THESEUS Conference 2021

Welcome!

theseus

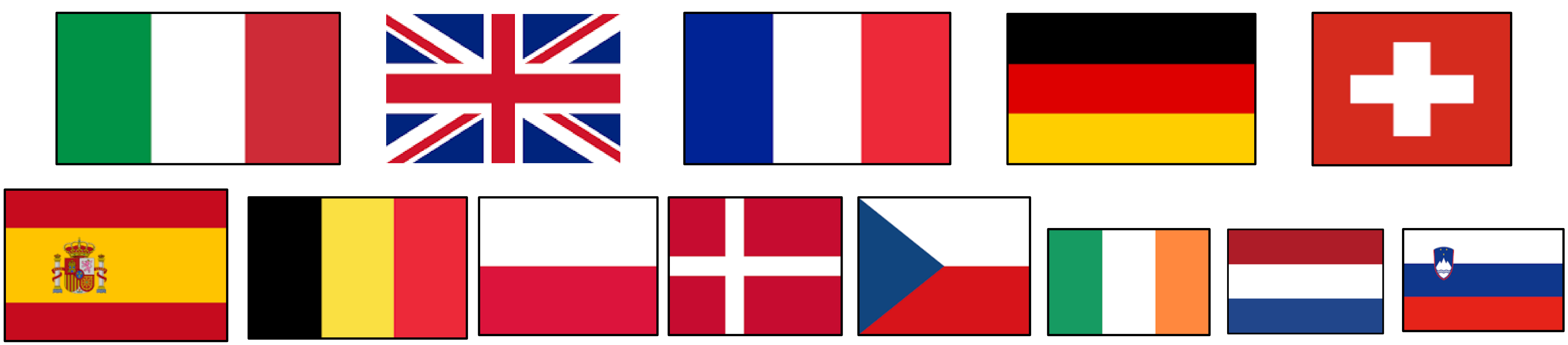
transient high energy sky and early universe surveyor

23-26 March 2021

esa

European Space Agency

Welcome address by L. Amati and S. Paltani



The THESEUS Conference 2021

- **Organized by** THESEUS Consortium and the THESEUS Science Study Team (TSST) nominated by ESA

- **Celebrating the ESA/M5 Phase A** study of the mission together with the worldwide scientific community

- **Formerly to be held in Malaga** (Spain), turned to virtual conference due to COVID-19 related limitations

- **Great participation: more than 460 registrants!**

- **A beautiful scientific programme** including almost 80 presentations by THESEUS key persons (ESA, consortium and community) and worldwide top-level scientists in related fields

The THESEUS Conference 2021

- **Follows** successful THESEUS Workshop 2017 (Naples) and THESEUS scientific meetings in 2019 (Bologna) and 2020 (virtual)

- **Hosted by University of Geneva** (Switzerland, one of the main partners of THESEUS Consortium)

- **SOC:** **L. Amati** (INAF-OAS Bologna, IT; CHAIR); **D. Gotz** (CEA Saclay, FR; co-chair); **P. O'Brien** (Univ. Leicester, UK; co-chair); **S. Basa** (LAM Marseille, FR); **M. D. Caballero-Garcia** (IAA-CSIC, Spain); **A. J. Castro-Tirado** (IAA Granada, ES); **L. Christensen** (Univ. Copenhagen, Denmark); **M. Guainazzi** (ESA/ESTEC); **L. Hanlon** (UCD, IE); **S. Paltani** (Univ. Geneva, CH); **V. Reglero** (Univ. Valencia, ES); **A. Santangelo** (Univ. Tubingen, DE); **G. Stratta** (INAF-OAS Bologna, IT); **N. Tanvir** (Univ. Leicester, UK).

- **Special thanks to E. Bozzo and C. Ferrigno for great efforts**

The THESEUS Conference 2021

- **ESA/M5 Phase A Study and selection process:** mission selection review (MSR) and Science Assessment Review (SAR) currently on-going; selection of final M5 candidate (THESEUS or EnVision)` expected in early June 2021

- **Thank you so much** to the many excellent scientists and technologists of the Consortium for their great efforts put in THESEUS Phase A study, as well as to the THESEUS ESA Study Team and the Coordination Office for continuous nice and efficient interactions and support

- **Wish you a nice confererence,** look forward forward meeting you at next THESEUS Conference (hopefully in Malaga!). **And… let's keep fingers crossed!!!**

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

The THESEUS Mission Concept

L. Amati (INAF) on behalf of the THESEUS Consortium

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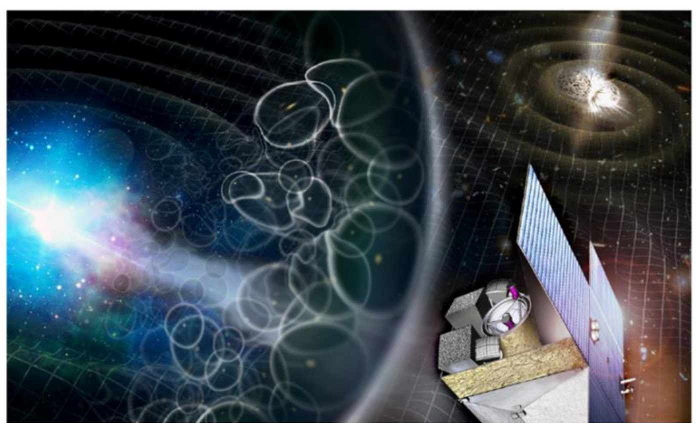

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THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021

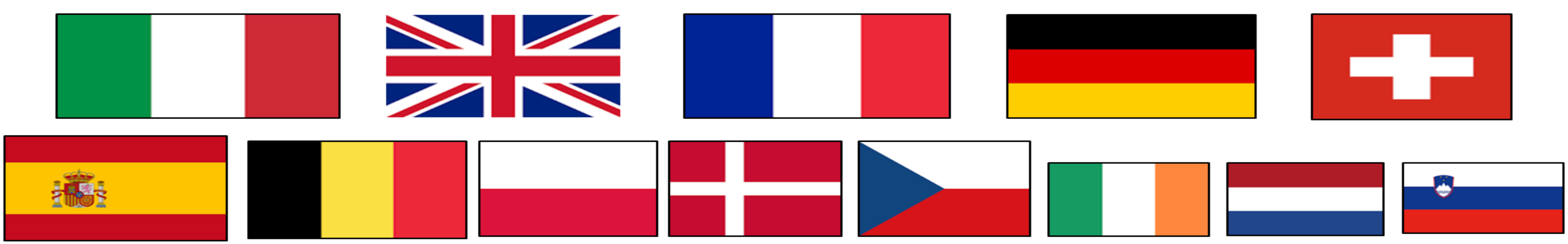
THESEUS

Transient High Energy Sky and Early Universe Surveyor

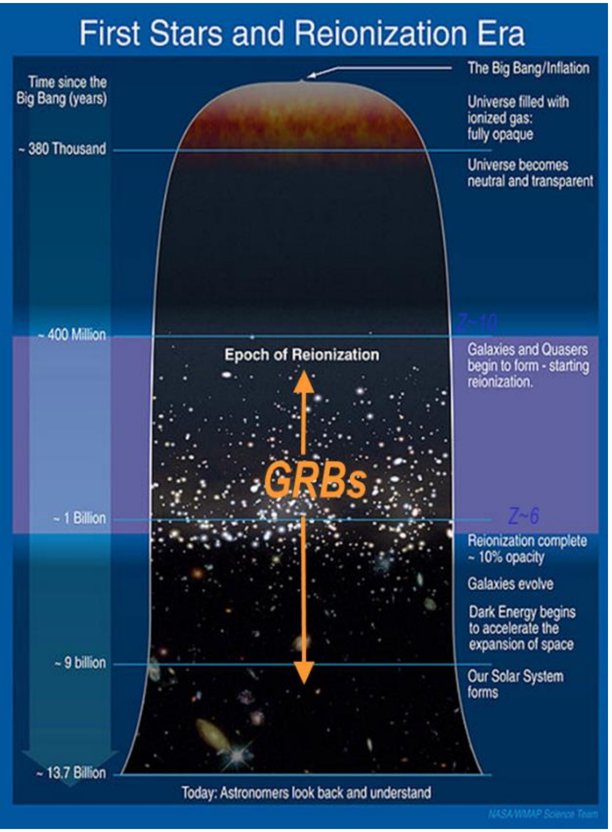
Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

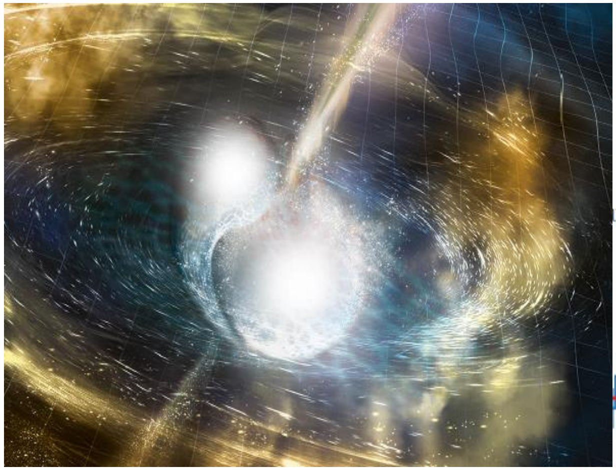
Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), A. Santangelo (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

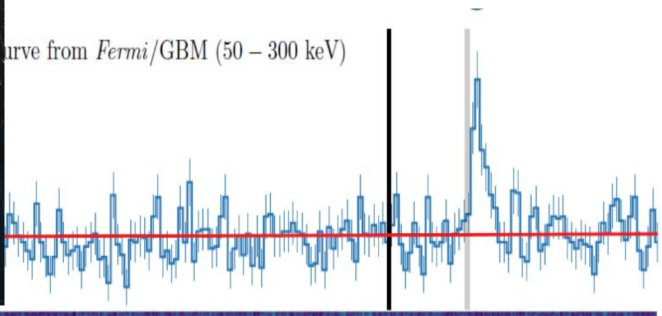
Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA

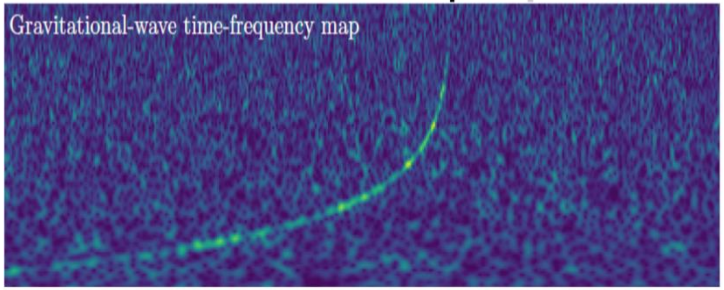


Probing the Early Universe with GRBs
Multi-messenger and time domain Astrophysics
The transient high energy sky
Synergy with next generation large facilities (E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors)







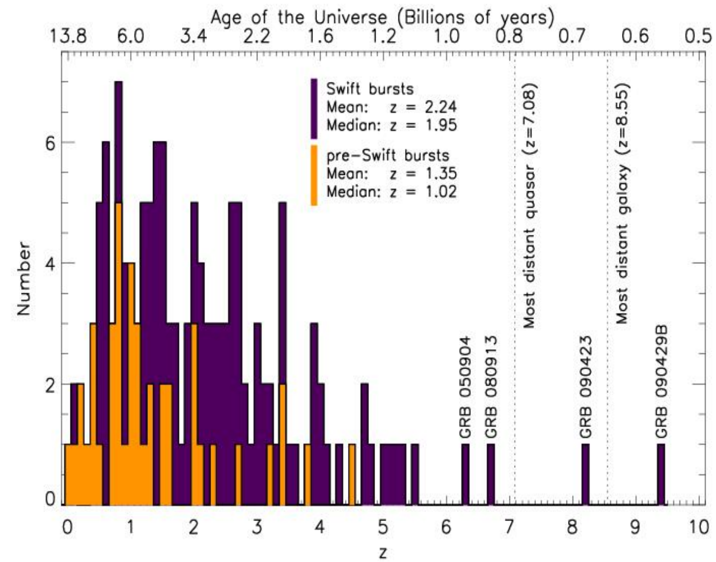


May 2018: THESEUS selected by ESA for Phase 0/A study (with SPICA and ENVISION)

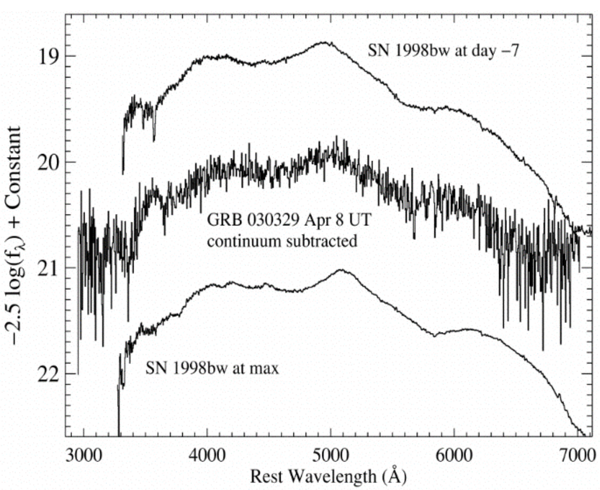
Activity	Date
Phase 0 kick-off	June 2018
Phase 0 completed (EnVision, SPICA and THESEUS)	End 2018
ITT for Phase A industrial studies	February 2019
Phase A industrial kick-off	June 2019
Mission Selection Review (technical and programmatic review for the three mission candidates)	Completed by June 2021
SPC selection of M5 mission	June 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

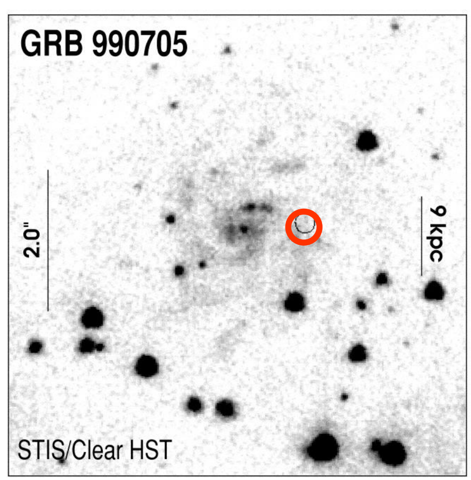
Shedding light on the early Universe with GRBs

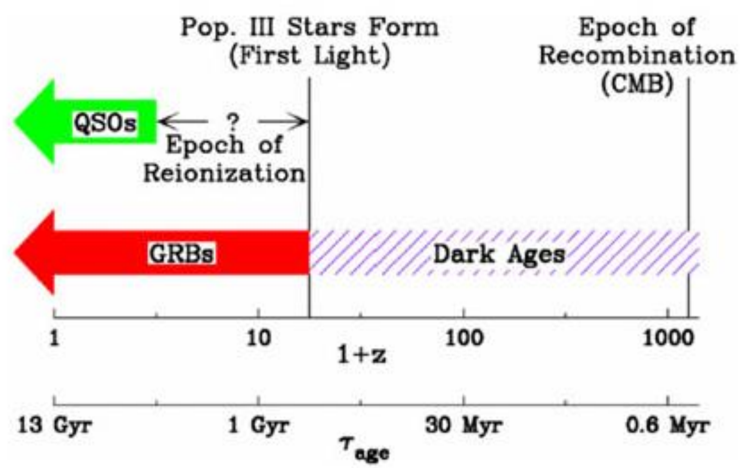
- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays
- **Redshift distribution** extending at least to z ~9 and association with exploding massive stars
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars



GRBs in Cosmological Context







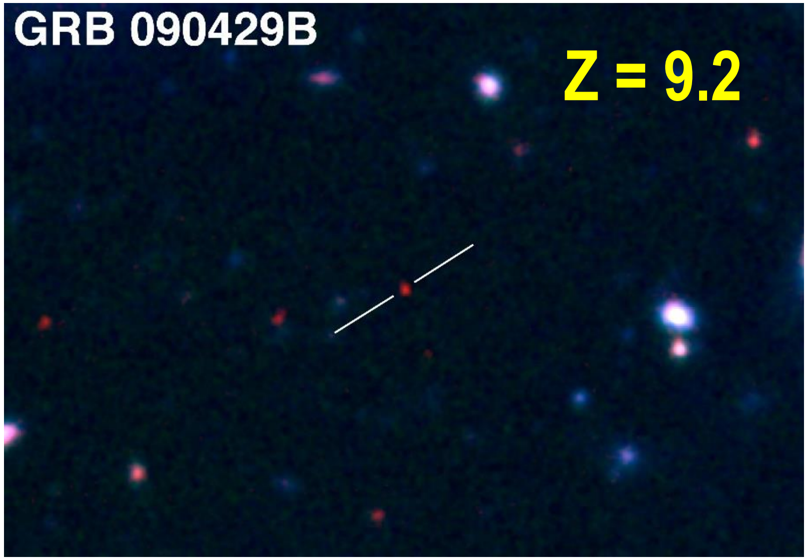
Lamb and Reichart (2000)

