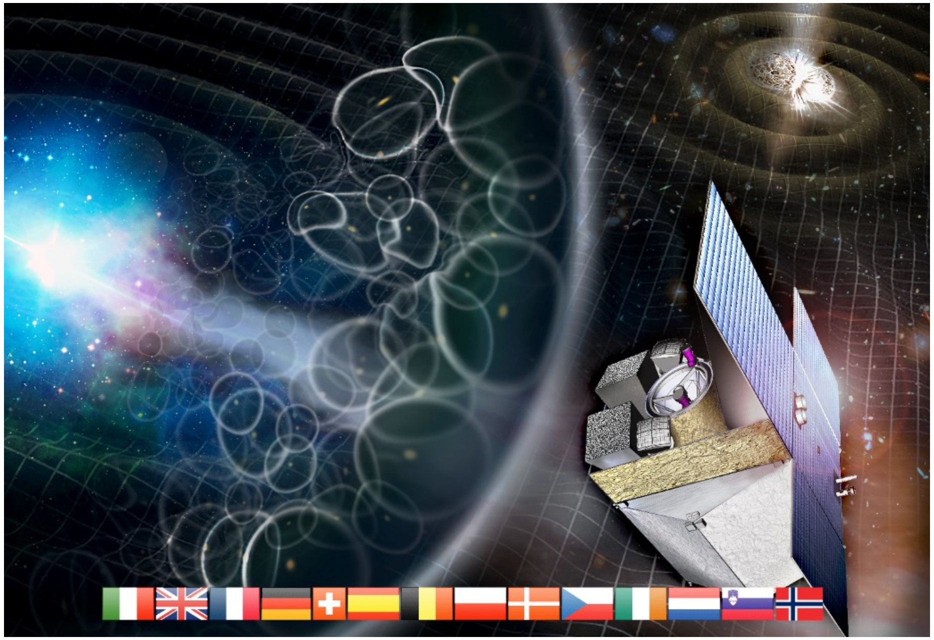
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

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

https://theseus.astro-ge.ch/

AHEAD2020 – EGO 21-23 Oct 2024

- **THESEUS** is a mission project which is now participating to the 7th ESA call for medium size mission (expected launch on 2037)



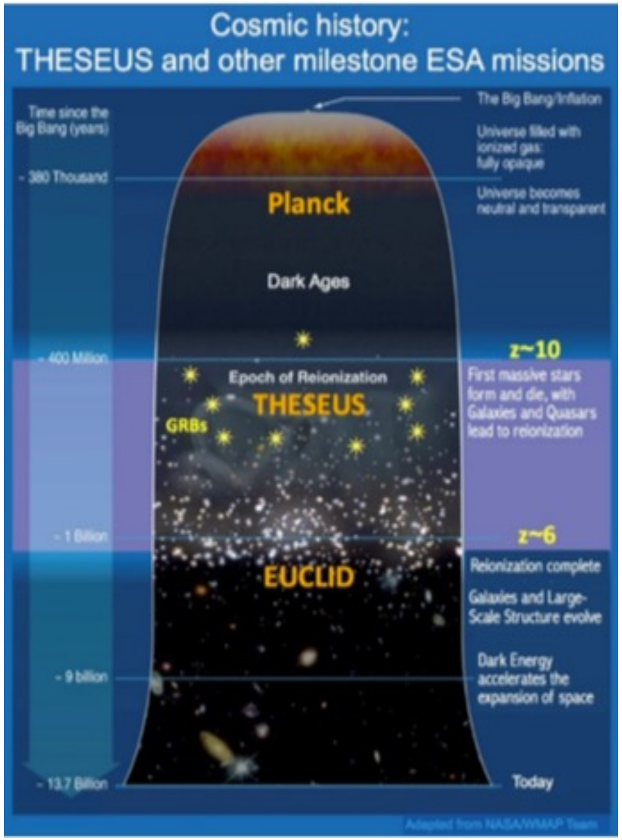
Payload consortium: Italy, Germany, UK, France, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, The Netherlands, Norway, Slovenia, Ireland (+ Hungary?)

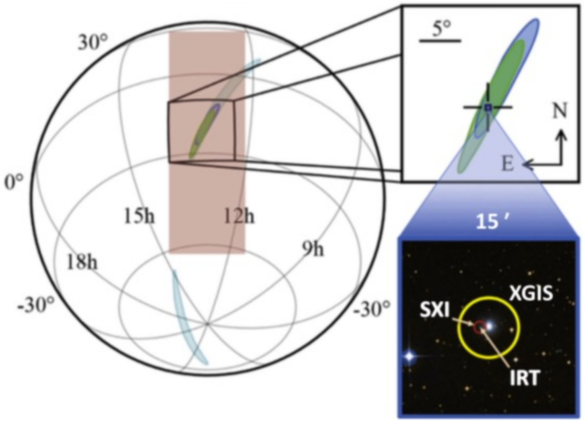
Leads: L. Amati (INAF – OAS Bologna, Italy, lead proposer), A. Santangelo (Un. Tuebingen, D), P. O'Brien (Un. Leicester, UK), D. Gotz (CEA-Paris, France), E. Bozzo (Un. Genève, CH)

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





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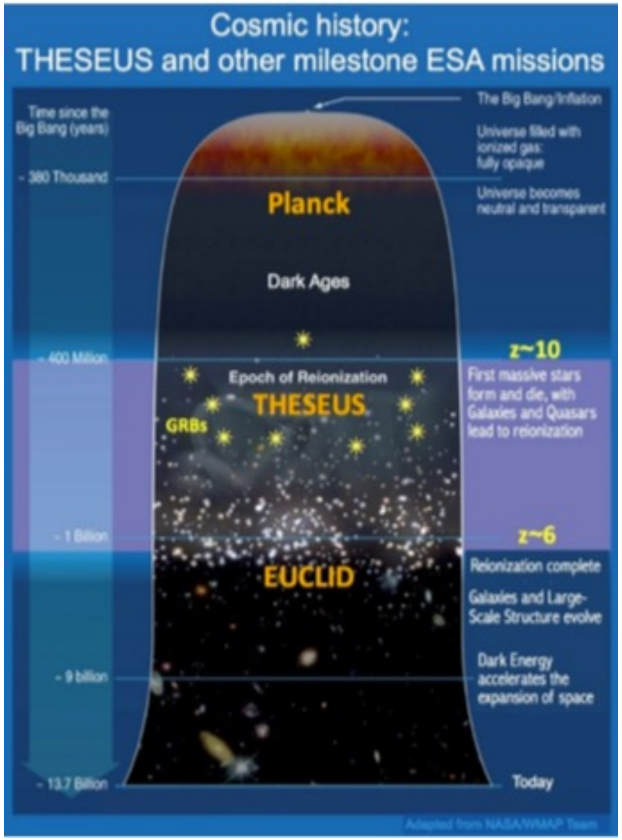
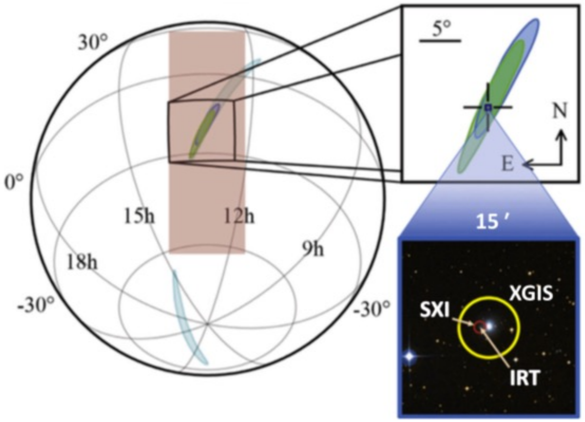


Providing a substantial advancement of multi-messenger and time-domain astrophysics

This talk



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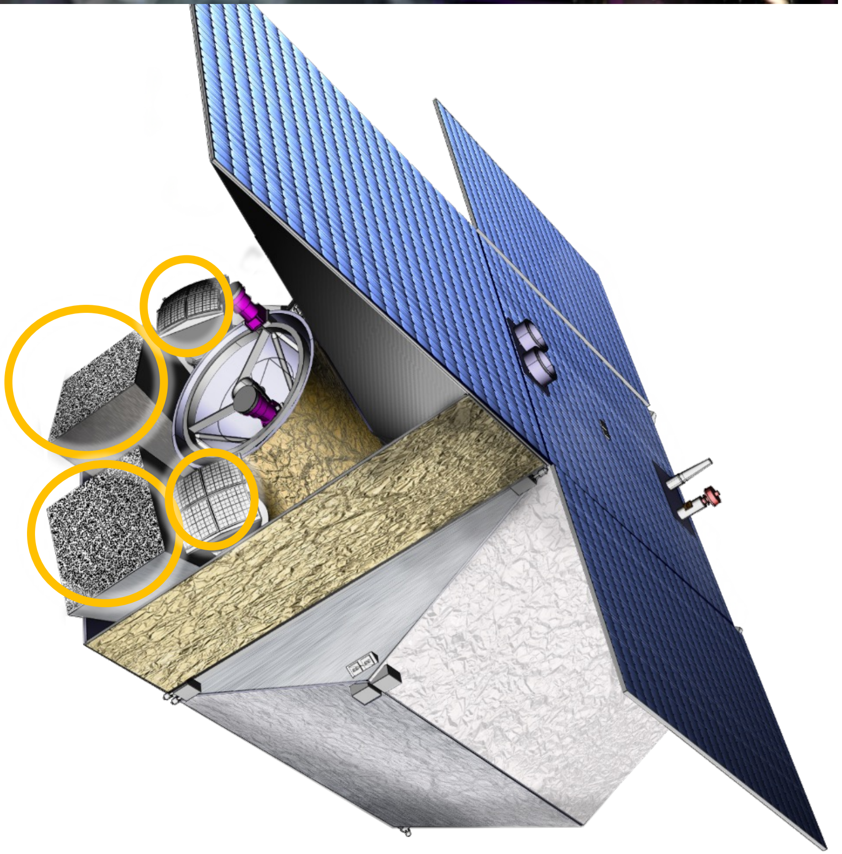
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

