THESEUS

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

Lorenzo Amati

(INAF – IASF Bologna)

on behalf of the THESEUS international collaboration

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

15th **AGILE** Science Workshop

AGILE is 10

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THESEUS
Transient High Energy Sky and Early Universe Surveyor

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

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

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

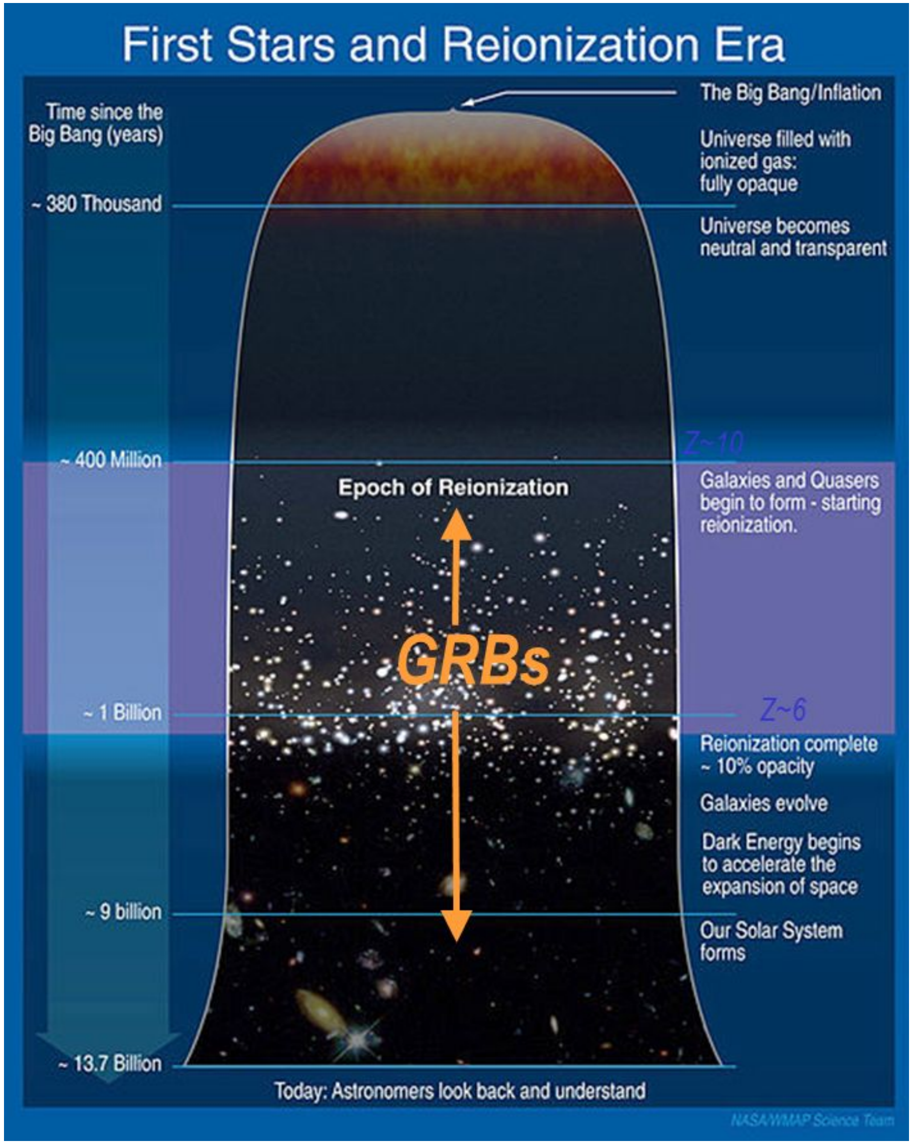
Interested international partners: USA, China, Brazil

THESEUS: 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?*



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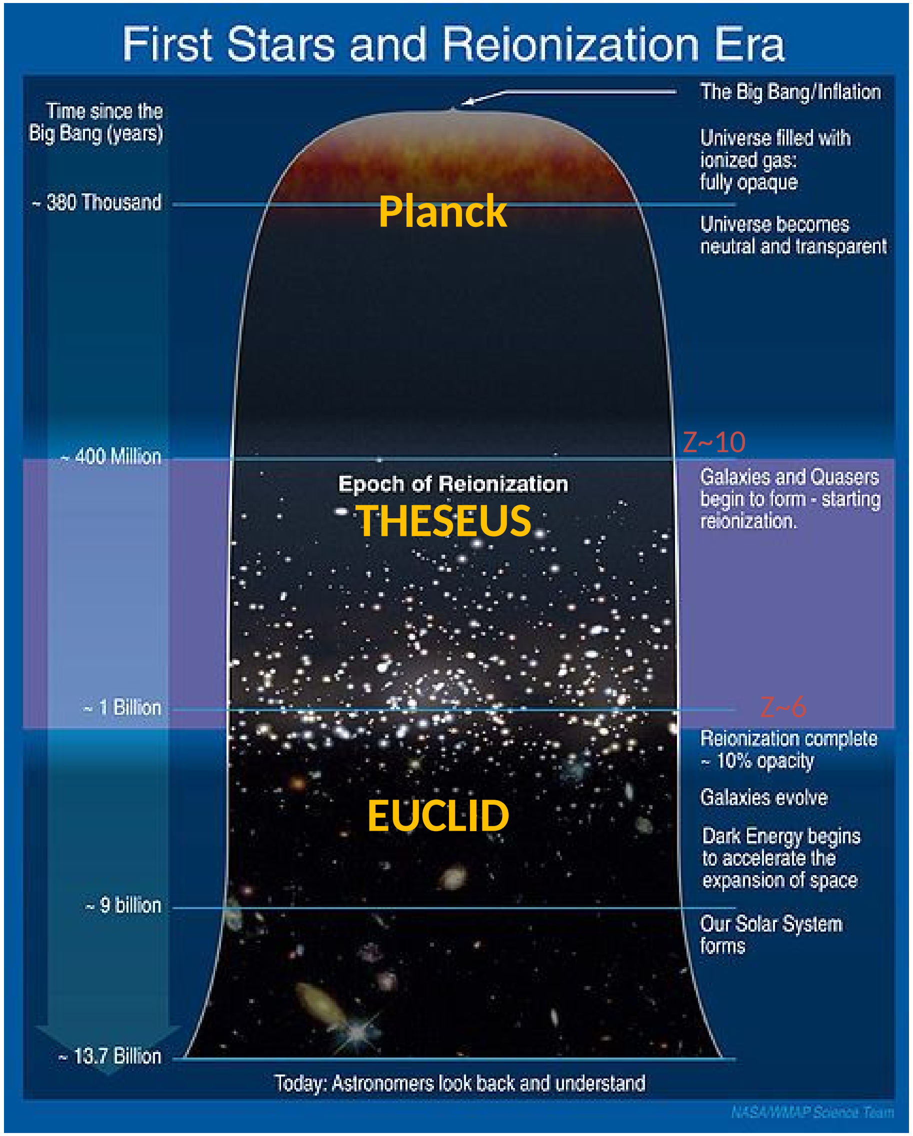
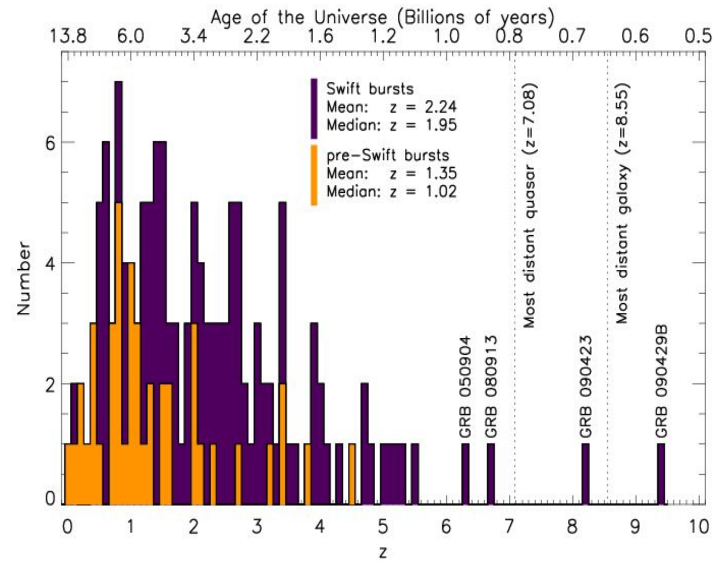
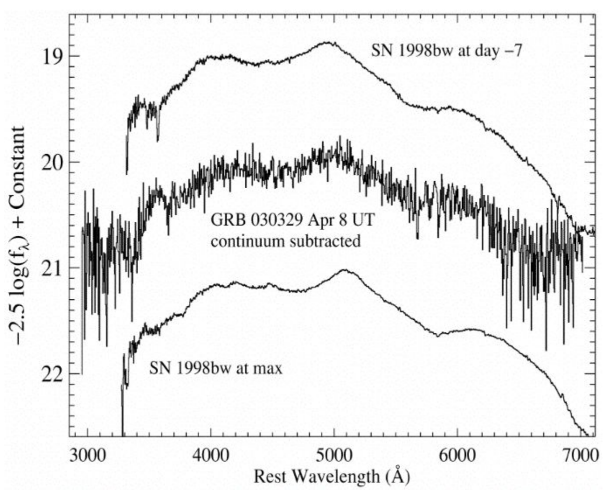
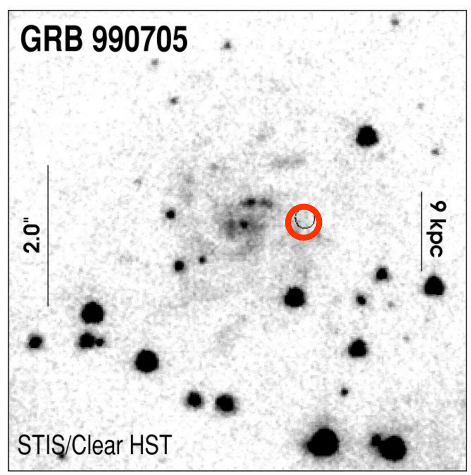


