theseus

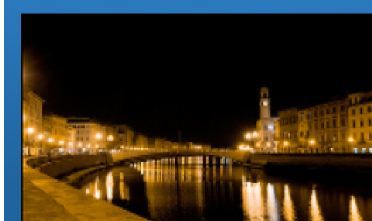
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

L. Amati & G. Stratta

(INAF – IASF Bologna, Univ. Urbino)

on behalf of the THESEUS international collaboration

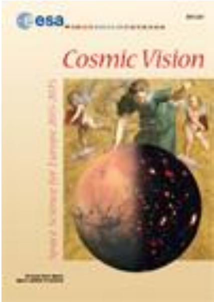
http://www.isdc.unige.ch/theseus/



SciNeGHE 2016 High-energy gamma-ray experiments at the dawn of gravitational wave astronomy

18-21 October 2016

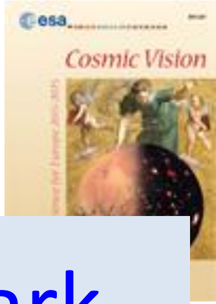
The ESA Cosmic Vision Programme



❖ Selected missions

- M1: Solar Orbiter (solar astrophysics, 2017)
- M2: Euclid (cosmology, 2020)
- L1: JUICE (exploration of Jupiter system, 2022)
- S1: CHEOPS (exoplanets, 2017)
- M3: PLATO (exoplanets, 2024)
- L2: ATHENA (X-ray observatory, cosmology 2028)
- L3: gravitational wawe observatory (LISA, 2034) ?
- M4: TBD (2025) [XIPE (X-ray pol.), ARIEL (exoplanets), THOR (plasma, interaction star-planet)]

The ESA Cosmic Vision Programme



Resonant keywords: cosmology (dark energy, dark matter, re-ionization, structures formation and evolution)**, fundamental physics** (relativity, quantum gravity, QCD, **gravitational waves**)**, exoplanets** (planets formation + evolution + census **-> life**), **solar system exploration** (as for exoplanets)

THE ESA/M5 Call (for launch in ~2029)

Activity	Date
Release of Call for M5 mission	April 29, 2016
Letter of Intent submission deadline	June 6, 2016, 12:00 (noon) CEST
Briefing meeting (ESTEC)	June 24, 2016 (TBC)
Proposal submission deadline	October 5, 2016, 12:00 (noon) CEST
Letters of Endorsement deadline	February 8, 2017, 12:00 (noon) CET
Selection of missions for study	June 2017
Phase 0 completed	November 2017
Phase A kick-off	January 2018
Mission selection	November 2019
Mission adoption	November 2021

- More typical medium-size mission w/r to M4: larger CaC (Costs at Completion to ESA, 550 ME w/r to 450 ME), more relaxed schedule
- As for M4, first selection based on technical – programmatic evaluation

THESEUS
Transient High Energy Sky and Early Universe Surveyor

Lead Proposer: 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

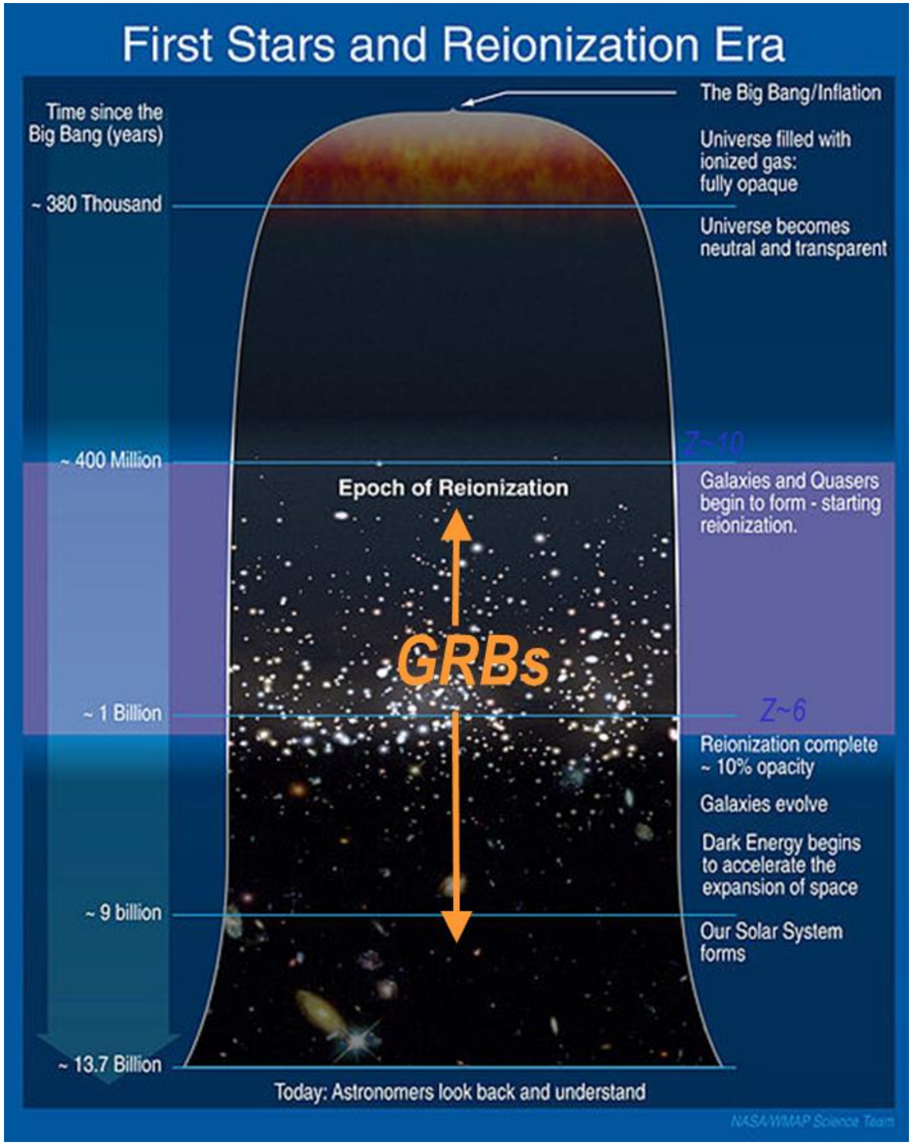
Interested international partners: USA, China, Brazil

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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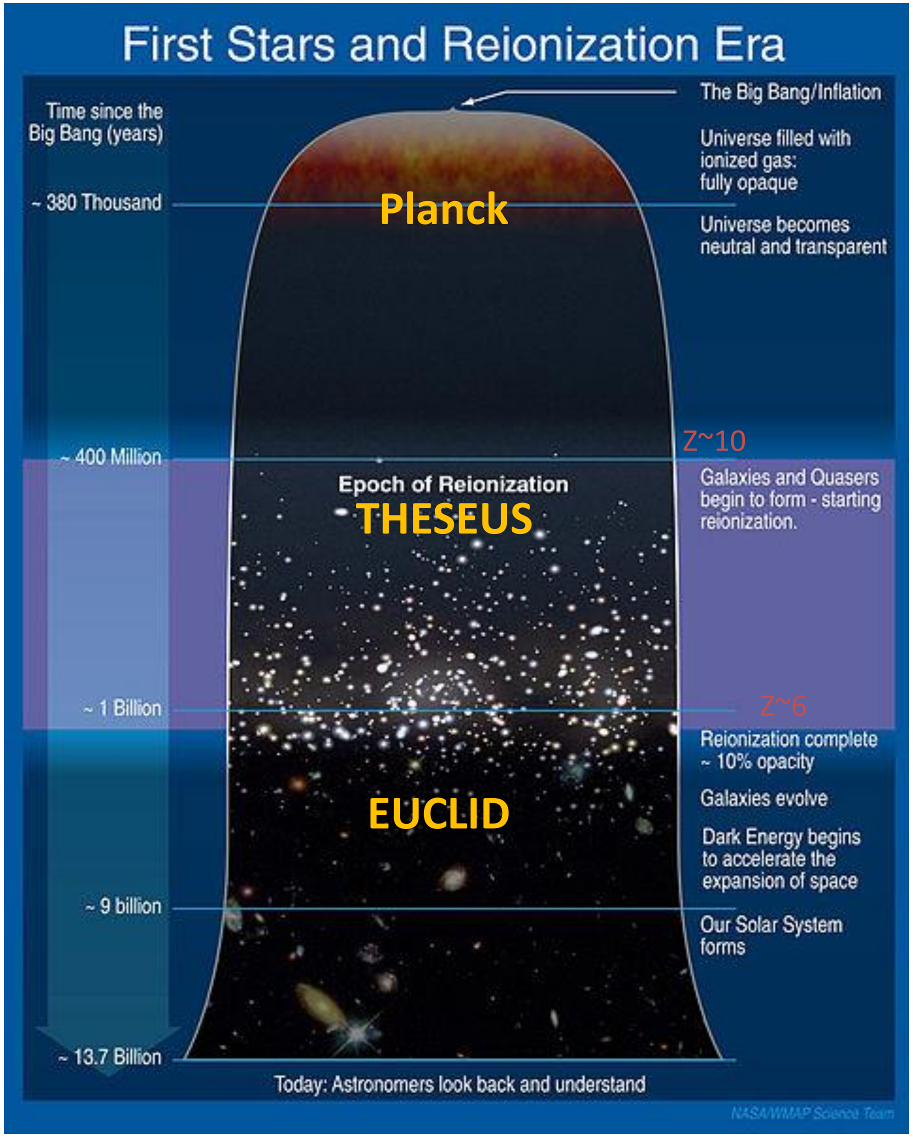
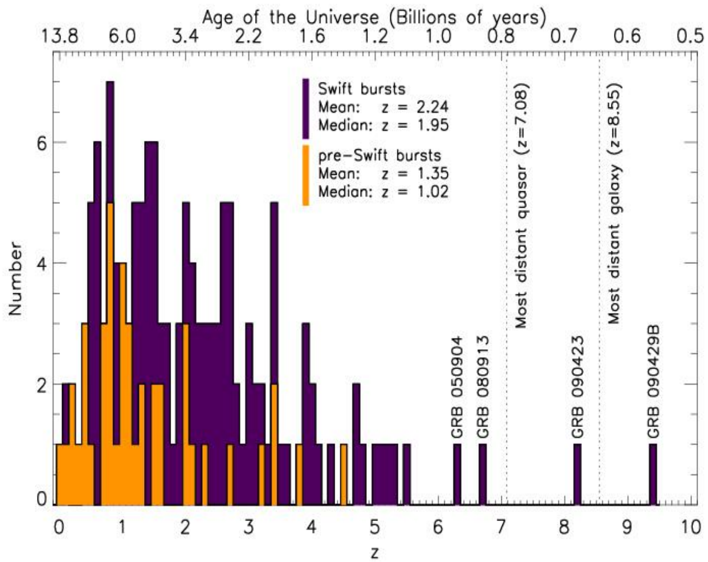
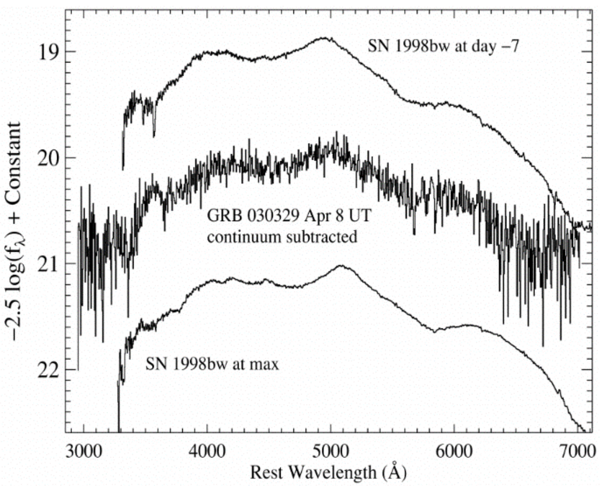
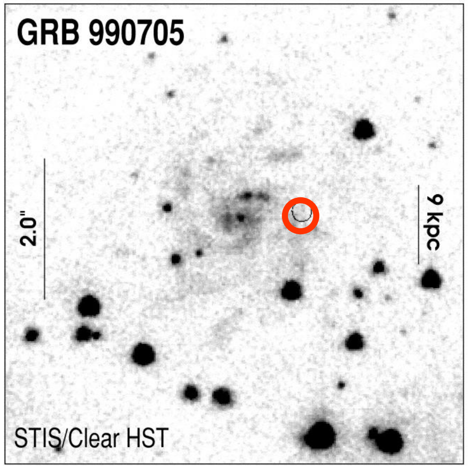


