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

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

Journal Club for Nuclear and Particle Astrophysics Course

Trieste – April 9, 2021

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

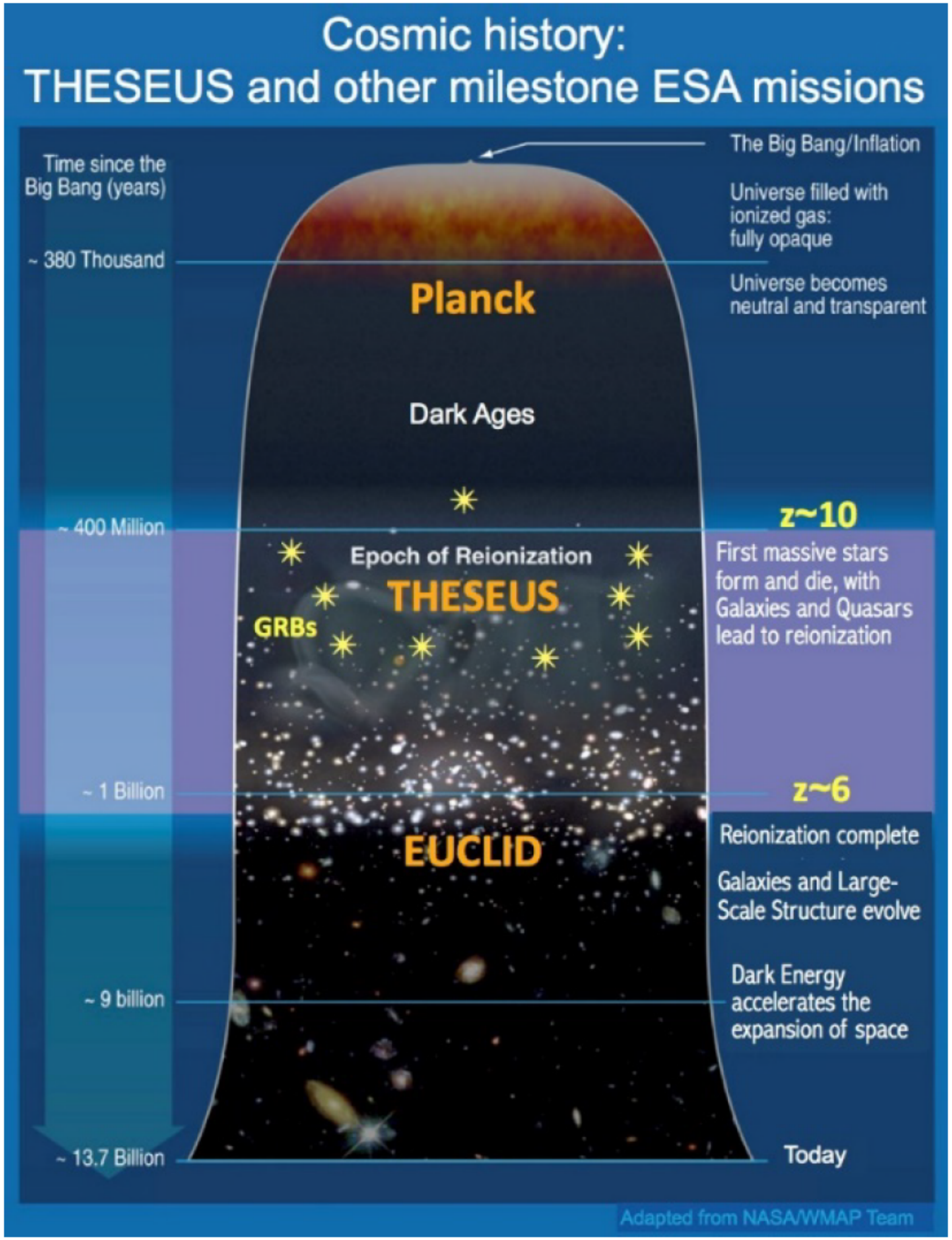
L. Amati; P. O'Brien; D. Götz; E. Bozzo; C. Tenzer; F. Frontera; G. Ghirlanda; C. Labanti; J. P. Osborne; G. Stratta; N. Tanvir; R. Willingale; P. Attina; R. Campana; A.J. Castro-Tirado; C. Contini; F. Fuschino; A. Gomboc; R. Hudec; P. Orleanski; E. Renotte; T. Rodic; Z. Bagoly; A. Blain; P. Callanan; S. Covino; A. Ferrara; E. Le Floch; M. Marisaldi; S. Mereghetti; P. Rosati; A. Vacchi; P. D'Avanzo; P. Giommi; S. Piranomonte; L. Piro; V. Reglero; A. Rossi; A. Santangelo; R. Salvaterra; G. Tagliaferri; S. Vergani; S. Vinciguerra; M. Briggs; E. Campolongo; R. Ciolfi; V. Connaughton; B. Cordier; B. Morelli; M. Orlandini; C. Adami; A. Argan; J.-L. Atteia; N. Auricchio; L. Balazs; G. Baldazzi; S. Basa; R. Basak; P. Bellutti; M. G. Bernardini; G. Bertuccio; J. Braga; M. Branchesi; S. Brandt; E. Brocato; C. Budtz-Jorgensen; A. Bulgarelli; L. Burderi; J. Camp; S. Capozziello; J. Caruana; P. Casella; B. Cenko; P. Chardonnet; B. Ciardi; S. Colafrancesco; M. G. Dainotti; V. D'Elia; D. De Martino; M. De Pasquale; E. Del Monte; M. Della Valle; A. Drago; Y. Evangelista; M. Feroci; F. Finelli; M. Fiorini; J. Fynbo; A. Gal-Yam; B. Gendre; G. Ghisellini; A. Grado; C. Guidorzi; M. Hafizi; L. Hanlon; J. Hjorth; L. Izzo; L. Kiss; P. Kumar; I. Kuvvetli; M. Lavagna; T. Li; F. Longo; M. Lyutikov; U. Maio; E. Maiorano; P. Malcovati; D. Malesani; R. Margutti; A. Martin-Carrillo; N. Masetti; S. McBreen; R. Mignani; G. Morgante; C. Mundell; H. U. Nargaard-Nielsen; L. Nicastro; E. Palazzi; S. Paltani; F. Panessa; G. Pareschi; A. Pe'er; A. V. Penacchioni; E. Pian; E. Piedipalumbo; T. Piran; G. Rauw; M. Razzano; A. Read; L. Rezzolla; P. Romano; R. Ruffini; S. Savaglio; V. Sguera; P. Schady; W. Skidmore; L. Song; E. Stanway; R. Starling; M. Topinka; E. Troja; M. van Putten; E. Vanzella; S. Vercellone; C. Wilson-Hodge; D. Yonetoku; G. Zampa; N. Zampa; B. Zhang; B. B. Zhang; S. Zhang; S.-N. Zhang; A. Antonelli; F. Bianco; S. Boci; M. Boer; M. T. Botticella; O. Boulade; C. Butler; S. Campana; F. Capitanio; A. Celotti; Y. Chen; M. Colpi; A. Comastri; J.-G. Cuby; M. Dadina; A. De Luca; Y.-W. Dong; S. Ettori; P. Gandhi; E. Geza; J. Greiner; S. Guiriec; J. Harms; M. Hernanz; A. Hornstrup; I. Hutchinson; G. Israel; P. Jonker; Y. Kaneko; N. Kawai; K. Wiersema; S. Korpela; V. Lebrun; F. Lu; A. MacFadyen; G. Malaguti; L. Maraschi; A. Melandri; M. Modjaz; D. Morris; N. Omodei; A. Paizis; P. Páta; V. Petrosian; A. Rachevski; J. Rhoads; F. Ryde; L. Sabau-Graziati; N. Shigehiro; M. Sims; J. Soomin; D. Szécsi; Y. Urata; M. Uslenghi; L. Valenziano; G. Vianello; S. Vojtech; D. Watson; J. Zicha.

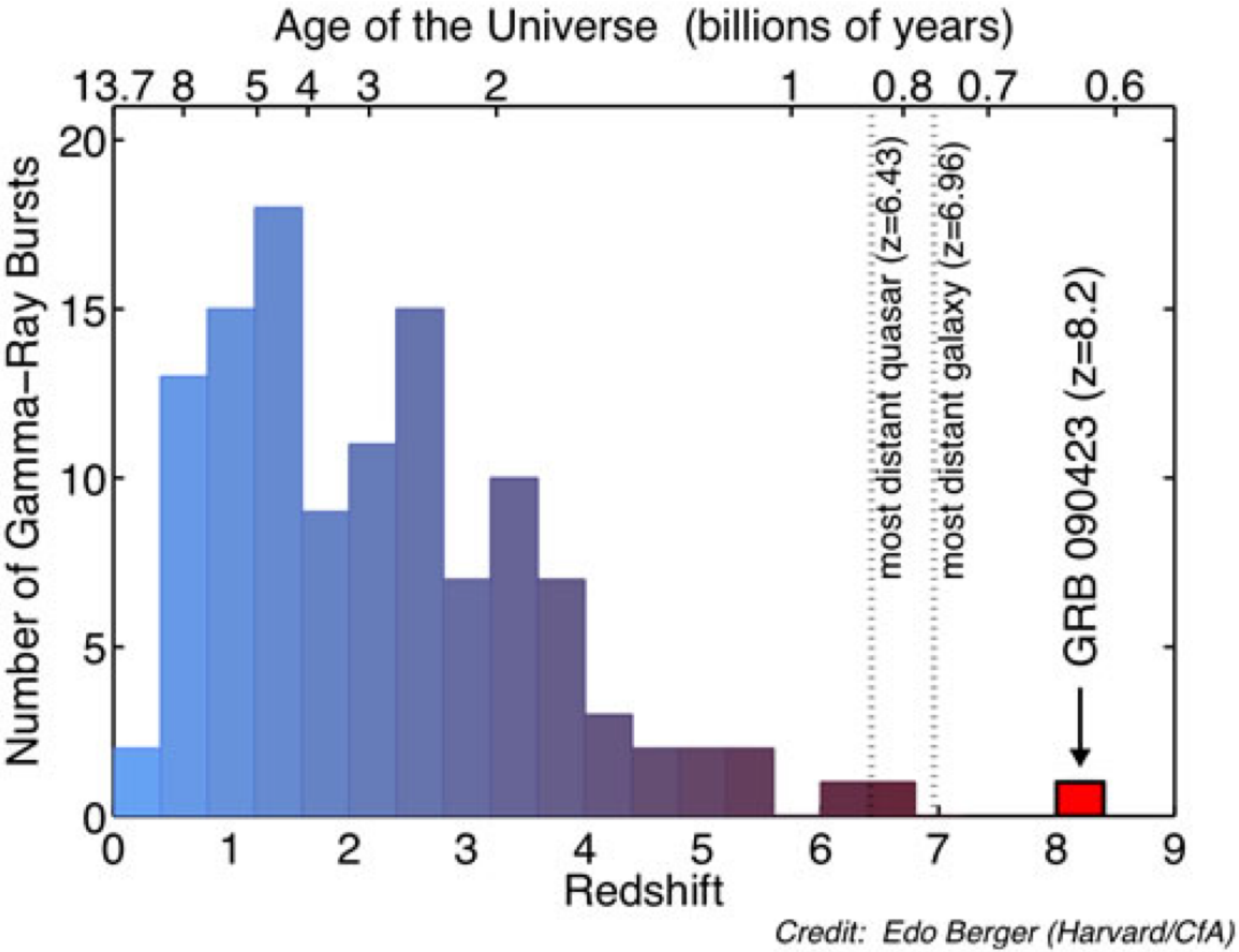
Abstract

- THESEUS is a space mission concept aimed at exploiting Gamma-Ray Bursts for investigating the early Universe and at providing a substantial advancement of multi-messenger and time-domain astrophysics.
- These goals will be achieved through a unique combination of instruments allowing GRB and X-ray transient detection over a broad field of view (more than 1sr) with 0.5-1 arcmin localization, an energy band extending from several MeV down to 0.3 keV and high sensitivity to transient sources in the soft X-ray domain, as well as on-board prompt (few minutes) followup with a 0.7 m class IR telescope with both imaging and spectroscopic capabilities.
- THESEUS will be perfectly suited for addressing the main open issues in cosmology such as, e.g., star formation rate and metallicity evolution of the inter-stellar and intra-galactic medium up to redshift ~10, signatures of Pop III stars, sources and physics of reionization, and the faint end of the galaxy luminosity function.
- In addition, it will provide unprecedented capability to monitor the X-ray variable sky, thus detecting, localizing, and identifying the electromagnetic counterparts to sources of gravitational radiation, which may be routinely detected in the late ’20s / early ’30s by next generation facilities like aLIGO/ aVirgo, eLISA, KAGRA, and Einstein Telescope. THESEUS will also provide powerful synergies with the next generation of multi-wavelength observatories (e.g., LSST, ELT, SKA, CTA, ATHENA).
- ***Keywords: Gamma-ray: bursts; Cosmology: observations, dark ages, re-ionization, first stars***