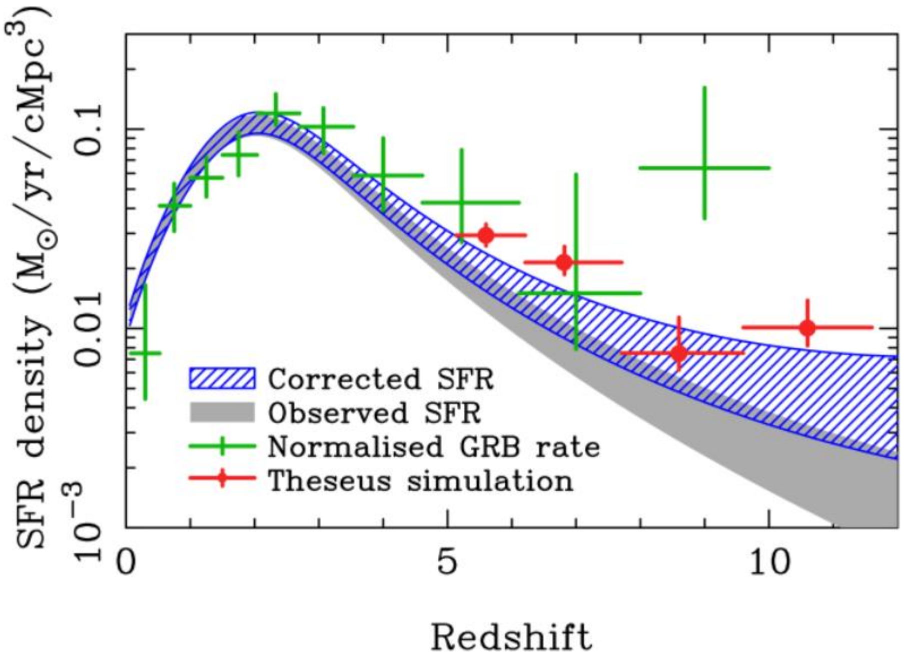
Shedding light on the early Universe with GRBs

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

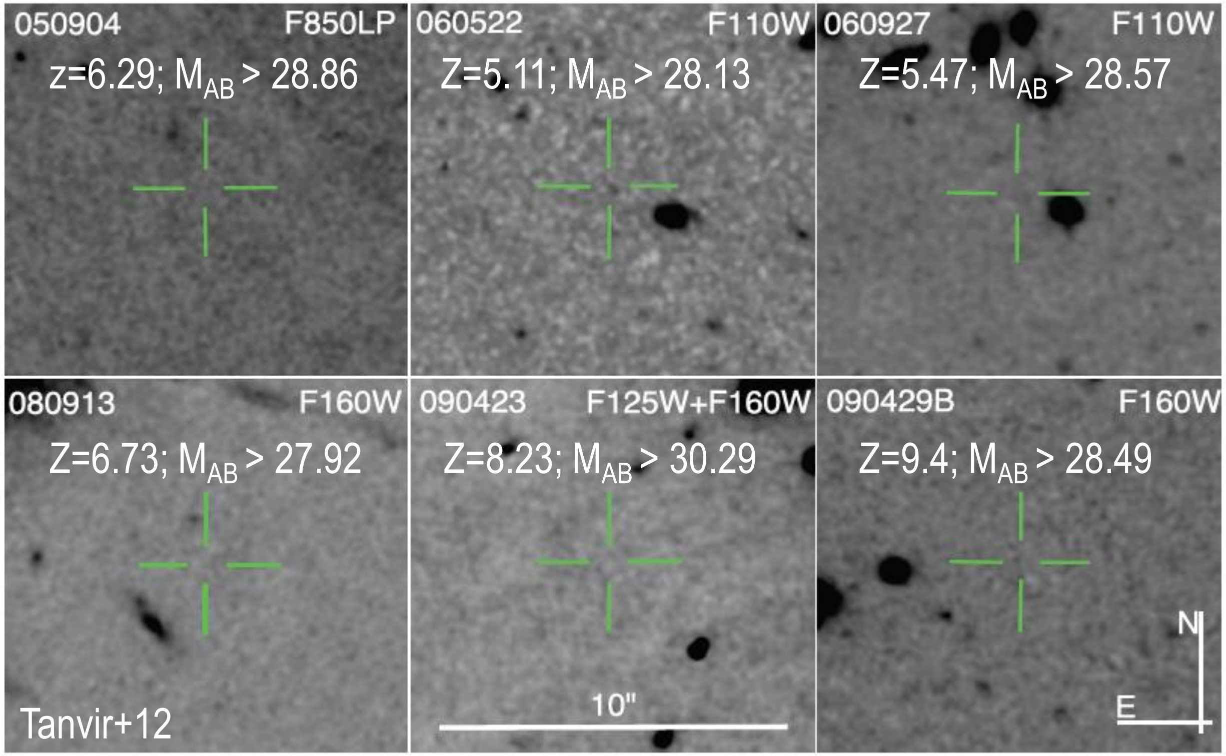
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

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





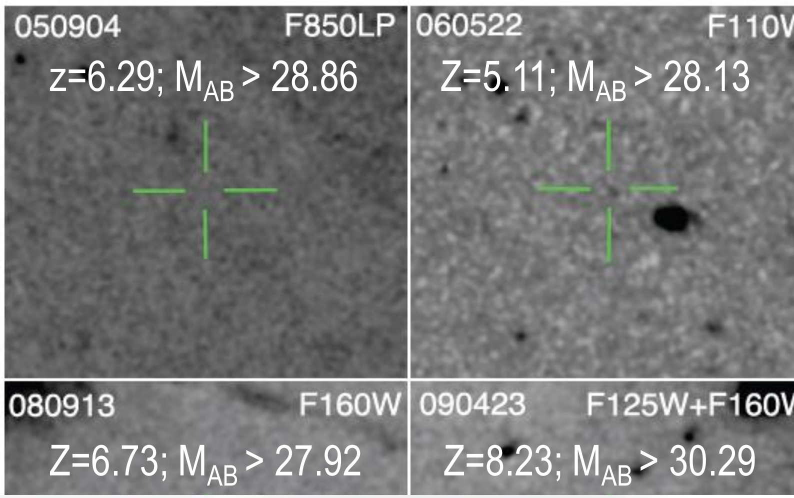
- **Detecting and studying primordial invisible galaxies**



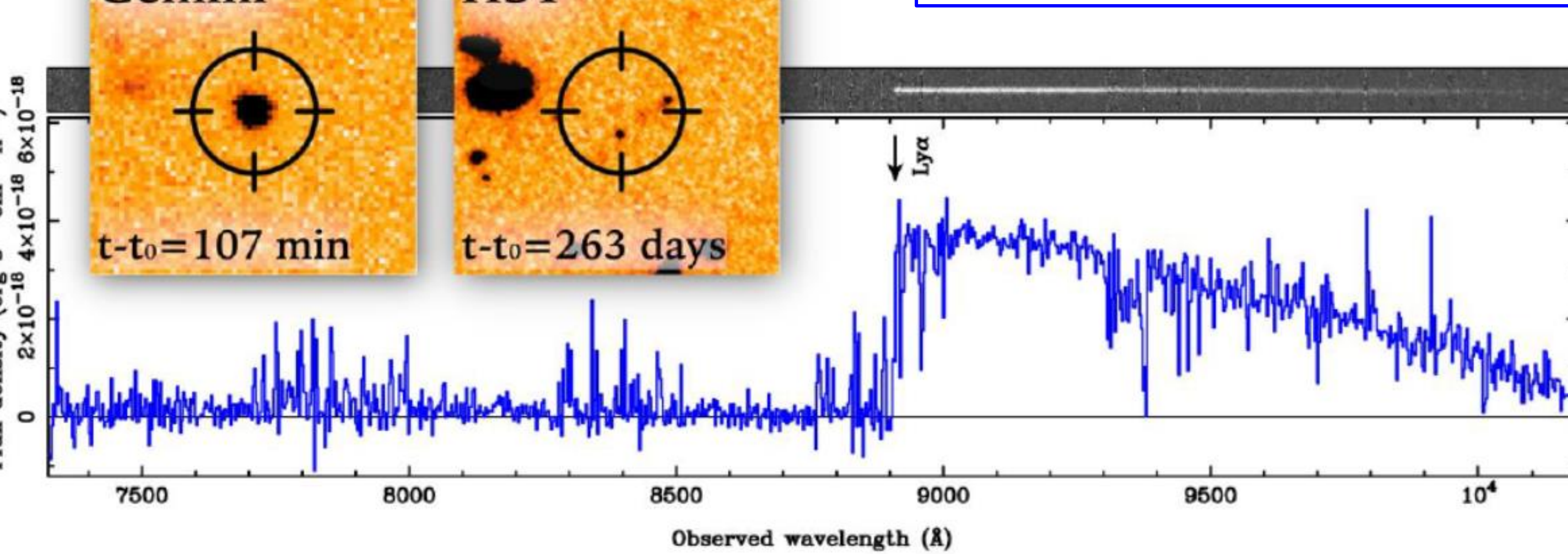
Robertson&Ellis12

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)

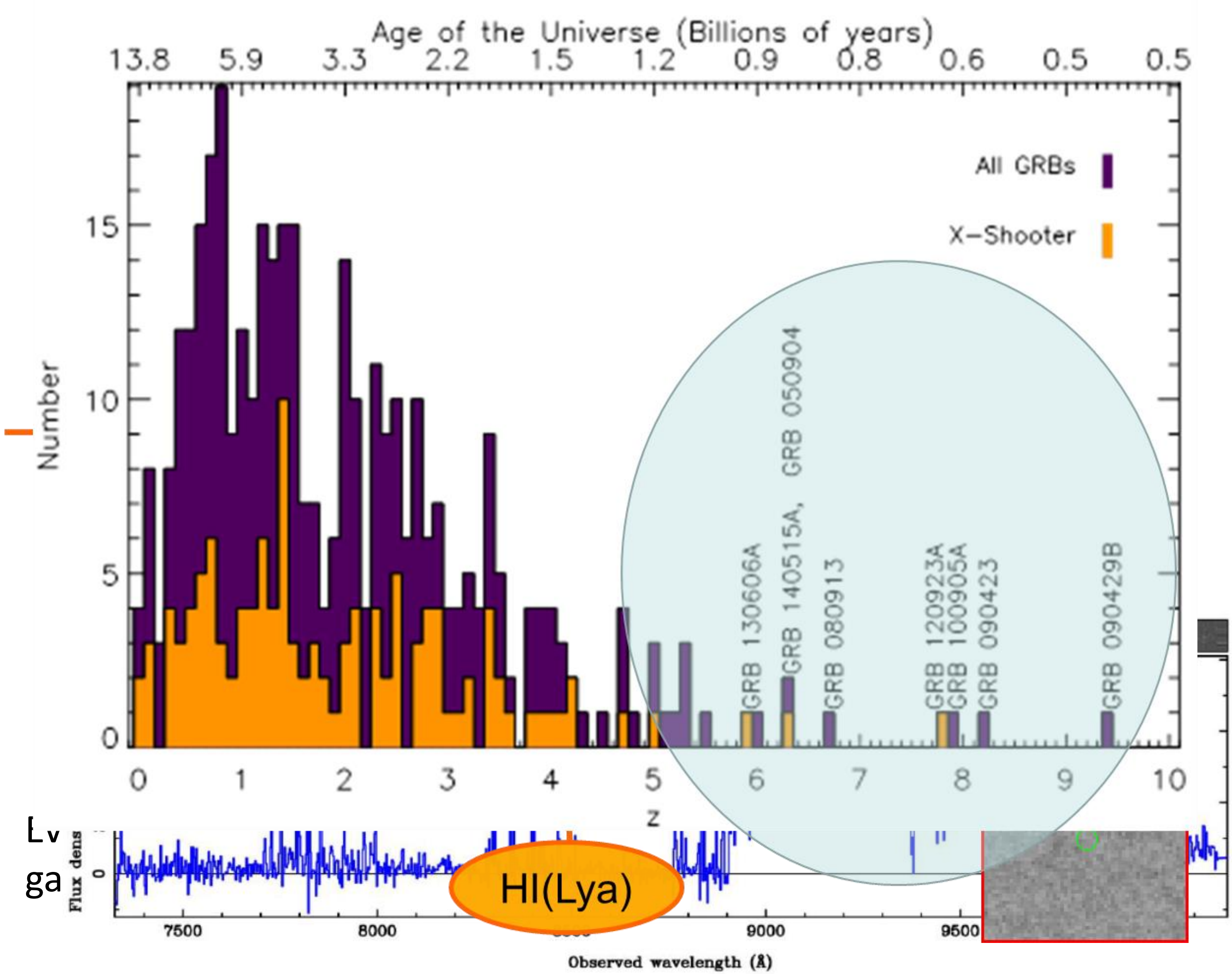
• Detecting and studying primordial invisible galaxies