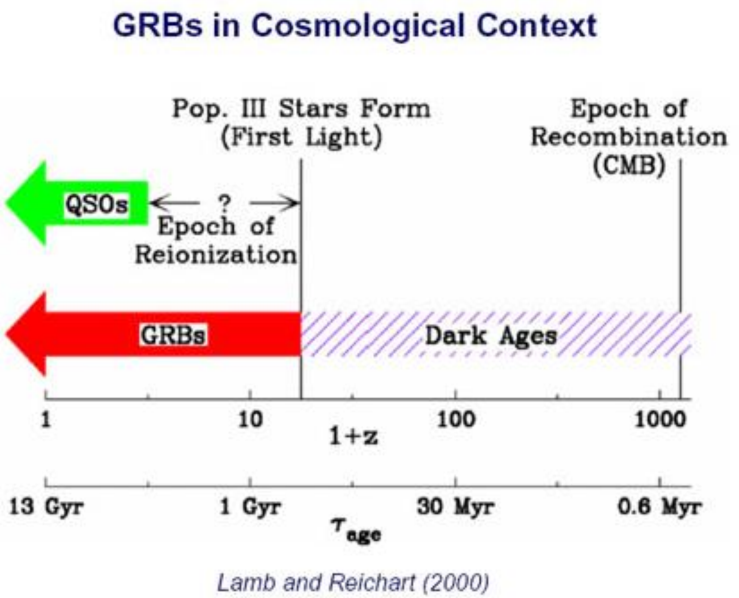
Shedding light on the early Universe with GRBs

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**





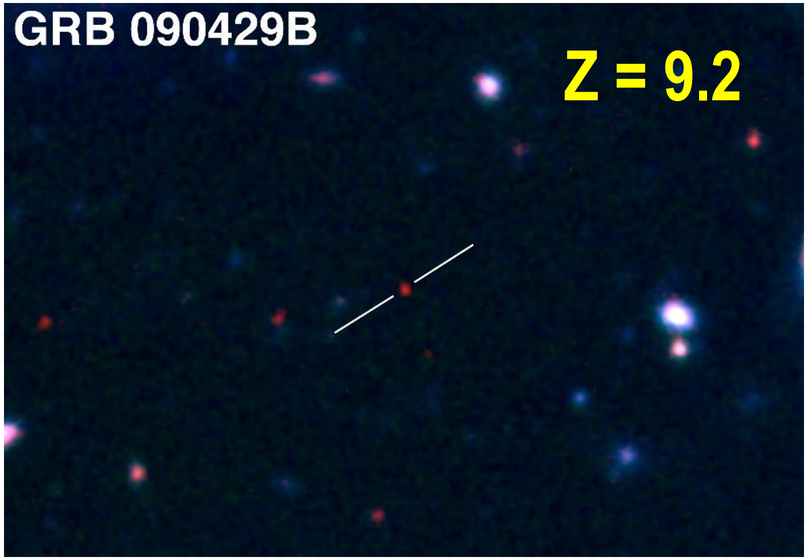


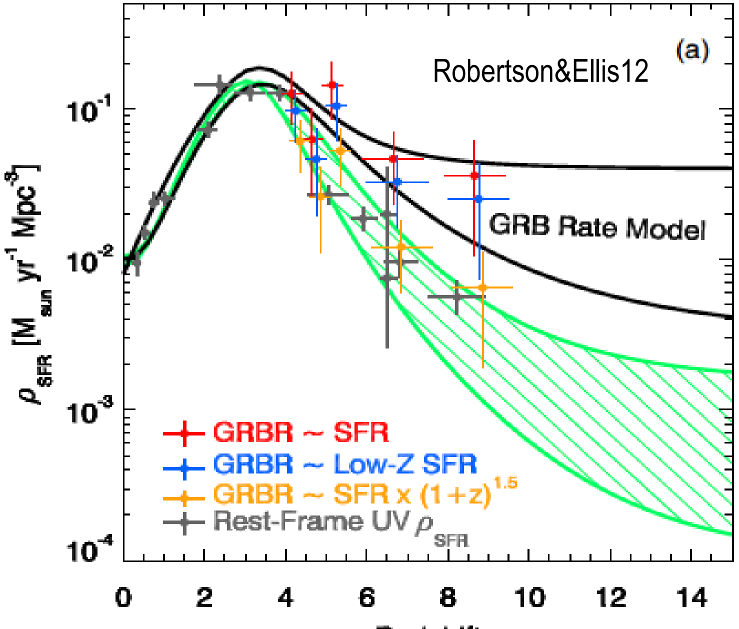


A statistical sample of high–z GRBs can provide fundamental information:

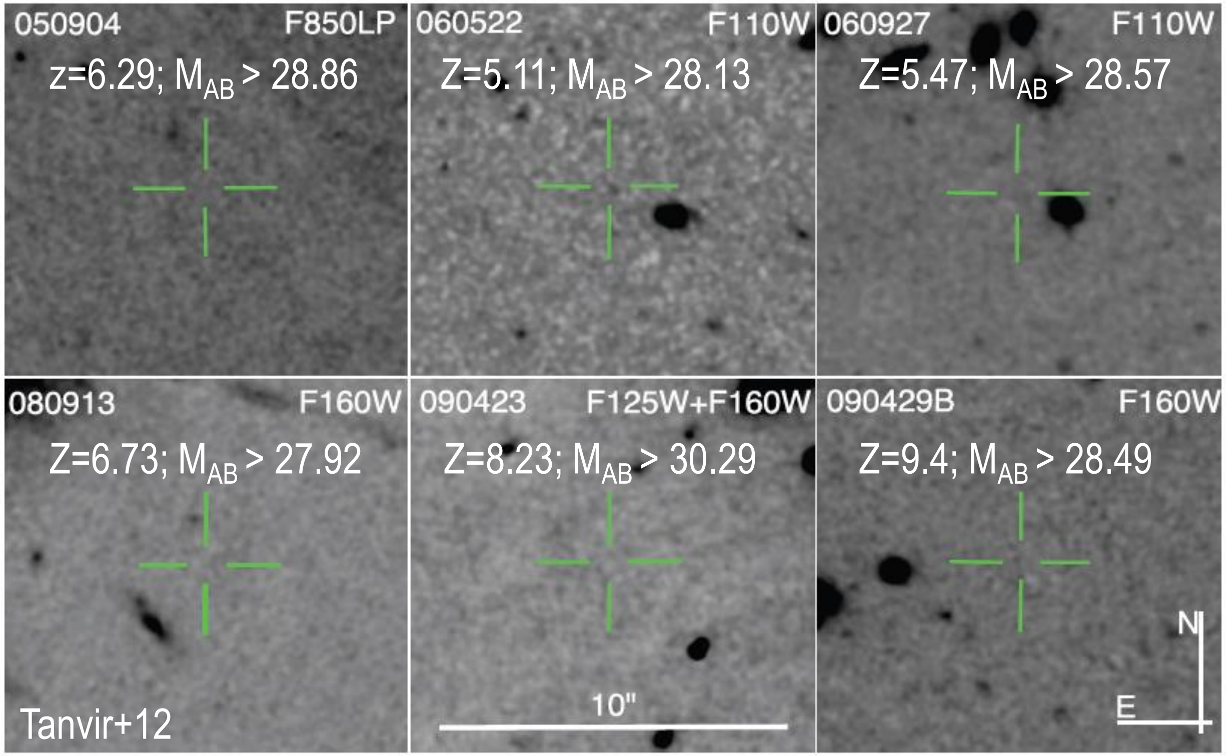
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