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



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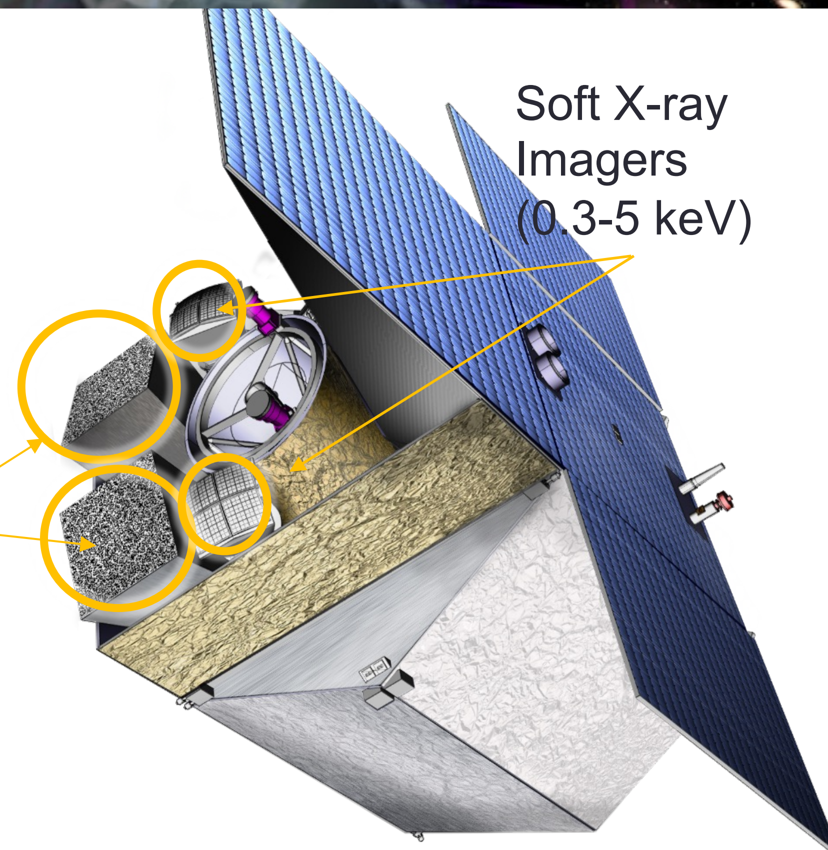
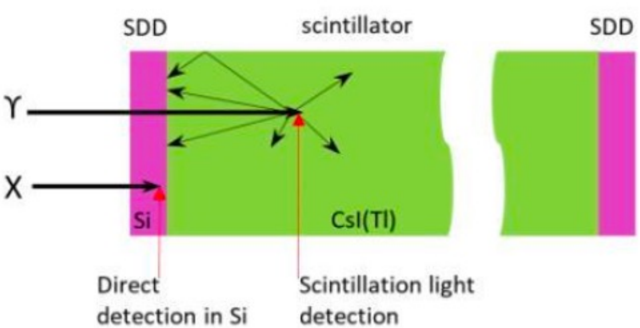
Soft X-ray Imagers (0.3-5 keV)



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



XGIS Pixel detector operation concept

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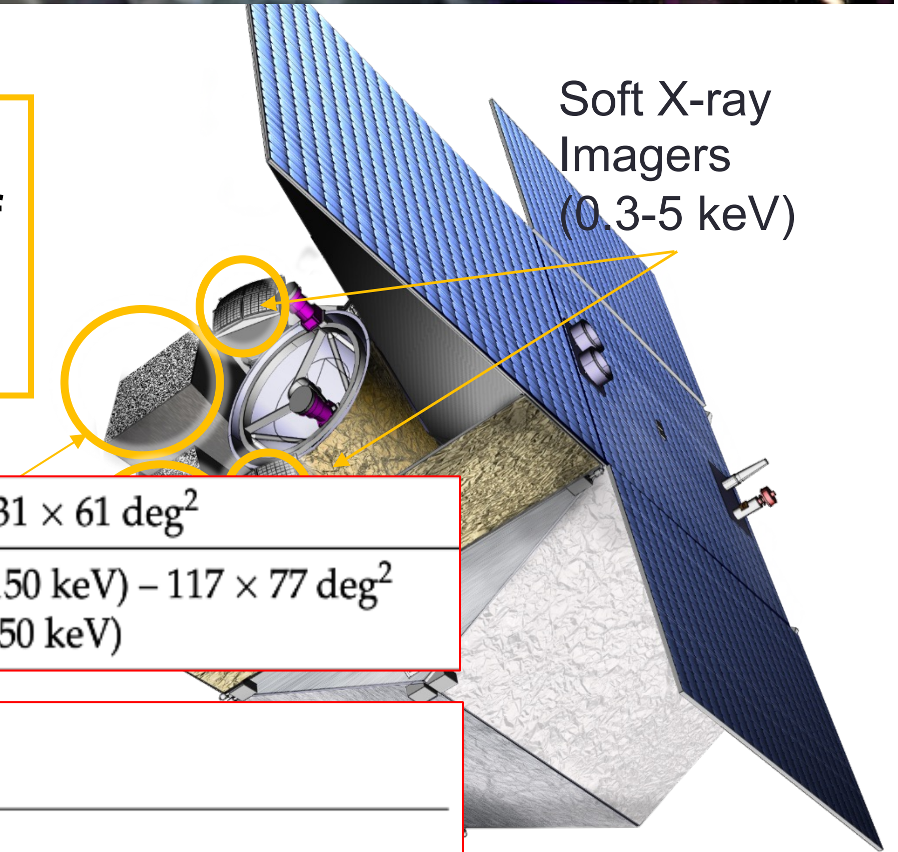

SXI FoV	0.5 sr – 31 × 61 deg^2
XGIS FoV (≥20% efficiency)	2 sr (2–150 keV) – 117 × 77 deg^2 4 sr (≥150 keV)

SXI positional accuracy (0.3–5 keV, 99% c.l.)	≤2 arcmin
XGIS positional accuracy (2–150 keV, 90% c.l.)	≤7 arcmin (50% of triggered short GRBs) ≤15 arcmin (90% of triggered short GRBs)

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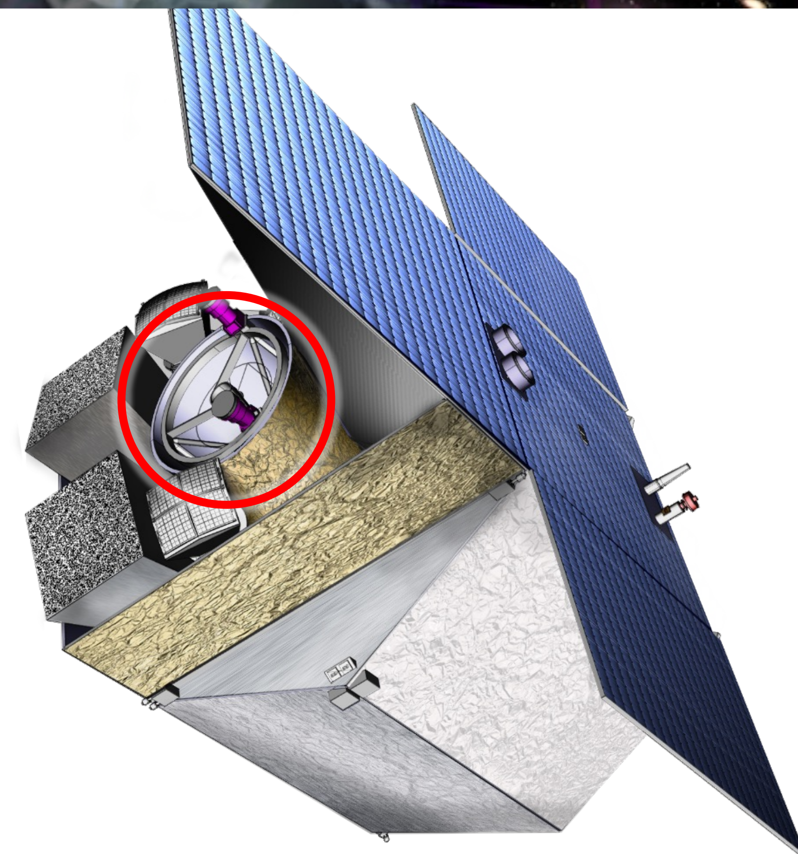
- Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**

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



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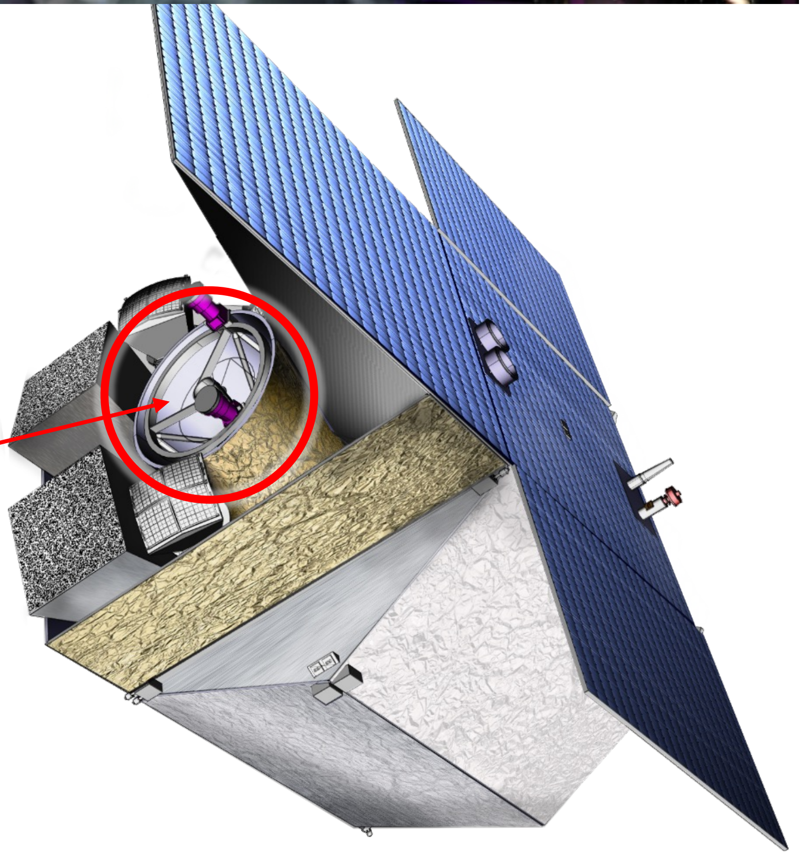
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

70 cm Korsch telescope

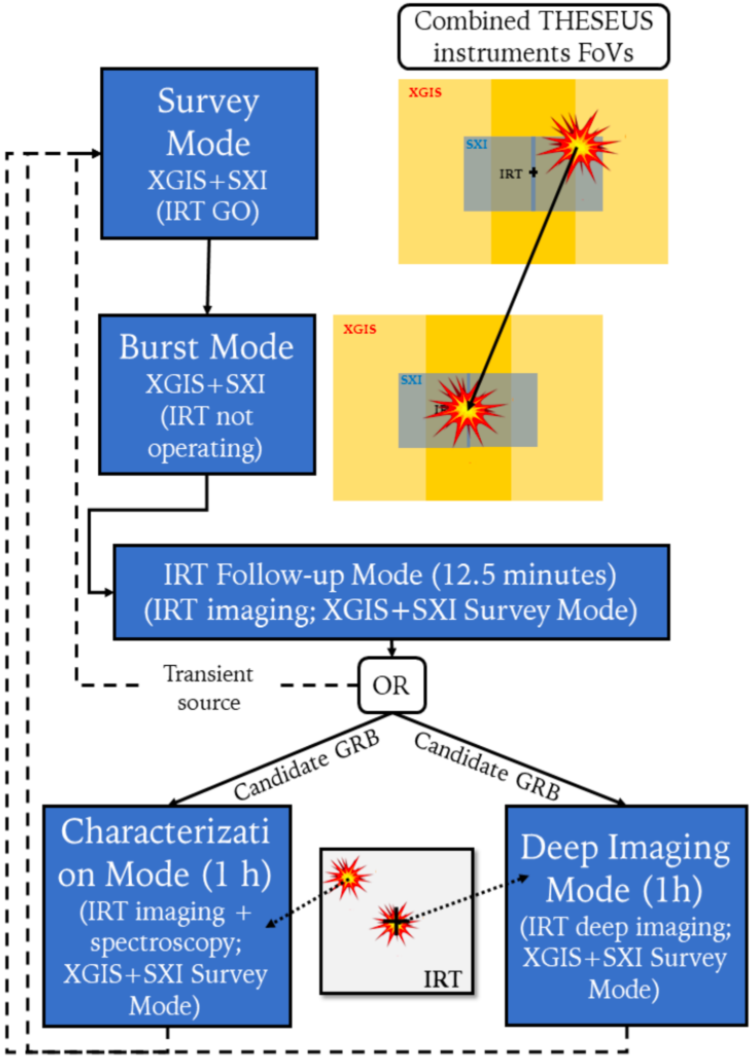
- Photometry:
  - FoV 15’x15’
  - 5 filters: I (20.9), Z (20.7), Y (20.4), J (20.7), H (20.8) for 150s and SNR=5
- Specroscopy:
  - FoV 2’x2’
  - R~400 resolution slit-less spectroscopy 0.8-1.6 micron

