theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

Lorenzo Amati

(INAF – OAS Bologna)

on behalf of the THESEUS international collaboration

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

Amati et al. 2017 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2017 (Adv.Sp.Res., arXiv:1712.08153)

ATHENA

esa

Exploring the Hot and Energetic Universe:
The second scientific conference dedicated to the Athena X-ray observatory

24-27 September 2018, Real Teatro Santa Cecilia, Palermo, Italy
www.astropa.inaf.it/athena18/

www.isdc.unige.ch/theseus/workshop2017-programme.html

Proceedings preprints on the arXiv in early February

(Mem.SAIt, Vol. 89 – N.2 - 2018)

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), C. Tenzer (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

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

Interested international partners: USA, China, Brazil

May 2018: THESEUS selected by ESA for M5 Phase 0/A study

Activity	Date
Phase 0 kick-off	June 2018
Phase 0 completed (EnVision, SPICA and THESEUS)	End 2018
ITT for Phase A industrial studies	February 2019
Phase A industrial kick-off	June 2019
Mission Selection Review (technical and programmatic review for the three mission candidates)	September 2021
SPC selection of M5 mission	November 2021
Phase B1 kick-off for the selected M5 mission	December 2021
Mission Adoption Review (for the selected M5 mission)	March 2024
SPC adoption of M5 mission	June 2024
Phase B2/C/D kick-off	Q1 2025
Launch	2032

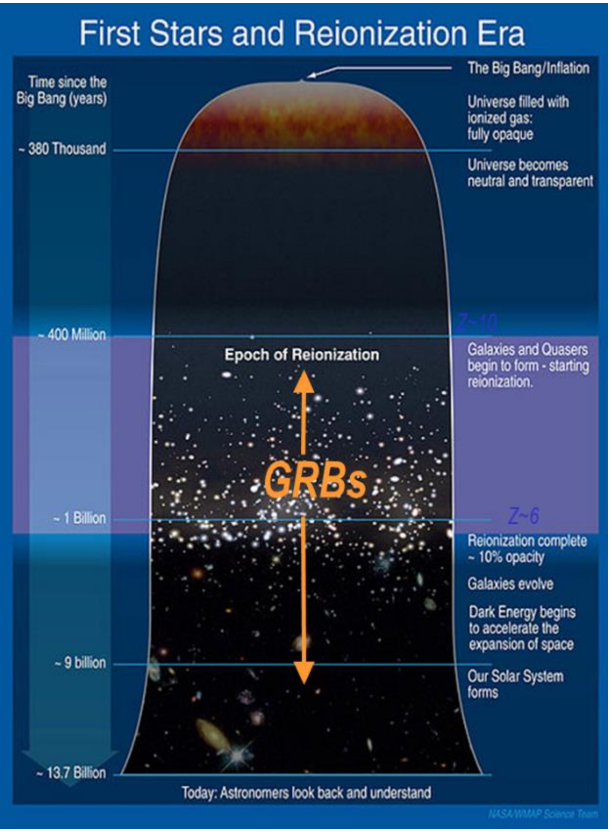
- THESEUS and ATHENA operations may overlap for several years

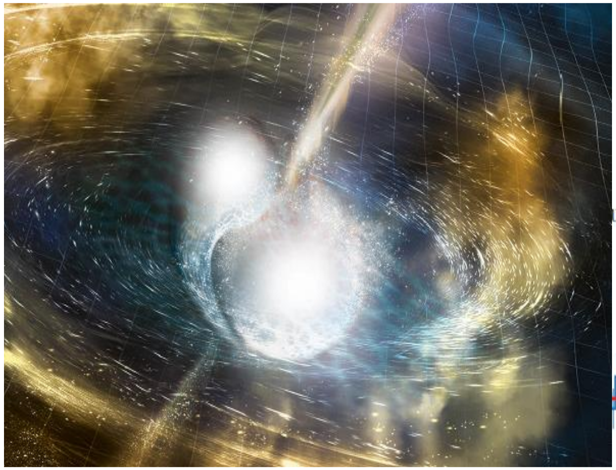
Probing the Early Universe with GRBs

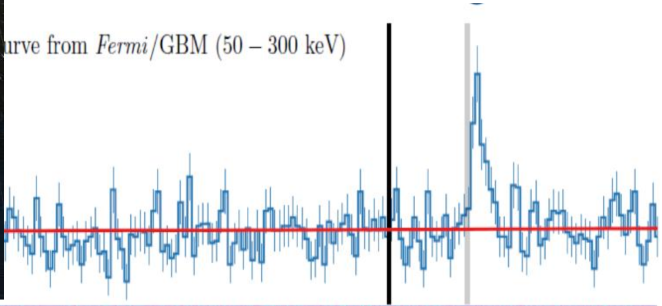
Multi-messenger and time domain Astrophysics

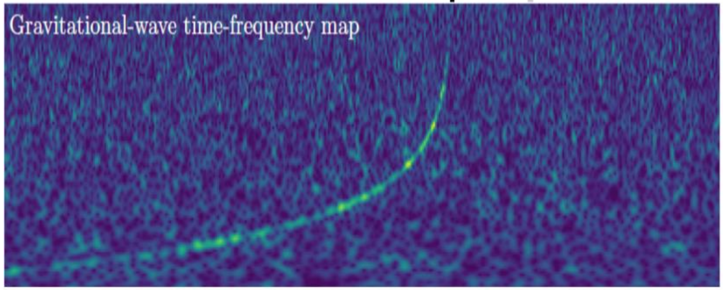
The transient high energy sky

Synergy with next generation large facilities (E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors)



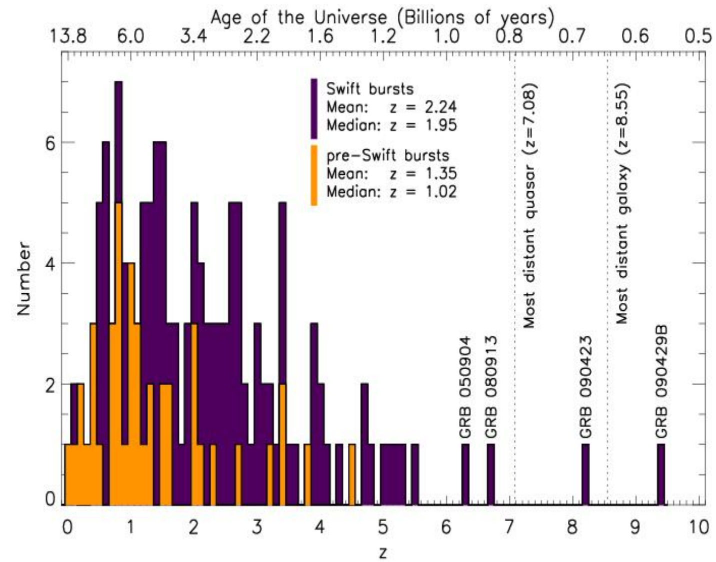




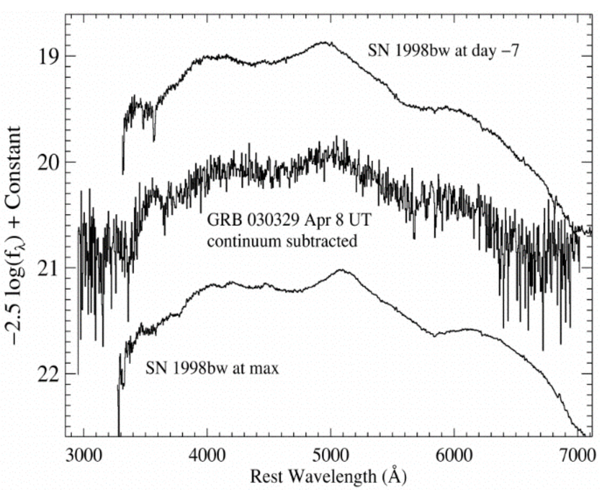


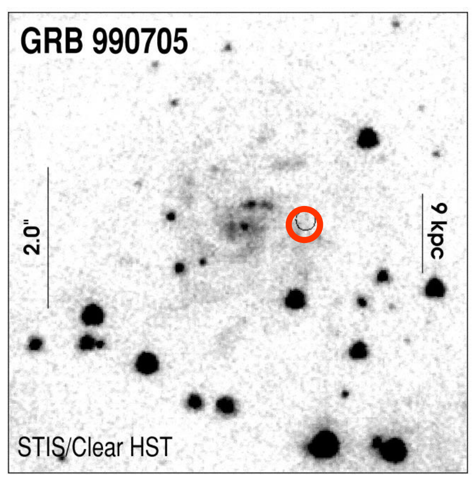
Shedding light on the early Universe with GRBs

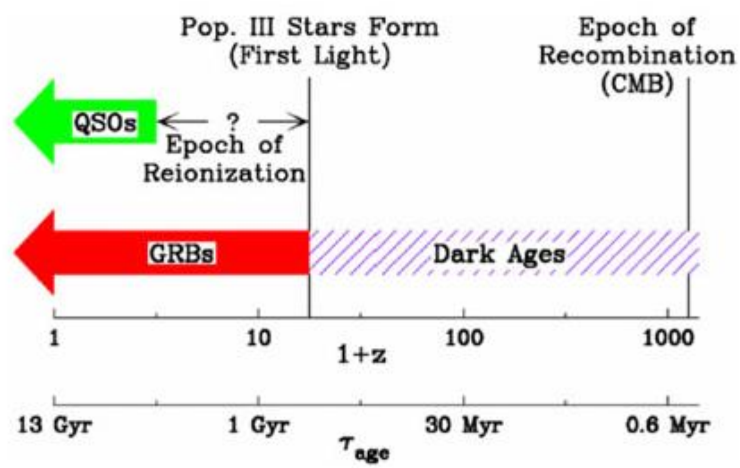
Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**



GRBs in Cosmological Context





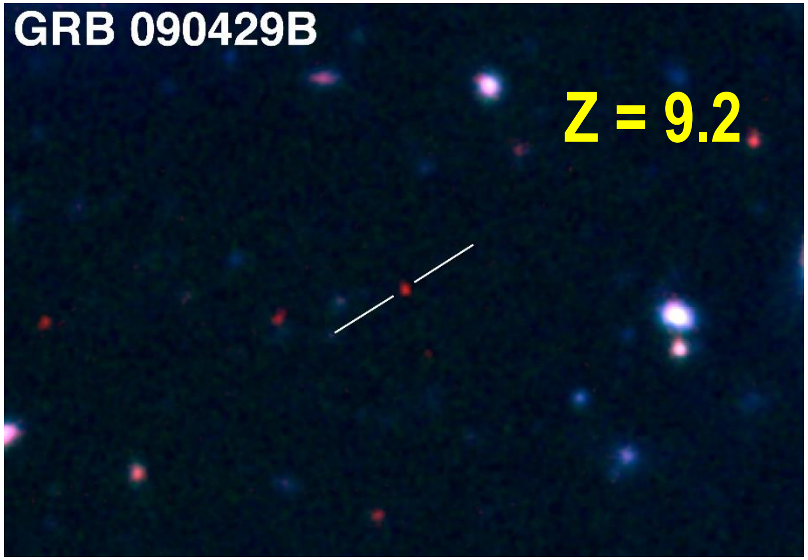


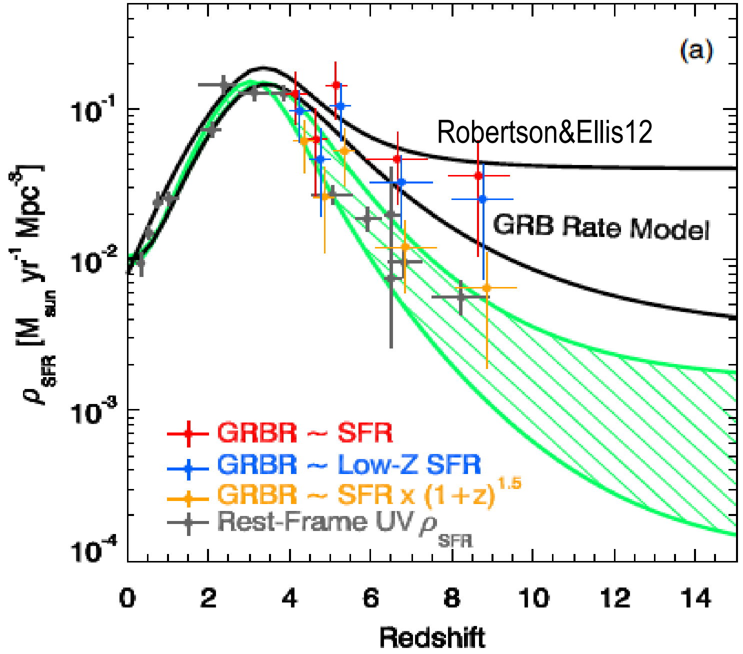
Lamb and Reichart (2000)

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

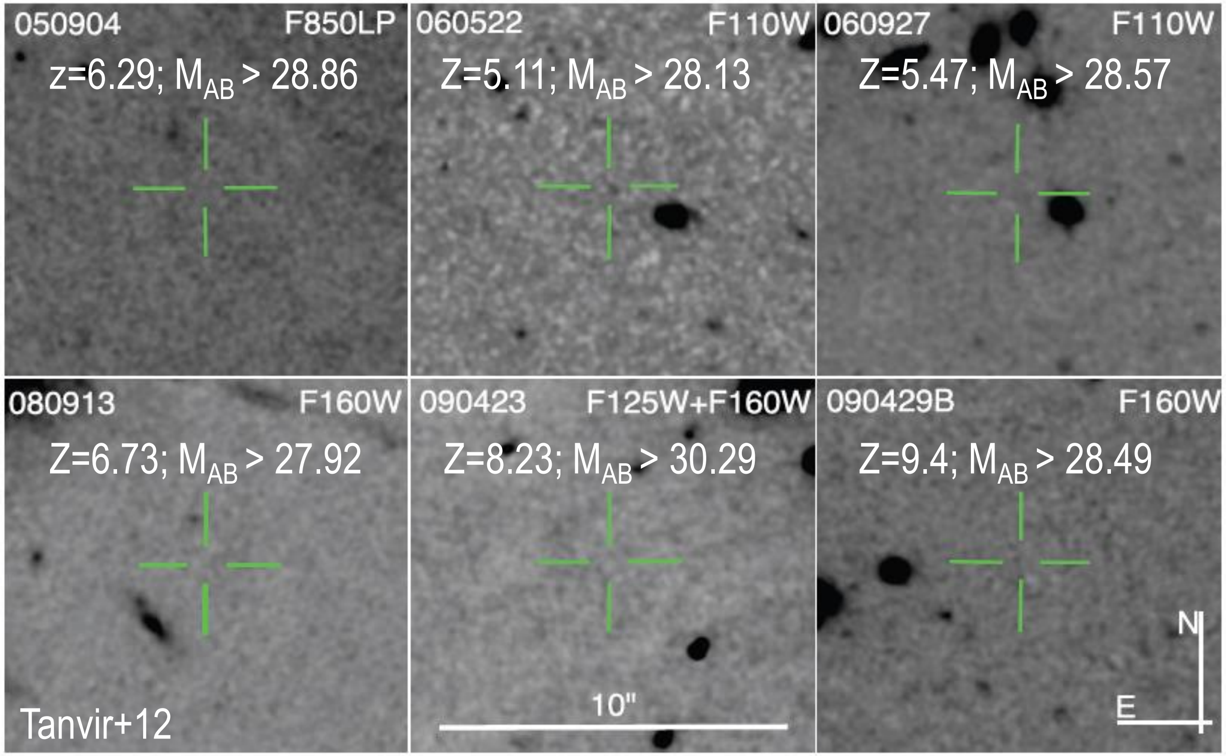
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

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





- the number density and properties of **low-mass galaxies**

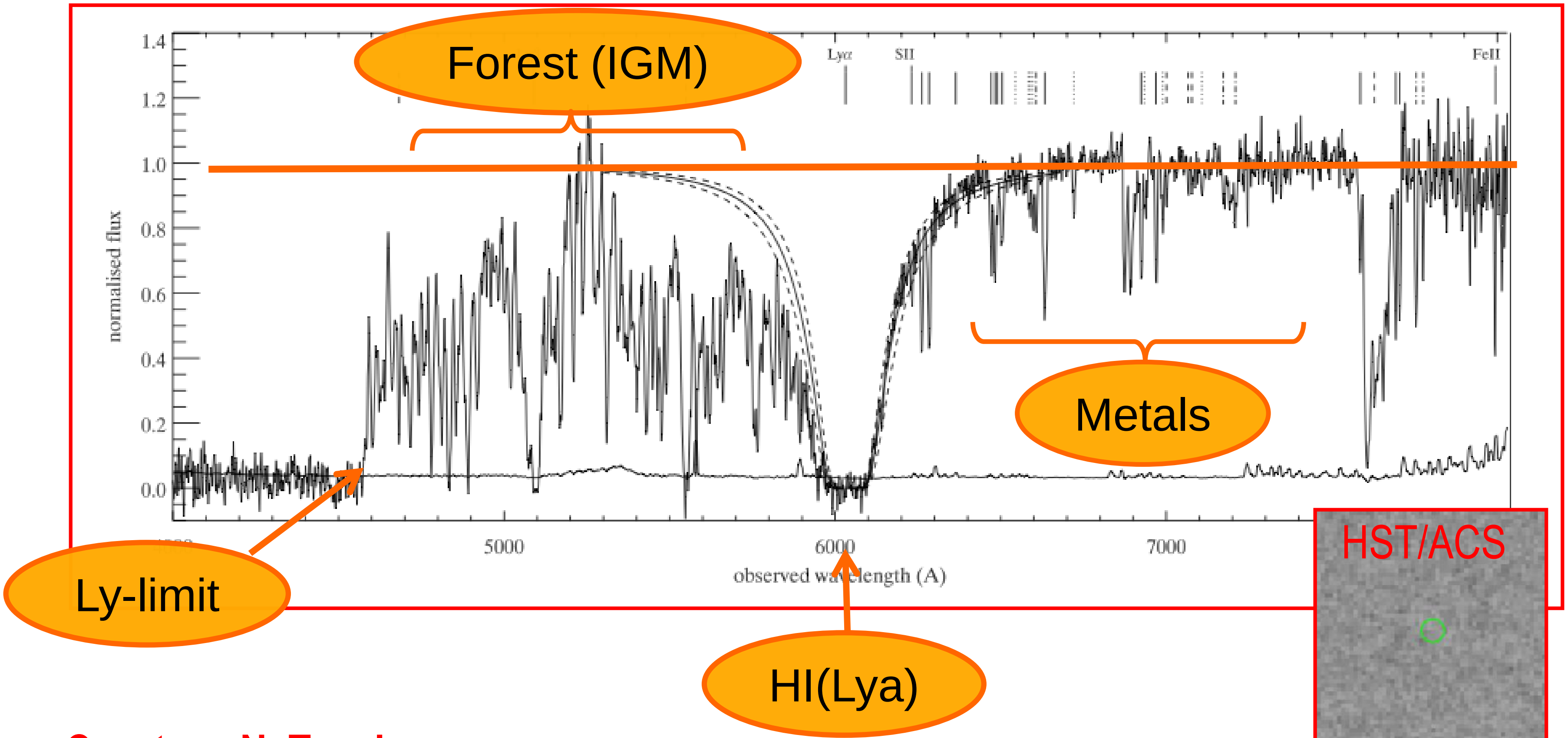


Robertson&Ellis12

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. Tanvir

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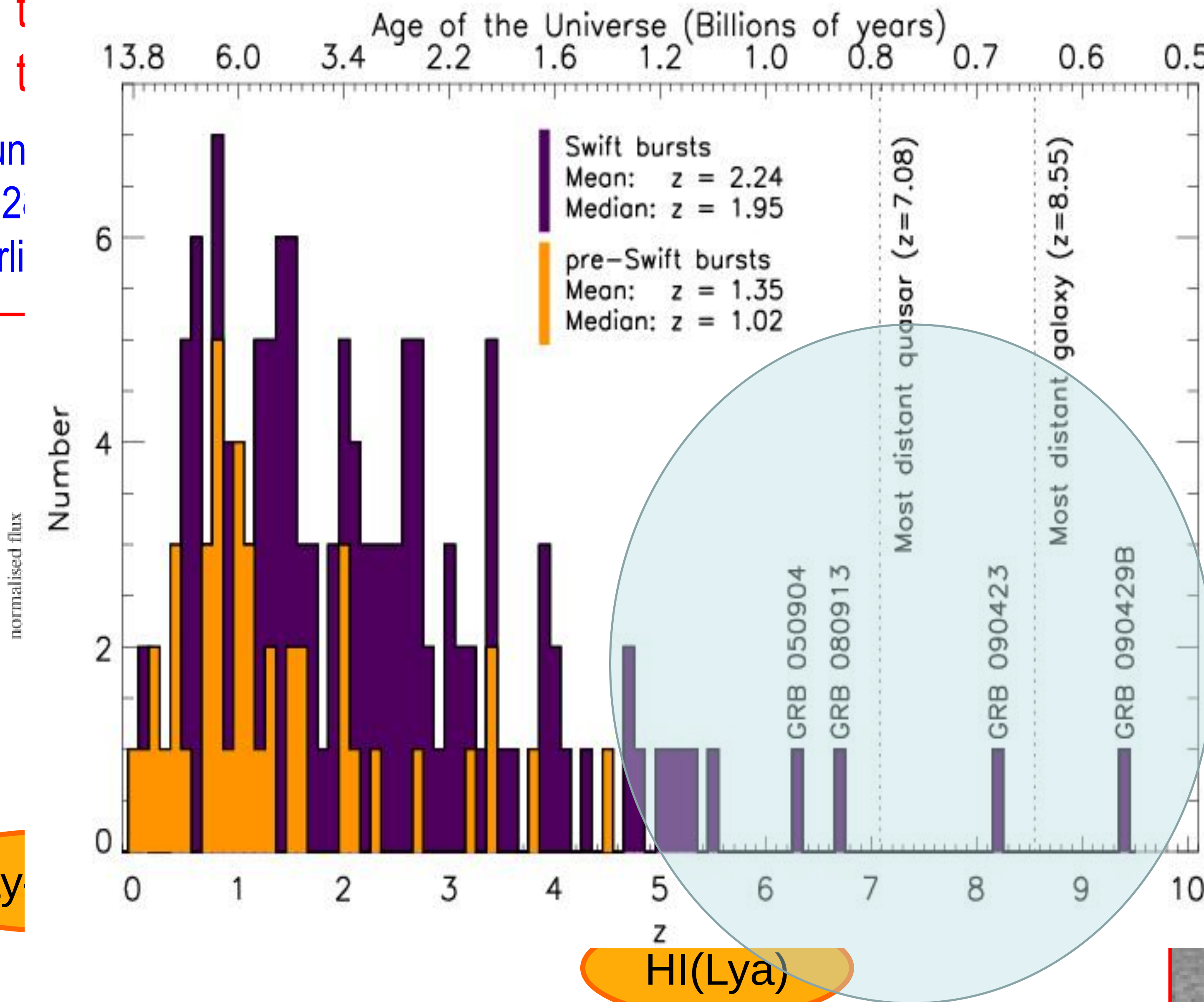

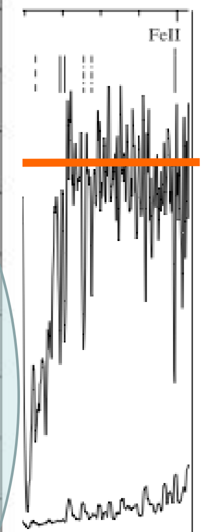

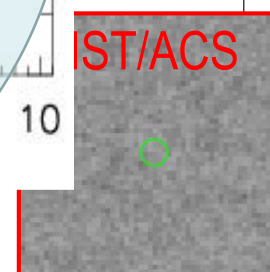

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HI(Lya)

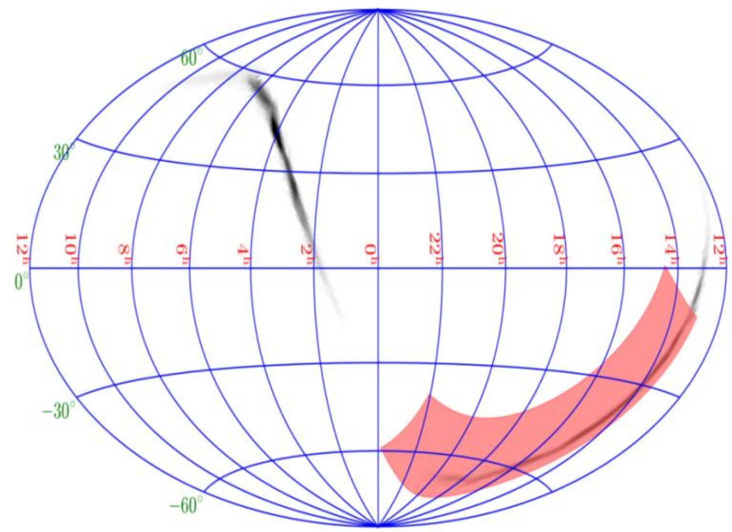
Courtesy N. Tanvir

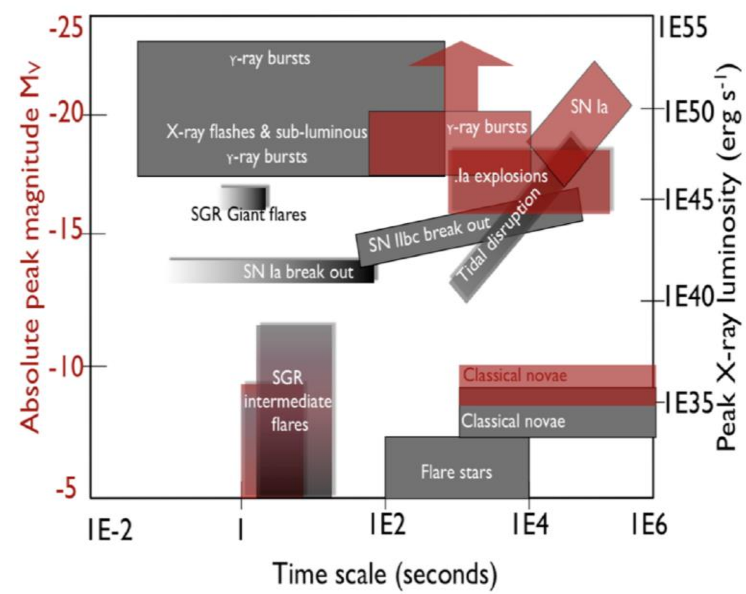
Exploring the multi-messenger transient sky

- **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;**

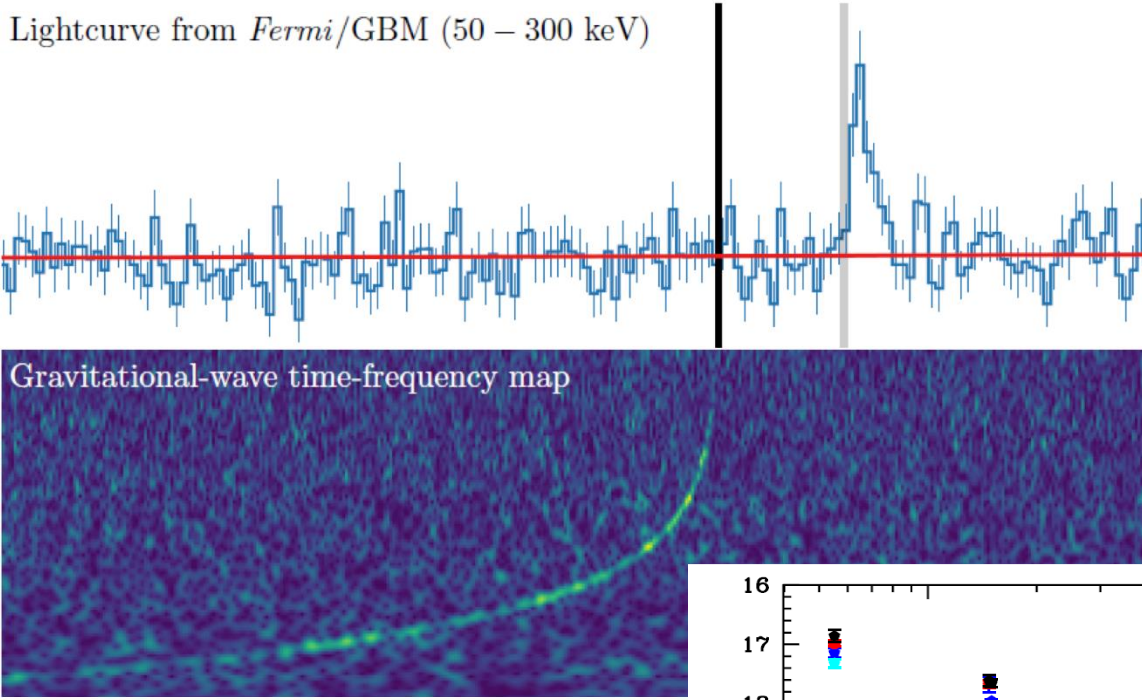
- Provide real-time triggers and accurate (~1 arcmin within a few seconds; ~1'' within a few minutes) **high-energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; synergy with LSST**

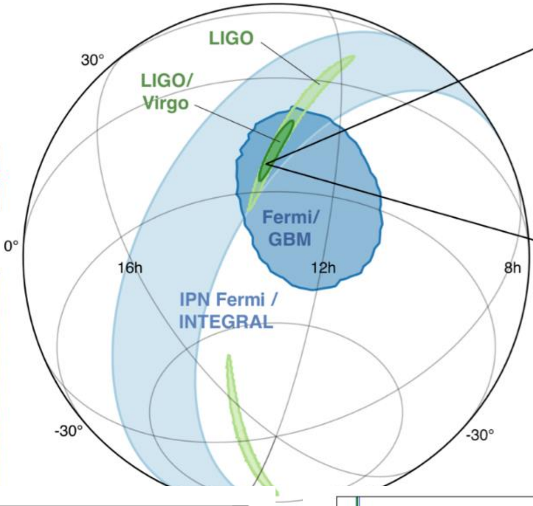
- Provide a fundamental step forward in the comprehension of the physics of various classes of transients and **fill the present gap in the discovery space of new classes of transients events**

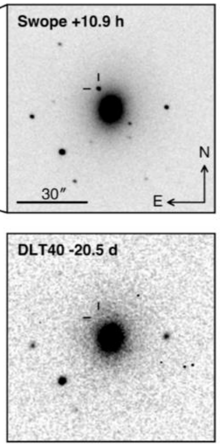


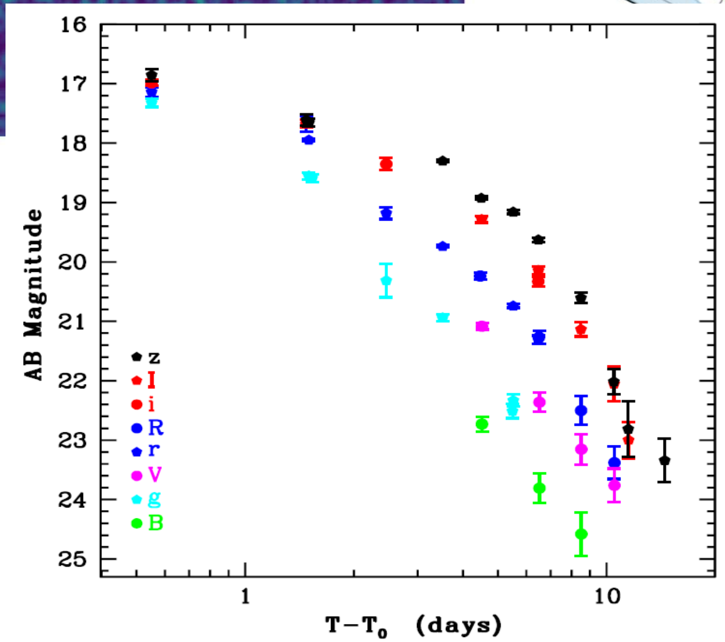


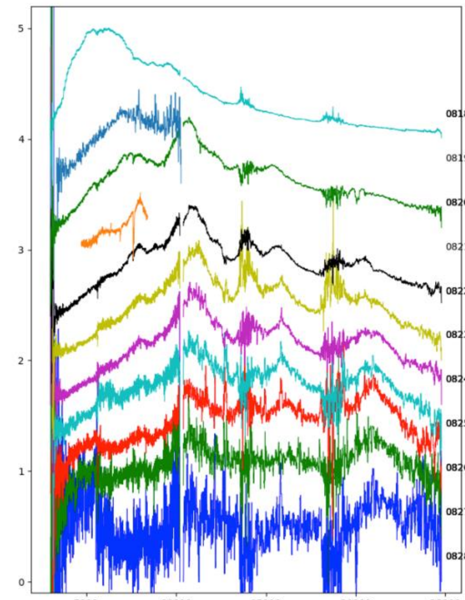
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars





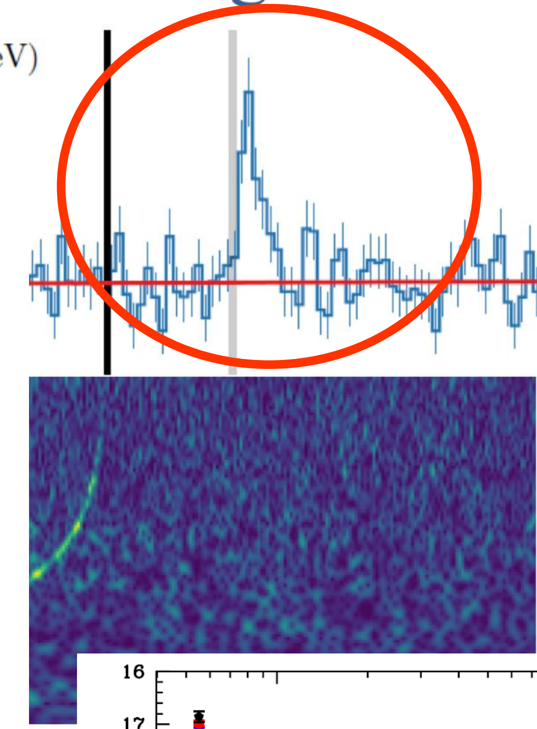






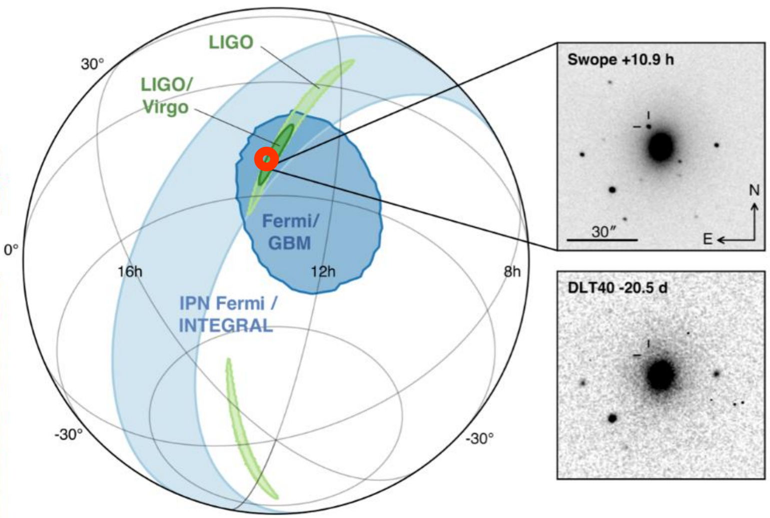
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

