The synergy of ASTRI and CTA with future GRB missions

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

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(INAF – OAS Bologna)

(8 June 2022)

OAS

theseus
transient high energy sky and early universe surveyor

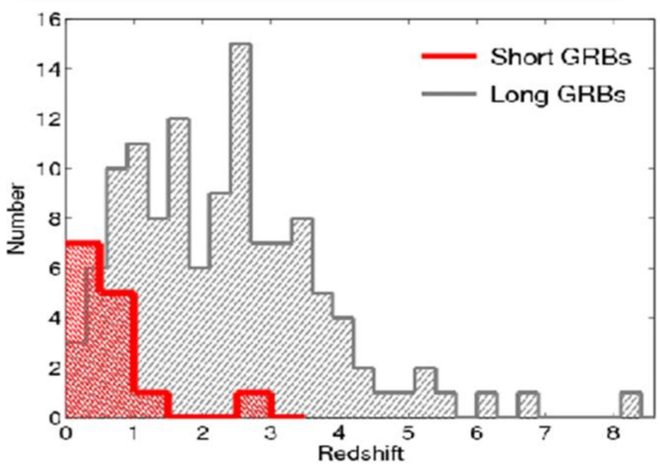
HERMES
Scientific Pathfinder

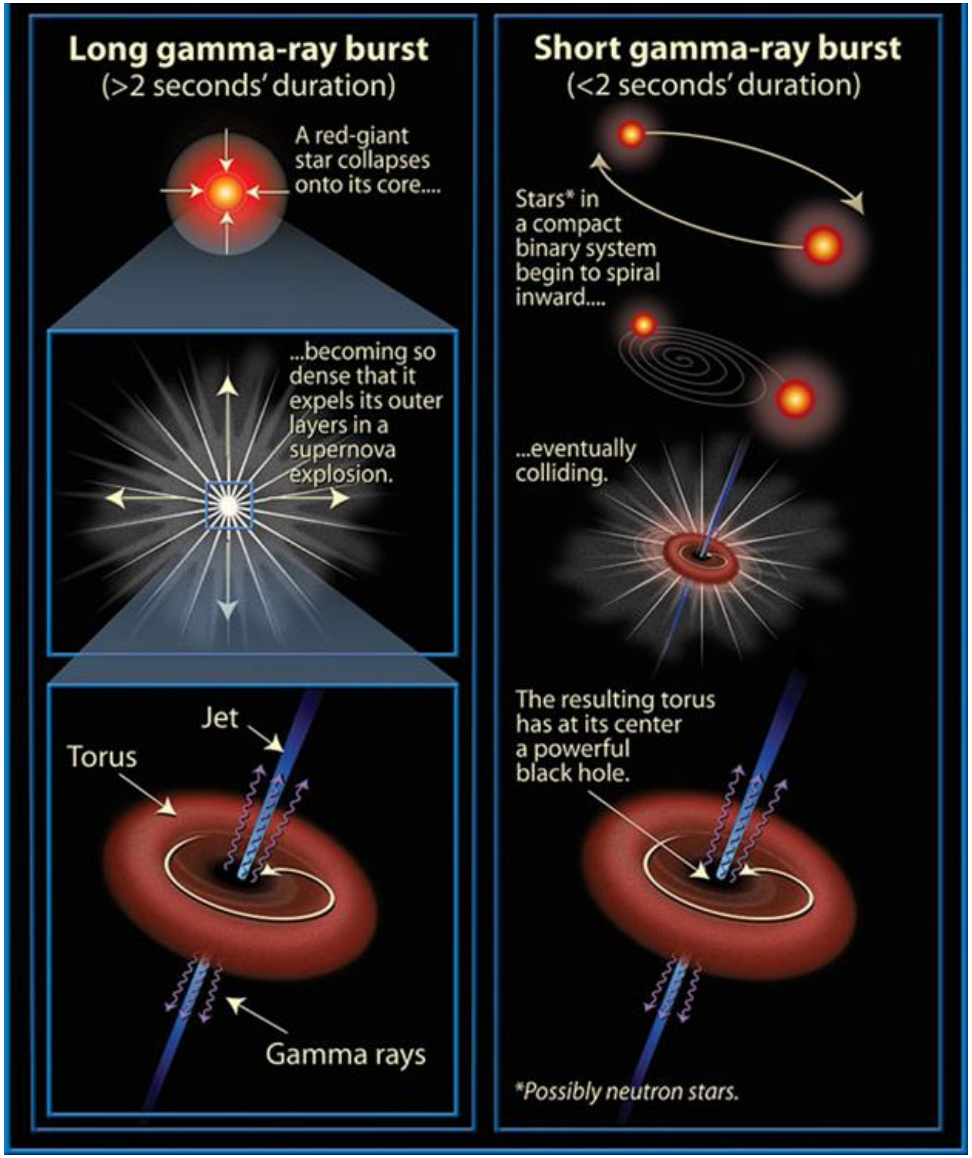
OAS Very High Energy Meeting: towards Astri and CTA

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

Long GRBs: core collapse of massive stars, **tracing primordial stars & galaxies**

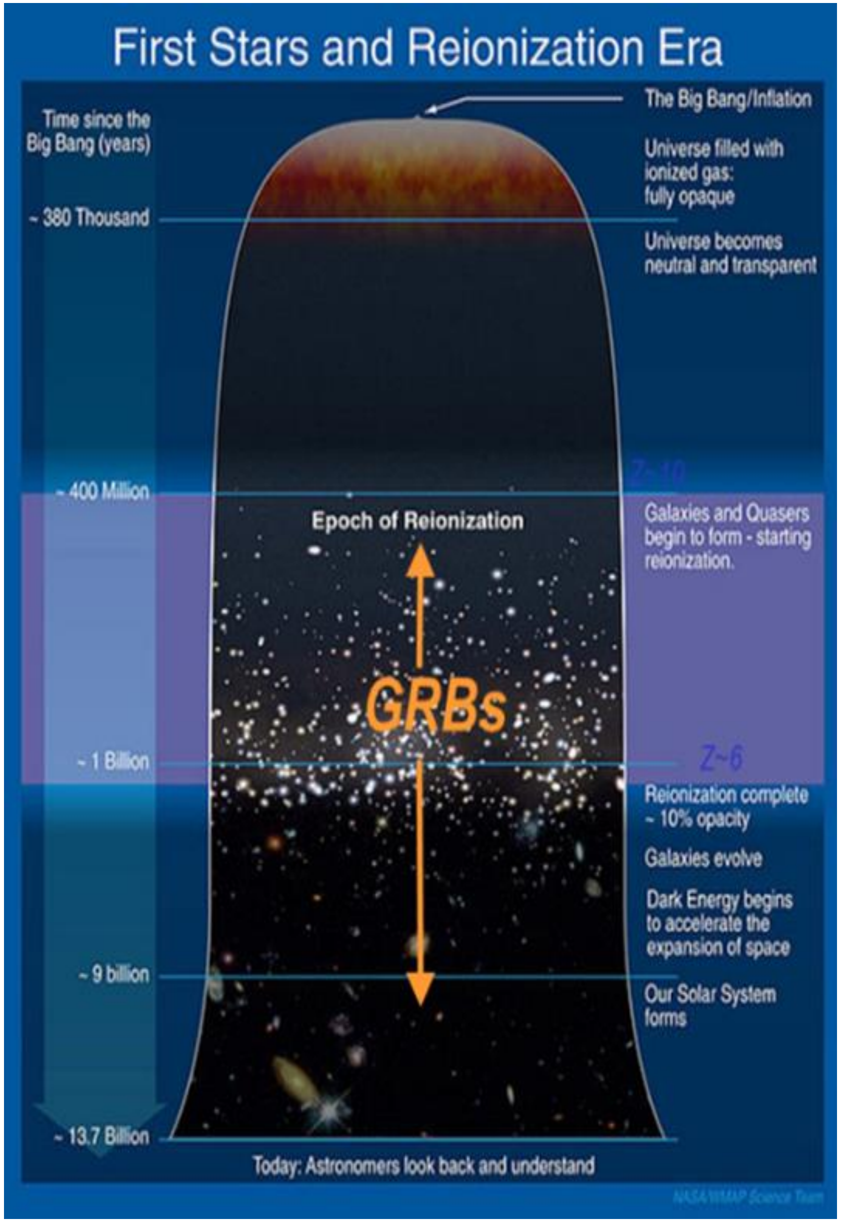
Short GRBs: NS-NS or NS-BH mergers, **association with GW sources**





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

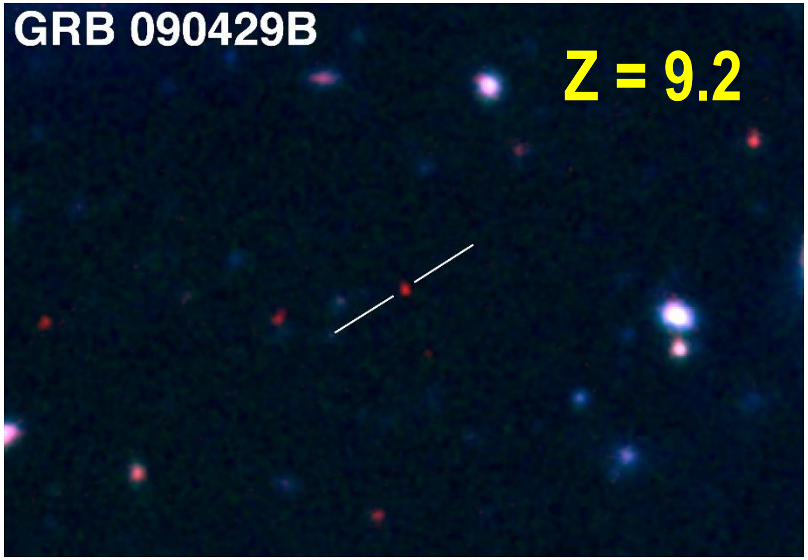


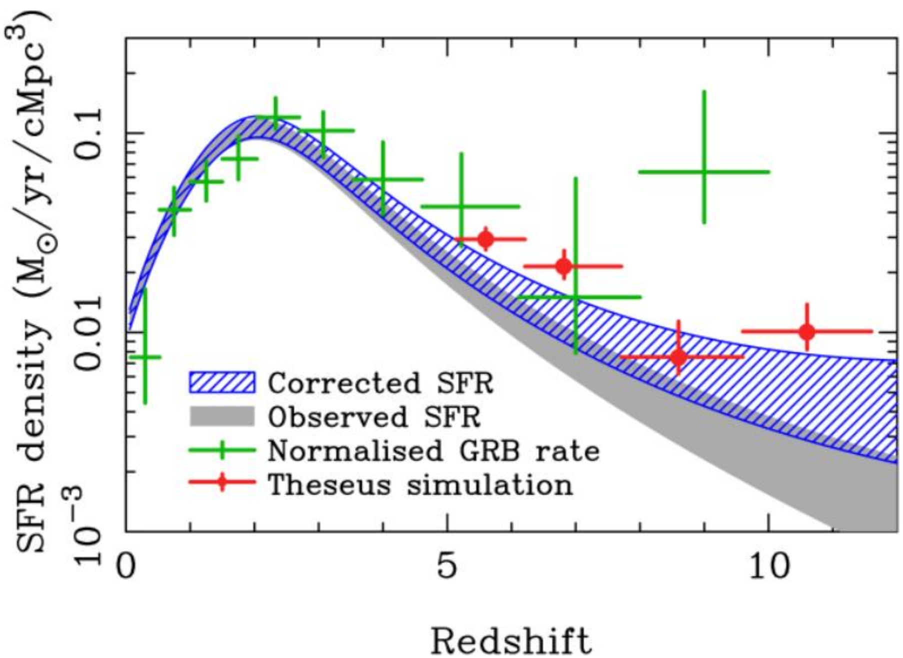
Shedding light on the early Universe with GRBs

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

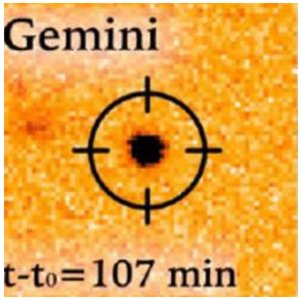
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

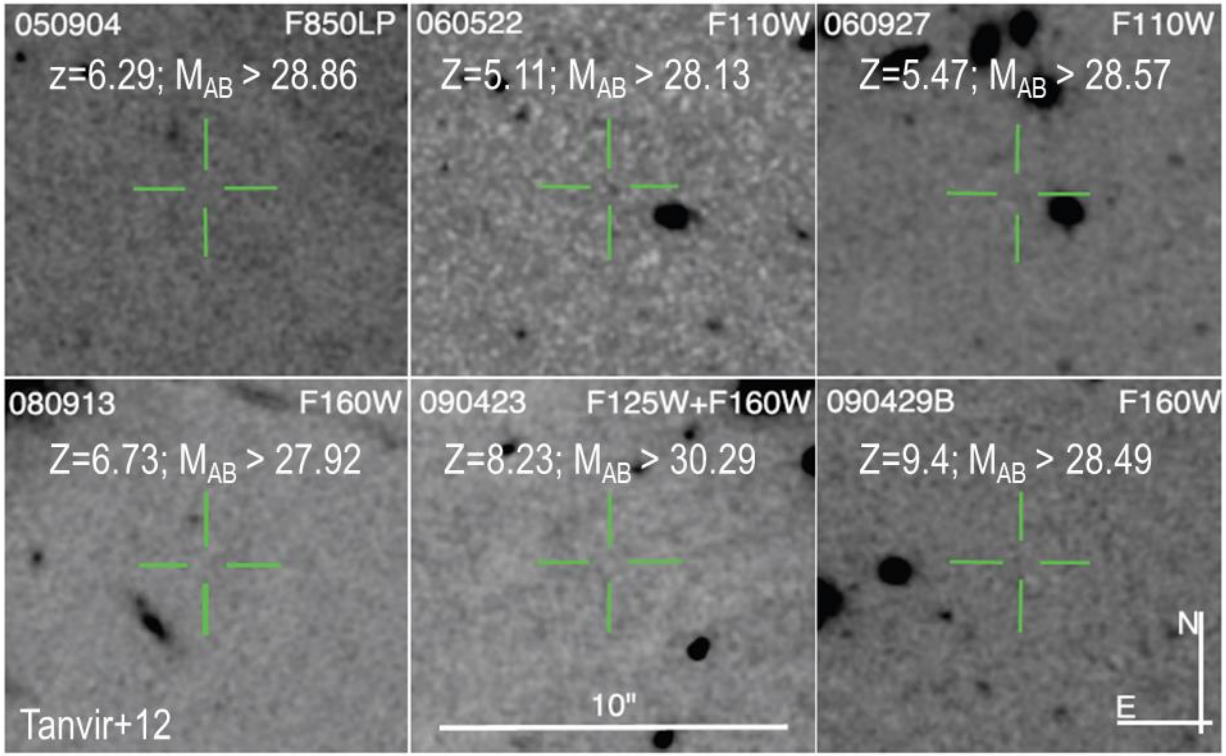
- directly (or indirectly) detect the **first population of stars (pop III)**





• Detecting and studying primordial invisible galaxies

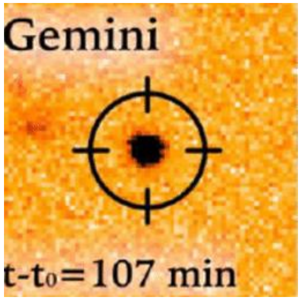


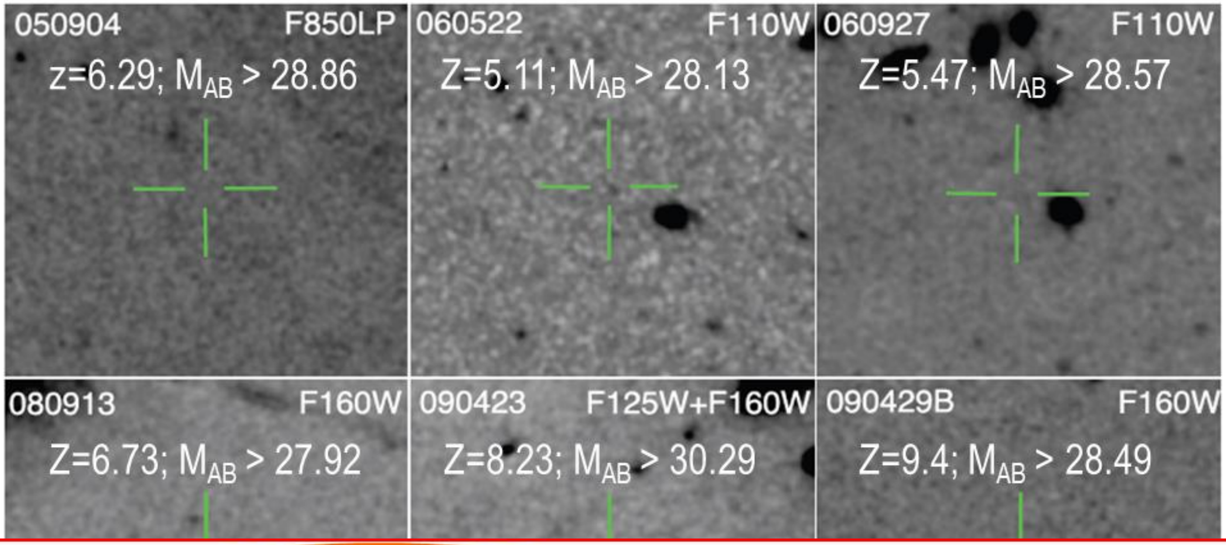


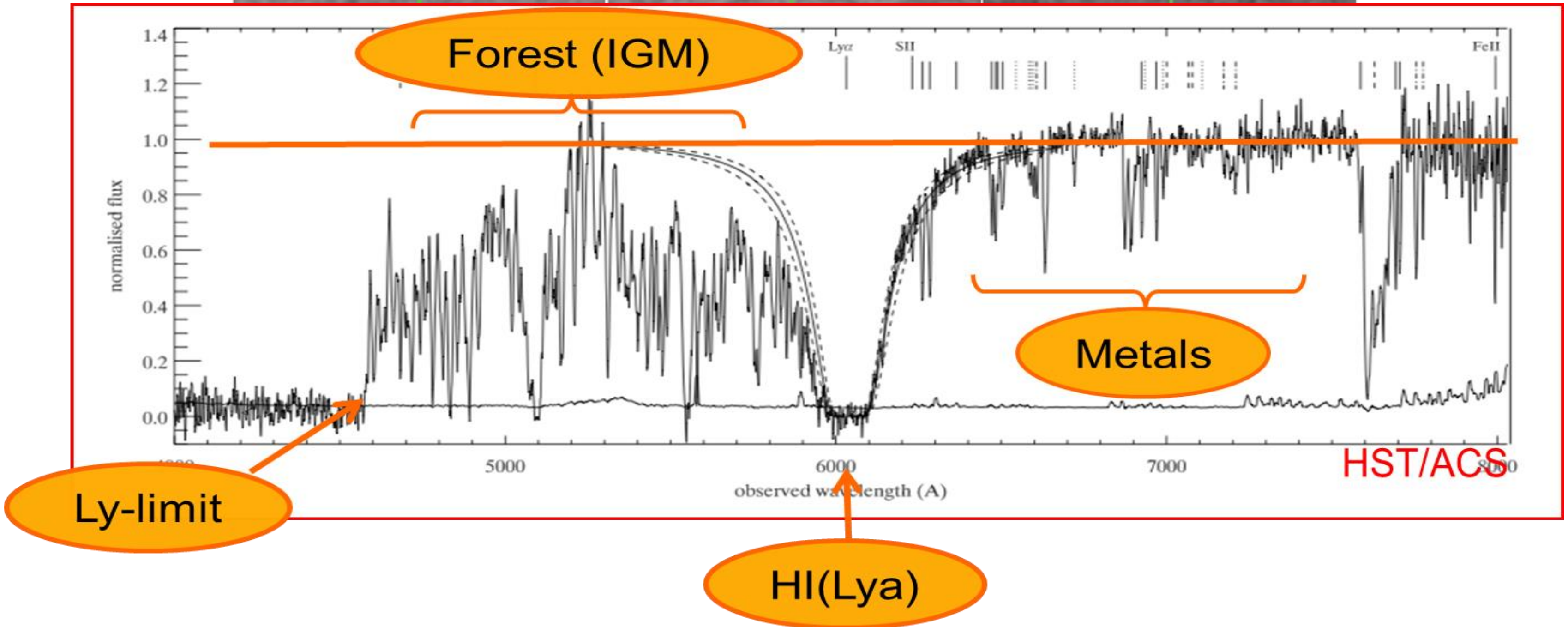
Robertson&Ellis12

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)

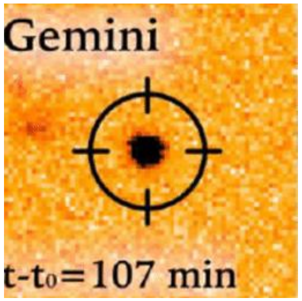
- **Detecting and studying primordial invisible galaxies**

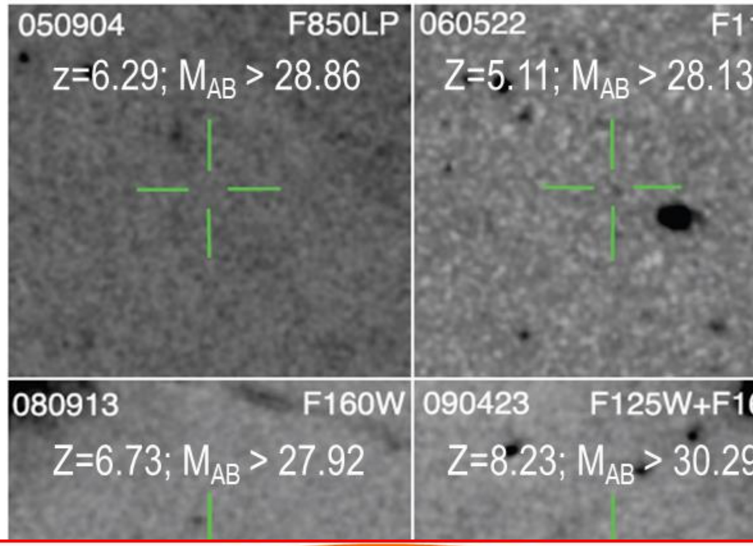




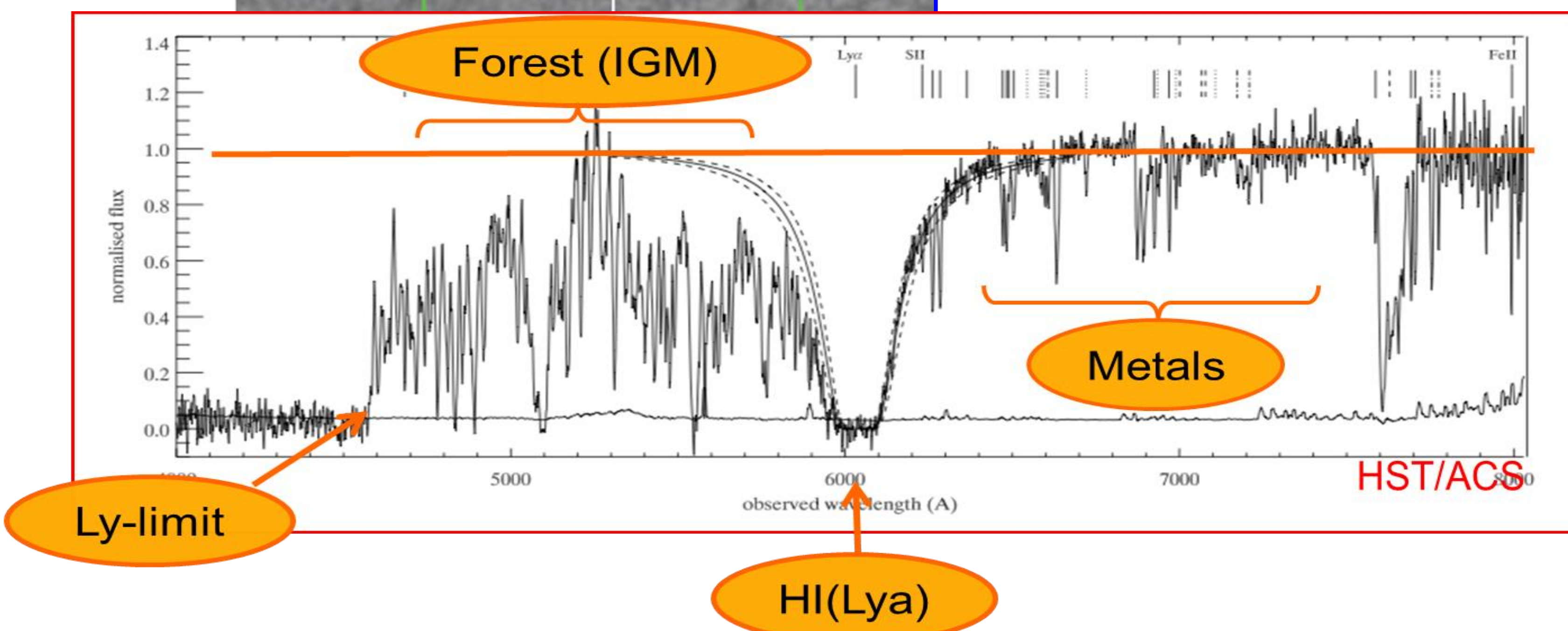


• Detecting and studying primordial invisible galaxies





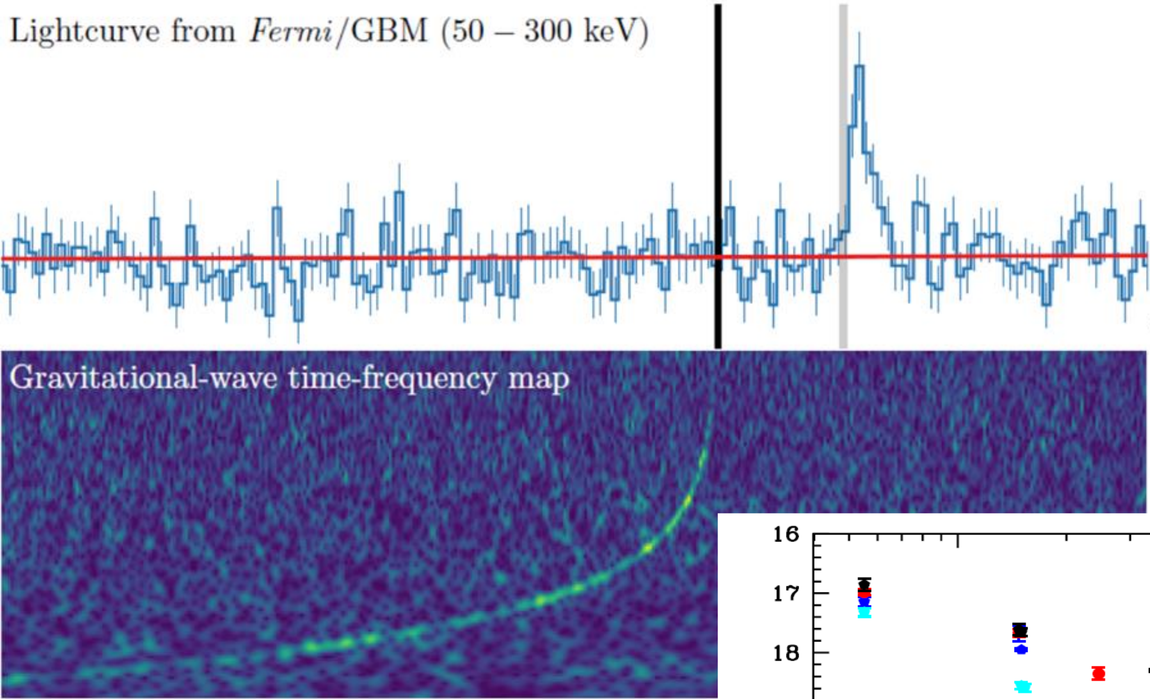
- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

