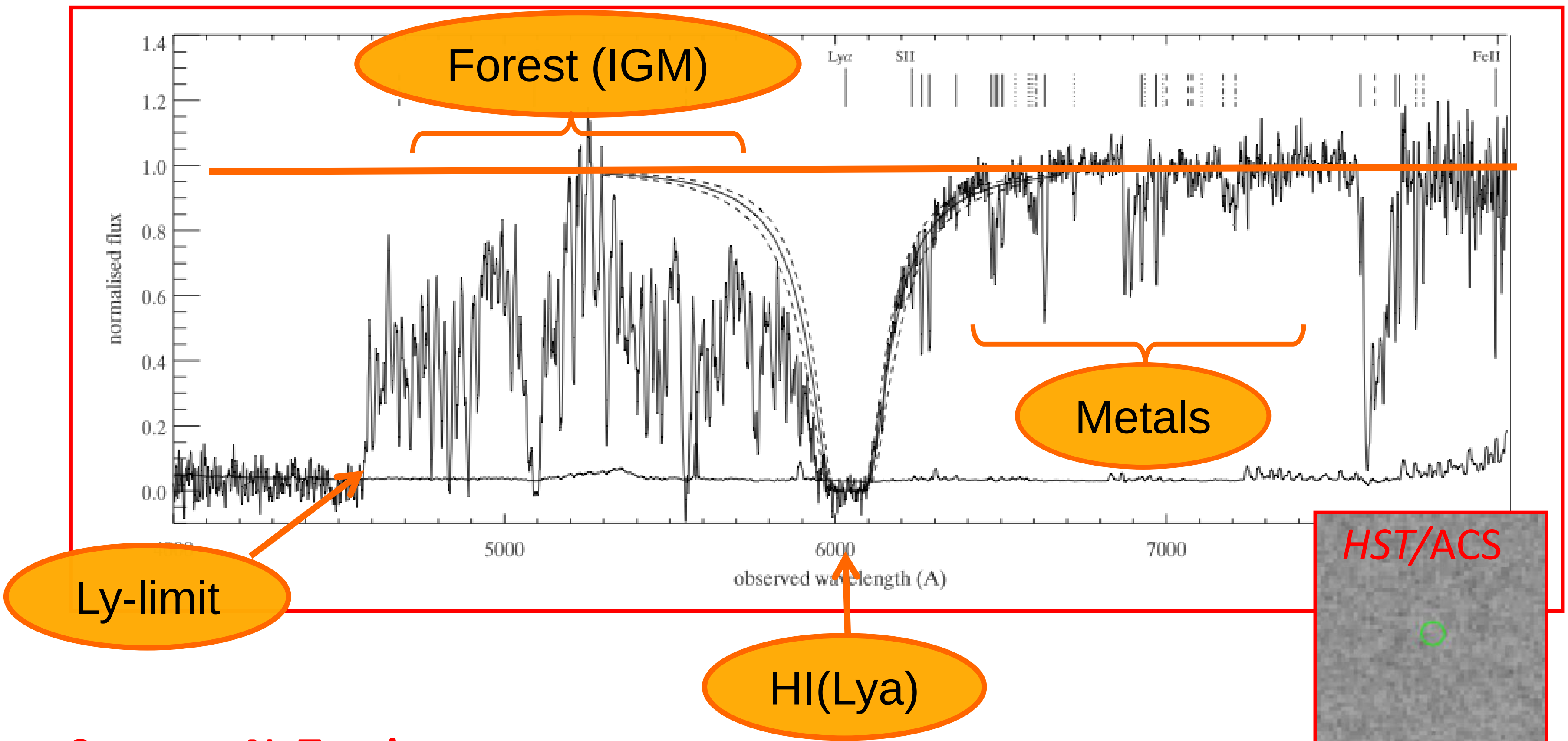


Robertson&Ellis12

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)

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

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).



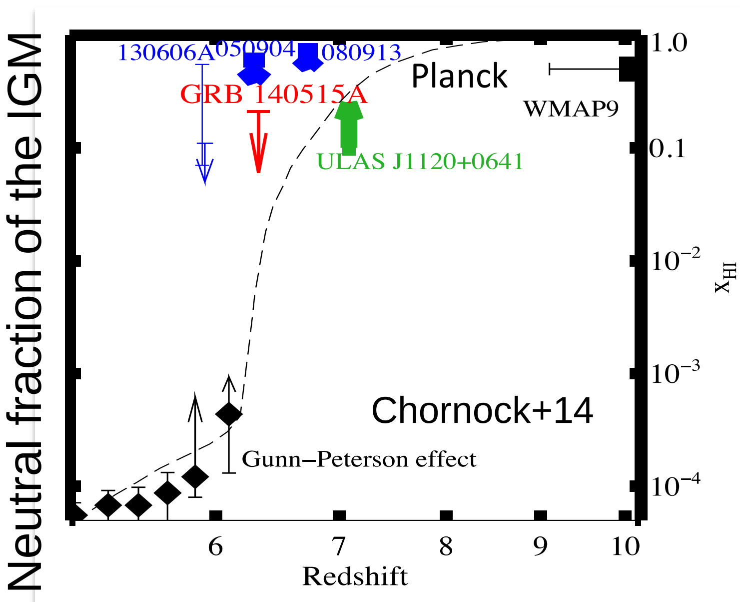
Courtesy N. Tanvir

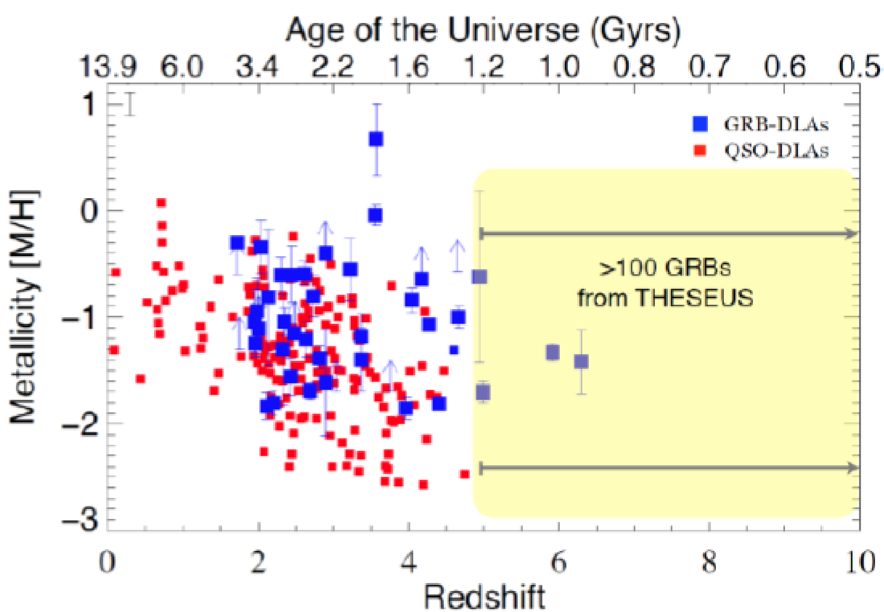
- the first generation of stars (pop III)

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 to the absorption features of PopII GRBs blowing out in a medium enriched by the first PopIII supernovae (Wang+12).

