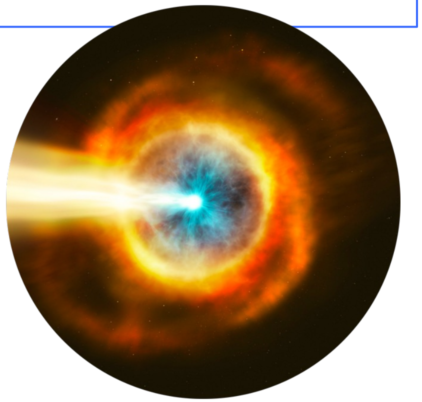
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

G. Stratta
ITP/GU,INAF/IAPS, INAF/OAS
on behalf of the THESEUS international collaboration

GRBV

V Congresso Nazionale GRB 2022



May 2018-June2021: THESEUS ESA M5 phase 0/A

https://www.esa.int/Our_Activities/Space_Science/ESA_selects_three_new_mission_concepts_for_study

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 selected from 25 proposals put forward by the scientific community.

Theseus, Spica and EnVision will be studied in parallel and a final decision is expected in 2021.

Dec 2021- April 2022: THESEUS enters ESA M7 Phase II

End of 2021 → ESA M7 mission call → launch 2037

Februrary 2022: THESEUS successfully passed first pre-selection

15 July 2022 → proposal sent for phase A participation where 3 missions will be selected

November 2022: selection of max 3 missions for Phase A

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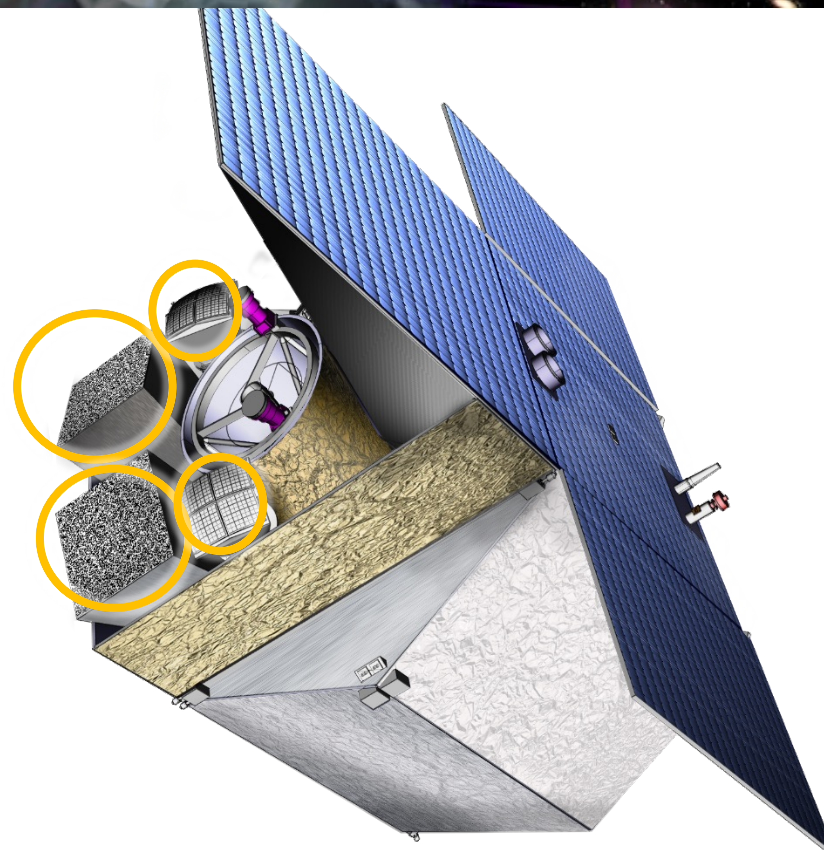
- Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**



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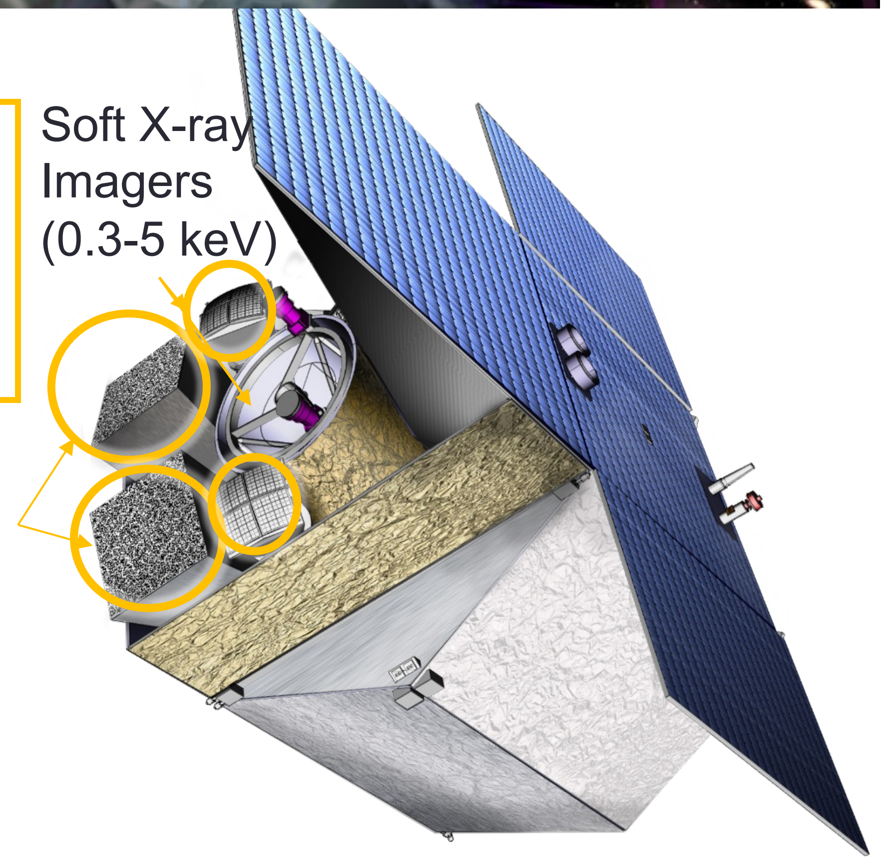

X-gamma-ray Imager Spectrometers
(2 keV – 1 MeV)

see talk by Marchesini

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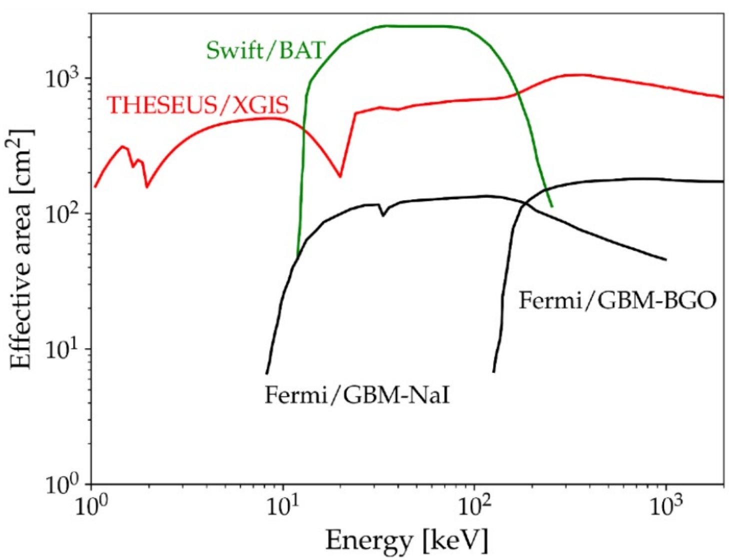

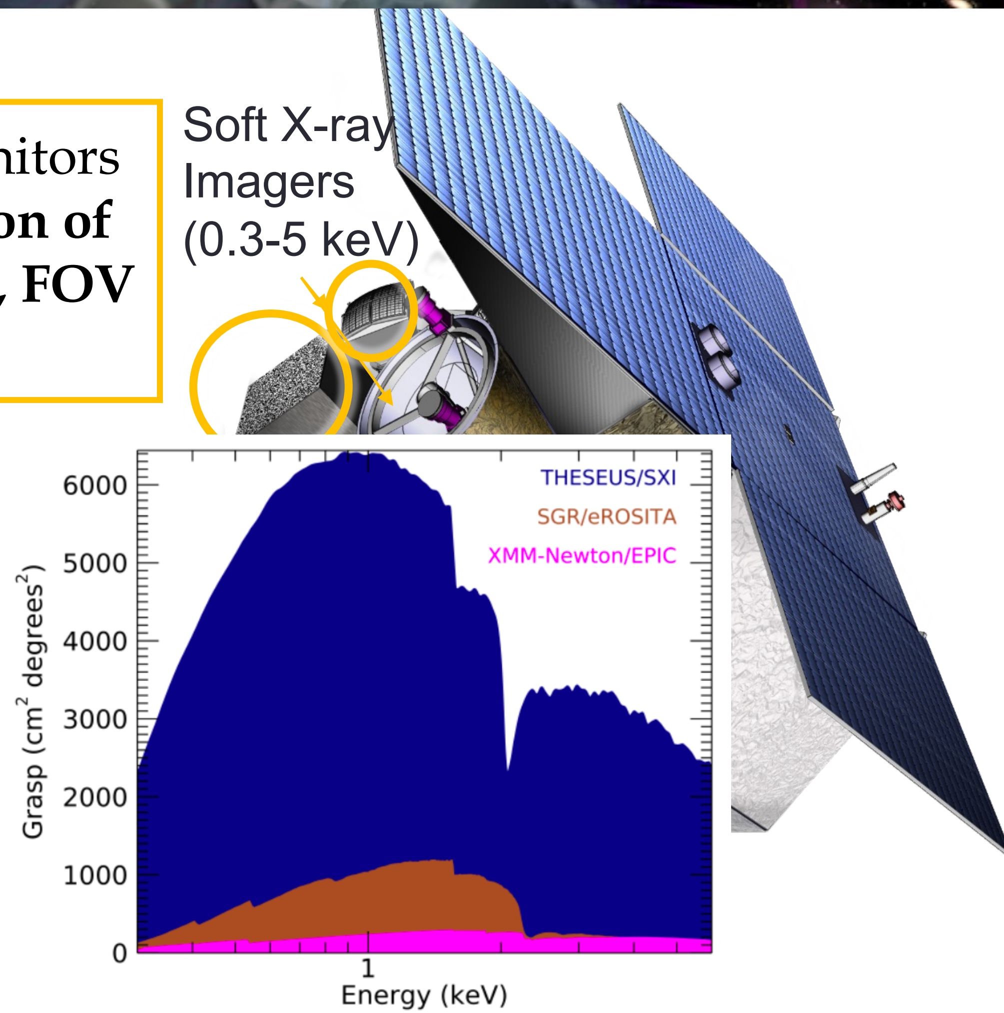

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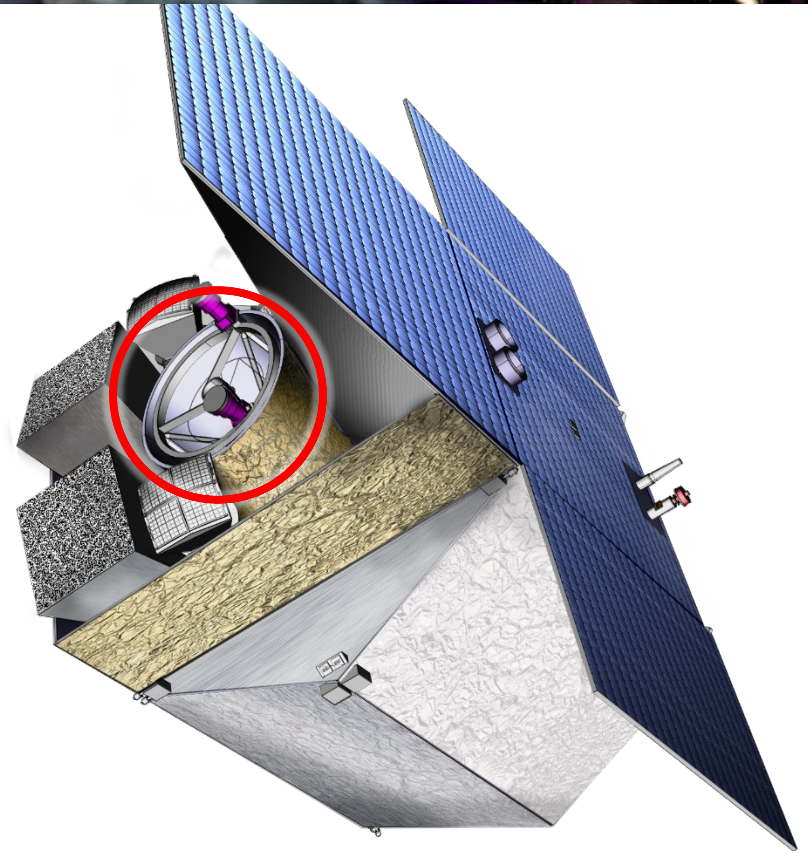

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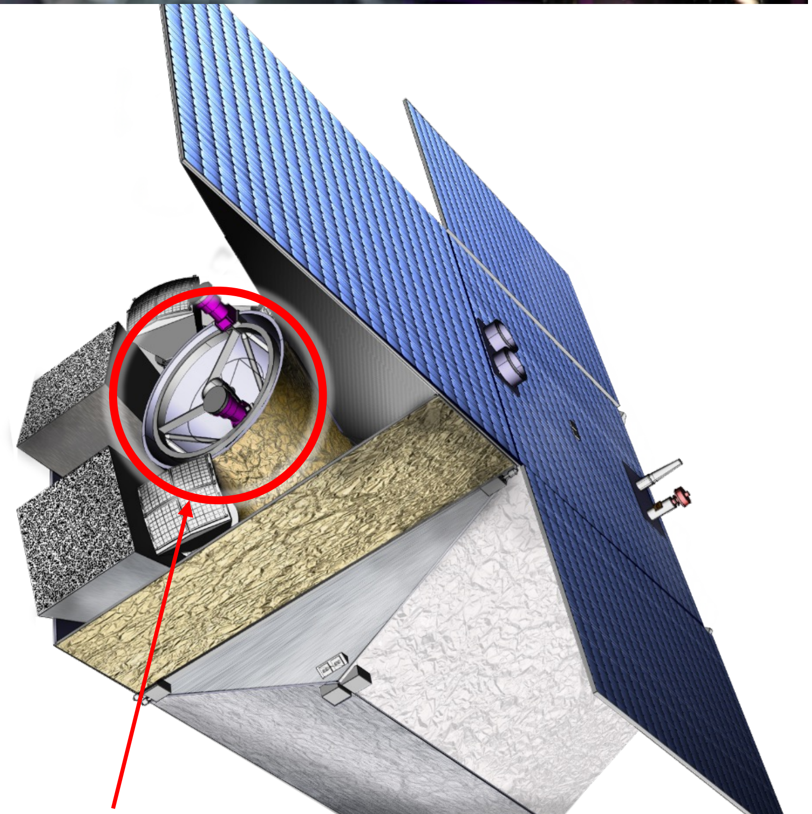
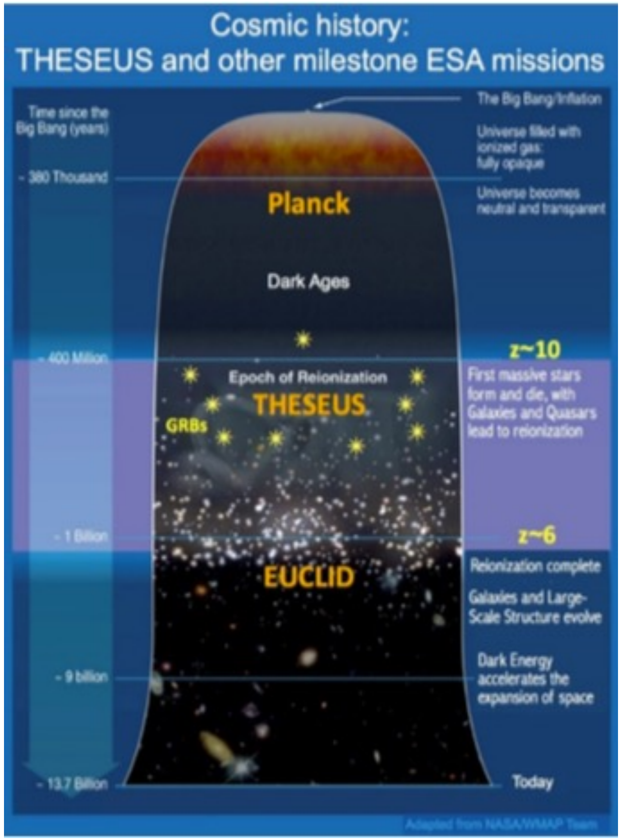


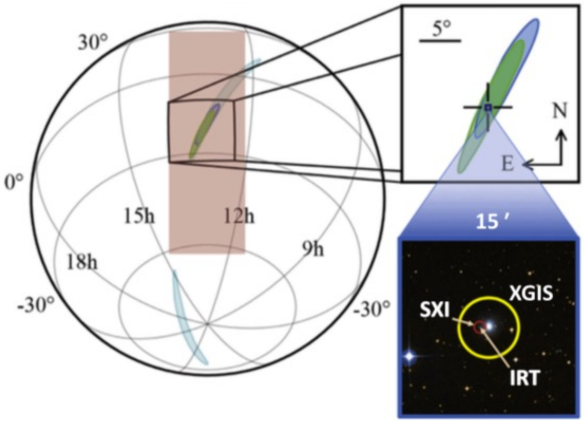
IR off-axis Koarsch Telescope 0.7m
(I (20.9),Z (20.7),Y (20.4),J (20.7),H (20.8)
for 150s and SNR=5)