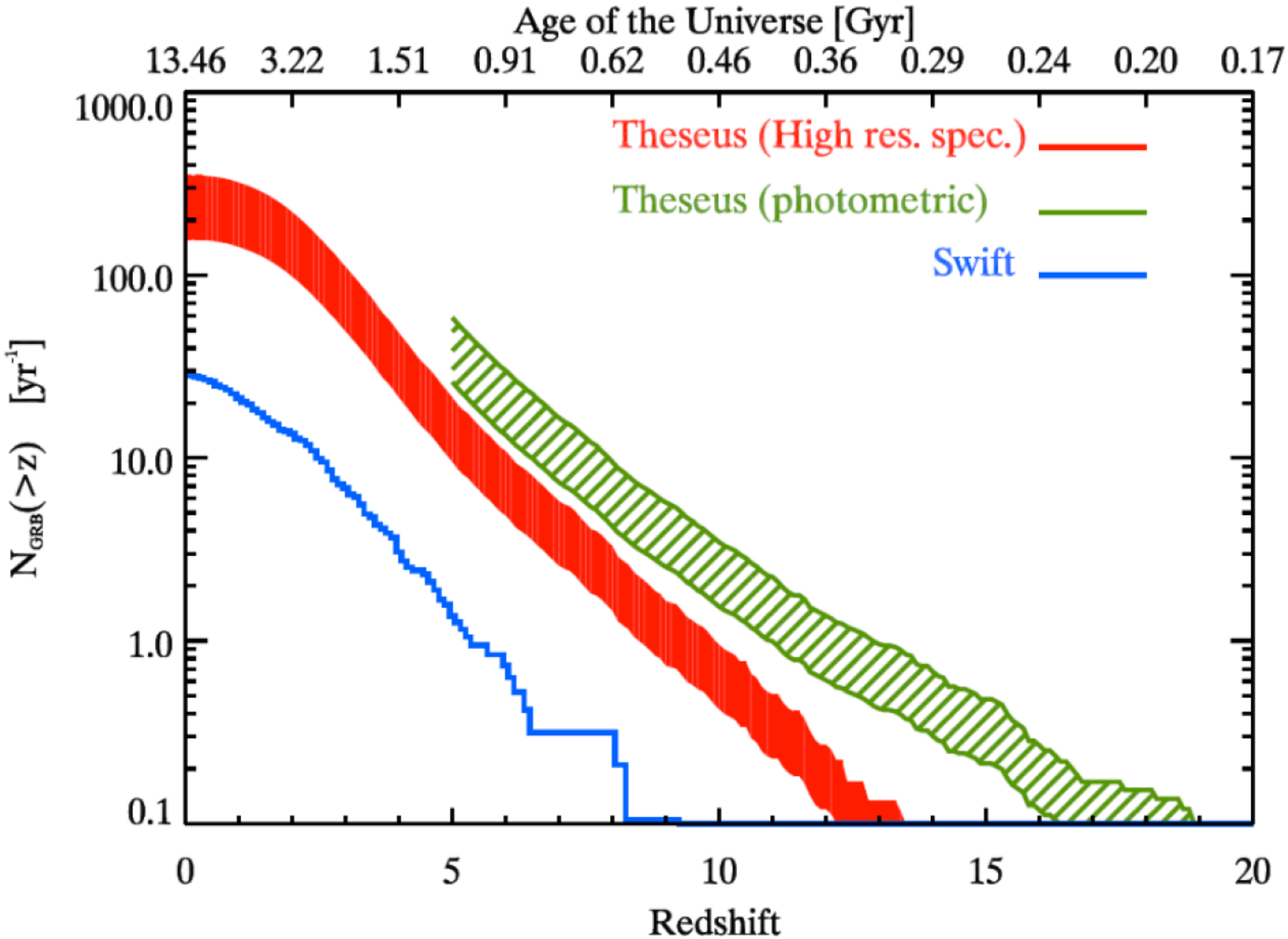
Structure of the paper

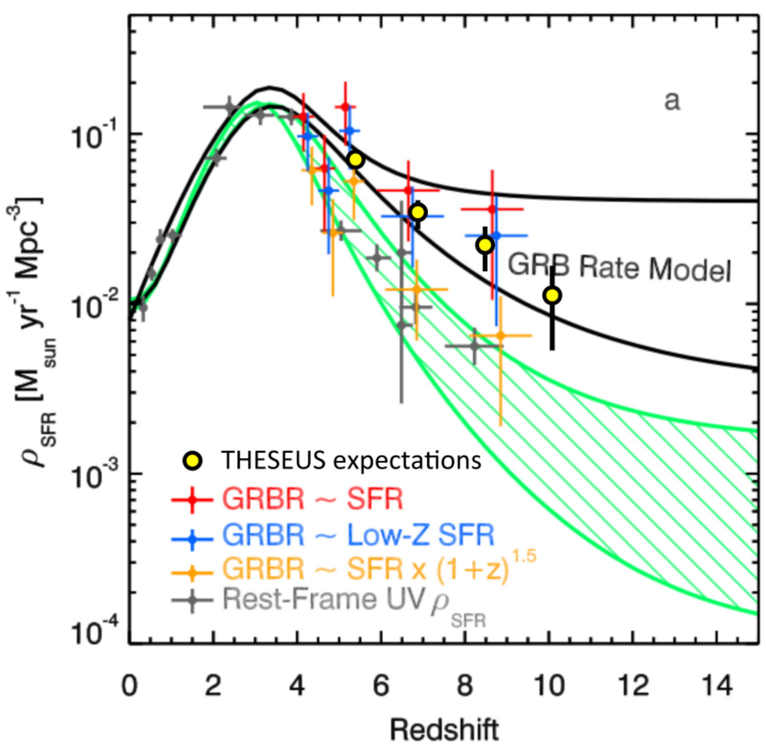
- 1. Introduction
- 2. Science Case
- 3. Scientific Requirements
- 4. Scientific Instruments
- 5. Satellite configuration and mission profile
- 6. Scientific operations, quick-look activities and data distribution


Cosmic history:
THESEUS and other milestone ESA missions
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Planck
Dark Ages
z~10
Epoch of Reionization
THESEUS
GRBs
First massive stars form and die, with Galaxies and Quasars lead to reionization
z~6
EUCLID
Reionization complete
Galaxies and Large-Scale Structure evolve
Dark Energy accelerates the expansion of space
Today
Adapted from NASA/WMAP Team

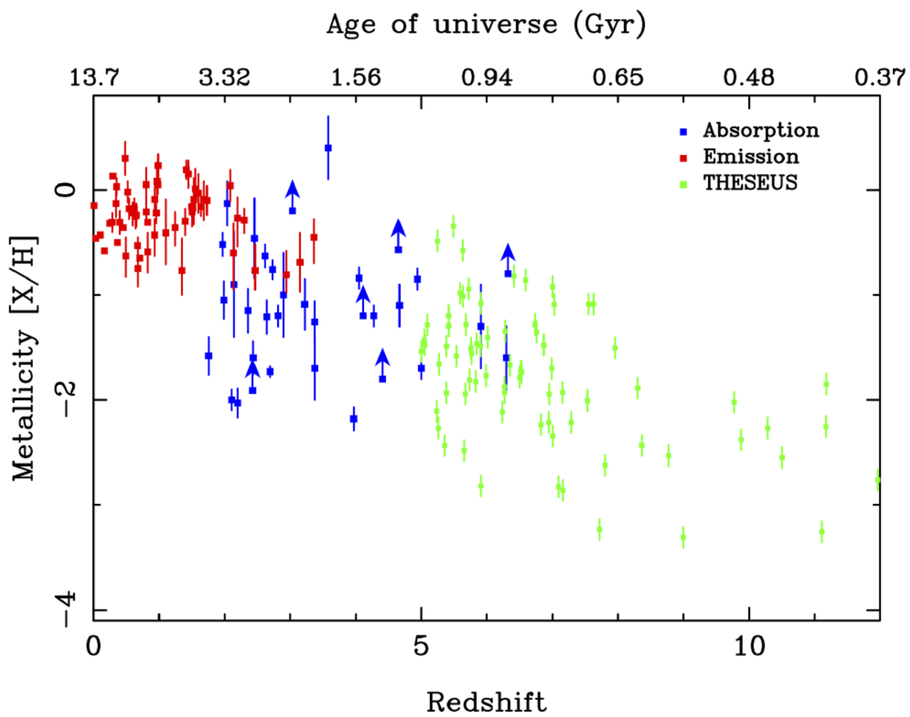


Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
0 5 10 15 20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0 1 2 3 4 5 6 7 8 9
Redshift
Credit: Edo Berger (Harvard/CfA)