IRT will:

- **autonomously identify the GRB afterglow**
- **Refine sky coordinates to < 5 arcsec real time (<1 arcsec post-processing)**



Pointing strategy



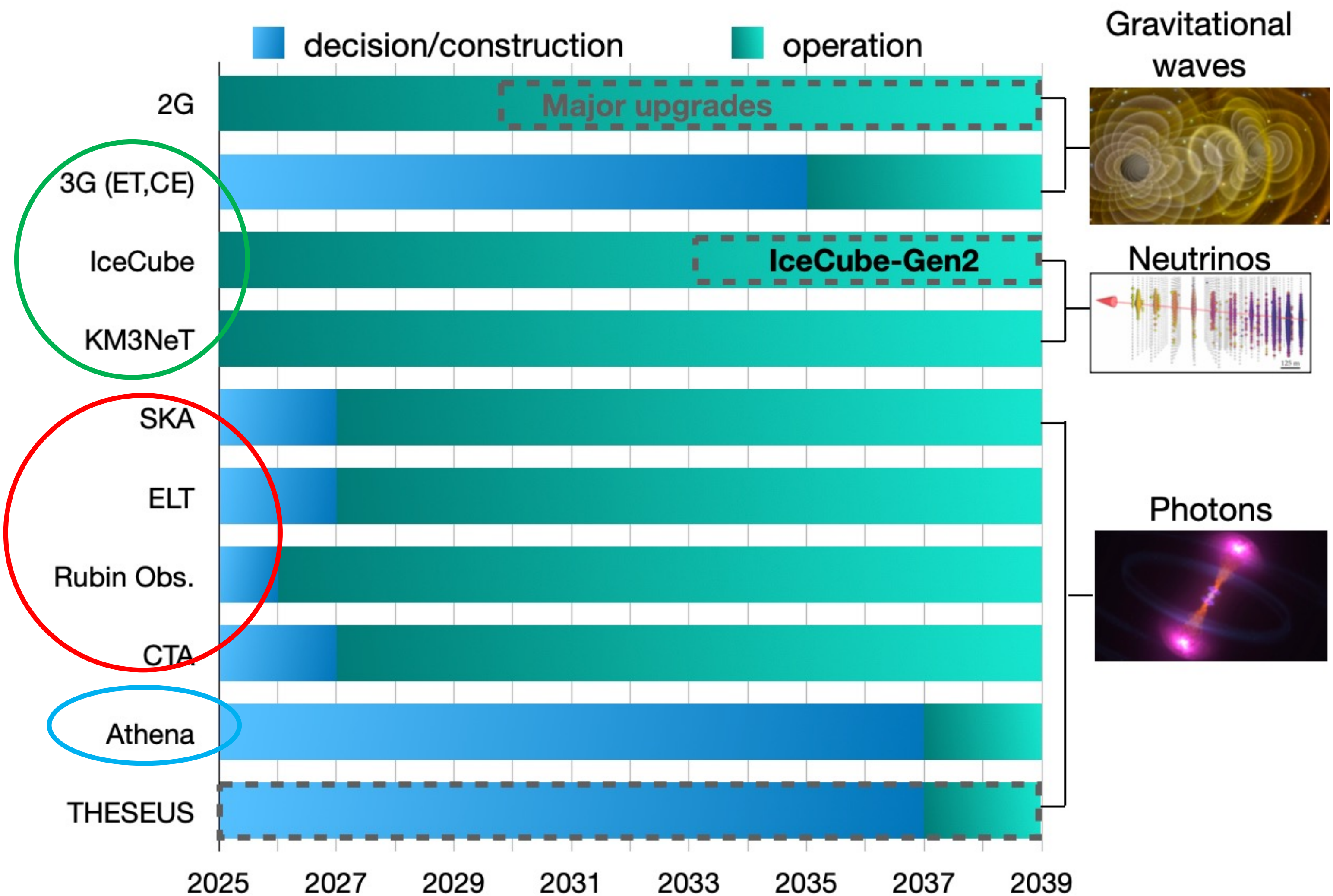
1. **Survey Mode** -> waiting for a GRB trigger, IRT, SXI and XGIS take data, with IRT pointed at a specific target (~1000/month) within a list of core and GO targets
2. **Burst Mode** → GRB detection and first sky localization with XGIS and SXI (*) → Slew to put the source in the IRT FoV
3. **Follow-up Mode**: within 10 min (3 min goal), 5 filter IRT imaging acquisition starts for 12.5 min
4. If an optical counterpart is detected, depending on its brightness:
   -> **Charactherization mode**
   OR
   -> **Deep Imaging mode**

(*) THESEUS shall be able to distribute Burst/Transient alerts (sky coordinates, error box, trigger time) to ground observers (via the SDC)

- < 30 sec for 65%
- < 20 min for 95% burst

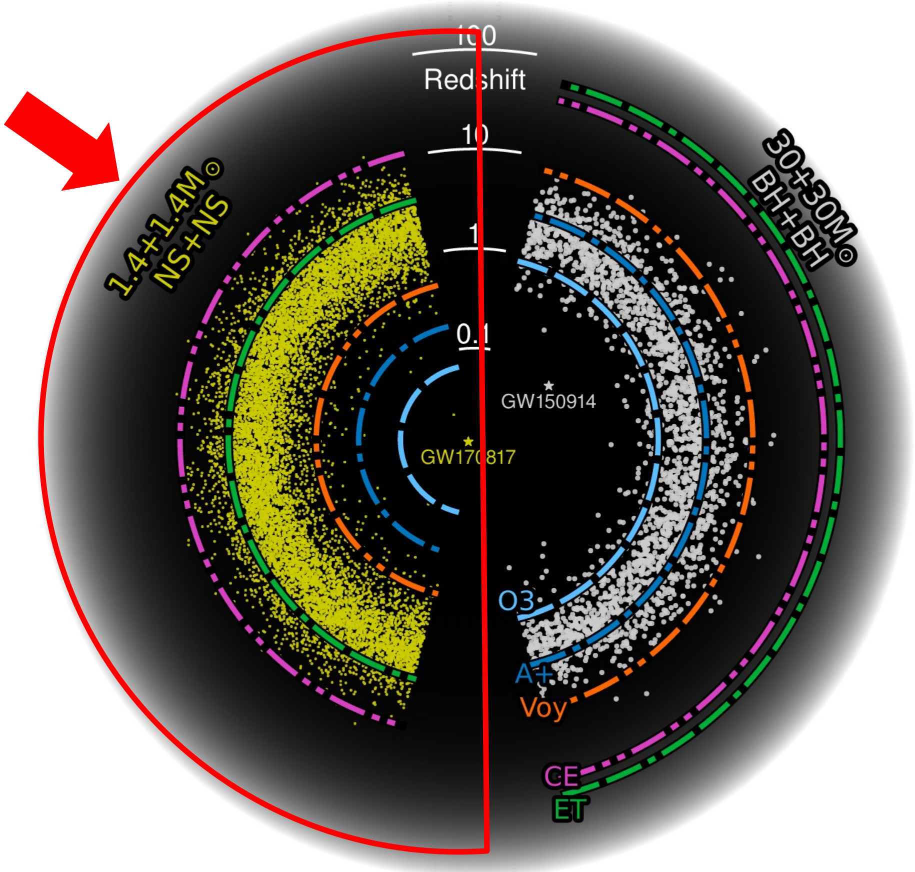
THESEUS ESA "Yellow Book" https://sci.esa.int/s/8Zb0RB8

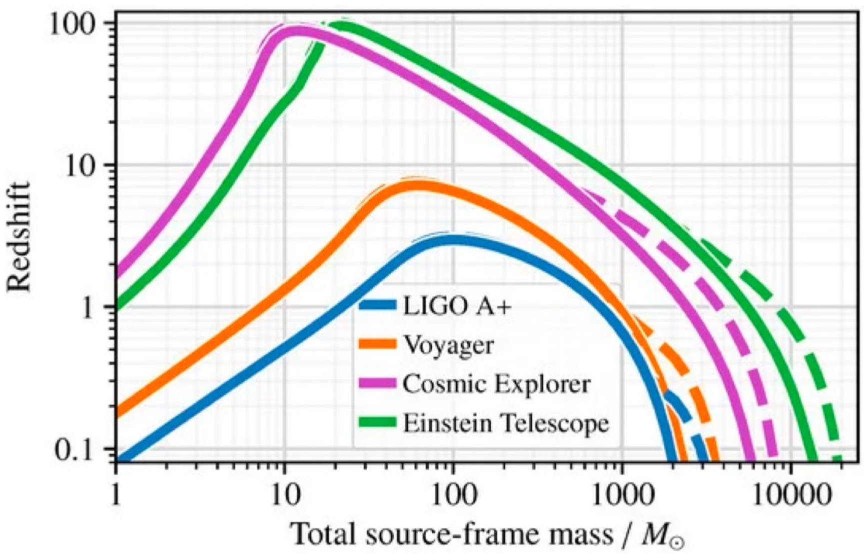
THESEUS synergies



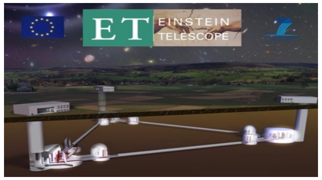
NS-NS merger with 3G GW detectors

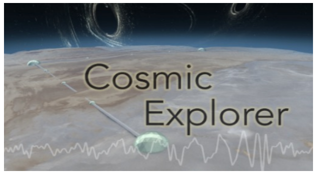
By >2035 ~10^5/yr BNS will be detected up to z>1-2 with 3G GW detectors





