The THESEUS space mission concept

Transient High-Energy Sky and Early Universe Surveyor

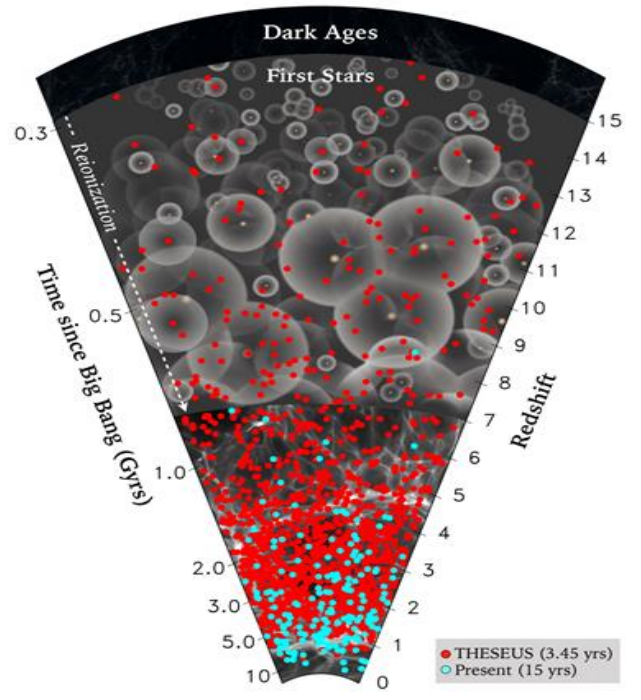
Lorenzo Amati
on behalf of the
THESEUS Consortium

INTEGRAL Workshop 2024
(ESAC – October 24th 2024)

THESEUS Science Case

Core Science pillars:

- Probe the **early Universe (first stars, first galaxies, cosmic reionization)**, by unveiling and exploiting the population of high redshift Gamma-Ray Bursts (GRB)

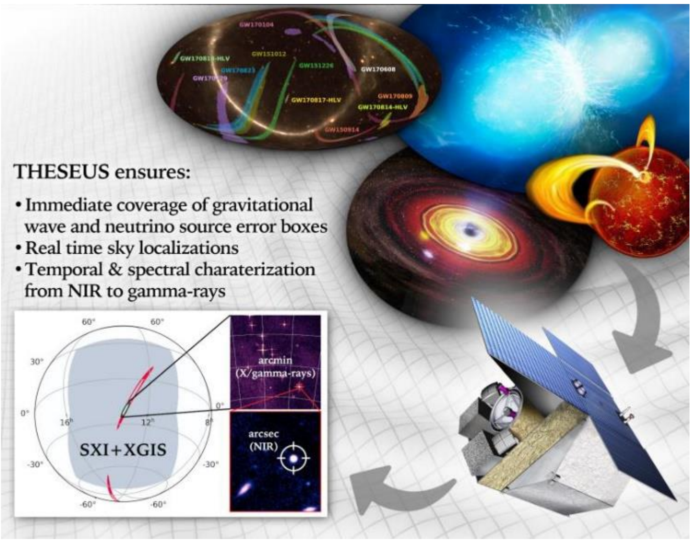


- Provide a **fundamental contribution to multi-messenger time domain astrophysics** through short GRB and other transients

Observatory Science includes:

- Study of thousands of faint to bright X-ray sources by exploiting the **simultaneous broad band X-ray and NIR observations**

- Provide a **flexible follow-up observatory** for fast transient events with multi-wavelength ToO capabilities and **GO programmes**



theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- 2018-2021: ESA Phase-A study (2018-2021) as M5 candidate
- 2022: Selected for Phase 0 study (2023) within M7 process
- 2023: Selected for Phase-A study (2024-2026) as M7 candidate
- M7 timeline: Phase-A (2024-2026), adoption 2028, launch 2037

Payload consortium: Italy, Germany, UK, France, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, The Netherlands, Norway, Slovenia, Ireland (+ Hungary?)

Leads: L. Amati (INAF – OAS Bologna, Italy, lead proposer), A. Santangelo (Un. Tuebingen, D), P. O'Brien (Un. Leicester, UK), D. Gotz (CEA-Paris, France), E. Bozzo (Un. Genève, CH)

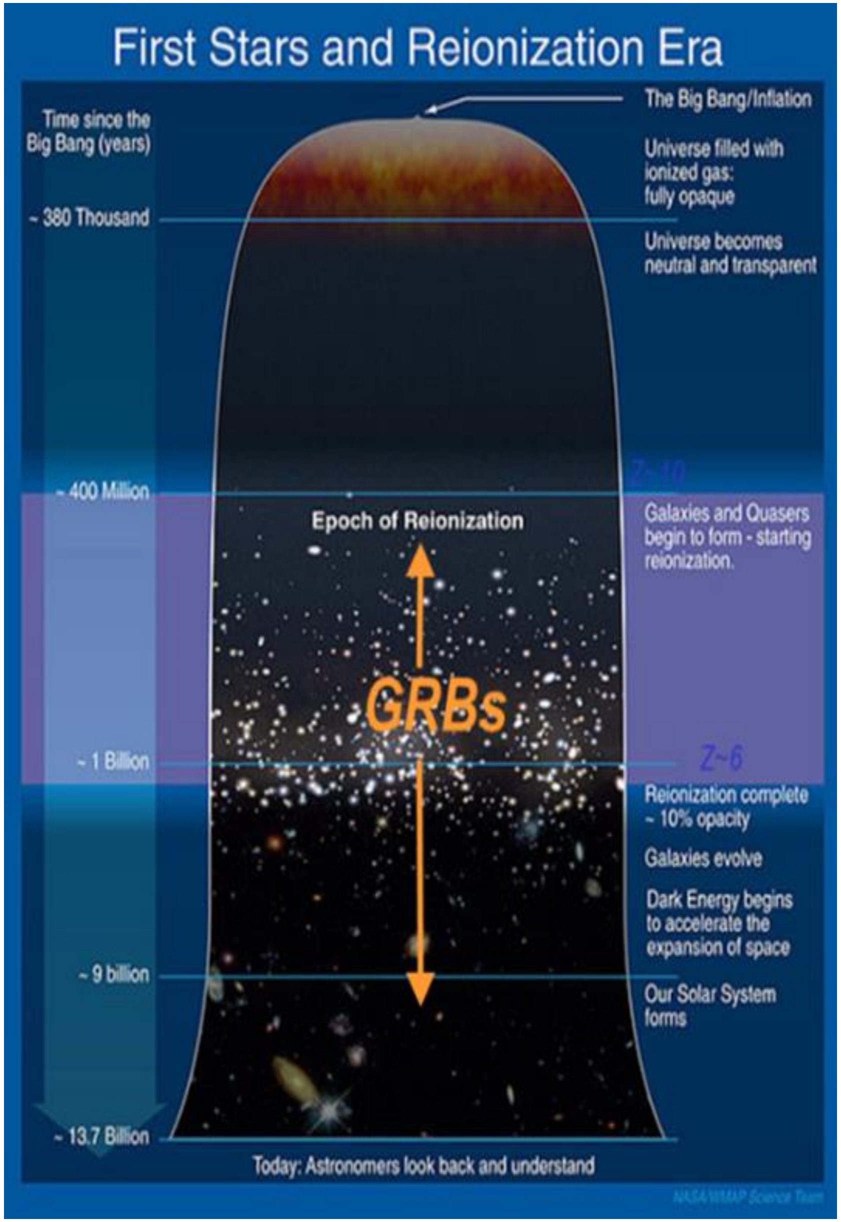
Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)
Articles for SPIE 2020 and Exp..Astr. (all on arXiv)
http://www.isdc.unige.ch/theseus

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

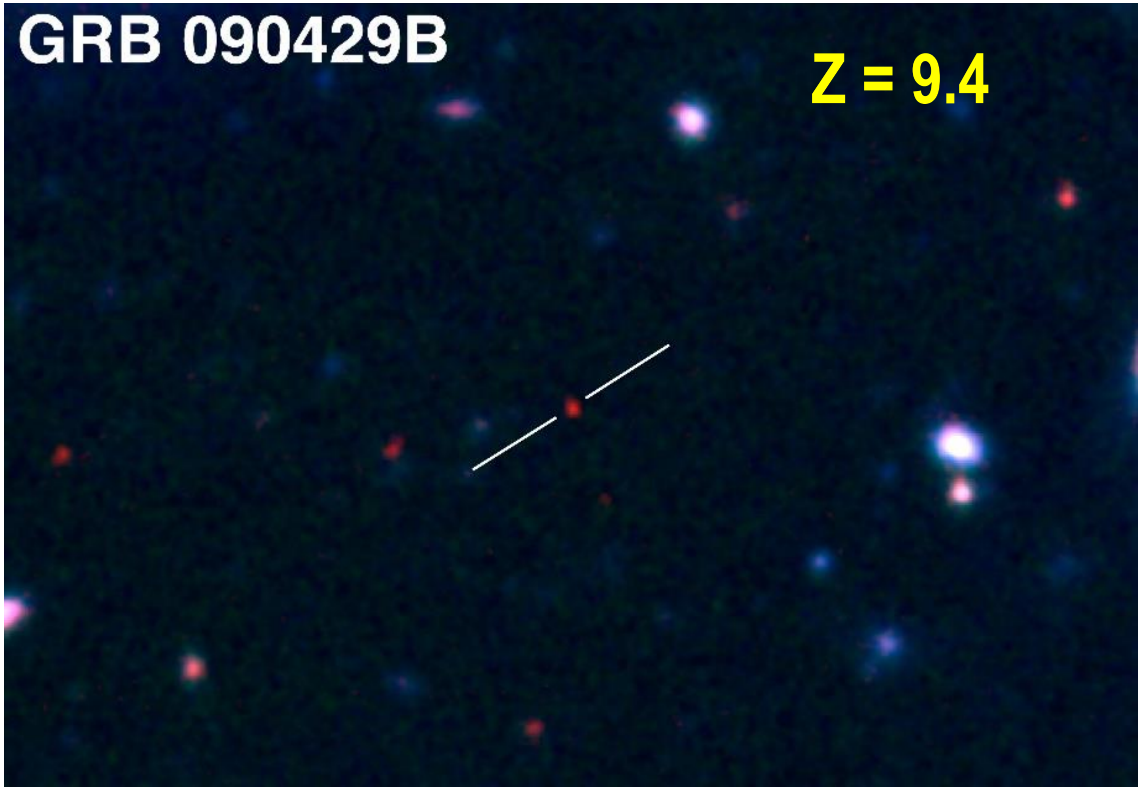
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars



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)**



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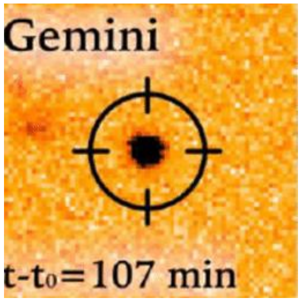
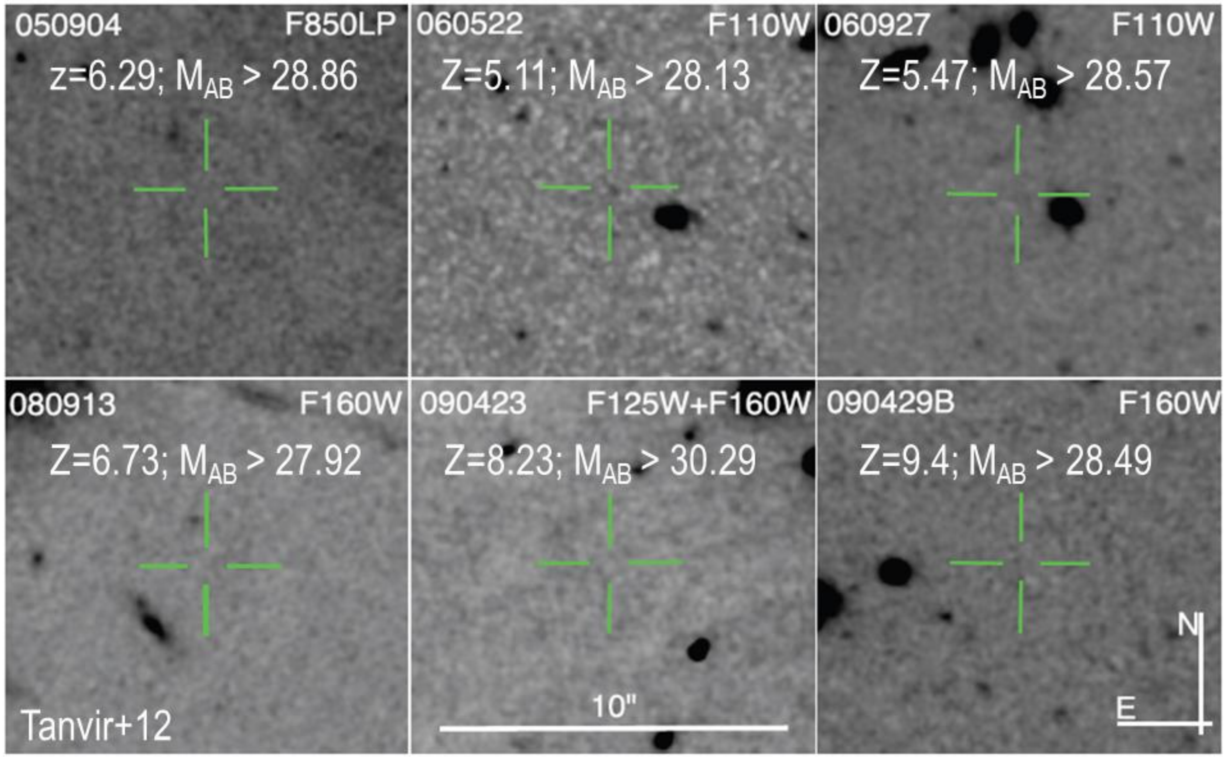
Detecting and studying primordial invisible galaxies

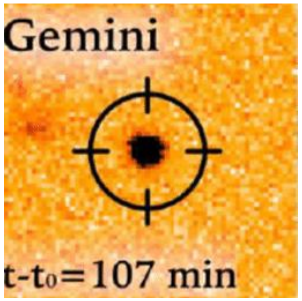


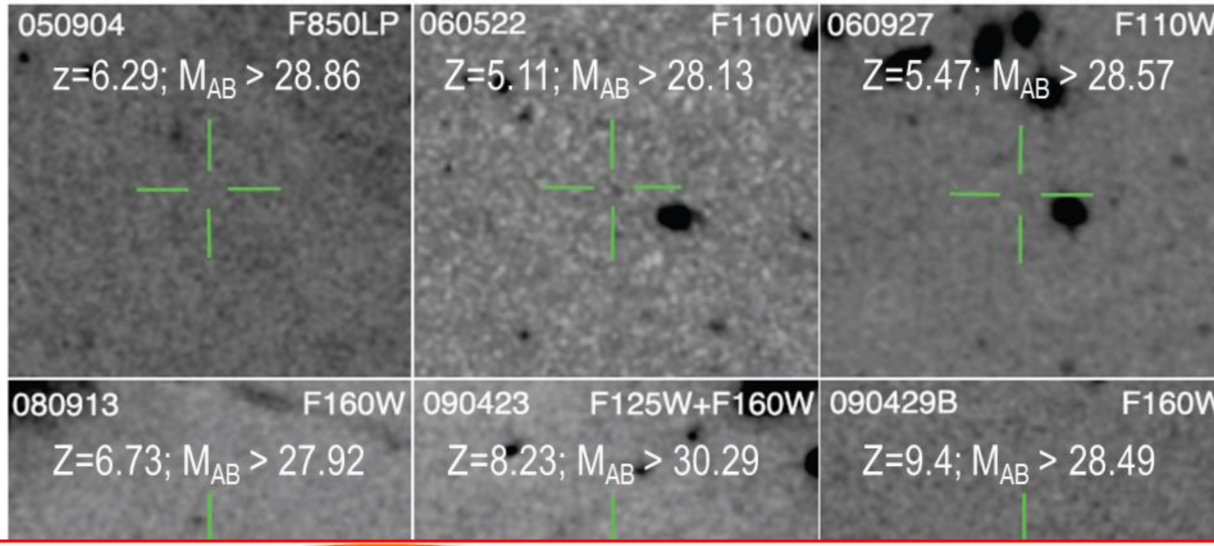


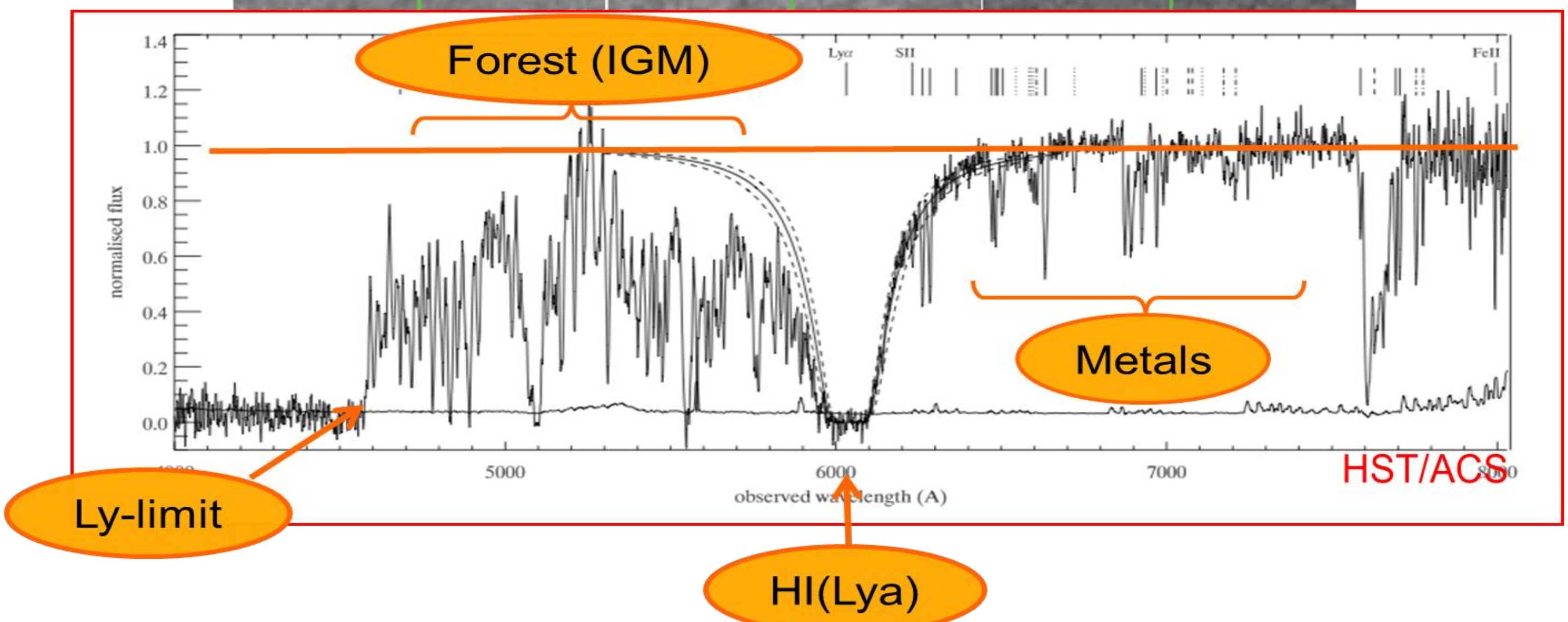
Robertson&Ellis12

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







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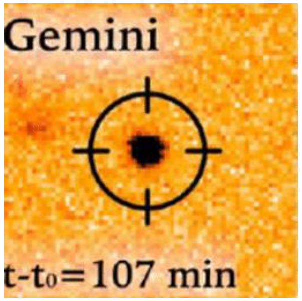
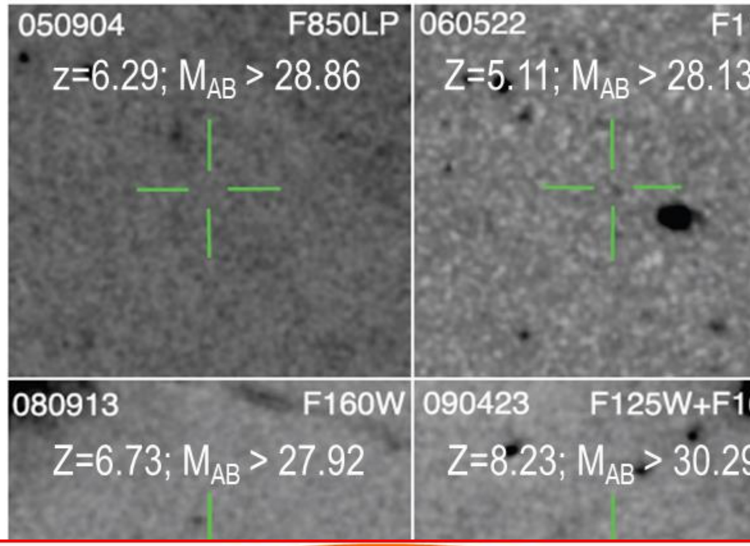
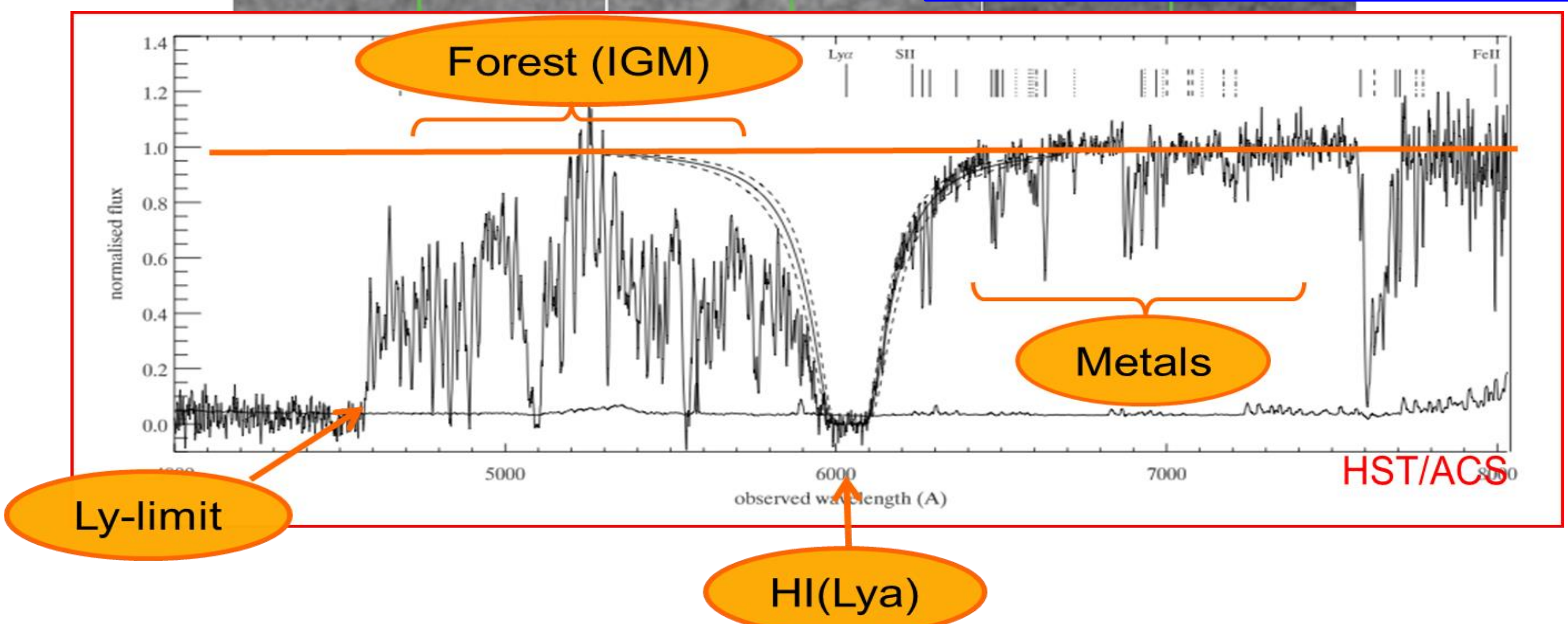




- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution



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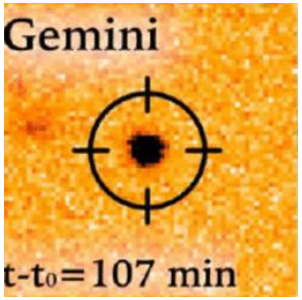
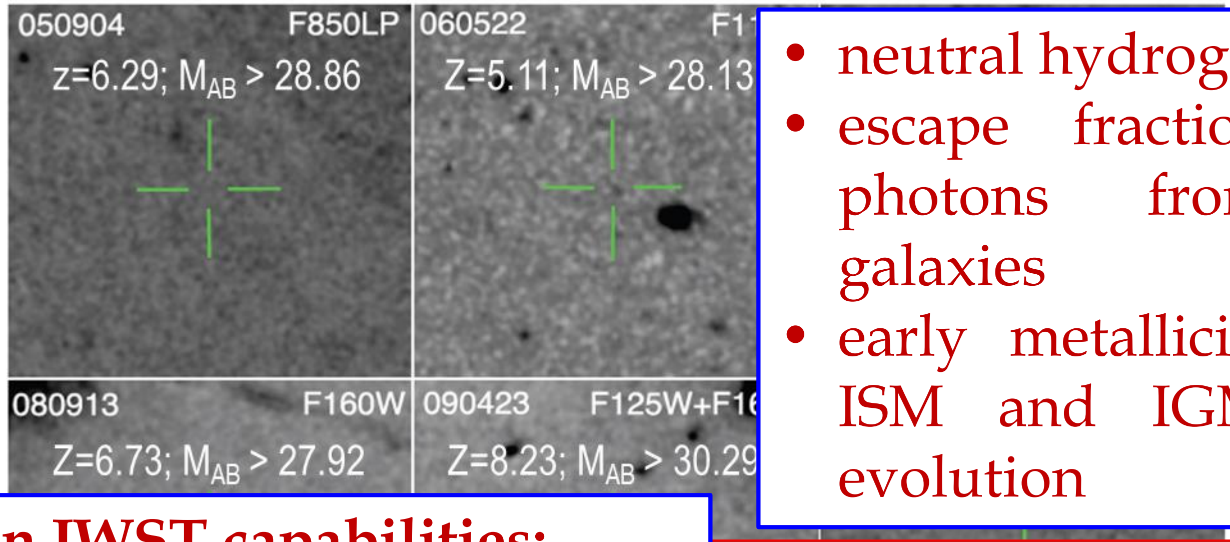
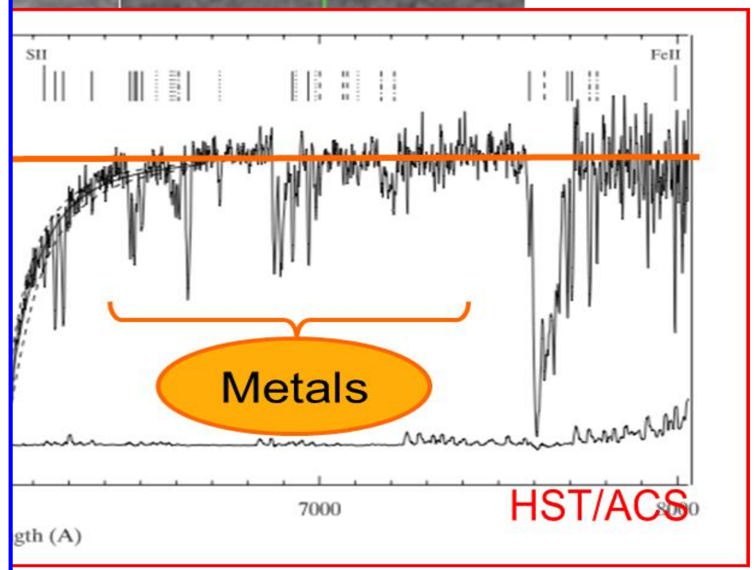




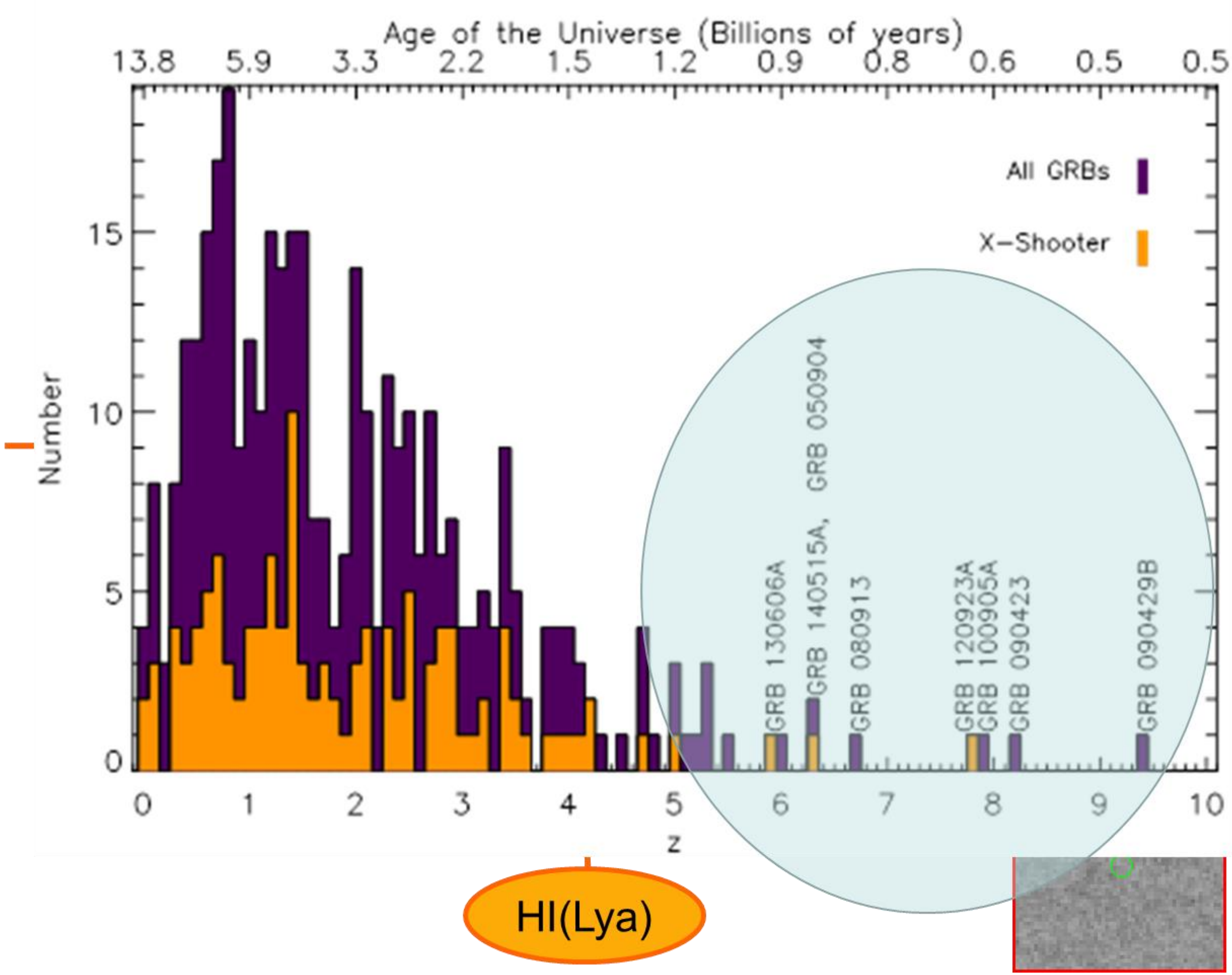
- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

Beyond even JWST capabilities:

- Primordial galaxies detection and characterization Independent on mass and luminosity
- Allow absorption spectroscopy (needed because most metals are in neutral gas and and for dust ratio)
- Properties of primordial IGM
- Targets for JWST

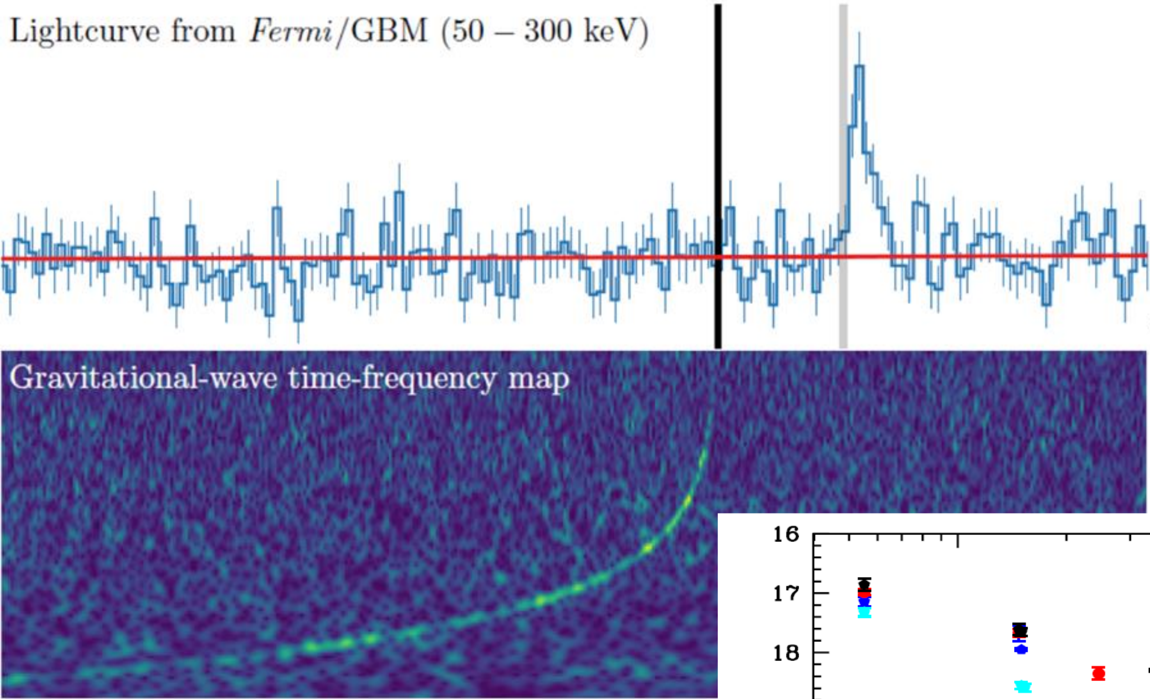


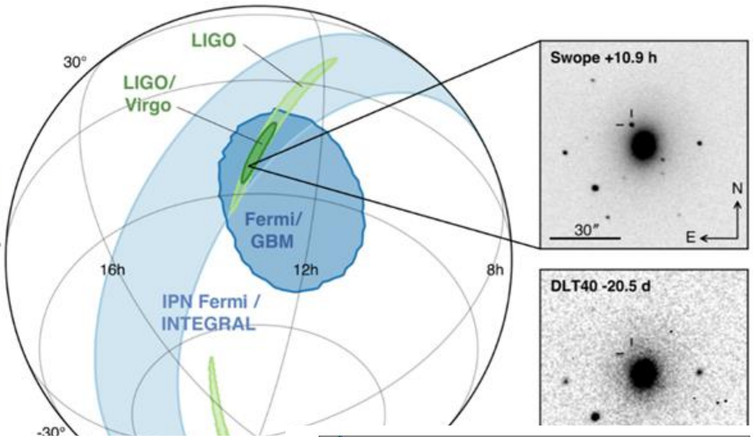
Shedding light on the early Universe with GRBs

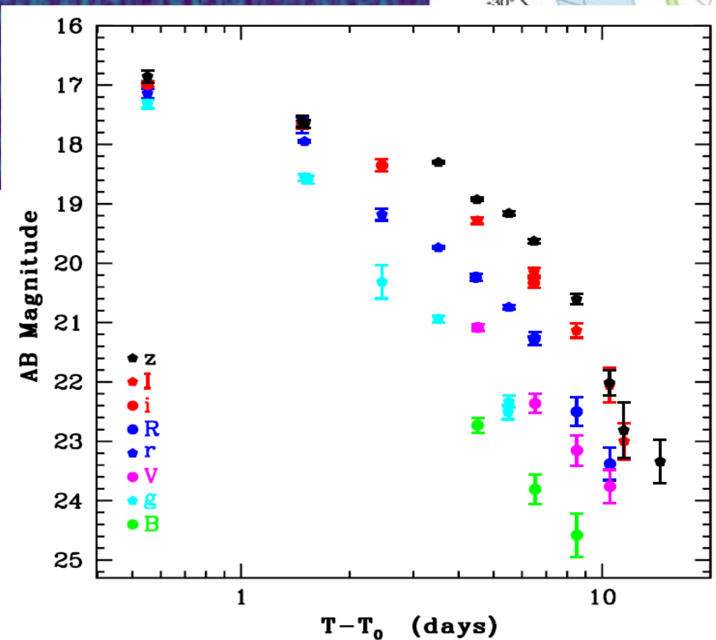


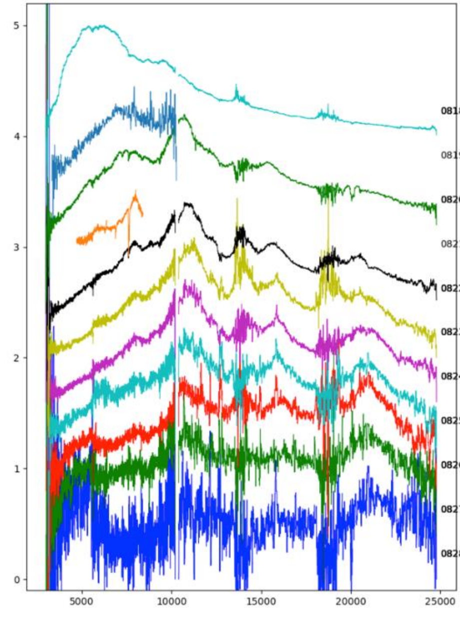
Short GRBs and multi-messenger astrophysics

GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):









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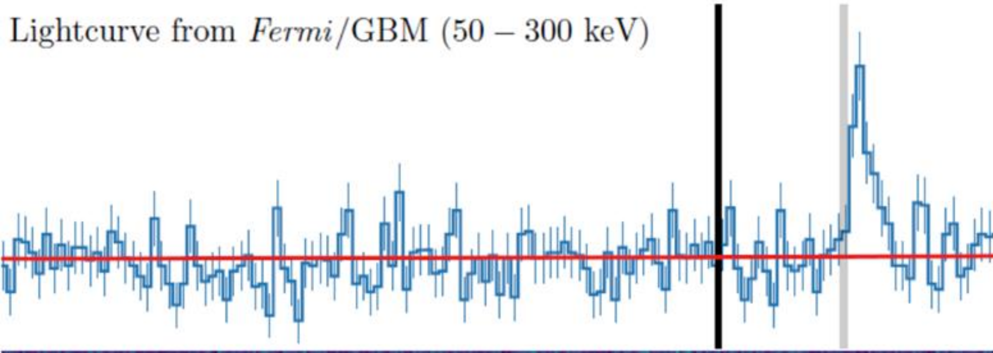
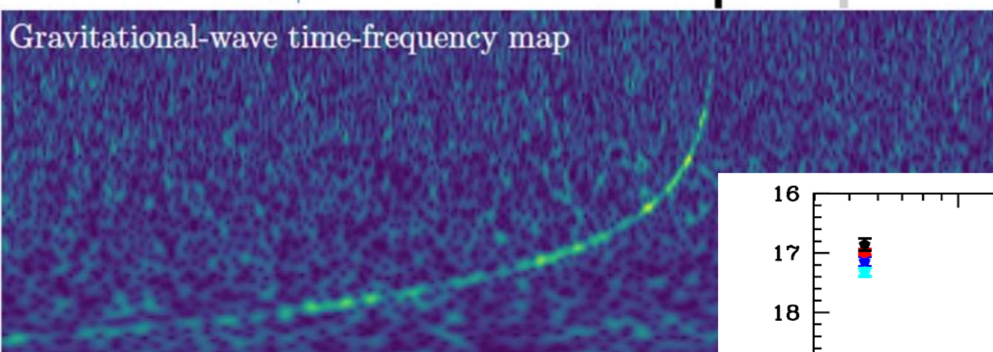
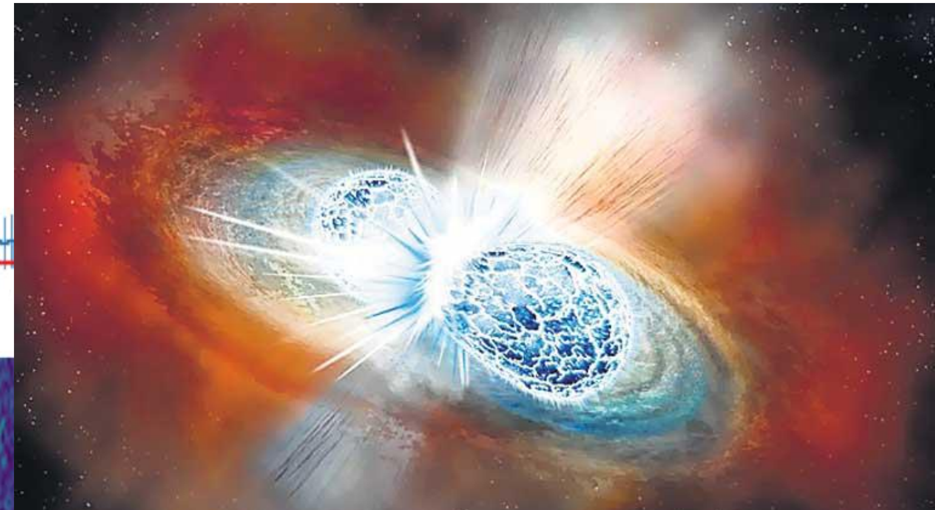
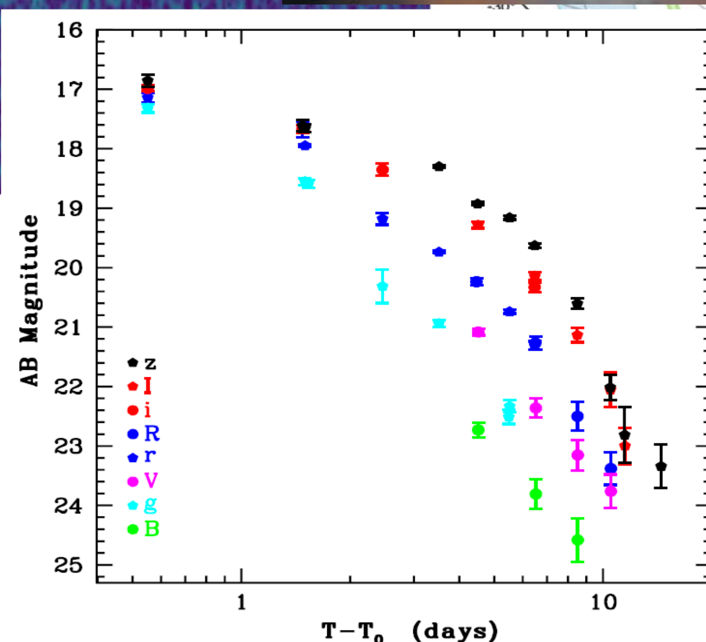
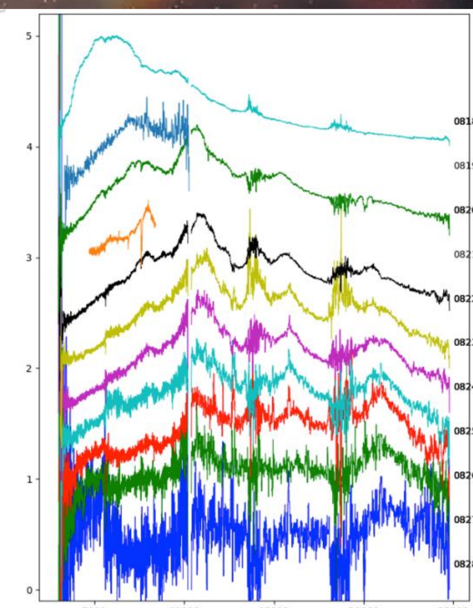






