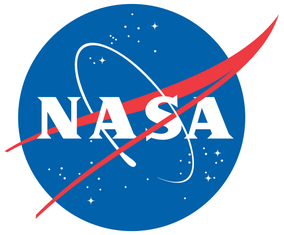
UVEX

National Aeronautics and
Space Administration



Autonomous Surveys and Community ToOs on the

UltraViolet EXplorer (UVEX)

Leo P. Singer[1], Michael W. Coughlin[2], and friends

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2]University of Minnesota, Minneapolis, MN, USA

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RAPID Response Meeting
California Institute of Technology
Pasadena, CA, USA

UVEX Science Leadership Team

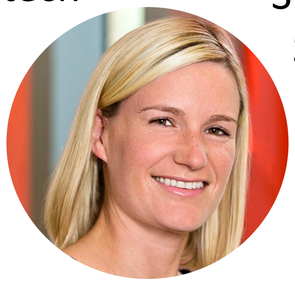
Fiona Harrison, Caltech
PI

Brian Grefenstette, Caltech
Project Scientist

Shri Kulkarni, Caltech
Science Team Lead

Hannah Earnshaw, Caltech
Science Team Coordinator

Dan Weisz, UC Berkeley
Low Mass Galaxy Frontier Lead



Suvi Gezari, STScI
Dynamic Universe Lead

Keivan Stassun, Vanderbilt
Legacy Survey Lead

Danielle Berg, UT Austin
galaxy spectroscopy lead

Hugues Sana, Leuven
LMC/SMC lead

Mansi Kasliwal, Caltech
EMGW lead

Rafaella Margutti, UCB
CCSNe Lead

Matthew Graham,
Caltech Synoptic
Survey lead

Harry Teplitz, IPAC,
Imaging survey lead

image: BBC, https://www.doctorwho.tv/news-and-features/what-is-the-tardis

Outline

- Mission Overview
- All-Sky Survey Strategy
- EM-GW Strategy

UVEX

Kulkarni+ 2023,
arXiv:2111.15608

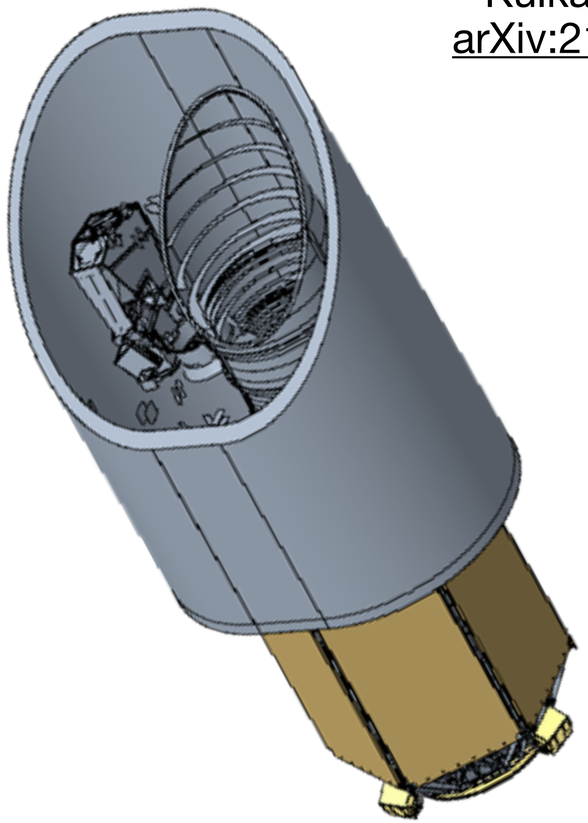


Image Bandpasses	1390–1900, 2030-2700 Å
Image Quality	<2.25″ HPD
FOV	3.5°×3.5°
Sensitivity	>24.5 AB (S/N 5, 900 s)
Survey Depth	>25.8 AB
Spectroscopy	1150–2650 Å, R>1000
Prime Mission	2 years
Launch	2030

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**.

