Commissariat à l'Energie atomique
et aux Energies alternatives

ULTRASAT within the

Multi-Mission Multi-Messenger Observation Planning Toolkit (M^{4}OPT)

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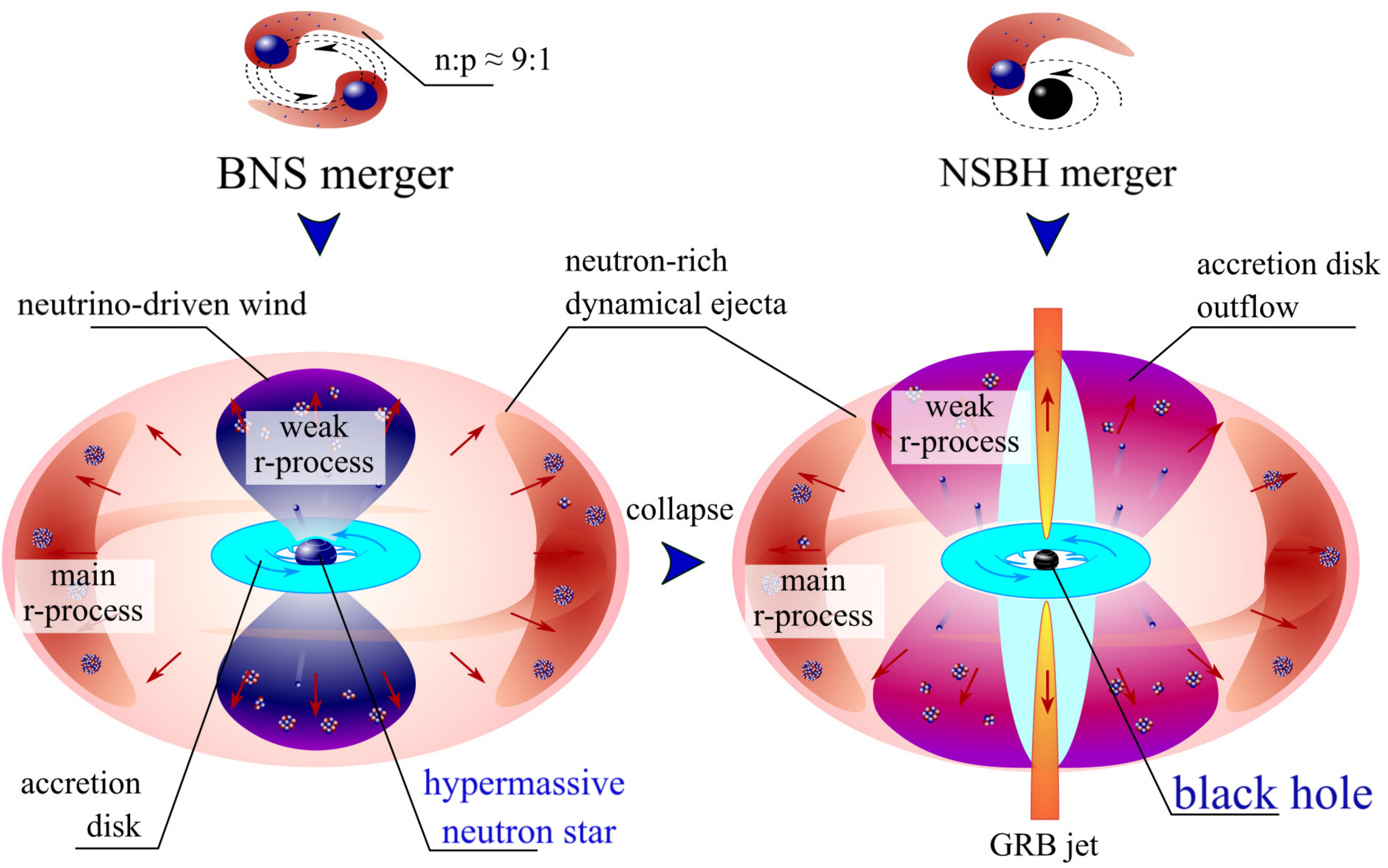
GW170817 / AT2017gfo

- Kilonova emit across UV / Optical / IR emissions.
- Swift: first UV data ~15h after GW (Evans+ 2017)
- Early models → bright optical/UV (Li & Paczyński 1998)
- Lanthanide opacity → faint IR (Kasen+ 2013; Metzger & Berger 2012).
- GEO GW170817 → unexpectedly bright & blue early (Pian+ 2017)
- Origin uncertain: high-Y_e ejecta vs Shock heating from jet cocoon

Image adapted from M.R. Mumpower (concept from Korobkin et al. 2019)



Blue KN:	Red KN:
$Y_e > 0.25$ —> low opacity	$Y_e < 0.25$ —> high
lanthanide-free	lanthanide-rich

$$Y_e = \frac{n_e}{n_p + n_n}$$

Early UV light reveals what powers a kilonova

Why the Early UV observations matter?

- The first hours post-merger are crucial for distinguishing between **shock-powered** and **r-process powered** emission predictions, particularly in the near-ultraviolet (**NUV**) and far-ultraviolet (**FUV**) bands.
- **NUV alone is ambiguous**; while early FUV observations provide the clearest diagnostic.
- **UVEX** (**launch 2030**): NASA's next Mid-Explorer mission, performing deep, cadenced **NUV/FUV** time-domain surveys with high image quality, and following up multi-messenger and community targets.

ULTRASAT: Paving the Way Before UVEX

- **ULTRASAT's wide-field NUV coverage** and **rapid response** enable the **earliest kilonova detections** and trigger deeper UV, optical, and IR follow-up to break model degeneracies.