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





- the number density and properties of low-mass galaxies

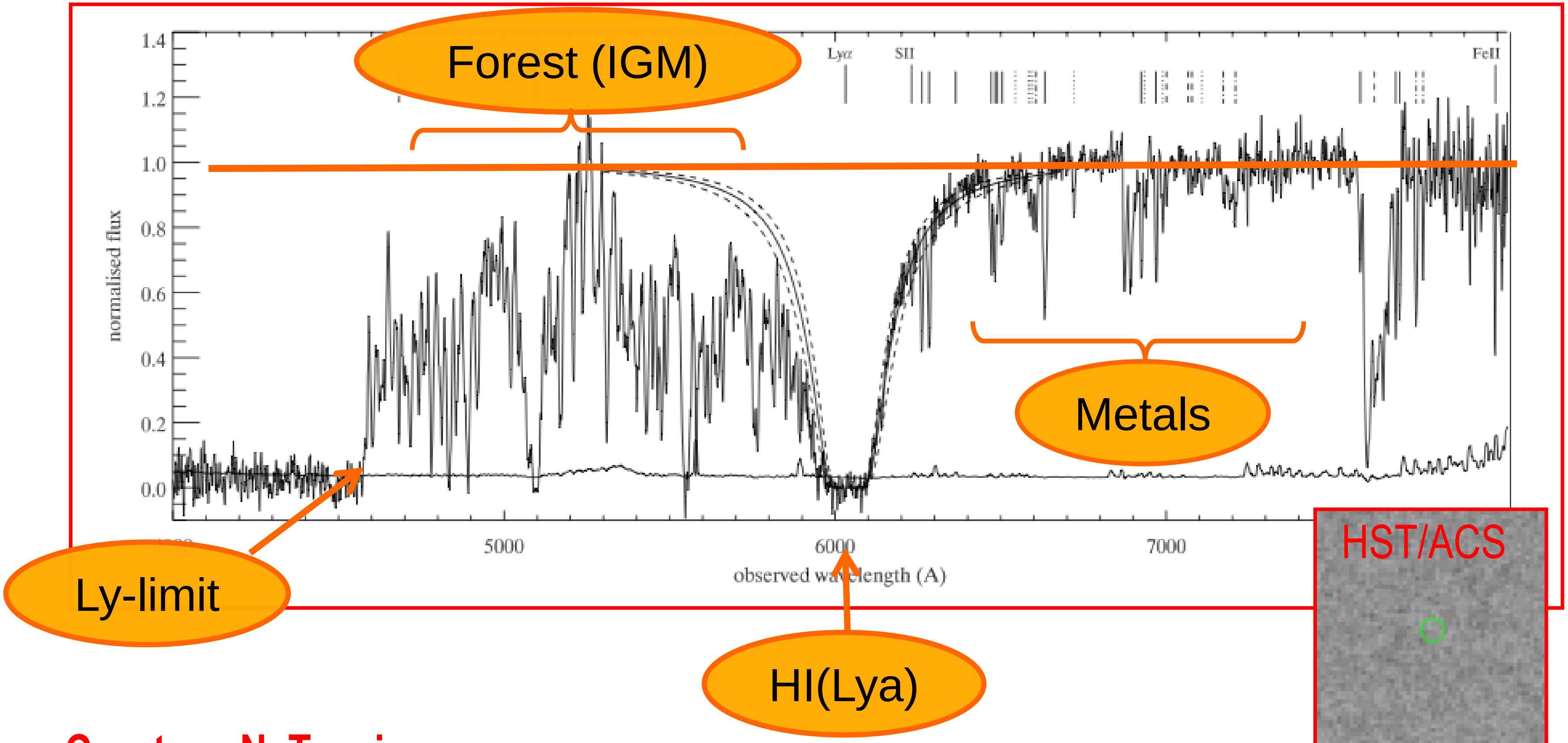


Robertson&Ellis12

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

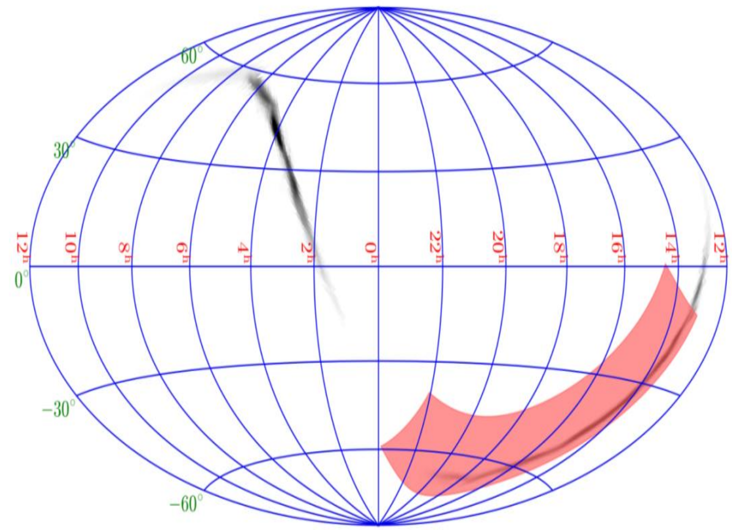
Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).



Courtesy N. Tanvir

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}
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}

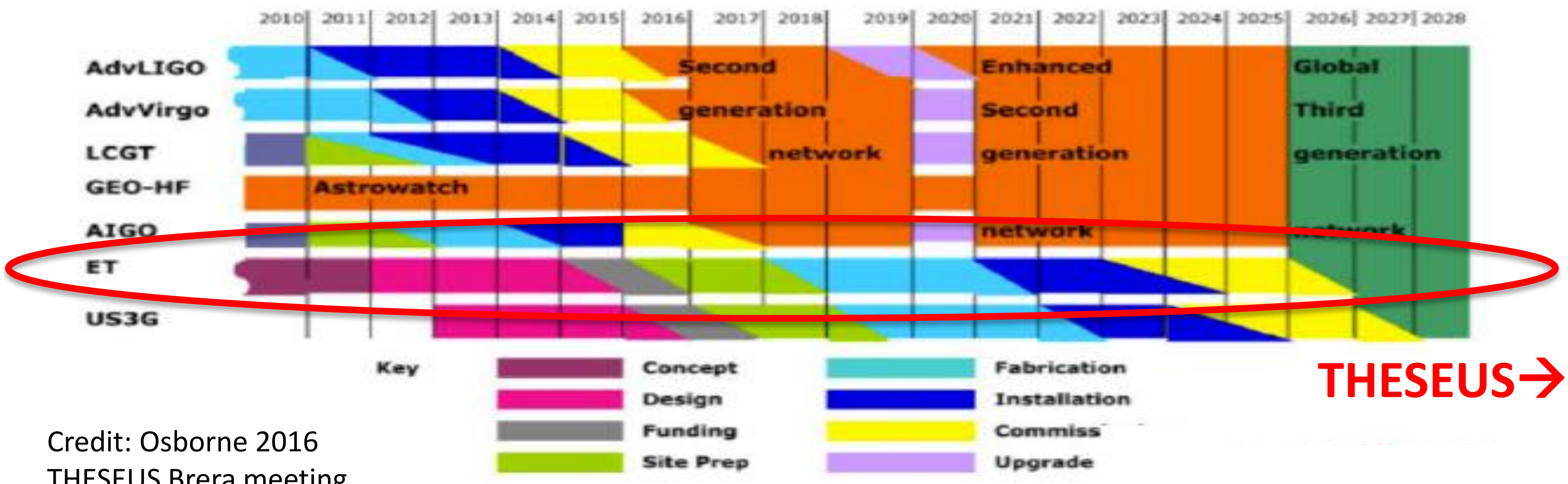
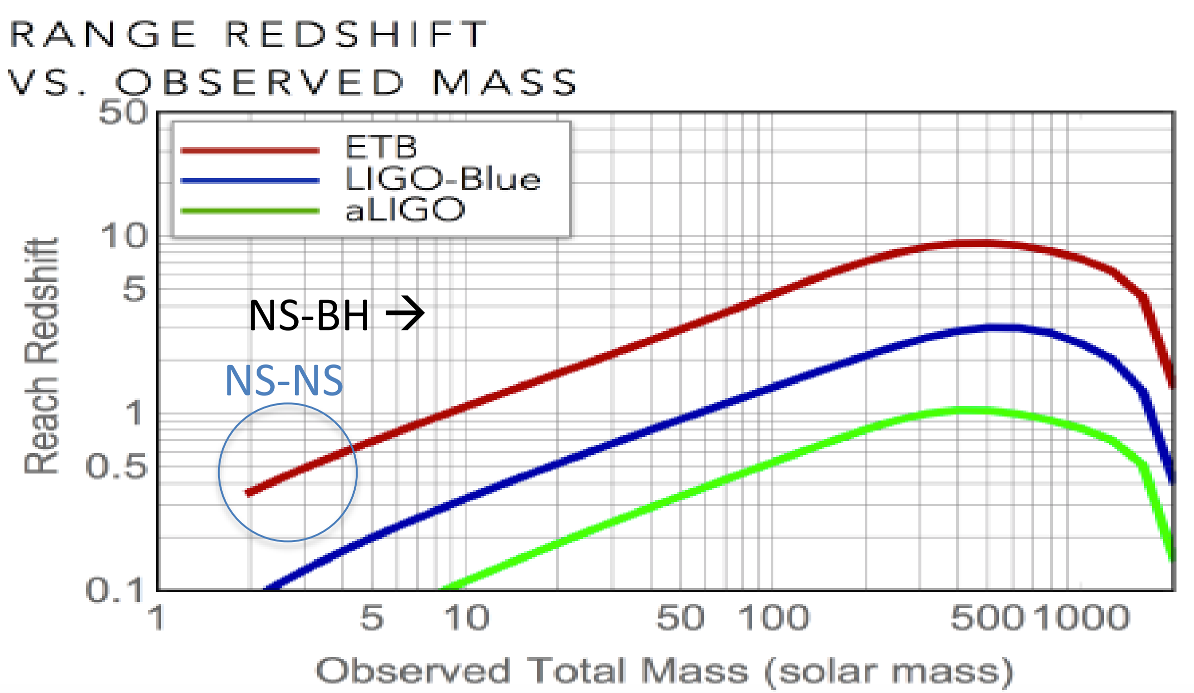