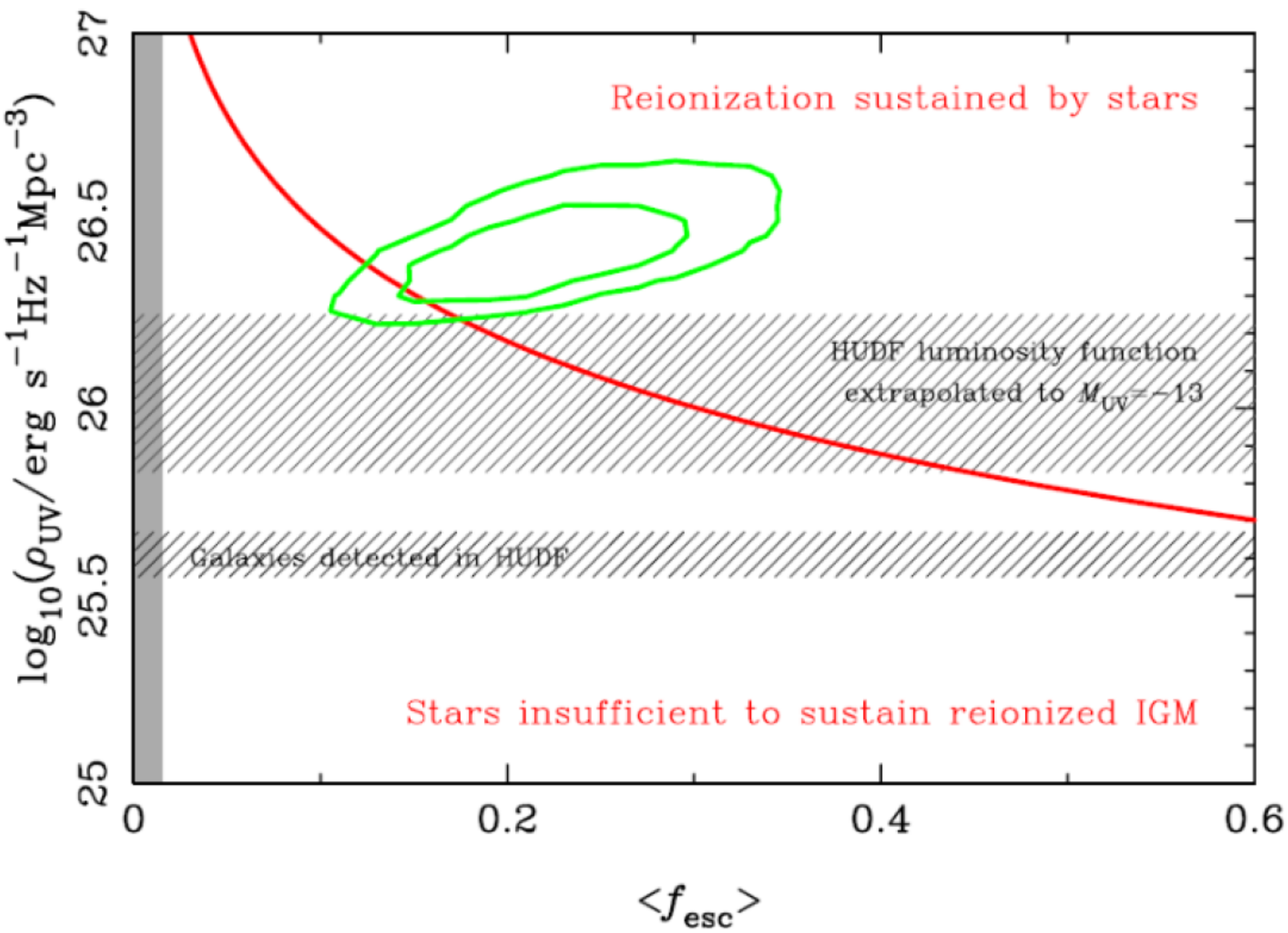

Age of the Universe [Gyr]
13.46
3.22
1.51
0.91
0.62
0.46
0.36
0.29
0.24
0.20
0.17
1000.0
100.0
10.0
1.0
0.1
$N_{GRB}(>z)$ [yr^{-1}]
Theseus (High res. spec.)
Theseus (photometric)
Swift
0
5
10
15
20
Redshift



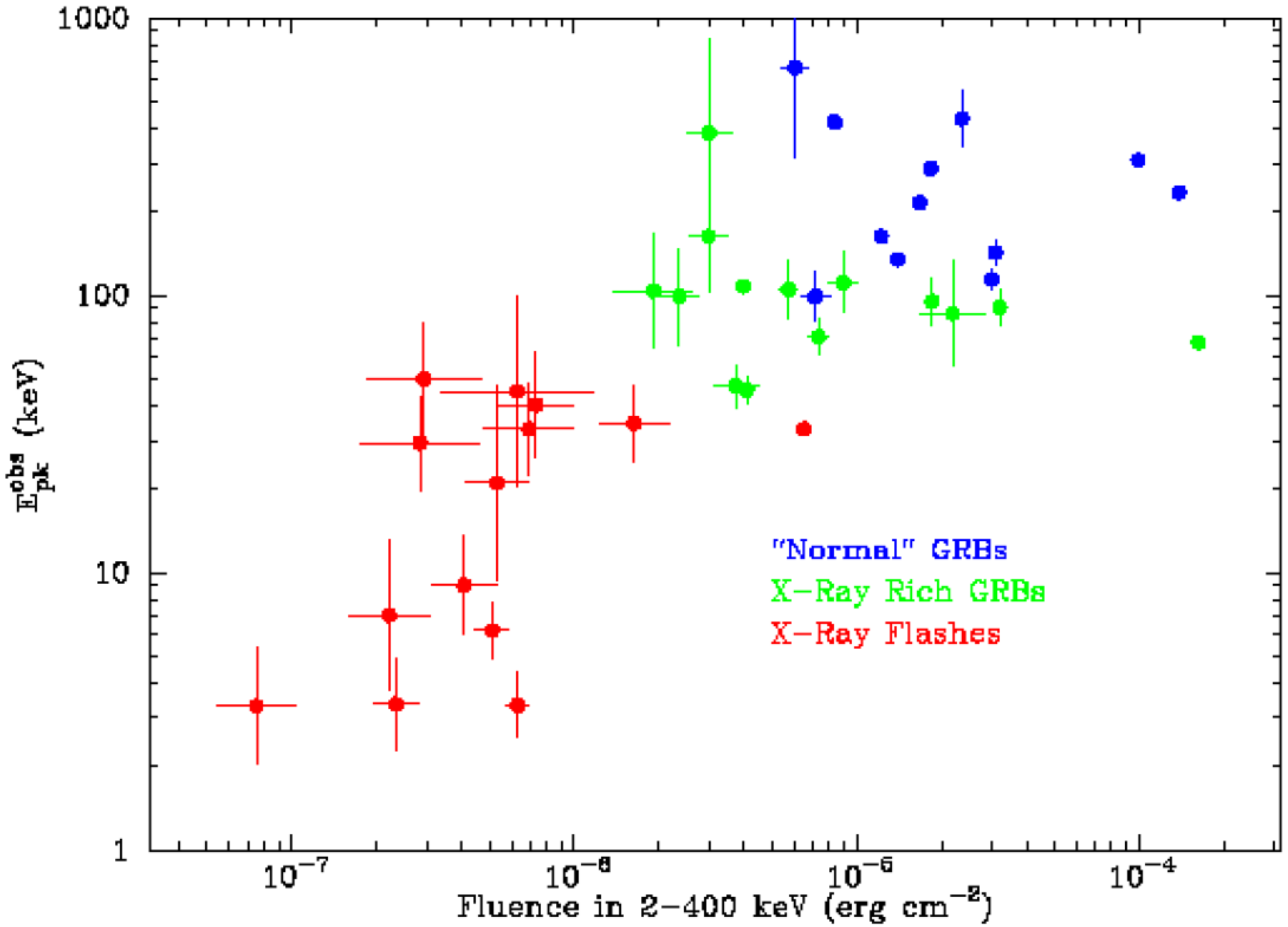
a
GRB Rate Model
THESEUS expectations
GRBR ~ SFR
GRBR ~ Low-Z SFR
GRBR ~ SFR x (1+z)^1.5
Rest-Frame UV ρ_SFR
ρ_SFR [M_sun yr^-1 Mpc^-3]
Redshift



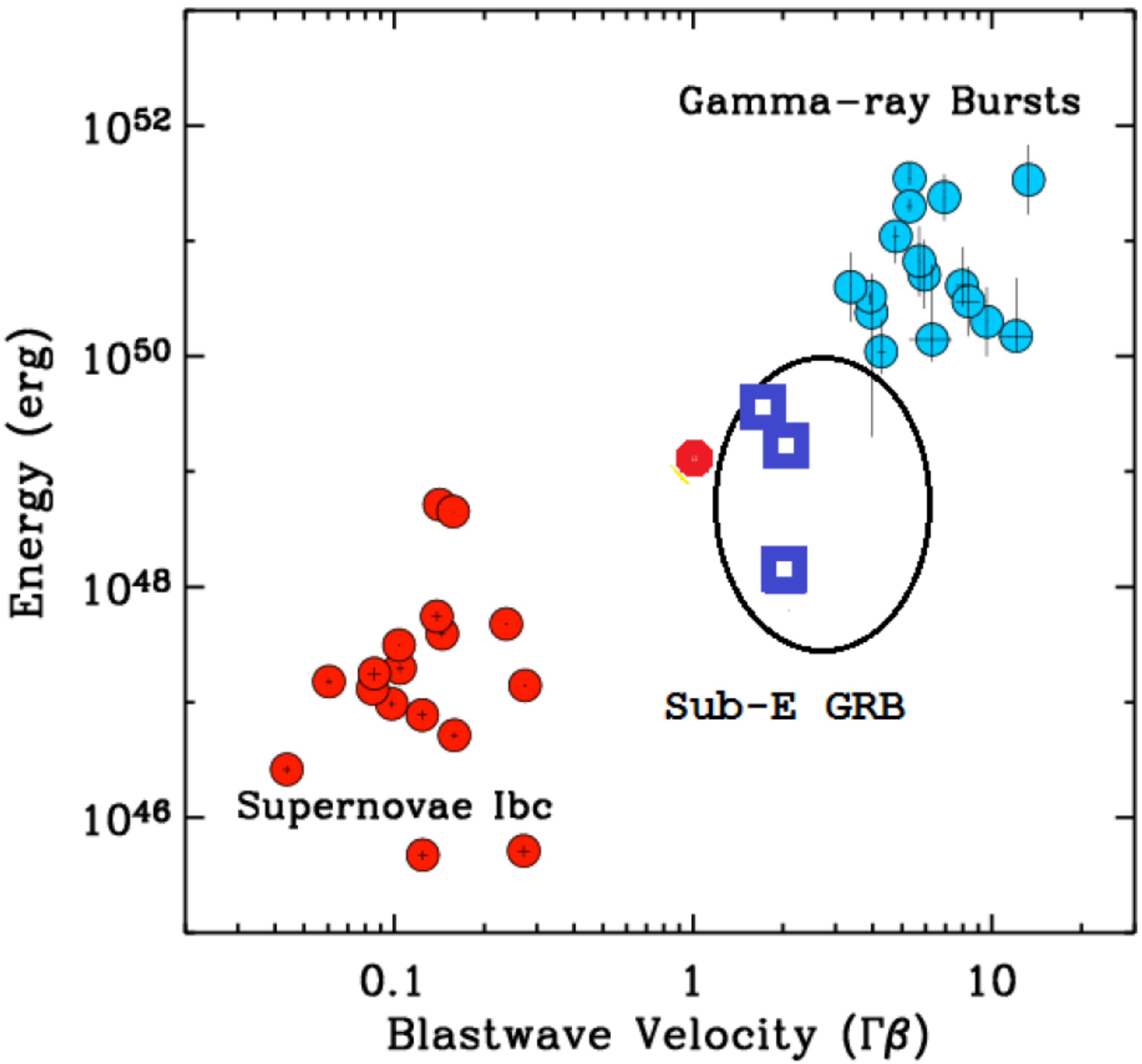
Age of universe (Gyr)
13.7
3.32
1.56
0.94
0.65
0.48
0.37
Absorption
Emission
THESEUS
Metallicity [X/H]
Redshift