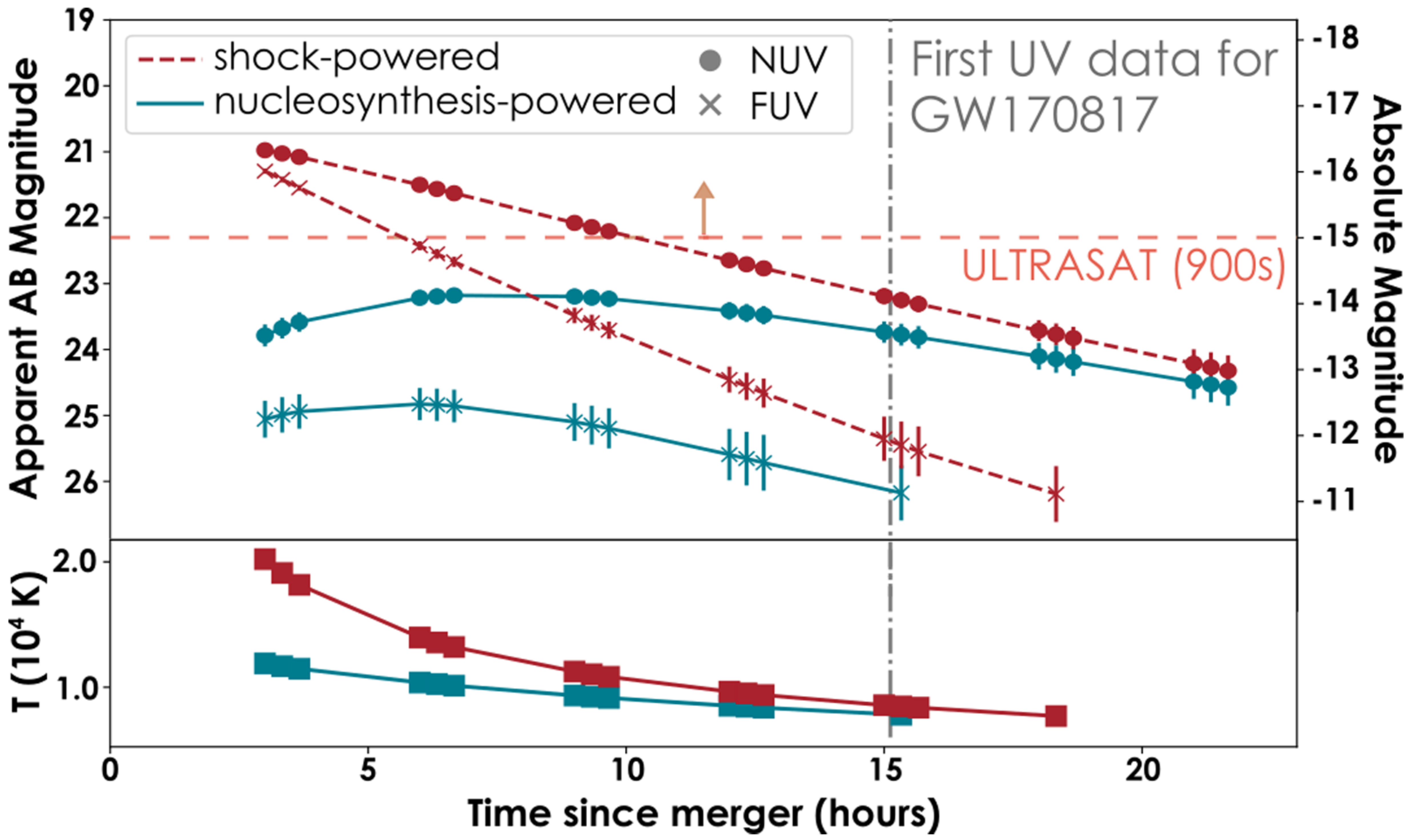
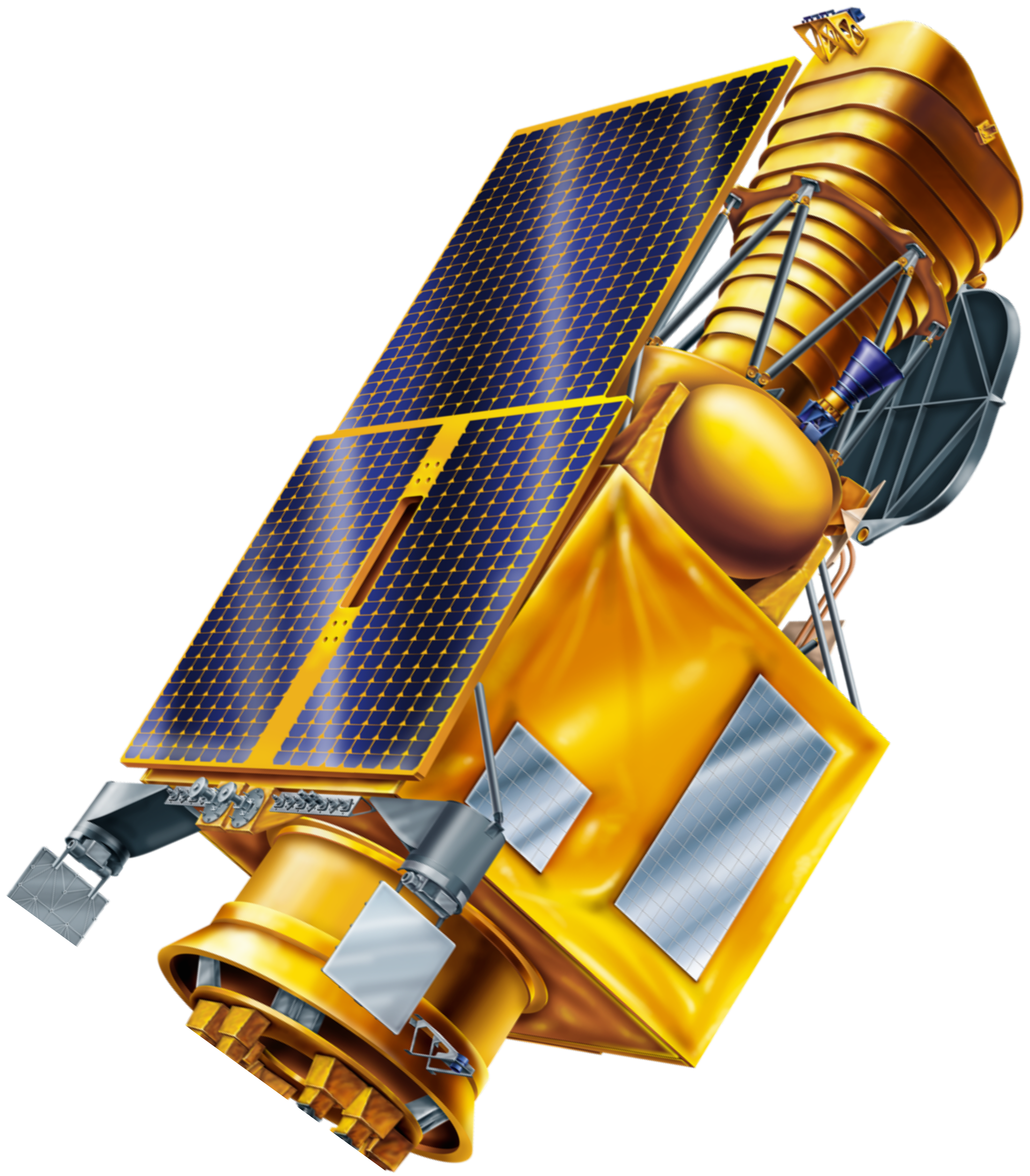