Fig. 5.1 – Time-line for ground based detector developments

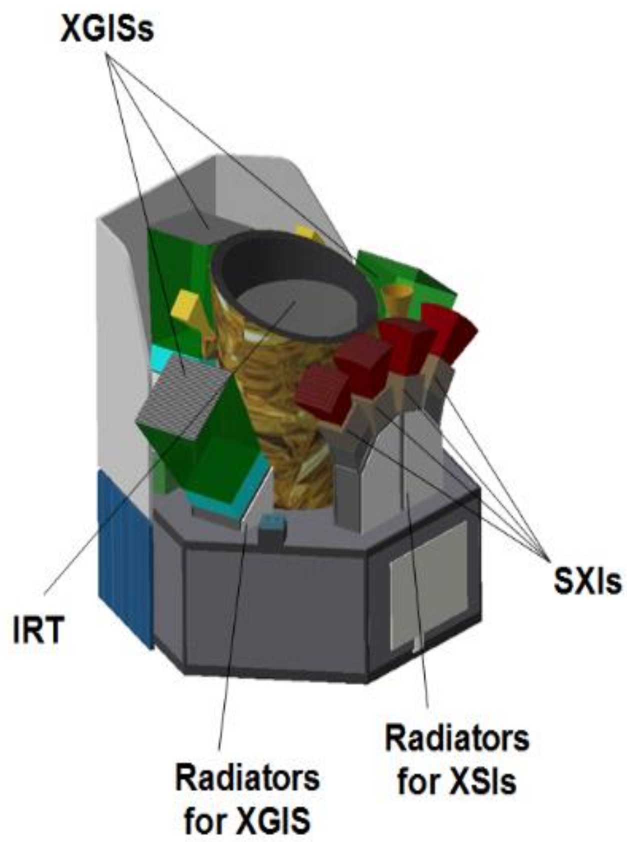
Credit: Osborne 2016
THESEUS Brera meeting



Credit:
Sathyaprakash 2016
7° ET Symposium

THESEUS payload

- **Soft X-ray Imager (SXI):** a set of four sensitive lobster-eye telescopes observing in the 0.3 - 5 keV band, providing a total FOV of ~1sr with source location accuracy < 1-2’;
- **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;
- **X-Gamma rays Imaging Spectrometer (XGIS,)**: 3 coded mask X-gamma rays cameras based on bars of Silicon diodes coupled with CsI crystal scintillators providing 2 keV – 10 MeV band and a FOV of ~1sr overlapping that of the SXI with ~5’ source loc. accuracy



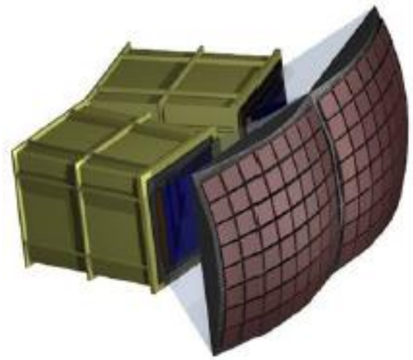
Mission profile and budgets

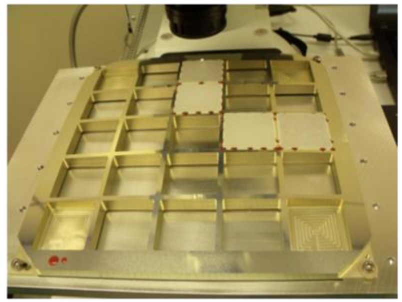
FUNCTIONAL SUBSYSTEMS	Basic Mass (kg)	Margin (%)	Margin (kg)	Current Mass (Kg)
SERVICE MODULE				
AOCS (gyro, RW, SAS, ST)	115,1	10%	11,5	126,6
PDHU + X BAND	31,4	10%	3,1	34,5
DATA HANDLING	24,4	5%	1,2	25,6
EPS (PCU, Battery, SA)	85,1	10%	8,5	93,6
SYSTEM STRUCTURE	129,1	10%	12,9	142,0
PROPULSION	17,0	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

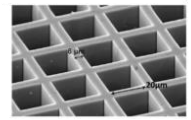
Total Service Module Mass (kg)	512,8
Total Payload Module Mass (kg)	375,3
System level margin (20%)	177,6
Dry Mass at launch (kg)	**1065,6**
Propellant	100,0
Launcher adapter	31,7
Total mass at launch (kg)	**1197,3**

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

The Soft X-ray Imager (SXI)







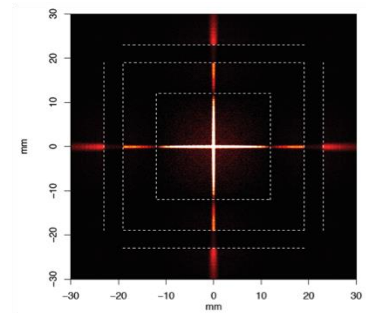
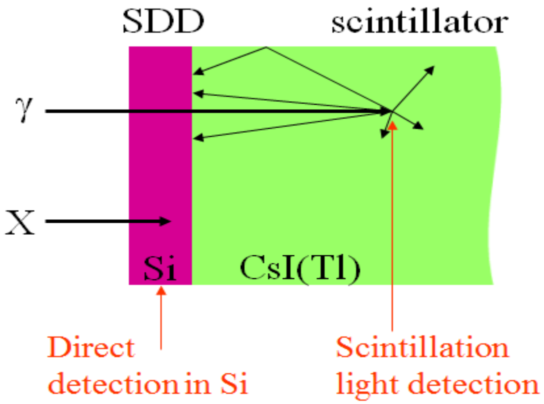
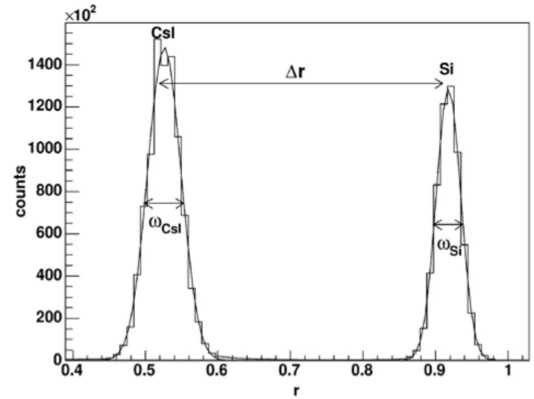


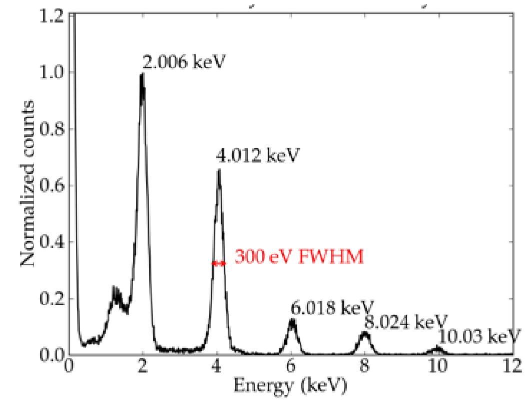
Table 4 : : SXI detector unit main physical characteristics

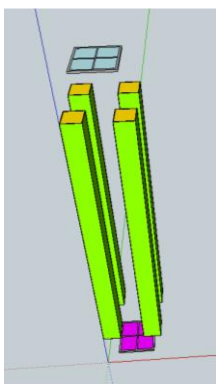
Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics aperture (mm2)	320x320
Optics configuration	8x8 square pore MCPs
MCP size (mm2)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD (mm2)	81.2x67.7
Pixel size (μm)	18
Pixel Number	4510 x 3758 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

