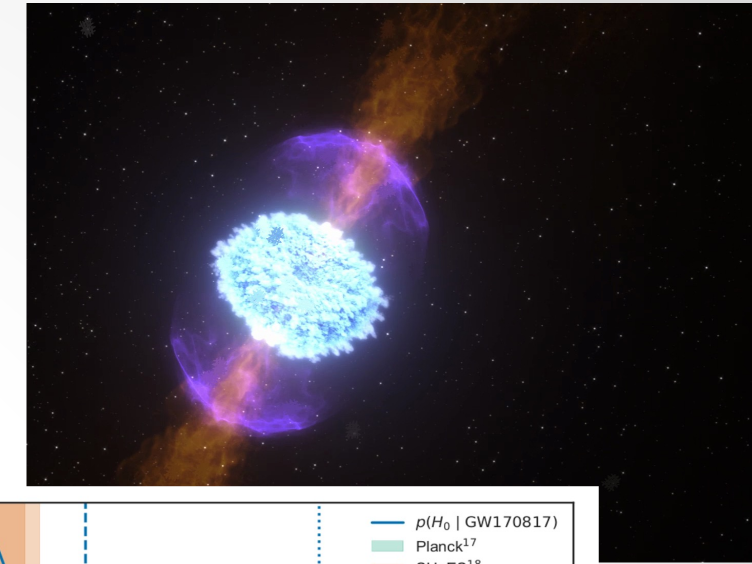
GW-EM observations

a (biased) view on the next decade

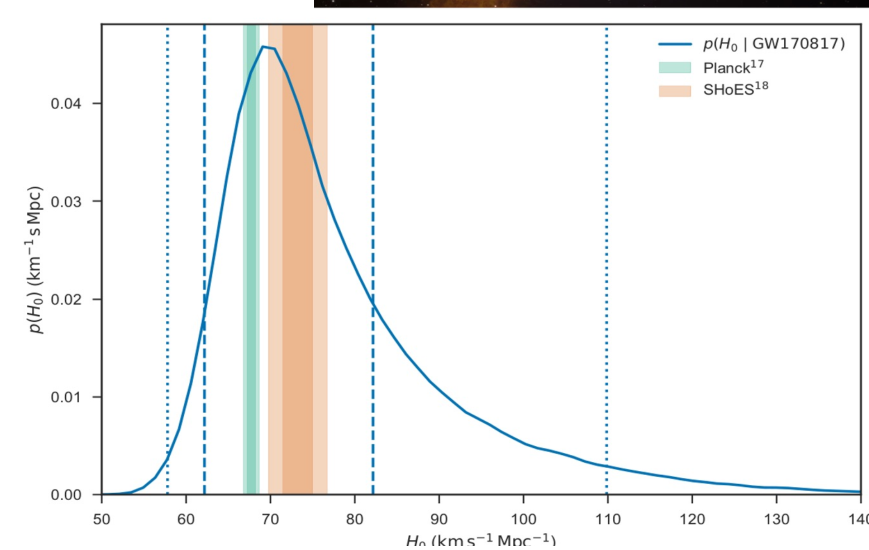
Nicolas Leroy – IJCLab

Journées thématiques Ondes Gravitationnelles à Lyon 2023

GW – EM observations



With a single event (!) :



Constraints on nuclear equation of state

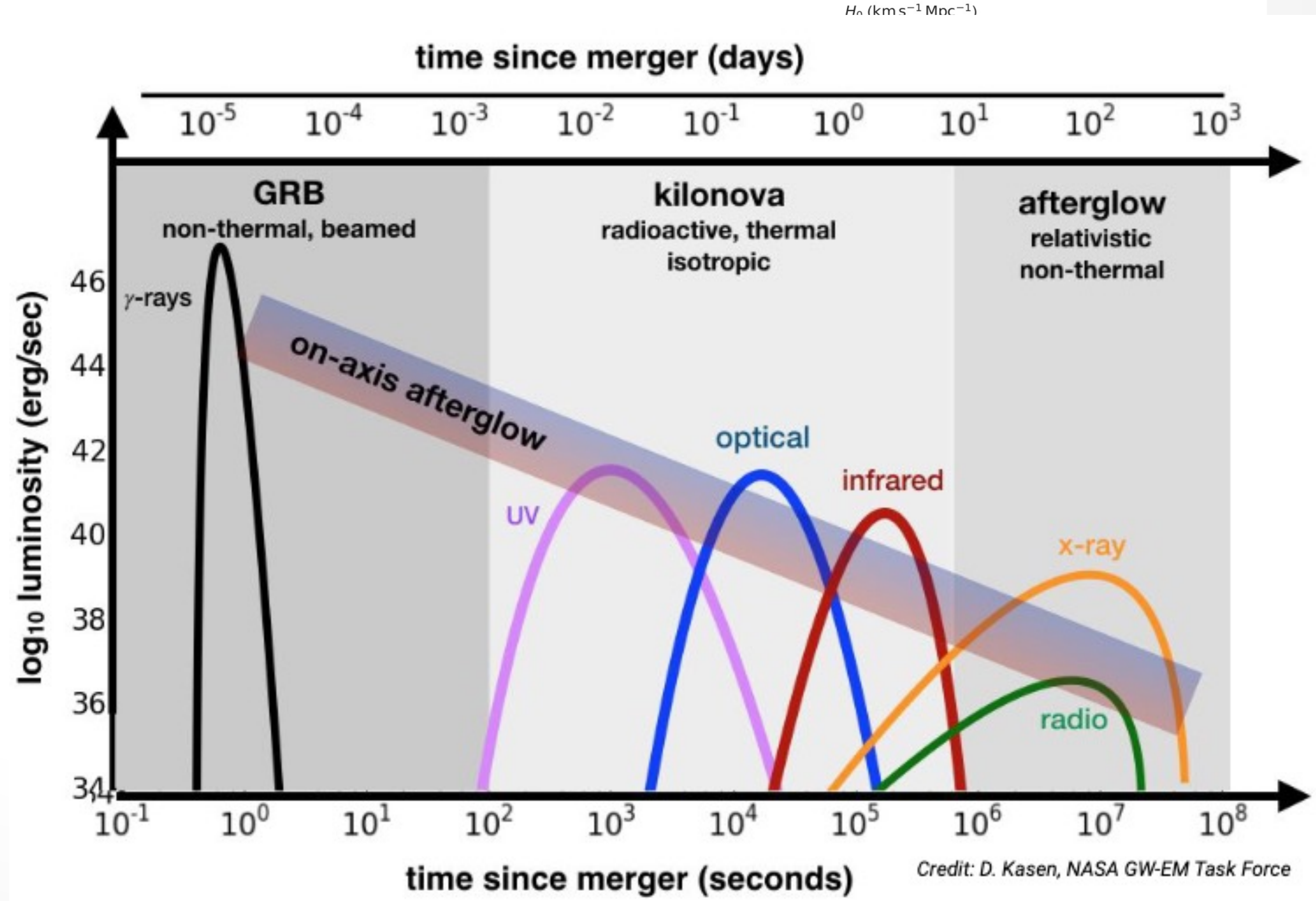
Tests of General Relativity (celerity of GWs…)

Cosmology (measure of H_0)

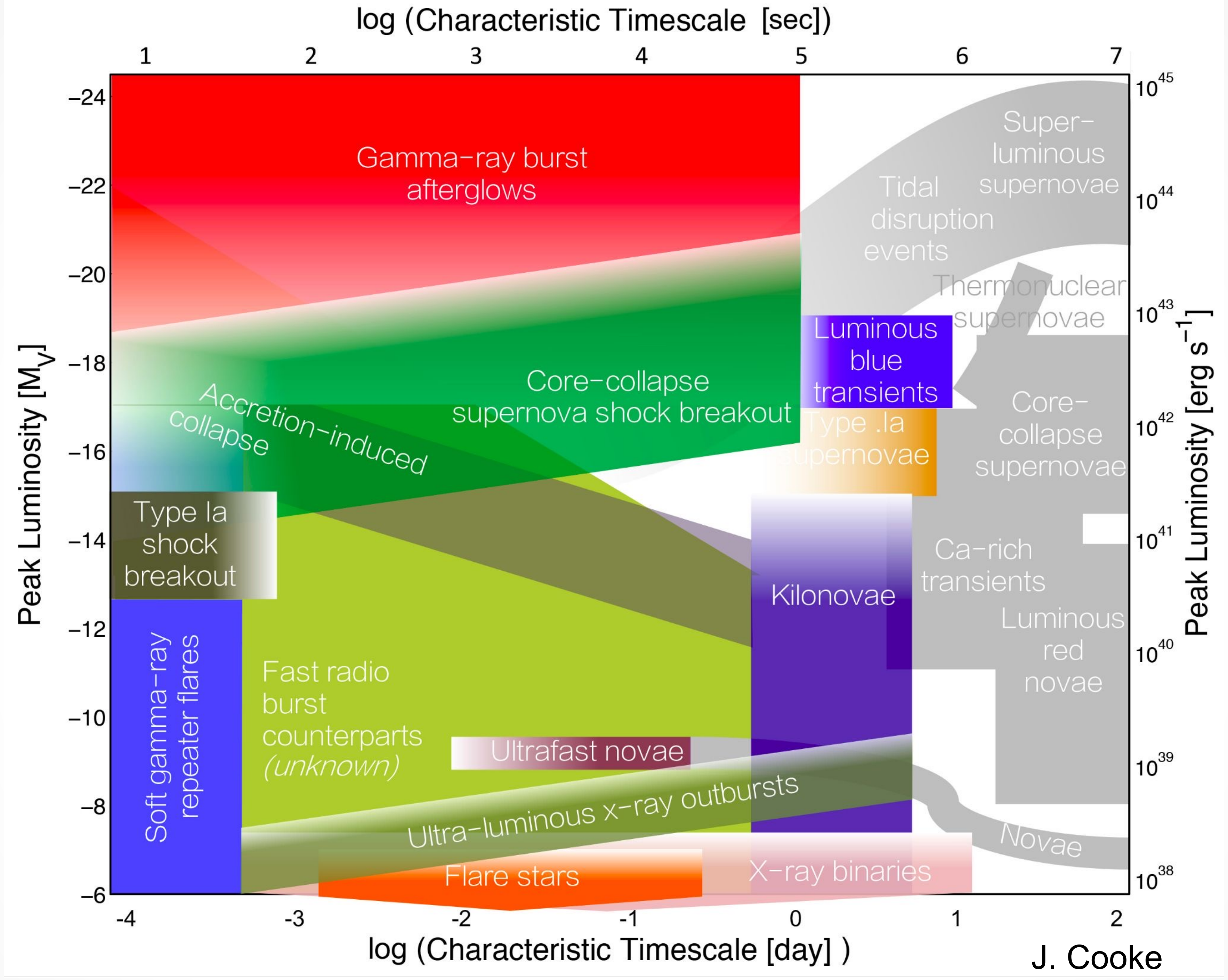
Stellar population

Kilonovae an r-process !!!

…



Exploring the transient sky



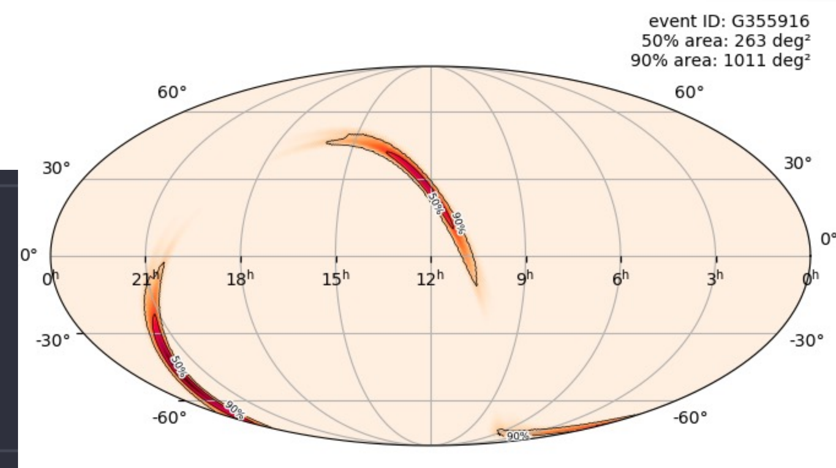
A large diversity of objects with a quite large range of time scales and magnitudes

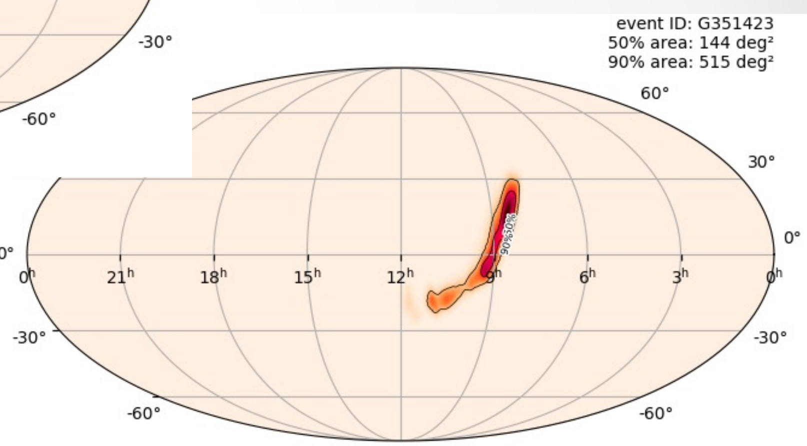
Finding the EM counterpart …

What can we expect during next runs O4 and O5 ?

- If we take all possible alerts ie 1 to 4 detectors alerts

Observing run	Network	Source class		
		BNS	NSBH	BBH
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}





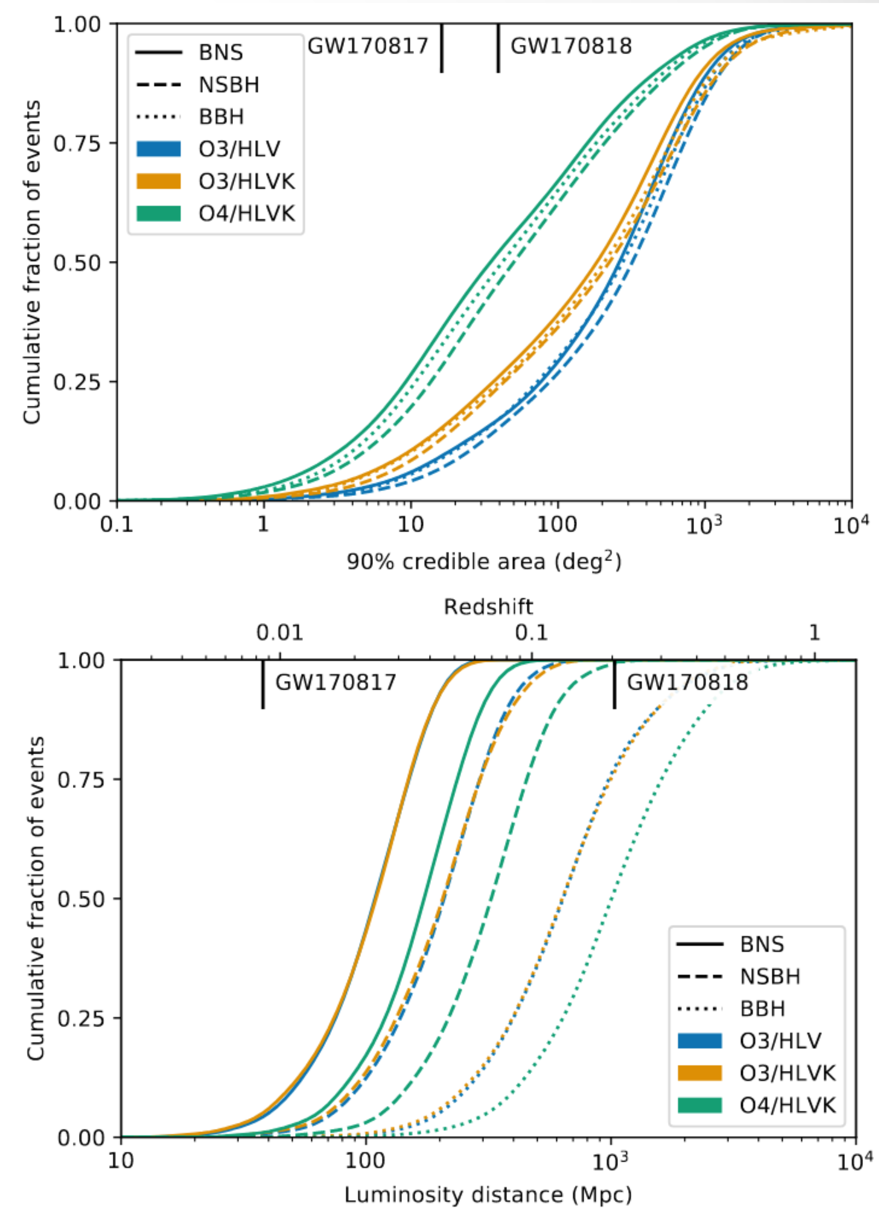
Median luminosity distance (Mpc, Monte Carlo uncertainty)				
O4	HKLV	398^{+15}_{-14}	770^{+67}_{-70}	2685^{+53}_{-40}
O5	HKLV	738^{+30}_{-25}	1318^{+71}_{-100}	4607^{+77}_{-82}
Median 90% credible area (deg^2, Monte Carlo uncertainty)				
O4	HKLV	1860^{+250}_{-170}	2140^{+480}_{-530}	1428^{+60}_{-55}
O5	HKLV	2050^{+120}_{-120}	2000^{+350}_{-220}	1256^{+48}_{-53}

- We could expect more than 1 evt/day even in O4
- Possibly one GRB event in common with GW emission (using short GRBs in O3)

What can we expect during next runs O4 and O5 ?