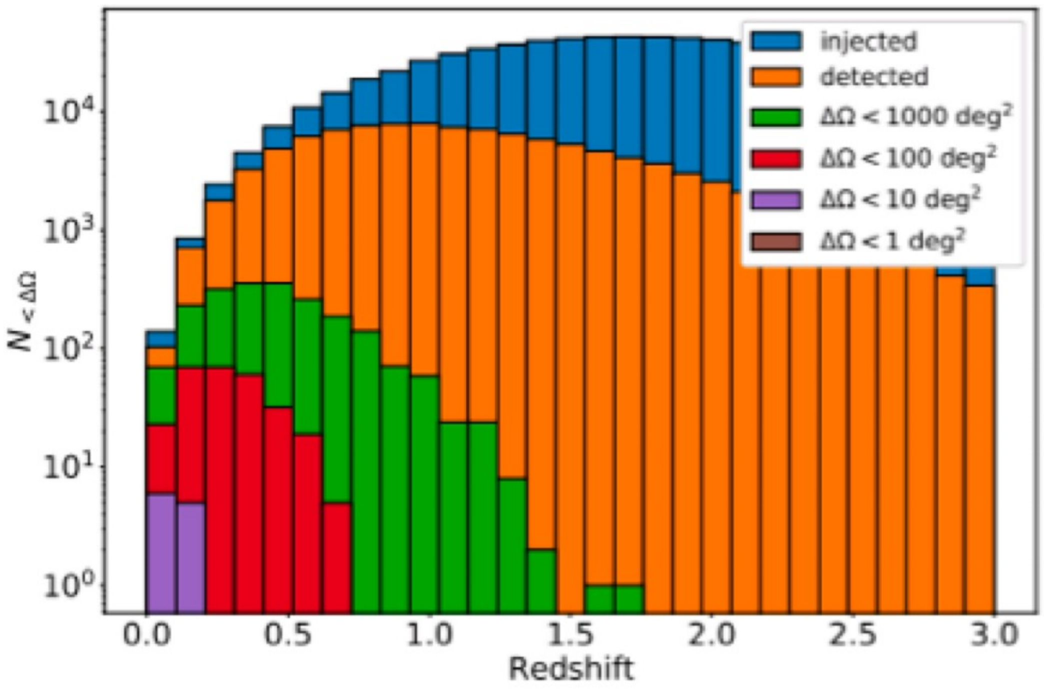
E. D. Hall, 2022 Galaxies



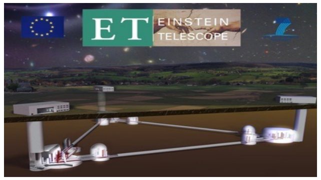


EM counterparts of BNS

BNS / yr with ET – Branchesi+2023



(a) Δ 10 km HFLF cryo.



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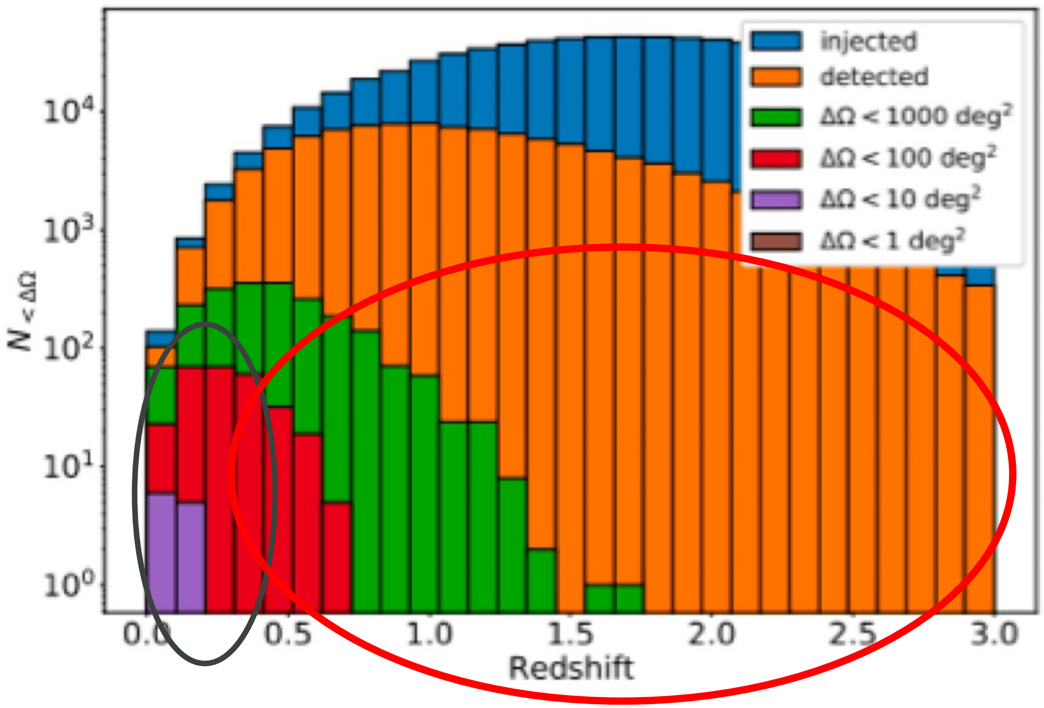
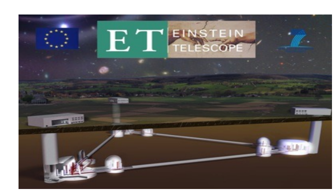


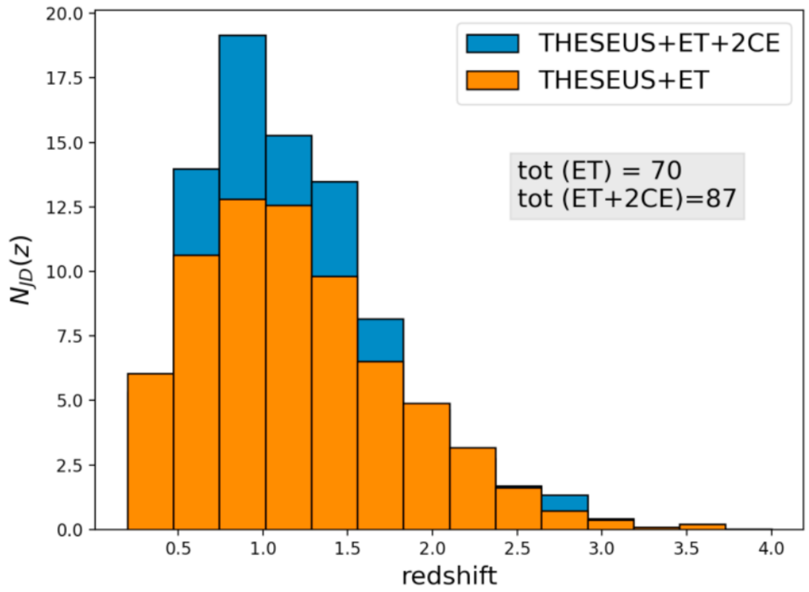
(a) Δ 10 km HFLF cryo.

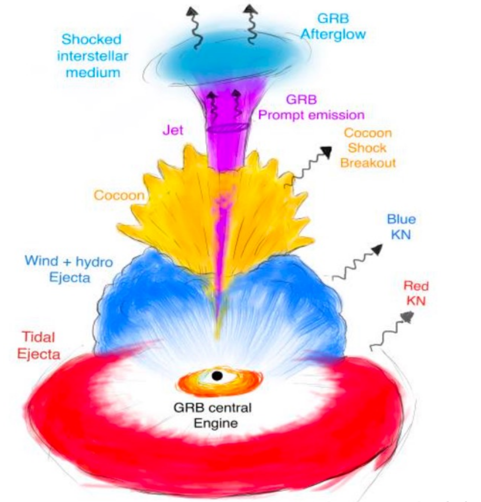
KNe detection in optical surveys at z<0.3-0.4

GRBs detection in X/gamma-ray **surveys** at z>0.4-0.5



short GRB+GW science





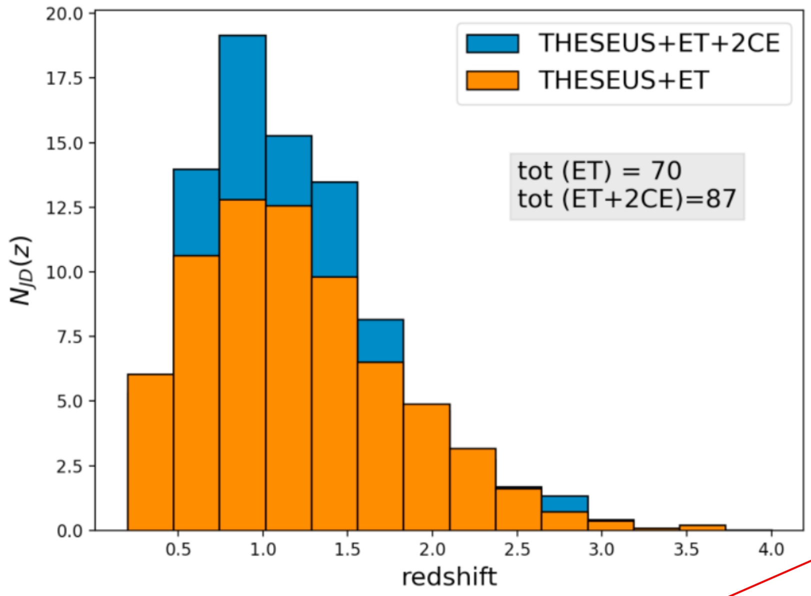
Ascenzi+21

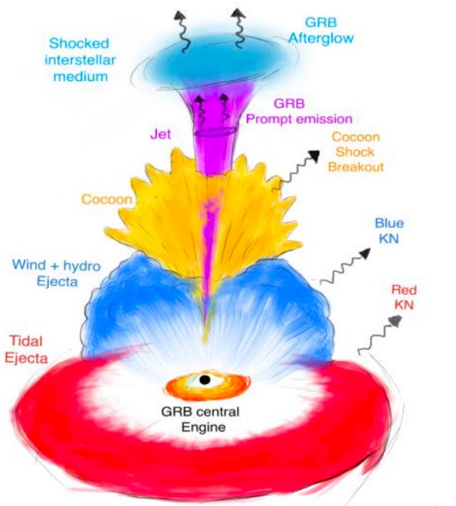
Several tens of short GRB+GW are expected to be detected with THESEUS

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





Ascenzi+21

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

Short GRB+GW with accurate sky localization (arcmin to arcsec level)
NOTE: not considered:
- GRB detected **outside XGIS FoV** with E >150 keV (with coarse localization of ~500 deg^2, ~30/yr)
- **peculiar short/long GRB** (e.g. short GRB with Extended Emission)

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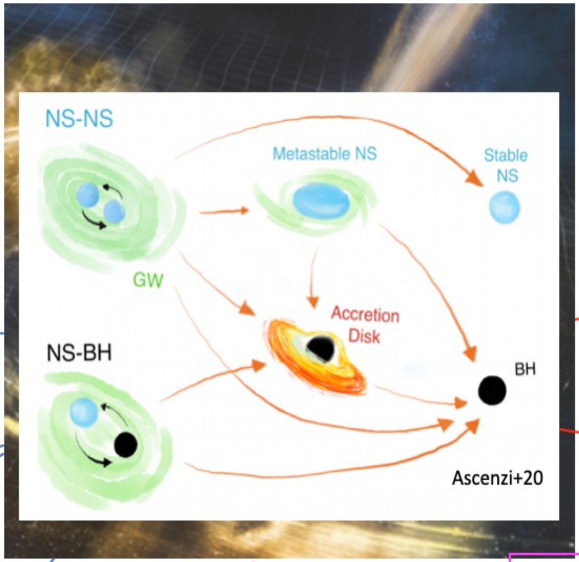
No follow-up with other factilities is required:

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)



< few hours follow-up with other facilities required:

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?