UVEX's 3 science pillars

The Low-Mass, Low-Metallicity Galaxy Frontier

UVEX will uncover the lowest mass, most pristine local galaxies and diagnose their unique cosmic ecosystems. **2020 Decadal priority area: Drivers of Galaxy Growth**

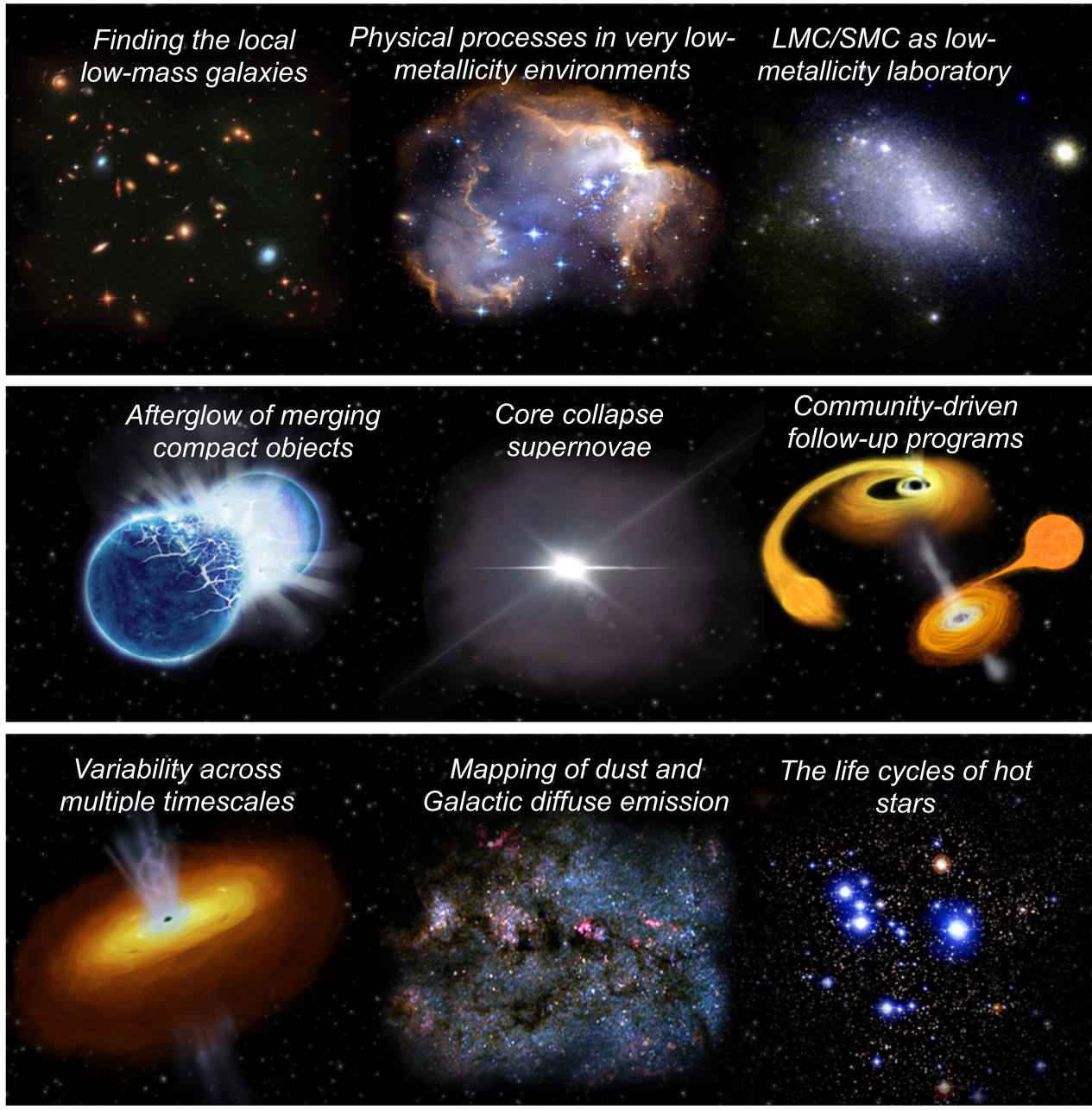
New Views of the Dynamic Universe

UVEX will follow-up multi-messenger and community triggers to probe the early UV emission of transients 2020. **Decadal priority area: New Windows on the Dynamic Universe**

