Commissariat à l'Energie atomique
et aux Energies alternatives

Early UV follow-up of gravitational wave events with the

Ultraviolet Transient Astronomy Satellite (ULTRASAT)

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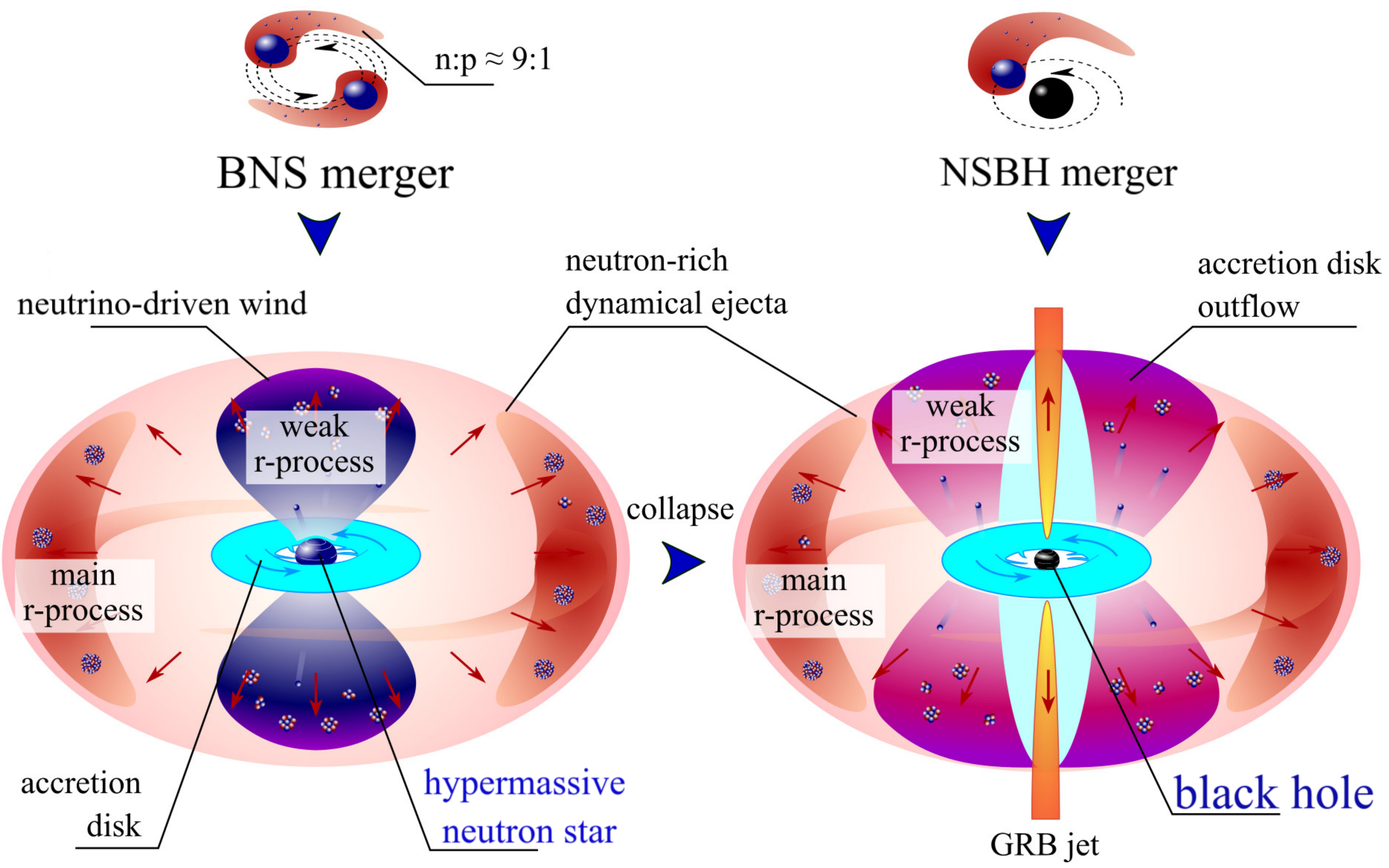
GW170817 / AT2017gfo

- 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:
$Y_e > 0.25$ —> low opacity
lanthanide-free

Red KN:
$Y_e < 0.25$ —> high
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.
- **ULTRASAT's wide-field NUV** and **rapid response** enable the **earliest kilonova detections** and trigger deeper UV, optical, and IR follow-up to break the degeneracy.