- If we limit to 2 to 4 detectors alerts

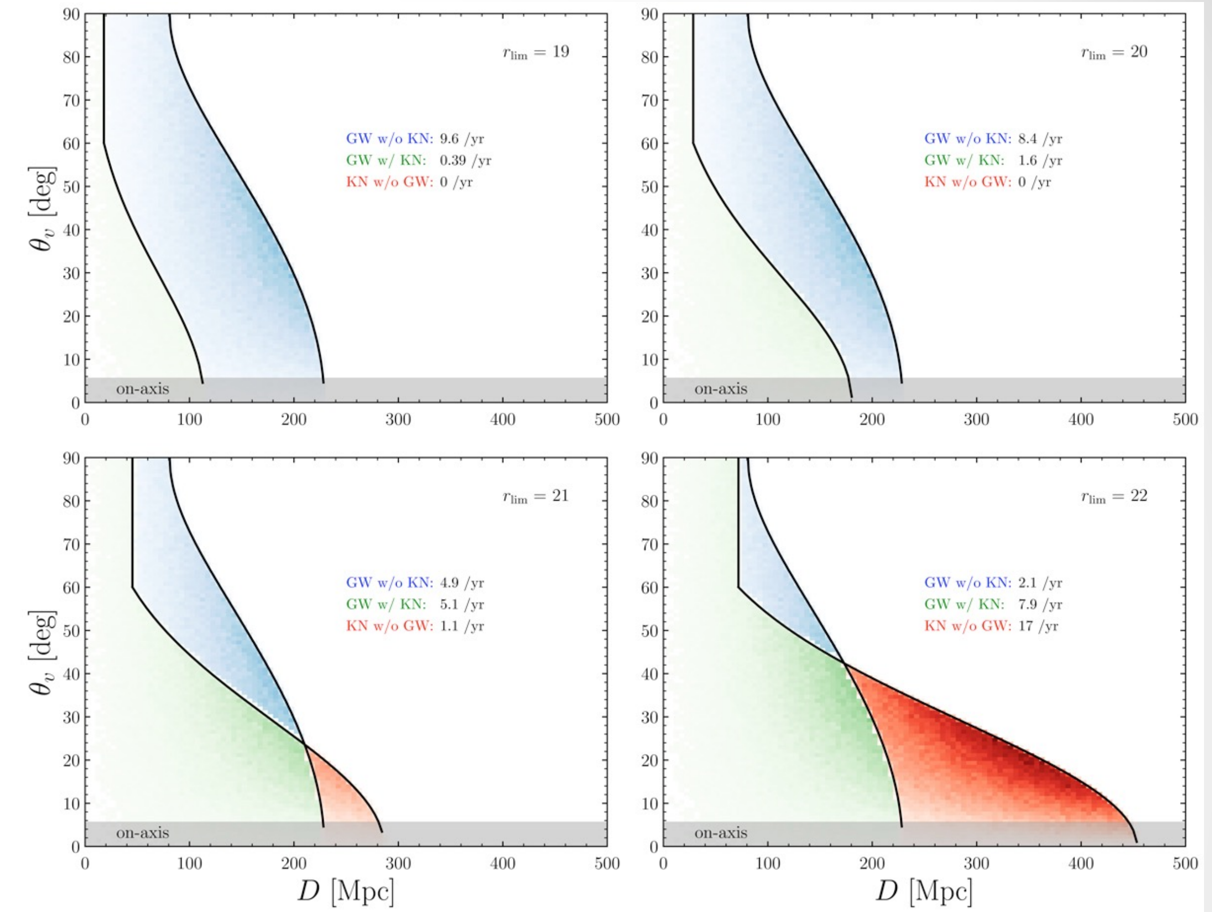
- We could expect up to 1 evt/day
- Possibly one GRB event in common with GW emission (using short GRBs in O3)
- O5 will be 2 times more sensitive
-> 10 times more sources



Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

Filtering alerts

- Limit to our capability to detect en EM counterpart
  - o kilonovae magnitude of 20.5 at 200 Mpc
  - o visible/IR counterpart for NSBH may be even fainter
  - o X-ray emission, power law fading quite quickly (ie within 1 day)



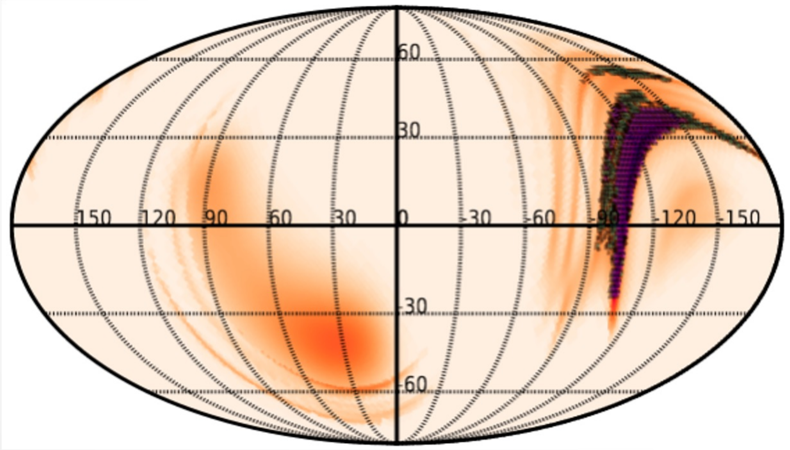
Mochkovitch et al, A&A, 651 (2021) A83

- o Need to filter with galaxies compatible when possible

Observation strategy

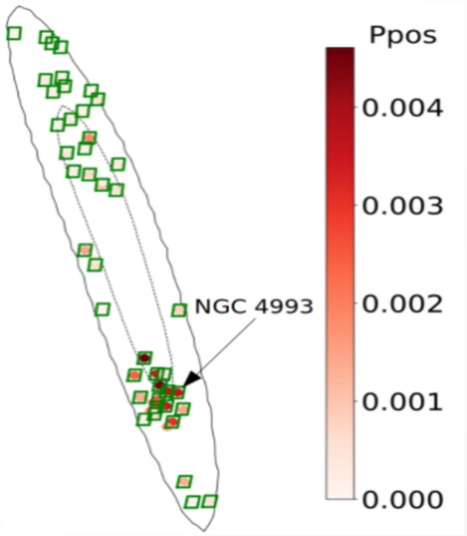
Tilling

- Cover the sky localisation map of GW
- Look for new object that are related to the GW
- Best suited for large FoV (>1deg²) instruments
- Widely used by current survey (PAN-STARRS, ZTF, TAROT,...)



Galaxy Targeting

- Observed the galaxy compatible with the spatial information provided by GW
- Galaxies classified with
  - spatial information
  - Stellar mass estimation
- Catalog developed at IJClab : MANGROVE [8]
- Best suited for small FoV instruments
- Technique used for 170817



Large error region follow-up

- Need either large field of view or a large number of telescopes !

Global **R**apid **A**dvanced **N**etwork **D**evoted to **M**ulti-messenger **A**ddicts

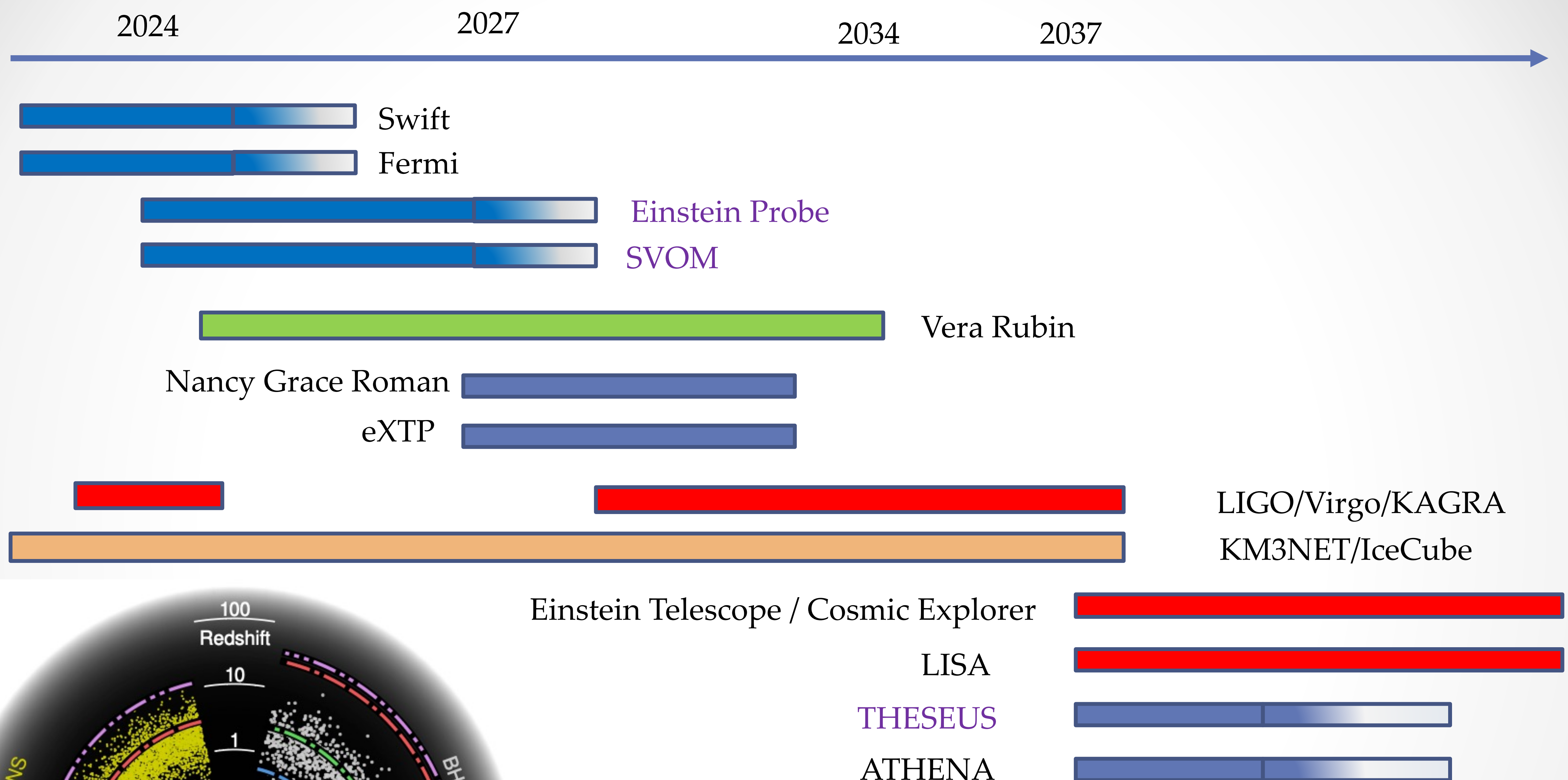
GRANDMA : Created in 2018 by IJCLab for Gravitational Waves follow-up

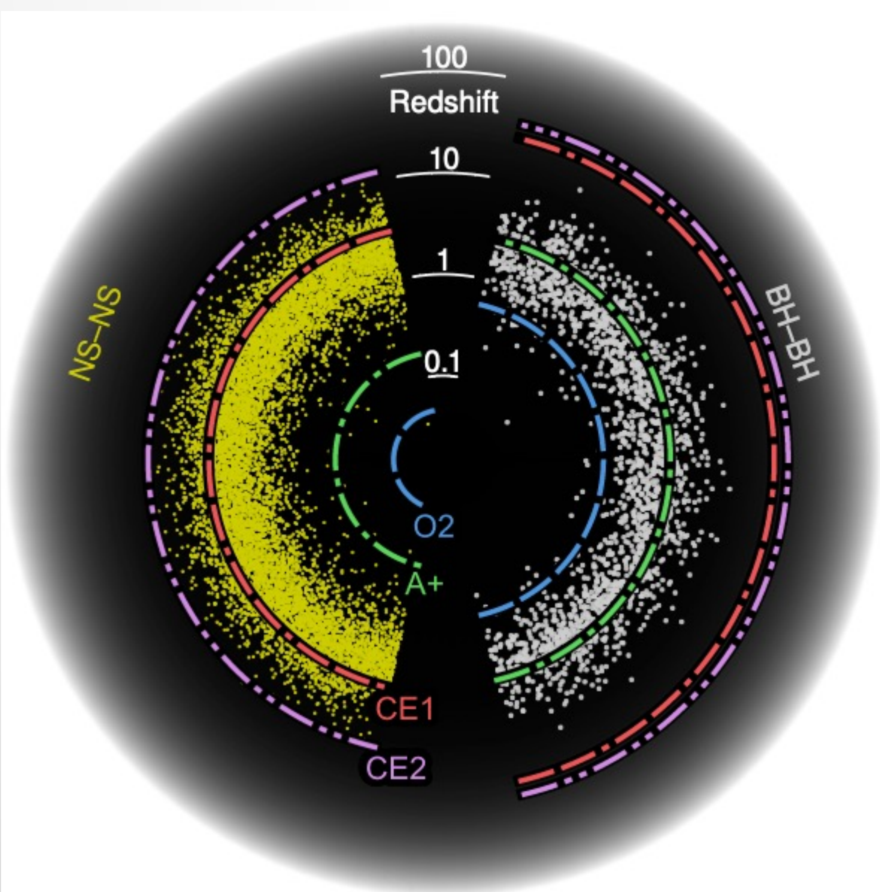
- Wide-fields down to 20 mag
- EM candidates ~ 23 mag in photometry
- 22 mag in spectroscopy

GRANDMA's citizen science program : **Kilonova-Catcher**

O(100) amateur astronomers

Timeline

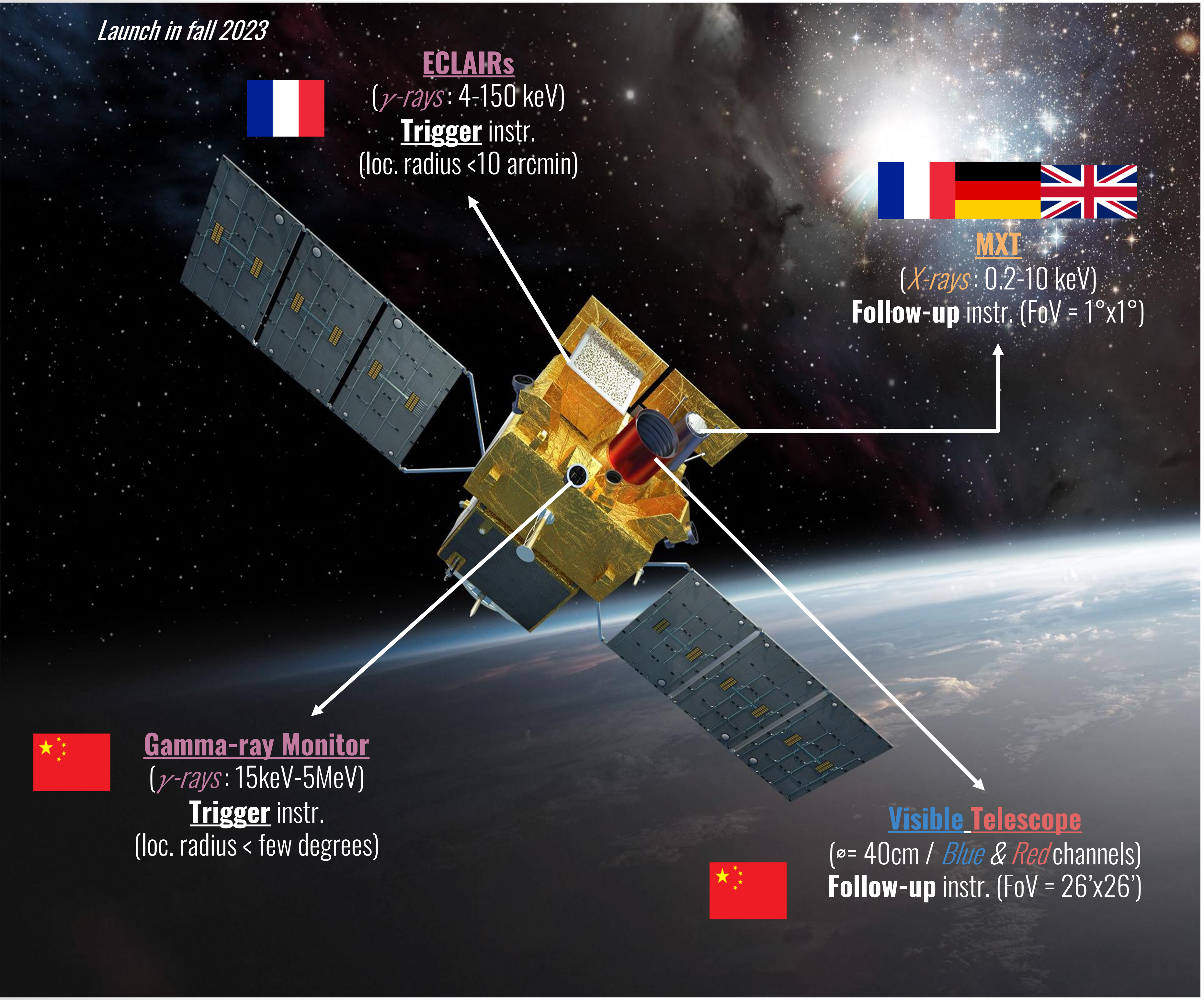

2024
2027
2034
2037
Swift
Fermi
Einstein Probe
SVOM
Vera Rubin
Nancy Grace Roman
eXTP
LIGO/Virgo/KAGRA
KM3NET/IceCube
Einstein Telescope / Cosmic Explorer
LISA
THESEUS
ATHENA


100
Redshift
10
1
0.1
NS–NS
BH–BH
O2
A+
CE1
CE2

SVOM

• • •

Take-off expected December 2023



A multi wavelengths mission
Including a satellite :

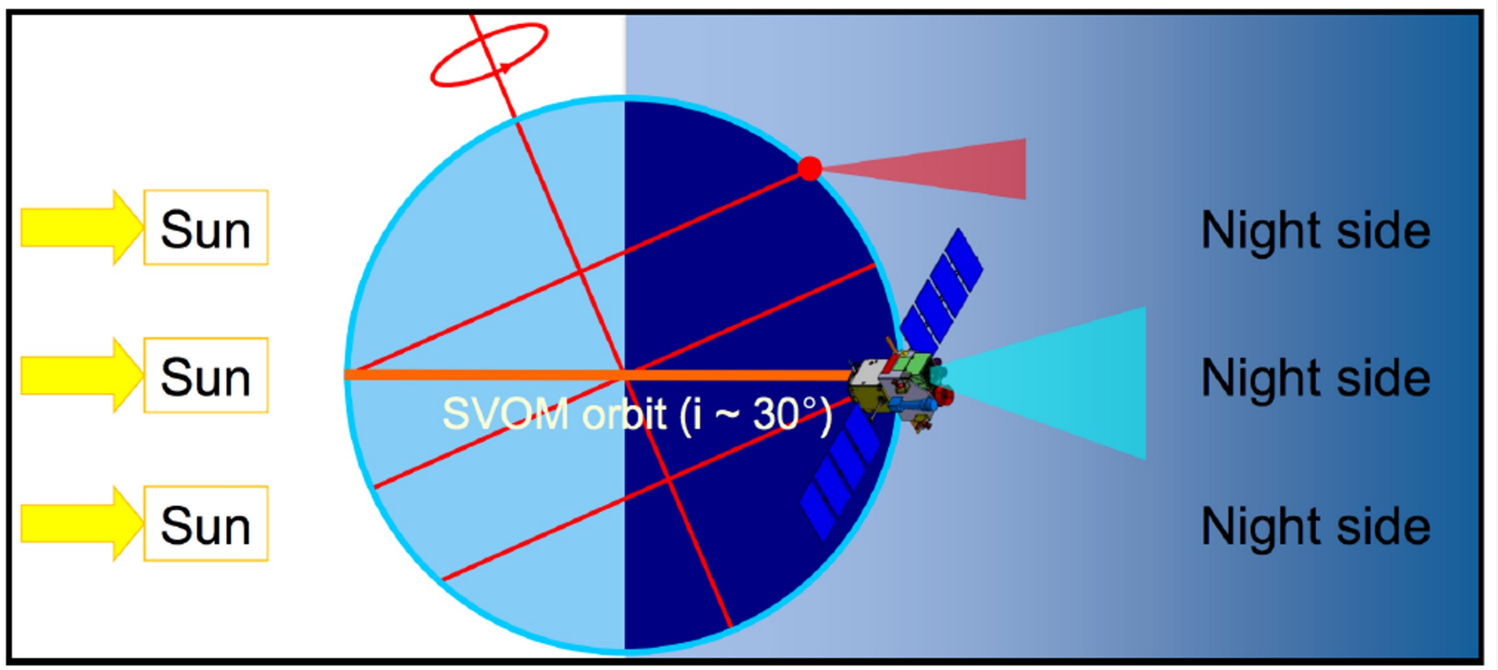
- 4 multi-wavelength instruments (ECLAIRs, GRM, MXT, VT)
- Trigger on gamma-ray events (4-150keV & 15keV-5MeV)
- Real-time ECLAIRs and GRM trigger alerts broadcasted on ground via a VHF antenna network
- Automatic follow-up sequence on board (slew & fast x-ray/opt follow-up with MXT and VT)
- Capability to perform quick ToO via VHF and BeiDou systems with MXT and VT instr.

