Cosmology and Multi-Messenger Astrophysics with Gamma-Ray Bursts

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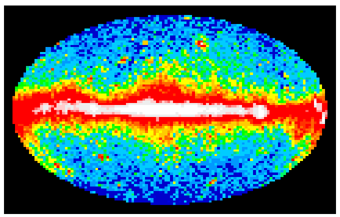
ISTITUTO NAZIONALE DI ASTROFISICA INAF

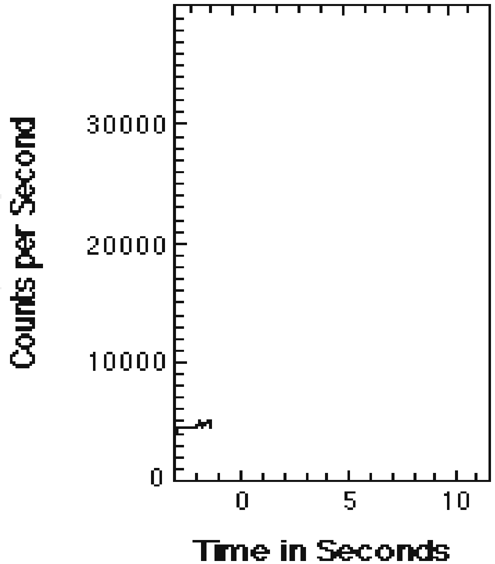
OAS

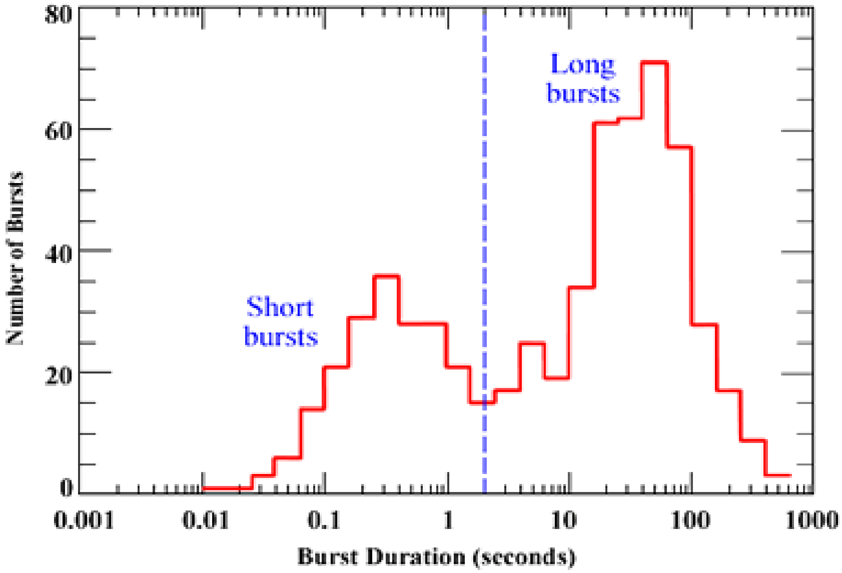
MG15 ROME 1-7 JULY 2018
CELEBRATING THE 50TH ANNIVERSARY OF THE FIRST NEUTRON STAR DISCOVERY MARKING THE BIRTH OF RELATIVISTIC ASTROPHYSICS
FIFTEENTH MARCEL GROSSMANN MEETING

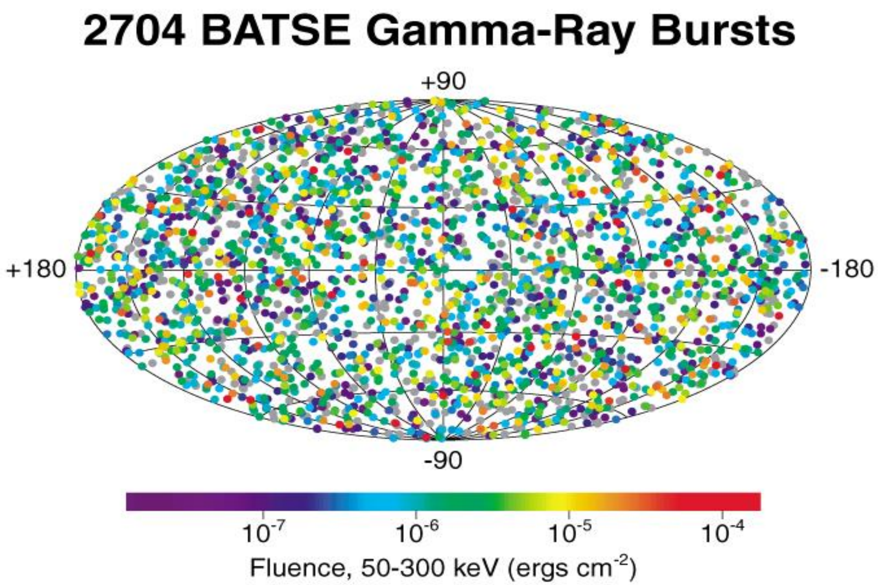
UNESCO
United Nations Educational, Scientific and Cultural Organization

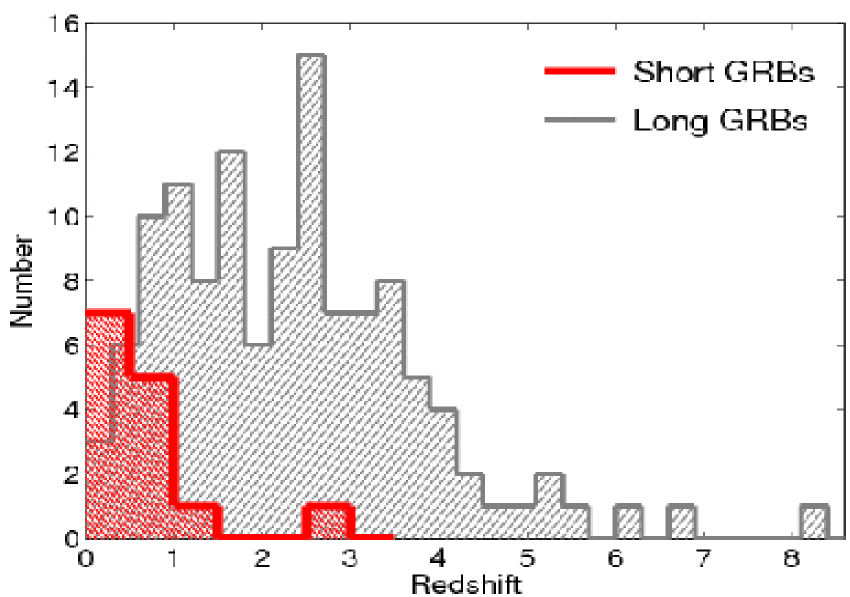
Gamma-Ray Bursts: the most extreme phenomenon in the Universe





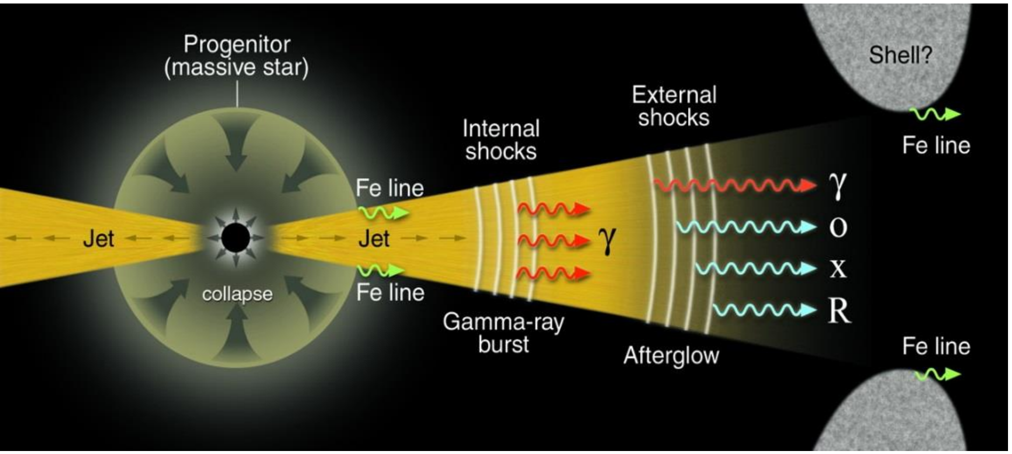






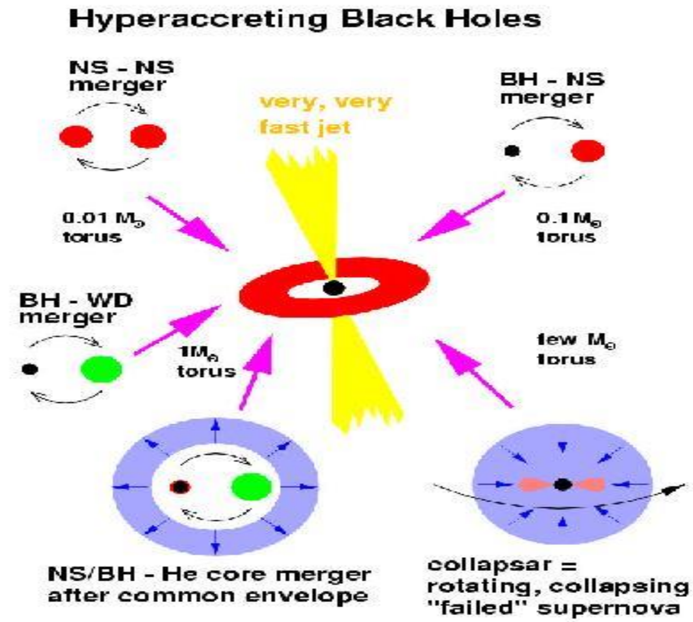
Standard scenarios for GRB progenitors

LONG



- energy budget up to >10^{54} erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

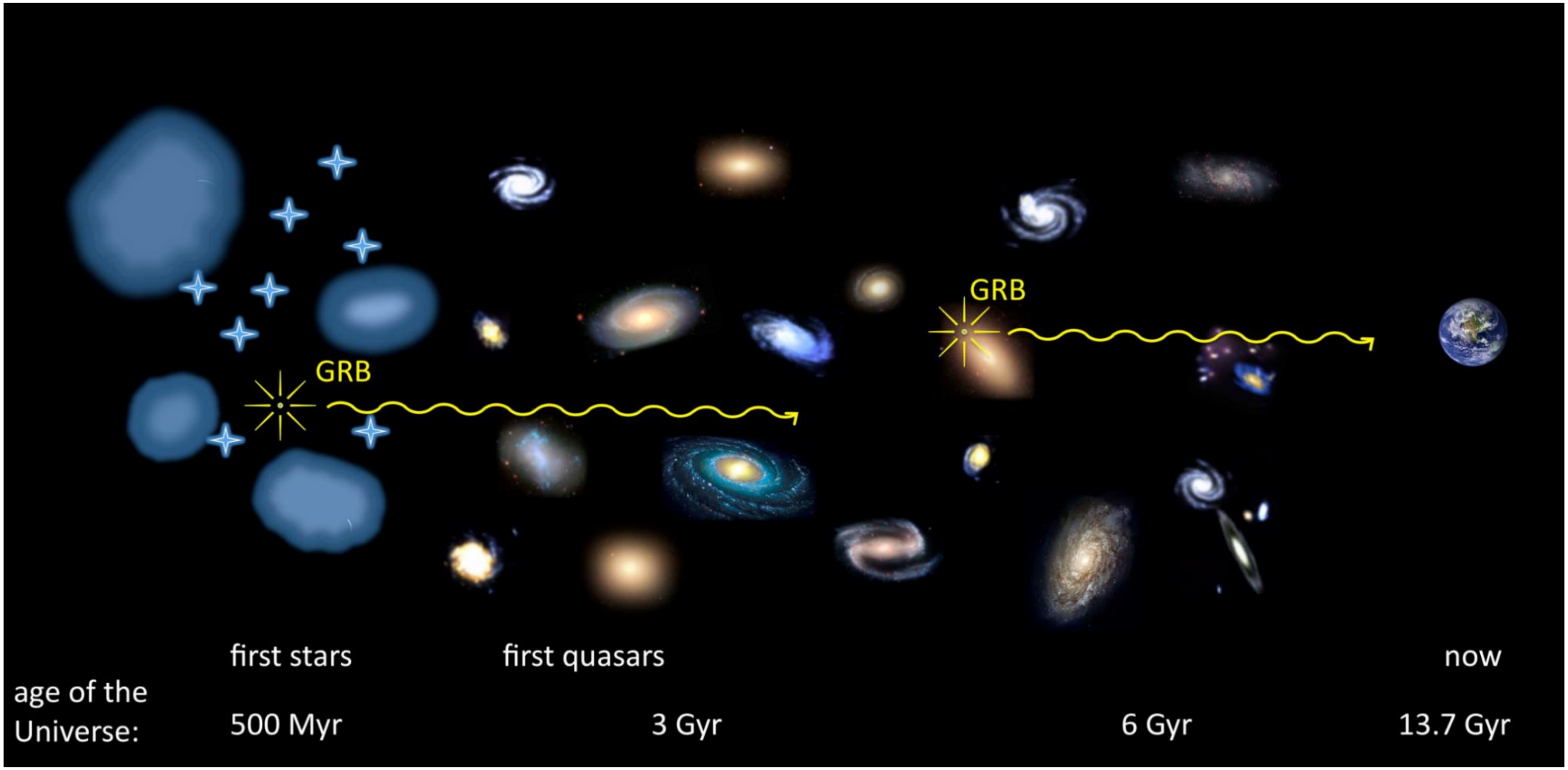
SHORT



- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

Long GRBs

- direct detection and accurate location of exploding stars (and their host galaxies) up to the Cosmic Dawn!!!
- cosmological «beacons»
- standardizable cosmological candles??