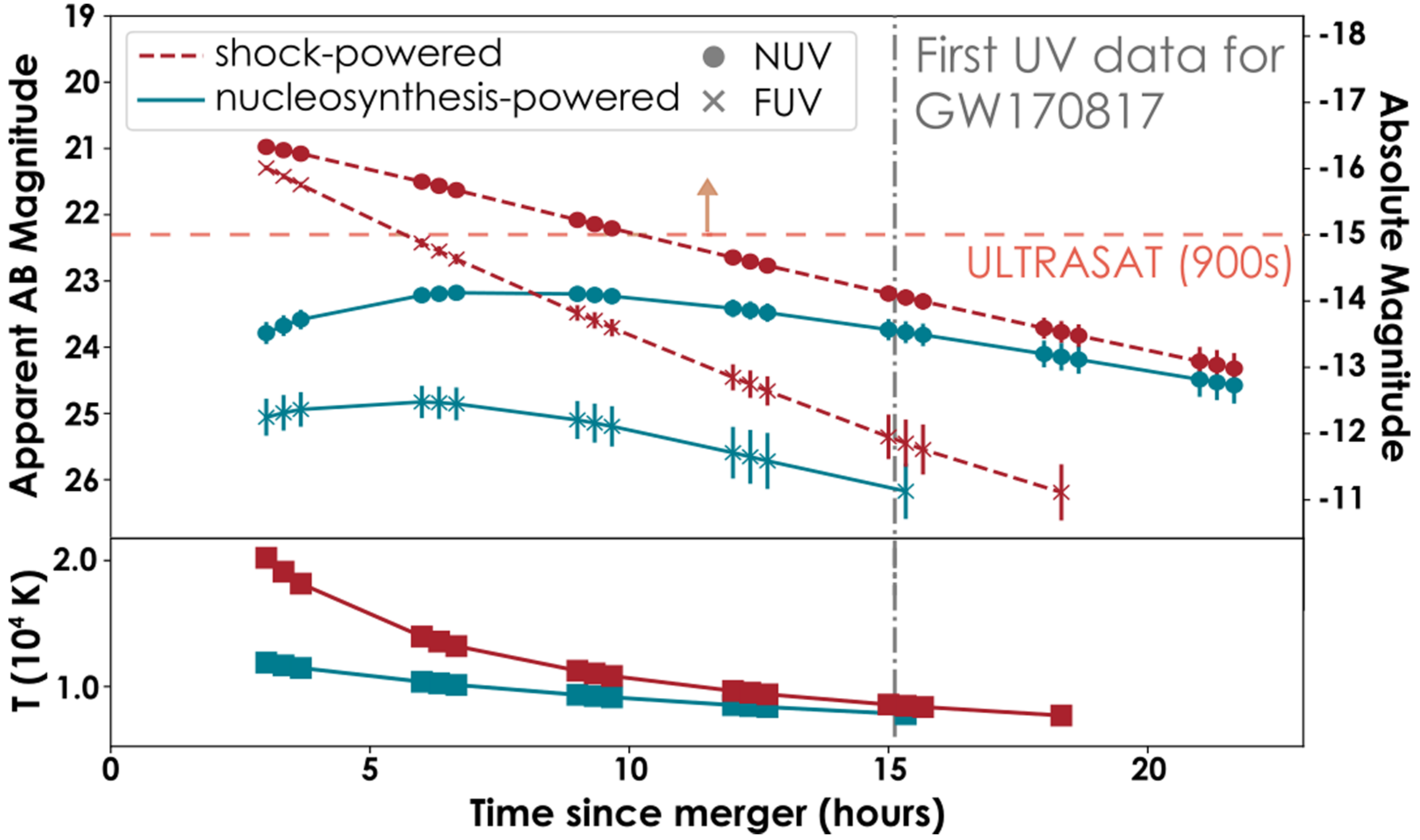


Figure from UltraViolet EXplorer (UVEX) simulation (Kulkarni+ 2023, arXiv:2111.15608)

ULTRASAT
SKYLIGHT TO SPACE

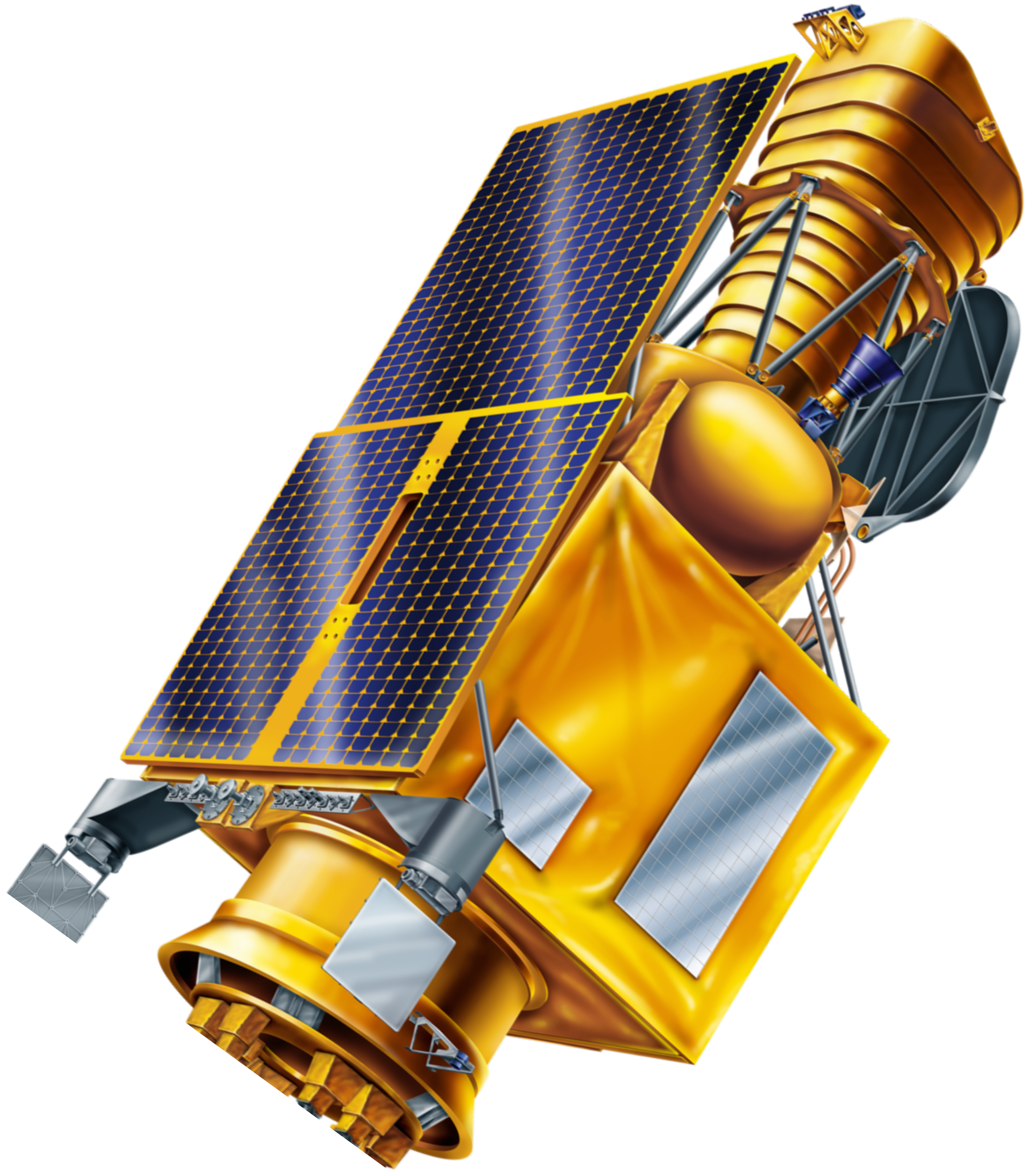


Image credit : https://www.weizmann.ac.il/ultrasat/

Next-generation NUV time-domain space telescope

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?

