UVEX

National Aeronautics and Space Administration

Optimal Follow-Up of Gravitational-Wave Events with the

UltraViolet EXplorer (UVEX)

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March 26, 2025
Transients From Space
Florence, Italy

NEUTRON STAR MERGER

Swift and *NuSTAR* observations of GW170817: Detection of a blue kilonova

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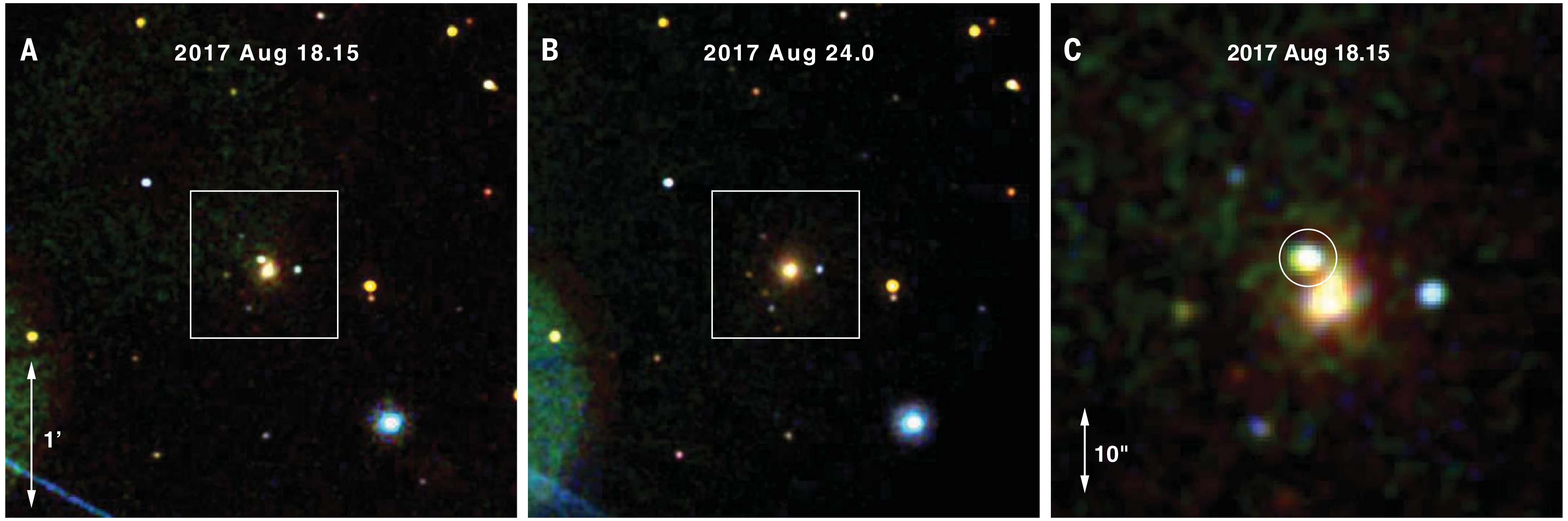
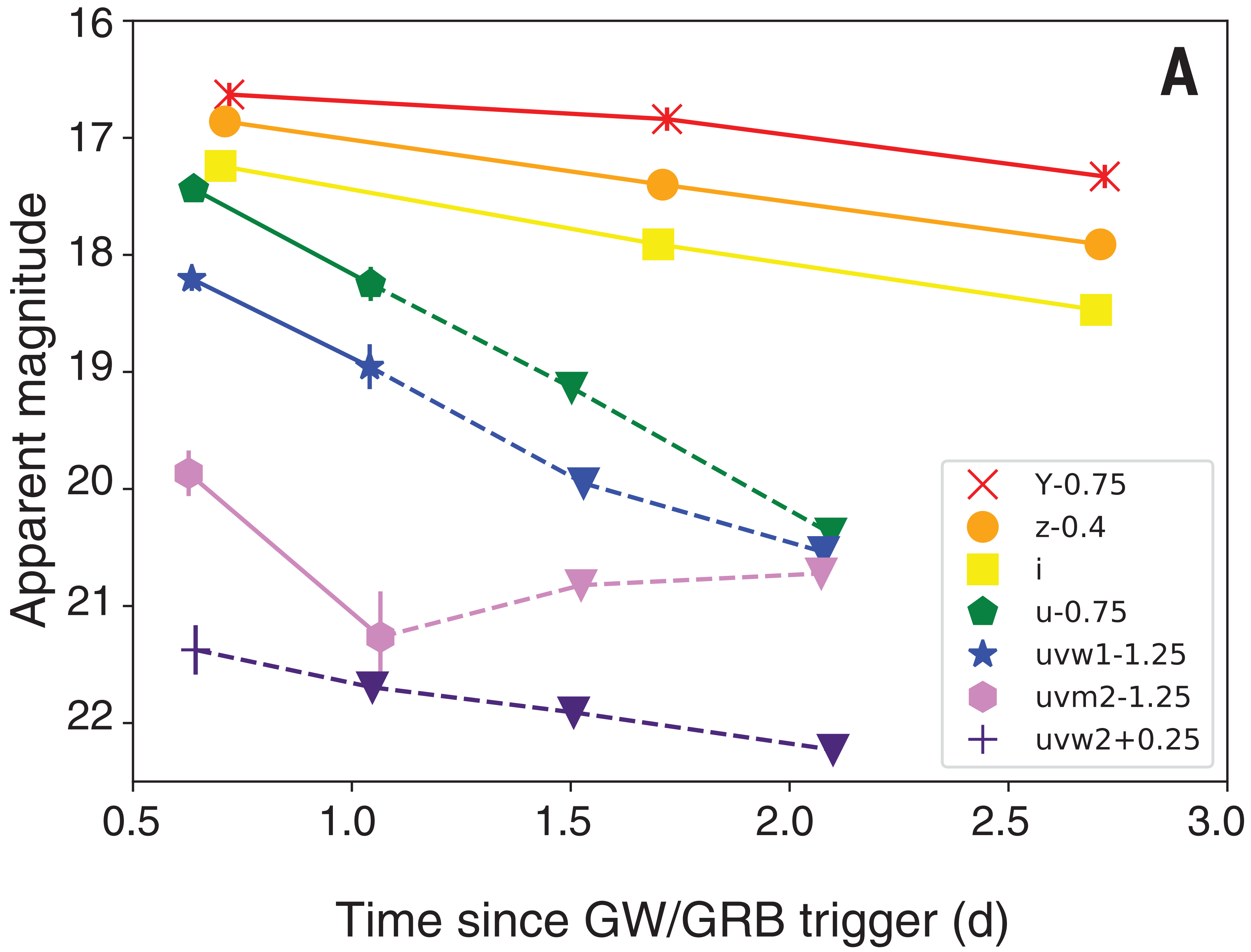
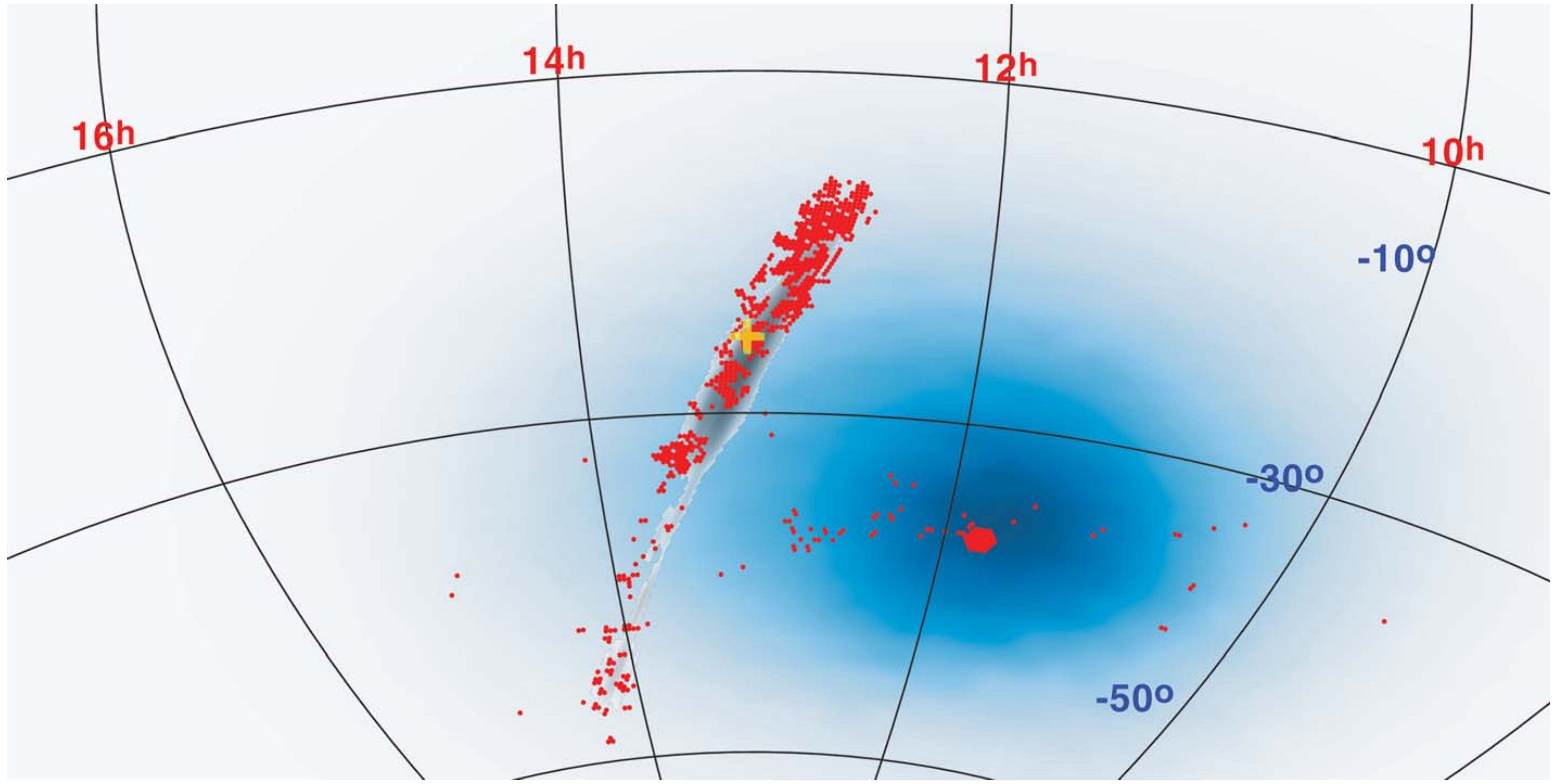






Images: Evans, Cenko, Kennea, et al. (2017), Science

GW170817: Why so blue?