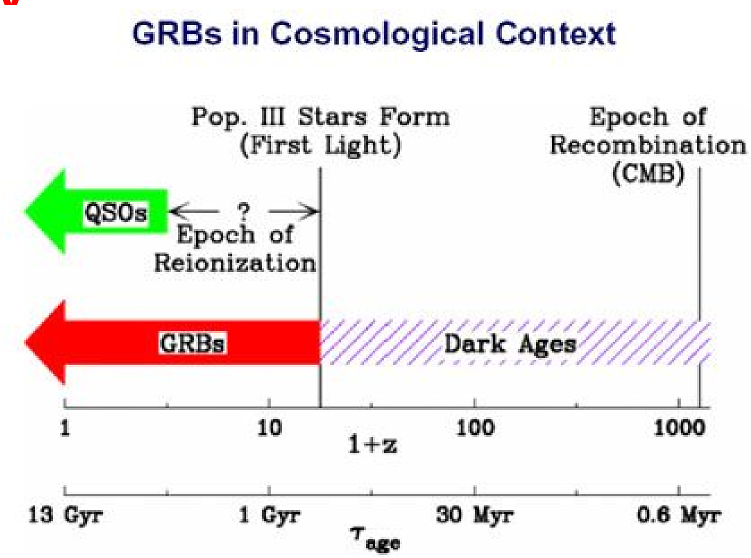
Shedding light on the early Universe with GRBs

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 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**







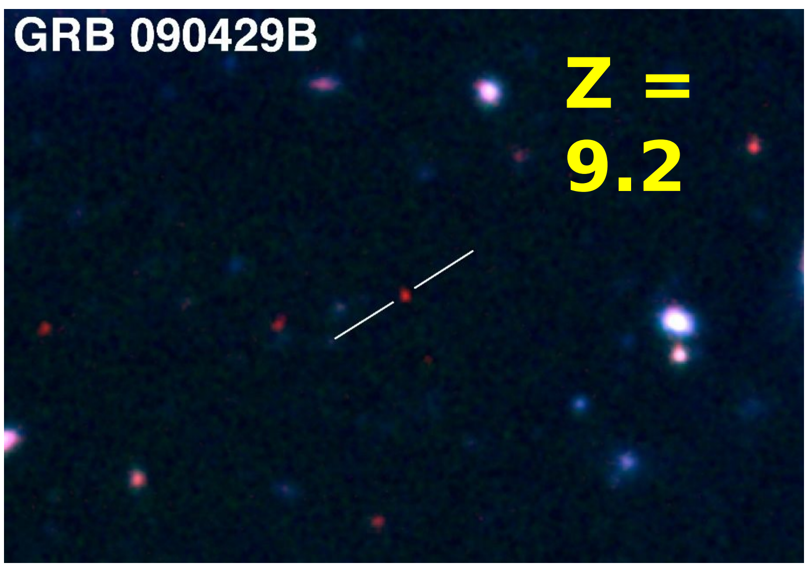


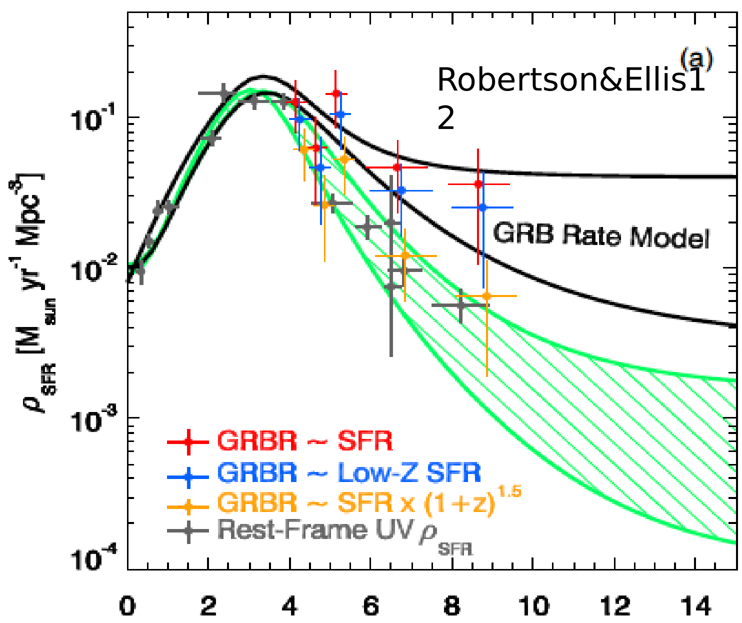
Lamb and Reichart (2000)

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

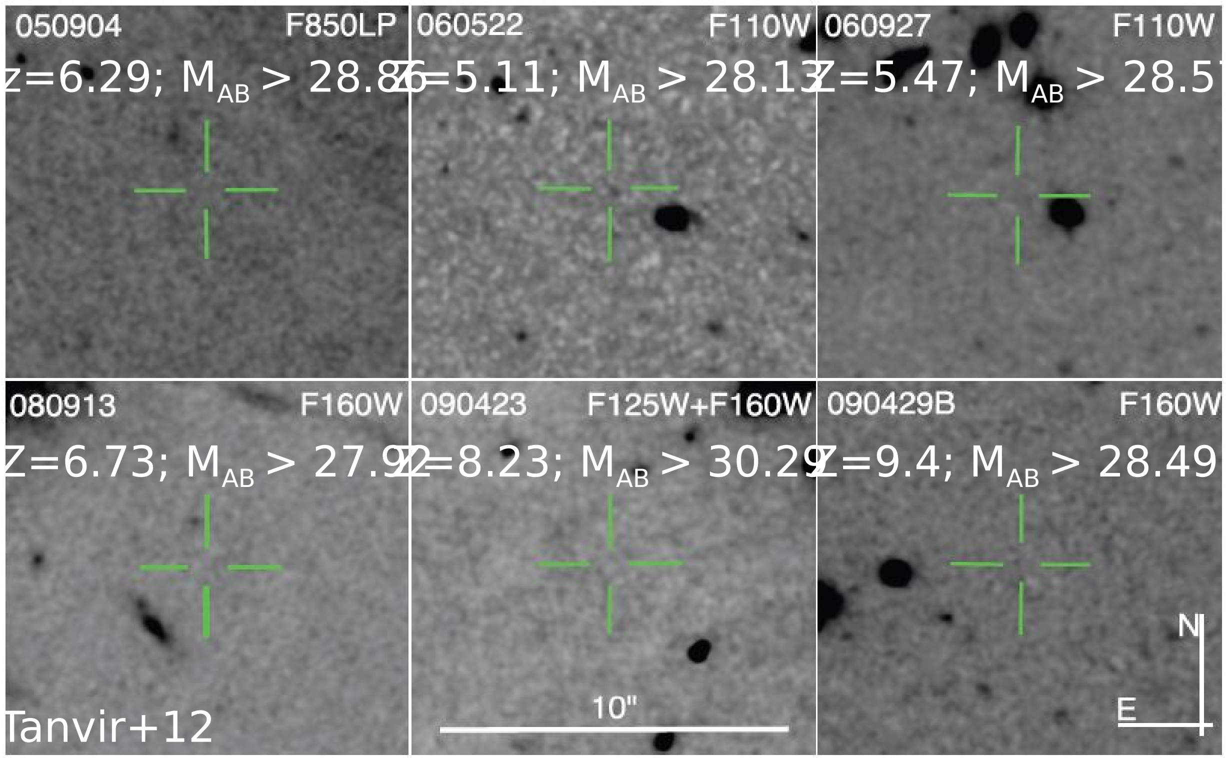
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