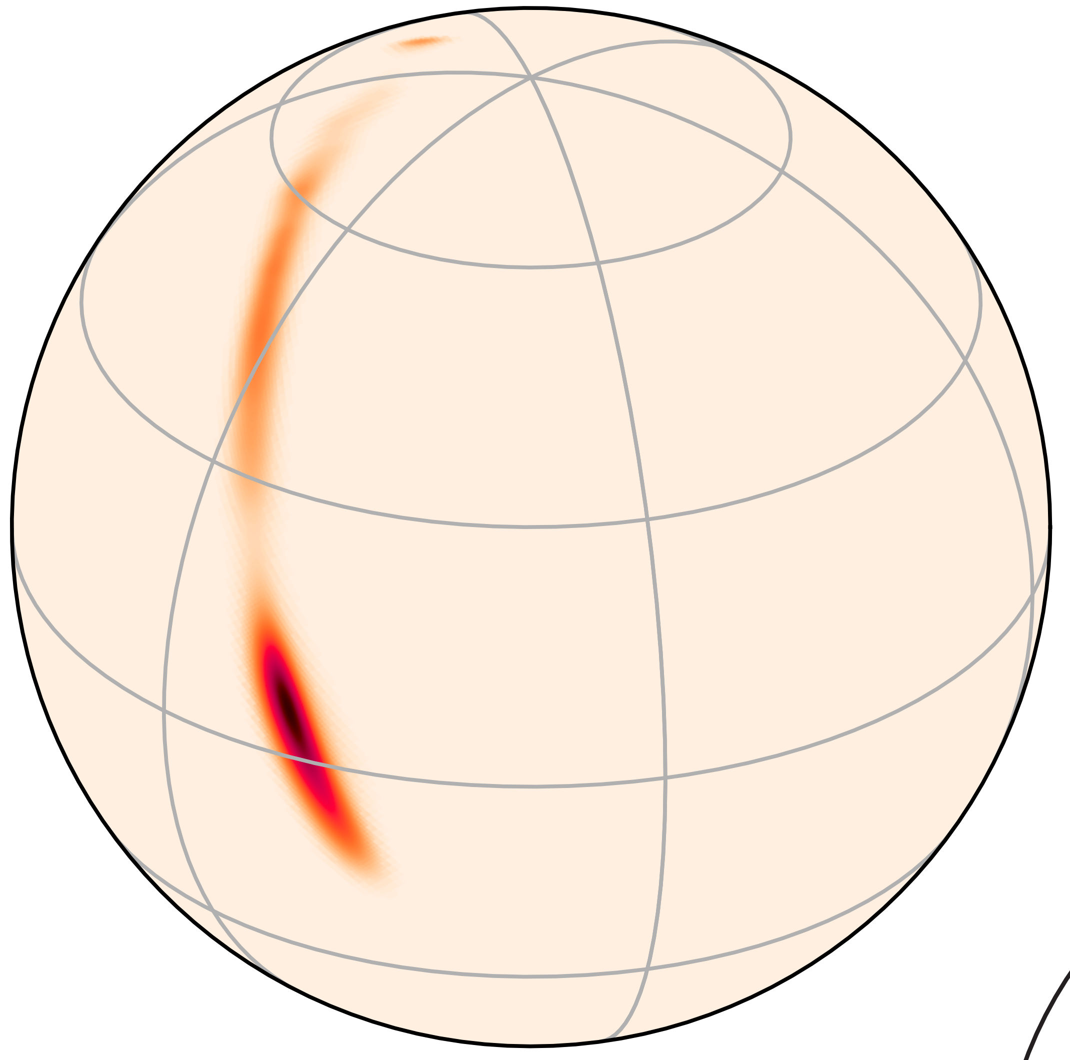
Problem

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

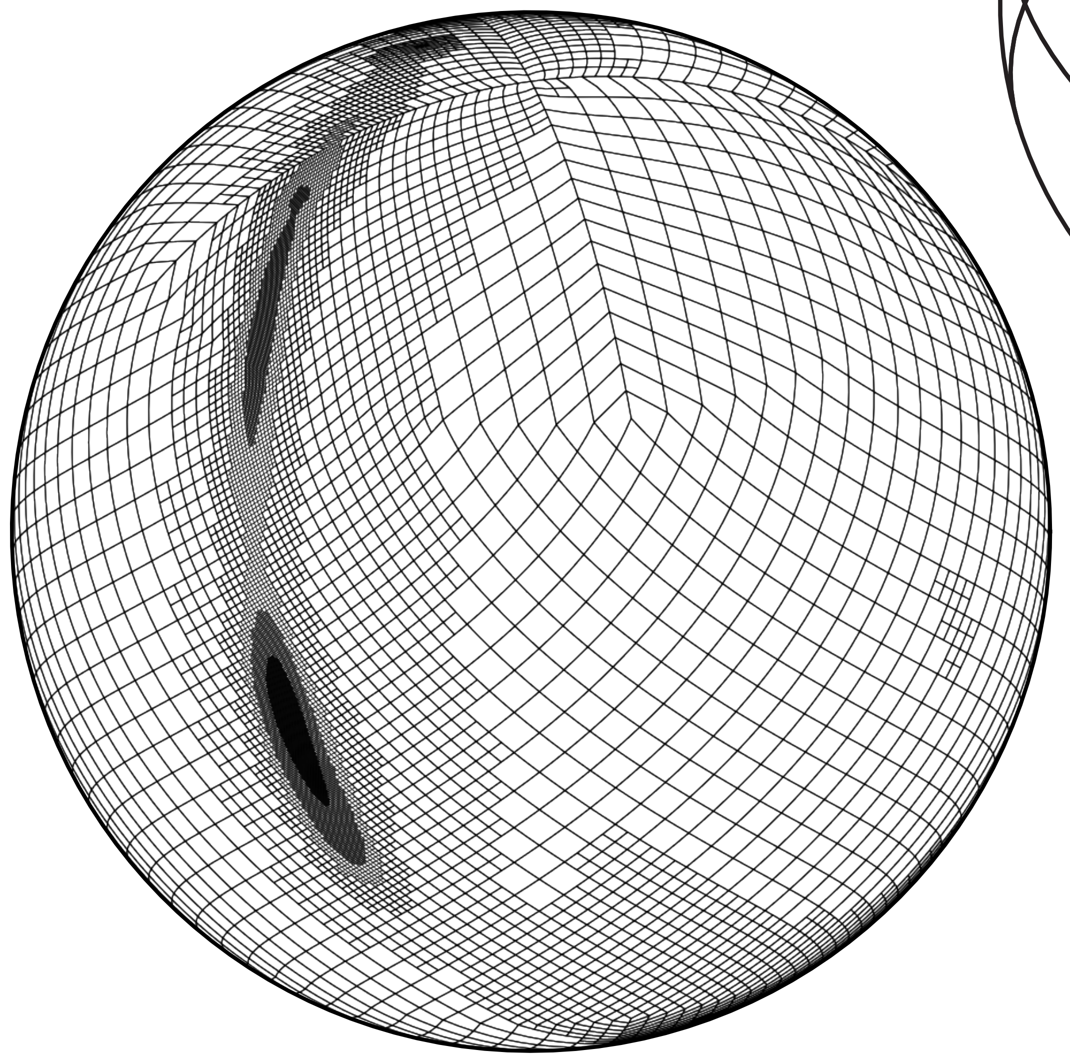
Solution

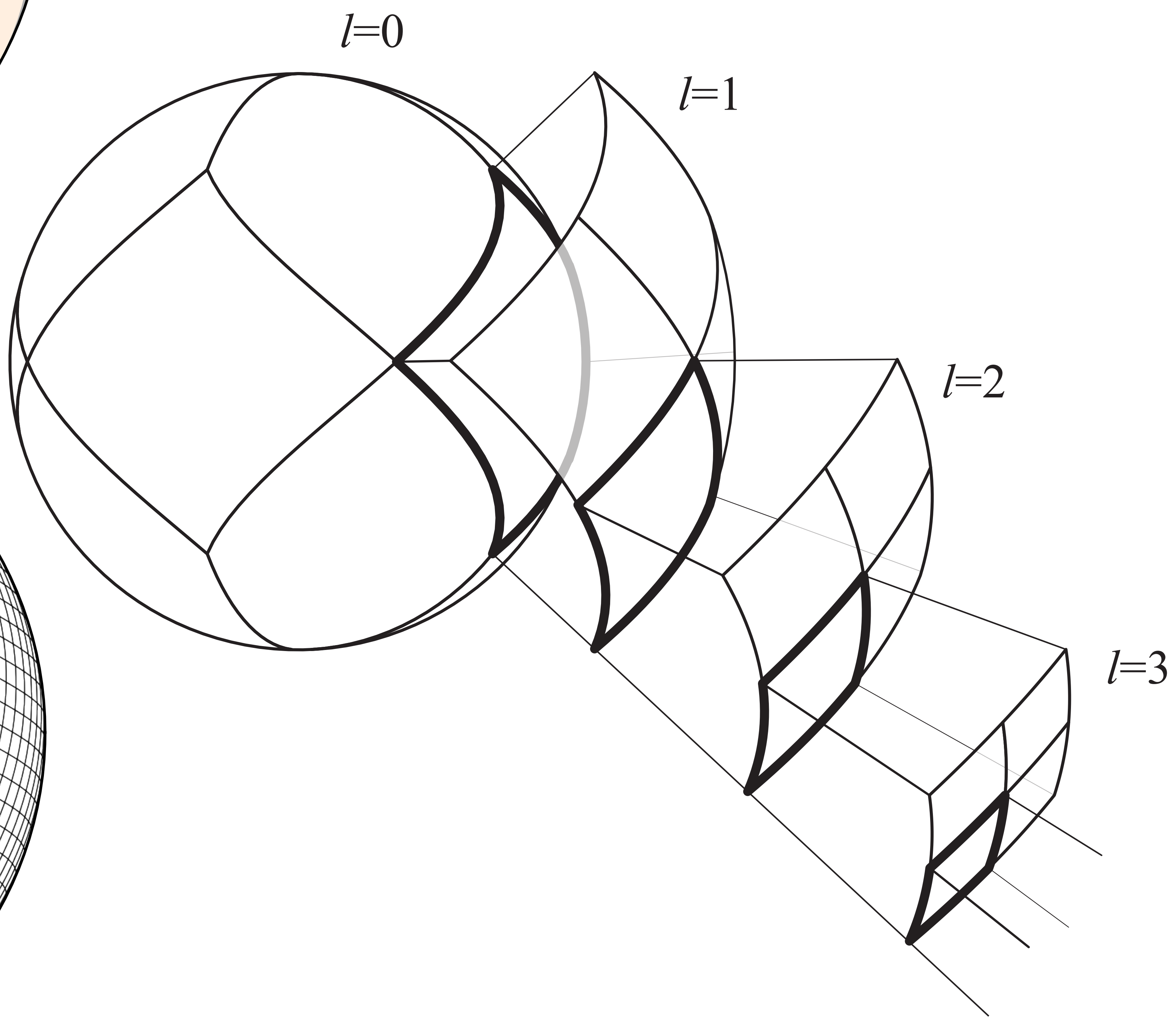
- Optimal strategy: dynamically adjust exposure time for each field
- Modeled as Mixed Integer Linear Programming (MILP) → solved with IBM CPLEX
- Implemented in M^{4}OPT (open-source, multi-mission, multi-messenger scheduling toolkit)
- Accounts for **source brightness** (absolute magnitude modeled 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^{4}OPT **extends this** with flexible exposure times and additional observational constraints for globally optimal plans
- Both **tilepy** and M^{4}OPT were developed with significant contributions from **CEA/IRFU**

Probability Sky Map



Multi-Resolution HEALPix Tiles





(Leo Singer et al. 2025, [DOI:10.1088/1538-3873/adcfc6](https://doi.org/10.1088/1538-3873/adcfc6))

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)