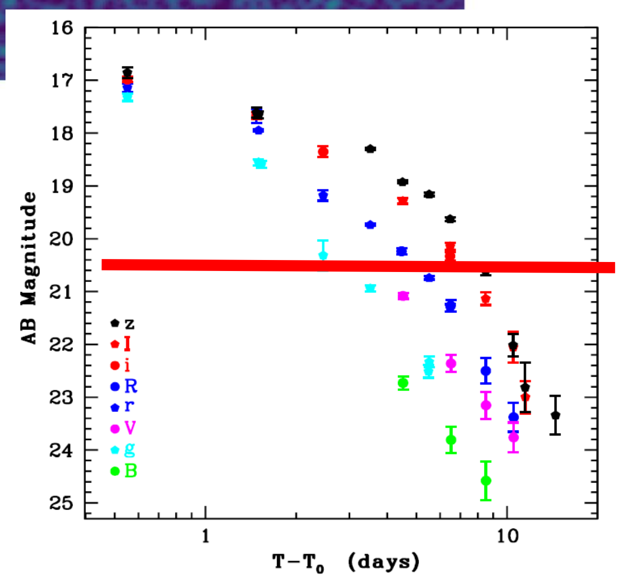
Lightcurve from *Fermi*/GBM (50 – 300 keV)

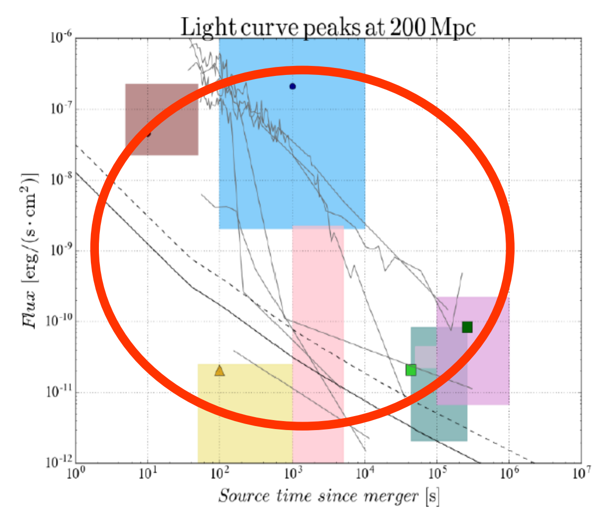


THESEUS:

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

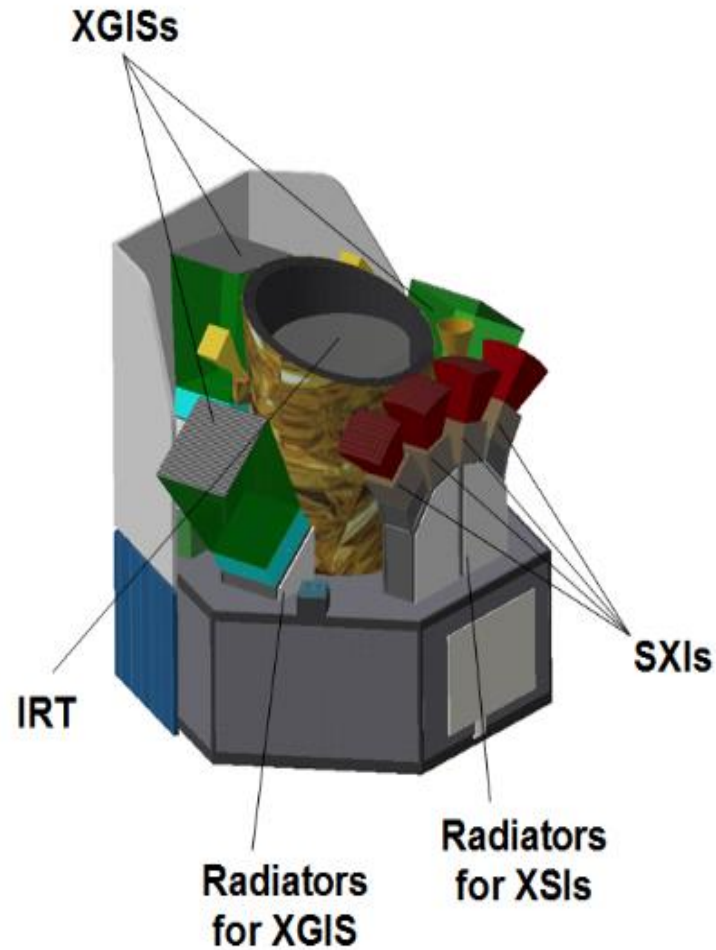






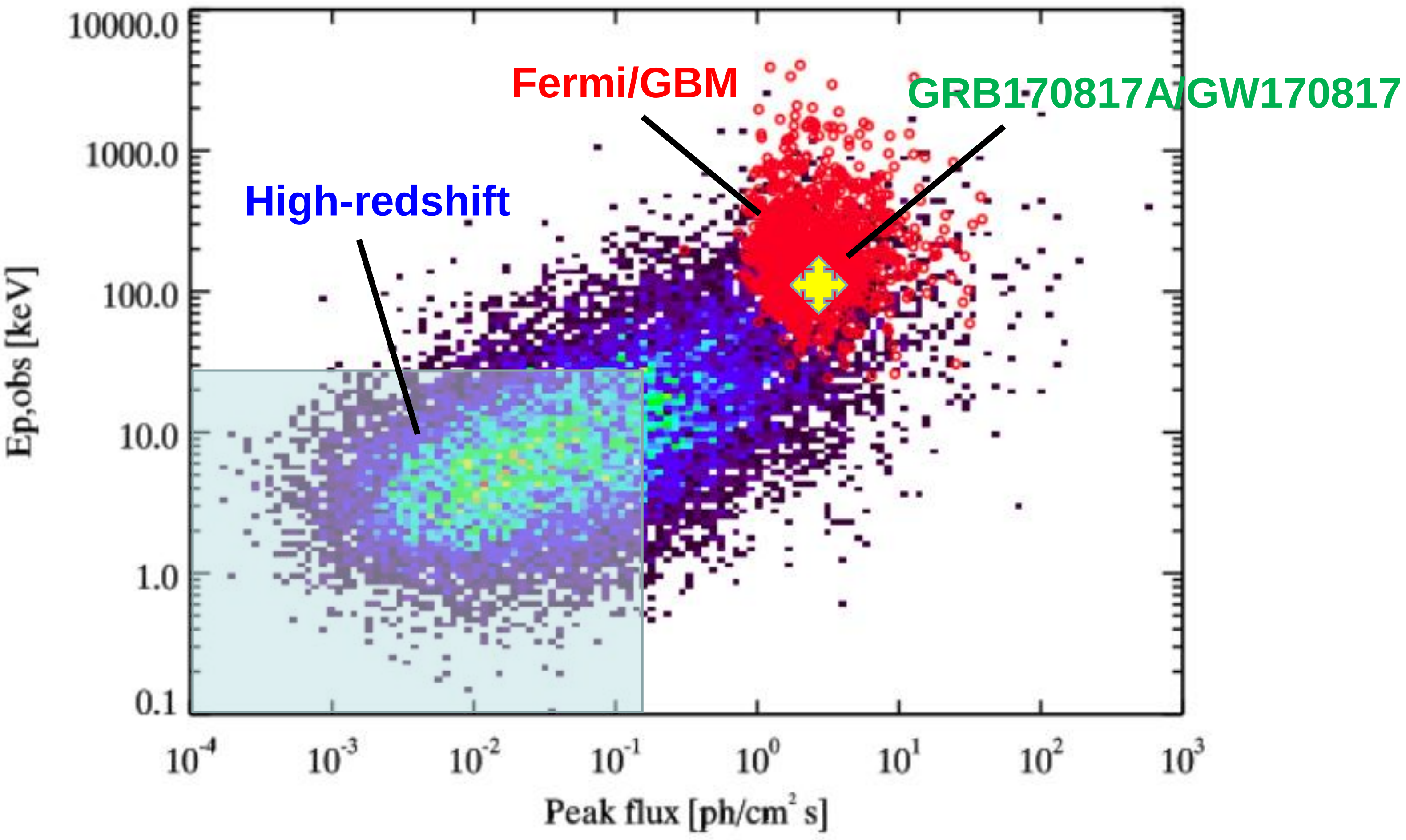
THESEUS mission concept

- **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 0.5-1';**
- **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 ~2-4 sr, 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 (-> redshift)**

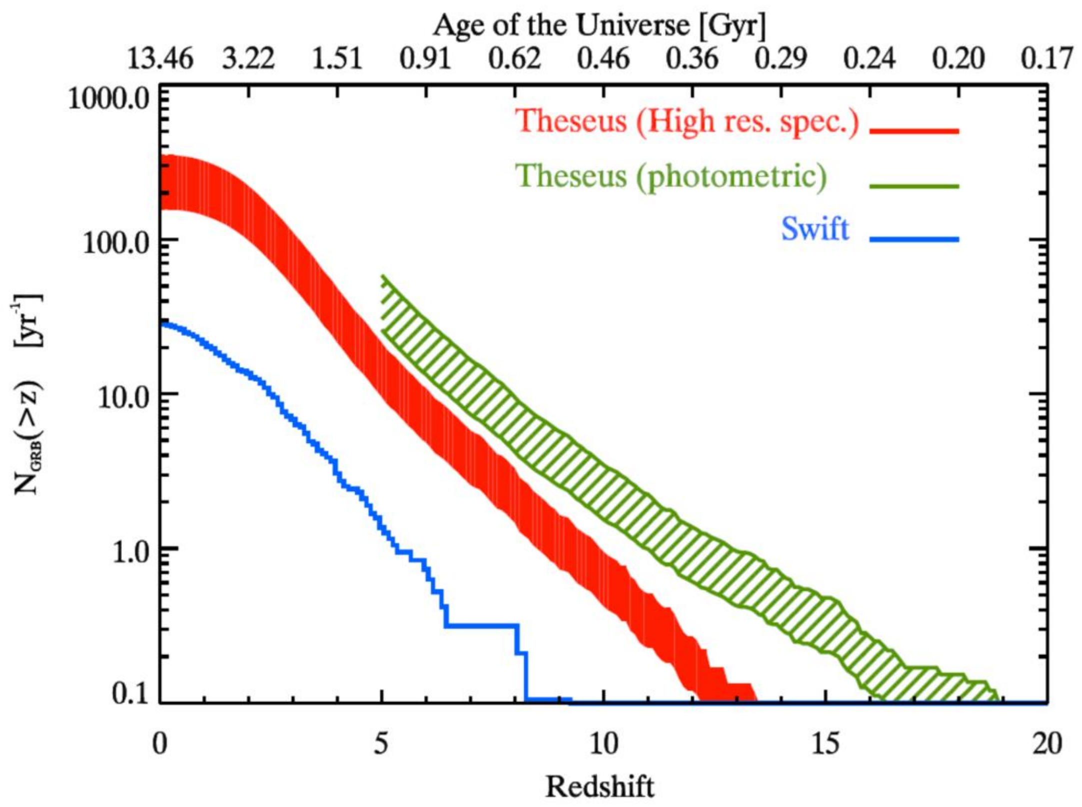


LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink

❑ THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), localizing them from a few arcmin down to arsec and measure the redshift for a large fraction of them



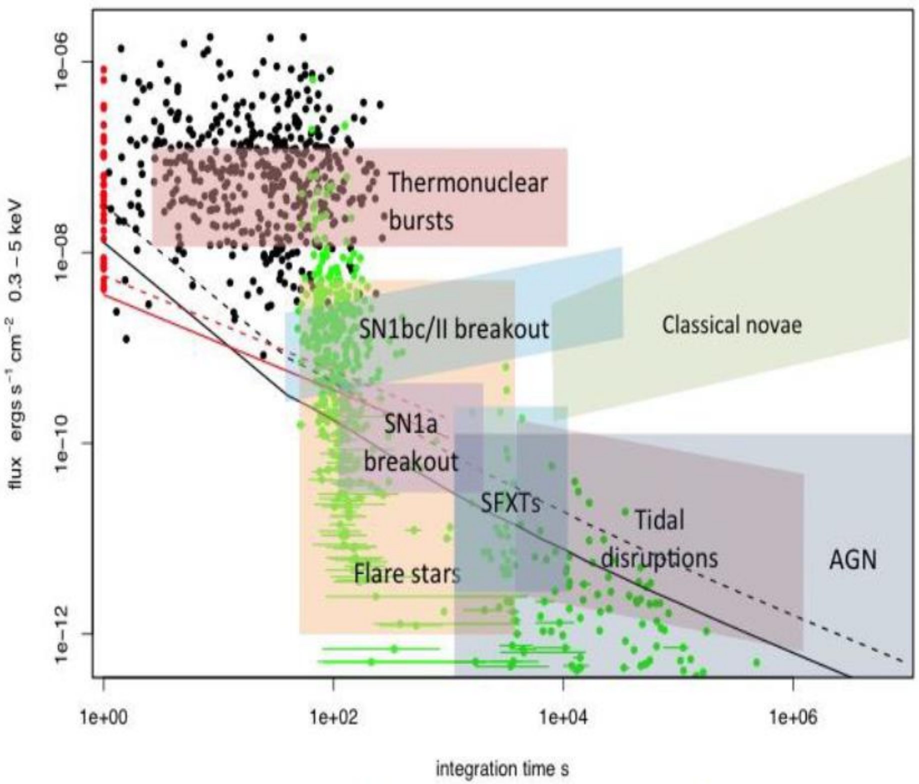
❑ Shedding light on the early Universe with GRBs

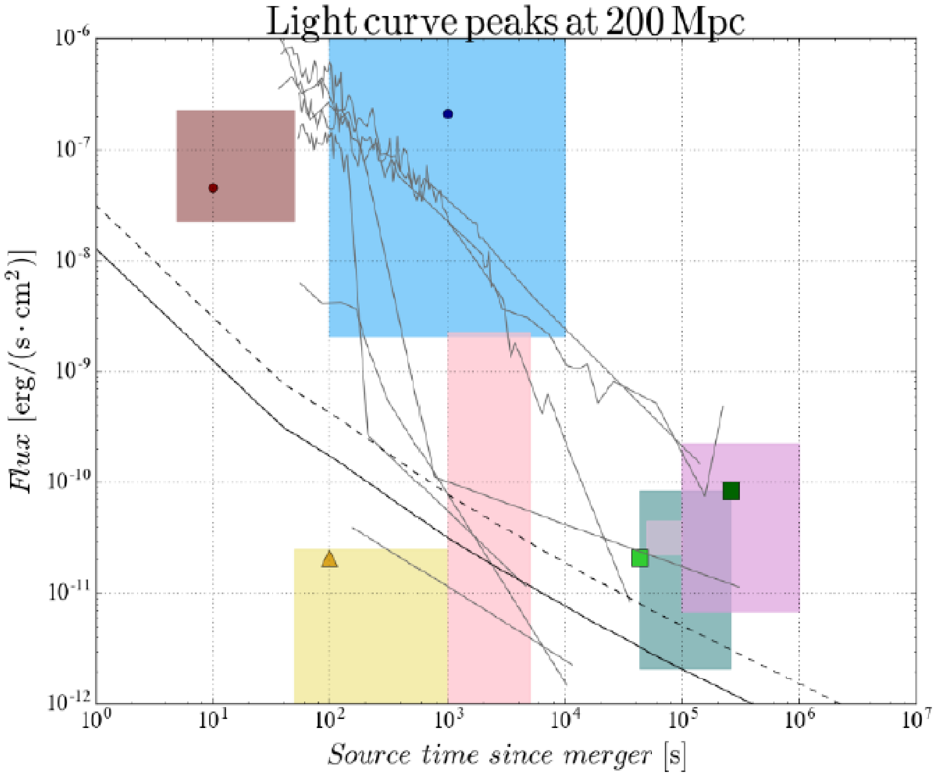


THESEUS GRB#/yr	All	z > 5	z > 8	z > 10
Detections	387 - 870	25 – 60	4 – 10	2 - 4
Photometric z		25 – 60	4 – 10	2 - 4
Spectroscopic z	156 - 350	10 - 20	1 - 3	0.5 - 1

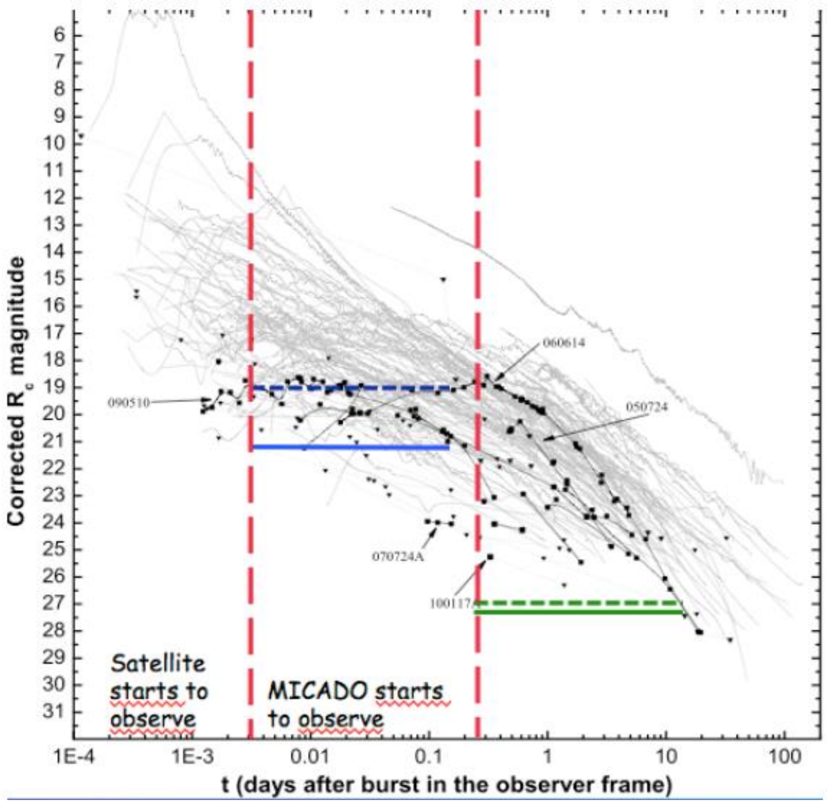
❑ THESEUS will also detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS (BH) mergers and of many classes of galactic and extra-galactic transients

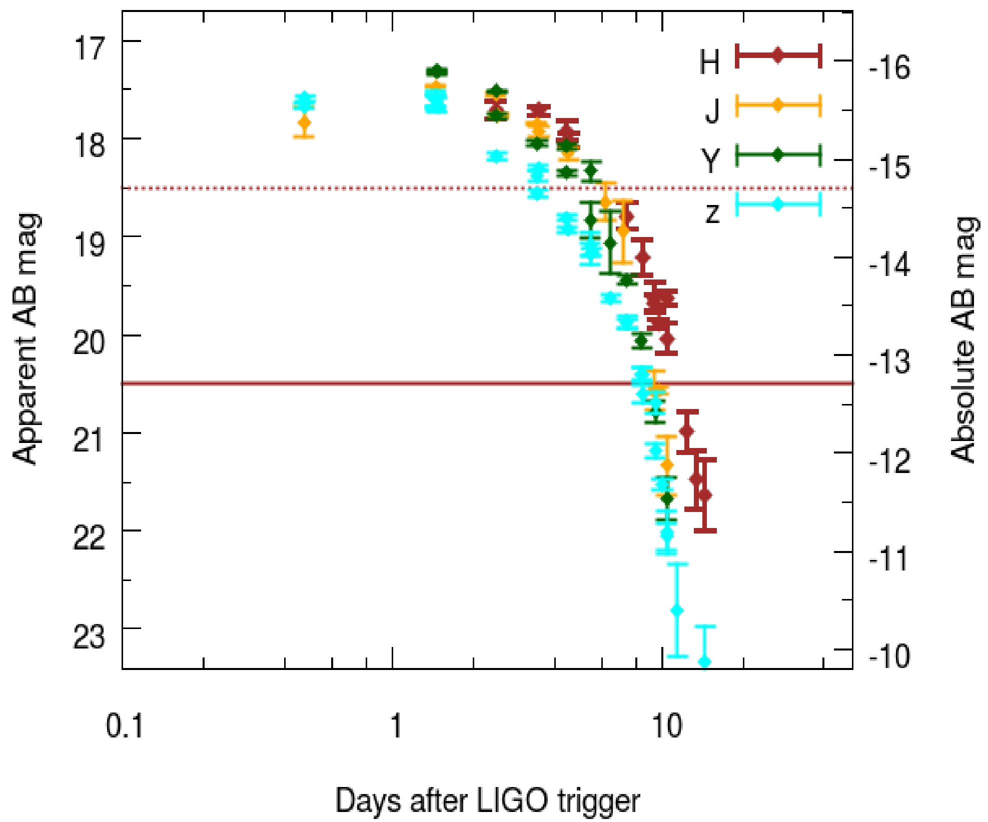
❑ For several of these sources, THESEUS/IRT will provide detection and study of associated NIR emission, location within 1 arcsec and redshift





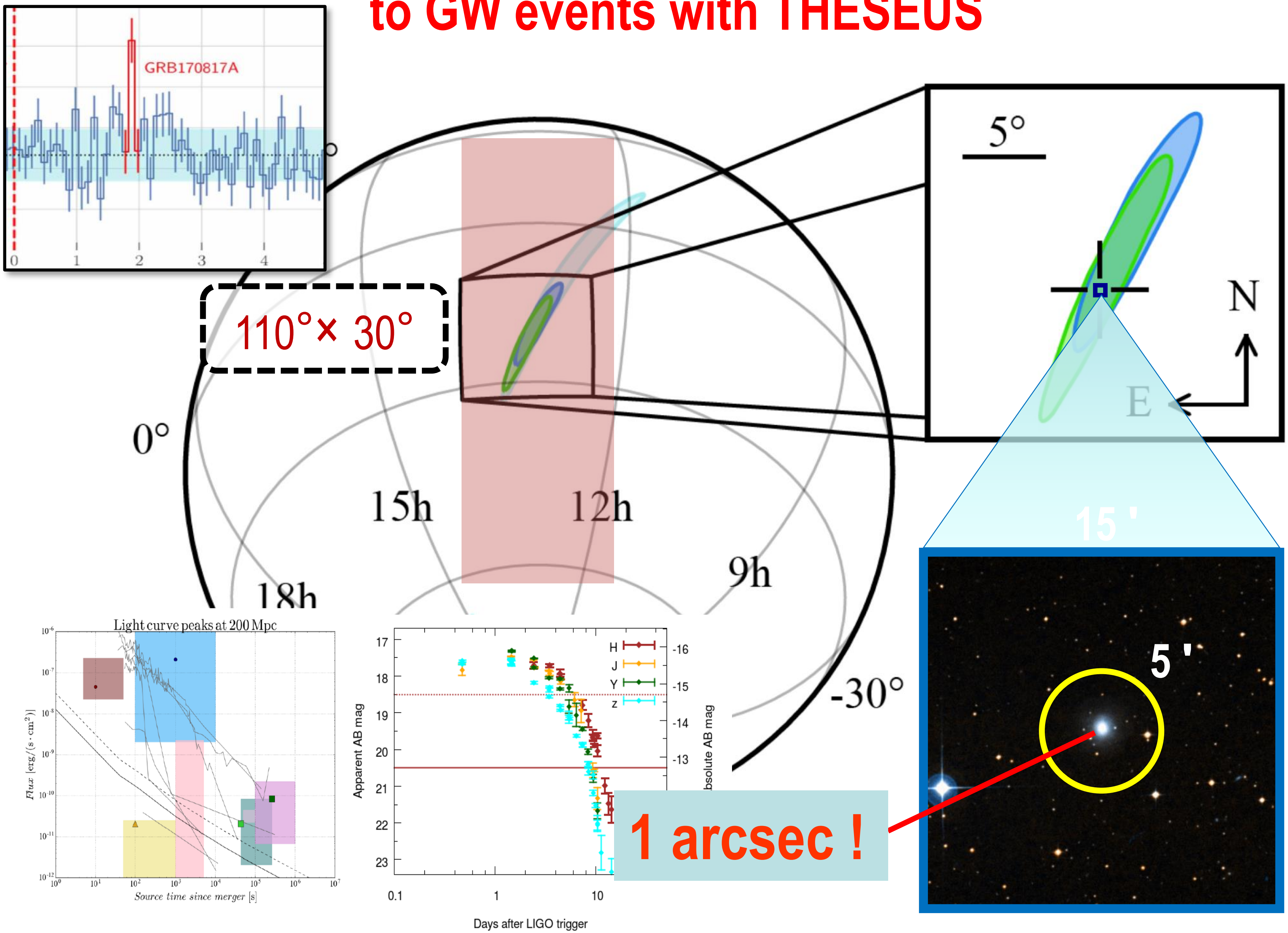
- Detection, study, arcsecond localization and redshift of afterglow and kilonova emission from shortGRB/GW events with THESEUS/IRT





Precise localization is mandatory to activate large ground-based telescopes as VLT or ELT from which detailed spectral analysis will reveal the intrinsic nature of these newly discovered phenomena

❑ Promptly and accurately localizing e.m. counterparts to GW events with THESEUS



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TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- ***THESEUS* Core Science is based on two pillars:**
  - probe the **physical properties of the early Universe**, by discovering and exploiting the population of high redshift GRBs.
  - provide an **unprecedented deep monitoring** of the soft X-ray transient Universe, providing a fundamental contribution to multi-messenger and time domain astrophysics in the early 2030s (synergy with aLIGO/aVirgo, eLISA, ET, Km3NET and EM facilities e.g., LSST, E-ELT, SKA, CTA, ATHENA).

- ***THESEUS* Observatory Science includes:**
  - study of thousands of faint to bright X-ray sources by exploiting the **unique simultaneous availability of broad band X-ray and NIR observations**
  - provide a **flexible follow-up observatory** for fast transient events with multi-wavelength ToO capabilities and **guest-observer programmes**.

Fundamental role of THESEUS for ATHENA science

(with inputs from L. Piro and P. O'Brien)

- Fundamental role of THESEUS for primary Athena science goals involving GRBs:

(1) Locate the missing baryons in the Universe by probing the Warm Hot Intergalactic Medium (the WHIM)

(2) Probe the first generation of stars by finding high redshift GRBs

- THESEUS will:

(1) localise bright GRBs with sufficient accuracy to enable a rapid repointing of the Athena X-IFU for X-ray spectroscopy of the WHIM

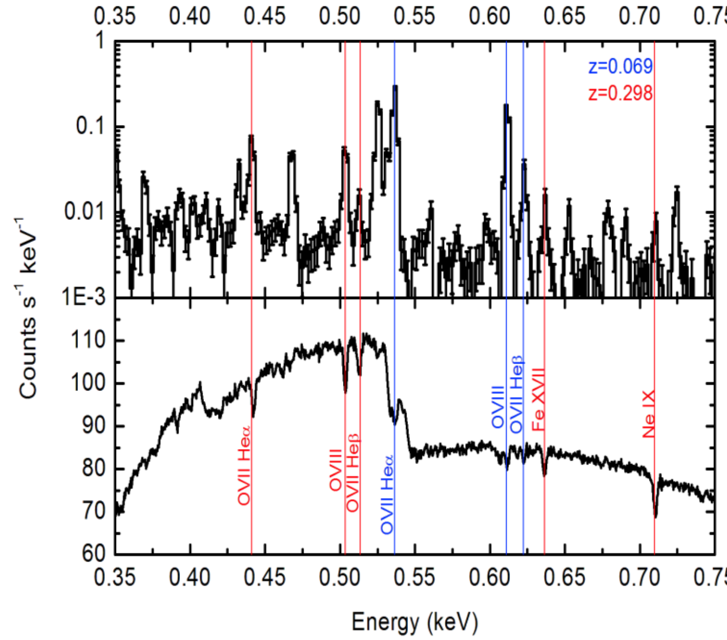
(2) find high-redshift GRBs using the SXI and XGIS and accurately localising them using the IRT for redshift determination on-board to provide reliable high-redshift targets for Athena.

- Many other transients found by THESEUS (e.g., TDEs, magnetars, flaring binaries and e.m. counterparts (short GRBs, soft X-ray transients) of GW events will also be high-value targets for Athena.

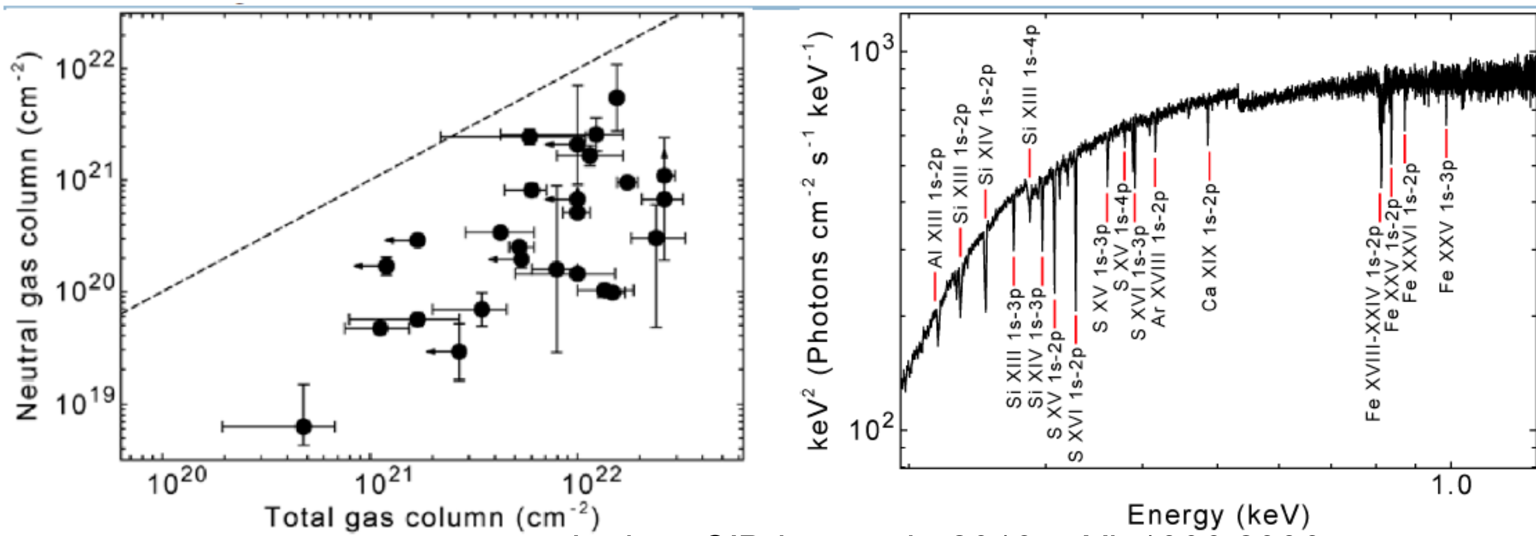
GRB are in the core science of Athena as beacons to:

- ❑ **Find the missing baryons in the WHIM: about 10 GRB afterglows per year selected for brightness (prompt emission as proxy)**

- ❑ **Find primordial stars sites in the High-z Universe: 5 GRB afterglows per year selected for redshift (photo-z with IR telescopes, other indicators…)**



Kaastra et al., 2013 arXiv 1306.2324



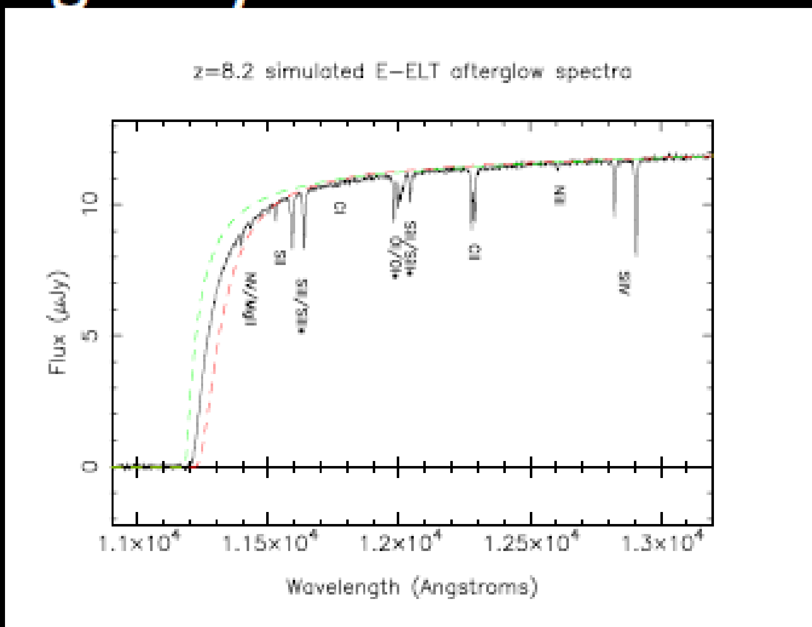
Jonker, O'Brien et al., 2013 arXiv1306.2336

ATHENA+

Follow-up of high-z GRB with large facilities

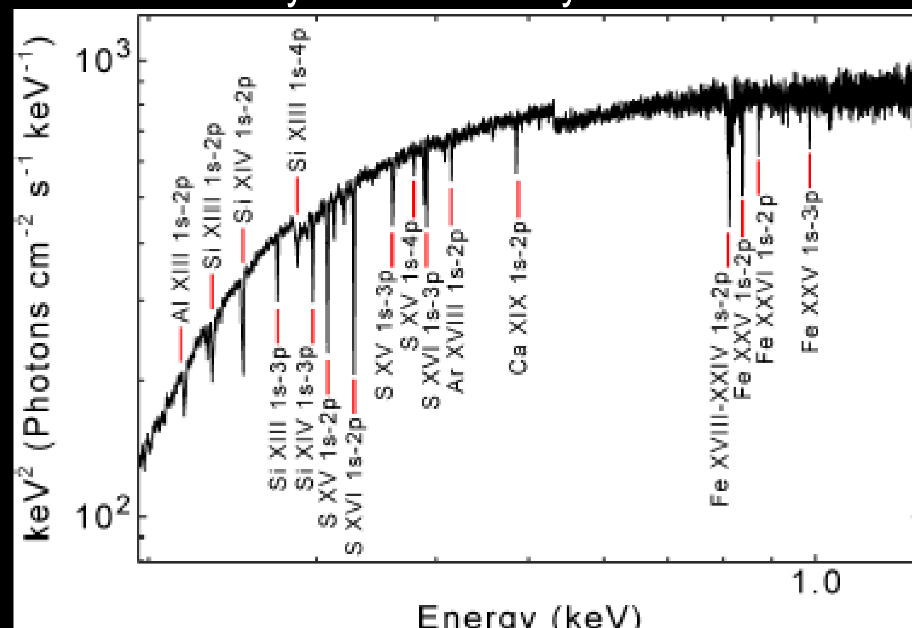
- Optical/IR abs. spectroscopy of the host galaxy