THESEUS Core science

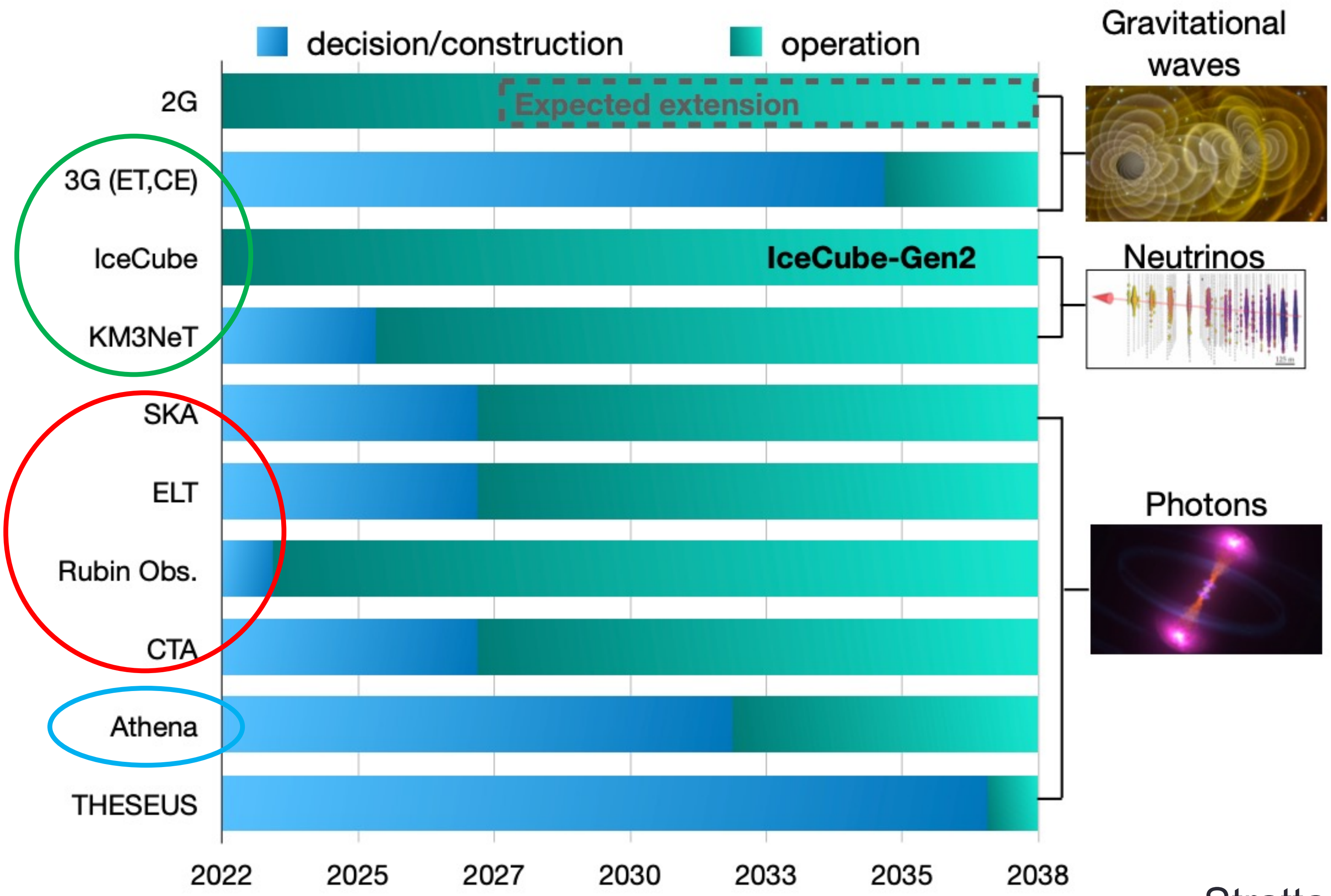


Investigating the first billion years of the Universe through high-redshift GRBs

Providing a substantial advancement of multi- messenger and time-domain astrophysics



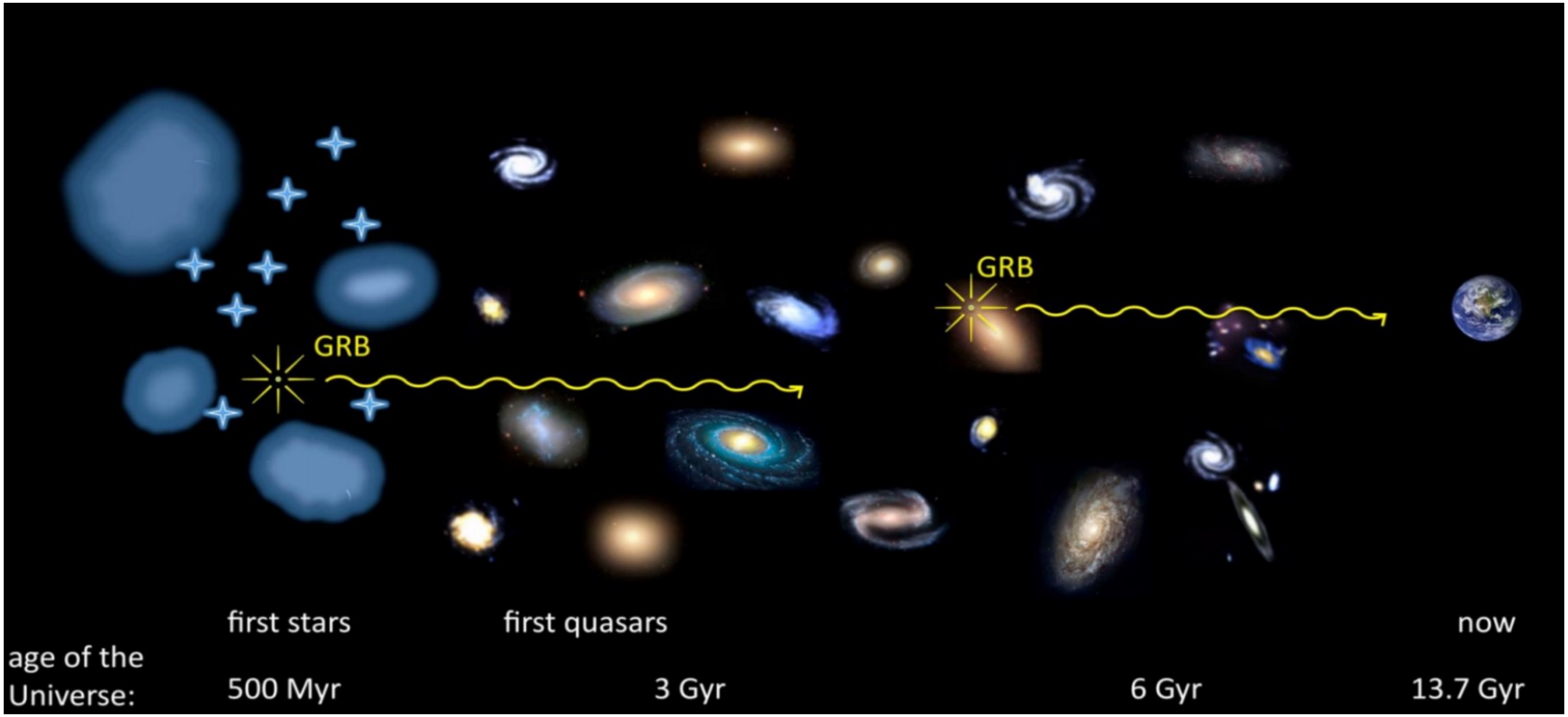
THESEUS synergies in >2037



Stratta+2022

Investigating the early Universe

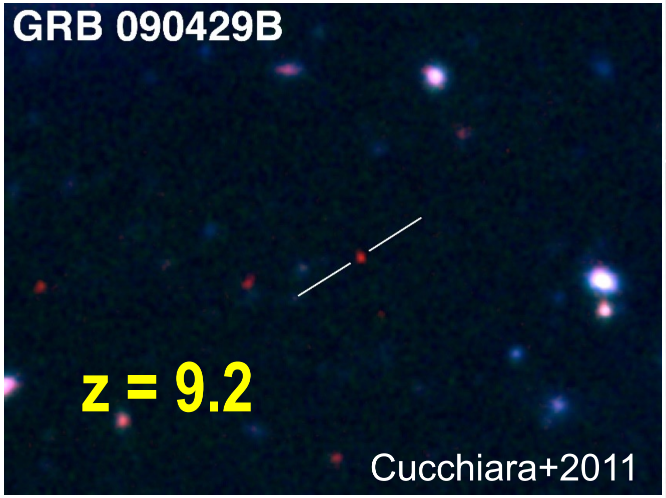
GRBs sky position individuate the position of a "normal" galaxy representative of the bulk population from local to the infant Universe

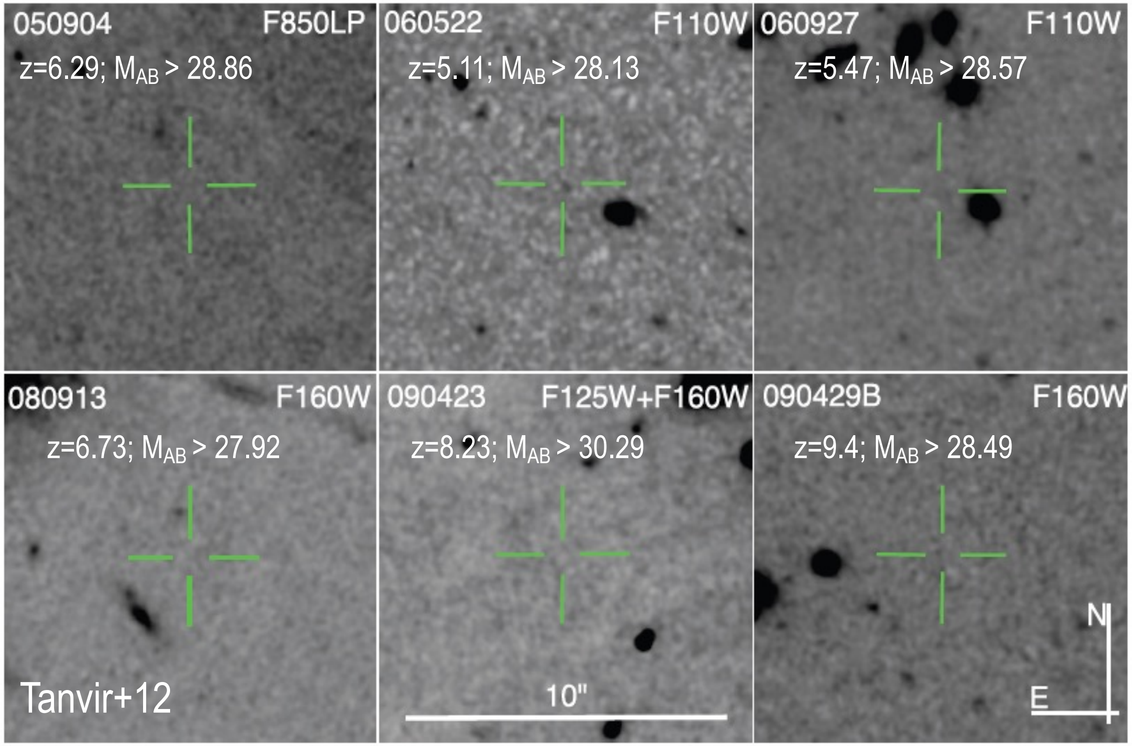


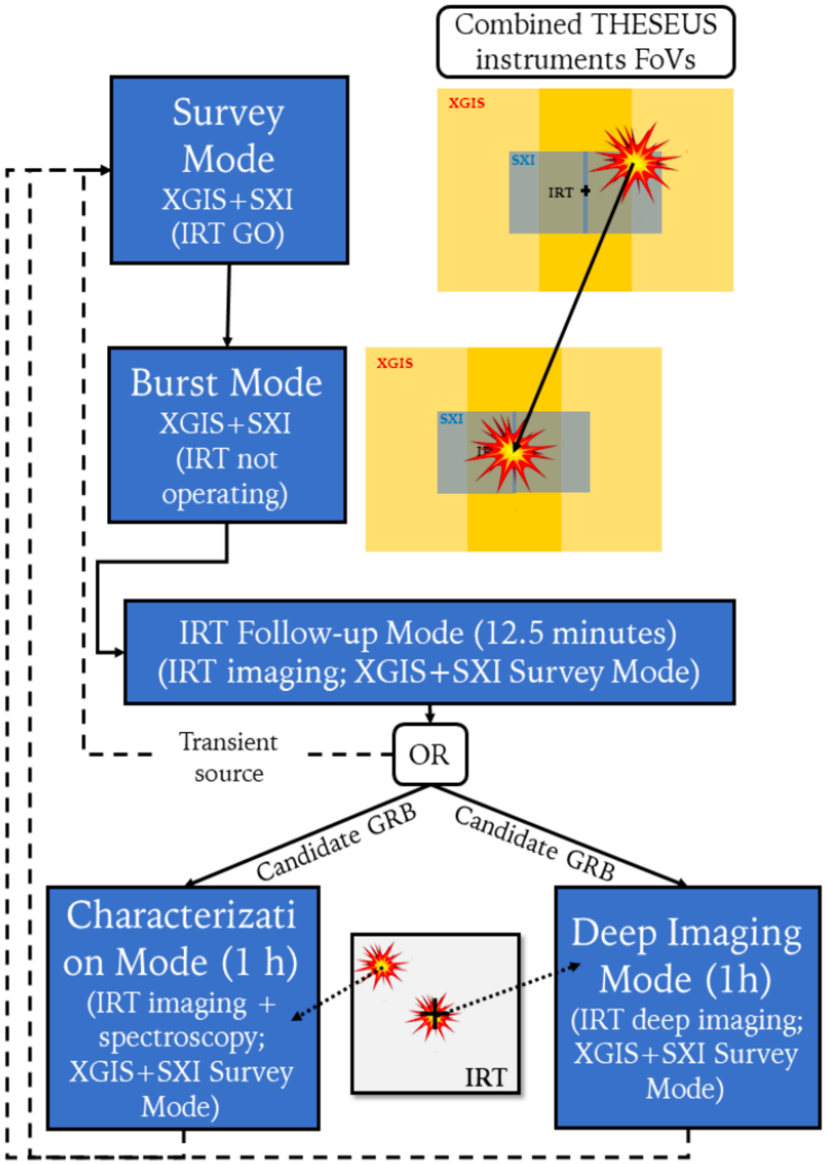
Investigating the early Universe

At the highest z, "normal" galaxies are too faint also for *JWST* and the future ELTs → GRB optical afterglow spectra/SED can characterize the host galaxy

....But how to recognize a high-z GRB?



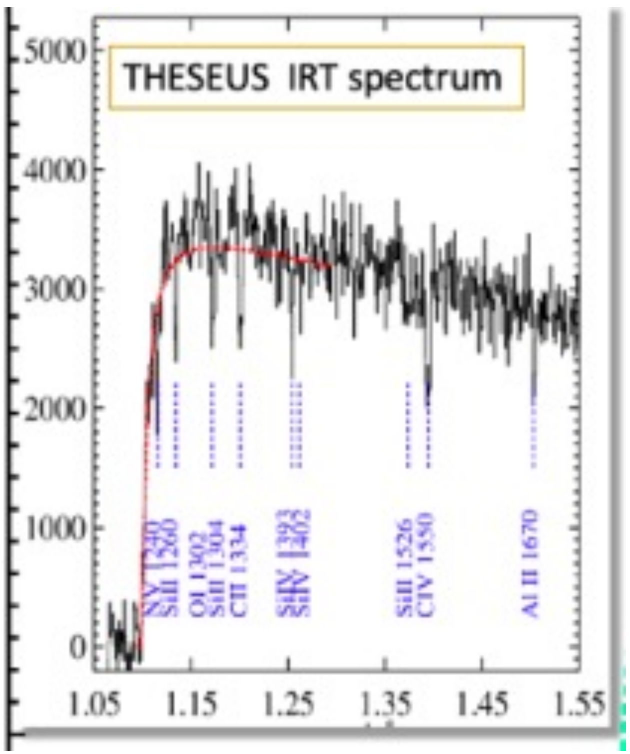




1. Burst detection → first sky localization with XGIS and SXI
2. Slew to put the source in the IRT FoV
3. 5 filter iRT imaging acquisition
4. **If an optical counterpart is detected than photometric or spectroscopic redshift is measured**

THESEUS ESA "Yellow Book" https://sci.esa.int/s/8Zb0RB8

Afterglow spectroscopy of THESEUS GRBs



Simulated z=8 GRB spectrum taken with THESEUS/IRT at 0.5 hrs (J_{AB}=16 mag)