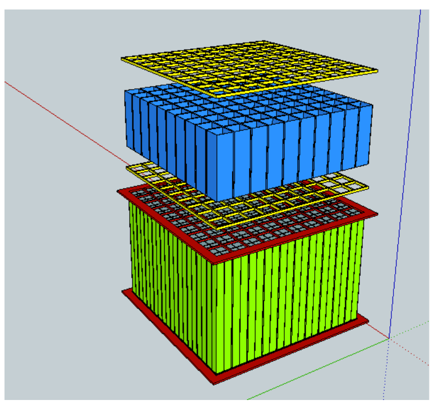
The X-Gamma-rays spectrometer (XGS)

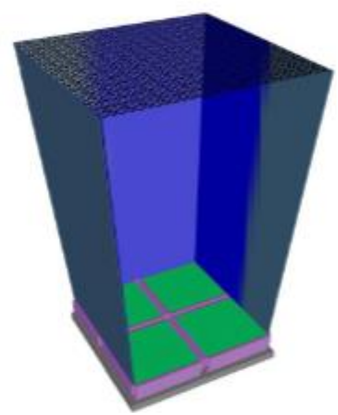






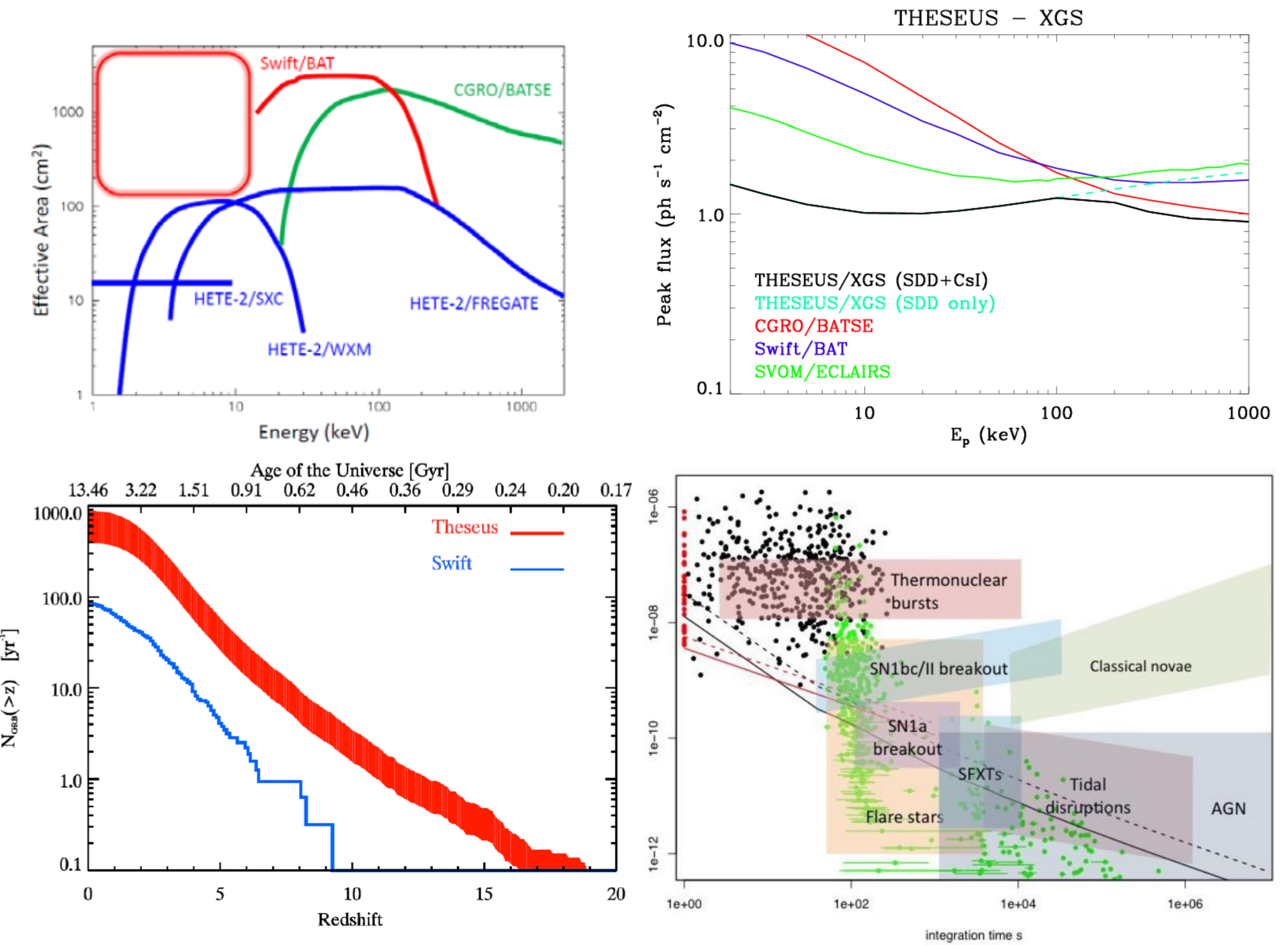




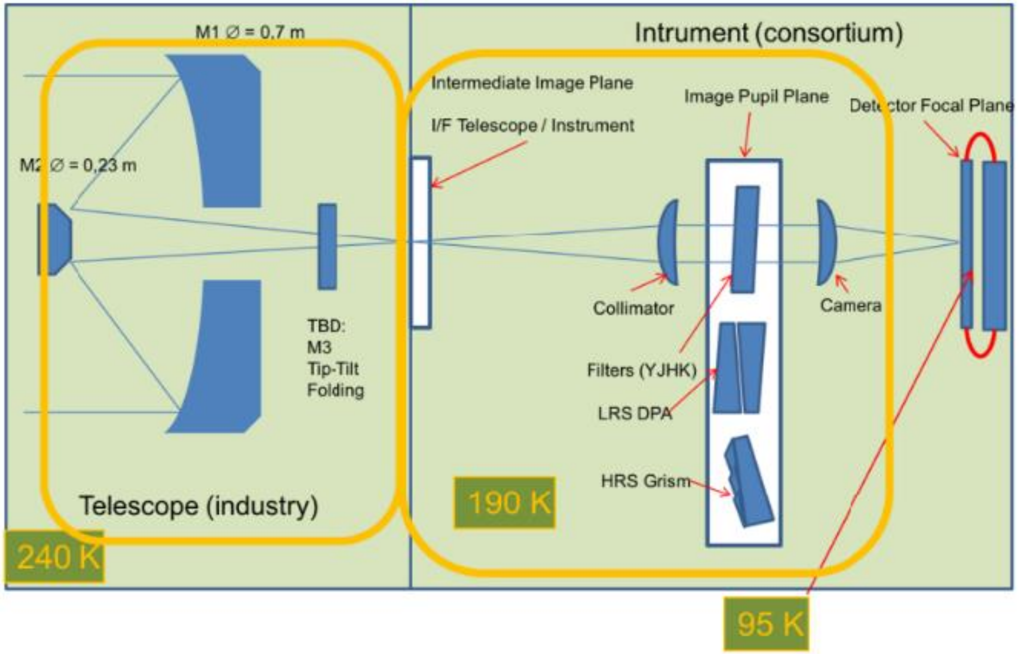


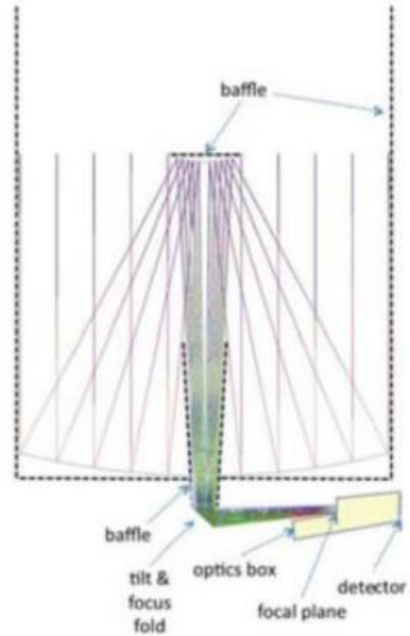
Energy band	*2 keV – 20 MeV*
# detection plane modules	*4*
# of detector pixel / module	*32x32*
pixel size (= mask element size)	*5x5 mm*
Low-energy detector (2-30 keV)	*Silicon Drift Detector 450 μm thick*
High energy detector (> 30 keV)	*CsI(Tl) (3 cm thick)*
Discrimination Si/CsI(Tl) detection	*Pulse 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


Swift/BAT
CGRO/BATSE
Effective Area (cm²)
HETE-2/SXC
HETE-2/WXM
HETE-2/FREGATE
Energy (keV)
THESEUS – XGS
Peak flux (ph s⁻¹ cm⁻²)
THESEUS/XGS (SDD+CsI)
THESEUS/XGS (SDD only)
CGRO/BATSE
Swift/BAT
SVOM/ECLAIRS
Eₚ (keV)
Age of the Universe [Gyr]
Theseus
Swift
N_GRB(>z) [yr⁻¹]
Redshift
Thermonuclear bursts
SN1bc/II breakout
Classical novae
SN1a breakout
SFXTs
Tidal disruptions
AGN
Flare stars
integration time s