- Early models (Lattimer+Schramm 1974, Eichler+ 1989, Li+Paczyński 1998) predicted **bright, fast, optical/UV** kilonova emission.
- Realistic modeling of lanthanide atomic structure (Kasen+ 2013) led people to expect high optical opacities and **faint, slow, infrared** emission which would be **much harder** to hunt down (Mezger+Berger 2012).
- Spectral sequence of the GW170817 kilonova matched those predictions well (Pian+ 2017), but it was **unexpectedly bright and blue at early times**.
- The cause of the bright UV/optical emission remains one of the **greatest mysteries surrounding GW170817**.
- Leading explanations are **radioactive power** from fast, high Y_e polar ejecta or **shock heating** of the ejecta by the emerging jet ("cocoon")

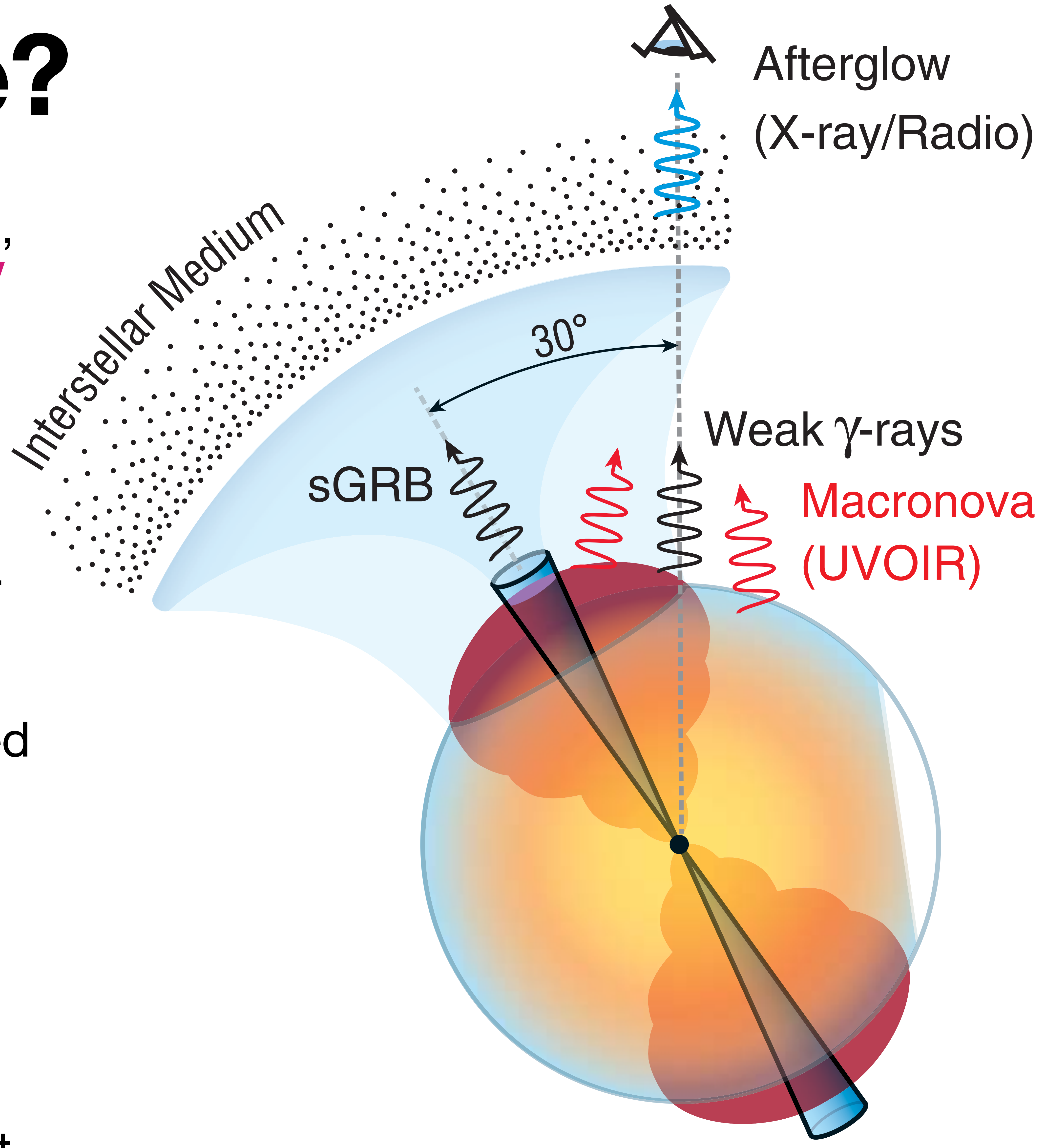
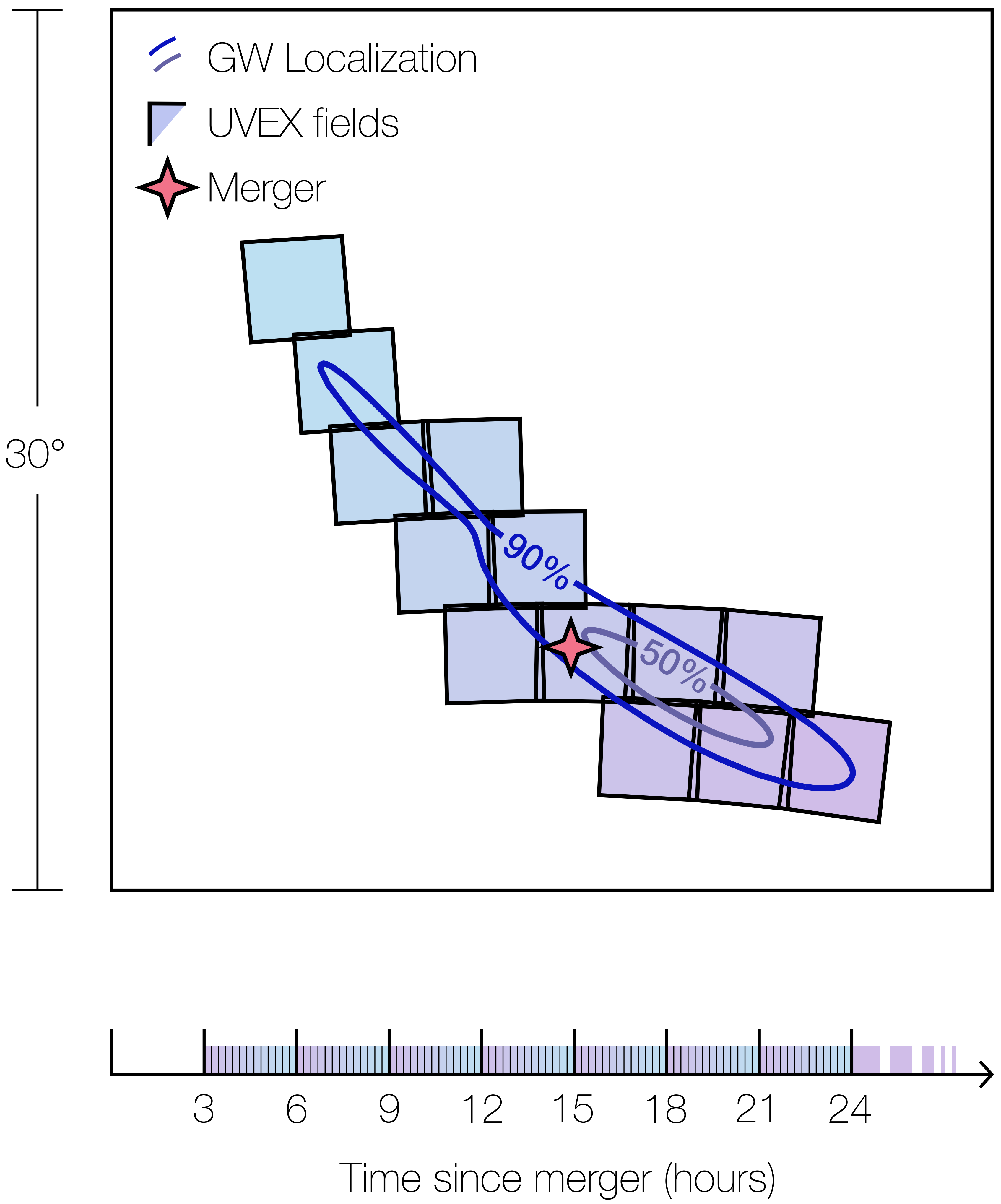
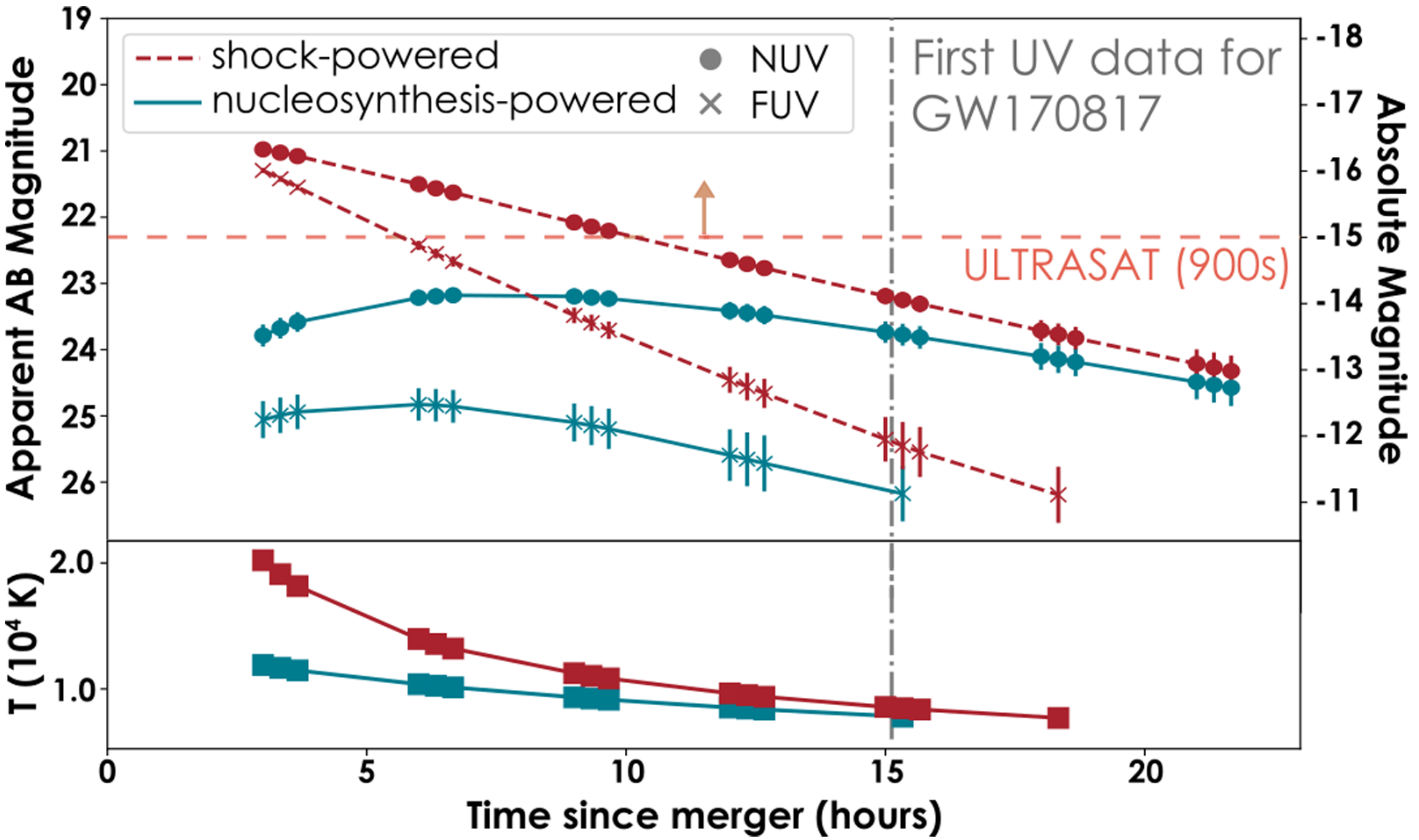