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



• Detecting and studying primordial invisible galaxies



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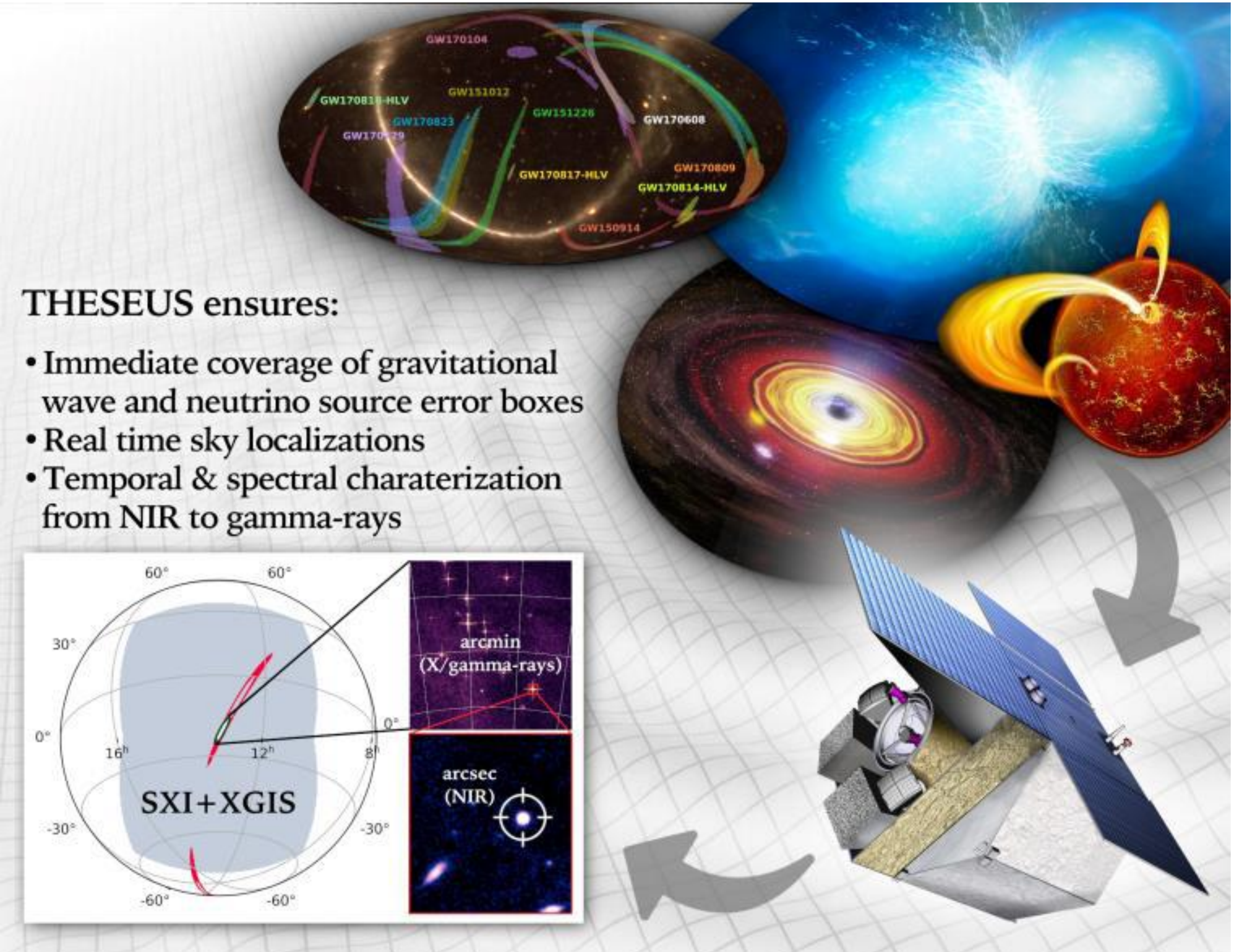
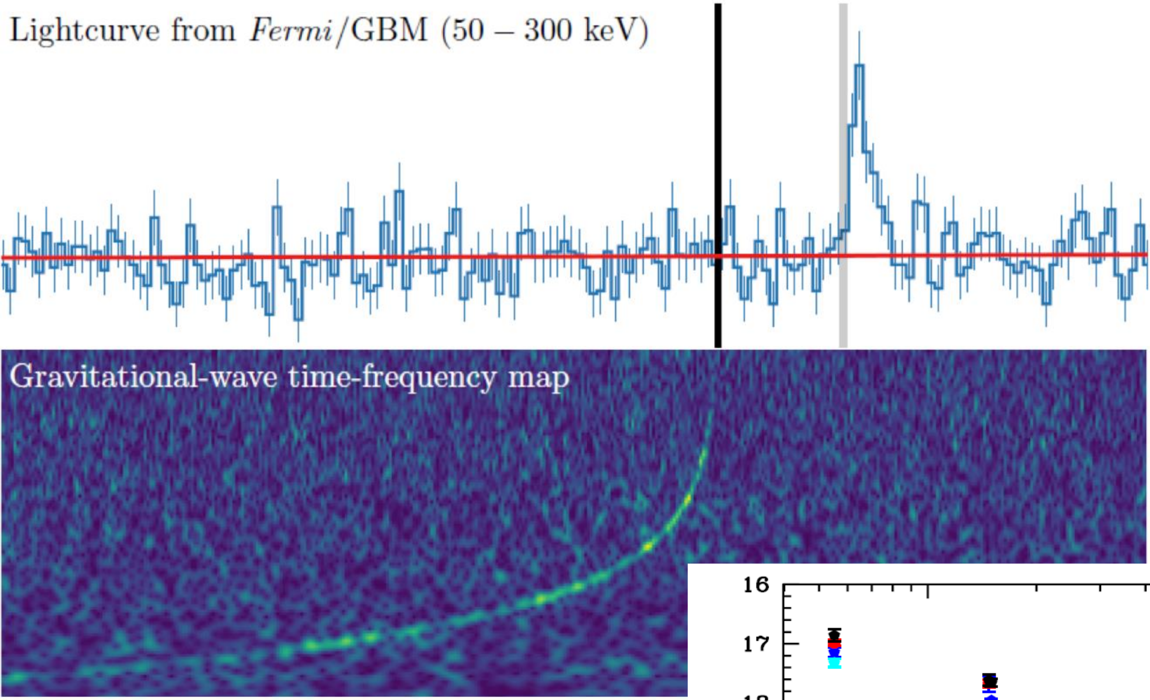
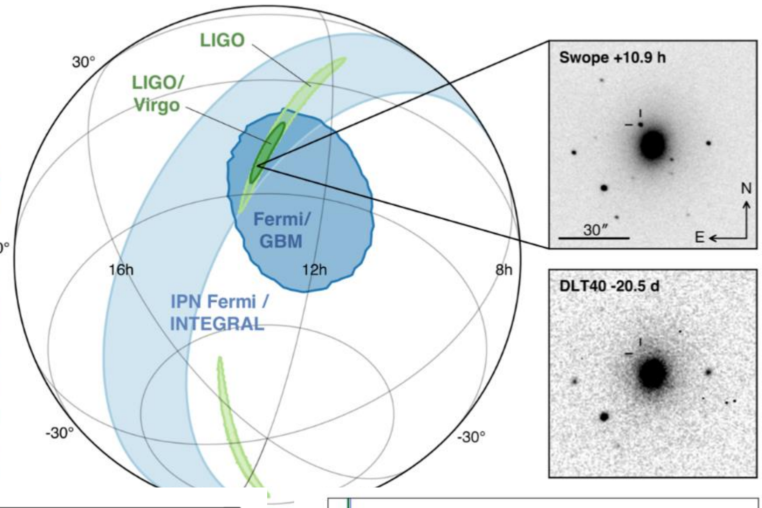
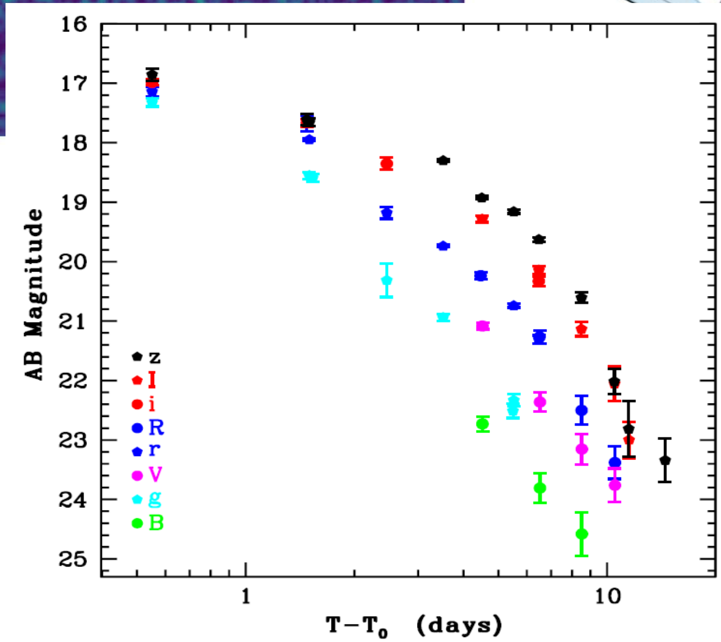
Exploring the multi-messenger transient sky

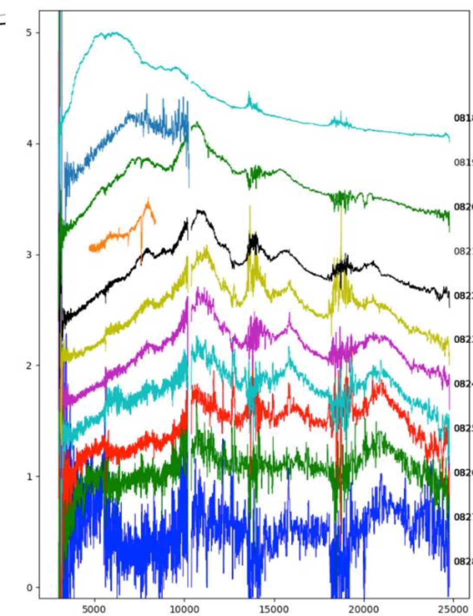


LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars



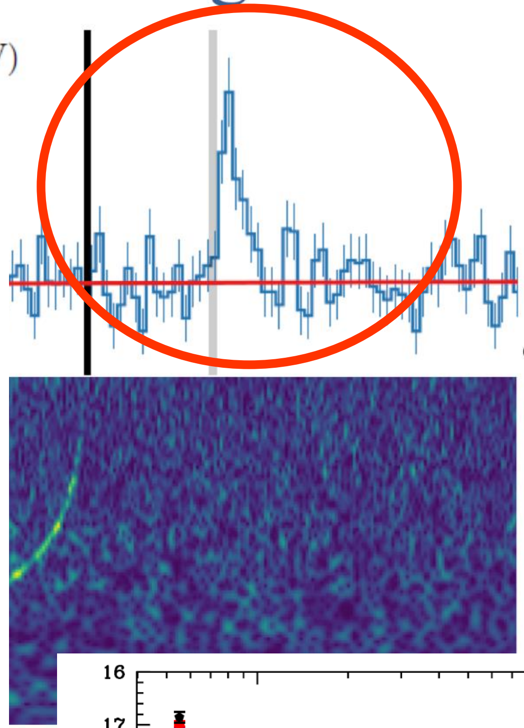






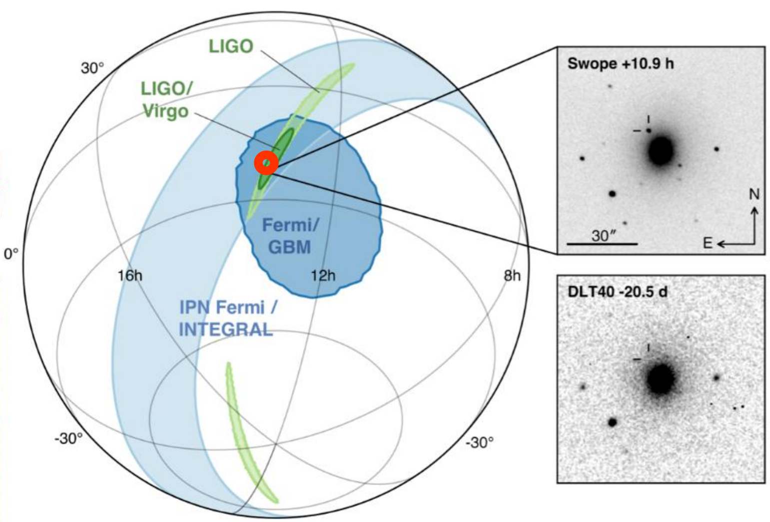
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

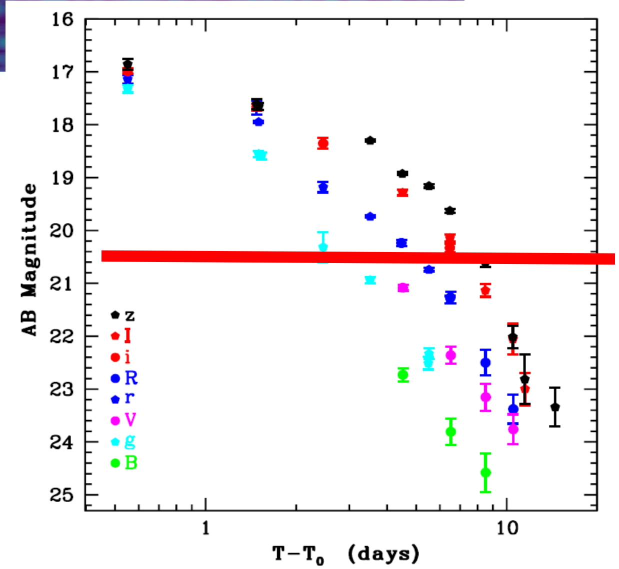
Lightcurve from *Fermi*/GBM (50 – 300 keV)

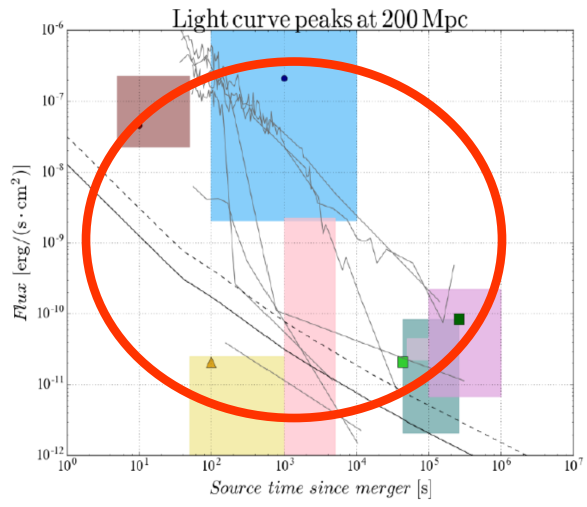


THESEUS:

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

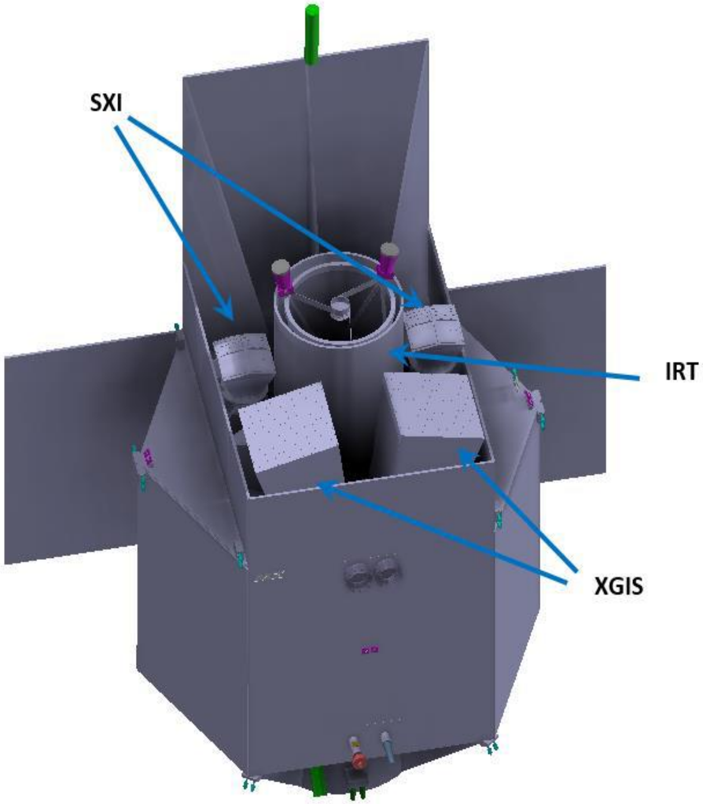






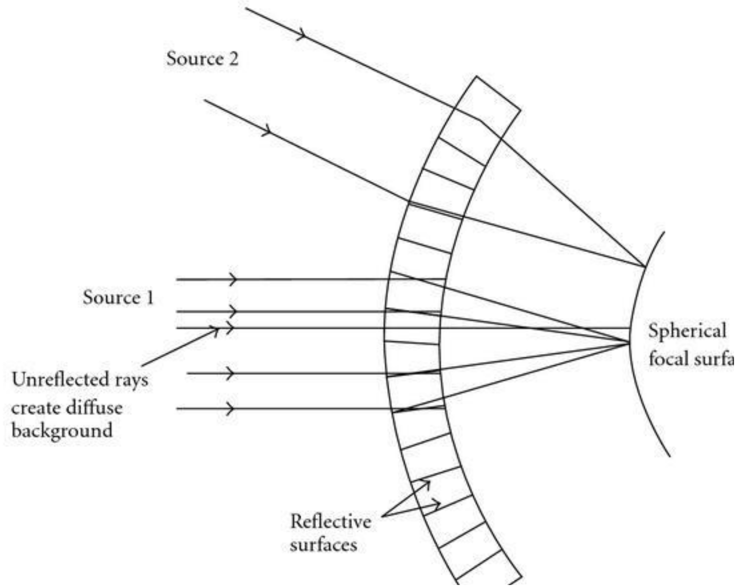
THESEUS mission concept

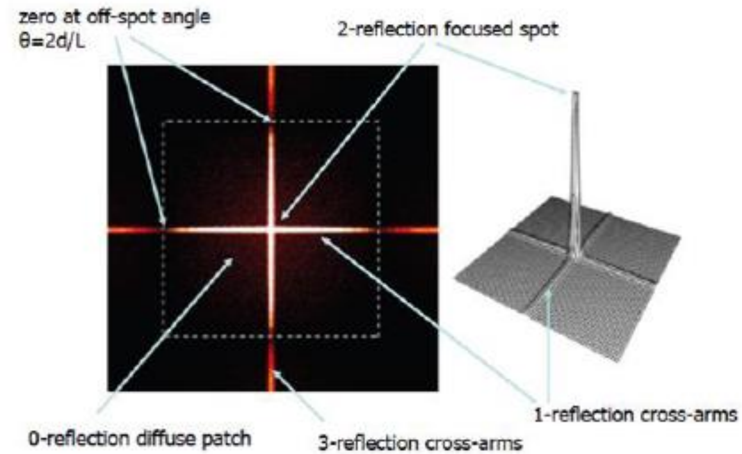
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in **0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2';**
- **X-Gamma rays Imaging Spectrometer (XGIS,):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in **2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15' GRB location accuracy** in 2-150 keV
- **InfraRed Telescope (IRT):** a 0.7m class IR telescope observing in the **0.7 – 1.8 μm band, providing a 15'x15' FOV, with both imaging and moderate resolution spectroscopy capabilities** (-> redshift)