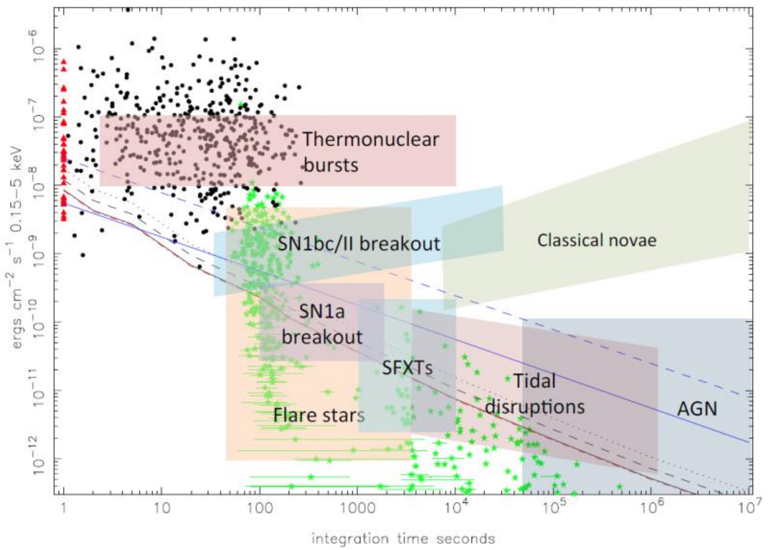
More generally, what is **the cosmic chemical evolution** at early times?





b) 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.**



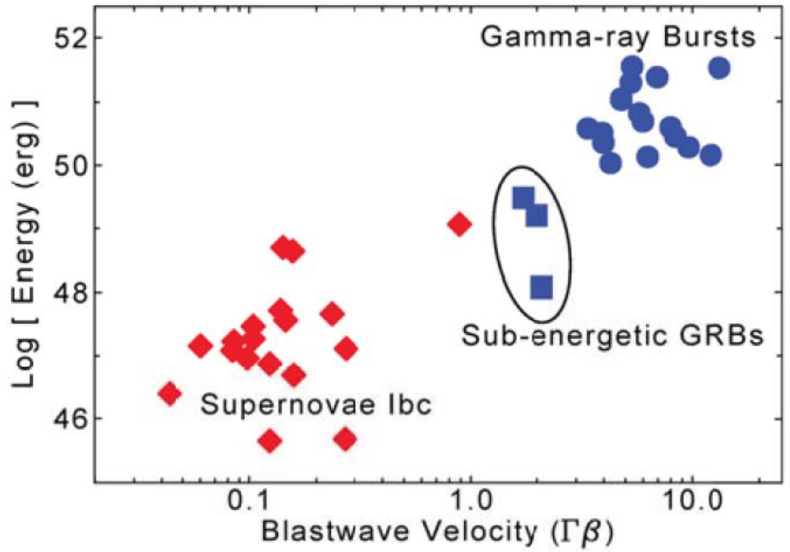
Transient type	SXI Rate
GW sources	0.03-33 yr^{-1}
Magnetars	40 day^{-1}
SN shock breakout	4 yr^{-1}
TDE	50 yr^{-1}
AGN+Blazars	350 day^{-1}
Thermonuclear bursts	35 day^{-1}
Novae	250 yr^{-1}
Dwarf novae	30 day^{-1}
SFXTs	1000 yr^{-1}
Stellar flares	400 yr^{-1}
Stellar super flares	200 yr^{-1}

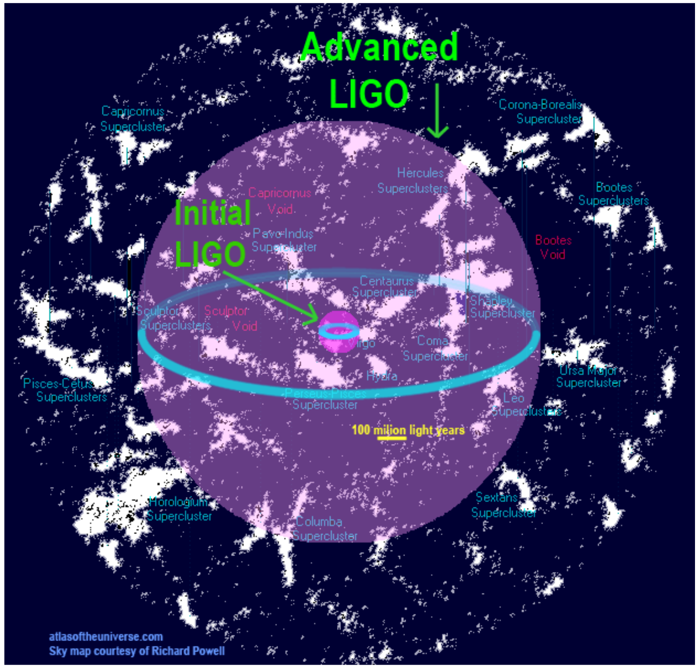
- unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse Sne;

- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;

- IR survey and guest observer possibilities, thus allowing a strong community involvement;

- **survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific sinergy can be anticipated.**





THESEUS Main Requirements

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

- 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)

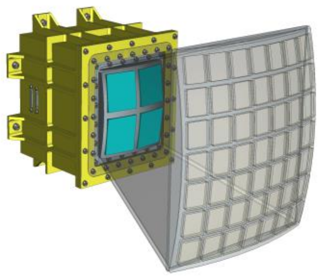
- In order to *identify, classify and study* the high-z GRB counterparts, an near-infrared (due to cosmological Ly-alpha suppression) telescope is needed on board. It will provide accurate positions, GRB redshifts, and GRB afterglows *spectra* (R~1000).

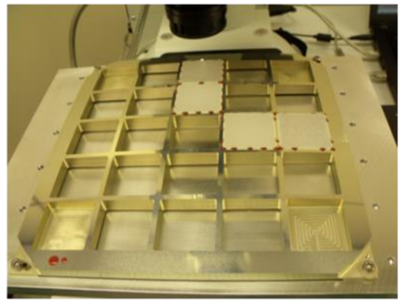
- An agile and autonomous platform (Swift-like) is required in order to point at the GRB position quickly, as well as a prompt downlink of GRB trigger, position and redshift

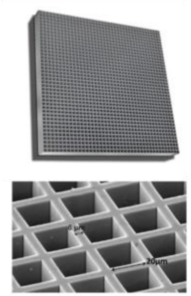
THESEUS payload

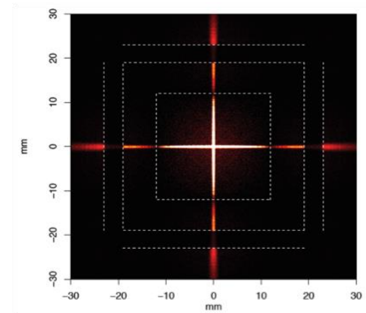
- **Soft X-ray Imager (SXI):** a set of « Lobster-Eye » X-ray (0.3 - 6 keV) telescopes covering a total FOV of 1 sr field with 0.5 – 1 arcmin source location accuracy, provided by a **UK** led consortium (+ **Czech Repubblic**)
- **InfraRed Telescope (IRT):** a 70 cm class near-infrared (up to 2 microns) telescope (IRT) with imaging and moderate spectral capabilities provided by a **Spanish** led consortium (+ **ESA, + Ireland ?**)
- **X-Gamma-rays 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 (+**USA ?**) (-> TECNO INAF 2014)
- **Payload Data Handling System (PDHS): Poland** led consortium (+ **Denmark, Finland**)