Image: Kasliwal, Nakar, Singer, et al. (2017), Science

Early UV observations can discriminate between shock vs. radioactively powered kilonova emission.

Simulated O5 Event at 167 Mpc





See also Villar (2017), Gottlieb (2017), Piro+Kollmeier (2018), Arcavi (2018), etc.
Left: UVEX/Leo Singer/NASA. Right: Kulkarni+ 2023, arXiv:2111.15608

UVEX

Image Bandpasses	1390–1900, 2030-2700 Å
Image Quality	<2.25″ HPD
FOV	3.5°×3.5°
Sensitivity	>24.5 AB (S/N 5, 900 s)
Survey Depth	>25.8 AB
Spectroscopy	1150–2650 Å, R>1000
Prime Mission	2 years
Launch	2030

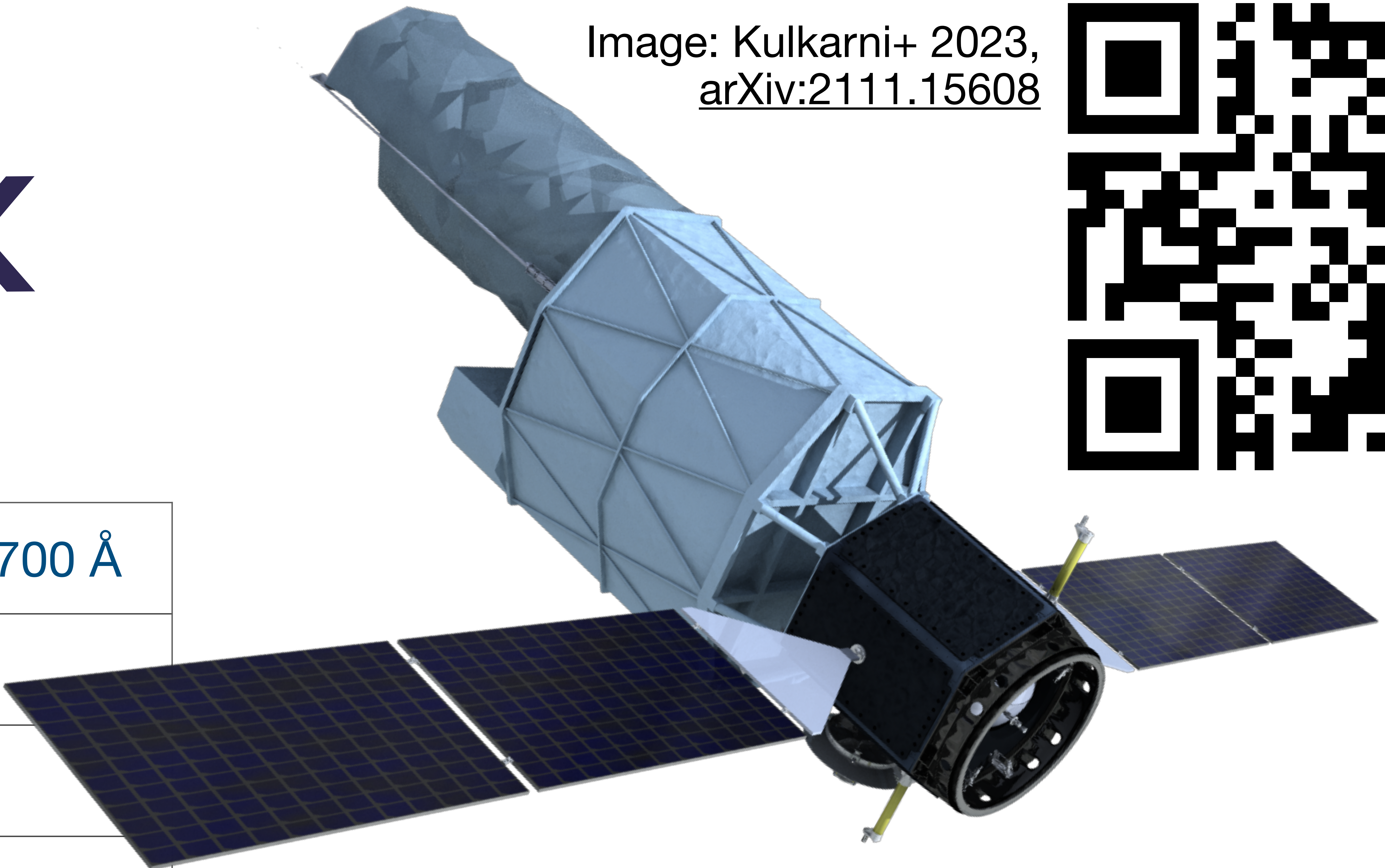
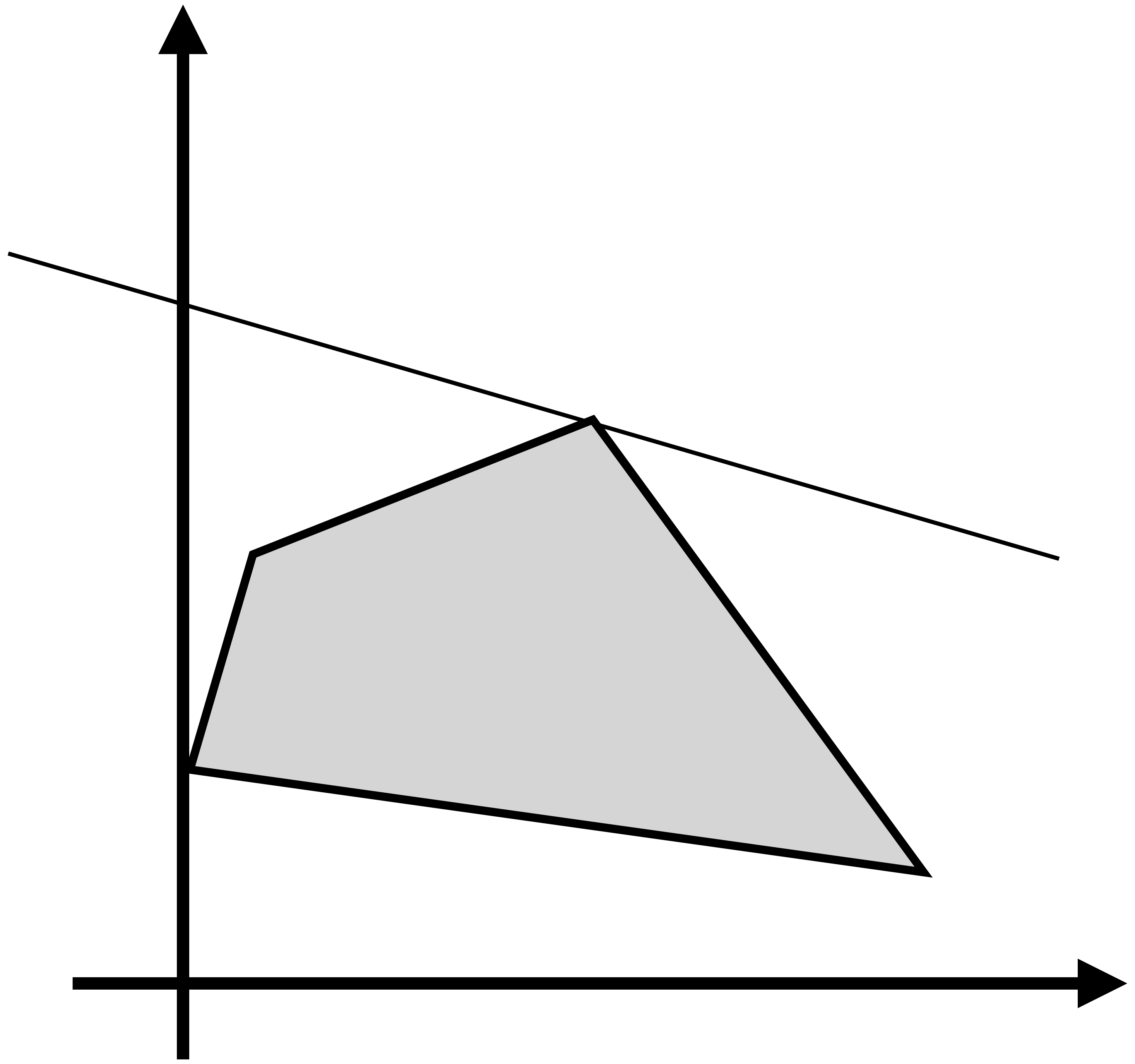