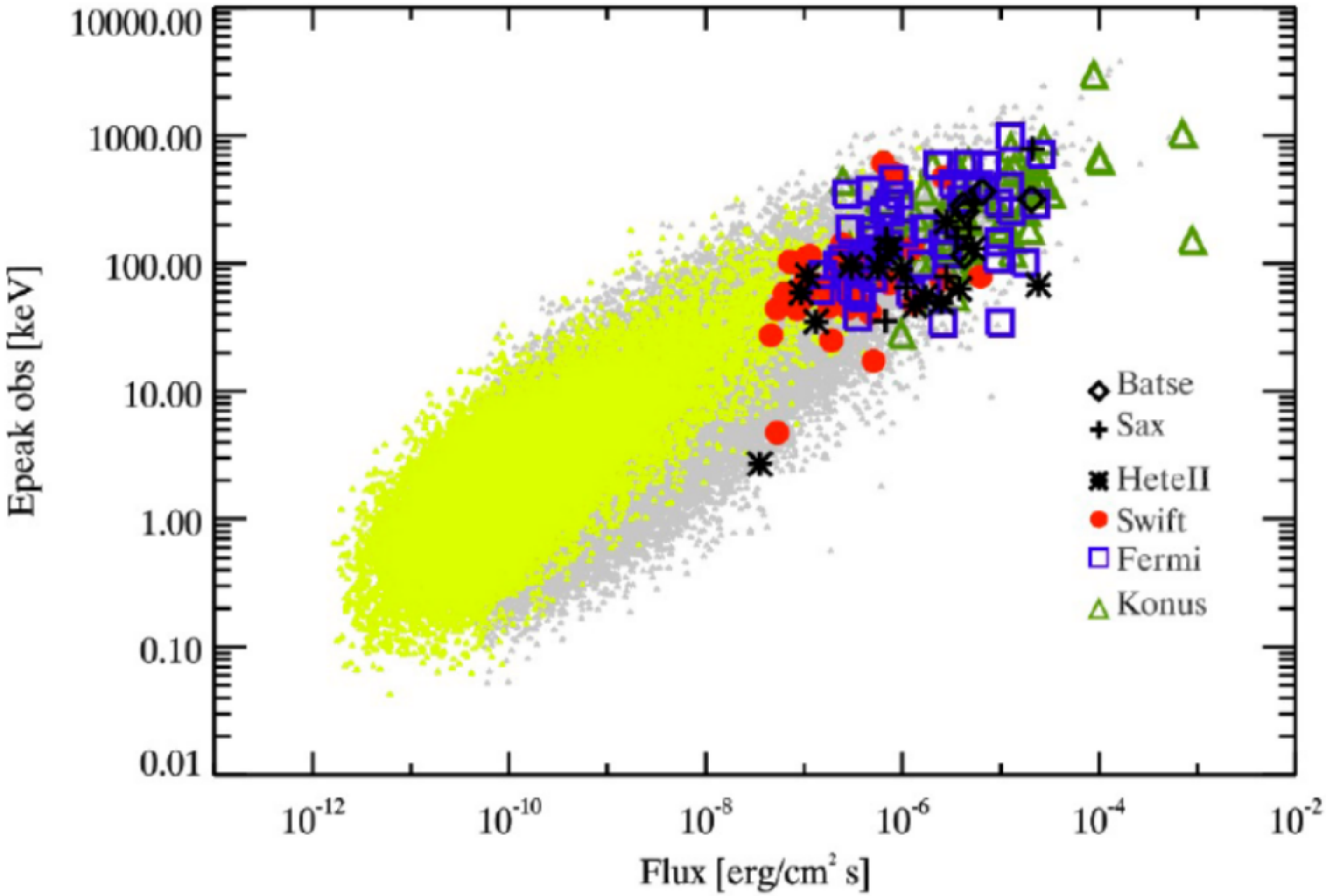
Reionization sustained by stars
HUDF luminosity function
extrapolated to $M_{UV}=-13$
Galaxies detected in HUDF
Stars insufficient to sustain reionized IGM
$\log_{10}(\rho_{UV}/\mathrm{erg\ s^{-1}Hz^{-1}Mpc^{-3}})$
27
26.5
26
25.5
25
0
0.2
0.4
0.6
$\langle f_{esc} \rangle$

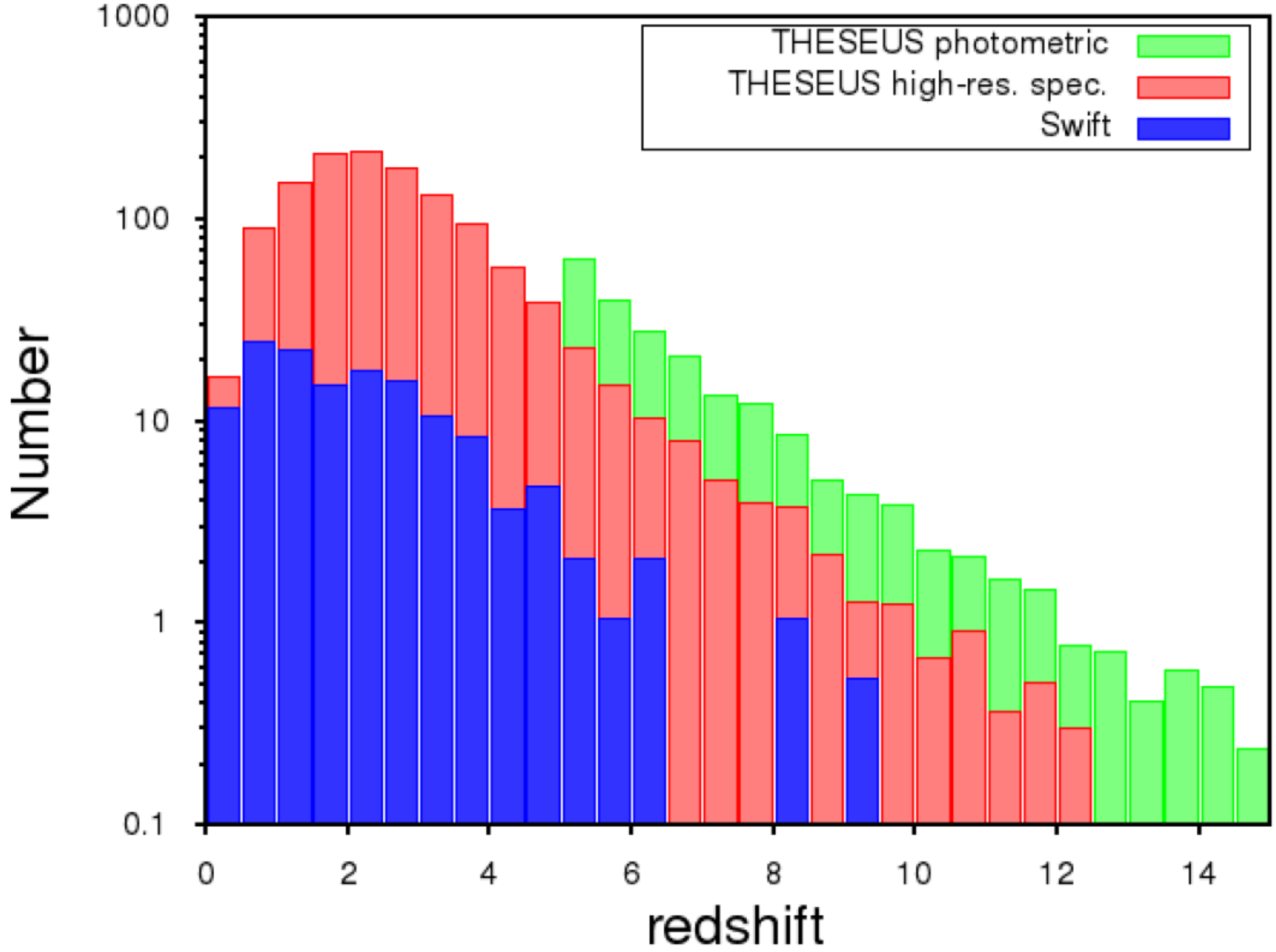


1000
100
10
1
10^{-7}
10^{-6}
10^{-5}
10^{-4}
E_{pk}^{obs} (keV)
Fluence in 2–400 keV (erg cm^{-2})
"Normal" GRBs
X–Ray Rich GRBs
X–Ray Flashes



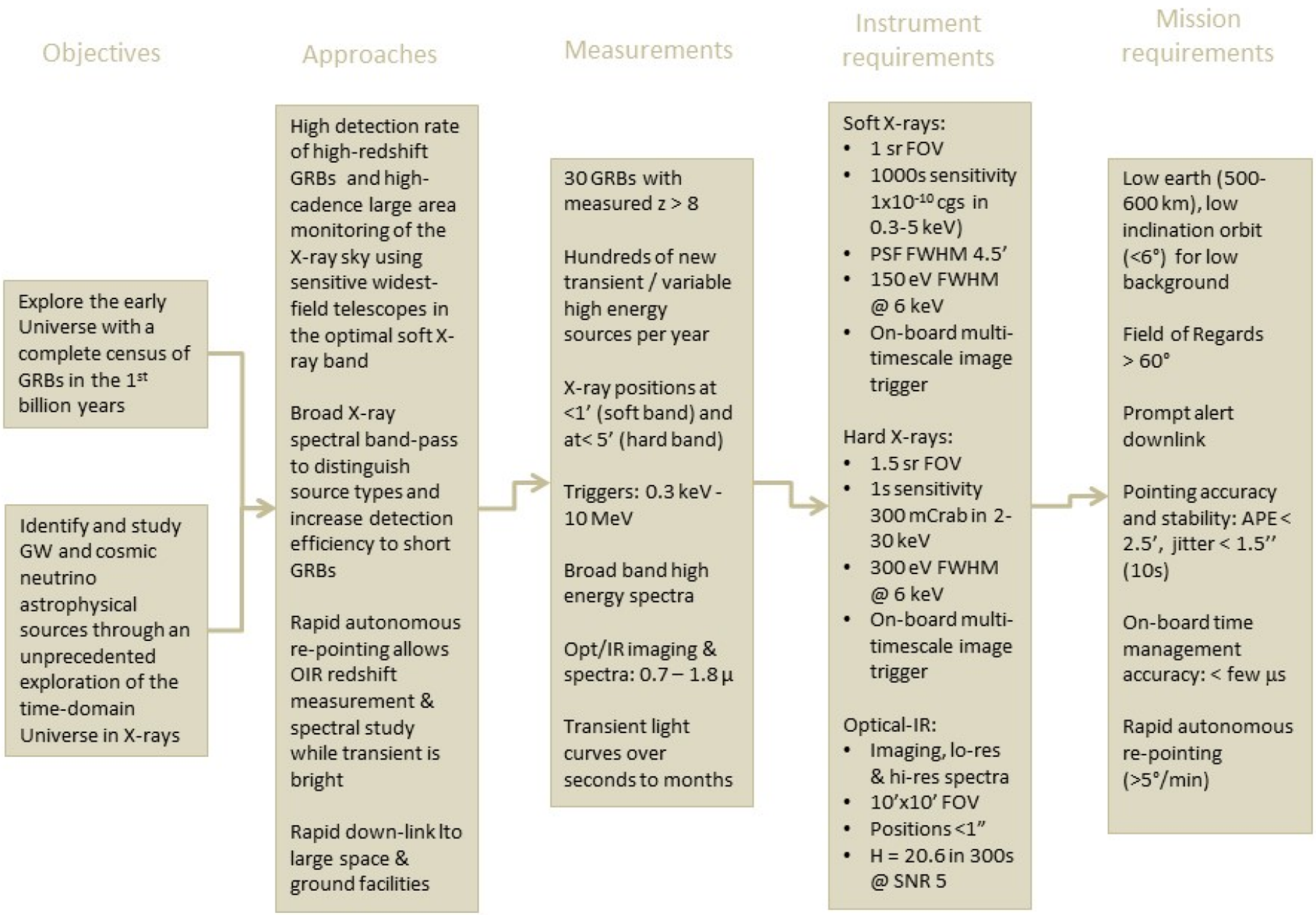
Gamma-ray Bursts
Sub-E GRB
Supernovae Ibc
Energy (erg)
Blastwave Velocity (Γβ)
10^52
10^50
10^48
10^46
0.1
1
10


Epeak obs [keV]
Flux [erg/cm² s]
Batse
Sax
HeteII
Swift
Fermi
Konus

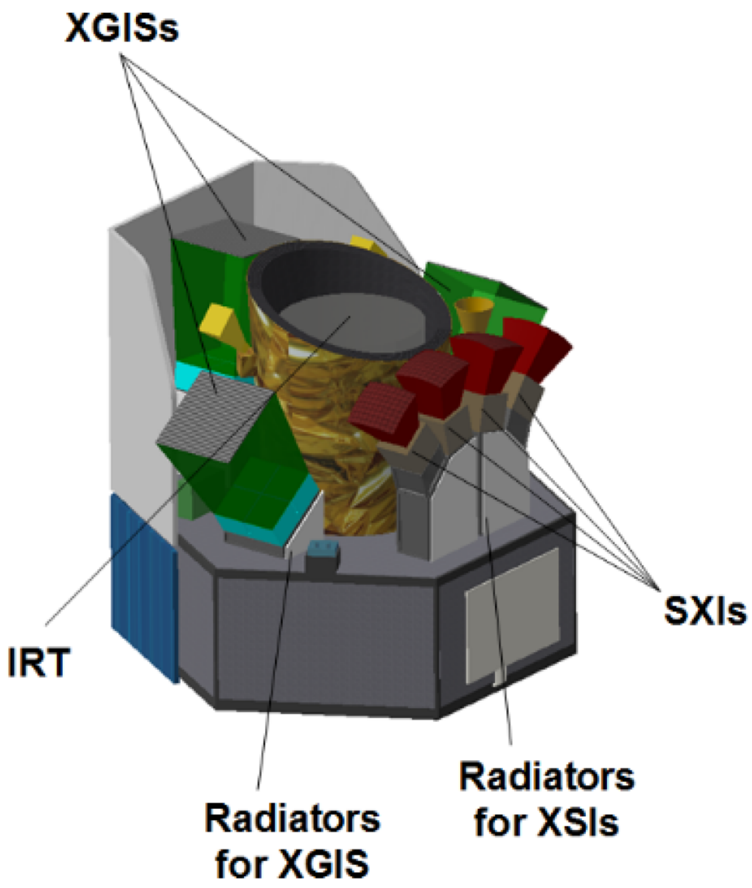


THESEUS photometric
THESEUS high-res. spec.
Swift
1000
100
10
1
0.1
Number
0
2
4
6
8
10
12
14
redshift