A Legacy of Deep, Synoptic All-Sky Surveys

UVEX cadenced all-sky imaging leaves a legacy dataset for the entire community. **2020 Decadal priority areas: Drivers of Galaxy Growth, New Windows on the Dynamic Universe**

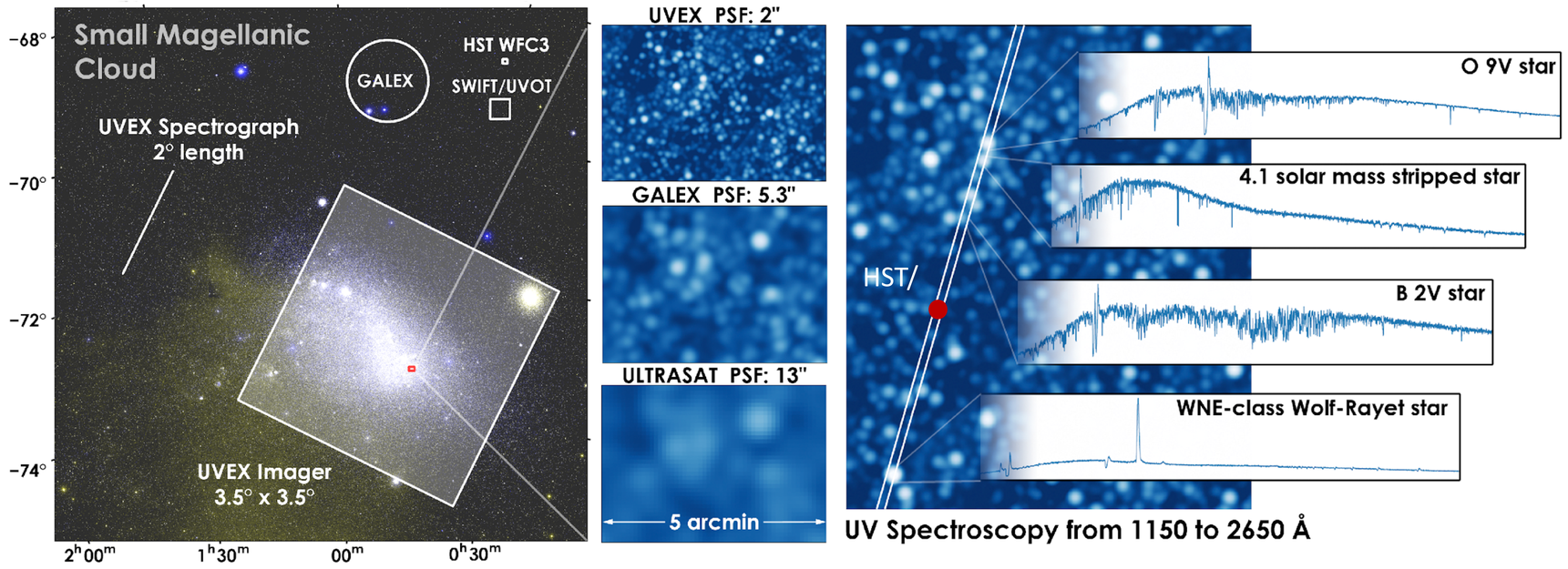
UVEX addresses Astro2020 Decadal Survey priorities.