Image: Kulkarni+ 2023, arXiv:2111.15608

UVEX is NASA's next Mid-range Explorer (MIDEX), scheduled for launch in **2030**. It will perform **deep, cadenced time-domain survey** in **two UV bands** with **high image quality** and will follow up **multi-messenger targets of opportunity** and **community targets**.

Linear programming (LP)

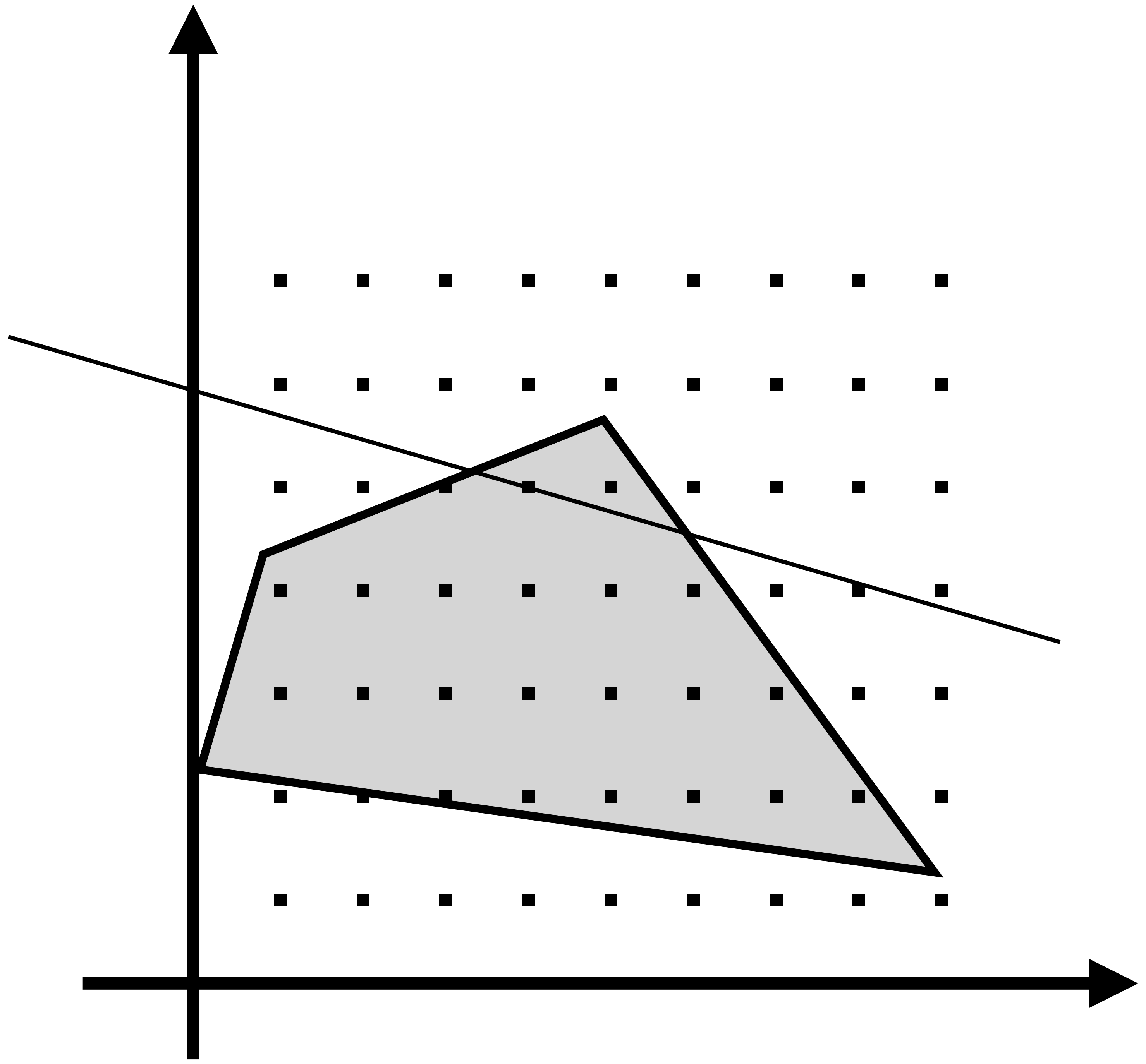


Maximize a **linear combination** of decision variables, subject to **linear inequality constraints**.

- Studied at least as early as 1827 (Fourier) but algorithms for solving large scale problems were in 1946-47 (Dantzig, von Neumann).
- The global optimum (if it exists) can be found in **polynomial time** (Khachiyan, 1979).
- Important **applications** in economics and finance, game theory, industrial engineering, etc.

Canonical form

Maximize	$\mathbf{c}^{\mathrm{T}}\mathbf{x}$
subject to	$\mathbf{A}\mathbf{x} \leq \mathbf{b}$
and	$\mathbf{x} \geq 0.$



Integer linear programming (ILP)

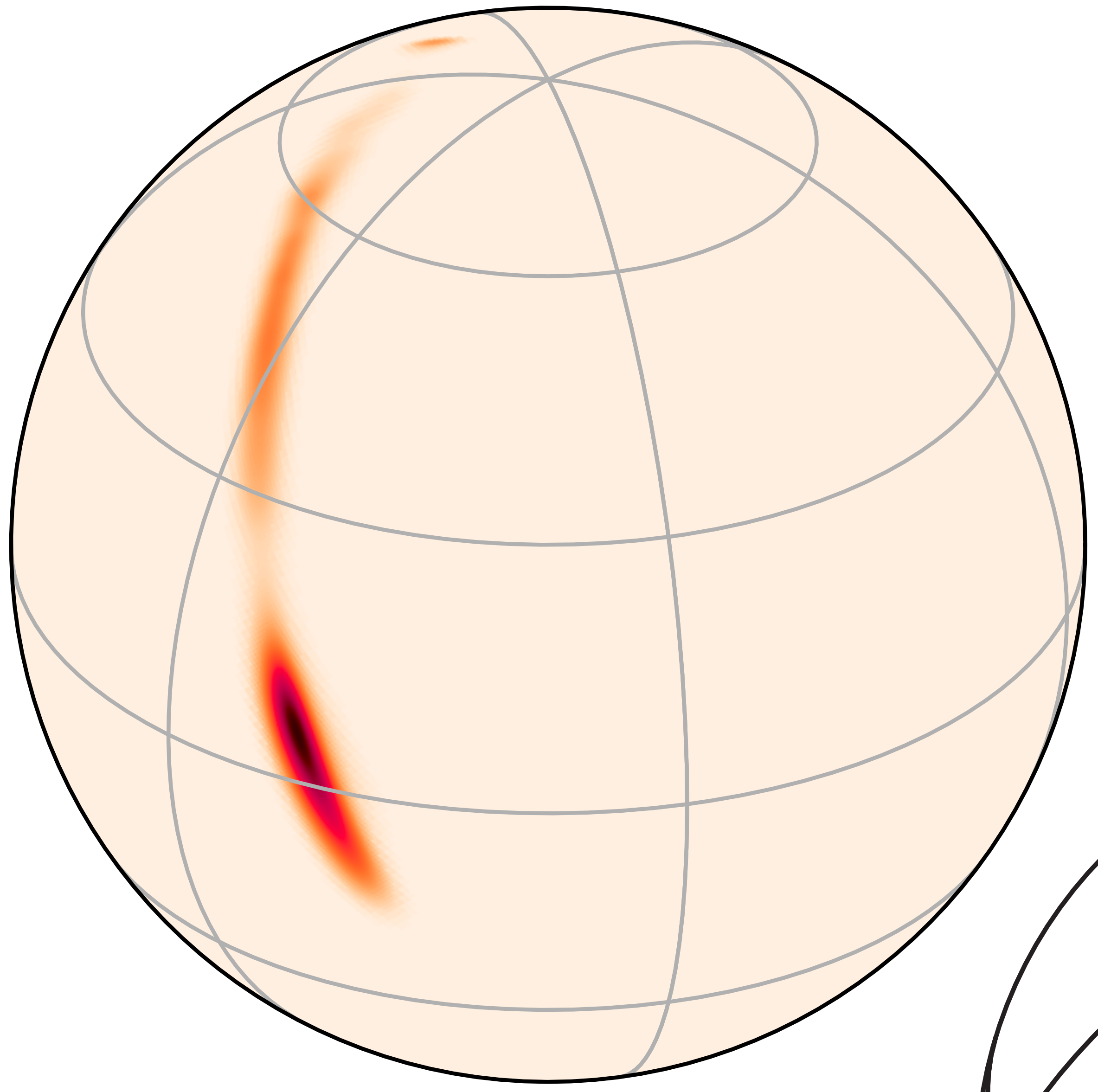
All variables must take integral (or binary) values.