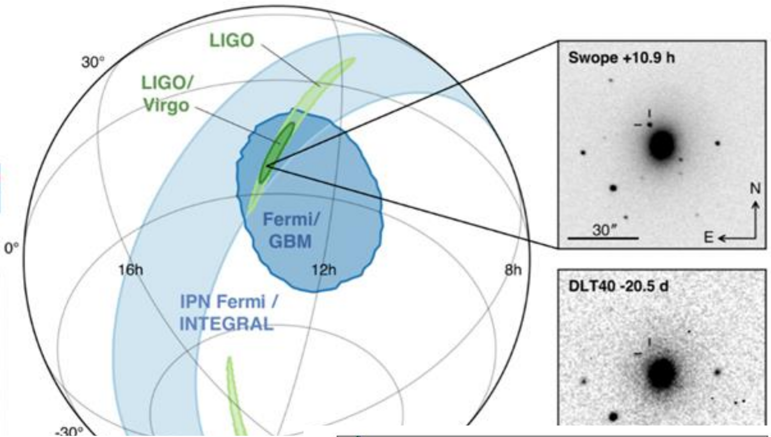


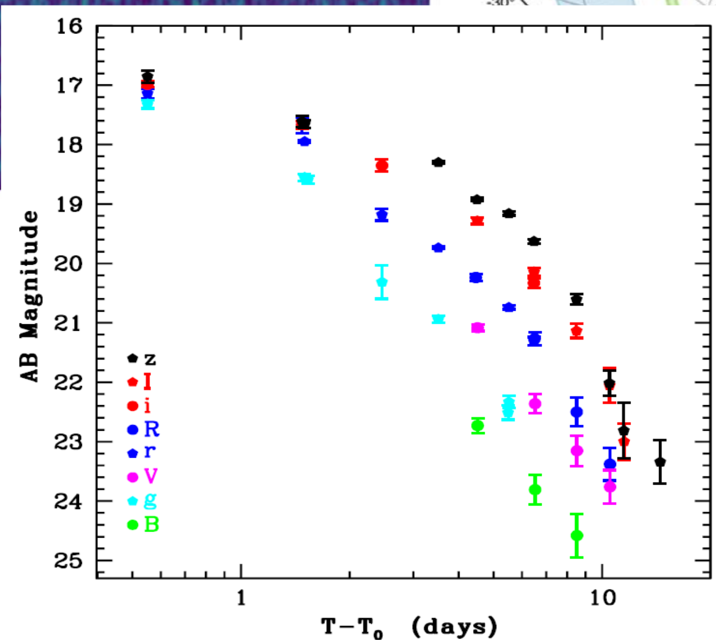
Short GRBs and multi-messenger astrophysics

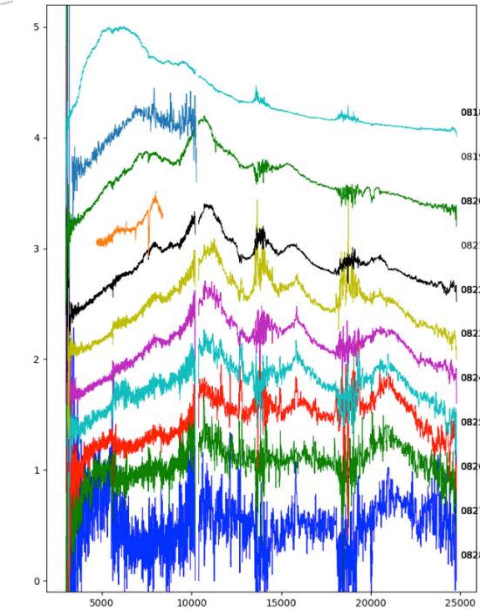
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics









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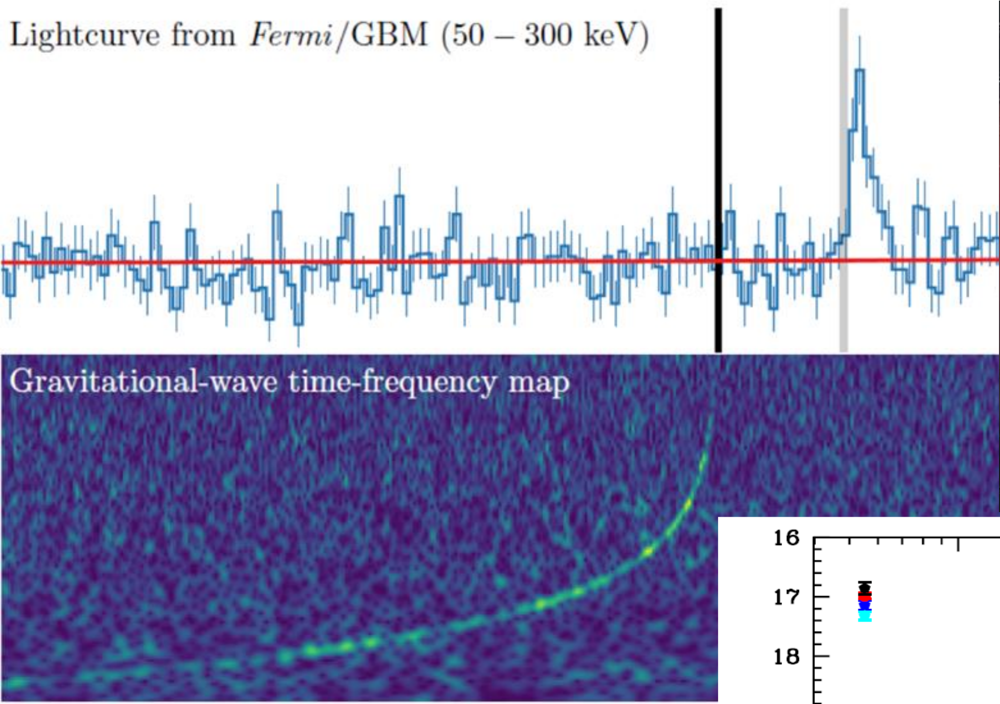
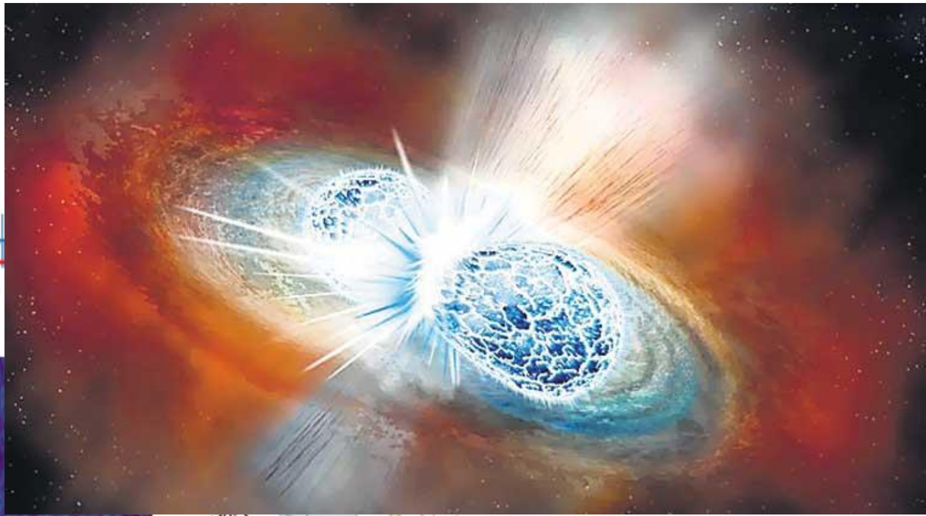
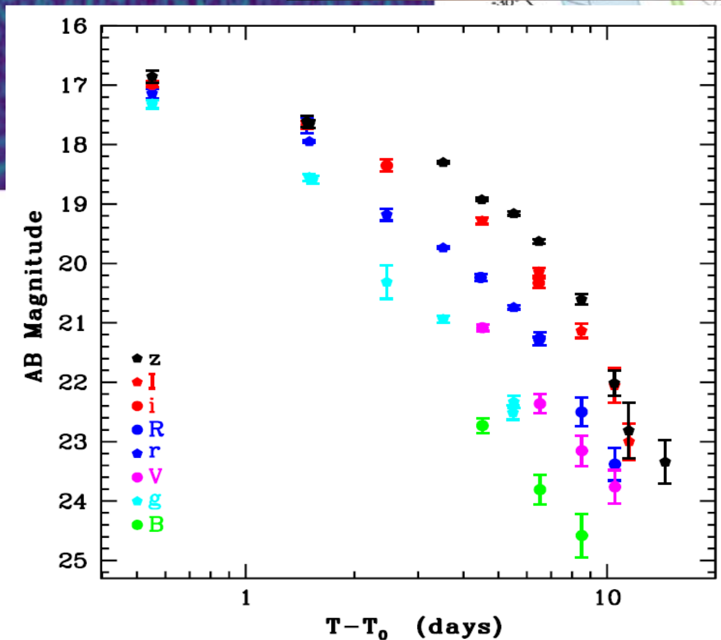
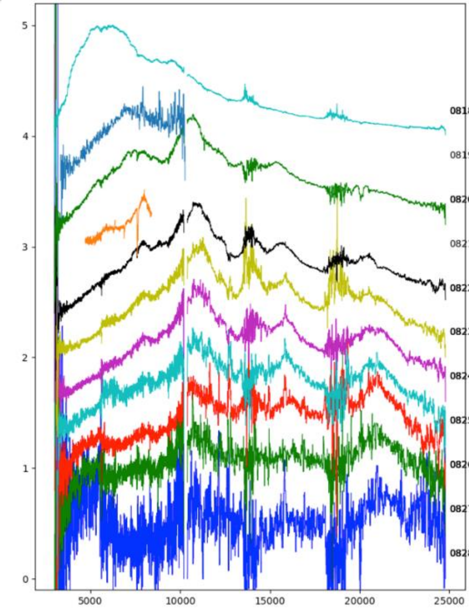




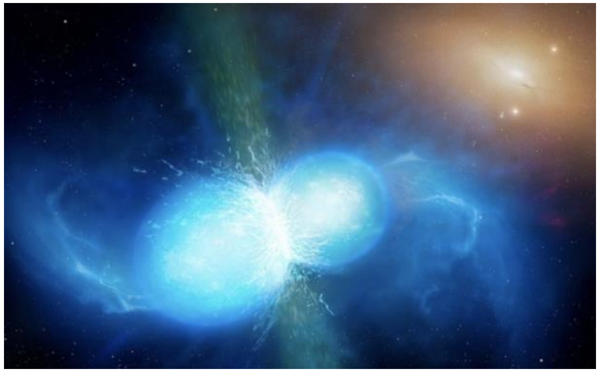




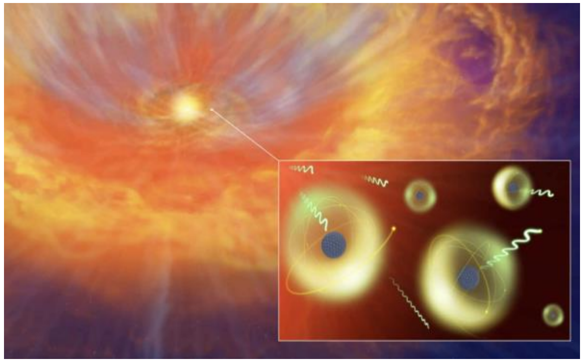
Short GRBs and multi-messenger astrophysics

GW170817 + SHORT GRB 170817A + KN AT2017GFO
THE BIRTH OF MULTI-MESSENGER ASTROPHYSICS

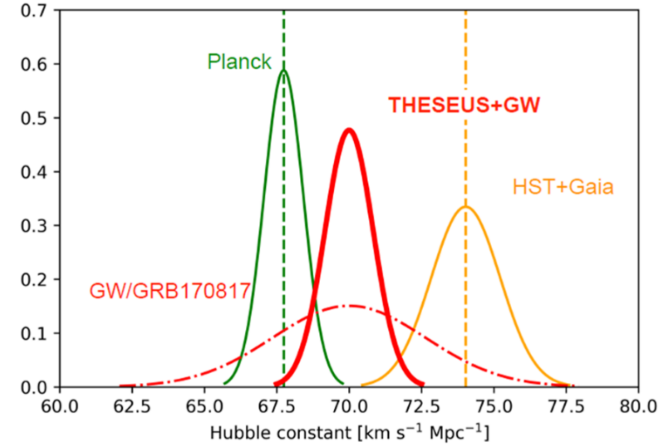
Relativistic jet formation, equation of state, fundamental physics



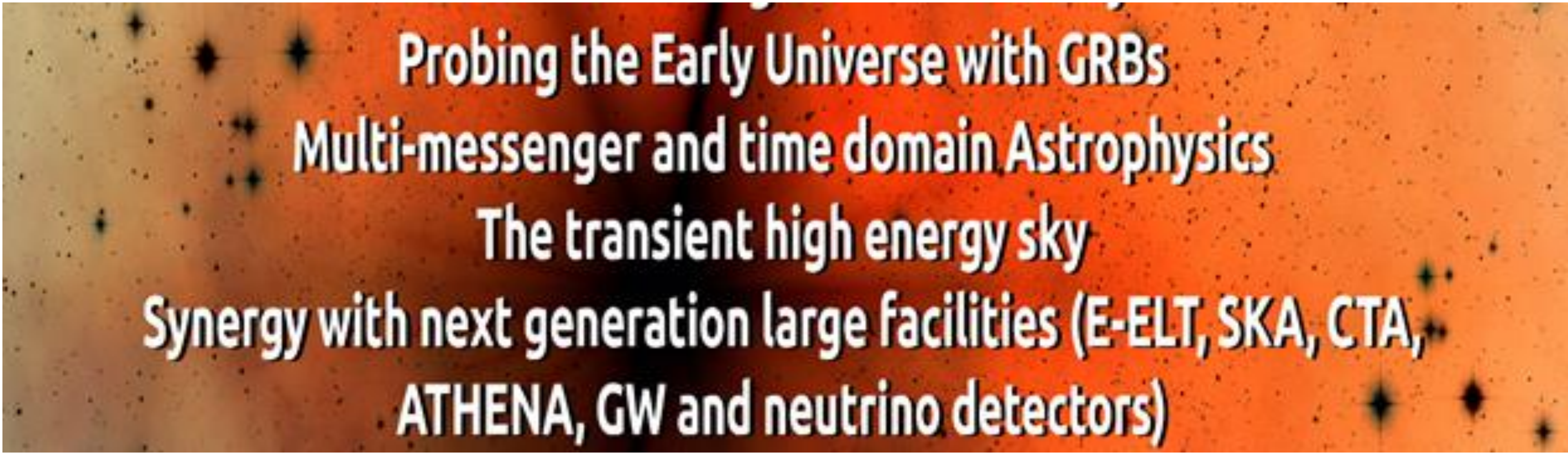
Cosmic sites of r-process nucleosynthesis



New independent route to measure cosmological parameters



Future GRB missions (late'20s and '30s)



- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (idea for NASA probe-class mission**), Gamow Explorer** (proposal for NASA MIDEX**): prompt emission down to soft X-rays, source location accuracy of few arcmin**, **prompt follow-up with NIR telescope**, **on-board REDSHIFT**

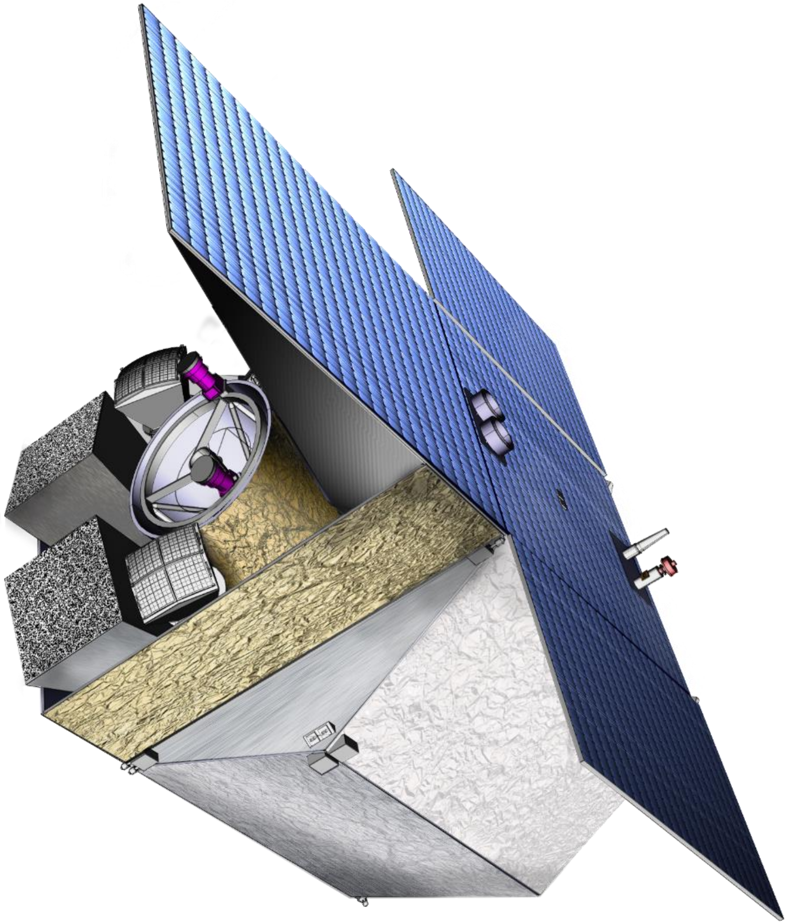
Future GRB missions: the case of THESEUS

(led by Italy; ESA/M5 Phase-A study, re-proposed for M7)

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, sensitivity, FOV and localization accuracy**

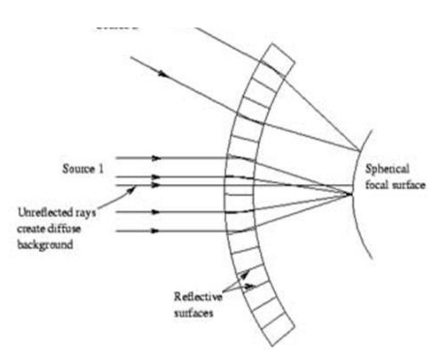
On-board **autonomous fast follow-up** in optical/NIR, arcsec location and **redshift measurement** of detected GRB/transients

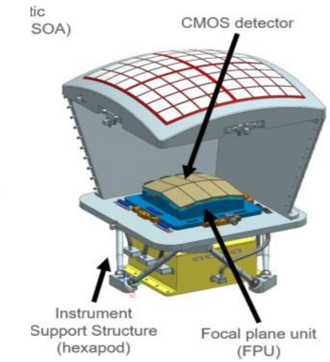


Future GRB missions: the case of THESEUS

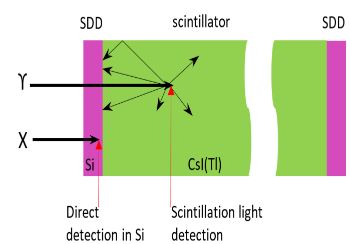
(led by Italy; ESA/M5 Phase-A study, re-proposed for M7)

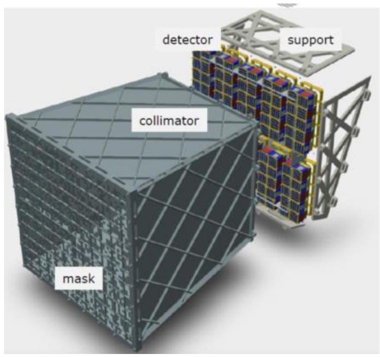
- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2′



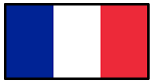


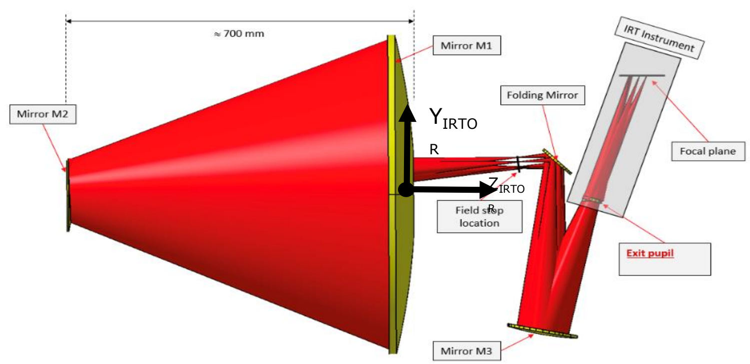
- **X-Gamma rays Imaging Spectrometer (XGIS):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy





- **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





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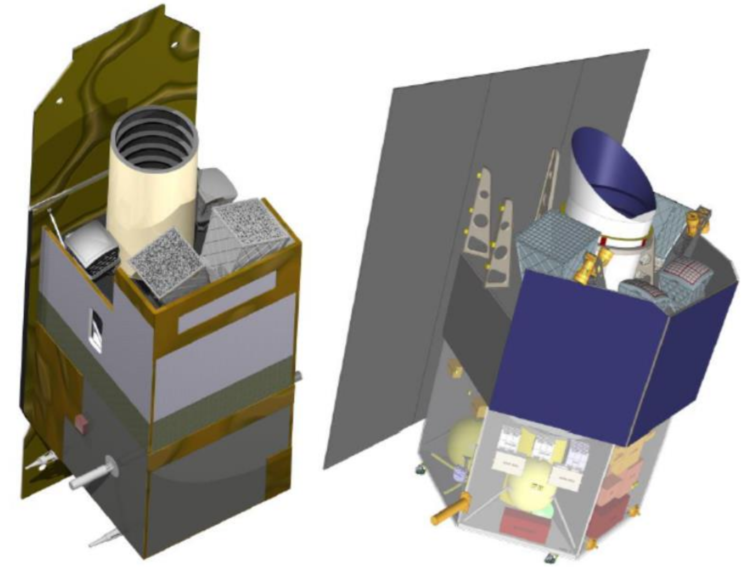
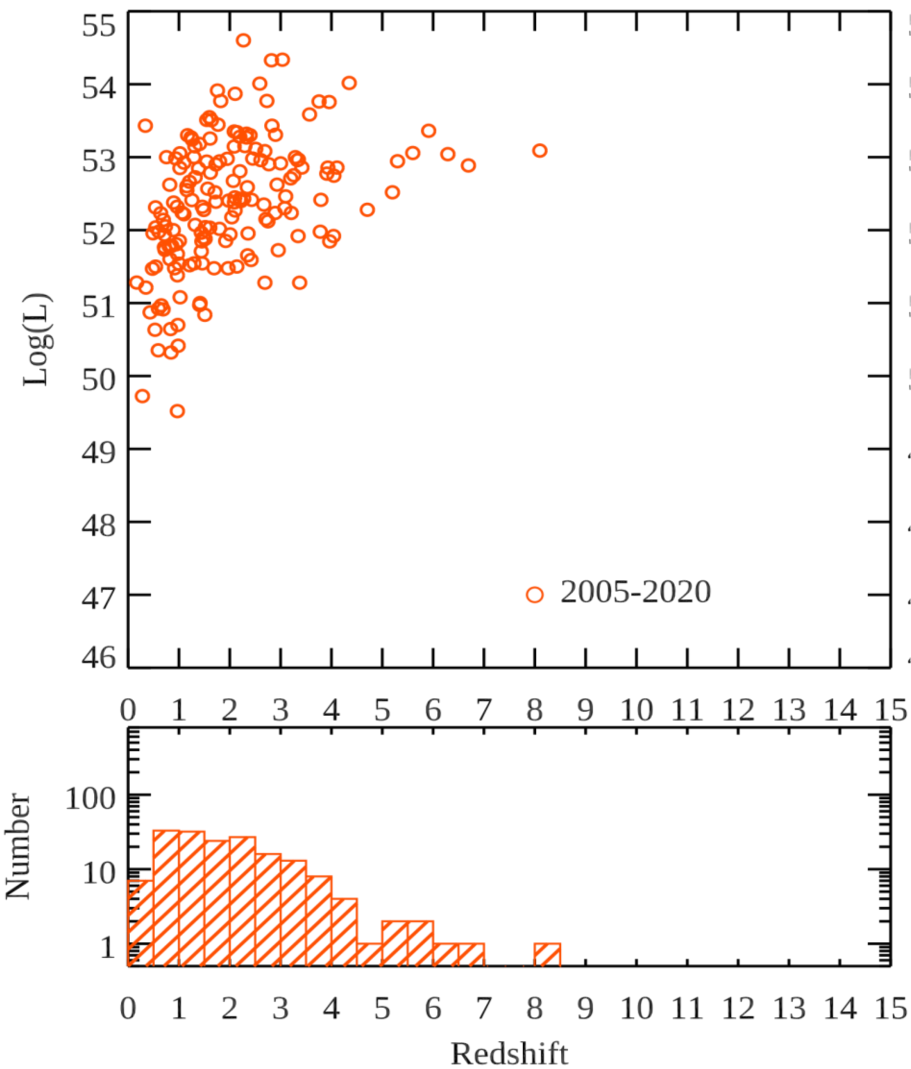
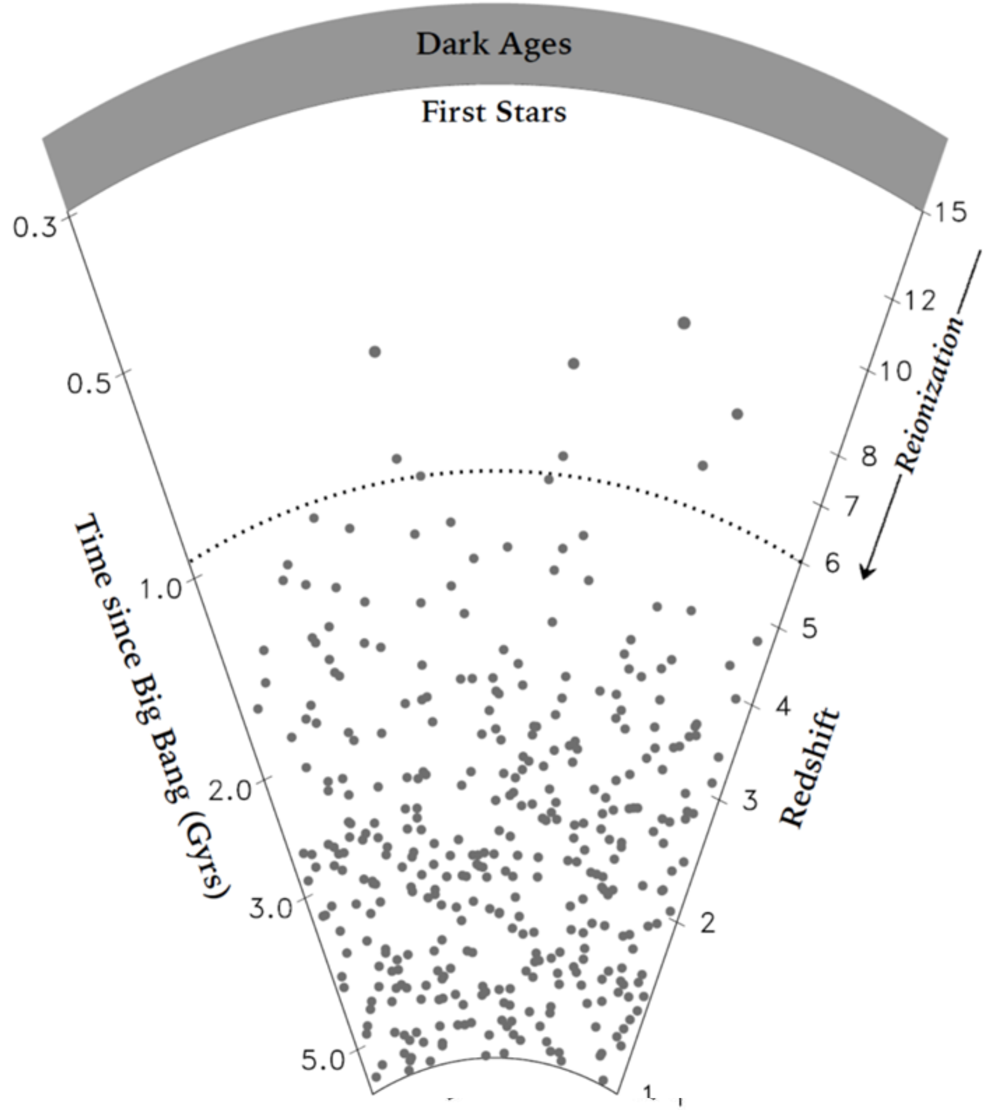


Figure 5-4 - Schematic view of the spacecraft design for the Phase A ADS (left) and TAS (right) Studies.

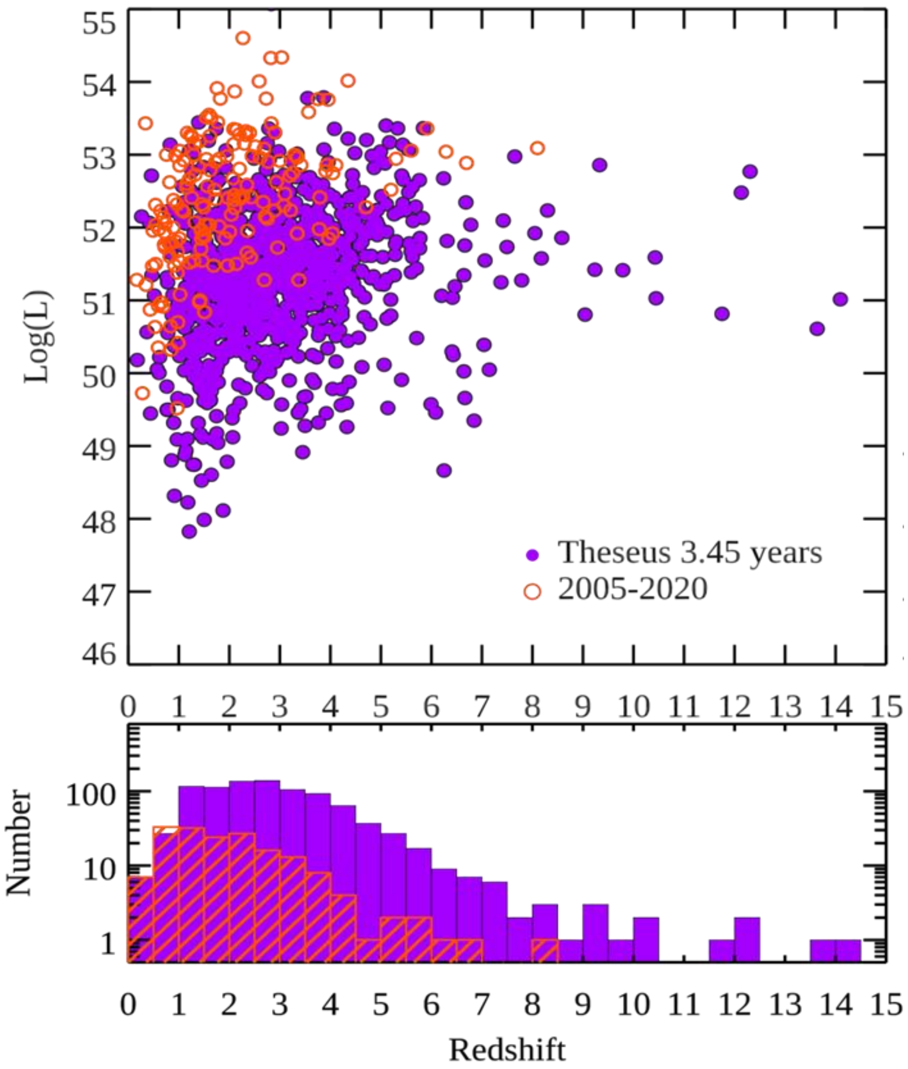
- **Low Earth Orbit (< 5°, ~600 km)**
- **Autonomously rapid slewing bus**
- **4-years nominal**

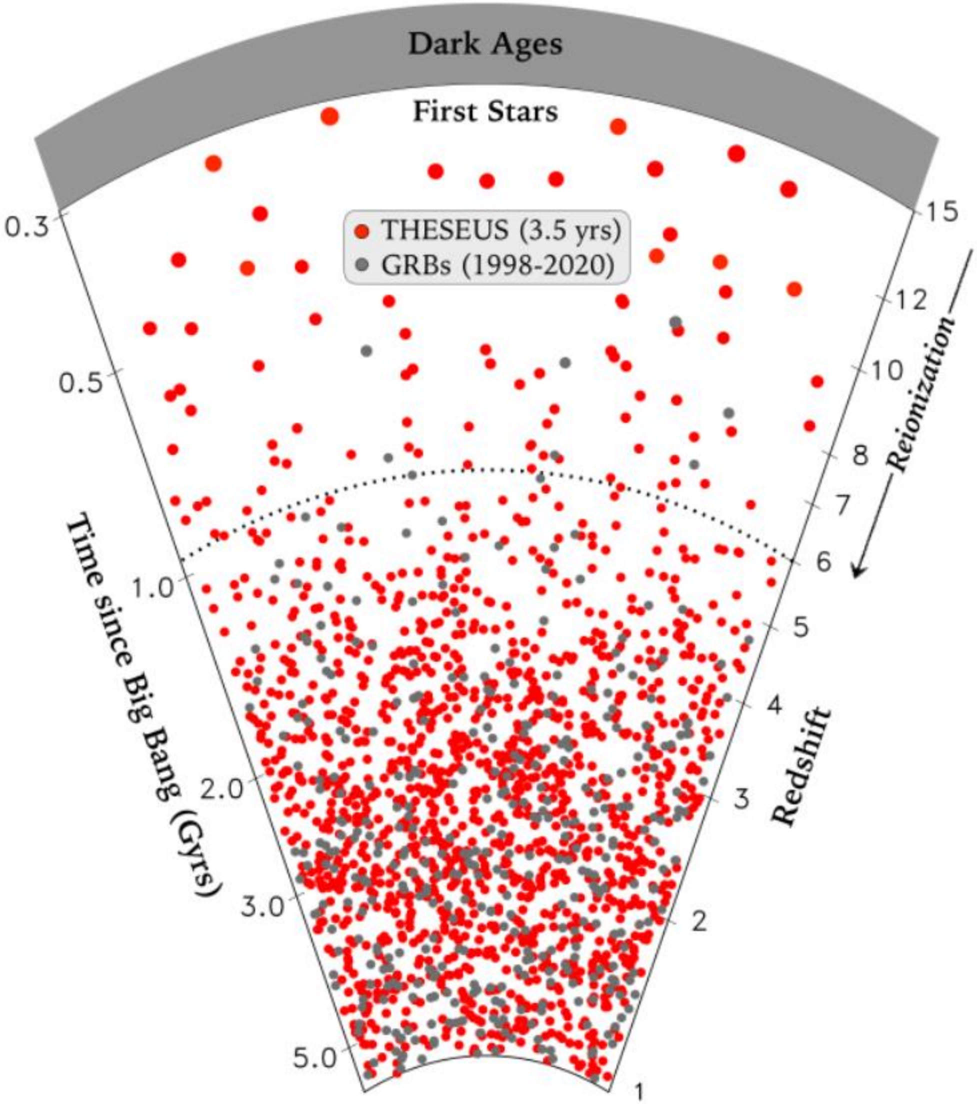
Shedding light on the early Universe with GRBs



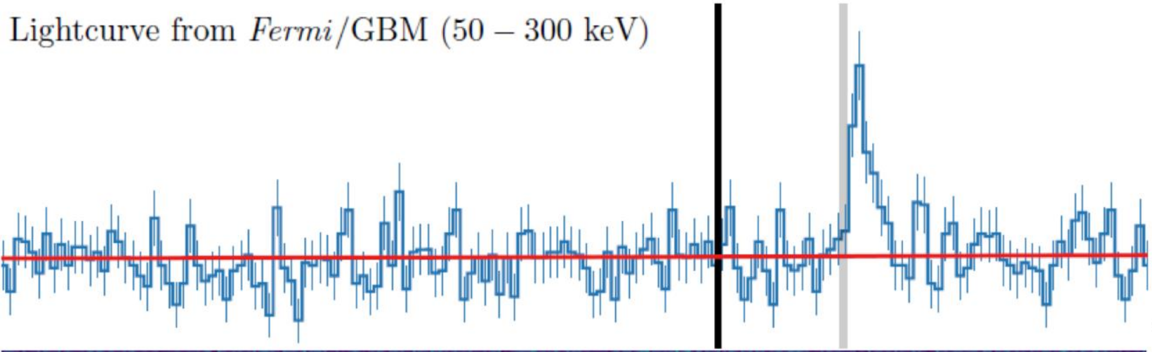


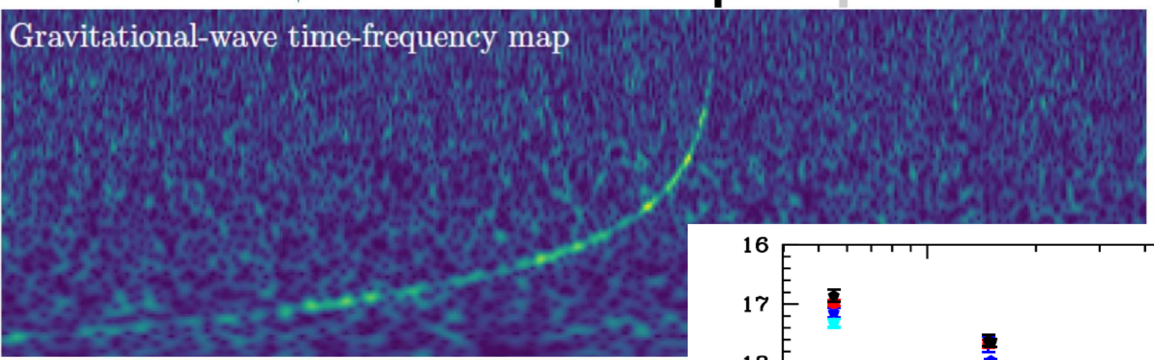
Shedding light on the early Universe with GRBs

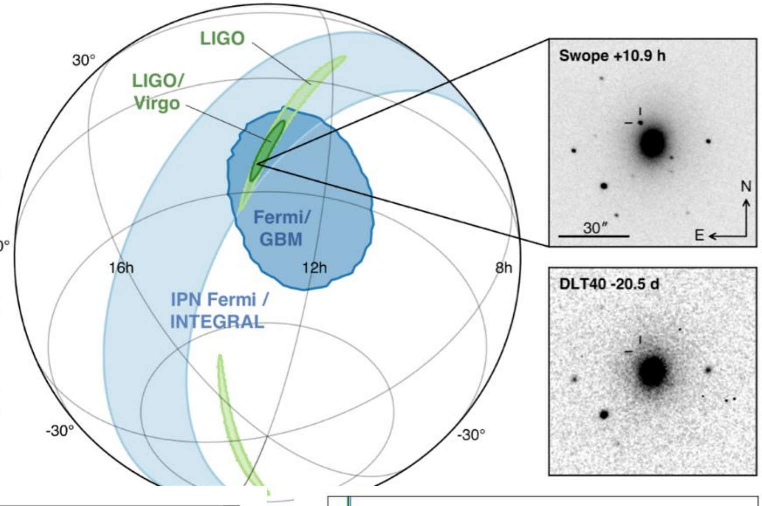


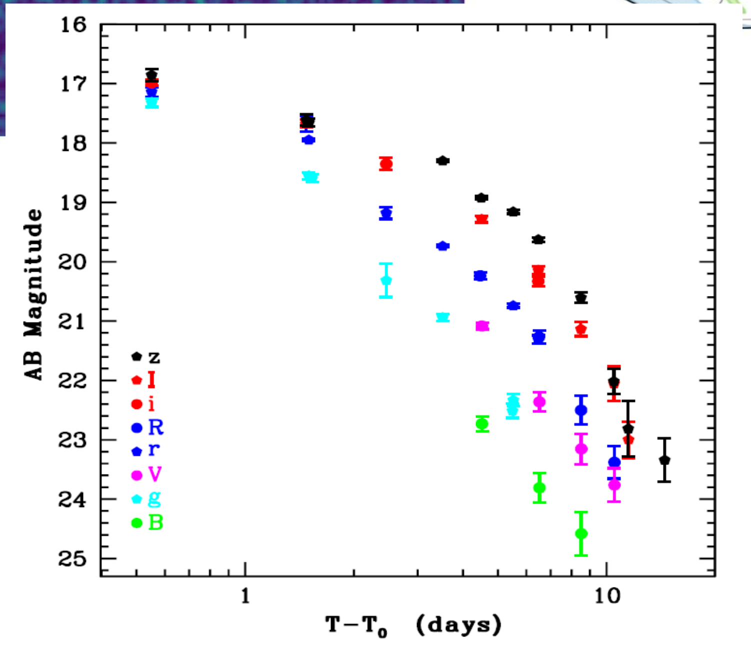


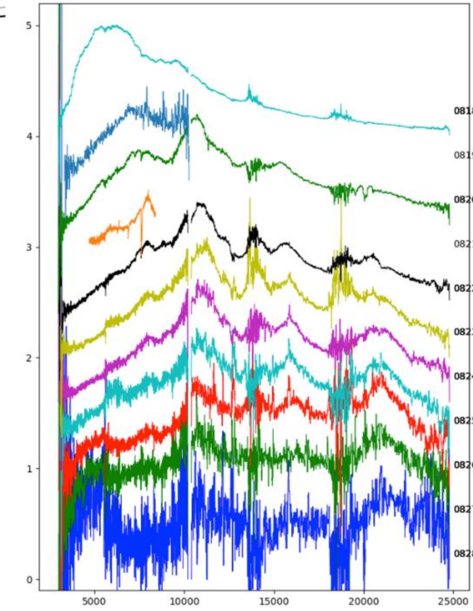
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars





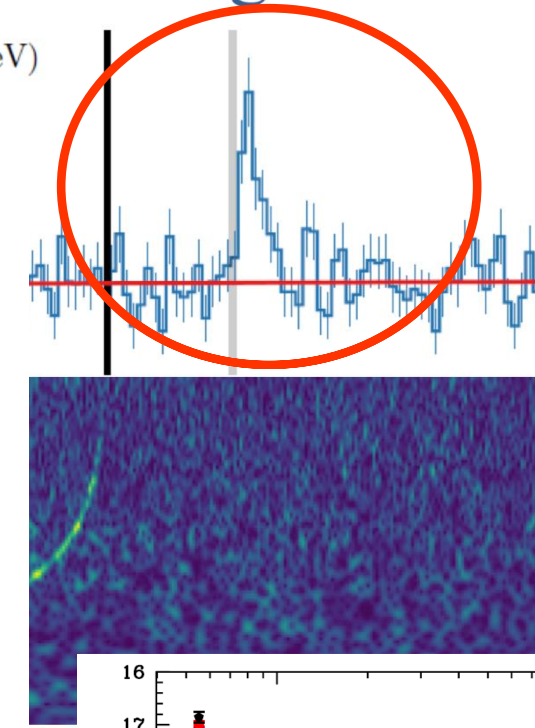






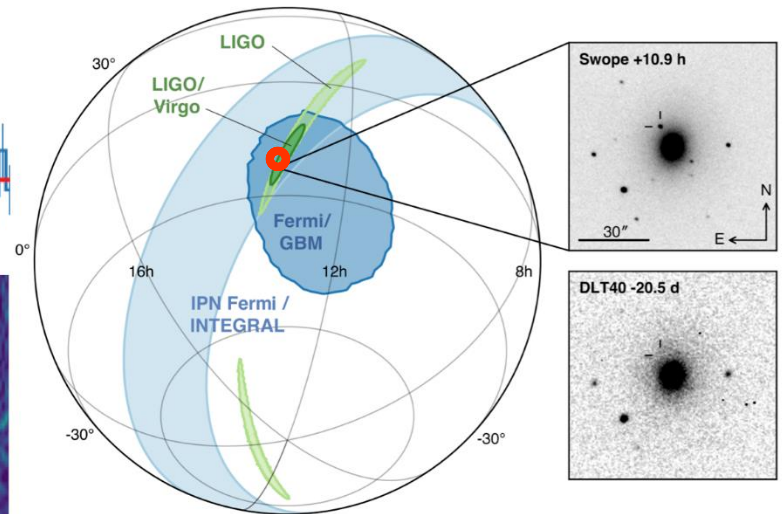
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

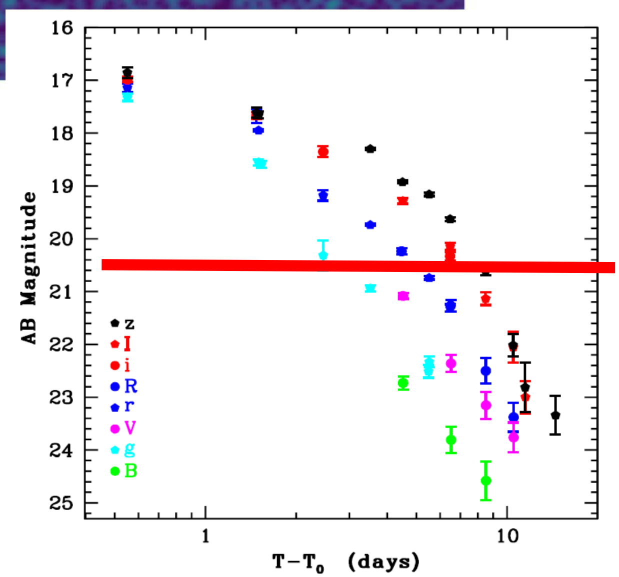
Lightcurve from *Fermi*/GBM (50 – 300 keV)

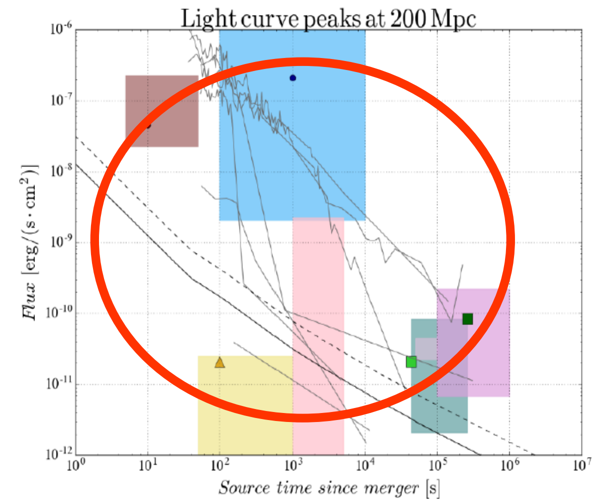


THESEUS:

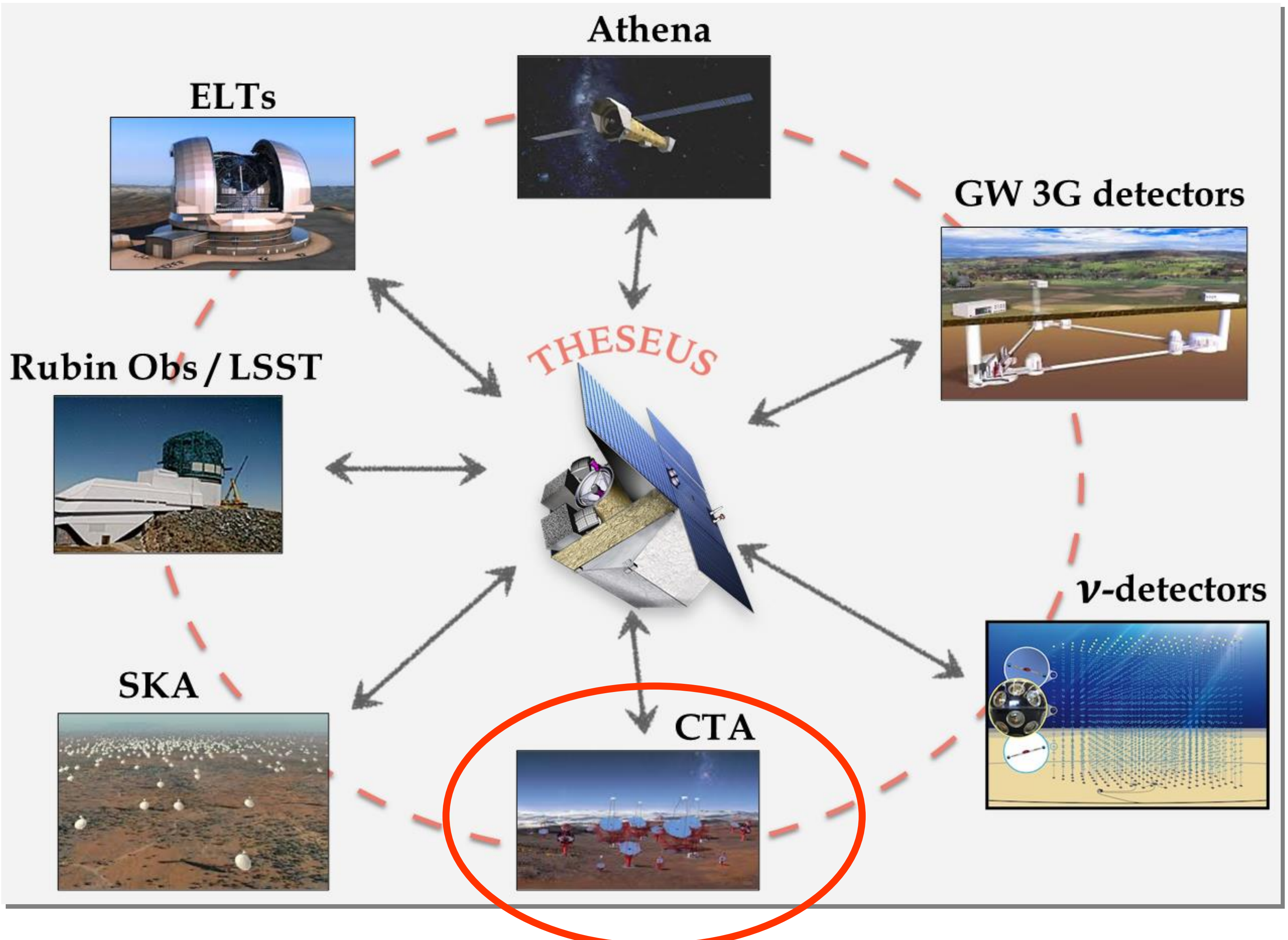
- ✓ **short GRB detection over large FOV with arcmin localization**
- ✓ **Kilonova detection, arcsec localization and characterization**
- ✓ **Possible detection of weaker isotropic X-ray emission**







Multi-wavelength/messenger synergies



Synergy with CTA (and ASTRI)

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Memorie della

Synergies between the Cherenkov Telescope Array and THESEUS

M. G. Bernardini[1,2] for the CTA consortium[3]

[1] Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, Montpellier, France
[2] INAF–Osservatorio Astronomico di Brera, via E. Bianchi 46, I–23807 Merate, Italy
[3] See http://www.cta-observatory.org/consortium_authors/authors_2017_10.html for full author and affiliation list
e-mail: bernardini@lupm.in2p3.fr

Abstract. The Cherenkov Telescope Array (CTA) is designed to be the next major observatory operating in the Very High Energy (VHE, $\gtrsim$ 100 GeV) gamma-ray band. It will build on the imaging atmospheric Cherenkov technique but will go much further in terms of performance than current instruments. Its sensitivity at short timescales and the rapid repointing system will make CTA a perfect facility to observe the gamma-ray transient sky. In this respect, the synergies between CTA and other multi-wavelength and multi-messenger facilities are expected to further enhance CTA's scientific scope. Thanks to its characteristics, THESEUS will perform an unprecedented monitoring of the X-ray variable sky, detecting, localising, and identifying transients. It will provide external triggers and accurate location for the CTA follow-up of transients, and their broadband characterisation, playing a key role for CTA after the next decade.

5. Synergies with future facilities		
Surname and Name	**Country**	**Institute**
Basa Stephane	France	CEA
Rosati Piero	Italy	University of Ferrara
Branchesi Marica	Italy	GSSI
5.1 SVOM, EP, and GRB missions of the 20s		
Cordier Bertrand	France	CEA
5.2 Athena		
O'Brien Paul	United Kingdom	University of Leicester
5.3 LISA		
Sesana Alberto	Italy	Milano-Bicocca University
5.4 3G GW detectors (ET, CE)		
Maggiore Michele	Switzerland	University of Geneva
5.5 SKA, Alma and large radio facilities		
Ferrara Andrea	Italy	Scuola Normale Superiore di Pisa
5.6 Extremely large telescopes (ELT/TMT)		
Vergani Susanna	France	Observatoire de Paris
5.7 CTA		
Schussler Fabian	France	CEA
Zanin Roberta	Italy	INAF-OAS Bologna
Longo Francesco	Italy	University of Trieste
5.8 Km3Net and neutrino detectors		
Spurio Maurizio	Italy	University of Bologna
5.9 LSST		
Andreja Gomboc	Slovenia	University of Nova Gorica

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Synergies betwe
Arra

M. G. Bern

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CNRS/IN2P3, Montpellier, Fr
[2] INAF–Osservatorio Astronom
[3] See http://www.cta-observato
author and affiliation list
e-mail: bernardini@lupm.i

Abstract. The Cherenkov Teles
tory operating in the Very High E
the imaging atmospheric Chere
mance than current instruments.
system will make CTA a perfe
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million bodies in the Solar System. It is very likely that Rubin observations, with emphasis on variable and transient sources, will continue after the first 10 years of operations.

Science operations of the VRO are planned to start in 2024 and continue through the next decade. Its four main science drivers are: (1) understanding dark matter and dark energy, (2) hazardous asteroids and the remote Solar System (3) formation and structure of the Milky Way, and (4) variable and transient sources. In particular, it will be a revolutionary and powerful transient machine: a stream of 1-10 million time-domain events per night are expected to be detected with real-time data analysis. They will be transmitted within 60 seconds of observation. A number of observing strategies are under study, with different combinations of cadence and sky coverage, to provide adequate discovery space for a variety of classes of transients.

THESEUS has survey capabilities for high-energy transient phenomena complementary to VRO in the optical. Their joint availability in the next decade will enable a remarkable scientific synergy between them. Specifically:

a) The catalogue of 20 billion galaxies provided by the VRO (combined magnitudes $r < 27.5$ and time resolved measurements to $r < 24.5$) – characterized in shape, colour, and variability – will be an invaluable resource for identification studies of THESEUS transients, including location and properties of the host galaxies of GRBs, GW events, TDEs etc. and their galactic environments.

b) Real-time observations of various classes of high energy transients will be possible. Although triggering and follow-up observations with the Rubin Obs-LSST/VRO are not envisaged, a wealth of unique data will be available in the LSST images taken (serendipitously) just prior, during or soon after transient events detected by THESEUS (GRBs, GW events, TDEs, magnetars/SGRs, SN shock break-outs, SFXTs, thermonuclear bursts from accreting neutron stars, Novae, dwarf novae, stellar flares, AGNs and Blazars). LSST will conservatively generate thousands of transient alerts of interest to HE scientists every night and will support public distribution of these alerts. The success rate of such simultaneous observations will depend on the adopted cadence strategy.

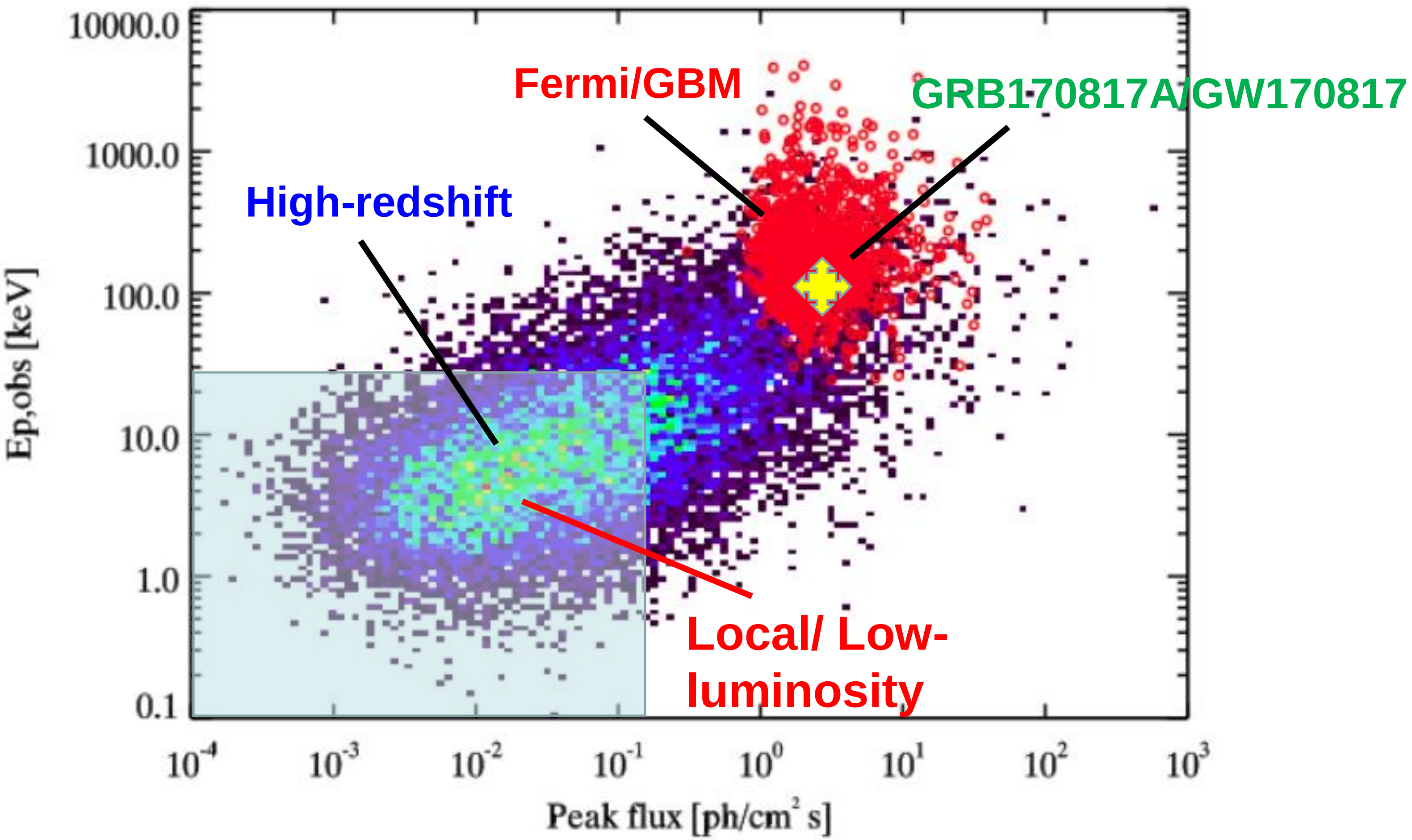
2.7.4 Cherenkov Telescope Array

The Cherenkov Telescope Array [214] is a global, next-generation observatory studying very-high-energy (VHE) gamma rays in the energy range from tens of GeV to hundreds of TeV. The observatory will consist of a range of Imaging Air Cherenkov Telescopes (IACTs) in two sites (Paranal, Chile and Canary Islands, Spain), and will have unprecedented sensitivity as well as unique angular and energy resolutions over a large energy range. CTA is building on the success of the current generation of IACTs, namely H.E.S.S., MAGIC, VERITAS and FACT. Its construction is expected to be completed around 2025. After a number of Key Science Projects defined by the CTA Consortium are completed, the fraction of the time allocated to guest observer programs will increase rapidly. It is thus expected that CTA will be a fully open observatory at the timescale of the THESEUS mission.

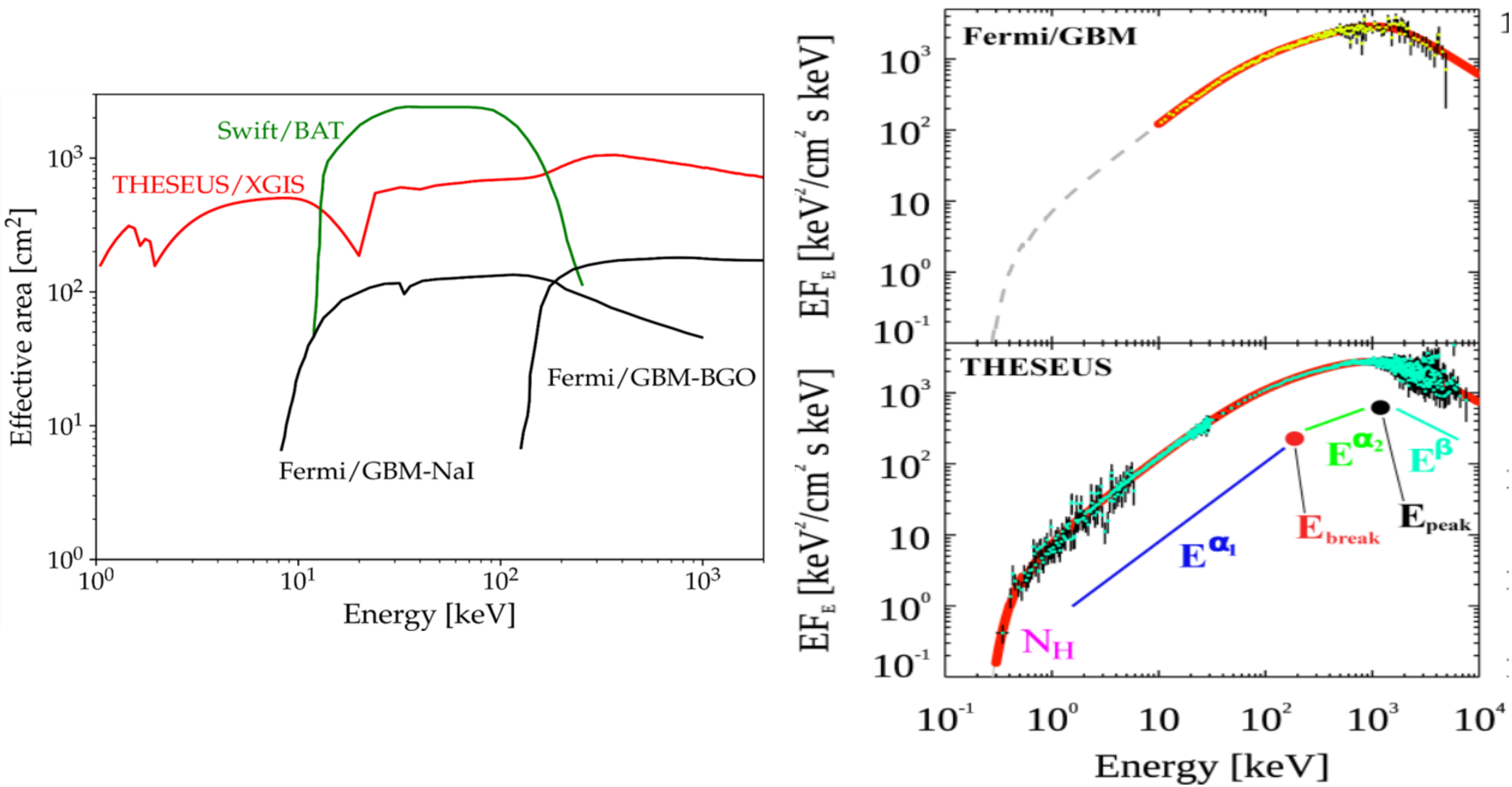
We expect strong synergies between the CTA science programs and THESEUS. One of the main science drivers for both observatories is the study of transient phenomena and especially GRBs. This field has recently seen tremendous breakthroughs with the detection of VHE emission from the GRBs detected by H.E.S.S. (GRB 180720B, [215], and GRB 190829A) and MAGIC (GRB 190114C, [216]). As an example, the detection of the nearby and very low luminosity burst GRB 190829A may indicate that the phase space of low luminosity events detectable in large numbers with THESEUS will enable many further joint CTA-THESEUS observations and studies. Access to this new phase space, combined with the high sensitivity of CTA and its fast reaction to multi-wavelength alerts within 30 s over the full sky, will enable detailed joint studies of GRB light-curves across many orders of magnitude in energy and covering long time ranges. These studies will naturally be extended into the multi-messenger domain through searches for VHE counterparts of GW events. The rapid and precise localisation of GW electromagnetic counterparts by THESEUS will enable to

future facilities	
	Institute
	CEA
	University of Ferrara
	GSSI
	CEA
	University of Leicester
	Milano-Bicocca University
	University of Geneva
	Scuola Normale Superiore di Pisa
	Observatoire de Paris
	CEA
	INAF-OAS Bologna
	University of Trieste
	University of Bologna
	University of Nova Gorica

❑ **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**

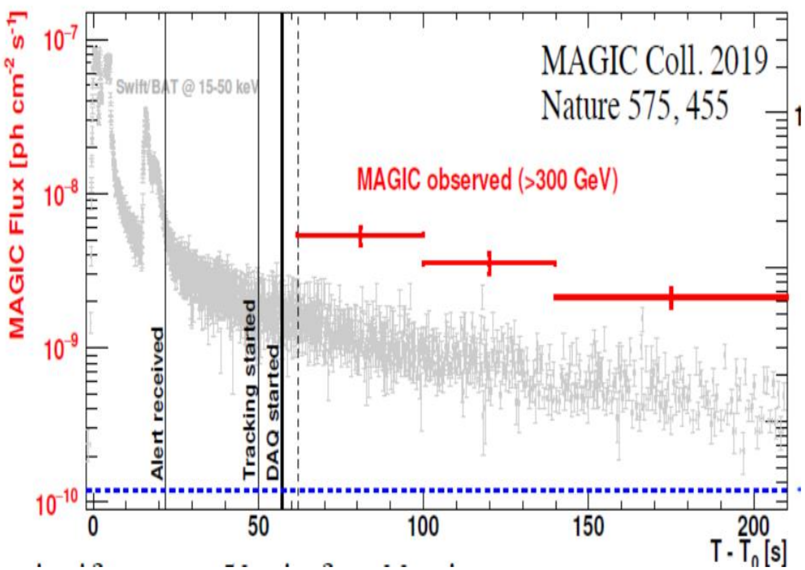


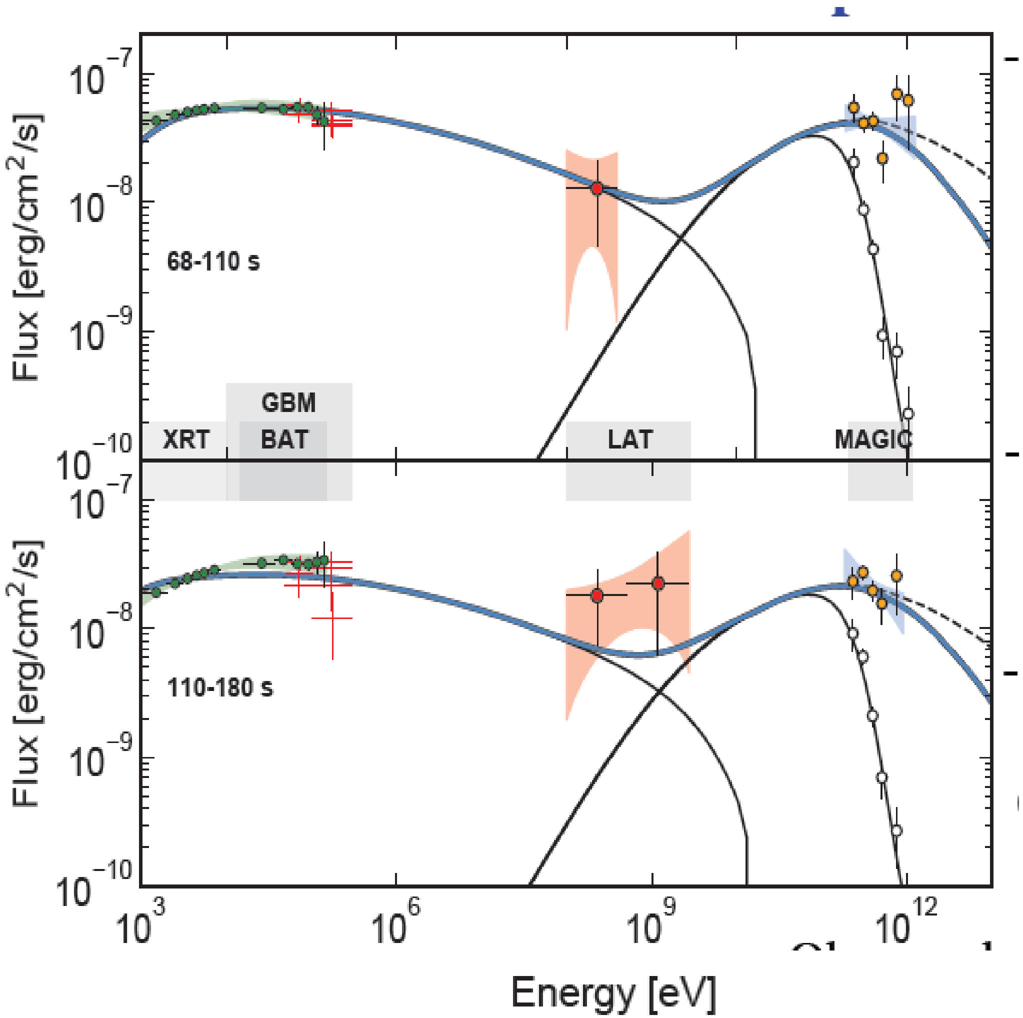
Unprecedented GRB prompt emission physics with THESEUS



Detection of TeV photons from GRBs by Cherenkov telescopes!!!

- ❑ Long GRB180720B (HESS) and GRB190114C (MAGIC), plus two more events
- ❑ Further evidence of possible SSC or IC component in GRB afterglow emission

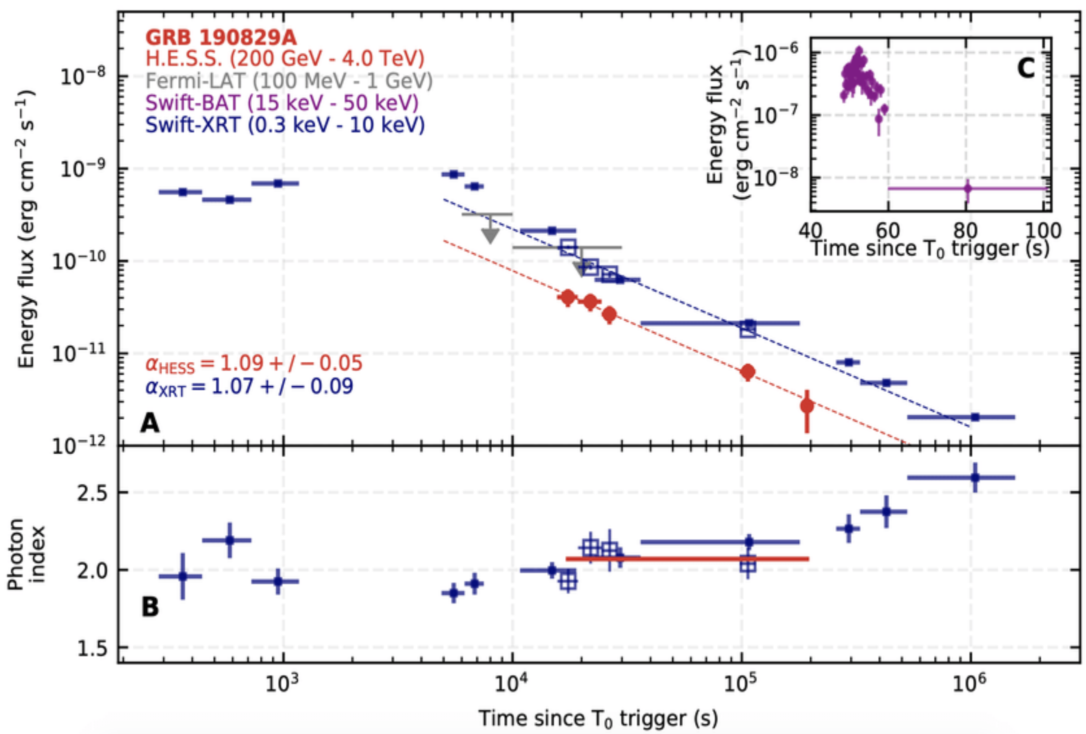


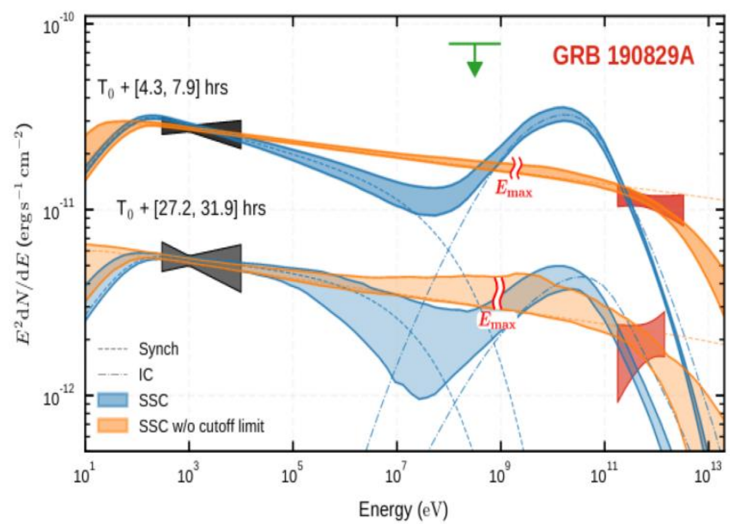


GRB190114C: TeV prompt emission

Detection of TeV photons from GRBs by Cherenkov telescopes!!!