The Soft X-ray Imager (SXI)





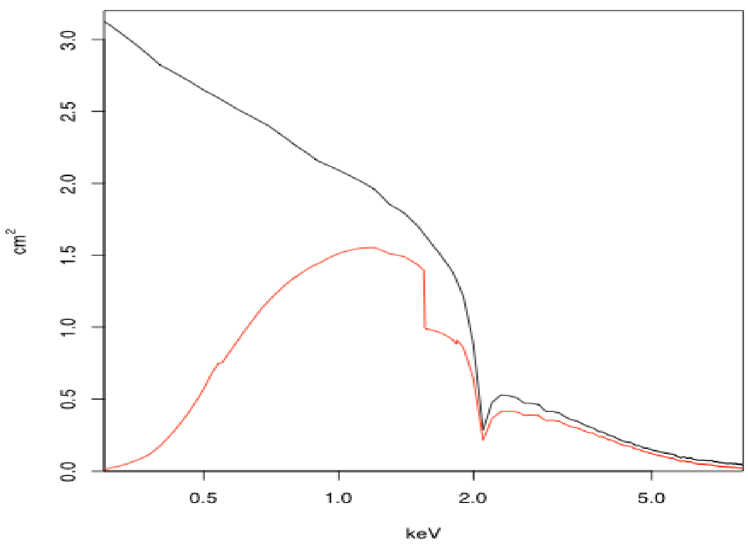


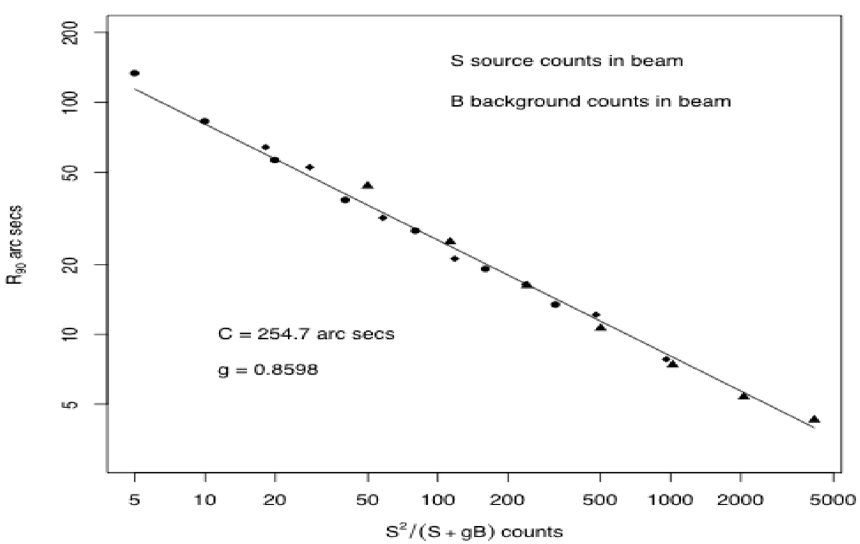


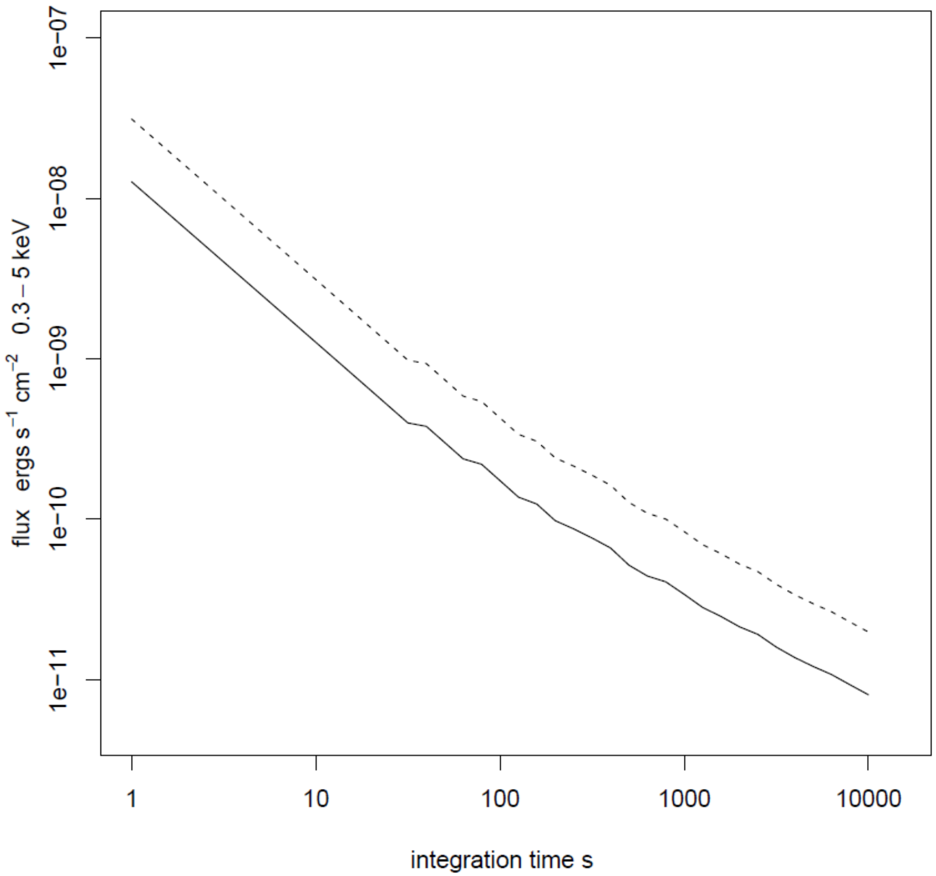
Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics aperture (mm^2)	290x290
Optics configuration	7x7 square pore MCPs
MCP size (mm^2)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD (mm^2)	61x61
Pixel size (μm)	30
Pixel Number	1024 x 1024
Number of CCDs	4
Field of View (square deg)	542.8
Angular accuracy (best, worst) (arcsec)	(<10, 105)

Table 3.1 – Specifications of each SXI module

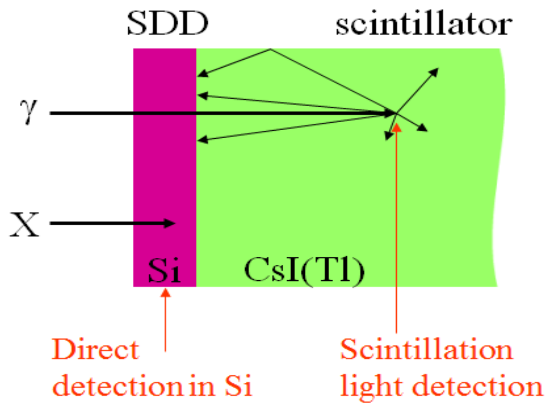
The Soft X-ray Imager (SXI)