The SVOM consortium

- **China (PI J. Wei**
  - SECM Shanghai
  - NSSC Beijing
  - NAOC Beijing
  - IHEP Beijing
  - GuangXi University
- Mexico UNAM (Colibr
- UK University of Leicester (MXT)
- Germany MPE Garching & IAAT Tübingen (MXT)
- **France (PI B. Cordie**
  - CNES Toulouse
  - APC Paris
  - CEA Saclay
  - CPPM Marseille
  - GEPI Meudon
  - IAP Paris
  - IJCLab Orsay
  - IRAP Toulouse
  - LAM Marseille
  - LUPM Montpellier
  - ObAS Strasbourg

SVOM orbit and pointing law

- **Launch from Xichang by a LM-2C rocket**
  - Low Earth Orbit (625 km, 96 min), 30° inclination
  - 1 orbit in 90 minutes

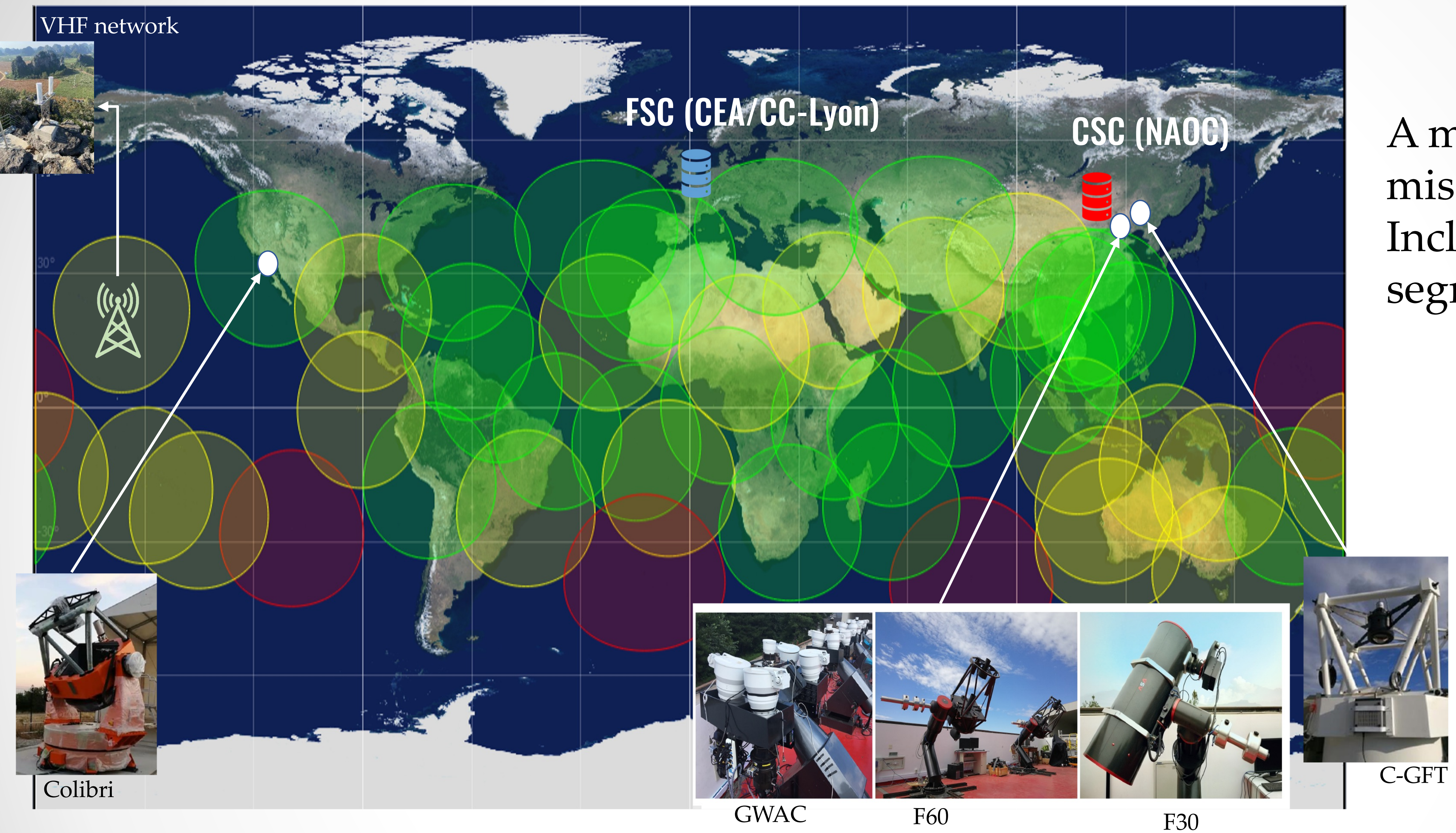


Nearly anti-solar pointing to facilitate follow-up observations from ground

Redshift measurement for ~2/3 of detected GRBs
Earth in the FoV: 65% duty cycle for ECLAIRs (50% for MXT and VT)
ECLAIRs FoV: avoidance of Galactic plane and Sco-X1

Repointing in <5 min, GRB follow-up up to 14 orbits (~1 day)

Slew capability : 9deg/min including arcsec stabilization



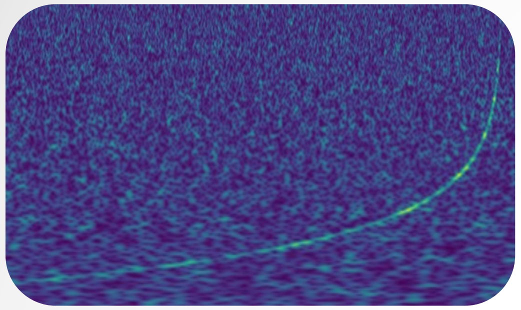
A multi wavelengths mission
Including a ground segment :

- A Very High Frequency (VHF) antenna network to communicate (downlink only) in real-time with the satellite – Beidou system under review
- optical/IR dedicated robotic follow-up telescopes + partnership with (TAROT, LCOGT, NOT2.5m, Xinglong2.12m, Lijiang 2.4m + ...

VHF : 65 % of the alerts within 30s on ground – X-band (full data) within 12h

Science topics

Target-of-Opportunity Program (ToO)



Multi-messenger astronomy

- EM counterparts from GW sources (GRBs & kilonovae)
- EM counterparts from external very high-energy triggers (KM3NeT/IC, CTA, MAGIC, HESS, etc.)
- Follow-up of "special" events (FRBs, FBOTs, etc.)
- Other scientific opportunities….

15% mission time
up to 1 ToO/day

↓

40% mission time
up to 1 ToO/day

Mission Core Program (CP)

Gamma-ray Burst science

- GRB physics (prompt & afterglow, progenitor systems, etc.)
- GRB environment (host and ISM)
- Star formation history (high-z GRBs)
- Cosmology

25% mission time
60-90 GRB/yr

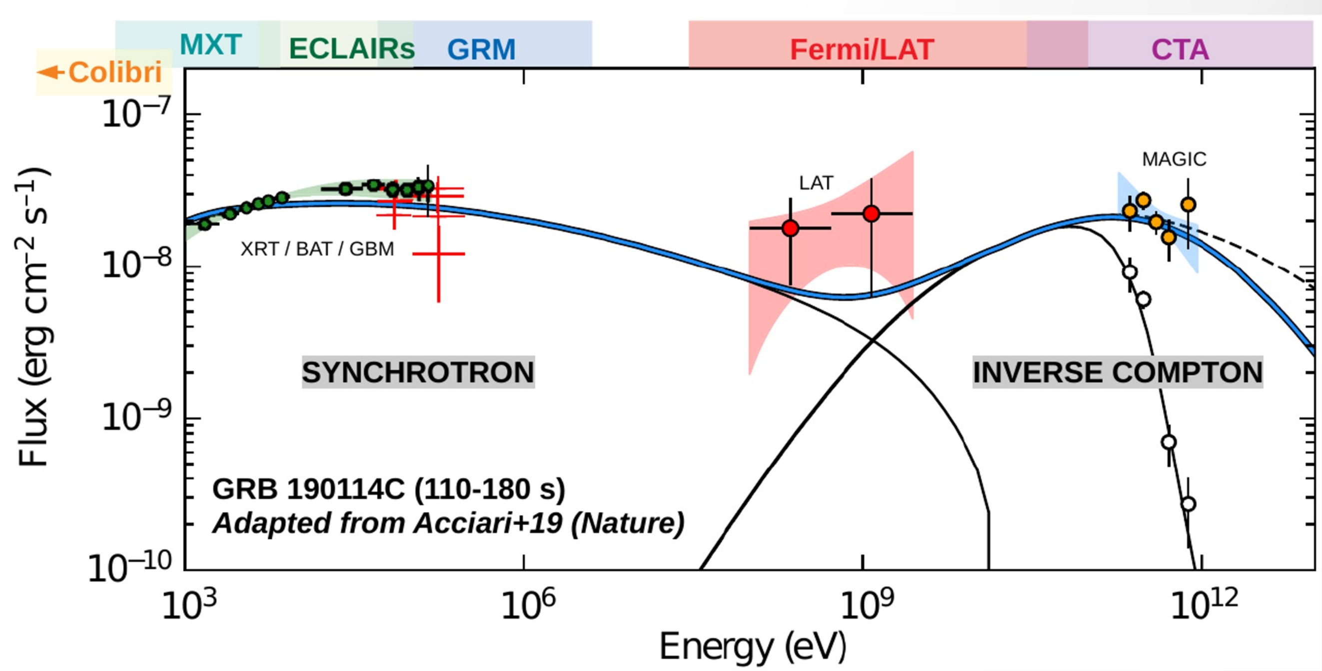
General Program (GP)

SVOM as an open Observatory

Any science that would require the SVOM instrument capabilities

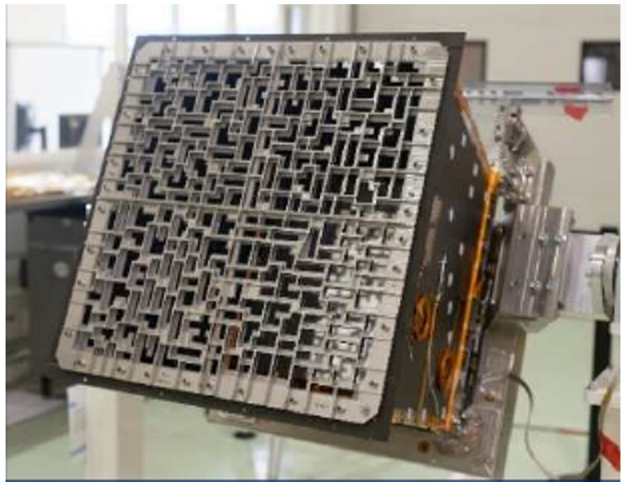
Open call for proposals

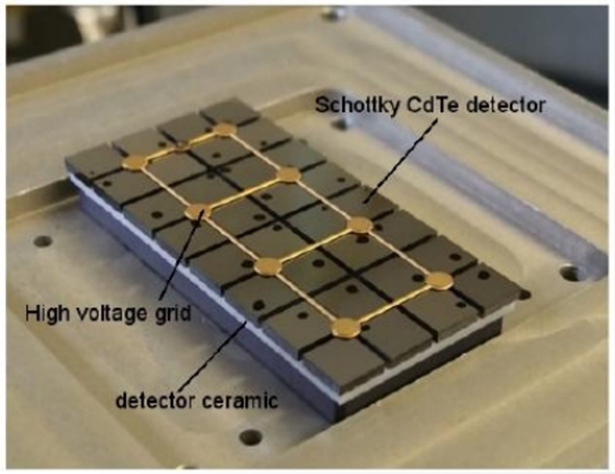
60% mission time → **35% mission time**

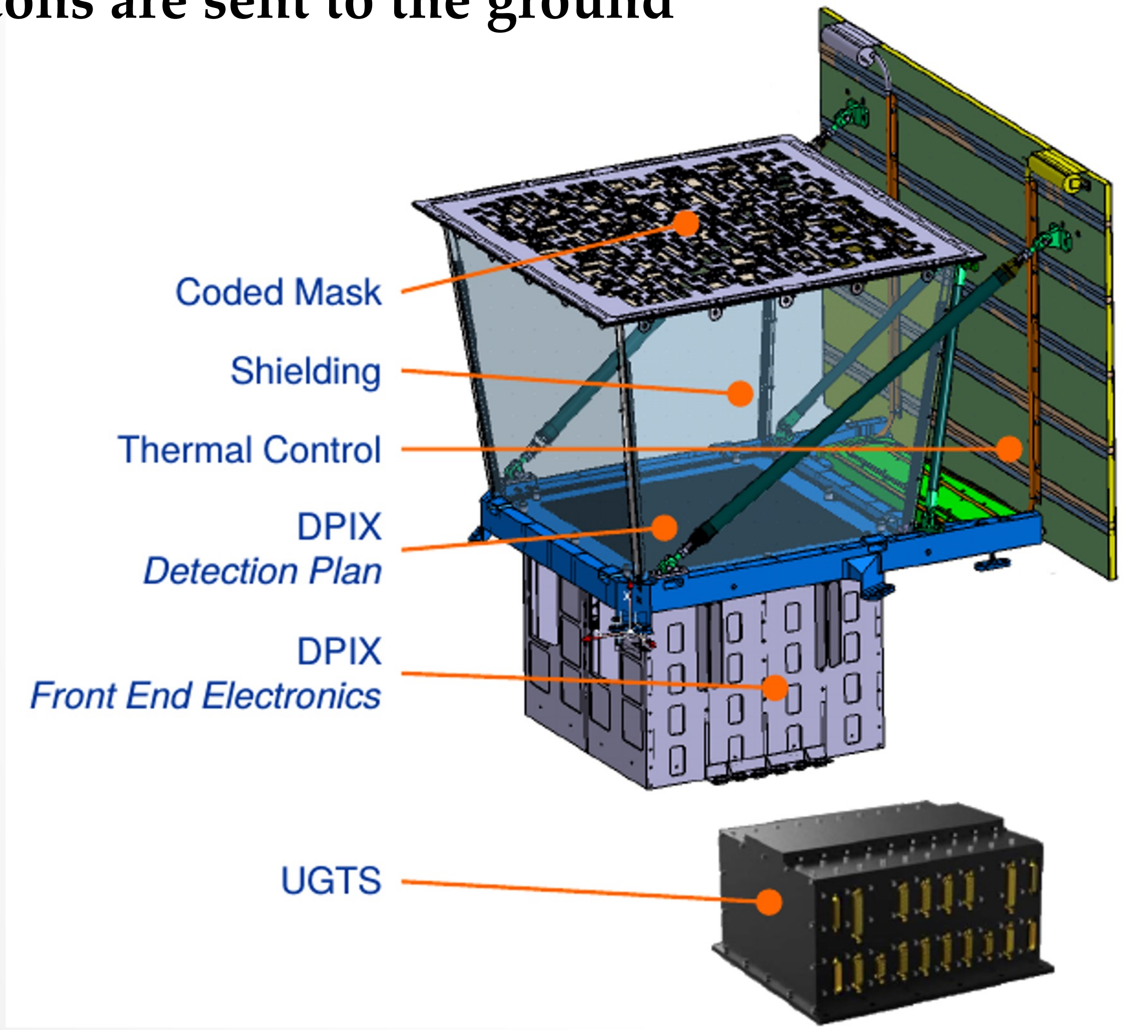


ECLAIRs : gamma-ray imager

- **54x54 cm² coded mask**
  - 40% open fraction
  - 46 cm above detection plane
- **Detecting area 1024 cm²**
  - 6400 CdTe pixels (4x4x1 mm^3)
- **All photons are sent to the ground**