- Long GRB180720B (HESS) and GRB190114C (MAGIC), plus two more events
- Further evidence of possible SSC or IC component in GRB afterglow emission





GRB190829A at z=0.08: TeV afterglow emission

Fundamental physics with GRBs: testing LI / QG

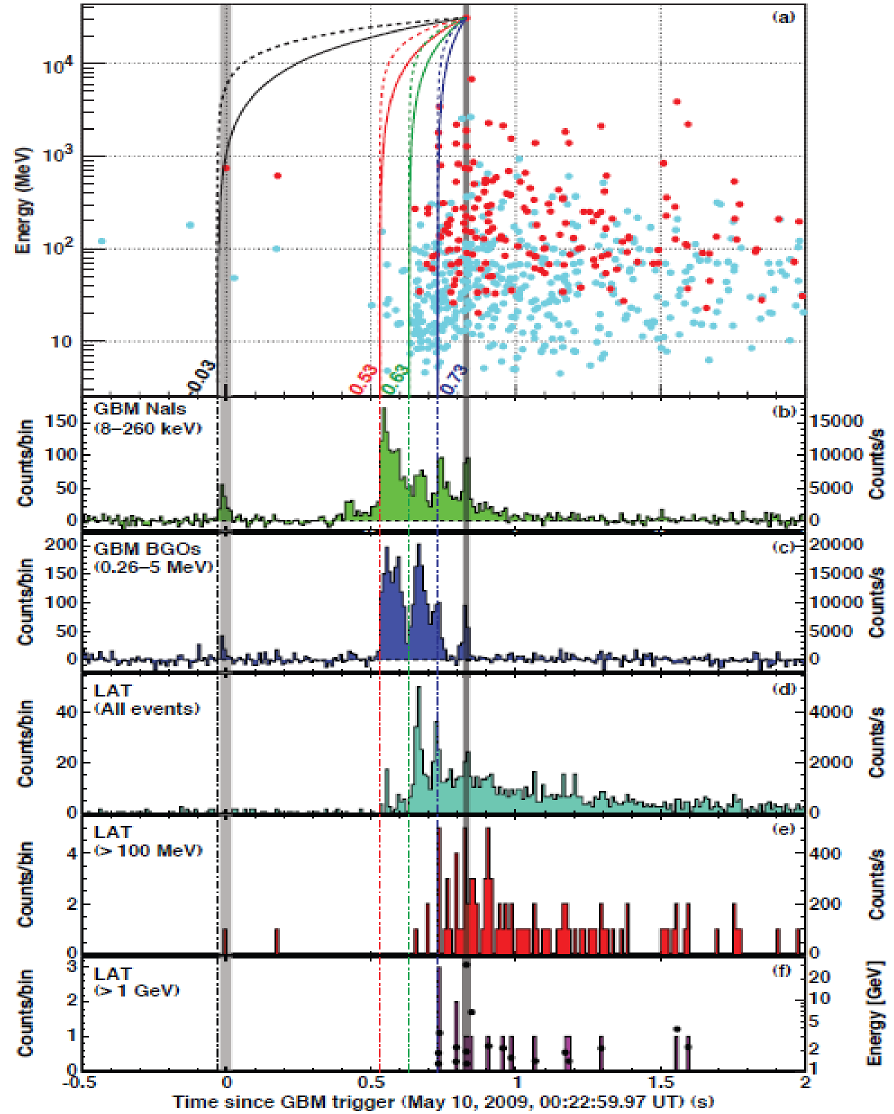
- Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

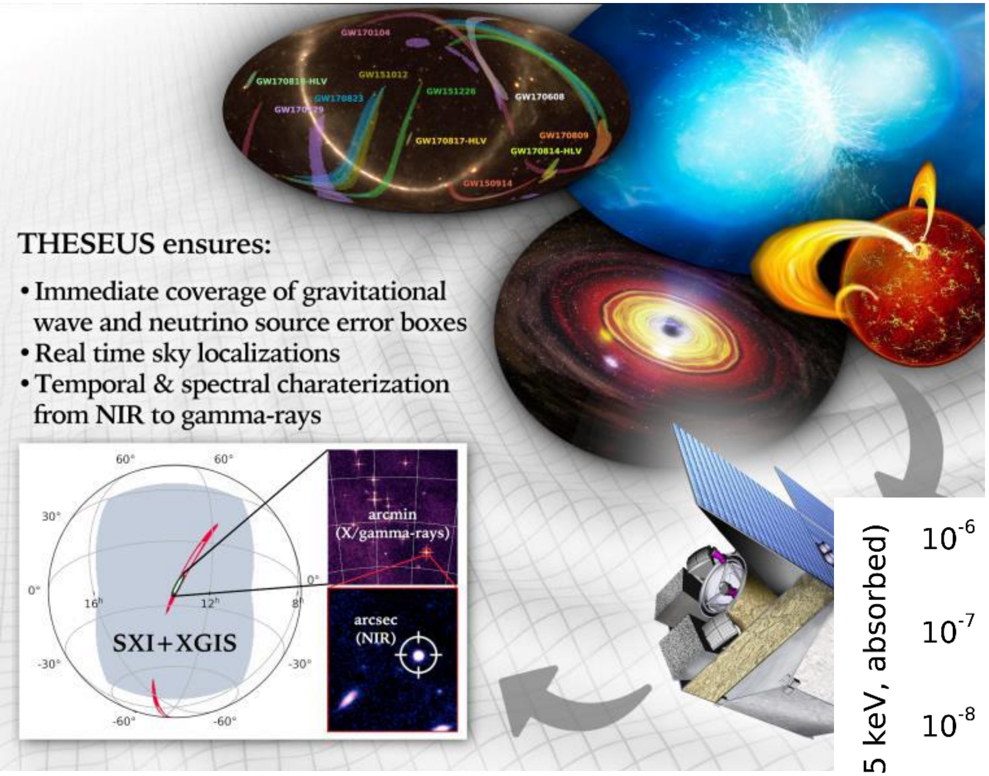
$$\Delta t = s_n \frac{(1+n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\, dz'$$

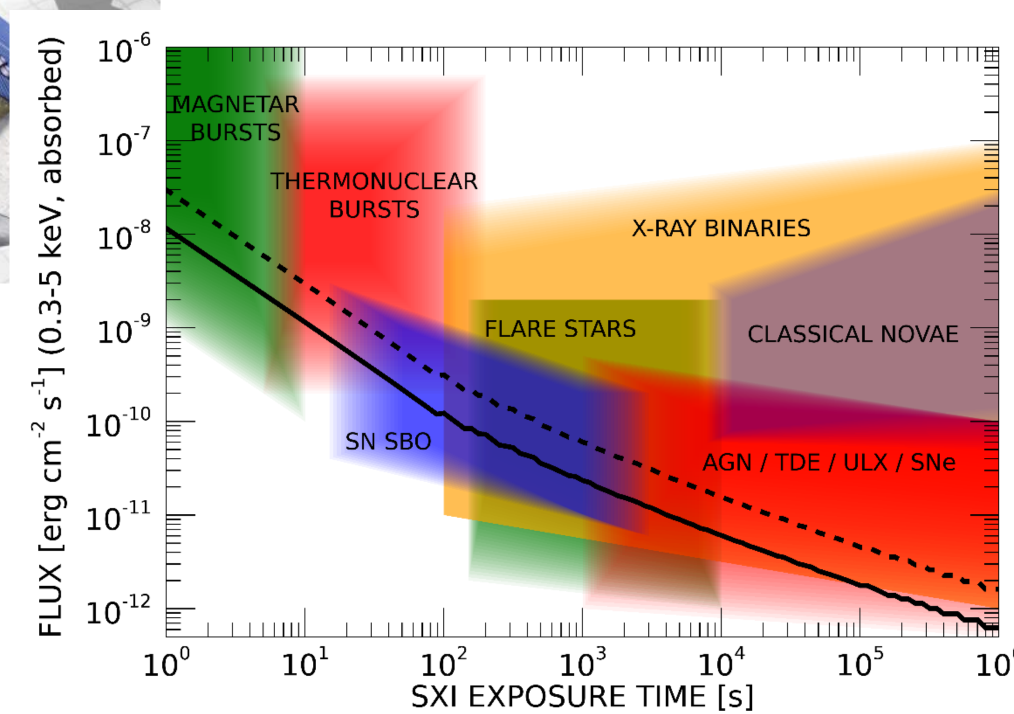
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (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 1[st] 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



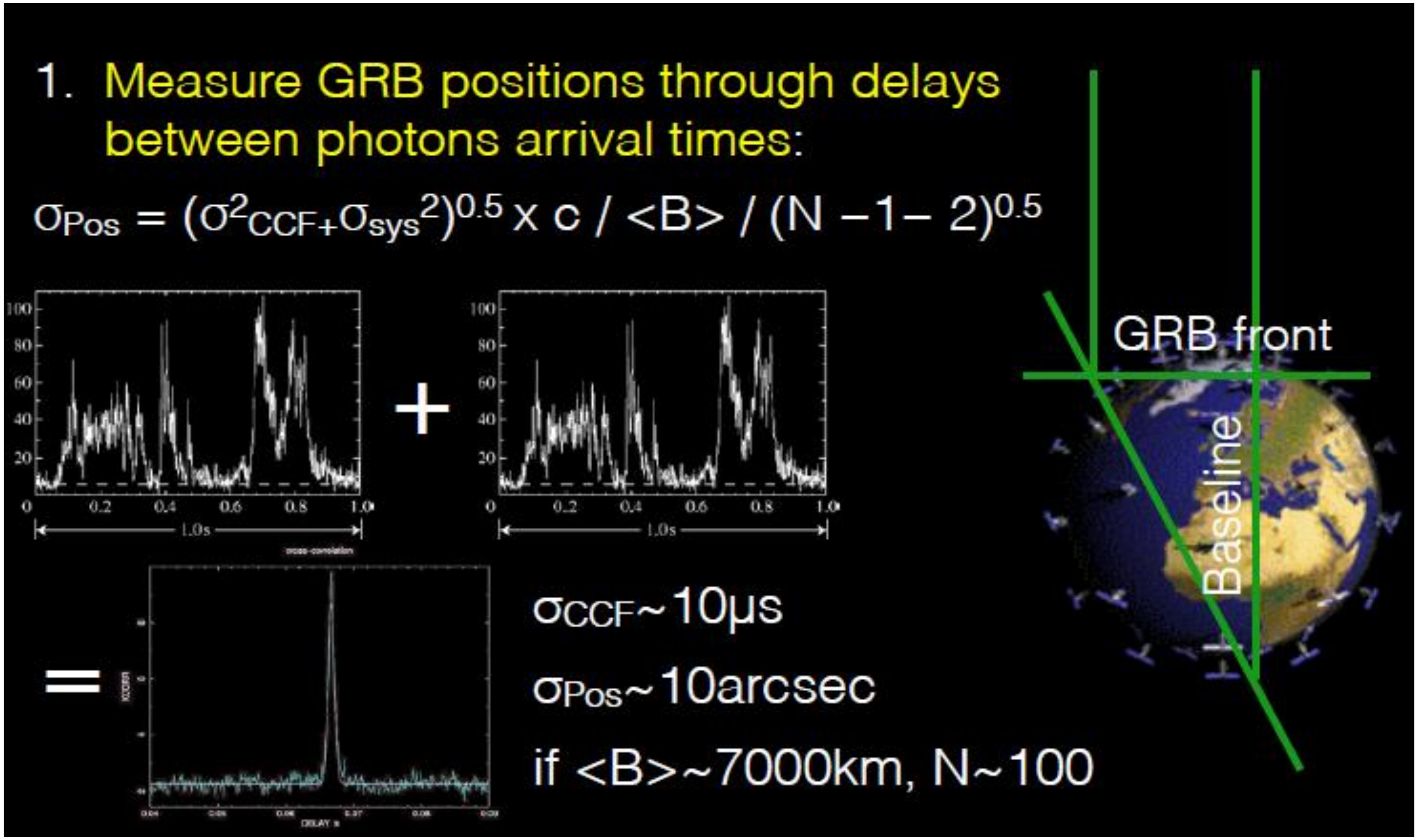
Exploring the multi-messenger transient sky





Nanosatellites programmes: case of HERMES

- Accurate location of GRBs for multi-messenger astrophysics
- Accurate GRB timing over wide energy band for LIV tests



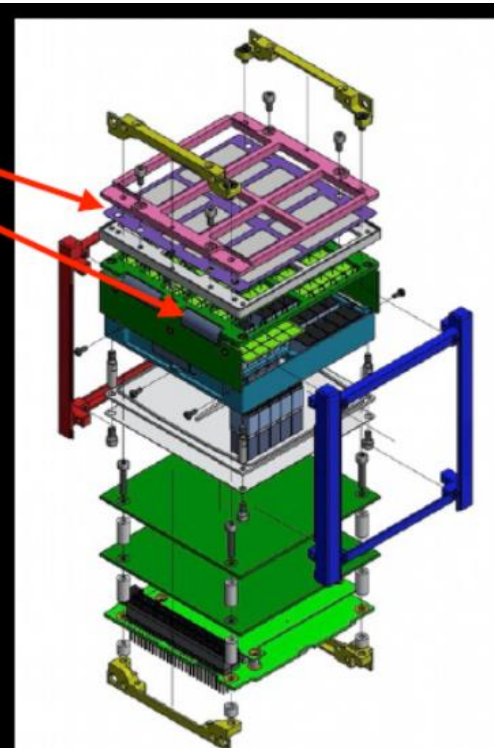
Nanosatellites programmes: case of HERMES

3U minimum, simplest basic configuration
50 cm² detector: Pathfinder

6U more performing configuration
~200cm² detector, more accurate GPS, more accurate AOCS: Full Constellation

- Photo detector, SDD
  Scintillator crystal GAGG
- 5-300 keV (3-1000 keV)
- ≥50 cm² coll. area
- a few st FOV
- Temporal res. ≤300 nsec
- ~1.6kg

Fuschino+2018, 2020
Evangelista+2020
Campana+2020



Nanosatellites programmes: case of HERMES

HERMES performances

$$\sigma_{Pos} = 2.4°[(\sigma_{CCF}{}^2 + \sigma_{sys}{}^2)/(N-3)]^{0.5}$$

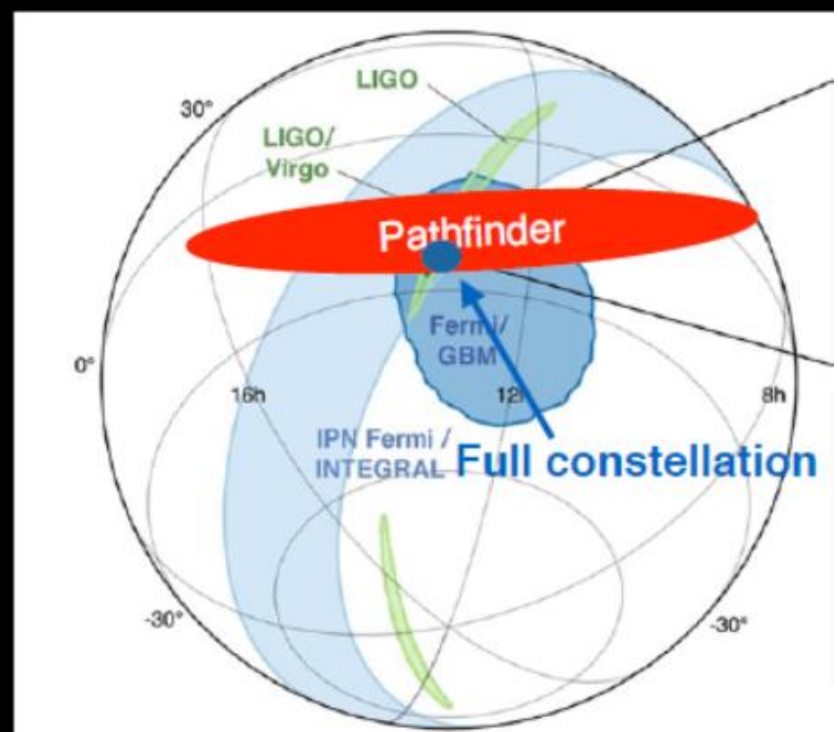
<B>~7000km

N(pathfinder)~6-8, active simultaneously 4-6

σ_{Pos}~ 2.4 deg if $\sigma_{CCF}, \sigma_{sys}$~1ms

N(Full constellation) ~100, active 50

$\sigma_{Pos(FC)}$ ~ 15 arcmin if $\sigma_{CCF}, \sigma_{sys}$~1ms



THESEUS Italian community and heritage

- Science case & requirements, design, R&D simulations: **INAF** (PI; OAS, IASF-MI, IAPS, IASF-PA, Oss. Napoli, Oss. Roma, …), **Universities** (Politecnico Milano, Univ. Pavia, Univ. Ferrara, Univ. Udine, Univ. Bologna, Univ. Cagliari, SNS Pisa, Univ. Federico II Napoli, Univ. Urbino, GSSI, …) **FBK** Trento; interest and contribution by scientists and technologists from **INFN (**Ferrara, Bologna, Trieste, Napoli, Salerno, …)

- Industries in THESEUS study: **OHB-I** (XGIS), **TAS-I** (s/c), **GPAP** (TBU)

- Building on the unique heritage in GRB and transients science and technology (e.g., BeppoSAX, HETE-2, Swift, INTEGRAL, AGILE, Fermi)

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

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

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Mostly the same for HERMES, coordinated by INAF – Trieste and Univ. Cagliari

Key roles of INAF-OAS in THESEUS and HERMES

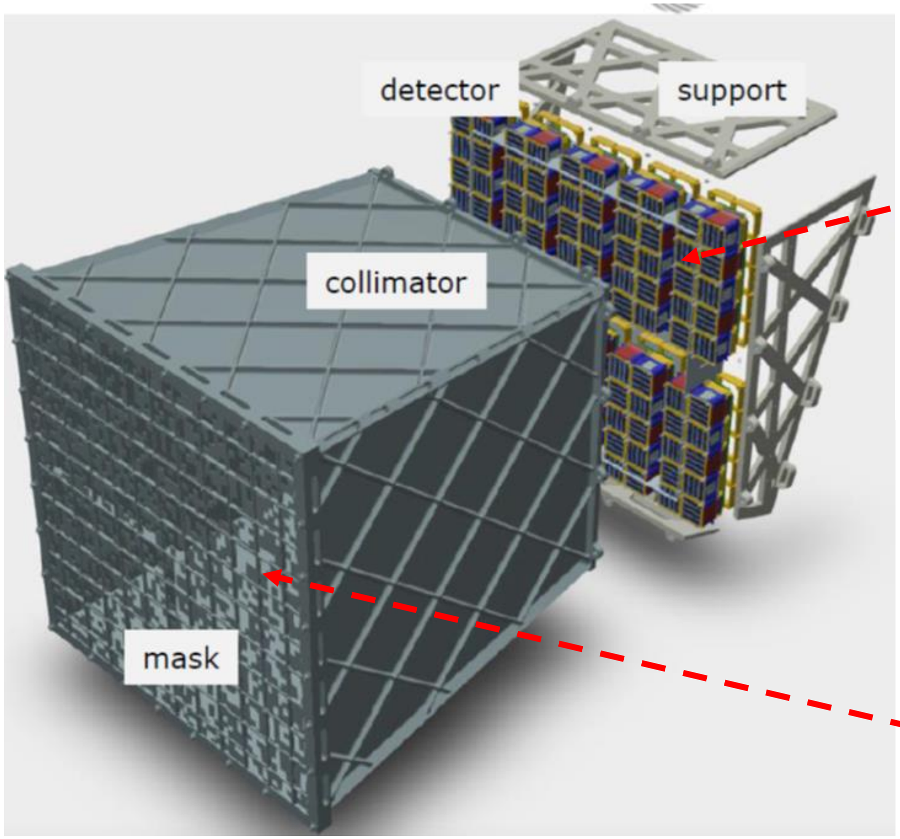
- **THESEUS consortium coordination: INAF-OAS Bologna** (Lead Proposer, project office)
- **PIship of THESEUS/XGIS instrument: INAF (PI@OAS**, + IASF-MI, IAPS, IASF-PA, …), **Universities** (Politecnico Milano, Univ. Pavia, Univ. Ferrara, Univ. Udine), **FBK** Trento
- **Key role in THESEUS Science case, requirements, simulations: INAF** (Lead Scientist; 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, …)
- **Key role in HERMES detection system:** concept, R&D, design and testing
- **Contribution to HERMES Science:** science case, requirements, simulations, follow-up strategy

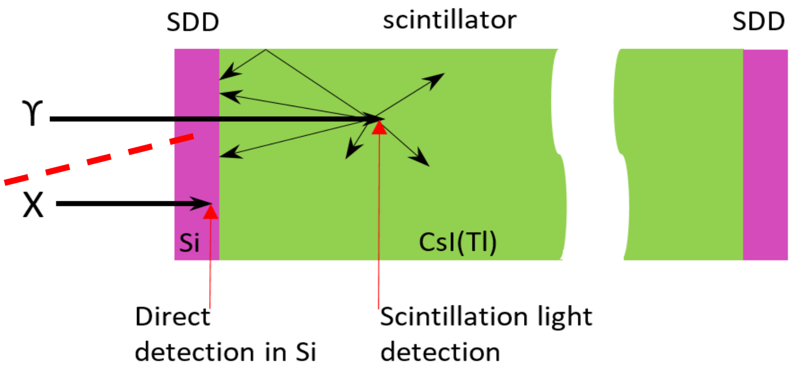
Great perspective interactions between THESEUS, HERMES and CTA teams at OAS for further assessment, simulations and optimization of synergies between CTA and future GRB / high-energy transients missions

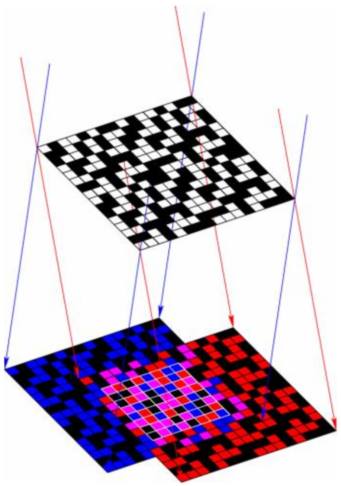
Back-up slides

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)

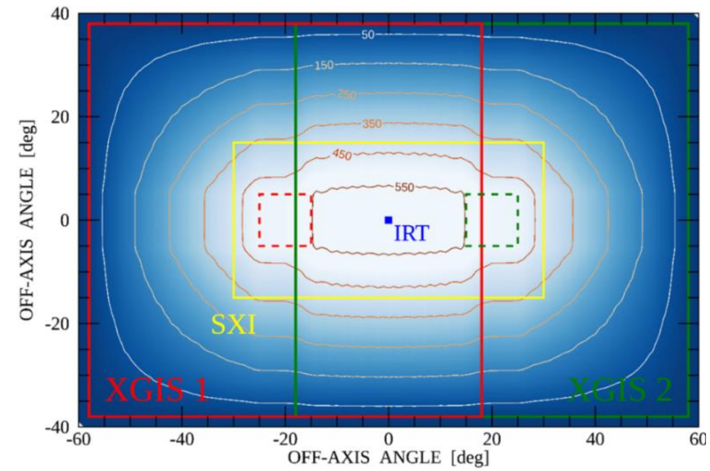


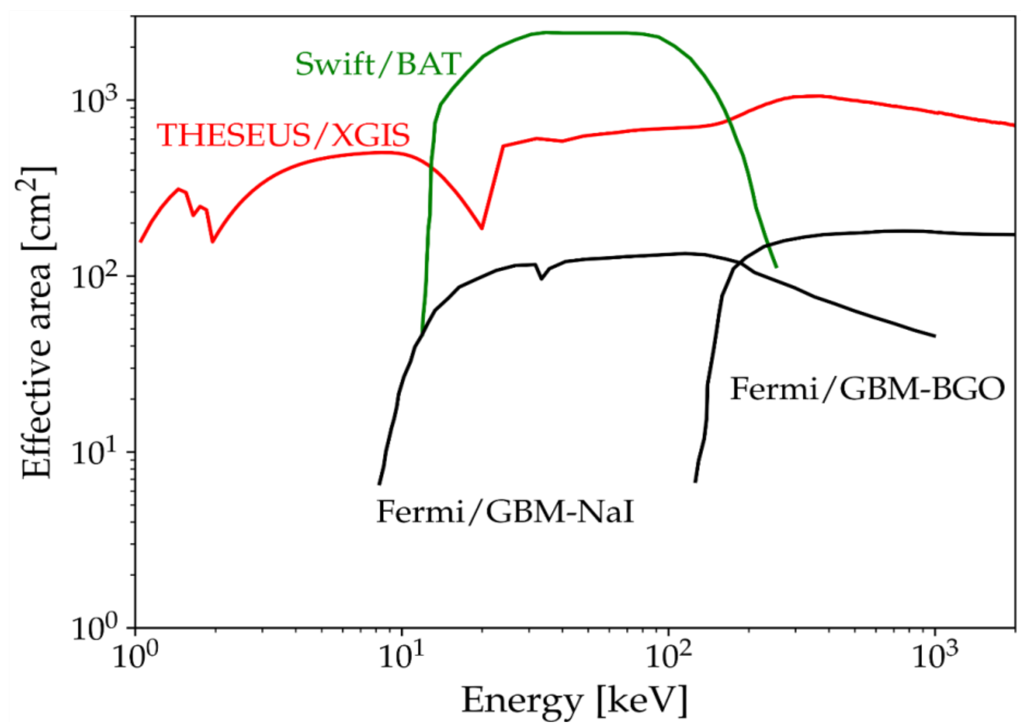




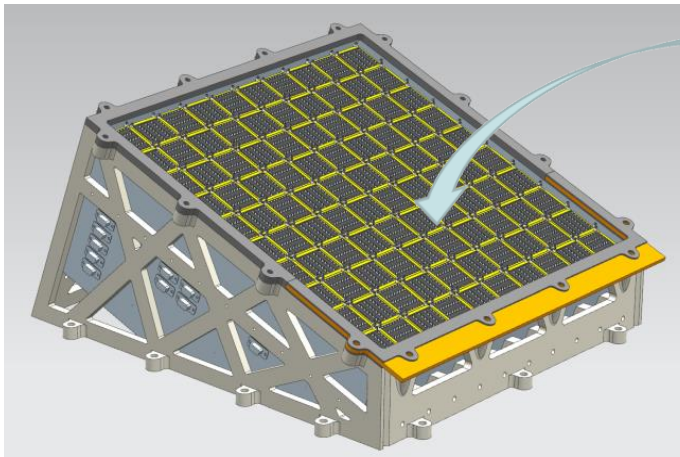
The X-Gamma Ray Imaging Spectrometer (XGIS)