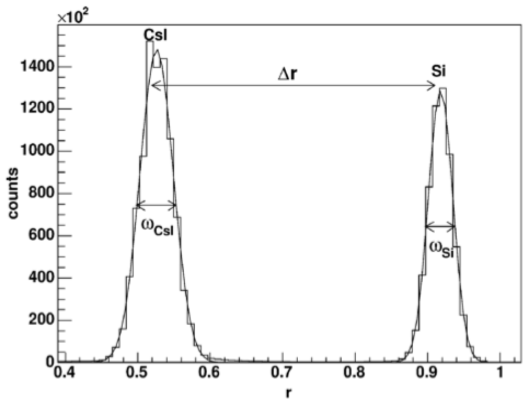


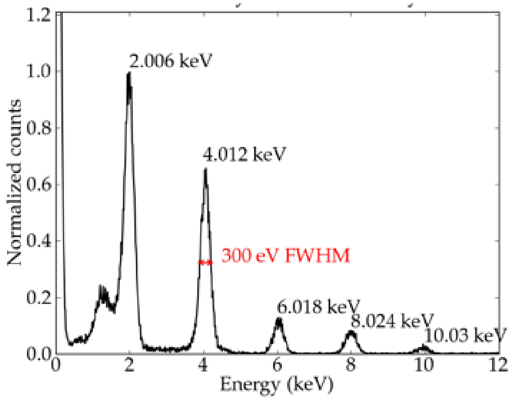


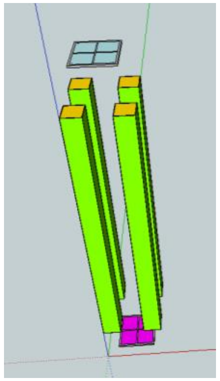


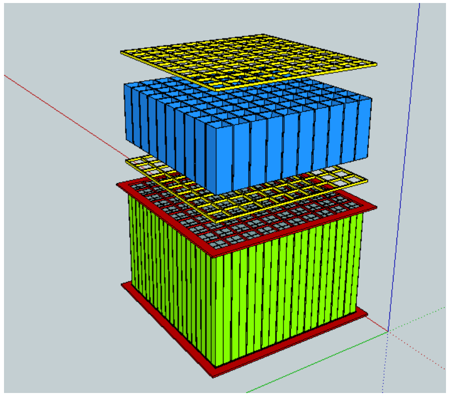
The X-Gamma-rays spectrometer (XGS)







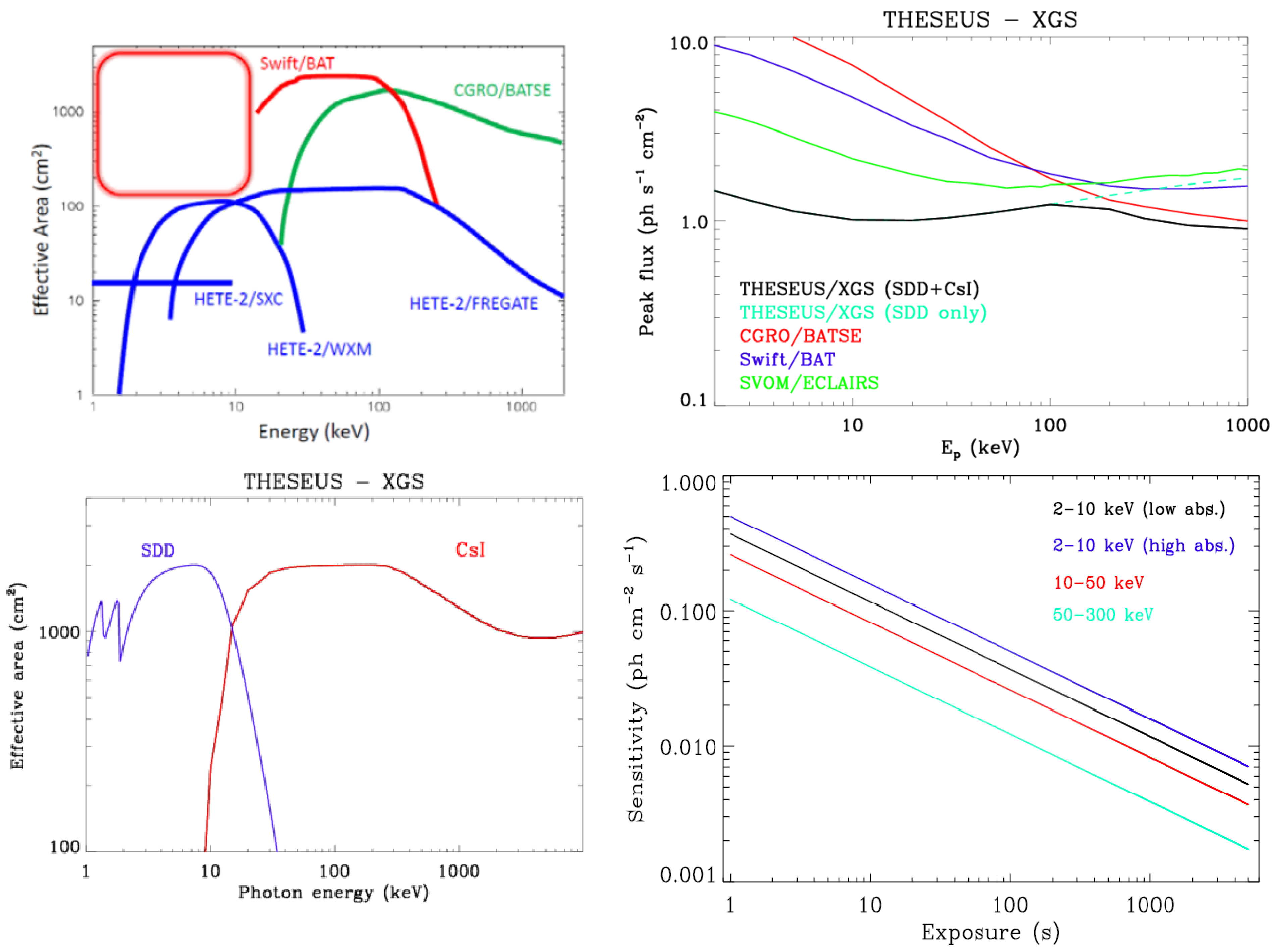




Energy band (keV)	2-20000
Detection principle	Siswitch
Low-energy detector	Silicon Drift Detector
High energy detector	CsI(Tl)
Separation of energy losses in Si and CsI(Tl)	Pulse shape analysis
Number of modules	25
Size of each module (mm^3)	130x130x100
Lateral passive shielding/module	0.5 mm W
Slat collimator/module	0.5 mm W
Overall collimator FOV (FWHM)	
Average useful area in the SXI FOV (cm^2)	~2000

Italian contribution: technological heritage

- **Scintillator-based detectors for high energy astrophysics:** BeppoSAX PDS & GRBM, INTEGRAL/PiCSIT, AGILE/MCAL (leading roles of IASF – Bologna) + R&D projects funded by ASI
- **SDD as detectors for high energy astrophysics and associated electronics (ASIC)**: R&D projects funded by INFN, ASI, INAF
- **Concept and earliest testing of SDD+CsI ("siswich")** (e.g., Marisaldi et al. 2005)
- **Concept studies of next generation GRB Monitors for future opportunities:** supported by ASI-INAF contract during 2006-2011 (p.i. L. Amati)
- **Innovation:** SDD+CsI detection system, ASIC
- **Development and testing of an XGS module prototype is supported by TECNO INAF 2014**



Swift/BAT
CGRO/BATSE
HETE-2/SXC
HETE-2/WXM
HETE-2/FREGATE
Effective Area (cm²)
Energy (keV)
1
10
100
1000
THESEUS – XGS
Peak flux (ph s⁻¹ cm⁻²)
10.0
1.0
0.1
THESEUS/XGS (SDD+CsI)
THESEUS/XGS (SDD only)
CGRO/BATSE
Swift/BAT
SVOM/ECLAIRS
Ep (keV)
THESEUS – XGS
SDD
CsI
Effective area (cm²)
Photon energy (keV)
2–10 keV (low abs.)
2–10 keV (high abs.)
10–50 keV
50–300 keV
Sensitivity (ph cm⁻² s⁻¹)
1.000
0.100
0.010
0.001
Exposure (s)

	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)	140cm^2	1 arcmin	ended
HETE-2/WXM	2–25 keV	0.8 sr	1.7 keV (6 keV)	350cm^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 ?