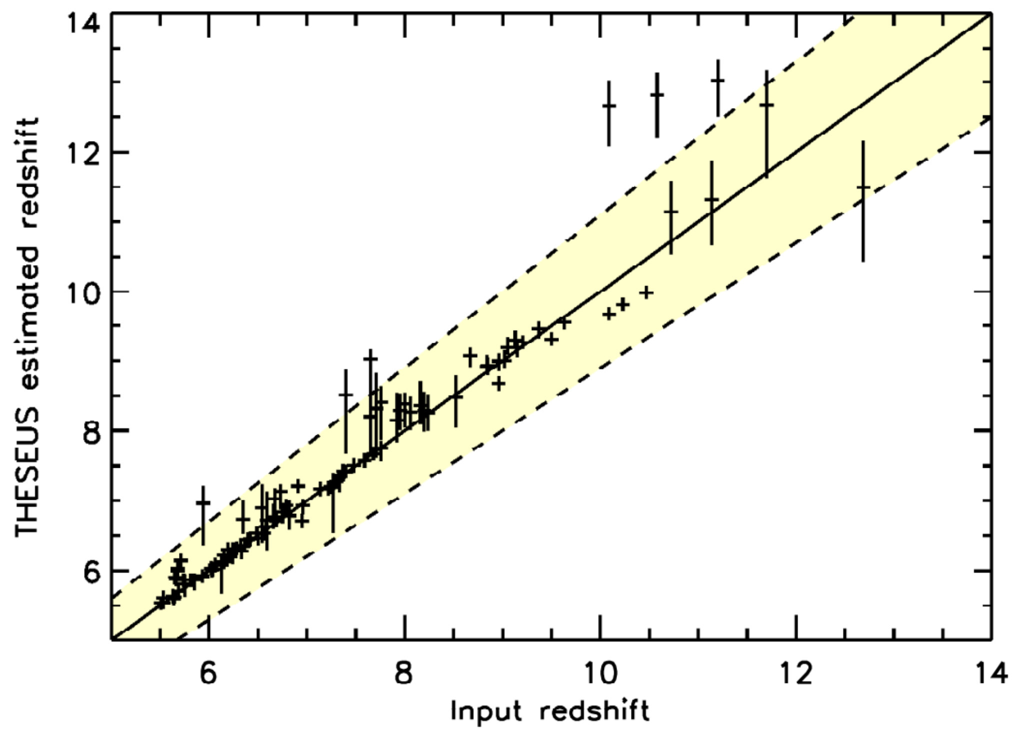
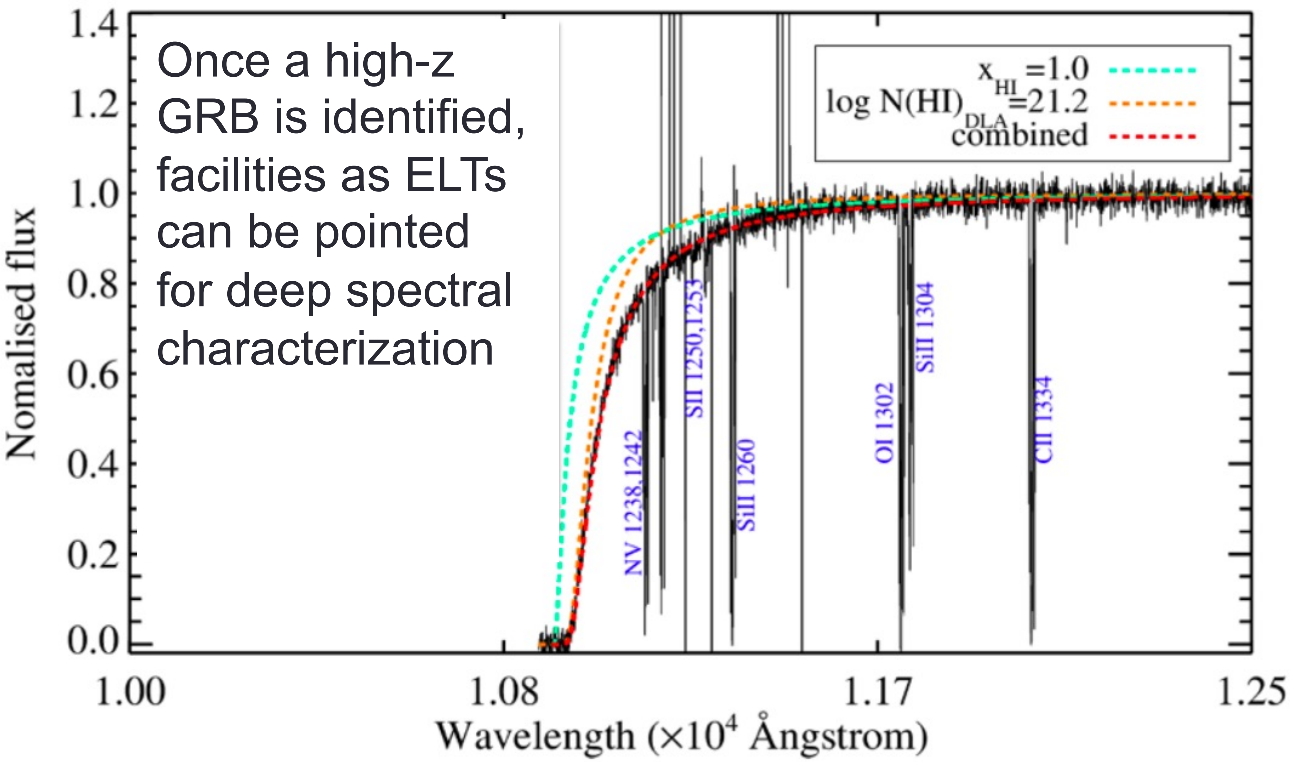


photo-z vs input z from Monte-Carlo simulations of the IRT observation sequence for a sample of 113 z>6 GRBs extracted from synthetic population model

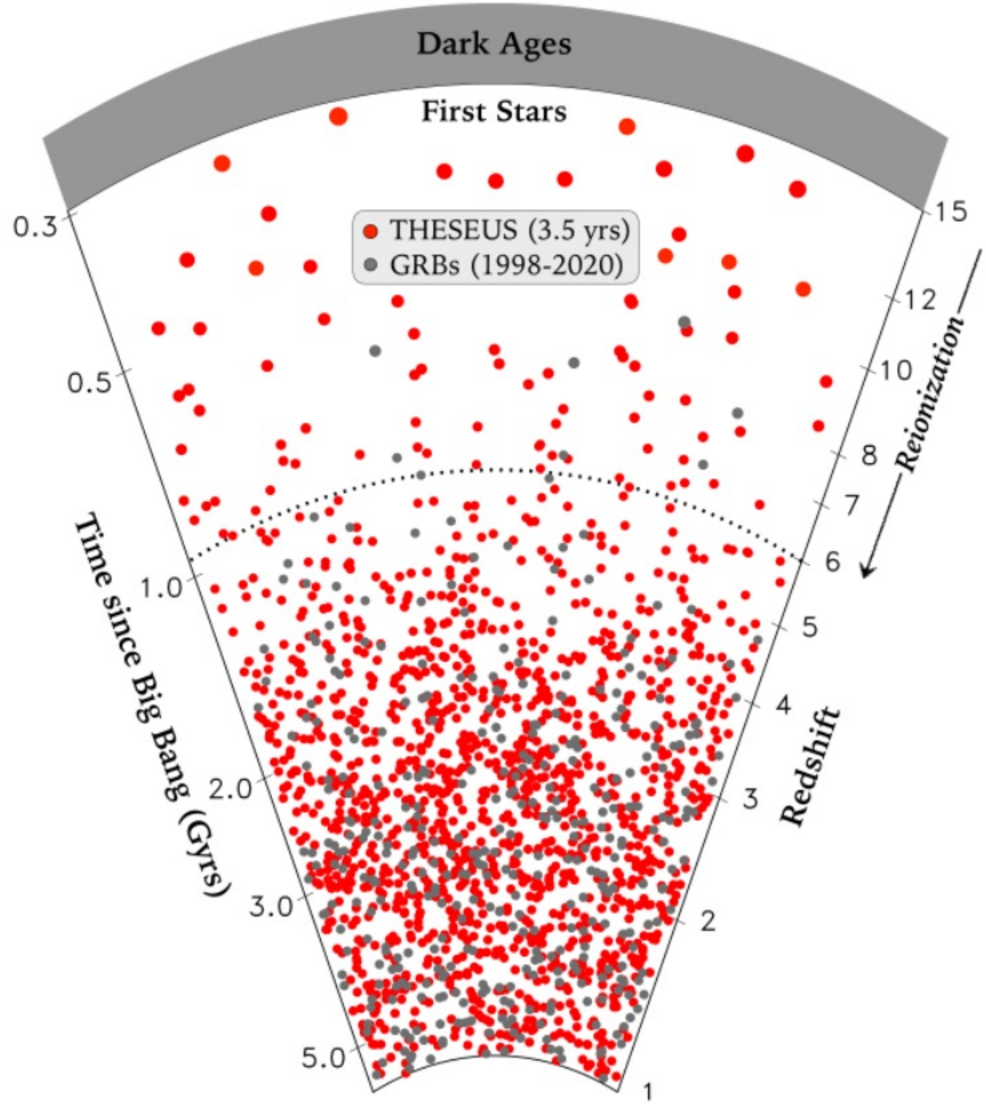
Afterglow spectroscopy of THESEUS GRBs

Once a high-z GRB is identified, facilities as ELTs can be pointed for deep spectral characterization



Simulated z=8 GRB spectrum taken at 0.5 days with ELT (J_{AB}=20 mag)

THESEUS capabilities are expected to significantly increase high-z GRBs to >40 GRBs at z>6



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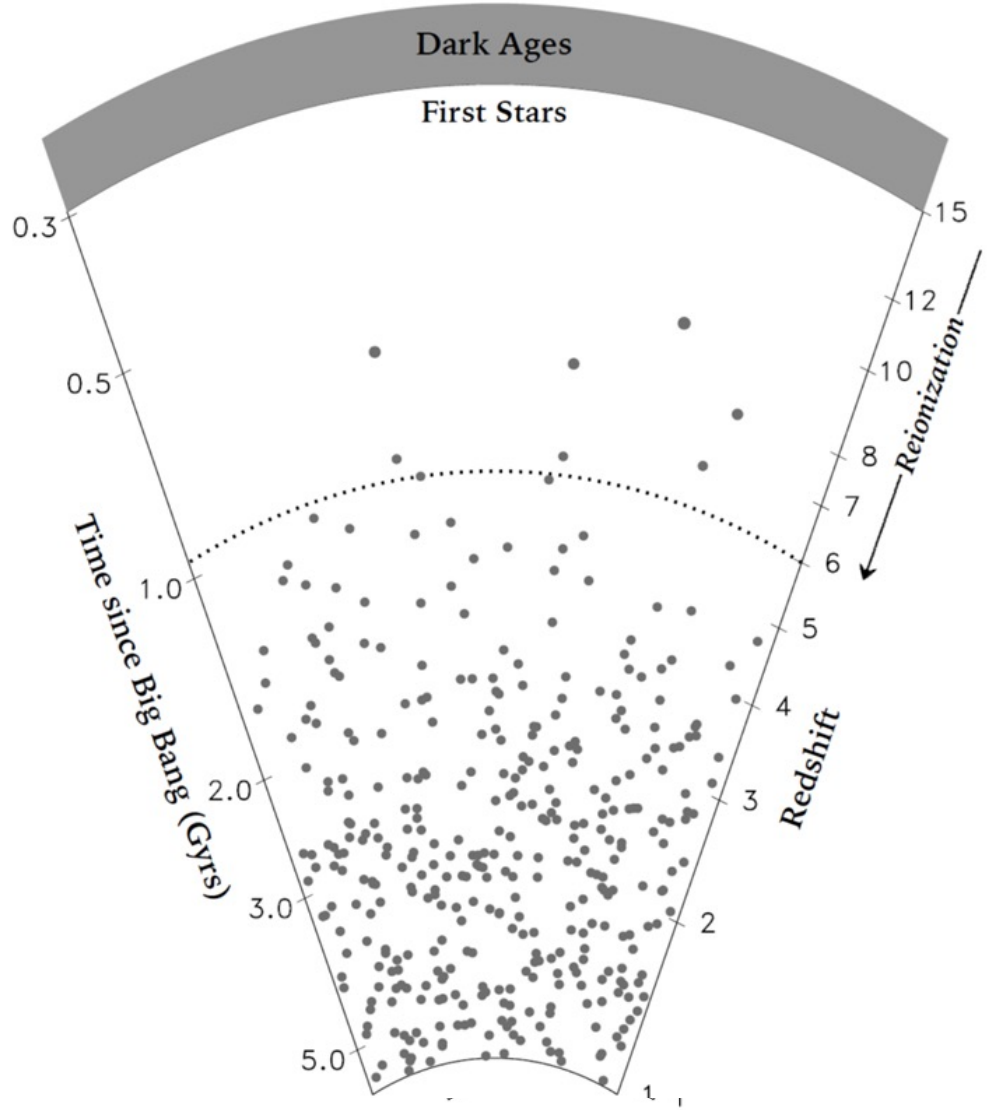

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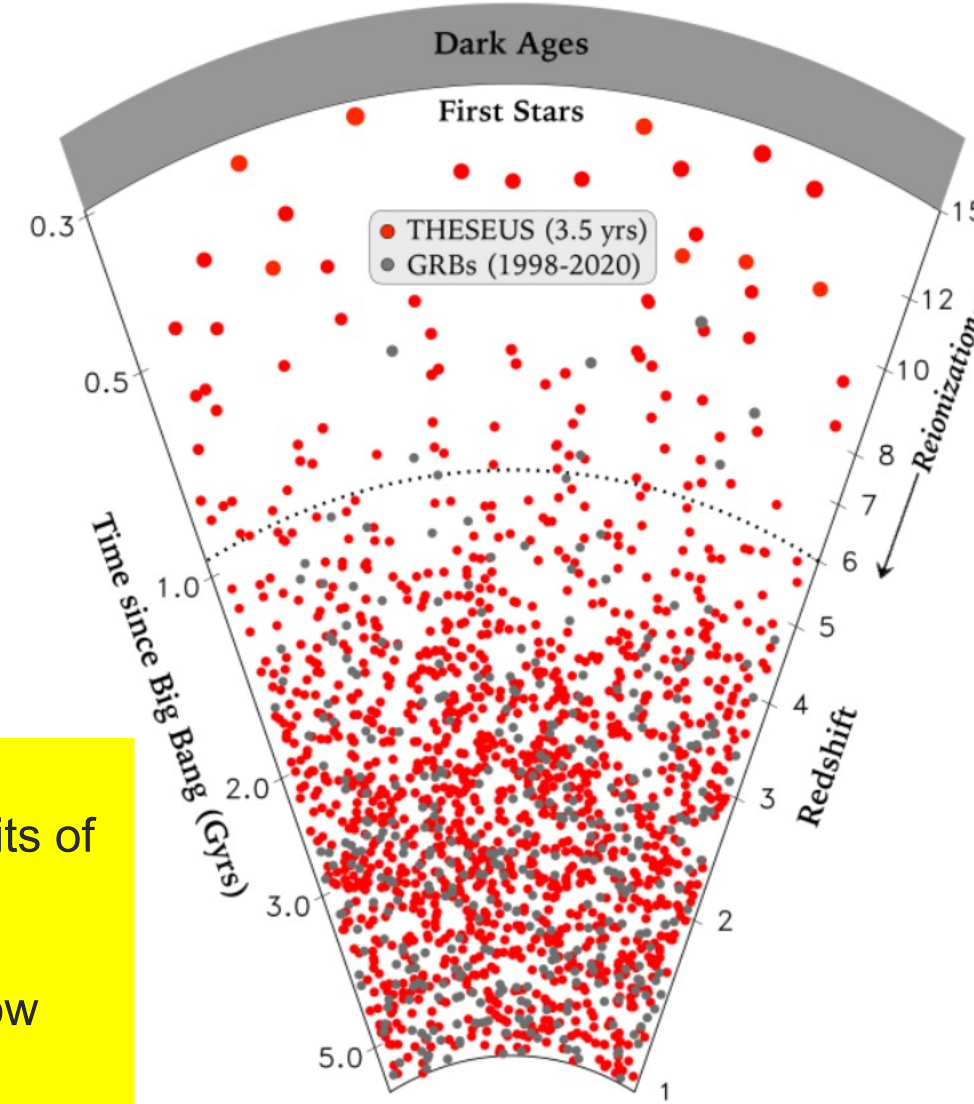
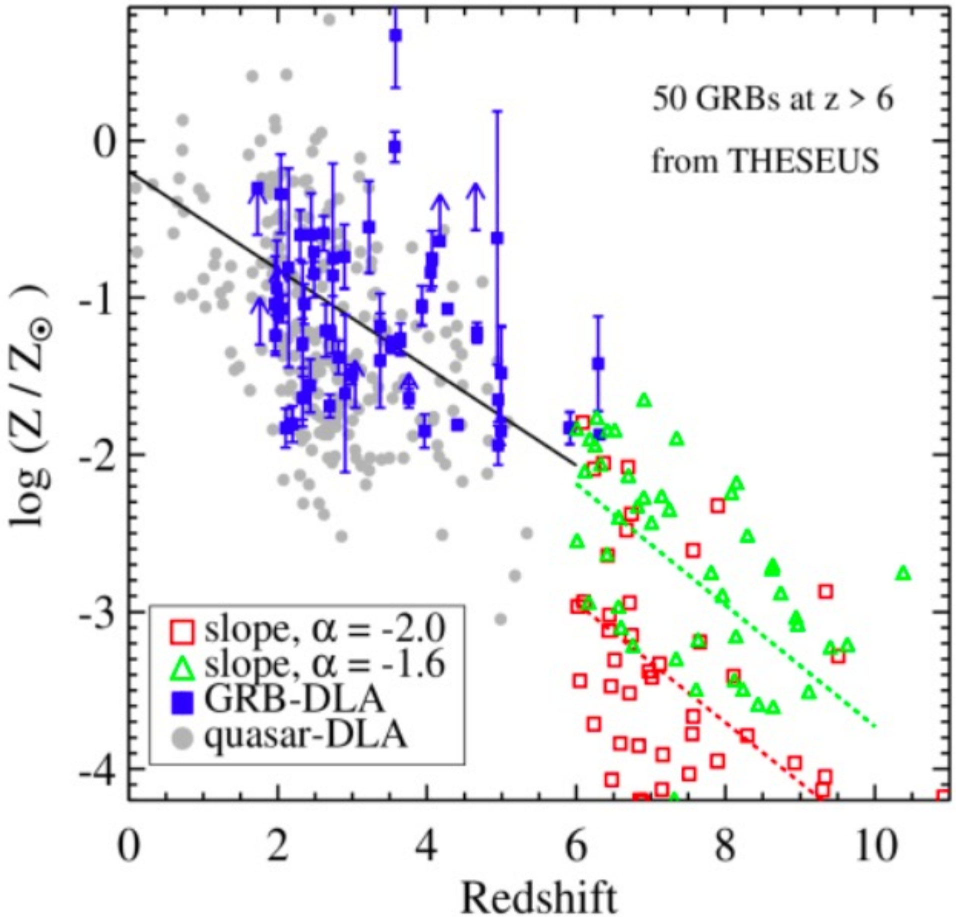


- ❖ First generation stars (pop III)
- ❖ Cosmic SFR (even beyond the limits of current/future galaxy surveys)
- ❖ Galaxy metallicity evolution and luminosity function, particular for low mass galaxies
- ❖ Physics of reionization

THESEUS ESA "Yellow Book" https://sci.esa.int/s/8Zb0RB8

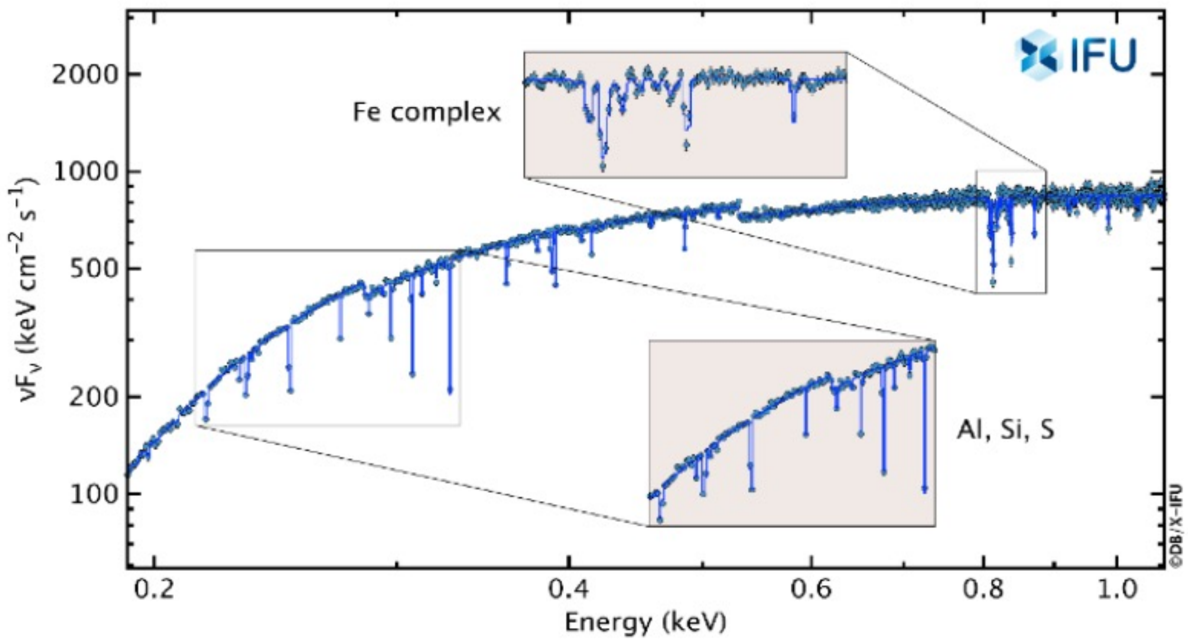
Afterglow spectroscopy of THESEUS GRBs



predicted metallicities by 50 high-z GRBs discovered with THESEUS assuming a galaxy LF with different slopes along with mass- or luminosity-metallicity relation