Long GRBs

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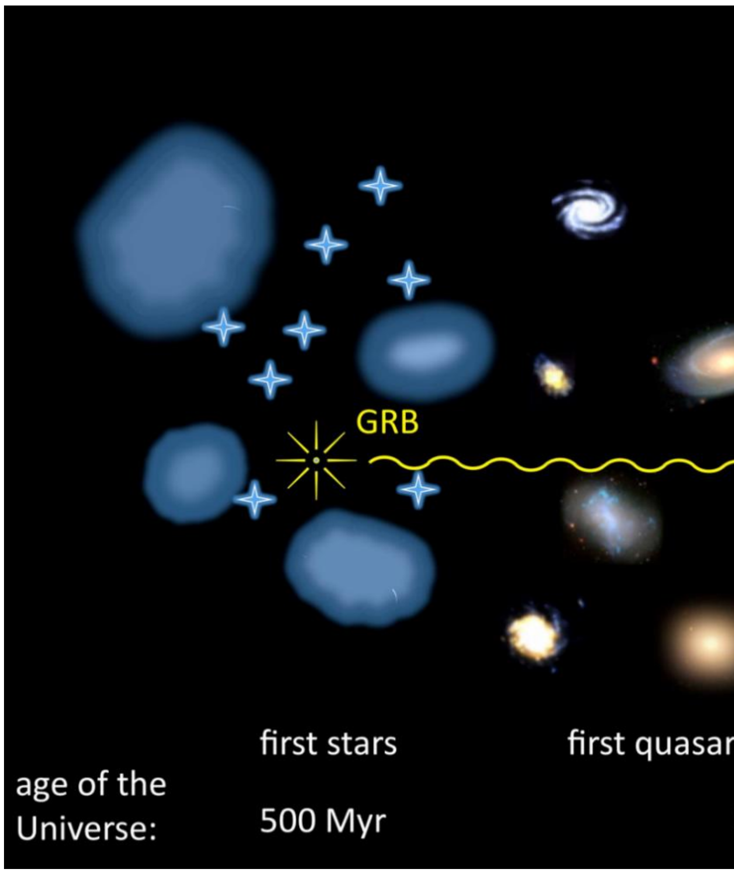
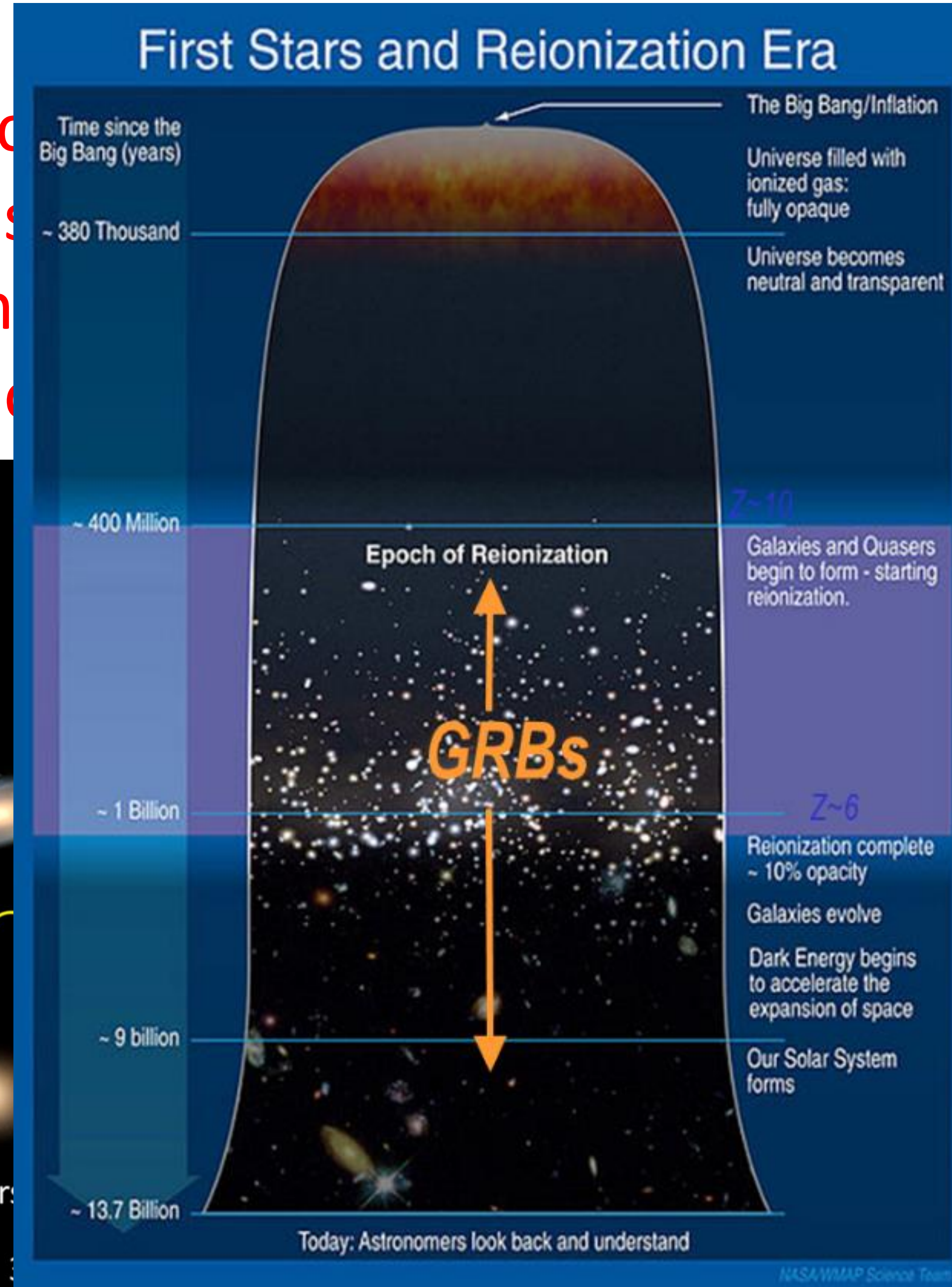
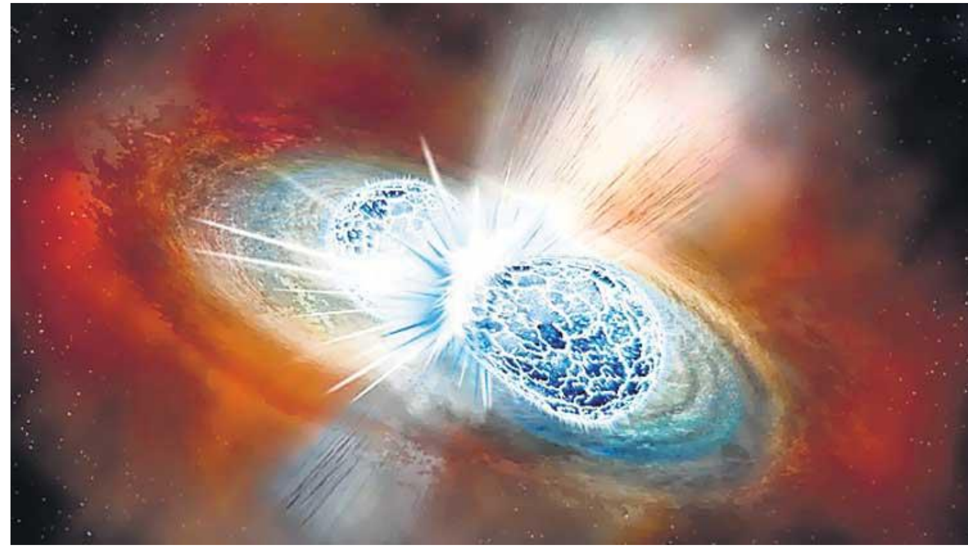
- cosmological «beacon
- standardizable cosmolo

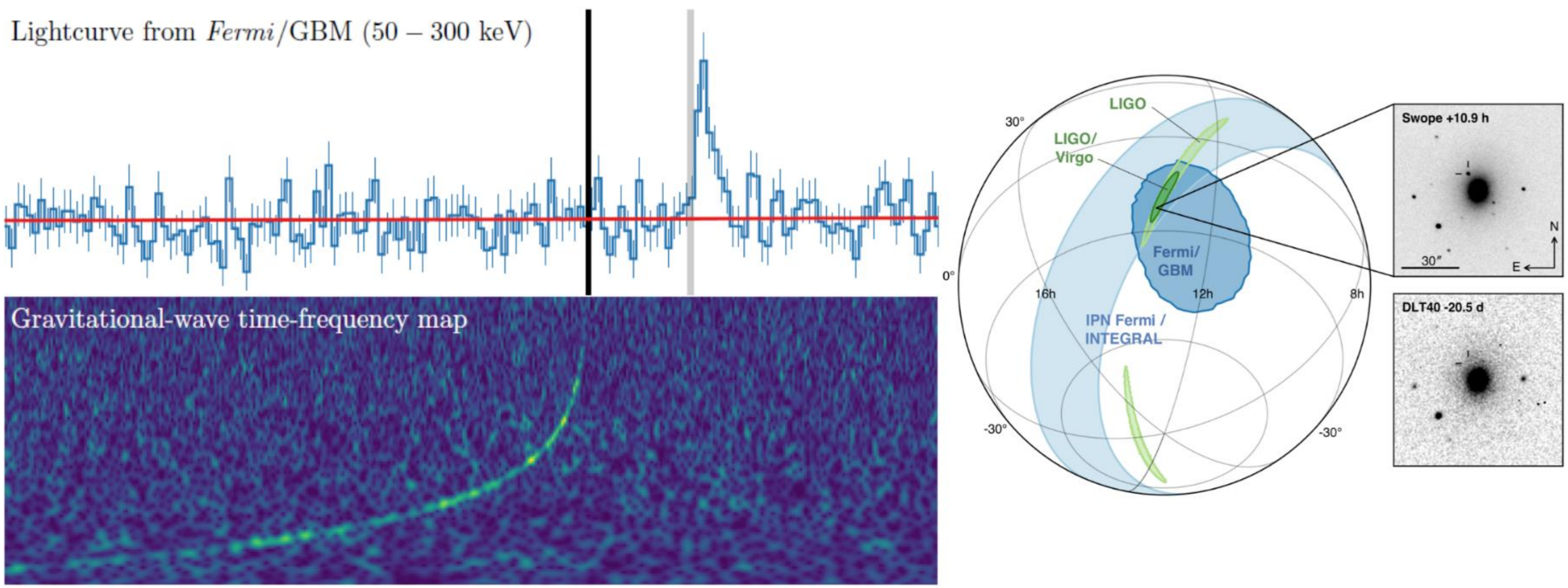




Short GRBs: e.m. counterparts of gravitational-waves sources!!!



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



Cosmology and multi-messenger astrophysics (and extreme physics) with Gamma-Ray Bursts

theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

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)

www.isdc.unige.ch/theseus/workshop2017-programme.html
Proceedings preprints on the arXiv in early February
(Mem.SAIt, Vol. 89 – N.1 - 2018)

THESEUS
Transient High Energy Sky and Early Universe Surveyor

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

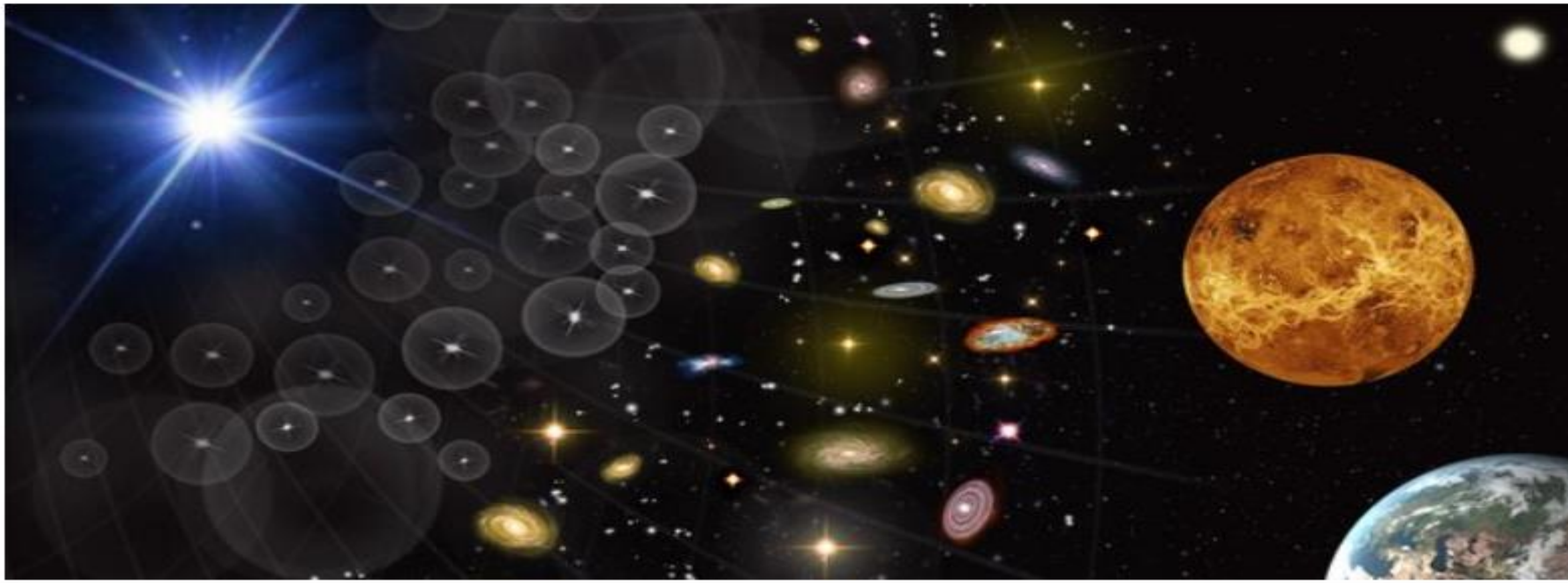
Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), C. Tenzer (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

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 Phase 0/A study !!!!!

(2018-2021, launch 2032)



M5 mission themes

ESA SELECTS THREE NEW MISSION CONCEPTS FOR STUDY

7 May 2018 A high-energy survey of the early Universe, an infrared observatory to study the formation of stars, planets and galaxies, and a Venus orbiter are to be considered for ESA's fifth medium class mission in its Cosmic Vision science programme, with a planned launch date in 2032.