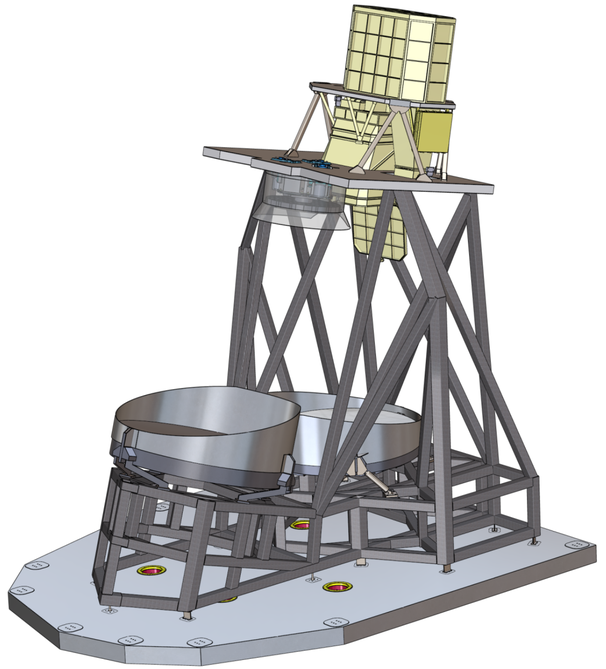


UVEX's Capabilities

UVEX provides three crucial capabilities:

- **Sensitive wide-field imaging** in two ultraviolet bands
- **High angular resolution** across large field of view
- **Broadband** ultraviolet spectroscopy



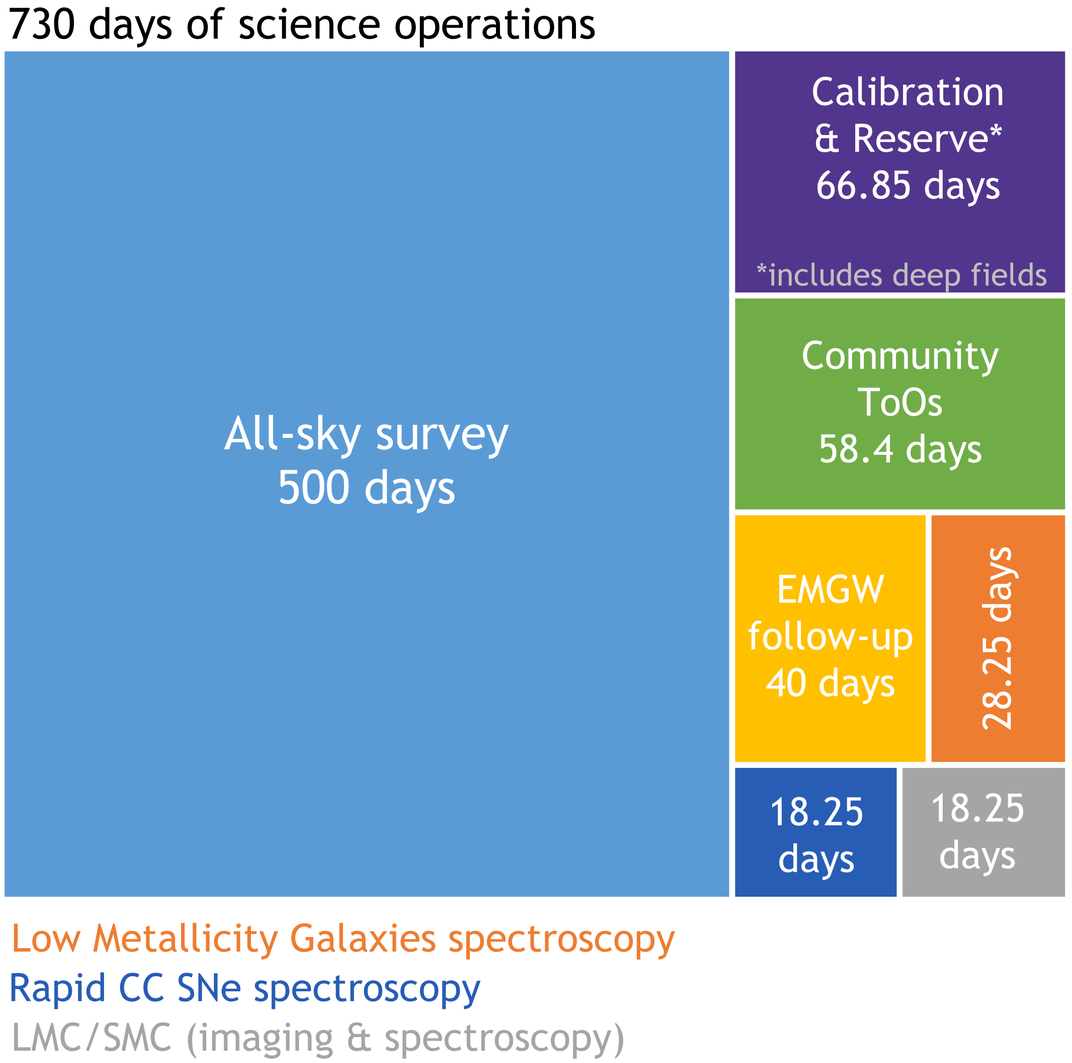


Telescope design enables **wide field imaging** and **spectroscopy** at the **same time**