Mixed integer linear programming (MIP, MILP)

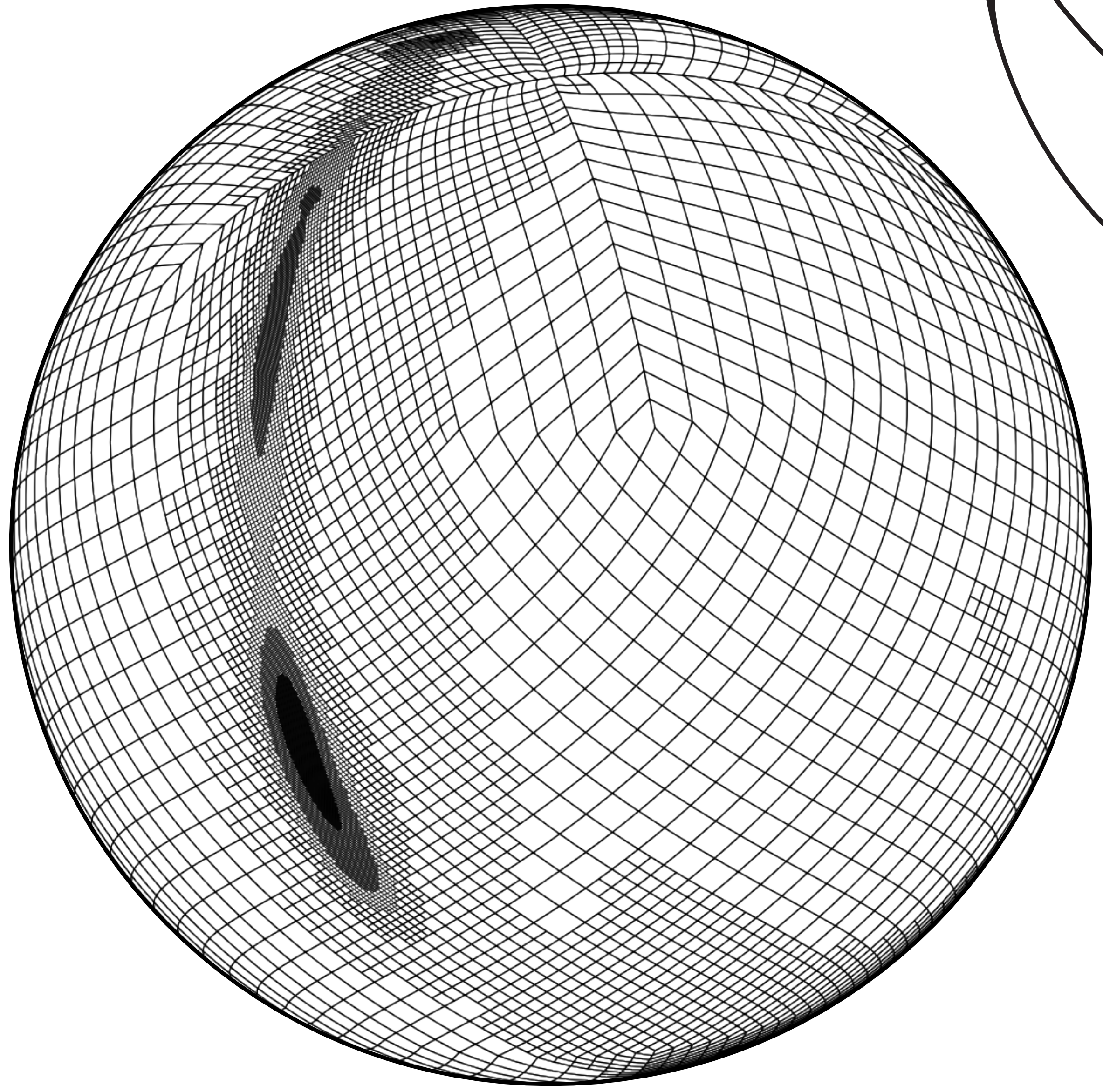
Some specific variables (but not all of them) must take integral (or binary) values.

- Non-convex and famously NP-complete (Karp 1972)
- However, solvable by dynamic programming methods such as branch-and-bound or branch-and-cut :-)
- **Algorithms are well studied** due to important **commercial applications** (industrial process optimization, IC and PCB design, oil & gas, etc.)
- **Powerful, general-purpose solvers** have been available since the 1980s
- **Focus more on describing your science requirements, and less on *how* to get there**