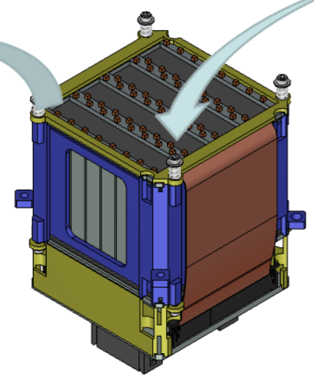
- **Unprecedented combination of effective area** (min. >500 cm^2, max. >1000 cm^2) and **energy band** (2 keV – 10 MeV)
- Total FoV ~6 sr (2 sr imaging)
- GRB location accuracy <15' in imaging FoV
- Excellent timing (< 5 μs)
- **Sensitivity to high-z GRBs**
- Under study: polarimetry, lower energy threshold, non imaging localization

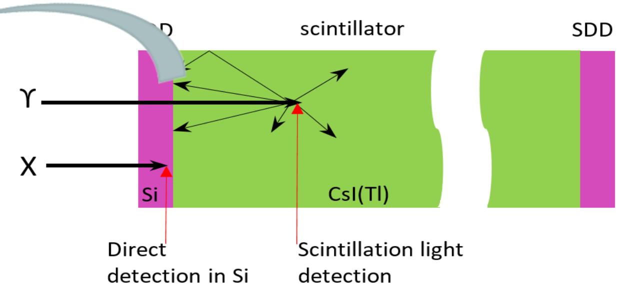




The X-Gamma Ray Imaging Spectrometer (XGIS)







❑ XGIS Phase A study:

- R&D on detectors (SDD+CsI) and electronics (ASIC, BE)
- Trade-offs and optimization of design
- detection module prototype manufacturing and testing (ESA-OHB +ASI-INAF partners)

XGIS: Italian community and heritage

- Science case & requirements, design, R&D simulations: **INAF** (PI; OAS, IASF-MI, IAPS, IASF-PA, Oss. Napoli, Oss. Roma, …), **Universities** (Politecnico Milano, Univ. Pavia, Univ. Ferrara, Univ. Udine, Univ. Bologna, Univ. Cagliari, SNS Pisa, Univ. Federico II Napoli, Univ. Urbino, GSSI, …) **FBK** Trento; interest and contribution by scientists and technologists from **INFN (**Ferrara, Bologna, Trieste, Napoli, Salerno, …)

- Industries in THESEUS study: **OHB-I** (XGIS), **TAS-I** (s/c), **GPAP** (TBU)

- Building on the unique heritage in GRB and transients science and technology (e.g., BeppoSAX, HETE-2, Swift, INTEGRAL, AGILE, Fermi)

- Taking advantage of leadership in key enabling technologies based on R&D supported by ASI, INAF and INFN in the last years (e.g., silicon drift detectors + scintillators)
- Strengthening and exploiting the fundamental contribution to time domain and gravitational waves astrophysics (EGO-Virgo, EM follow-up with major facilities like VLT)

ASI funding for Phase A study: ~500 KE (2019-2021); Co-funding from INAF + Universities: ~660 KE; ESA-OHB-I contract (INAF/OAS involved): ~480KE; AHEAD2020

Perspectives for the XGIS

- An XGIS-like instrument will improve substantially the capability of future missions for multi-messenger astrophysics and GRB science

- The Phase A study of THESEUS and related TDAs grants an already good TRL level (e.g., detection module prototype, SDD detectors and specifically designed ASIC already under testing).

- Modularity grants great flexibility in adapting design for specific scientific objectives and available resources;

- Possibility of extended capabilities by exploiting 3D detection plane: Compton polarimetry and source location outside imaging FoV

- **Perspective 1: inclusion in the payload of a mid/large GRB mission**: es., THESEUS (Phase-II proposal for ESA M-class 2037) and Gamow Explorer (under evaluation by NASA as possible candidate for MIDEX to be launched in 2028; an ASI contribution has already been discussed)

❑ Perspective 2: dedicated mission

- **Small mission "a la AGILE"** (~300-350 kg), with scientific P/L based on one/two THESEUS/XGIS – like cameras (mass ~80 kg, power ~100 W, volume ~60x60x90 cm^3), possibly re-designed to optimize combination of FoV and location accuracy or on a set of misaligned simply collimated detection (super) modules;
- could be launched in LEO or to L2; latter case would optimize synergy with Gamow Explorer, and NASA my be interested in contributing the launcher (high-interest of Gamow community and possibility of using same launcher);
- **Two mini-satellites** (~100-150 kg each) in LEO in conjugate constellation layout on both sides of the earth ("a la GECAM"), with only misaligned XGIS detection modules (maximum FOV, i.e. almost full sky at all time)

❑ **Remark:** XGIS, ALBATROS, DAMA and partly SWIPE and ASTENA, come from the same large scientific community and are partly based on same R&D (e.g., HERMES, THESEUS/XGIS, ASTENA/WFI) : maximum effort will be done for converging (main trade-offs include compact vs. distributed)

TRL: status and needed activities

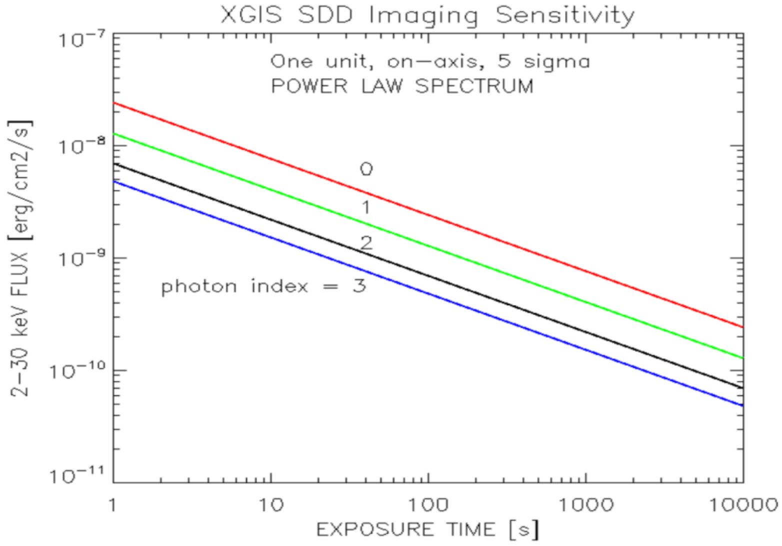
- R&D activities during THESEUS Phase A Study as ESA/M5 candidate allowed to reach a TRL of at least 4 for the ASIC and 5 for the SDD+CsI detection elements (with identified path for reaching TRL 6 by 2024).

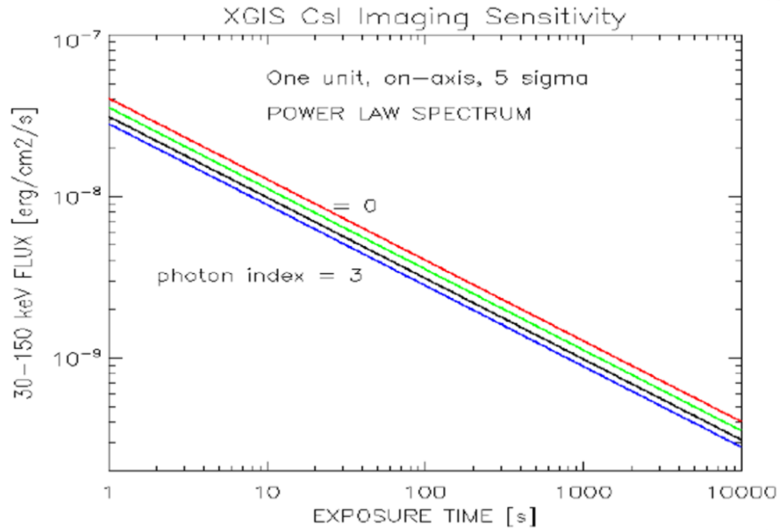
- TDA study by OHB-I and INAF-OAS, funded by ESA, was dedicated to define requirements, to design, manufacture, and test a XGIS Detection Module (DM) prototype; achieved maturity level of TRL 4/5.

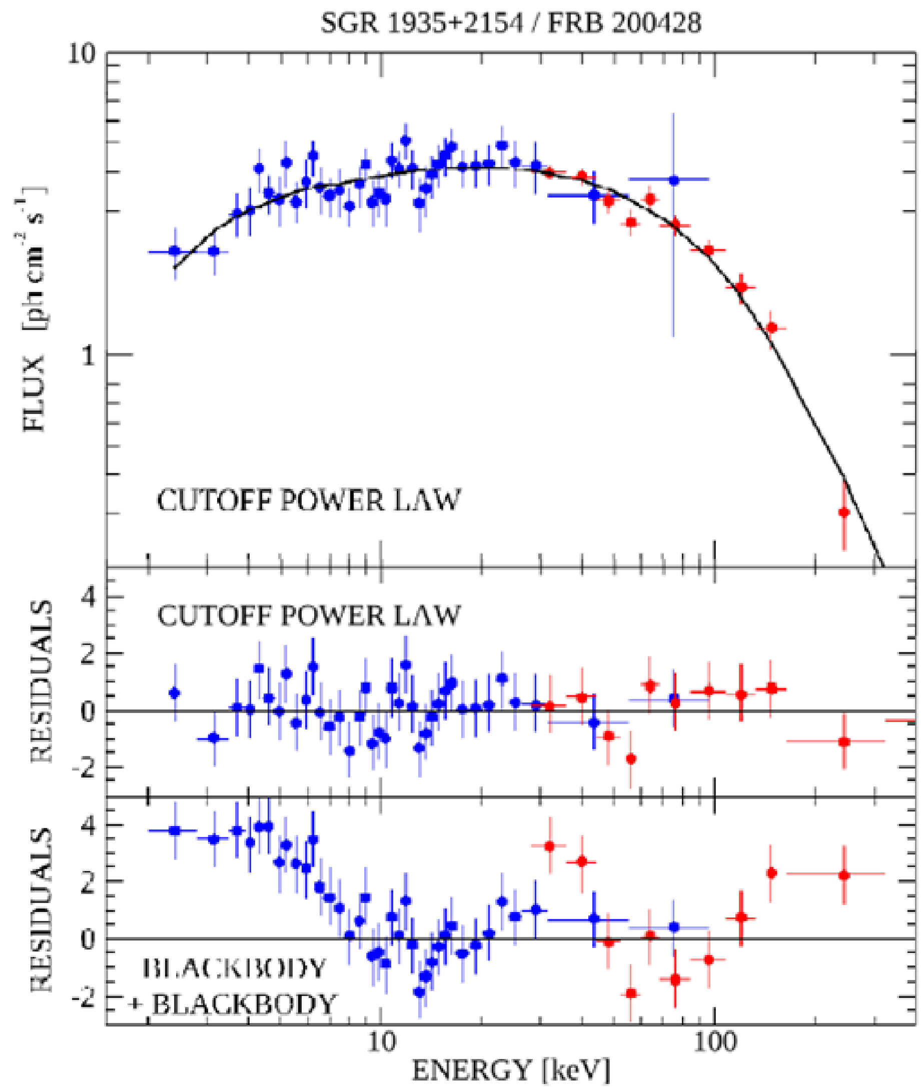
- In order to obtain a TRL6, the XGIS DM would need a more robust mechanical design able to withstand the launch loads and the use of new ASIC component of the Orion family, designed and produced specifically for the XGIS and currently under testing

- Study of Alternative DM concepts with larger sub-array dimensions and a smaller pixel size to improve spatial resolution and provide polarimetric capabilities

XGIS capabilities for time domain astronomy

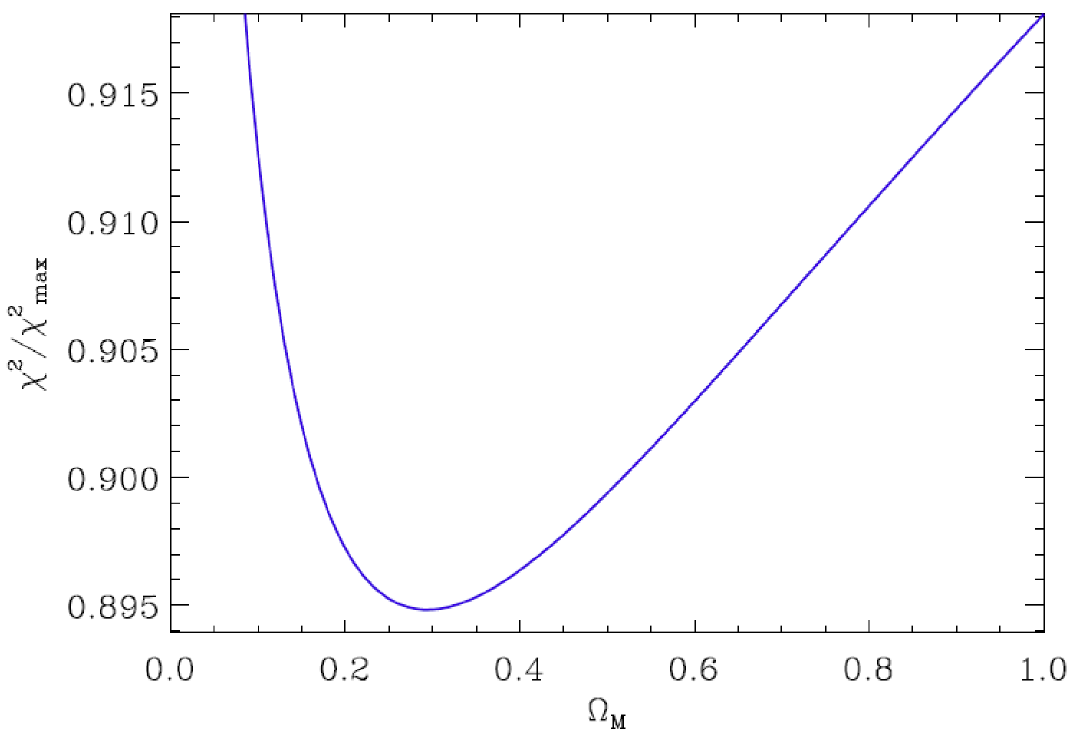




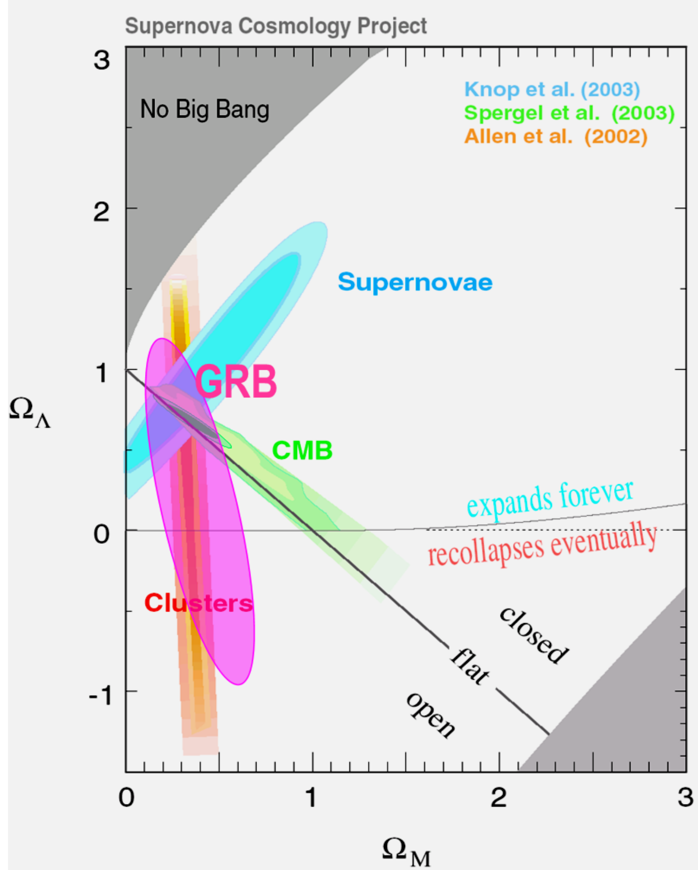


Measuring cosmological parameters with GRBs

- a fraction of the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation is indeed due to the cosmological parameters used to compute E_{iso}
- **Evidence, independent on other cosmological probes, that, if we are in a flat ΛCDM universe , Ω_M is lower than 1 and around 0.3**



Amati et al. 2008, Amati & Della Valle 2013



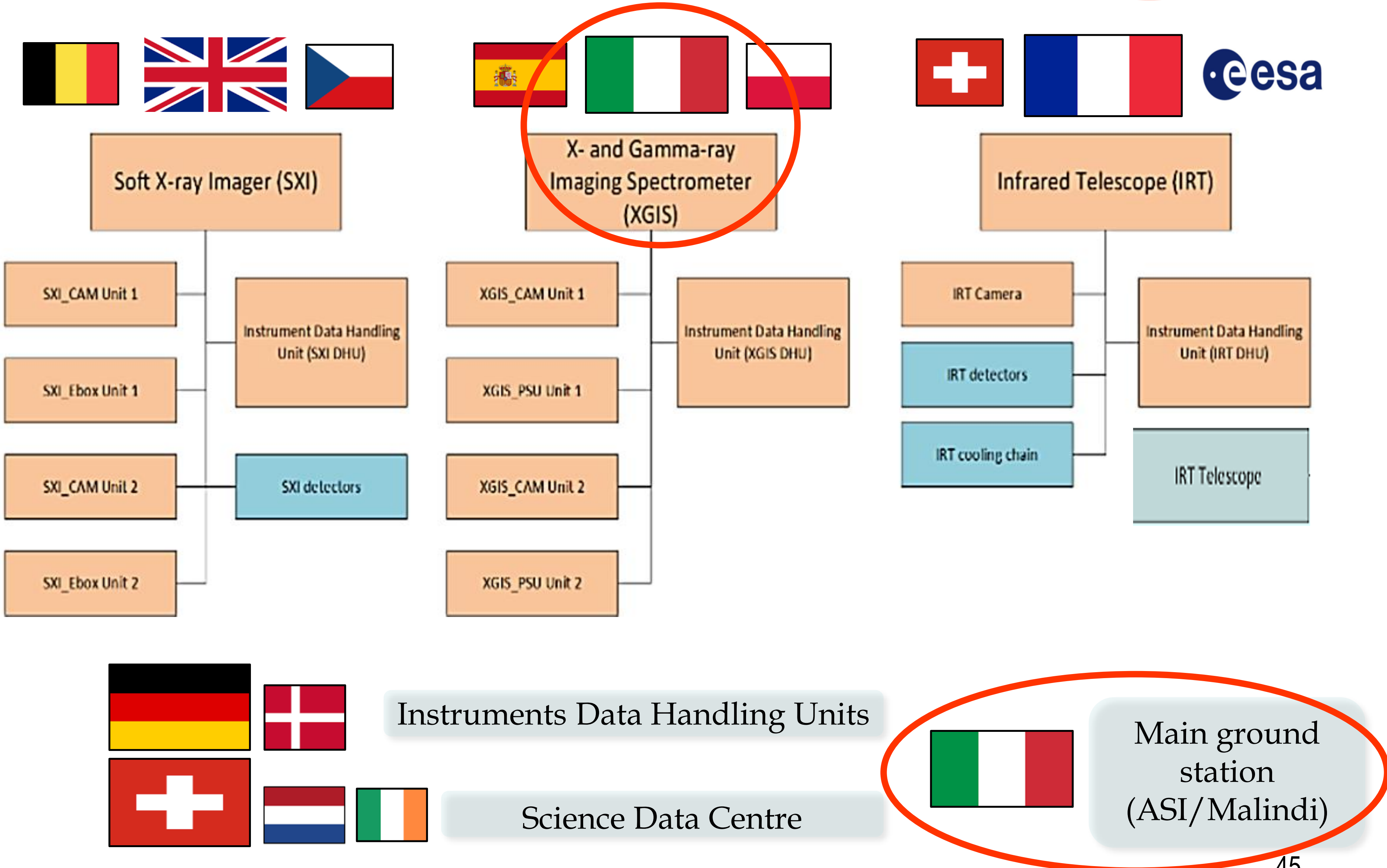
The key role of Italy in THESEUS

- Building on the unique heritage in GRB and transients science and technology of the last 15-20 years (BeppoSAX, HETE-2, Swift, INTEGRAL, AGILE, Fermi

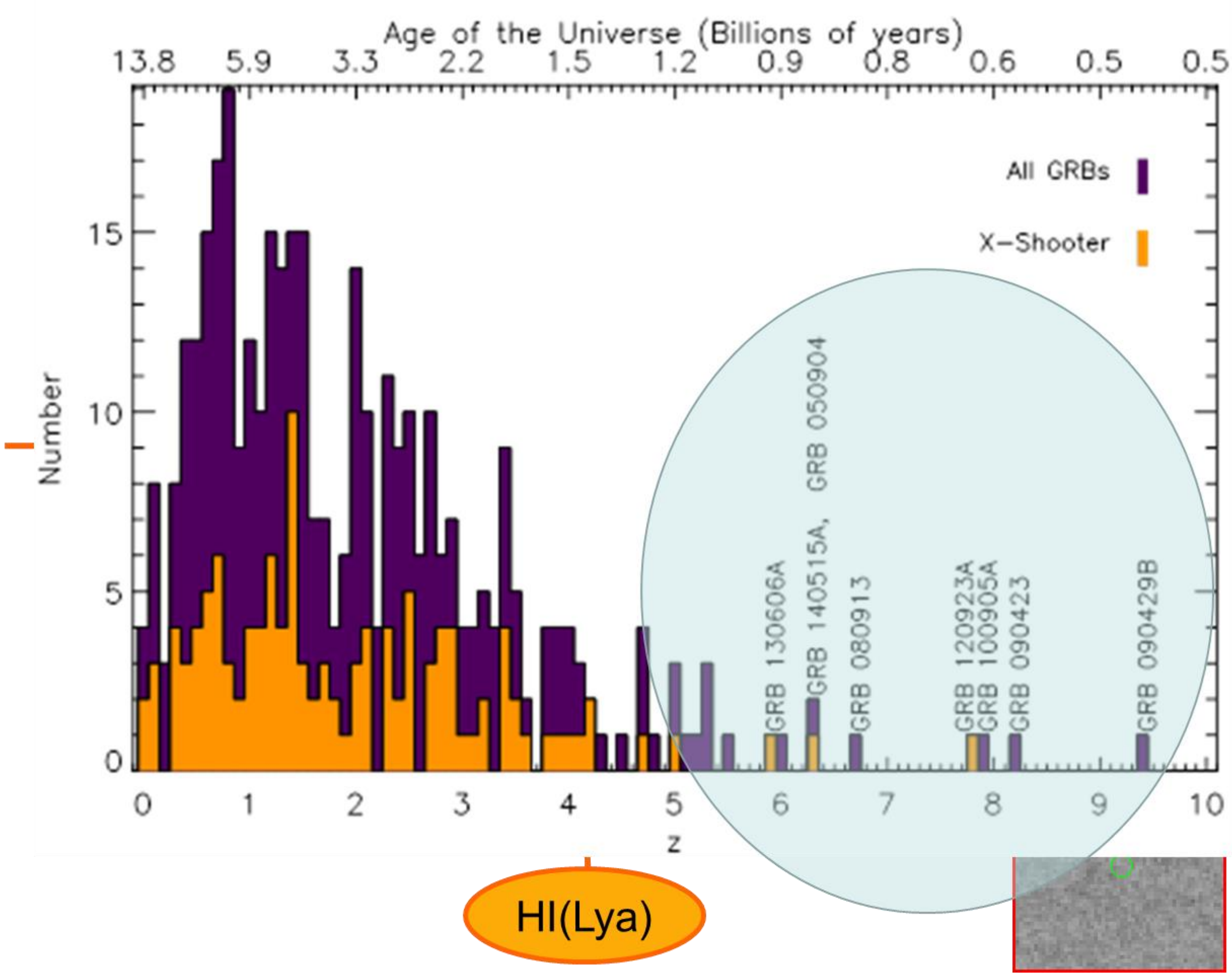
- Taking advantage of leadership in key enabling technologies based on R&D supported by ASI, INAF and INFN in the last years (e.g., silicon drift detectors + scintillators)