Figure from UltraViolet EXplorer (UVEX) simulation (Kulkarni+ 2023, arXiv:2111.15608)

Next-generation NUV time-domain space telescope

ULTRASAT
SKYLIGHT TO SPACE



Ultraviolet Transient Astronomy Satellite

Image credit : https://www.weizmann.ac.il/ultrasat/

Mission facts

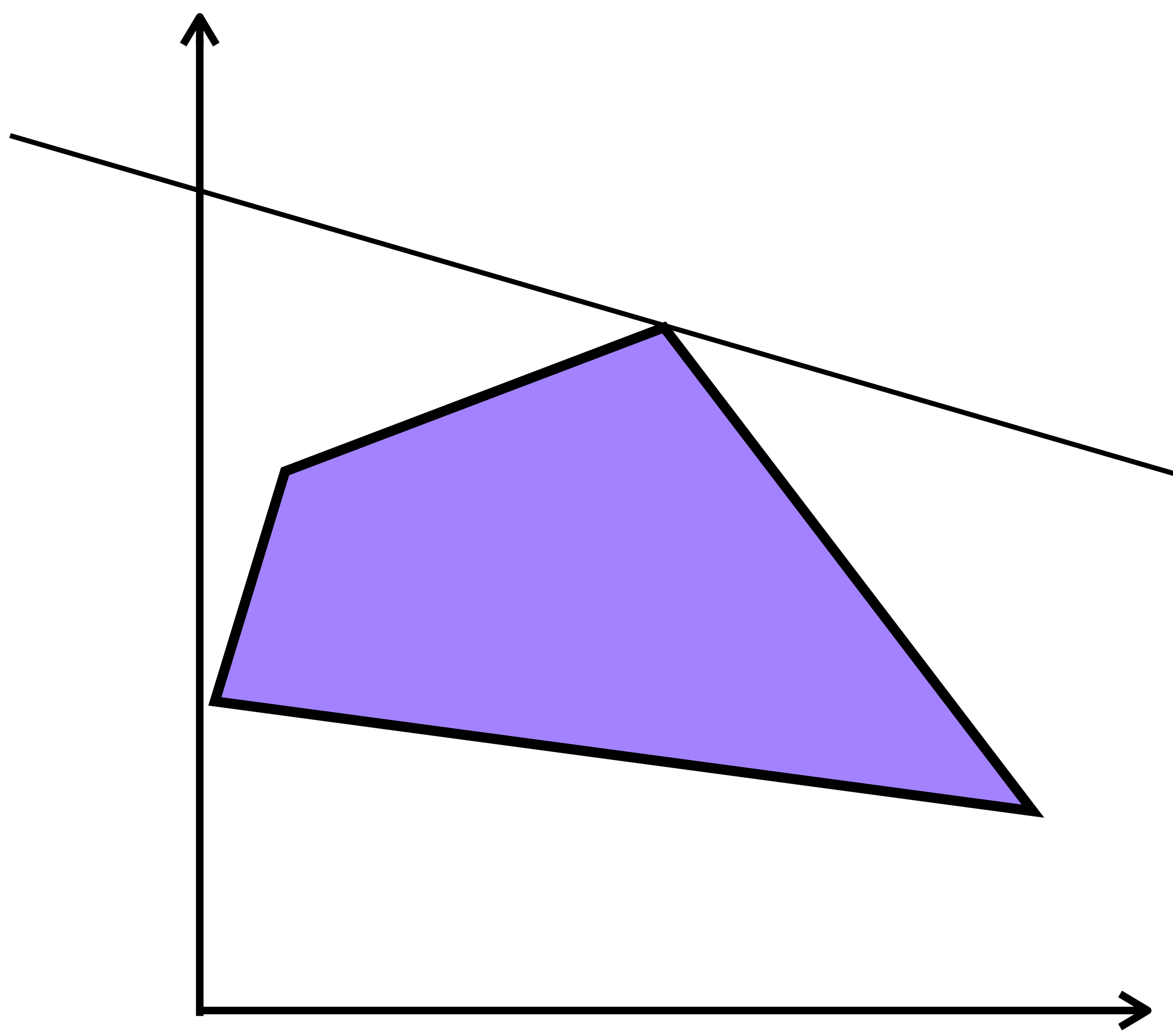
- Funded by **ISA** & **WIS** (Israel), **Zeuthen** (Germany)
- Launch by **NASA** (2027)
- NUV deep time-domain survey
- Fast response: slew in minutes to >50% sky
- Wide FoV facilitates GW follow-up
- GEO orbit, 3 years (extendable to 6)
- Complements: UVEX (UV), ZTF/Rubin (optical–IR), JWST/Roman (IR)

NUV Imaging Bandpass	2300-2900 Å
FOV	4 ×7.14°×7.14°
Sensitivity	>22.5 AB (S/N 10, 900 s)
Prime Mission	3 years
Launch	2027

How to react faster to catch the early-time UV of kilonovae?

Problem

- Early UV emission fades within hours → fast reaction is crucial
- Naive scheduling wastes exposure time, lowering detection probability