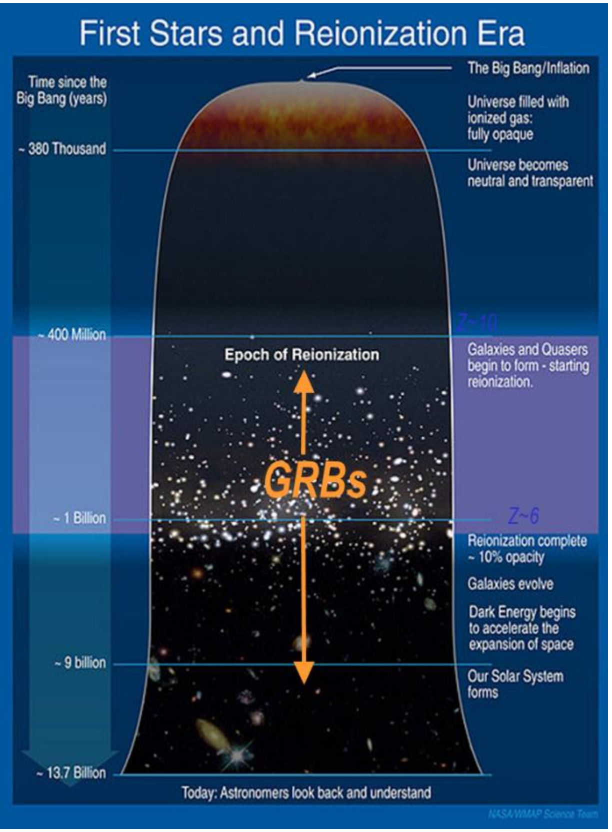
The three candidates, the Transient High Energy Sky and Early Universe Surveyor (Theseus), the SPace Infrared telescope for Cosmology and Astrophysics (Spica), and the EnVision mission to Venus were

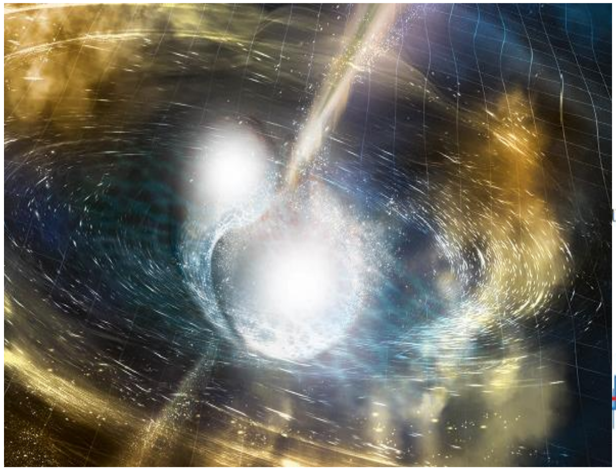
Probing the Early Universe with GRBs

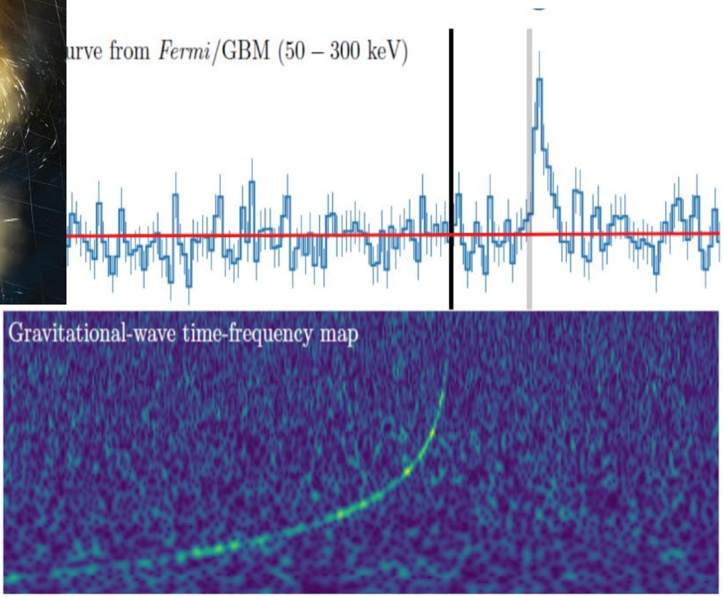
Multi-messenger and time domain Astrophysics

The transient high energy sky

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

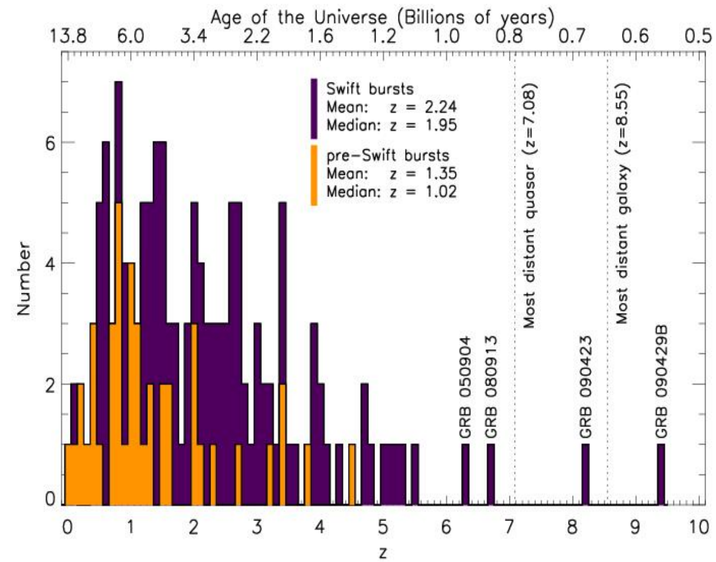




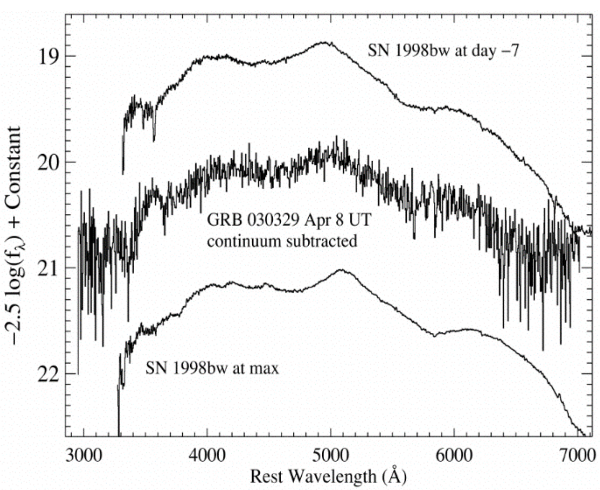


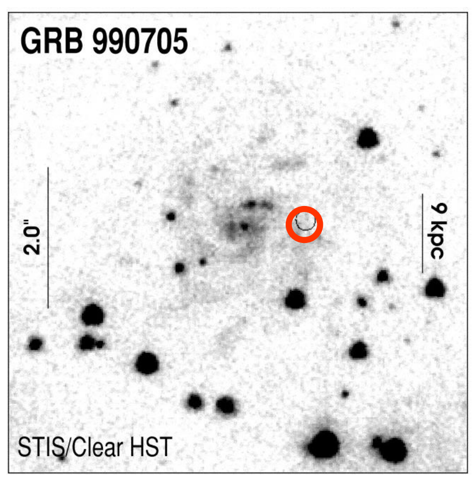
Shedding light on the early Universe with GRBs

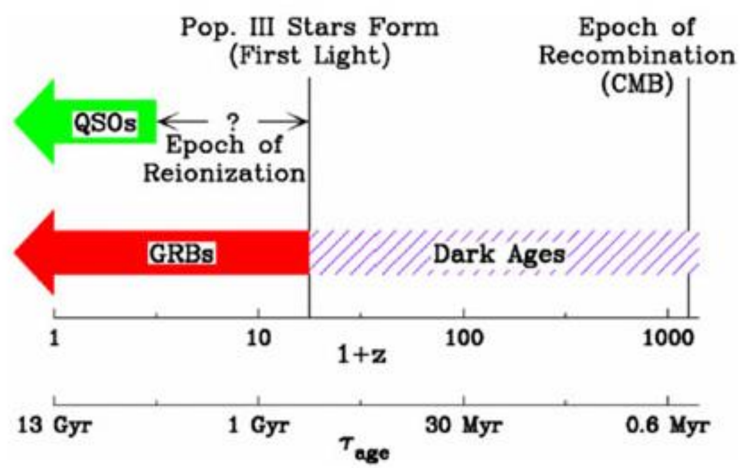
Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution,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



GRBs in Cosmological Context





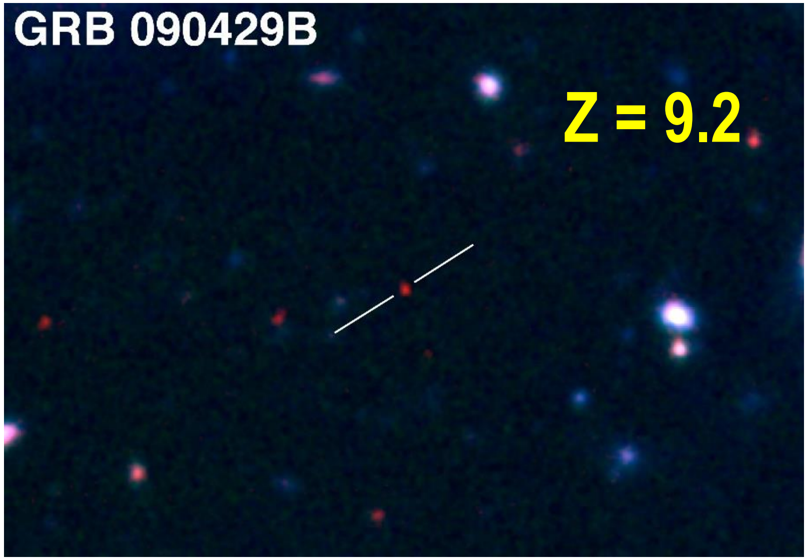


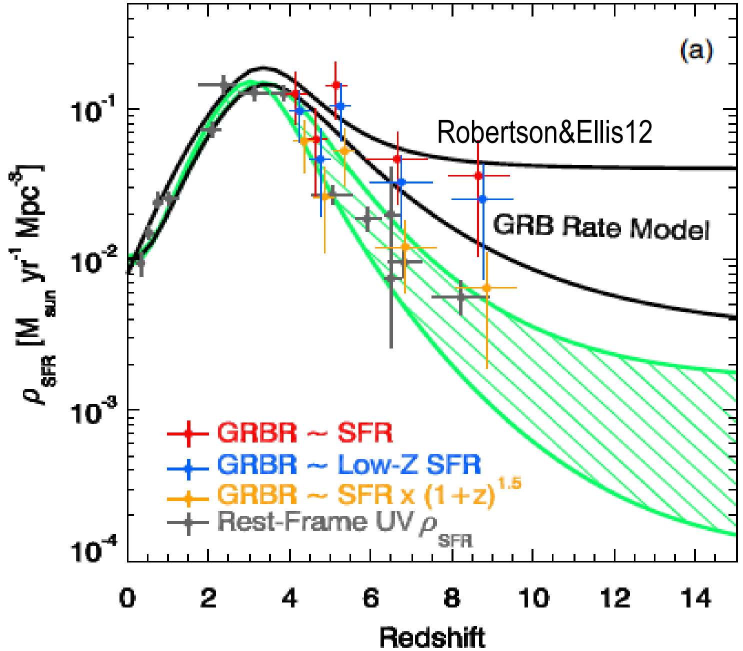
Lamb and Reichart (2000)

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

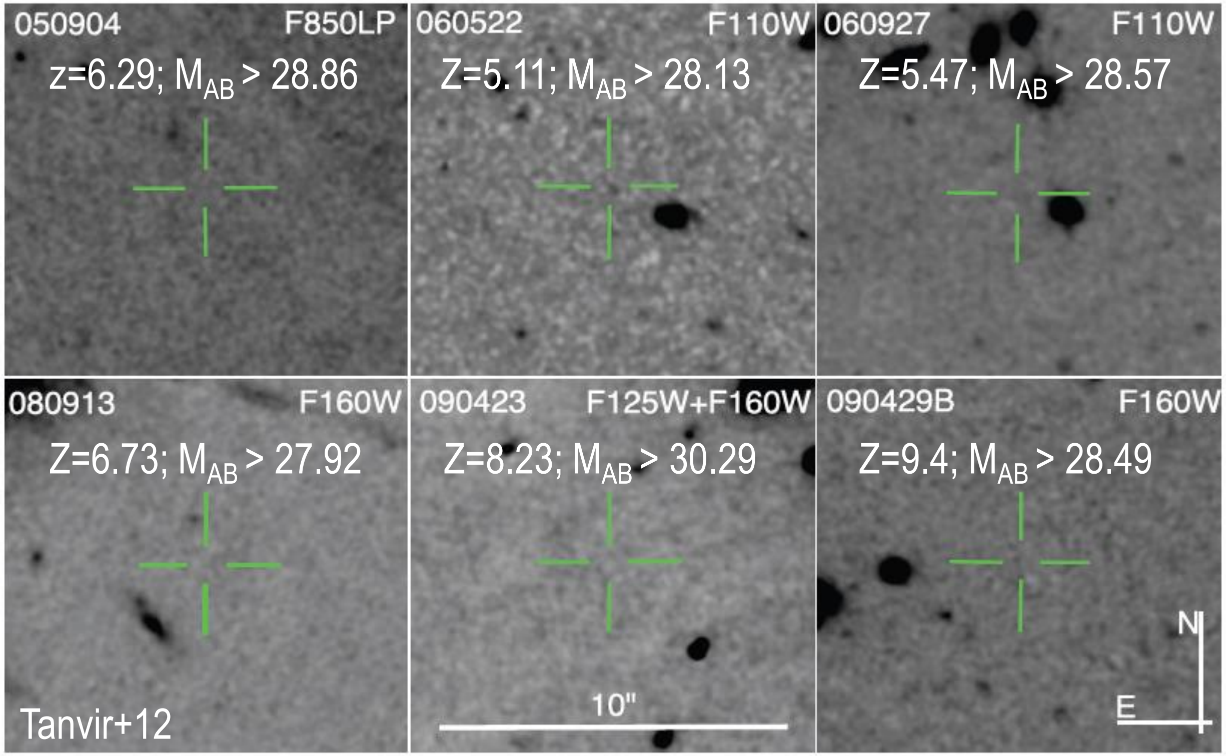
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