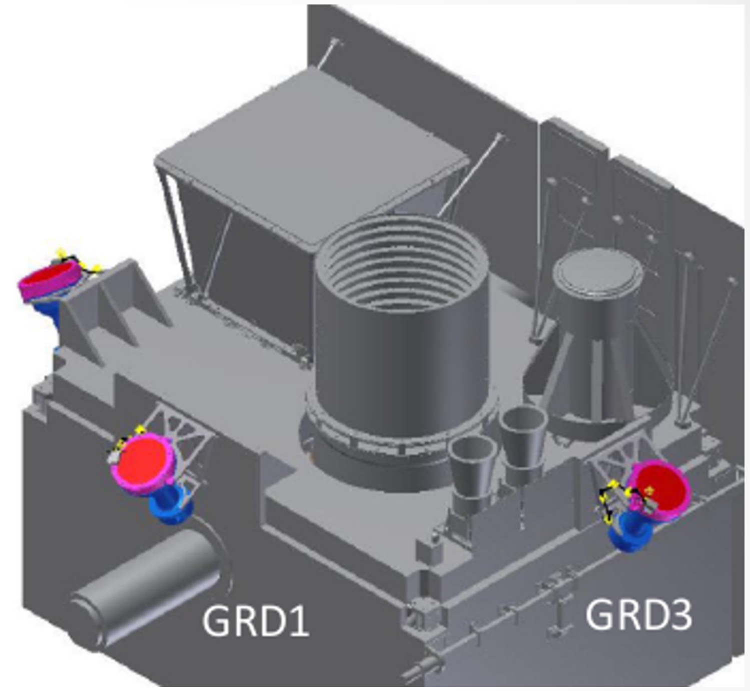


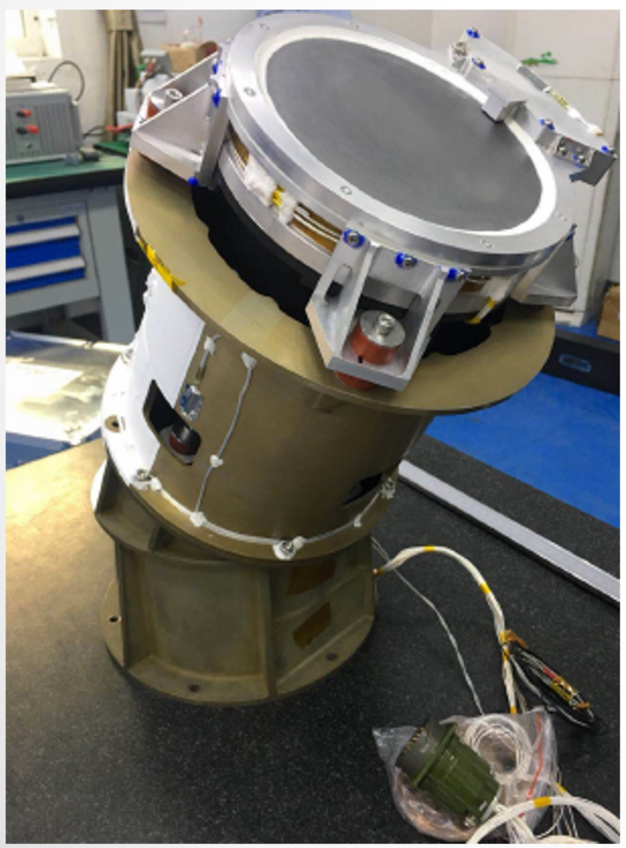


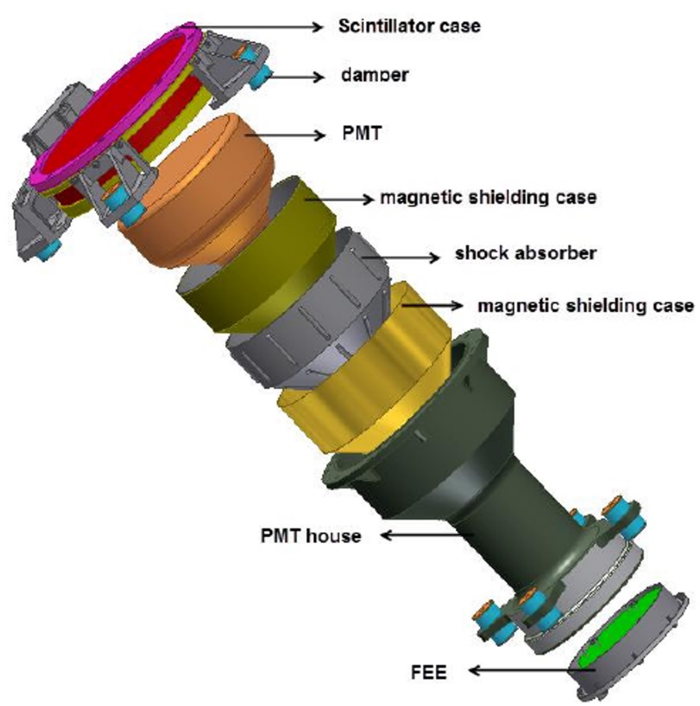
- **Onboard trigger and localization**
  - Strongly varying background modulated by Earth transit through the FoV every orbit
  - Time scales from 10 ms to 20 min
  - 4 energy bands, 9 detector zones
  - Rate trigger and image trigger
- **Performance**
  - FoV ~ 2 sr total
  - Energy range: 4-150 keV
  - Energy resolution <1.6 keV @60 keV
  - A_{eff} = 200 cm² @6 keV
  - Localisation accuracy <12' for 90% of the sources at detection limit

Gamma-Ray Monitor (GRM)

- **3 Gamma-Ray Detectors (GRDs)**
  - NaI(Tl) (16 cm Ø, 1.5 cm thick)
  - Plastic scintillator (6 mm) to monitor particle flux and reject particle events
  - 30° inclination w.r.t. ECLAIRs optical axis



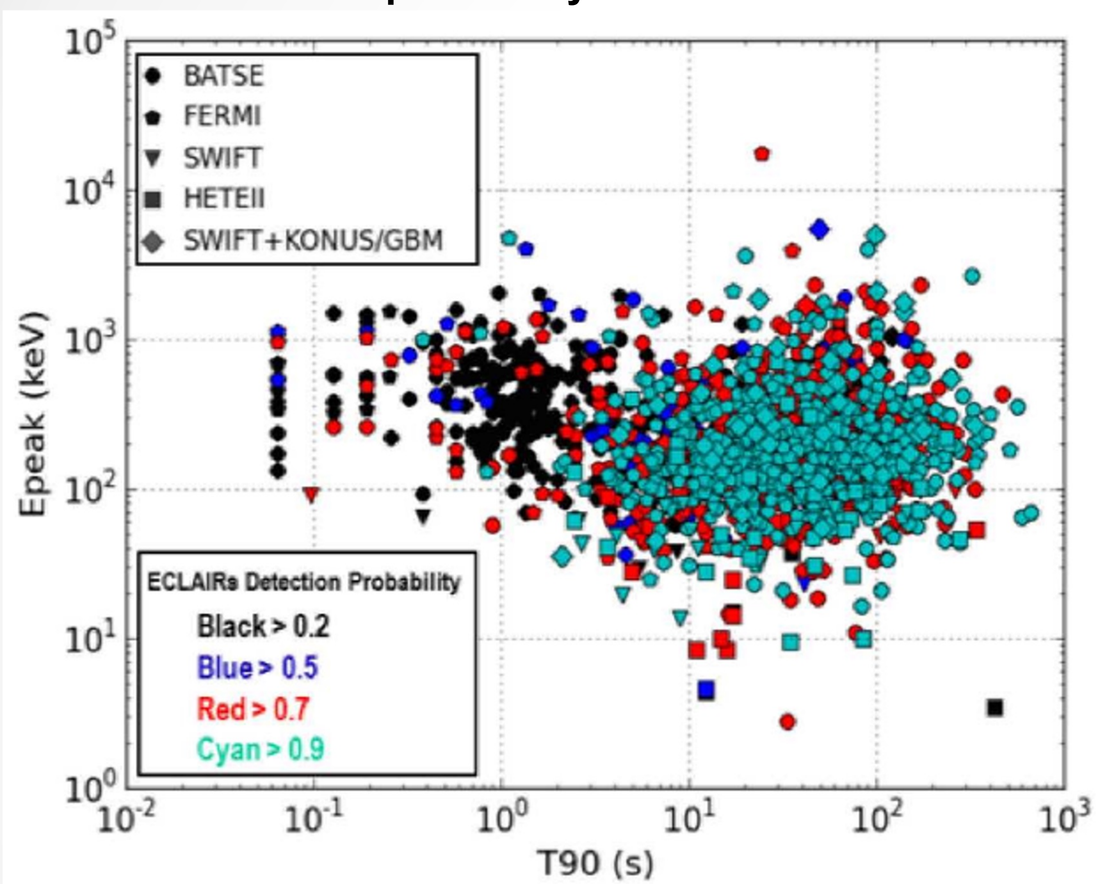




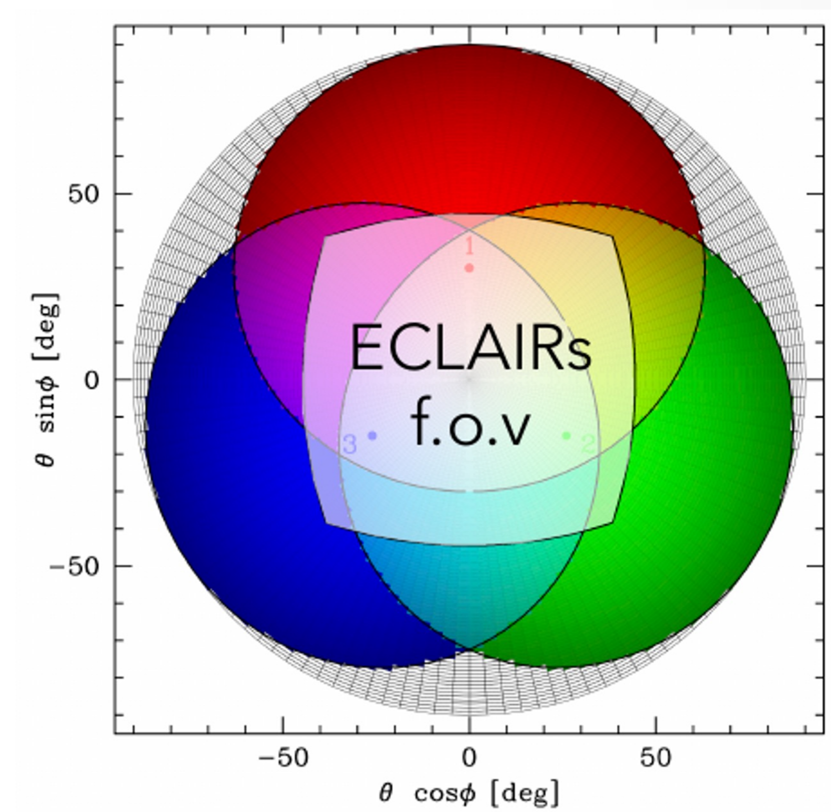
- **Onboard rate trigger (2 GRDs)**
- **Performance**
  - FoV ~ 5.6 sr (~2 sr per GRD)
  - Energy range: 15-5000 keV
  - A_{eff} = 190 cm² at peak (each unit)
  - Rough localization accuracy

GRB detection

Detection probability for ECLAIRs

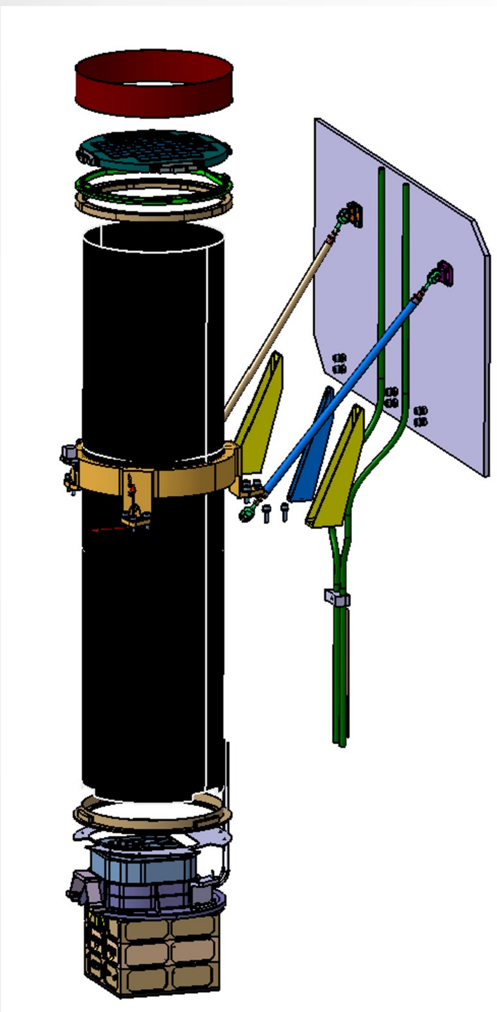


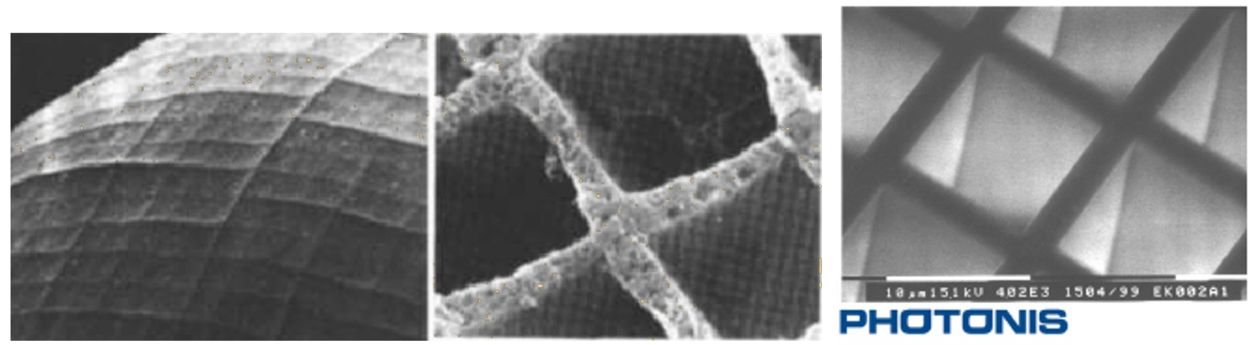
- **ECLAIRs is sensitive to all classes of GRBs**
  - Classical long GRBs
  - Soft GRBs (XRR, XRF)
  - Short GRBs (with a moderate efficiency)
  - **42 to 80 GRBs / year**
  - **Including 3-4 GRBs / year at z>5**
  - **Loc. <12′**

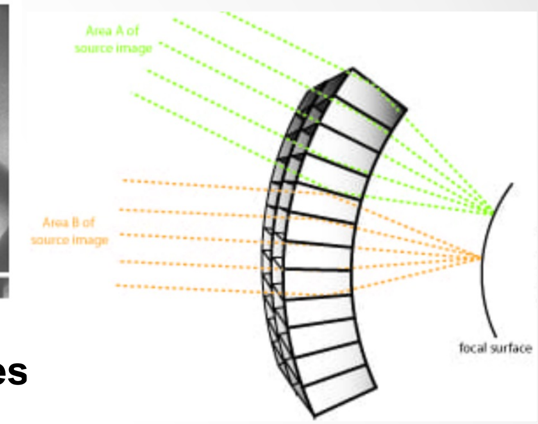


- **GRM has a larger FoV than ECLAIRs**
  - **~90 GRBs / year**
  - **Loc. ~ 5-10 deg (3 GRDs)**
  - ECLAIRs sensitivity to short GRBs can be improved when combined with the GRM

The Micro-channel X-ray telescope



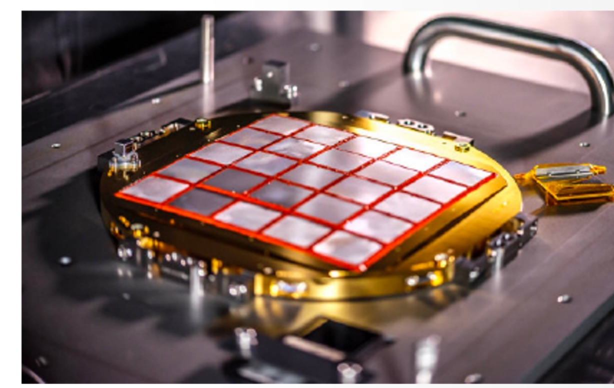




Real vs. manufactured "lobster eyes

- **Micro-channel plate optics**
  - 20 micron size pores in a "lobster eye" configuration
  - Focal length: 1 m
  - pnCCD camera (256x256 pixels of 75 microns)

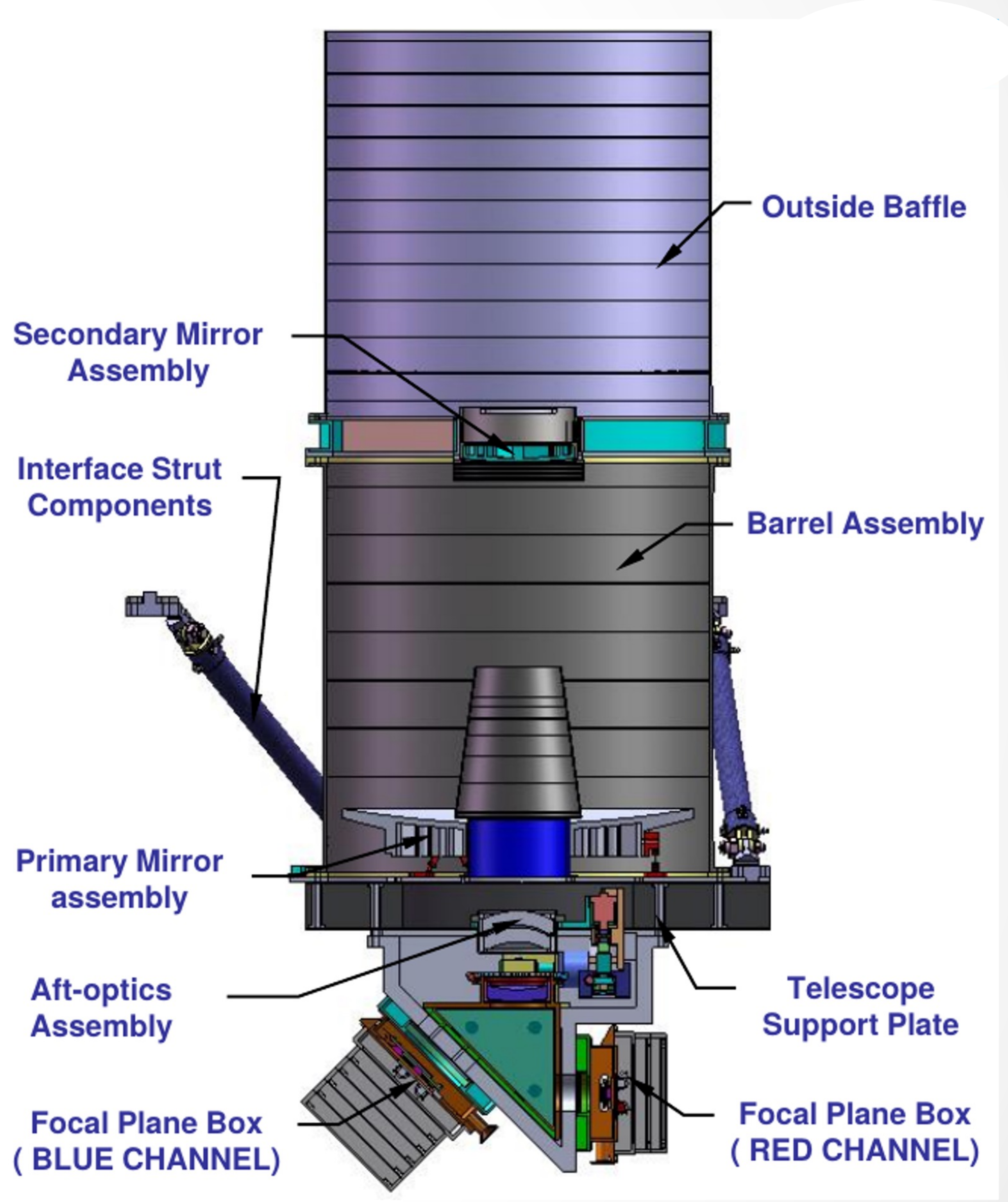
- **Performance**
  - FoV = 64x64 $arcmin^2$
  - Energy range: 0.2-10 keV
  - Energy resolution ~60 eV @5.9 keV
  - A_{eff} = 27 cm^2 @1 keV (central spot)
  - Localization accuracy <13" within 5 min from trigger for 50% of GRBs