Table 2: Characteristics of the THESEUS X/gamma-ray instruments compared with the main past and present GRB–dedicated instruments (CGRO/BATSE, Swift, Fermi/GBM, Konus–WIND), the two main instruments 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).

+ Infrared telescope and fast slewing !!!

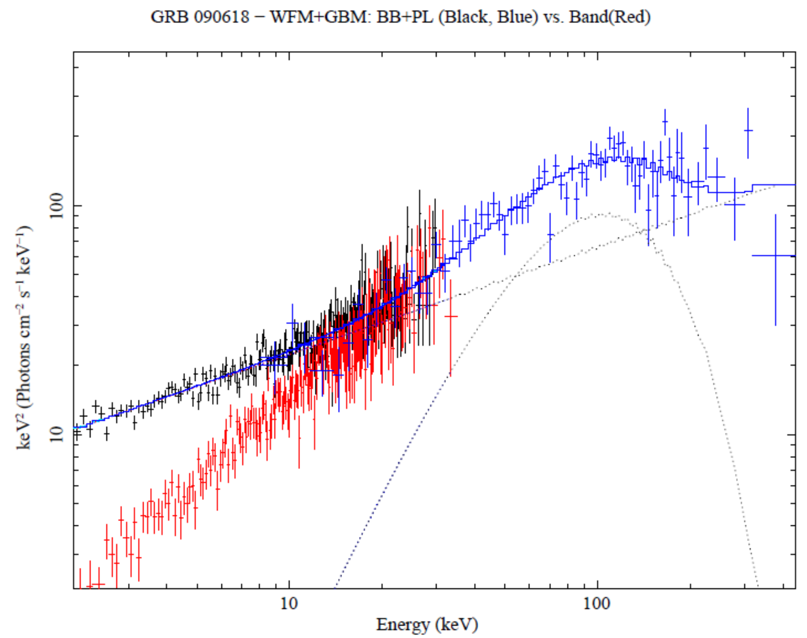
❑ Physics of GRBs and other high-energy transients

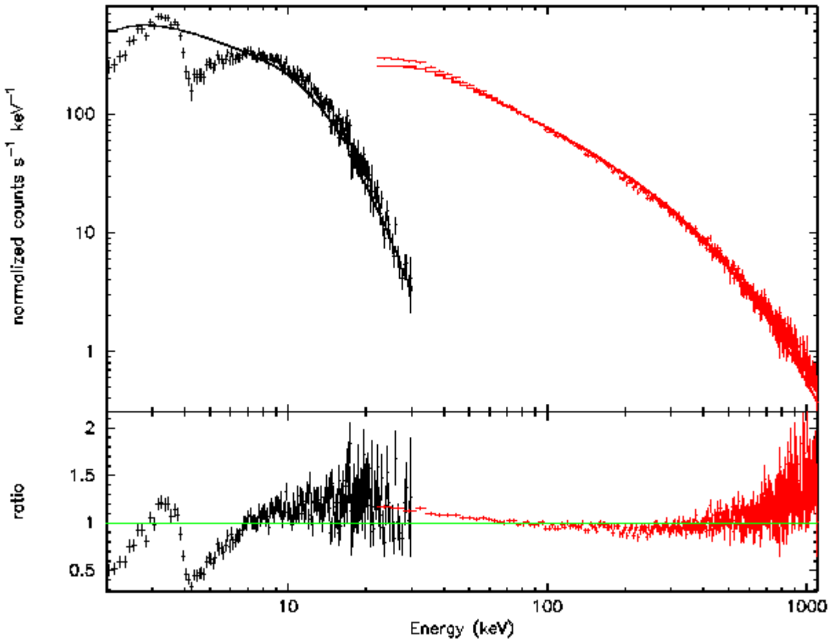
❑ It is recognized that the GRB phenomenon can be understood only going back to the study of the Prompt Emission