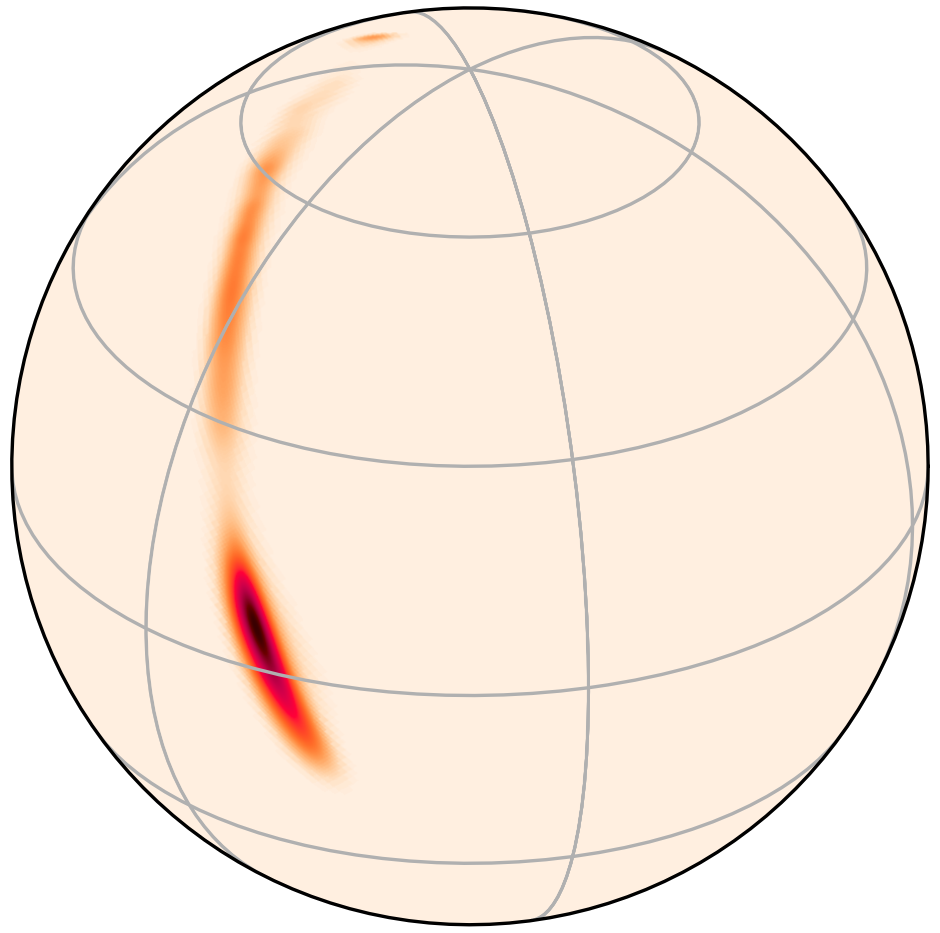


Linear Programming

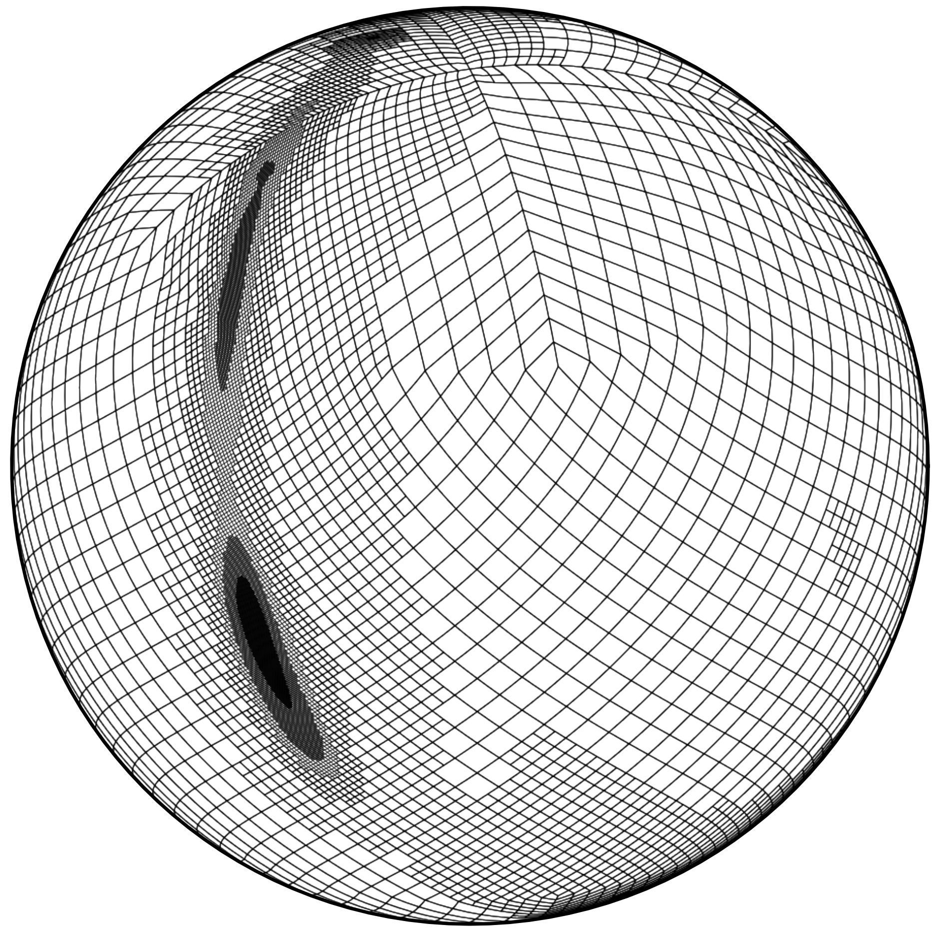
Solution

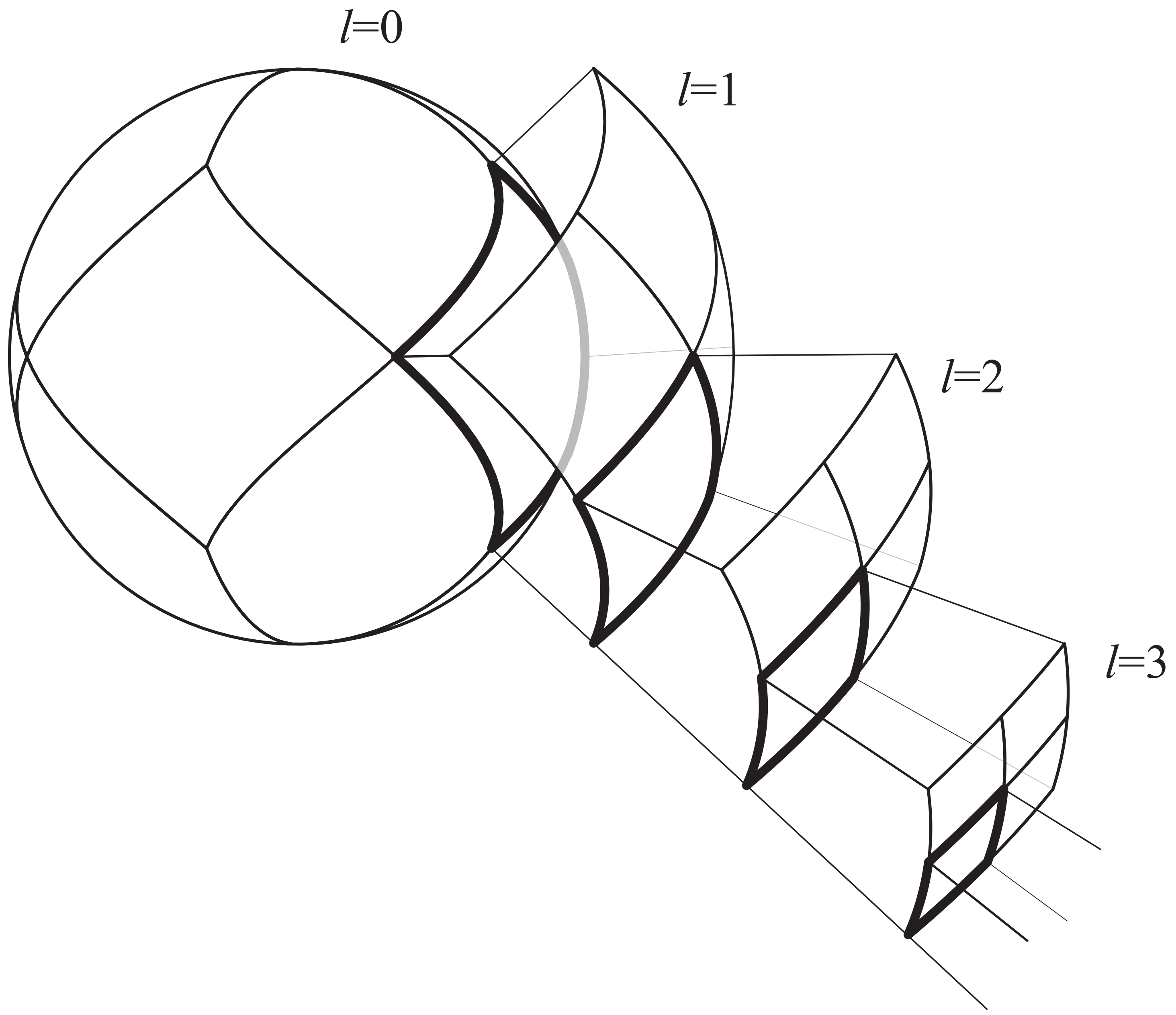
- Optimal strategy: dynamically adjust exposure time for each field
- Modeled as Mixed Integer Linear Programming (MILP) → solved with IBM CPLEX
- Implemented in **M^4OPT** (open-source, multi-mission, multi-messenger scheduling toolkit)
- Accounts for **source brightness** (absolute magnitude modeled as a Gaussian distribution) and full **3D GW localization** (sky + distance)
- **Compared to tilepy** (**Seglar-Arroyo et al. 2025**, open source), which focuses on *fast tiling*, **M^4OPT extends this** with flexible exposure times and additional observational constraints for globally optimal plans