Probability Sky Map



Multi-Resolution HEALPix Tiles



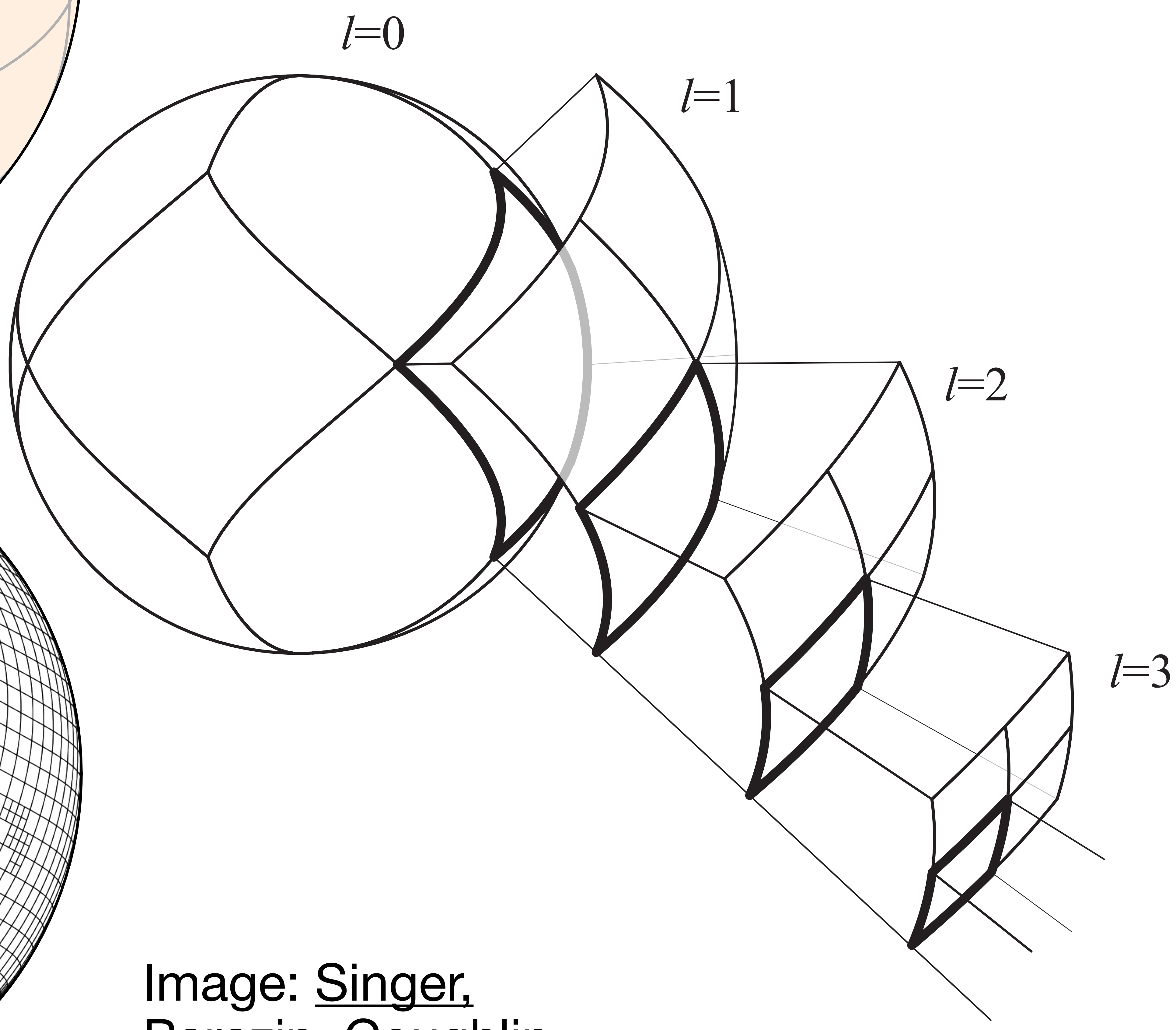


Image: Singer, Parazin, Coughlin, et al. (2022), AJ

HEALPix

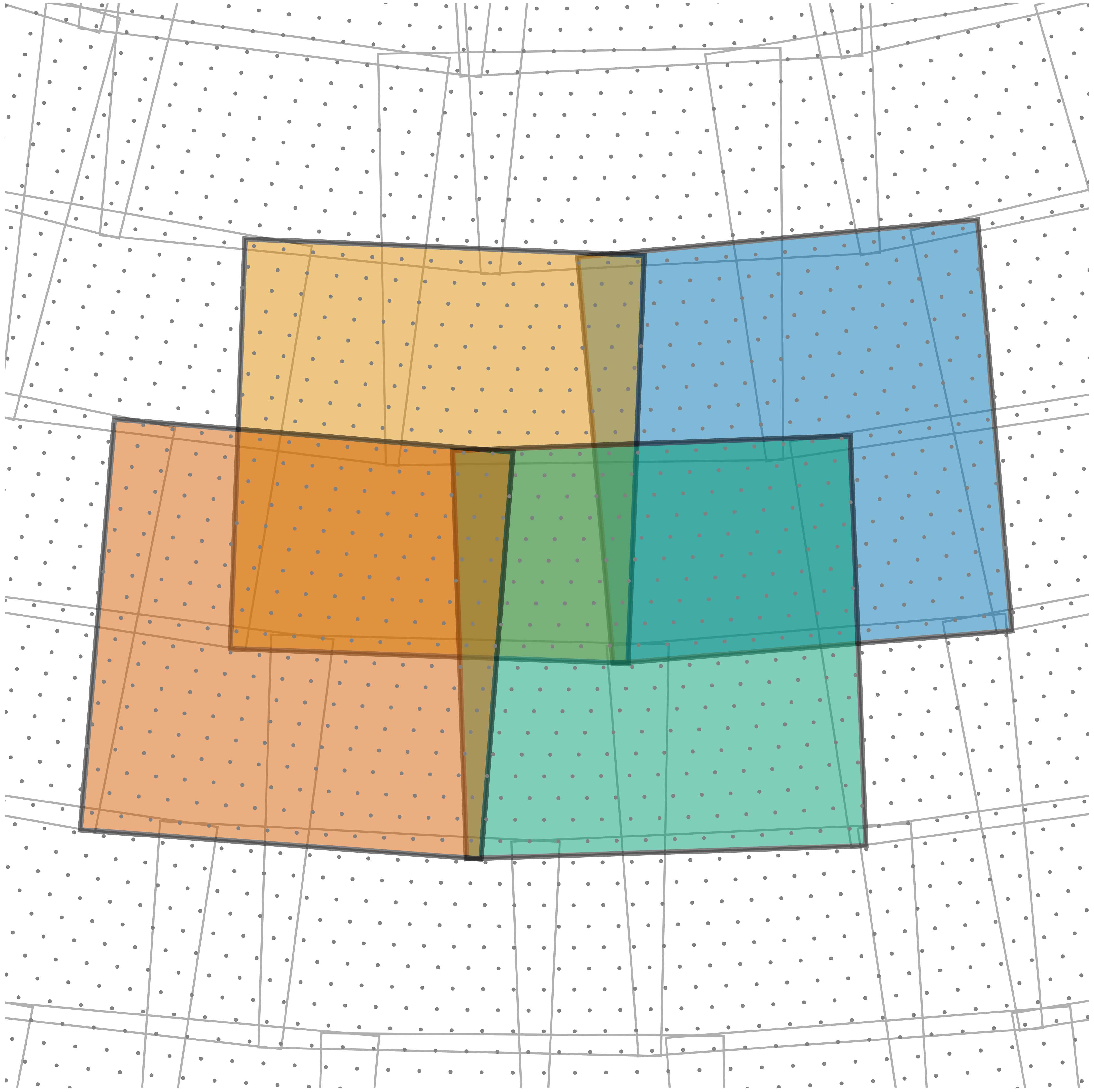
Hierarchical Equal Area isoLatitude Pixelization

- 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
- was brought (by me) to the gravitational-wave community as the **standard format for probability maps**

Max weighted coverage

elements = HEALPix pixels
weights = HEALPix probability map
subsets = field footprints

about 100k elements, 1k subsets



A classic ILP problem:

Max weighted coverage

Find more in our recorded lecture on MILP for astronomy in the ZTF Summer School 2024: **AI in Astronomy**

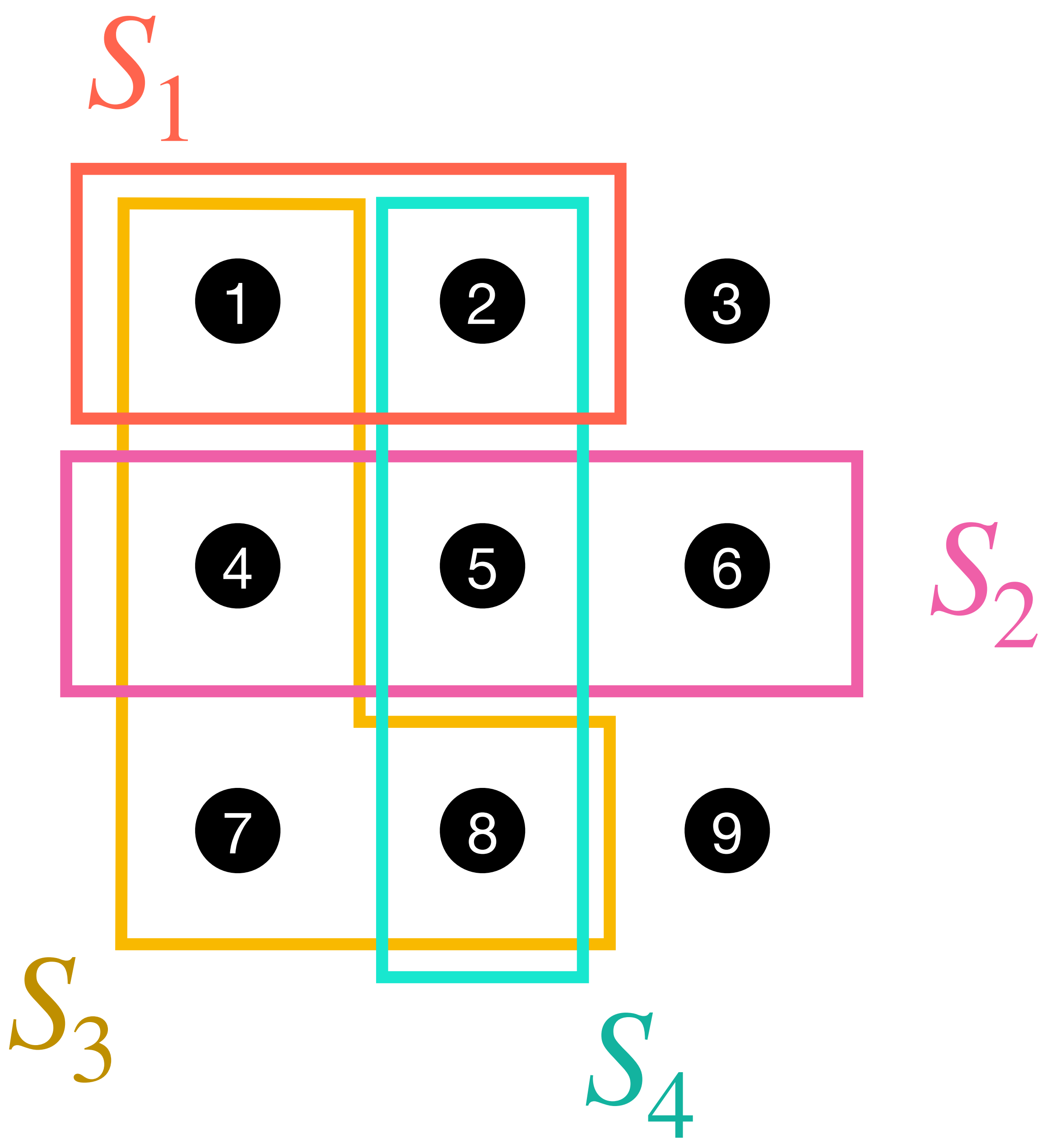
Given sets $S = \{S_1, S_2, \ldots, S_m\}$

over elements $\{1, 2, \ \ldots, n\}$

with weights $\{w_1, w_2, \ldots, w_n\}$,

find the subset $S' \subseteq S, \quad |S'| \leq k$

that maximizes $\sum_{j \in \bigcup S'} w_j$.



ILP formulation:

Maximize $\sum_j y_j w_j$

Subject to $\sum_i x_i \leq k$

and $\sum_{i | j \in S_j} x_i \geq y_j$

with binary variables $y_j \in \{0,1\}, x_i \in \{0,1\}$

and weights $w_j \in \mathbb{R}_+$.