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





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

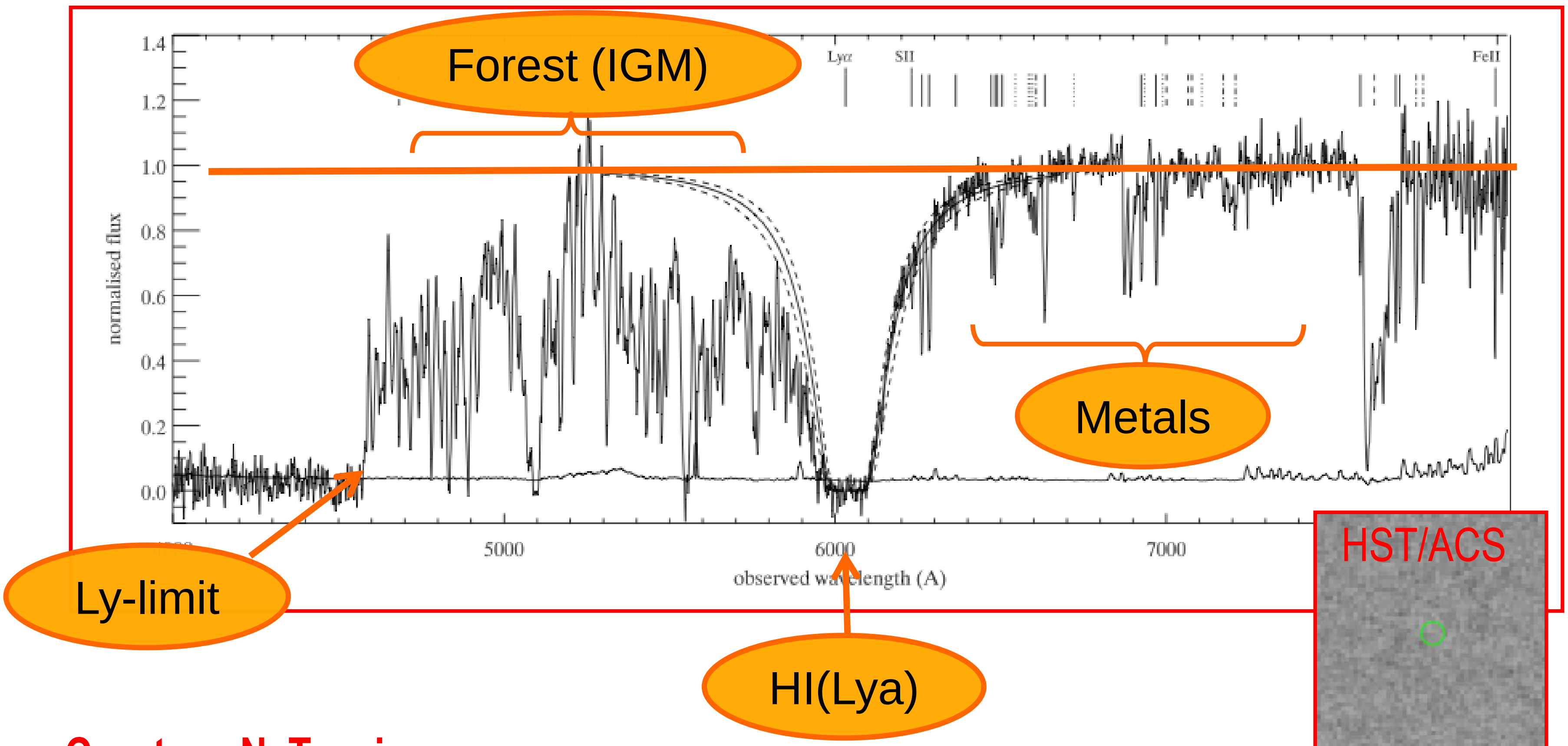


Robertson&Ellis12

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)

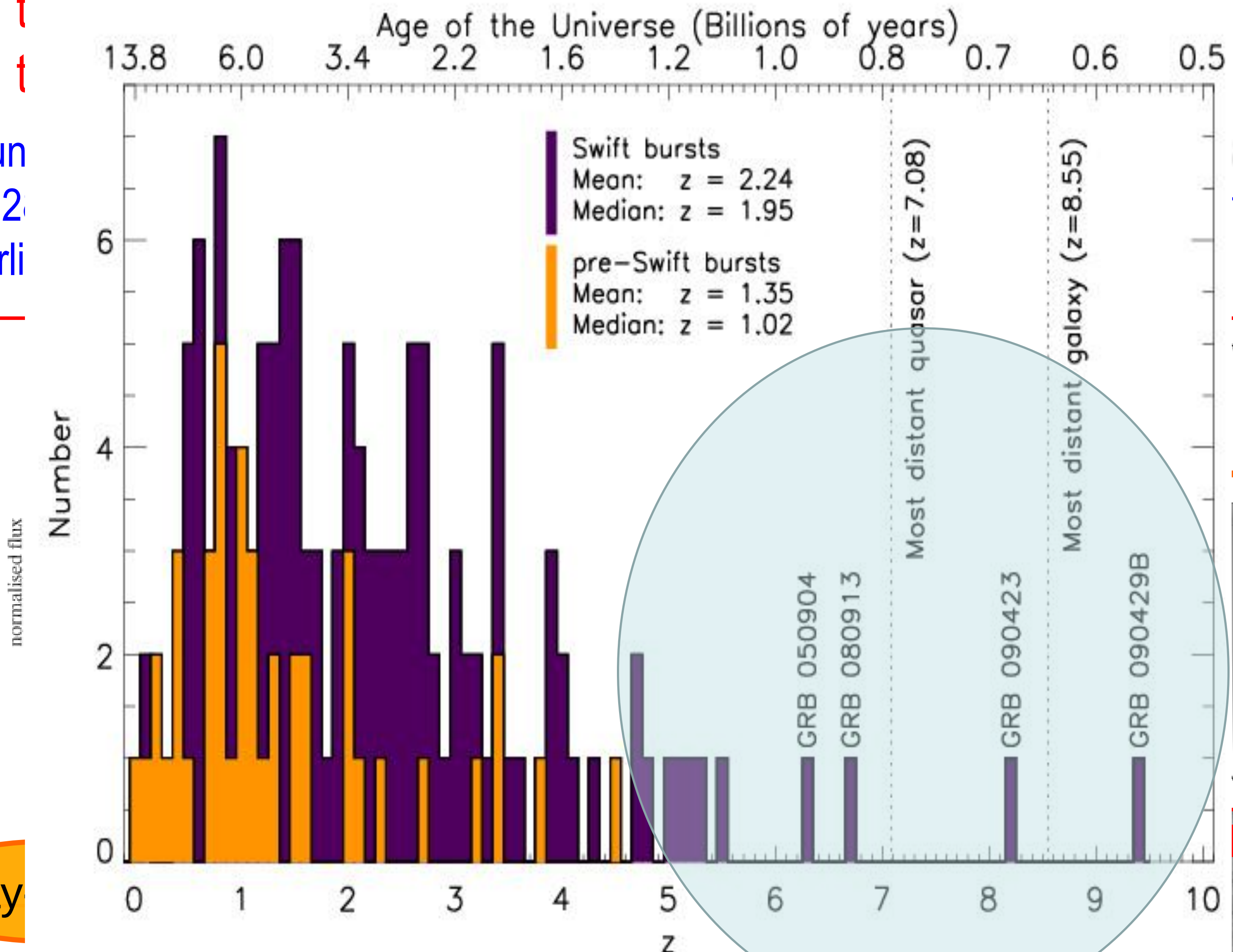
- **the neutral hydrogen fraction**
- **the escape fraction of UV photons from high-z galaxies**
- **the early metallicity of the ISM and IGM and its evolution**

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

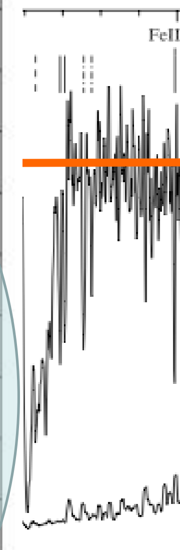
- the neutral hydrogen fraction
- t
- t



Abun ... 0: faint host

(R>2 ... t al. 2005;

Starli



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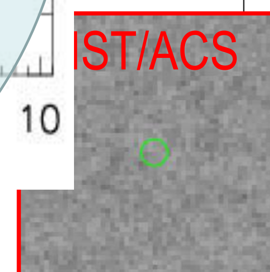
HI(Lya)

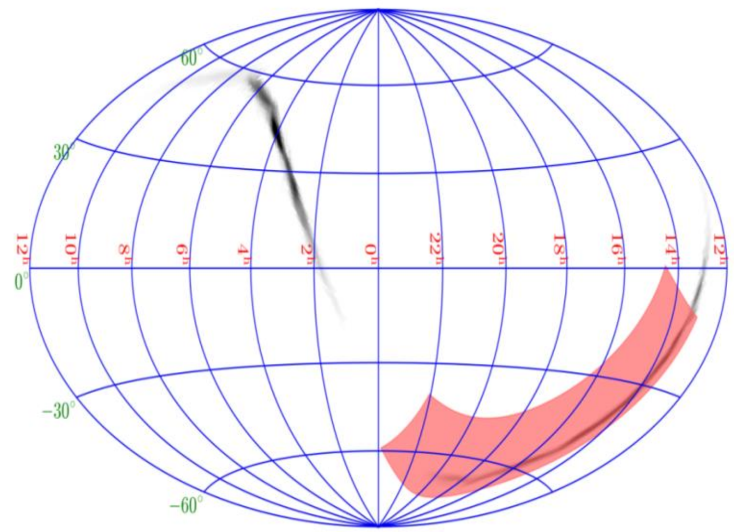
IST/ACS



Courtesy N. Tanvir

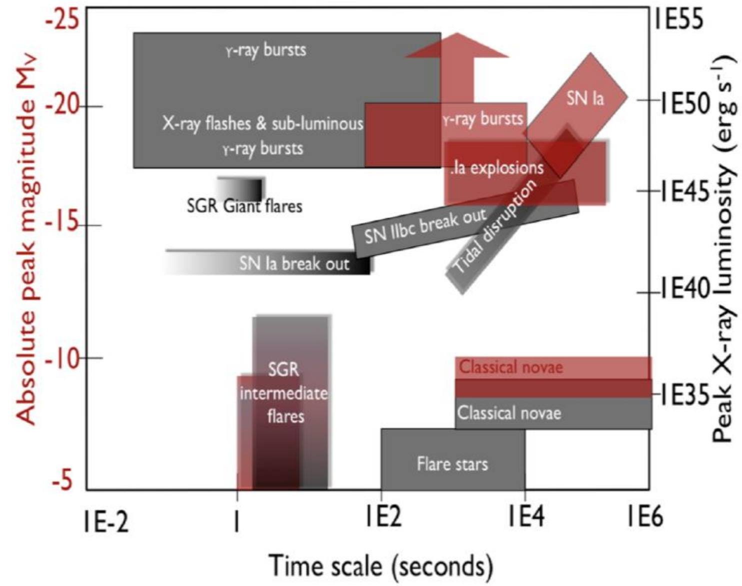
Exploring the multi-messenger transient sky