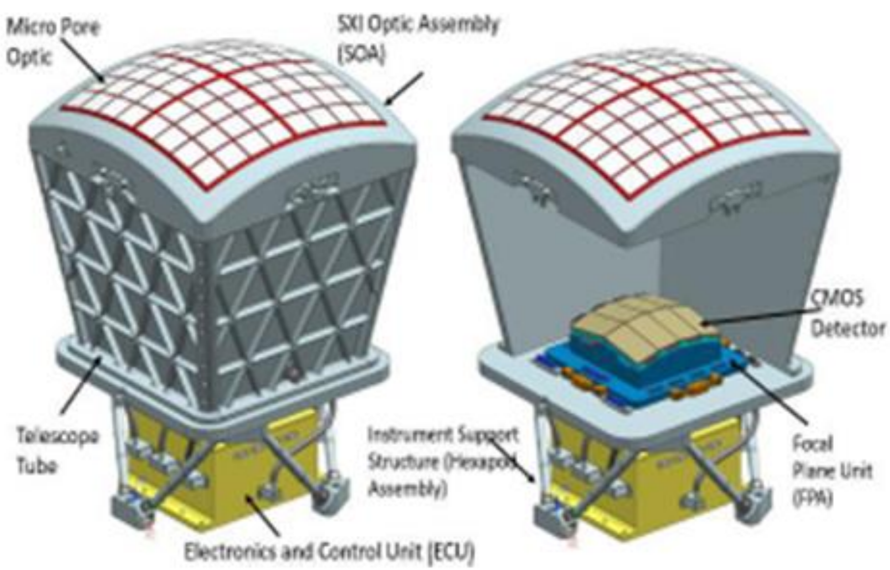


- **Low Earth Orbit (< 5°, ~600 km)**
- **Autonomously rapid slewing bus**
- **4-years nominal**

The Soft X-ray Imager (SXI)

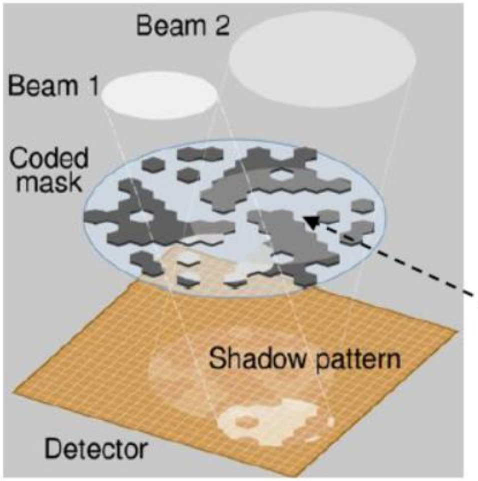




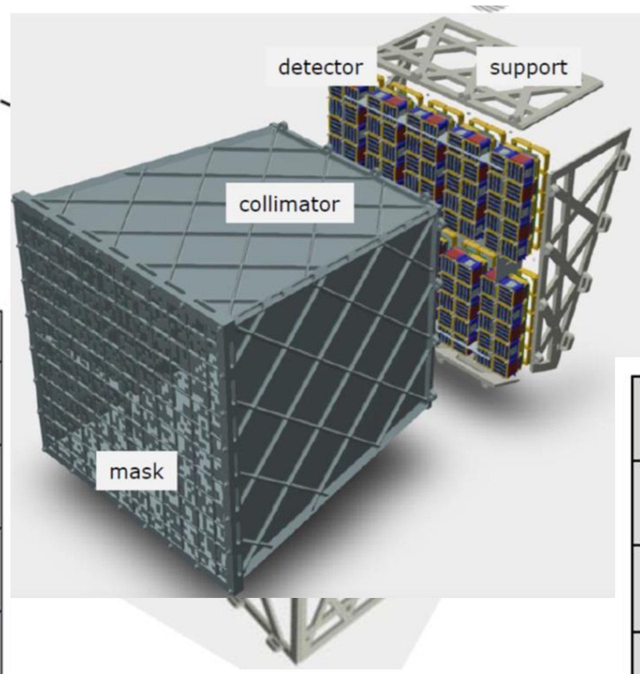


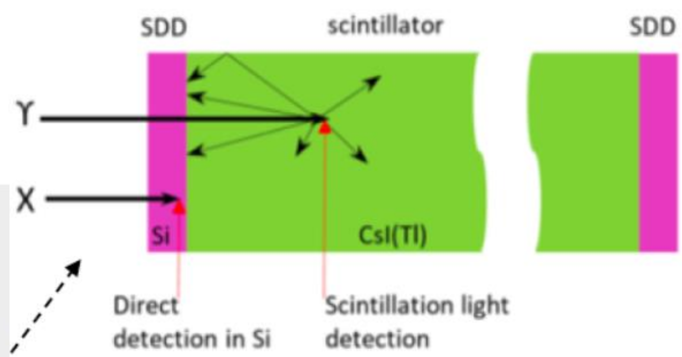
Energy band (keV)	0.3-5
Optics configuration	8x8 square pore MPOs
MPO size (mm^2)	40x40
Focal length (mm)	300
Focal plane detectors	CMOS array
CMOS size (mm^2)	80x40
CMOS pixel size (μm)	40
CMOS pixel Number	2000x1000
Number of CMOS	8
Module Field of View (sr)	0.25
Centroiding accuracy (best, worst) (arcsec)	(<30, 180)

The X-Gamma-ray imaging spectrometer



Targets: long (hi-z) and short (black-hole mergers/GW counterparts) GRBs



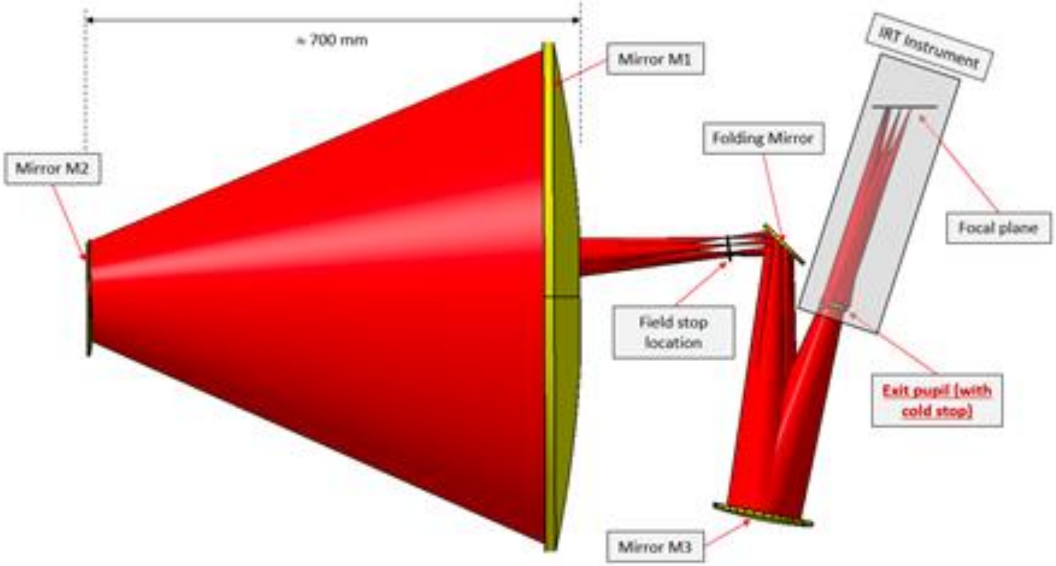


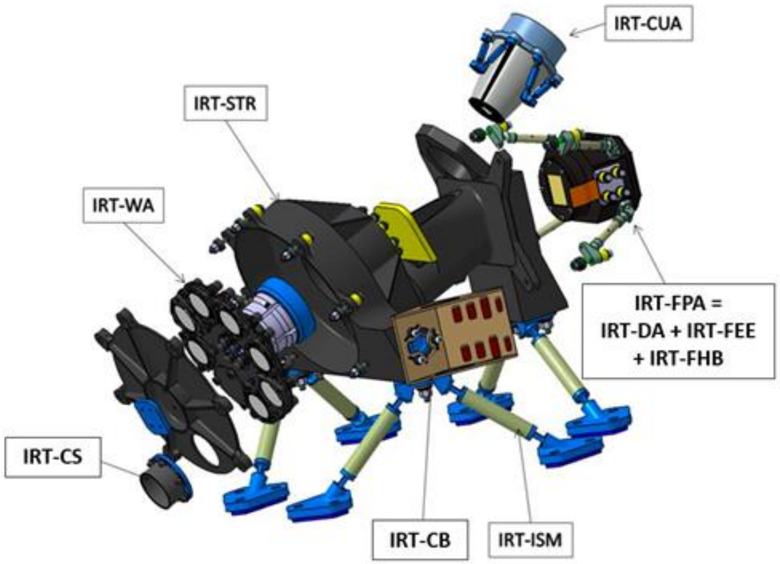
Coded mask telescopes with scintillator crystal

Energy band	*2 keV – 20 MeV*
# detection plane modules	*100*
# of detector pixel /module	*8x8*
pixel size (= mask element size)	*4.5x4.5 mm²*
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]	*49x49x74*
Power [W]	*123.0*
Mass [kg]	*72.0*

XGIS	**Lead: INAF Bologna, IT**		**2x units**
Budgets (total)	158 kg	211 W	25 Gbit/day
Dimensions/ unit (mm)	740 (h) x 600x600 (@ mask) 490x490 (@ detector)		
Energy ranges	2-30 keV	30 – 150 keV	150 keV- 10 MeV
Detector technologies	Silicon drift detectors (SDD)	CsI(Tl) scintillating crystal + SDD	
Imaging capability	<15′ loc. accuracy FoV 2 sr		None, 4 sr
Energy resolutions	20% @ 6keV	6% @ 600 KeV	

The InfraRed Telescope (IRT)





IRT characteristic	Value
Photometric wavelength range	0.7-1.8 µm
Spectroscopic wavelength range	0.8-1.6 µm
Photometric field of view	15 x 15 arcmin (goal: 17' x 20')
Pixel size/scale	18 µm / 0.6 arcsec
Required Photometric sensitivity (AB, in150 s, SNR=5) for each implemented filter	I: 20.9 (goal: 21.3) Z: 20.7 (goal 21.2) Y: 20.4 (goal: 20.8) J: 20.7 (goal: 21.1) H: 20.8 (goal: 21.1)
Expected photo-z accuracy	< 10%
Astrometric accuracy	< 5 arcsec in near-real time < 1 arcsec after ground processing
Spectroscopic field of view	2 x 2 arcmin
Resolving Power at 1.1 µm	> 400
Required Spectroscopic sensitivity (AB, H filter, 1800 s, SNR=3 for each spectral bin)	17.5 (goal: 19)

Possible spacecraft design (ESA/M5 Phase A)

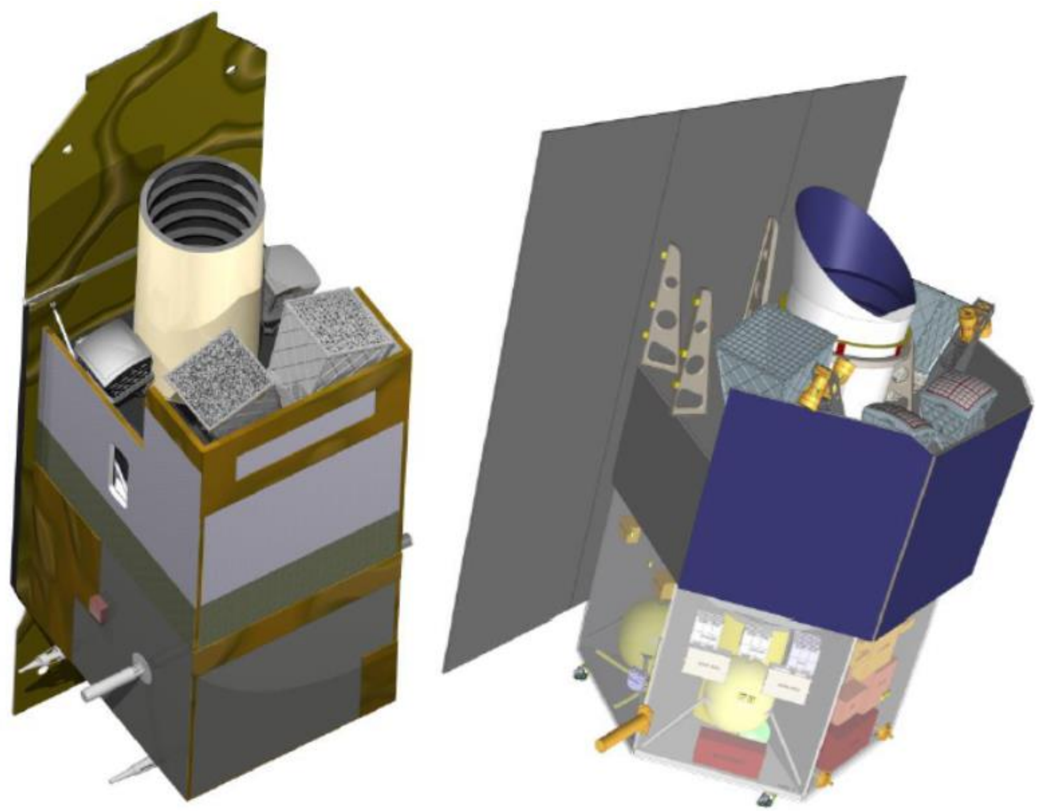
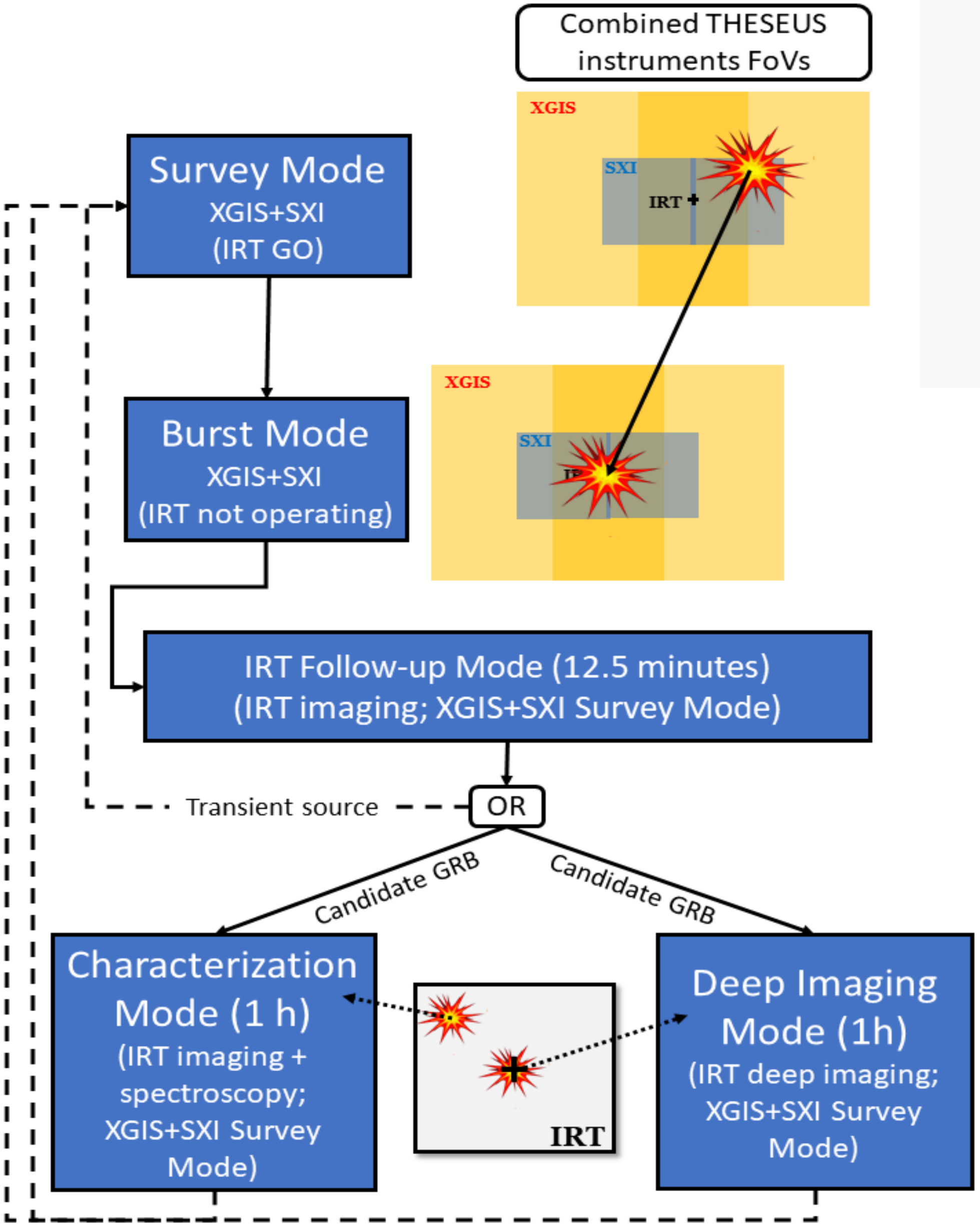
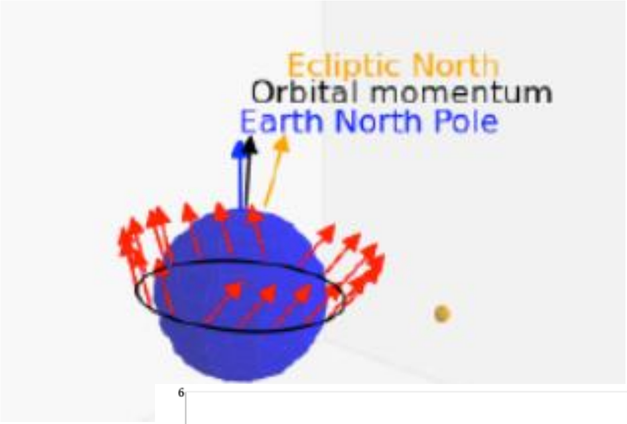