Absorption line based metallicity of QSO-DLA and GRB-DLA

Afterglow spectroscopy of THESEUS GRBs

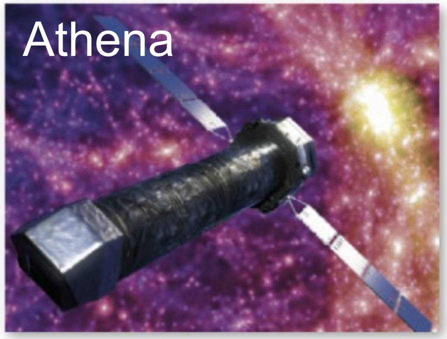


Simulated Athena/IFU 50ks spectrum of a medium bright z=7 GRB with fluence = 4×10^{-7} erg cm^{-2}, NH = 2×10^{22} cm^{-7} [Credit: X-IFU Consortium]

Piro et al. 2022 Exp Astronomy https://rdcu.be/cUNT4

THESEUS will provide burst trigger and sky localization to Athena

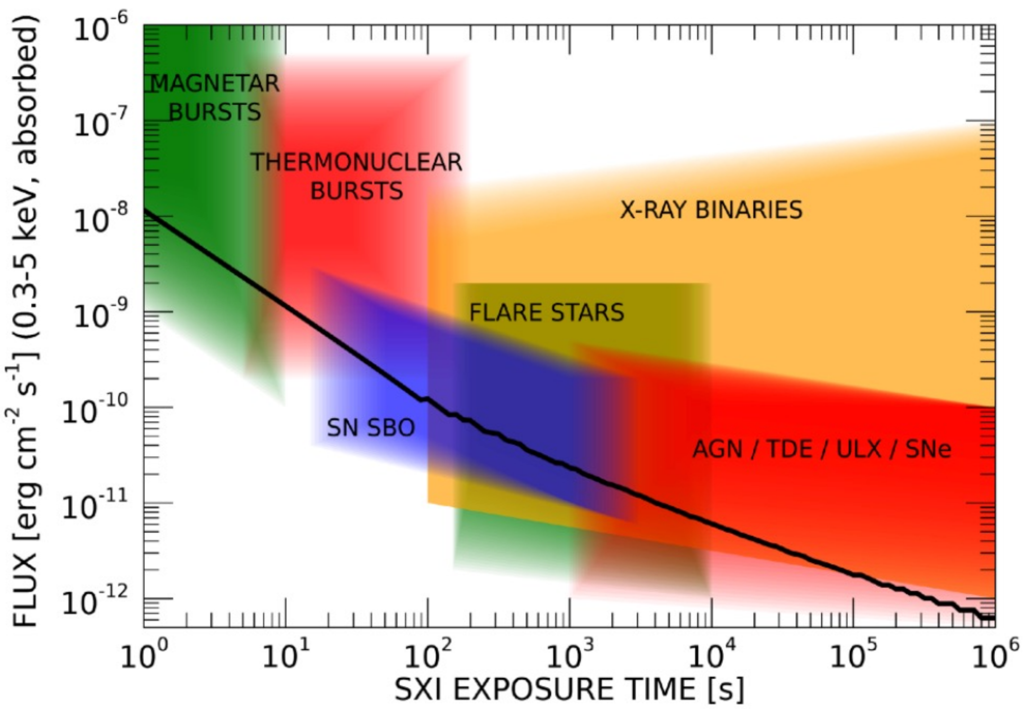
X-ray spectroscopy with Athena will reveal high ionization species → gas proximate to the GRB



Exploring the HE transient Universe

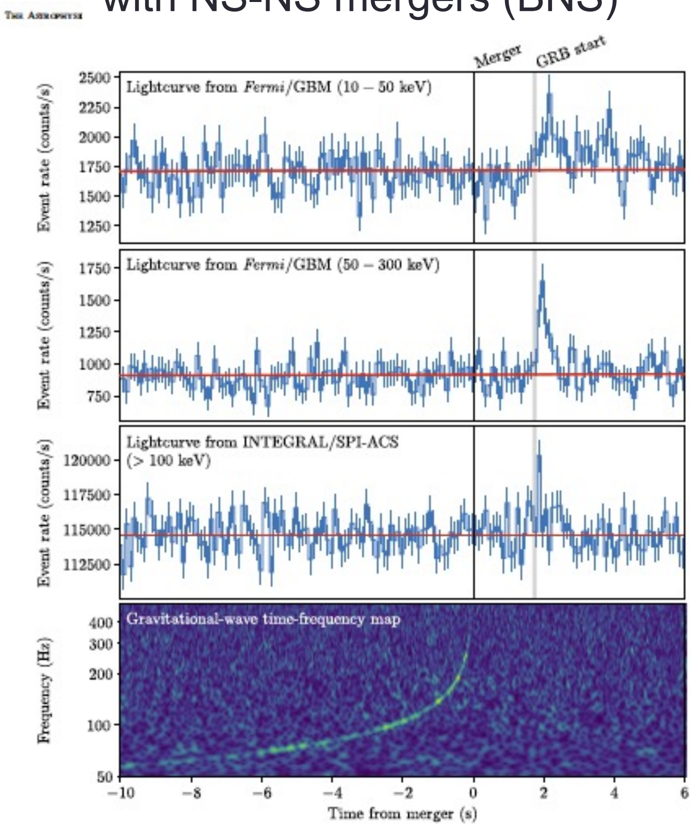
THESEUS will perform **deep monitoring of the X-ray transient sky:**

- GRBs,TDE,novae,SN shock breakout, AGN,etc.
- **counterparts of GW and neutrino sources** (routinely detected by the end of 2030s)



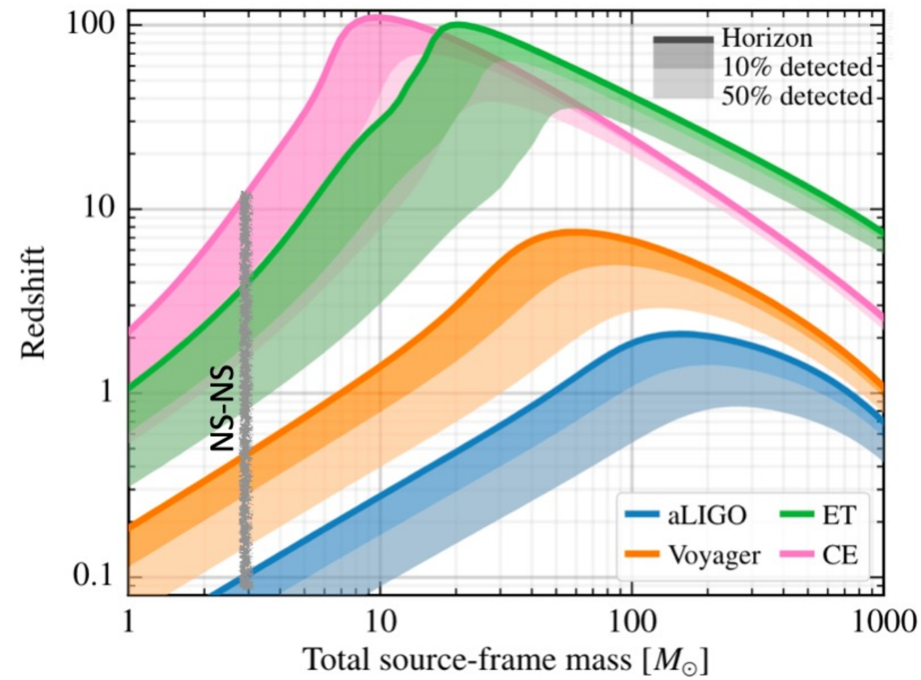
NS-NS merger with 3G GW detectors

From GW/GRB170817 we know that short GRBs are associated with NS-NS mergers (BNS)



Abbott et al. 2017 ApJL 13, 848

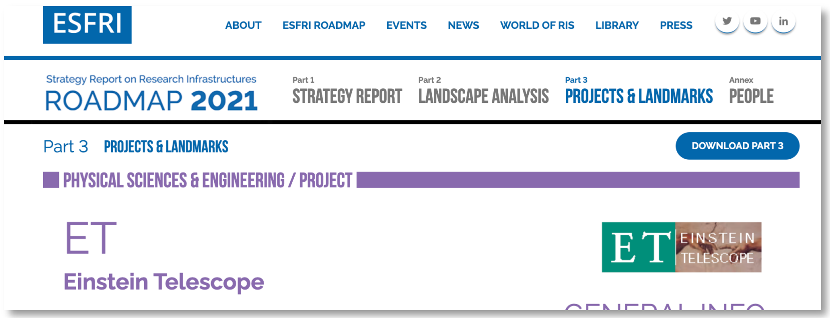
By >2035 ~10^5/yr BNS will be detected up to z>1-2 with 3G GW detectors



Hall & Evans 2019

3G GW detectors

- ET starting observations in 2035 → roadmap of the European Strategy Forum on Research Infrastructures (ESFRI)



https://roadmap2021.esfri.eu/projects-and-landmarks/browse-the-catalogue/et/

- Same starting period also in
  - the Gravitational Wave International Committee (GWIC) roadmap (Bailes et al. 2021, Nature Reviews Physics, 3, 344)
  - the mid-term review of the AstroParticle Physics European Consortium (APPEC) roadmap

Mid-term review of the
European Astroparticle Physics Strategy 2017-2026
in preparation for the 2022 APPEC Town Meeting

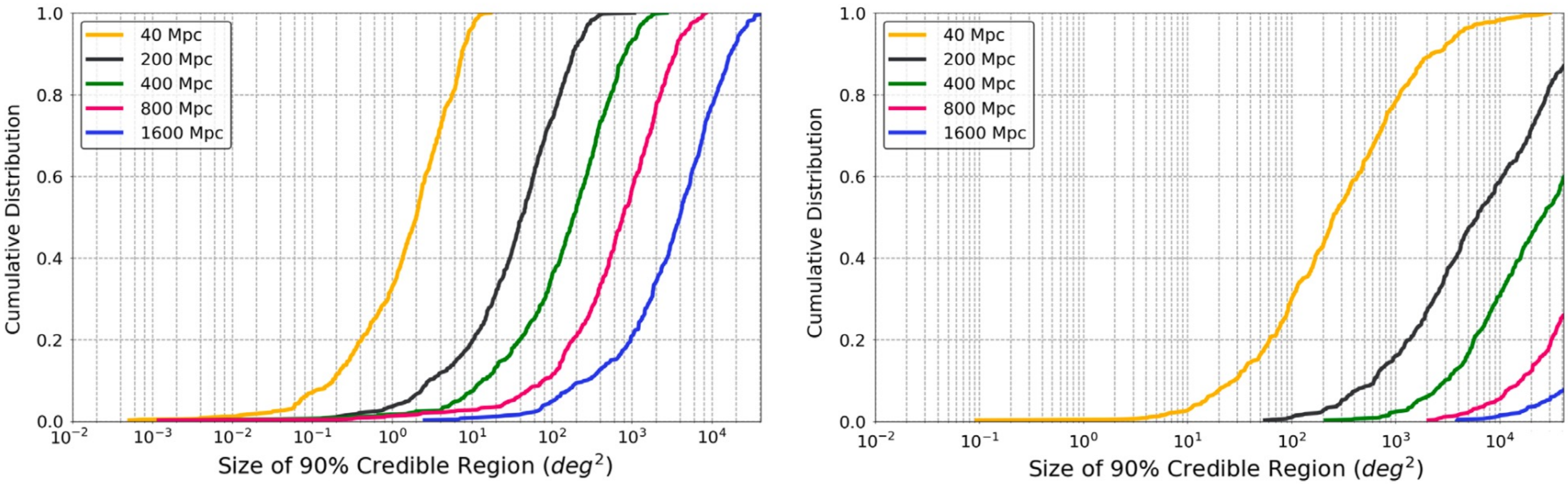
APPEC Scientific Advisory Committee

7 March 2022

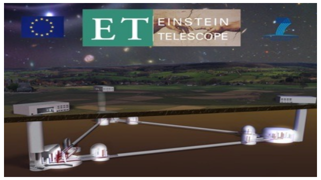
- https://indico.desy.de/event/32140/attachments/69790/92895/APPEC_Strategy_SAC_Midterm_Review_2022.pdf

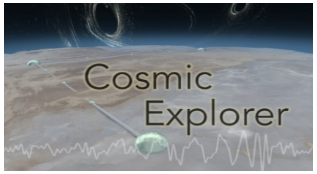
3G GW detector sky localization

BNS mergers - Chan+2018

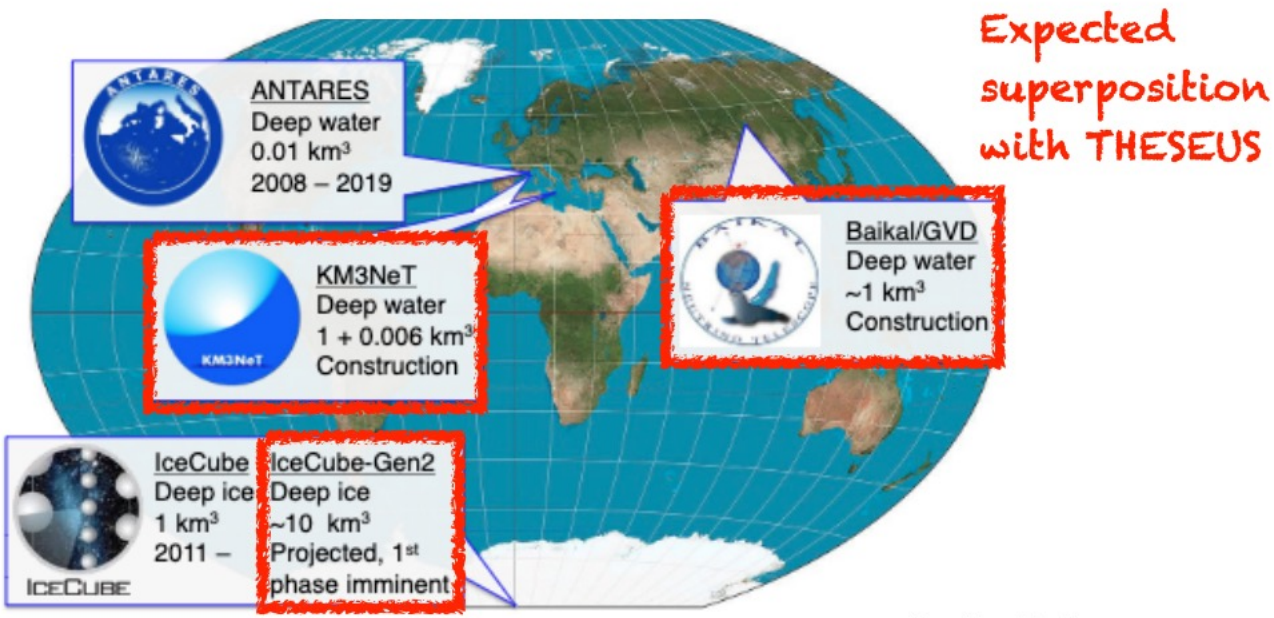


(a) (b)





Next generation neutrino detectors



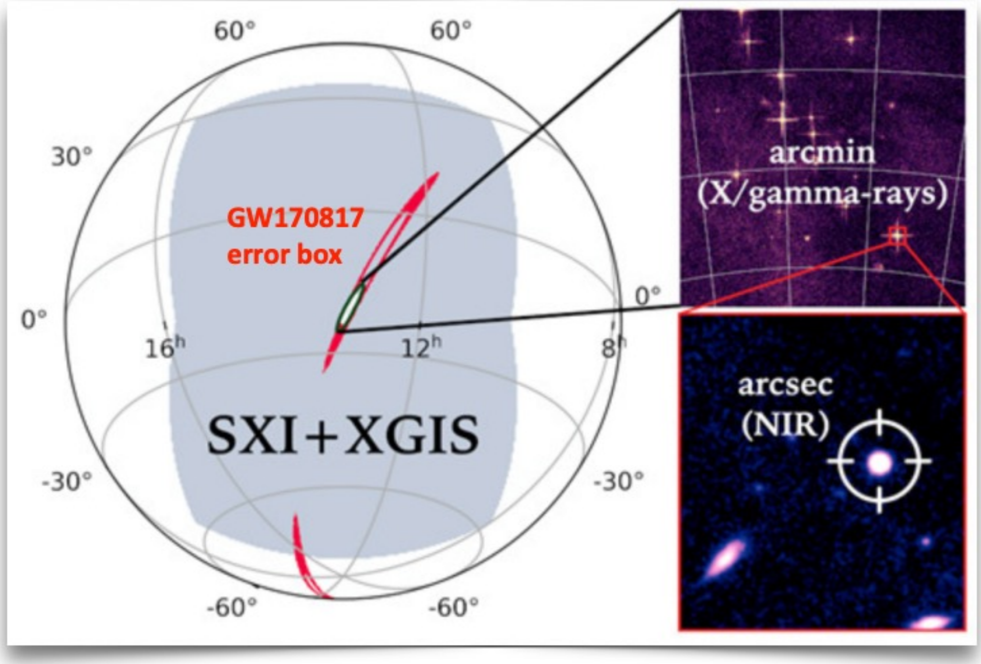
Credit: U. Katz

Sky localization:
- Long tracks topology (for nu_μ) → 0.1-0.2 deg
- Cascade topology (for nu_e and most nu_tau) → 3-5 deg