Probability Sky Map



Multi-Resolution HEALPix Tiles





$$\begin{cases} \ell = \log_2(\text{nside}) \\ \text{nside} = 2^{\ell} \\ N_{\text{pix}} = 12 \times \text{nside}^2 \end{cases}$$

(Singer et al. 2022, [DOI:10.3847/1538-3881/ac5ab8](https://doi.org/10.3847/1538-3881/ac5ab8))

HEALPix

Hierarchical Equal Area isoLatitude Pixelization

- is a **map projection** that is **area-preserving** and **minimizes artifacts** at the poles and seams
- is a **spatial indexing scheme** that is popular in astronomy
- is very much like a **geocode**
- maps 2 angle coordinates (longitude/right ascension, latitude/declination) to one integer using a **space-filling curve**
- is a multi-resolution **tree** data structure
- was invented for **cosmic microwave background** astronomy
- extensively used by the gravitational-wave community as the **standard format for probability maps**

Constraints

The scheduler optimizes the detection probability subject to these constraints:

Field of regard: stay out of Sun, Earth, and Moon avoidance zones

Slew time: limits on angular acceleration and rate

Roll: must observe at the optimal roll angle for the solar array

Visits: visit each field twice (to increase transient detection probability)

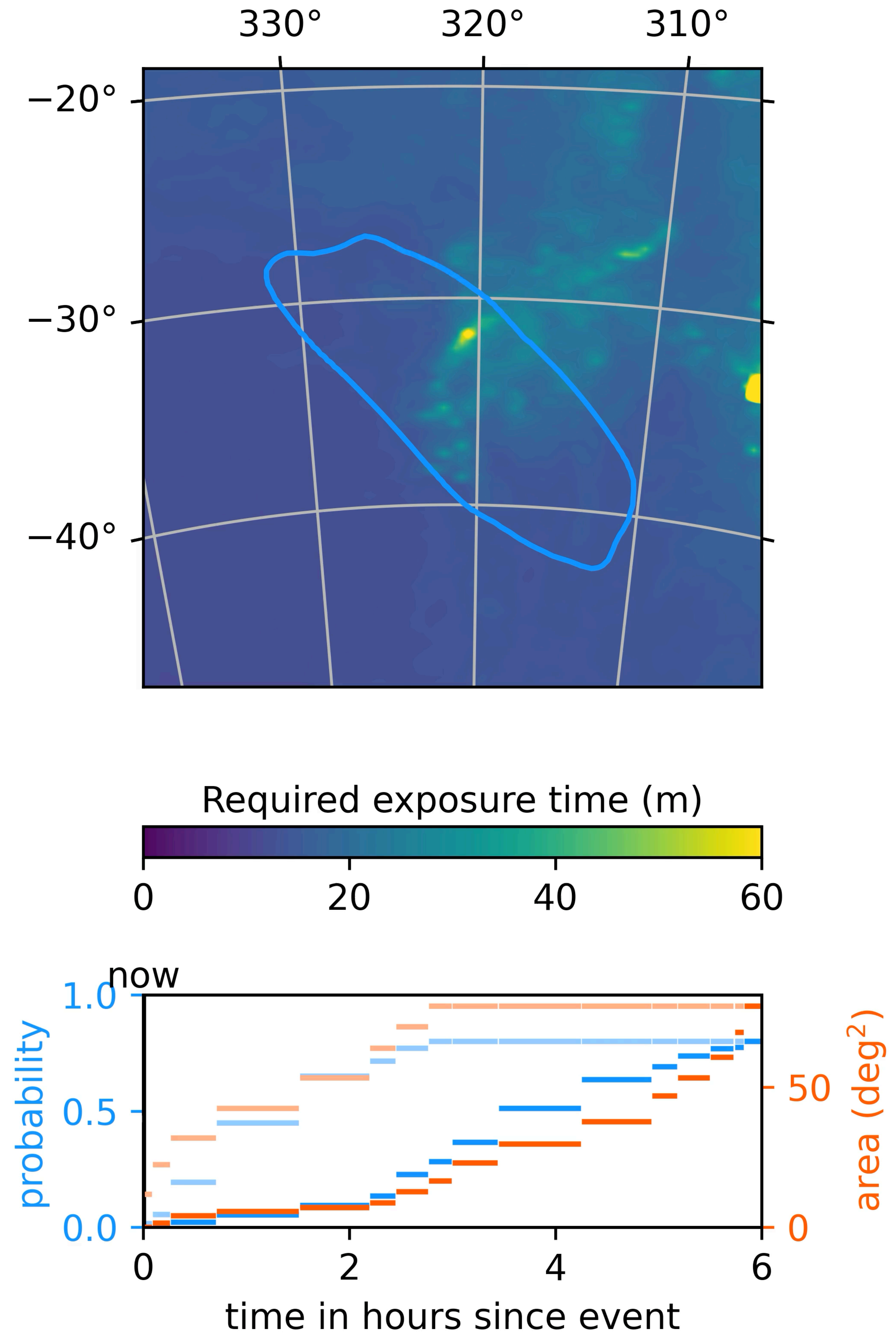
Cadence: minimum time between revisits of a field