The Visible Telescope

- **Ritchey-Chretien telescope**
  - 40 cm Ø, f=9
  - Focal length: 3.6 m
- 2 channels: blue (400-650 nm) and red (650-1000 nm)
- 2k * 2k CCD detector each

- **Performance**
- FoV 26x26 arcmin²
- → covering ECLAIRs error box in most cases
- Sensitivity M_V=22.5 in 300 s
- → will detect ~80% of ECLAIRs GRBs
- Localization accuracy <1”



Ground segment telescopes



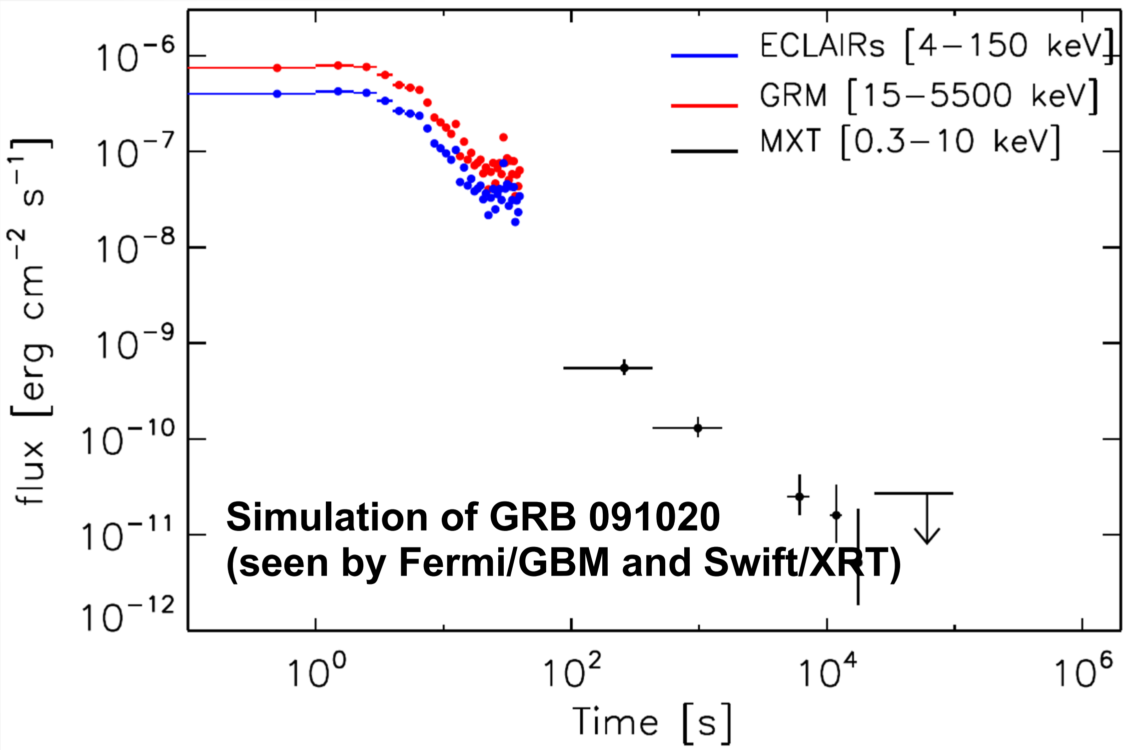
- **Ground-based Wide Angle Camera (GWAC)**
  - 36 camera units covering 5400 deg^2 (~1/2 ECLAIRs FoV)
  - Installed in Ali (China) and CTIO (Chile)
  - 500-800 nm; m_{lim}=16-17 (10 s exposure)
  - Explore the prompt optical emission
  - Also F30 and F60 telescopes for follow-up

- **Ground Follow-up Telescopes (GFTs)**
  - Robotic 1-m class telescopes (fast repointing, <30 s)
  - San Pedro Martir (Mexico) and Xinglong observatory (China)
  - C-GFT: 1.2 m, FoV = 21x21 $arcmin^2$, 400-950 nm
  - F-GFT (a.k.a. Colibri): 1.3 m, FoV = 26x26 $arcmin^2$, multi-band photometry (400-1700 nm, 3 simultaneous bands)
  - Accurate GRB localization → observations with large telescopes

- **Agreement to use the LCOGT network**
- **>75% of ECLAIRs GRBs immediately visible by one ground telescope (GFTs+LCOGT)**
- **Early observation by large telescopes favored by pointing strategy → redshift measurement expected in ~2/3 of cases**

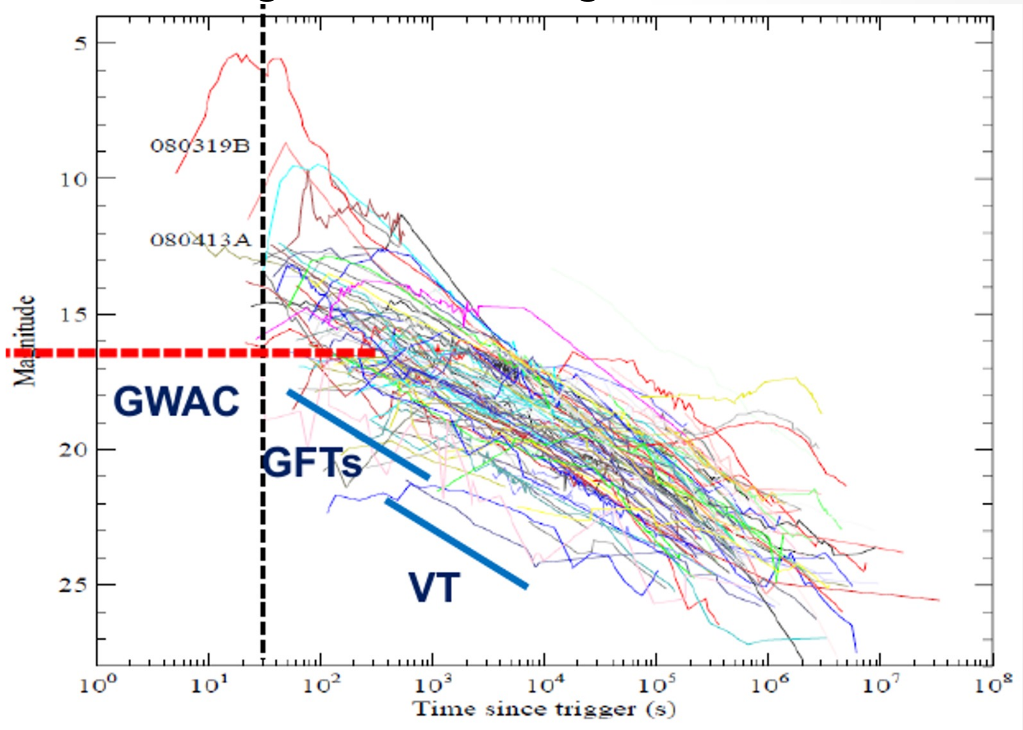
GRB afterglow emission

- **ECLAIRs will cause a slew of the satellite for 36-72 GRBs / year**
- **MXT will detect and localize the X-ray afterglow in >90% of GRBs after a slew**



- **VT, C-GFT and F-GFT will detect, localize and characterize the NIR / visible afterglows**
- **(lightcurve + photo-z)**

Visible light curves of long GRBs Wang+2013



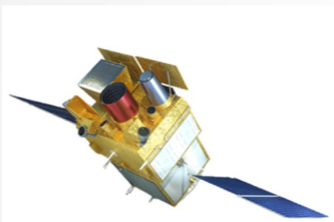
GRB sample

- **A unique sample of 30-40 GRBs / year with**
  - Prompt emission over 3 decades (+ optical flux/limit: 16%)
  - X-ray and visible / NIR afterglow
  - Redshift

	Swift	Fermi	SVOM
Prompt	Poor	Excellent 8 keV -100 GeV	**Very Good 4 keV - 5 MeV**
Afterglow	Excellent	> 100 MeV for LAT GRBs	**Excellent**
Redshift	~1/3	Low fraction	**~2/3**

- **Physical mechanisms at work in GRBs**
  - Nature of GRB progenitors and central engines
  - Acceleration, composition, dissipation & radiation processes of the relativistic ejecta
- **Diversity of GRBs: event continuum following the collapse of a massive star**
  - Low-luminosity GRBs / X-ray rich GRBs / X-ray Flashes and their afterglow
  - GRB/SN connection
- **Short GRBs and the merger model**
  - GW association / Short GRBs with extended soft emission
- **GRBs as a tool to study the distant Universe**

Real Time alert for GRB



space to ground

VHF antenna location to SVOM/FSC

- 30s to reach the subscribers
- All VHF scientific products are public!
- The content of the SVOM alert notices is now under construction (VOEvent)

SVOM Real-time alerts system
at the French Science Center (CC Lyon/IN2P3)

broadcast

we are going to follow the GCN notices system to quickly broadcast our alerts

broadcast

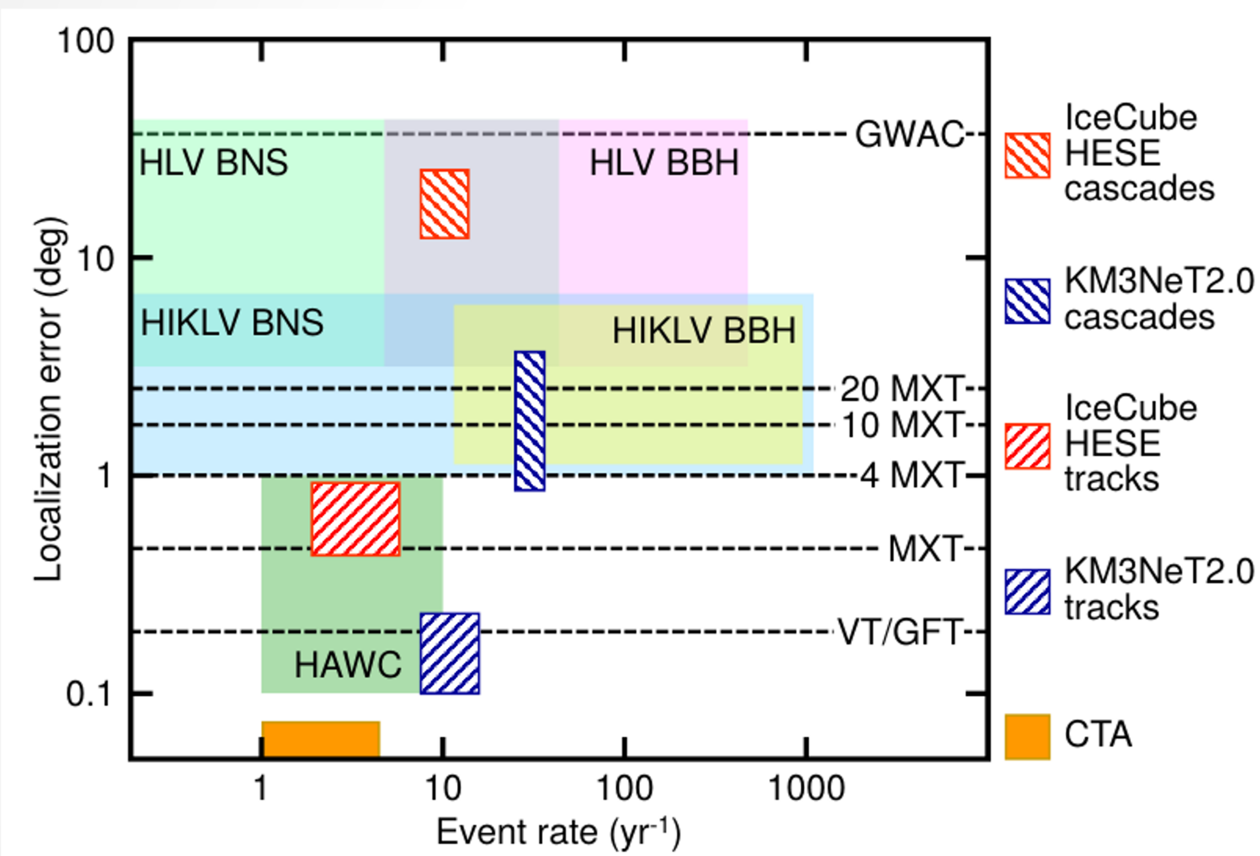
we also have our own SVOM alert broker (Comet broker sending VOEvent messages) at the SVOM/FSC

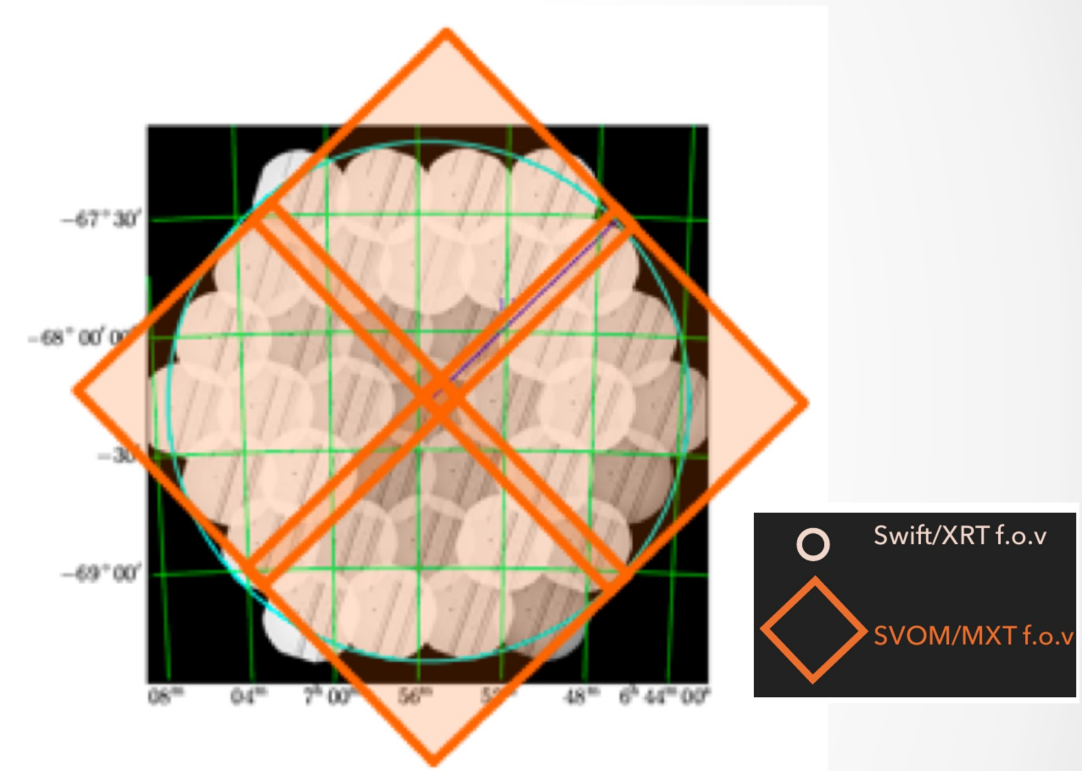
Alert subscribers

FSC

MM strategy

- **Search for X-ray / visible counterparts to MM events with MXT and VT**
  - Examples: Gravitational Wave sources (large error boxes), kilonova / afterglow (expectations depend on the viewing angle), neutrinos, VHE transients
  - Requires a tiling strategy





- **Search for NIR / visible counterparts to MM events with the GFTs**
  - Search: galaxy targeting within error box
  - Photometric follow up to characterize the counterpart (e.g. kilonova from BNS): requires accurate localization (<30’)

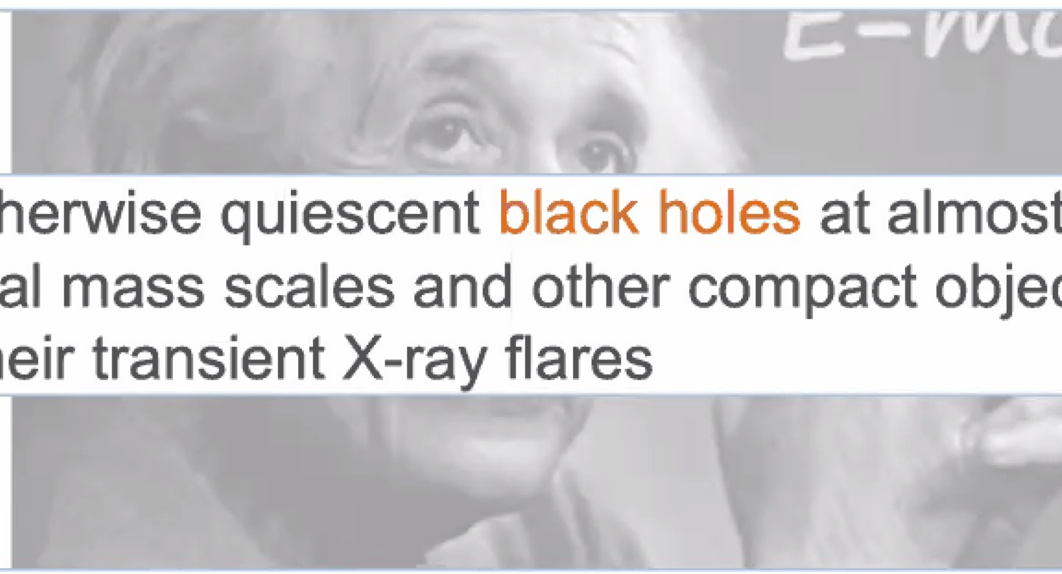
Einstein Probe

• • •

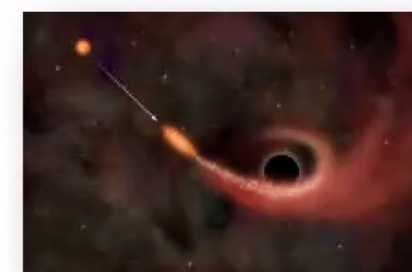
Take-off expected November 2023

Main science objectives

Systematic survey of soft X-ray transients and variability of X-ray sources with unprecedented combination of sensitivity and cadence