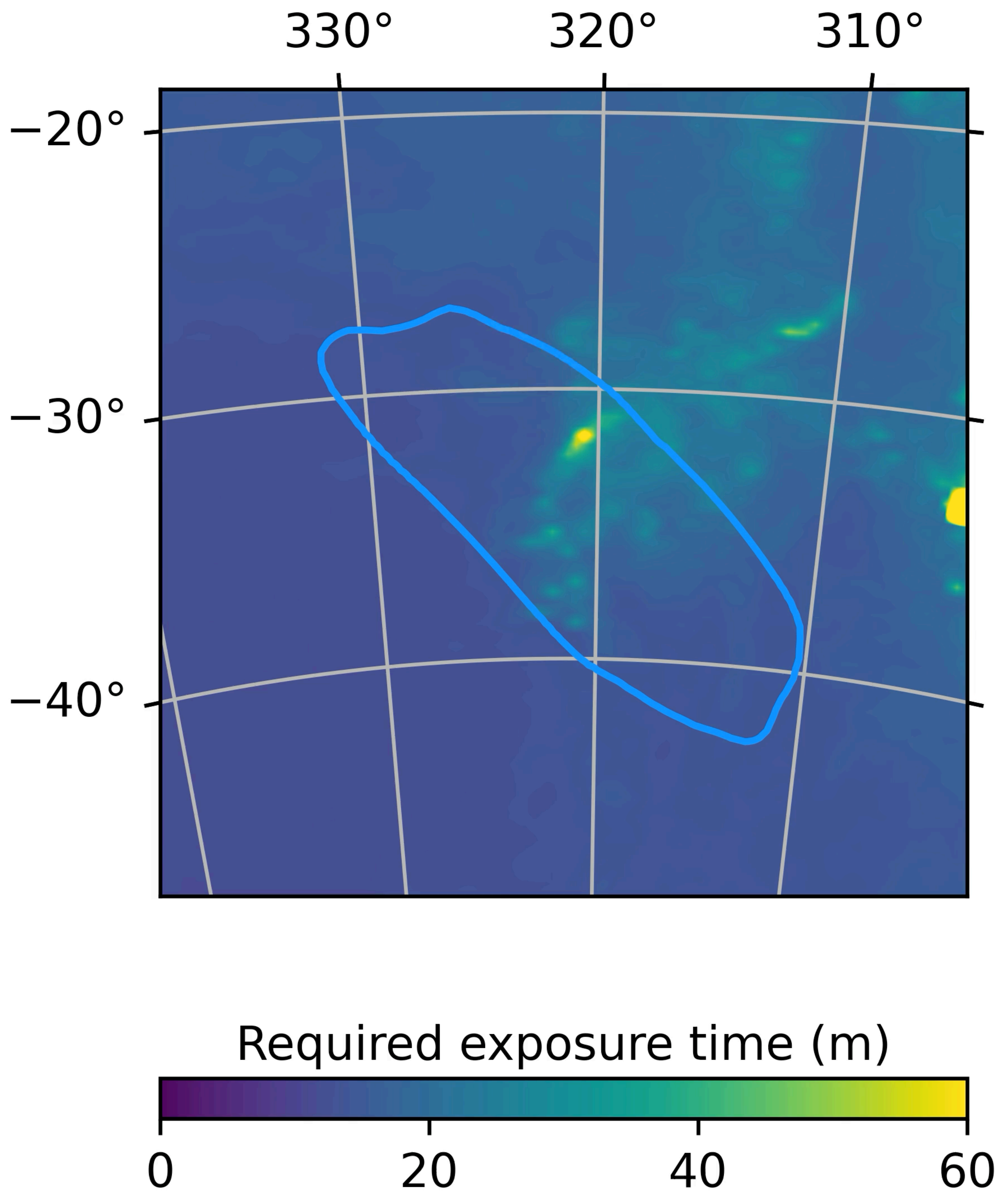
Cadence: minimum time between revisits of a field

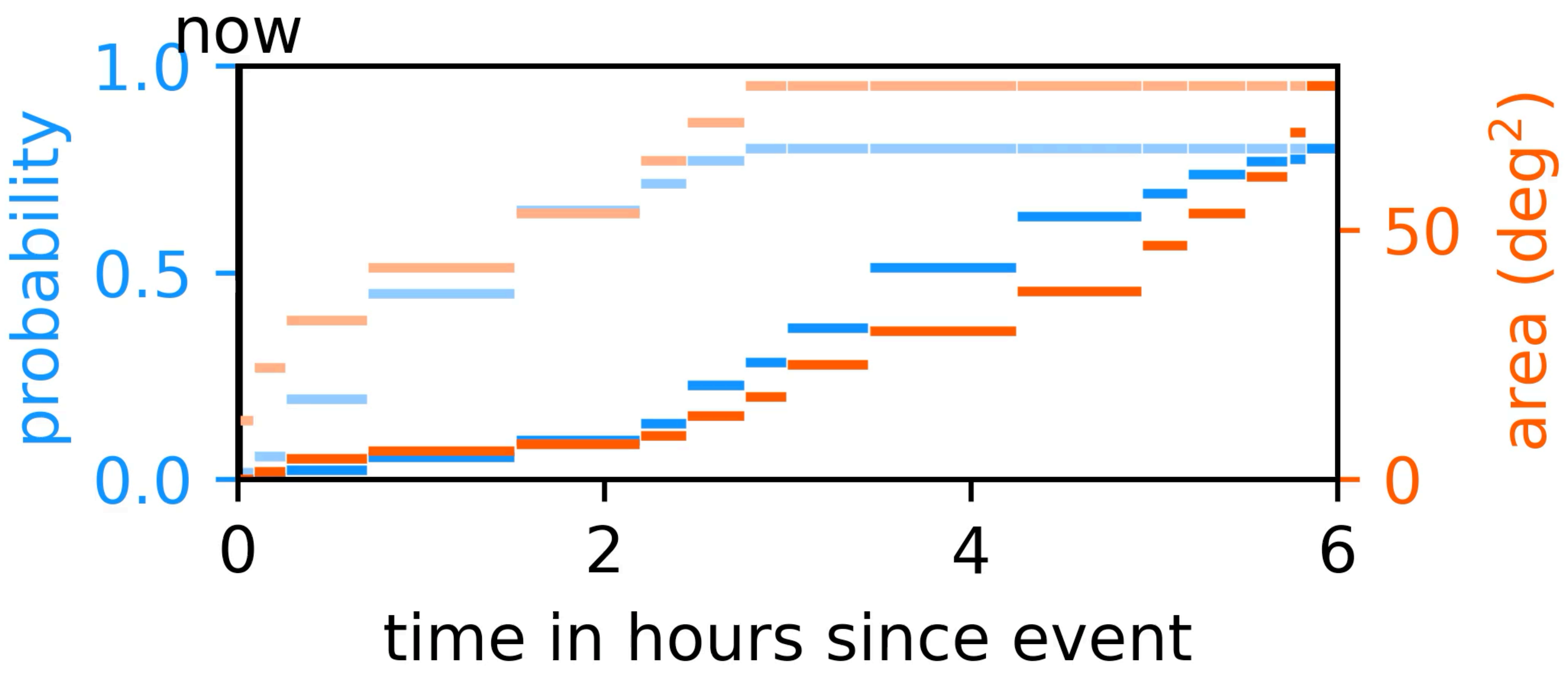
Localization: 3D prob. distribution over source's unknown sky location, distance