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

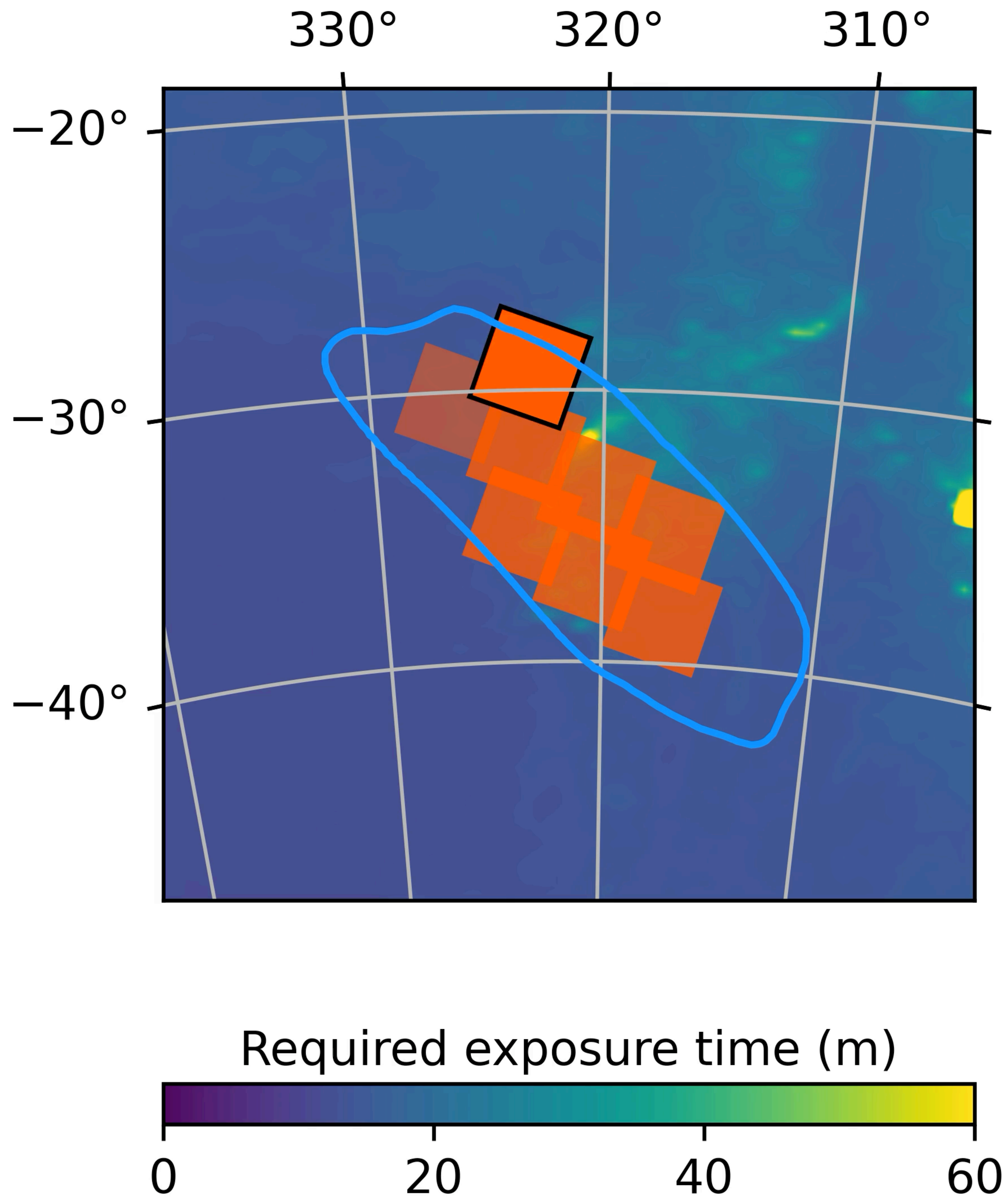
Cadence: minimum time between revisits of a field

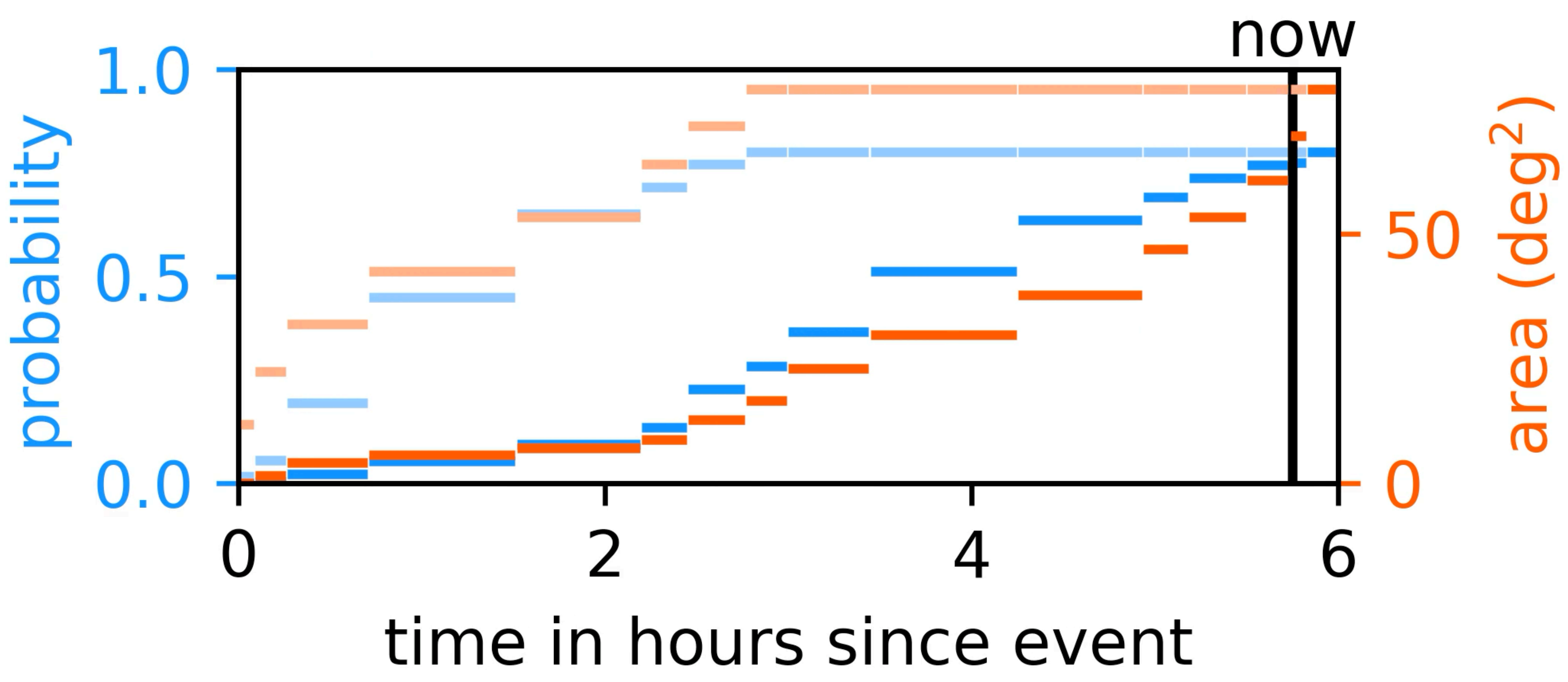
Localization: 3D prob. distribution over source's unknown sky location, distance

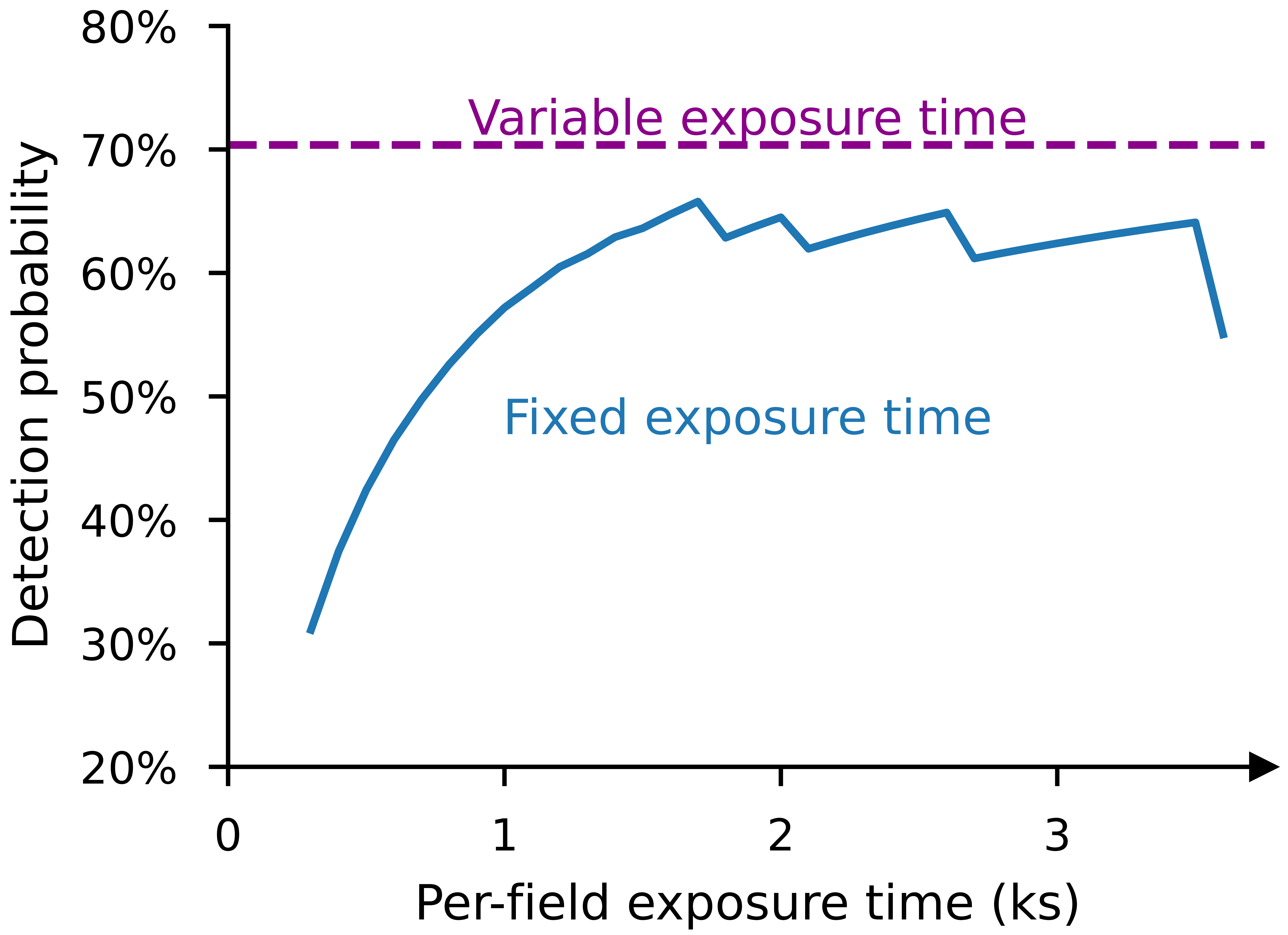
Luminosity function: distribution of source's unknown abs. magnitude