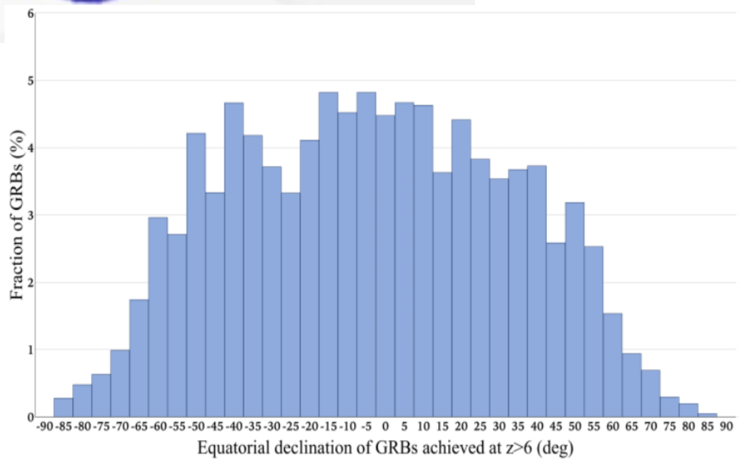
Figure 5-4 - Schematic view of the spacecraft design for the Phase A ADS (left) and TAS (right) Studies.

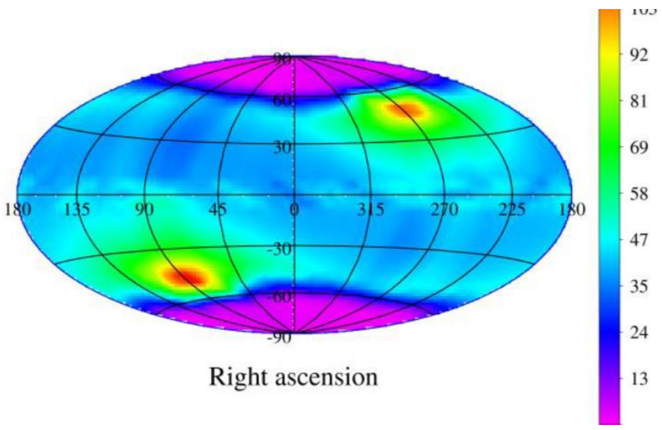
THESEUS (dry mass)	1583	100%
System margin (20%)	316.7	
Satellite (dry mass incl. system margin)	1900	
Propellant (incl. 2% residuals)	290.0	
Satellite (wet mass)	2190	

THESEUS mission operation concept

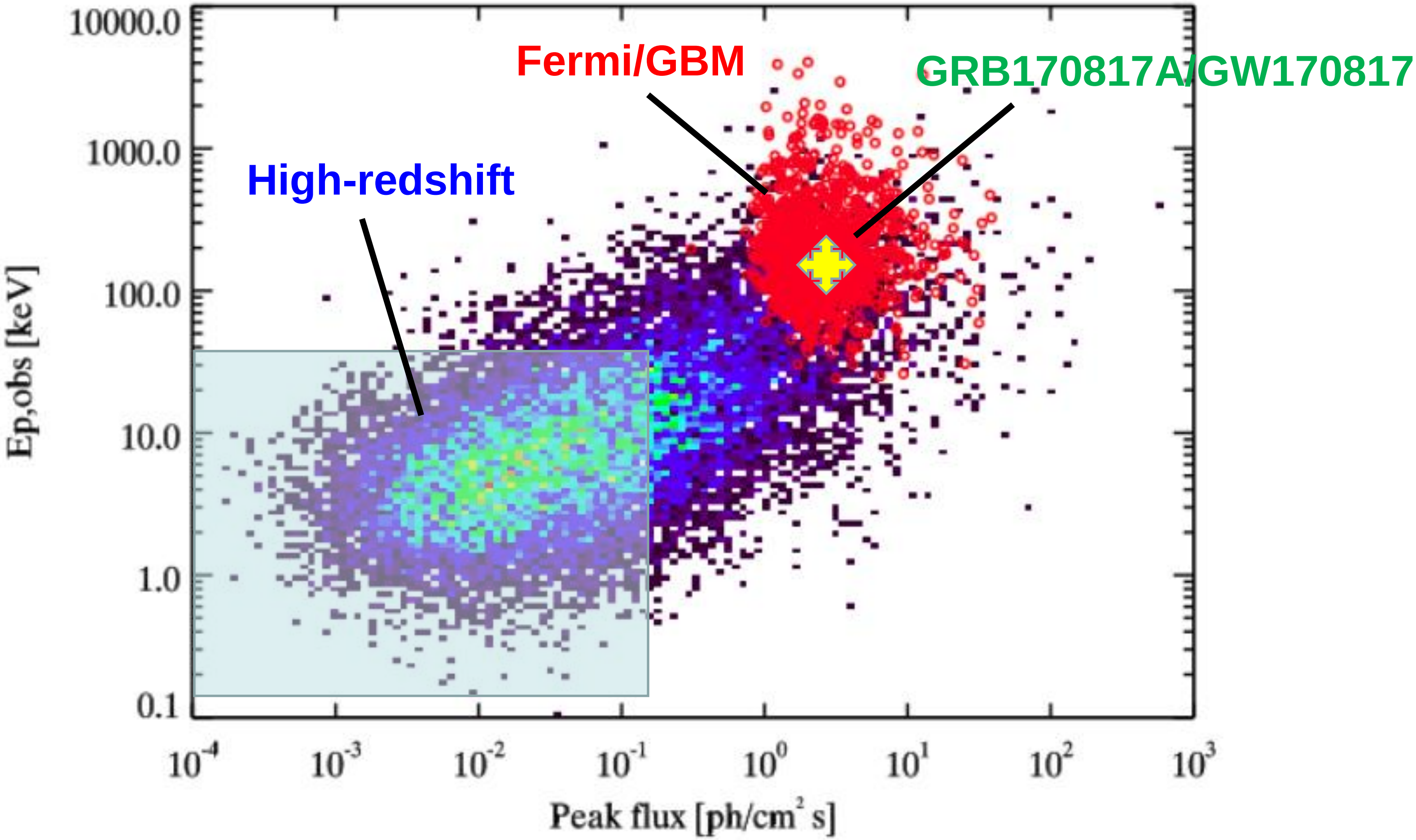




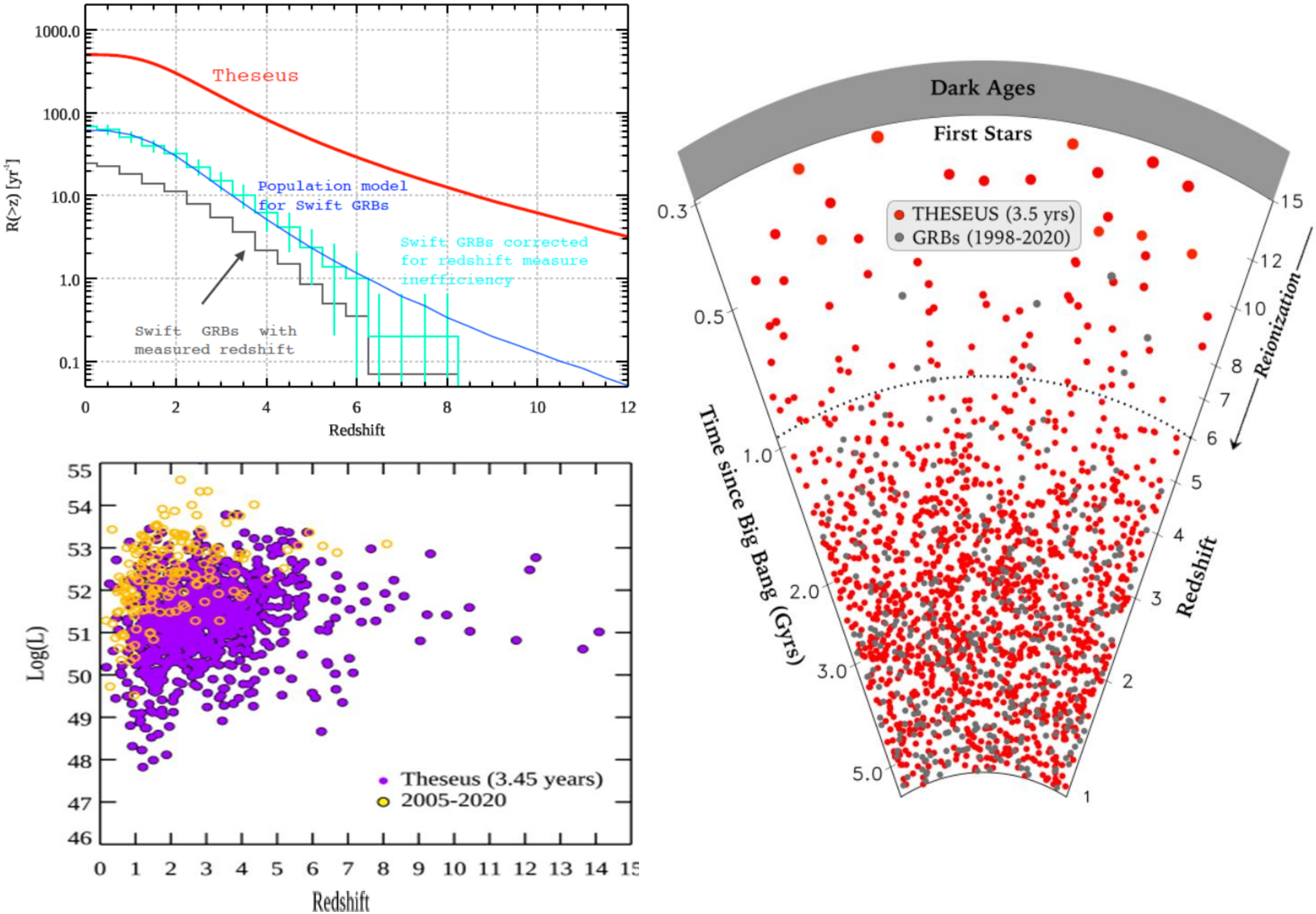


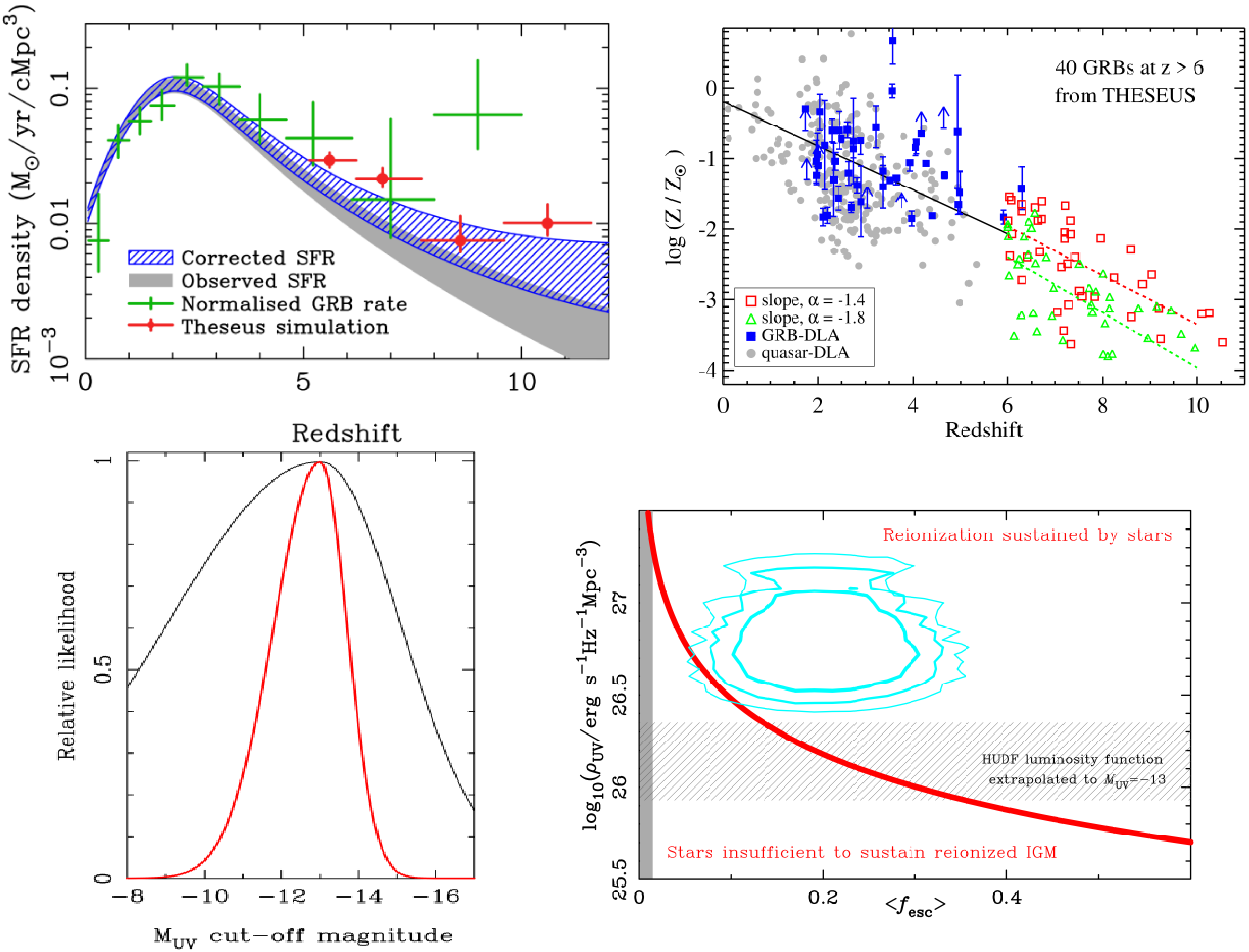


THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), providing accurate location and redshift for a large fraction of them