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





- the number density and properties of low-mass galaxies

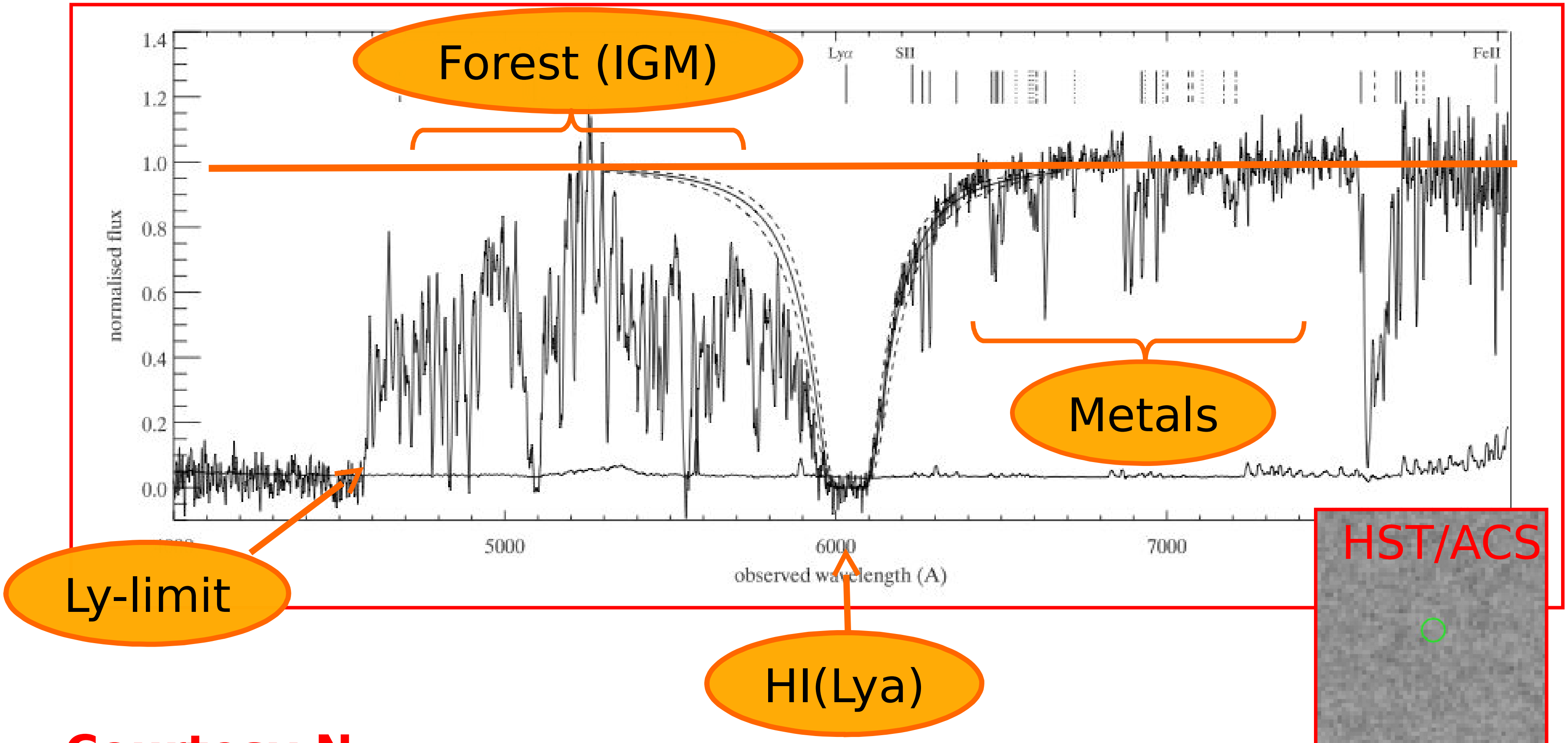


Robertson&Ellis12

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

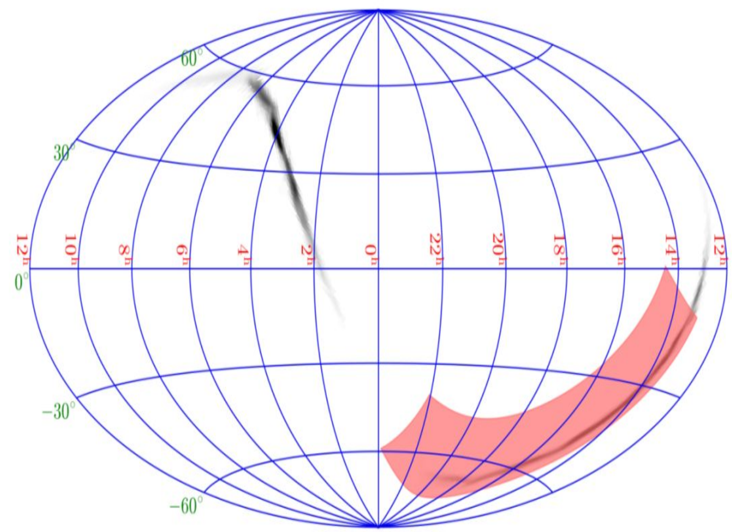
Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).



Courtesy N.

B) Perform an unprecedented deep monitoring of the soft X-ray transient Universe in order to:

- ❑ **Locate and identify the electromagnetic counterparts to sources of gravitational radiation and neutrinos, which may be routinely detected in the late '20s / early '30s by next generation facilities like aLIGO/aVirgo, eLISA, ET, or Km3NET;**



- ❑ Provide real-time triggers and accurate (~1 arcmin within a few seconds; ~1'' within a few minutes) **high-energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; synergy with LSST**

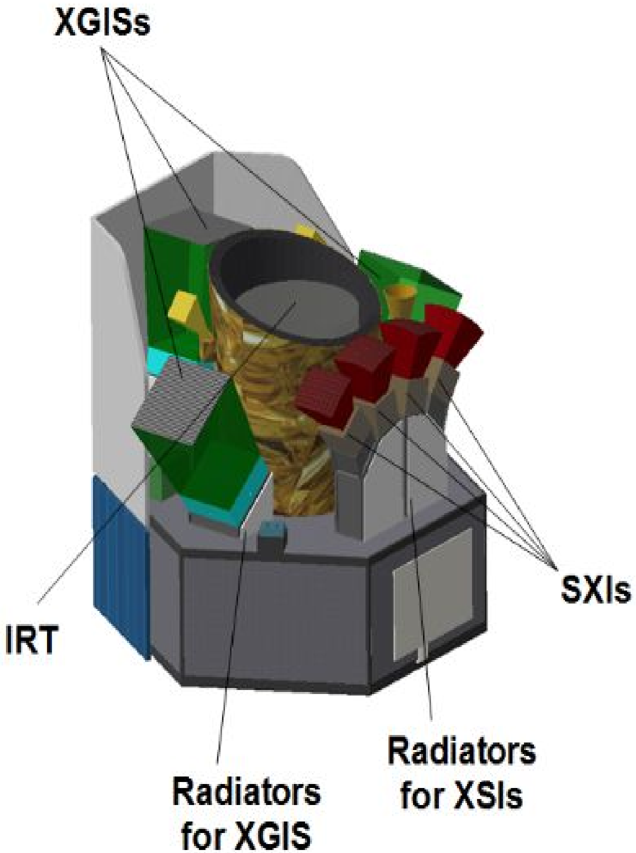
- ❑ Provide a fundamental step forward in the comprehension of the physics of various classes of transients and **fill the present gap in the discovery space of new classes of transients events**

Transient type	SXI Rate
GW sources	0.03-33 yr^{-1}
SN shock breakout	4 yr^{-1}
Tidal Disruptions Events	50 yr^{-1}
Thermonuclear bursts	35 day^{-1}
Novae	250 yr^{-1}
Dwarf novae	30 day^{-1}
Stellar flares	400 yr^{-1}
Stellar super flares	200 yr^{-1}

probe GRB physics

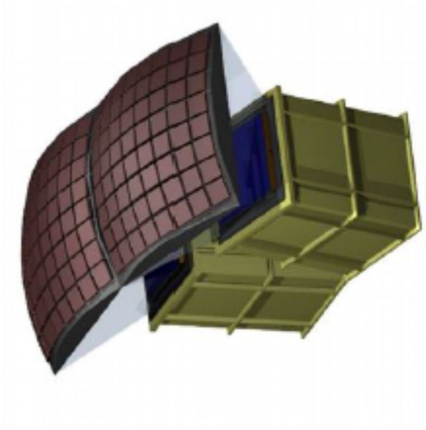
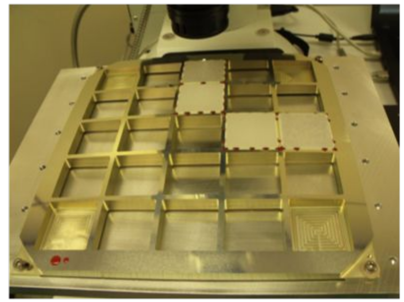
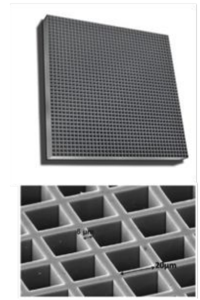
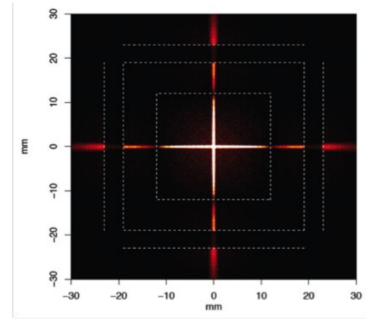
THESEUS payload