X-ray spectroscopy of the progenitor environme



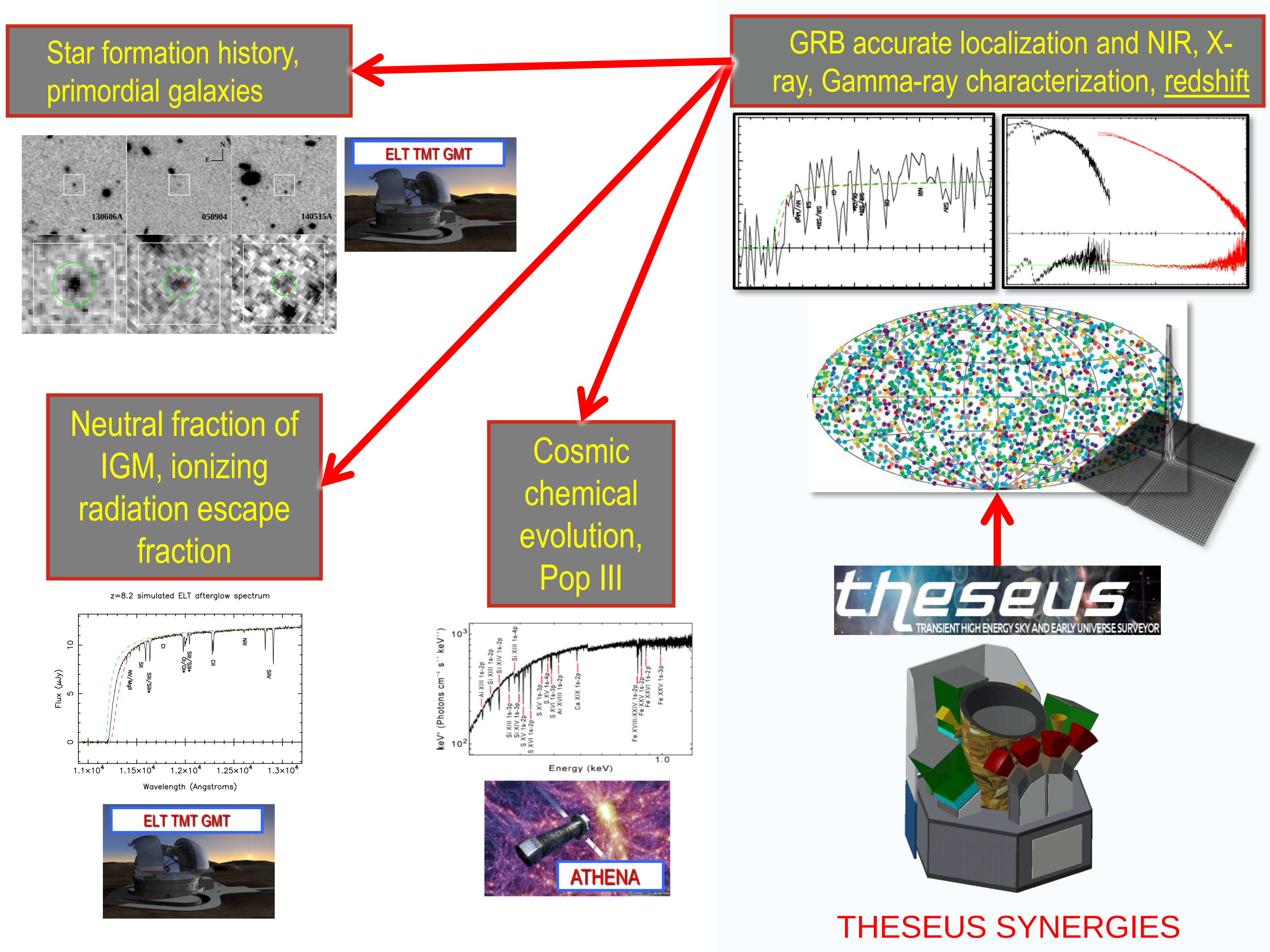
30+ m class ELTs

Gamma Ray Burst at z=7 by ATHENA-XIFU



ESA L2 X-ray Observatory

Jonker, O'Brien et al., 2013 arXiv1306.2336


Star formation history, primordial galaxies
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
130606A
050904
140515A
ELT TMT GMT
Neutral fraction of IGM, ionizing radiation escape fraction
Cosmic chemical evolution, Pop III
z=8.2 simulated ELT afterglow spectrum
Flux (μJy)
Wavelength (Angstroms)
Energy (keV)
ELT TMT GMT
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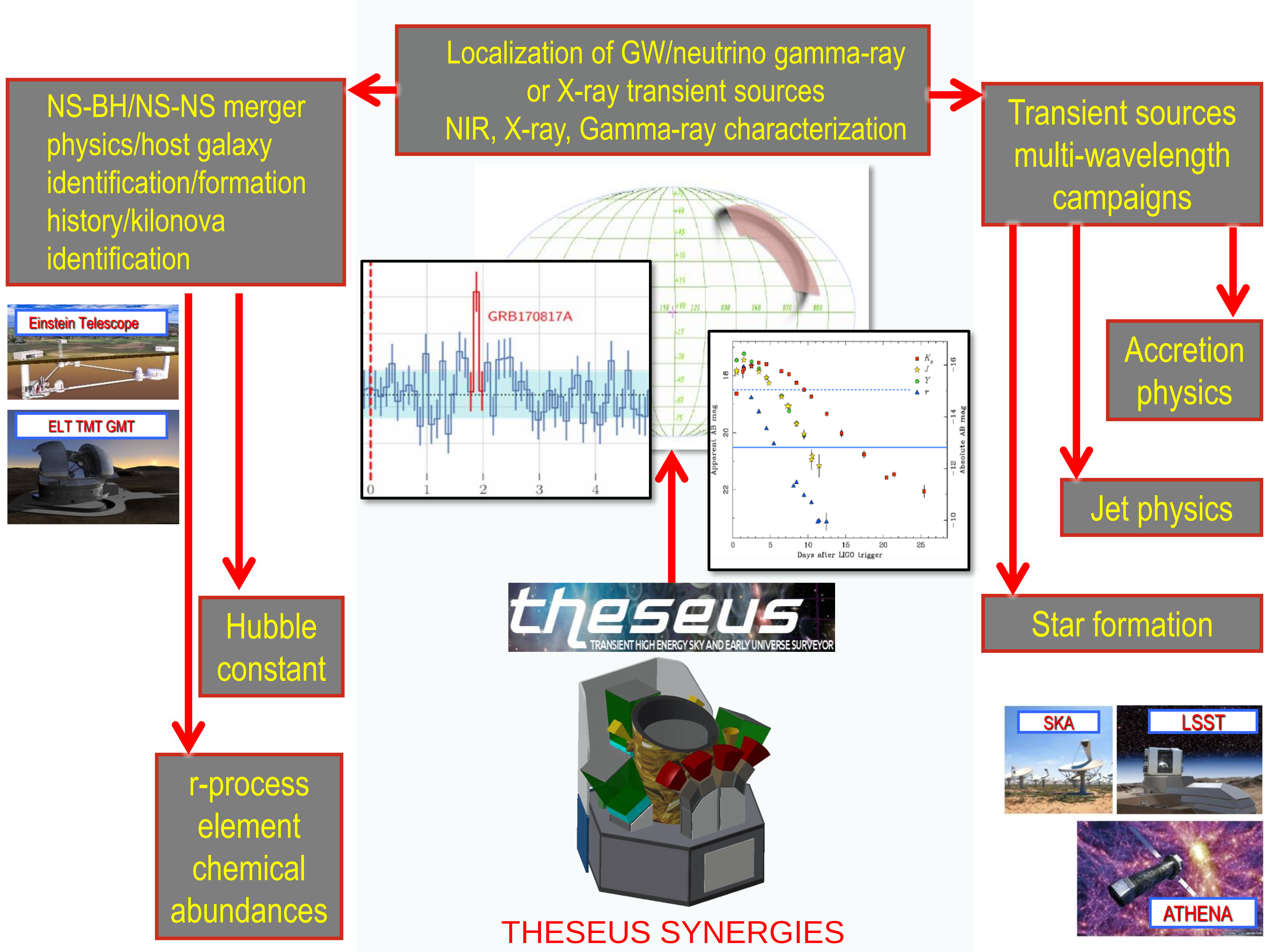
THESEUS SYNERGIES


Localization of GW/neutrino gamma-ray or X-ray transient sources
NIR, X-ray, Gamma-ray characterization
NS-BH/NS-NS merger physics/host galaxy identification/formation history/kilonova identification
Transient sources multi-wavelength campaigns
Einstein Telescope
ELT TMT GMT
GRB170817A
Apparent AB mag
Absolute AB mag
Days after LIGO trigger
Accretion physics
Jet physics
Star formation
Hubble constant
r-process element chemical abundances
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
SKA
LSST
ATHENA
THESEUS SYNERGIES

Summary of THESEUS – ATHENA synergies

- ❑ **Theseus providing triggers (time, location, flux, redshift) to Athena for GRBs (high-z Universe, pop-III stars, WHIM studies), e.m. counterparts of GW sources (short GRBs, soft X-ray emission)** and other transients relevant to Athena core science (TDEs, Magnetars, SNe, Nova, flare stars, SgrA*)

- ❑ **Athena providing triggers for Theseus IRT for follow-up** of transients found in the WFI, including triggering campaign on AGN in outburst.

- ❑ **Simultaneous Athena/Theseus broad band observations** of relatively bright sources

- ❑ Cross Calibration of Theseus SXI instrument on Athena sources

Will be investigated by Athena – Theseus synergy WG (P. O'Brien et al.)

In summary

- THESEUS, under study by ESA and a large European collaboration with strong interest by international partners (e.g., US) 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 play a fundamental role for GW/multi-messenger and time domain astrophysics at the end of next decade, also by providing a flexible follow-up observatory for fast transient events with multi-wavelength ToO capabilities and guest-observer programmes

- THESEUS is a unique occasion for fully exploiting the European leadership in time-domain and multi-messenger astrophysics and in key-enabling technologies (lobster-eye telescopes, SDD by INAF, INFN, FBK, Un.)

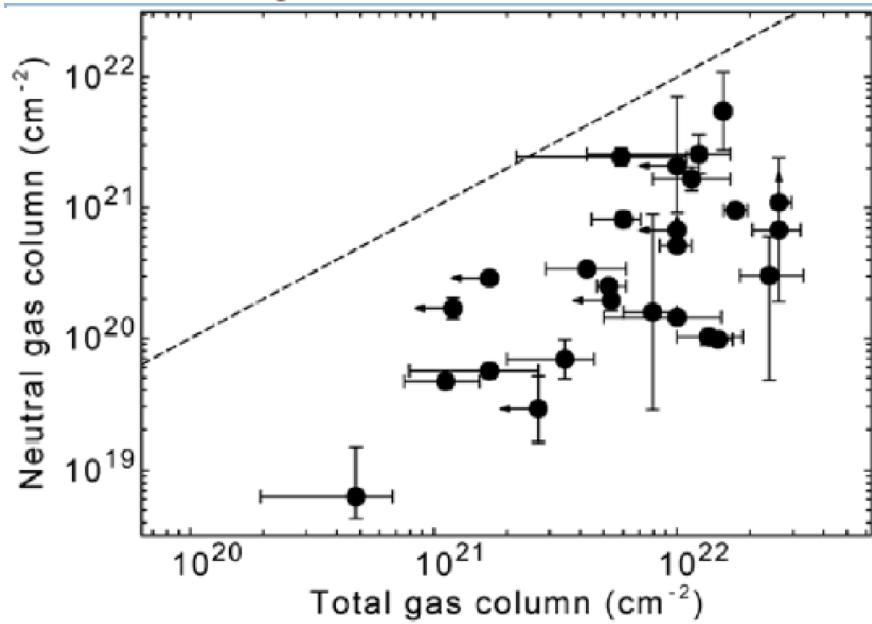
- THESEUS will enhance importantly the scientific return of next generation facilities in the multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET) and e.m. (e.g., LSST, E-ELT, SKA, CTA, ATHENA) domain

- Strong straightforward synergy with Athena: THESEUS will be the optimal GRB/transients machine for Athena core and obs. science

- *ESA L2/L3 review:* “The SSC strongly endorses the need to continue pursuing in the future the discovery of GRBs”

- THESEUS will be a really unique and superbly capable facility, one that will do amazing science on its own, but also will add huge value to the currently planned new photon and multi-messenger astrophysics infrastructures in the 2020s to > 2030s.

Back-up slides



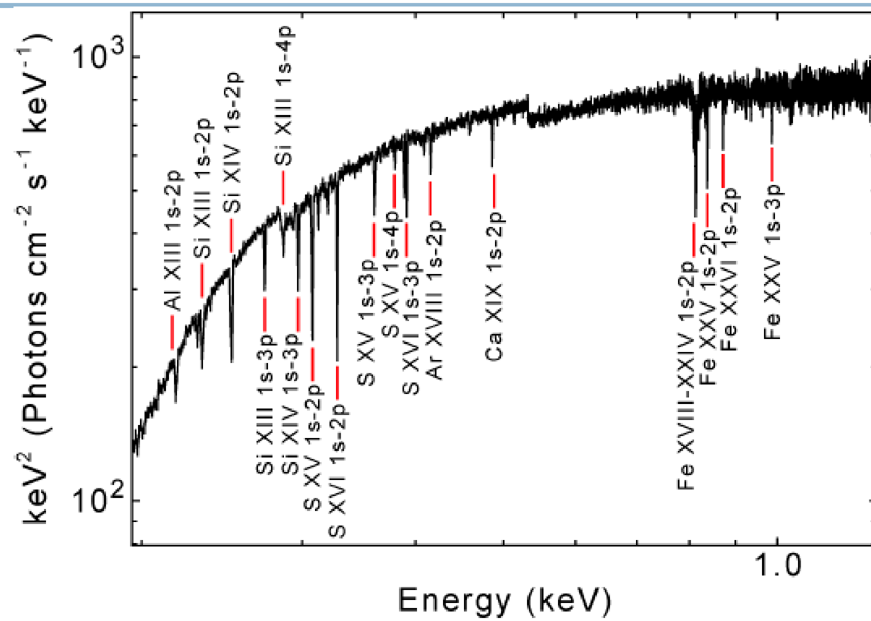
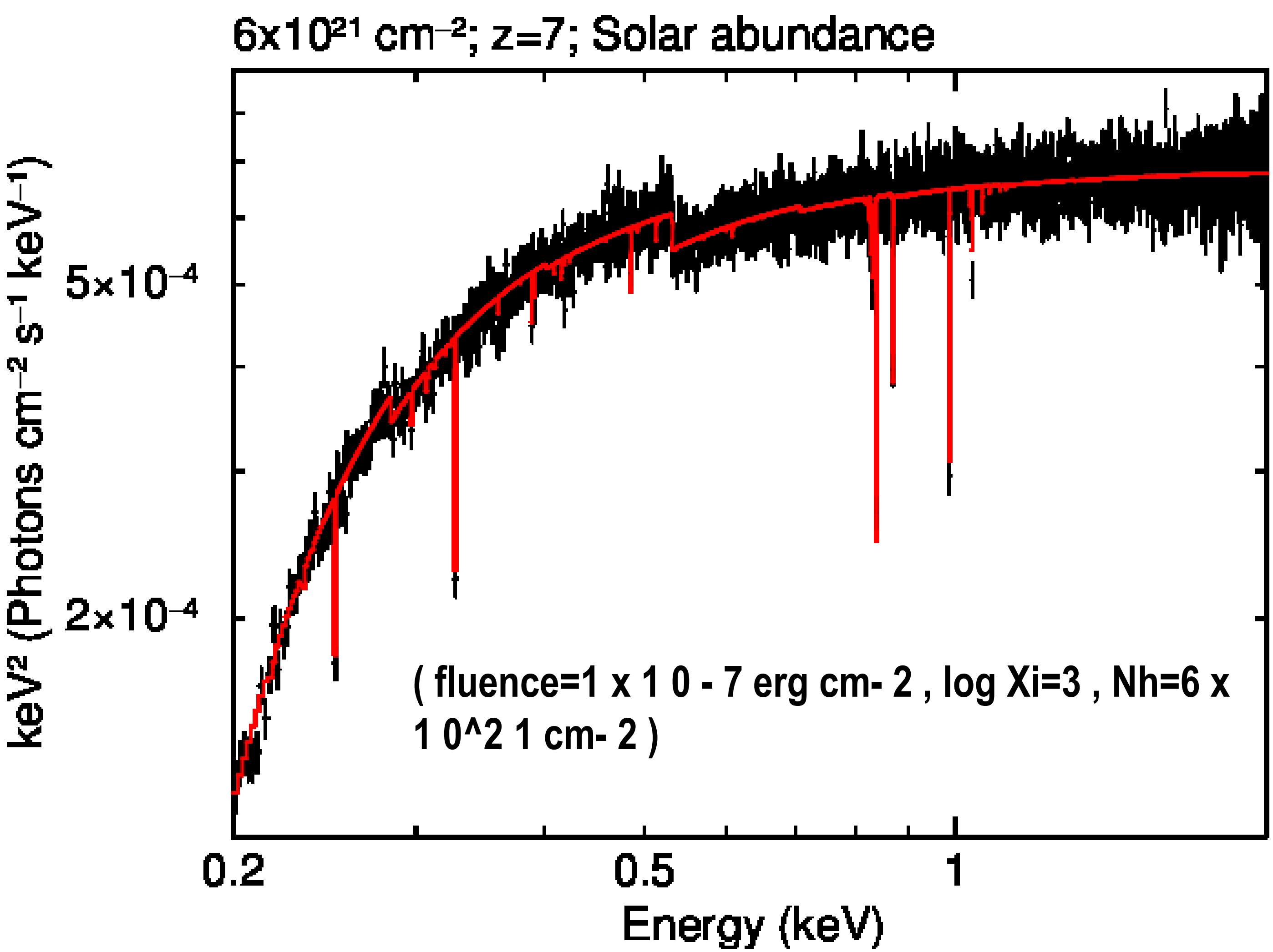
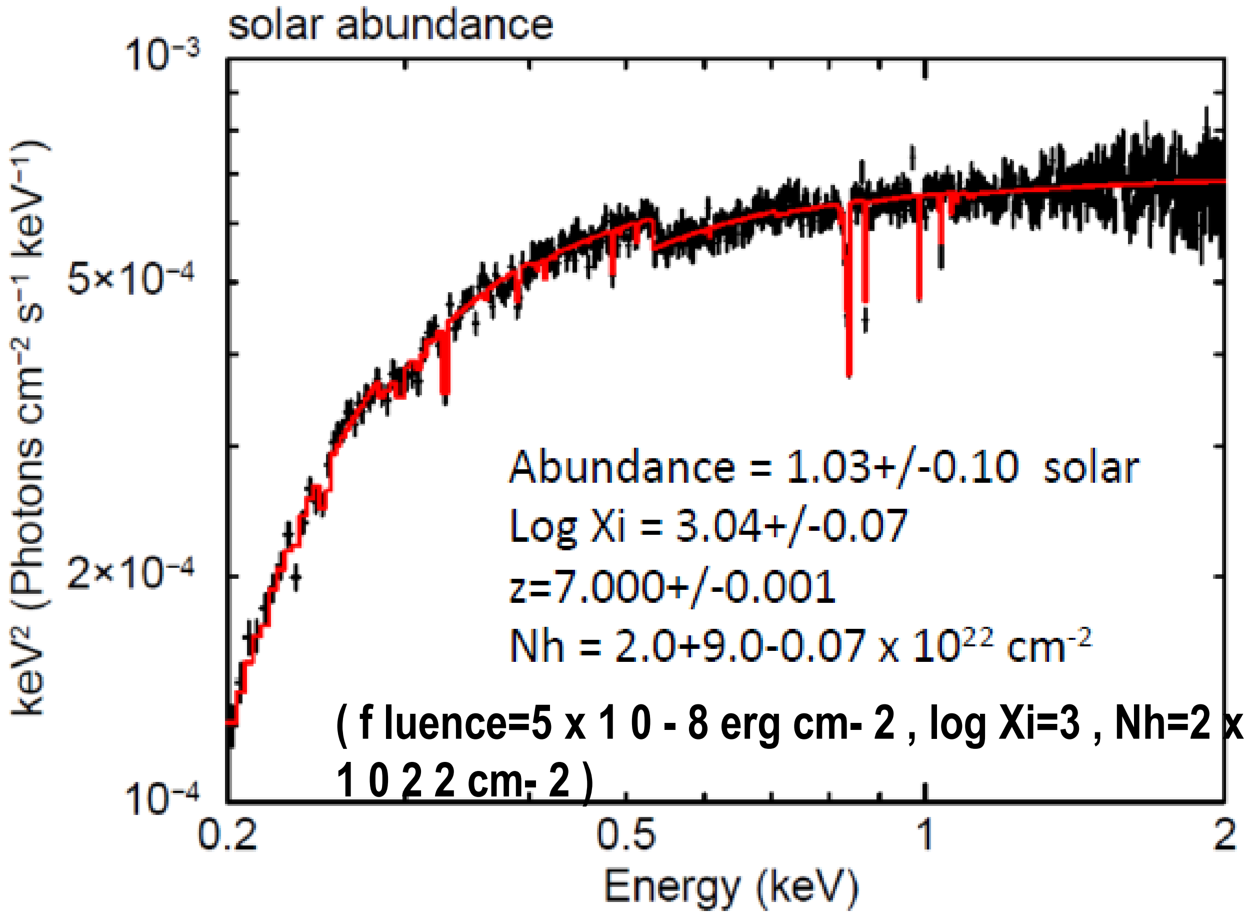


Figure 2: The neutral gas column density derived from optical spectroscopy compared to the total gas column density derived from X-ray observations of GRBs. The neutral column density is about 2 orders of magnitude lower, indicating that the bulk of the absorbing gas is ionized making it observable in X-rays (Schady et al. 2010).

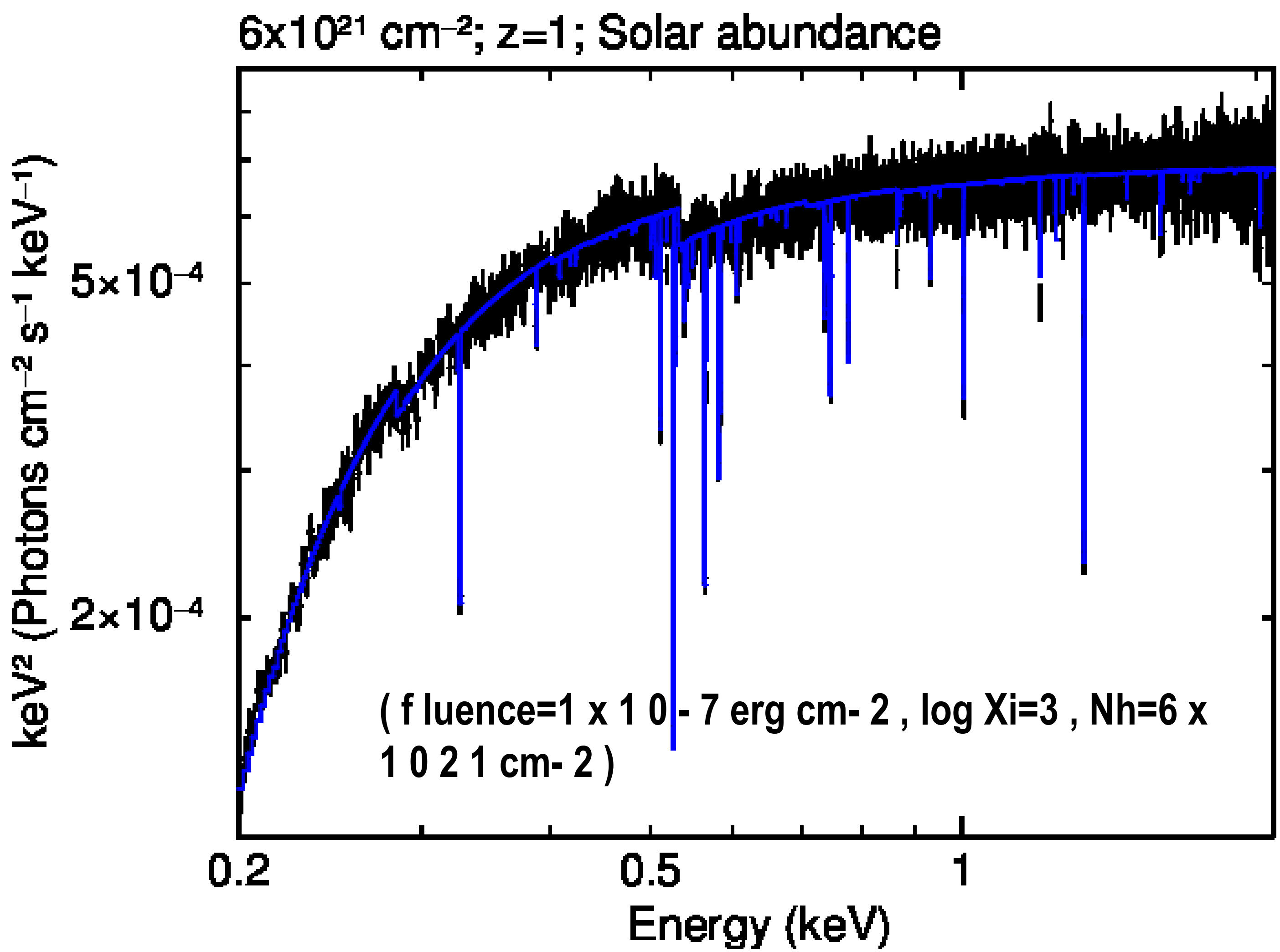
Figure 3: A simulated X-IFU X-ray spectrum of a GRB afterglow at z=7, showing the capability of *Athena+* in tracing the primordial stellar populations. This medium bright afterglow (fluence=0.4×10^{-6} erg cm^{-2}) is characterized by deep narrow resonant lines of Fe, Si, S, Ar, Mg, from the ionized gas in the environment of the GRB. An effective column density of 2×10^{22} cm^{-2} has been adopted. The abundance pattern measured by *Athena+* can distinguish Population III from Population II star forming regions.

Jonker, O'Brien et al., 2013 arXiv1306.2336


6x10²¹ cm⁻²; z=7; Solar abundance
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
5×10⁻⁴
2×10⁻⁴
0.2
0.5
1
Energy (keV)
(fluence=1 x 1 0 - 7 erg cm- 2 , log Xi=3 , Nh=6 x 1 0^2 1 cm- 2)

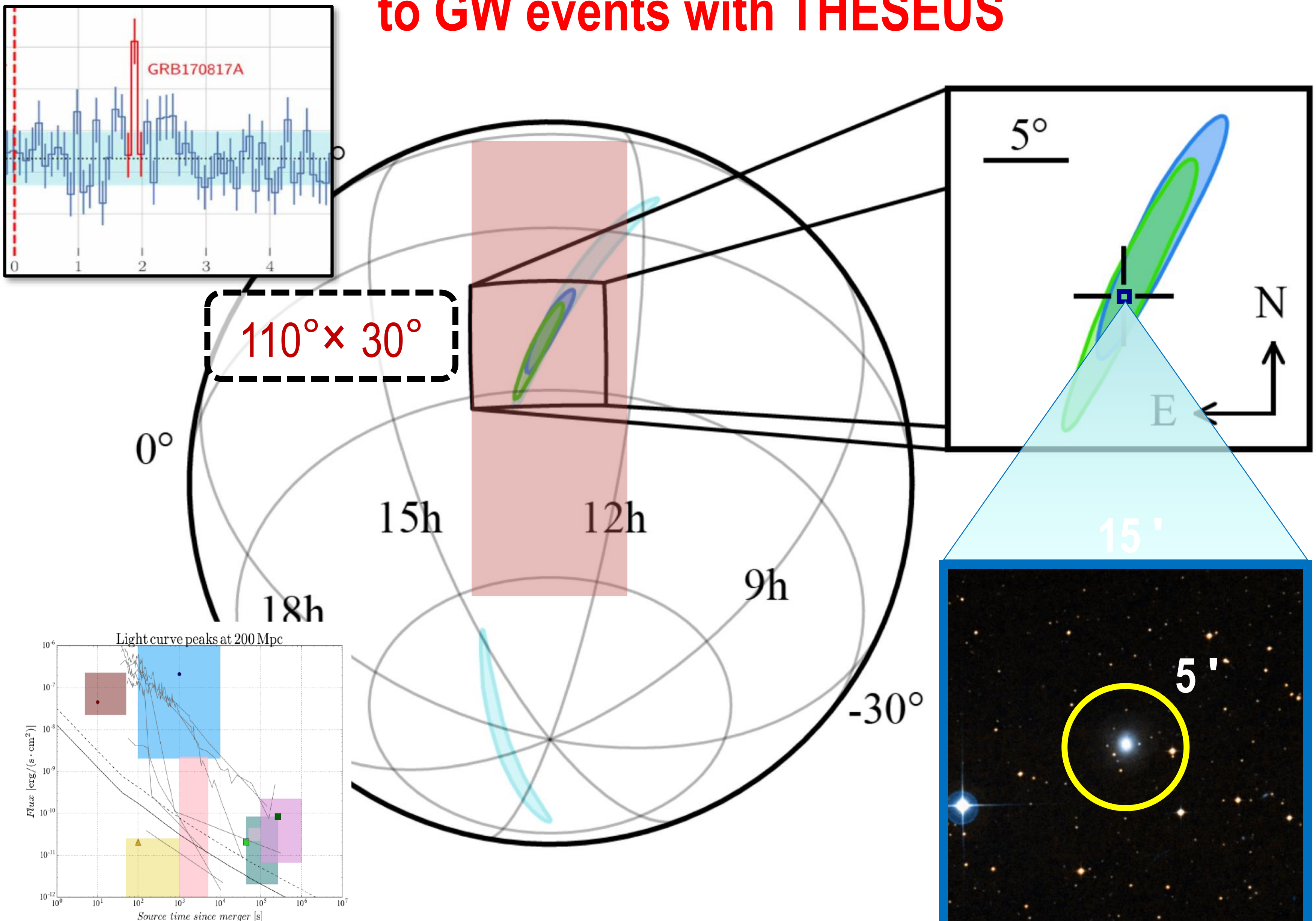


solar abundance
10⁻³
5×10⁻⁴
2×10⁻⁴
10⁻⁴
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
0.2
0.5
1
2
Energy (keV)
Abundance = 1.03+/-0.10 solar
Log Xi = 3.04+/-0.07
z=7.000+/-0.001
Nh = 2.0+9.0-0.07 x 10²² cm⁻²
(f luence=5 x 1 0 - 8 erg cm- 2 , log Xi=3 , Nh=2 x 1 0 2 2 cm- 2)



6x10²¹ cm⁻²; z=1; Solar abundance
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
5×10⁻⁴
2×10⁻⁴
0.2
0.5
1
Energy (keV)
(f luence=1 x 1 0 - 7 erg cm- 2 , log Xi=3 , Nh=6 x
1 0 2 1 cm- 2)

❑ Promptly and accurately localizing e.m. counterparts to GW events with THESEUS



❑ GW/multi-messenger and time-domain astrophysics

GW transient sources that will be monitored by THESEUS include:

- ❑ 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)

Table 2: Number of NS-NS (BNS) mergers expected to be detected in the next years by second- (2020+) and third- (2030+) generation GW detectors and the expected detection number of electromagnetic counterparts as short GRBs (collimated) and X-ray isotropic emitting counterparts (see §3.1 and 3.2) with THESEUS SXI and XGIS (see text for more details). BNS rate is a realistic estimate from Abadie et al. 2010 and Sathyaprakash et al. 2012 and the BNS range indicates the sky- and orbital inclination-averaged distance up to which GW detectors can detect a BNS with $SNR = 8$.