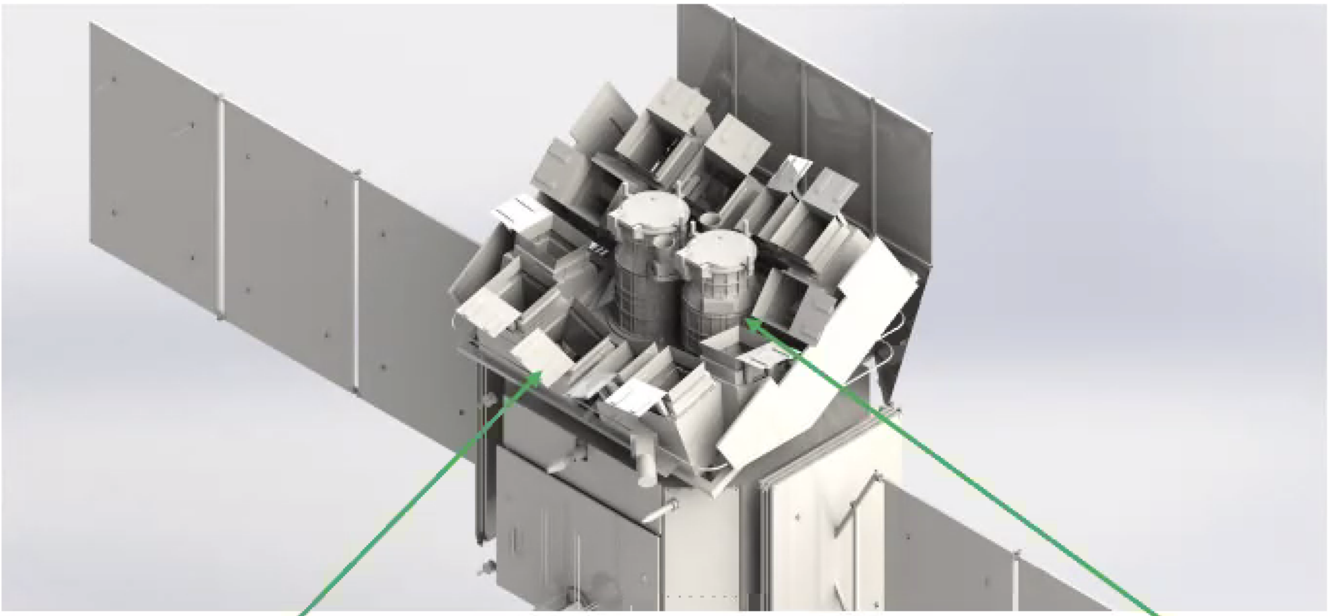


Discover otherwise quiescent black holes at almost all astrophysical mass scales and other compact objects by capturing their transient X-ray flares



Detect and localise the electromagnetic-wave sources of gravitational-wave events by synergy with gravitational-wave detectors

Instruments & spacecradt



Spacecraft

On-board data processing
Quick slew & autonomous follow-up

Telemetry

esa

X/S-band
Beidou system (down/up-link)
VHF network (down-link)

Wide-field X-ray Telescope

WXT (12 modules)

esa

Optics: lobster-eye MPO
Detectors: CMOS
FoV: 3,600 sq deg (1.1 sr)
Band: 0.5 – 4 keV
Spatial resolution: ~ 5' (FWHM)
sensitivity: 1-2 orders of mag. improvement

Follow-up X-ray Telescope

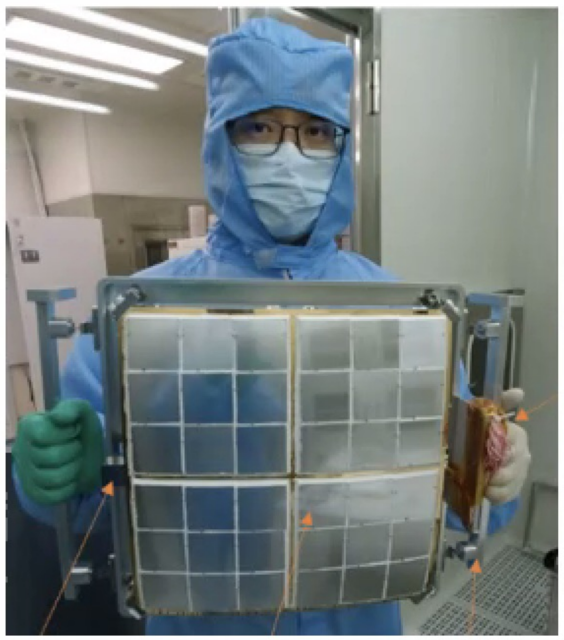
FXT (2 units)

esa

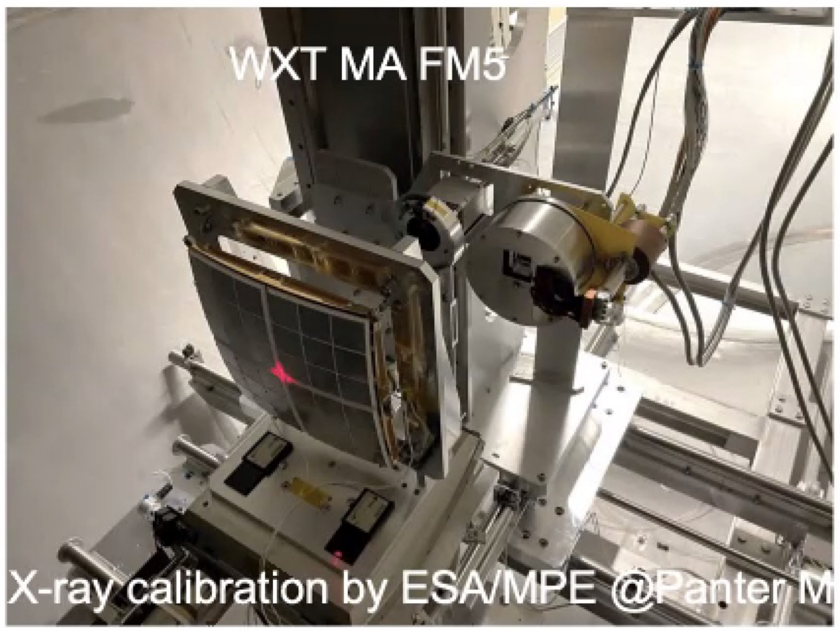
Optics: Wolter-1
Detectors: pn-CCD
FoV: ~1 deg
Band: 0.3 -10keV
spatial resolution: <30" (HPD, on-axis)
Effective area: 300 cm^2 @1keV (x 2 units)

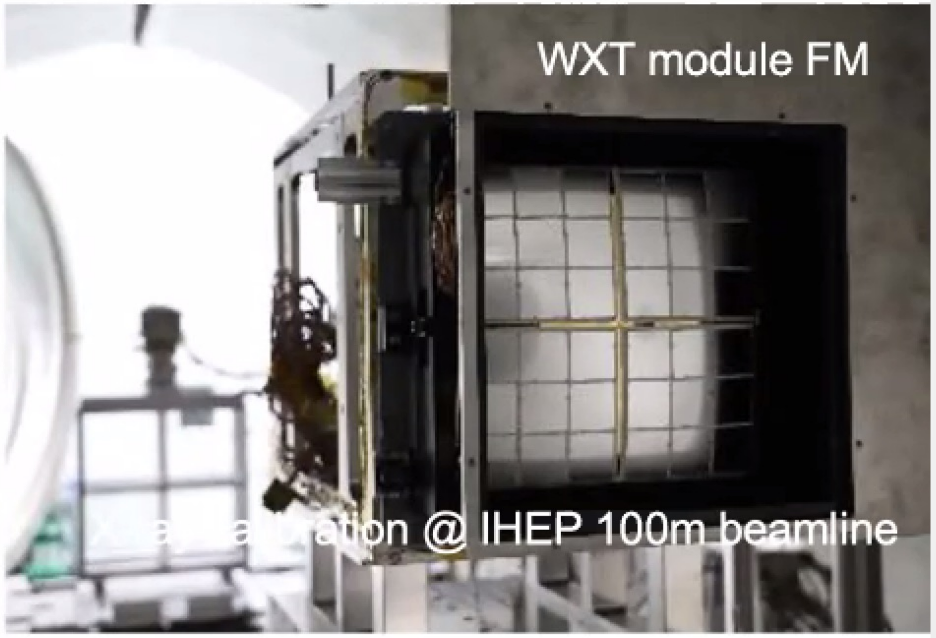
WXT status

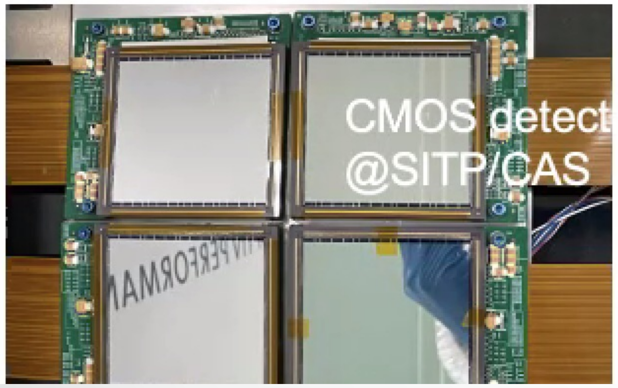
- 12 flight models built, being tested and calibrated
- 1MA calibrated at MPE, 3 e2e calibration at IHEP (1 done, 2 in April/May)

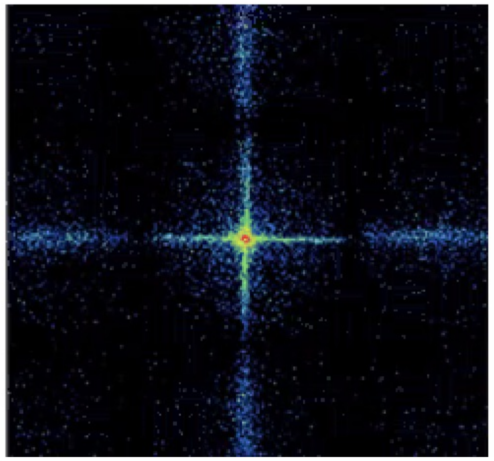


WXT MA (NAOC/CAS)





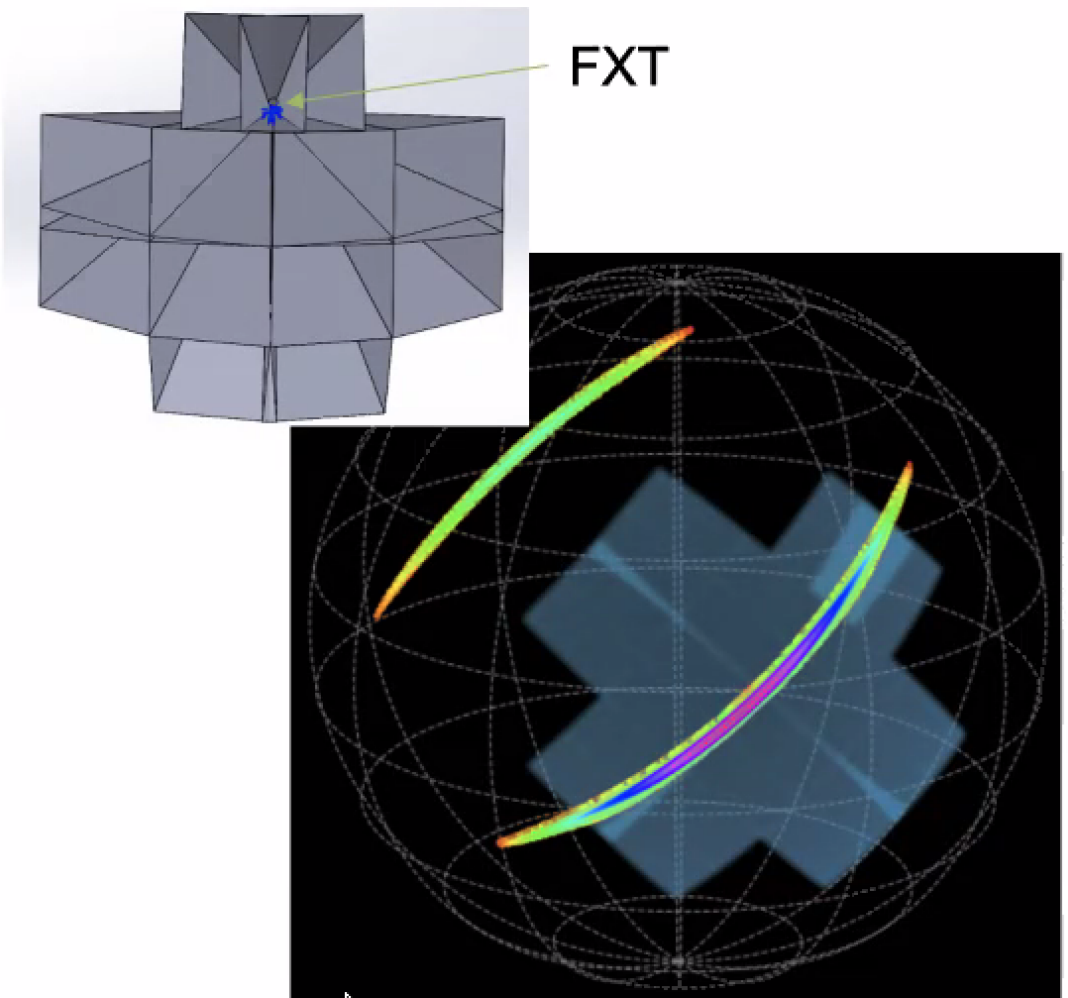




- Lead of full modules: SITP/CAS NAO/CAS (Sun X., Ling Z.)
- Lobster-eye telescopes: NAO/CAS (C. Zhang)
- MPO plates (NNVT)

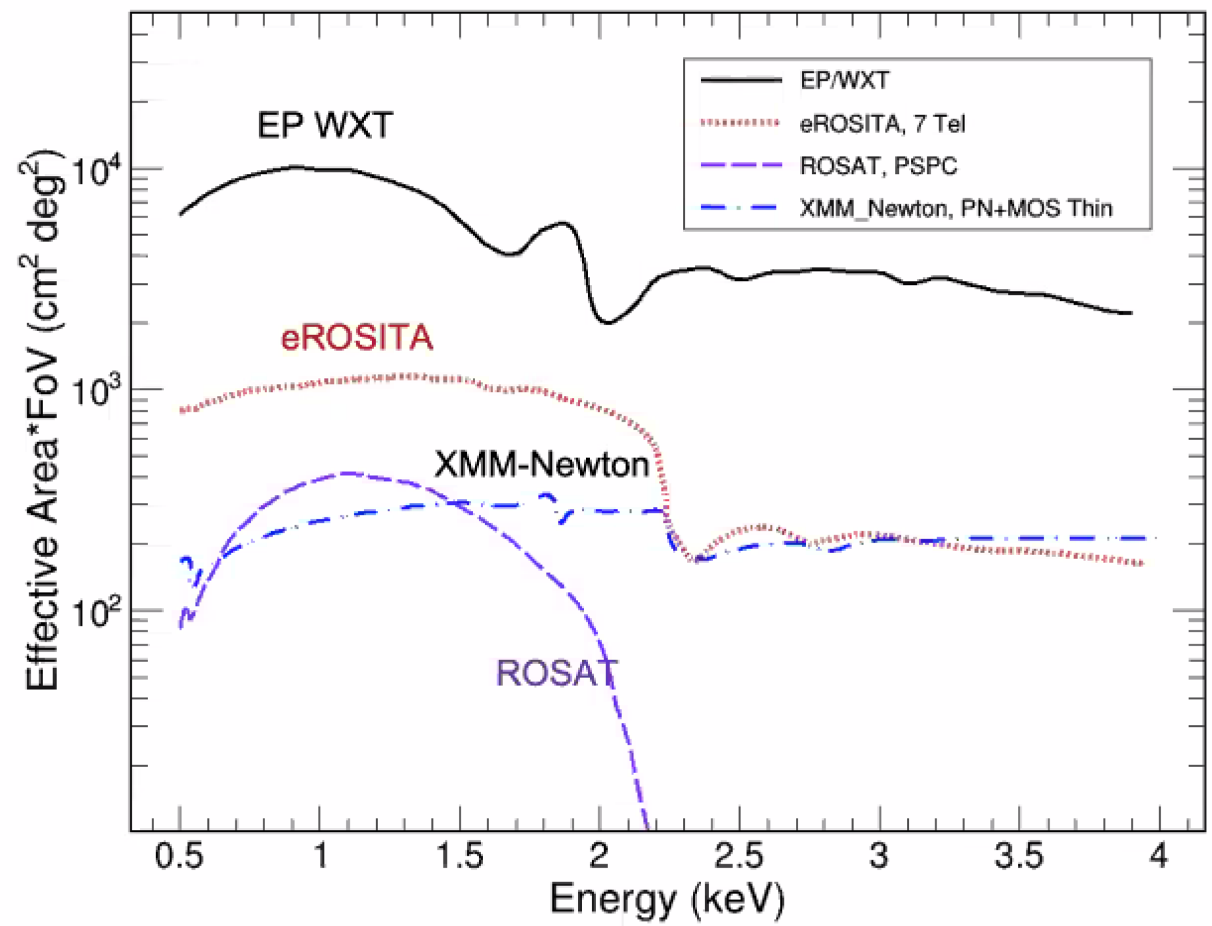
WXT FoV & Grasp

WXT FoV 3600 sq deg (1.1sr)



FoV size compared with typical GW source locus

Grasp parameter

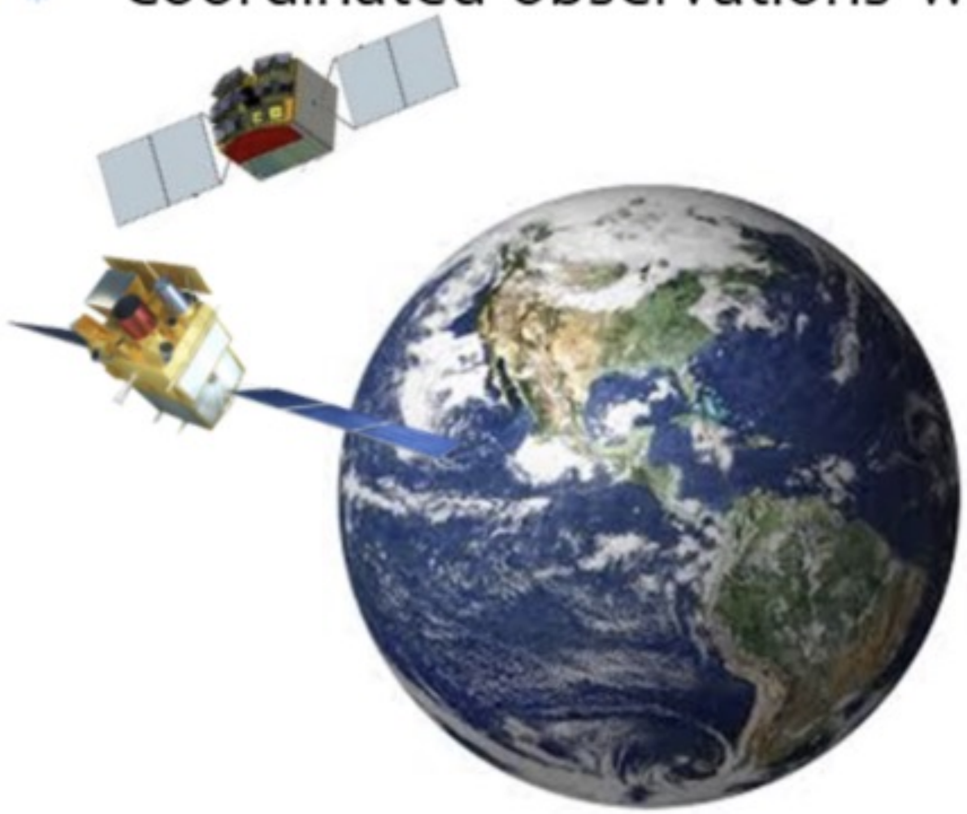


Simulation result. *(Zhao D. et al. 2017)*

Possible synergies

Synergy with SVOM

- The two missions are well complementary
  - Truly multi-waveband, better positioning by EP, … …
- Operating at same time
- Coordinated observations will maximise science return