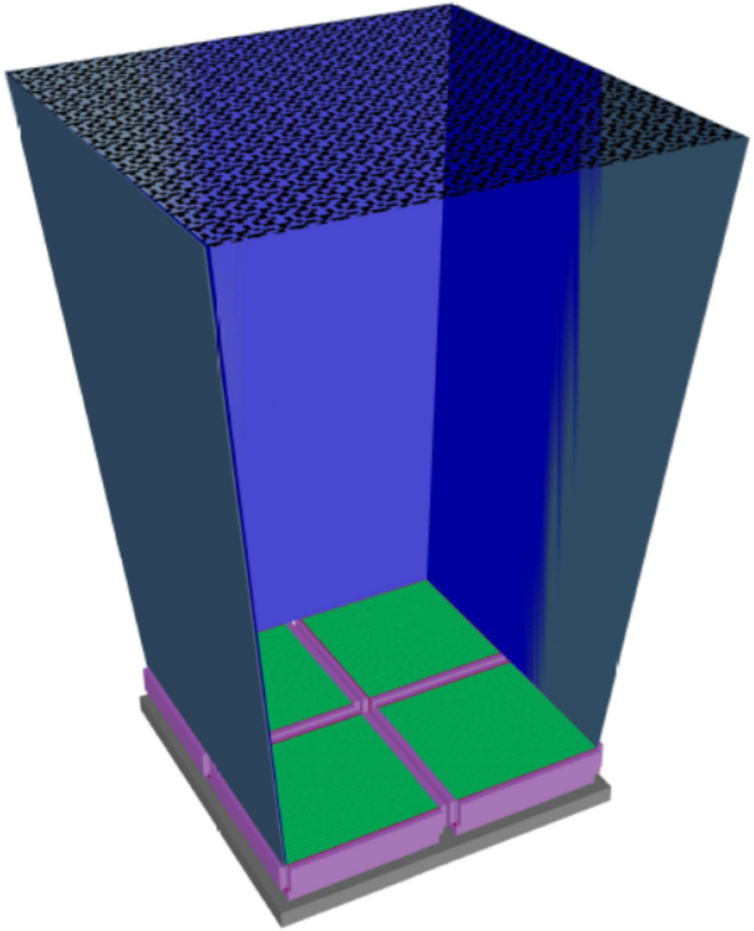
THESEUS GRB/yr	All	z>5	z>8	z>10
Detections	387-870	25-60	4-10	2-4
Photometric z		25-60	4-10	2-4
Spectroscopic z	156-350	10-20	1-3	0.5-1

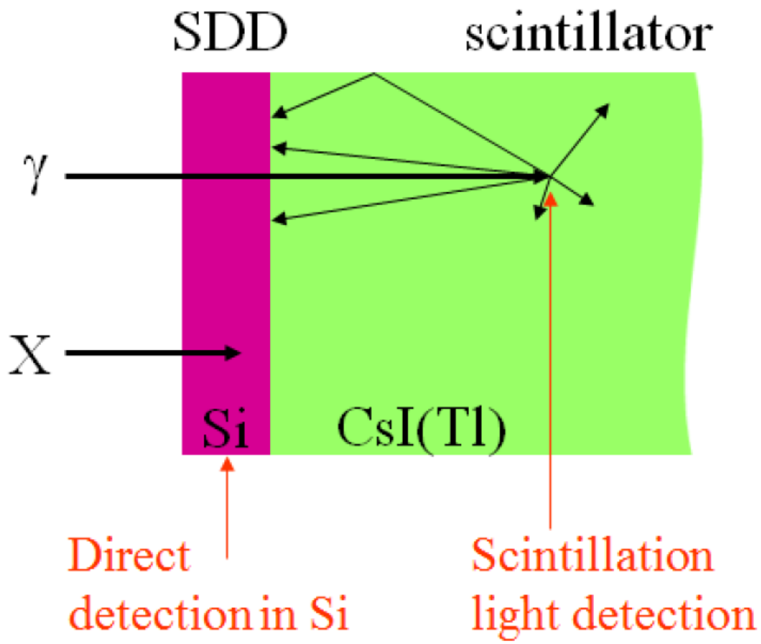


Objectives
Approaches
Measurements
Instrument requirements
Mission requirements
Explore the early Universe with a complete census of GRBs in the 1st billion years
Identify and study GW and cosmic neutrino astrophysical sources through an unprecedented exploration of the time-domain Universe in X-rays
High detection rate of high-redshift GRBs and high-cadence large area monitoring of the X-ray sky using sensitive widest-field telescopes in the optimal soft X-ray band
Broad X-ray spectral band-pass to distinguish source types and increase detection efficiency to short GRBs
Rapid autonomous re-pointing allows OIR redshift measurement & spectral study while transient is bright
Rapid down-link lto large space & ground facilities
30 GRBs with measured z > 8
Hundreds of new transient / variable high energy sources per year
X-ray positions at <1′ (soft band) and at< 5′ (hard band)
Triggers: 0.3 keV - 10 MeV
Broad band high energy spectra
Opt/IR imaging & spectra: 0.7 – 1.8 μ
Transient light curves over seconds to months
Soft X-rays:
• 1 sr FOV
• 1000s sensitivity 1x10-10 cgs in 0.3-5 keV)
• PSF FWHM 4.5′
• 150 eV FWHM @ 6 keV
• On-board multi-timescale image trigger
Hard X-rays:
• 1.5 sr FOV
• 1s sensitivity 300 mCrab in 2-30 keV
• 300 eV FWHM @ 6 keV
• On-board multi-timescale image trigger
Optical-IR:
• Imaging, lo-res & hi-res spectra
• 10′x10′ FOV
• Positions <1″
• H = 20.6 in 300s @ SNR 5
Low earth (500-600 km), low inclination orbit (<6°) for low background
Field of Regards > 60°
Prompt alert downlink
Pointing accuracy and stability: APE < 2.5′, jitter < 1.5″ (10s)
On-board time management accuracy: < few μs
Rapid autonomous re-pointing (>5°/min)



- Soft X-ray Imager (SXI): a set of 4 “Lobster-Eye” X-ray (0.3-6 keV) telescopes covering a total FOV of ~1 sr with 0.5-1 arcmin source location accuracy, provided by a UK led consortium;
- InfraRed Telescope (IRT): a 70 cm class near-infrared (up to 2 μm) telescope with imaging and moderate spectral capabilities provided by a France led consortium (including ESA, Switzerland, and Germany);
- X-Gamma ray Imaging Spectrometer (XGIS): a spectrometer comprising 3 detection units based on SDD+CsI(Tl) modules (2 keV-20 MeV), covering twice the FOV of the SXI. This instrument will be provided by an Italian led consortium (including Spain).





SDD
scintillator
γ
X
Si
CsI(Tl)
Direct detection in Si
Scintillation light detection

Table 5: XGIS detector unit main physical characteristics.

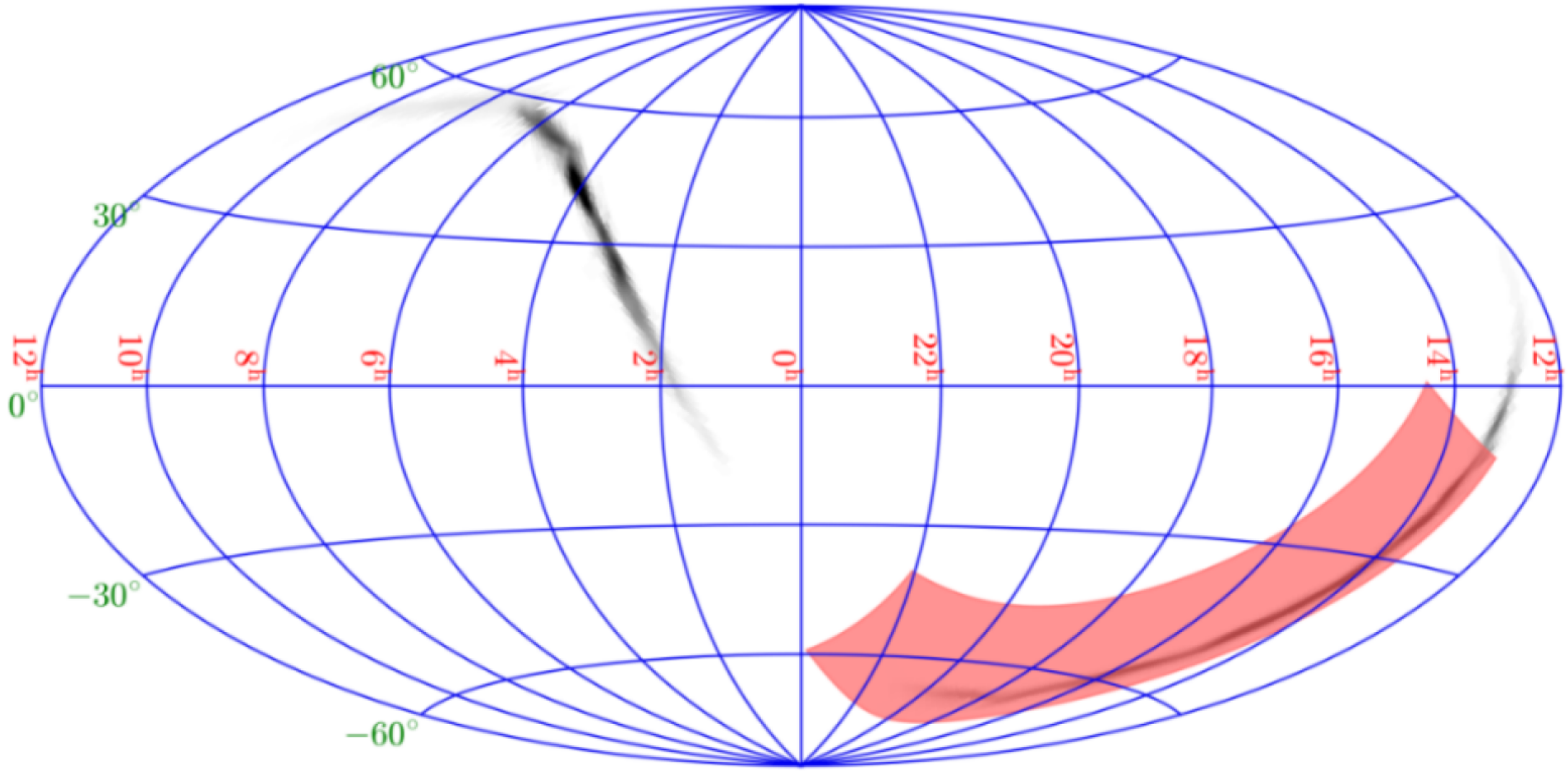
Energy band	2 keV-20 MeV
Detection plane modules	4
detector pixel/module	32×32
pixel size (= mask element size)	5×5 mm
Low-energy detector (2-30 keV)	Silicon Drift Detector 450 μm thick
High energy detector (>30 keV)	CsI(Tl) 3 cm thick
Discrimination Si/CsI(Tl) detection	Pulse shape analysis
Dimension	50×50×85 cm
Power	30.0 W
Mass	37.3 kg

Table 6: XGIS unit characteristics vs energy range.