Shedding light on the early Universe with GRBs





SFR density (M⊙/yr/cMpc³)
0.1
0.01
10⁻³
0
5
10
Redshift
Corrected SFR
Observed SFR
Normalised GRB rate
Theseus simulation
40 GRBs at z > 6
from THESEUS
log (Z / Z⊙)
0
-1
-2
-3
-4
slope, α = -1.4
slope, α = -1.8
GRB-DLA
quasar-DLA
0
2
4
6
8
10
Redshift
Relative likelihood
0
0.5
1
−8
−10
−12
−14
−16
M_UV cut−off magnitude
Reionization sustained by stars
HUDF luminosity function
extrapolated to M_UV=−13
Stars insufficient to sustain reionized IGM
log₁₀(ρ_UV/erg s⁻¹Hz⁻¹Mpc⁻³)
25.5
26
26.5
27
0
0.2
0.4
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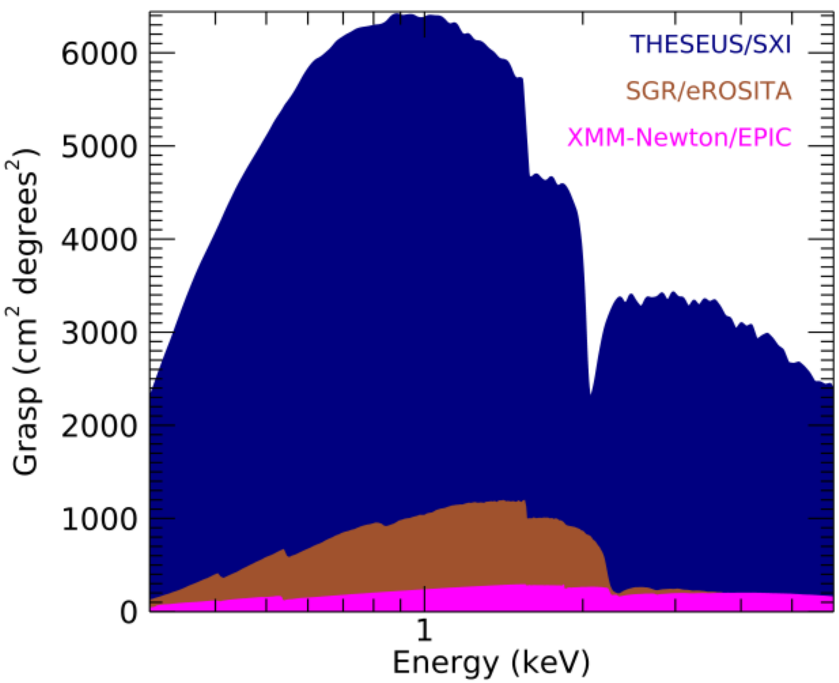
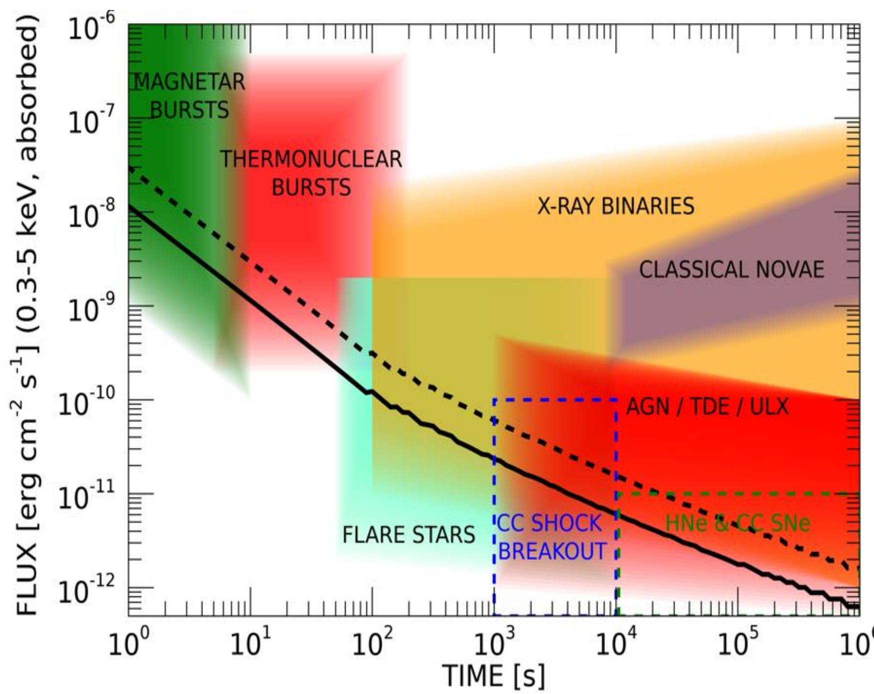
Exploring the multi-messenger transient sky

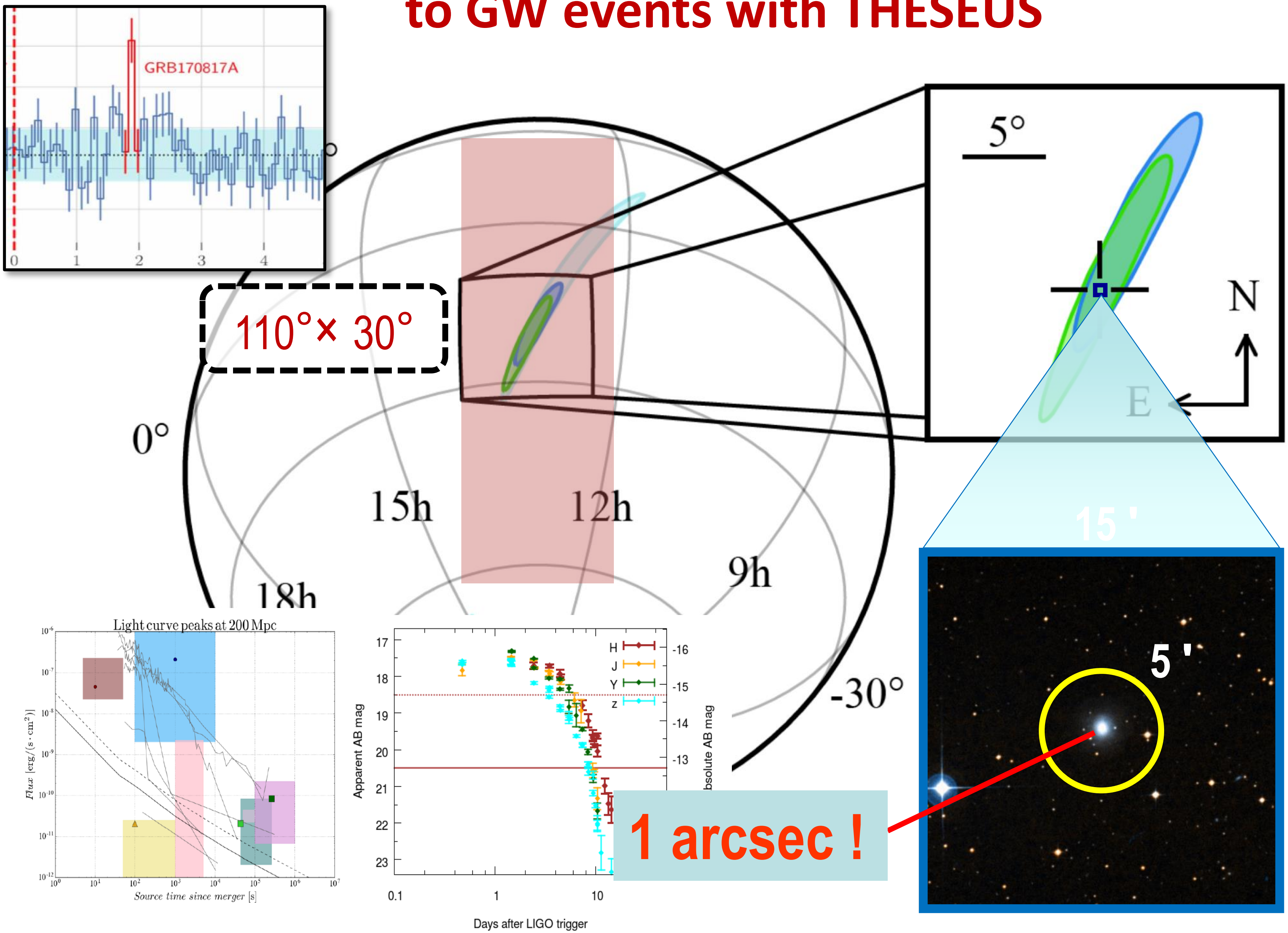
- THESEUS will detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS mergers and of many classes of galactic and extra-galactic transients

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

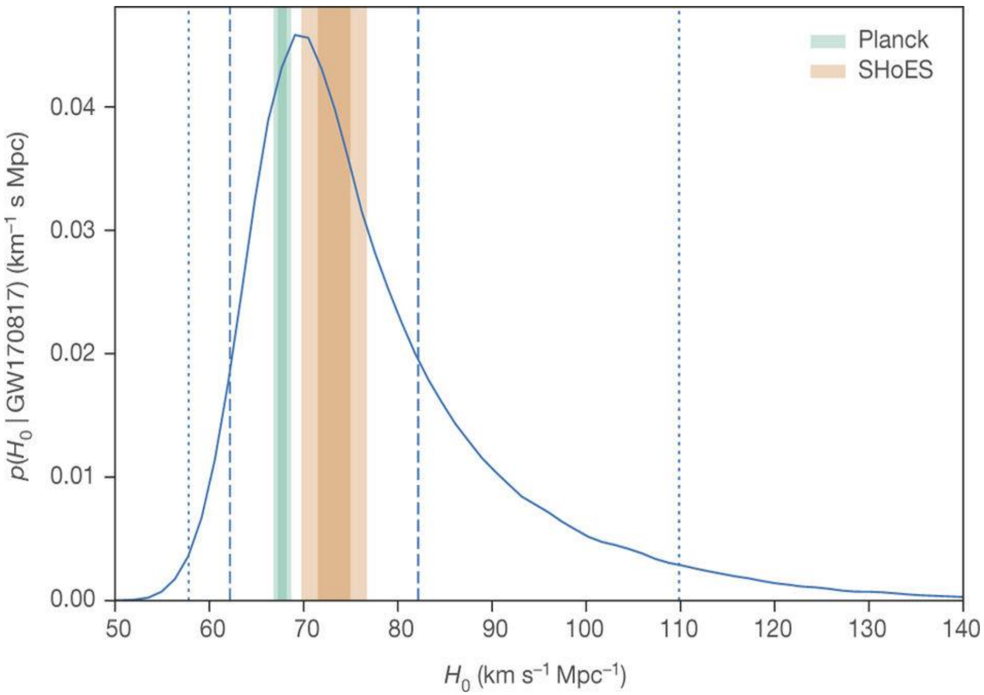




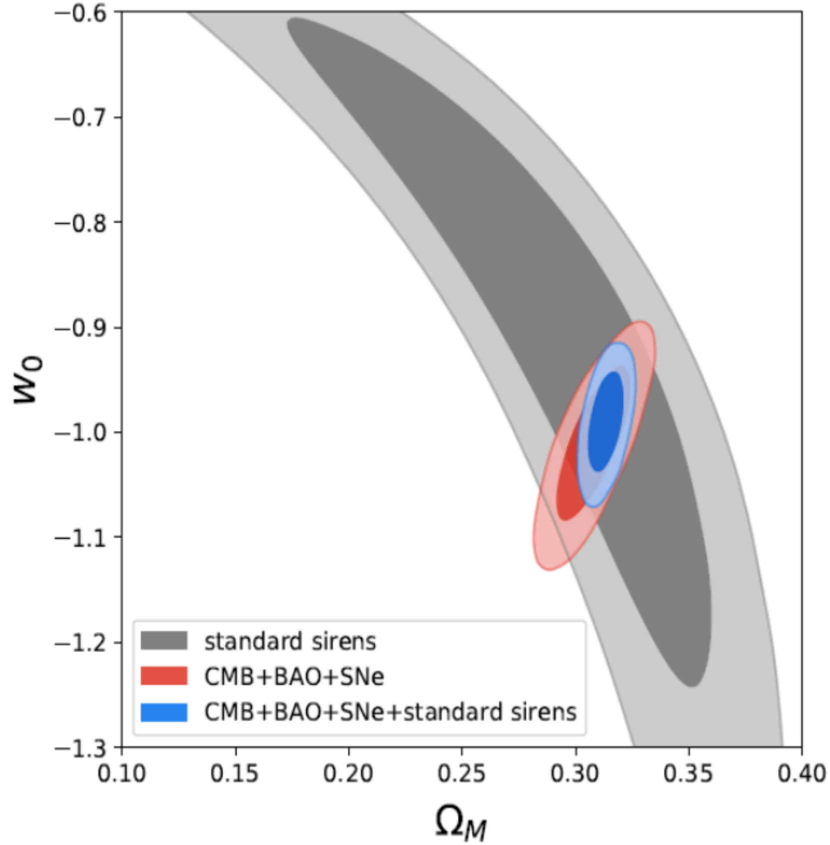
❑ Promptly and accurately localizing e.m. counterparts to GW events with THESEUS



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

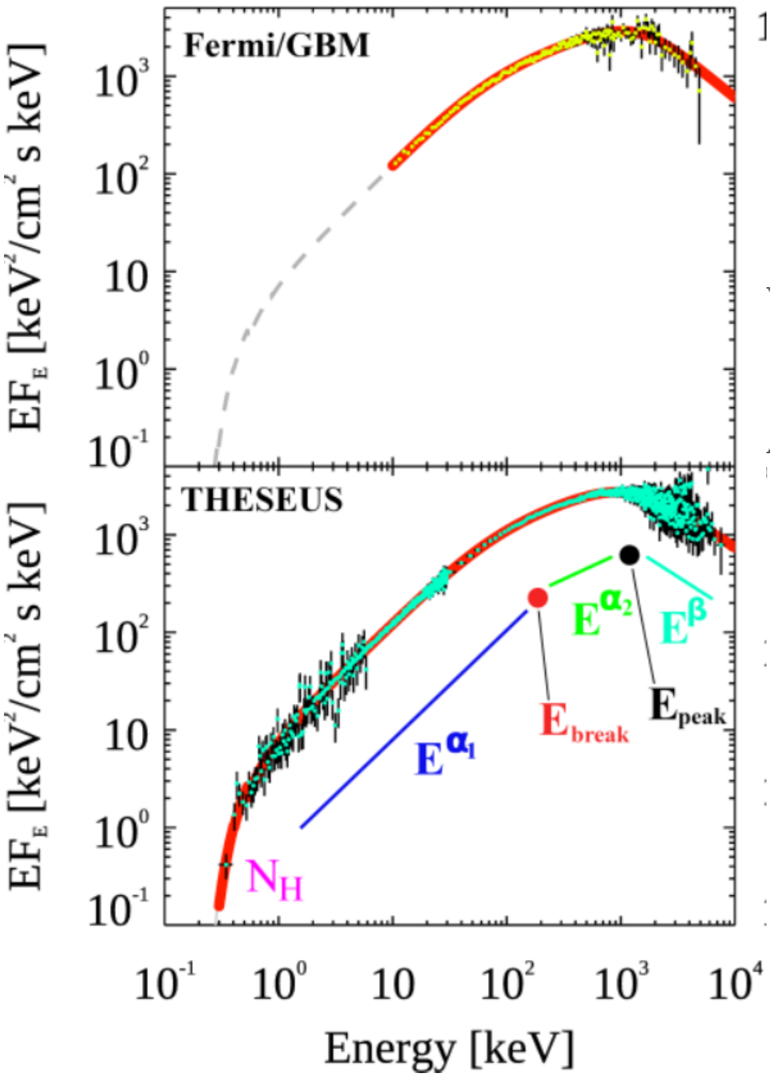


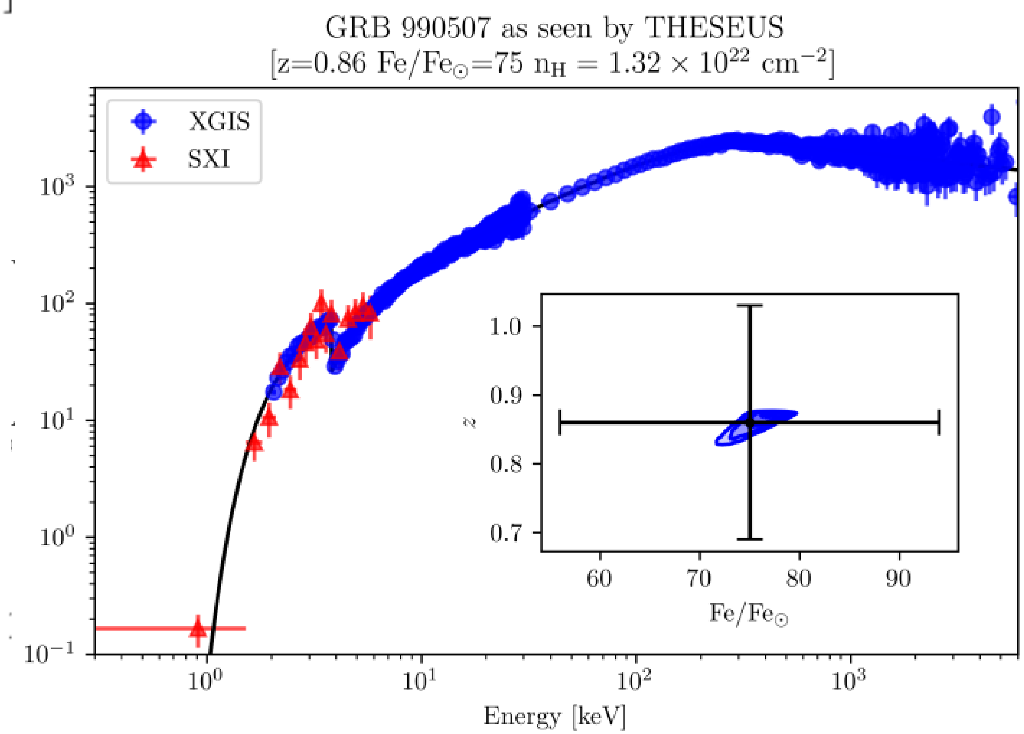
Estimating H0 with GW170817A (LVC 2017)