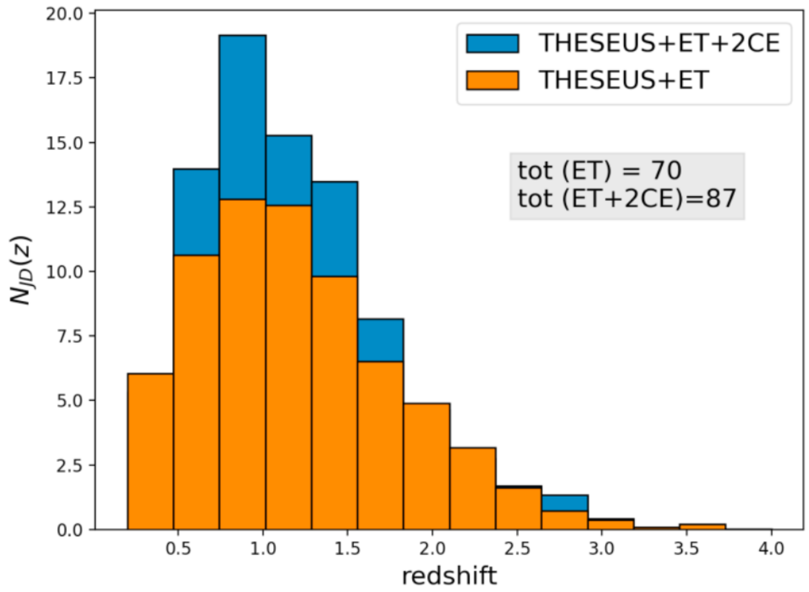
The role of THESEUS in MMA

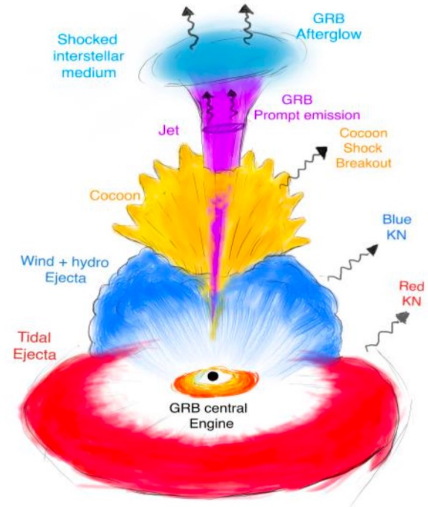
1. **Independent detection** of the electromagnetic counterpart of neutrino and/or GW —> increase statistical confidence of astrophysical nature of GW or ν event
2. **Autonomous source characterization** and identification (large spectral coverage of onboard instrumentations, from γ-rays to NIR)
3. **Accurate sky coordinate dissemination** —> follow-up campaigns with large facilities of 2030s as ELT, Athena, SKA,CTA, etc.

independent detection of a Short GRB with THESEUS



short GRB+GW science





Several tens of short GRB+GW are expected to be detected with THESEUS

GW detectors	**Total detections with XGIS and SXI**	Prompt emission detections with XGIS	HLE+afterglow detections with SXI	HLE+afterglow detections with XGIS and SXI
ET	70 [56 - 87]	22 [13 - 34]	28 [21 - 36]	55 [43 - 70]
ET+2 CE	87 [72 - 107]	34 [25 - 47]	34 [26 - 44]	65 [53 - 82]

From BNS pop. Synthesis + accurate structured jet model (see Ronchini+2022) + duty cycle (65% for XGIS and 75% for SXI)

short GRB+GW science

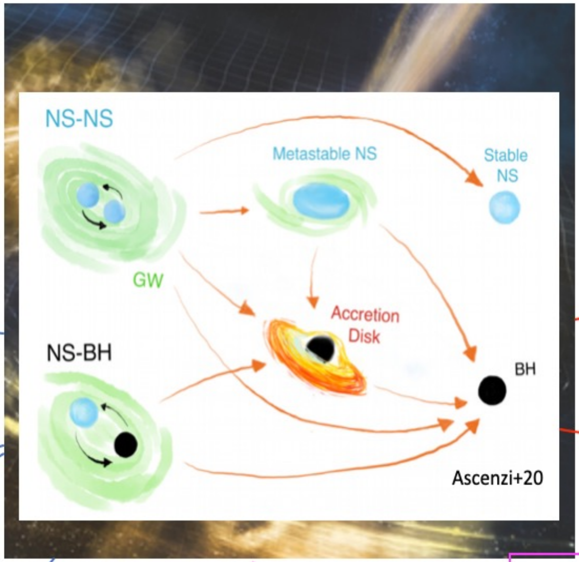
No follow-up with other factilities is required:

What is the nature of merger remnant from NS-NS mergers and their link with burst prompt properties?

Are there any systematic differences between NS-BH and NS-NS jets formation efficiencies?

What is the jet launching mechanism and its efficiency?

Fundamental physics (e.g. photon/GW propagation)



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What is the Universe expansion rate (H0 measure)?

What role plays NS-NS/ NS-BH in Universe chemical enrichment of heavy elements?

What is the jet structure?

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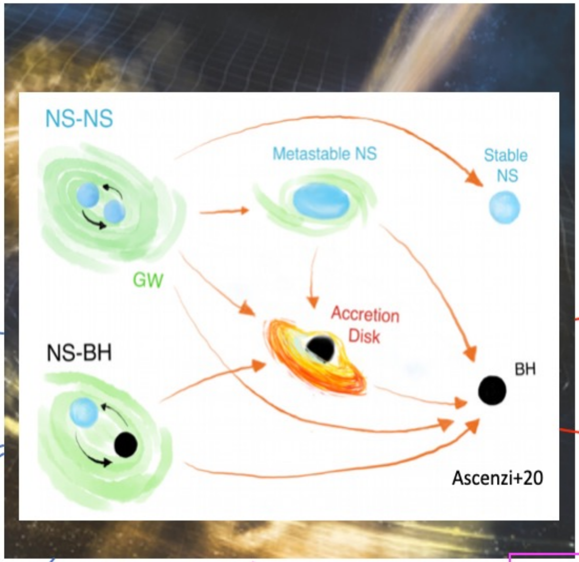

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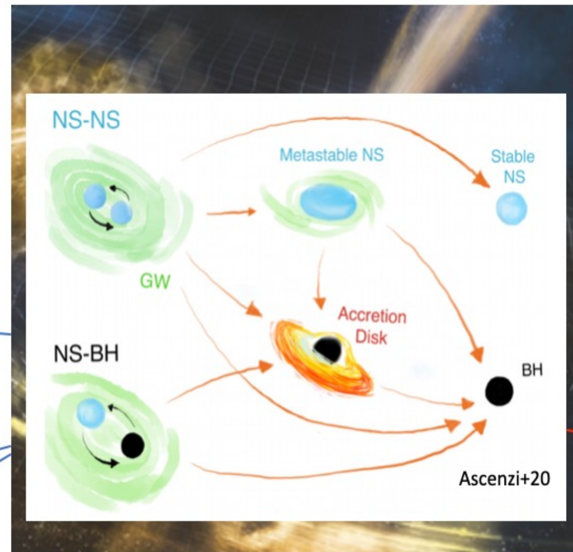

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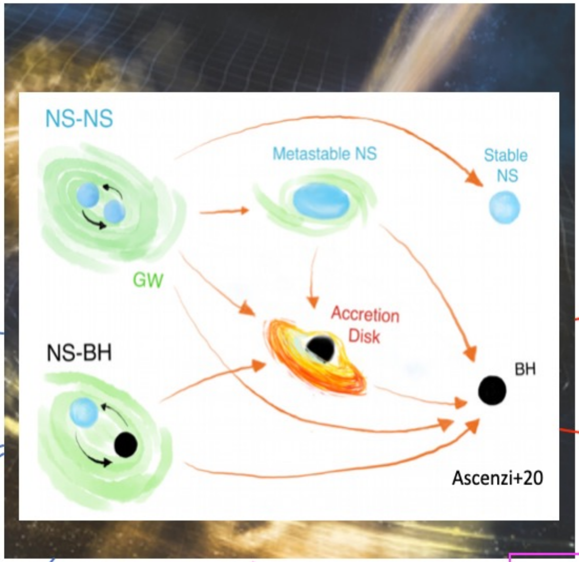

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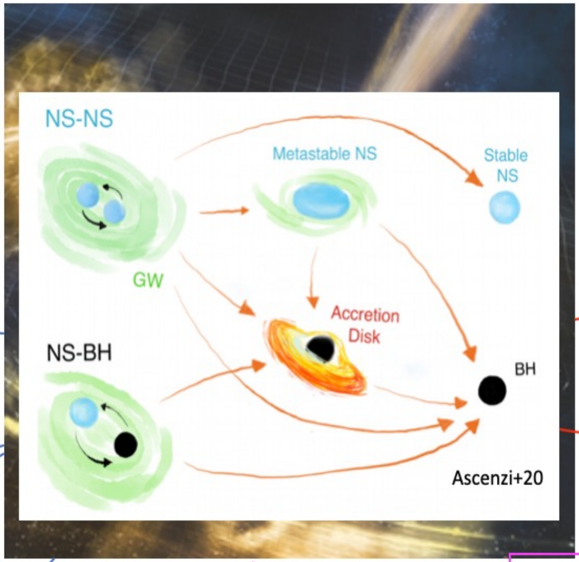

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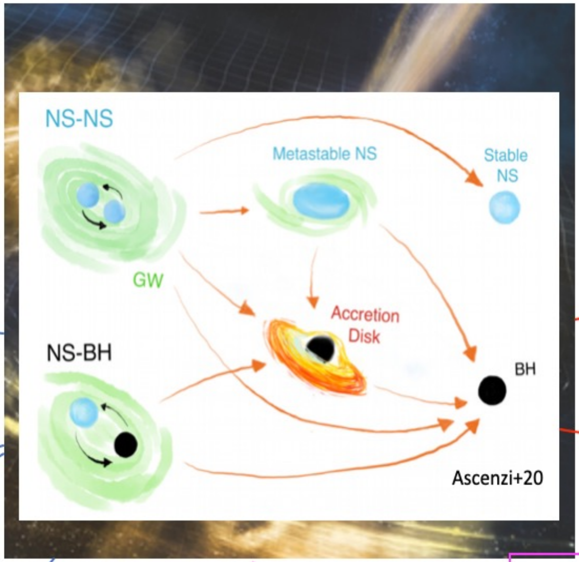

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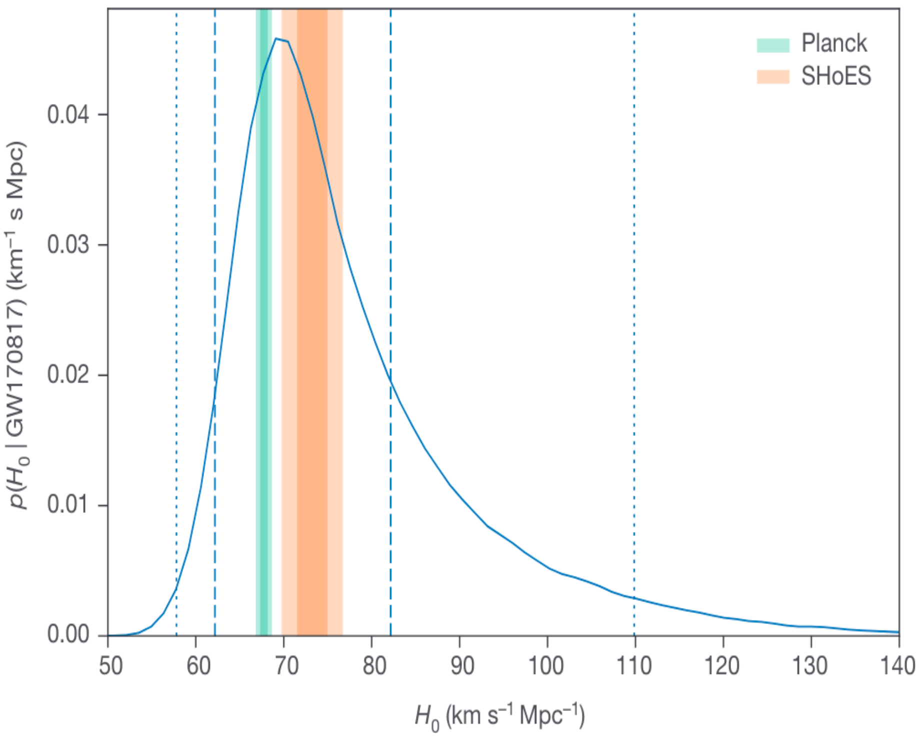
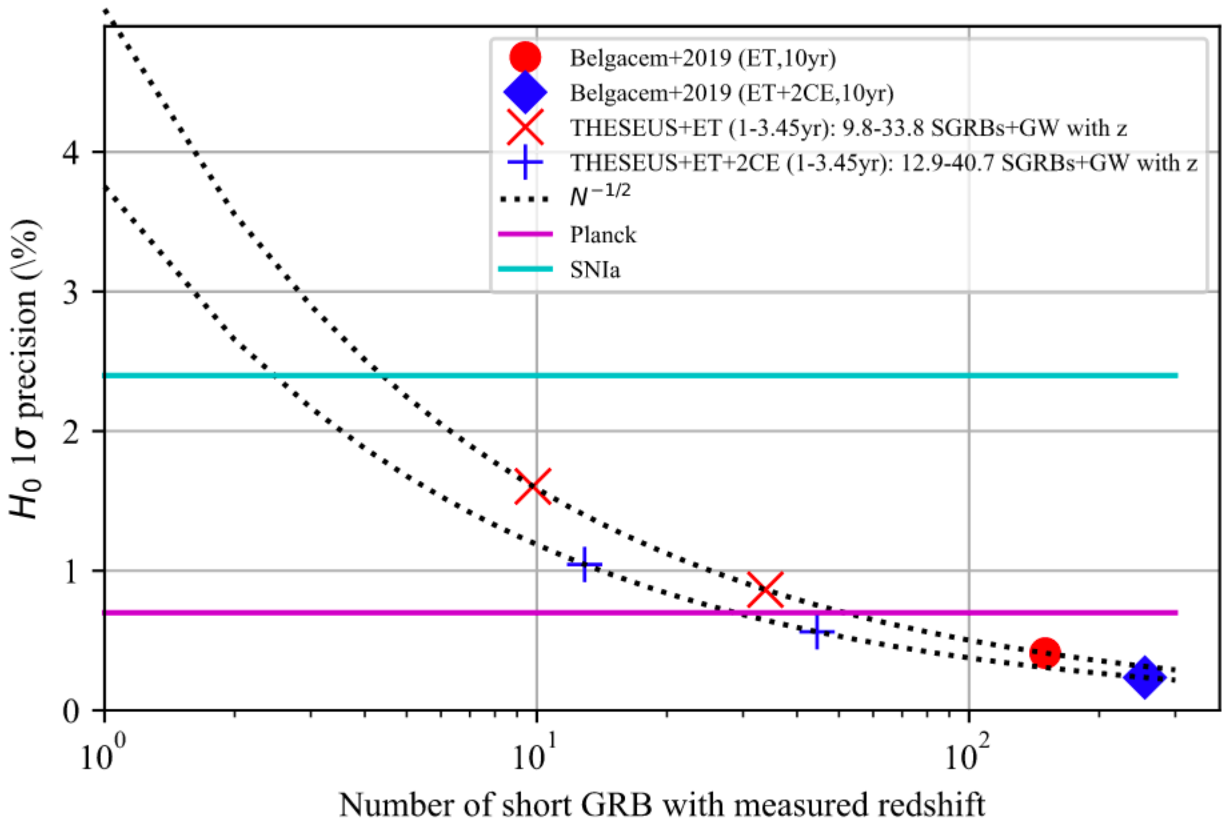
Hubble constant measure



- BNS are "standard sirens" and from GW waveform DL can be measured
- From the EM counterpart the cosmological redshift can be measured
- By combining the luminosity distance and redshift from BNS →**indepedent H0 estimate**

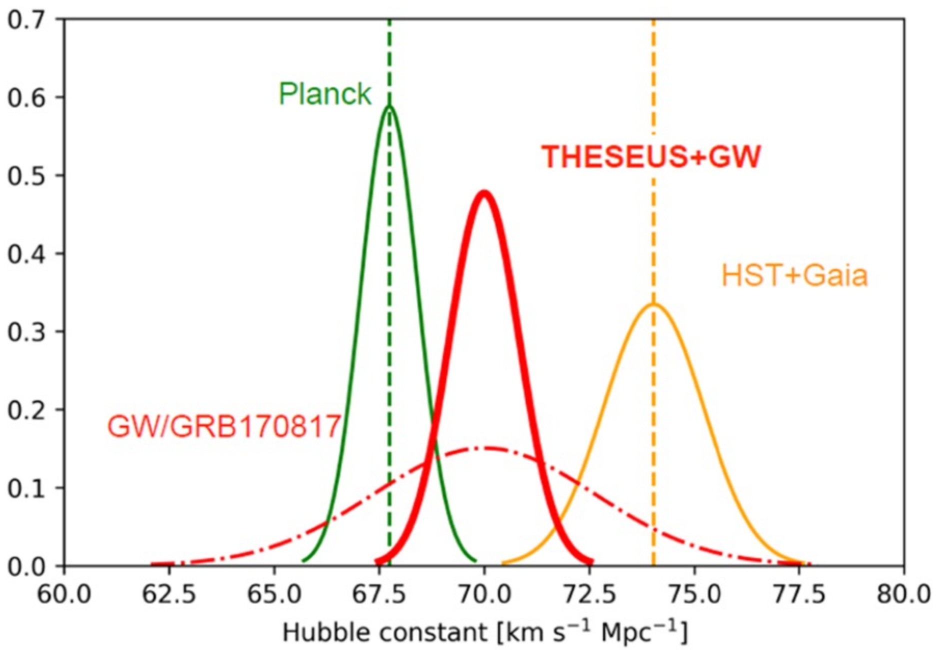
Abbott+2017, Nature

Hubble constant measure



We expect THESEUS to detect >20 short GRB+GW with measured z, ~1% accuracy can be reached

Hubble constant measure



THESEUS + 3G GW detectors will allow to solve the current tension in the H0 inferred from local distance indicators and the angular scale of fluctuations in CMB