GW observations			THESEUS XGIS/SXI joint GW+EM observations		
Epoch	GW detector	BNS range	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
2020+	Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)	~200 Mpc	~40*	~5-15	~1-3 (simultaneous) ~6-12 (+follow-up)
2030+	Second + Third-generation (e.g. ET, Cosmic Explorer)	~15-20 Gpc	>10000	~15-35	$\gtrsim$100

* from Abadie et al. 2010a

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)**

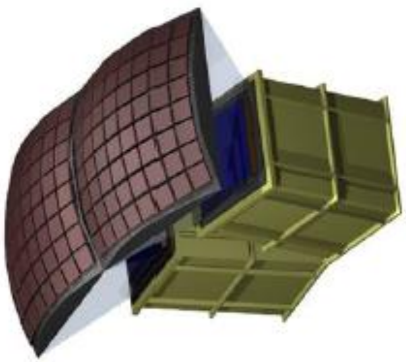
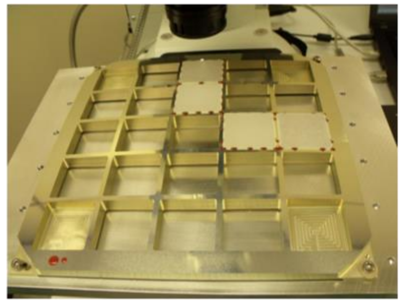
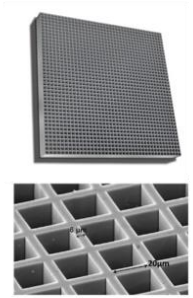
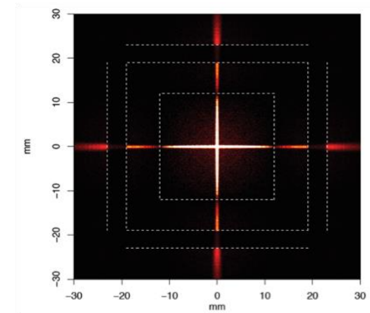
ESA Study Team for THESEUS

ESA	
Study Manager	Philippe Gondoin
System Eng.	Jonan Larranaga
Payload SM	Thibaut Prod'homme
Payload System Engineer	Tim Oosterbroek
Study Scientist	Matteo Guainazzi
Optics	Isabel Escudero Sanz

+ ESOC + ESAC + DTEC (to be defined)

- **Supervision: P. Falkner (head future missions department), L. Colangeli**

The Soft X-ray Imager (SXI) – led by UK


4 DUs, each has a 31 x 26 degree FoV

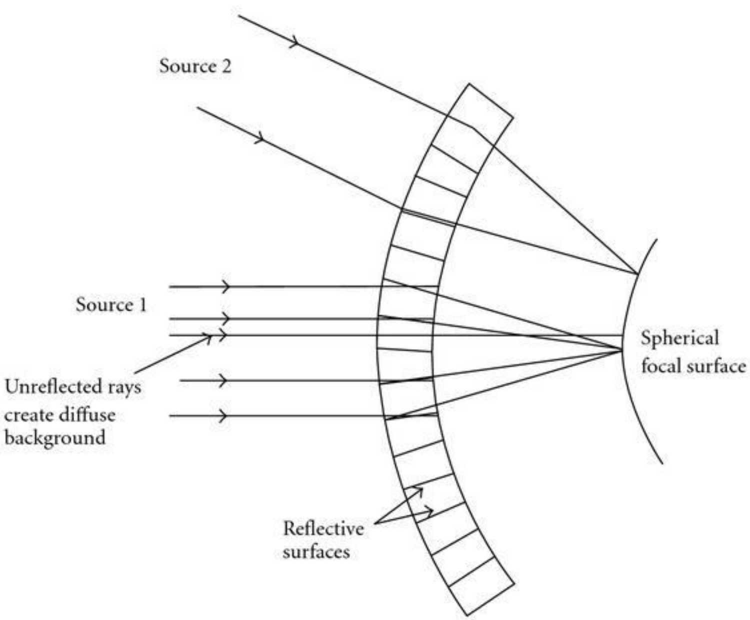
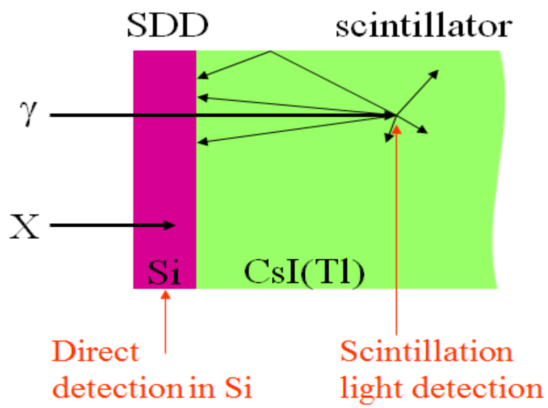
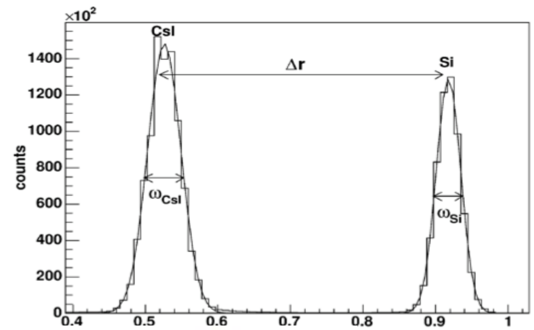


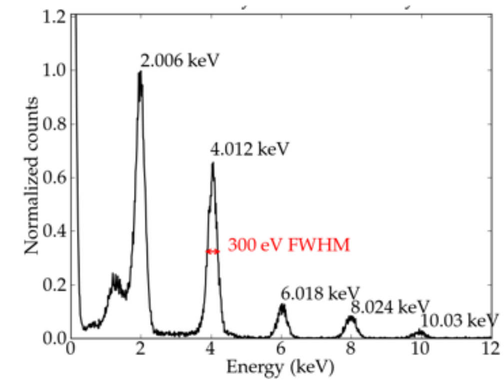
Table 4 : : SXI detector unit main physical characteristics

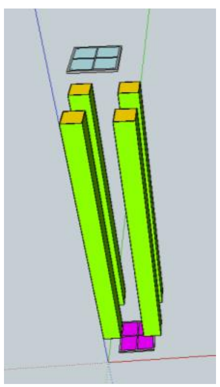
Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics aperture (mm2)	320x320
Optics configuration	8x8 square pore MCPs
MCP size (mm2)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD (mm2)	81.2x67.7
Pixel size (µm)	18
Pixel Number	4510 x 3758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

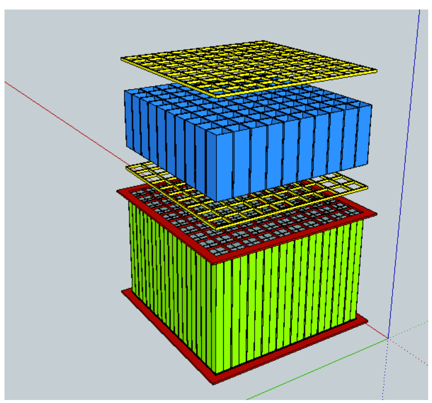
The X-Gamma-rays imaging spectrometer (XGIS) – led by IT

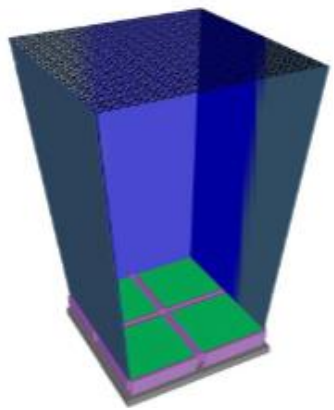






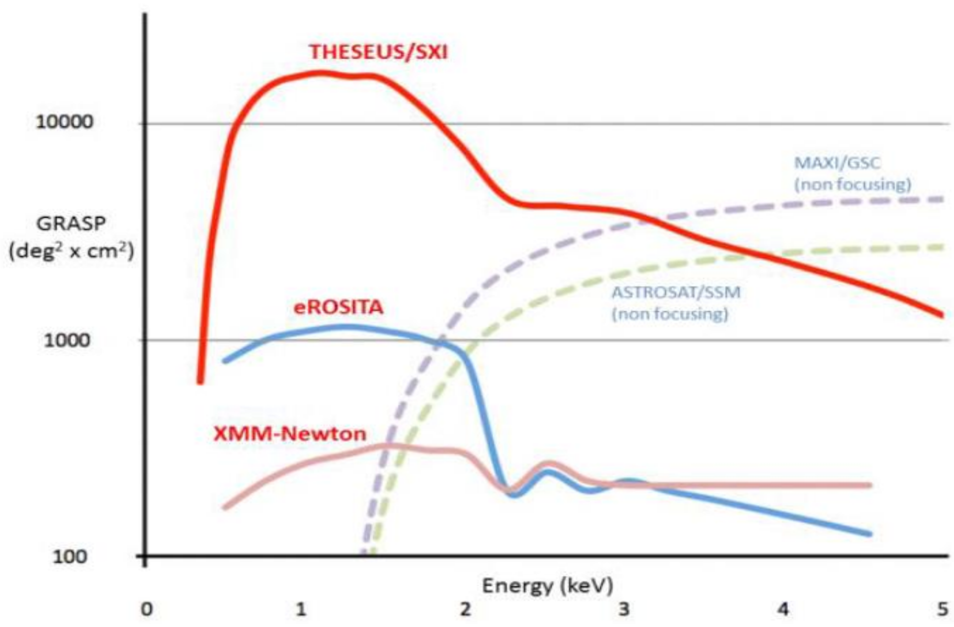


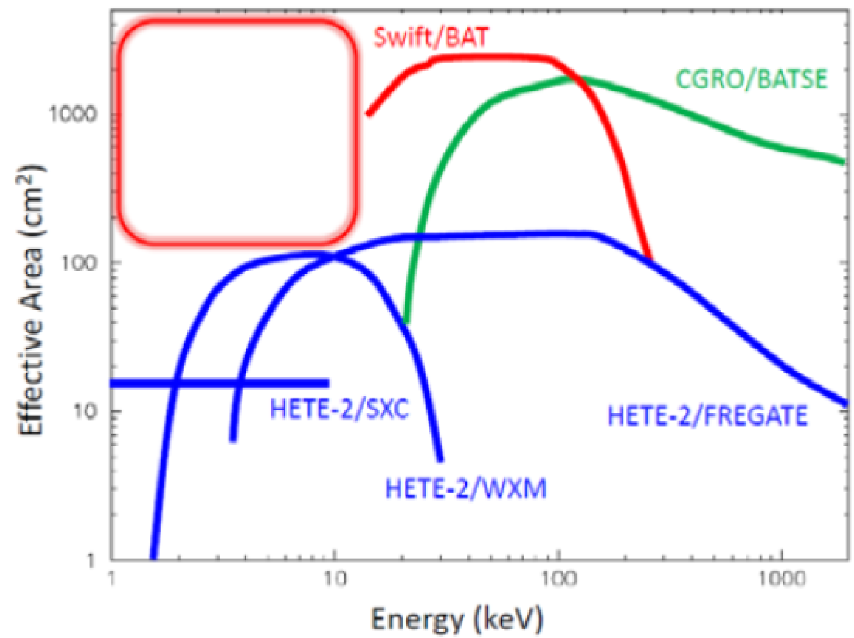




Energy band	*2 keV – 20 MeV*
# detection plane modules	*4*
# of detector pixel / module	*32x32*
pixel size (= mask element size)	*5x5 mm*
Low-energy detector (2-30 keV)	*Silicon Drift Detector 450 μm thick*
High energy detector (> 30 keV)	*CsI(Tl) (3 cm thick)*
Discrimination Si/CsI(Tl) detection	*Pulse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

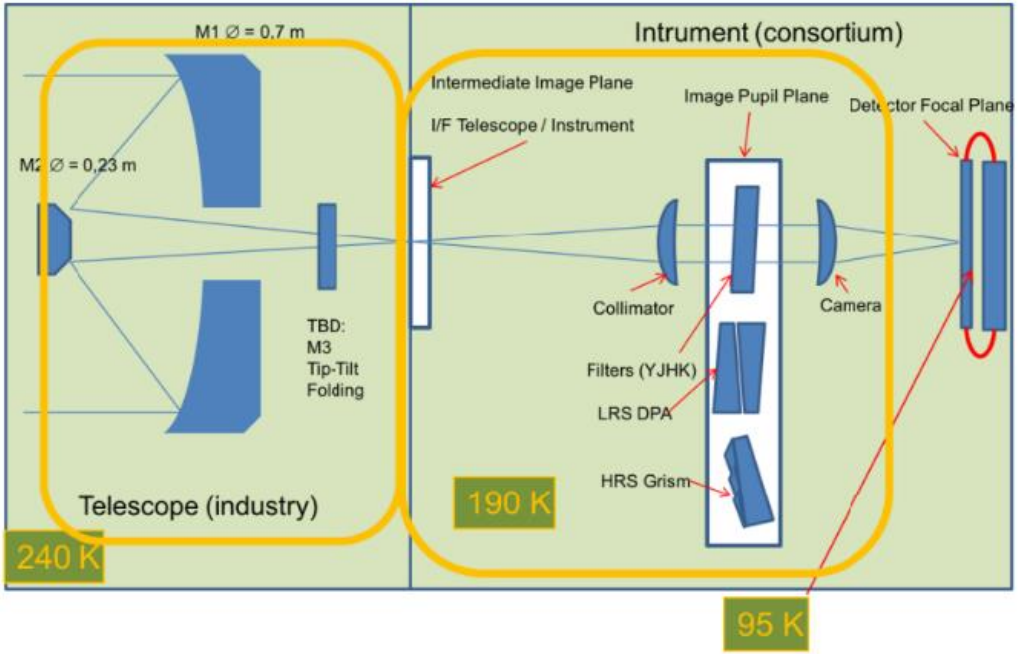


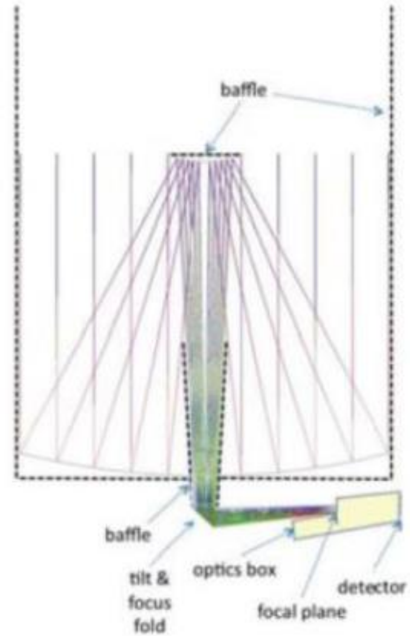


	Energy Band	FOV	Energy resolution	Peak eff. area	Source location	Operation
CGRO/BATSE	20–2000 keV	open	10 keV (100 keV)	~1700 cm^2	>1.7 deg	ended
Swift	15–150 keV	1.4 sr	7 keV (60 keV)	~2000 cm^2	1–4 arcmin	active
Fermi/GBM	8 keV – 40 MeV	open	10 keV (100 keV)	126 cm^2	>3 deg	active
Konus–WIND	20 keV – 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	2032
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) – led by FR





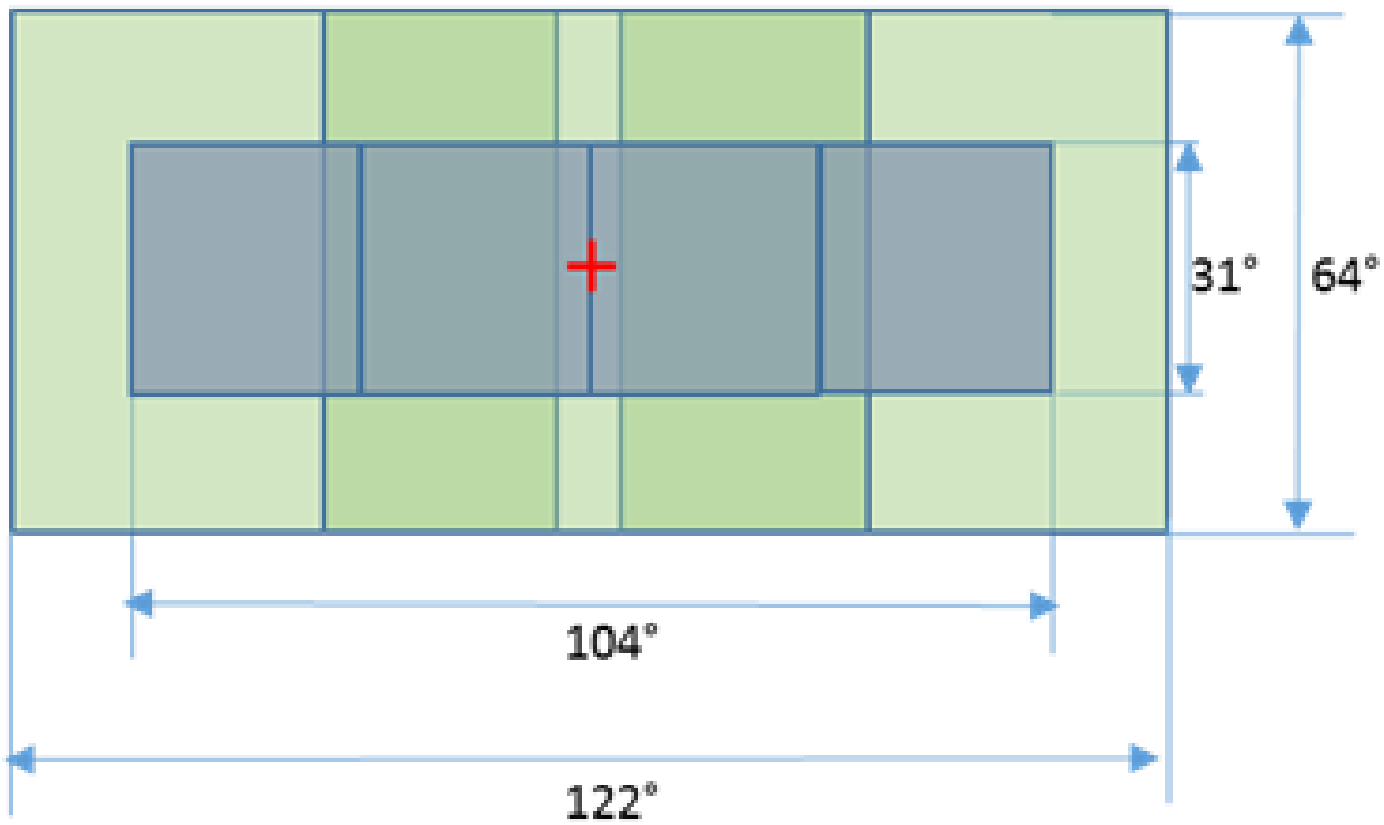
Telescope type:	Cassegrain		
Primary & Secondary size:	700 mm & 230 mm		
Material:	SiC (for both optics and optical tube assembly)		
Detector type:	Teledyne Hawaii-2RG 2048 x 2048 pixels (18 µm each)		
Imaging plate scale	0”.3/pixel		
Field of view:	10’ x 10’	10’ x 10’	5’ x 5’
Resolution (λ/Δλ):	2-3 (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		

Field of view

XGIS

SXI

IRT



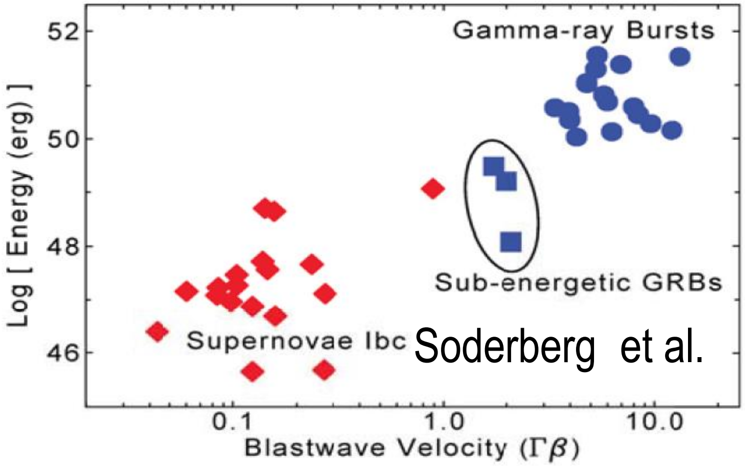
❑ Time-domain astronomy and GRB physics

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

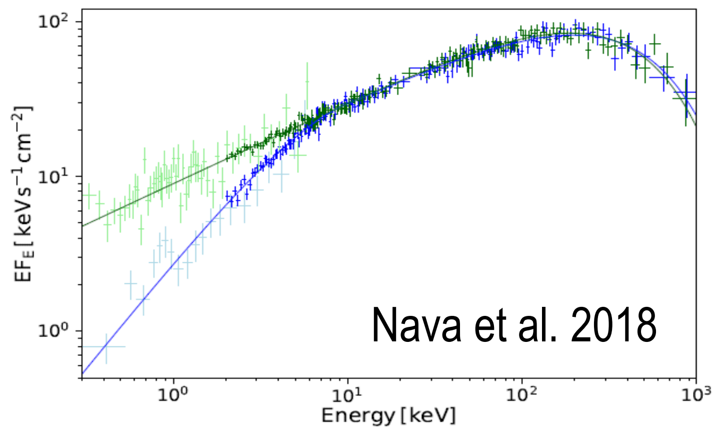
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;

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

Transient type	SXI rate
Magnetars	40 day^{-1}
SN shock breakout	4 yr^{-1}
TDE	50 yr^{-1}
AGN+Blazars	350 yr^{-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}

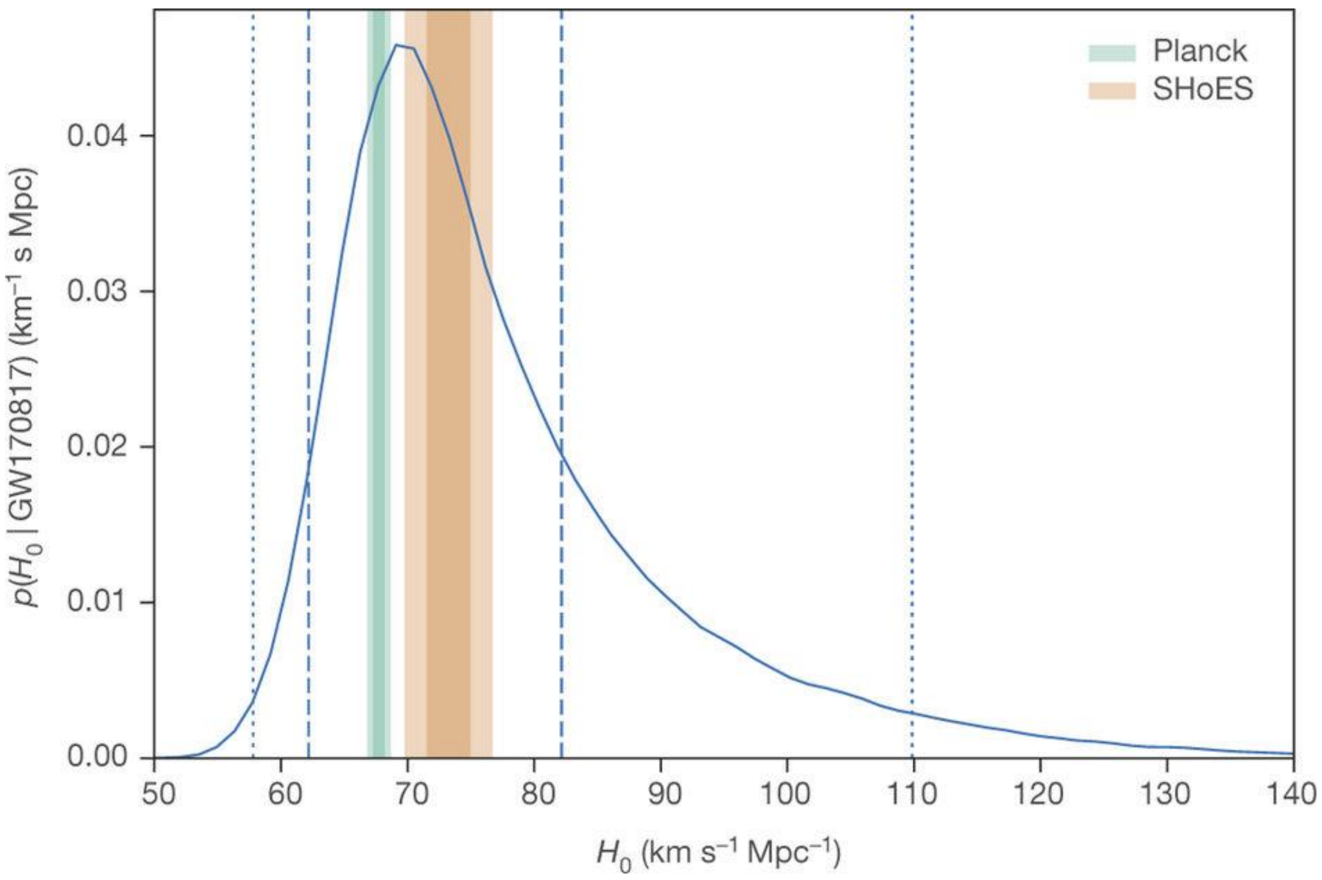


Soderberg et al.



Nava et al. 2018

- THESEUS measurements + sinergy with large e.m. facilities -> substantial improvment of redshift estimate for e.m. counterparts of GW sources -> **cosmology**

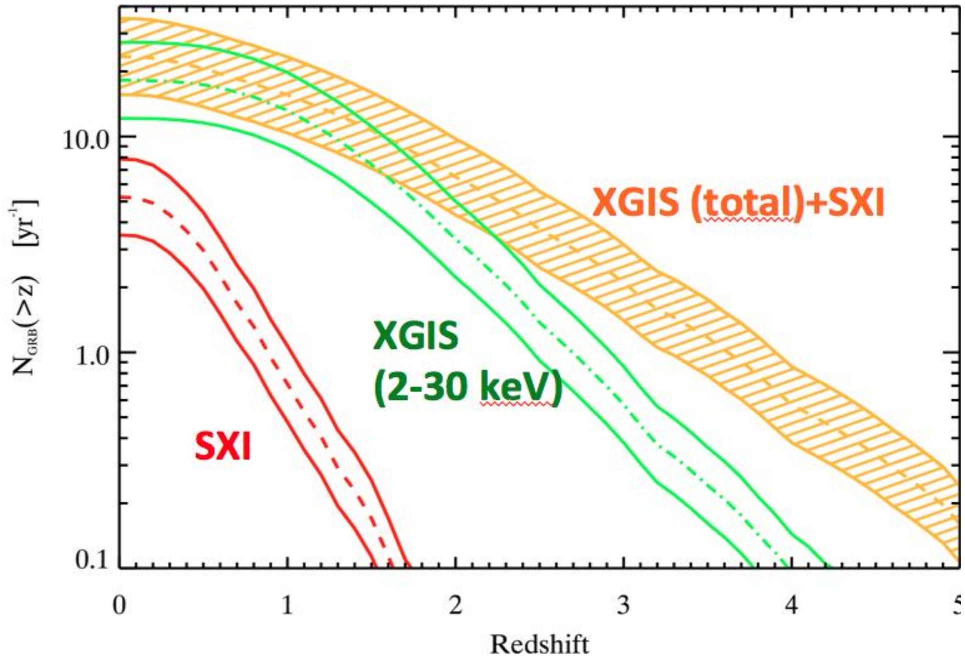


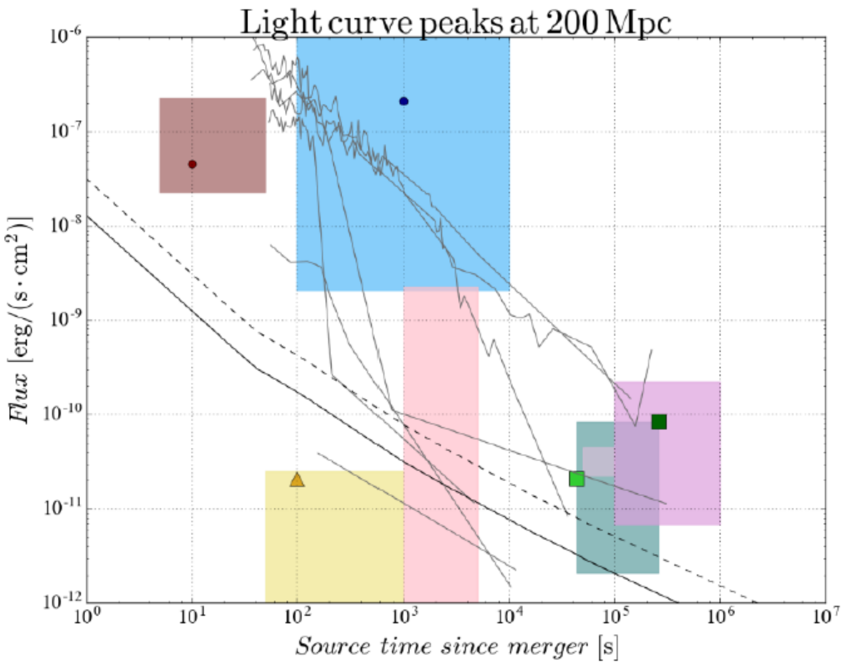
Estimating H0 with GW170817A

❑ GW/multi-messenger time-domain astrophysics

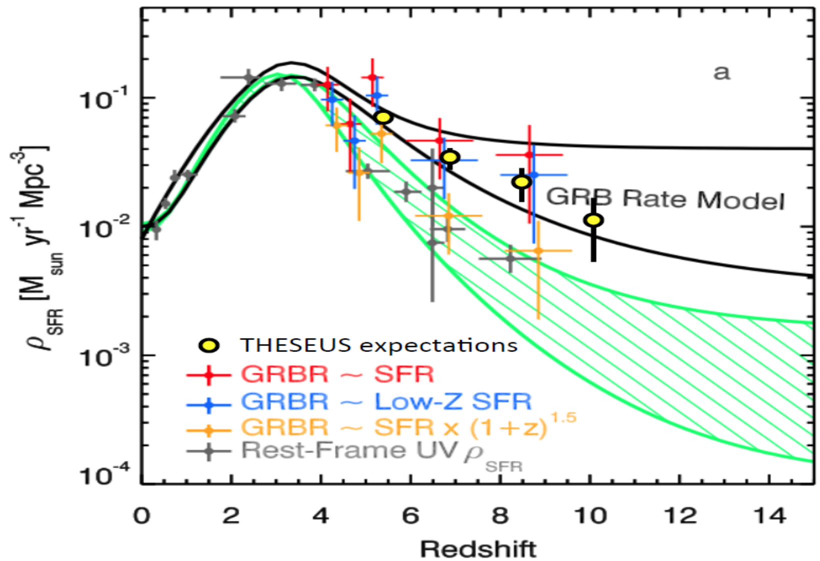
GW transient sources that will be monitored by THESEUS include **NS-NS / NS-BH mergers**:

- ❑ **collimated** on-axis and off-axis prompt gamma-ray emission from short GRBs
- ❑ Optical/NIR and soft X-ray **isotropic** emissions from kilonovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown

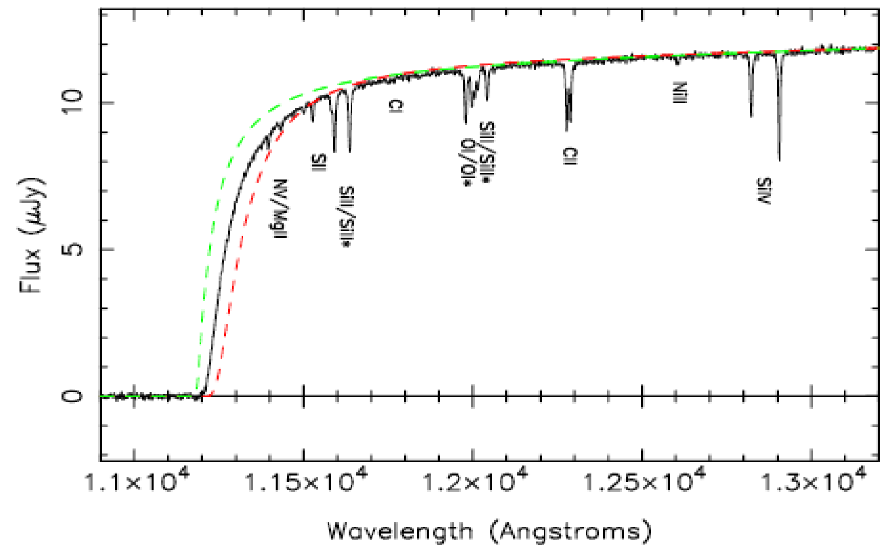


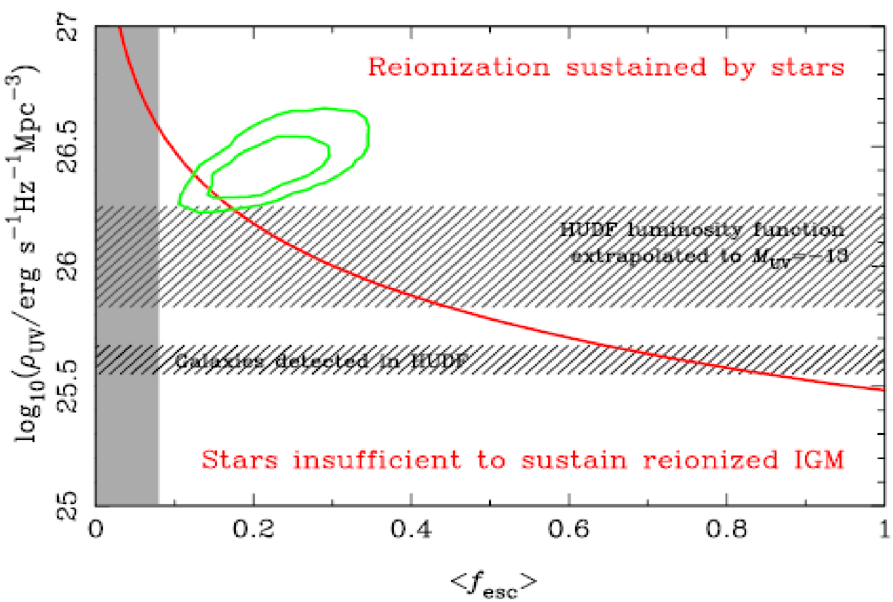


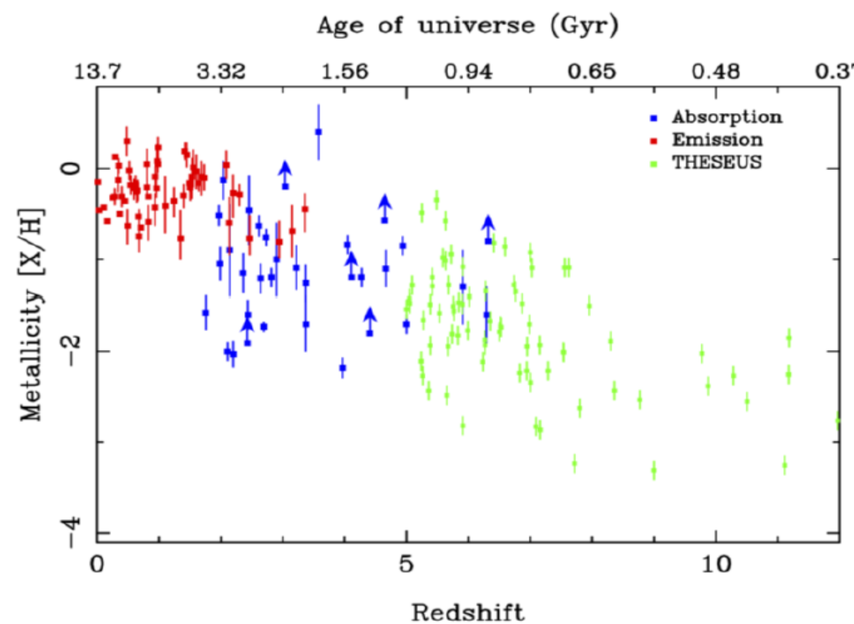
❑ Shedding light on the early Universe with GRBs