Localization: 3D prob. distribution over source's unknown sky location, distance

Luminosity function: distribution of source's unknown abs. magnitude

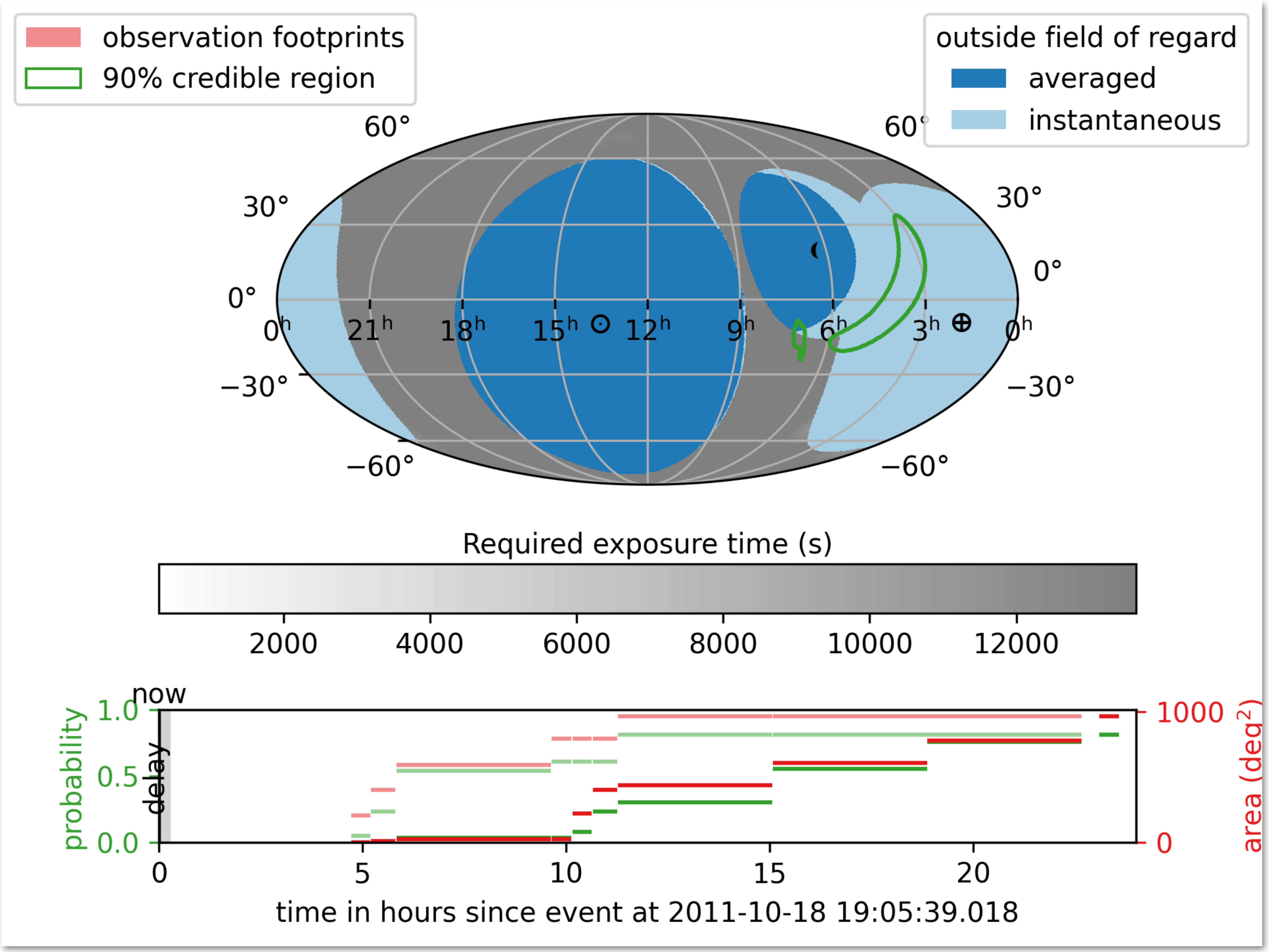
Exposure time: varied dynamically for each field; limiting magnitude for each pixel depends on zodiacal light, Galactic diffuse background, and dust extinction

Detection probability: integral over the footprint of the selected fields of the luminosity function, sky location probability distribution, and distance