Investigating dark energy with a statistical sample of GW + e.m. (Sathyaprakash et al. 2019)

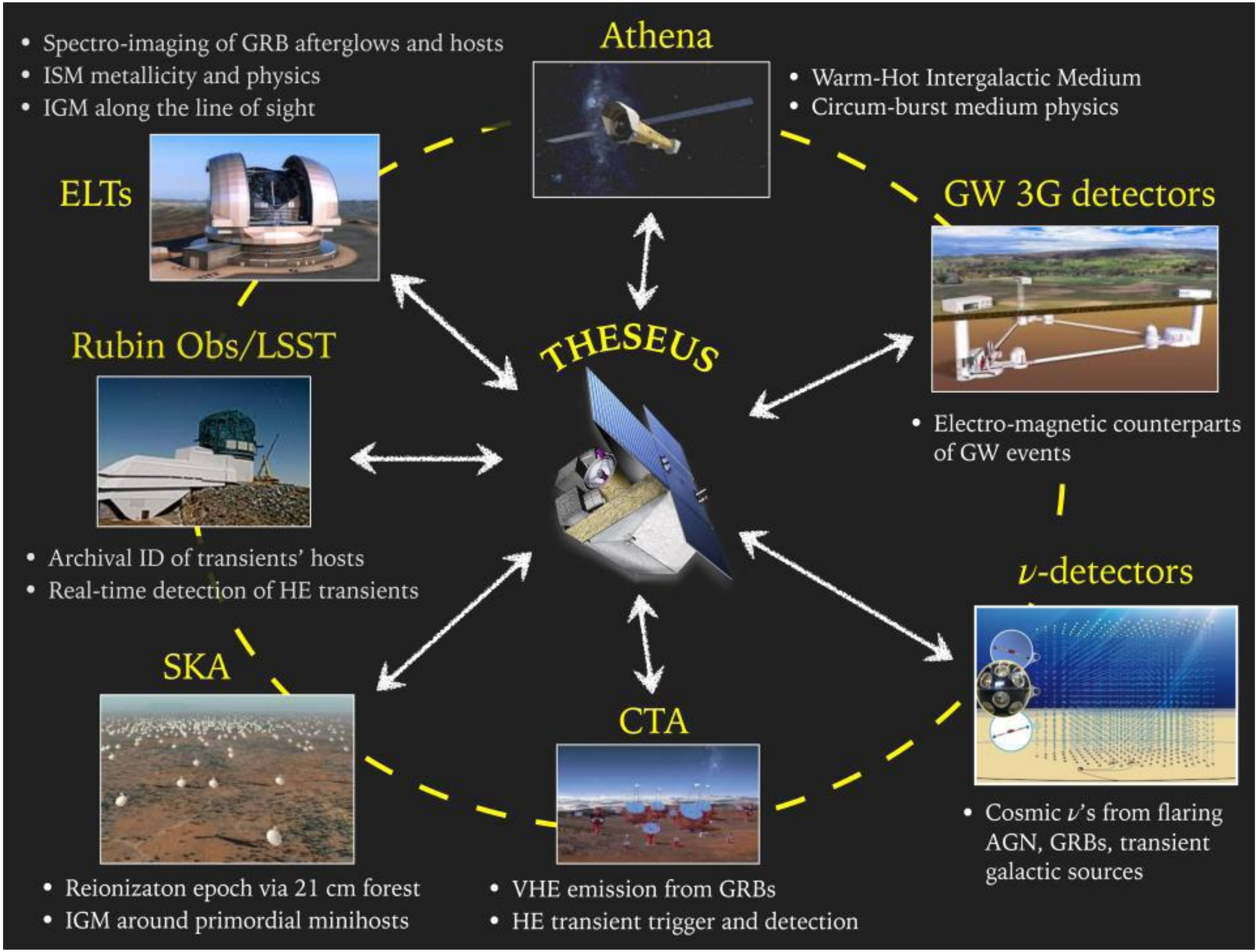
GRB prompt emission physics through unprecedented SXI+XGIS energy band (0.3 keV – 20 meV)

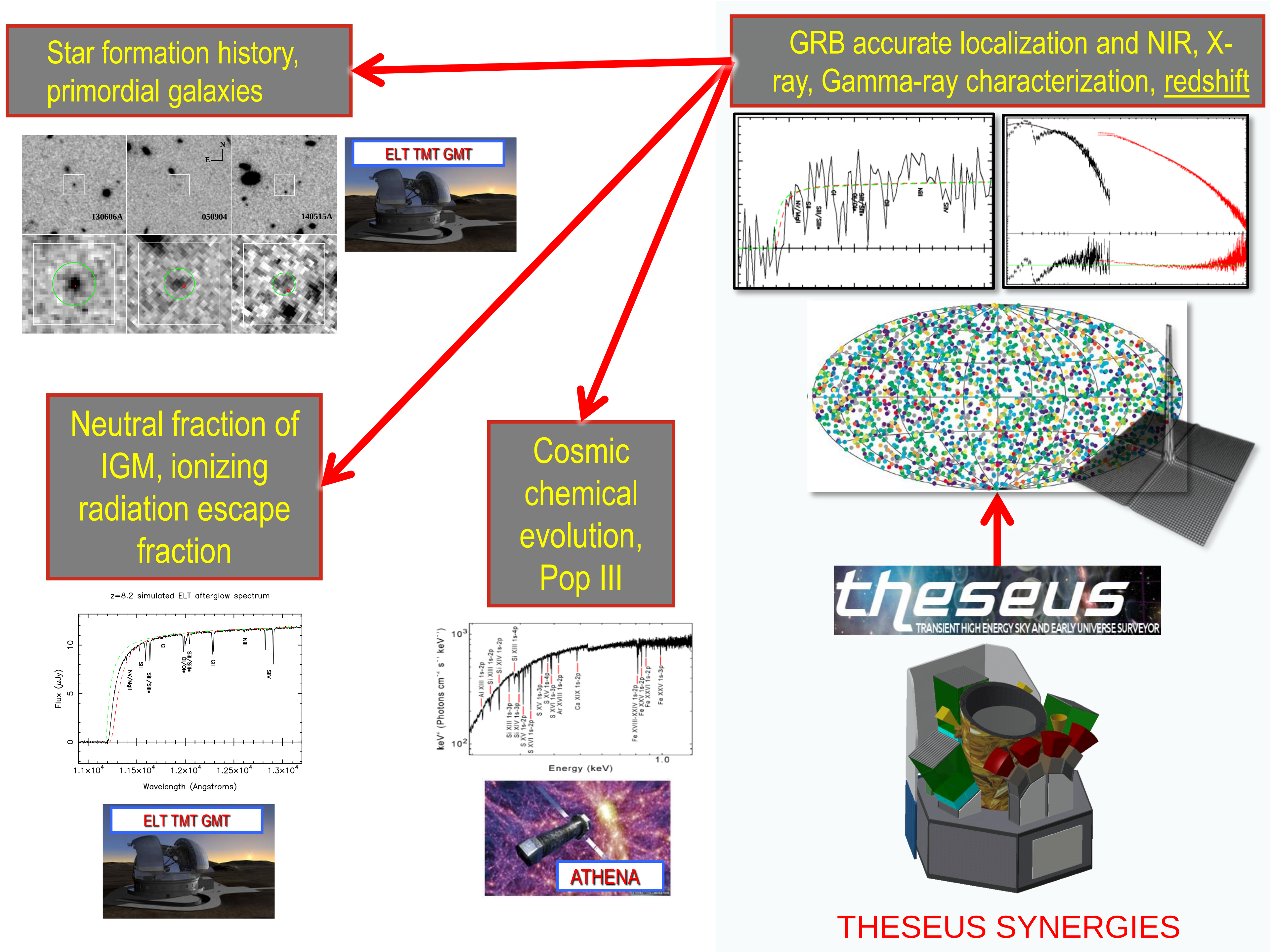




GRB spectrum measured simultaneously over 5 orders of magnitudes in energy!!!

THESEUS Synergies




Star formation history, primordial galaxies
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
130606A
050904
140515A
N
E
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)
ELT TMT GMT
Energy (keV)
ATHENA
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
THESEUS SYNERGIES

theseus

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**.

In summary

- THESEUS, submitted to ESA/M5 by a large European collaboration 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 related key-enabling technologies

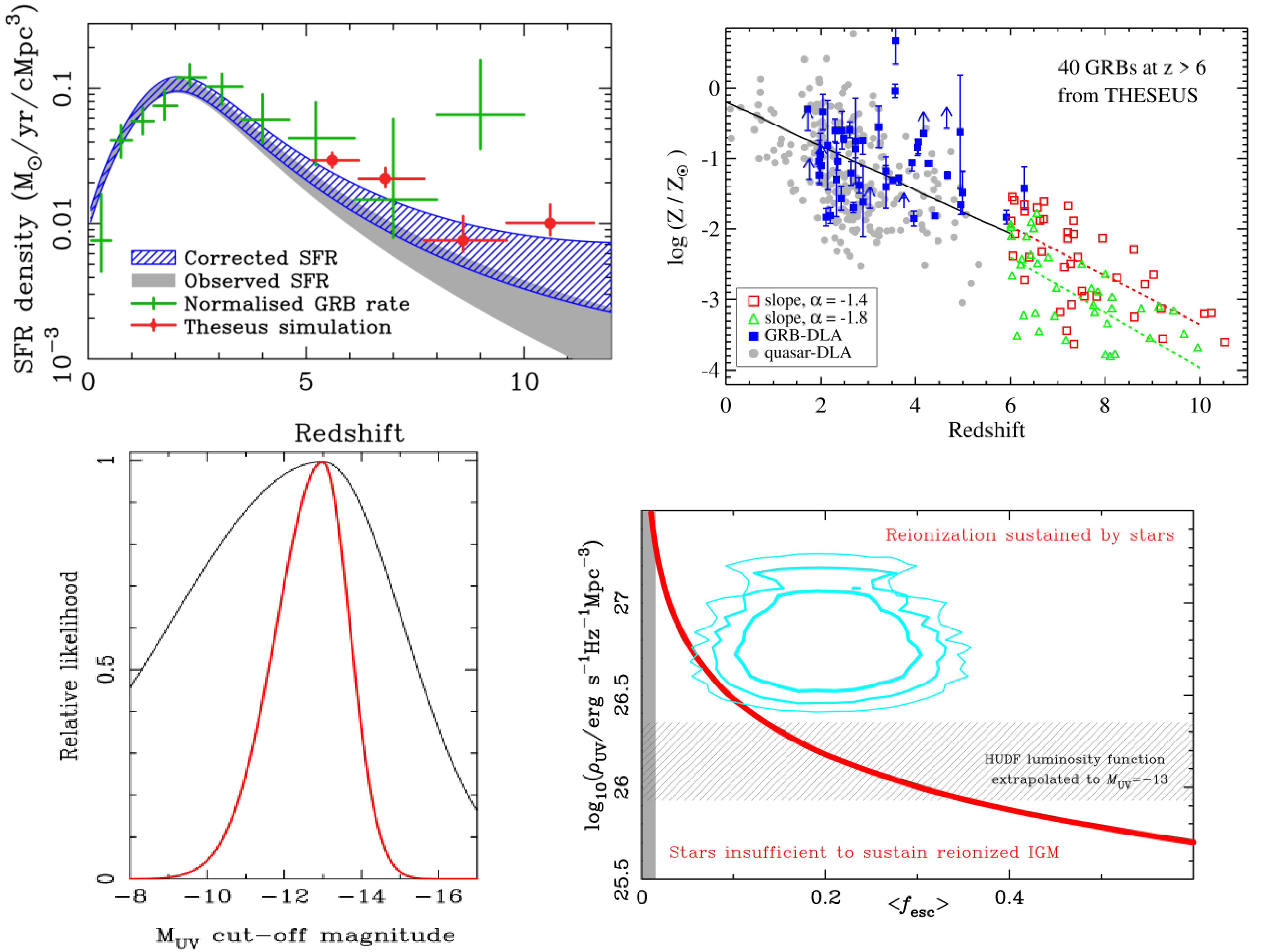
- THESEUS observations will impact on several fields of astrophysics, cosmology and fundamental physics and will enhance importantly the scientific return of next generation multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

- **Phase A will be concluded in Spring 2021; final selection on June**

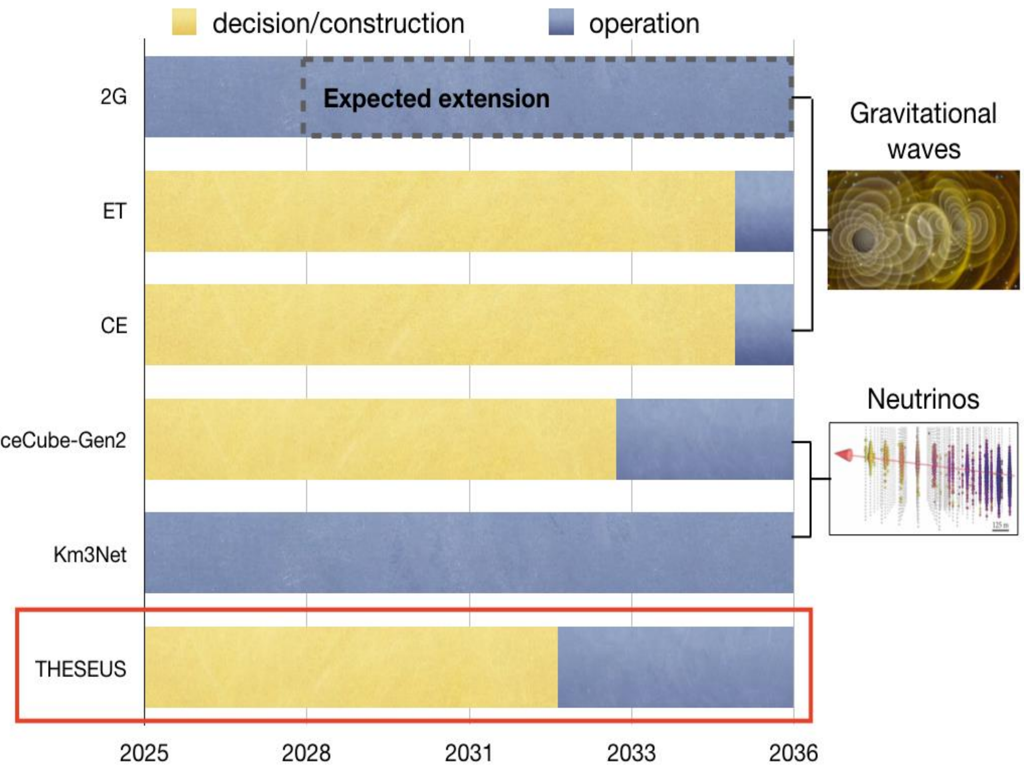
SPIE articles on THESEUS already out. Science papers on Exp.Astr. coming.