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

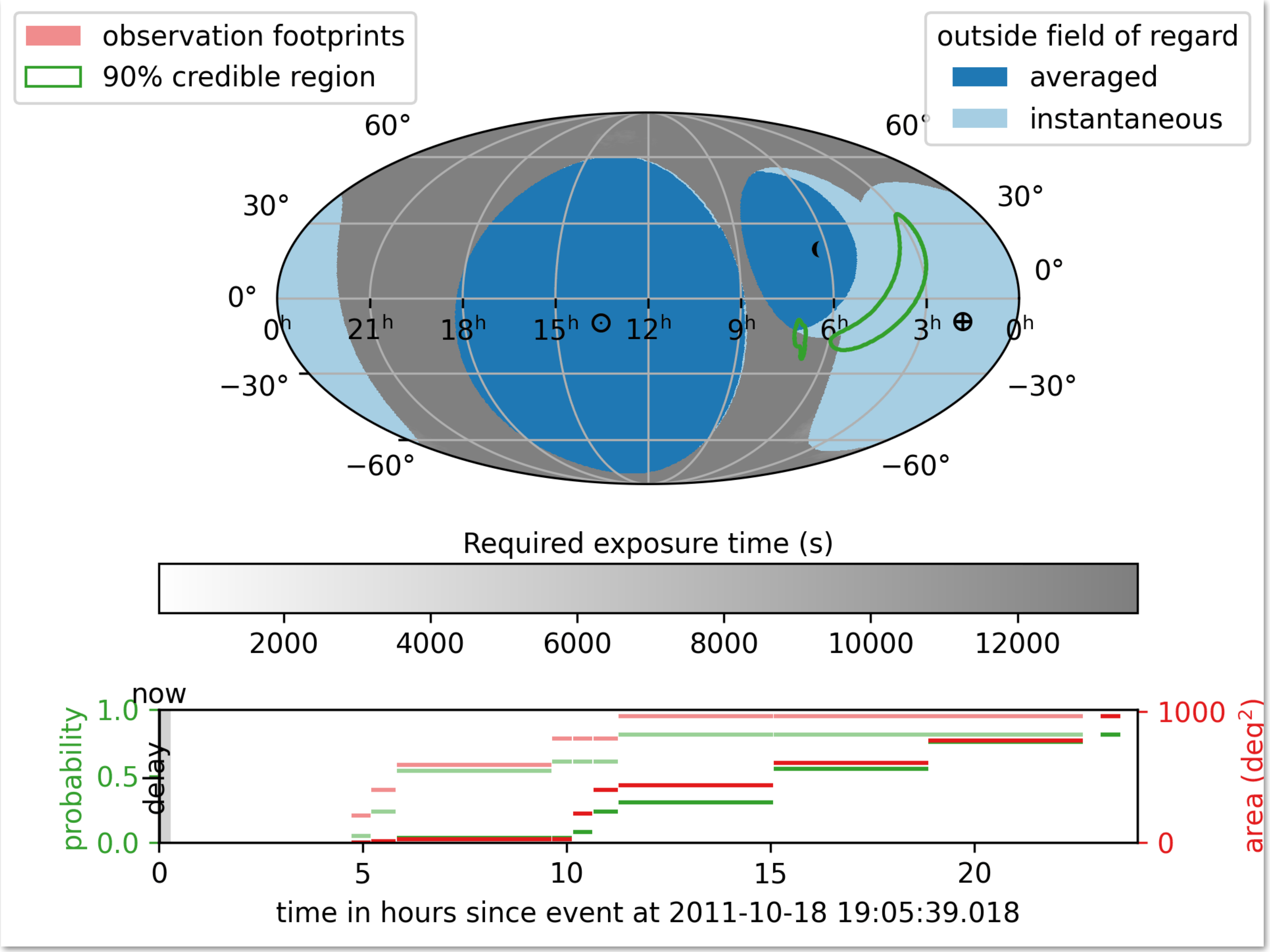
Detection probability: integral over the footprint of the selected fields of the luminosity function, sky location probability distribution, and distance