UVEX provides an unprecedented combination of capabilities designed to achieve its scientific objectives.

UVEX surveys

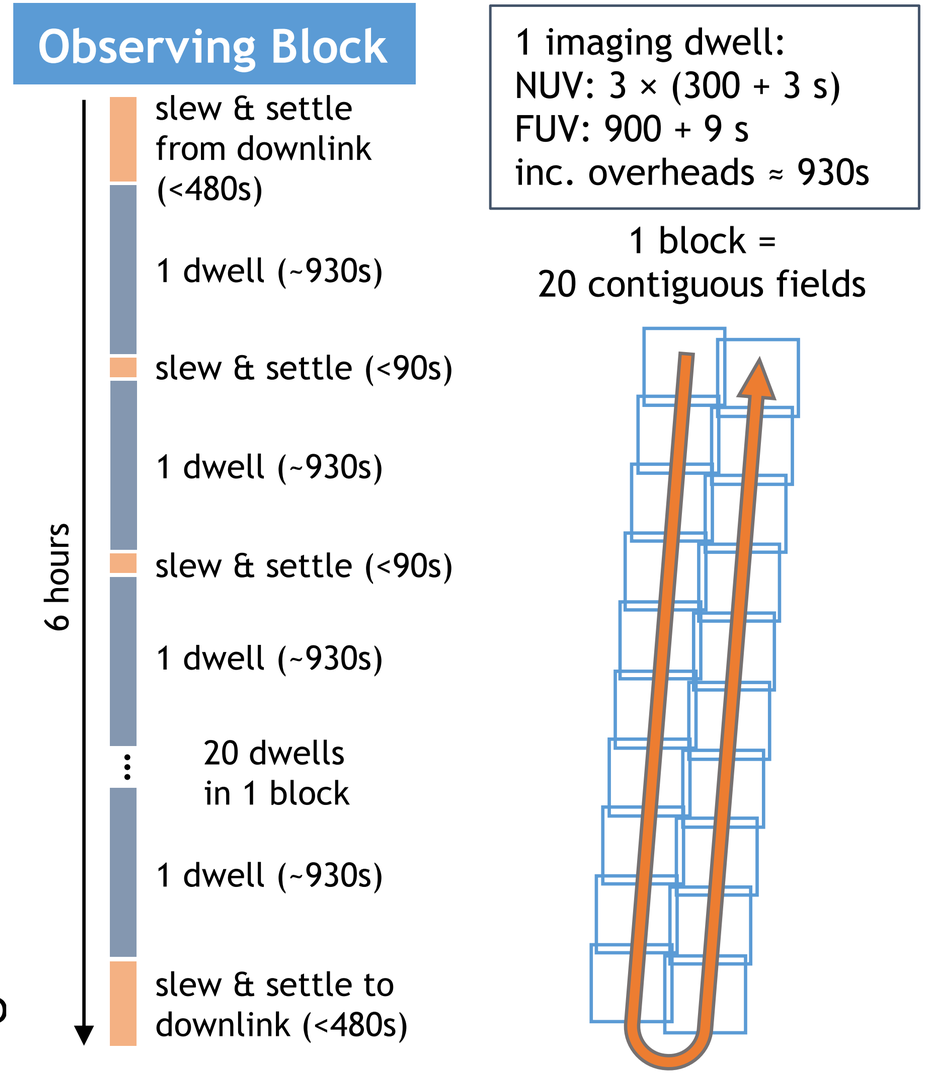
- All-sky imaging survey: imaging over 4π w/ cadence distributed over 1 day to 4 months
- Low-Mass Low-Redshift (LMLZ) imaging survey: ~5 visits over 7500 deg^2, ~50 visits over 500 deg^2
- SMC/LMC imaging survey: cadence of ~2/week
- Spectroscopy: LMLZ, stripped stars in the Magellanic clouds
- Rapid ToOs: gravitational wave imaging searches, core collapse supernovae spectroscopy
- Community ToOs