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



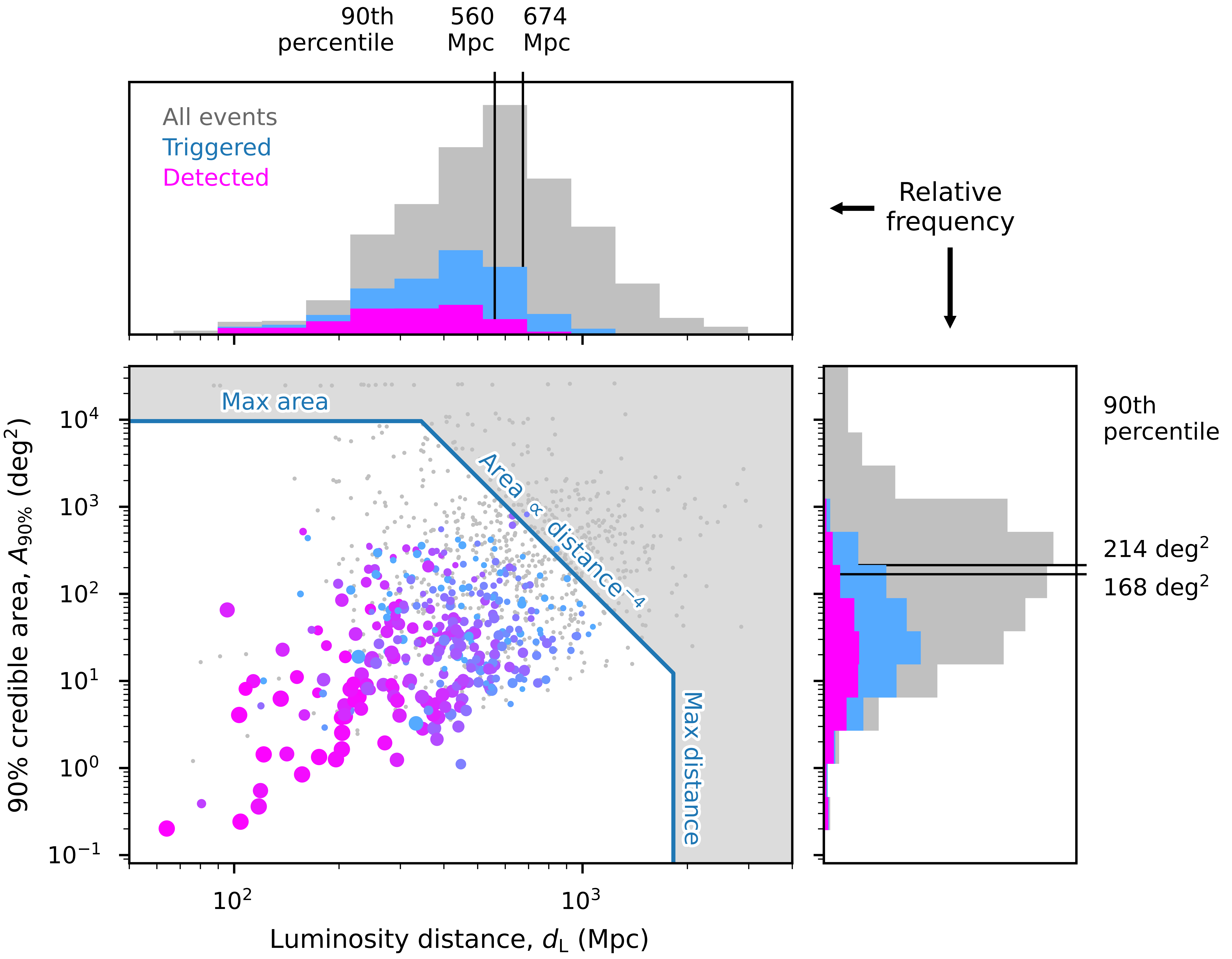




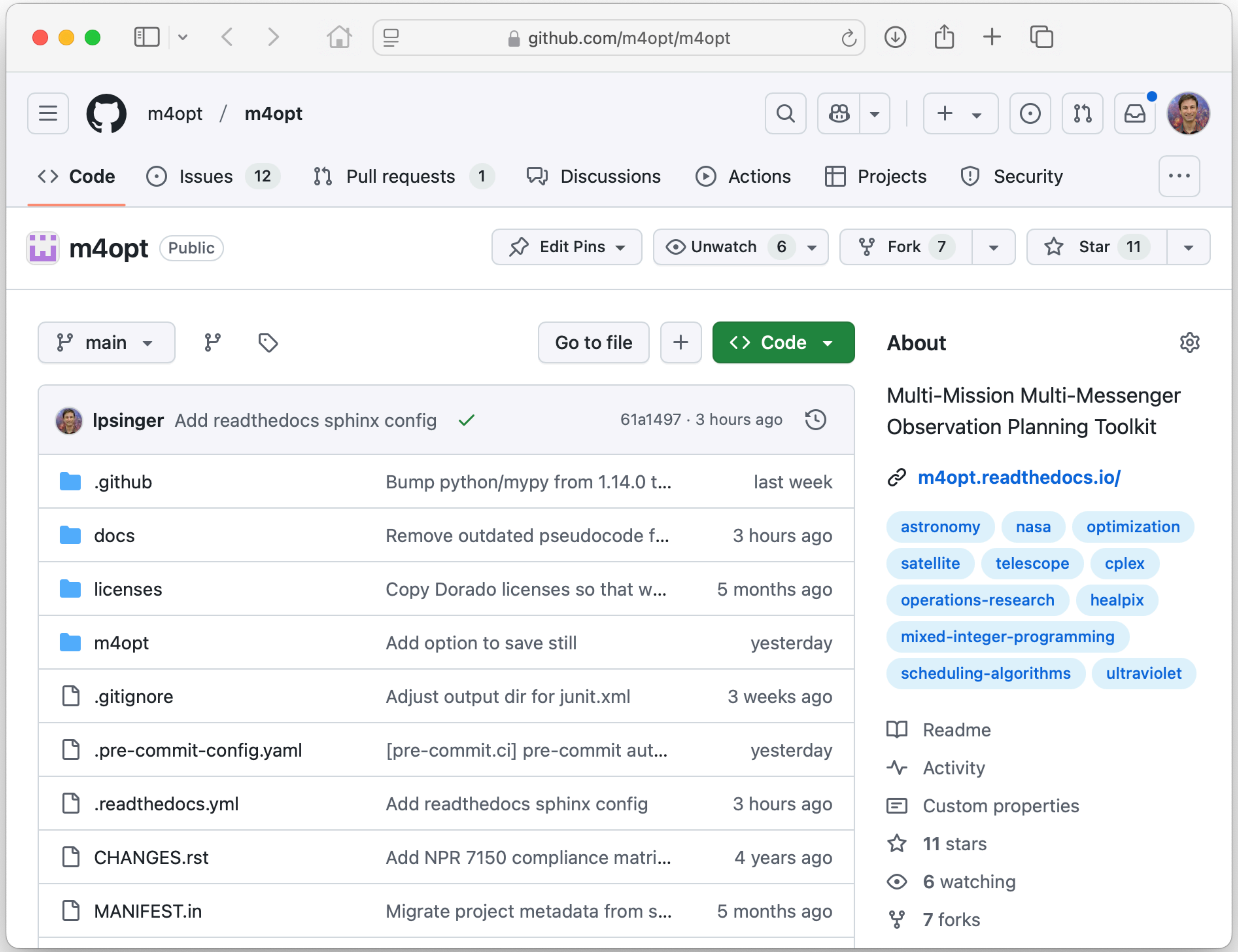
The dynamic exposure time strategy is more likely to detect kilonovae than any fixed exposure time.

Observing strategy

- Run the scheduler **for all events**.
- Trigger follow-up for all events that have a **detection probability ≥10%**.
- There is **no explicit threshold** on sky area or distance.



M⁴OPT: Multi-Mission Multi-Messenger Observation Planning Toolkit



- Mixed integer linear programming scheduler for targets of opportunity
- Deeply integrated with the Astropy ecosystem
- Vector-accelerated synthetic photometry for larger parameter sweeps than are practical with synphot
- Observing constraint modeling framework inspired by astroplan
- Free and open source

Join M4OPT on GitHub

- It already supports both **UVEX** and **ULTRASAT**. Some modules being used with **Pandora**.
- Support for **ground-based observations** coming soon!
- **Use M4OPT** for your project!
- **Contribute to M4OPT** with issues and pull requests!
- Find our **papers on arXiv**!
  https://arxiv.org/abs/2501.14109
  https://arxiv.org/abs/2502.17560

https://github.com/m4opt/m4opt