What link with remnant nature and plateau/flare features?

< 1 hours follow-up with other facilities required:

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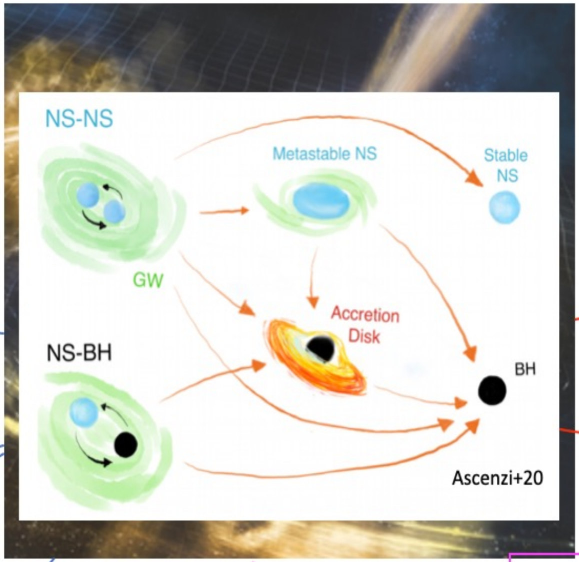

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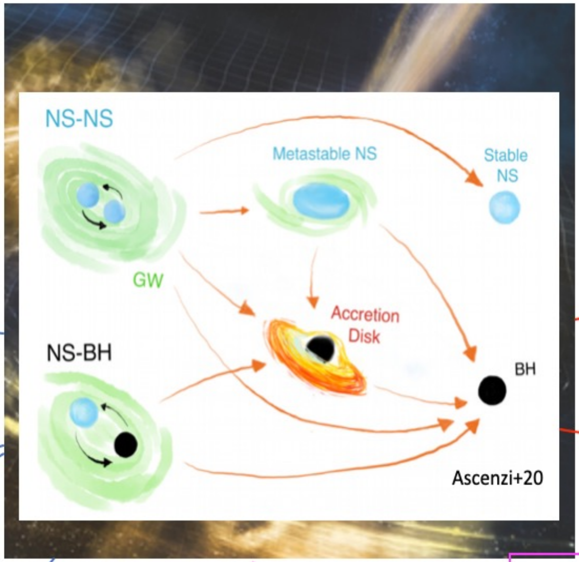

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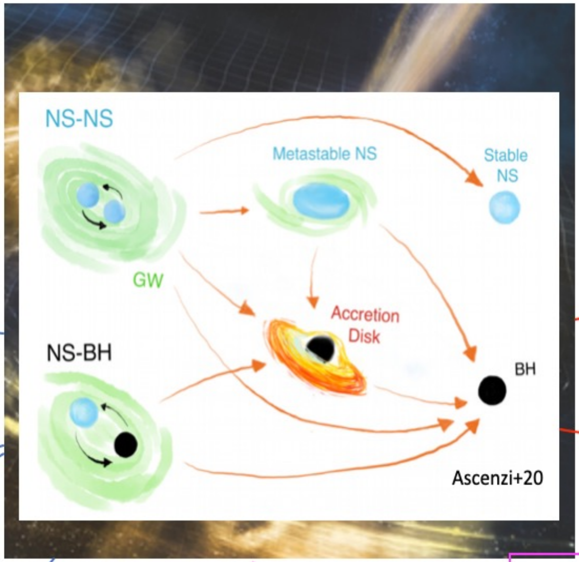

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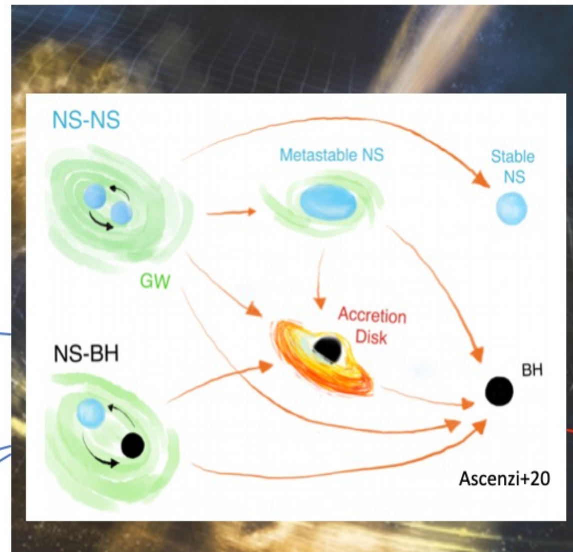

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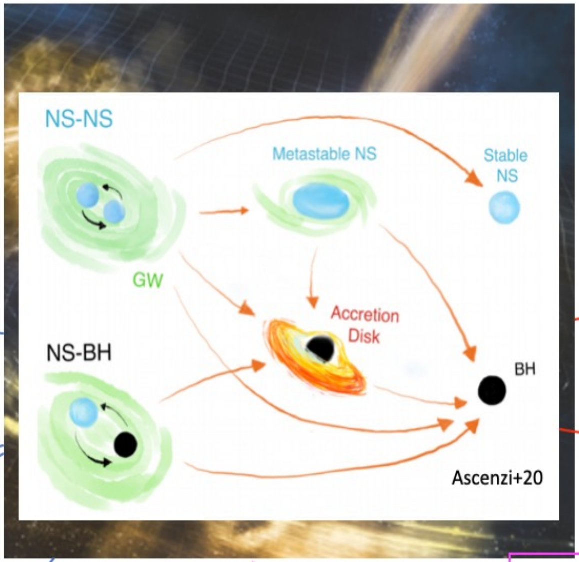

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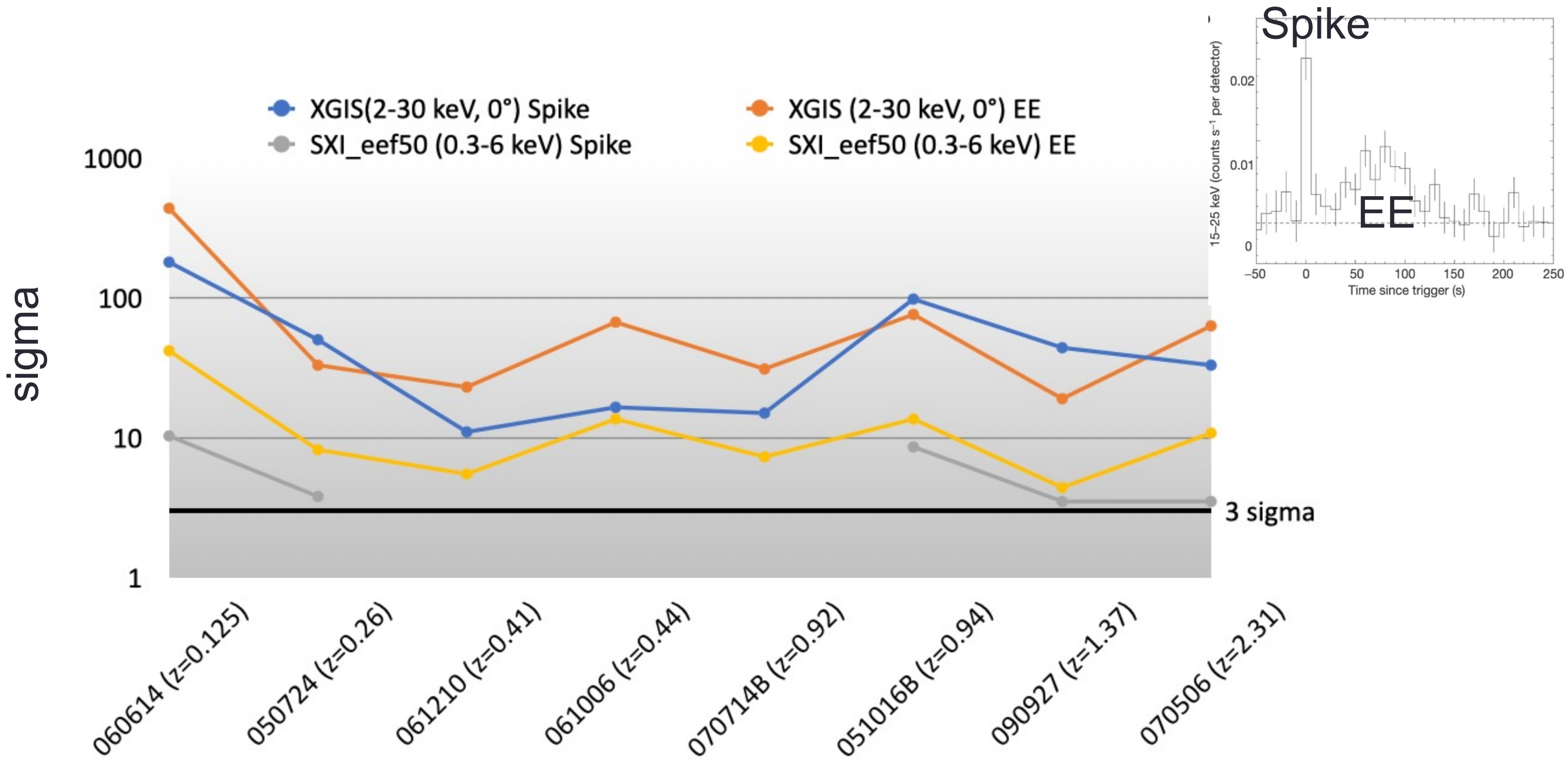
Unveiling the origin of SGRB+EE

THESEUS XGIS+SXI simulations of a sample of short GRB with Extended Emission 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?	
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

Unveiling the origin of SGRB+EE



THESEUS XGIS+SXI are ideal to identify and characterize SGRB+EE and their connection with CBC and their remnant properties → only with 3G