- ❑ **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**



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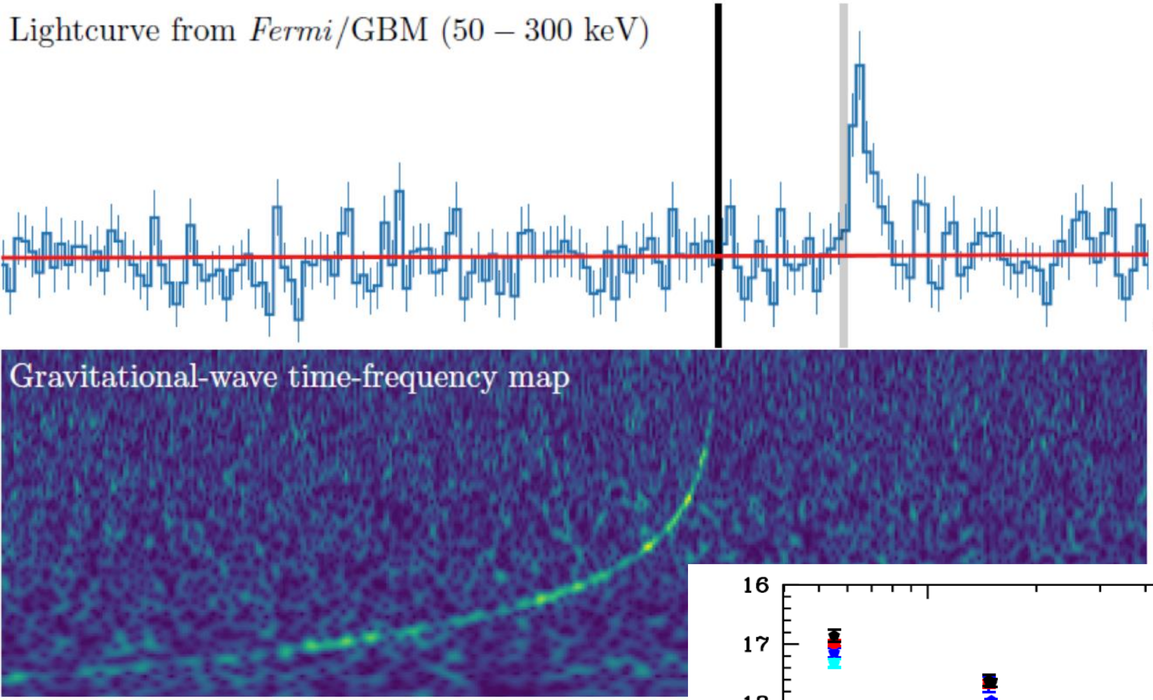
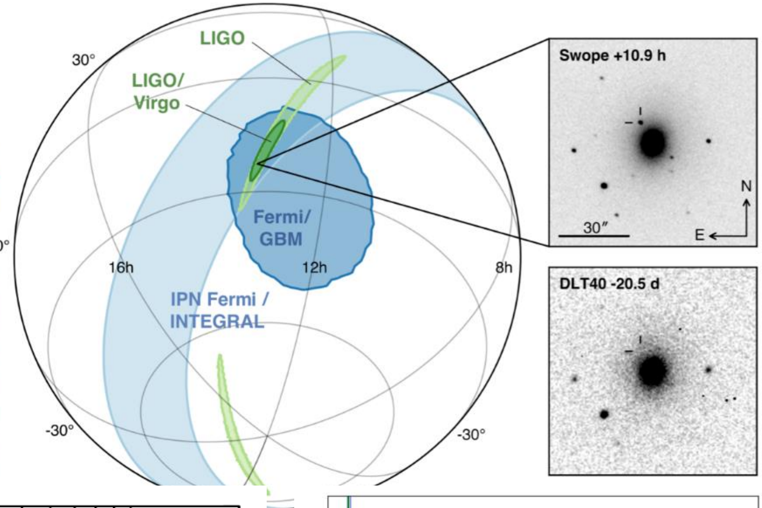
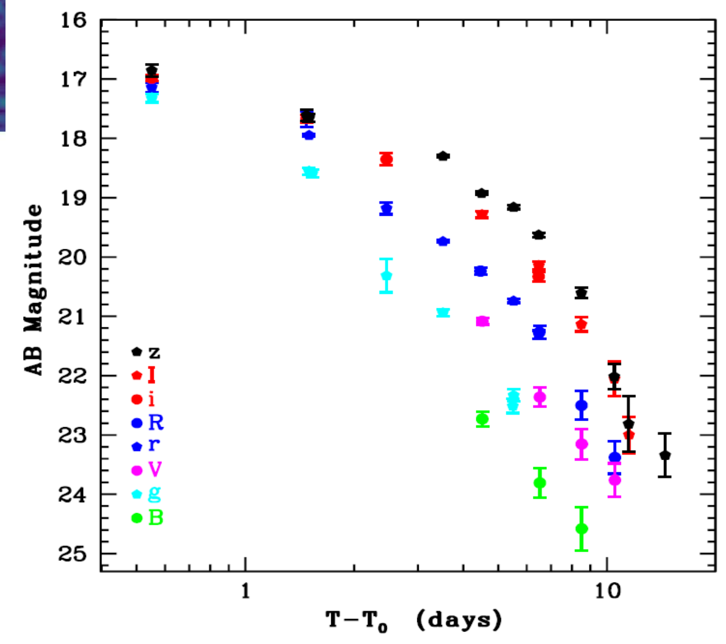
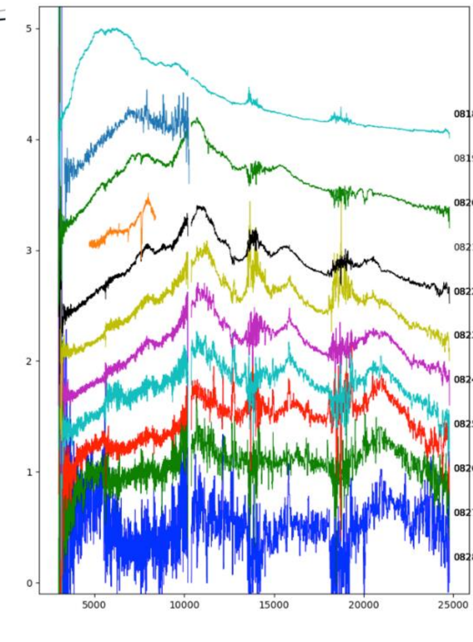


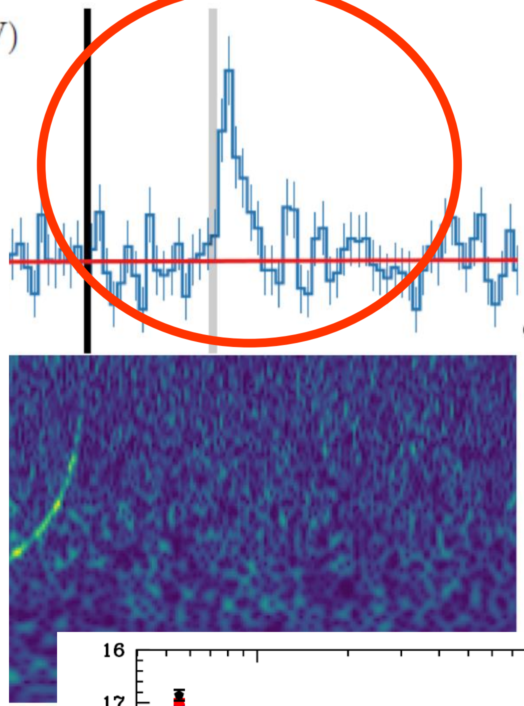






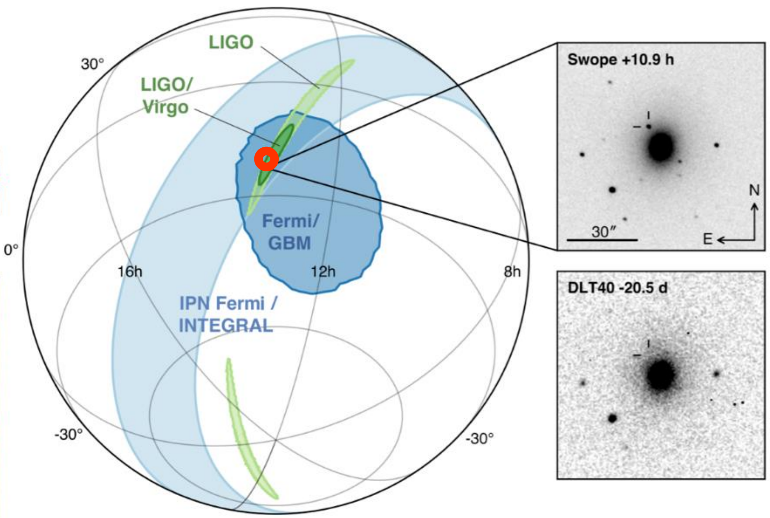
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

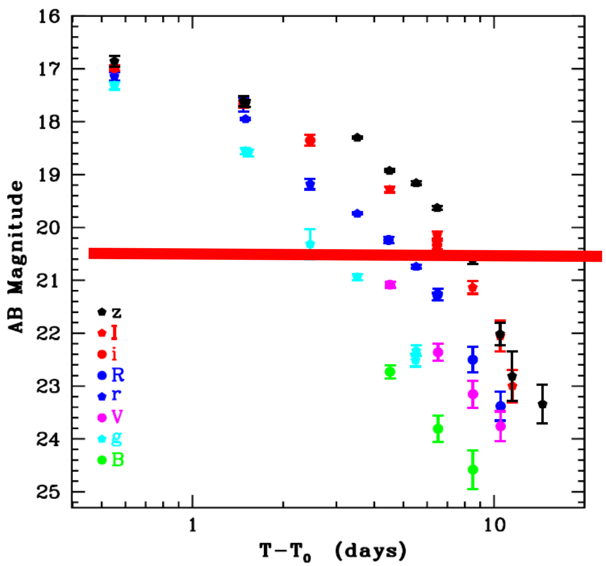
Lightcurve from *Fermi*/GBM (50 – 300 keV)

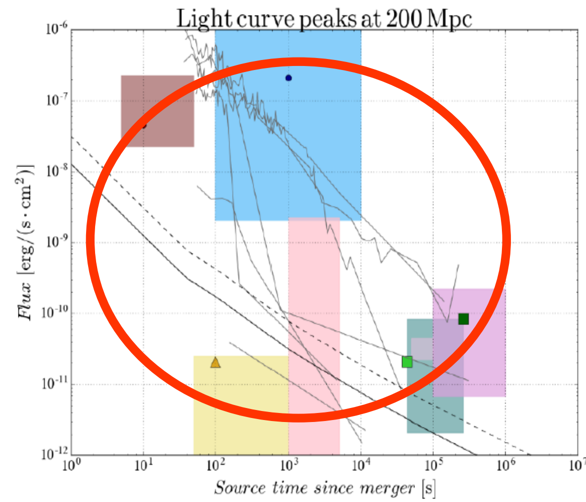


THESEUS:

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

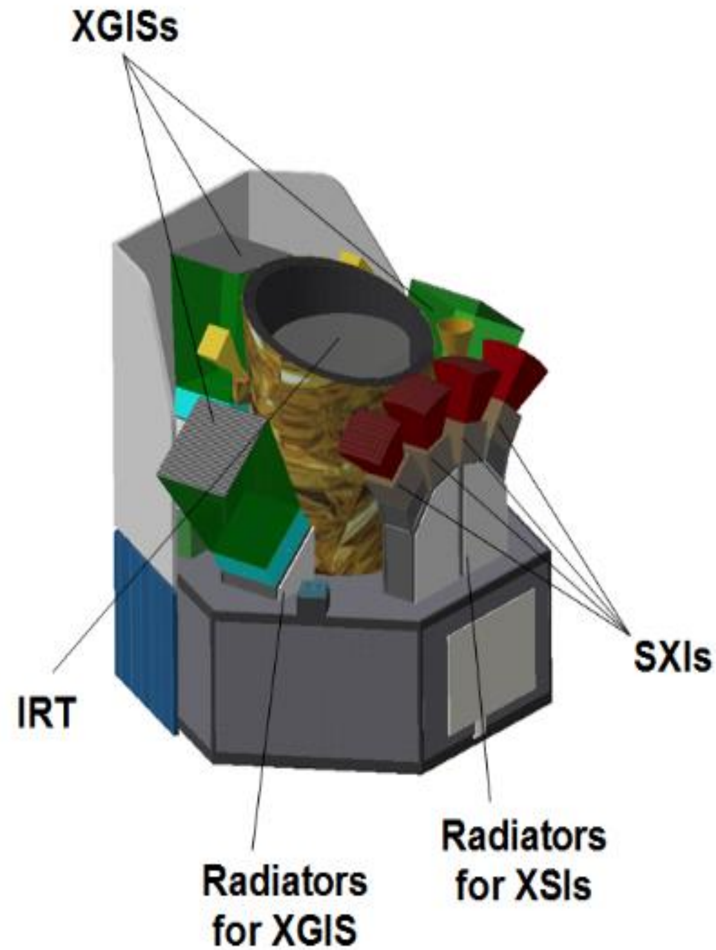






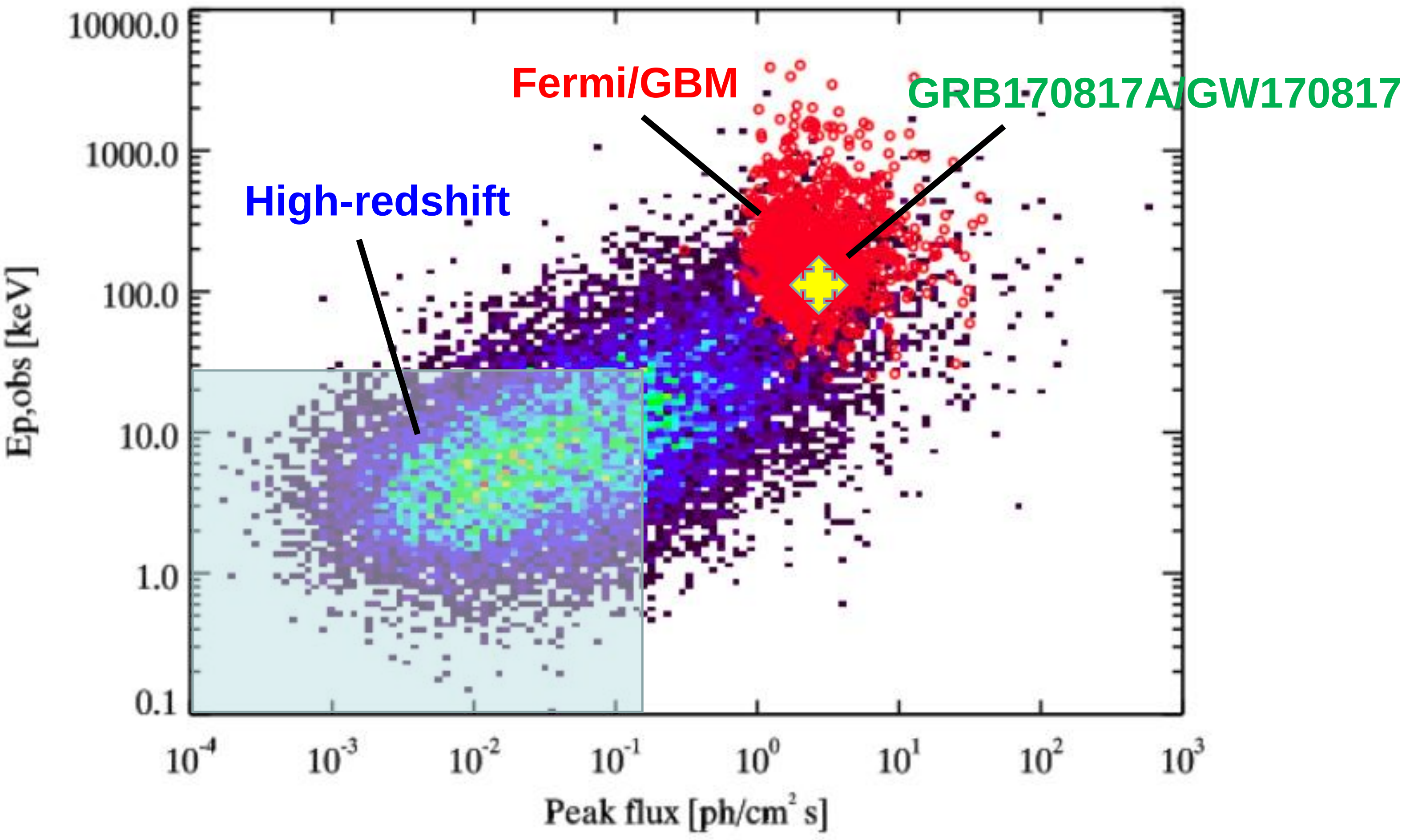
THESEUS mission concept

- **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)**



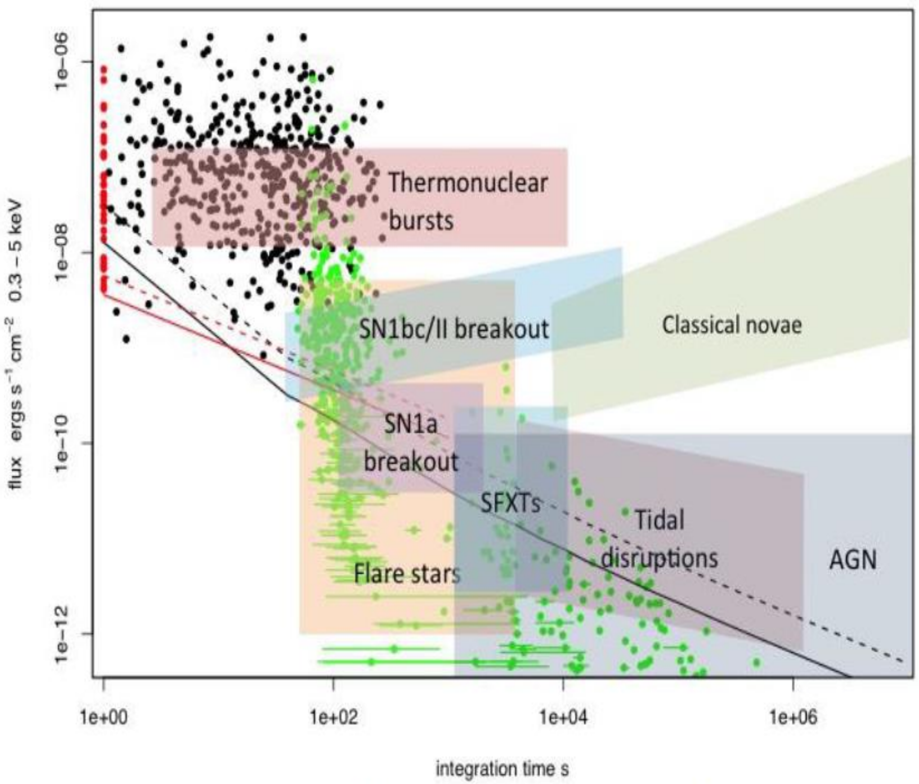
LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink

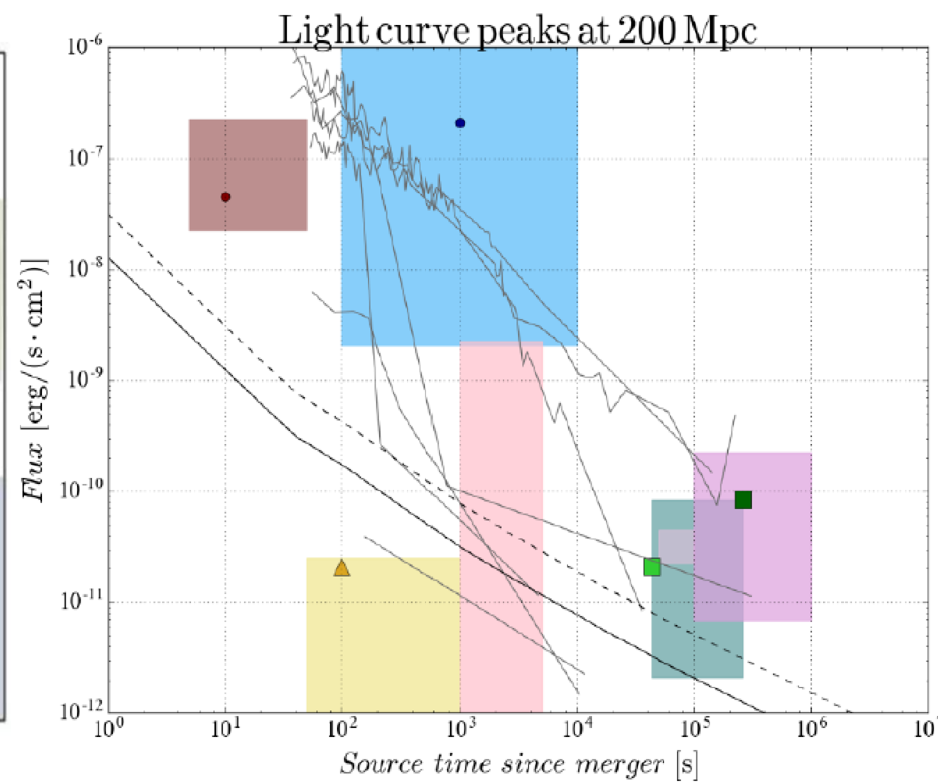
❑ THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), localizing them from a few arcmin down to arsec and measure the redshift for a large fraction of them



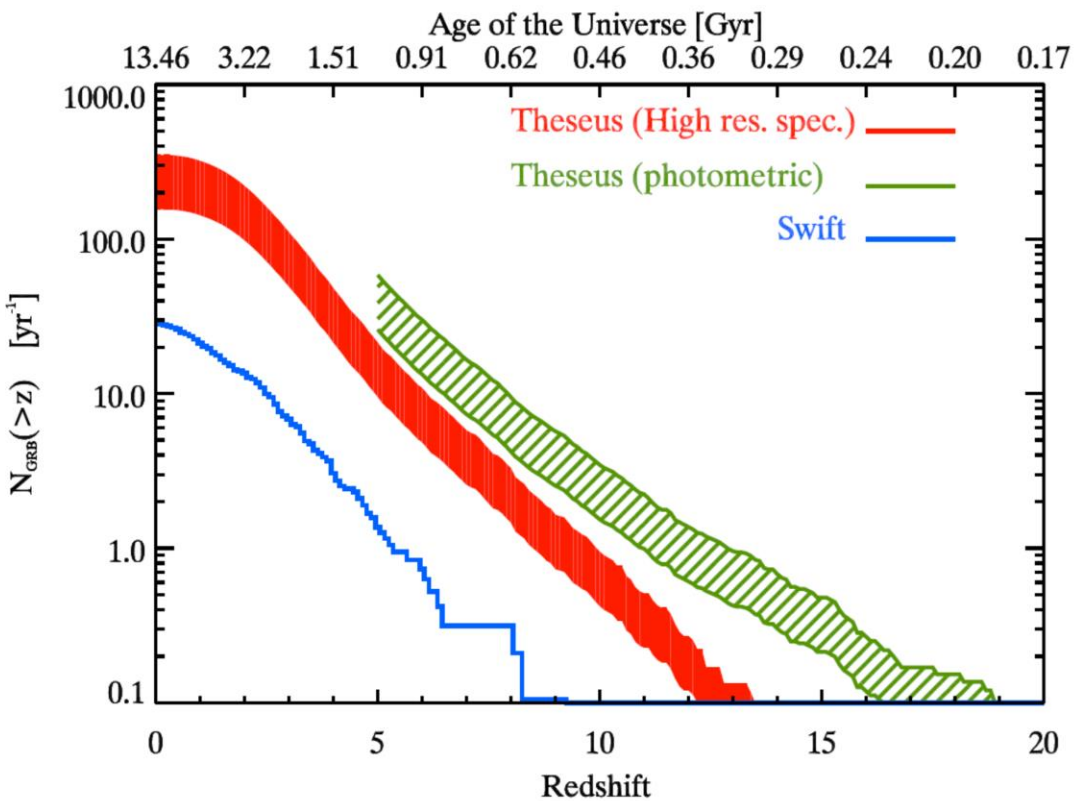
- THESEUS will also detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS (BH) mergers and of many classes of galactic and extra-galactic transients

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





❑ 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

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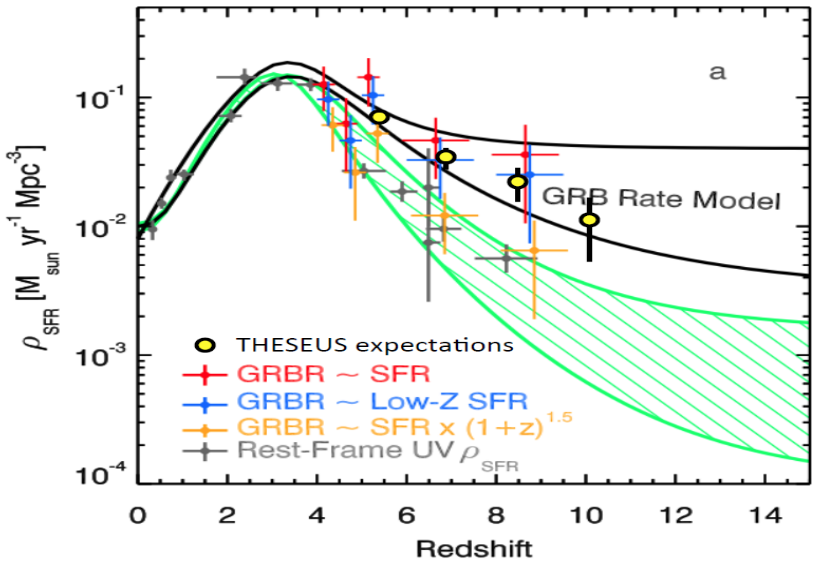
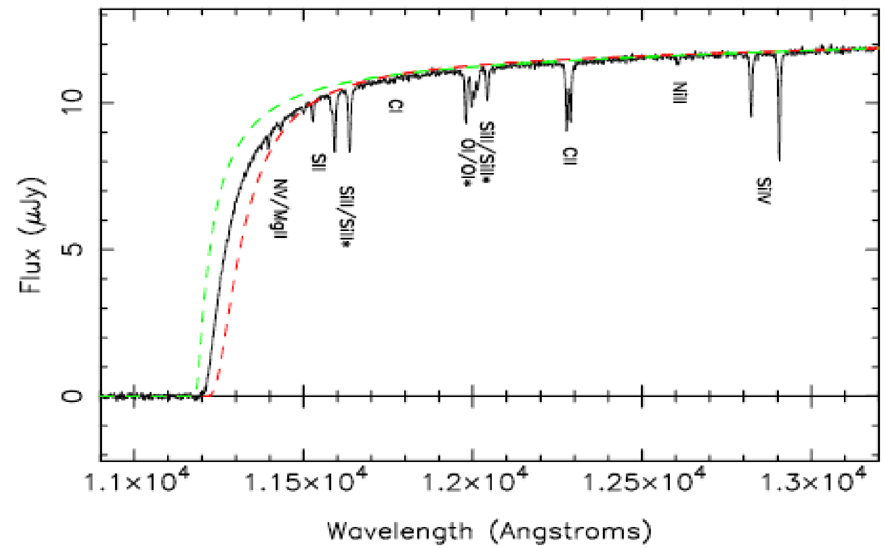
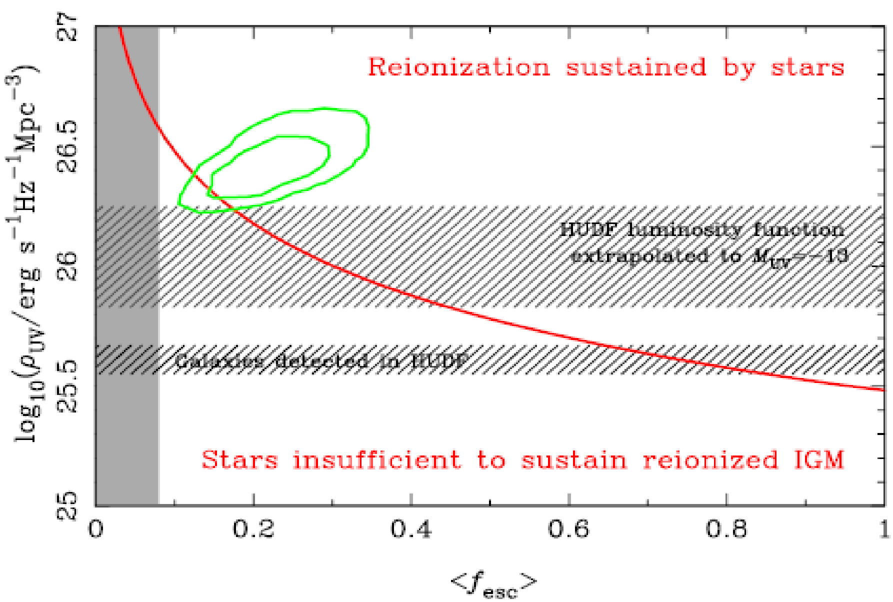
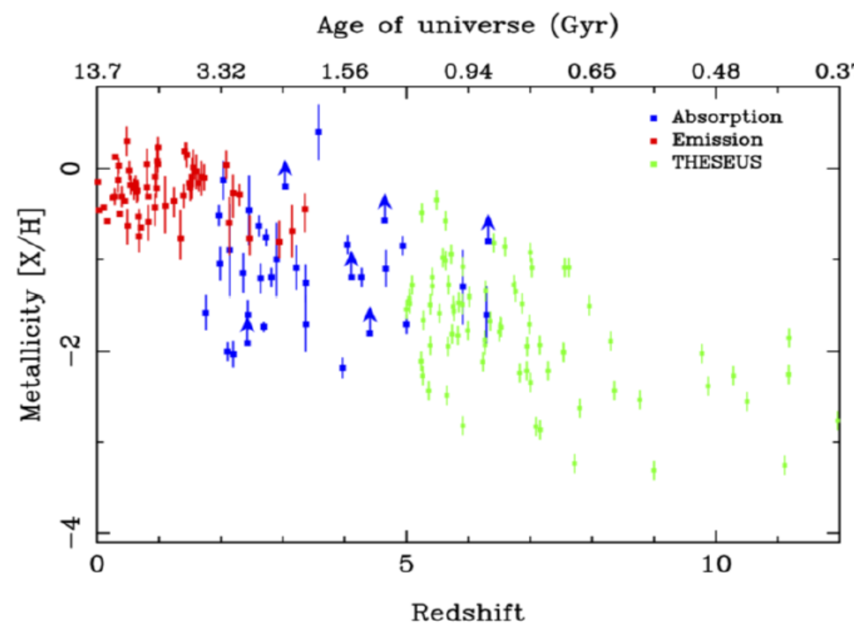
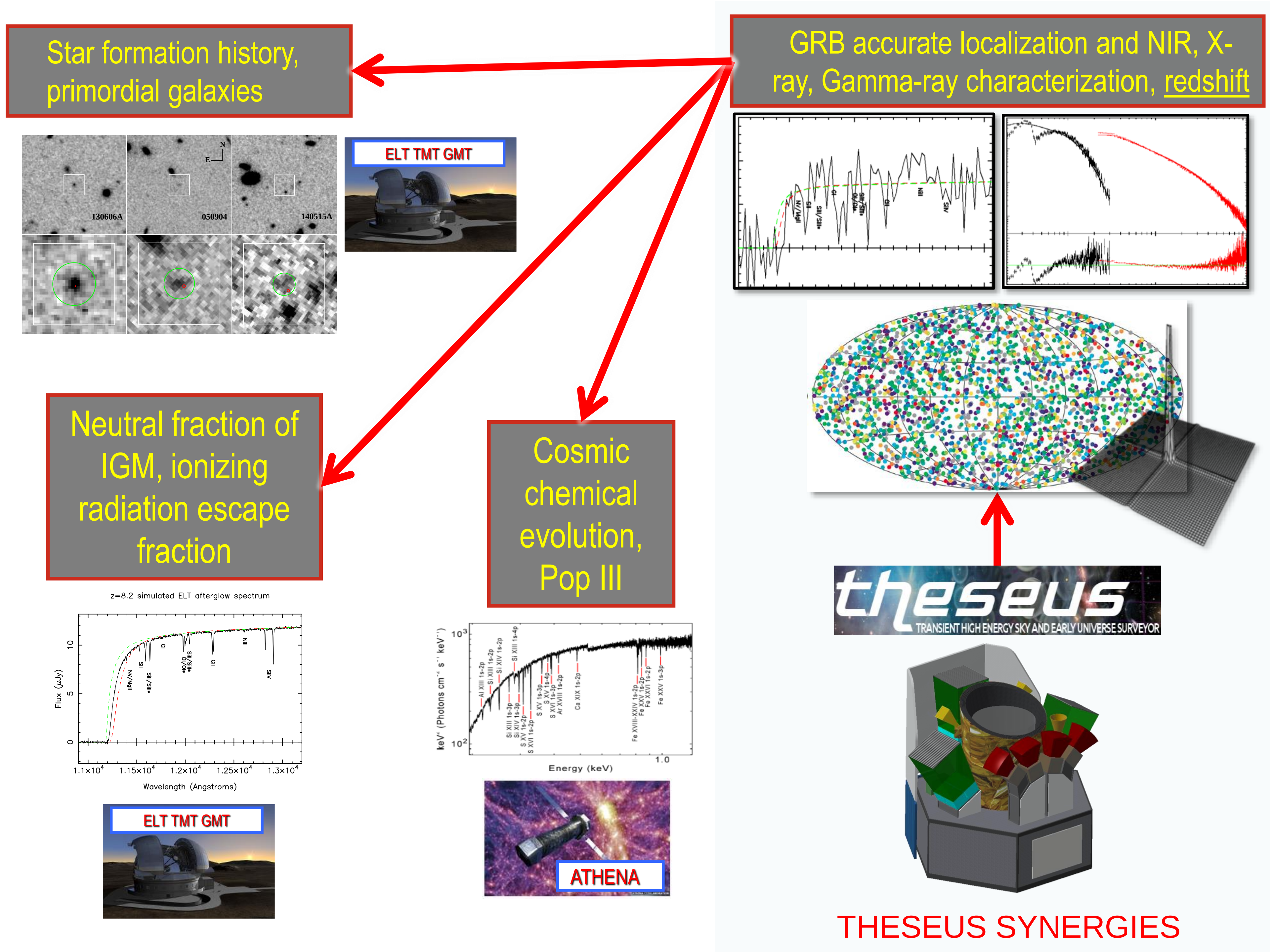