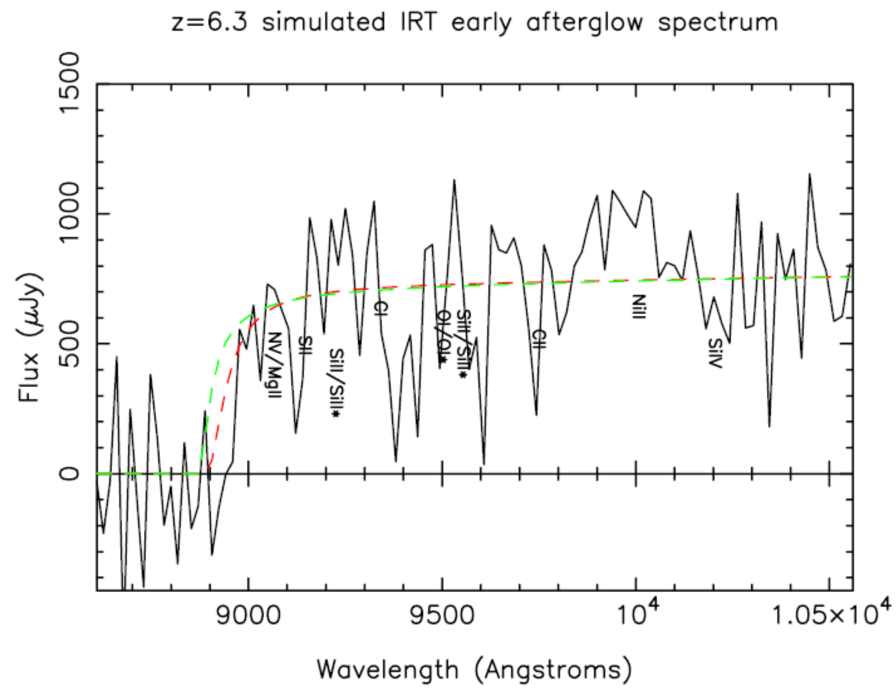
The InfraRed Telescope (IRT)





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



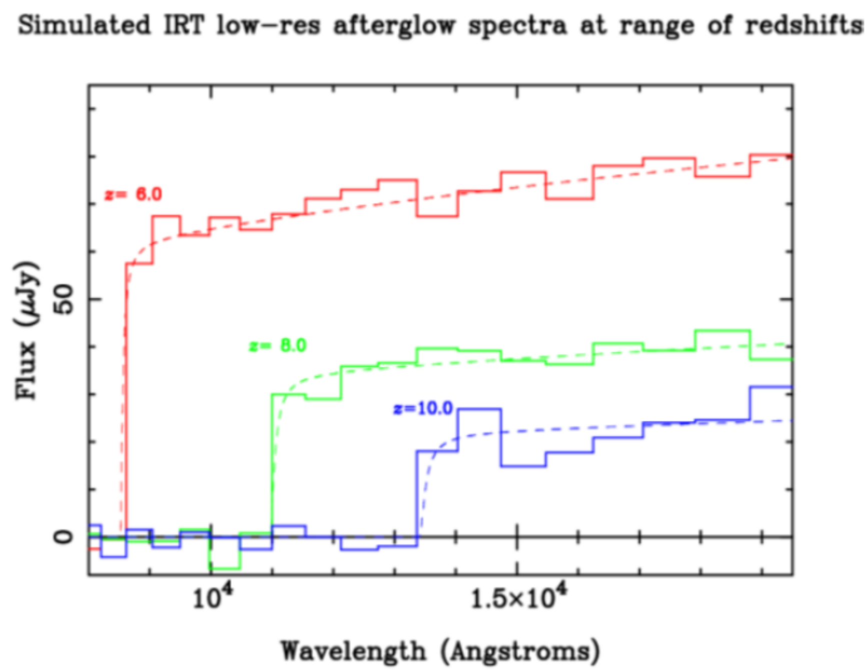
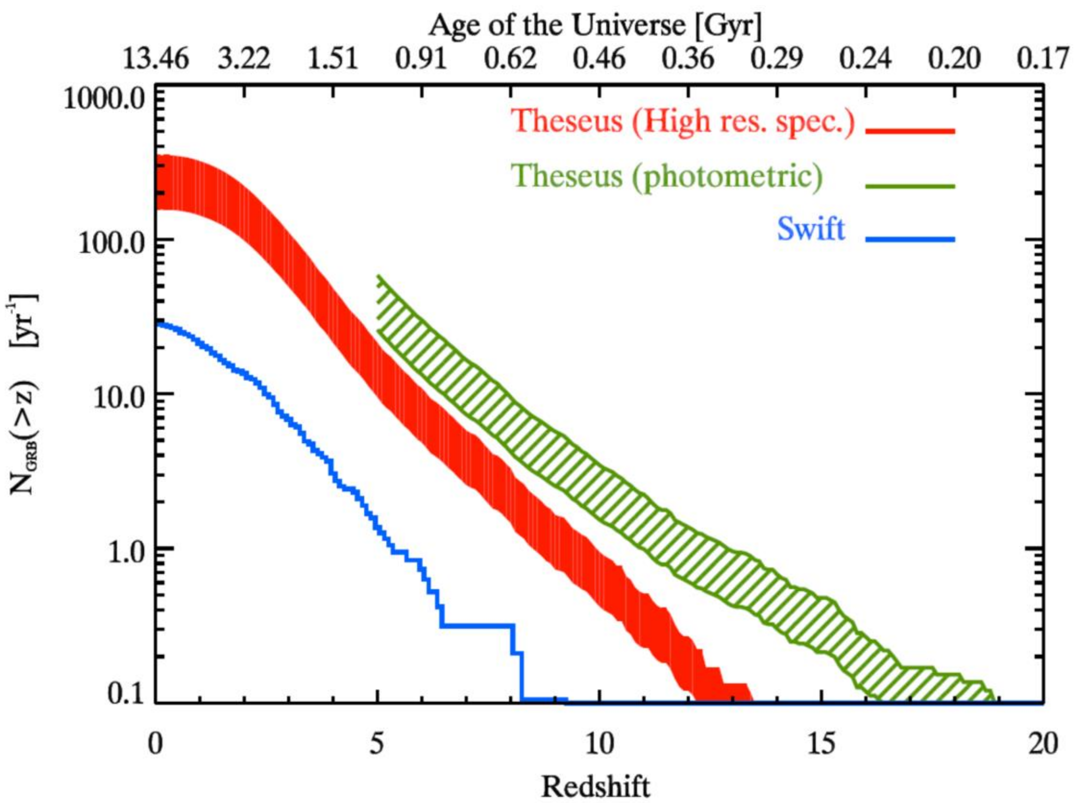


Figure 11: Left: a simulated IRT high resolution (R=500) spectrum for a GRB at z=6.3 observed at 1 hour post trigger assuming a GRB similar to GRB 050904. The spectrum has host log(NH)=21 and neutral fraction Fx=0.5 (and metallicity 0.1solar). The two models are: Red: log(NH)=21.3, Fx=0 Green: log(NH)=20.3,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