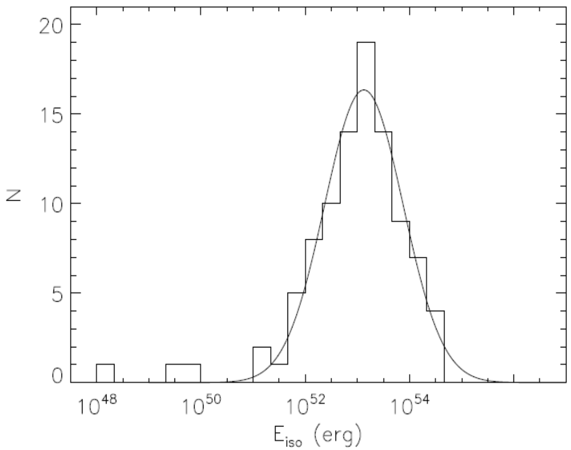
z=8.2 simulated E−ELT afterglow spectra

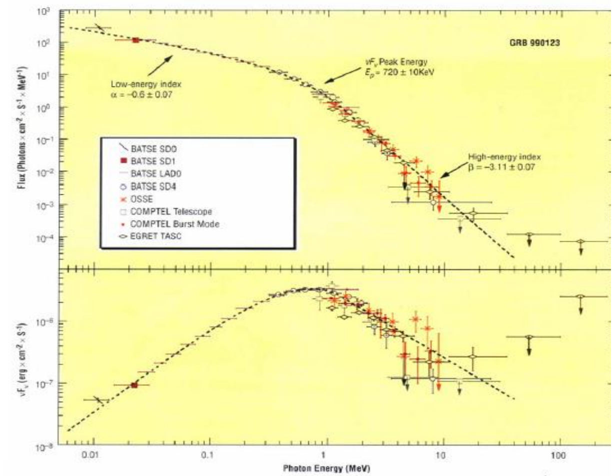


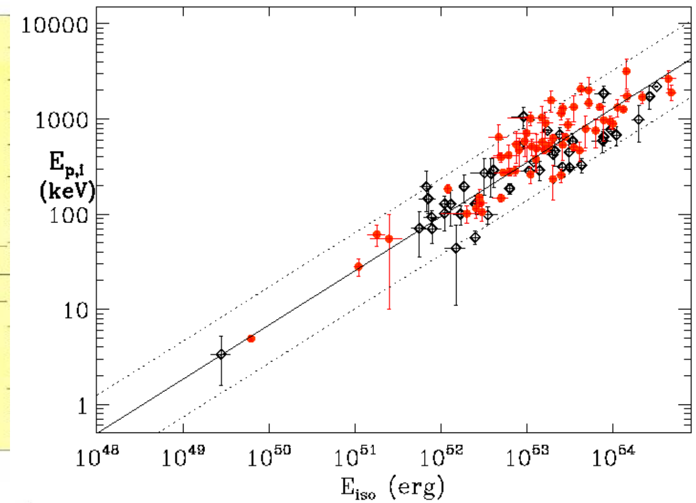


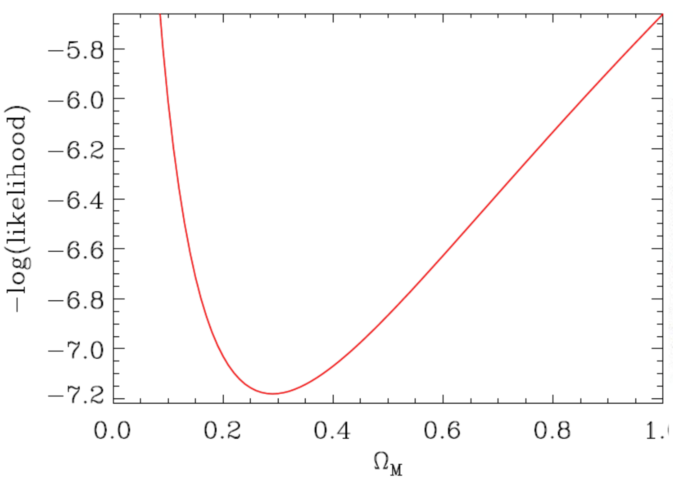


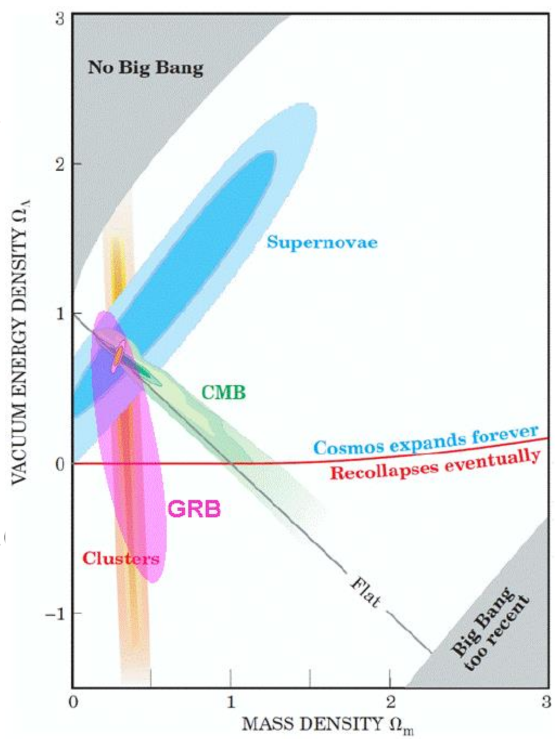
❑ measuring cosmological parameters with GRBs

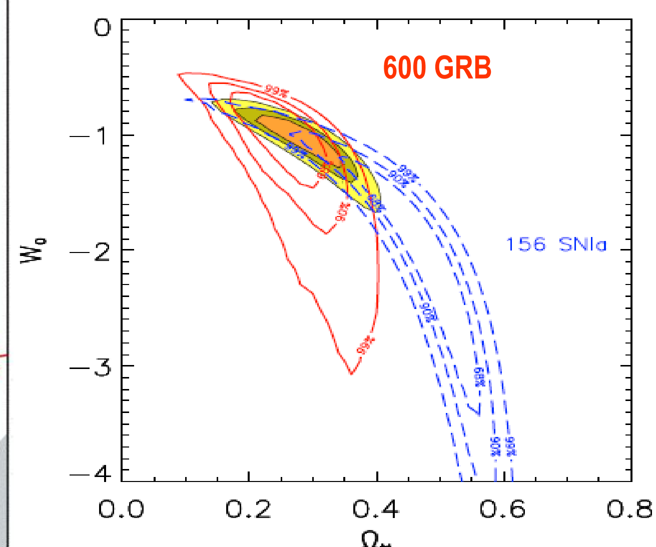






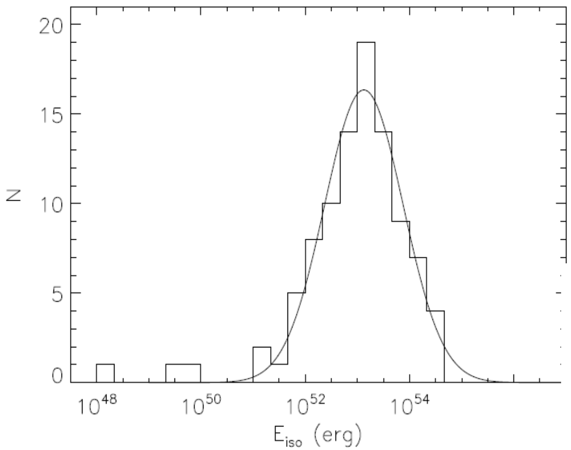


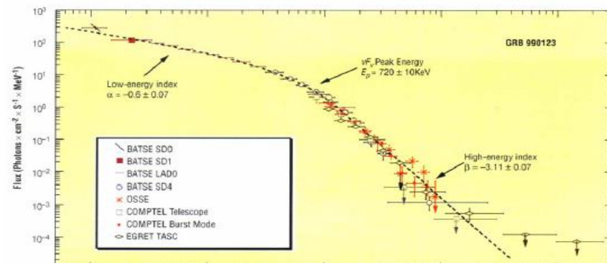


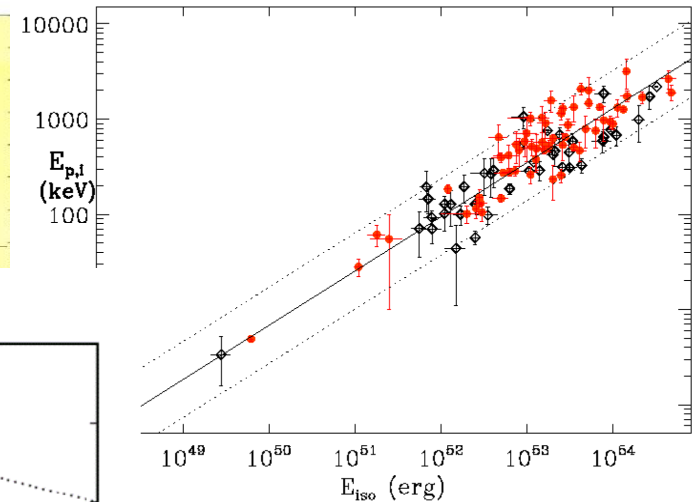


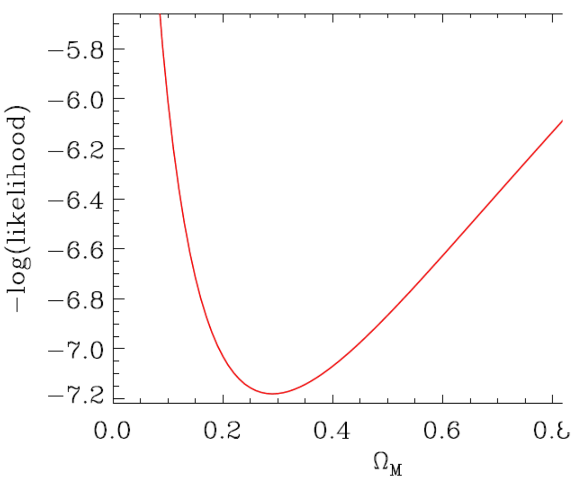
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

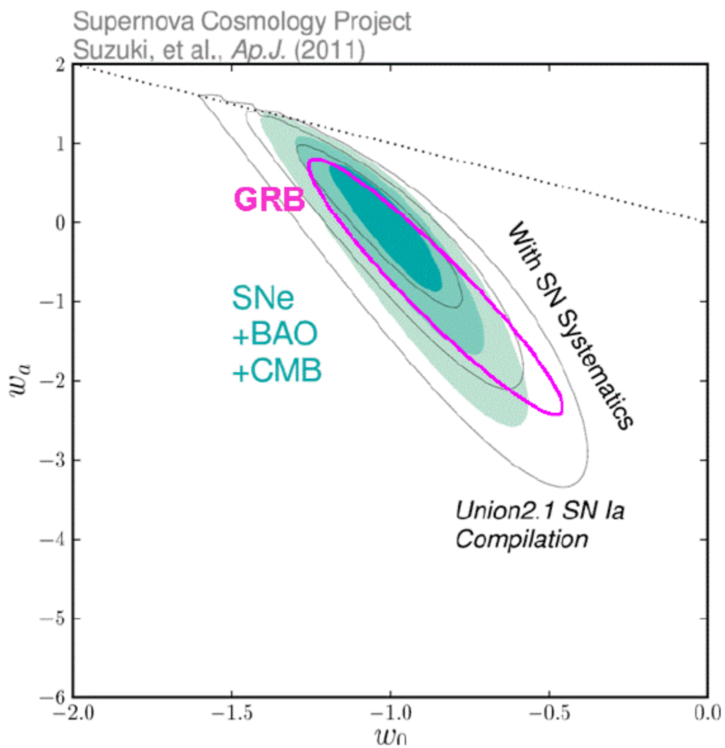
❑ measuring cosmological parameters with GRBs

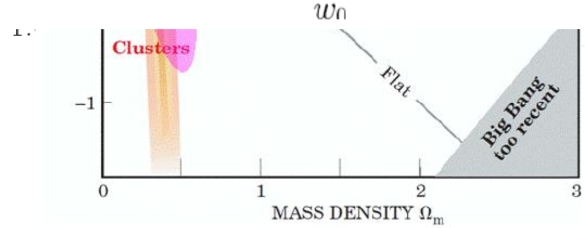


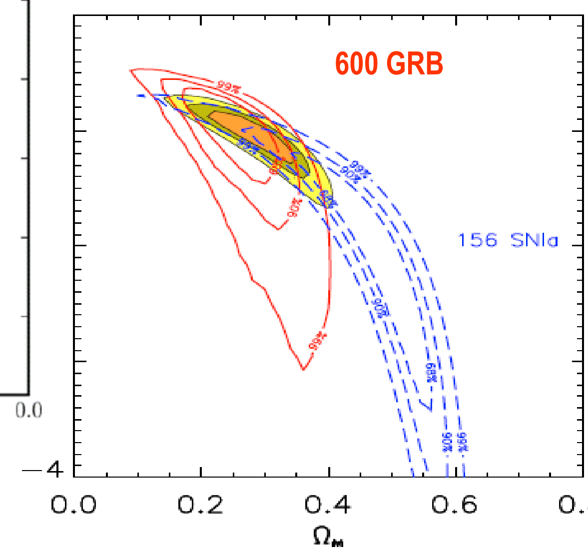








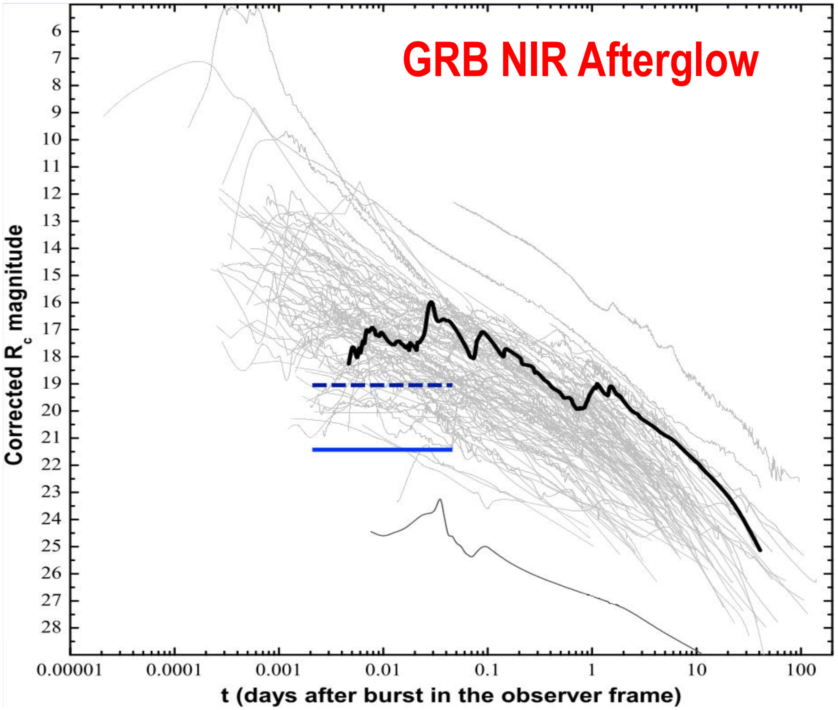


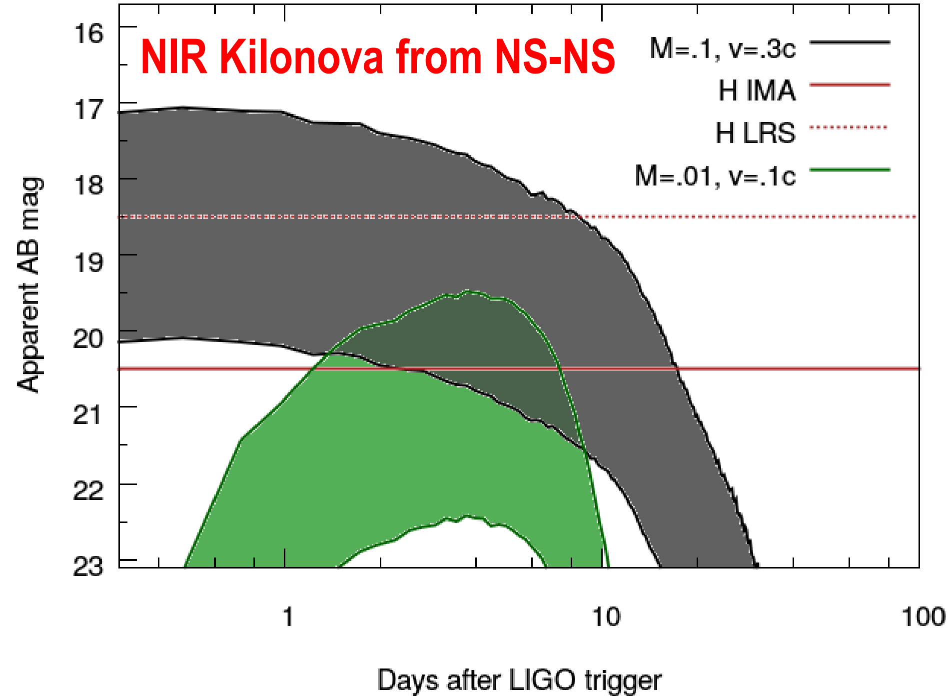


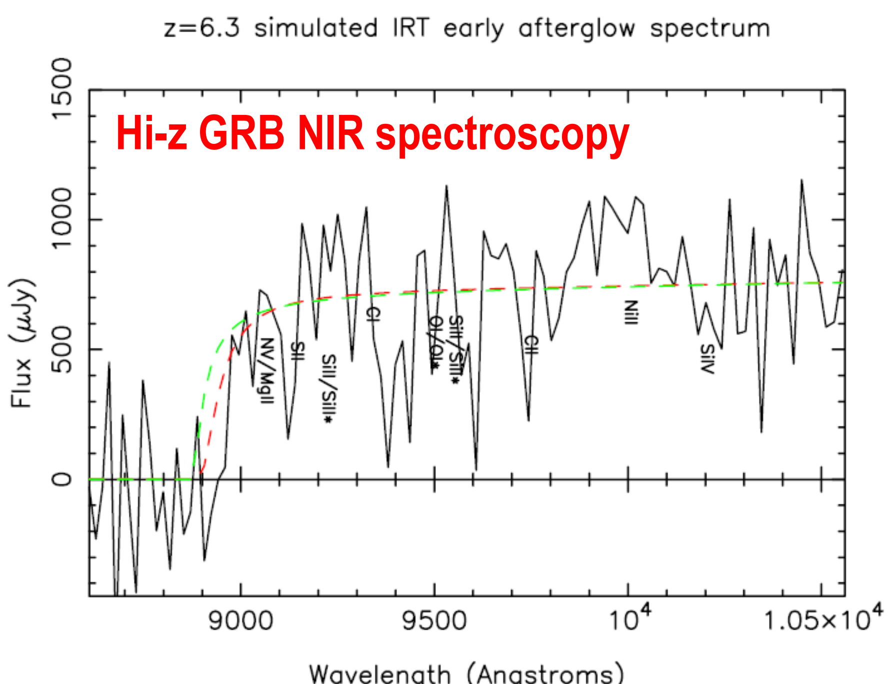
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

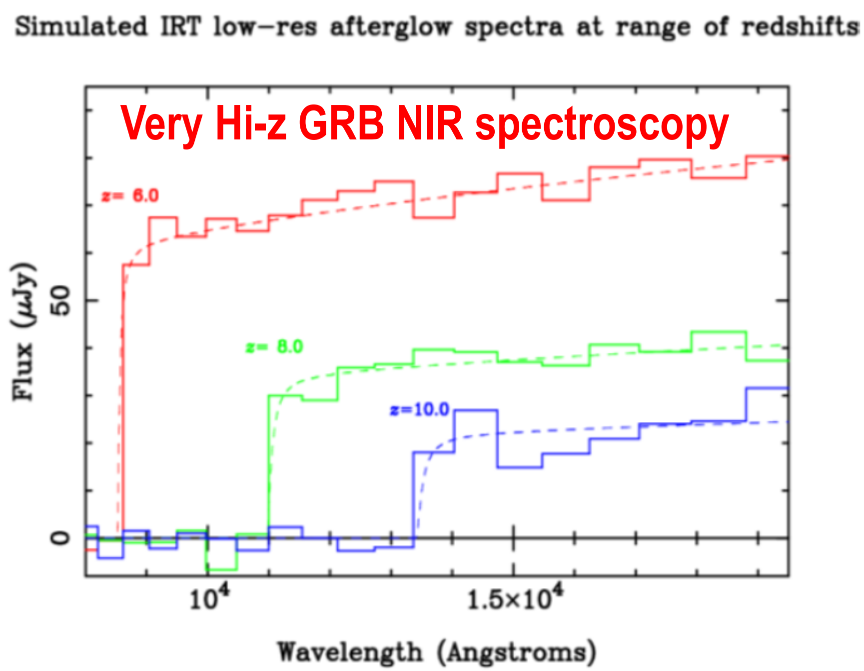
M5 - Way forward Phase 0/A

- Team nominations ESA (ESTEC, ESAC, ESOC) & external Study Science Teams – on th
- 3 x M5 CDF studies Jun-Nov 2018:
    - Theseus: Sep-Oct 2018 (session 13/18/20 Sep 2/4/9/11/18 Oct)
- Mission Definition Review (MDR): end Nov 2018 (date TBD)
- Phase 0 completed by: end 2018
- Prep ITT for Phase A/B1 , ITT: Feb 2019
- Industrial Phase-A KO: Jun 2019
- Yellow books: Mid July 2021
- Mission Selection Review: Sep 2021
- SPC Selection of one M5: Nov 2021 ⇨ transition into Phase B1


GRB NIR Afterglow
Corrected R_c magnitude
t (days after burst in the observer frame)
0.00001
0.0001
0.001
0.01
0.1
1
10
100


NIR Kilonova from NS-NS
M=.1, v=.3c
H IMA
H LRS
M=.01, v=.1c
Apparent AB mag
Days after LIGO trigger


z=6.3 simulated IRT early afterglow spectrum
Hi-z GRB NIR spectroscopy
NV/MgII
SII
SiII/SiII*
CI
OI/OI*
SiII/SiII*
CII
NiII
SiIV
Flux (μJy)
Wavelength (Angstroms)


Simulated IRT low−res afterglow spectra at range of redshifts
Very Hi-z GRB NIR spectroscopy
z= 6.0
z= 8.0
z=10.0
Flux (μJy)
Wavelength (Angstroms)

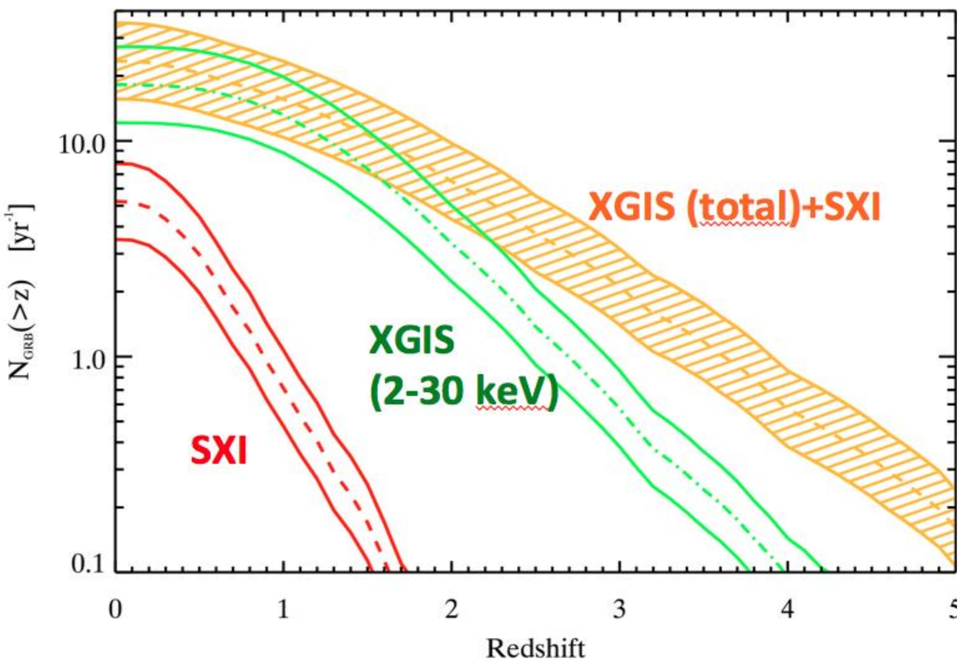
THESEUS payload consortium

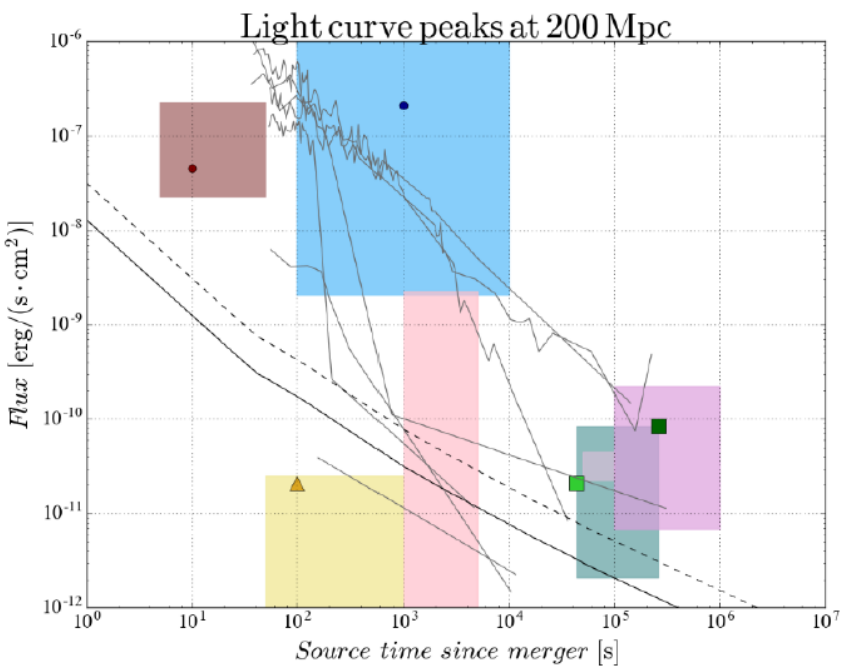
- **ITALY -** L.P. / project office, XGIS, Malindi antenna (+ contrib. to SDC, VHF transm.)
- **UK -** SXI (optics + detectors + calibration) + S/W (SXI pipeline and remote contribution to SDC)
- **France -** IRT (coordination and IR camera, including cooler) **, ESA -** IRT optics + SXI CCDs
- **Germany, Poland, Denmark** - 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)
- **Industrial partners:** OHB-I, GPAP

❑ GW/multi-messenger time-domain astrophysics

GW transient sources that will be monitored by THESEUS include **NS-NS / NS-BH mergers**:

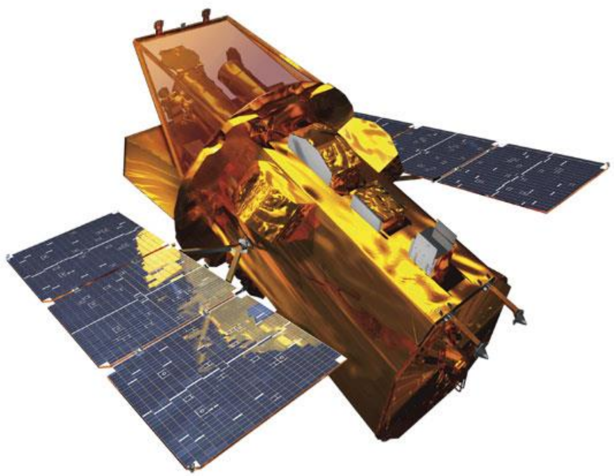
- ❑ **collimated** on-axis and off-axis prompt gamma-ray emission from short GRBs
- ❑ Optical/NIR and soft X-ray **isotropic** emissions from kilonovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown

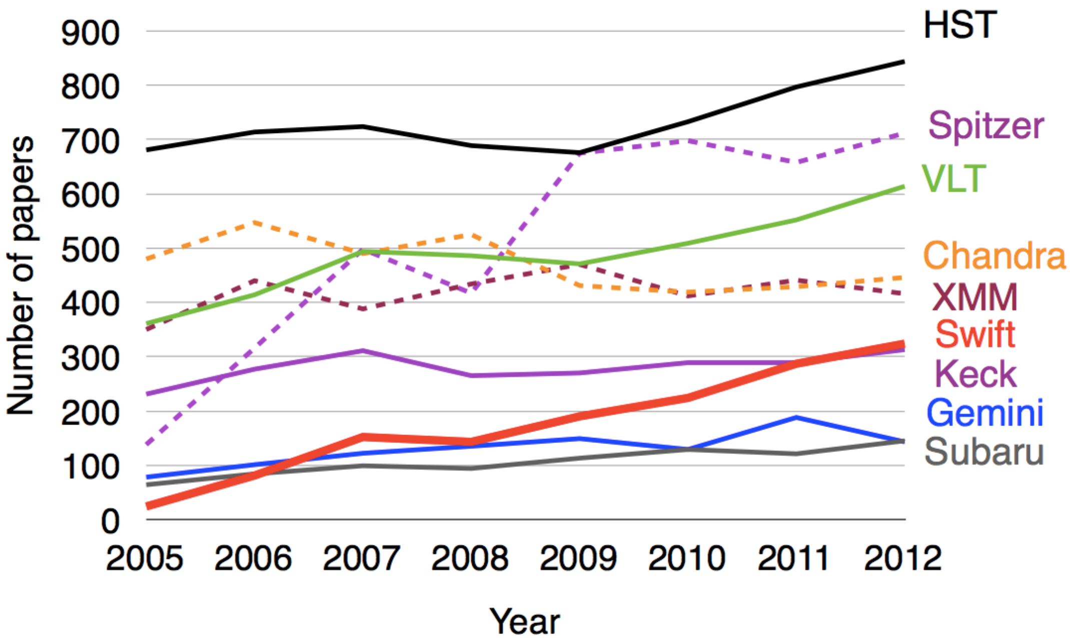




The Swift experience

- A flexible, rapid-slewing, multi-wavelength observatory has proven a very powerful facility.
- New, frequently unanticipated, discoveries throughout mission.
- High publication rate, particularly of high impact papers (e.g. >50 Nature papers)





Subject: Letter of Endorsement for the THESUES M5 mission candidate

Dr Lorenzo Amati
INAF – Istituto di Fisica Spaziale e Fisica Cosmica di Bologna (IASF-Bo)
Via P. Gobetti 101, 40129 – Bologna (ITALY)
Telephone: (+39) 0516398745
Fax: (+39) 0516398723
e-mail: amati@iasfbo.inaf.it

Dear Dr Amati,

We have received a description of the THESEUS mission that will be proposed to the European Space Agency (ESA) for consideration as a Cosmic Vision M5 mission.

The mission's science objectives are of strong interest for the multi-messenger astronomy, including the gravitational waves. The astrophysical sources that THESEUS will observe are expected to be detectable by ground based gravitational wave detectors (10-1000 Hz). The simultaneous multi-wavelength electromagnetic and gravitational wave observations maximize the scientific return of each detection.

The Virgo Collaboration and the European Gravitational Wave Observatory (EGO) strongly support the THESEUS proposal and express interest to collaborate on the exploitation of scientific data in a multi-messenger context.

Sincererly,

Prof. Fulvio Ricci
Virgo spokesperson

Prof. Federico Ferrini
EGO Director

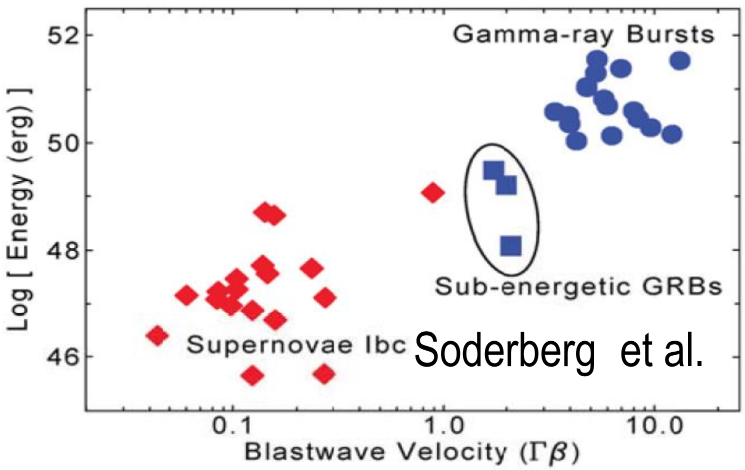
❑ Time-domain astronomy and GRB physics

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

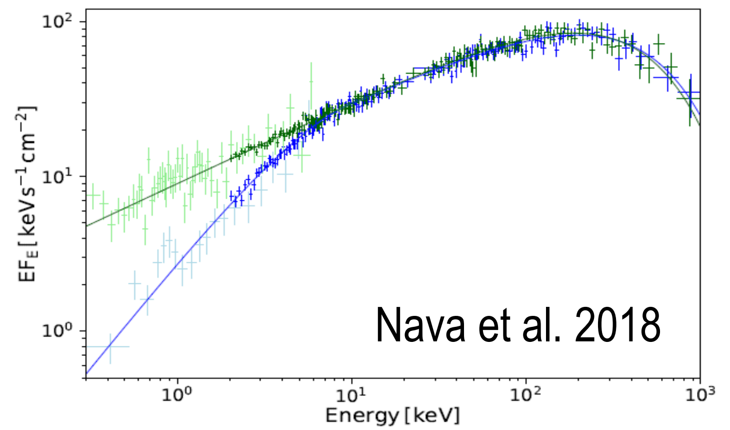
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;

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

Transient type	SXI rate
Magnetars	40 day^{-1}
SN shock breakout	4 yr^{-1}
TDE	50 yr^{-1}
AGN+Blazars	350 yr^{-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}

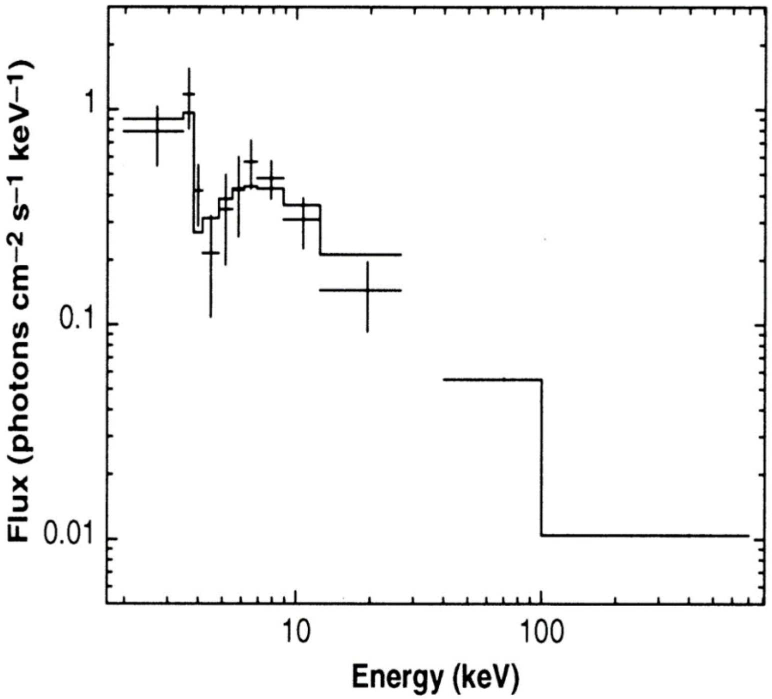


Soderberg et al.