❑ **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





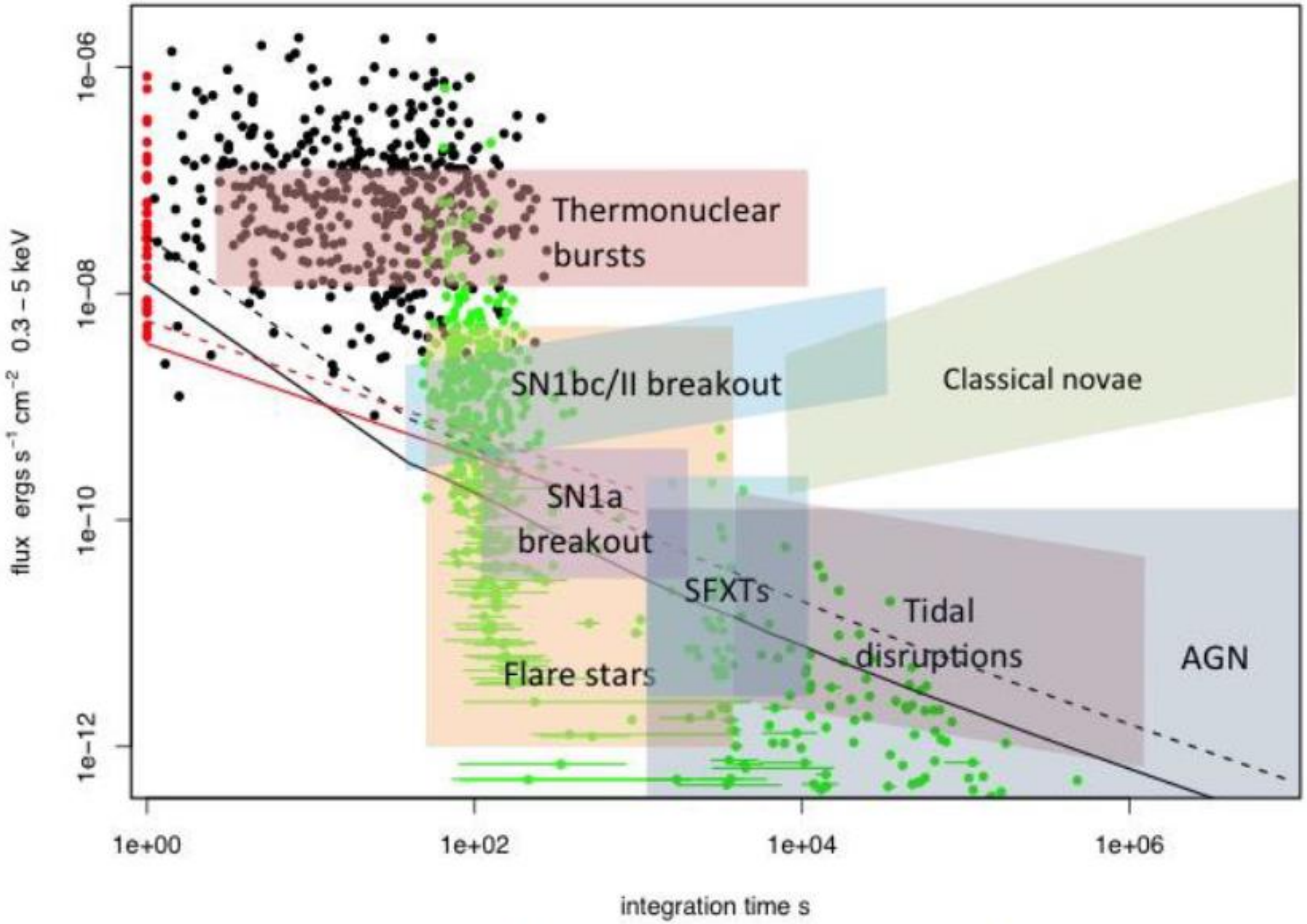
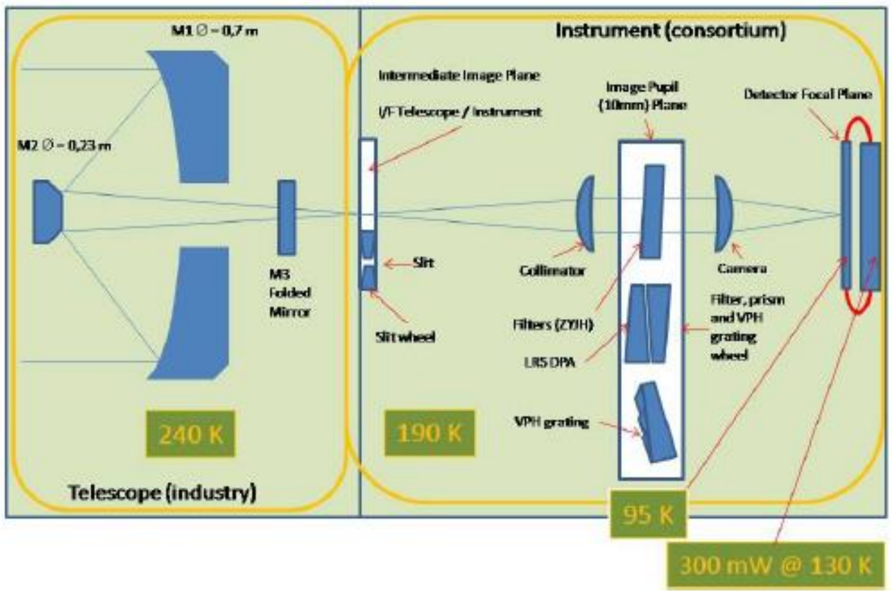
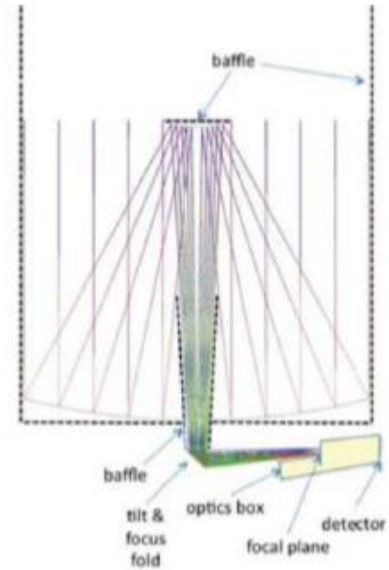


Figure 2.4: Sensitivity of the SXI (black curves) and XGS (red) vs. integration time. The solid curves assume a source column density of 5×10^{20} cm^{-2} (i.e. well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 10^{22} cm^{-2} (significant 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.

The InfraRed Telescope (IRT)





Telescope type:	Cassegrain		
Primary & Secondary size:	700 mm & 230 mm		
Material:	SiC (for both optics and optical tube assembly)		
Detector type:	Teledyne Hawaii-2RG 2048 x 2048 pixels (18 µm each)		
Imaging plate scale	0".3/pixel		
Field of view:	10' x 10'	6' x 6'	2".1 x 2".1
Resolution ($\lambda/\Delta\lambda$):	2-3 (imaging)	20 (low-res)	1700 (high-res) with 0".4 slit
Sensitivity (AB mag):	H = 22.5 (30s)	H = 20.8 (300s)	H = 19.3 (1800s)
Filters:	ZYJH	Prism	VPH grating
Wavelength range (µm):	0.7-1.8 (imaging)	0.7-1.8 (low-res)	0.7-1.8 (high-res)
Total envelope size (mm):	800 Ø x 1800		
Power (W):	95		
Mass (kg):	112.6		