z=8.2 simulated E-ELT afterglow spectra









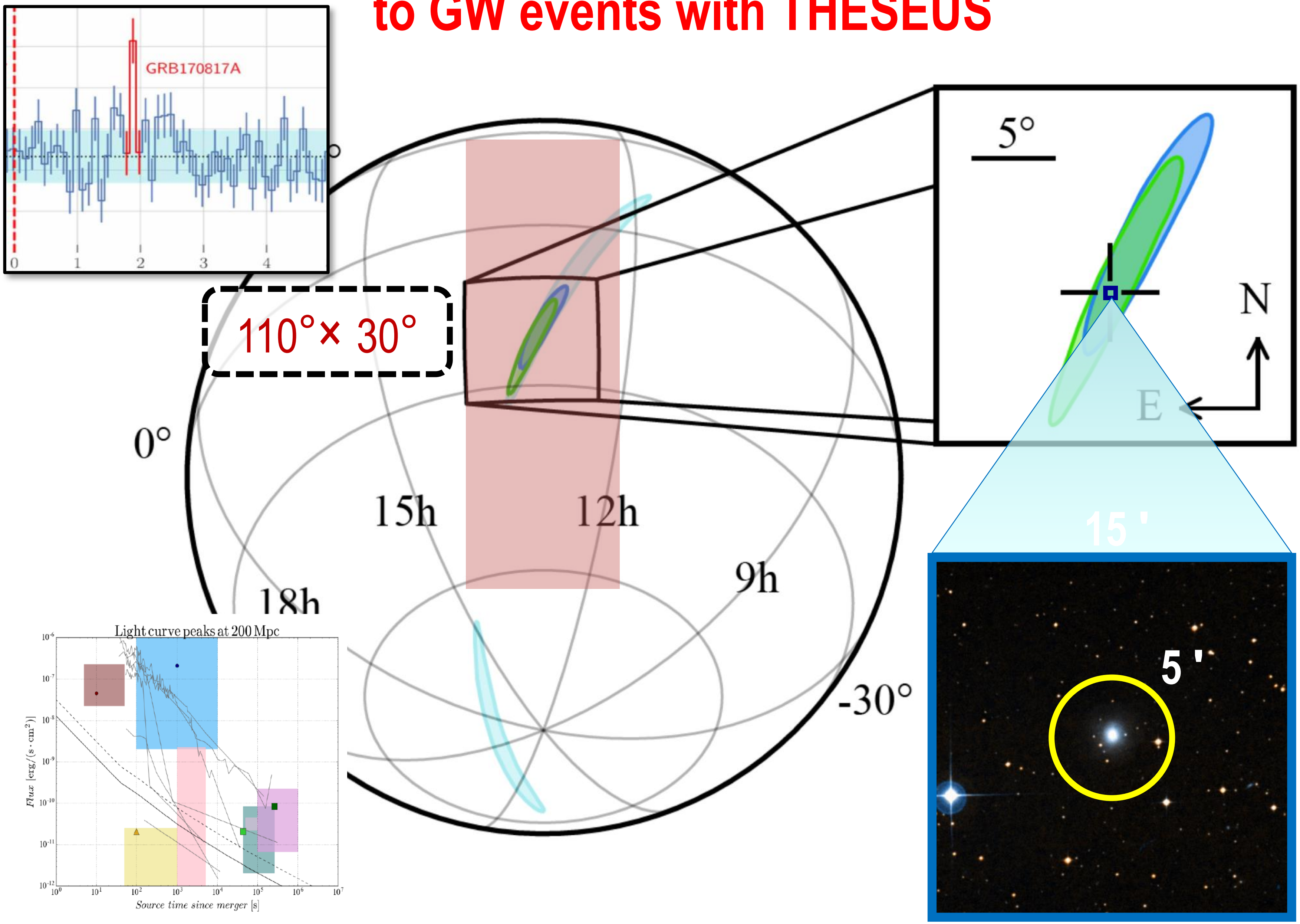
Star formation history, primordial galaxies
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
130606A
050904
140515A
ELT TMT GMT
Neutral fraction of IGM, ionizing radiation escape fraction
Cosmic chemical evolution, Pop III
z=8.2 simulated ELT afterglow spectrum
Flux (μJy)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

❑ GW/multi-messenger and time-domain astrophysics

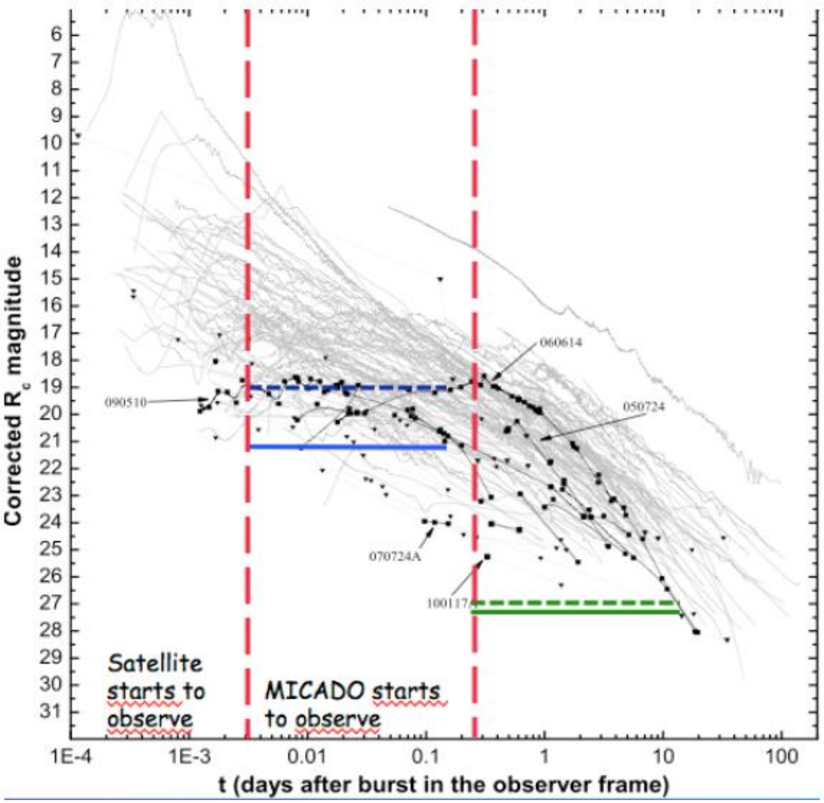
GW transient sources that will be monitored by THESEUS include:

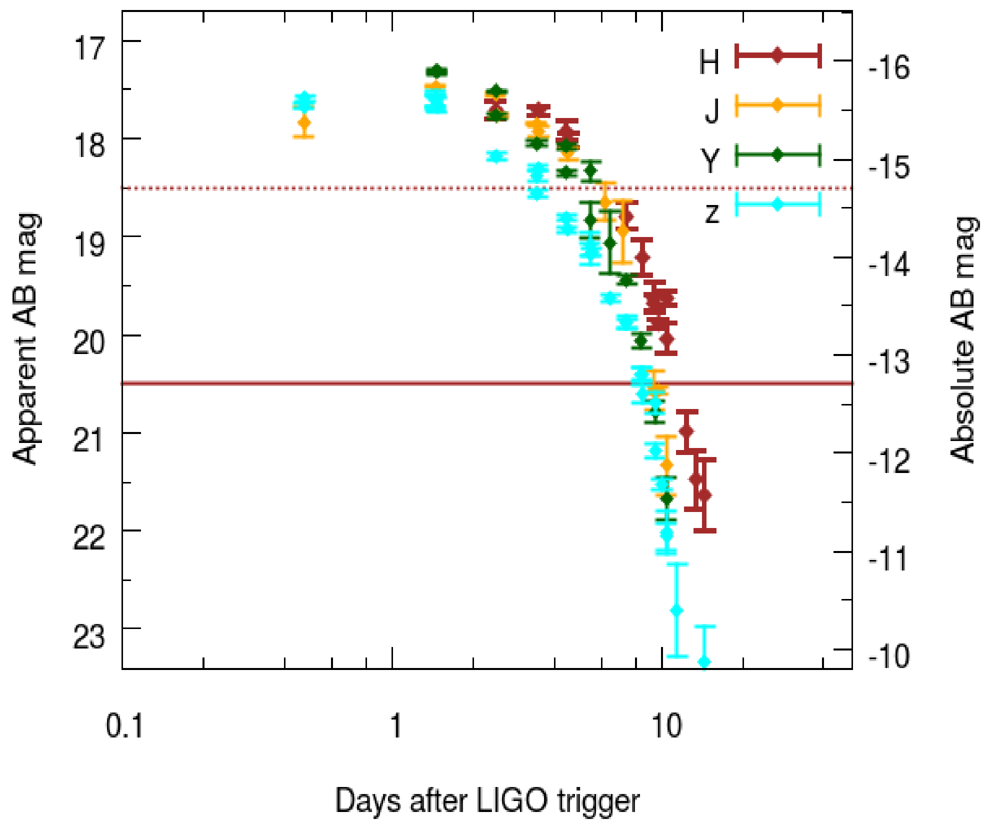
- ❑ NS-NS / NS-BH mergers:
  - ❑ **collimated** EM emission from short GRBs and their afterglows (rate of ≤ 1/yr for 2G GW detectors but up to 20/yr for 3G GW detectors as Einstein Telescope)
  - ❑ Optical/NIR and soft X-ray **isotropic** emissions from **macronovae, off-axis afterglows** and, for NS-NS, 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)