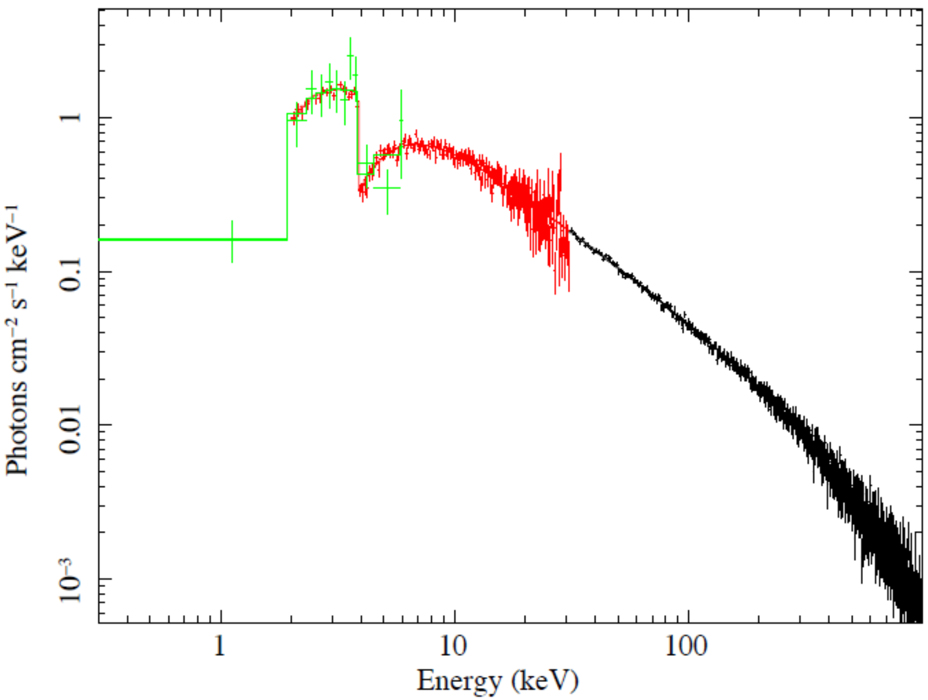


Nava et al. 2018

❑ Absorption features: the case of GRB990705 (edge at 3.8 keV -> redshifted neutral iron k-edge -> z = 0.85 -> confirmed by host galaxy spectroscopy: redshift estimate through X-ray spectroscopy

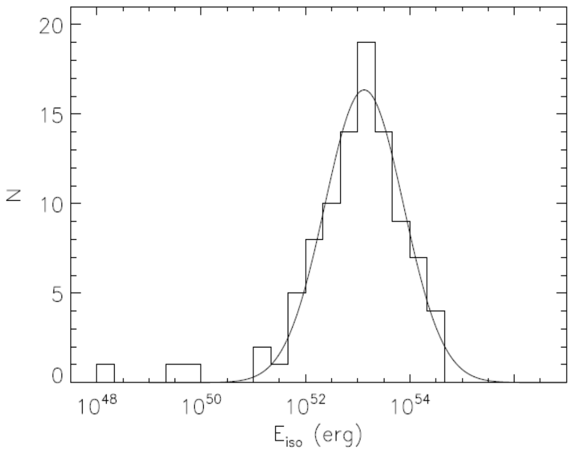


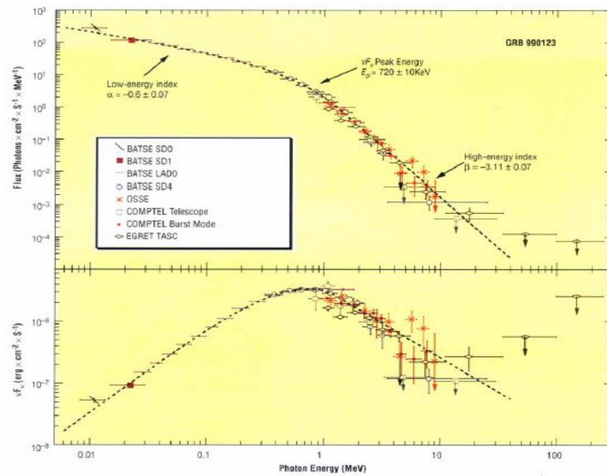
BeppoSAX WFC + GRBM
(Amati et al. 2000)

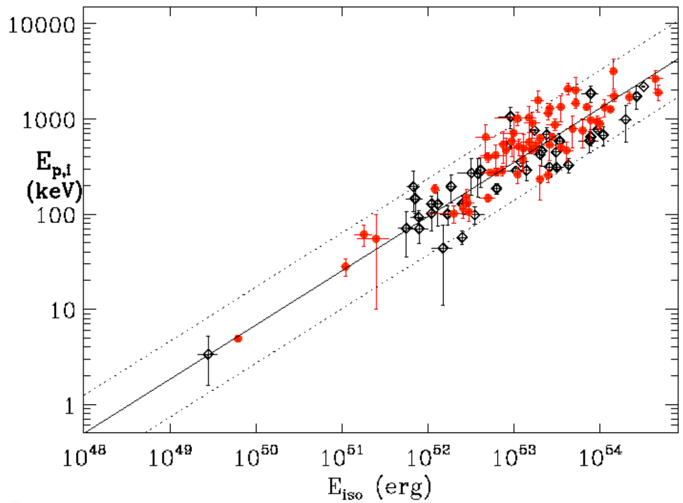


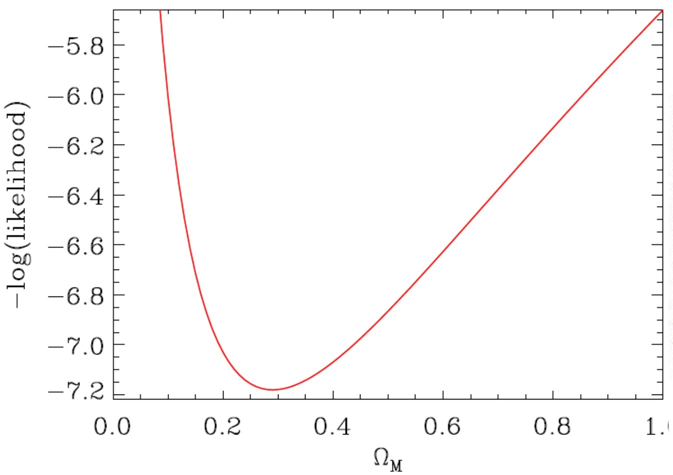
THESEUS SXI + XGIS
(Nava et al. 2018)

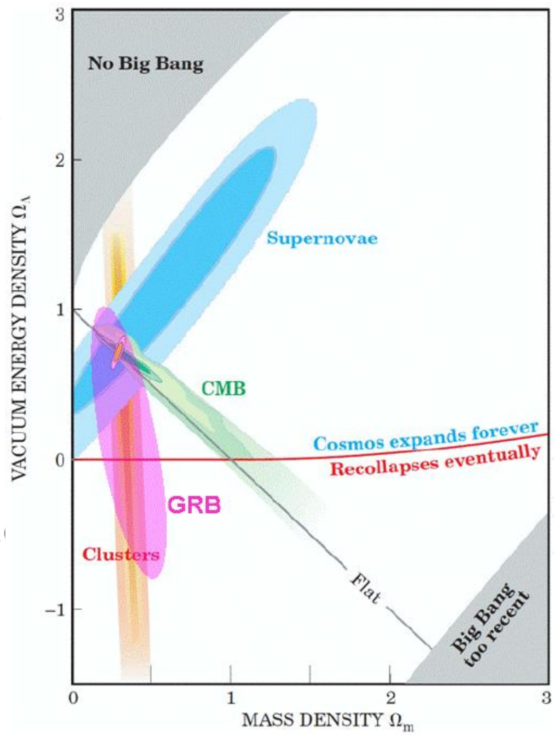
❑ measuring cosmological parameters with GRBs

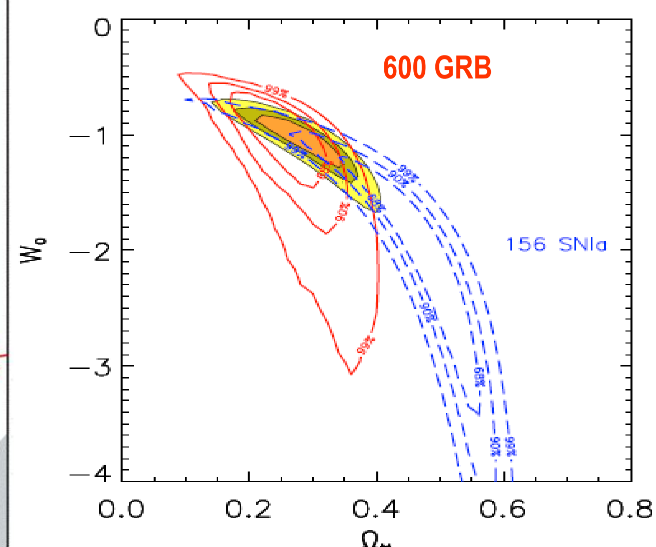






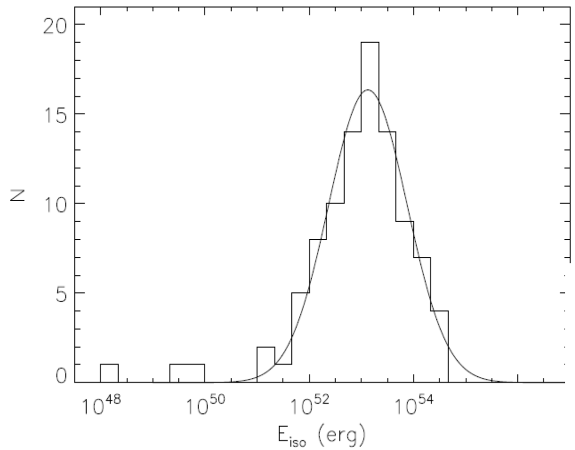


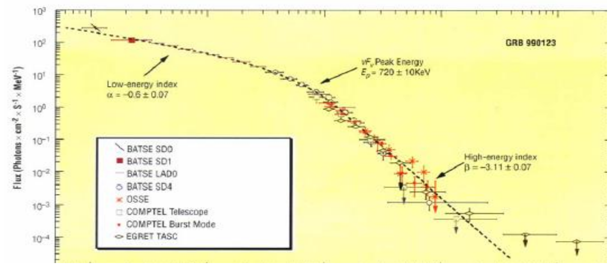


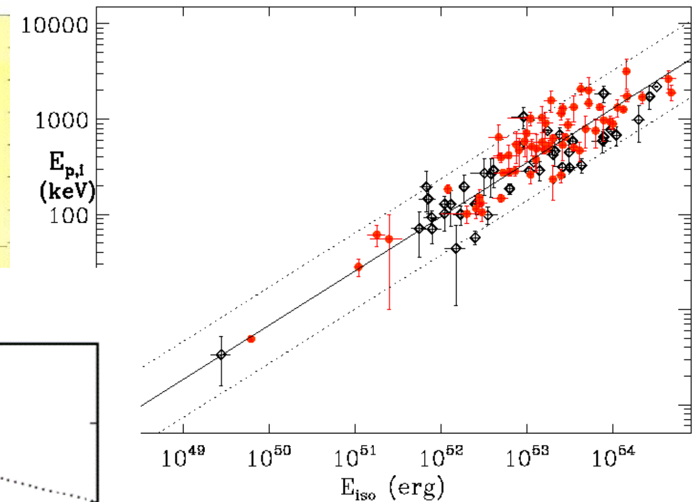


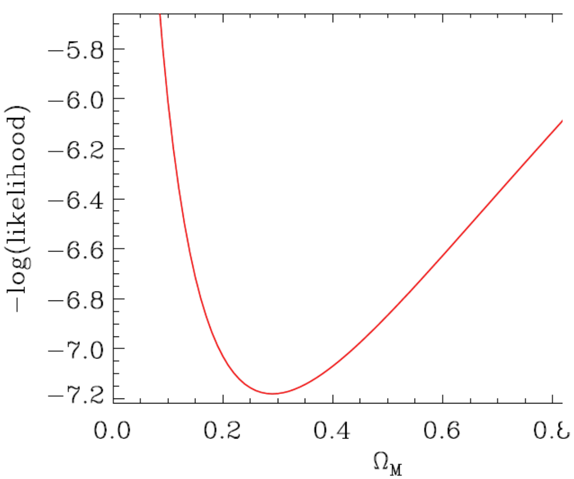
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

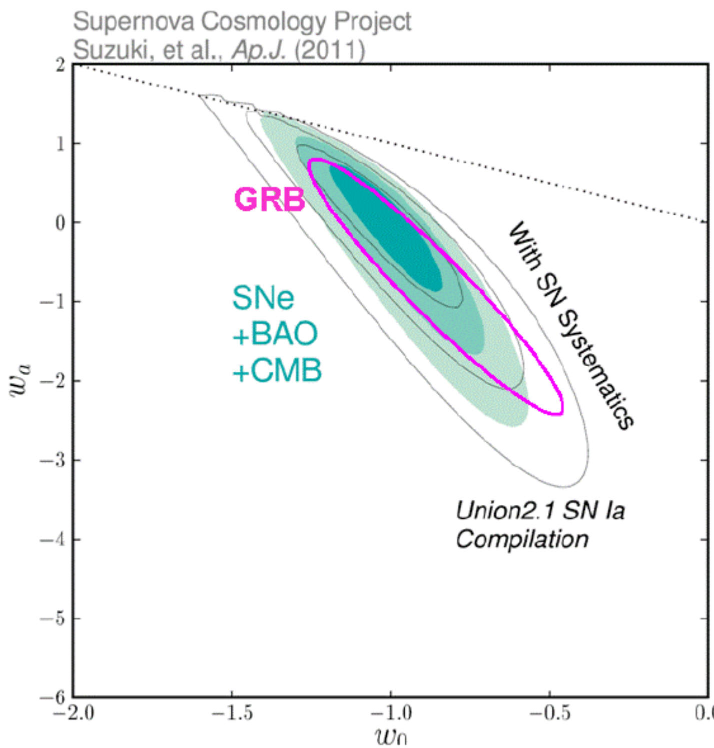
❑ measuring cosmological parameters with GRBs

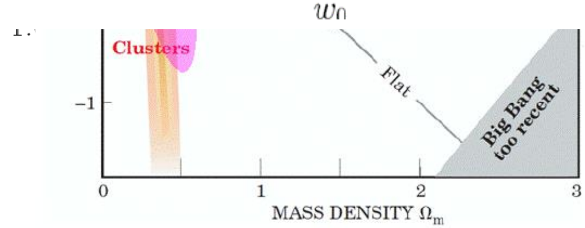


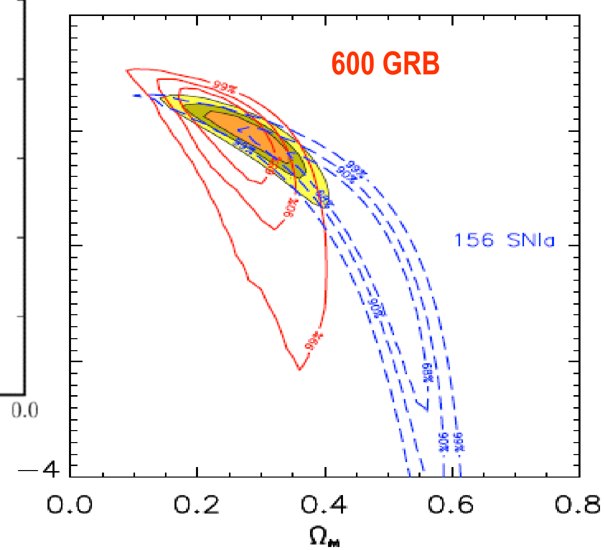






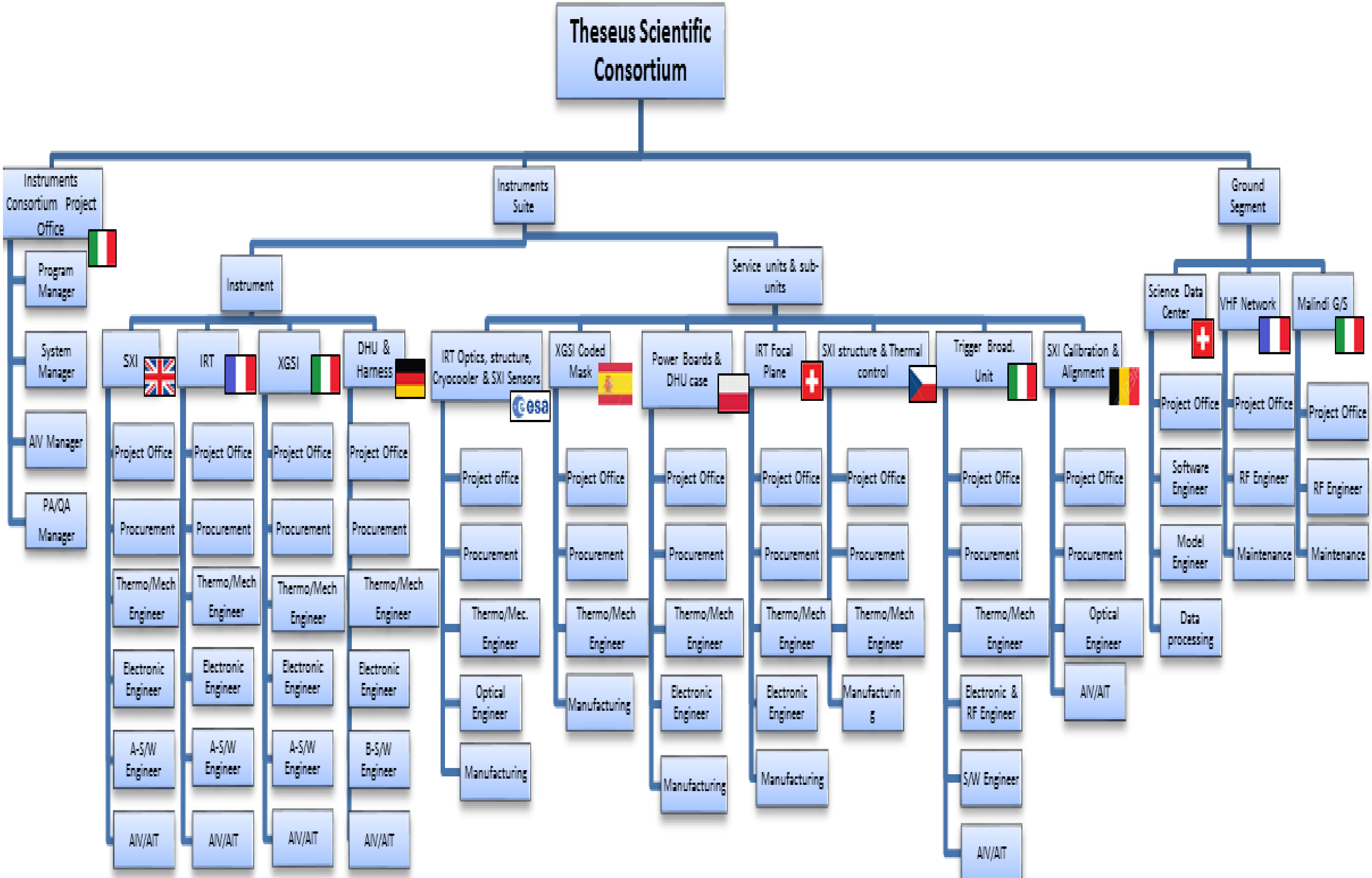






$$w(z) = w_0 + \frac{w_a z}{1+z}$$

THESEUS consortium WBS (M5)



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

The Italian contribution to THESEUS

- **Science: INAF** (Lead Proposer & coordination; OAS, IASF-MI, Oss. Brera, IAPS, IASF-PA, Oss. Napoli, Oss. Roma, …), **Universities** (e.g., Univ. Ferrara, Pol. Milano, SNS Pisa, Univ. Federico II Napoli, Univ. Urbino, …), **INFN** (Trieste, Napoli, Bologna, Ferrara, …)

- **XGIS: INAF** (PI; OAS, IASF-MI, IAPS, IASF-PA, …), **INFN** (Trieste, Bologna), **Universities** (Politecnico Milano, Univ. Pavia, Univ. Ferrara, Univ. Udine, **FBK** Trento

- **Malindi ground station & VHF transmitter: ASI**

- **SSDC: ASI**

- **Industrial support for M5 proposal: OHB-Ita, GPAP**

The key role of Italy in THESEUS

- Building on the unique heritage in GRB and transients science of the last 15-20 years (BeppoSAX, HETE-2, Swift, INTEGRAL, AGILE, Fermi, optical/NIR follow-up)

- Strengthening and exploiting the fundamental contribution to time domain and gravitational waves astrophysics (EGO-Virgo, EM follow-up with major facilities like VLT)

- Taking advantage of leadership in key enabling technologies based on R&D supported by INFN, INAF, ASI in the last years (e.g., silicon drift detectors + scintillators,)

Italian contribution: technological heritage

- **Scintillator-based detectors for high energy astrophysics:** BeppoSAX PDS & GRBM, INTEGRAL/PiCSIT, AGILE/MCAL (leading roles of INAF - IASF – Bologna) + R&D projects funded by ASI

- **SDD detectors for high-energy astrophysics and associated electronics (ASIC)**: R&D projects funded by INFN (e.g., REDSOX), FBK, 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 XGIS module prototype is supported by TECNO INAF 2014 (P.I. L. Amati, INAF – IASF Bologna)**

M5 - Tentative Schedule

Activity	Date
Phase 0 kick-off	June 2018
Phase 0 completed (EnVision, SPICA and THESEUS)	End 2018
ITT for Phase A industrial studies	February 2019
Phase A industrial kick-off	June 2019
Mission Selection Review (technical and programmatic review for the three mission candidates)	September 2021
SPC selection of M5 mission	November 2021
Phase B1 kick-off for the selected M5 mission	December 2021
Mission Adoption Review (for the selected M5 mission)	March 2024
SPC adoption of M5 mission	June 2024
Phase B2/C/D kick-off	Q1 2025
Launch	2032

M5 - Way forward Phase 0/A

- Team nominations ESA (ESTEC, ESAC, ESOC) & external Study Science Teams – on th
- 3 x M5 CDF studies Jun-Nov 2018:
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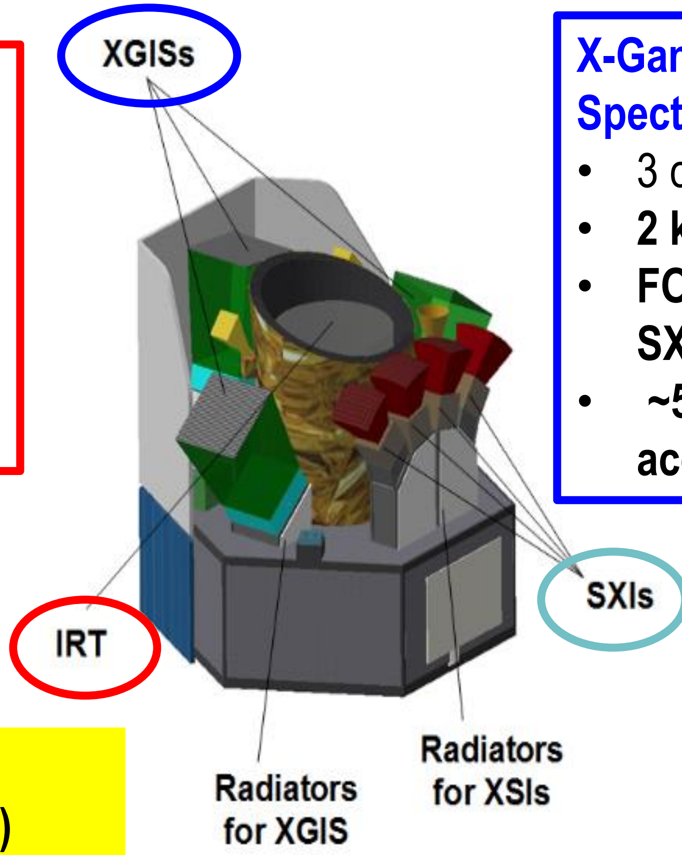
THESEUS mission concept

InfraRed Telescope (IRT)
- 0.7m class IR telescope
- **0.7 – 1.8 μm band**
- **10'x10' FOV**
- **Imaging + moderate resolution spectroscopy capabilities**



X-Gamma rays Imaging Spectrometer (XGIS)
- 3 coded-mask X-γ ray cameras
- **2 keV – 10 MeV band**
- **FOV of ~2-4 sr, overlapping the SXI,**
- **~5 arcmin source location accuracy**

Soft X-ray Imager (SXI)
- set of 4 sensitive lobster-eye telescopes
- **0.3 - 5 keV band,**
- **FOV of ~1sr**
- **0.5-1 arcmin source location accuracy**

Low-Earth Orbit, <5°
Rapid slewing bus (>10°/min)
Prompt downlink (< 10-20s)
64% sky coverage
Launch with VEGA-C

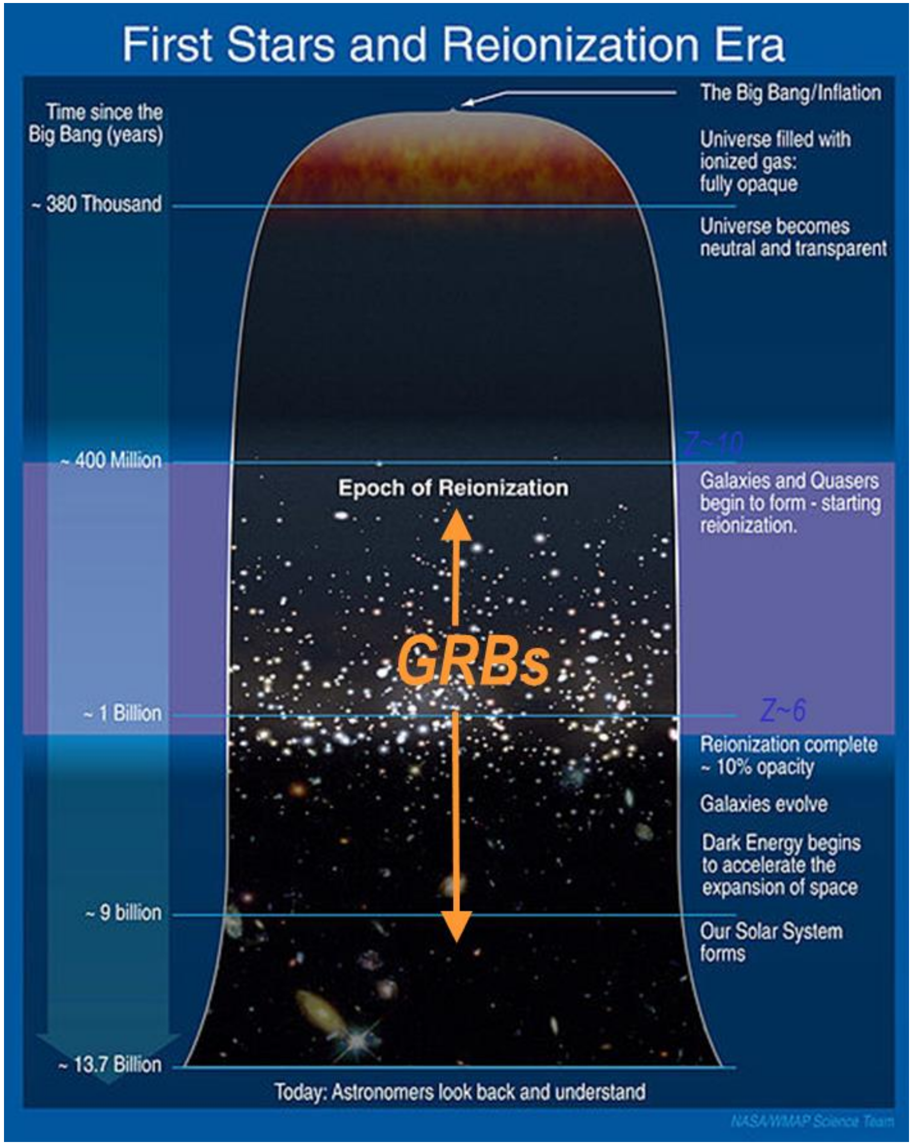
❑ GW/multi-messenger and time-domain astrophysics

GW transient sources that will be monitored by THESEUS include:

- ❑ 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)

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?*

THESEUS: Main scientific goals

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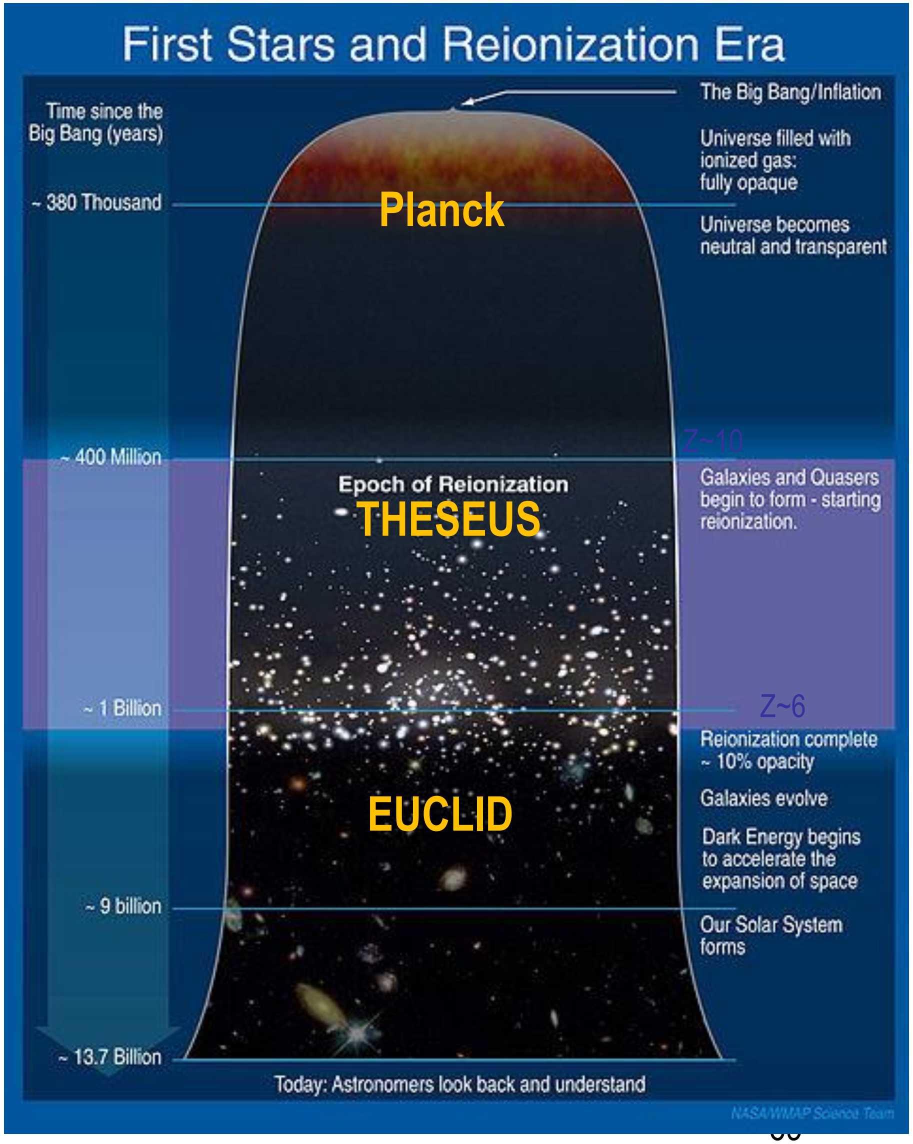
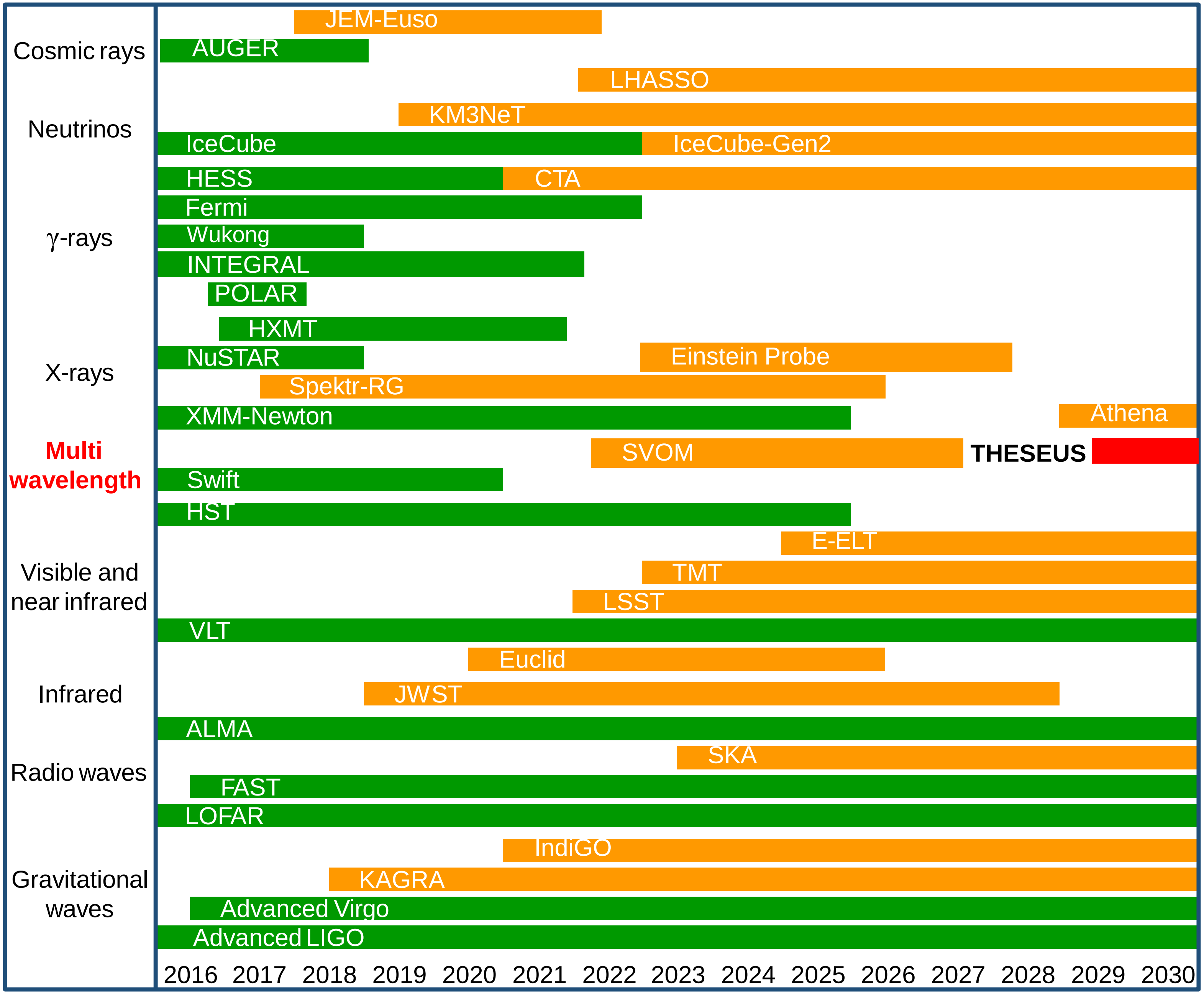
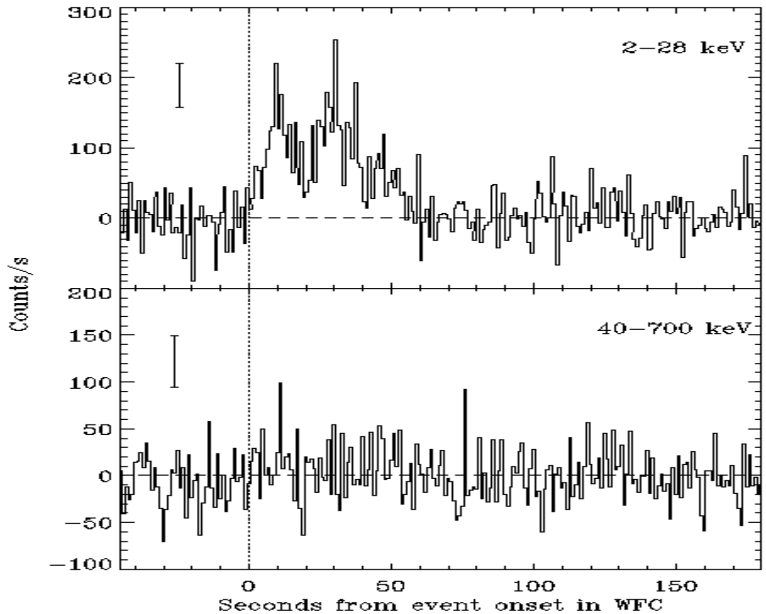
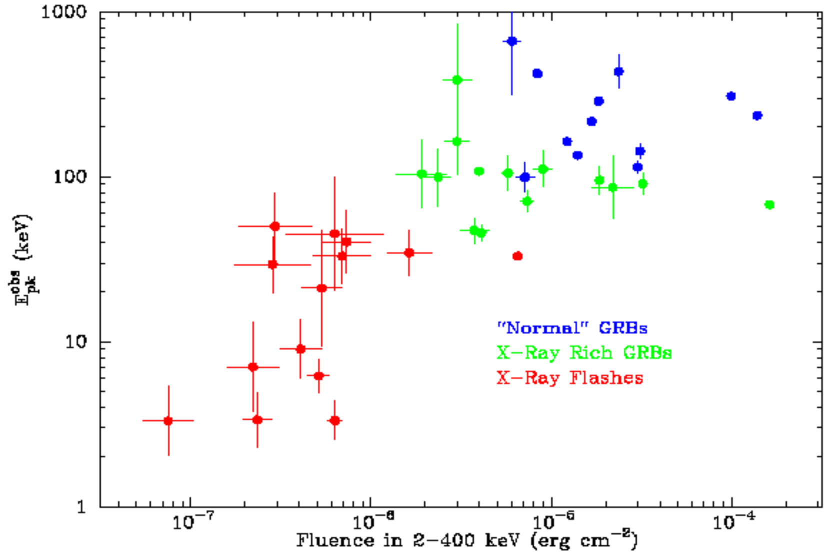