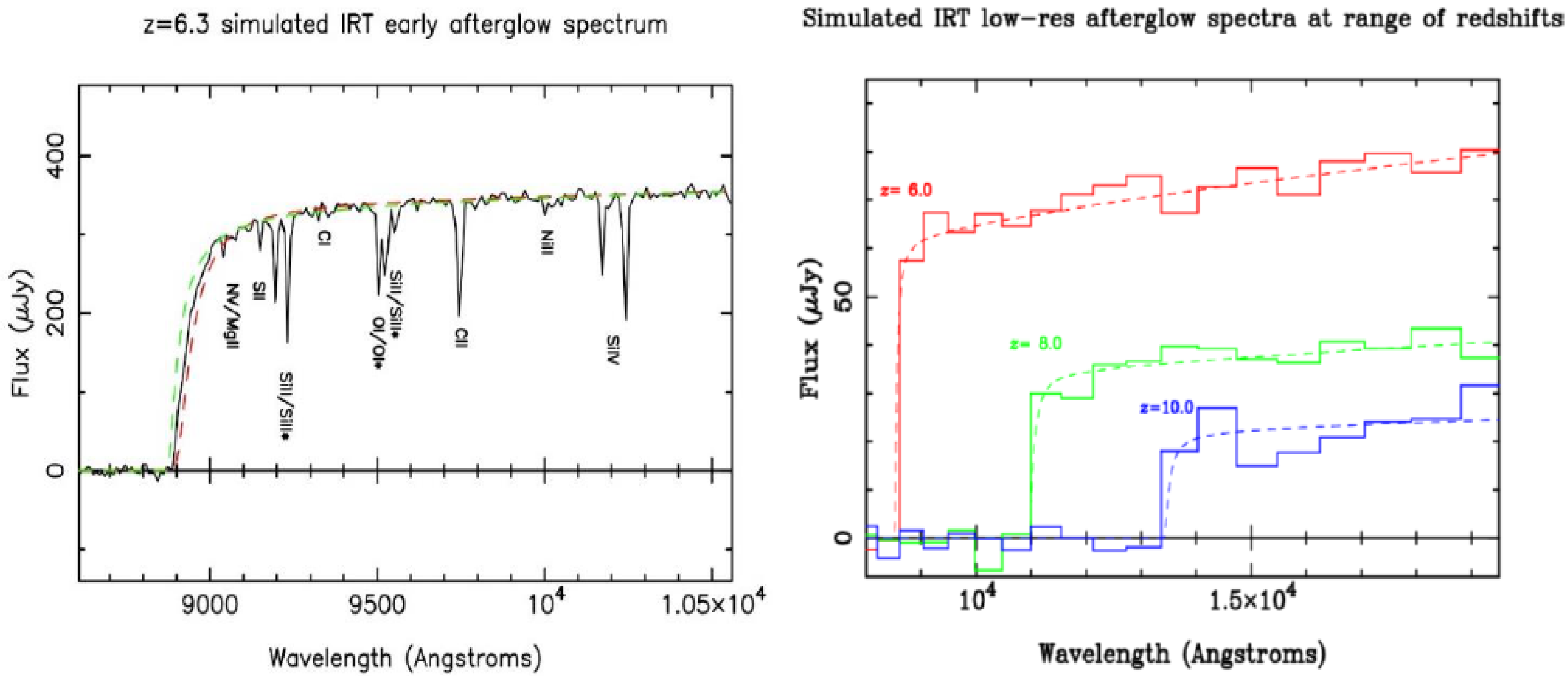


Figure 2.6 – Left: a simulated IRT high resolution (R=1000) spectrum for a GRB at z=6.3 observed at 1 hour post trigger assuming a GRB similar to GRB 050903. The black spectrum has host log(NH)=21 and neutral fraction Fx=0.5 (and metallicity 0.1solar). The two models are: Red: log(NH)=21.3, Fx=0 Green: 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.

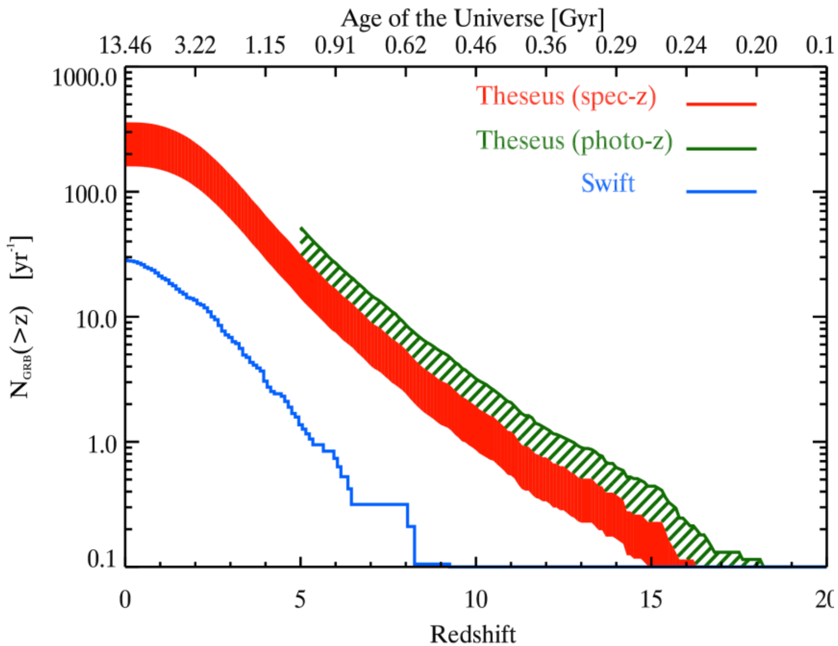
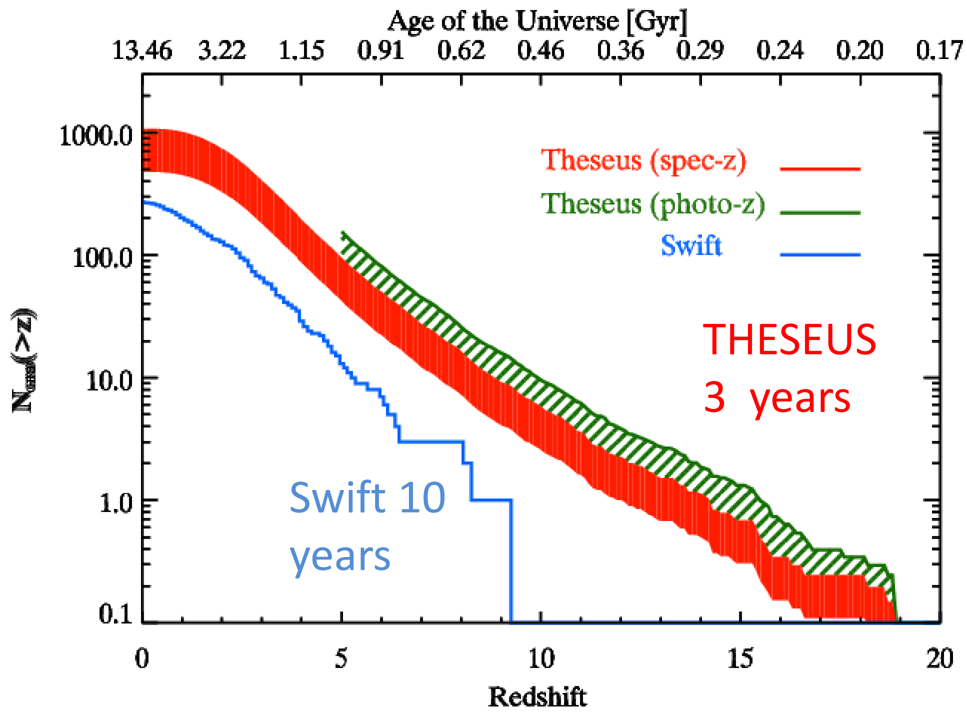


Figure 1. Rate of redshift measurement by Theseus. The solid filled (red) region repres
the rate of bursts as a function of redshift (cumulative distribution as in Fig.1) that wil