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

THESEUS consortium responsibilities (Lead: ITALY)



- **Requirements:**



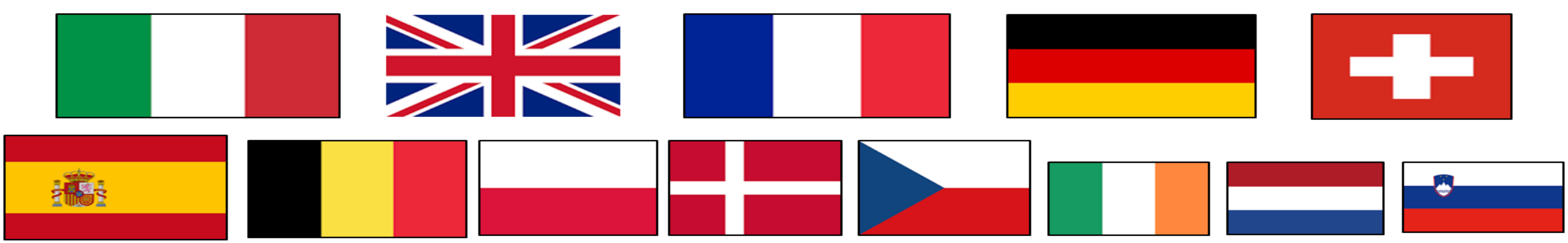
Future missions: the case of THESEUS

Transient High Energy Sky and Early Universe Surveyor

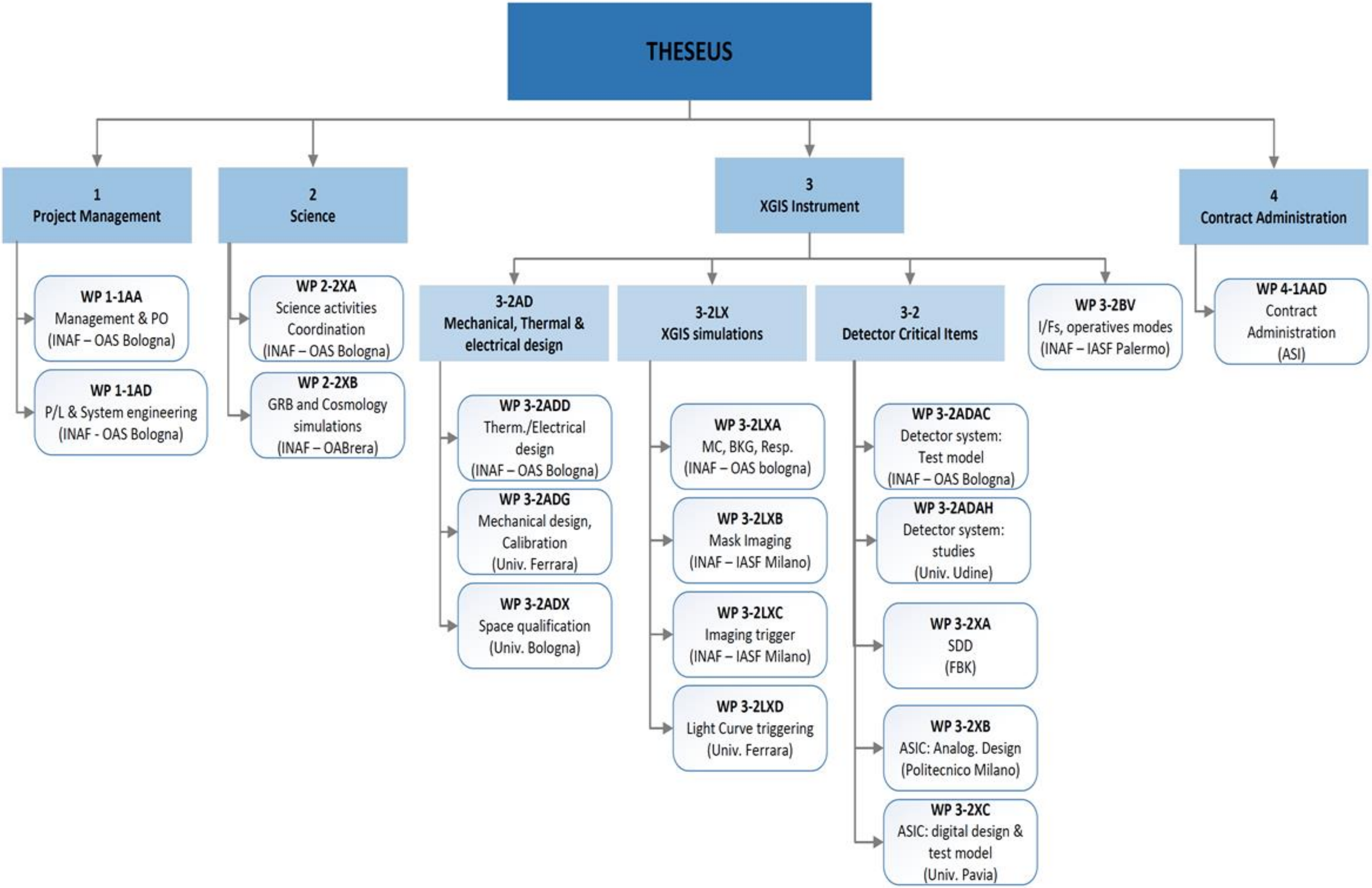
Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

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



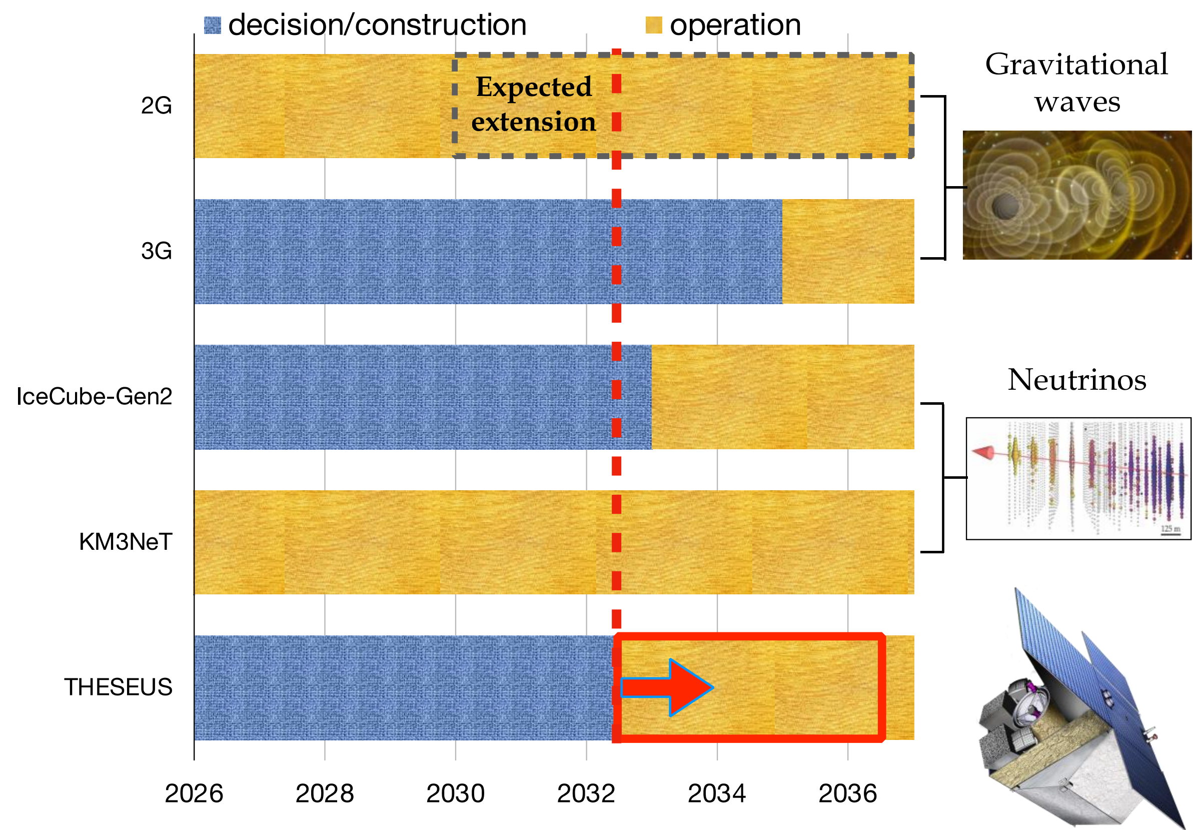
ASI-INAF agreement: break-down



Future GRB missions: synergies

ENTERING THE GOLDEN ERA OF MULTI-MESSENGER ASTROPHYSICS

Synergy with future GW and neutrino facilities will enable transformational investigations of multi-messenger sources



https://www.nature.com/articles/s42254-021-00303-8

April 2021

GWIC Roadmap and Letter of Endorsement from EGO/virgo clearly mention further upgrades of 2G to bridge in the 3G era

ROADMAP

Check for updates

Gravitational-wave physics and astronomy in the 2020s and 2030s

M. Bailes[1], B. K. Berger[2], P. R. Brady[3], M. Branchesi[4,5], K. Danzmann[6,7], M. Evans[8], K. Holley-Bockelmann[9,10], B. R. Iyer[11], T. Kajita[12], S. Katsanevas[13], M. Kramer[14,15], A. Lazzarini[16], L. Lehner[17], G. Losurdo[18], H. Lück[6,7], D. E. McClelland[19], M. A. McLaughlin[20], M. Punturo[21], S. Ransom[22], S. Raychaudhury[23], D. H. Reitze[16,24]✉, F. Ricci[25,26], S. Rowan[27], Y. Saito[28,29], G. H. Sanders[30], B. S. Sathyaprakash[31,32], B. F. Schutz[32], A. Sesana[33], H. Shinkai[34], X. Siemens[35], D. H. Shoemaker[8], J. Thorpe[36], J. F. J. van den Brand[37,38] and S. Vitale[39]

Abstract | The 100 years since the publication of Albert Einstein's theory of general relativity saw significant development of the understanding of the theory, the identification of potential astrophysical sources of sufficiently strong gravitational waves and development of key technologies for gravitational-wave detectors. In 2015, the first gravitational-wave signals were detected by the two US Advanced LIGO instruments. In 2017, Advanced LIGO and the European Advanced Virgo detectors pinpointed a binary neutron star coalescence that was also seen across the electromagnetic spectrum. The field of gravitational-wave astronomy is just starting, and this Roadmap of future developments surveys the potential for growth in bandwidth and sensitivity of future gravitational-wave detectors, and discusses the science results anticipated to come from upcoming instruments.

The past five years have witnessed a revolution in astronomy. The direct detection of gravitational waves (GW) emitted from the binary black hole (BBH) merger GW150914 (FIG. 1) by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detector[1] on September 14, 2015 (REF.[2]) was a watershed event, not only in demonstrating that GWs could be directly detected but more fundamentally in revealing new insights into these exotic objects and the Universe itself. On August 17, 2017, the Advanced LIGO and Advanced Virgo[3] detectors jointly detected GW170817, the merger of a binary neutron star (BNS) system[4], an equally momentous event leading to the observation of electromagnetic (EM) radiation emitted across the entire spectrum through one of the most intense astronomical observing campaigns ever undertaken[5].

Coming nearly 100 years after Albert Einstein first predicted their existence[6], but doubted that they could ever be measured, the first direct GW detections have undoubtedly opened a new window on the Universe. The scientific insights emerging from these detections have already revolutionized multiple domains of physics and astrophysics, yet, they are 'the tip of the iceberg', representing only a small fraction of the future potential of GW astronomy. As is the case for the Universe seen through EM waves, different classes of astrophysical sources emit GWs across a broad spectrum ranging over more than 20 orders of magnitude, and require different detectors for the range of frequencies of interest (FIG. 2).

In this Roadmap, we present the perspectives of the Gravitational Wave International Committee (GWIC, https://gwic.ligo.org) on the emerging field of GW astronomy and physics in the coming decades. The GWIC was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major GW detection facilities worldwide. Its primary goals are: to promote international cooperation in all phases of construction and scientific exploitation of GW detectors, to coordinate and support long-range planning for new instruments or existing instrument upgrades, and to promote the development of GW detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics. Our intention in this Roadmap is to present a survey of the science opportunities and to highlight the future detectors that will be needed to realize those opportunities. The recent remarkable discoveries in GW astronomy have spurred the GWIC to re-examine and update the GWIC roadmap originally published a decade ago[7].

We first present an overview of GWs, the methods used to detect them and some scientific highlights from the past five years. Next, we provide a detailed survey

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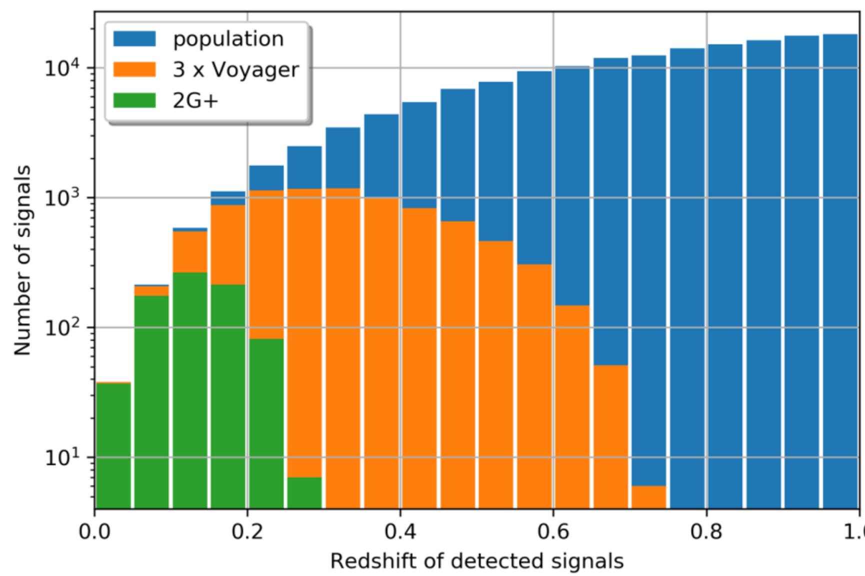
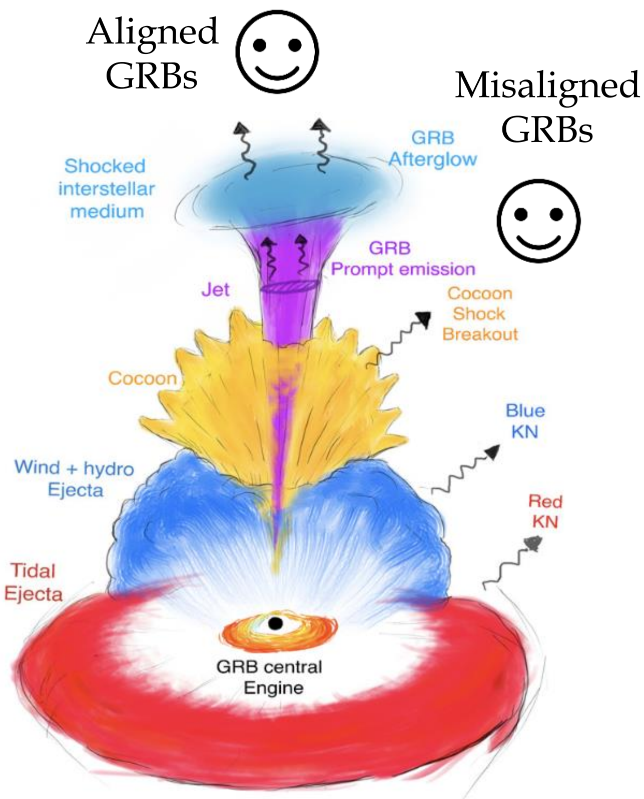


NS-NS merger detection efficiency with 2G and 2G++ will sensibly improve at z>0.1 with 2G++

Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A



Expected rates:

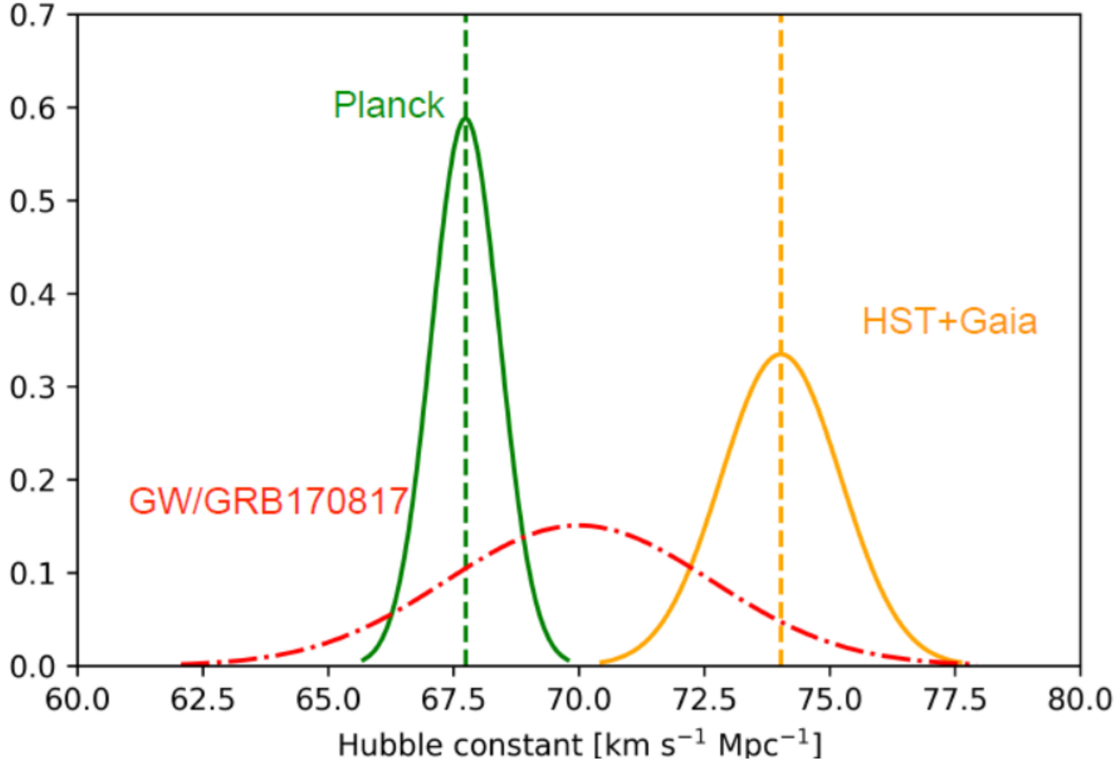
THESEUS + 3G:

- ~50 aligned+misaligned short GRBs
- ~200 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

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

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



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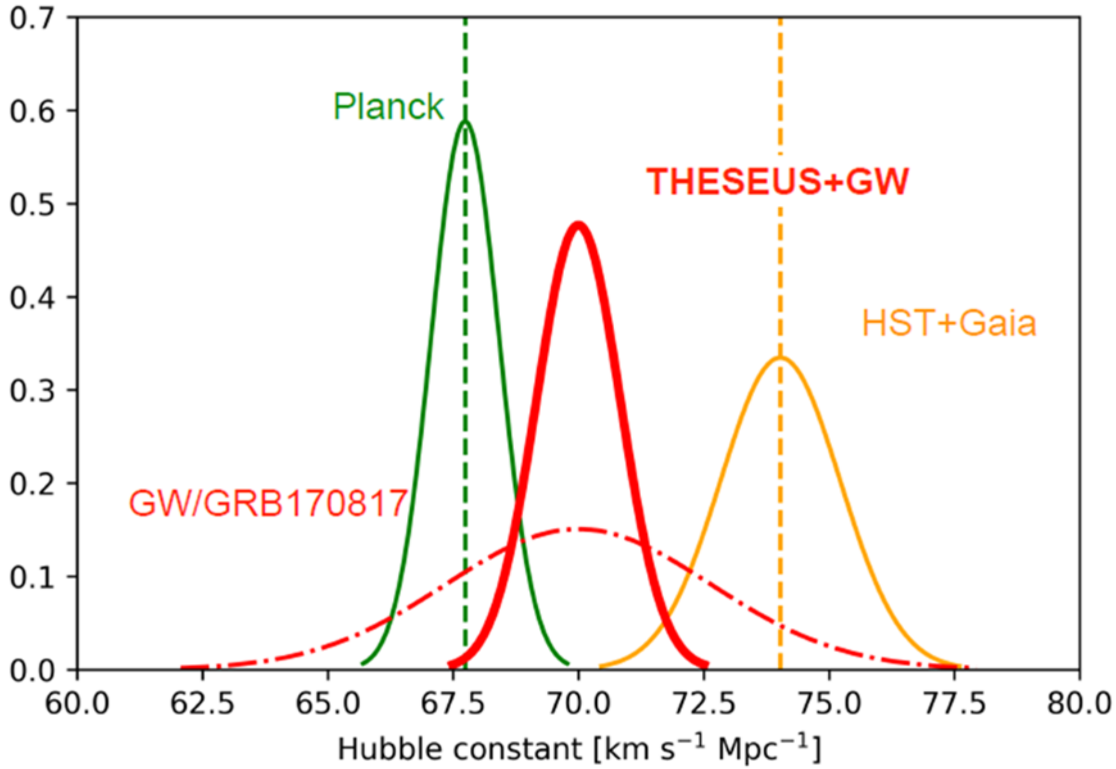
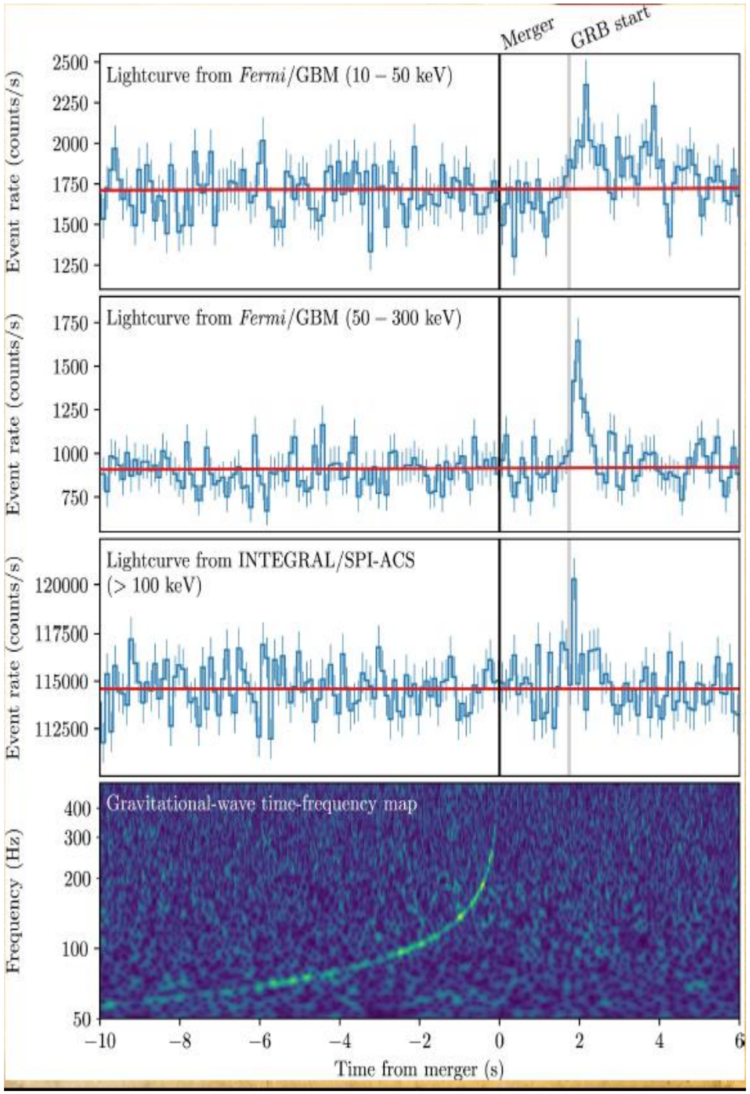