- **Soft X-ray Imager (SXI):** a set of four sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~1sr with source location accuracy < 1-2';
- **X-Gamma rays Imaging Spectrometer (XGIS,)**: 3 coded-mask X-gamma ray cameras using bars of Silicon diodes coupled with CsI crystal scintillators observing in 2 keV – 10 MeV band, a FOV of ~1sr, overlapping the SXI, with ~5' source location accuracy;
- **InfraRed Telescope (IRT)**: a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 10'x10' FOV, with both imaging and moderate resolution spectroscopy capabilities



LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink

The Soft X-ray Imager (SXI)


4 DUs, each has a 31 x 26 degree FoV

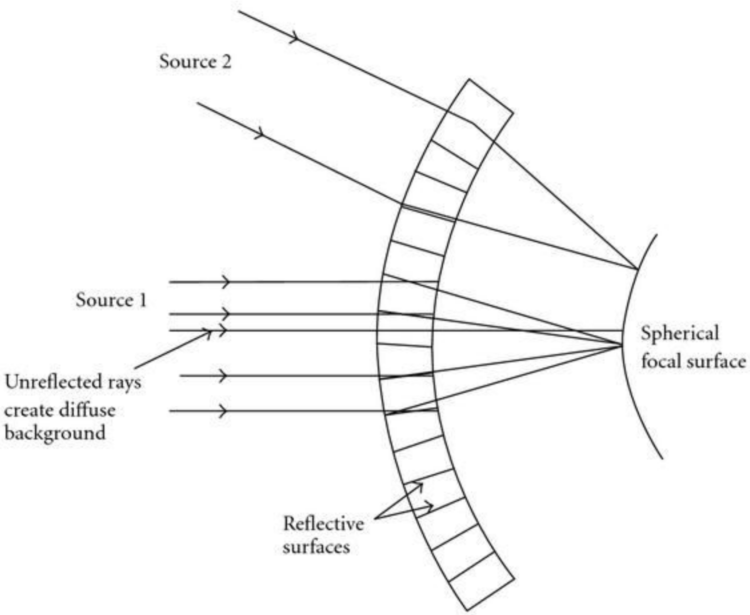
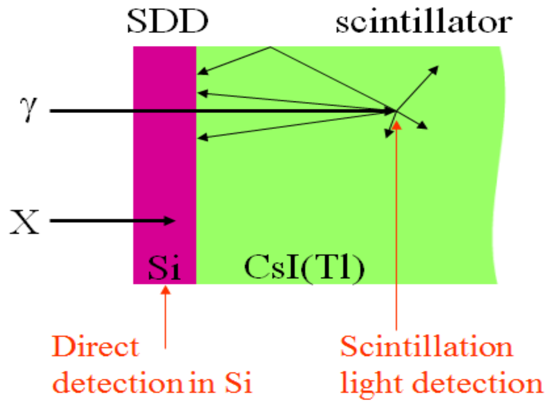
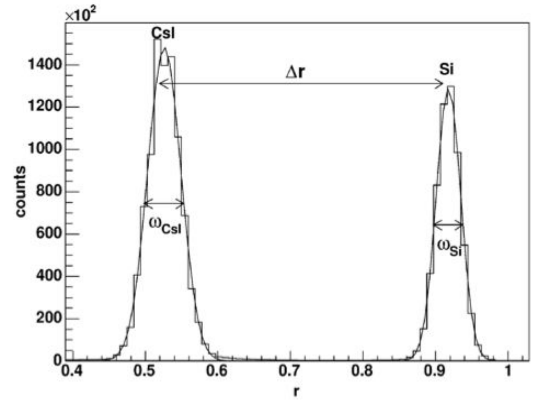


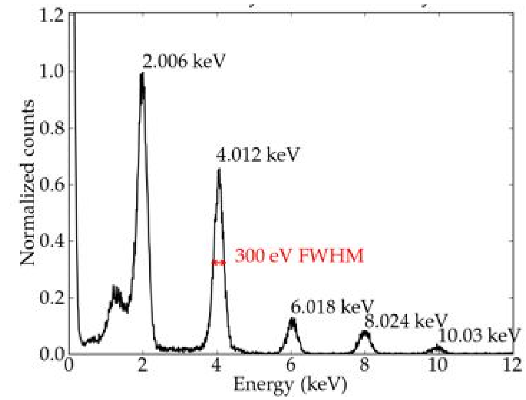
Table 4 : : SXI detector unit main physical characteristics

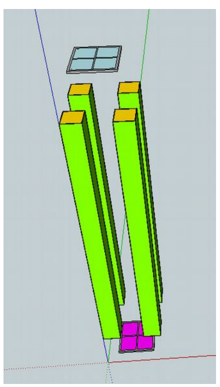
Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics aperture (mm2)	320x320
Optics configuration	8x8 square pore MCPs
MCP size (mm2)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD (mm2)	81.2x67.7
Pixel size (µm)	18
Pixel Number	4510 x 3758 per CCD
Number of CCDs	4
Field of View (square deg)	~1sr
Angular accuracy (best, worst) (arcsec)	(<10, 105)
Power [W]	27,8
Mass [kg]	40

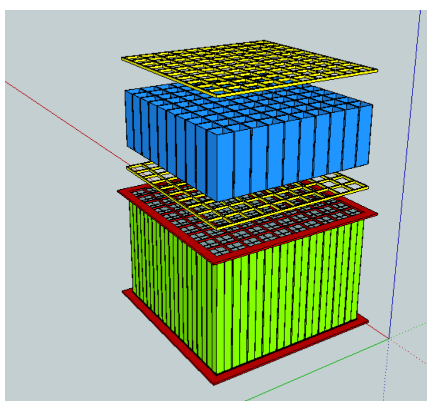
The X-Gamma-rays spectrometer (XGS)