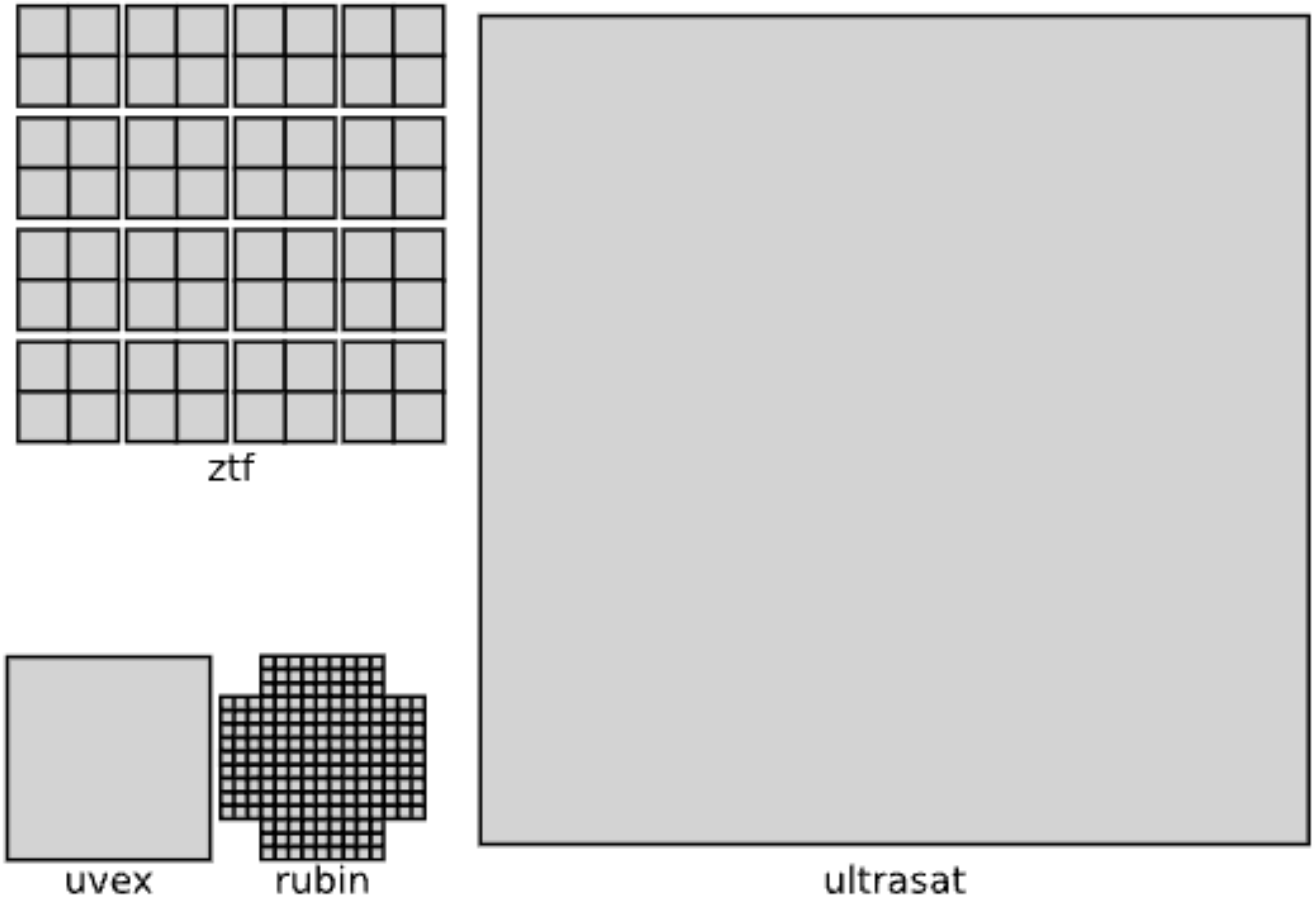
Animation adapted from Leo Singer

M4OPT Observation Scheduler and Field of Regard



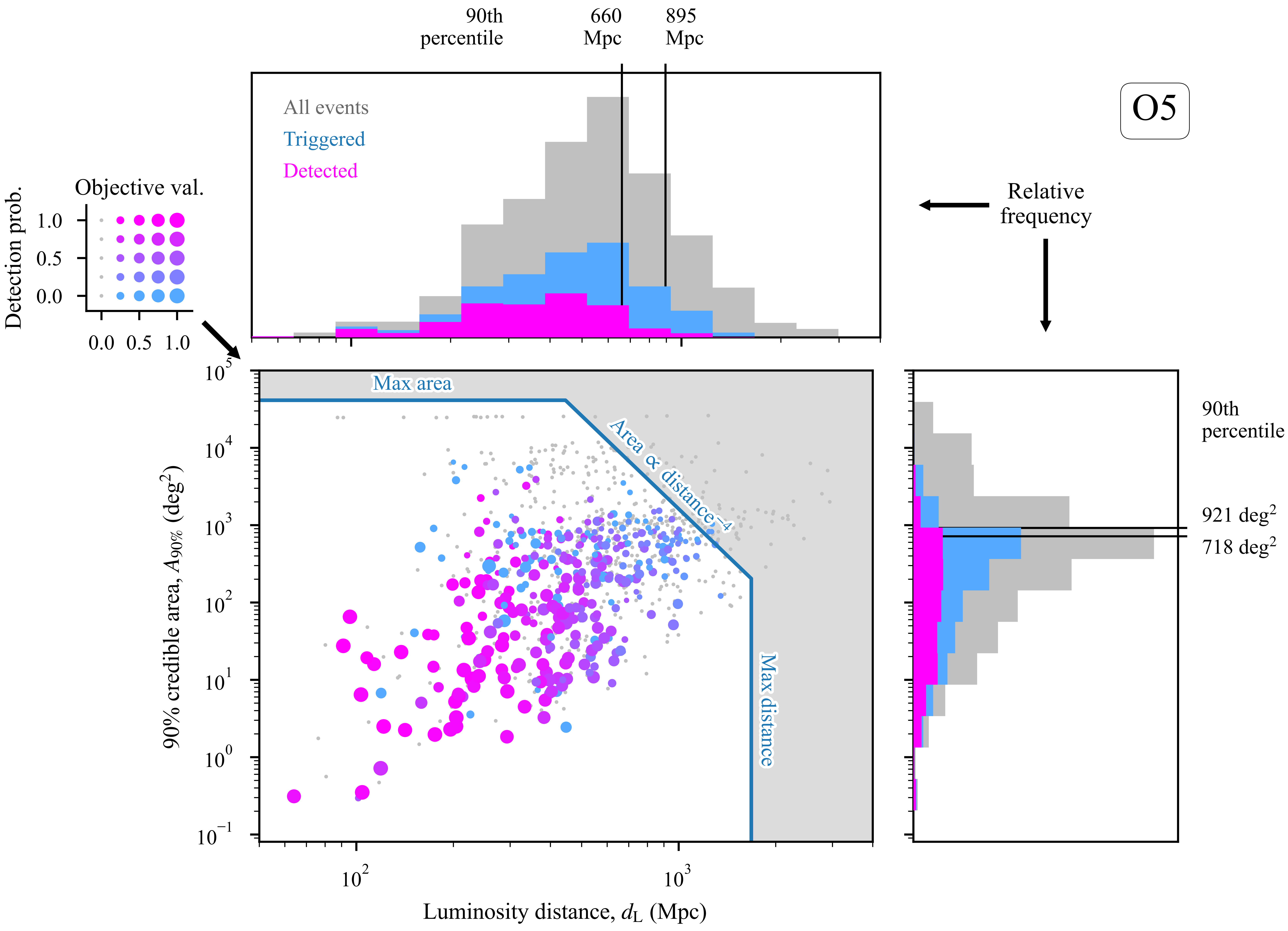
Supported Mission Field of View in M⁴OPT

Mission	Field of View (deg^2)
ULTRASAT	204
ZTF	47
UVEX	12.25
LSST / Rubin	9.6



Observing strategy

- Run the scheduler **for all events** (simulated GW mergers detected during O5 and O6)
- Trigger follow-up for all events that have a **detection probability ≥10%**.
- There is **no explicit threshold** on sky area or distance.