THESEUS timeline

→ THE EUROPEAN SPACE AGENCY esa

Final three for ESA's next medium science mission

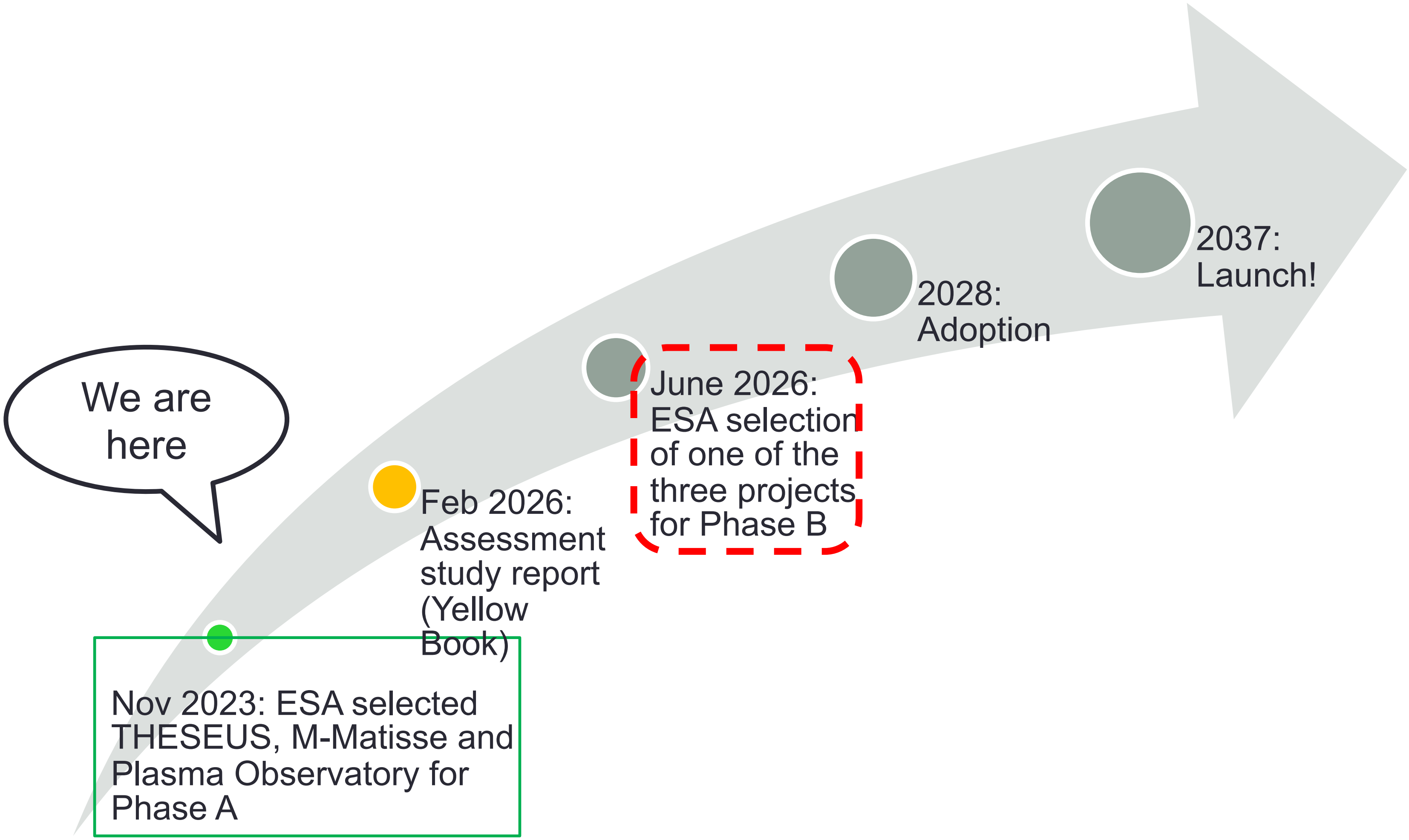
08/11/2023 13934 VIEWS 98 LIKES

ESA / Science & Exploration / Space Science

The space science community has narrowed down the shortlist for ESA's next 'medium' mission to three finalists: M-Matisse, Plasma Observatory and Theseus.

https://www.esa.int/Science_Exploration/Space_Science/Final_three_for_ESA_s_next_medium_science_mission

THESEUS timeline



Everything you wanted to know about THESEUS...

Galaxies 2022, 10, 60

galaxies MDPI

Article

Breakthrough Multi-Messenger Astrophysics with the THESEUS Space Mission †

Giulia Stratta [1,2,*], Lorenzo Amati [2], Marica Branchesi [3], Riccardo Ciolfi [4], Nial Tanvir [5], Enrico Bozzo [6], Diego Götz [7], Paul O'Brien [5] and Andrea Santangelo [8]

Advances in Space Research, Vol, 62, 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]

SPIE 2024, Vol 13093

THESEUS: Transient High Energy Sky and Early Universe Surveyor

Enrico Bozzo, Lorenzo Amati, Paul O'Brien, Diego Goetz, Andrea Santangelo
Author Affiliations +

Experimental Astronomy issue 2021

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

Multi-messenger astrophysics with THESEUS in the 2030s

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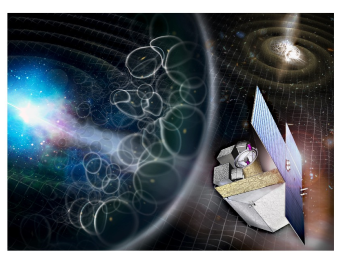
THESEUS conference 2021

THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021

Home Program Registration Participants Posters & Slides Contact



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

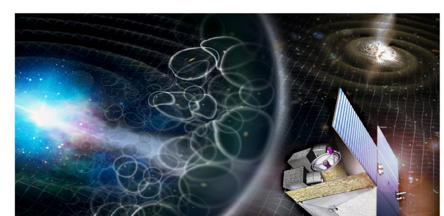
2021 ESA Yellow Book

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

esa ESA/SCI(2021)2 February 2021

THESEUS

Transient High-Energy Sky and Early Universe Surveyor



https://theseus.astro-ge.ch/

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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 A in competition with other two missions -> next selection mid-2026**

- **Only X/gamma-ray surveyors like THESEUS will catch the EM counterparts of poorly localized GW sources at z>0.4-0.5**

- **THESEUS will provide:**
  - → Autonomous detection of the source
  - → Autonomous characterization of the source from MeV to NIR
  - → Quick broadcast of sky localization down to arcmin/arcsec levels -> Activation of MW observational campaigns

- THESEUS **will enhance the scientific return of next generation multi messenger** (ET, Cosmic Explorer, LISA and Km3NET, IceCube-Gen2;) **and e.m. facilities** (e.g., ELT, SKA, CTA, newATHENA)

- **THESEUS is in competition with other two projects -> a strong sustain from the community is needed!**

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transient high energy sky and early universe surveyor

Keep calm
and
Support
THESEUS!

Extra slides

Mission	Autonomous rapid repointing	Arcsec localisation	Optical imaging	Near-IR imaging	Near-IR spectroscopy	On-board redshift broadcasting	<10 keV X-ray coverage	>10 keV X-ray coverage	MeV -ray coverage
Swift	✓	✓	✓	✗	✗	✗	✓	✓	✗
Fermi/GRB	✗	✗	✗	✗	✗	✗	✗	✓	✓
Integral	✗	✗	✓	✗	✗	✗	✗	✓	✓
SVOM	✓	✓	✓	✗	✗	✗	✓	✓	✓
Einstein Probe	✓	✗	✗	✗	✗	✗	✓	✗	✗
eXTP	✓	✓	✗	✗	✗	✗	✓	✗	✗
THESEUS	✓	✓	✓	✓	✓	✓	✓	✓	✓

Detection performance of THESEUS compared with current and upcoming high-energy space missions.

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	$\leq$10% over 10 min
Field-of-Regard	$\geq$50% of the sky
Trigger broadcasting delay to ground-based networks	$\leq$30 s (65% of the alerts) $\leq$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.)	$\leq$2 arcmin
XGIS positional accuracy (2–150 keV, 90% c.l.)	$\leq$7 arcmin (50% of triggered short GRBs) $\leq$15 arcmin (90% of triggered short GRBs)
IRT positional accuracy (5σ detections) real time post-processing	 $\leq$5 arcsec $\leq$1 arcsec

Stratta+2022

ELSEVIER
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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]

~2000 deg^2 0.3-5 keV

>10000 deg^2 2 keV -1 MeV

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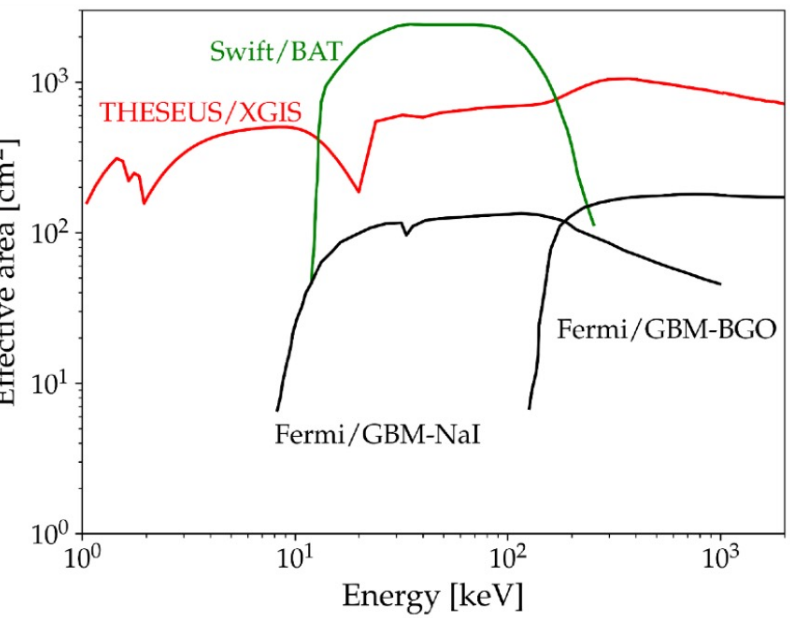