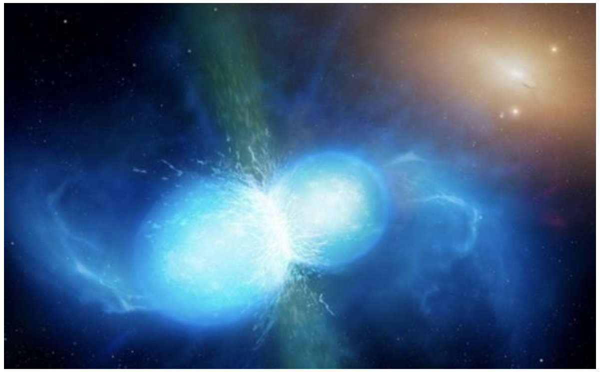




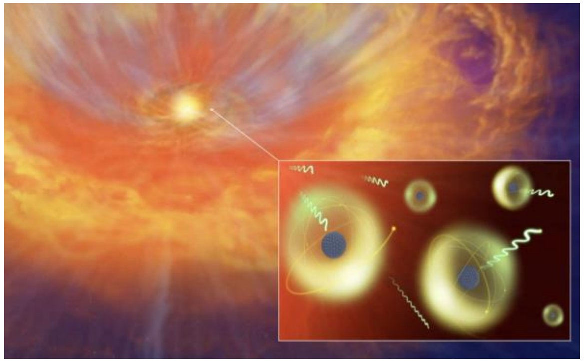
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

GW170817 + SHORT GRB 170817A + KN AT2017GFO

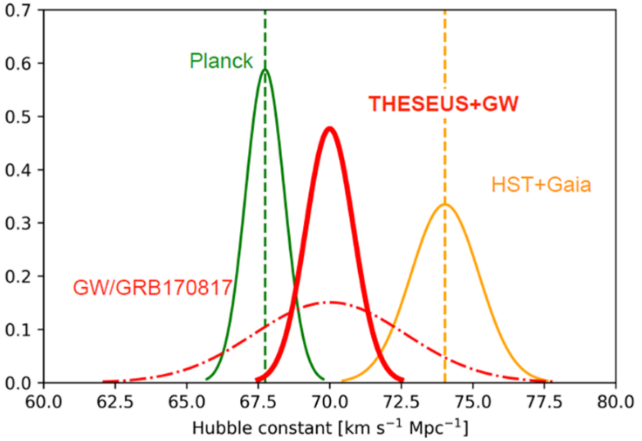
Relativistic jet formation, equation of state, fundamental physics



Cosmic sites of r-process nucleosynthesis



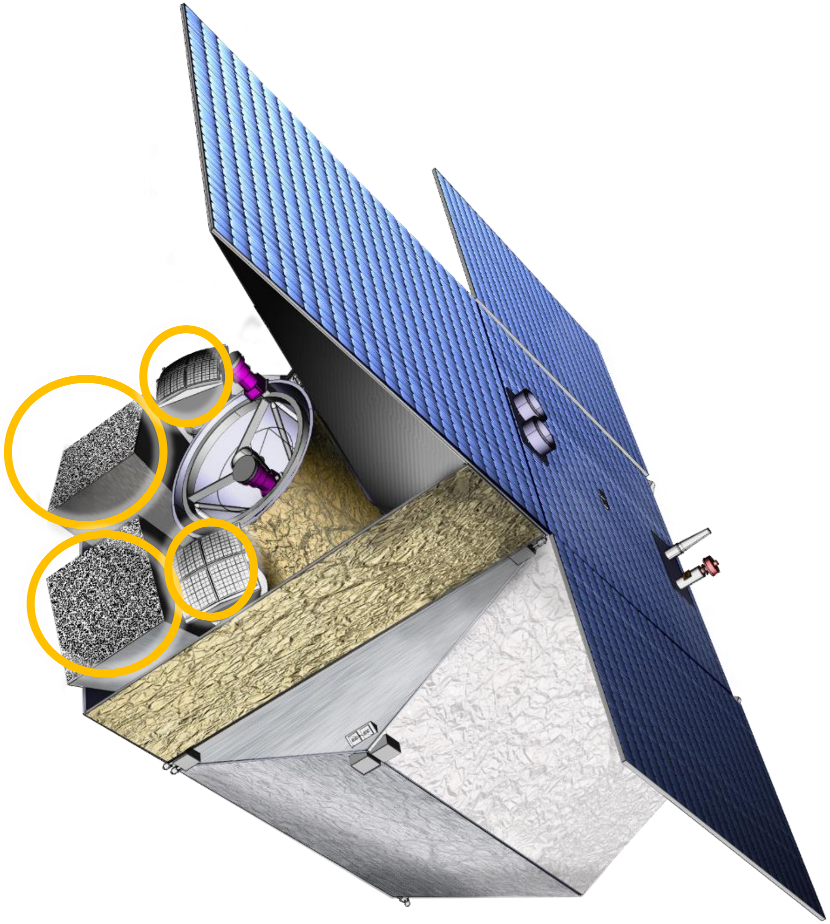
New independent route to measure cosmological parameters



THESEUS Mission Concept

THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

Set of innovative wide-field monitors with **unprecedented combination of broad energy range from gamma-rays down to soft X-rays, FOV and localization accuracy**



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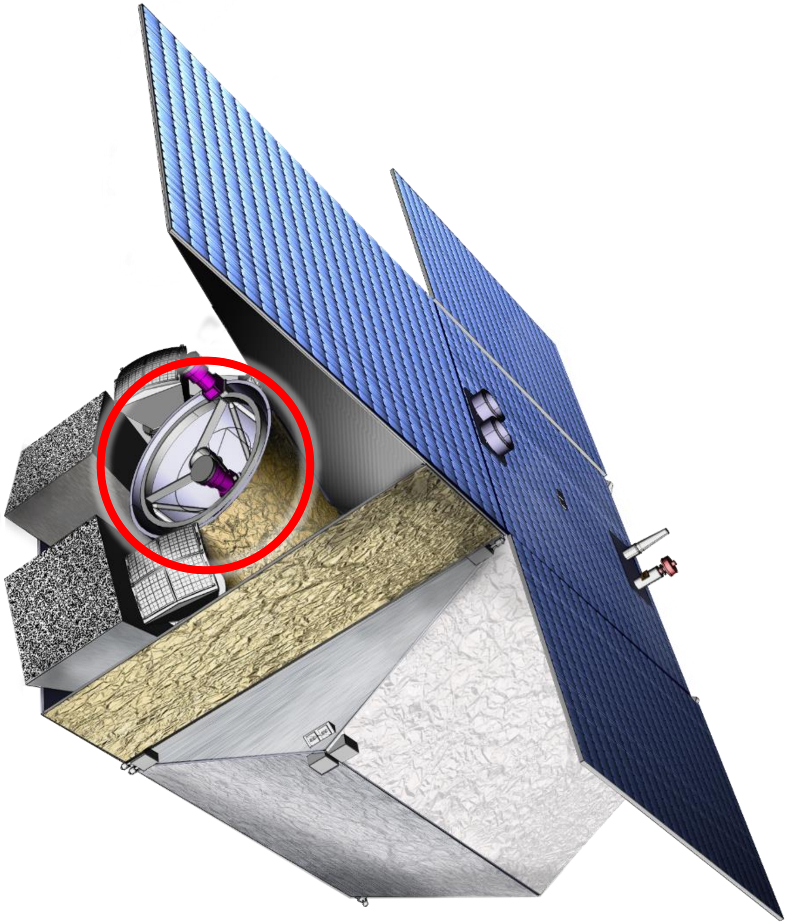
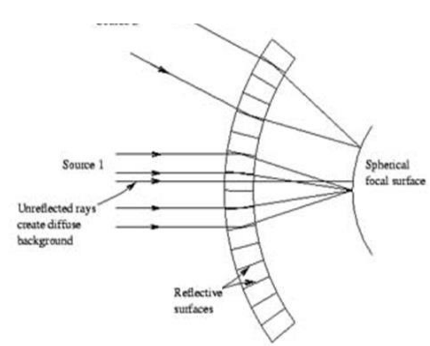
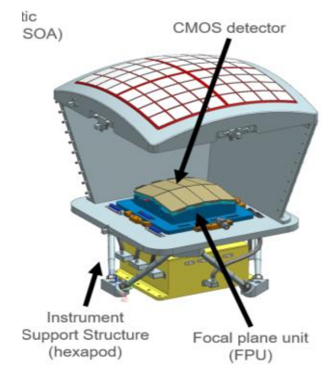
On-board **autonomous fast follow-up in optical/NIR**, arcsec location and **redshift measurement** of detected GRB/transients



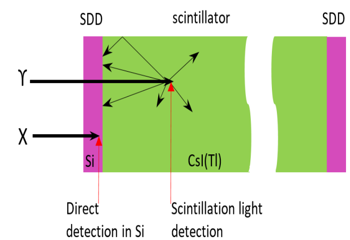
THESEUS Mission Concept

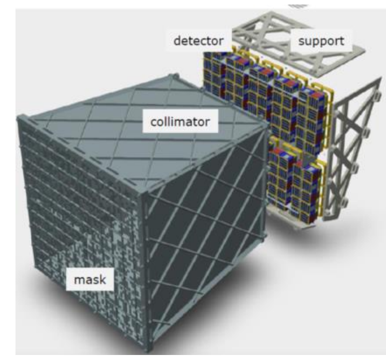
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′



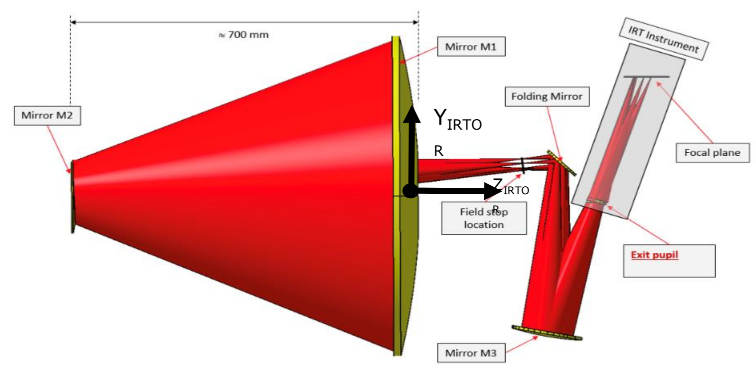


- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy





- **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

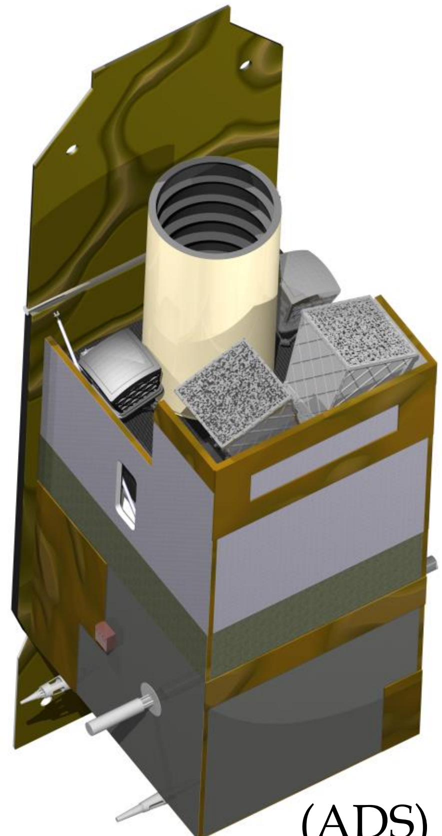


THESEUS Mission Concept

- **Fast slewing capability** (>10°/min), granting prompt NIR follow-up of GRBs and transients

- **Low-Earth Orbit (LEO),** with about 4° inclination and 550-640 km altitude, granting low and stable BKG for the monitors

- The weight (about 2 tons) and dimensions are suitable for **launch with VEGA-E**



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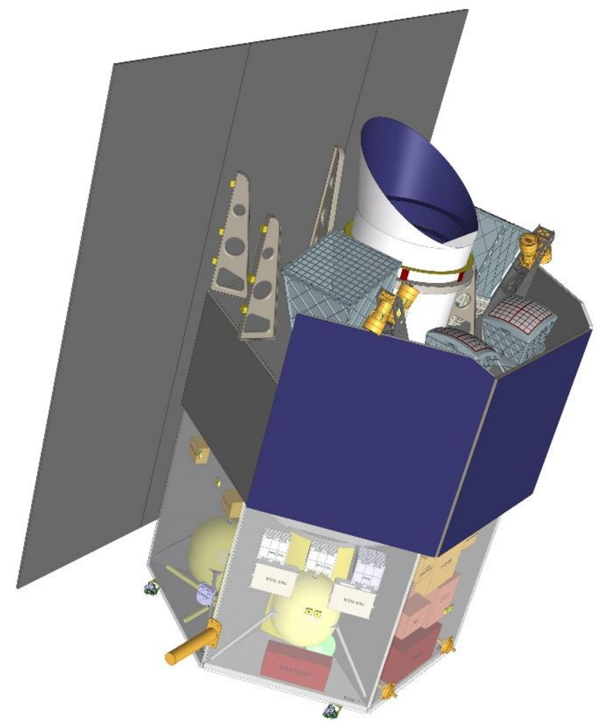
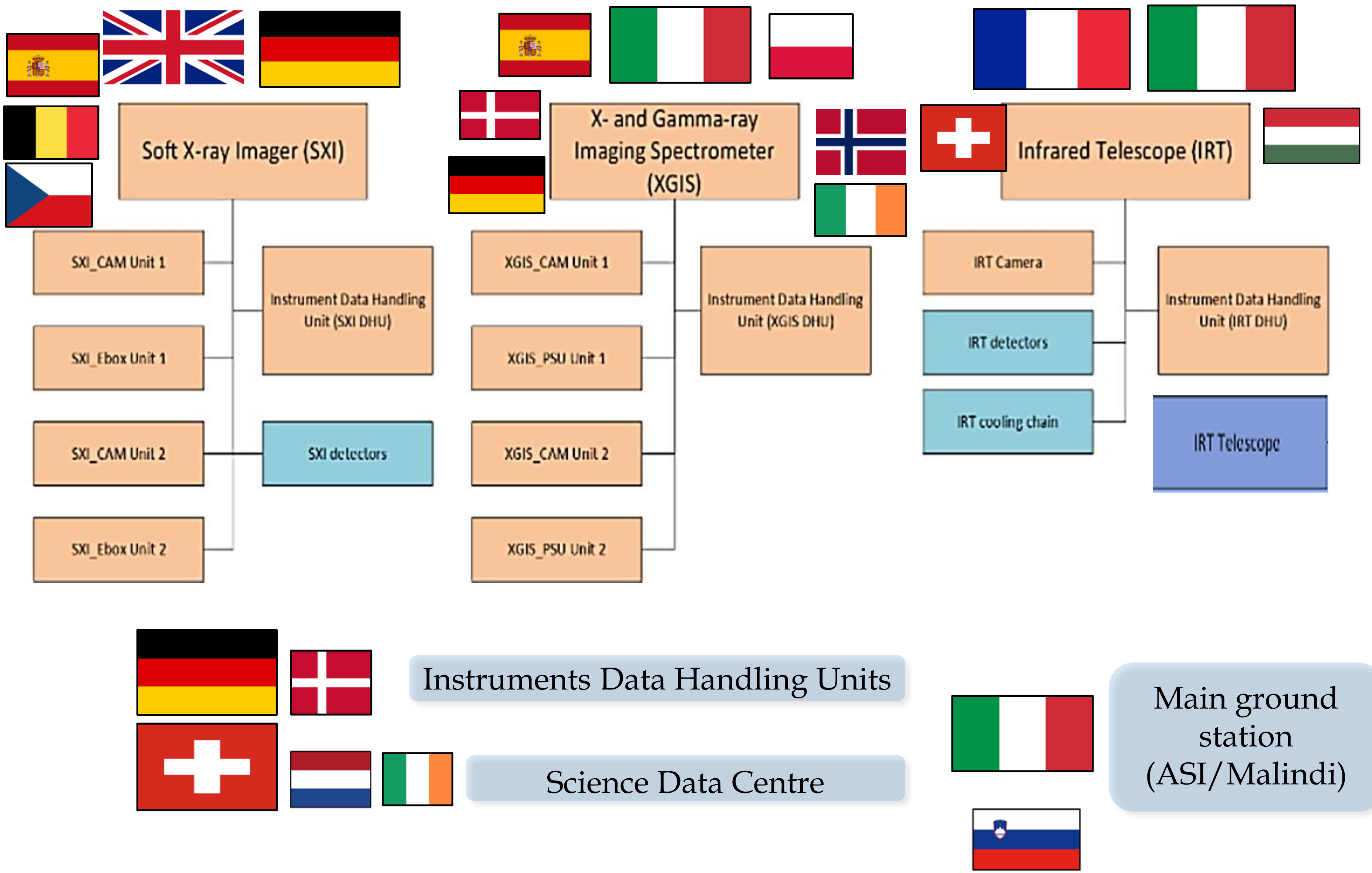
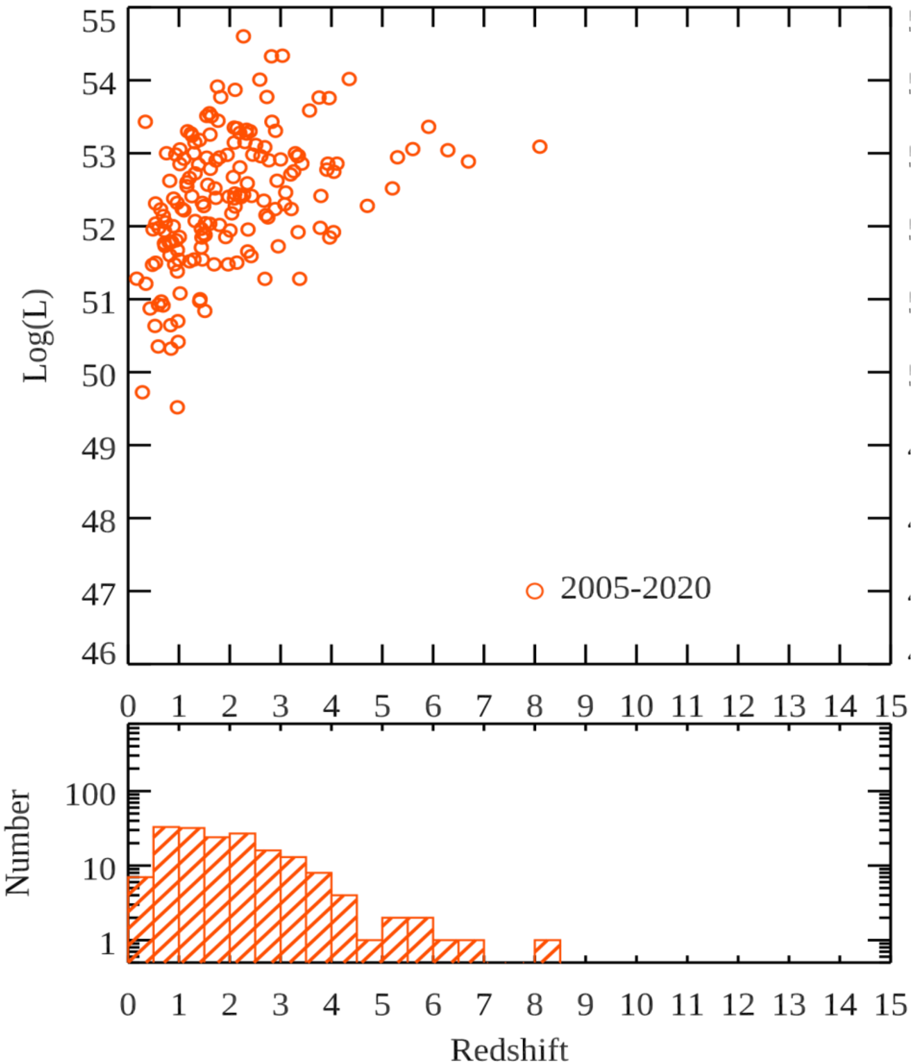