Following Singer et al. 2025

Catching Early UV Counterparts: ULTRASAT vs. UVEX in GW O5-O6

ULTRASAT (Israel's UV space mission)	O5	O6
Number of events selected	45^{+59}_{-27}	60^{+78}_{-35}
Number of events detected	20^{+27}_{-13}	27^{+36}_{-17}

UVEX (NASA's next Mid-range Explorer)	O5	O6
Number of events selected	29^{+39}_{-18}	43^{+56}_{-26}
Number of events detected	12^{+18}_{-9}	17^{+24}_{-11}

Join M^{4}OPT on GitHub

- It already supports **UVEX** and **ULTRASAT**, **ZTF** and **Rubin**
- **Use M^{4}OPT** for your project!
- **Contribute to M^{4}OPT** with issues and pull requests!
- Our first paper on **UVEX** has been published (**Singer et al. 2025**, PASP 137, 074501),
- The second paper, on **ULTRASAT**, will appear on **arXiv soon**.

https://github.com/m4opt/m4opt

EarthOrbitPlan: An Educational Framework for Multimessenger Observing Scenarios

https://earthorbitplan.readthedocs.io/en/latest/

EarthOrbitPlan

Edit on GitHub

EarthOrbitPlan: An Educational Framework for Multimessenger Observing Scenarios

EarthOrbitPlan is an educational framework that introduces students and researchers to an end-to-end workflow for simulating compact binary coalescences (CBC), from the detection of gravitational-wave events by the International Gravitational-wave Network (IGWN) to the preparation of electromagnetic follow-up observation plans using both **tilepy** and the M^{4}OPT toolkit. These follow-up campaigns span a wide range of facilities, from gamma-ray burst (GRB) observatories such as H.E.S.S. and Cherenkov Telescope Array (CTA), Far-UV instruments such as UVEX, to Near-UV missions like UVEX and ULTRASAT, and optical surveys including ZTF and Rubin.

See also

See the glossary for definitions of technical terms and abbreviations used throughout this documentation.

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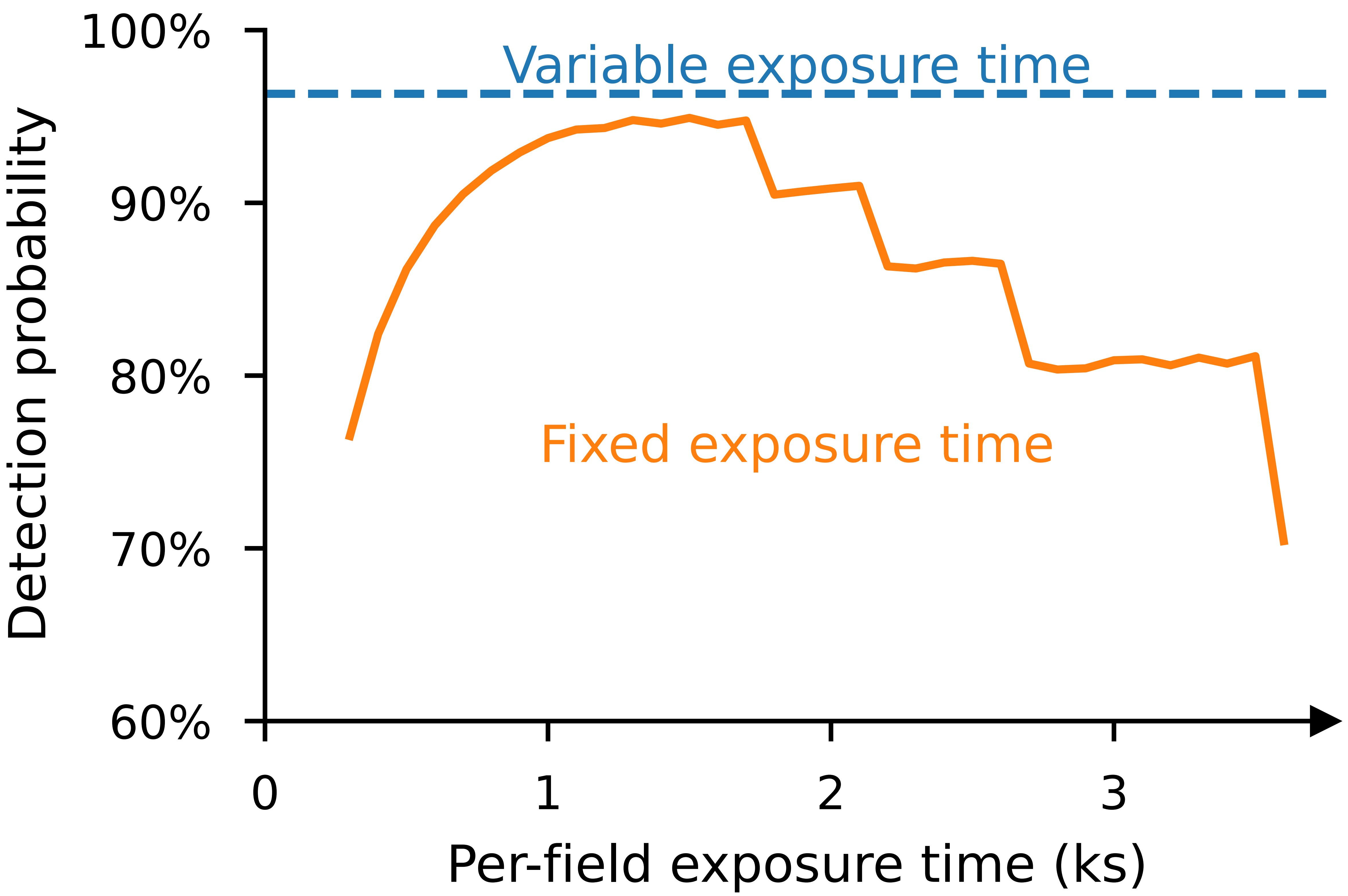
Dynamic exposure time strategy



Singer et al. 2025

Configuration parameters for ULTRASAT observations

Parameter	Design Specification
Optical characteristics	
Field of view	$4 \times 7.14^\circ \times 7.14^\circ$
Pixel scale	5.4 arcsec/pixel
Effective aperture	33 cm
NUV imaging bandpass	2300–2900 Å
Slew capabilities	
Maximum angular velocity	1 deg/s
Maximum angular acceleration	$0.025\ \mathrm{deg/s^2}$
Exclusion angles	
Sun exclusion	70°
Moon exclusion	35°
Earth exclusion	48°
Mission parameters	
Mission duration	3 yr
Launch date	2027

Estimated annual detection rates of CBCs for upcoming observing runs O5 and O6, with a signal-noise-ratio of 10.

Run	Network	BNS	NSBH	BBH
Annual Number of Detections				
O5	HLVK	67^{+86}_{-40}	13^{+19}_{-10}	480^{+600}_{-270}
O6	HLVK	79^{+101}_{-47}	15^{+23}_{-10}	570^{+720}_{-320}

Kiendrebeogo et al. 2023