~20 joint GRB+GW events

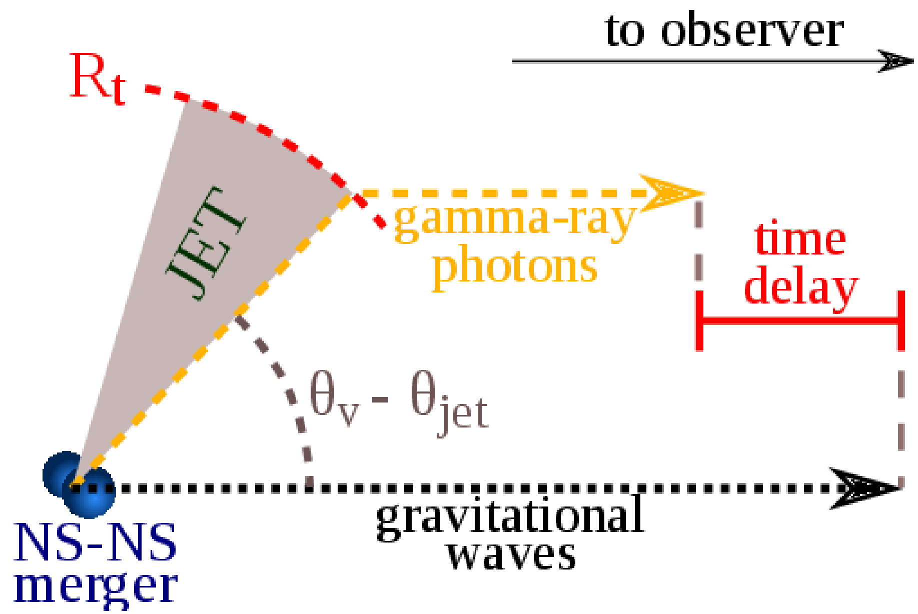
Fundamental physics with GRBs: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

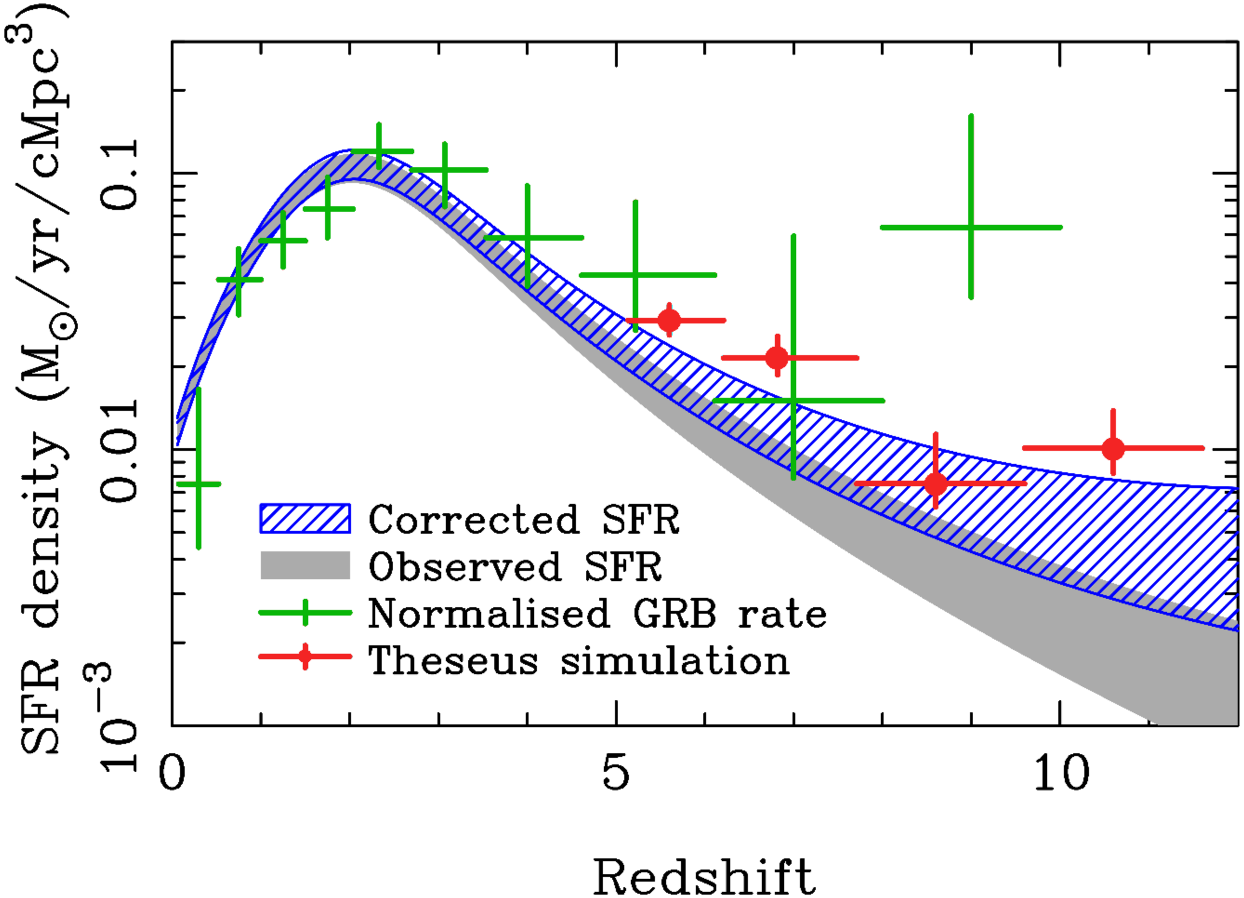
V_{gw} / c < 4x10^{-16}



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

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

- **Independent measure of cosmic SFR at high-z (possibly including pop-III stars)**

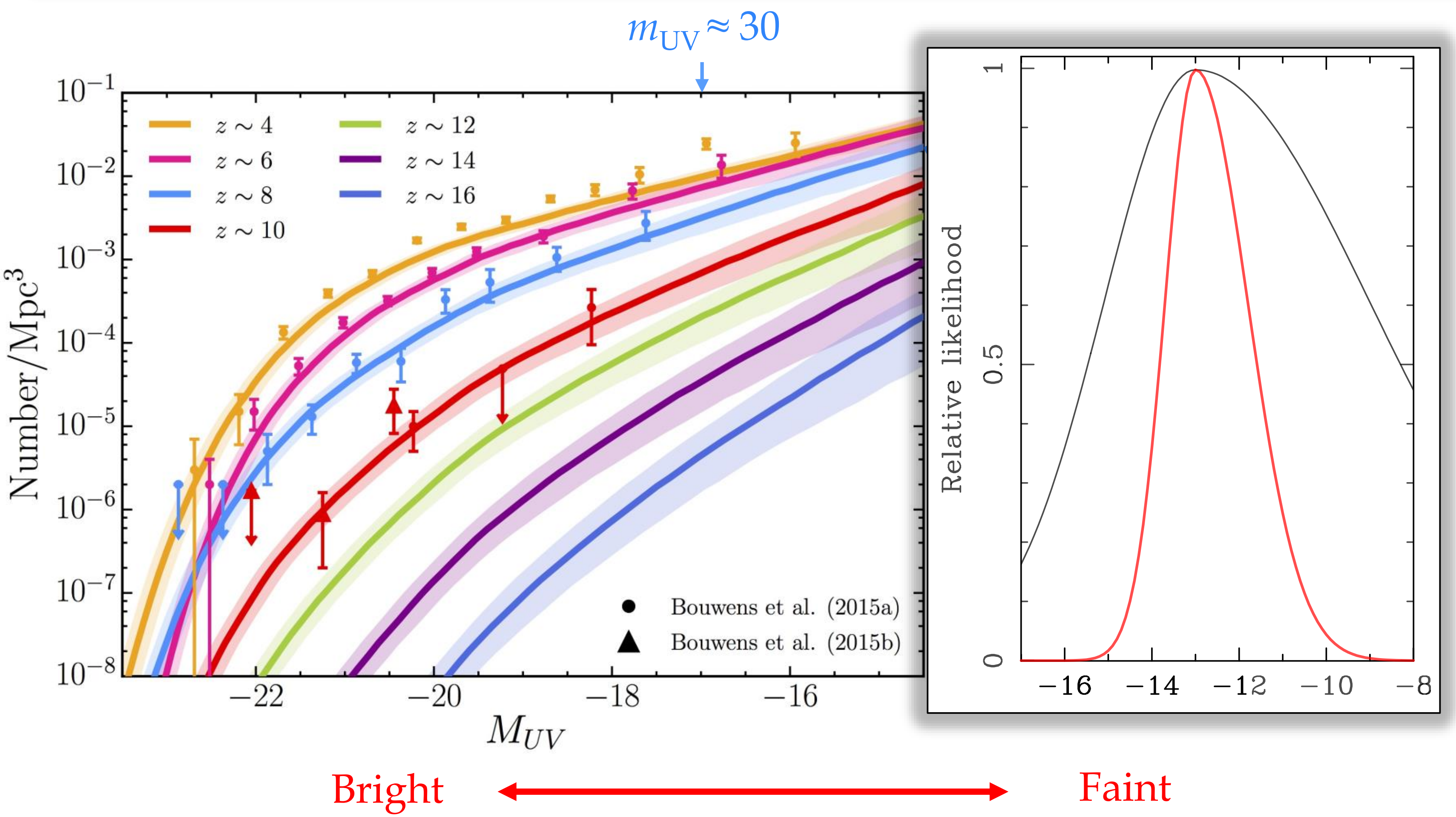


A statistical sample of high–z GRBs will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

THESEUS Consortium 2021

• 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



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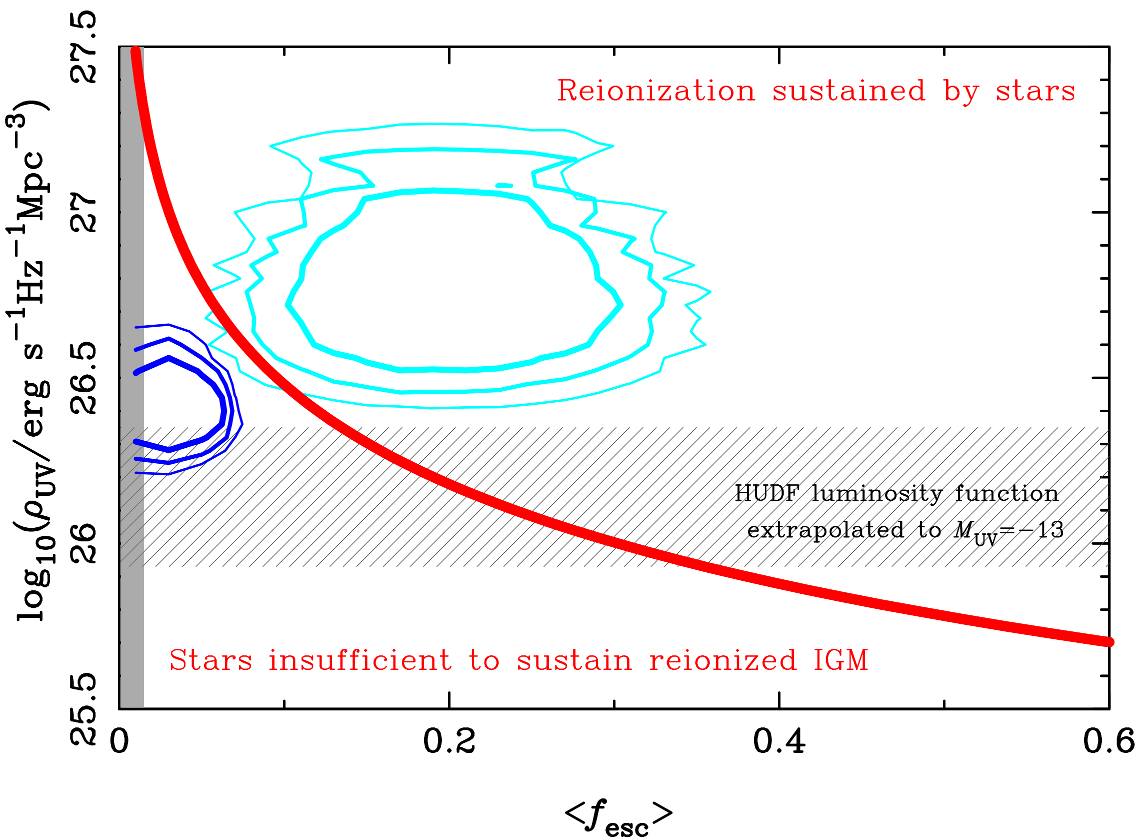
- **Shedding light on cosmic reionization**



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

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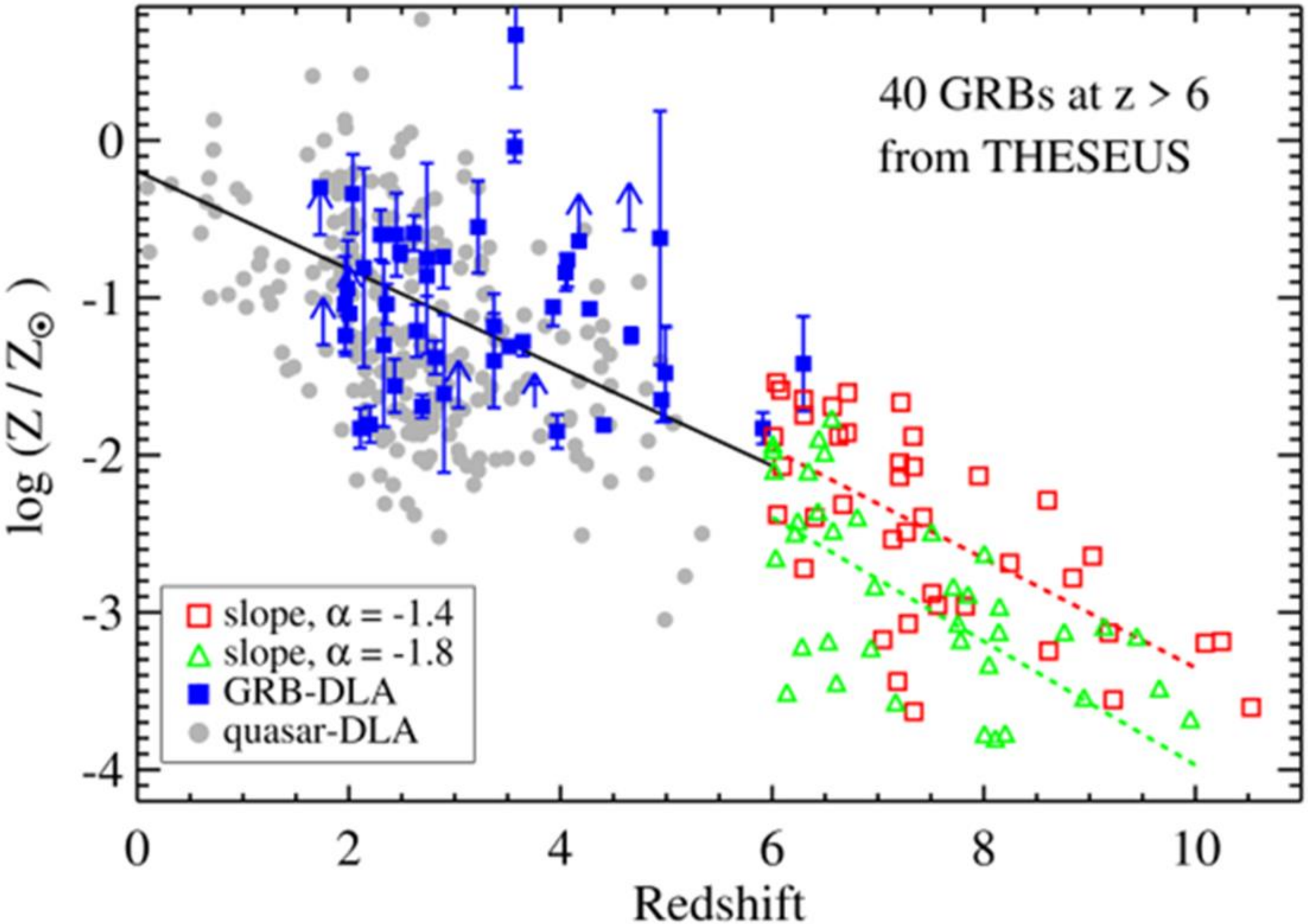
- **Cosmic chemical evolution at high-z**



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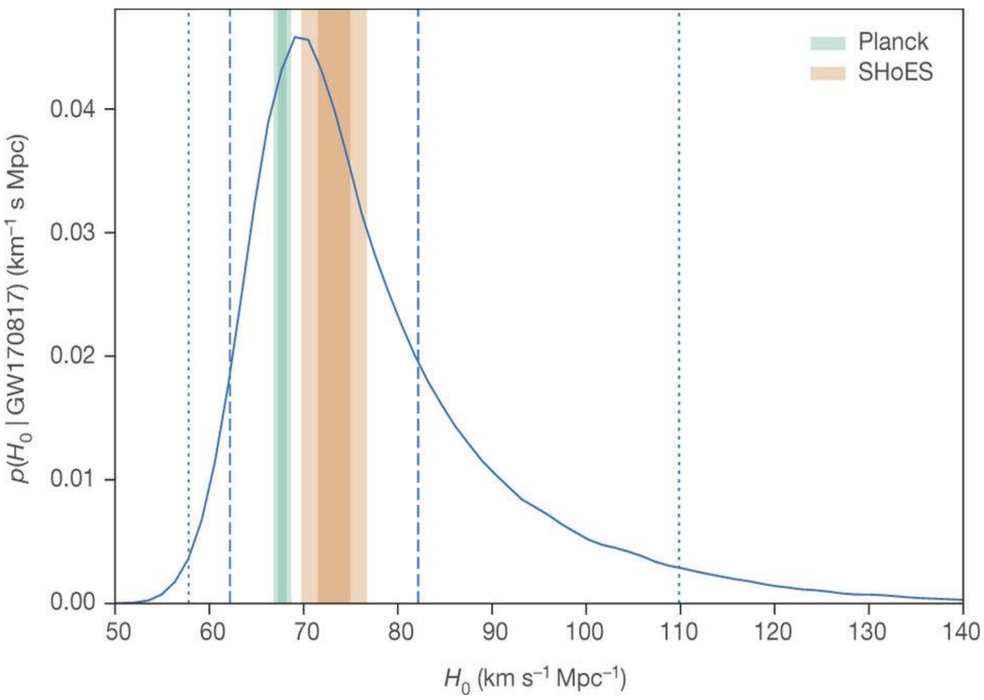
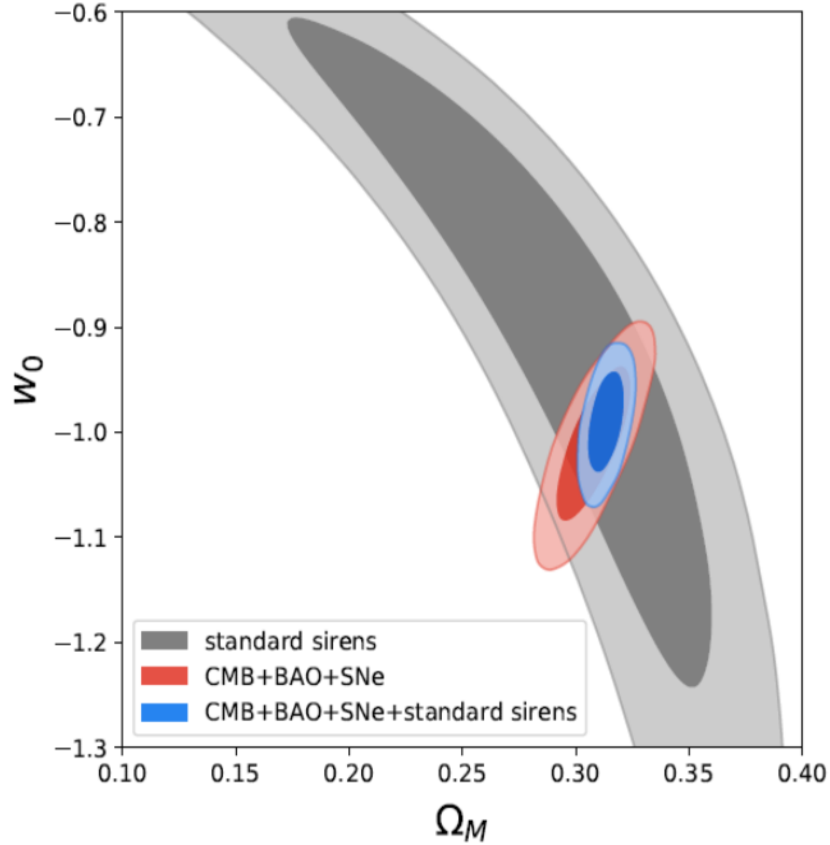
MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



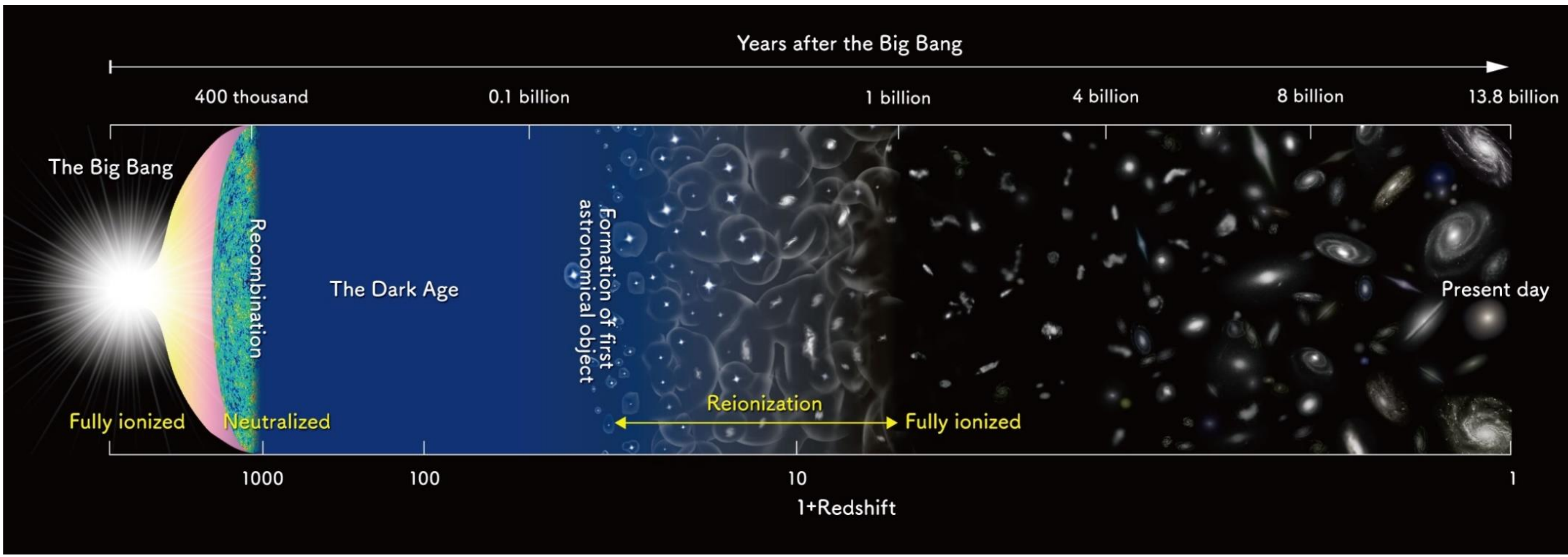
Estimating H0 with GW170817A (LVC 2017)



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

Shedding light on the early Universe with GRBs

- A major goal of contemporary cosmology is to reveal the emergence of primordial stars and galaxies, and the contemporaneous reionization of the intergalactic medium, in the **first billion years of the Universe**



What was the timeline of reionization?

What sources were responsible?

How did the chemical elements build up?

Fundamental physics with GRBs: 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)

$$|v_{\rm PHOT}/c - 1| \approx \xi \left(\frac{E_{\rm PHOT}}{\zeta m_{\rm PLANCK} c^2} \right)^n \qquad \epsilon = E_{\rm PHOT}/(\zeta m_{\rm PLANCK} c^2)$$

$$\Delta t_{\rm QG} = \pm \xi \left(\frac{D_{\rm TRAV}}{c} \right) \left(\frac{\Delta E_{\rm PHOT}}{\zeta m_{\rm PLANCK}\, c^2} \right)^n$$

Energy band MeV	$E_{\rm AVE}$ MeV	N ($\beta = -2.5$) photons	$E_{CC}(N)$ μs	N ($\beta = -2.0$) photons	$E_{CC}(N)$ μs	$\Delta t_{\rm QG}$ ($\xi = 1.0$, $\zeta = 1.0$) μs $z = 0.1$	μs $z = 0.5$	μs $z = 1.0$	μs $z = 3.0$
0.005 – 0.025	0.0112	3.80×10^8	0.38	3.02×10^8	0.43	0.04	0.25	0.51	1.42
0.025 – 0.050	0.0353	1.40×10^8	0.62	1.17×10^8	0.69	0.13	0.72	1.46	4.10
0.050 – 0.100	0.0707	1.10×10^8	0.71	9.98×10^7	0.74	0.27	1.43	2.93	8.21
0.100 – 0.300	0.1732	8.98×10^7	0.79	1.00×10^8	0.74	0.66	3.51	7.19	20.10
0.300 – 1.000	0.5477	2.07×10^7	1.64	3.82×10^7	1.20	2.09	11.11	22.72	63.56
1.000 – 2.000	1.4142	2.63×10^6	4.56	8.20×10^6	2.60	5.40	28.68	58.67	164.12
2.000 – 5.000	3.1623	1.07×10^6	7.19	4.92×10^6	3.35	12.07	64.12	131.19	367.00
5.000 – 50.00	15.8114	3.52×10^5	12.54	2.95×10^6	4.33	60.35	320.62	656.00	1834.98