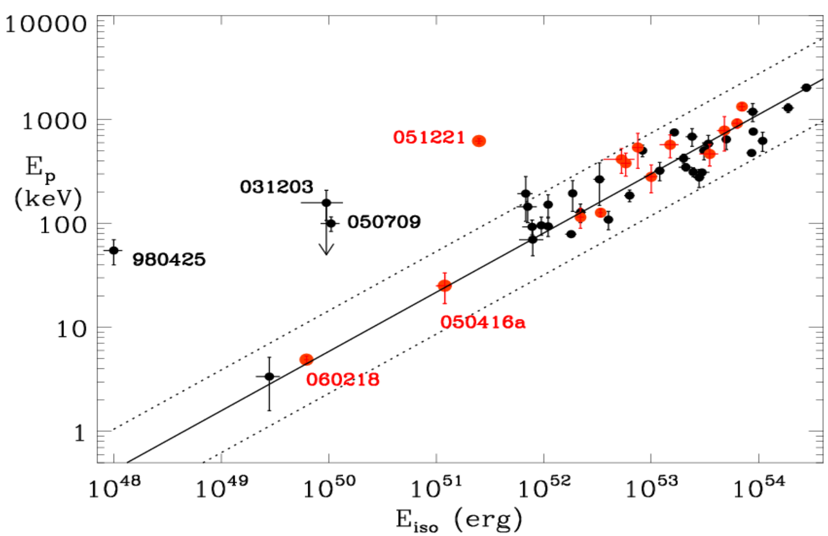
THESEUS synergy with next generation large observatories

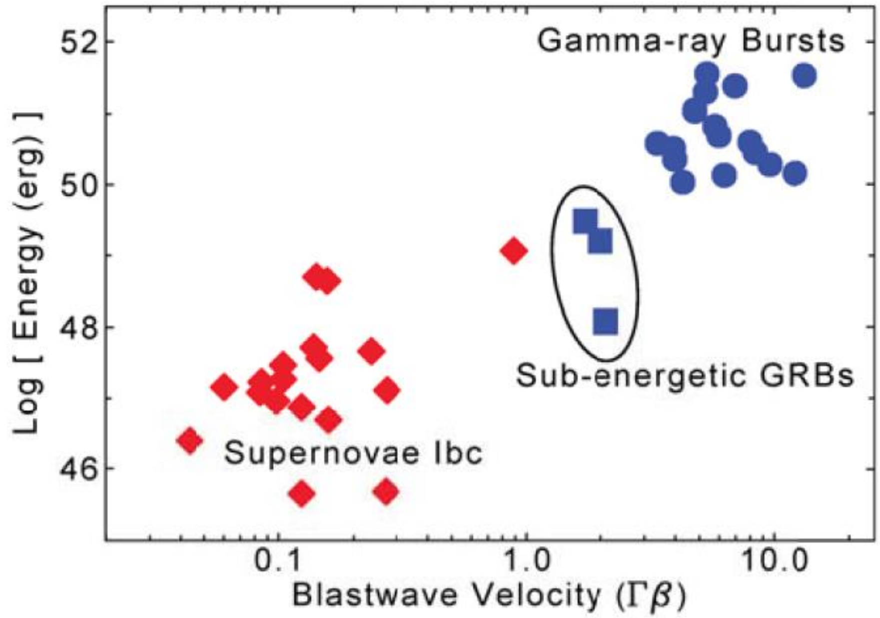


❑ X-Ray flashes and subluminous GRBs









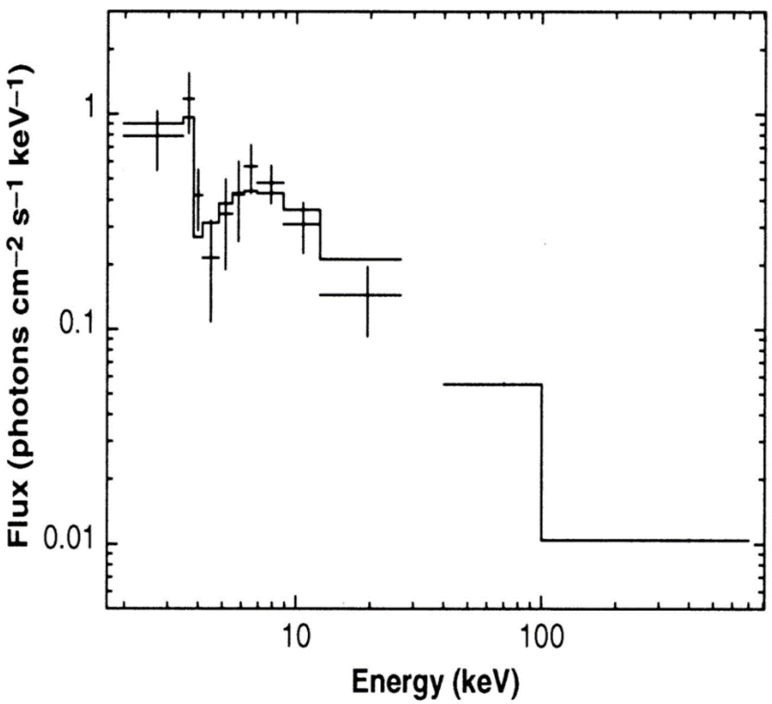
FUNCTIONAL SUBSYSTEMS	Nominal Avg Power (Watt)	Margin (%)	Margin (Watt)	Current Avg Power (Watt)
SERVICE MODULE				
AOCS	*79*	*10%*	*8*	*87*
DATA HANDLING	*37*	*10%*	*4*	*41*
EPS	*39*	*10%*	*4*	*43*
PROPULSION	*1*	*10%*	*0*	*1*
THERMAL CONTROL (incl. PLM)	*83*	*20%*	*17*	*100*
PDHU + X BAND	*42*	*10%*	*4*	*46*
Total Service Module Power	*282*	*13%*	*36*	*318*
PAYLOAD MODULE				
SXI	*93*	*20%*	*19*	*111*
XGIS	*75*	*20%*	*15*	*90*
IRT	*96*	*20%*	*19*	*115*
NGRM+TBU	*93*	*20%*	*19*	*111*
I-DHU + i-DU (TBC)	*25*	*20%*	*5*	*30*
Total Payload Module Power	*381*	*20%*	*76*	*457*

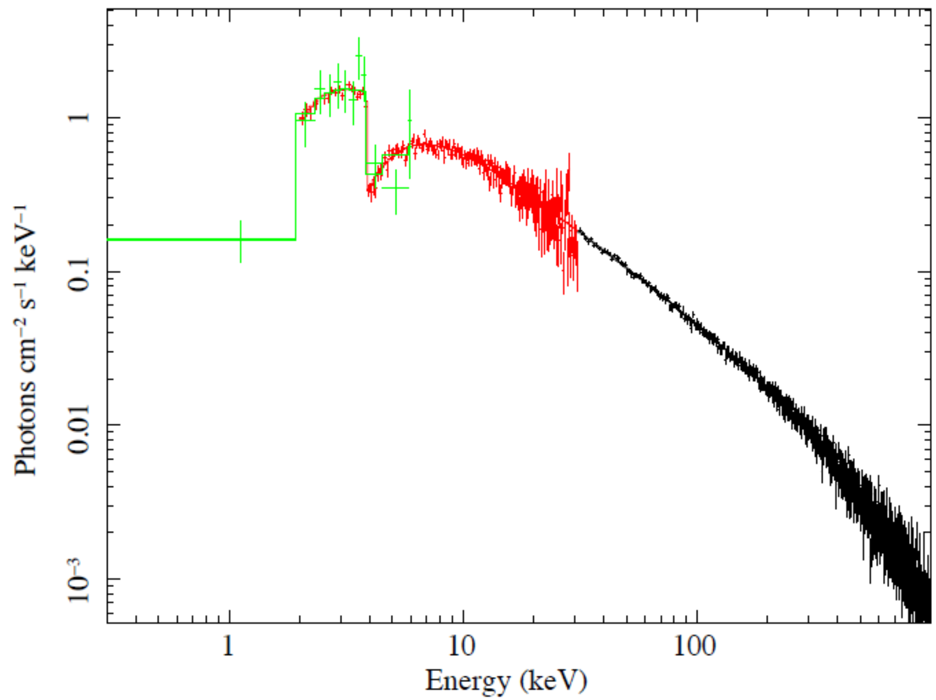
Satellite Nominal Power (W)	
Service Module	282
Payload Module	381
20% System Margin	132
Harness Loss	18
Total power with losses and margin	813

Table 21: Cost Estimates to ESA

Activity	CAC (M€)
ESA Project Office	54
Satellite (incl. 20% contingency)	165
ESA contribution to P/L	120
Launch (VEGA)	45
Ground Segment & Operations	84
Contingency (15% of subtotal)	70
Total cost for ESA	538

❑ Absorption features: the case of GRB990705 (edge at 3.8 keV -> redshifted neutral iron k-edge -> z = 0.85 -> confirmed by host galaxy spectroscopy: redshift estimate through X-ray spectroscopy



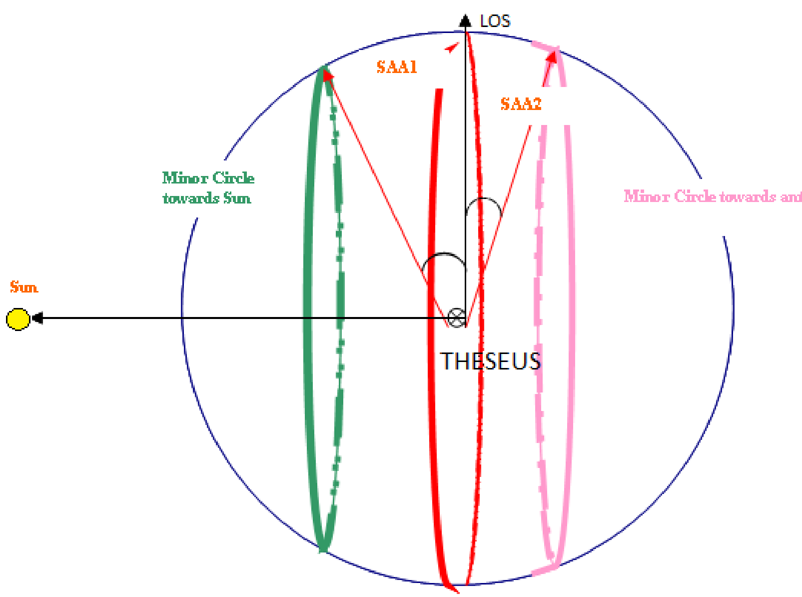


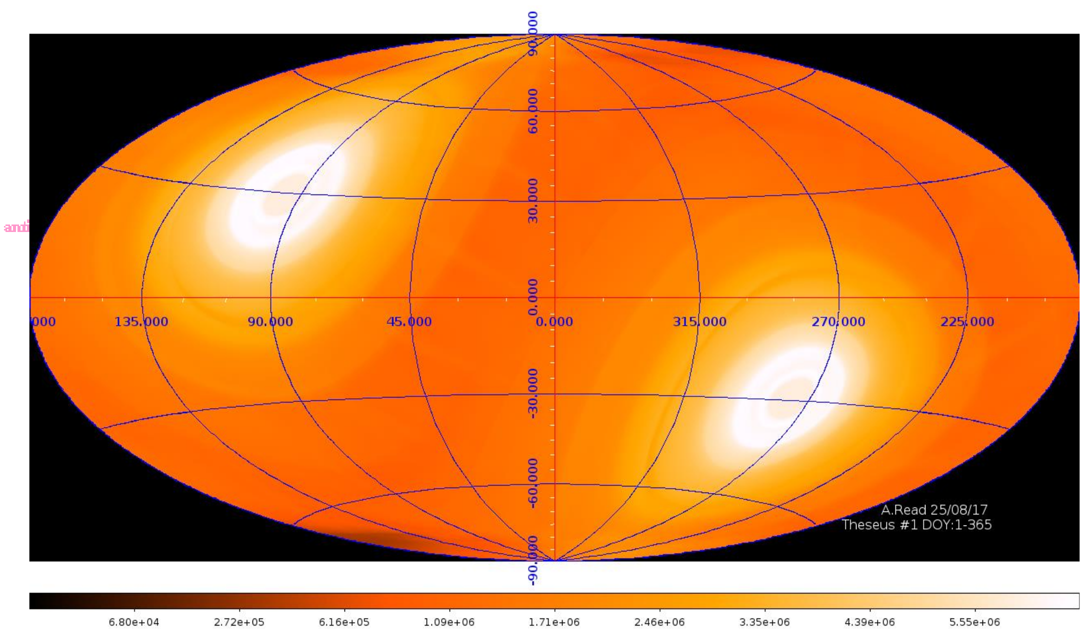
BeppoSAX WFC + GRBM
(Amati et al. 2000)

THESEUS SXI + XGIS
(Nava et al. 2018)

THESEUS mission profile

- Low-Earth Orbit (LEO), (< 5°, ~600 km)
- Rapid slewing bus (>10°/min)
- Prompt downlink (< 10-20s)
- Sky fraction that can be observed: 64%





THESEUS after JWST and SKA

- **Even JWST and E-ELTs surveys, in the 2020s, will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8).**

- The first, metal–free stars (the so–called **Pop III 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 Pop III stars in **enriching the first galaxies** with metals can be studied by looking to the absorption features of Pop II GRBs blowing out in a medium enriched by the first Pop III supernovae (Wang+12).

- This is intimately connected to the reionization of the IGM and build up of global metallicity. The latter is very poorly constrained, and **even in the *JWST* era will rely on crude emission line diagnostics for only the brightest galaxies.**

- Regarding **reionization**, measurements of the Thomson scattering optical depth to the microwave background by the Planck satellite now suggest it substantially occurred in the redshift range $z \sim 7.8 - 8.8$ (e.g., Planck collaboration. 2016), whereas the observations of the Gunn-Peterson trough in the spectra of distant quasars and galaxies indicate it was largely finished by $z \sim 6.5$ (e.g., Schenker et al. 2014). Statistical measurements of the fluctuations in the redshifted 21 cm line of neutral hydrogen by experiments such as LOFAR and SKA are expected to soon provide further constraints on the time history (e.g, Patil et al. 2014). ***The central question, however, remains whether it was predominantly radiation from massive stars that both brought about and sustained this phase change, or whether more exotic mechanisms must be sought?*** With samples of several tens of GRBs at z > 7-8, we can begin to statistically investigate the average and variance of the reionization process as a function of redshift (e.g., McQuinn et al. 2008).

- Even though some constraints on fainter galaxies can be obtained through observations of lensing clusters (e.g. Atek et al. 2015 ApJ 7 814 69), which will be improved further by *JWST*, simulations **suggest star formation was likely occurring in considerably fainter systems still** (Liu et al. 2016).

THESEUS IRT Observatory Science

- Fielding an IR-specified spectrograph in space, THESEUS would provide a unique resource for understanding the evolution of large samples of obscured galaxies and AGN. With a rapid slewing capability, and substantial mission duration, the mission provides a very flexible opportunity to take efficient images and spectra of large samples of galaxies with minute-to-many-hour-long cumulative integrations

- The capability to cover the redshift range from $0.07<z<1.74$ for H-alpha and $0.44<z<2.29$ for H-beta enables Balmer decrement measurements of the extensive evolution of the AGN and galaxy luminosity functions at redshift ~0.5-1.5, a spectral region that simply cannot be covered from the ground. These key diagnostic rest-optical emission lines will be observed for galaxies in this substantial range of redshifts, reaching out towards the peak of AGN and galaxy formation activity, over a continuous redshift range where the bulge-blackhole mass relation is being built up and established, and the main sequence of star formation is well-studied. With excellent image quality, THESEUS~Rs R~500 grism can also provide spatially-resolved spectral information to highlight AGN emission, and identify galaxy asymmetries.

- The imaging sensitivity of THESEUS is about 6 magnitudes lower than for JWST in the same exposure time; nevertheless, its availability ensures that many important statistical samples of active and evolved galaxies, selected from a wide range of sources can be compiled and diagnosed in detail at these interesting redshifts. Samples can be drawn from the very large WISE- and Herschel-selected infrared samples of galaxies, from EUCLID~Rs 24-mag large-area near-infrared galaxy survey, augmented by near-infrared selection in surveys from UKIDSS (whose deepest field reaches approximately 1 mag deeper than EUCLID~Rs wide-area survey in the H band) and VISTA, and in the optical from LSST and SDSS.

- Spectra for rare and unusual galaxies and AGNs selected from wide-field imaging surveys can be obtained using the wide-field of THESEUS grism, thus building an extensive reference sample for studying the environments of the selected galaxies and AGNs, identifying large-scale structures and allowing overdensities to be measured.

A flexible and efficient use of the non-GRB THESEUS time with GO and ToO programs will enable to tackle a wide range of studies of variable and transients sources. The near-infrared bands are critical for Solar-system object tracking and multi-epoch variability studies. Cool stars, whose photon fluxes peak in the near-IR, are ideal targets for the detection and characterization of exoplanets using the transit technique, either in surveys or for follow-up
observations of individual sources (see, e.g., Clinton et al. 2012, PASP, 124, 700 and references therein). Simultaneous X-ray and NIR monitoring of samples of T-Tauri stars will shed light on the mechanisms responsible for the onset of the observed outbursts, and how the accretion rate of matter on these stars and the emission of jets can influence the formation of proto-planetary systems. Several open questions for low-mass X-ray binaries, hosting either neutron stars or stellar-mass black holes, require simultaneous IR and X-ray photometry (e.g. concerning the physics of jet emission from these sources; see, e.g., Migliari et al. 2010, ApJ, 710, 117; Russell et al. 2013, MNRAS, 429, 815). Recent studies have found that the peak luminosity of SNe Ia are genuine standard candles in the NIR (e.g. Krisciunas et al. 2004, ApJ 602 L81; Burns et al. 2014, ApJ 789 32). Considering also the reduced systematics in the NIR related to host-galaxy reddening, the IRT will represent an very efficient tool to construct a low-z sample of SNe Ia to be compared with the high-z samples that will be built by forthcoming IR facilities (e.g. JWST). In addition, gravitational time delays (a technique increasingly exploited in recent years for competitive H0 measurements) and AGN reverberation mapping variability projects will be particularly advantageous for THESEUS, where the cadence can be chosen more flexibly.

Possible THESEUS Data Policy

- In order to increase the follow-up from ground based facilities GRB positions and redshifts will be made immediately public

- GRB data will be owned by the consortium and made public after 1 year (TBC)

- X-ray survey alerts (i.e. non-GRB) will be made immediately public

- X-ray survey data will be owned by the consortium and made public within 1 year (TBC)

- THESEUS can be used as an observatory between one GRB follow-up and the other **a la Swift/XRT**

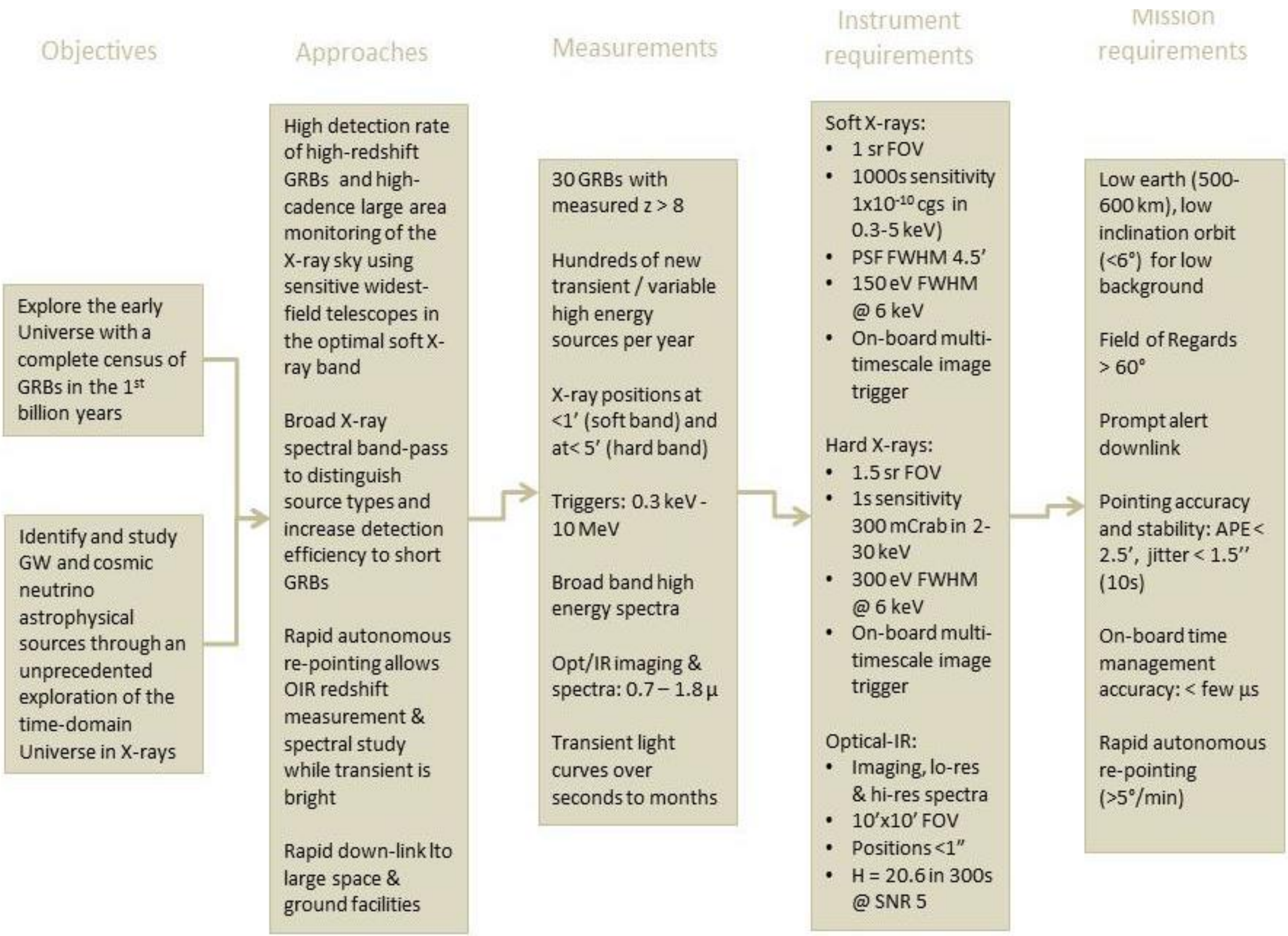
Table 17: Instruments TM summary

Instrument Suite	TM load (Gbit/orbit)
SXI	0.3
XGIS	2.4
IRT	2.2
Total P/L telemetry	4.5

Table 18: Summary of Instrument Suite temperatures

Instrument Element	Operative range (°C)	Cooling
SXI- structure/optics	-20 ÷ +20	passive
SXI- detectors	-65	active
XGIS-detectors	-20 ÷ +10	passive
IRT-structure	-30	active
IRT-optics	-83	active

SXI (4 units)	400 MCPs	4.0	Quotation Photonis	Mass production	UK, , Czech Republic, Germany, Belgium, ESA (contribution of the CCDs)
	30 CCDs	12	Quotation EEV	Mass production	
	Optics build test	10	100% FTE	Working time	
	Focal plane build test	11	100% FTE	Working time	
	Module structure/thermal/integration	11	100%FTE	Working time	
	Calibration 5 modules	2.0	100% FTE	Working time	
	Instrument controller into I-DHU	2.0	100%FTE	Working time and materials	
XGIS (3 units)	Man power for a) system management; b)electrical,mech & therm. des.; c) material procurement logistics; d) mass production (180 boards); e) AIV of the 26 modules; f) program management; g) Product assurance	9.0	Quotation	Mass production	Italy, Poland
	ASICs	1.0	Quotation	Mass production	
	SDD-PD units	2.4	Quotation	Mass Production	
	CsI bars	0.6	Quotation	Mass Production	
	Electronic board materials	1.3	Quotation	Mass production	
	Mechanical structure and collimators	1.5	Quotation	Mass production	
	Ground Support Equipment	0.2	Quotation	Working time	
	Spare materials	0.3	Quotation		
	Instrument Controller into I-DHU	1.25	100%FTE	Working time	
IRT	Telescope Mirror	100	Quotation		ESA (telescope and overall cooling system, including MPTC), France, Switzerland, Germany, Poland, Belgium
	Cost for a) management; b) System Engineering; c) Product Assurance; d) Camera optics and CCD e) Camera mechanical design; f) Camera thermal design; g) GSe; h) Camera Assembly, i) AIV/AIT.	22	Quotation (EUCLID experience)	Working time plus materials	
	Camera cooling system including MPTC	3,1	Quotation from AirLiquide	Material	
	IRT focal plane	5	Quotation	Production	
	Instrument Controller into I-DHU	1.25	100%FTE	Working time and materials	
I-DHU &Power	Costs for a)Management; b) Structure; c) I-DHU HW; d) DHU SW; e) Power f) I-DHU&Powe board AITV.	6.2	ASIM Experience		Poland
SDC	Starting 6yrs ahead of launch. 3yrs of operations plus 2yrs of post-operations)	10	Based on the extensive experience of the UoG		Switzerland, Italy, UK, Spain
Instrument Operations Centers (one per instrument)		10	Past experience with flown missions & extended expertize from the UoG on past and running missions		All
Operational support		10	Past experience		All
Total		**237.1 (without ESA 117.1) M€)**			



Objectives
Approaches
Measurements
Instrument requirements
Mission requirements
Explore the early Universe with a complete census of GRBs in the 1st billion years
Identify and study GW and cosmic neutrino astrophysical sources through an unprecedented exploration of the time-domain Universe in X-rays
High detection rate of high-redshift GRBs and high-cadence large area monitoring of the X-ray sky using sensitive widest-field telescopes in the optimal soft X-ray band
Broad X-ray spectral band-pass to distinguish source types and increase detection efficiency to short GRBs
Rapid autonomous re-pointing allows OIR redshift measurement & spectral study while transient is bright
Rapid down-link lto large space & ground facilities
30 GRBs with measured z > 8
Hundreds of new transient / variable high energy sources per year
X-ray positions at <1′ (soft band) and at< 5′ (hard band)
Triggers: 0.3 keV - 10 MeV
Broad band high energy spectra
Opt/IR imaging & spectra: 0.7 – 1.8 μ
Transient light curves over seconds to months
Soft X-rays:
• 1 sr FOV
• 1000s sensitivity 1x10-10 cgs in 0.3-5 keV)
• PSF FWHM 4.5′
• 150 eV FWHM @ 6 keV
• On-board multi-timescale image trigger
Hard X-rays:
• 1.5 sr FOV
• 1s sensitivity 300 mCrab in 2-30 keV
• 300 eV FWHM @ 6 keV
• On-board multi-timescale image trigger
Optical-IR:
• Imaging, lo-res & hi-res spectra
• 10′x10′ FOV
• Positions <1″
• H = 20.6 in 300s @ SNR 5
Low earth (500-600 km), low inclination orbit (<6°) for low background
Field of Regards > 60°
Prompt alert downlink
Pointing accuracy and stability: APE < 2.5′, jitter < 1.5′′ (10s)
On-board time management accuracy: < few μs
Rapid autonomous re-pointing (>5°/min)

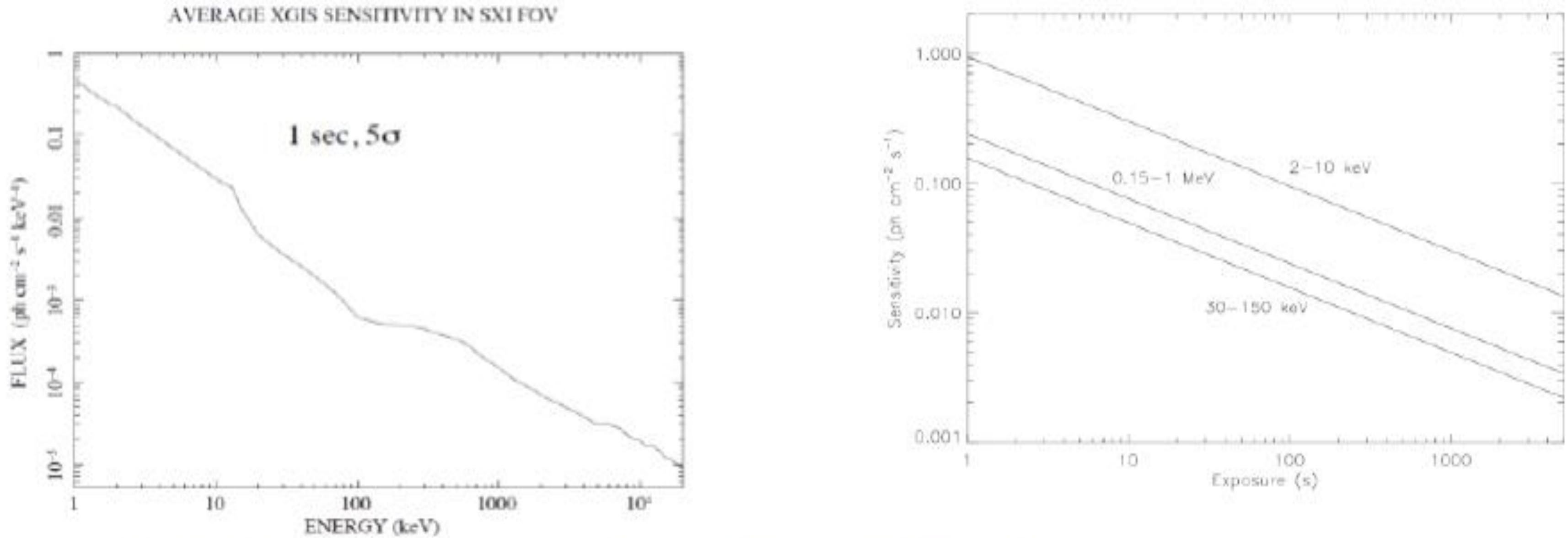
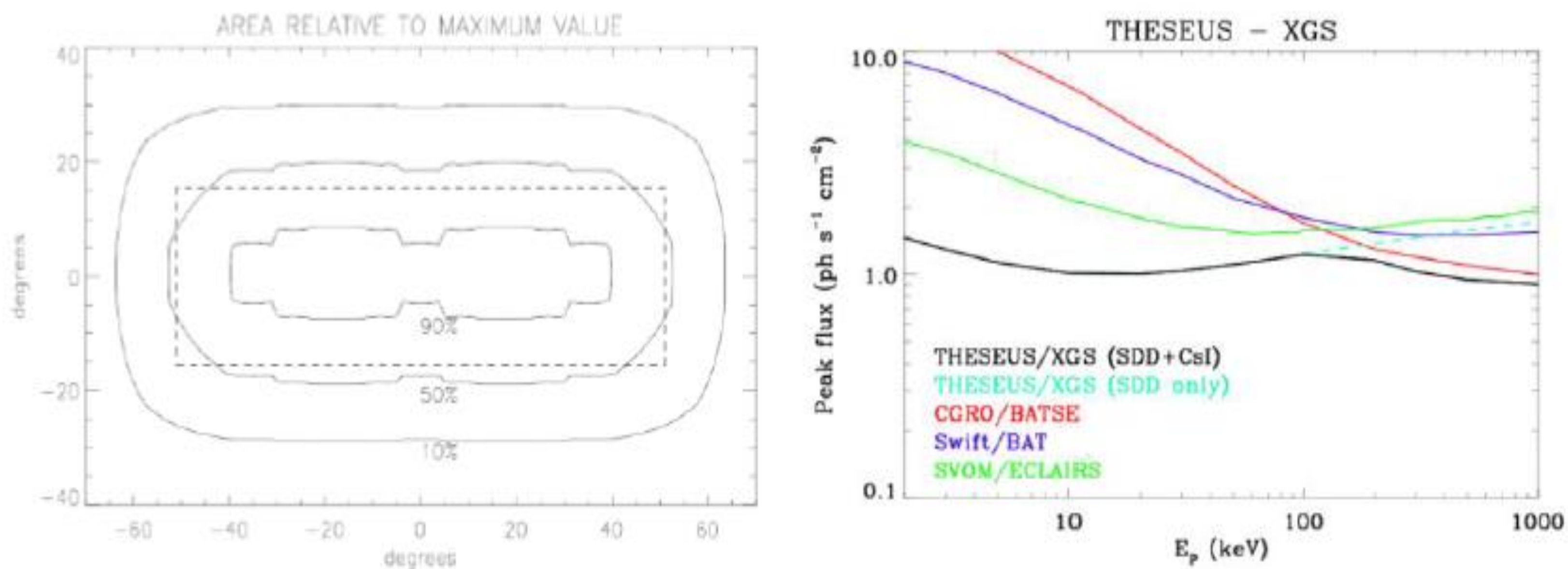
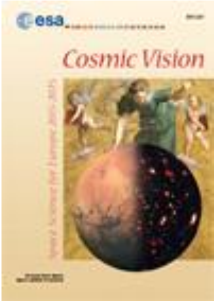


Figure 5: Left: XGIS sensitivity vs. energy in 1 second. Right: XGIS sensitivity as a function of exposure time in diffe bands.