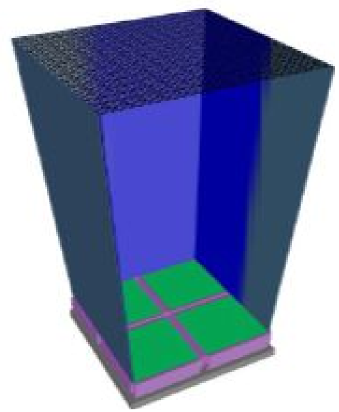






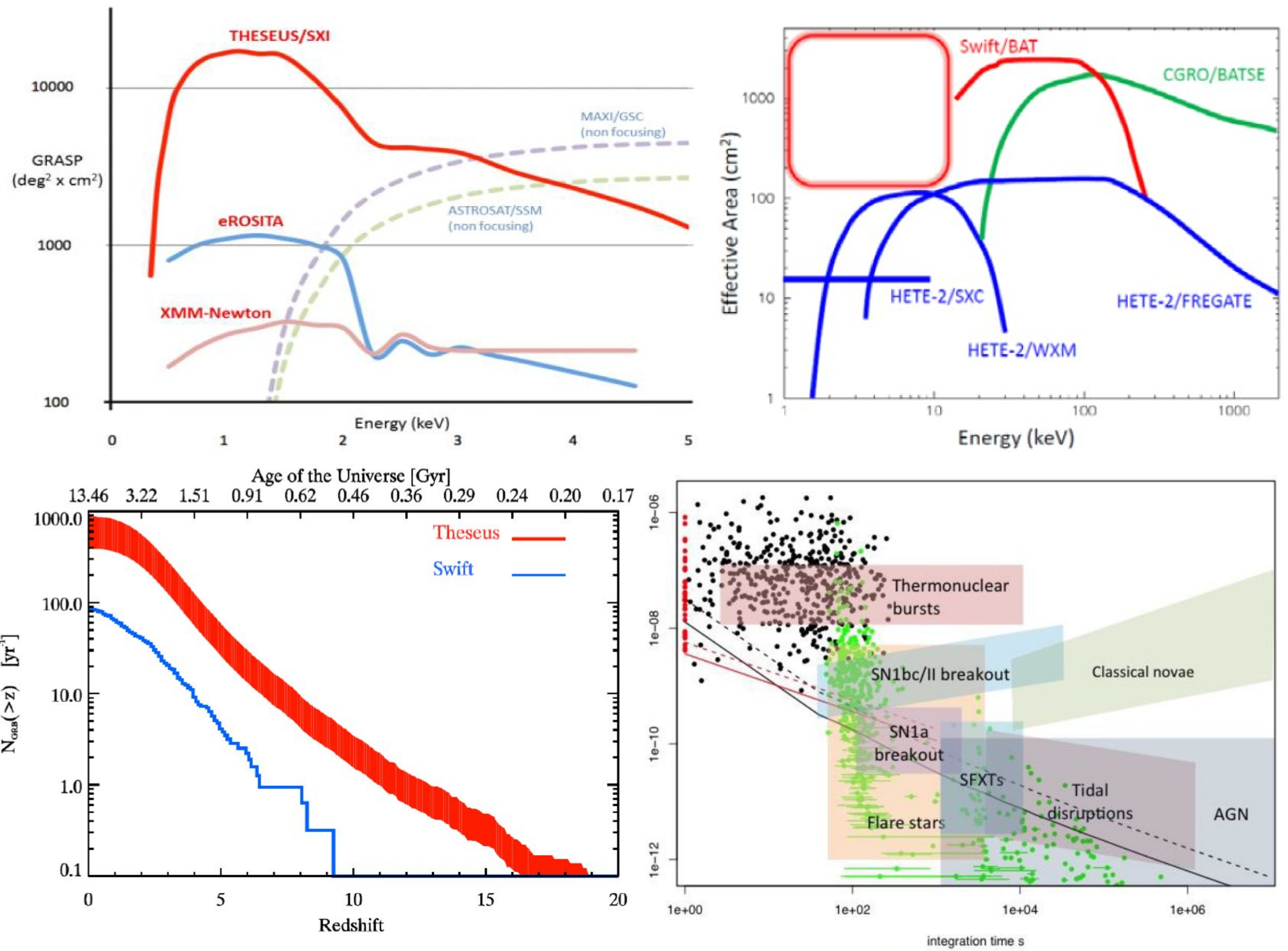






Energy band	*2 keV – 20 MeV*
# detection plane modules	*4*
# of detector pixel / module	*32x32*
pixel size (= mask element size)	*5x5 mm*
Low-energy detector (2-30 keV)	*Silicon Drift Detector 450 μm thick*
High energy detector (> 30 keV)	*CsI(Tl) (3 cm thick)*
Discrimination Si/CsI(Tl) detection	*Pulse shape analysis*
Dimension [cm]	*50x50x85*
Power [W]	*30,0*
Mass [kg]	*37.3*

	2-30 keV	30-150 keV	>150 keV
Fully coded FOV	9 x 9 deg²		
Half sens. FOV	50 x 50 deg²	50 x 50 deg² (FWHM)	
Total FOV	64 x 64 deg²	85 x 85 deg² (FWZR)	2π sr
Ang. res	25 arcmin		
Source location accuracy	~5 arcmin (for >6 σ source)		
Energy res	200 eV FWHM @ 6 keV	18 % FWHM @ 60 keV	6 % FWHM @ 500 keV
Timing res.	1 μsec	1 μsec	1 μsec

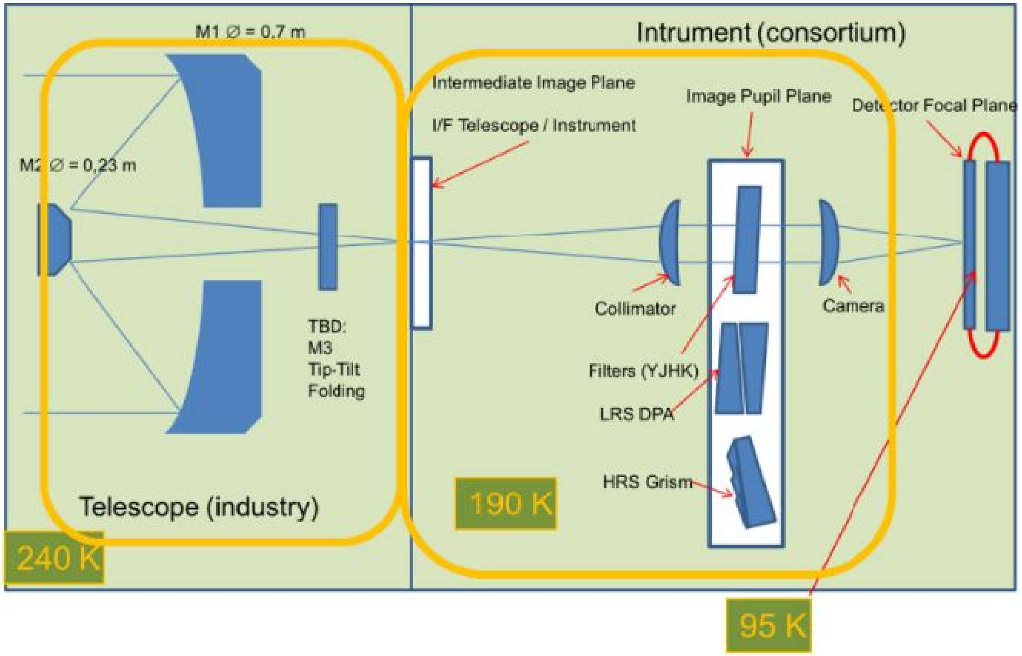


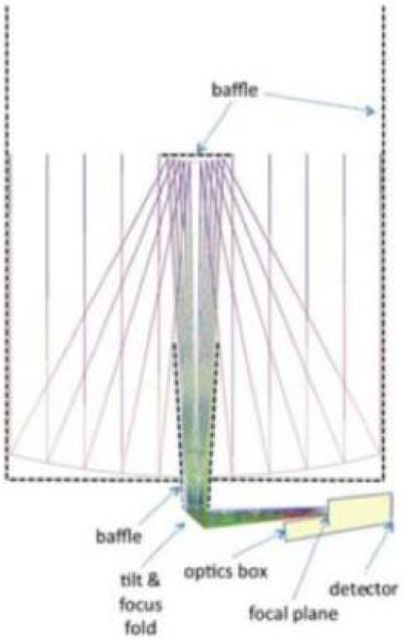
THESEUS/SXI
10000
GRASP
(deg² x cm²)
MAXI/GSC
(non focusing)
eROSITA
ASTROSAT/SSM
(non focusing)
1000
XMM-Newton
100
Energy (keV)
0
1
2
3
4
5
Swift/BAT
CGRO/BATSE
1000
100
10
1
Effective Area (cm²)
HETE-2/SXC
HETE-2/FREGATE
HETE-2/WXM
Energy (keV)
Age of the Universe [Gyr]
13.46 3.22 1.51 0.91 0.62 0.46 0.36 0.29 0.24 0.20 0.17
1000.0
100.0
10.0
1.0
0.1
Theseus
Swift
N_GRB(>z) [yr⁻¹]
0 5 10 15 20
Redshift
1e−06
1e−08
1e−10
1e−12
Thermonuclear
bursts
SN1bc/II breakout
Classical novae
SN1a
breakout
SFXTs
Tidal
disruptions
AGN
Flare stars
1e+00
1e+02
1e+04
1e+06
integration time 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	2029-2030
SVOM	4 keV – 5 MeV	1.5 sr	2 keV (60 keV)	1000 cm^2	2–10 arcmin	2022

+ Infrared telescope and fast slewing !!!

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'	10' x 10'	5' x 5'
Resolution (λ/Δλ):	2-3 (imaging)	20 (low-res)	500 (high-res), goal 1000
Sensitivity (AB mag):	H = 20.6 (300s)	H = 18.5 (300s)	H = 17.5 (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, TBC)
Total envelope size (mm):	800 Ø x 1800		
Power (W):	115 (50 W for thermal control)		
Mass (kg):	112.6		