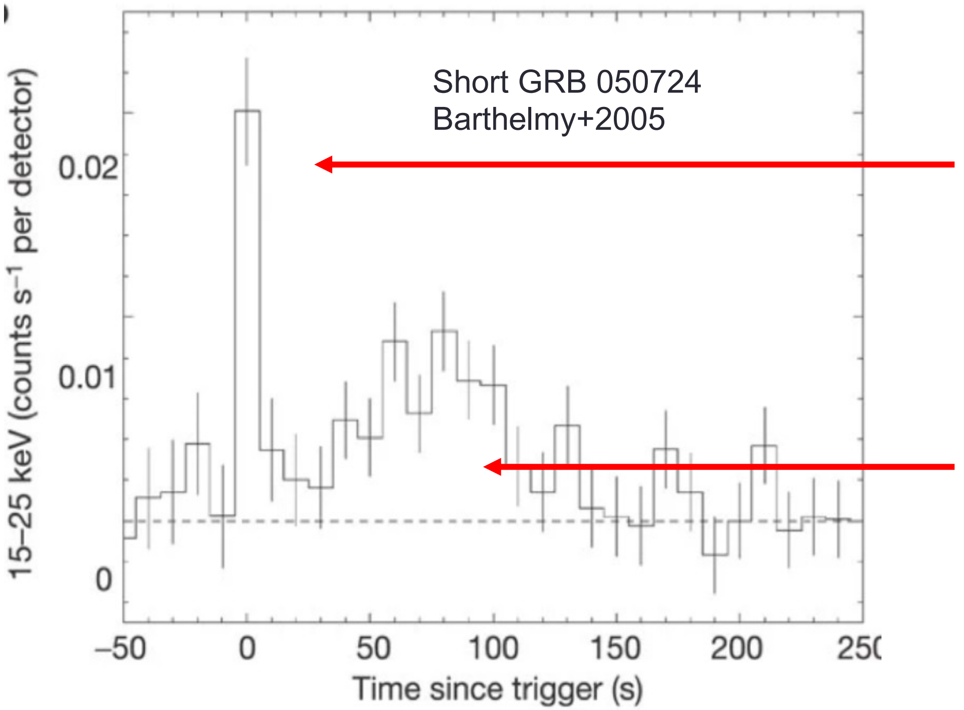
→ confirm/rule out the request for a new paradigm to the standard cosmological model

GRB classification and physics

Additional science from joint short GRB + GW detections:
the origin of short GRB "Extended Emission"

GRB classification and physics

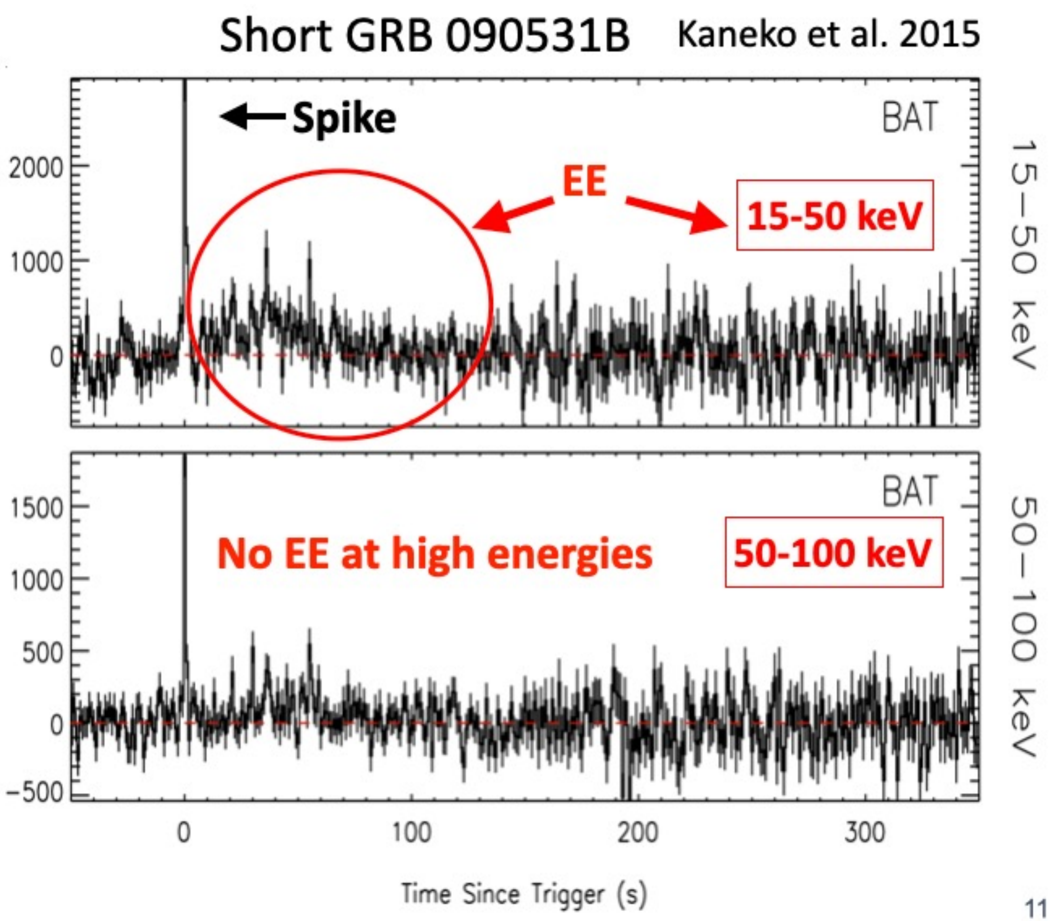
Additional science from joint short GRB + GW detections: the origin of short GRB "Extended Emission"



main hard spike typical of "standard" short GRBs

extended and softer emission the origin of which is still unknown

GRB classification and physics

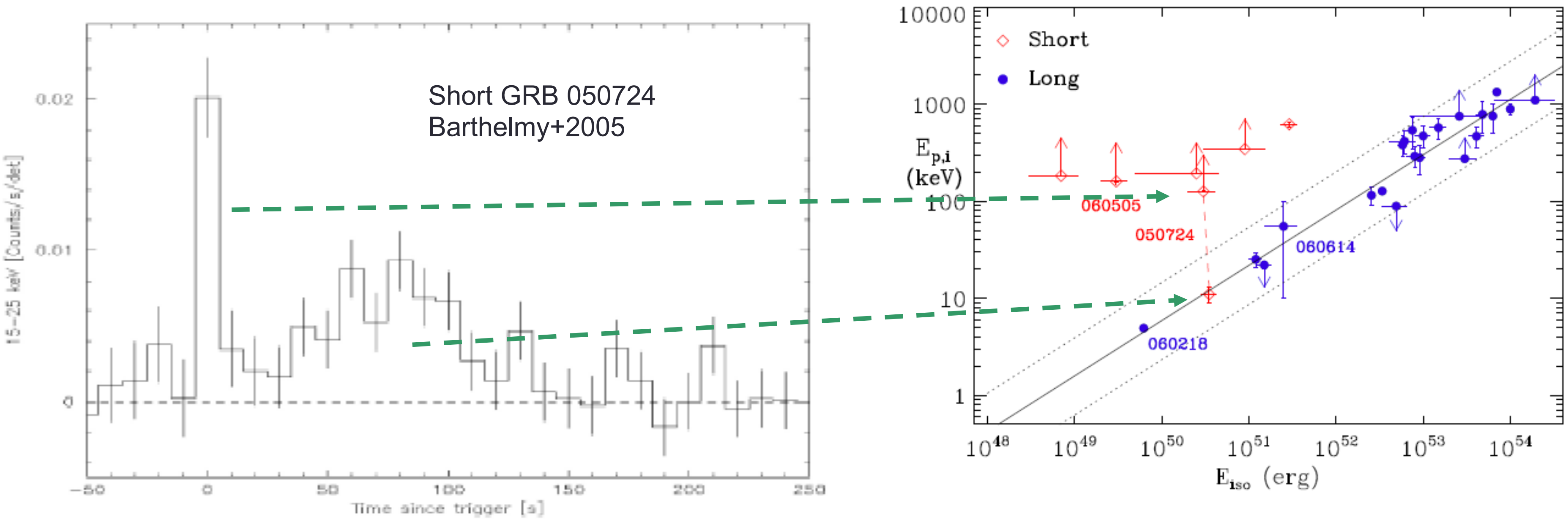


Which fraction of Short GRB with EE?

- 7% from BATSE data (Bostanci+13)
- 5% Fermi/GBM data (Kaneko+15)
- 2-25% from Swift/BAT (15-350 keV) data (Norris+10, Lien+16)
- **>75% from Swift/BAT+XRT data (Kisaka+17)**

GRB classification and physics

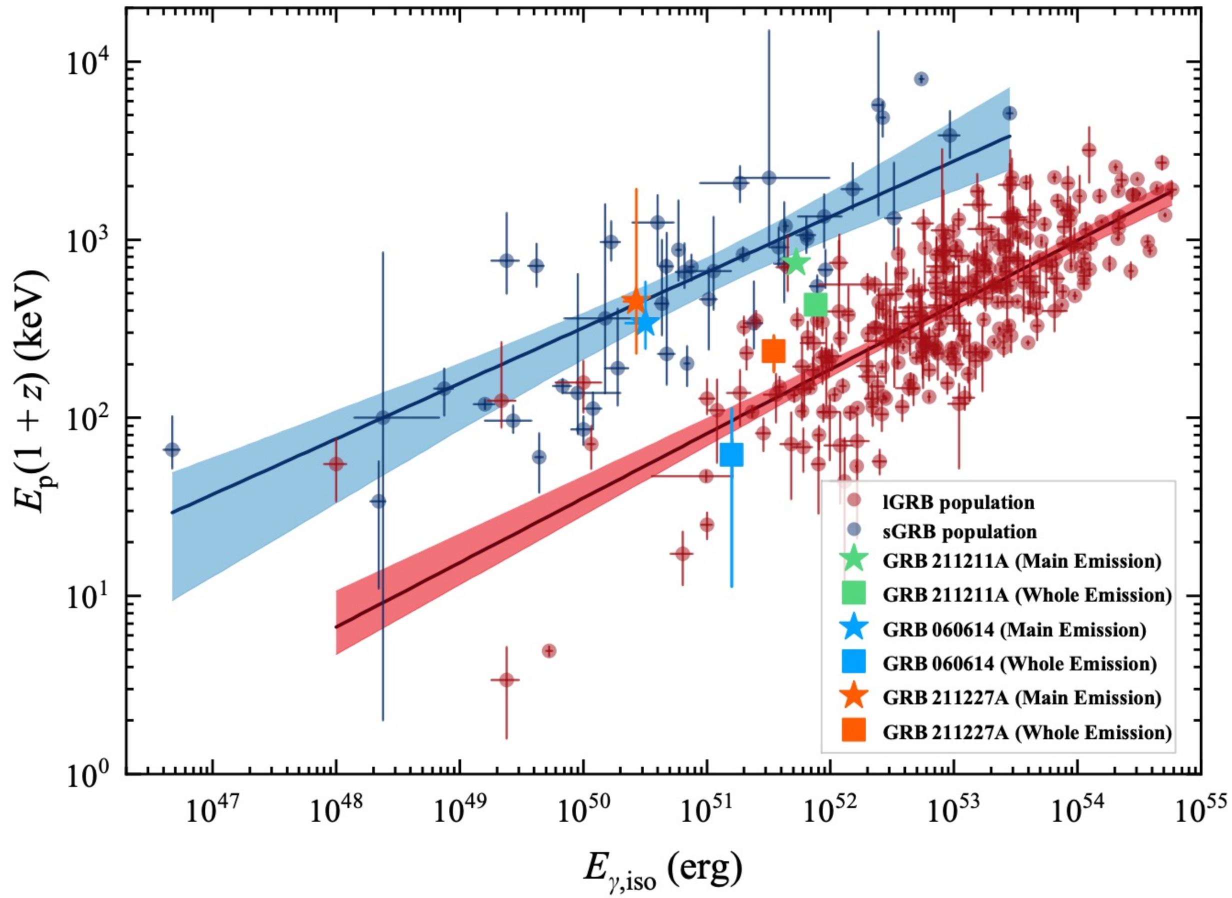
THESEUS XGIS+SXI suite is ideal to study this type of short GRBs

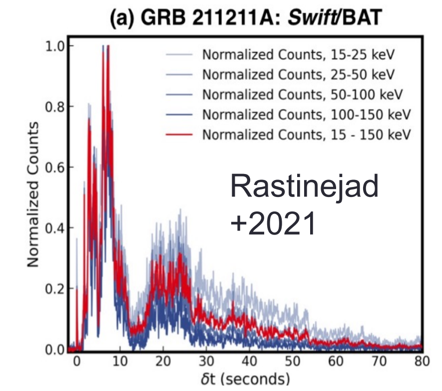


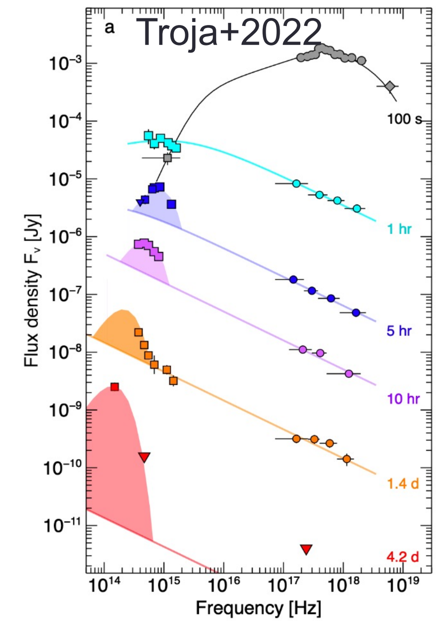
Credit: Amati

GRB classification and physics

Zhu et al. 2022

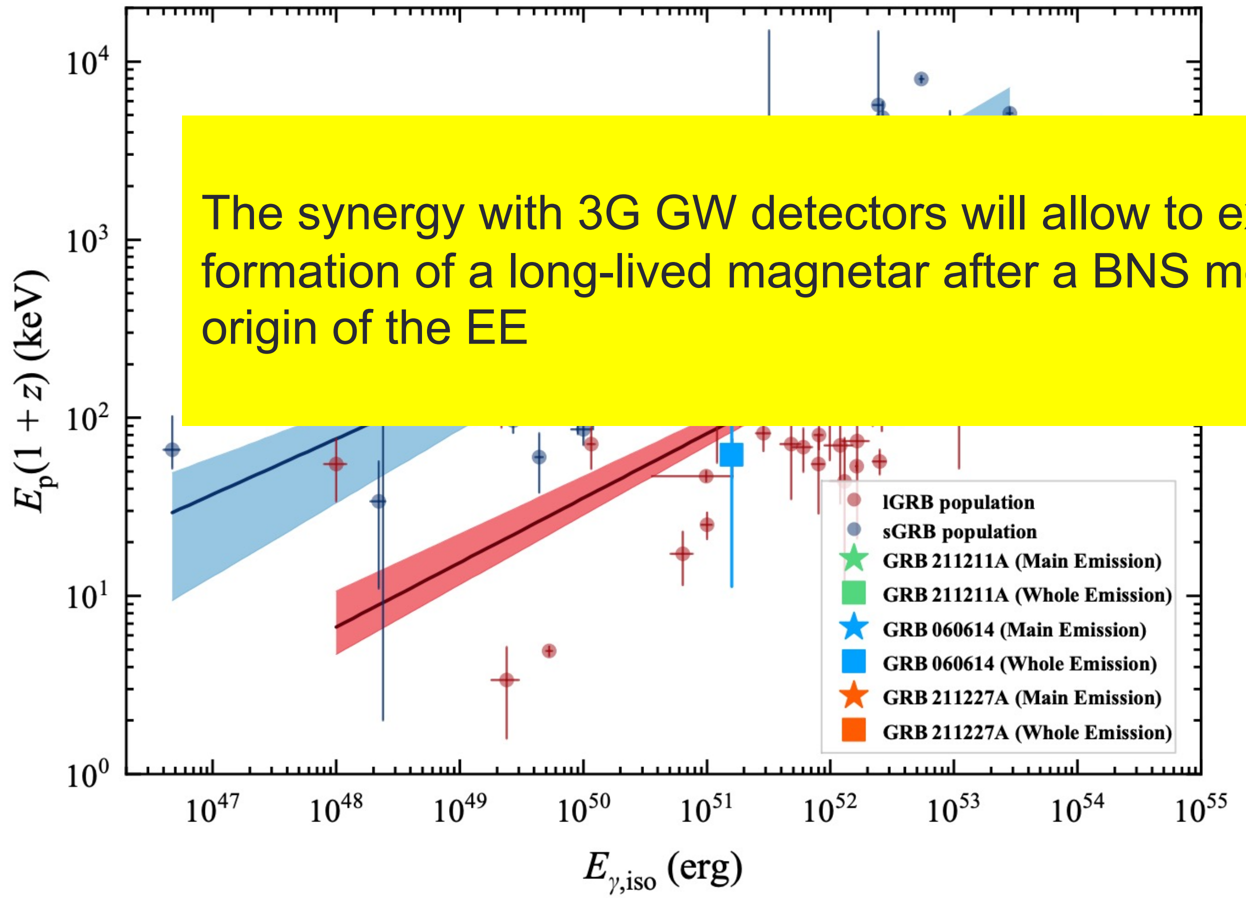




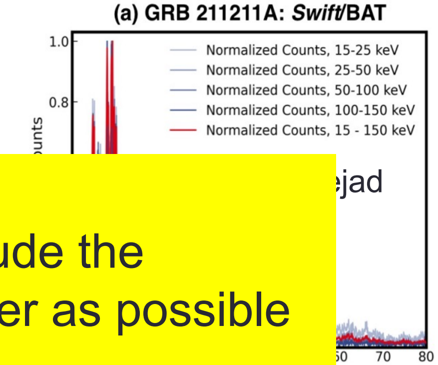


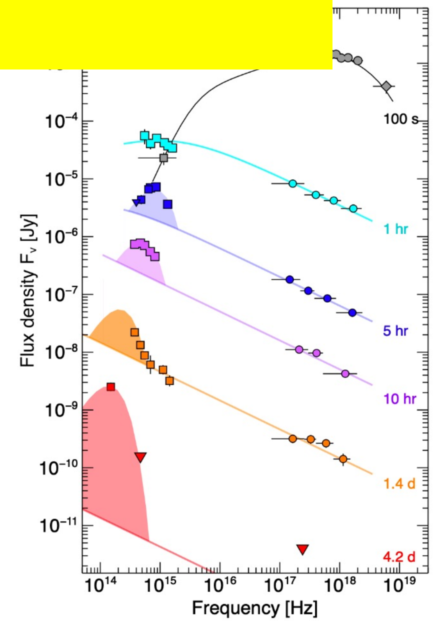
GRB classification and physics

Zhu et al. 2022



The synergy with 3G GW detectors will allow to exclude the formation of a long-lived magnetar after a BNS merger as possible origin of the EE