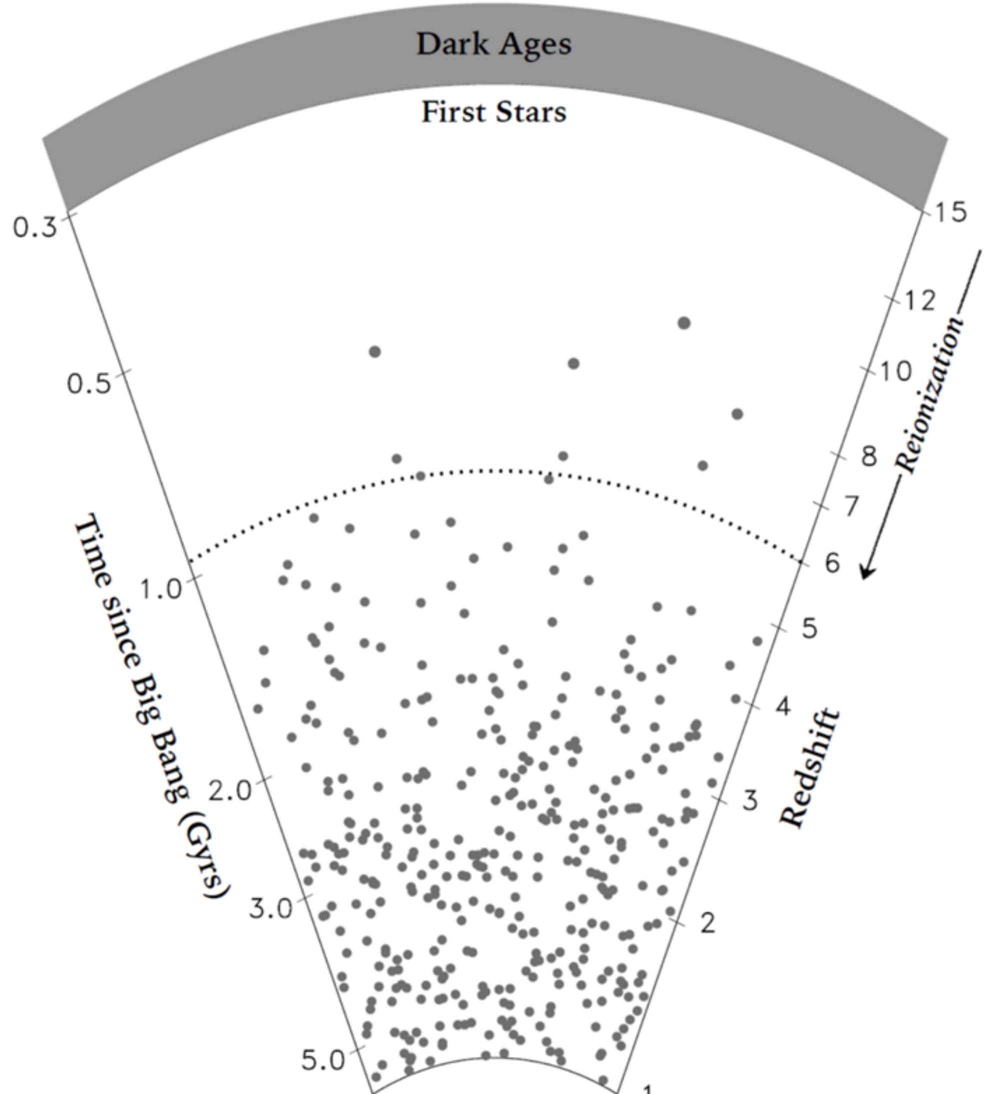
(THALES)

THESEUS payload procurement scheme M7



Expected performances: early Universe





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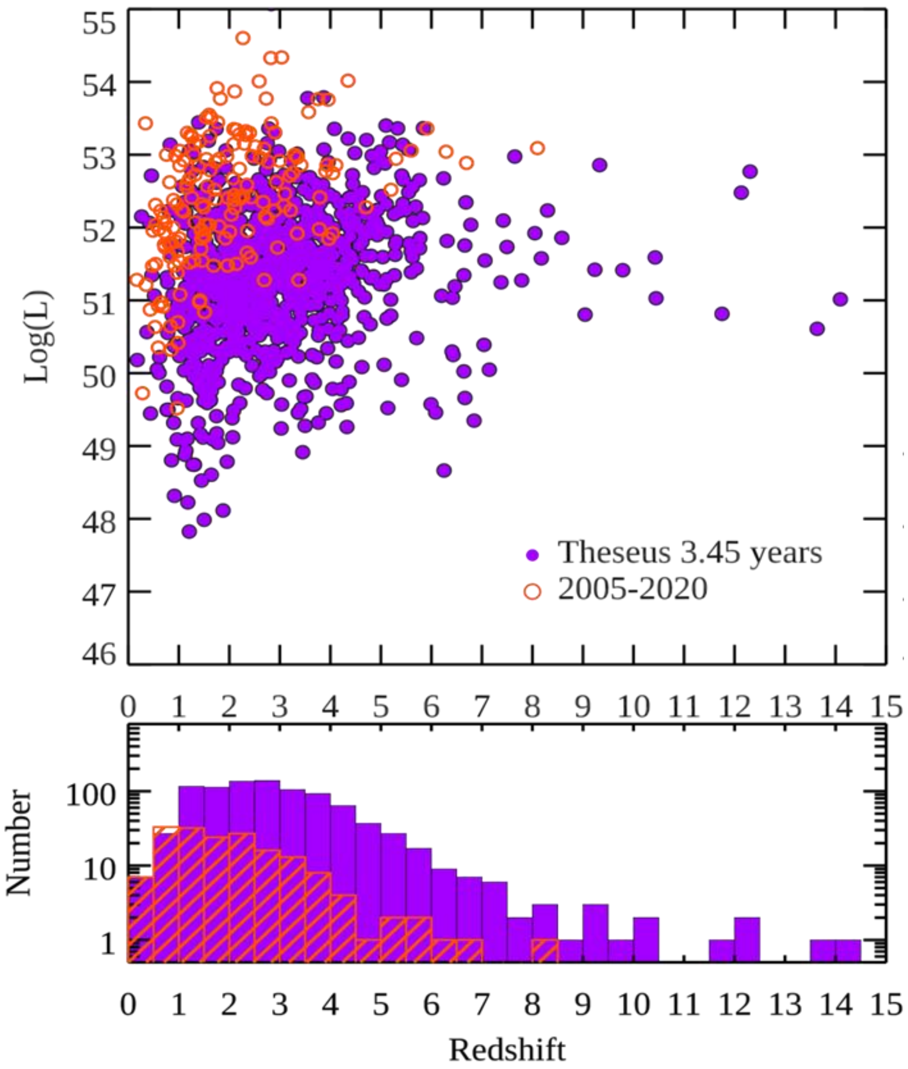
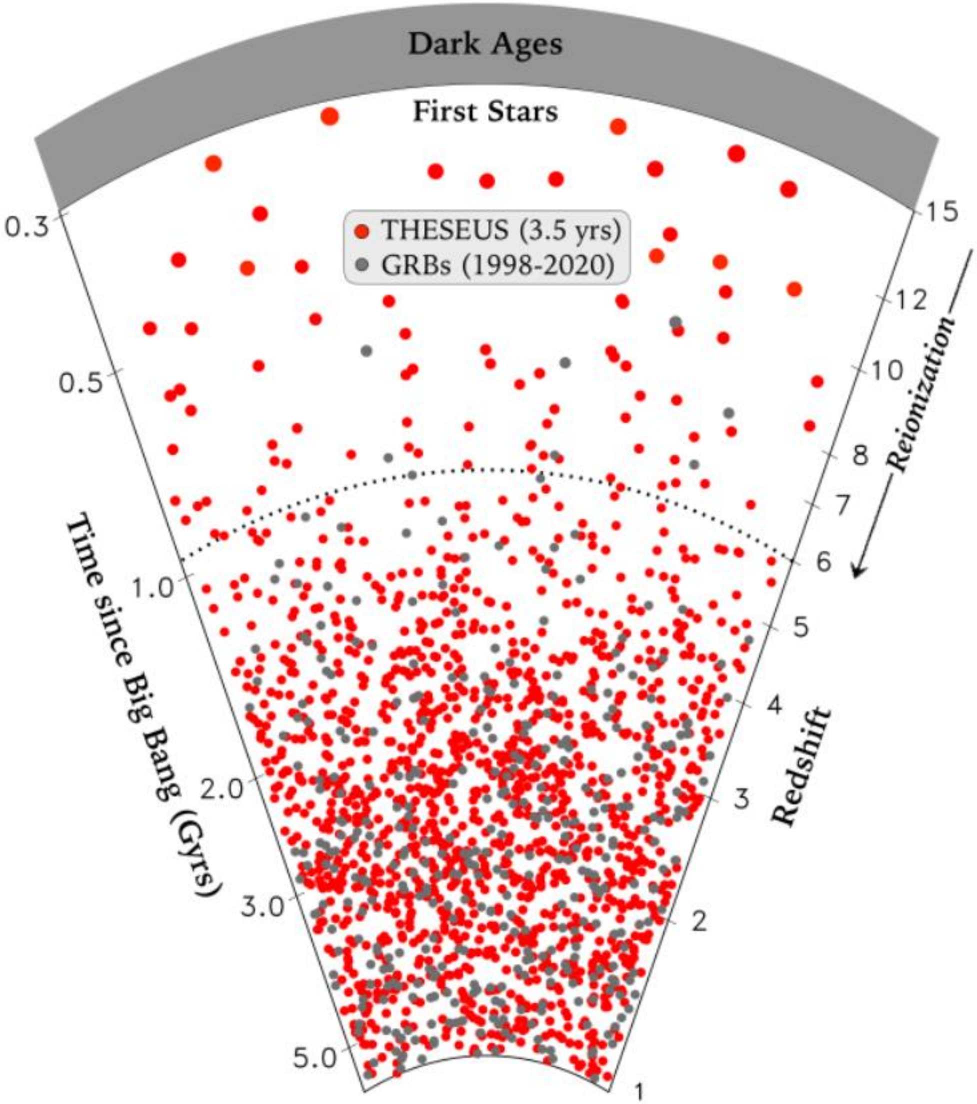
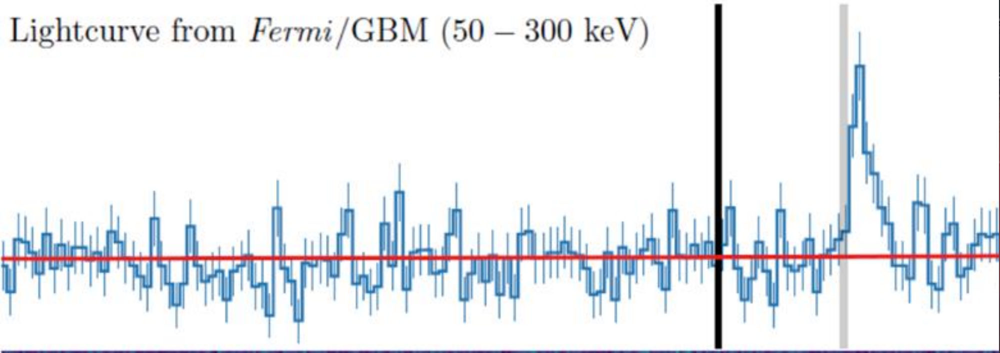


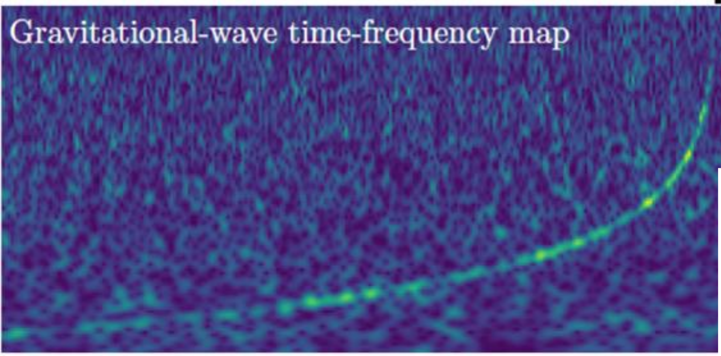


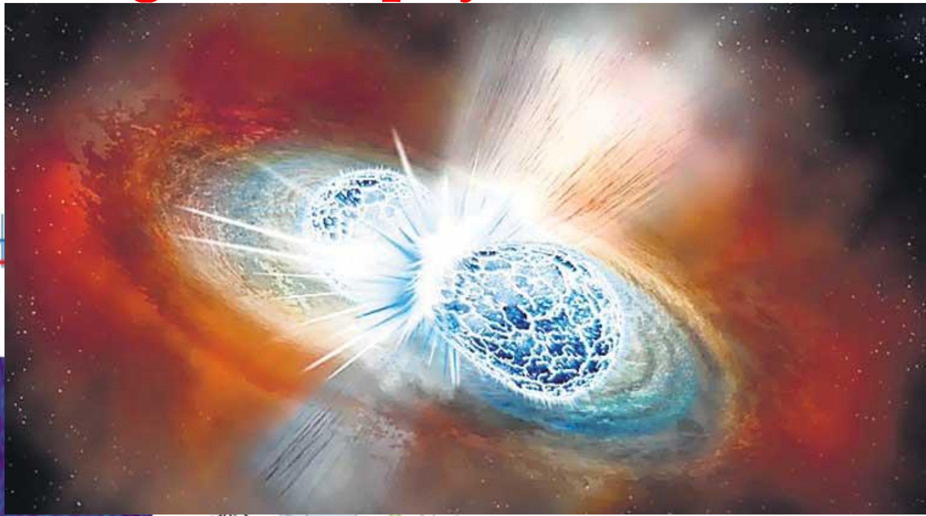
Expected performances: multi-messenger astr.

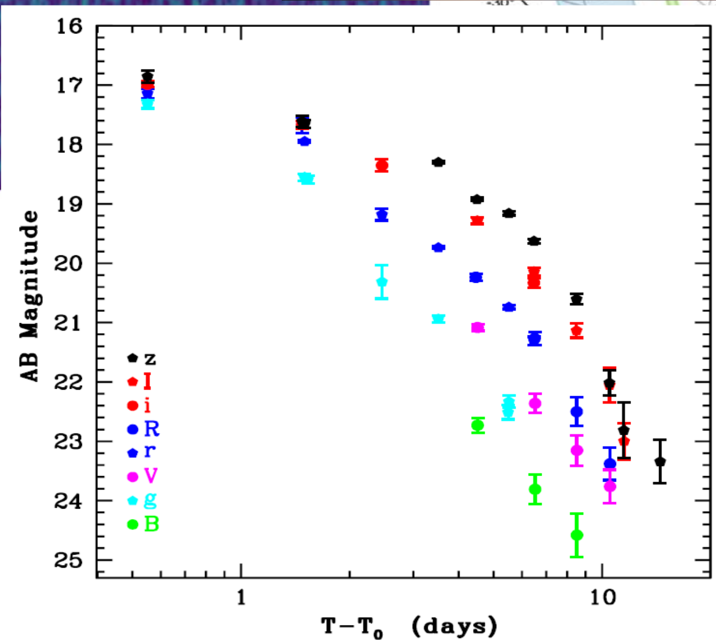
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

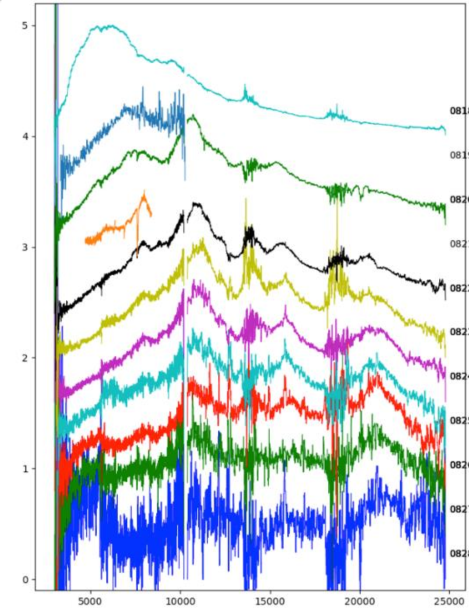
the birth of multi-.messenger astrophysics





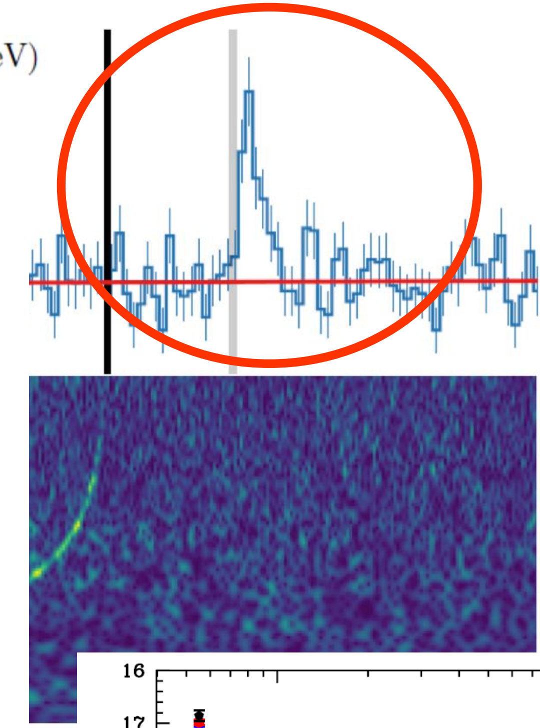






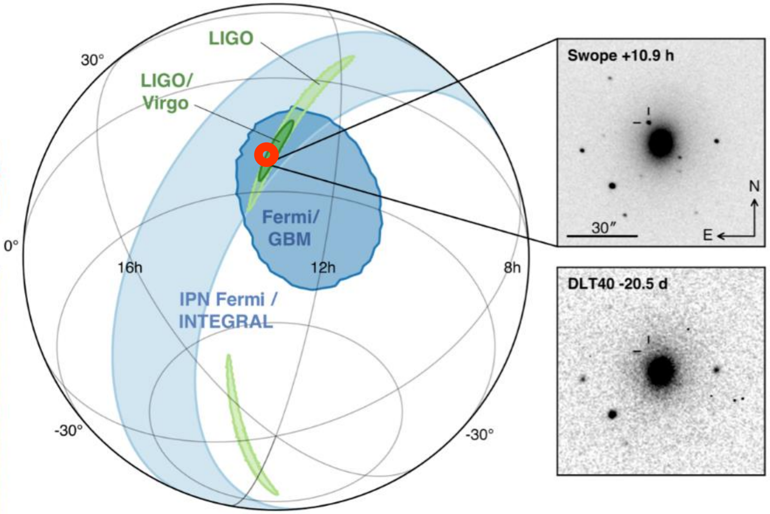
Expected performances: multi-messenger astr.

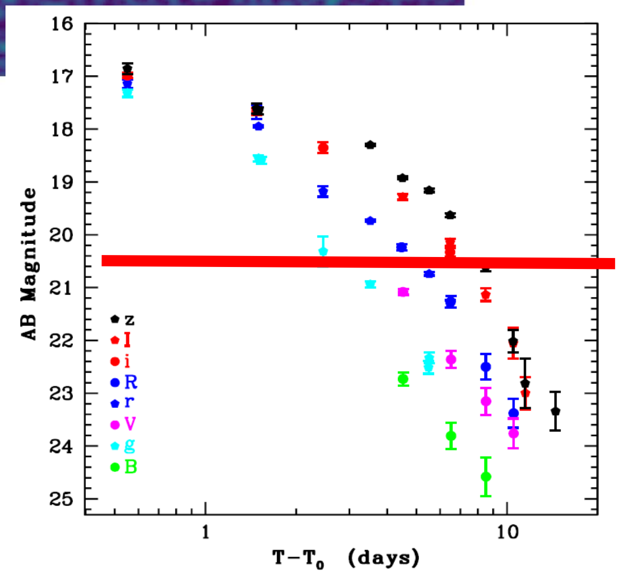
Lightcurve from *Fermi*/GBM (50 – 300 keV)

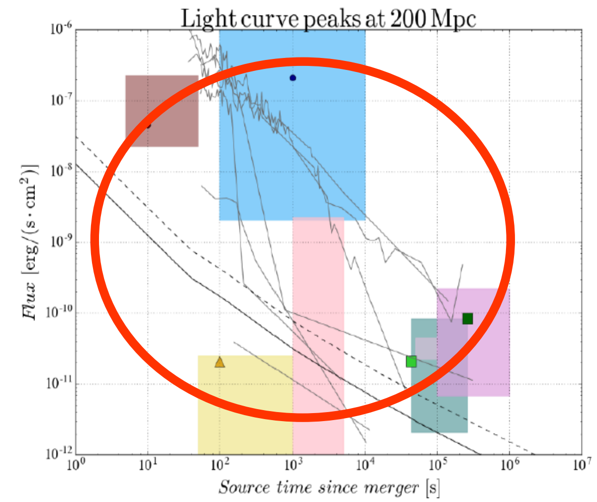


THESEUS:

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

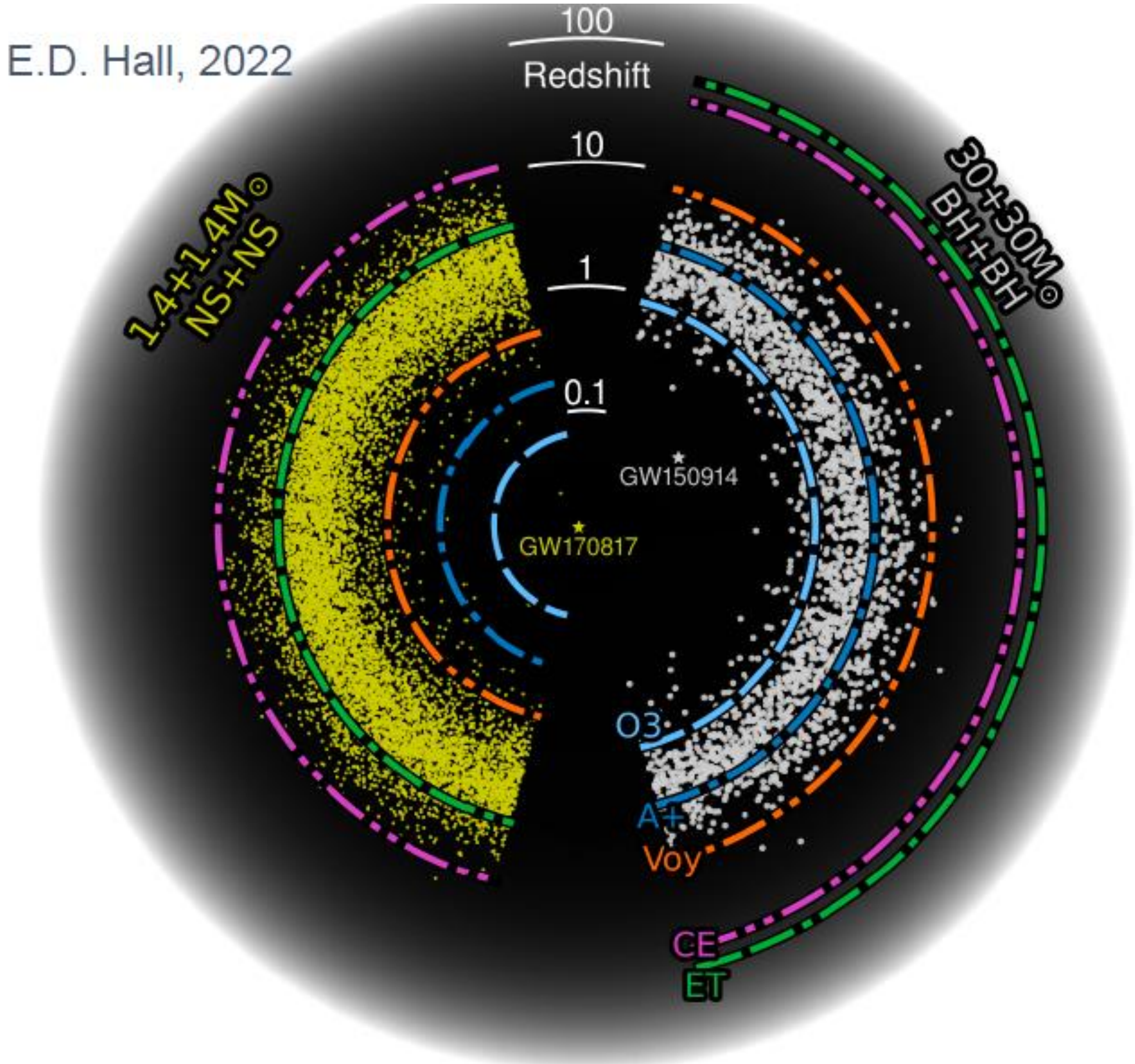






Multi-messenger science with THESEUS

M7 timeline: great synergy with 3G GW detectors (ET, CE)



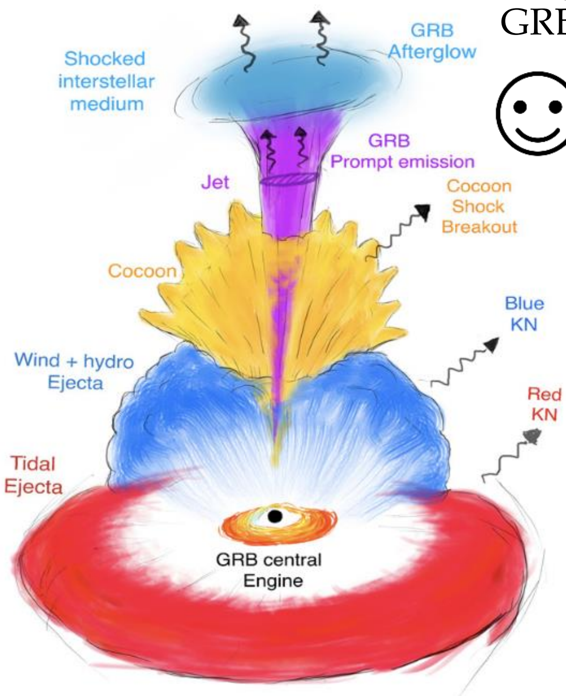
Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A

Aligned GRBs ☺

Misaligned GRBs ☺



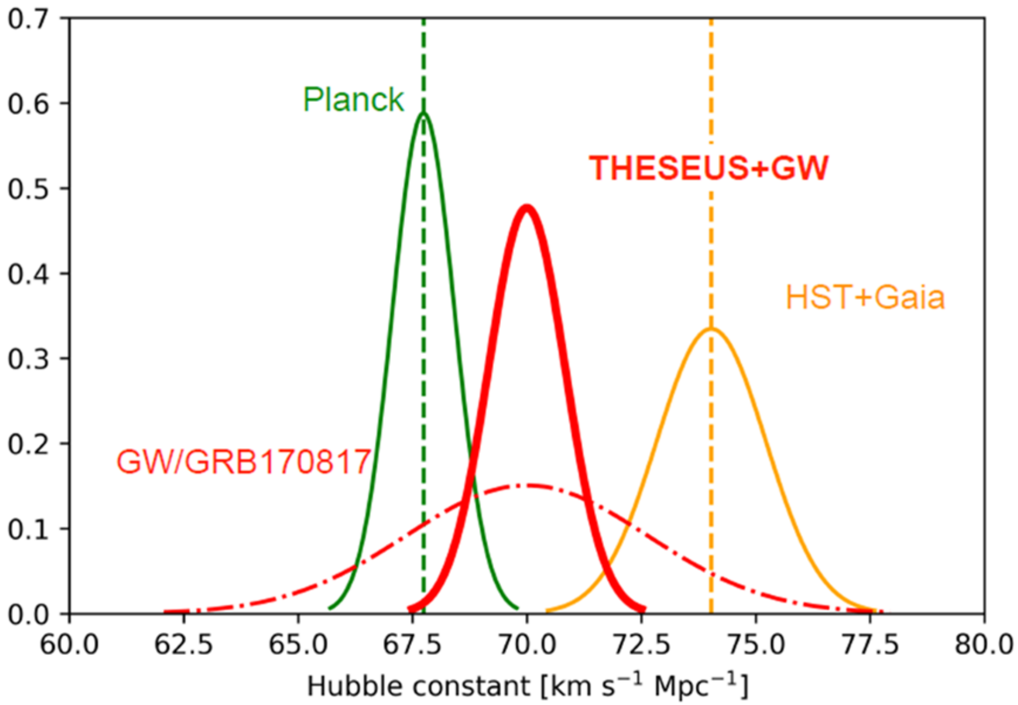
THESEUS + ET in 3 years:

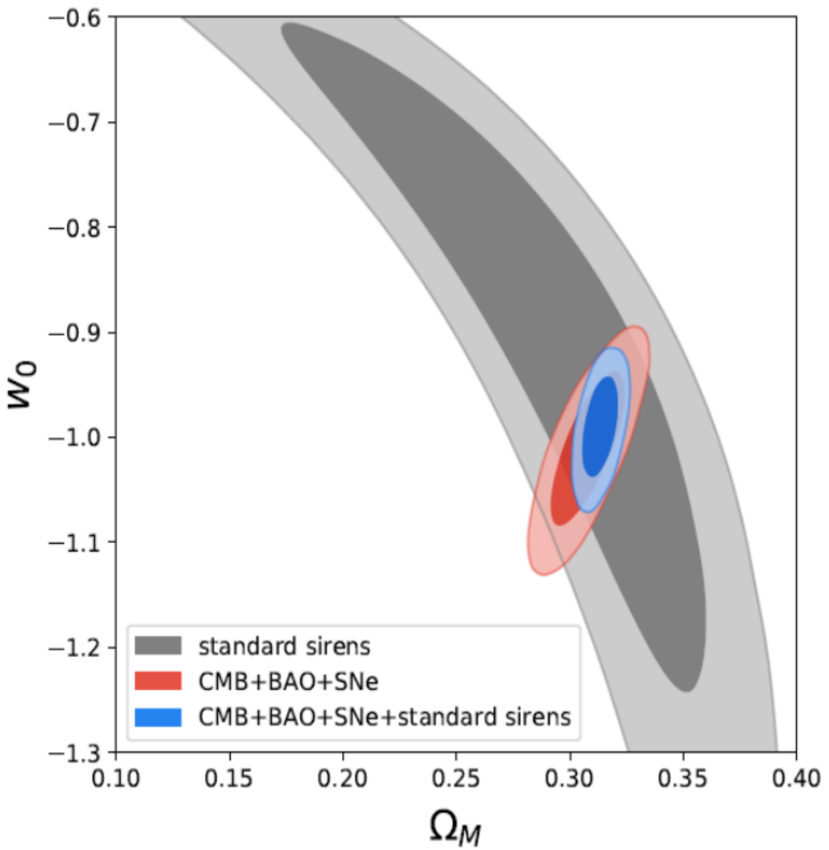
- ~70 aligned+misaligned short GRB
- additional long GRBs from mergers and possible GW-X-ray transients

Higher redshift events – X/γ is likely only route to EM detection: larger statistical studies including source evolution, probe of dark energy and test modified gravity on cosmological scales

Multi-messenger cosmology

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



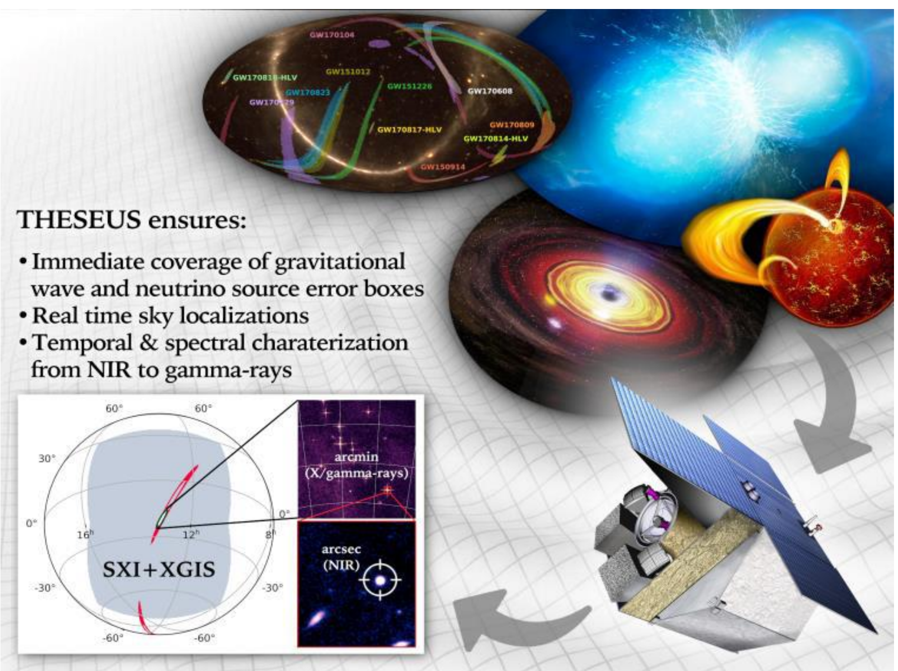


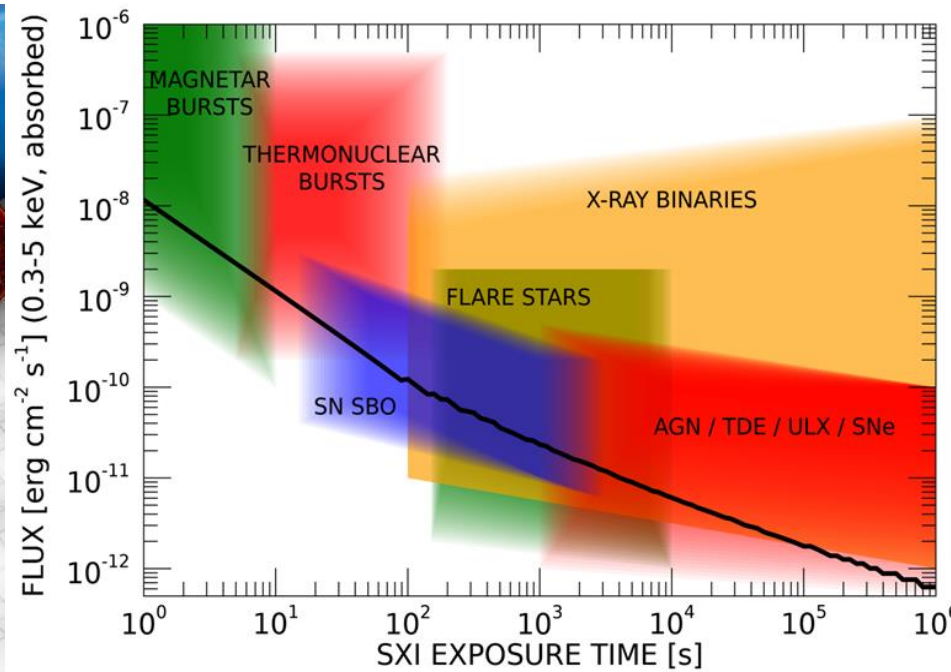
~20 joint GRB+GW events

ET collaboration

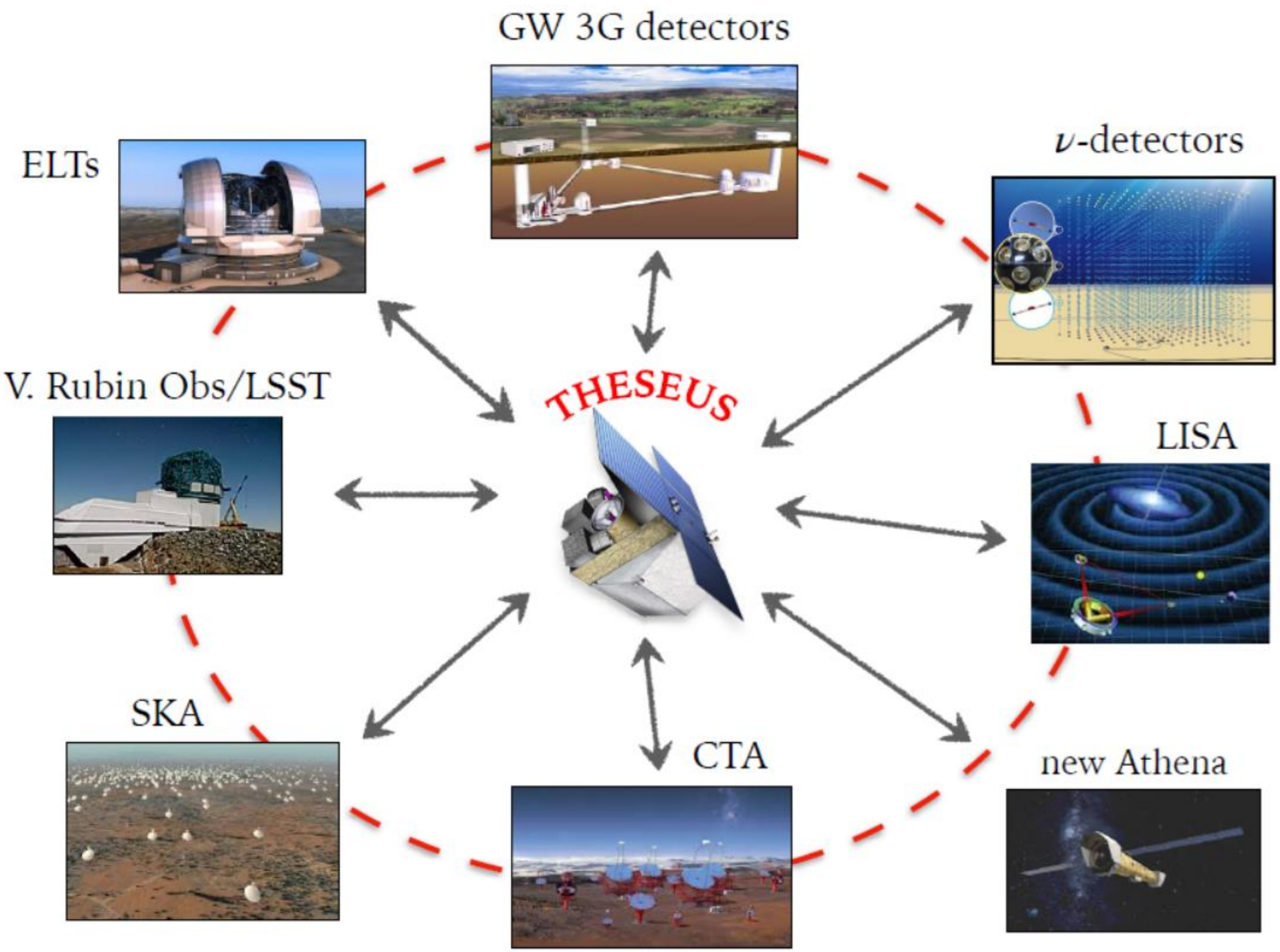
Exploring the transient sky

- **GRBs extreme emission physics**, central engine, sub-classes & progenitors, **cosmological parameters & fundamental physics**
- Study of **many classes of X-ray sources** by exploiting the **simultaneous 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**





THESEUS: crucial synergies in the late '30s



The «**M7**» **timeline** will allow to **widely broaden the mission scientific impact** by taking advantage of the **perfectly matched synergies** with major facilities coming fully operative in the 2030s **(e.g., 3G GW detectors)**

In summary

- GRBs are a key phenomenon for **cosmology**, **multi-messenger astrophysics** and **fundamental physics**

- **THESEUS**, developed by a large European collaboration, studied (M5 Phase A) and re-selected (M7 Phase-0) by ESA **will fully exploit these potentialities and also provide unprecedented clues to GRB physics and a substantial contribution to time-domain astronomy**

- The "M7" timeline will allow an **unprecedented great synergy with future very large observing** facilities in the e.m. and multi messenger domains, **enhancing their scientific return and fully exploiting the European leadership and investments put in them**.

- Because of the wide scope of its science goals, the great synergies and timeline and a **guest-observer programme**, **THESEUS scientific return will involve an unprecedented wide scientific community.**

- **THESEUS: ESA/M5 Phase A study and selected for M7 Phase 0 (->2037)**

SPIE articles on instruments, Adv.Sp.Res. & Exp.Astr. articles on science

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

Back-up slides

Mass budget	CBE with DM [kg]	Mass fraction (dry) [%]
Payload	**340**	**21%**
SXI instrument	75.8	5%
IRT	38.4	2%
XGIS	186.1	12%
Payload level system margin (10%)	30.9	2%
IRT telescope	**221**	**14%**
Platform	**1022**	**65%**
NGRM (Next Generation Radiation Monitor)	3.8	0%
Structure (SVM and PLM)	505.4	32%
Thermal control incl. instruments TCS	122.6	8%
Data handling	20.3	1%
Communications	28.3	2%
Propulsion	71.0	4%
Power	112.2	7%
AOCS	61.5	4%
Harness	97.3	6%
THESEUS (dry mass)	**1575**	**100%**
System margin (20%)	**315**	
Satellite (dry mass incl. system margin)	**1900**	
Propellant (incl. 2% residuals)	**290.0**	
Satellite (wet mass)	**2190**	

Power budget	CBE (Sci+TTC) [W]	Fraction [%]
Instruments	426.8	34%
Cryo-coolers	150.0	12%
IRT telescope TCS	80.0	6%
Sub-system Thermal (SVM and PLM)	70.0	6%
Communications	138.0	11%
Data handling	82.0	7%
Propulsion	1.0	0%
Data handling	82.0	7%
Power (incl. losses)	100.0	8%
AOCS	126.0	10%
Consumed power including DMM	**1256**	**100%**
System margin (30%)	376.7	
Consumed power including SM	**1633**	

Table 17: Instruments TM summary

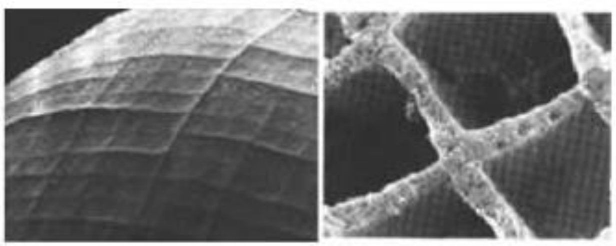
Instrument Suite	TM load (Gbit/orbit)
SXI	0.3
XGIS	2.4
IRT	2.2
Total P/L telemetry	4.5

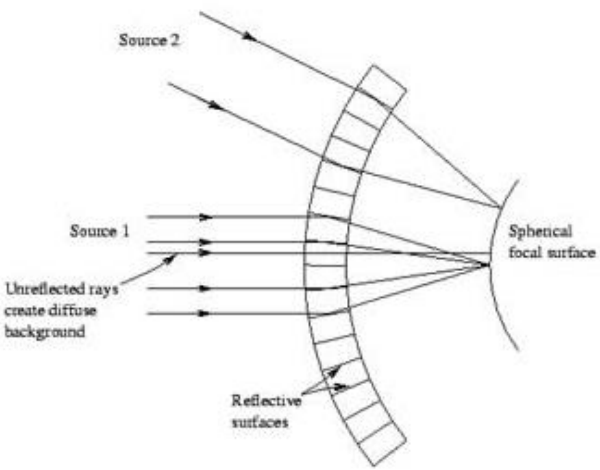
Table 18: Summary of Instrument Suite temperatures

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

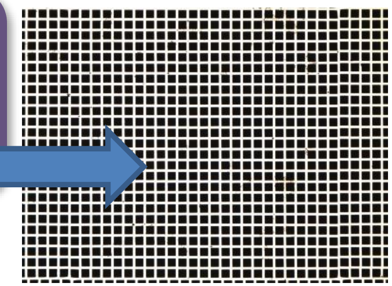
The Soft X-Ray Imager (SXI)

Two sensitive "lobster-eye" X-ray telescopes (0.3 - 5 keV); total FOV of 0.5sr (>1000 × conventional X-ray telescopes); 100ms photon timing; source location accuracy <2′