❑ Shedding light on the early Universe with GRBs

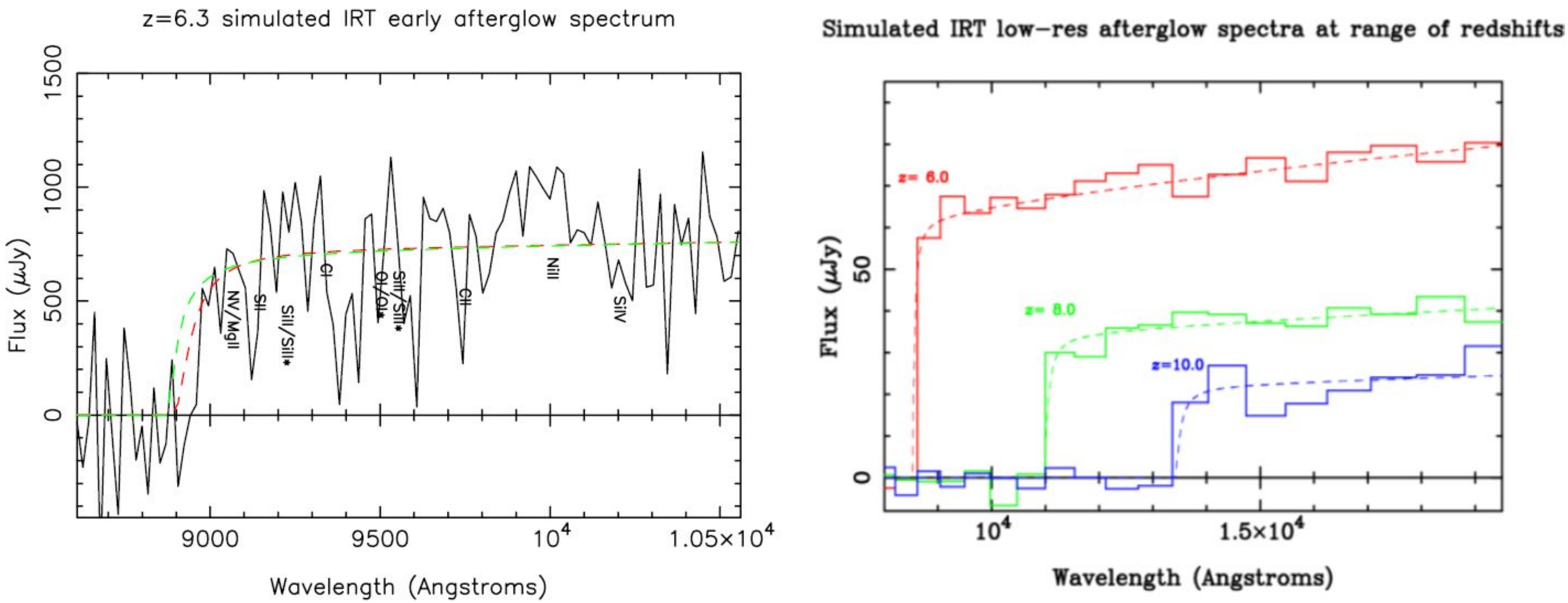
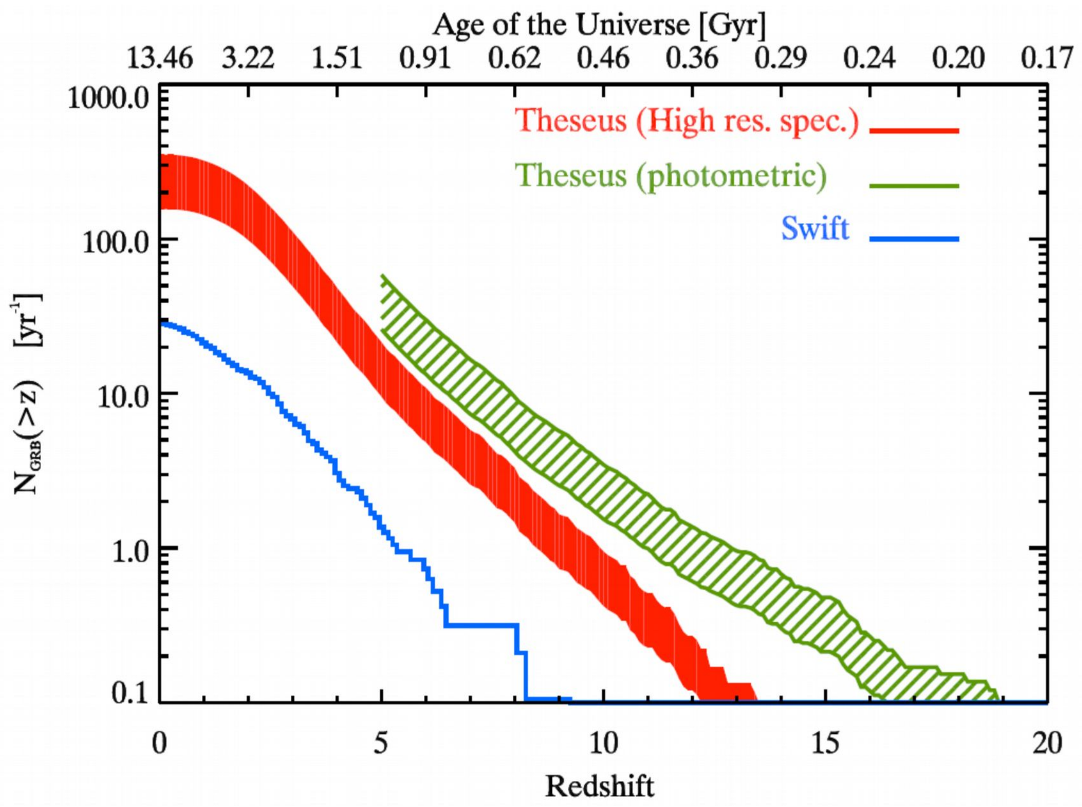


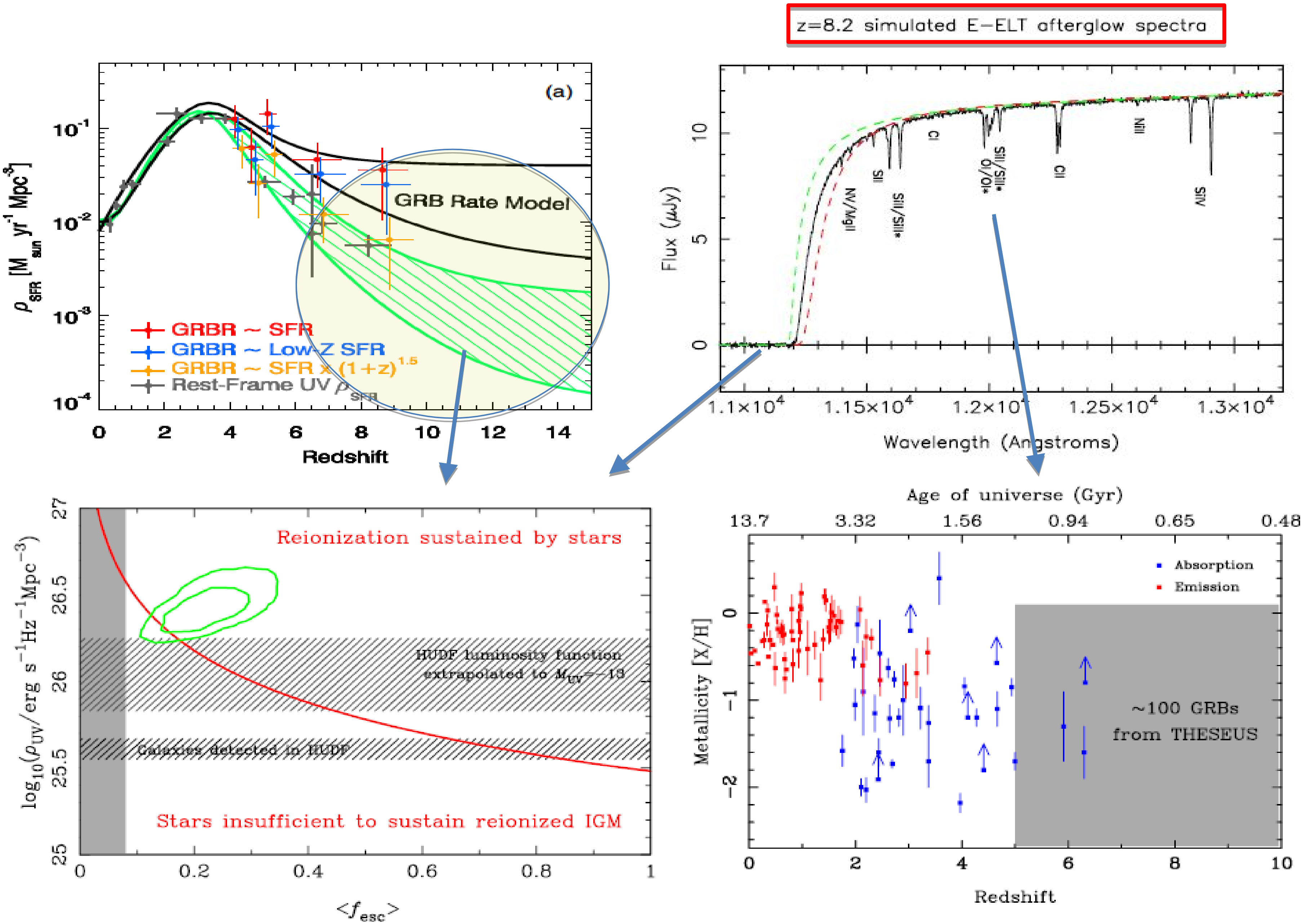
Figure 11: Left: a simulated IRT high resolution (R=500) spectrum for a GRB at z=6.3 observed at 1 hour post trigger assuming a GRB similar to GRB 050904. The spectrum has host log(NH)=21 and neutral fraction Fx=0.5 (and metallicity 0.1solar). The two models are: Red: log(NH)=21.3, Fx=0 Green: log(NH)=20.3, Fx=1. The IRT spectra provide accurate redshifts. 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.