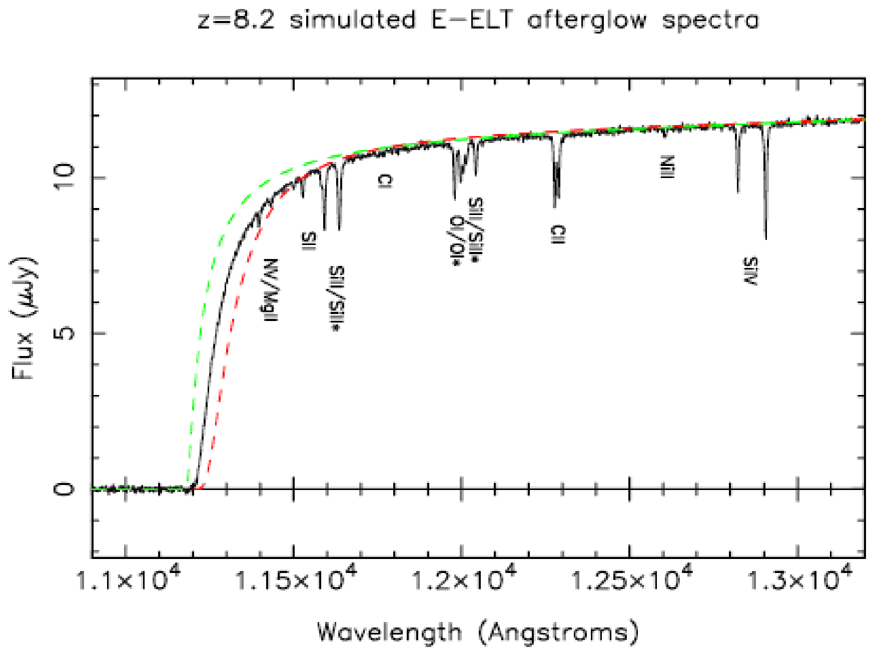
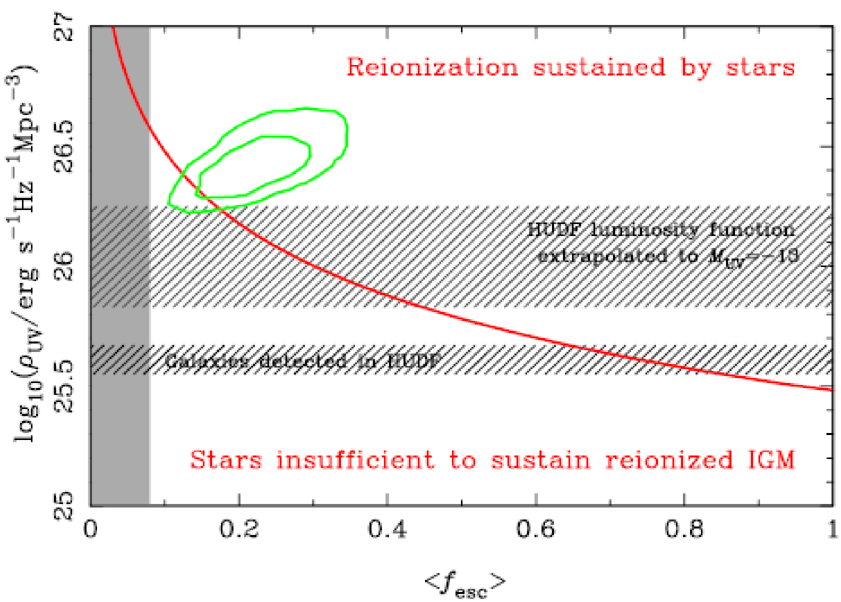
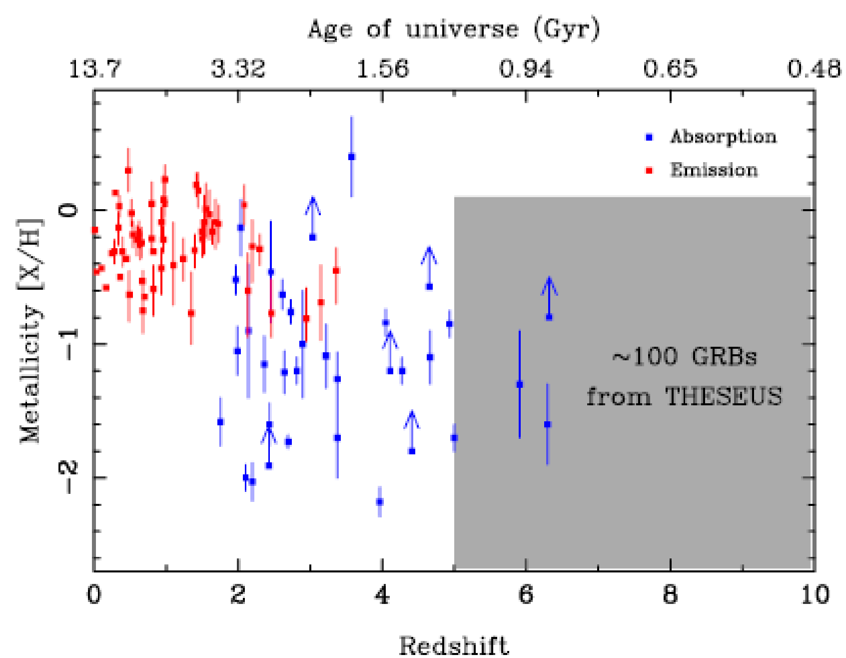
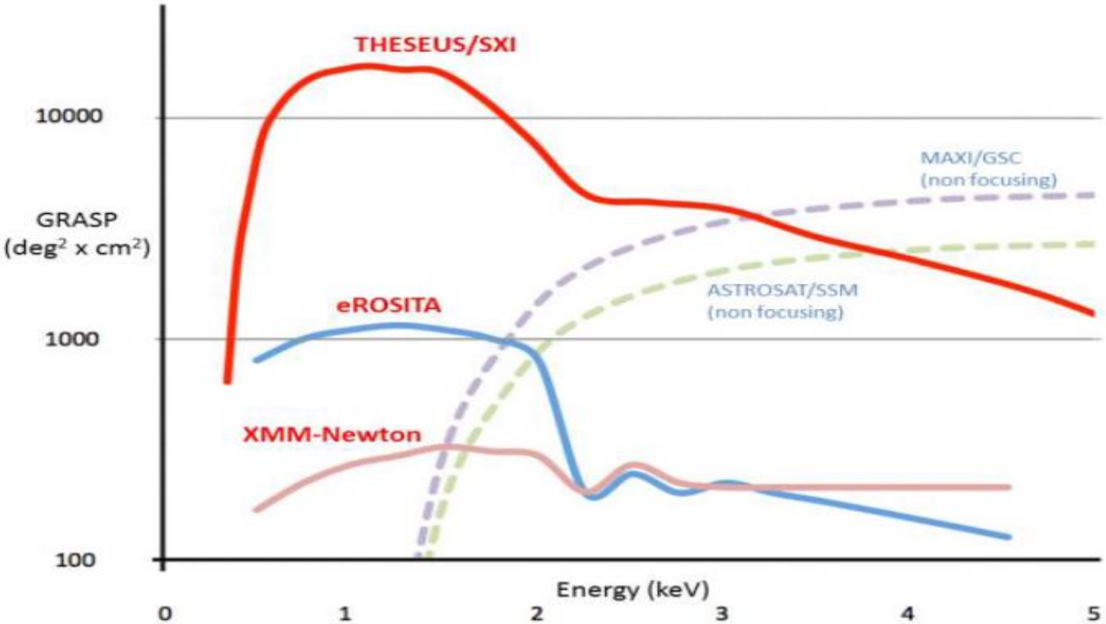


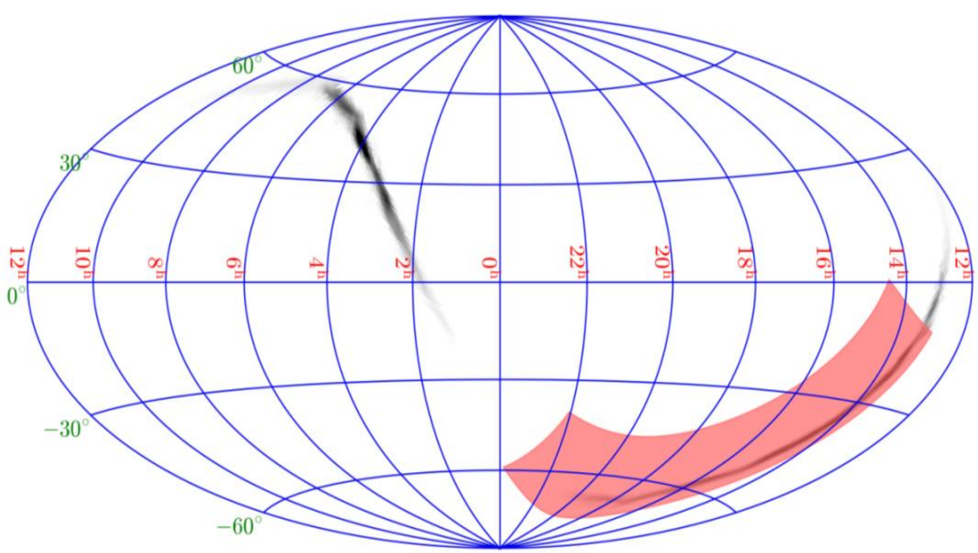
Fig. 1.4: simulated E-ELT 30 min spectrum of a faint GRB afterglow observed after ~1 day. The S/N provides exquisite abundance determinations while fitting the Ly-a damping wing simultaneously fixes the IGM neutral fraction and the host HI column density, as illustrated by the two extreme models, a pure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





❑ GW/multi-messenger and time-domain astrophysics





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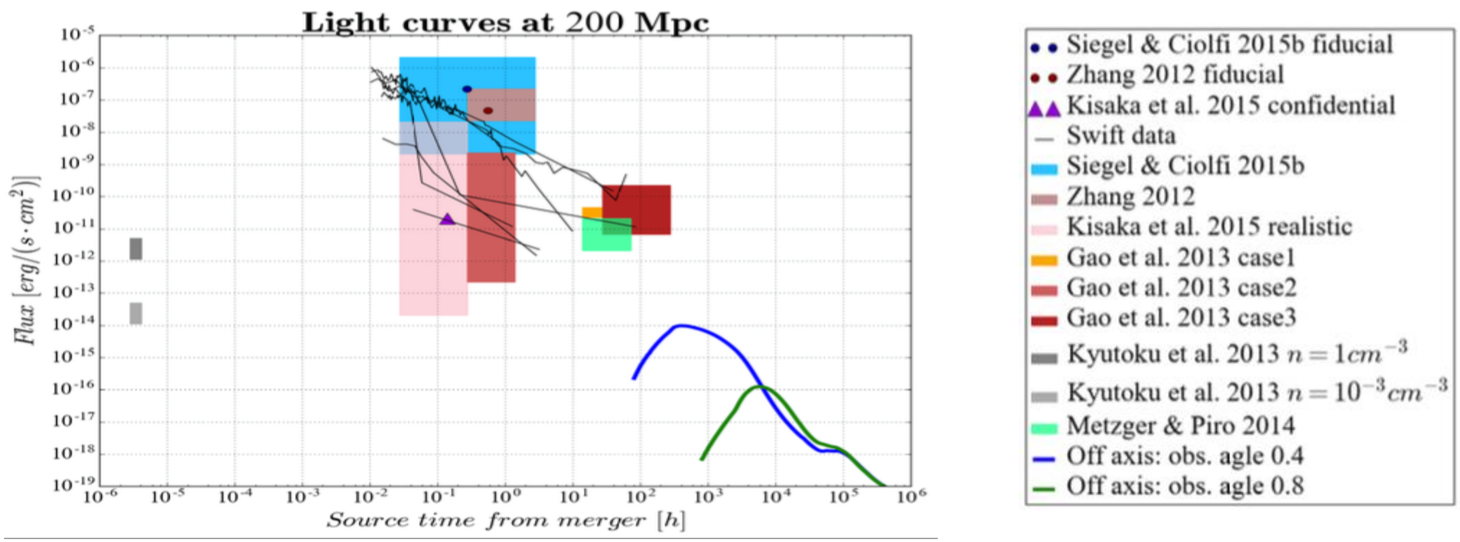
Magnetars	40 day^{-1}
SN shock breakout	4 yr^{-1}
TDE	50 yr^{-1}
AGN+Blazars	350 day^{-1}
Thermonuclear bursts	35 day^{-1}
Novae	250 yr^{-1}
Dwarf novae	30 day^{-1}
SFXTs	1000 yr^{-1}
Stellar flares	400 yr^{-1}
Stellar super flares	200 yr^{-1}

❑ 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

❑ GW/multi-messenger and time-domain astrophysics

- ❑ Several high energy sources that THESEUS will monitor are also thought to be strong neutrino emitters, in particular SNe and GRBs.