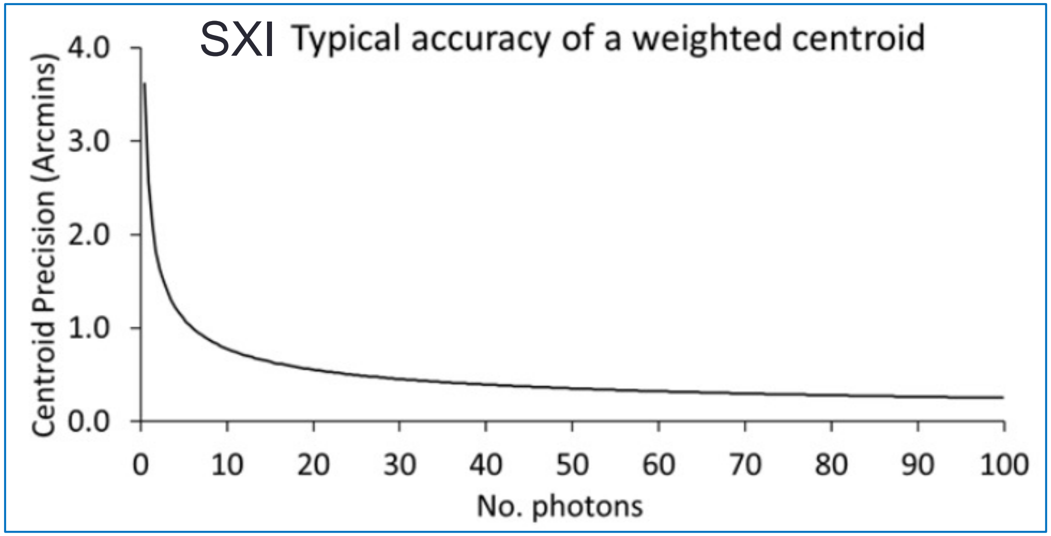

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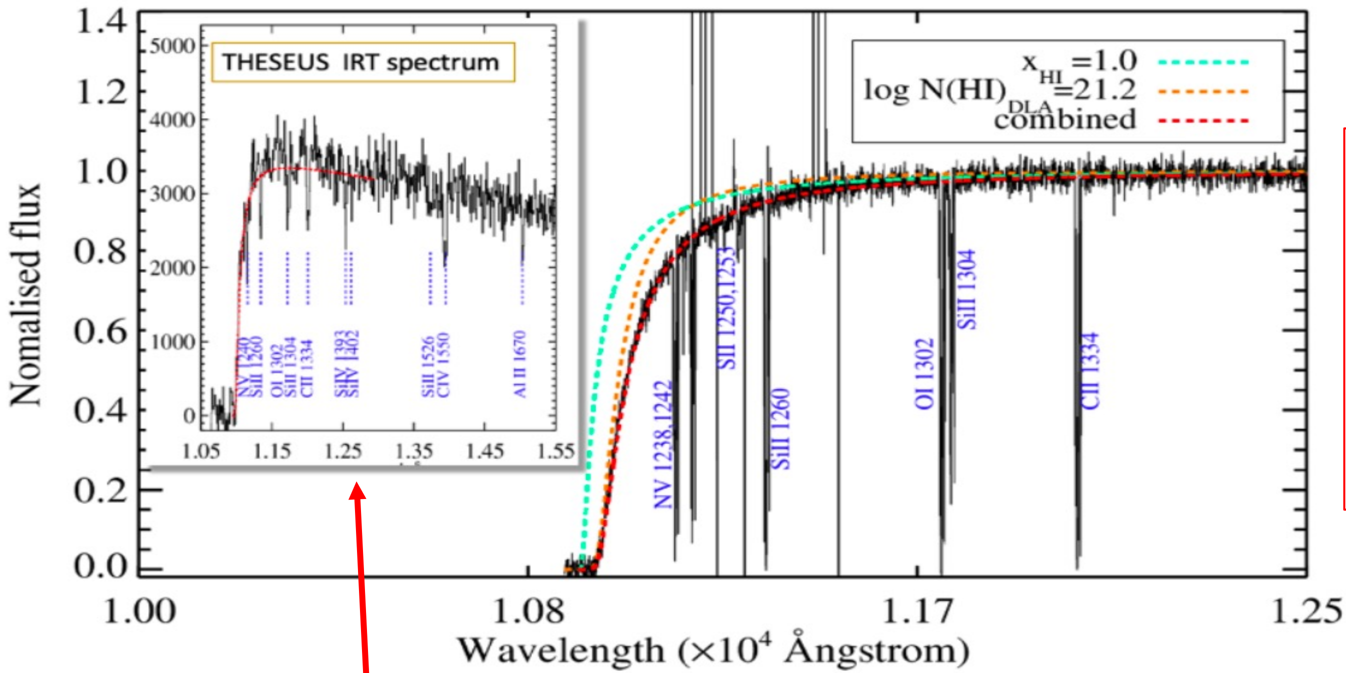

Simulated ELT 30' spectrum of a z=8.0 GRB afterglow with J(AB)=20 corresponding to **~0.5 days** post-burst

the same z=8 bright afterglow (JAB=16 mag or **~0.5 hours** post-burst) observed with THESEUS IRT

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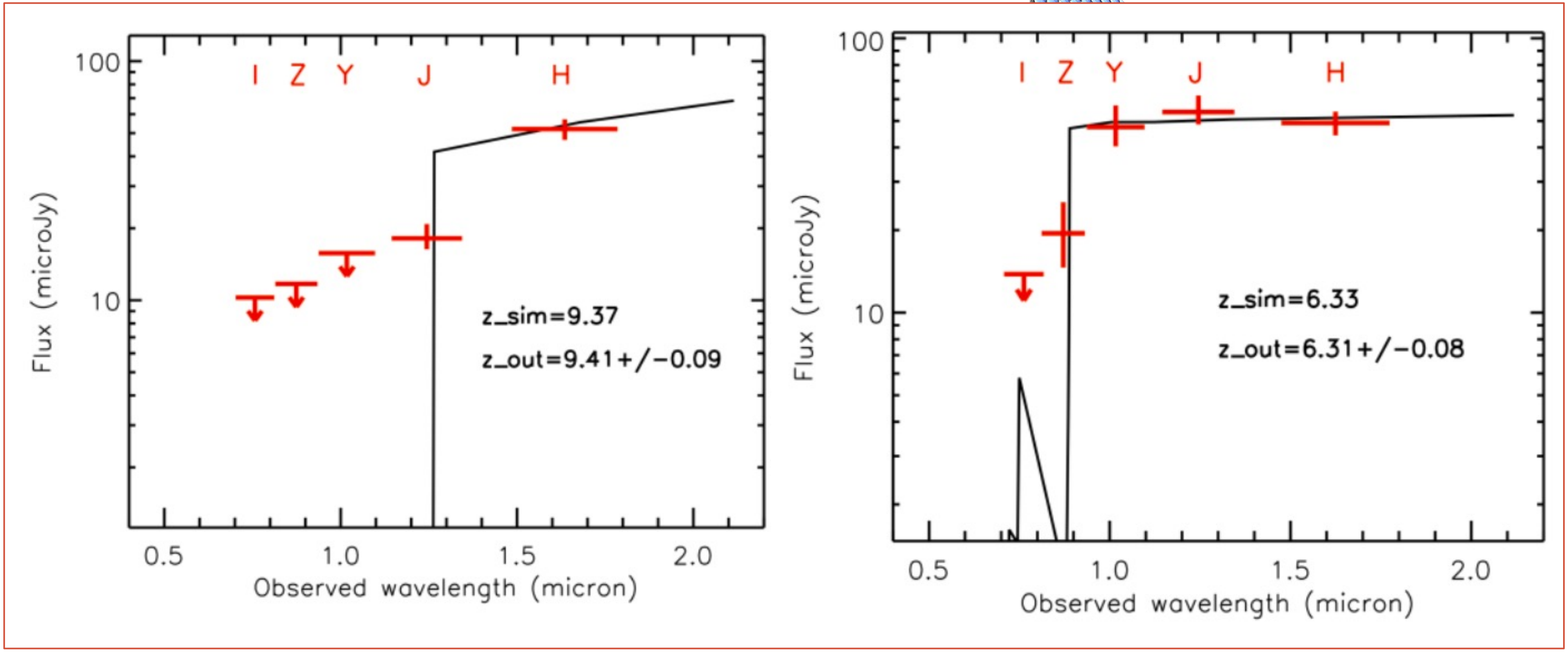

Two examples of simulated IRT photometric data and model fitting

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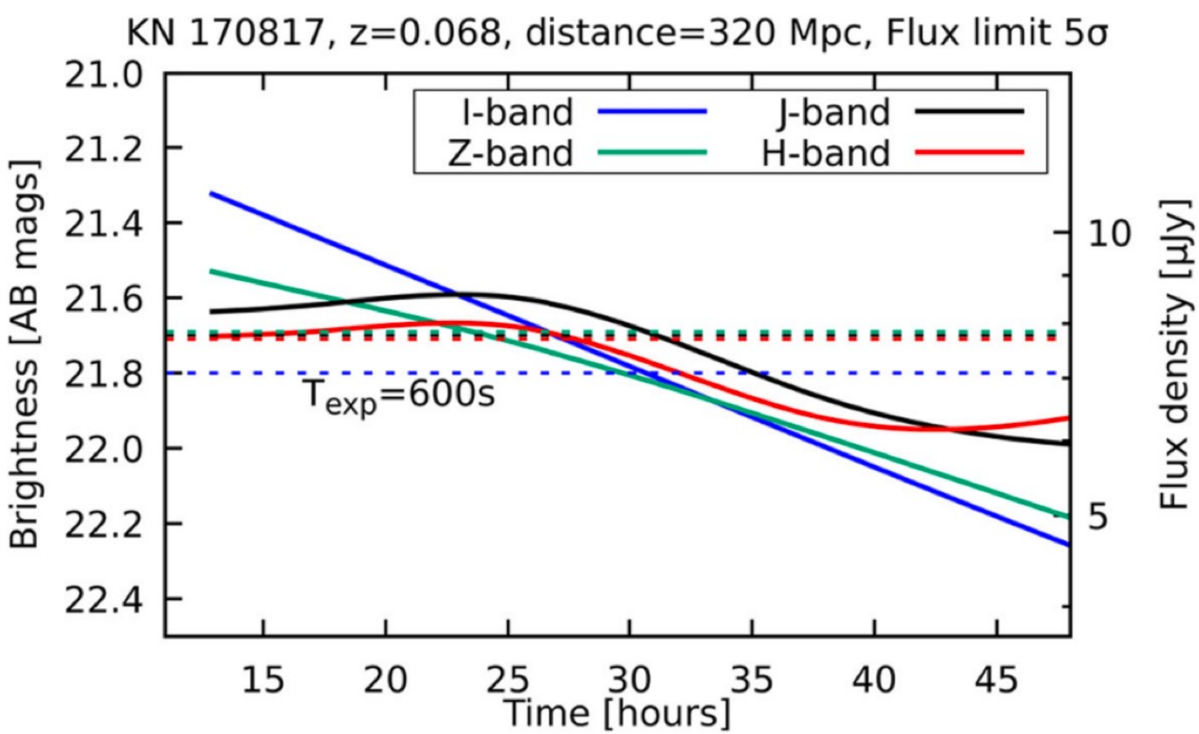
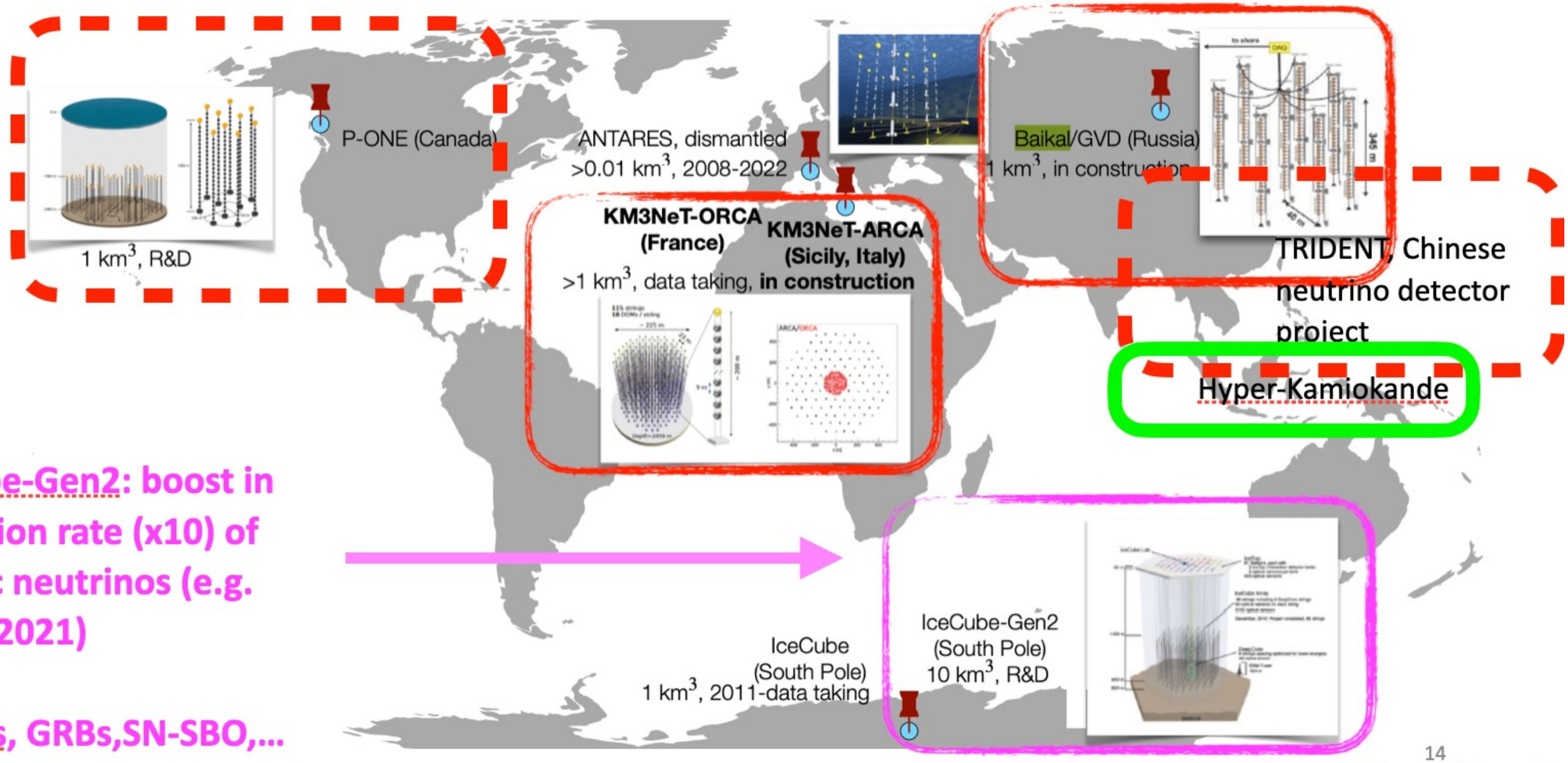
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