Maximise the study of source nature

Maximise finding more rare transients

- Data and mission centers are in the same place !
- On-going discussions to make this true

Later time

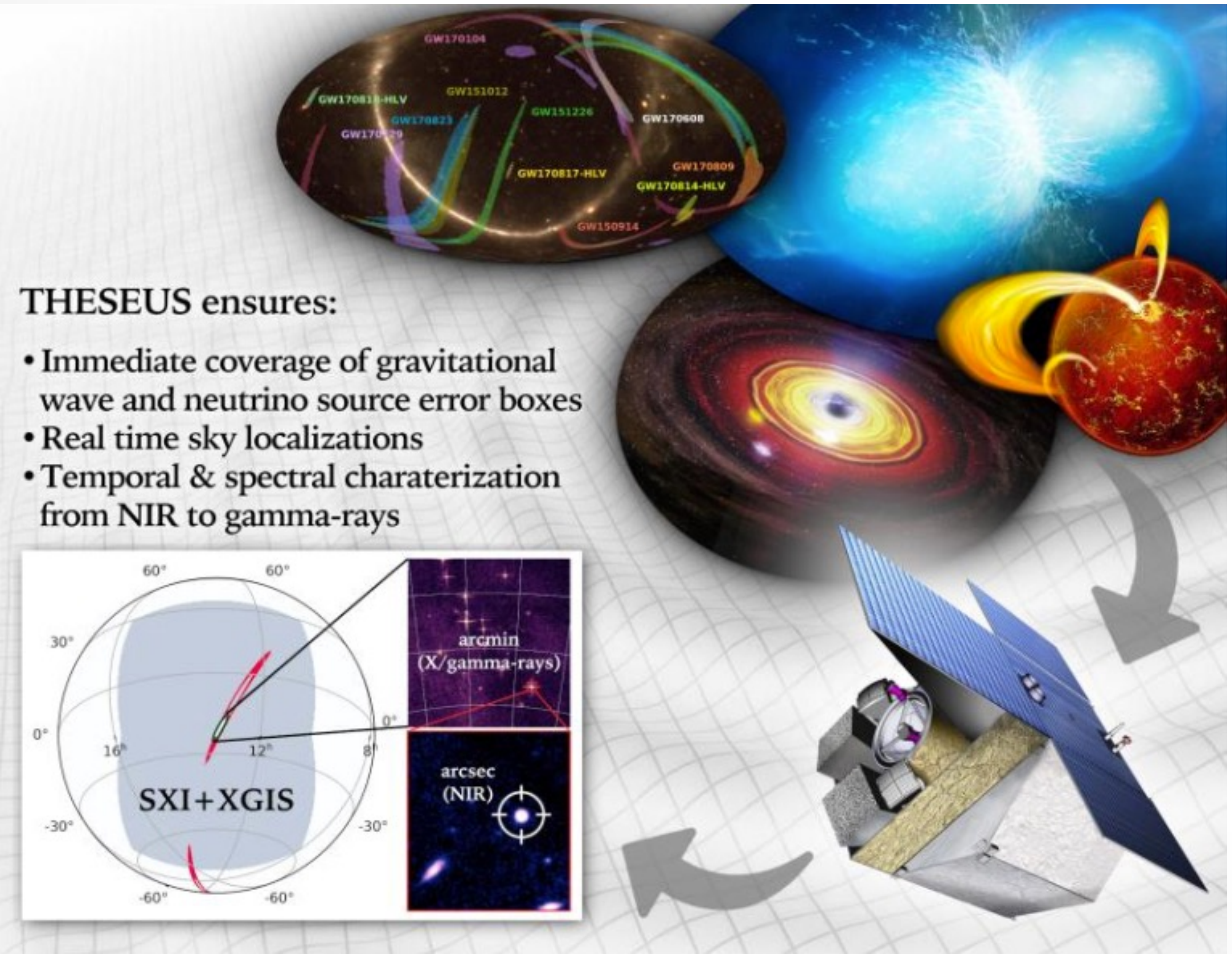
• • •

THESEUS : Selection in 2023 ? (launch expected in 2037)

LISA : almost completed final design phase (launch expected 2037)

Science objectives

- Time domain astronomy
- Use Gamma-ray bursts as a tool to study early universe
- Perform Multi-messenger – electromagnetic detections (GW and neutrinos)



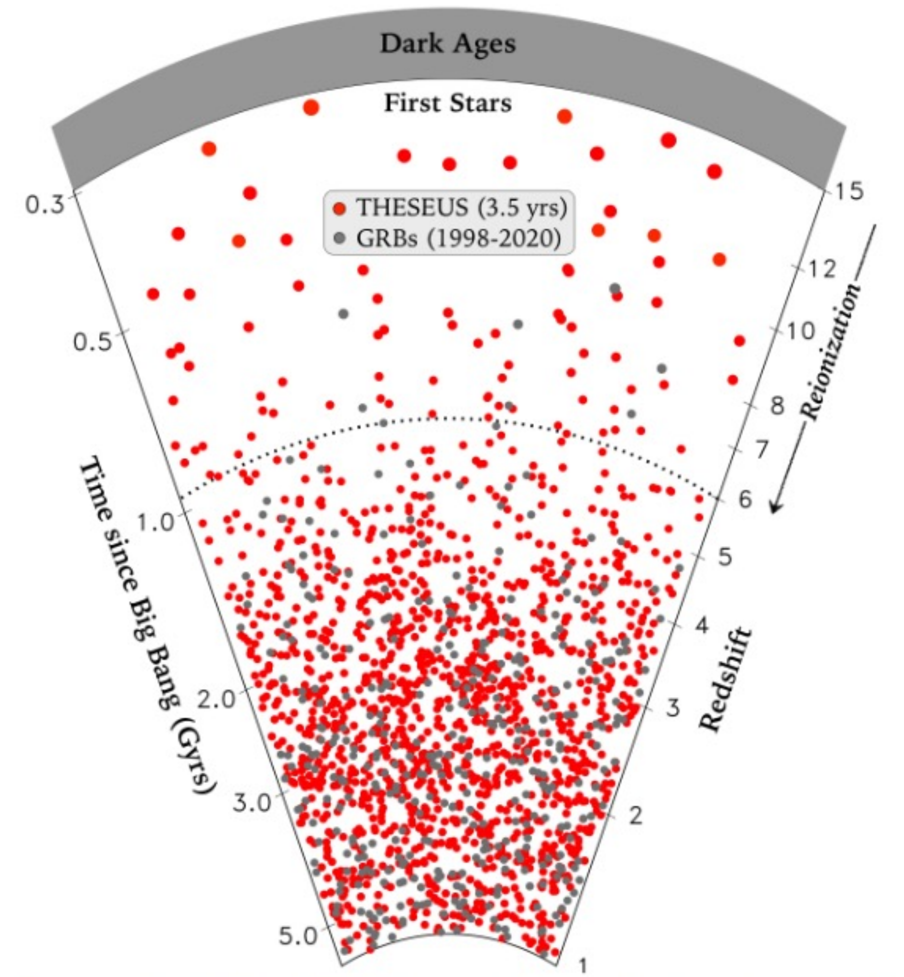
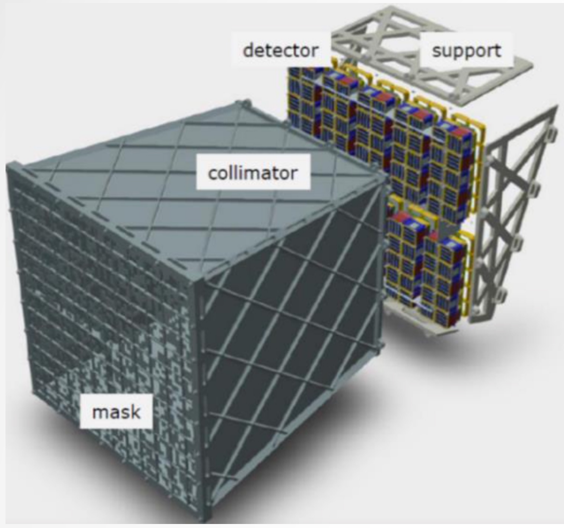


Figure 1-1 THESEUS capability of detecting and autonomously identifying high-redshift GRBs, as a function of cosmic age, in 4 years of operations (red dots) compared to what has been achieved in the last ~20 year.

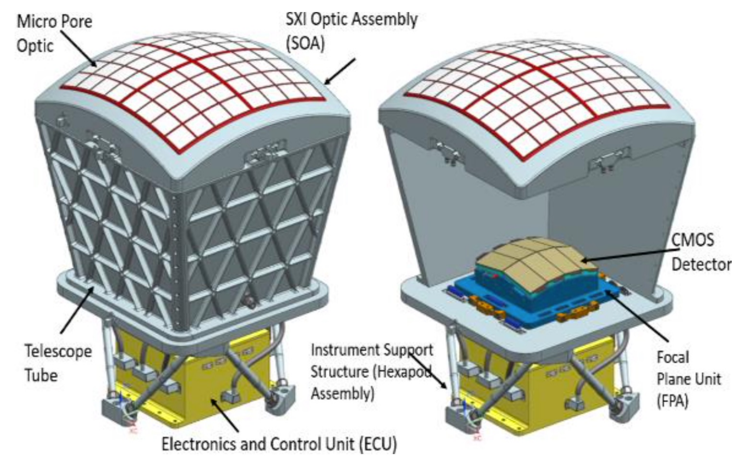
12 sGRBs/ year (well localized)
+ 28 sGRBs/year (500 deg2)

3 instruments on board

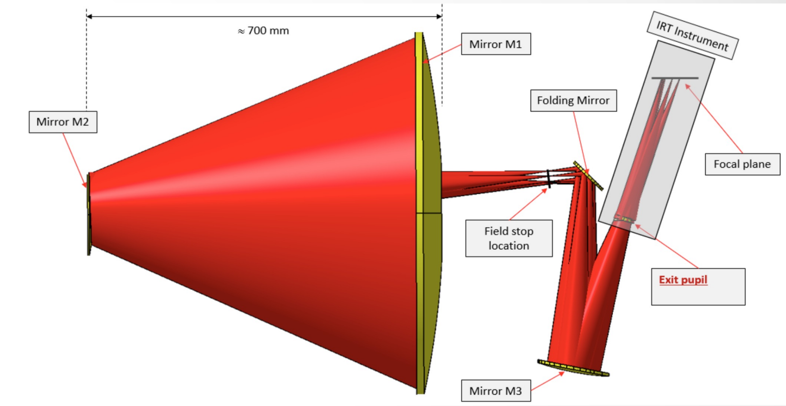
XGIS



SXI



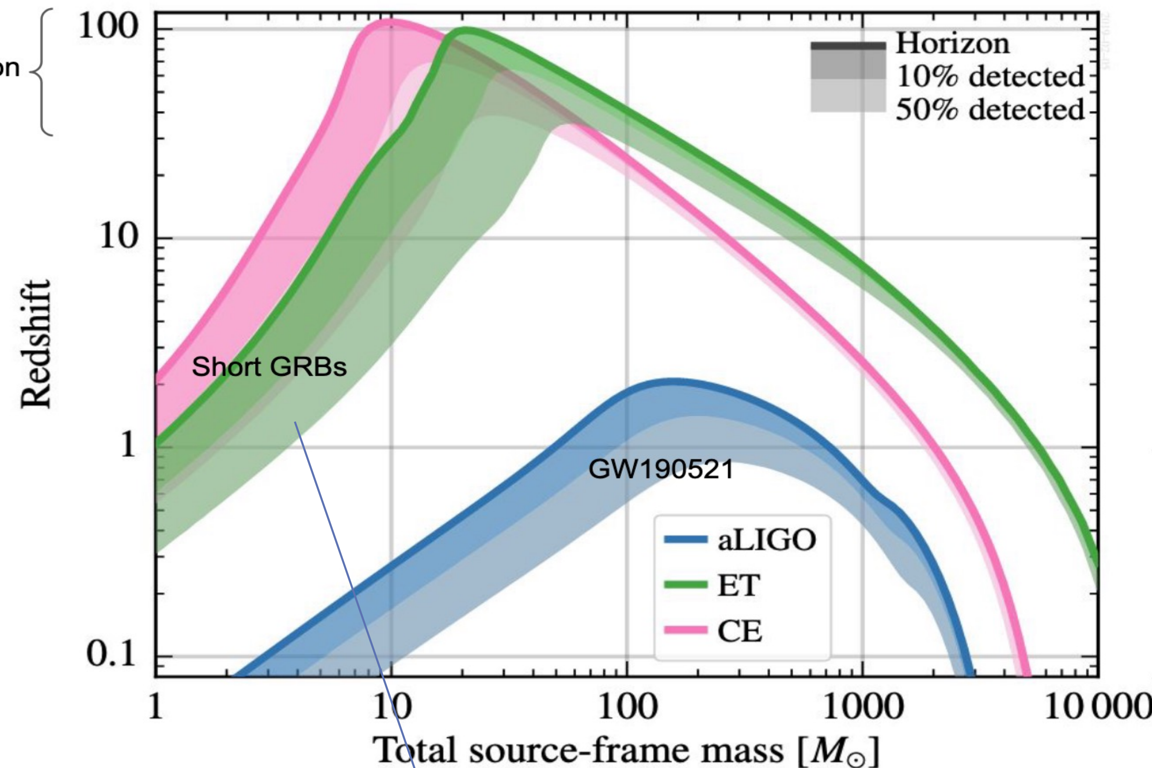
IRT



SXI sensitivity (3σ)	1.8x10^{-11} erg/cm^2/s (0.3-5 keV, 1500 s) 10^{-10} erg/cm^2/s (0.3-5 keV, 100 s)
XGIS sensitivity (1s, 3σ)	10^{-8} erg/cm^2/s (2-30 keV) 3x10^{-8} erg/cm^2/s (30-150 keV) 2.7x10^{-7} erg/cm^2/s (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 field-of-view	0.5 sr - 31x61 degrees^2
XGIS field-of-view (area corresponding to >20% efficiency)	2 sr (2-150 keV) – 117x77 degrees^2 4 sr (≥150 keV)
IRT field-of-view	15’x15’
SXI positional accuracy (0.3-5 keV, 99% c.l.)	≤2 arcminutes
XGIS positional accuracy (2-150 keV, 90% c.l.)	≤7 arcminutes (50% of the triggered sGRB) ≤15 arcminutes (90% of the triggered sGRB)
IRT positional accuracy (5σ detections)	≤5 arcsecond (real-time) ≤1 arcsecond (post-processing)

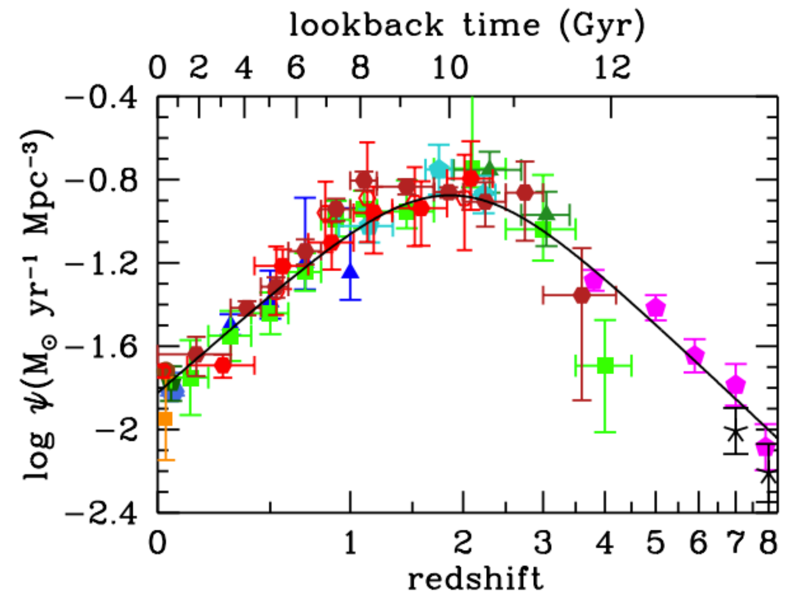
GW 3G + THESEUS

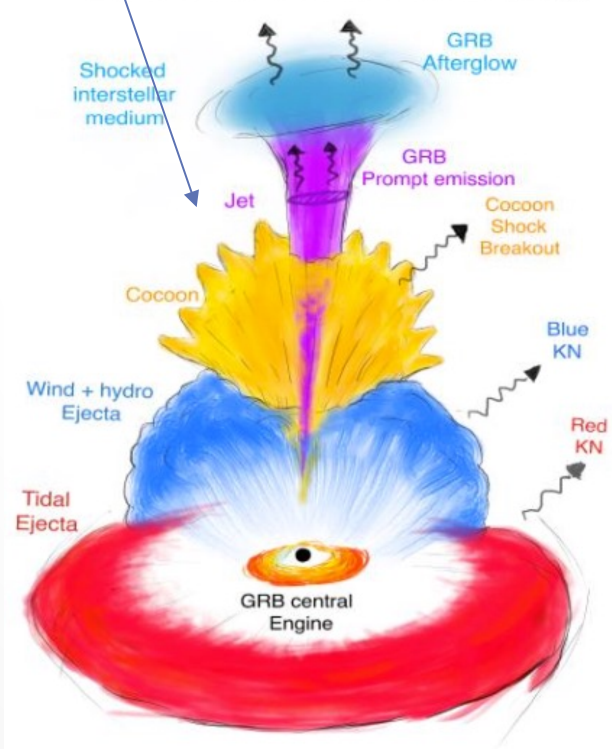
Before star formation

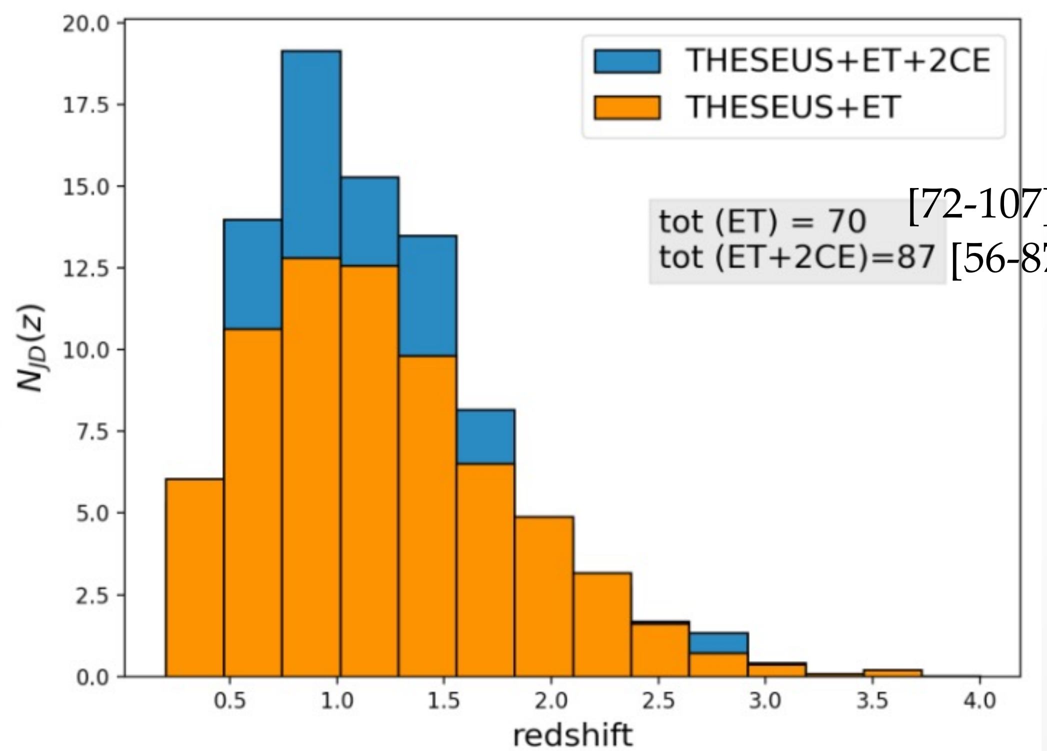


Signals with
S/N ~ 200
(~10x present)