  - ❑ High energy neutrinos (>10^5 GeV): ultra-relativistic jets produce shock-accelerated protons that, interacting with high energy photons, originate high energy neutrinos via charged pions decay (e.g. Waxman & Bachall 1997).

  - ❑ Pulsed of low energy neutrinos (< 10 MeV) are expected during CC-Sne. Low energy neutrinos has been detected from SN 1987 A at 50 kpc.

- ❑ GW and neutrino emissions provide important information from the innermost regions (e.g. as the degree of asymmetry in the matter distribution, the rotation rate and strenght of magnetic fields)

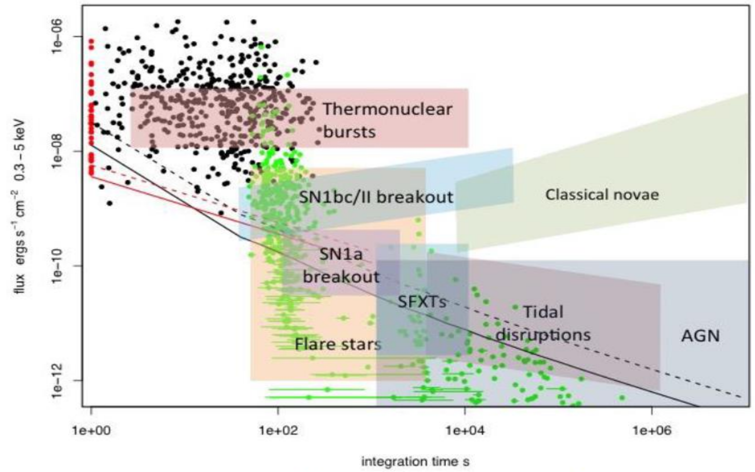
- ❑ Future Megatons detectors as Deep-TITAND are expected to work during the 3G GW detectors, will reach distance up to 8 Mpc thus guaranteeing simultaneous GW/neutrino and EM detections of 1 SN/yr.

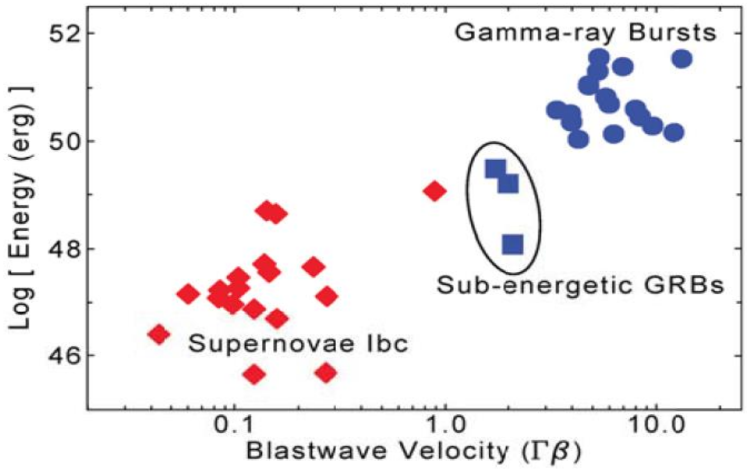
- ❑ Very promising for such multi-messenger sutdies are the LLGRBs given their expected larger rate than for standard LGRBs (up to 1000 higher) and their proximity.

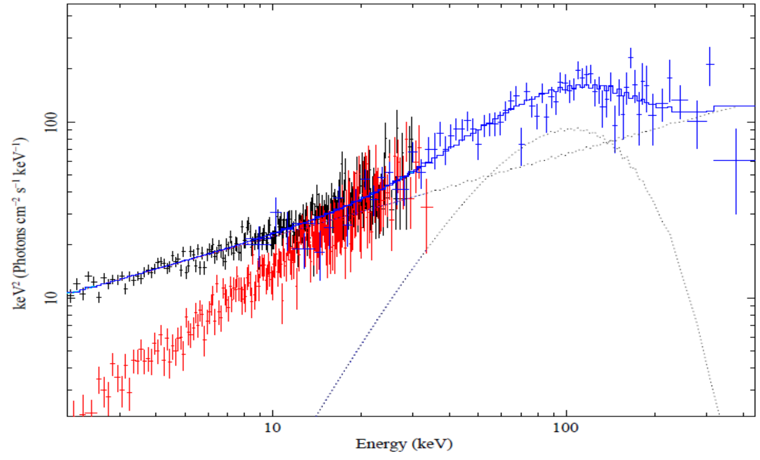
❑ Time-domain astronomy and GRB physics

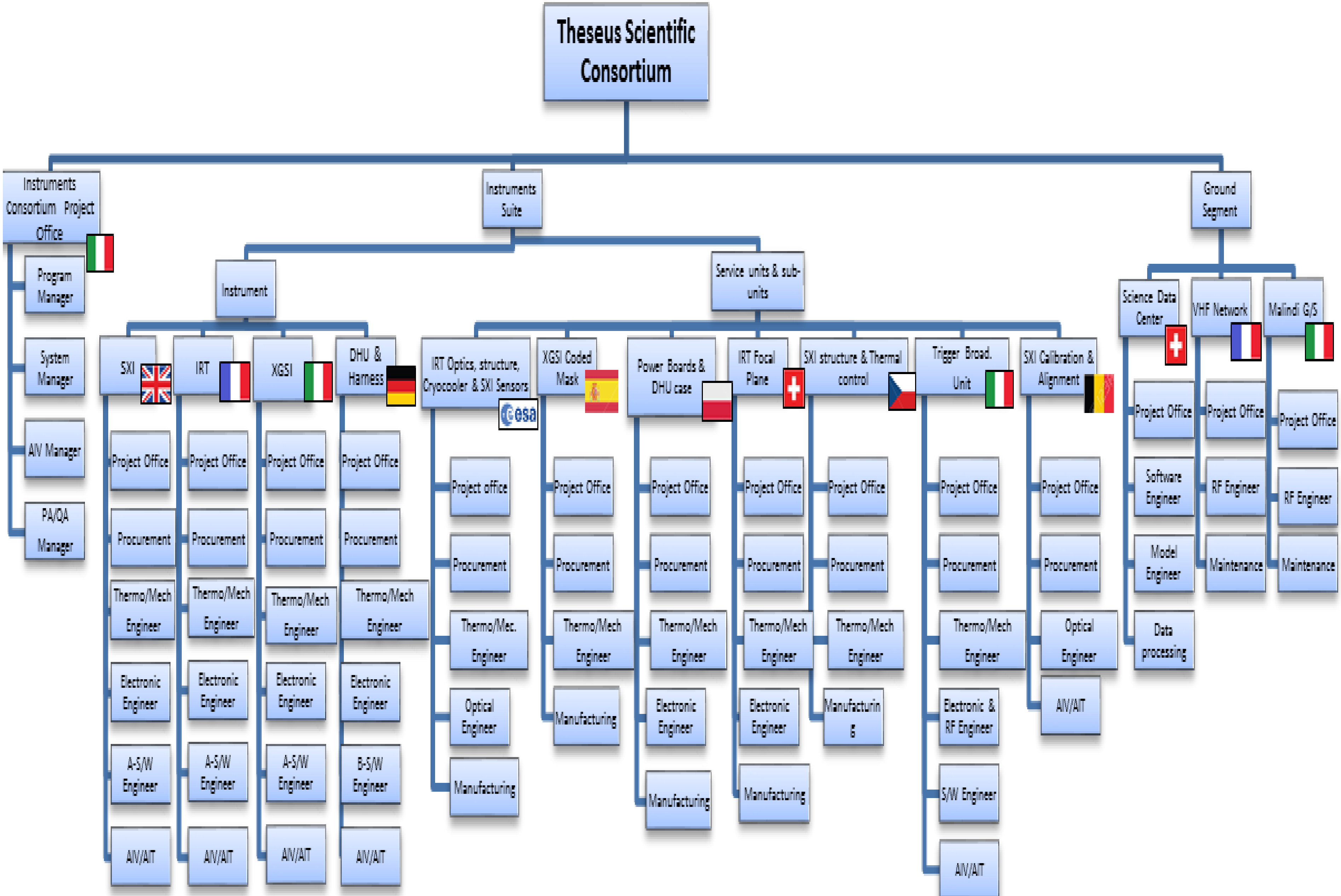
- **survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific sinergy can be anticipated.**
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;
- unprecedented insights in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









A-SW = Applicative Software
B-SW= Basic Software

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)**

- Contributions are very welcome from everybody willing to help (about 200 researcher from worldwide institutions already provided their support to THESEUS/M4). **Please, provide your interest / support to amati@iasfbo.inaf.it or through the THESEUS web-site: http://www.unige.ch/theseus/**