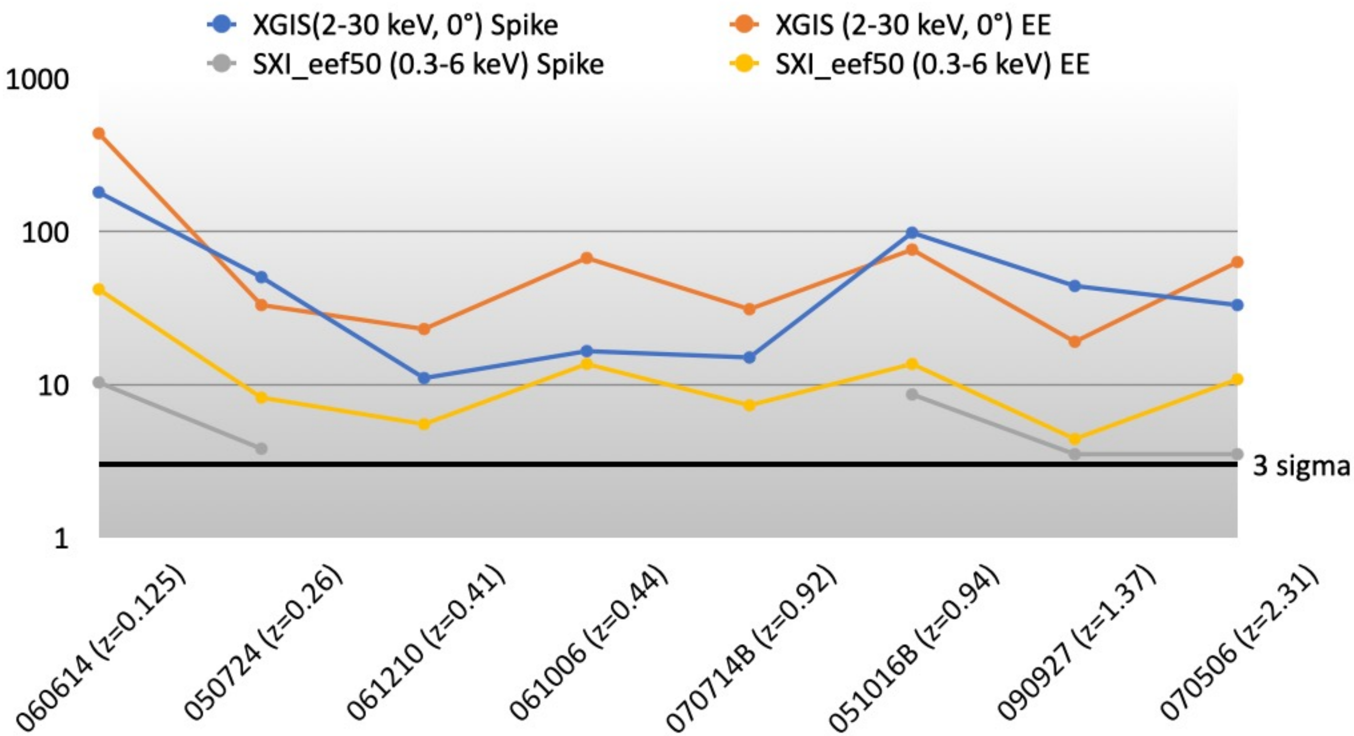
GRB classification and physics

THESEUS XGIS+SXI simulations of a sample of short GRB+EE with measured spectral parameters

GRB name	T_0 time UT	T_{90}[a] (s)	T_{spike} (s)	T_{EE} (s)	B_{spike}[b] (s)	B_{EE}[b] (s)	Afterglow[c]	z
BAT								
050724[d]	12:34:09	96	2.76	107	−0.02	3.04	XOR	0.258
051016B	18:28:09	4	4.03	33	0.07	4.23	XO	0.9364
060614[d]	12:43:49	108.7	5.89	169	−1.55	7.24	XO	0.125
061006[d]	16:45:51	129.9	2.05	113	−23.2	2	XO	0.4377
061210[d]	12:20:39	85.3	0.13	77	0.21	1.04	X	0.4095
070506	5:35:58	4.3	5.25	15	3.75	38	XO	2.31
070714B[d]	4:59:29	64	2.88	39	−0.8	32.29	XO	0.92
080503[d]	12:26:13	170	0.38	147	0.11	6	XO	–
090531B[d]	18:35:56	80	1.02	54	0.29	2.04	X?	[illegible]
090927	10:07:16	2.2	2.18	28	0.06	2.95	XO	1.37

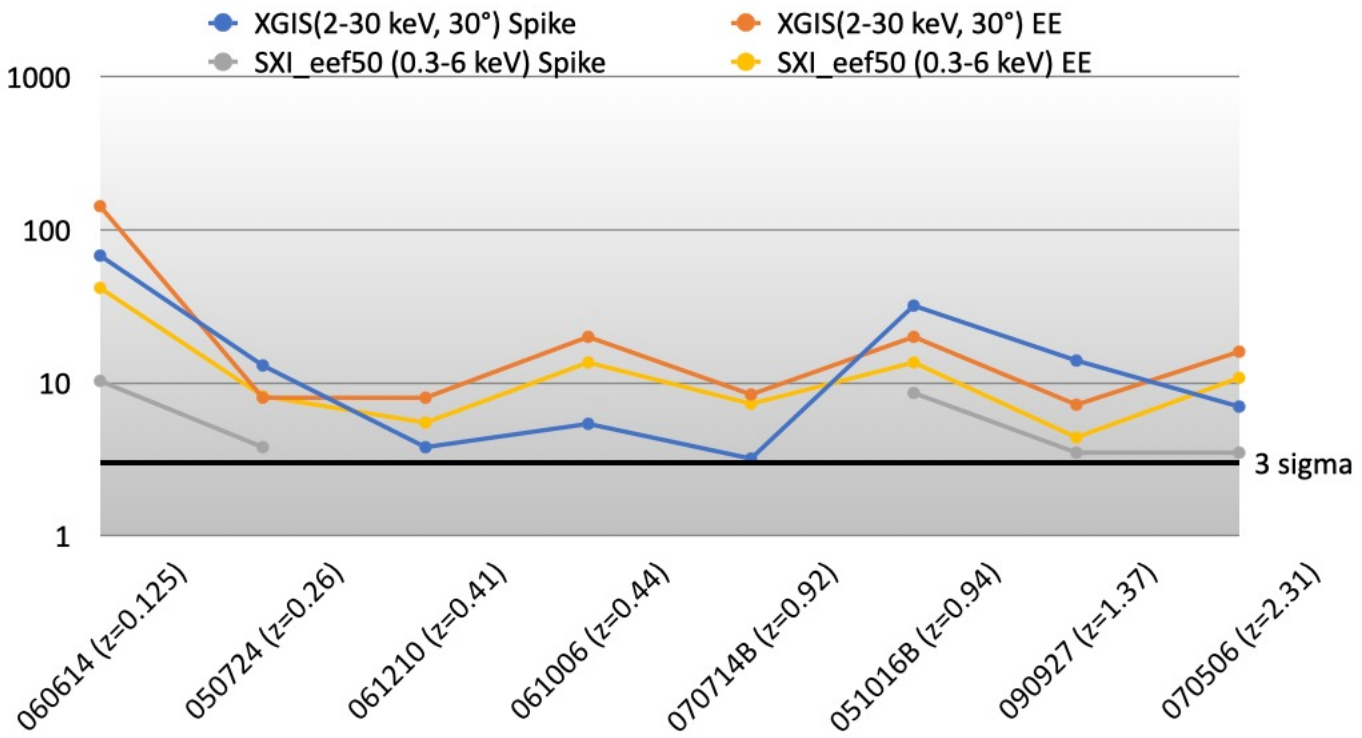
Swift/BAT Short GRB+EE at known redshift from Kaneko+15

GRB classification and physics



THESEUS XGIS+SXI are ideal to identify and characterize SGRB+EE

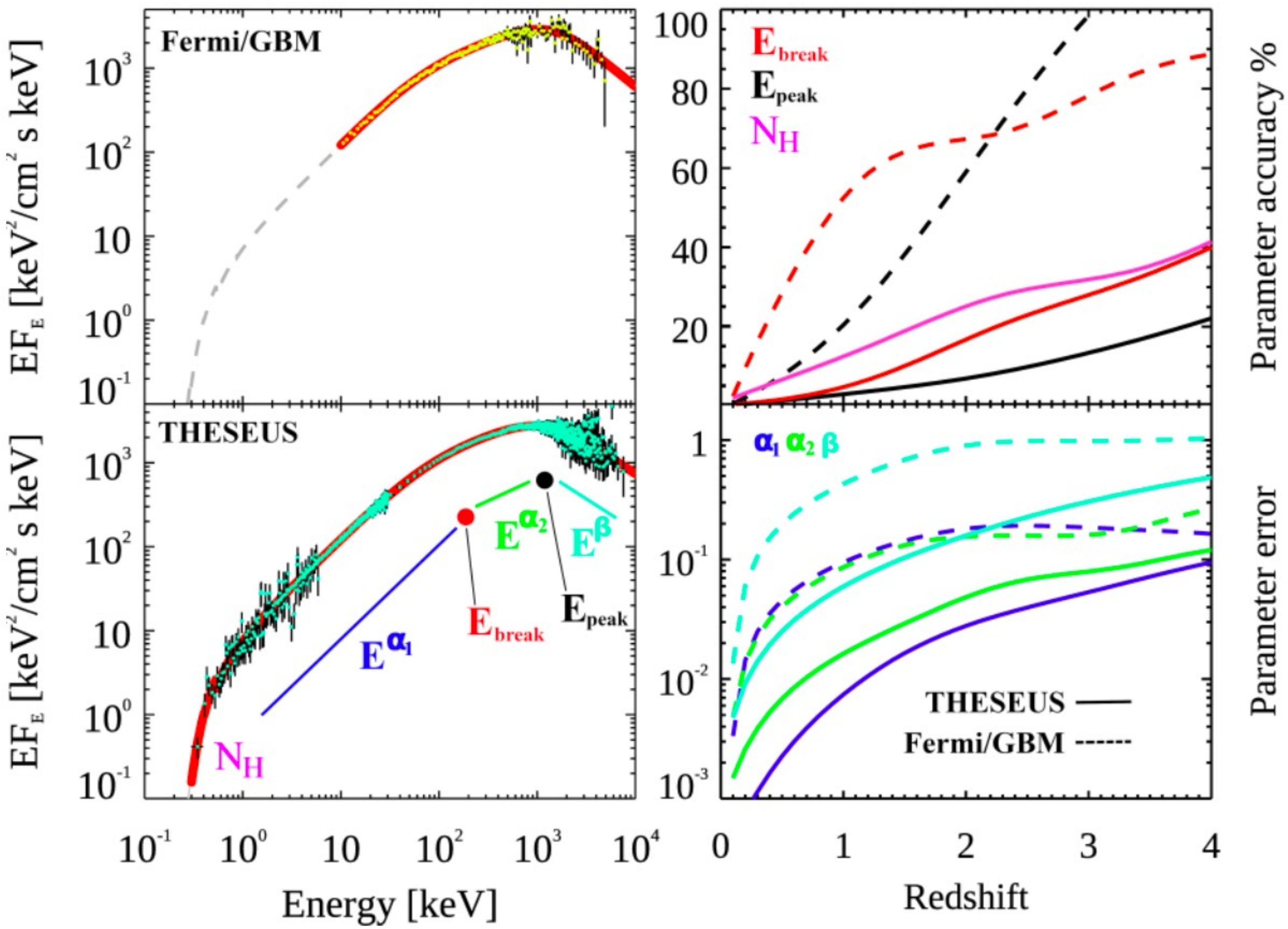
GRB classification and physics



THESEUS XGIS+SXI are ideal to identify and characterize SGRB+EE

GRB physics

simulation of prompt spectrum of GRB180720B



THESEUS wide energy range (0.3 keV-10 MeV) and larger effective area of THESEUS → accurate estimates of the key parameters of the prompt emission spectrum → underlying physics

Everything you wanted to know about THESEUS...

https://www.isdc.unige.ch/theseus/2017-workshop-proceedings-2.html

2017

2018

ELSEVIER
Advances in Space Research
Volume 62, Issue 1, 1 July 2018, Pages 191-244

The THESEUS space mission concept: science case, design and expected performances

L. Amati [a], P. O'Brien [b], D. Götz [c], E. Bozzo [d], C. Tenzer [e], F. Frontera [f, g], G. Ghirlanda [h], C. Labanti [a], J.P. Osborne [b], G. Stratta [i], N. Tanvir [j], R. Willingale [b], P. Attina [k], R. Campana [l], A.J. Castro-Tirado [m], C. Contini [n], F. Fuschino [a], A. Gomboc [o] ... J. Zicha [fs]

ELSEVIER
Advances in Space Research
Volume 62, Issue 3, 1 August 2018, Pages 662-682

THESEUS: A key space mission concept for Multi-Messenger Astrophysics

G. Stratta [a, b, l], R. Ciolfi [c, d], L. Amati [b], E. Bozzo [e], G. Ghirlanda [f], E. Maiorano [b], L. Nicastro [b], A. Rossi [b], S. Vinciguerra [g], F. Frontera [h, b], D. Götz [i], C. Guidorzi [h], P. O'Brien [j], J.P. Osborne [j], N. Tanvir [k], M. Branchesi [m, l], E. Brocato [x], M.G. Dainotti [n, b, aw] ... M. Bernardini [av]

2021 ESA Yellow Book

https://sci.esa.int/documents/34375/36249/Theseus_YB_final.pdf

2021

Experimental Astronomy
https://doi.org/10.1007/s10686-021-09795-9
ORIGINAL ARTICLE

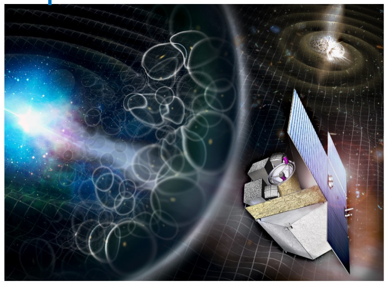
Multi-messenger astrophysics with THESEUS in the 2030s

Riccardo Ciolfi[1,2] · Giulia Stratta[3,4] · Marica Branchesi[5,6] · Bruce Gendre[7] · Stefan Grimm[5,6] · Jan Harms[5,6] · Gavin Paul Lamb[8] · Antonio Martin-Carrillo[9] · Ayden McCann[7] · Gor Oganesyan[5,6] · Eliana Palazzi[3] · Samuele Ronchini[5,6] · Andrea Rossi[3] · Om Sharan Salafia[10,11] · Lana Salmon[9] · Stefano Ascenzi[12,13] · Antonio Capone[14,15] · Silvia Celli[14,15] · Simone Dall'Osso[5] · Irene Di Palma[14,15] · Michela Fasano[14,15] · Paolo Fermani[14,15] · Dafne Guetta[16] · Lorraine Hanlon[9] · Eric Howell[7] · Stephane Paltani[17] · Luciano Rezzolla[18,19,20] · Serena Vinciguerra[21] · Angela Zegarelli[14,15] · Lorenzo Amati[3] · Andrew Blain[8] · Enrico Bozzo[22] · Sylvain Chaty[23,24] · Paolo D'Avanzo[10,11] · fnmMassimiliano De Pasquale[25] · Hüsne Dereli-Bégué[26,27] · Giancarlo Ghirlanda[10,11] · Andreja Gomboc[28] · Diego Götz[29] · Istvan Horvath[30] · Rene Hudec[31,32,33] · Luca Izzo[34] · Emeric Le Floch[35] · Liang Li[36] · Francesco Longo[37,38,39] · S. Komossa[40] · Albert K. H. Kong[41] · Sandro Mereghetti[42] · Roberto Mignani[42,43] · Antonios Nathanail[44] · Paul T. O'Brien[8] · Julian P. Osborne[8] · Asaf Pe'er[27] · Silvia Piranomonte[45] · Piero Rosati[46] · Sandra Savaglio[47] · Fabian Schüssler[48] · Olga Sergijenko[49,50] · Lijing Shao[51,52] · Nial Tanvir[8] · Sara Turriziani[53] · Yuji Urata[54] · Maurice van Putten[55,7] · Susanna Vergani[56] · Silvia Zane[57] · Bing Zhang[58]

THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021

Home Program Registration Participants Posters & Slides Contact

https://www.isdc.unige.ch/theseus/posters-slides.html

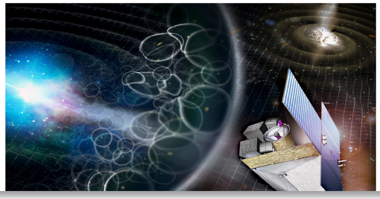


The Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is a space mission concept currently under Phase A study by the European Space Agency (ESA) as candidate M5 mission, in view of a launch opportunity in 2032. The current assessment phase will be concluded in mid-2021. Proposed and developed by a large international collaboration, the THESEUS project aims at fully exploiting Gamma-Ray Bursts for investigating the early Universe and at providing a substantial advancement of multi-messenger and time-domain astrophysics. Through an unprecedented combination of X-/gamma-rays monitors, an on-board NIR telescope and automated fast slewing capabilities, THESEUS will be a

esa
ESA/SCI(2021)2
February 2021

THESEUS

Transient High-Energy Sky and Early Universe Surveyor



theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

THESEUS is a mission concept developed by a large European collaboration and now selected for ESA M7 Phase II → November 2022: phase A final selection

- probe the **physical and chemical properties of the early Universe**, by discovering and exploiting the population of high redshift GRBs.

theseus
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- **provide an unprecedented deep monitoring of the soft X-ray transient Universe**