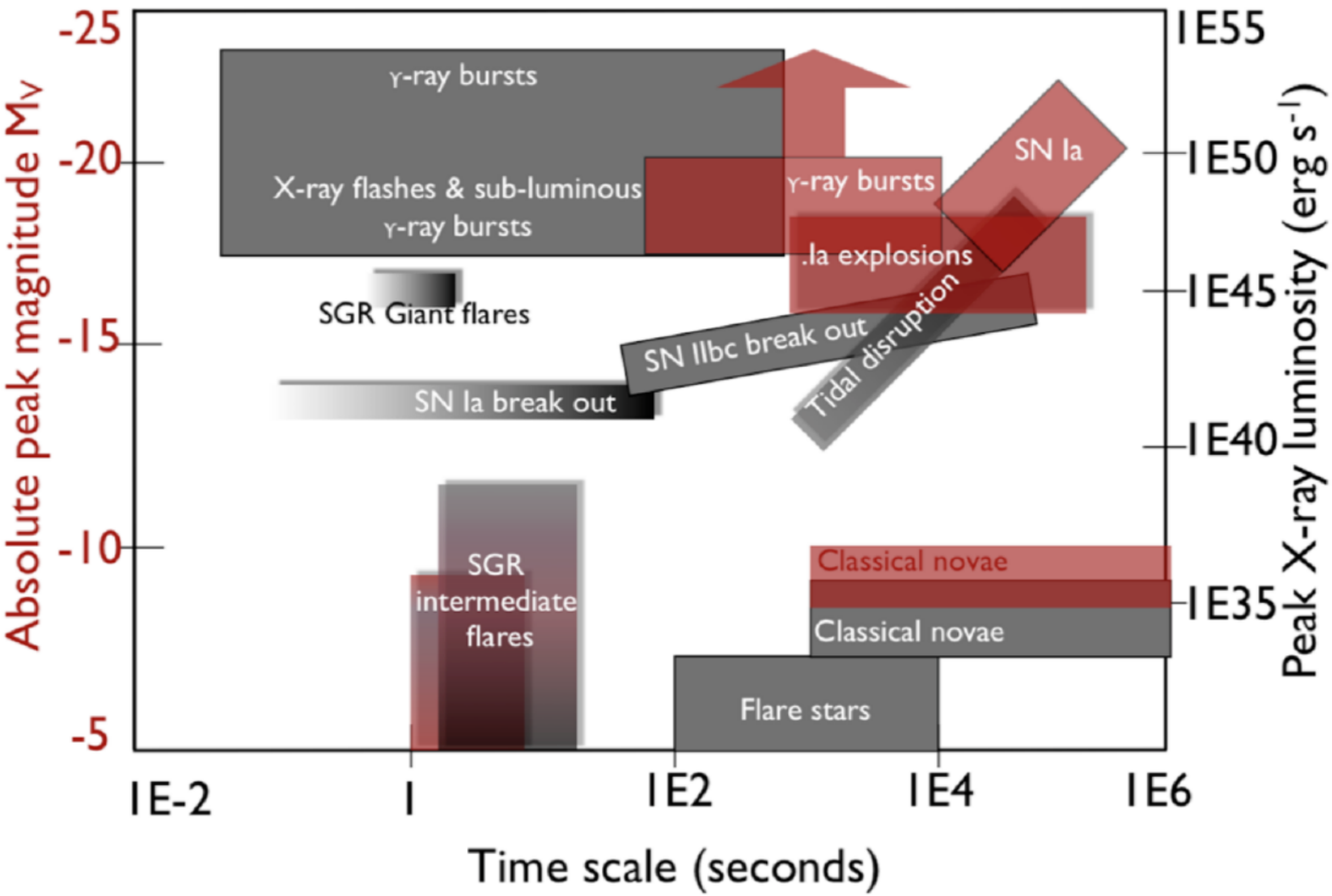
	2-30 keV	30-150 keV	>150 keV
Fully coded FOV	9×9 deg^2		
Half sens. FOV	50×50 deg^2	50×50 deg^2 (FWHM)	
Total FOV	64×64 deg^2	85×85 deg^2 (FWZR)	2πsr
Ang. res	25 arcmin		
Source location accuracy	~5 arcmin (for >6 σ source)		
Energy res	200 eV FWHM at 6 keV	18% FWHM at 60 keV	6% FWHM at 500 keV
Timing res.	1 μs	1 μs	1 μs
On axis useful area	512 cm^2	1024 cm^2	1024 cm^2

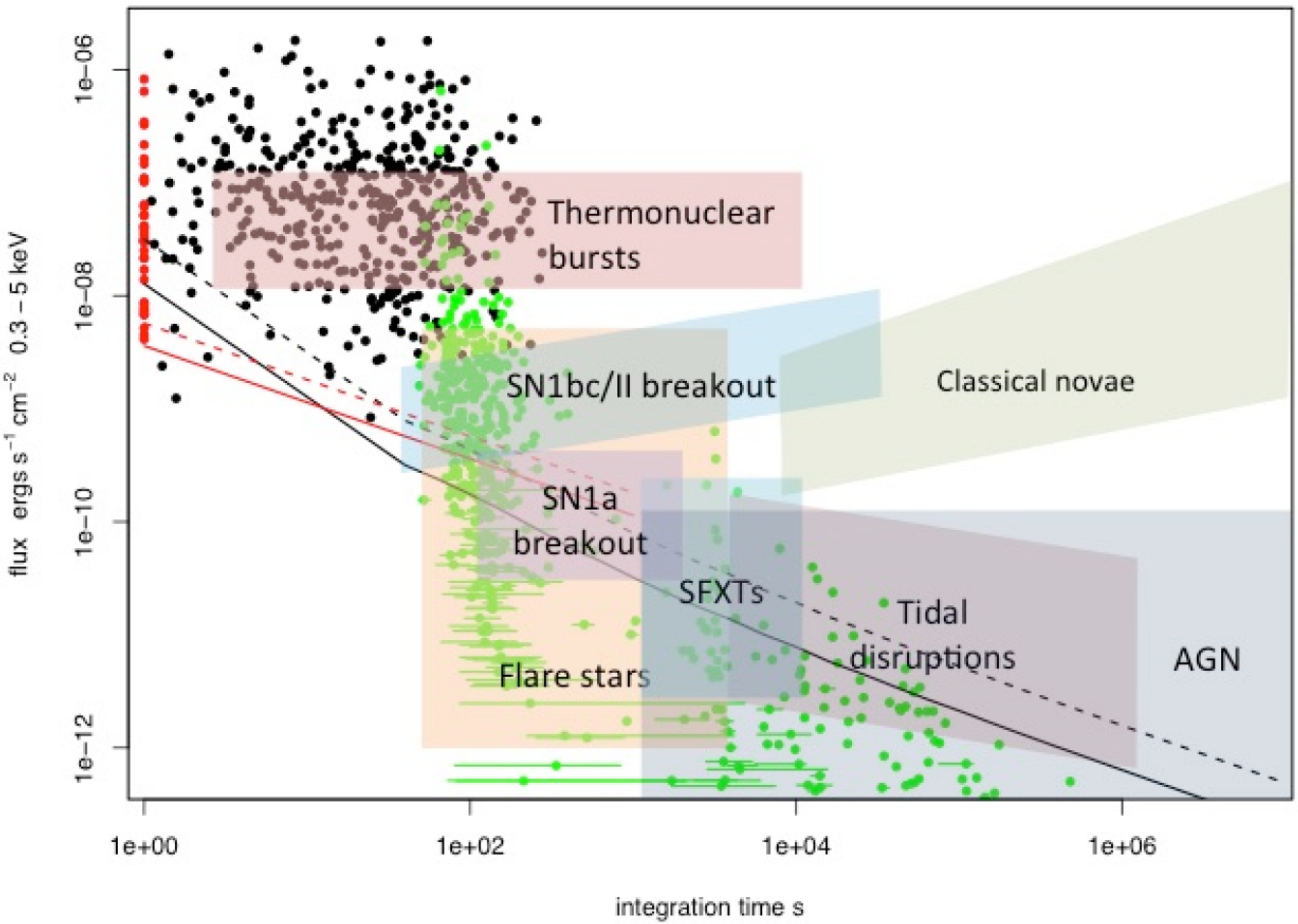
Table 4: SXI detector unit main physical characteristics.

Energy band (keV)	0.3-6
Telescope type	Lobster eye
Optics aperture	320×320 mm^2
Optics configuration	8×8 square pore MCPs
MCP size	40×40 mm^2
Focal length	300 mm
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD	81.2×67.7 mm^2
Pixel size	18 μm
Number of pixel	4510×3758 per CCD
Number of CCDs	4
Field of View	$\sim$1 sr
Angular accuracy (best, worst)	(<10, 105) arcsec



60°
30°
0°
−30°
−60°
12h
10h
8h
6h
4h
2h
0h
22h
20h
18h
16h
14h
12h


-25
-20
-15
-10
-5
Absolute peak magnitude MV
1E55
1E50
1E45
1E40
1E35
Peak X-ray luminosity (erg s-1)
1E-2
1
1E2
1E4
1E6
Time scale (seconds)
γ-ray bursts
X-ray flashes & sub-luminous
γ-ray bursts
γ-ray bursts
SN Ia
.Ia explosions
SGR Giant flares
SN IIbc break out
Tidal disruption
SN Ia break out
SGR
intermediate
flares
Classical novae
Classical novae
Flare stars


Thermonuclear
bursts
SN1bc/II breakout
Classical novae
SN1a
breakout
SFXTs
Tidal
disruptions
AGN
Flare stars
flux ergs s^{-1} cm^{-2} 0.3 – 5 keV
1e–06
1e–08
1e–10
1e–12
1e+00
1e+02
1e+04
1e+06
integration time s