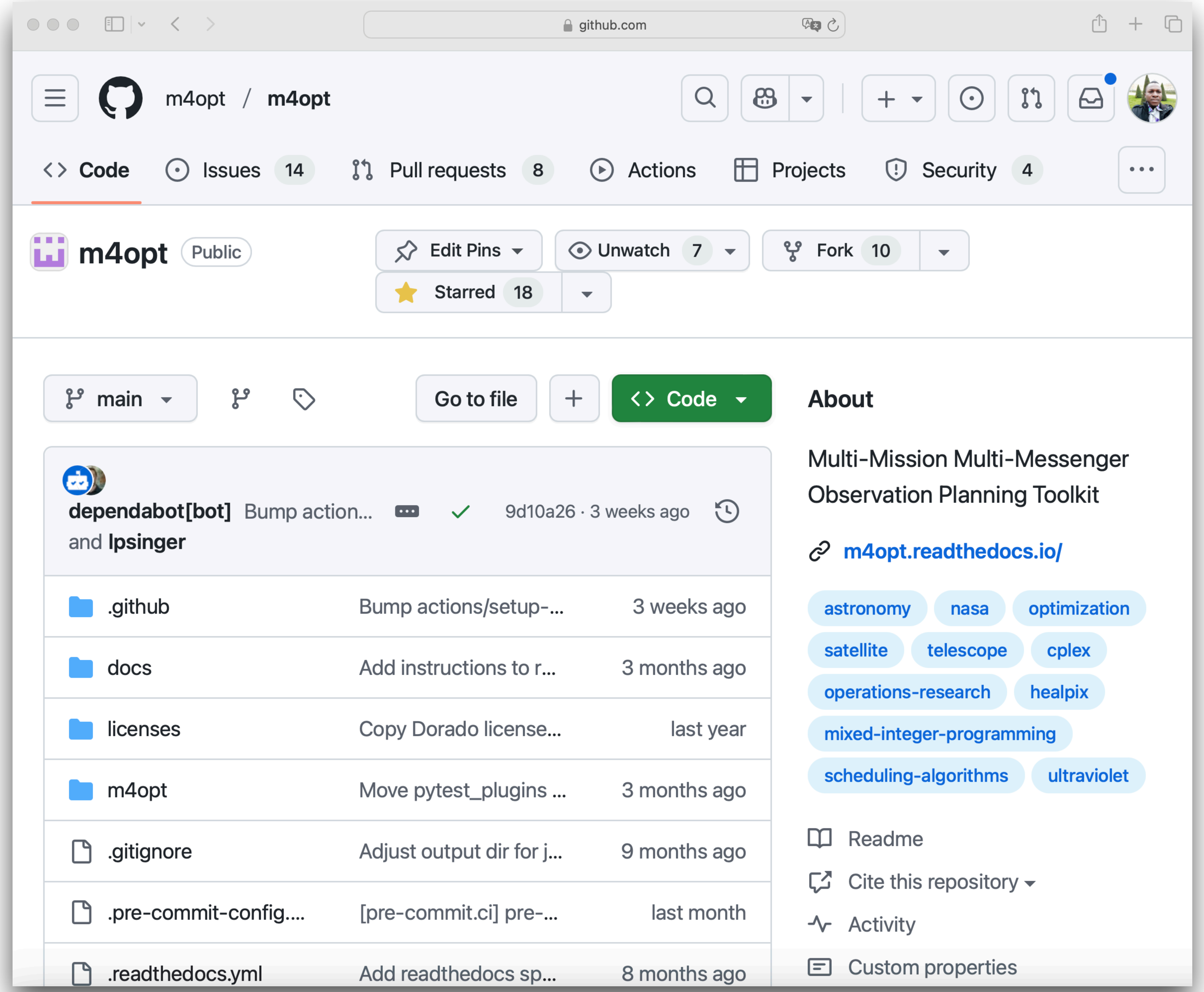


Animation adapted from Leo Singer

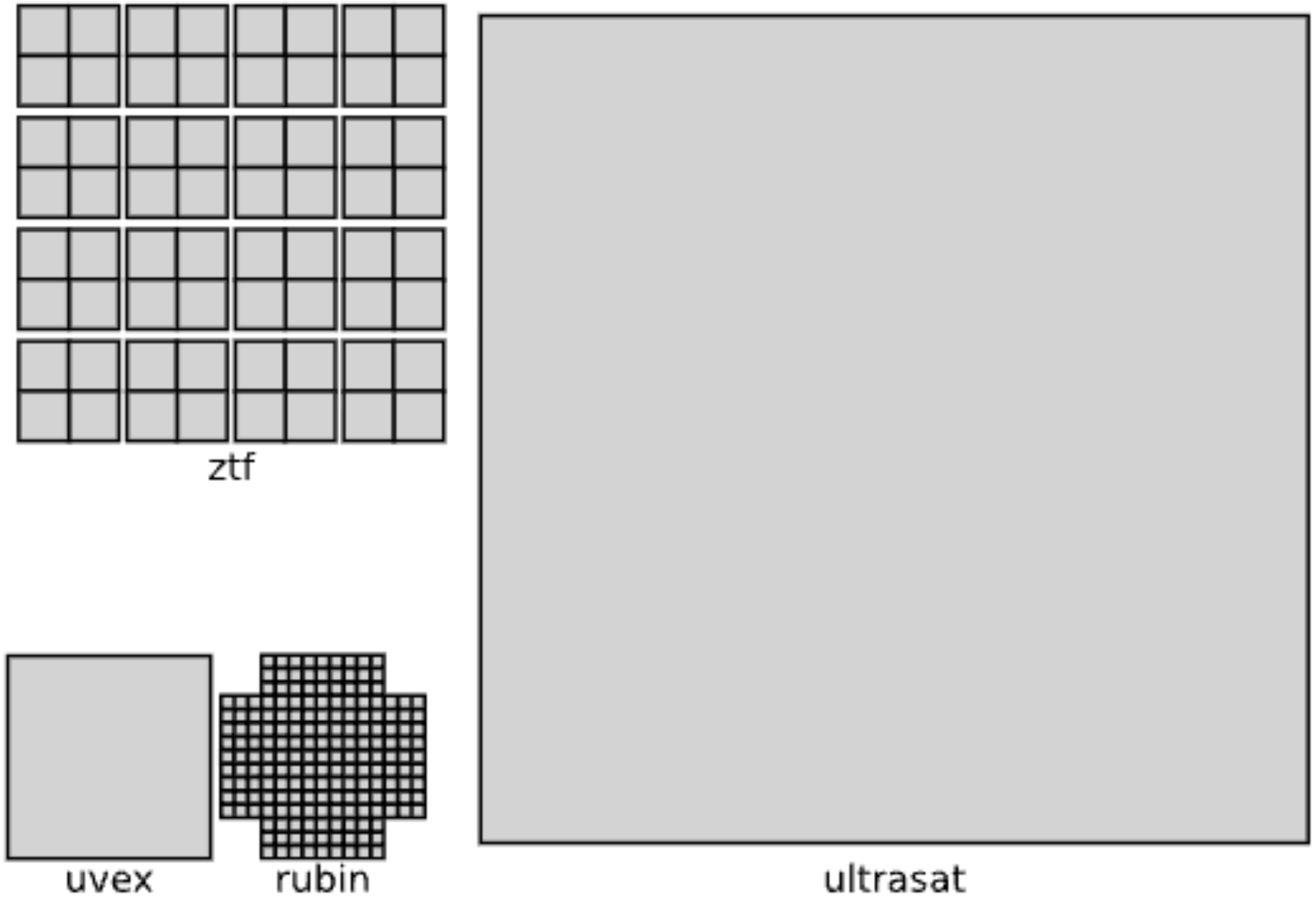
M4OPT Observation Scheduler and Field of Regard