UVEX scheduler modes

Divide-and-conquer approach

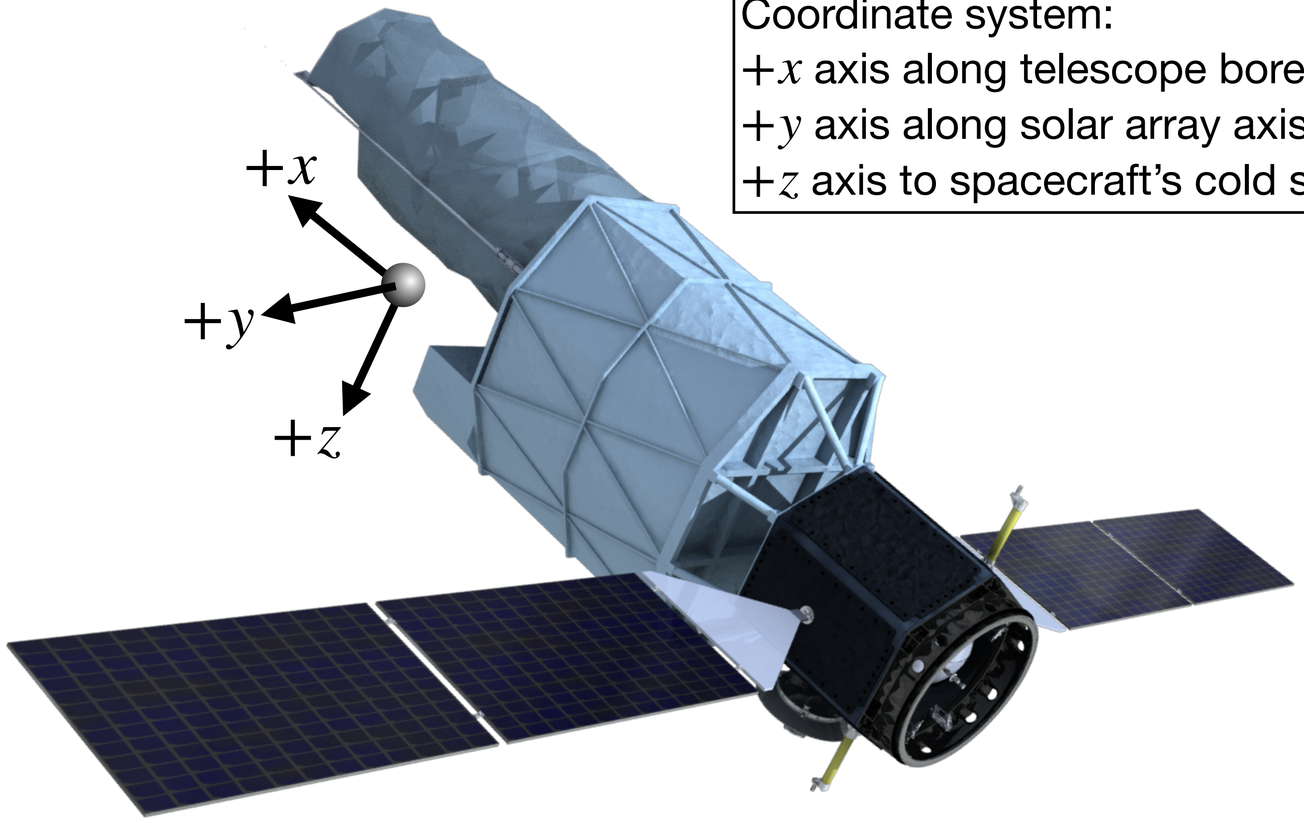
- UVEX has a scheduled contact **every 6 hours**. We call each 6-hour interval a **scheduling block**.
- We can image **19-20 fields per block**.
- For simplicity and efficiency, we define three scheduling modes, each treated as a separate subproblem:
  - **Imaging**: visit a prearranged set of 19-20 fields
  - **Spectroscopy**: service queue containing survey and community targets
  - **GW ToO**: tile a GW error region w/ variable exposure time
- Then we have an **uber-scheduler** which decides which mode to execute in each block.