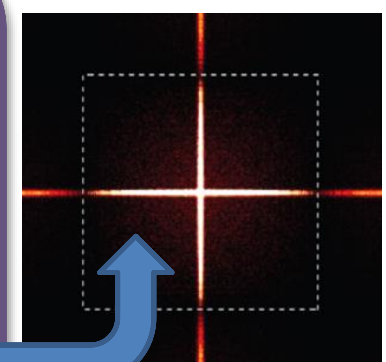


Mimic a lobster-eye using curved, square-pore MPOs



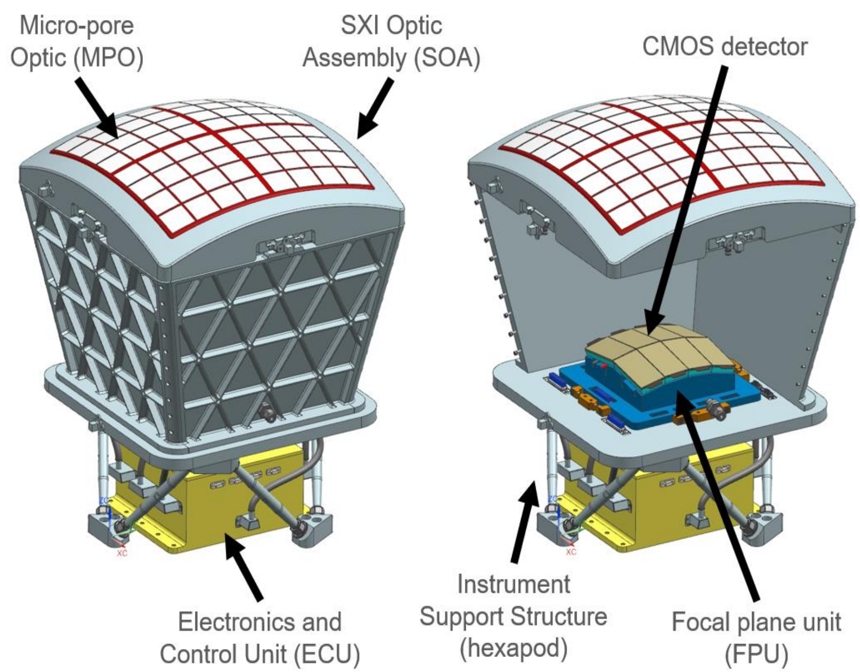
No single optical axis: get a wide field of view plus focusing with constant effective area

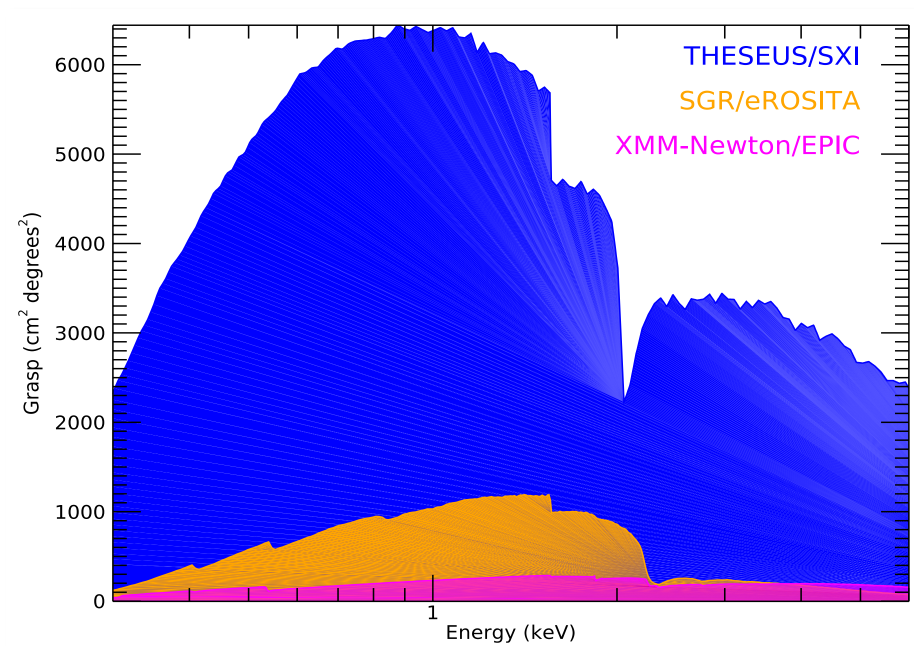
Spot (double reflection)
Lines (single reflections)



The Soft X-Ray Imager (SXI)

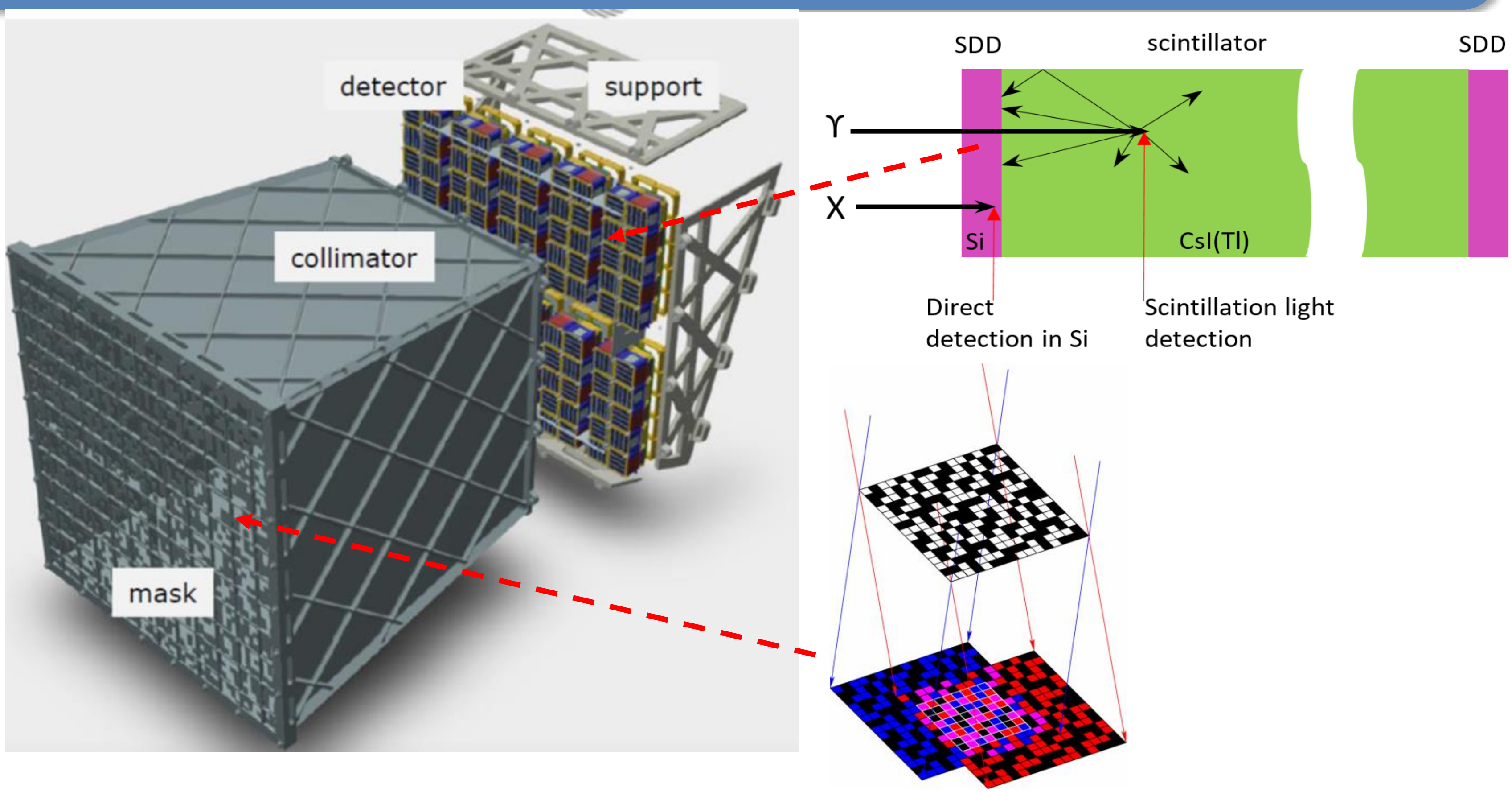
SXI will show a unique combination of FOV and effective area (GRASP), enabling simulatneous detection and localization of many transients in parallel.





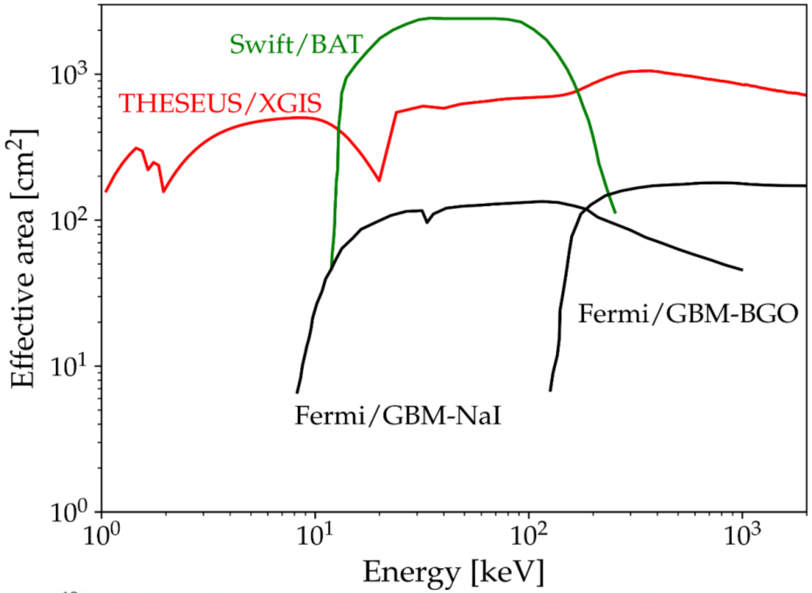
The X-Gamma Ray Imaging Spectrometer (XGIS)

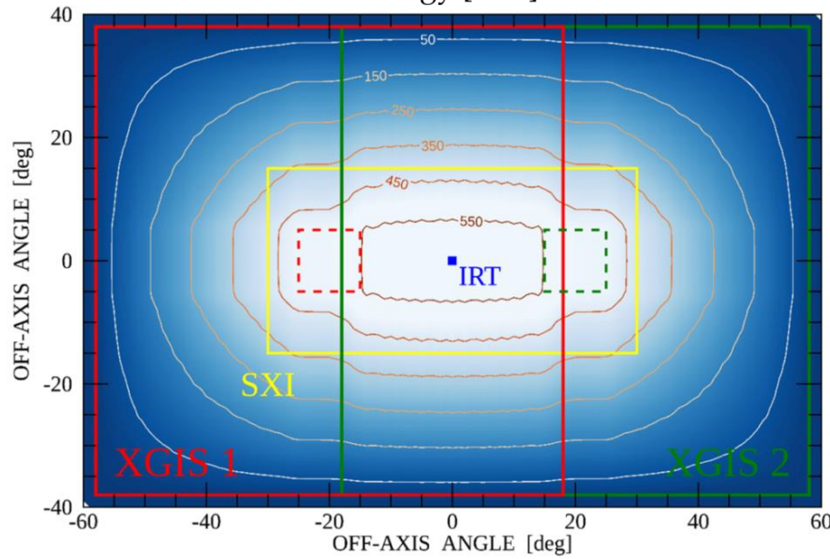
Two coded-mask X-gamma ray cameras using innovative coupling between Silicon drift detectors (2-30 keV) and CsI crystal scintillator bars (20 keV–10 MeV)



The X-Gamma Ray Imaging Spectrometer (XGIS)

- Unprecedented energy band (2 keV – 10 MeV)
- Large effective area down to 2 keV
- FOV >2 sr overlapping the SXI one
- GRB location accuracy <15′ in 2-150 keV
- Excellent timing (< a few μs)

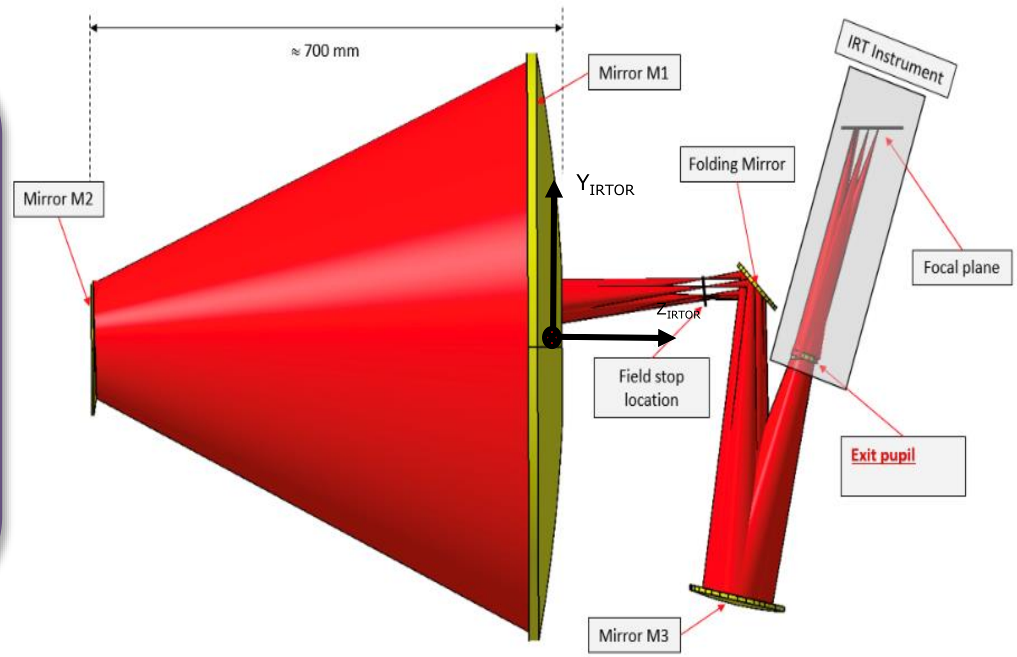




The Infra-Red Telescope (IRT)

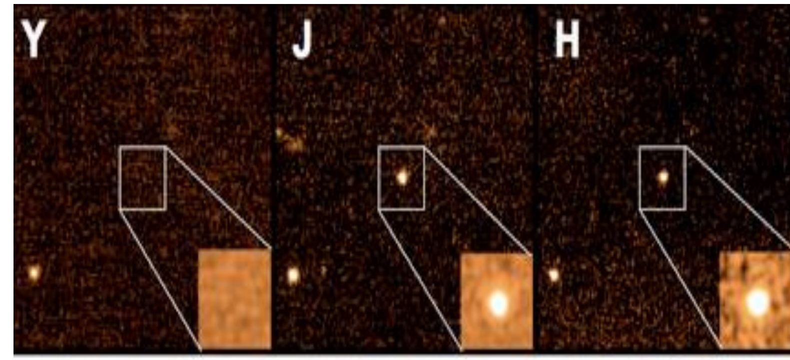
A 0.7 m class telescope with an off-axis Korsch optical design allowing for a large field of view (15′x15′) with imaging and moderate (R~400) spectroscopic capabilities

Teledyne H2RG sensitive in 0.7-1.8 microns
Expected sensitivity per filter (over 150 s): 20.9 (I), 20.7 (Z), 20.4 (Y), 21.1 (J), 21.1(H).
Spectral sensitivity limit (over 1800 s), about 17.5 (H) over the 0.8-1.6 microns

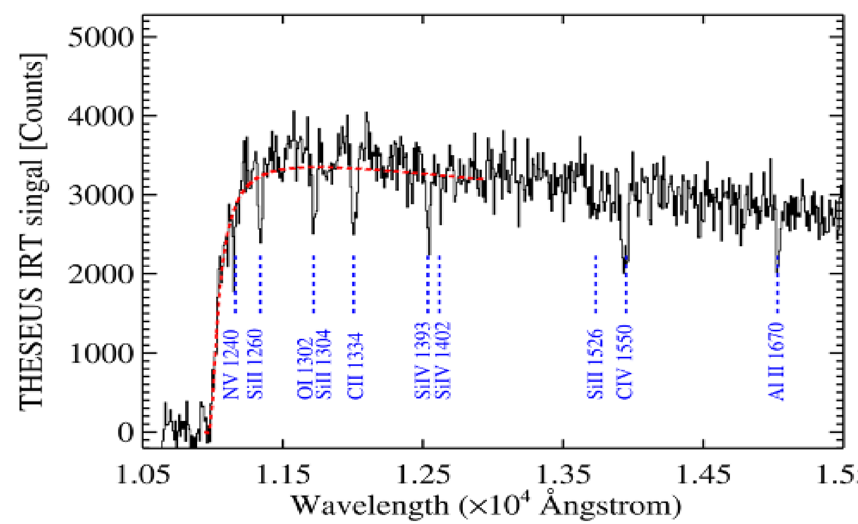


The Infra-Red Telescope (IRT)

On-board photometric redshift for >90% detected GRB afterglows



On-board sensitive absorption spectrosocpy for medium-bright events



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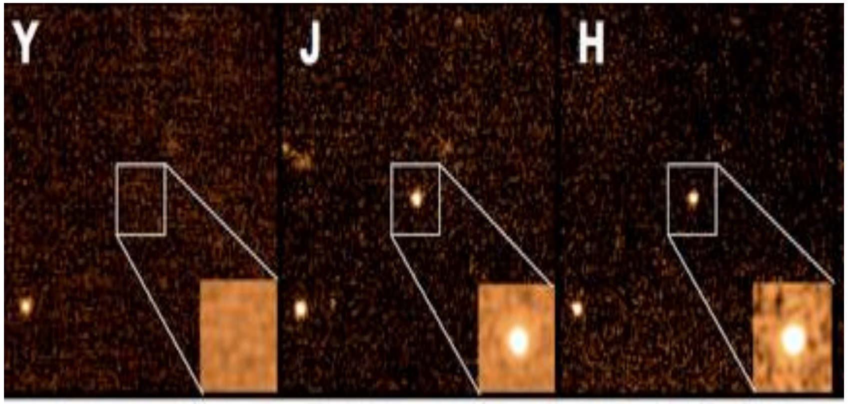
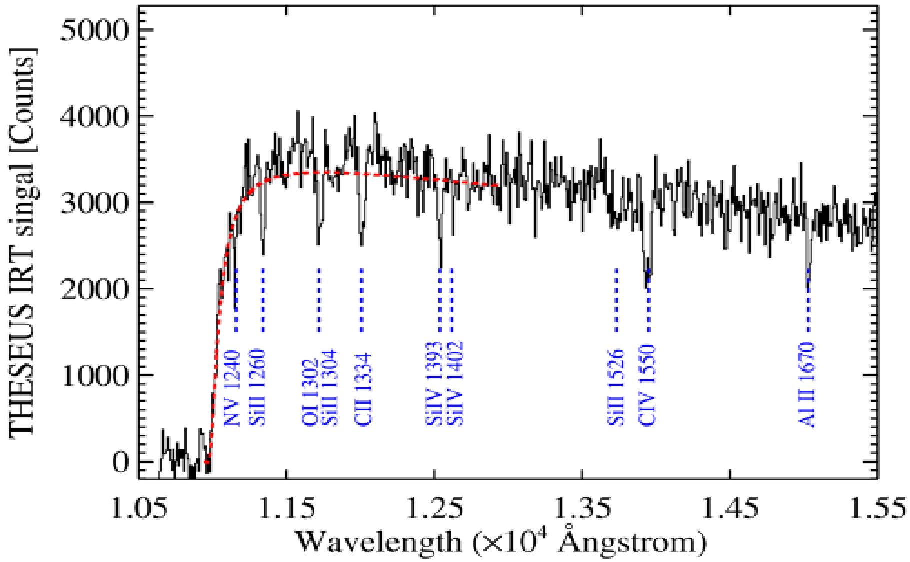
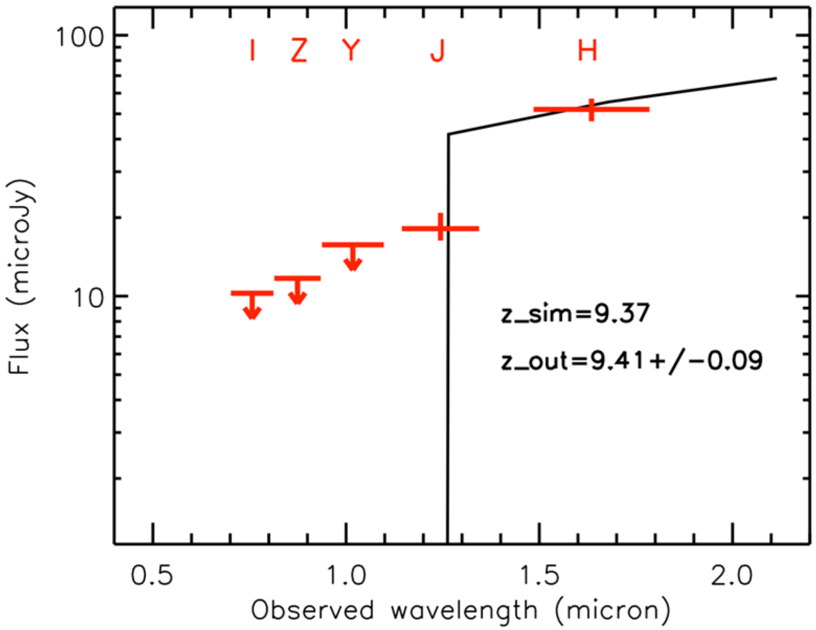
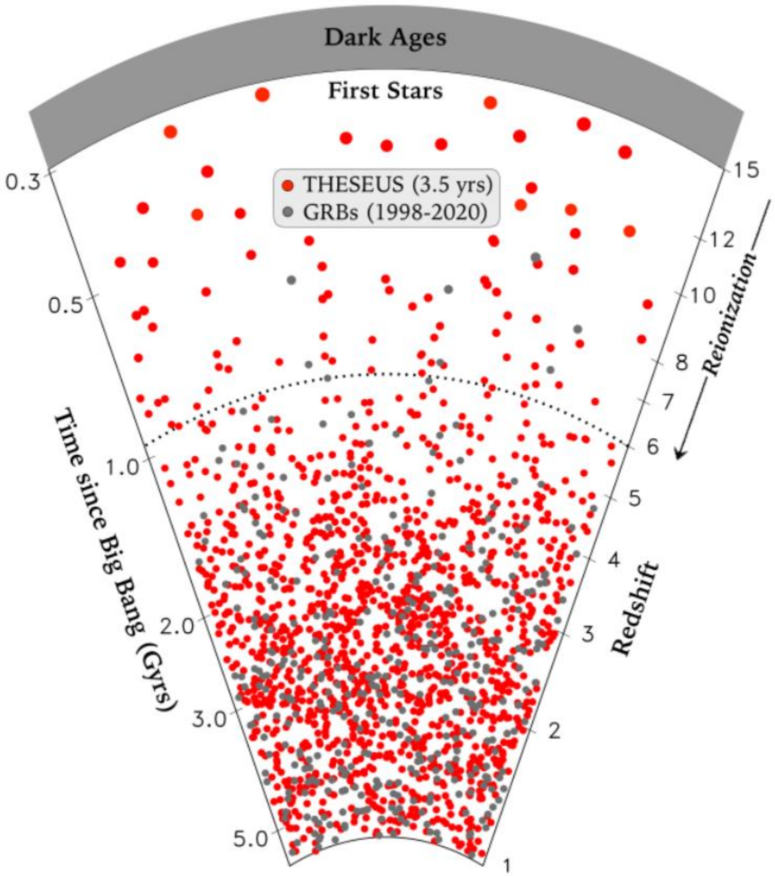