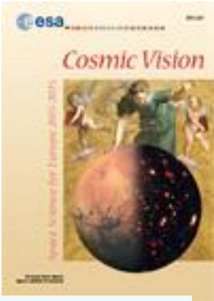
The ESA Cosmic Vision Programme



❖ Selected missions

- M1: Solar Orbiter (solar astrophysics, 2018)
- M2: Euclid (cosmology, 2021)
- L1: JUICE (exploration of Jupiter system, 2022)
- S1: CHEOPS (exoplanets, 2018)
- M3: PLATO (exoplanets, 2026)
- L2: ATHENA (X-ray observatory, cosmology, 2028)
- L3: LISA (gravitational wave observatory, 2034)
- M4: ARIEL (exoplanets, 2028)
- “S2” (ESA-CAS): SMILE (solar wind <–> magneto/ionosphere)

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 wave universe)**, life** (exoplanets formation + evolution + census, solar system exploration**)**

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

- **M5: launch in 2029-2030, ESA budget 550 MEuro, final selection of 3 missions for phase 0/A by May 2018**
- **June 2017: THESEUS passed the technical-programmatic evaluation and was admitted to the final scientific evaluation**

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

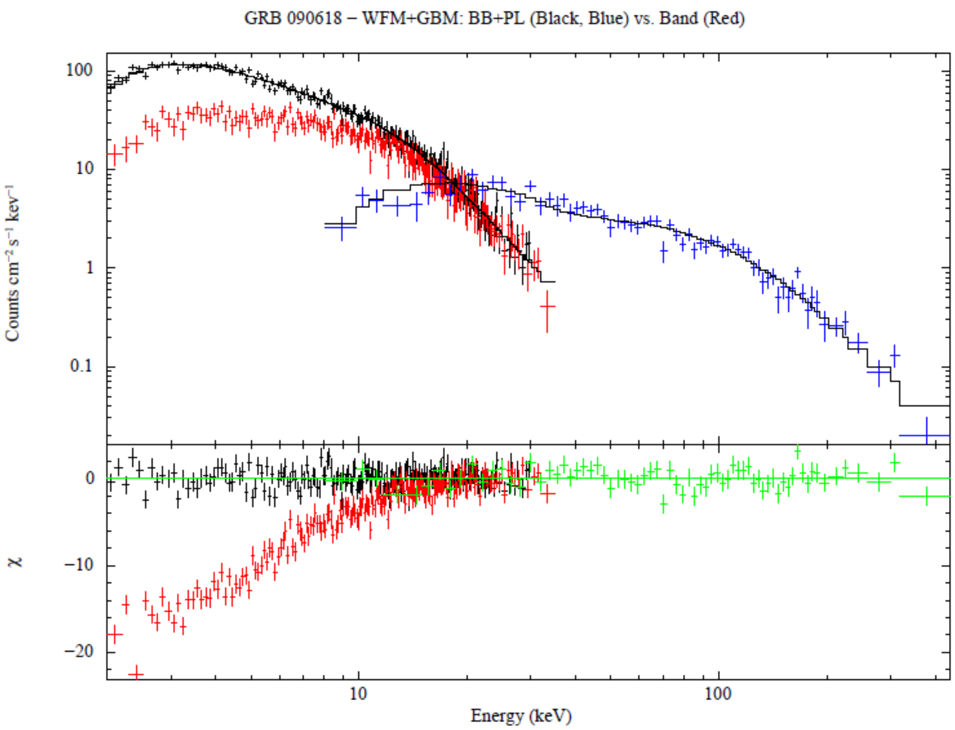
- AGILE (Italy): timing of prompt emission + X-ray detections

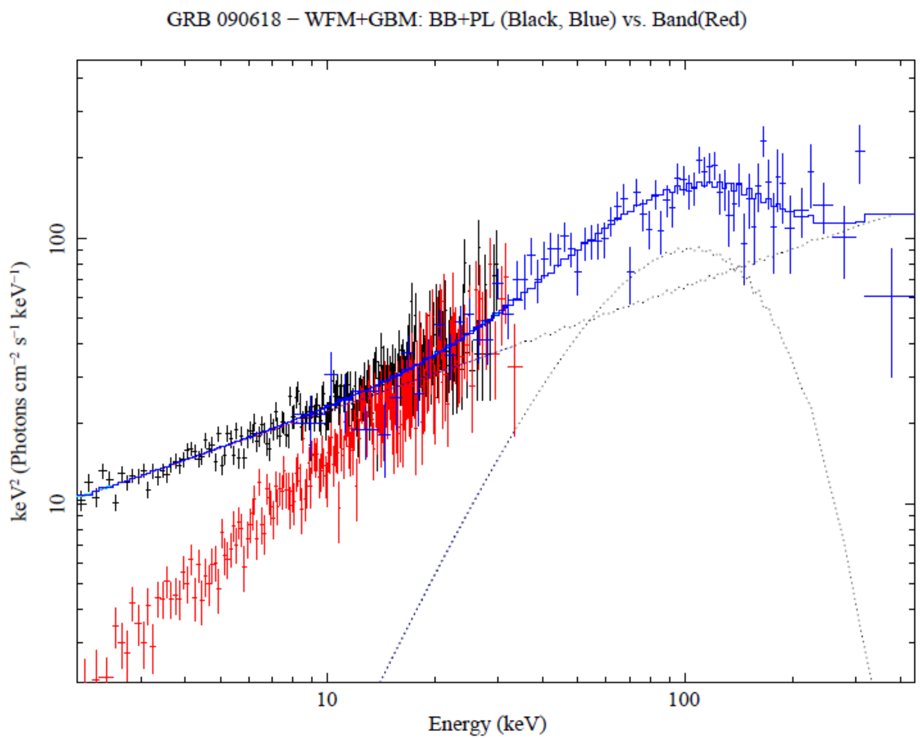
- Fermi (USA, Italian contribution): high energy emission, additional spectral features -> crucial tests for emission physics, engine (+ testing quantum gravity ?)

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

❑ Discriminating among different models - The case of GRB 090618:

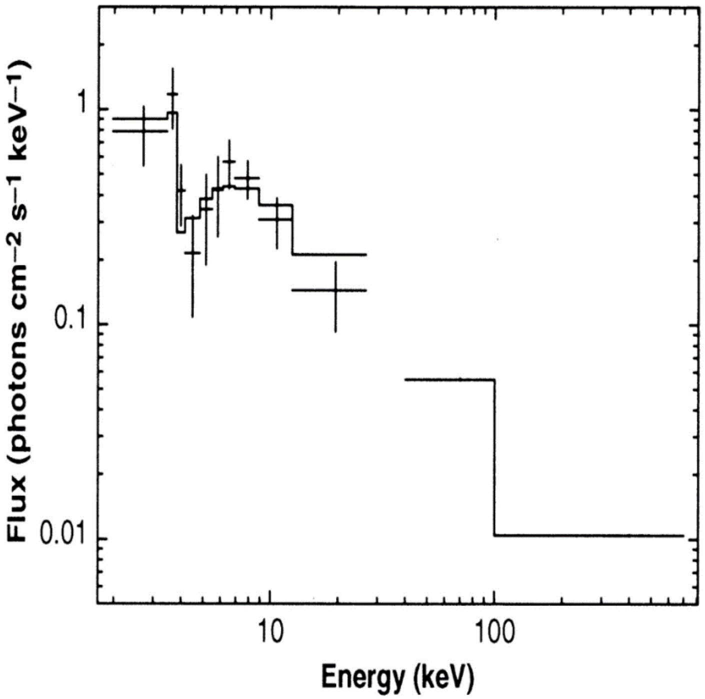
THESEUS/XGS will be capable of discriminating among Band and BB+PL thanks to its energy band extending below 10 keV

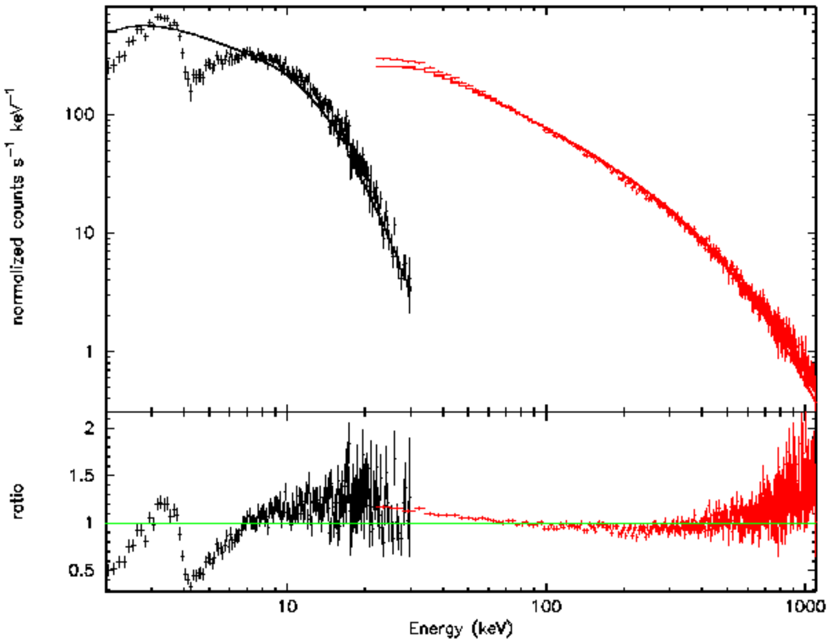




Fermi/GBM THESEUS/XGS (BB+PL) THESEUS /XGS (Band model)

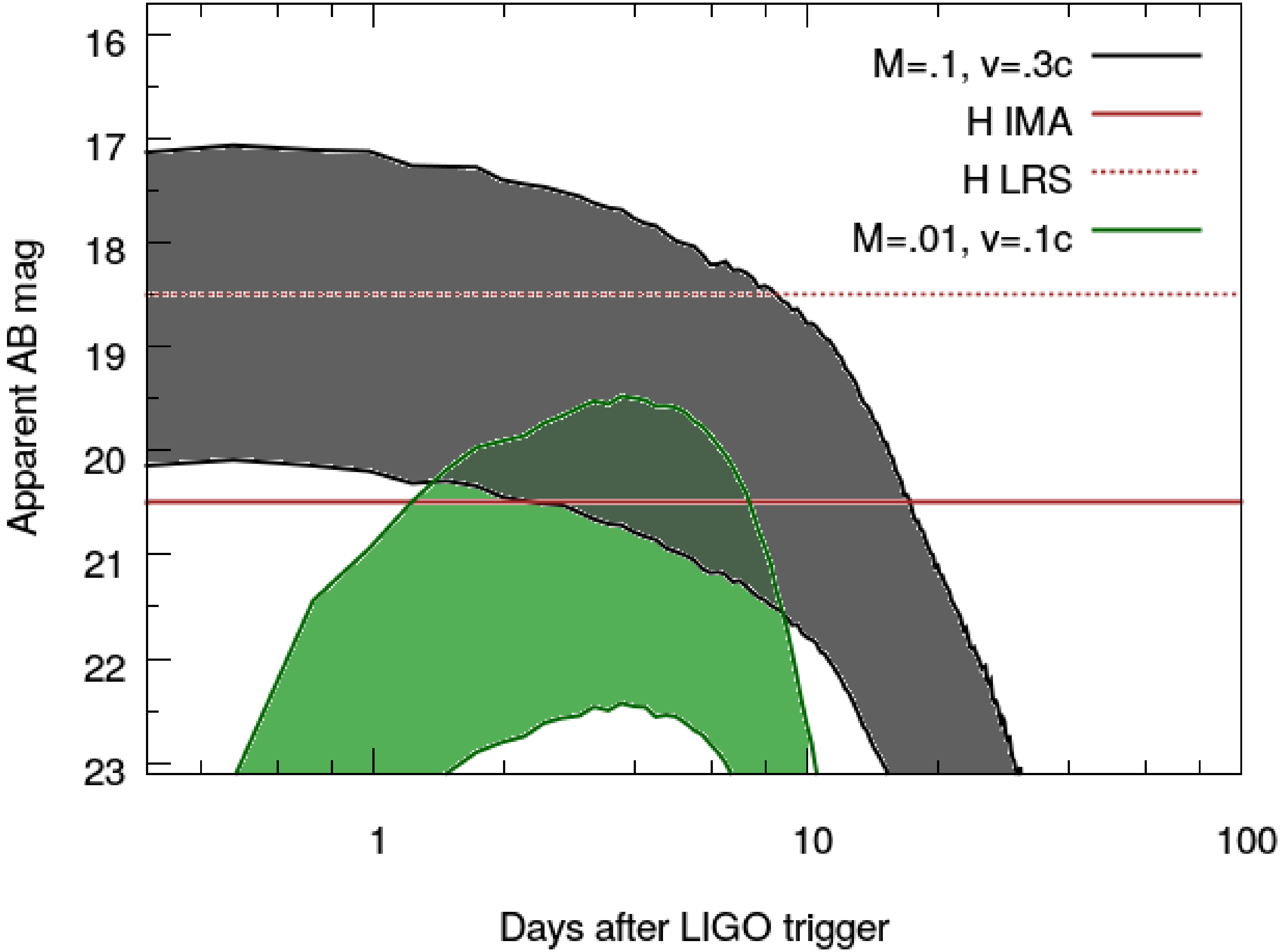
❑ Absorption features: the case of GRB990705 (edge at 3.8 keV -> redshifted neutral iron k-edge -> z = 0.85 -> confirmed by host galaxy spectroscopy: redshift estimate through X-ray spectroscopy





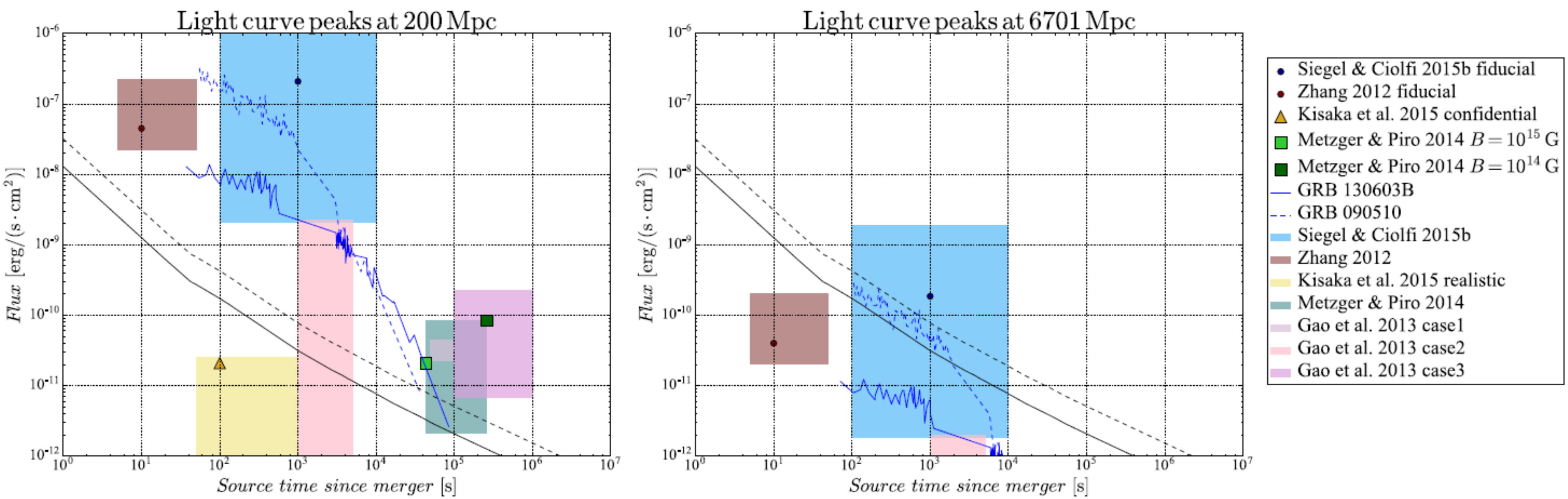
BeppoSAX WFC + GRBM

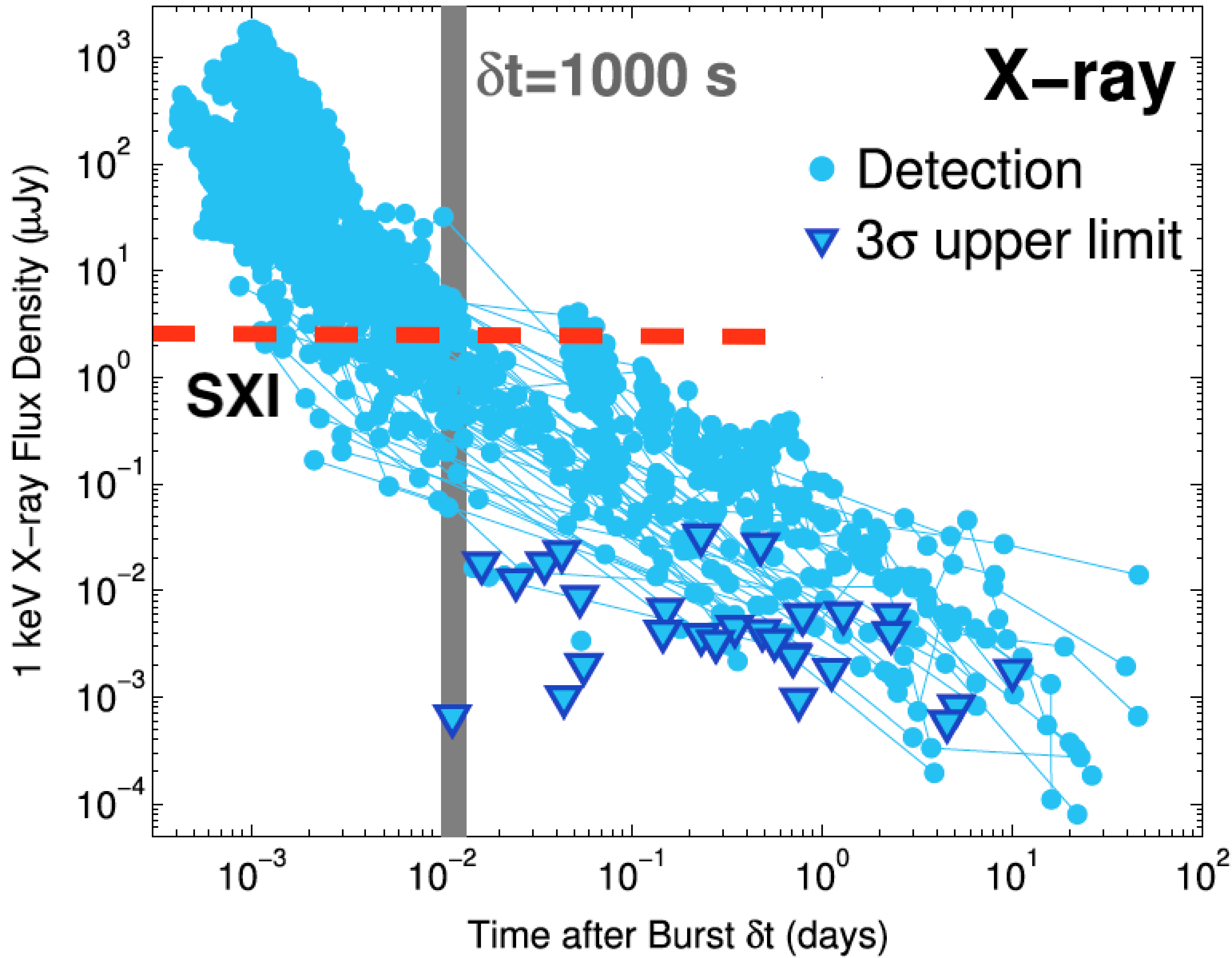
THESEUS XGS



Here we show theoretical H-band lightcurves of kilonova based on models from Barnes et al., 2016 (ApJ 829,110). The lightcurves are in observer frame for a source between 50 and 200 Mpc. Gray model is for the most optimistic case of a kilonova with $0.1 solar masses ejected with speed of 0.3,c. Green model is for a weaker emission, corresponding to $0.01 solar masses ejected with speed of 0.1 c.

GW observations			THESEUS XGIS/SXI joint GW+EM observations		
Epoch	GW detector	BNS horizon	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
2020+	Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)	~400 Mpc	~40	~5-15	~1-3 (simultaneous) ~6-18 (+follow-up)
2030+	Second + Third-generation (e.g. ET, Cosmic Explorer)	~15-20 Gpc	>10000	~15-25	$\gtrsim$100





δt=1000 s
X−ray
Detection
3σ upper limit
SXI
1 keV X−ray Flux Density (μJy)
Time after Burst δt (days)

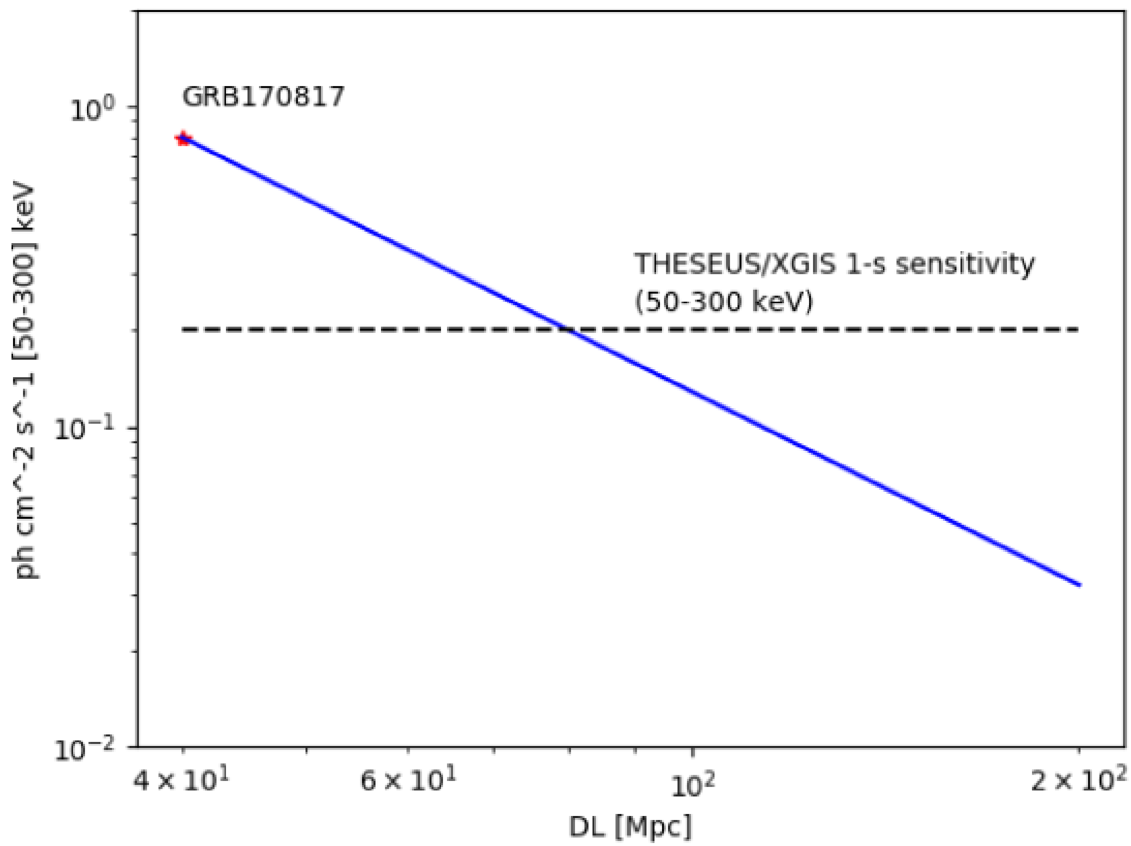
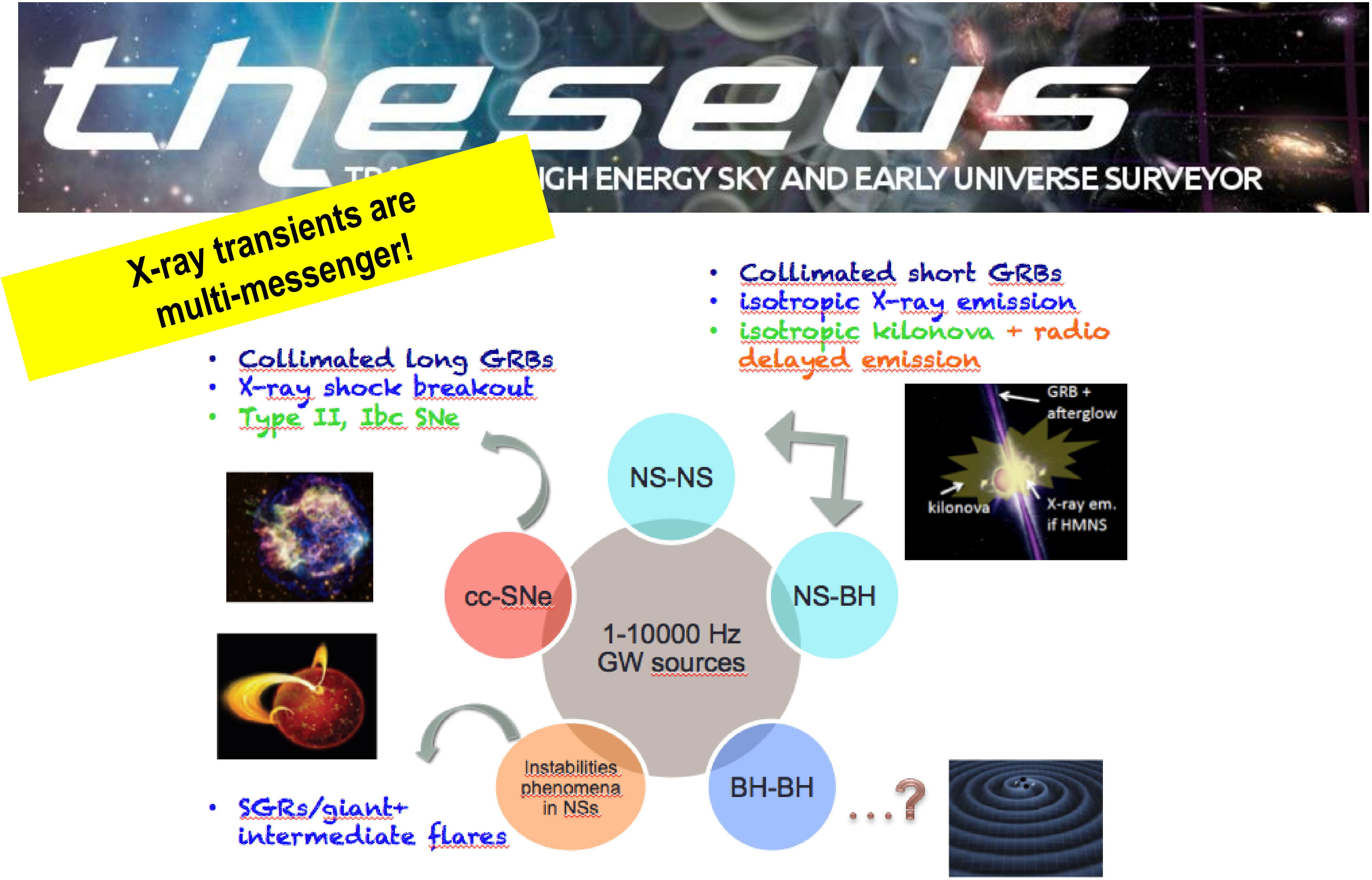


Figure 10: The Fermi/GBM peak photon flux of the short GW/GRB 170817 (red star, Goldstein et al. 2017) rescaled with the distance (blue line) and compared with THESEUS/XGIS 1-s sensitivity in the 50-300 keV energy range. Off-axis short GRB similar to GRB 170817 could had been detected with THESEUS/XGIS up to ~ 70 – 80 Mpc.


theseus
TR… HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
X-ray transients are multi-messenger!
• Collimated long GRBs
• X-ray shock breakout
• Type II, Ibc SNe
• Collimated short GRBs
• isotropic X-ray emission
• isotropic kilonova + radio delayed emission
GRB + afterglow
kilonova
X-ray em. if HMNS
NS-NS
cc-SNe
NS-BH
1-10000 Hz GW sources
Instabilities phenomena in NSs
BH-BH
...?
• SGRs/giant+ intermediate flares

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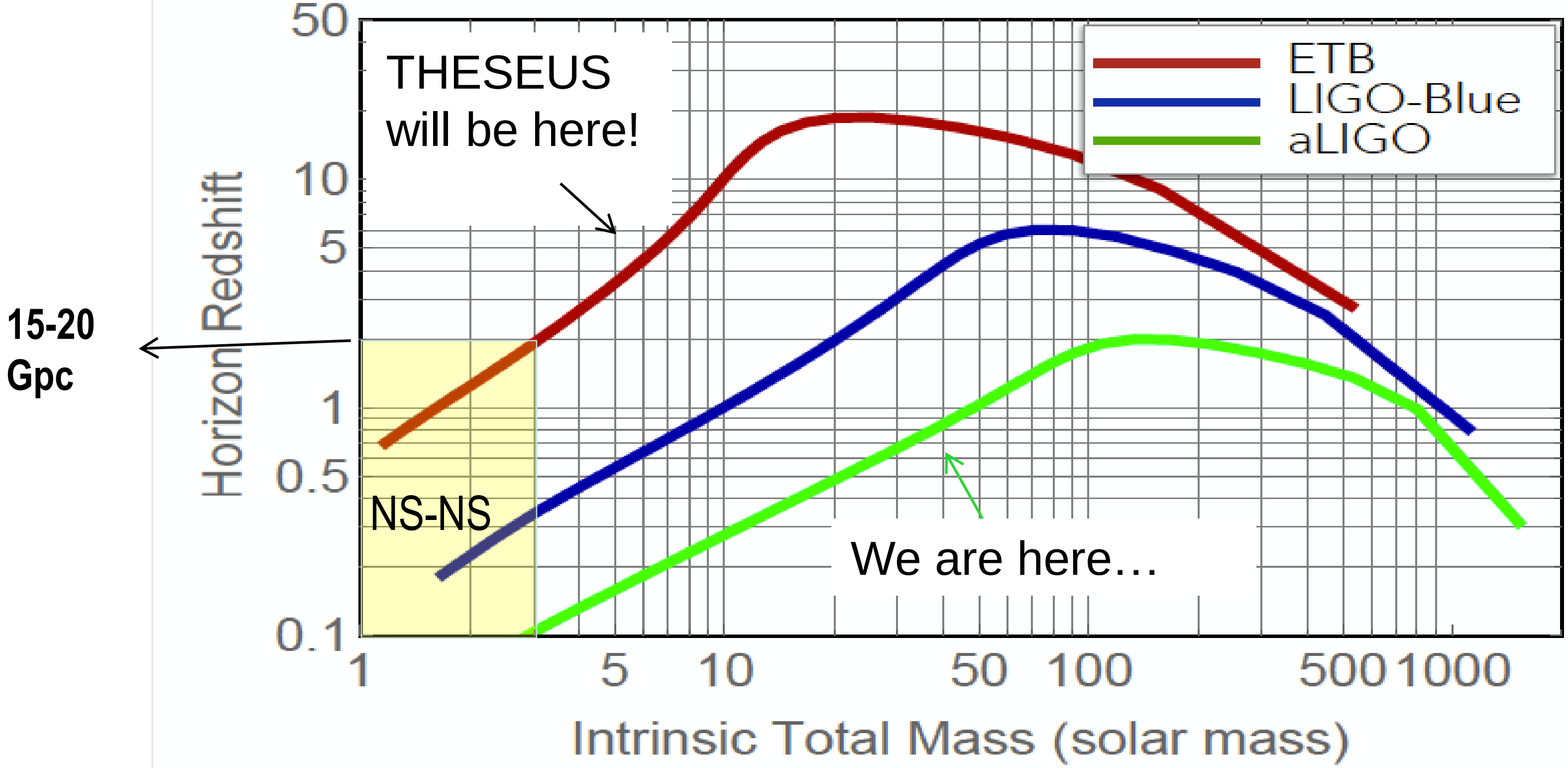
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

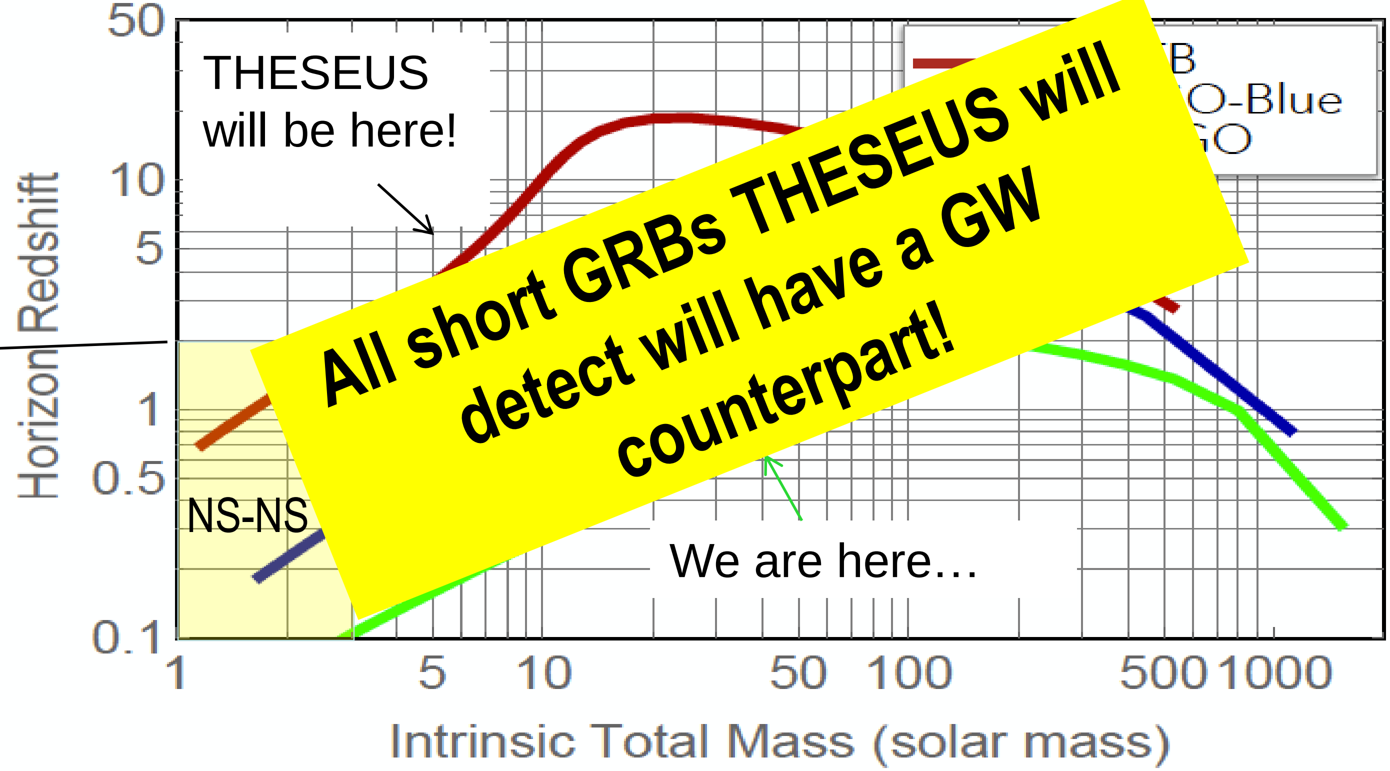
HORIZON REDSHIFT VS. INTRINSIC MASS FOR CBCs



Credit: Sathyaprakash - 7th ET Symposium 2016 theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

HORIZON REDSHIFT
VS. INTRINSIC MASS FOR CBCs



15-20 Gpc

Credit: Sathyaprakash - 7th ET Symposium 2016

G. Stratta - LVC Town Hall Meeting, 2018,
April 12-13, Amsterdam