Binary neutron stars



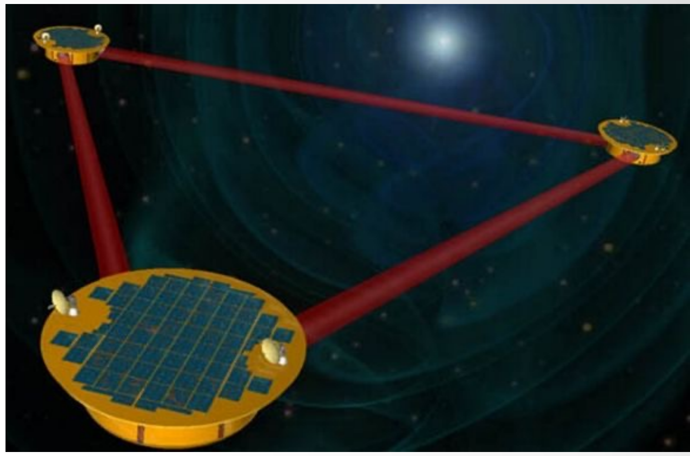




[72-107]
[56-87]

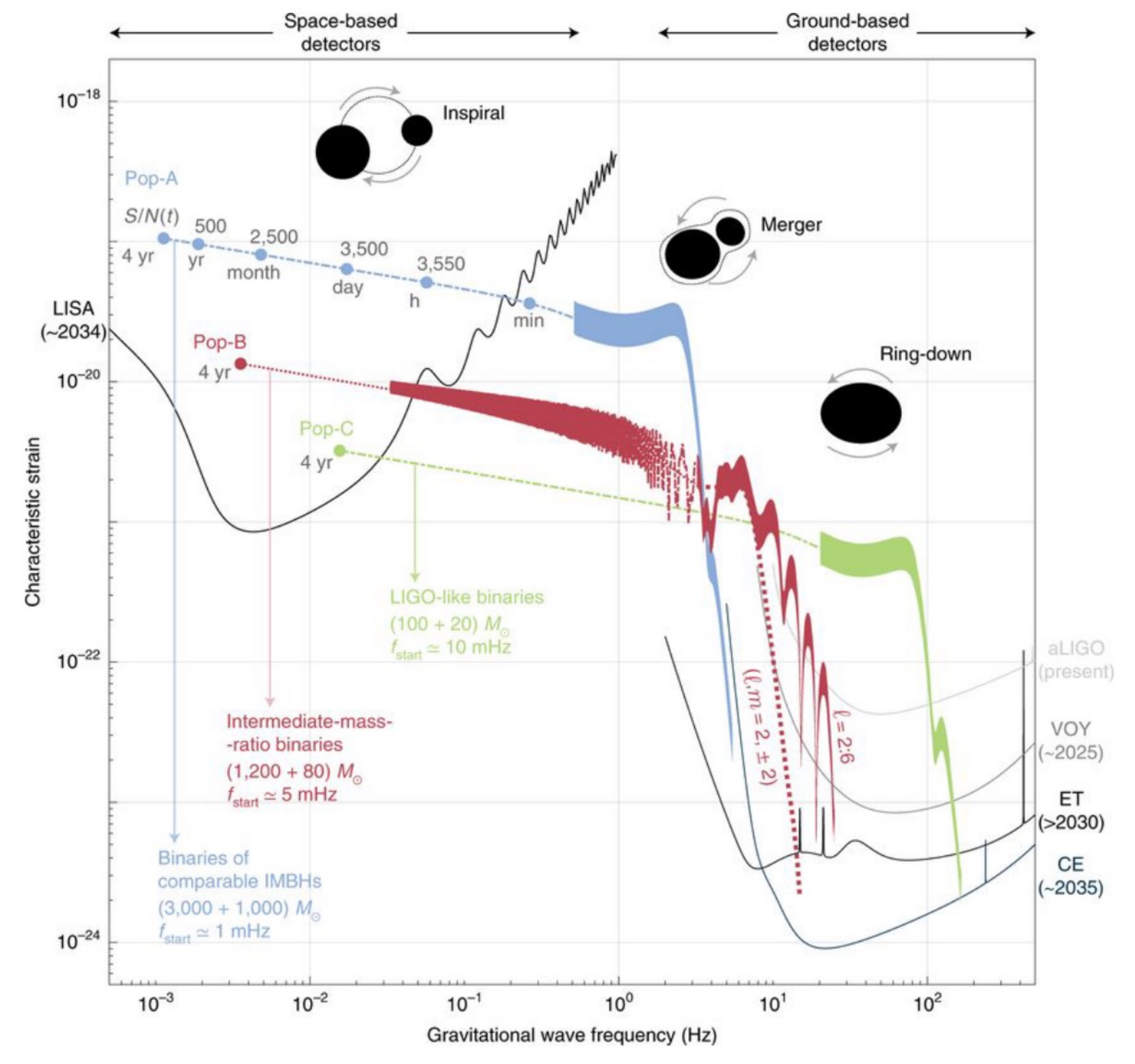
- Will allow to search on large error box with an accurate precision
- Need a dozen of detections to reach 1 % accuracy on H_0

Going into space : LISA



- 3 satellites, time delay interferometry
- Arms with few millions km
- Scientific case:
    - Merger of supermassive black holes
    - Compact solar masses binaries (WD and NS), observe accurately the inspiral phase
    - Extreme mass ratio inspirals , mass ratio > 200
    - BBH, can predict merger time for ground based detectors one year in advance
    - Stochastic background
- Test mission (Pathfinder) showed the readiness of the technics
- Planned for 2037

GW multi-wavelength



Other tools

…

Astronomy Time-domain challenges

One example

The Rubin Observatory will send about **10 million alerts per night over 10 years**

- Several orders of magnitude above current streams
- Current tools do not scale (~1TB / night)

Individually, each observatory of the next decade will not characterise all of its events

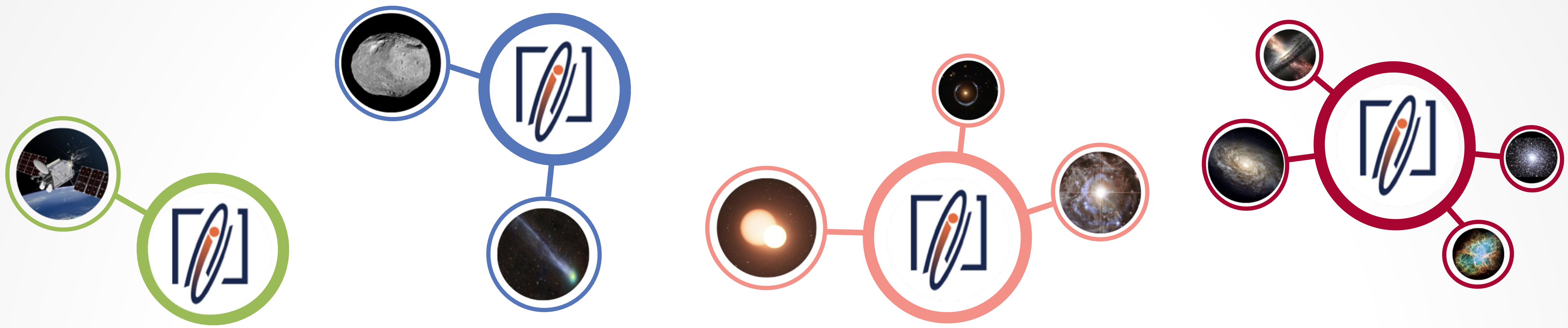
- Additional observations will be necessary, and often within a short time delay after initial discovery
- The need for **multi-messenger astronomy** is rising fast

Follow-up resources will be crucial but limited!

Brokers and TOM systems under development

FINK

Turning information into science



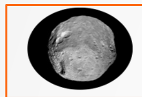
Alert information solely is not enough – we need experts to extract the science!

- More than 30 scientists worldwide contribute to the project.

Our ambition is to **study the transient sky as a whole**, from solar system objects to galactic and extragalactic science.

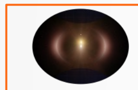
Ongoing science projects

 *Satellites – arxiv:2202.05719*

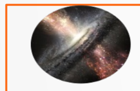
 *Solar System Objects – MITI grant – Rubin x Euclid*

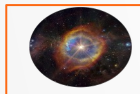
 *Variability in our Galaxy – Fink hackathon in Nov 2022*

 *Young Stellar objects*

 *Microlensing effect*

 *Kilonova – arxiv:2202.09766,2210.17433*

 *AGN – arxiv:2211.10987*

 *Supernovae & Core-collapse – arxiv:2111.11438*

 *Pair-instability Supernovae*

 *Orphan GRB*

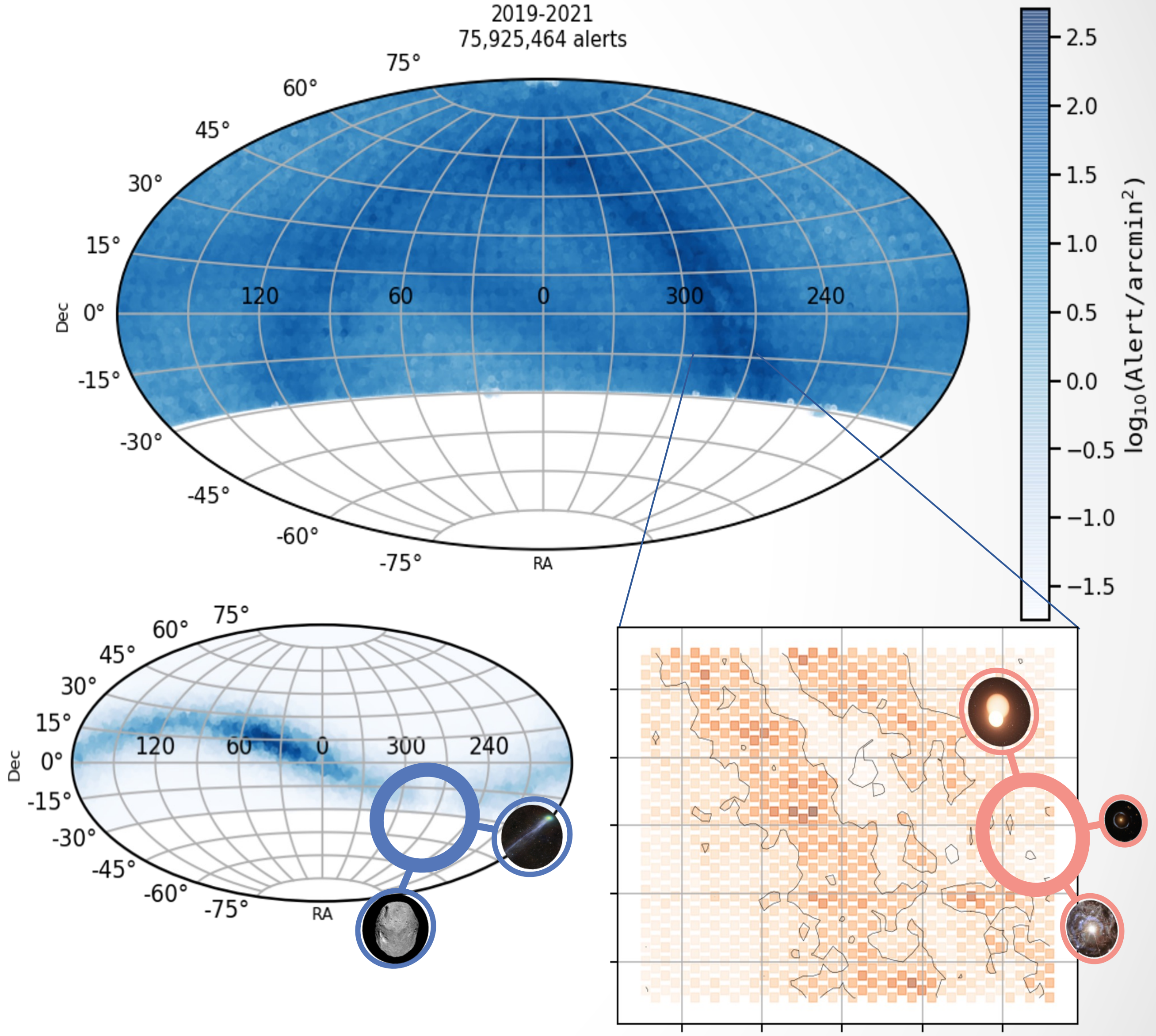
Multi-messenger analysis, Anomaly detection, and others!

ZTF/Fink statistics

163 million alerts received, 110 million processed (https://fink-portal.org/stats)

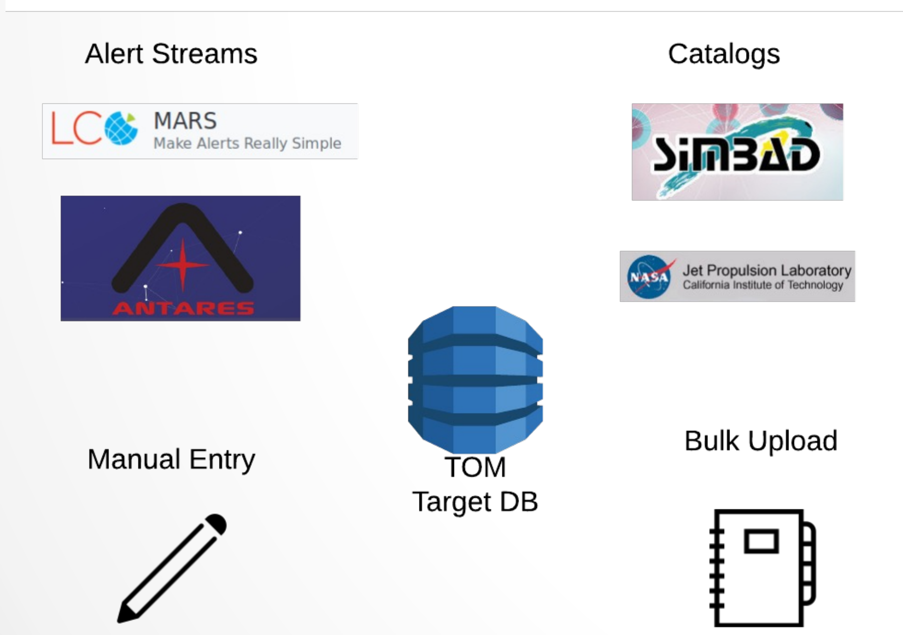
Typical nightly rates (200,000 alerts):

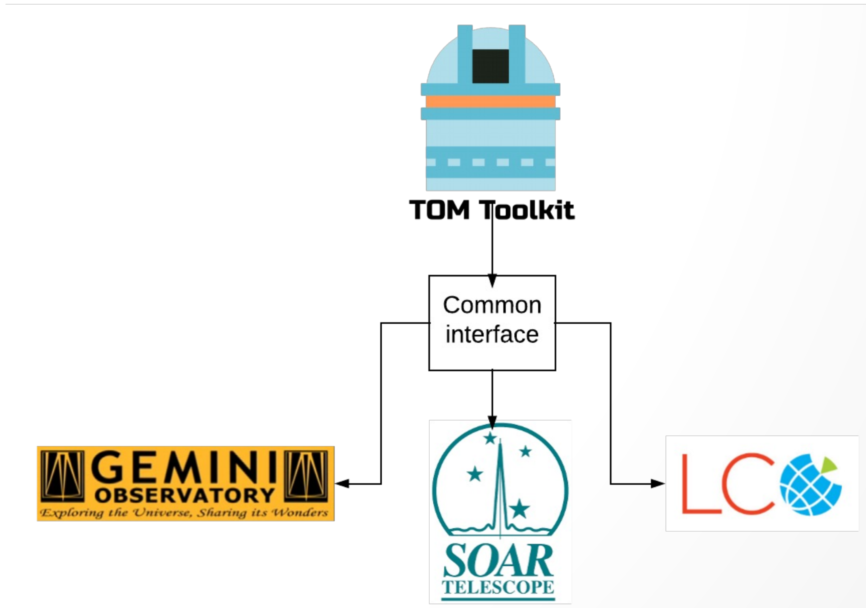
- ~75,000 known variable stars
- ~25,000 known SSO
- ~100 new SSO candidates
- ~100 new supernovae & core-collapse candidates
- ~10 (un)identified satellite glints
- ~5 new SN Ia candidates
- ~1 fast transient candidate (KN, GRB, CV ...)
- ~1 new microlensing candidate



Virtual observatory/ TOM

- Need tools for display/correlations/ … -> virtual observatory like the one in Strasbourg : aggregate all infos in one place
- Filtering and request follow-up observation, enrich filtering : Target and Observation Manager





Conclusions

- This is again only a part of the game, many observatories were not discussed here (like SKA, CTA, …) and messengers (neutrinos)
- The next decade will brings much more information and allow exciting mutli-messenger physics
- Time domain astronomy will be one of the key projects with lot of data to digest and filter
- The next generation of GW instruments will allow multi-wavelength study and several projects are under study to allow full science return