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

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

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

Journal Club for Nuclear and Particle Astrophysics Course

Trieste – April 9, 2021

THESEUS: a key space mission **concept** for Multi-Messenger Astrophysics

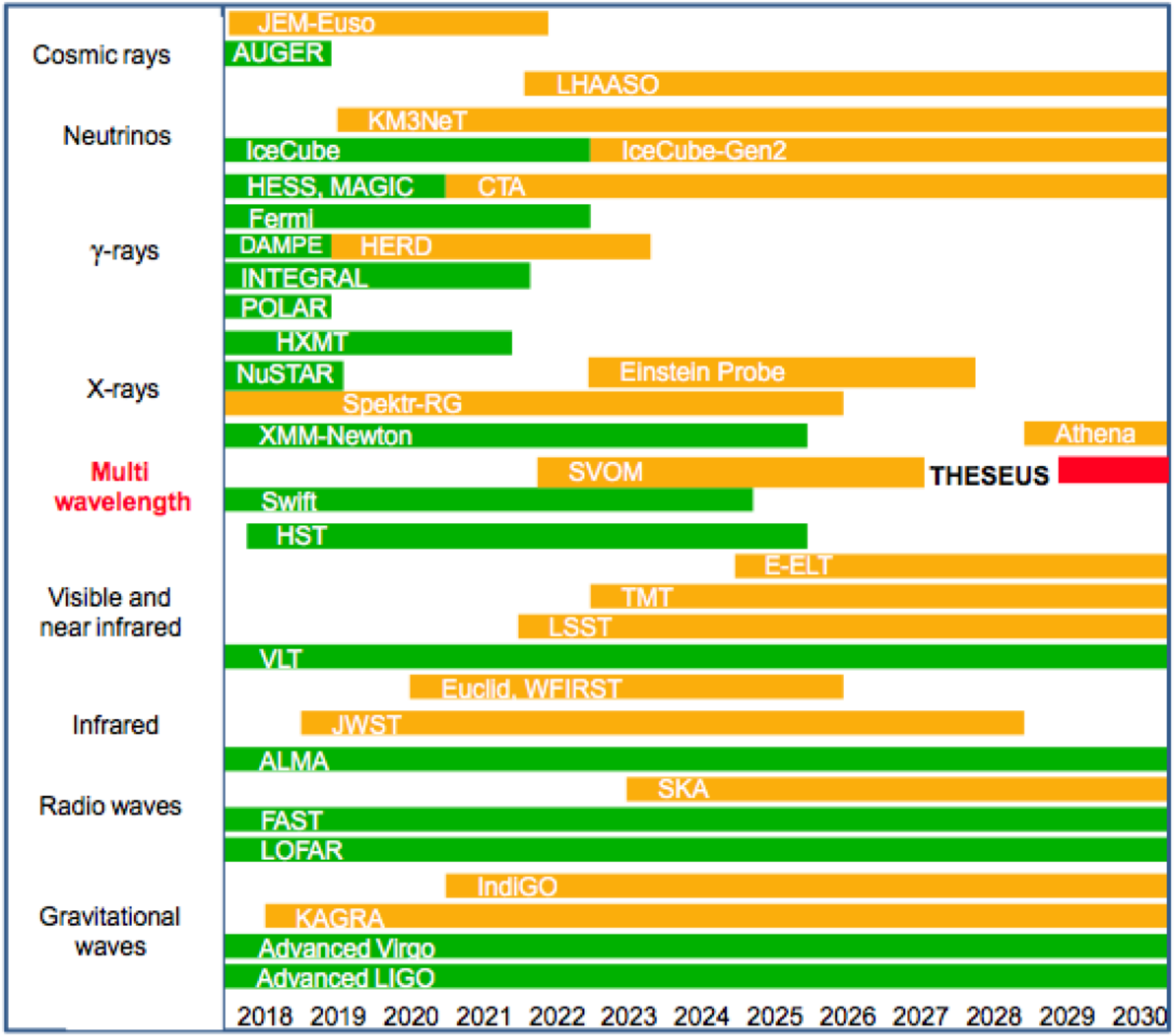
G. Stratta[a], R. Ciolfi[b,c], L. Amati[d], E. Bozzo[e], G. Ghirlanda[f], E. Maiorano[d], L. Nicastro[d], A. Rossi[d], S. Vinciguerra[g], F. Frontera[h,d], D. Götz[i], C. Guidorzi[h], P. O'Brien[j], J. P. Osborne[j], N. Tanvir[k], M. Branchesi[l,m], E. Brocato[n], M. G. Dainotti[o], M. De Pasquale[p], A. Grado[q], J. Greiner[r], F. Longo[s,t], U. Maio[u,v], D. Mereghetti[w], R. Mignani[w,x], S. Piranomonte[y], L. Rezzolla[z,aa], R. Salvaterra[w], R. Starling[j], R. Willingale[j], M. Böer[ab], A. Bulgarelli[d], J. Caruana[ac], S. Colafrancesco[ad], M. Colpi[ae], S. Covino[f], P. D'Avanzo[f], V. D'Elia[af,y], A. Drago[ag], F. Fuschino[d], B. Gendre[ah,ai], R. Hudec[aj,ak], P. Jonker[al,am], C. Labanti[d], D. Malesani[an], C. G. Mundell[ao], E. Palazzi[d], B. Patricelli[ap], M. Razzano[ap], R. Campana[d], P. Rosati[h], T. Rodic[av], D. Szécsi[ar,as], A. Stamerra[ap], M. van Putten[ai], S. Vergani[au,f], B. Zhang[av], M. Bernardini[aw]

Abstract

- The recent discovery of the electromagnetic counterpart of the gravitational wave source GW170817, has demonstrated the huge informative power of multi-messenger observations. During the next decade the nascent field of multi-messenger astronomy will mature significantly. Around 2030, third generation gravitational wave detectors will be roughly ten times more sensitive than the current ones. At the same time, neutrino detectors currently upgrading to multi km^3 telescopes, will include a 10 km^3 facility in the Southern hemisphere that is expected to be operational around 2030.
- In this review, we describe the most promising high frequency gravitational wave and neutrino sources that will be detected in the next two decades. In this context, we show the important role of the Transient High Energy Sky and Early Universe Surveyor (THESEUS), a mission concept proposed to ESA by a large international collaboration in response to the call for the Cosmic Vision Programme M5 missions. THESEUS aims at providing a substantial advancement in early Universe science as well as playing a fundamental role in multi–messenger and time–domain astrophysics, operating in strong synergy with future gravitational wave and neutrino detectors as well as major ground- and space-based telescopes. This review is an extension of the THESEUS white paper (Amati et al., 2017), also in light of the discovery of GW170817/GRB170817A that was announced on October 16th, 2017.
- ***Keywords: X-ray sources; X-ray bursts; gamma-ray sources; gamma-ray bursts; Astronomical and space-research Instrumentation***

Structure of the paper

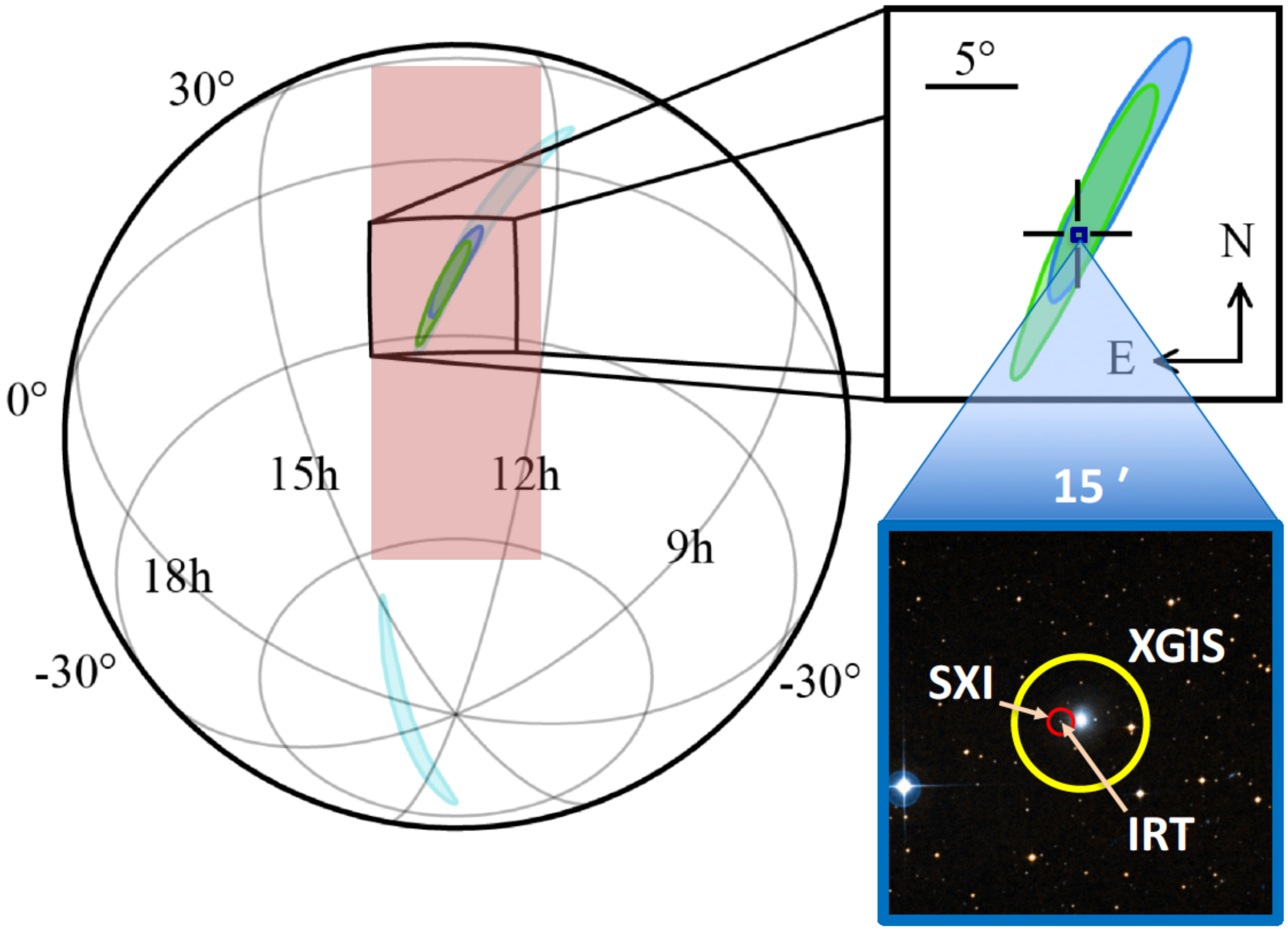
- 1. Introduction
- 2. The THESEUS Mission
- 3. The role of THESEUS in the Multi-Messenger Astronomy
- 4. Gravitational Wave Sources
- 5. Neutrino Sources
- 6. Summary



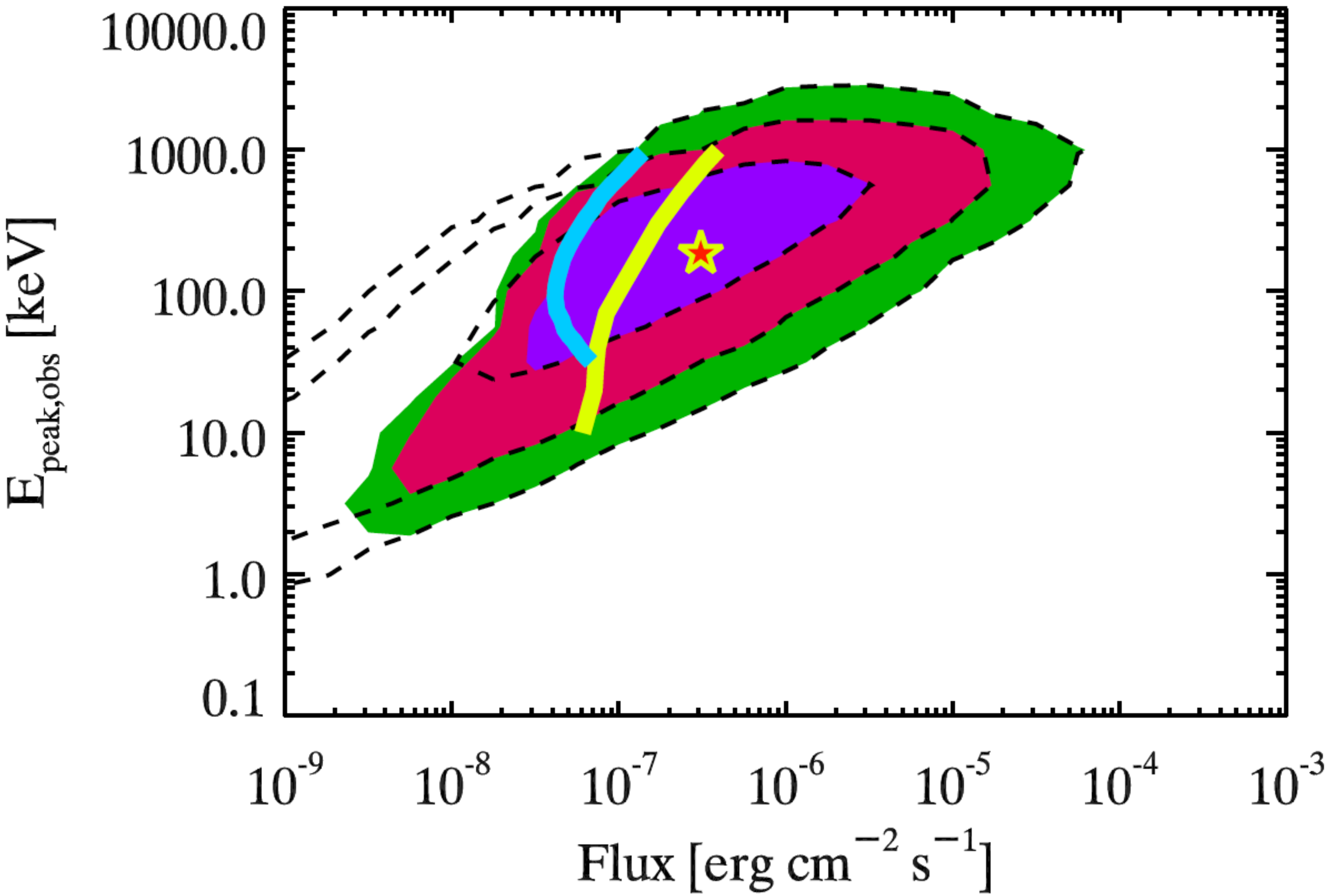
Cosmic rays
Neutrinos
γ-rays
X-rays
Multi wavelength
Visible and near infrared
Infrared
Radio waves
Gravitational waves
JEM-Euso
AUGER
LHAASO
KM3NeT
IceCube
IceCube-Gen2
HESS, MAGIC
CTA
Fermi
DAMPE
HERD
INTEGRAL
POLAR
HXMT
NuSTAR
Einstein Probe
Spektr-RG
XMM-Newton
Athena
SVOM
THESEUS
Swift
HST
E-ELT
TMT
LSST
VLT
Euclid, WFIRST
JWST
ALMA
SKA
FAST
LOFAR
IndiGO
KAGRA
Advanced Virgo
Advanced LIGO
2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