M4OPT: Multi-Mission Multi-Messenger Observation Planning Toolkit

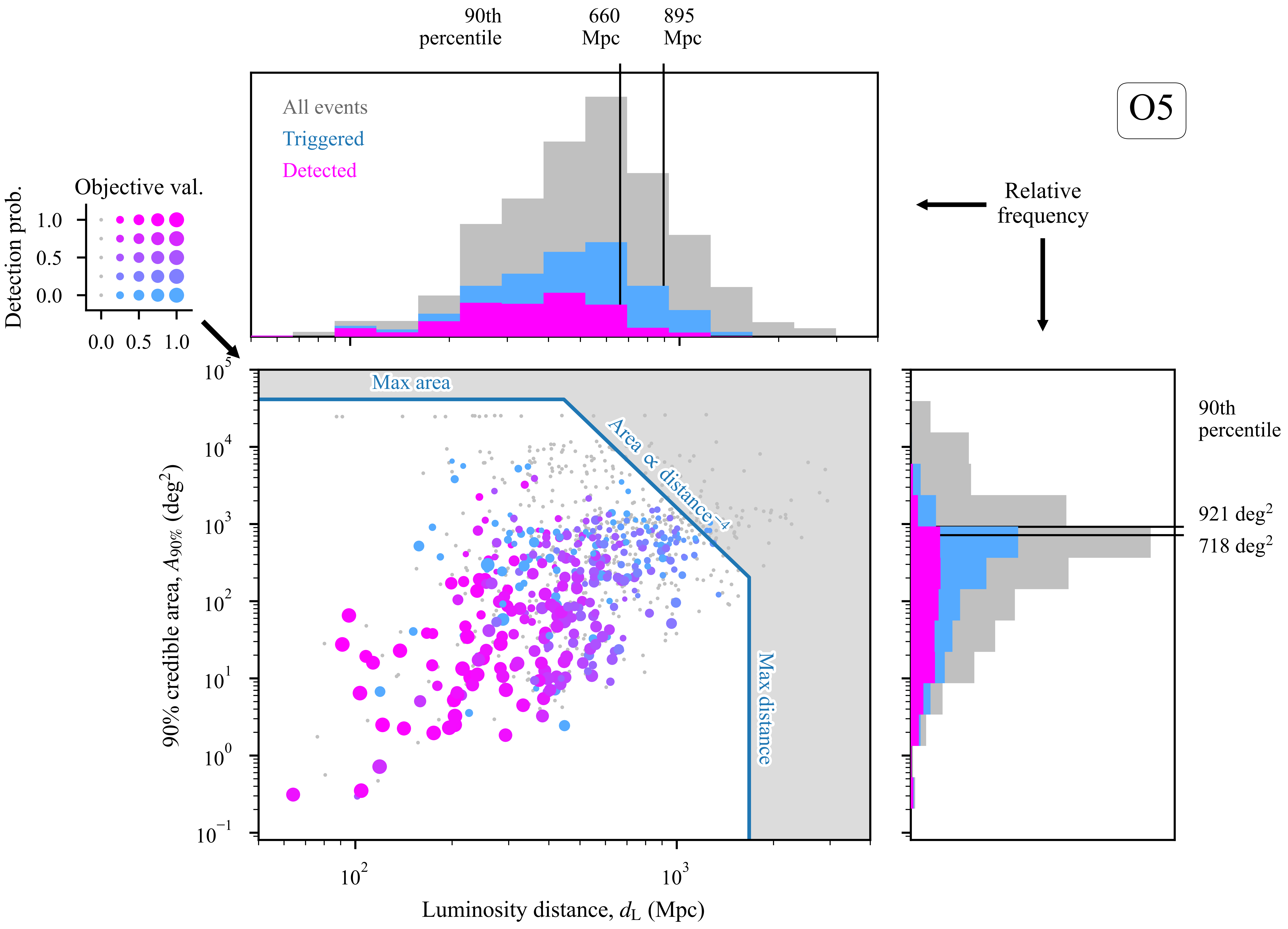


Supported Mission Field of View



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

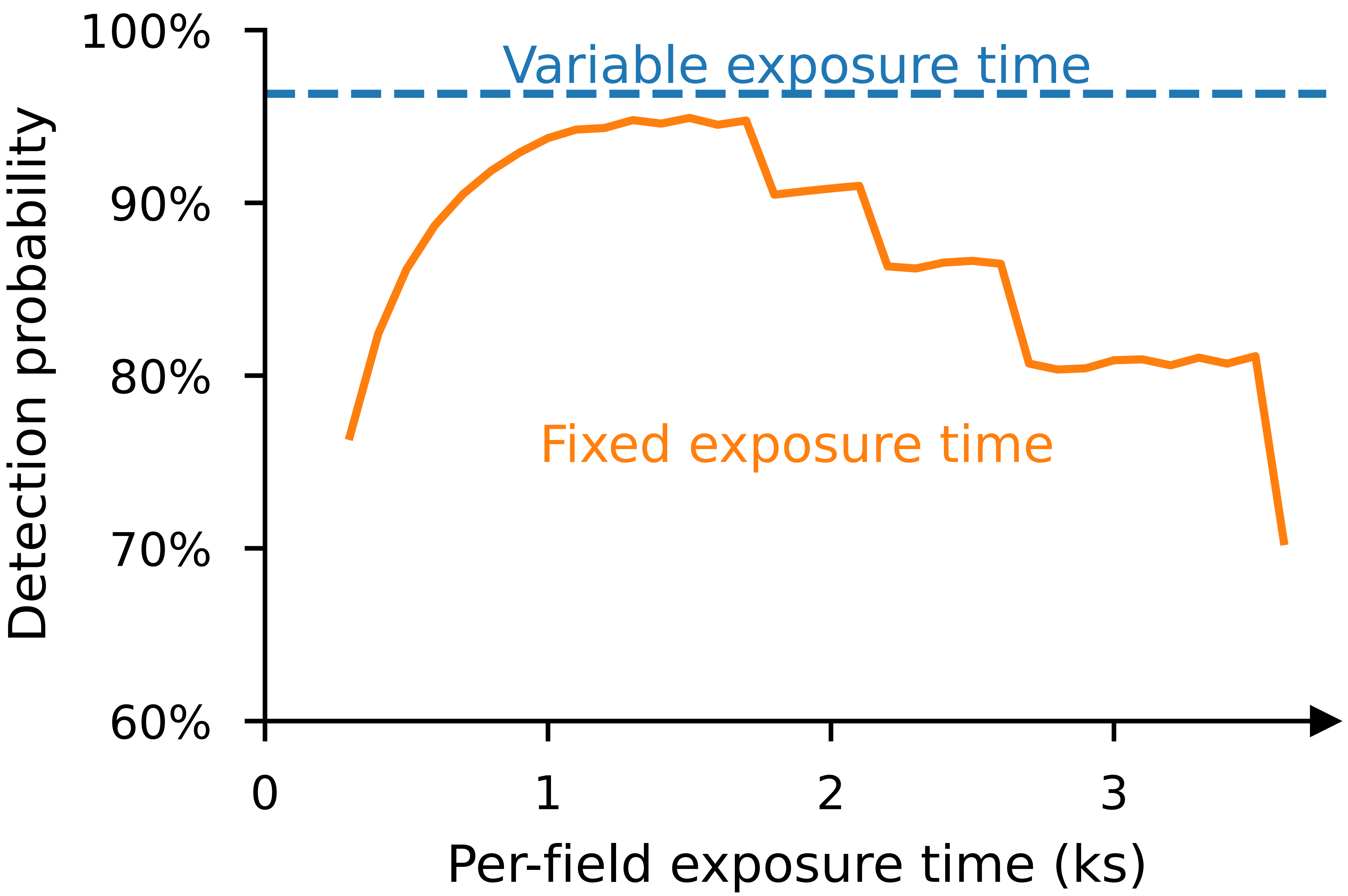
We are also looking for you!

tilepy

Seglar-Arroyo et al. 2025

https://github.com/astro-transients/tilepy

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 deg/s^2
Exclusion angles	
Sun exclusion	70°
Moon exclusion	35°
Earth exclusion	48°
Mission parameters	
Mission duration	3 yr
Launch date	2027