	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

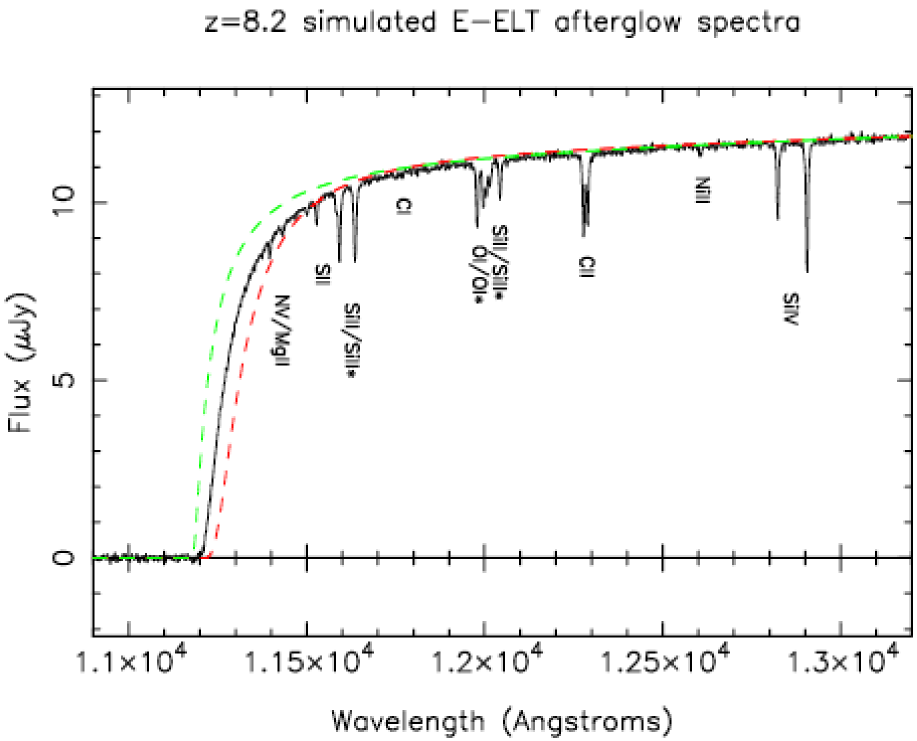


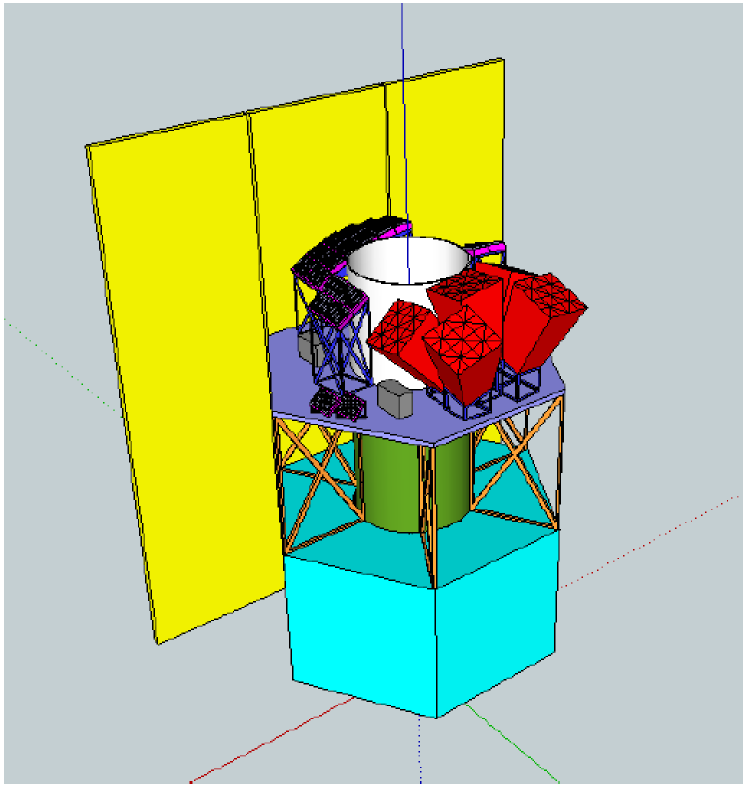
Fig. 1.4: simulated E-ELT 30 min spectrum of a faint GRB afterglow observed after ~1 day. The S/N provides exquisite abundance determinations while fitting the Ly-a damping wing simultaneously fixes the IGM neutral fraction and the host HI column density, as illustrated by the two extreme models, a pure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

N. Tanvir

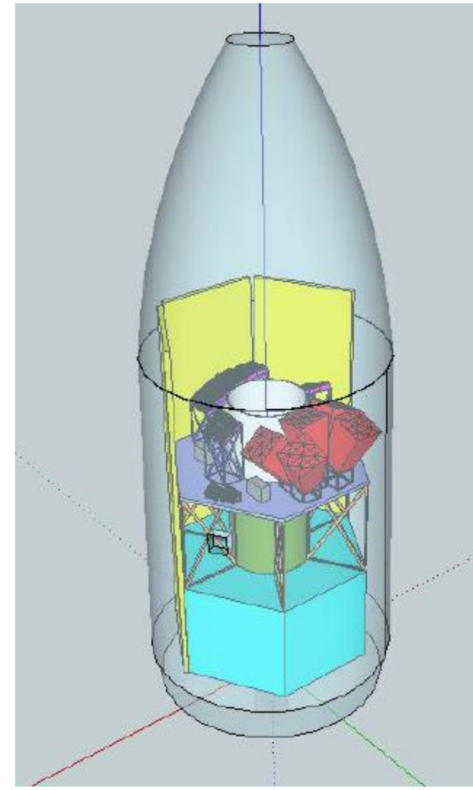
Payload accomodation and budgets

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

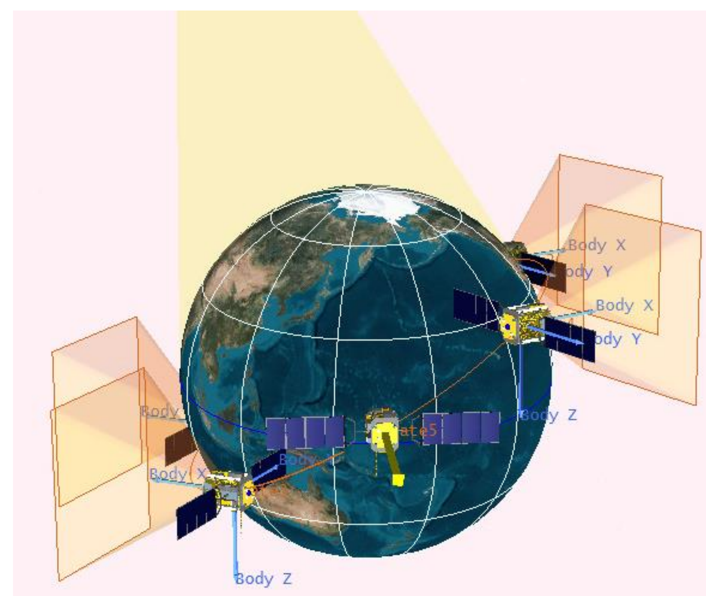
Total Service Module Mass (kg)	481.1
Total Payload Module Mass (kg)	349.3
System level margin (20%)	166.1
Dry Mass at launch (kg)	996.5
Propellant	16.0
Launcher adapter	77.0
Total mass at launch (kg)	1089.5



Mission profile



- Launch with VEGA into LEO (< 5°, ~600 km)
- **Spacecraft slewing capabilities (30° < 4 min)**
- Pointing anti-sun + ~polar
- Malindi antenna (+ Alcantara ?)
- **Prompt downlink options : NASA/TDRSS, ESA/EDRS, WHF network, IRIDIUM network, ORBCOMM**
- MOC, SOC -> ESA
- SDC -> ASDC (+FSC)



Conclusions

- The relevance of GRB science for several fields of astrophysics, for cosmology, for the large observational facilities of the 2020s (EELT, SKA, JWST, LSST, ATHENA, CTA, gravitational waves and neutrino detectors) and the high experience and level of the European GRB community (science, observations and technology) strongly push 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 also vastly increase the discovery space of the high energy transient phenomena over the entire cosmic history.**

- The THESEUS proposal for ESA is a unique occasion for the worldwide **GRB and time-domain astronomy community and for, for Italy, of exploiting the unique technological and scientific heritage in GRB / transients field**

- **THESEUS will be submitted to M5 (December 2015 ?), th consortium is re-organizing and the proposal being significantly improved. Please, provide your support through the web page: *http://goo.gl/forms/PFUfgjqNxG* or contact amati@iasfbo.inaf.it**