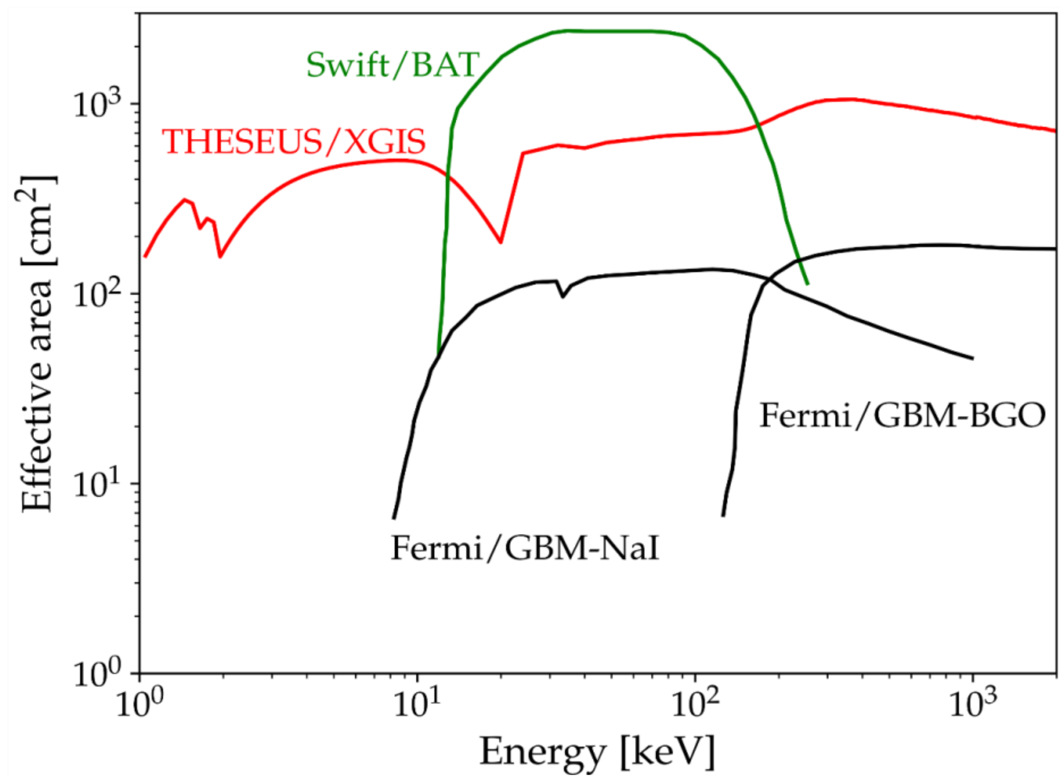




GRBs extreme and fundamental physics

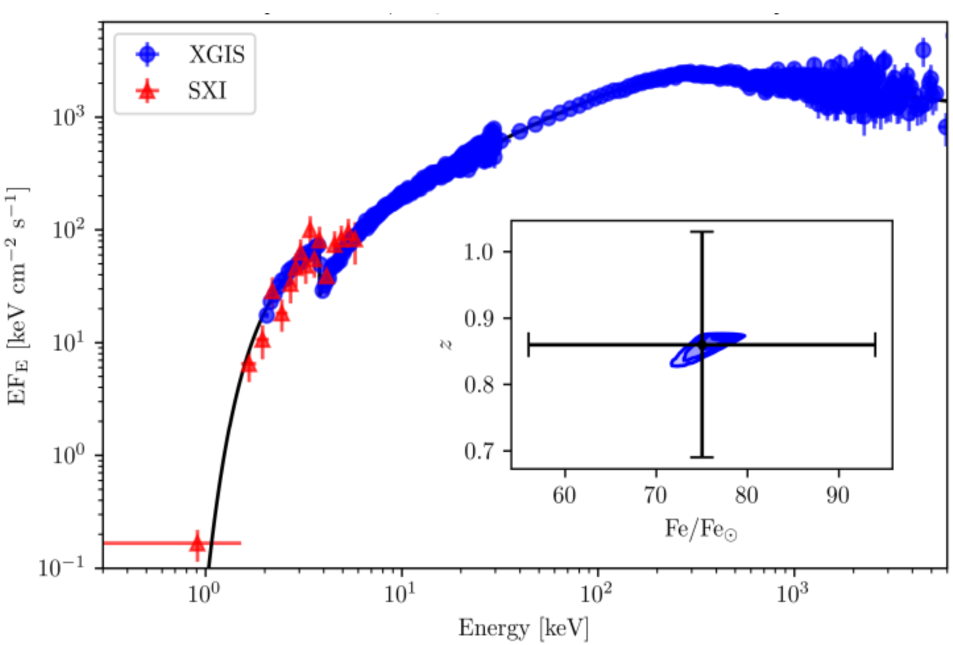
- THESEUS will measure the prompt and early afterglow emission of thousand GRBs over an unprecedented huge energy band (0.3 keV – 10 MeV) with great sensitivity, timing and spectroscopic capabilities, plus NR afterglow and redshift measurement

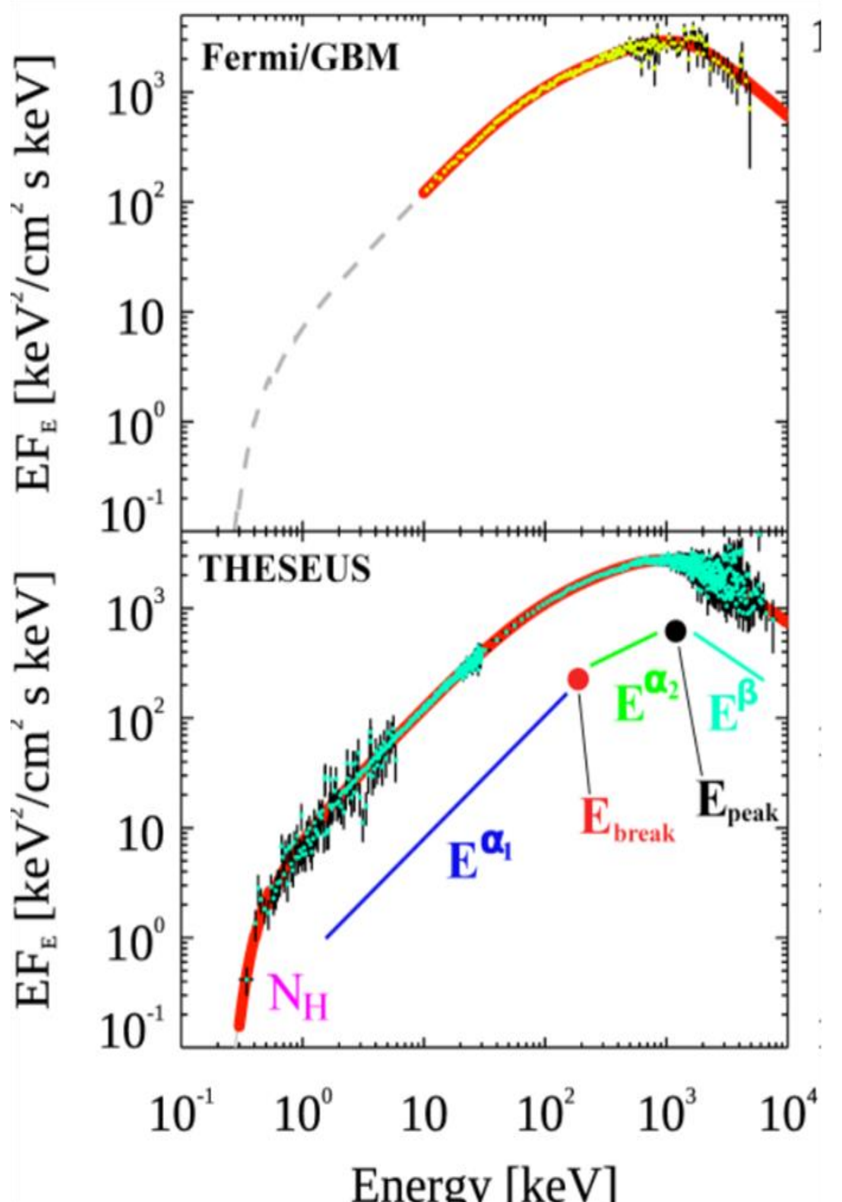




GRBs extreme and fundamental physics

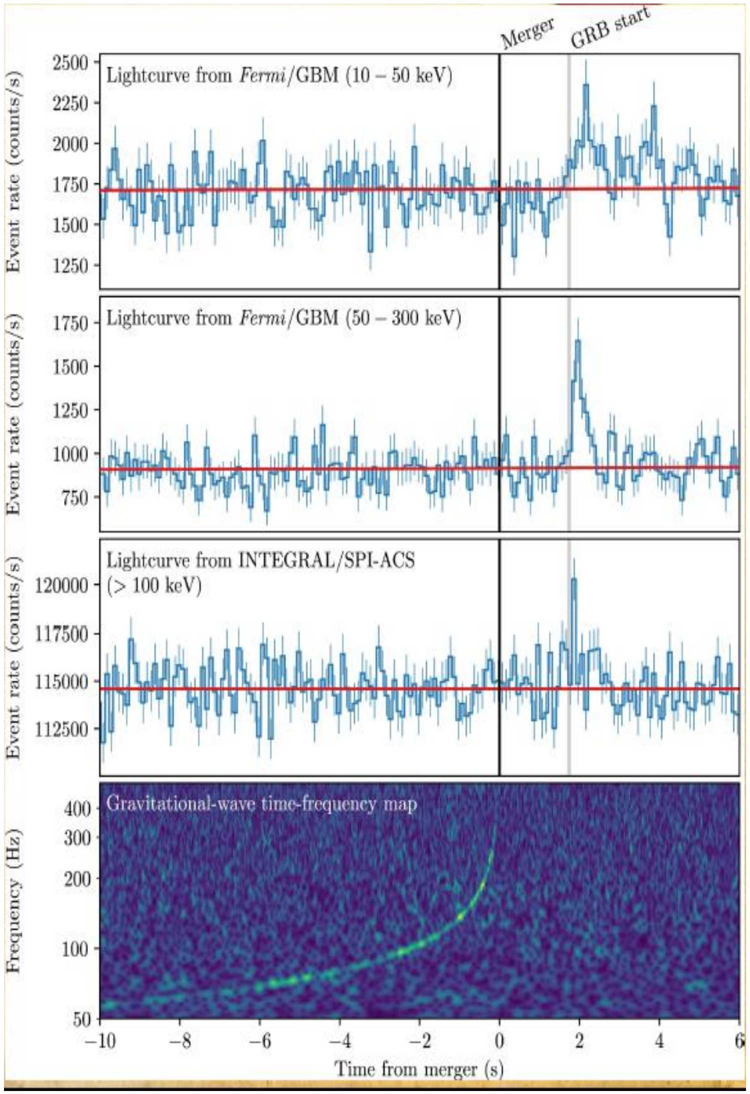
- Extreme prompt emission physics & jet structure
- Central engine, sub-classes & progenitors,
- Cosmological parameters & fundamental physics





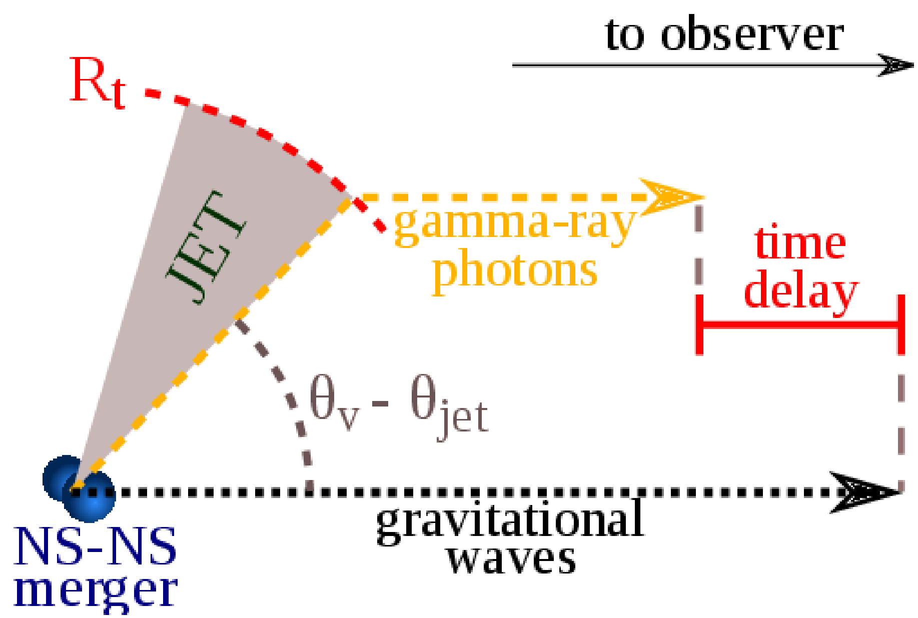
Fundamental physics: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

$|V_{gw} - C| / C < 10^{-16}$



$$\Delta t = (\Delta t_{\rm jet} + \Delta t_{\rm bo} + \Delta t_{\rm GRB})(1 + z)$$

$$\Delta t_{\rm GRB} \simeq (1 - \beta \cos\theta)\frac{R_{\rm GRB}}{c} \simeq \frac{R_{\rm GRB}}{\Gamma^2 c}$$

Fundamental physics: testing LI / QG

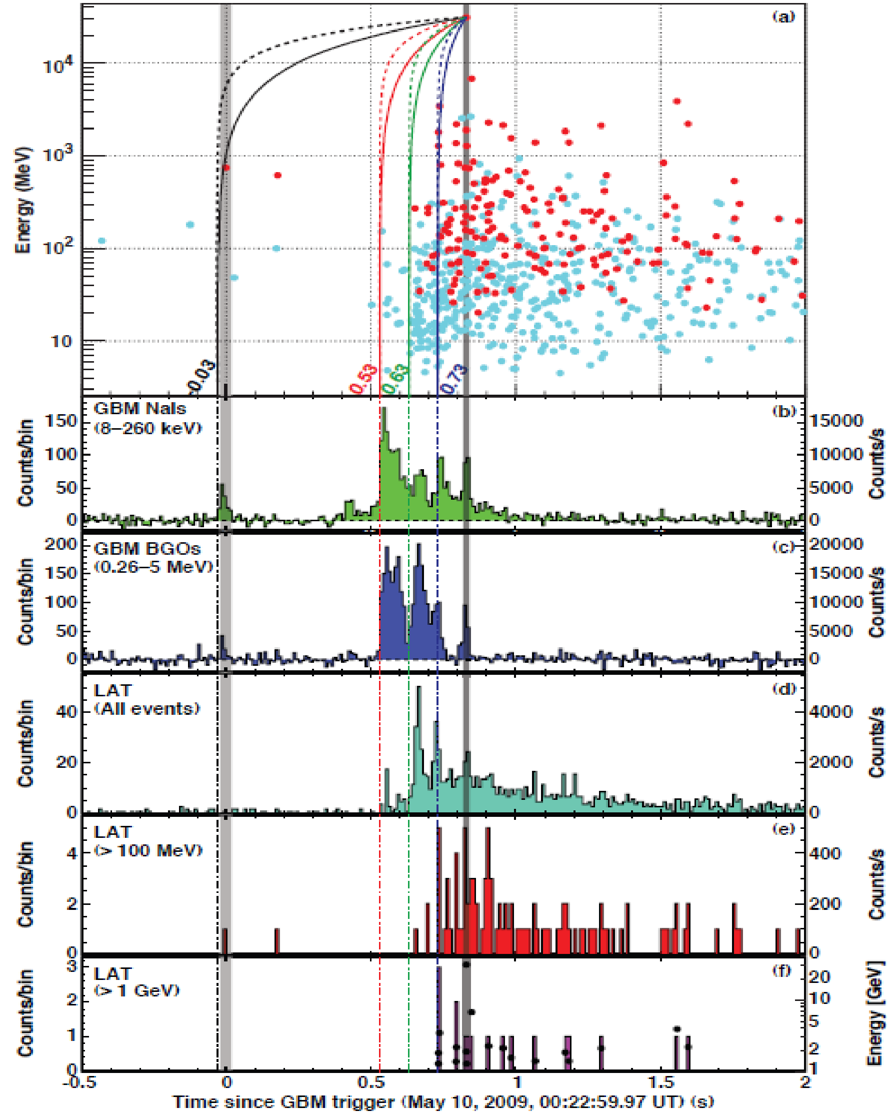
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

$$v_{\rm ph} = \frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c\left[1 - s_n \frac{n+1}{2}\left(\frac{E_{\rm ph}}{M_{{\rm QG},n}c^2}\right)^n\right]$$

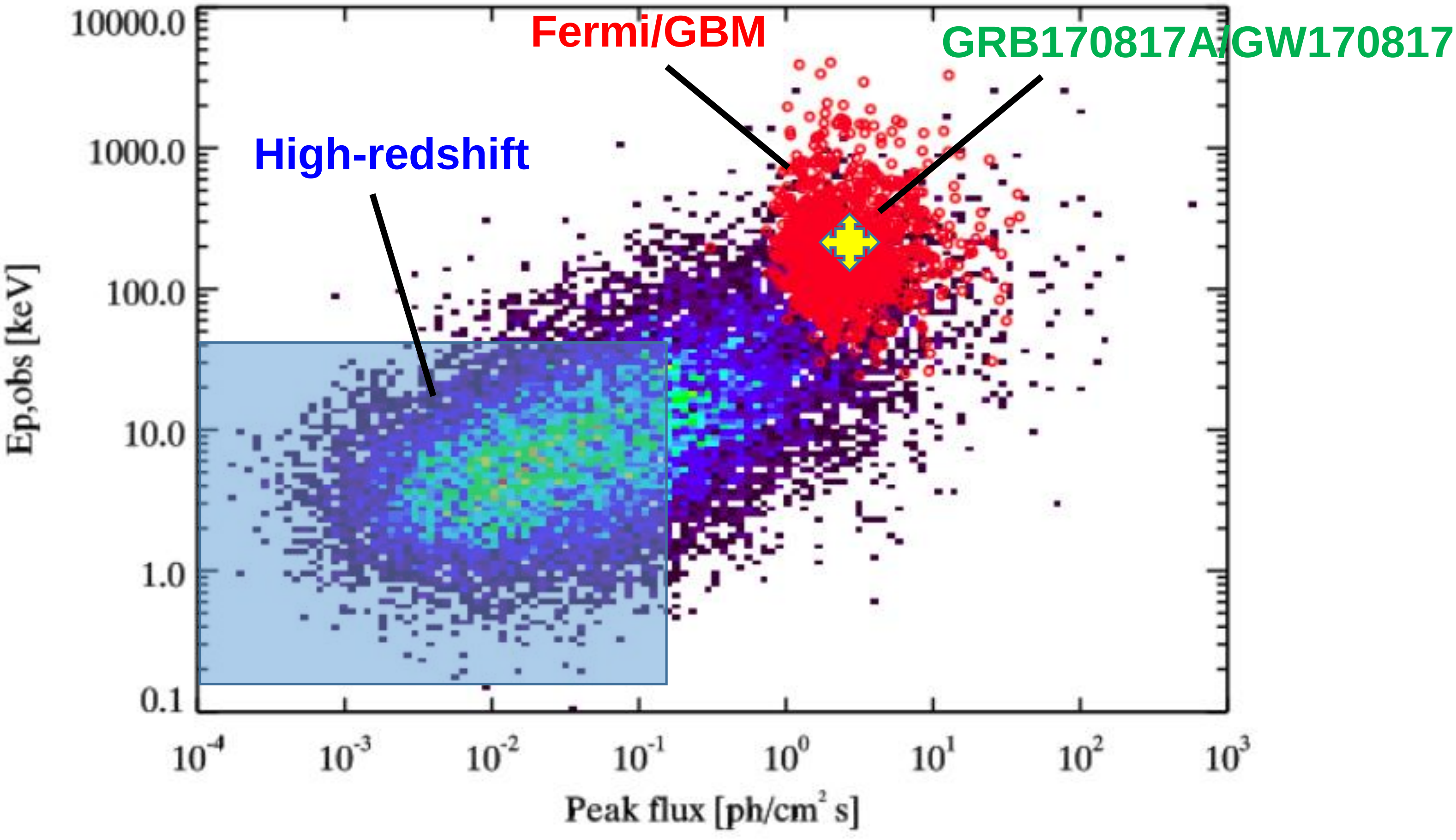
$$\Delta t = s_n \frac{(1+n)}{2H_0}\frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{{\rm QG},1}/M_{\rm Planck}$
−30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	±1	> 102
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	±1	> 1.33
$\left\lvert\frac{\Delta t}{\Delta E}\right\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22