→ **Localization of GW/neutrino EM counterpart in the X-gamma ray band down to 1-5 arcmin and 1” if an optical/NIR counterpart is present**
→ **Characterization of X-ray transient sources from keV to IR**
→ **Activation of MW observational campaigns**

theseus

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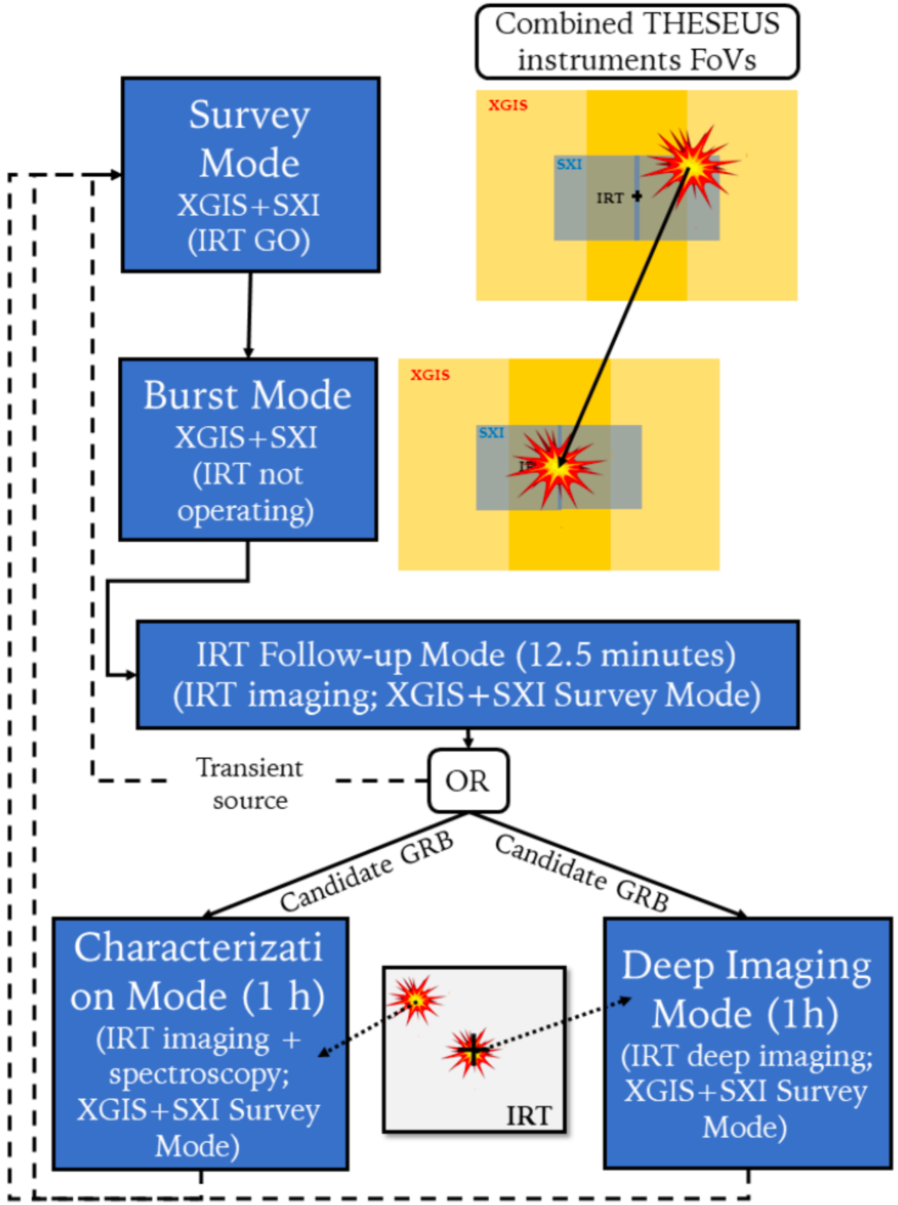
- THESEUS observations will impact on several fields of astrophysics, cosmology and even fundamental physics and **will enhance the scientific return of next generation multi messenger** (ET, Cosmic Explorer, LISA and Km3NET, IceCube-Gen2;) **and e.m. facilities** (e.g., LSST, ELT, SKA, CTA, ATHENA) theseus

transient high energy sky and early universe surveyor

Keep calm
and
stay
tuned!

Extra slides

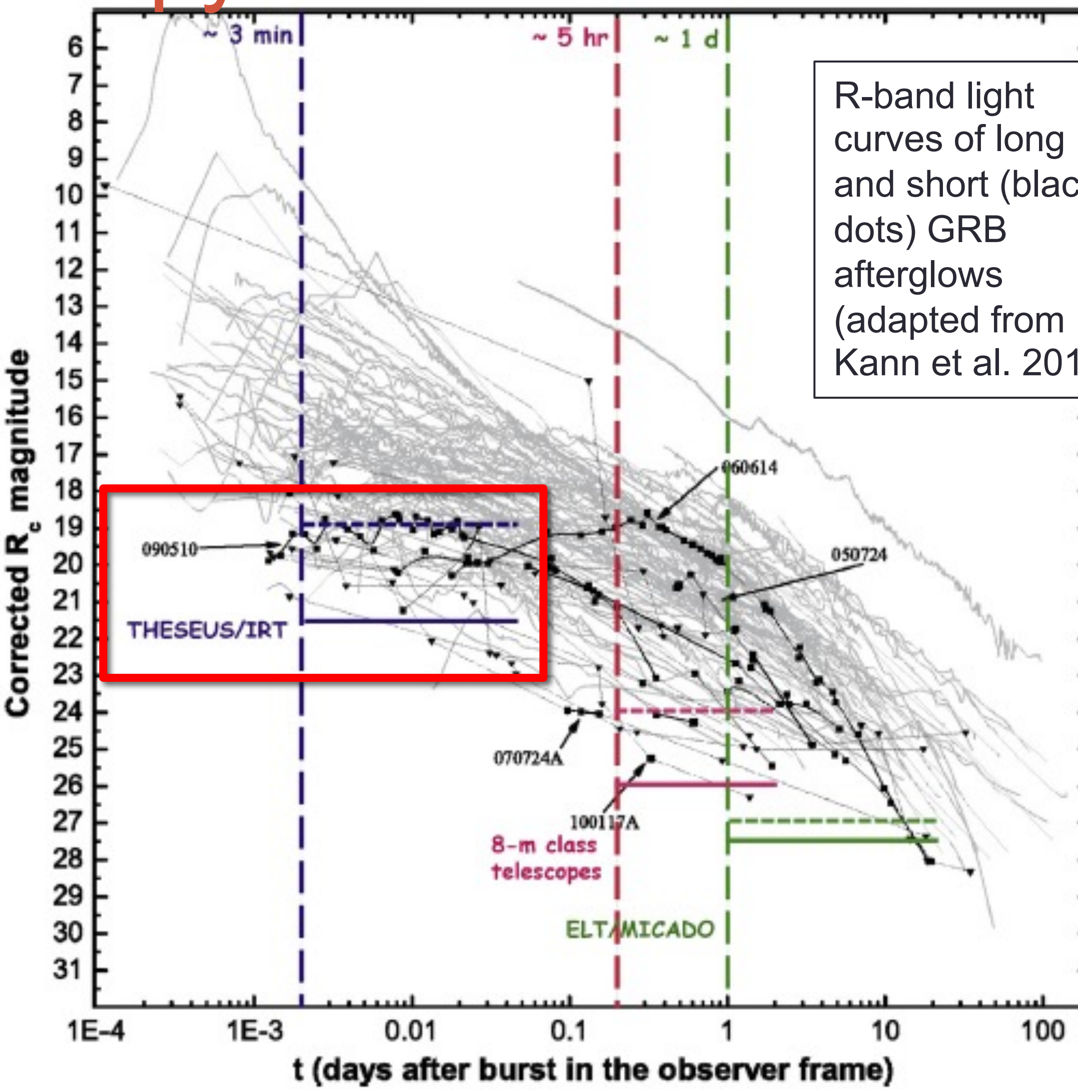


THESEUS ESA "Yellow Book" https://sci.esa.int/s/8Zb0RB8

Afterglow spectroscopy of THESEUS GRBs

IR Telescope will provide:
- arcsec localizations
- Redshift measures
- Luminosity estimates

These information will be used to optimise follow-up strategies (i.e. most appropriate facility, select highest priority target) for:
- **Deep host search**
- **High S/N afterglow spectroscopy**



R-band light curves of long and short (black dots) GRB afterglows (adapted from Kann et al. 2011)

Stratta et al. 2018

Table 1. Key science performance requirements of THESEUS[1]. The sensitivity requirements assume a power-law spectrum with a photon index of 1.8 and an absorbing column density of 5×10^{20} cm^{-2}.

SXI sensitivity (3σ)	1.8×10^{-11} erg cm^{-2} s^{-1} (0.3–5 keV, 1500 s) 10^{-10} erg cm^{-2} s^{-1} (0.3–5 keV, 100 s)
XGIS sensitivity (1 s, 3σ)	10^{-8} erg cm^{-2} s^{-1} (2–30 keV) 3×10^{-8} erg cm^{-2} s^{-1} (30–150 keV) 2.7×10^{-7} erg cm^{-2} s^{-1}(150 keV–1 MeV)
IRT sensitivity (imaging, SNR = 5, 150 s)	20.9 (I), 20.7 (Z), 20.4 (Y), 20.7 (J), 20.8 (H)
SXI FoV	0.5 sr – 31×61 deg^2
XGIS FoV ($\geq$20% efficiency)	2 sr (2–150 keV) – 117×77 deg^2 4 sr ($\geq$150 keV)
IRT FoV	$15' \times 15'$
Redshift accuracy ($6 \leq z \leq 10$)	$\leq$ 10%
IRT resolving power	$\geq$400
XGIS background stability	$\lesssim$10% over 10 min
Field-of-Regard	$\gtrsim$50% of the sky
Trigger broadcasting delay to ground-based networks	$\lesssim$30 s (65% of the alerts) $\lesssim$20 min (65% of the alerts)
External alert (e.g., GW or ν events) reaction time	>4–12 h
SXI positional accuracy (0.3–5 keV, 99% c.l.)	$\lesssim$2 arcmin
XGIS positional accuracy (2–150 keV, 90% c.l.)	$\lesssim$7 arcmin (50% of triggered short GRBs) $\lesssim$15 arcmin (90% of triggered short GRBs)
IRT positional accuracy (5σ detections) real time post-processing	 $\lesssim$5 arcsec $\lesssim$1 arcsec

Stratta+2022

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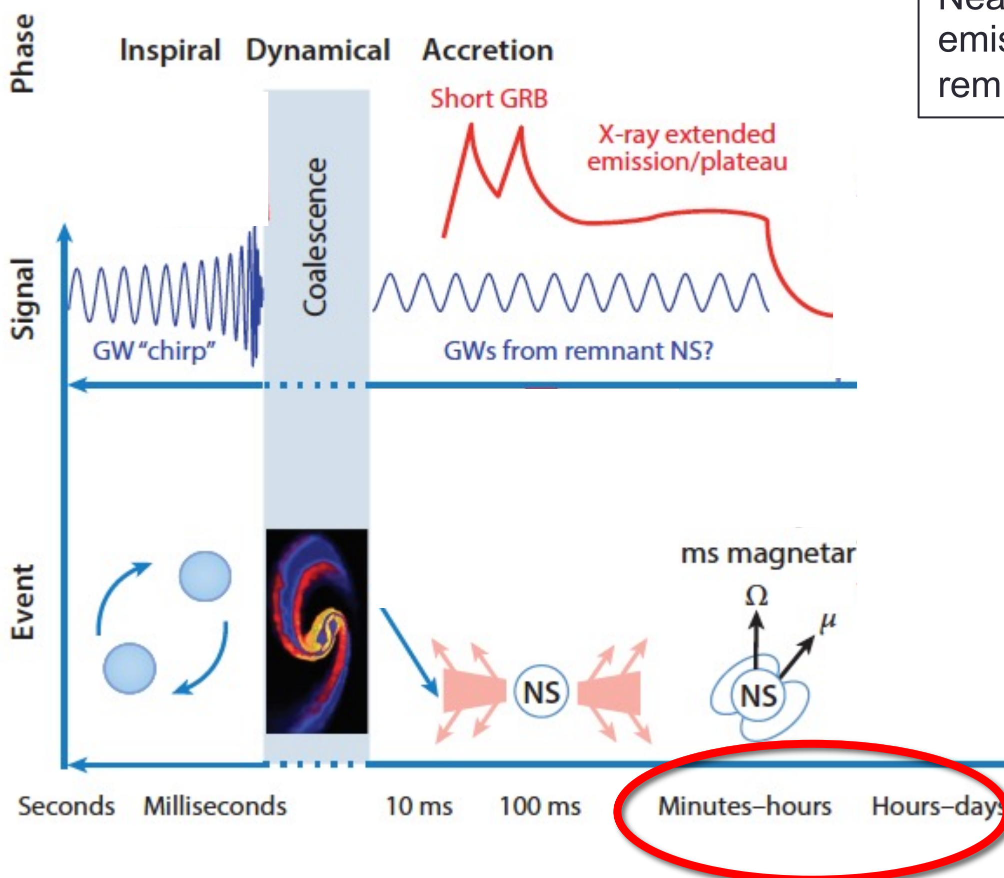
~2000 deg^2 0.3-5 keV

>10000 deg^2 2 keV -1 MeV

arcmin level sky localization accuracy in X/gamma-rays

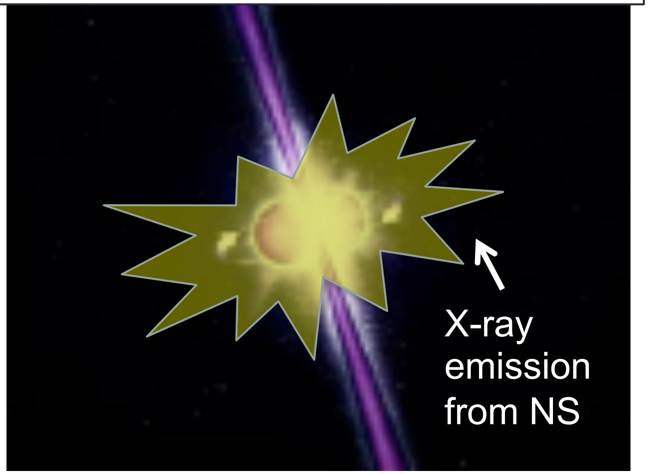
arcsec level accuracy in IR

NS-NS merger detections with THESEUS



From Fernandez & Metzger 2017

Nearly isotropic magnetar-powered X-ray emission from long-lived NS-NS merger remnants



$L_X \sim 10^{43} - 10^{48}$ erg/s

X-ray emission peak ~ min/hours

Can a binary black hole merger produce a detectable EM transient?

We don't expect a stellar-mass binary black hole system to have enough matter around for the final BH to accrete and form a relativistic jet [e.g., Lyutikov, arXiv:1602.07352] — or can it?

Various models have been proposed:

Single star [Fryer+ 2001; Reisswig+ 2013; Loeb 2016, ApJL 819]: collapse of a very massive, rapidly rotating stellar core, which fissions into a pair of black holes which then merge; but see Woosley, arXiv:1603.00511v2 for modeling that does not support

Instant BBH [Janiuk+ 2013, A&A 560; arXiv:1604.07132]: massive star-BH binary triggers collapse of star to BH, then immediate inspiral and merger; final BH can be kicked into circumbinary disk and accrete from it

BBH with fossil disk [Perna+ 2016, ApJL 821]: activates and accretes long-lived cool disk

BBH embedded in AGN disk [Bartos+, arXiv:1602.03831; Stone+ 2016, MNRAS]: binary merger assisted by gas drag and/or 3-body interactions in AGN disk, which provides material to accrete

Third body [Seto&Muto 2011, cited in Murase+ 2016, ApJL 822]: tidal disruption of a star in a hierarchical triple with the BBH at time of merger

Charged BHs [Zhang 2016, ApJL 827; Liebling&Palenzuela 2016, PRD 84]: Merging BHs with electric (or magnetic monopole!) charge could produce a detectable EM transient

Magnetic reconnection [Fraschetti, arXiv:1603.01950]

Also models for high-energy neutrino and ultra-high energy cosmic ray emission

Review – courtasy of Peter Shawhan (Maryland)

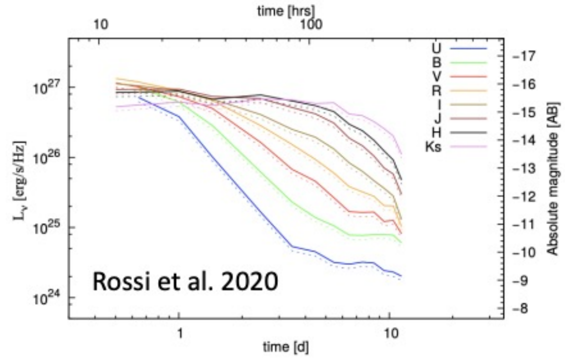
Kilonovae

✦**Thermal emission** following a NS-NS/NS-BH merger powered by radiactive decay of freshly formed, instable heavy nuclei

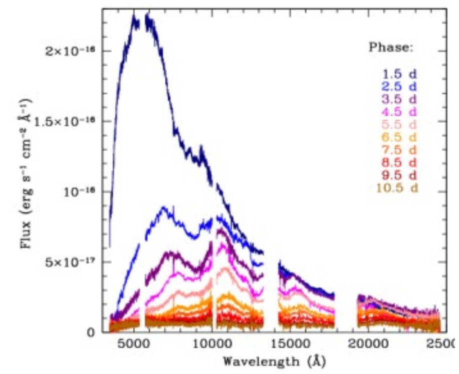
✦**AT2017gfo** is the best monitored kilonova so far associated with NS-NS merger source GW 170817

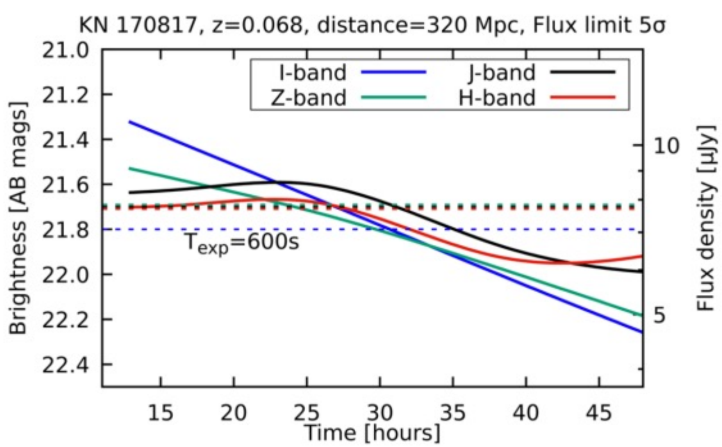
✦THESEUS/IRT can **detect** a kilonova AT2017gfo-like after a short GRB up to few x 100 Mpc

- Monitoring KN candidates localized by other facilities
- Discovery KN after a short GRB or an X-ray transient from long-lived magnetar



From Pian et al. 2017





Credit: E. Palazzi, A. Rossi (INAF-OAS)