THESEUS can detect a kilonova like AT2017gfo with 5 sigma up to ~300 Mpc in all bands with 600s of exposure, within 1-2 days from the merger epoch

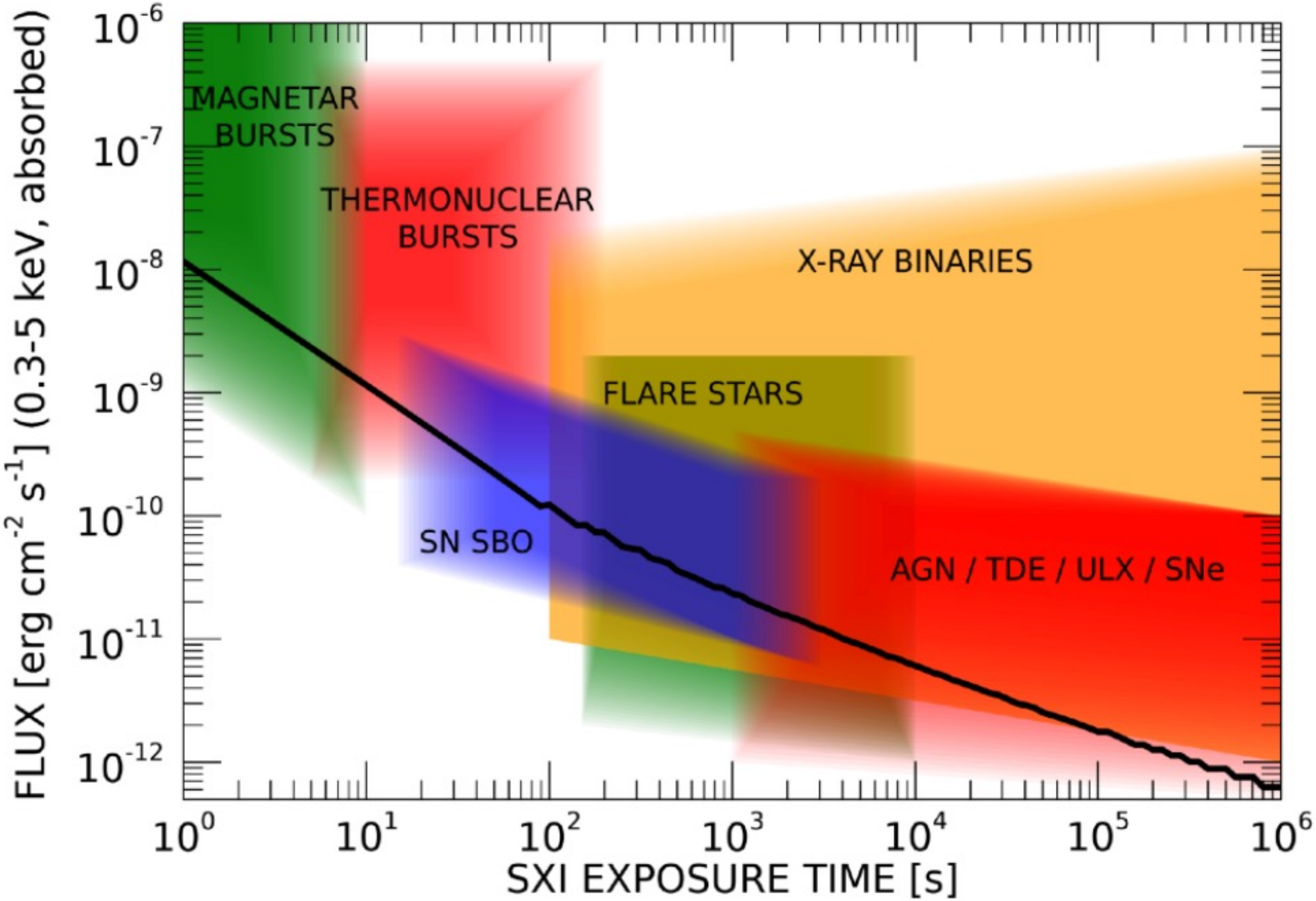
The growing neutrino detector network



IceCube-Gen2: boost in detection rate (x10) of cosmic neutrinos (e.g. Clark+2021)

Blazars, GRBs,SN-SBO,...

Credit: adapted from A. Zegarelli



MAGNETAR BURSTS
THERMONUCLEAR BURSTS
X-RAY BINARIES
FLARE STARS
SN SBO
AGN / TDE / ULX / SNe
FLUX [erg cm^{-2} s^{-1}] (0.3-5 keV, absorbed)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
SXI EXPOSURE TIME [s]

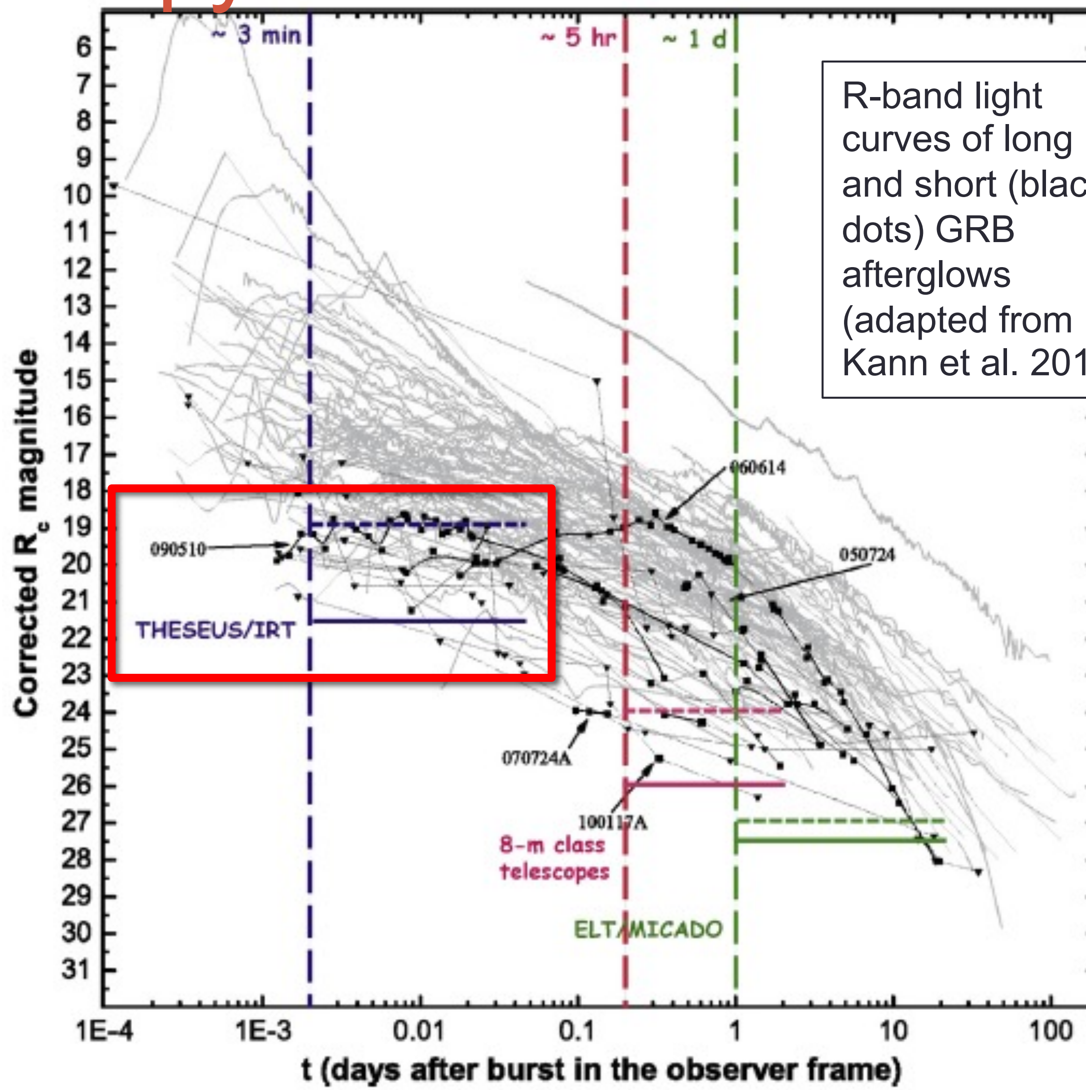
Afterglow spectroscopy of THESEUS GRBs

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

The role of THESEUS in MMA

- **Independent detection** of the EM counterpart of GW detected sources -> increase statistical confidence on astrophysical nature of subthreshold events
- **Autonomous source characterization** thanks to the large spectral coverage on onboard instruments
- **Accurate sky coordinate dissemination** -> allowing for follow-up campaigns with large telescopes as ELT, SKA, CTA, newAthena, etc.