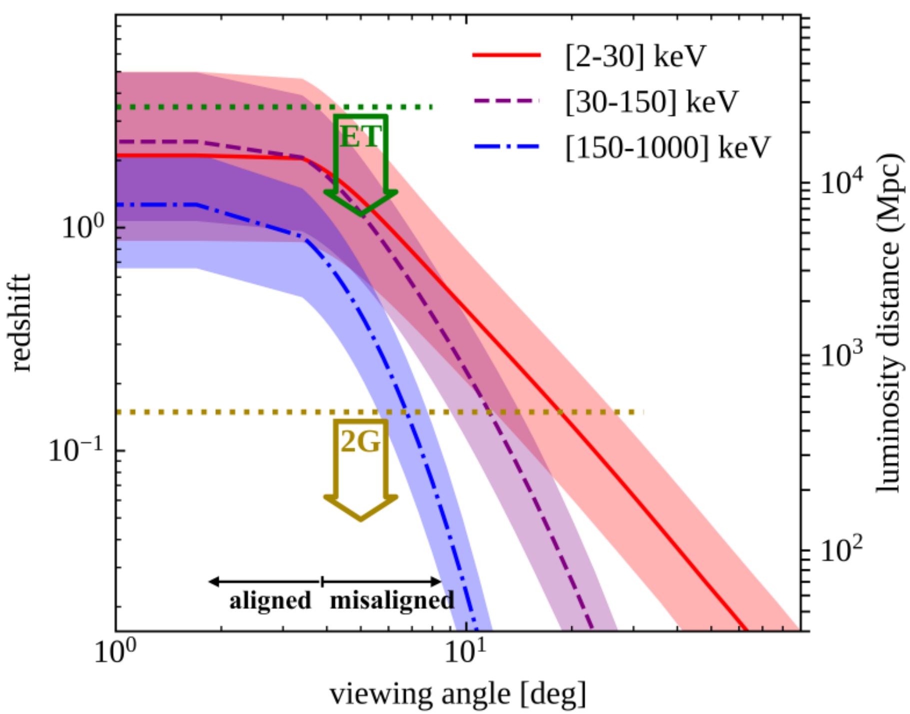
http://www.isdc.unige.ch/theseus/

Back-up slides


SFR density (M⊙/yr/cMpc3)
0.1
0.01
10−3
Corrected SFR
Observed SFR
Normalised GRB rate
Theseus simulation
0
5
10
Redshift
40 GRBs at z > 6
from THESEUS
log (Z / Z⊙)
0
-1
-2
-3
-4
slope, α = -1.4
slope, α = -1.8
GRB-DLA
quasar-DLA
0
2
4
6
8
10
Redshift
Relative likelihood
0
0.5
1
−8
−10
−12
−14
−16
MUV cut−off magnitude
Reionization sustained by stars
HUDF luminosity function
extrapolated to MUV=−13
Stars insufficient to sustain reionized IGM
log10(ρUV/erg s−1Hz−1Mpc−3)
25.5
26
26.5
27
0
0.2
0.4
<fesc>

❑ Theseus in multi-messenger astrophysics context





Theseus data policy

- **All other data taken during the nominal mission will be public as soon as they are processed.** The consortium will release regular XGIS and SXI survey products, and near real-time on-line data products will be available for monitoring many known transients and for alerting the community to new transients found in survey data processing

- All mission data are reserved to the instrument teams until and including the Early Orbit Phase (LEOP); data rights are extended to scientists in the whole THESEUS Consortium during the Performance Verification Phase (;

- GRB data at z > 6 will be reserved for the THESEUS Consortium for a period of 6 months during any mission phase; alerts will in anycase be diffused to the community, for most efficient follow-up observations.

- GO program data will be subjected to a proprietary period of 6 months for the proposer and will become public afterwards.

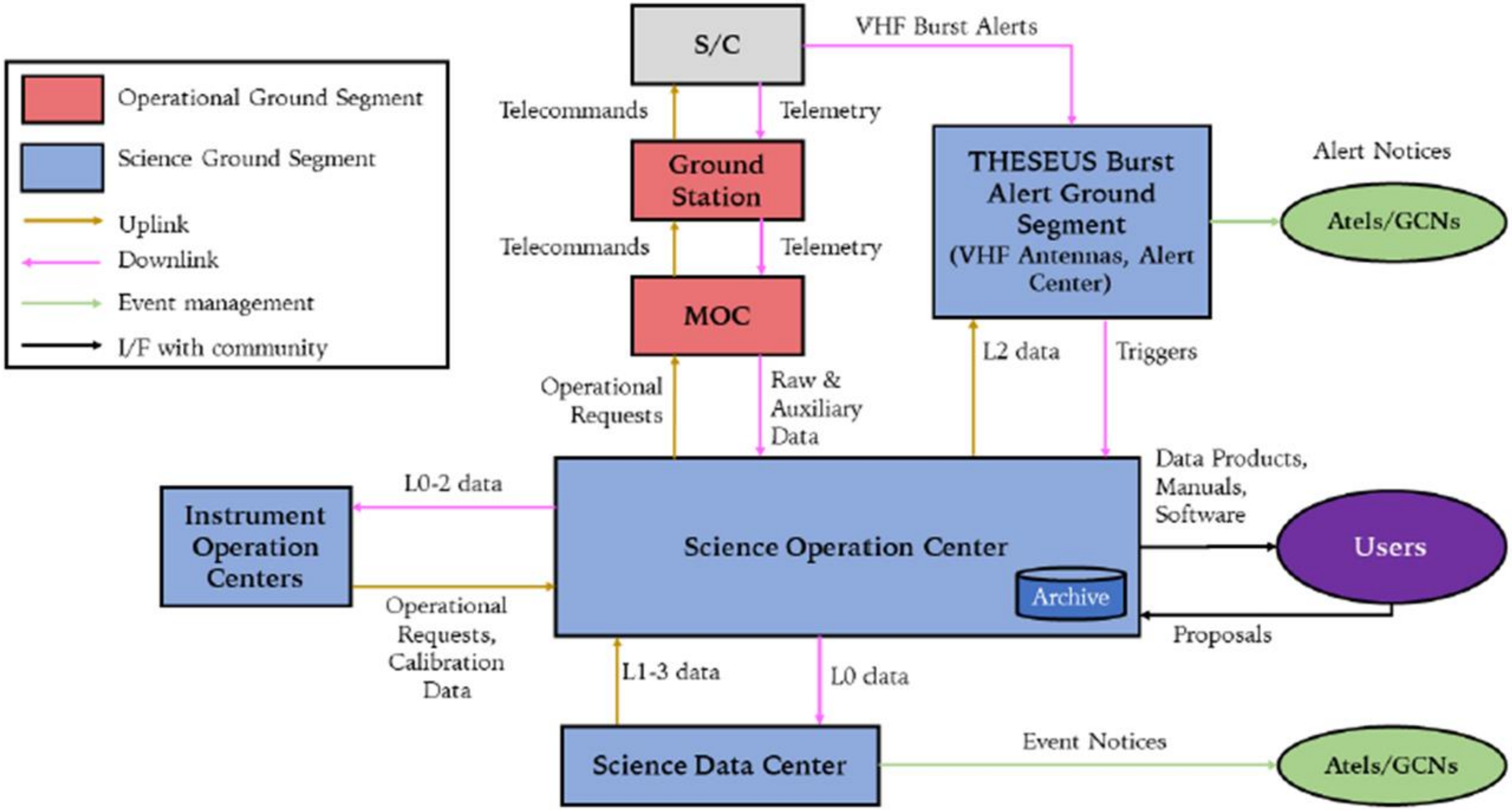
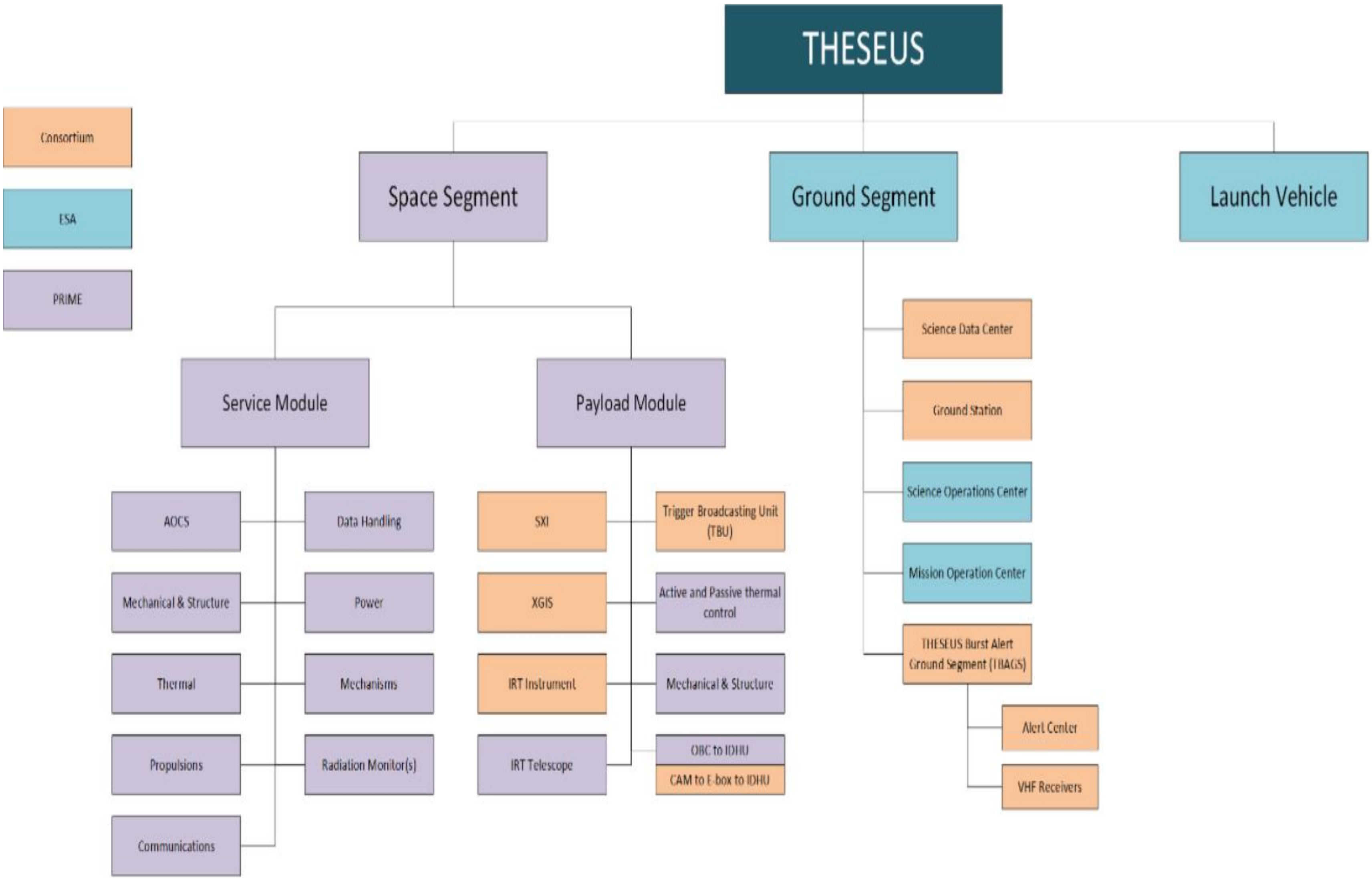
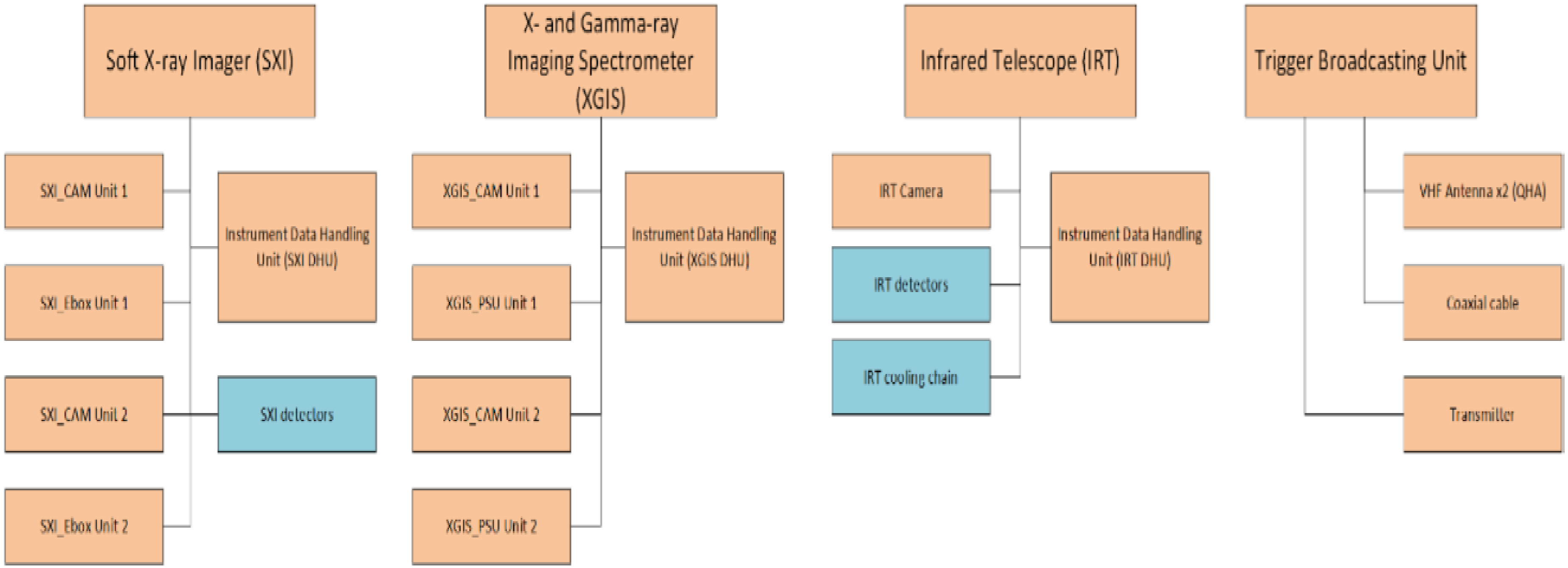


Figure 6-2: Overview of the THESEUS ground segment organization and data flow.

THESEUS product tree and responsibilities



THESEUS product tree and responsibilities



Italy	• THESEUS consortium lead • XGIS instrument PI • TBU PI • Consortium Project Office • XGIS instrument design, detection plane procurements and assembly, electronics, integration, testing, simulations, and calibrations. • Malindi ground station provision (ASI in-kind). • XGIS instrument operation centre lead • Contribution to the SDC
France	• THESEUS consortium co-lead • IRT instrument PI & IRT science lead • IRT instrument design, detection plane assembly, electronics, integration, testing, simulations, calibrations, filter wheel grism • IRT Telescope optical requirements • IRT instrument operation centre lead • Contribution to the SDC • Theseus Burst Alert Ground Segment (CNES VHF Network of ground receivers and the Burst Alert Centre)
Germany	• THESEUS consortium co-lead • SXI and IRT DHU design, electronics, integration, testing, and software development • Overviewing of the XGIS DHU development • Contribution to the consortium project office • SDC contribution
Denmark	• XGIS DHU design, electronics, integration, testing, and software development
Belgium	• Contribution to the SXI instrument integration, characterization, and tests
Slovenia	• Investigation of possible mobile round station additional antennas (for telemetry downlink) • Contribution to the SDC
Netherlands	• Contribution to the SDC
United Kingdom	• THESEUS consortium co-lead • SXI instrument PI • SXI instrument design, detection plane characterization, optics assembly, electronics, integration, testing, simulations, and calibrations • SXI instrument operation centre lead • Contribution to the SDC
Switzerland	• *THESEUS* consortium co-lead • SDC PI • Contribution to the consortium project office • SDC engineering, software development, data processing, quick-look, data scientific validation, sky monitoring, community alert broadcasting • IRT filter wheel mechanism and optical elements (filters)
Spain	• XGIS coded mask and collimator • Contribution to SXI focal plane assembly and mechanical structure
Poland	• XGIS power supply units
Czech Republic	• Contribution to the SXI instrument mechanical structures and thermal control
Ireland	• Contribution to the SDC