Table 1: THESEUS instruments

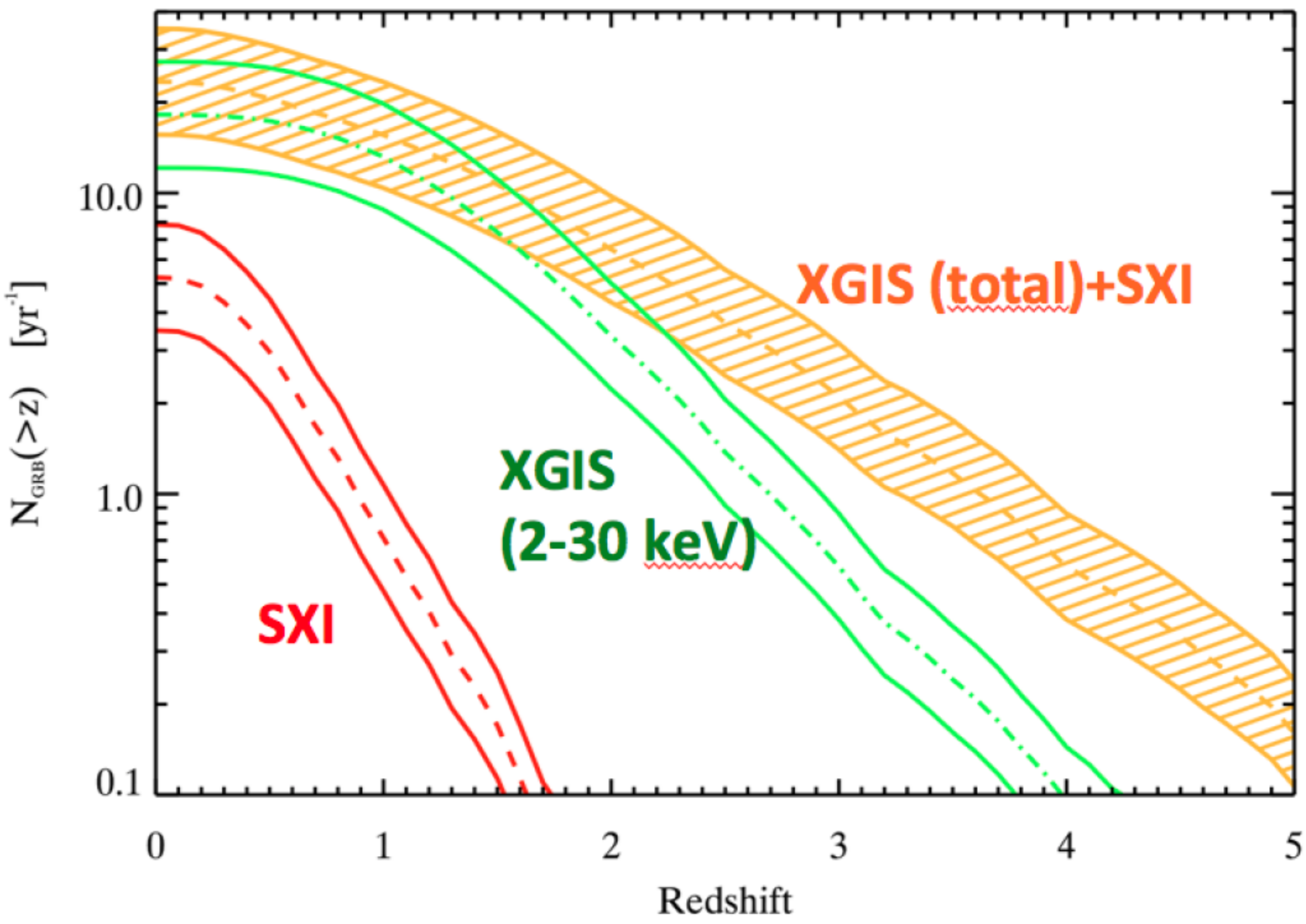
	SXI	XGIS					IRT
Energy range	0.3-6 keV		2 -30 keV	30-150 keV	$>$ 150 keV		ZYJH ($0.7 - 1.8\mu$m)
Field of View	1 sr	Half sens.: Total:	50×50 $\deg^2$ 64×64 $\deg^2$	50×50 $\deg^2$ 85×85 $\deg^2$	 2π sr	imaging low res high res	$10' \times 10'$ $10' \times 10'$ $5' \times 5'$
Source location accuracy	$< 10''$ (best) $105''$ (worse)		$5'$ (for $> 6\sigma$ source)	-	-		$< 1''$
Sensitivity	erg(ph) cm^{-2} s^{-1} 2×10^{-8}(10) (1s) 2×10^{-11}(0.01) (10 ks)		ph cm^{-2} s^{-1} 1 (1s) 0.02 (1ks)	 0.15 (1s) 0.004 (1ks)	 0.22 (1s) 0.008 (1ks)	 imaging low res. high res.	H (AB mag) 20.6 (300 s) 18.5 (300 s) 17.5 (1800 s)



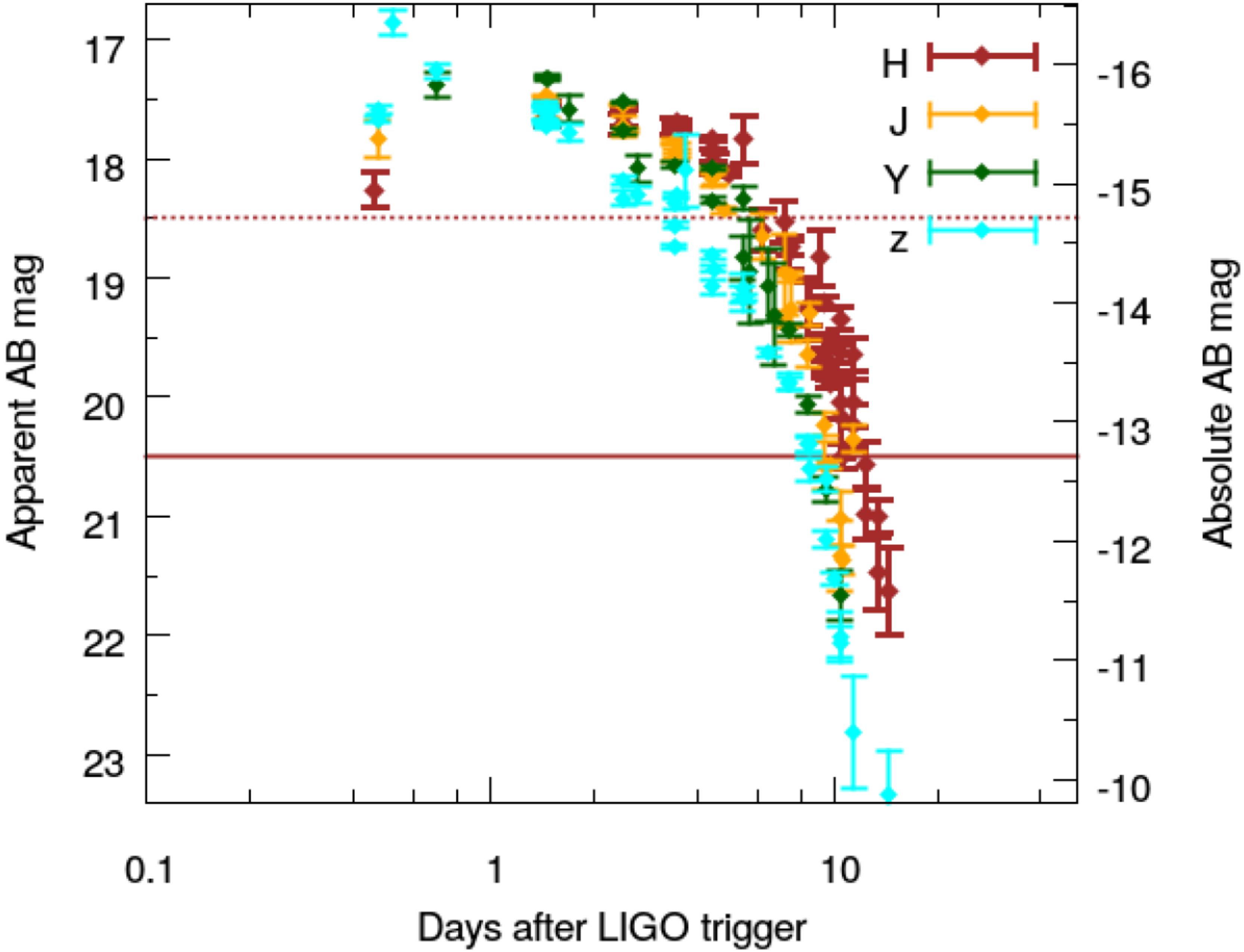
30°
0°
-30°
-30°
15h
12h
18h
9h
5°
N
E
15 ′
XGIS
SXI
IRT



10000.0
1000.0
100.0
10.0
1.0
0.1
E_peak,obs [keV]
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
Flux [erg cm^-2 s^-1]



XGIS (total)+SXI
XGIS
(2-30 keV)
SXI
10.0
1.0
0.1
0
1
2
3
4
5
Redshift
N_GRB(>z) [yr^-1]


Apparent AB mag
17
18
19
20
21
22
23
0.1
1
10
Days after LIGO trigger
Absolute AB mag
-16
-15
-14
-13
-12
-11
-10
H
J
Y
z

GW observations			THESEUS XGIS/SXI joint GW+EM observations		
Epoch	GW detector	BNS range	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
2020+	Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)	~200 Mpc	~40*	~5-15	~1-3 (simultaneous) ~6-12 (+follow-up)
2030+	Second + Third-generation (e.g. ET, Cosmic Explorer)	~15-20 Gpc	>10000	~15-35	$\gtrsim$100

* from Abadie et al. 2010a

Summary

- The first detection of the electromagnetic counterparts of a GW source has confirmed a number of theoretical expectations and boosted the nascent multi-messenger astronomy. In this review we have discussed several classes of sources, including compact binary coalescences, core-collapsing massive stars, and instability episodes on NSs that are expected to originate simultaneously high-frequency GWs, neutrinos and EM emission across the entire EM spectrum, including in particular high energy emission (in X-rays and gamma-rays).
- We have shown that the mission concept THESEUS has the potential to play a crucial role in the multi-messenger investigation of these sources. THESEUS, if approved, will have the capability to detect a very large number of transient sources in the X-ray and gamma-ray sky due to its wide field of view, and to automatically follow-up any high energy detection in the near infrared. In addition, it will be able to localise the sources down to arcminute (in gamma and X-rays) or to arcsecond (in NIR).
- The instrumental characteristics of THESEUS are ideal to operate in synergy with the facilities that will be available by the time of the mission: several new generation ground- and space-based telescopes, second- and third-generation GW detector networks and 10 km3 neutrino detectors. This makes THESEUS perfectly suited for the coming golden era of multi-messenger astronomy and astrophysics