❑ Shedding light on the early Universe with GRBs



THESEUS GRB#/yr	All	z > 5	z > 8	z > 10
Detections	387 - 870	25 – 60	4 – 10	2 - 4
Photometric z		25 – 60	4 – 10	2 - 4
Spectroscopic z	156 - 350	10 - 20	1 - 3	0.5 - 1

❑ Shedding light on the early Universe with GRBs

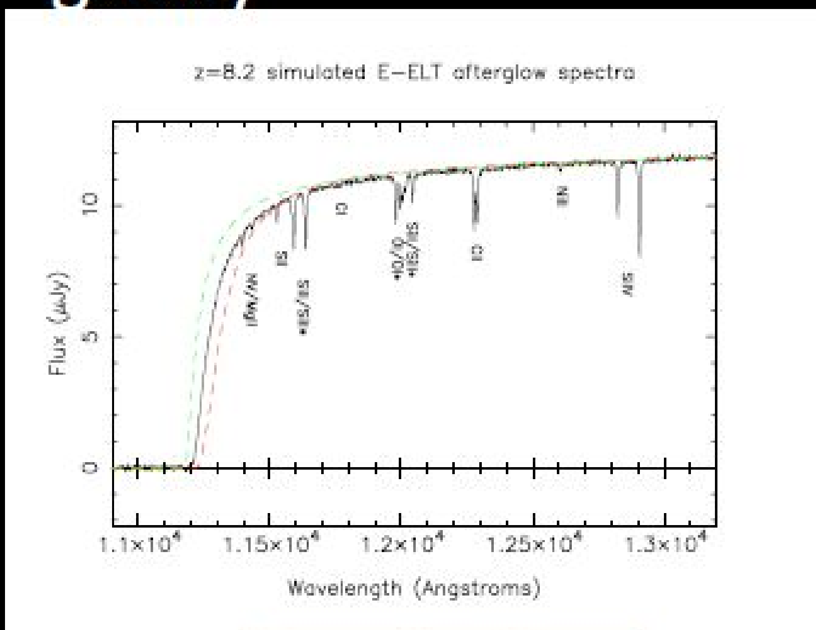


ATHENA+

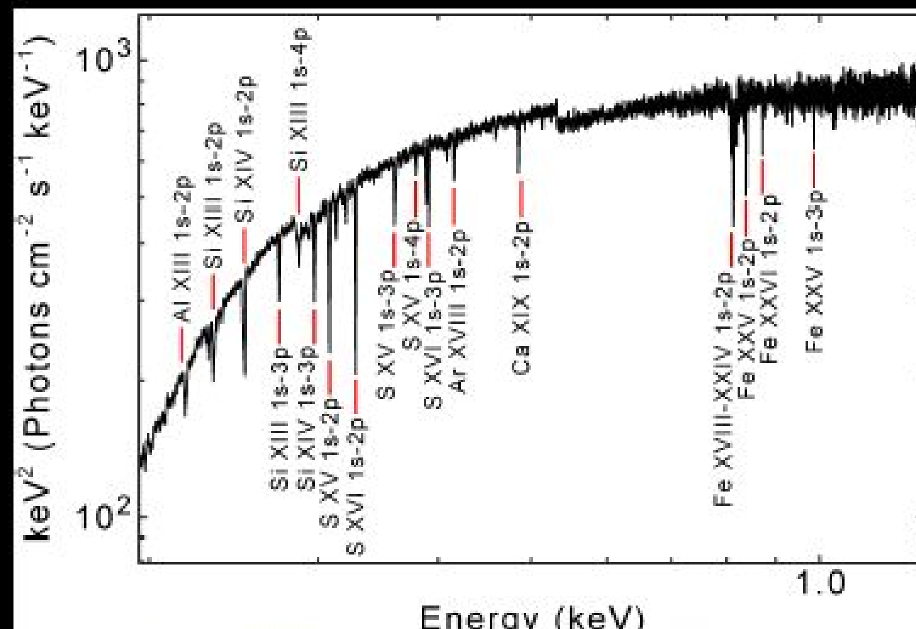
Follow-up of high-z GRB with large facilities

- Optical/IR abs. spectroscopy of the host galaxy

X-ray spectroscopy of the progenitor environme

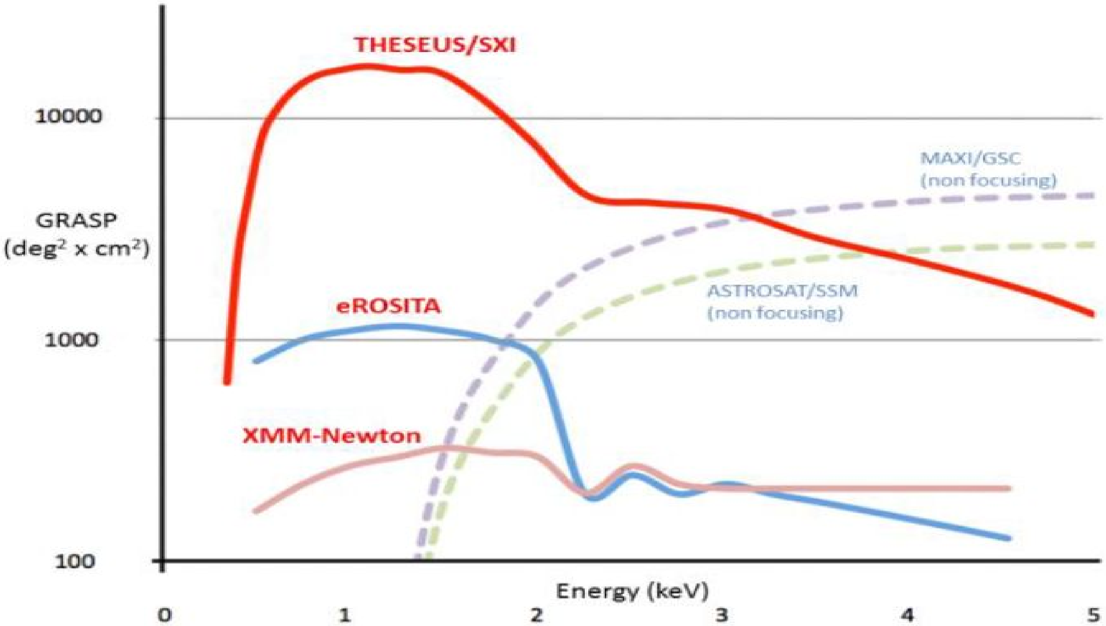


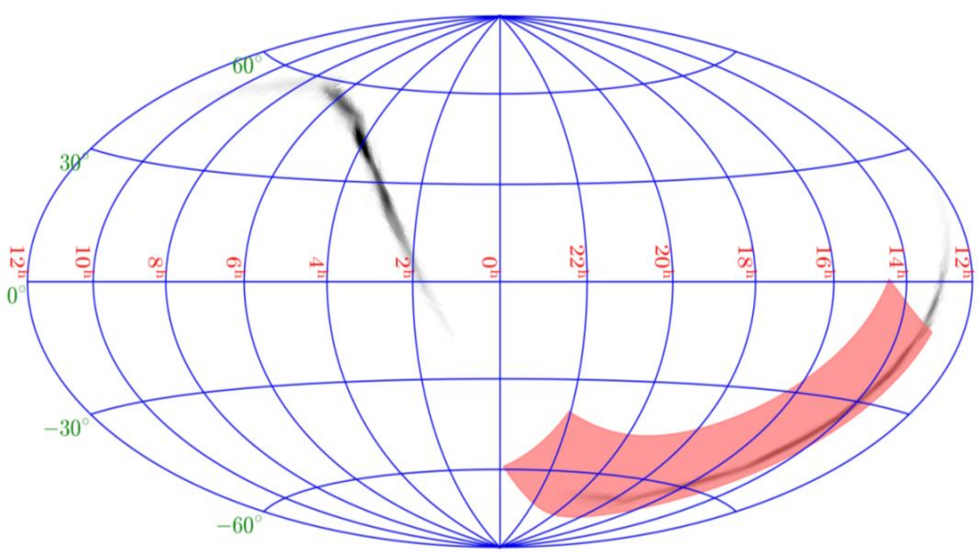
30+ m class ELTs



ESA L2 X-ray Observatory

❑ GW/multi-messenger and time-domain astrophysics





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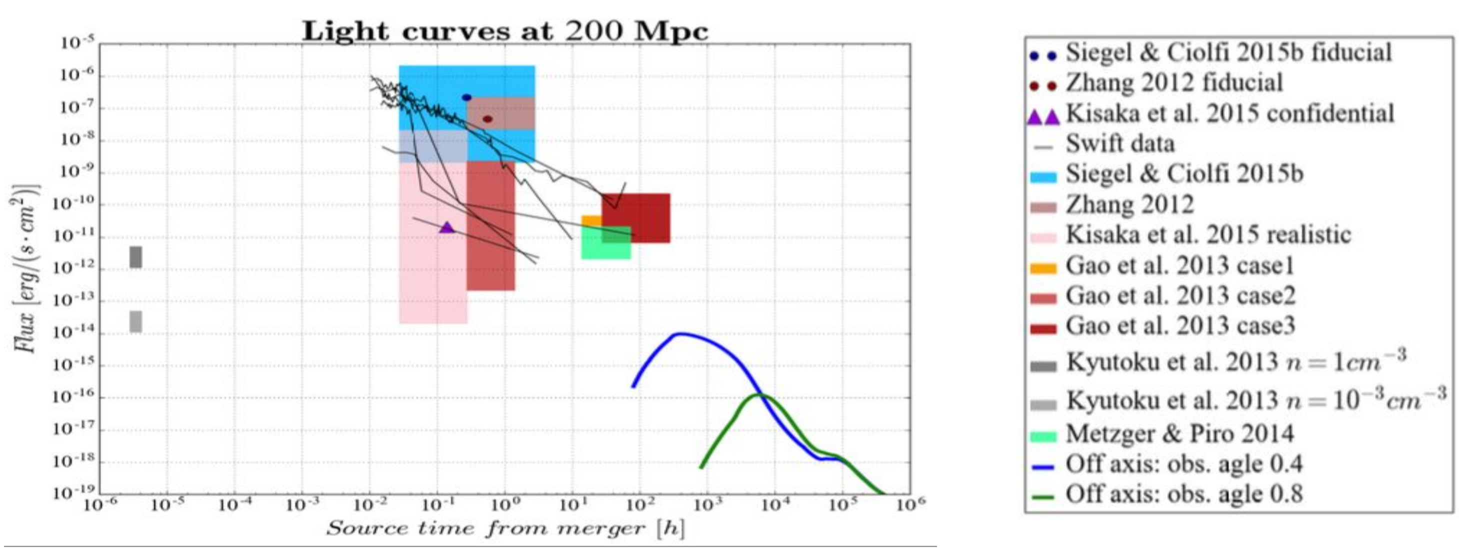
Novae	250 yr^{-1}
Dwarf novae	30 day^{-1}
Stellar flares	400 yr^{-1}
Stellar super flares	200 yr^{-1}

probe GRB physics

❑ GW/multi-messenger and time-domain astrophysics

Among the **GW transient sources that will be monitored by THESEUS** there are:

- ❑ NS-NS / NS-BH mergers:
  - ❑ **collimated** EM emission from short GRBs and their afterglows (rate of ≤ 1/yr for 2G GW detectors but up to 20/yr for 3G GW detectors as Einstein Telescope)
  - ❑ Optical/NIR and soft X-ray **isotropic** emissions from macronovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown (rate of GW detectable NS-NS or NS-BH systems, i.e. dozens-hundreds/yr)
- ❑ Core collapse of massive stars: Long GRBs, LLGRBs, ccSNe (much more uncertain predictions in GW energy output, possible rate of ~1/yr)
- ❑ Flares from isolated NSs: Soft Gamma Repeaters (although GW energy content is ~0.01%-1% of EM counterpart)

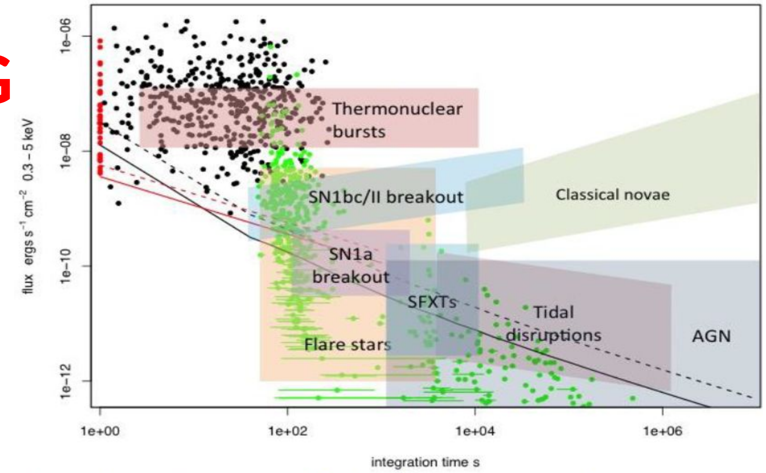


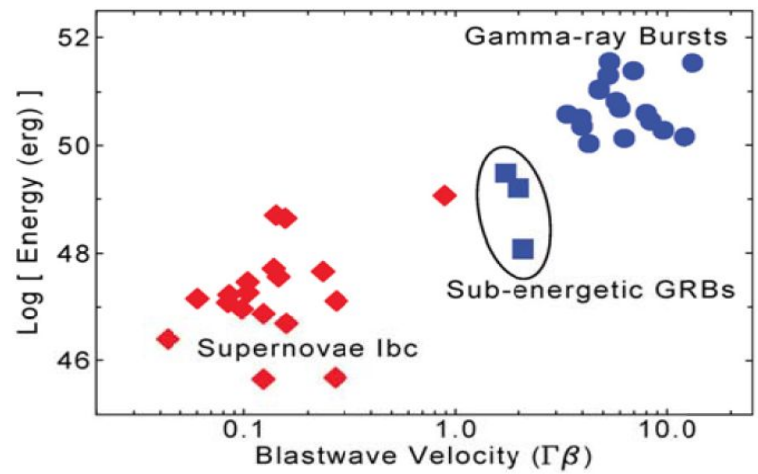
Credit: S. Vinciguerra

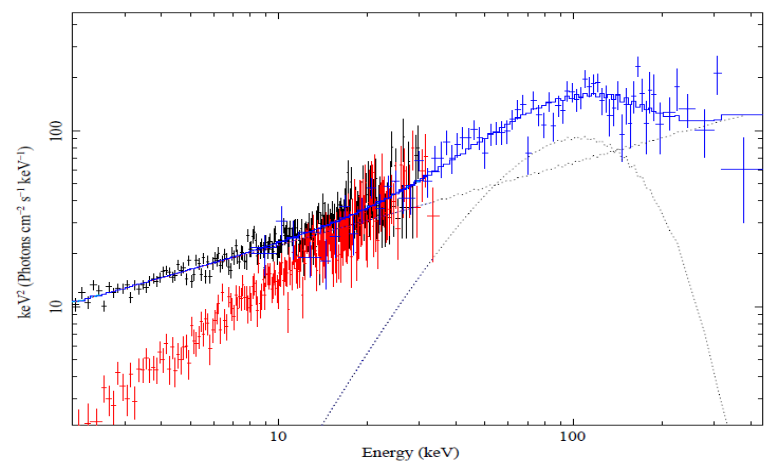
❑ Time-domain astronomy and G physics

- **survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific sinergy can be anticipated.**
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;
- unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse Sne;

- **IR survey and guest observer possibilities, thus allowing an even stronger community involvement**







Mission profile and budgets

FUNCTIONAL SUBSYSTEMS	Basic Mass (kg)	Margin (%)	Margin (kg)	Current Mass (Kg)
SERVICE MODULE				
AOCS (gyro, RW, SAS, ST)	115,1	10%	11,5	126,6
PDHU + X BAND	31,4	10%	3,1	34,5
DATA HANDLING	24,4	5%	1,2	25,6
EPS (PCU, Battery, SA)	85,1	10%	8,5	93,6
SYSTEM STRUCTURE	129,1	10%	12,9	142,0
PROPULSION	17,0	15%	2,5	19,5
THERMAL CONTROL (heaters+blankets)	14,2	10%	1,4	15,6
HARNESS	46,0	20%	9,2	55,2
Total Service Module Mass	462,3	11%	50,5	512,8
PAYLOAD MODULE				
SXI	100,0	20%	20,0	120,0
XGIS	93,0	20%	18,6	111,6
IRT	94,2	20%	18,8	116,0
i-DHU + i-DU + NGRM + TBU + harness (TBC)	23,1	20%	4,6	27,7
Total P/L Module Mass	310,3		62,1	375,3

Total Service Module Mass (kg)	512,8
Total Payload Module Mass (kg)	375,3
System level margin (20%)	177,6
Dry Mass at launch (kg)	**1065,6**
Propellant	100,0
Launcher adapter	31,7
Total mass at launch (kg)	**1197,3**

- Launch with VEGA-C into LEO (< 5°, ~600 km)
- **Spacecraft slewing capabilities (30° < 5 min)**
- **Prompt downlink options : WHF network (options: IRIDIUM network, ORBCOMM, NASA/TDRSS, ESA/EDRS)**

THESEUS payload consortium (M5)

- **ITALY -** L.P. / project office, XGIS, Malindi antenna
- **UK -** SXI (optics + detectors + calibration) + S/W (SXI pipeline and remote contribution to SDC)
- **France -** IRT (coordination and IR camera, including cooler) , **ESA -** IRT optics + SXI CCDs
- **Germany, Poland** - Data Processing Units (DPU) for both SXI and XGS, Power Supply Units (PSU)
- **Switzerland**: SDC (data archiving, AOs, + pipelines) + IRT focal plane assembly
- **Other contributions: Spain** (XGIS collimators), **Belgium** (SXI integration and tests), **Czech Rep.** (mechanical structures and thermal control of SXI), **Ireland** (IRT focal plane)**, Hungary** (spacecraft interface simulator, PDHU, IRT calib.), **Slovenia** (X-band transponder, mobile ground station)
- **International optional contributions: USA:** (TDRSS, contrib. to XGS and IRT detectors), **Brazil:** Alcantara antenna, **China** (SXI, XGS), **Japan** ?
- **Industrial partners:** CGS (OHB group), GPAP

Conclusions

- ❖ **THESEUS (submitted to ESA/M5 by an Italy-led European collaboration, with interest of USA, China, Brazil) 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 perform a deep wide field monitoring of the high-energy sky from X-rays (0.3 keV) to gamma-rays (tens of MeV) with unprecedented combination of sensitivity, FOV and source location accuracy in the soft X-rays, coupled with extension up to several MeVs**

- ❖ **THESEUS will also play a fundamental role for GW/multi-messenger and time domain astrophysics at the end of next decade, operating in perfect synergy with next generation multi messenger (aLIGO/aVirgo, eLISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)**

- ❖ **The THESEUS proposal for ESA is a unique occasion for the worldwide GRB community and <u>for exploiting the Italian leadership in the field and related R&D activities supported by ASI, INAF, INFN</u>**

- ❖ About 200 researcher from worldwide institutions already provided their support to THESEUS/M5). **Please, provide your interest / support to <u>amati@iasfbo.inaf.it</u> or through the THESEUS web-site:**
  http://www.isdc.unige.ch/theseus/