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



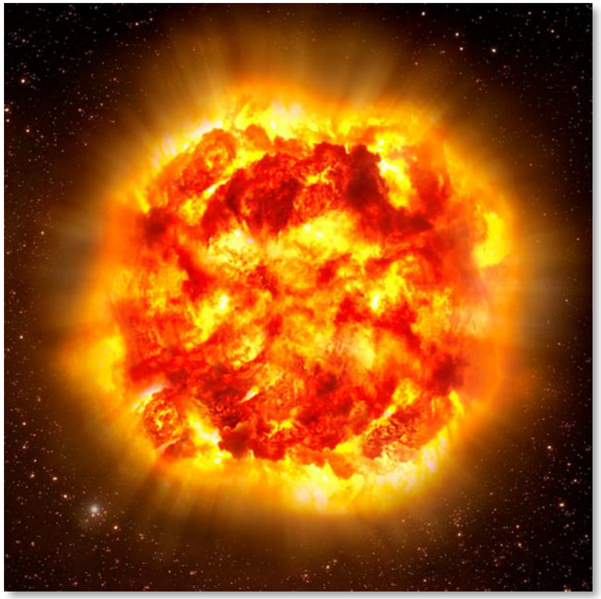
Multi-messenger science with THESEUS

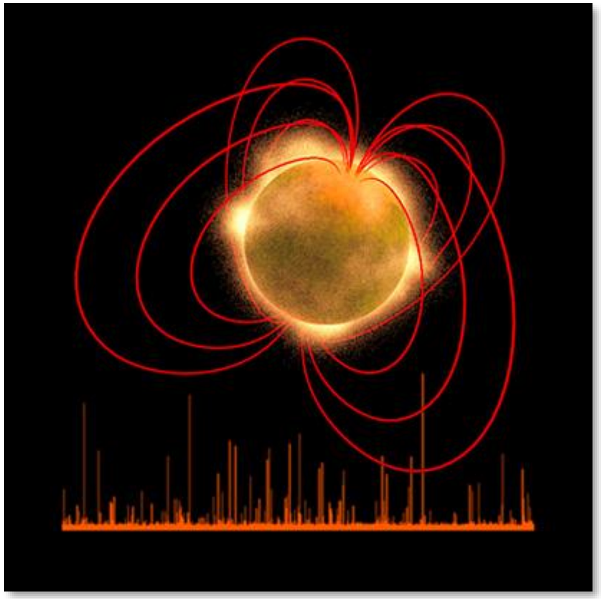
THESEUS & 3G SCIENCE

Main topics	THESEUS role	What will we learn?
Physics of compact binaries	short GRB+GW detection and localization	**relativistic jet formation mechanism/efficiency, remnant nature, NS EoS**
Relativistic plasma	accurate sky coordinates of GW events associated with misaligned afterglows	**Jet propagation, jet structure and its universality, NSBH vs NSNS**
Physics of kilonova	accurate sky coordinates of GW events	**Role of NS-NS/NSBH in r-process element nucleosynthesis**
Fundamental physics	Identify counterparts for events at z>0.3	**Tests of modified gravity theories**
Cosmology	accurate sky coordinates of GW events allowing redshift measurement	**Independent H_0 measure**

Multi-messenger science with THESEUS

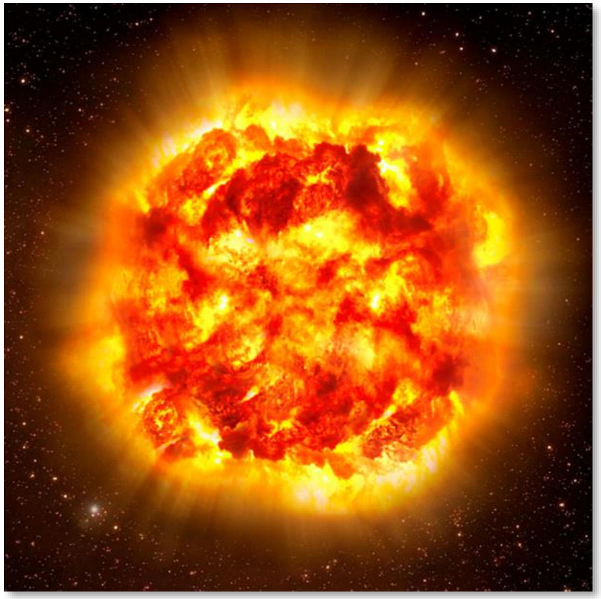
- **Short GRBs**
- Core-collapse stars
- Soft Gamma-ray Repeaters
- Unexpected transients…

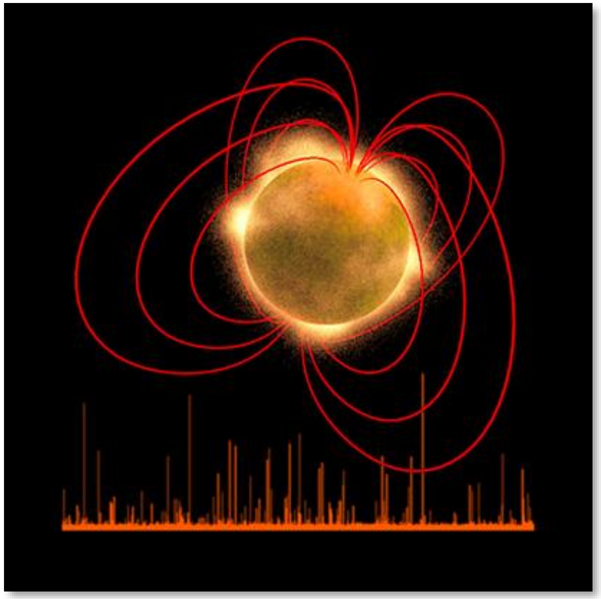


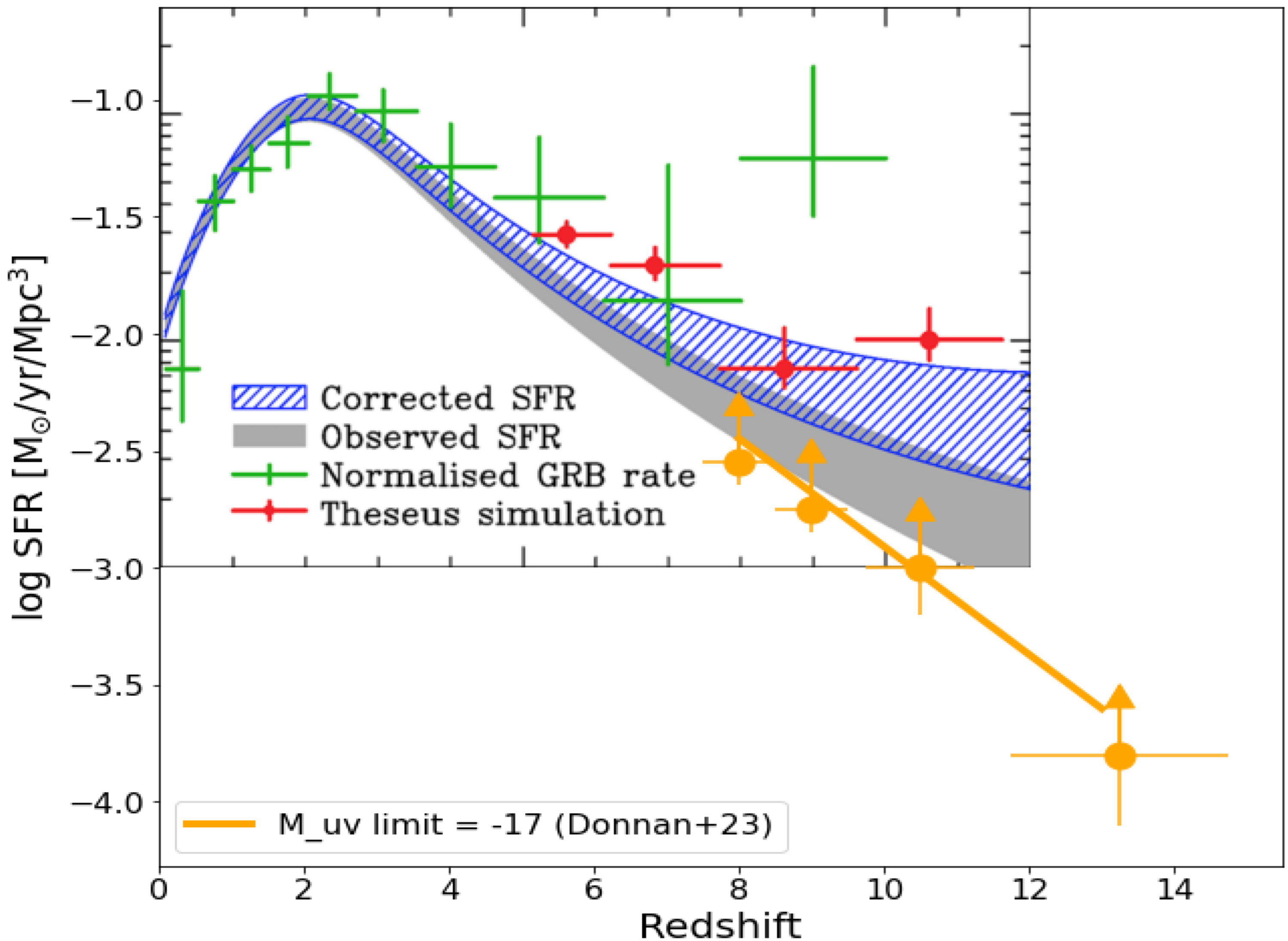


Multi-messenger science with THESEUS

- **Short GRBs**
- Core-collapse stars
- Soft Gamma-ray Repeaters
- Unexpected transients…



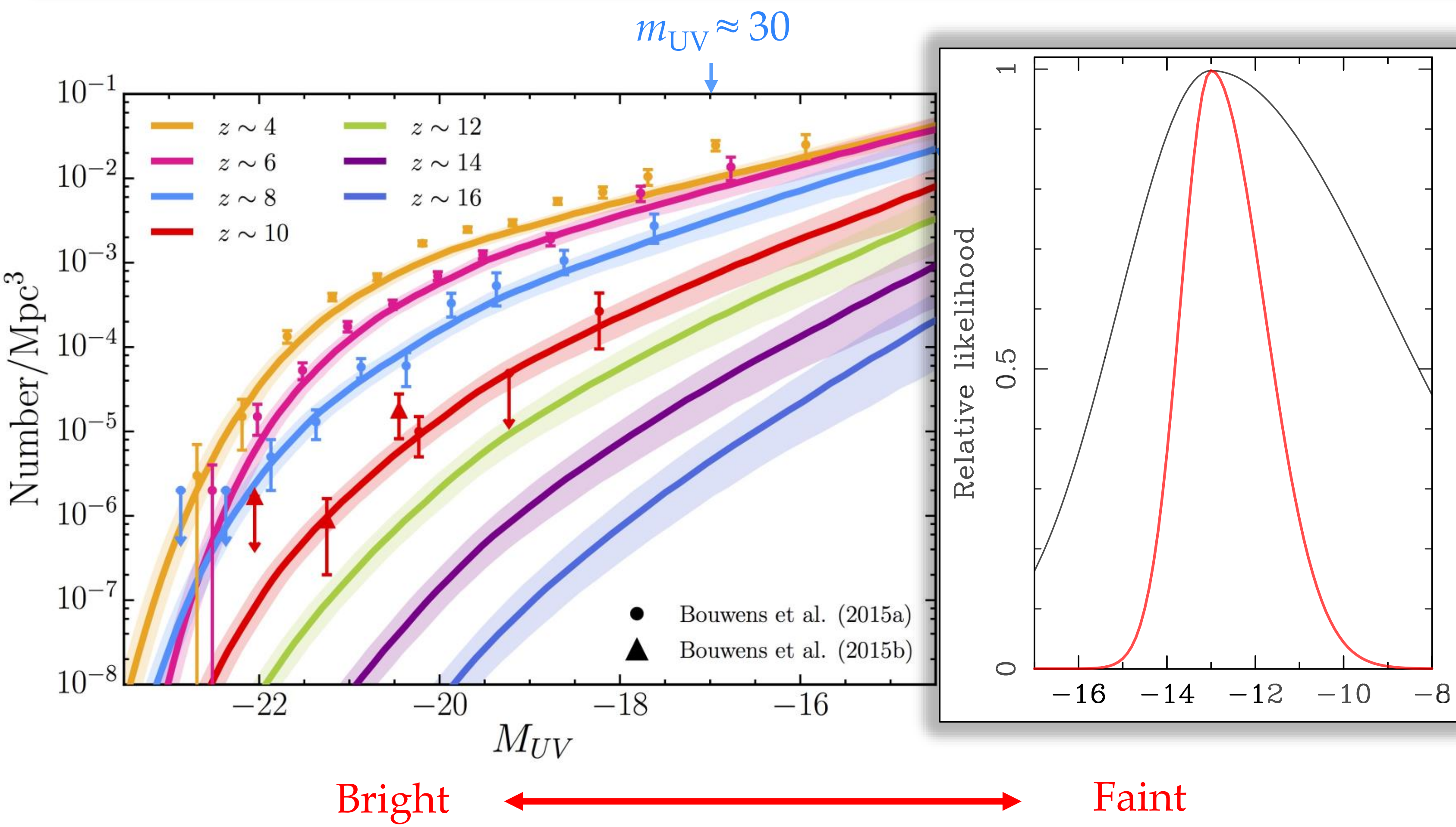




log SFR [M⊙/yr/Mpc³]
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
Corrected SFR
Observed SFR
Normalised GRB rate
Theseus simulation
M_uv limit = -17 (Donnan+23)
0
2
4
6
8
10
12
14
Redshift

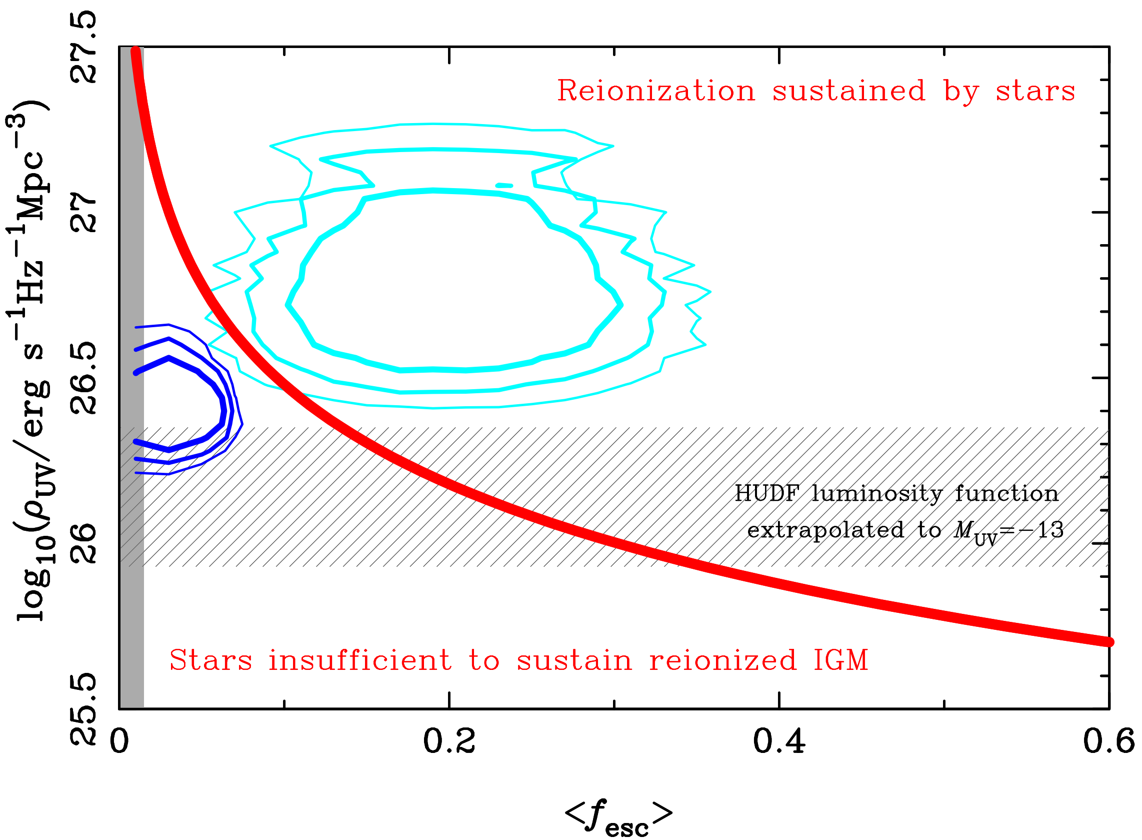
• Detecting and studying primordial invisible galaxies

The proportion of GRB hosts below a given detection limit provides an estimate of the fraction of star formation "hidden" in such faint galaxies



THESEUS Consortium 2021

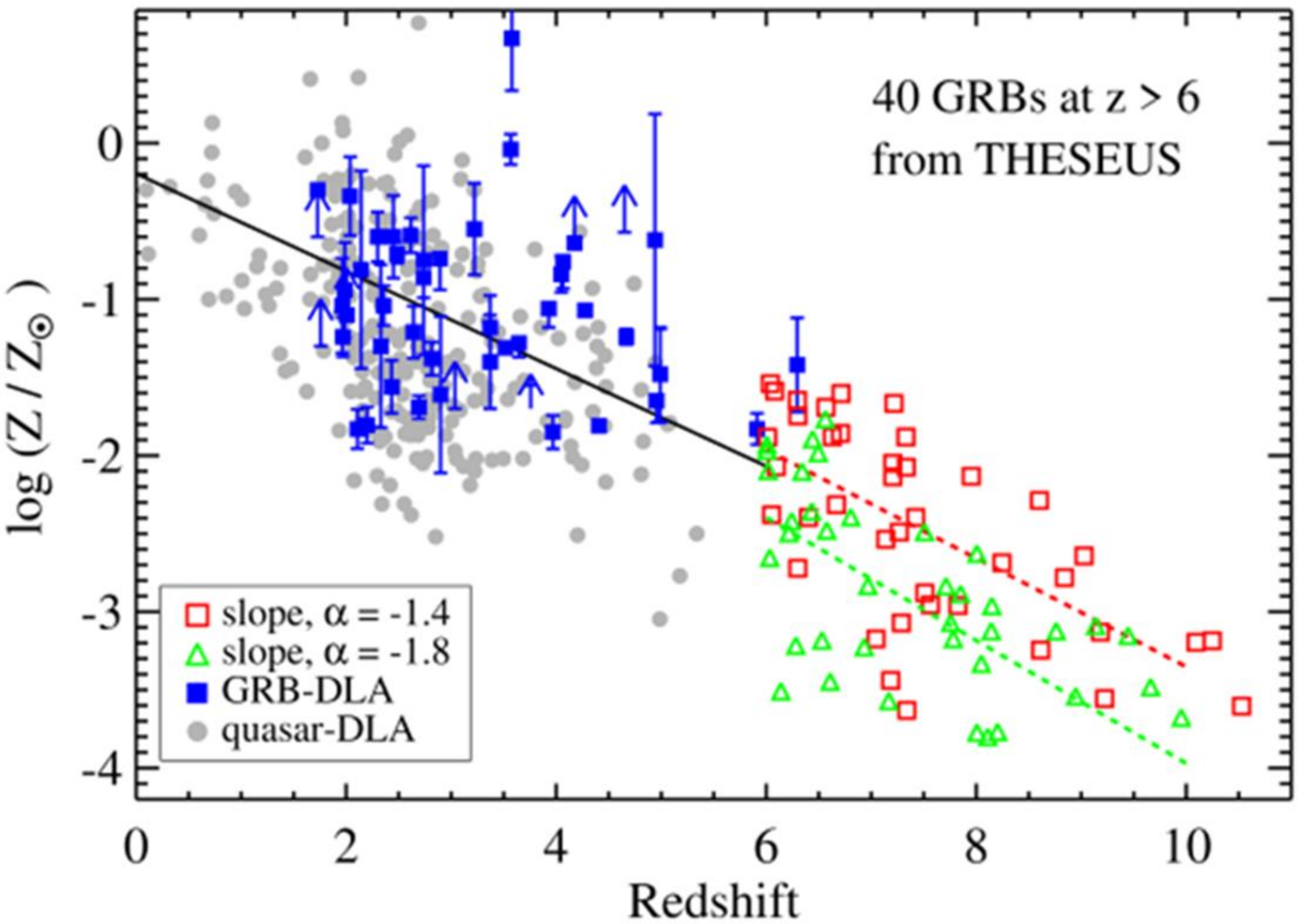
• Shedding light on cosmic reionization



Combination of massive star formation rate and ionizing escape fraction will establish whether stellar radiation was sufficient to reionize the universe, and indicate the galaxy populations responsible

THESEUS Consortium 2021

- **Cosmic chemical evolution at high-z**



THESEUS Consortium 2021