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



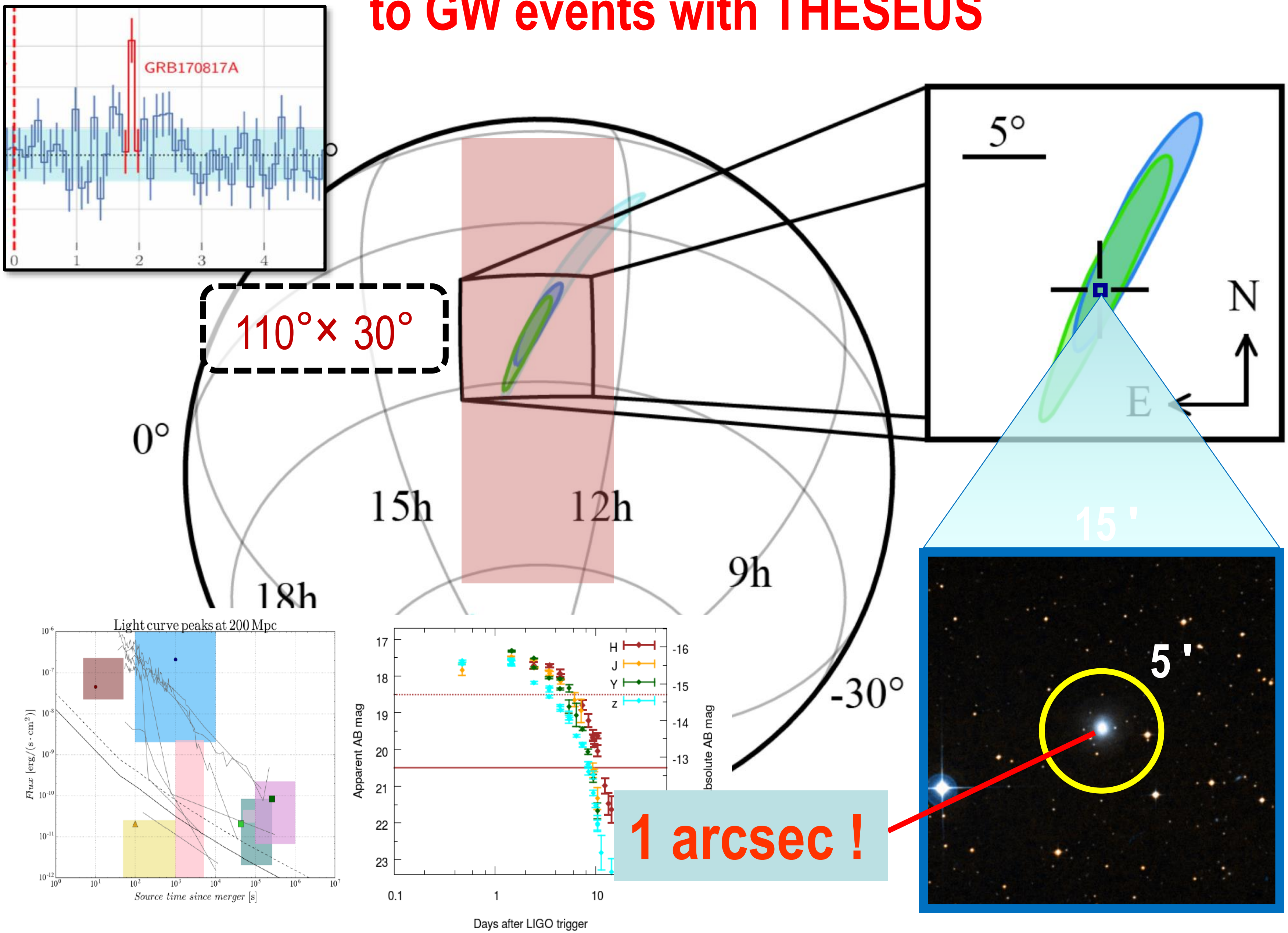
❑ Detection, study, arcsecond localization and redshift of afterglow and kilonova emission from shortGRB/GW events with THESEUS/IRT



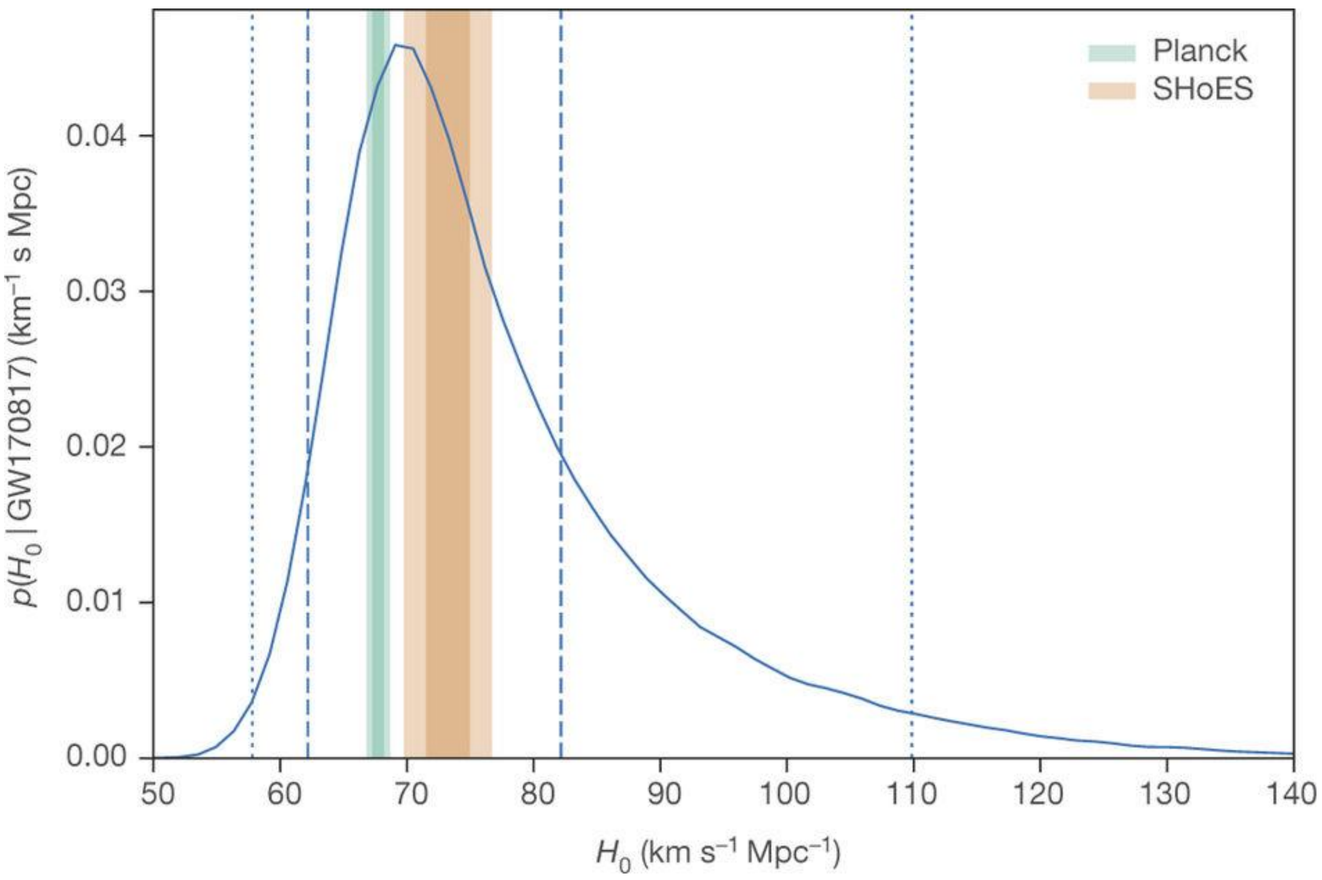


Precise localization is mandatory to activate large ground-based telescopes as VLT or ELT from which detailed spectral analysis will reveal the intrinsic nature of these newly discovered phenomena

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



- 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

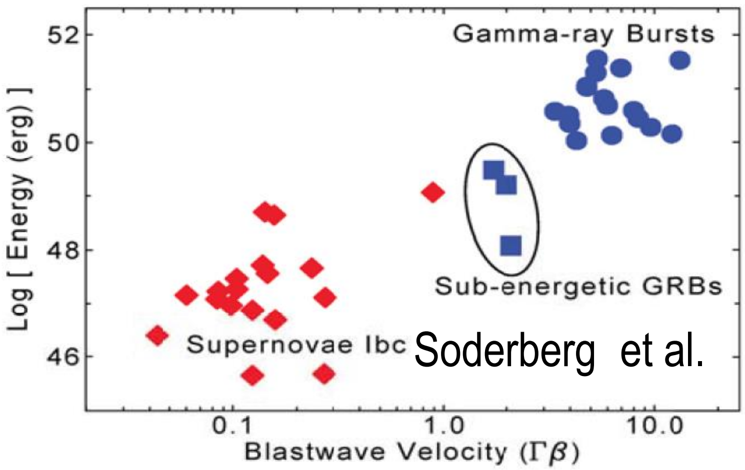
❑ Time-domain astronomy and GRB physics

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

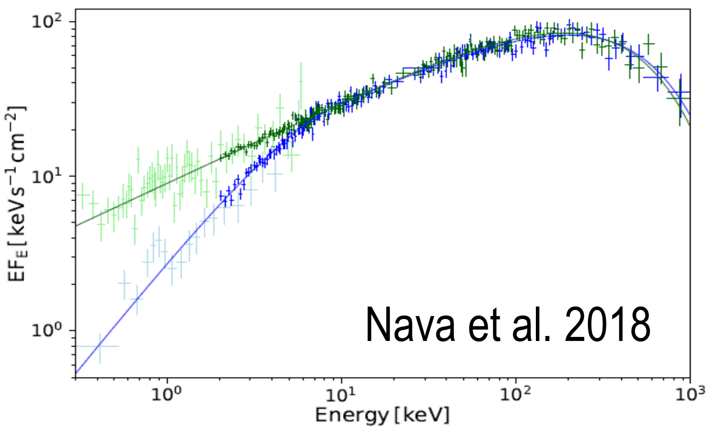
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;

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

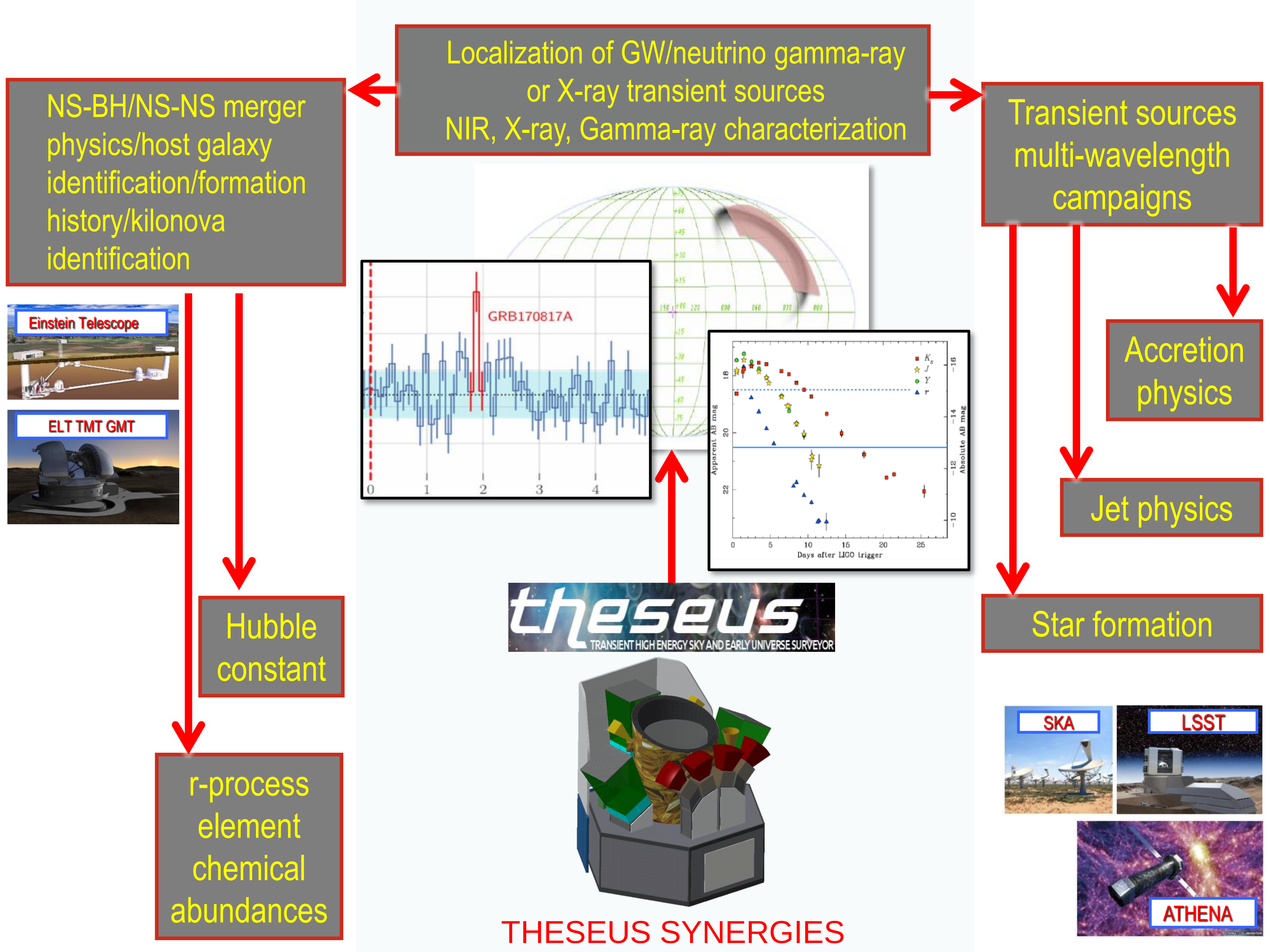
Transient type	SXI rate
Magnetars	40 day^{-1}
SN shock breakout	4 yr^{-1}
TDE	50 yr^{-1}
AGN+Blazars	350 yr^{-1}
Thermonuclear bursts	35 day^{-1}
Novae	250 yr^{-1}
Dwarf novae	30 day^{-1}
SFXTs	1000 yr^{-1}
Stellar flares	400 yr^{-1}
Stellar super flares	200 yr^{-1}



Soderberg et al.



Nava et al. 2018


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
Hubble
constant
Star formation
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
r-process
element
chemical
abundances
SKA
LSST
ATHENA
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 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+scint.)

- THESEUS observations will impact on several fields of astrophysics, cosmology and even 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)

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

Amati et al. 2017 (arXiv:1710.04638)
Stratta et al. 2017 (arXiv:1712.08153)

- *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