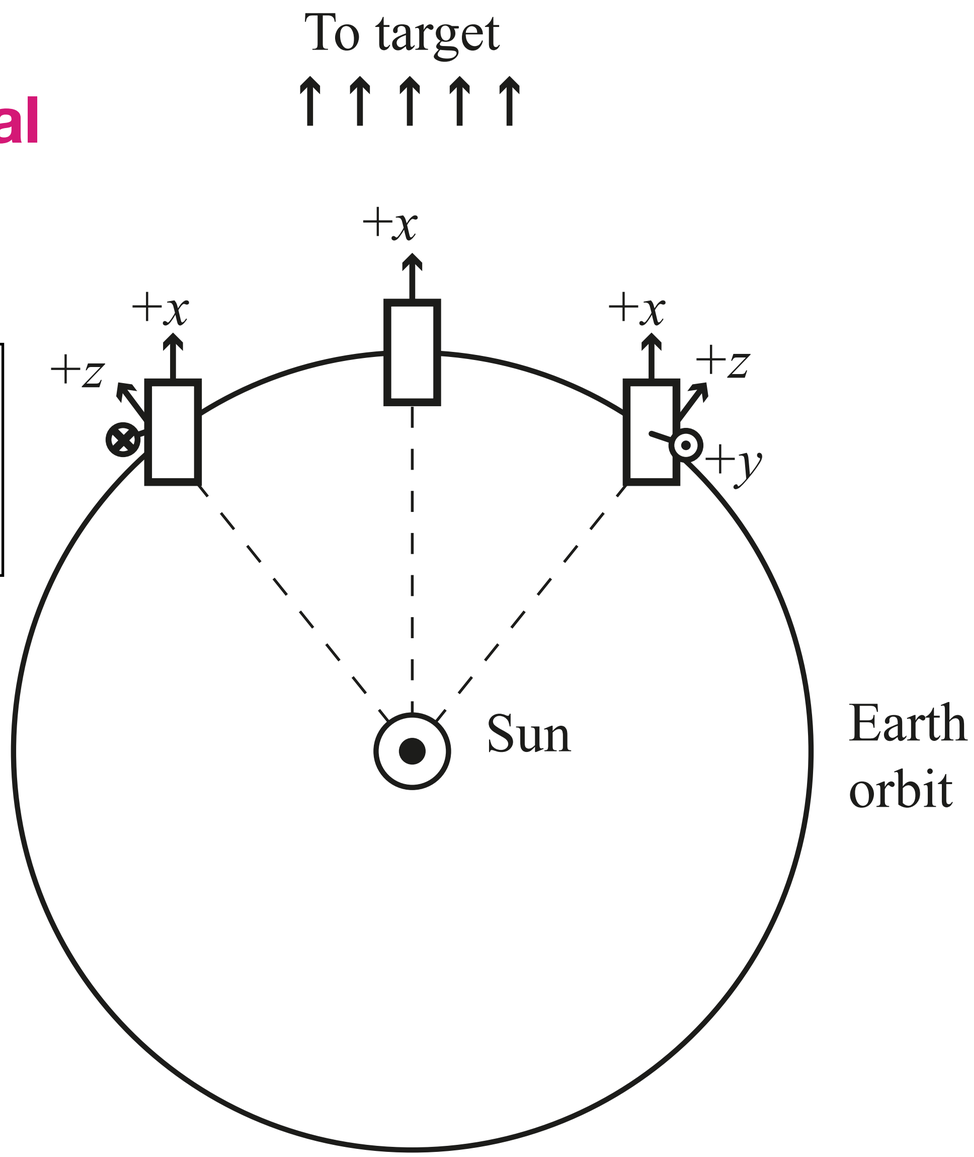


Roll angle constraints

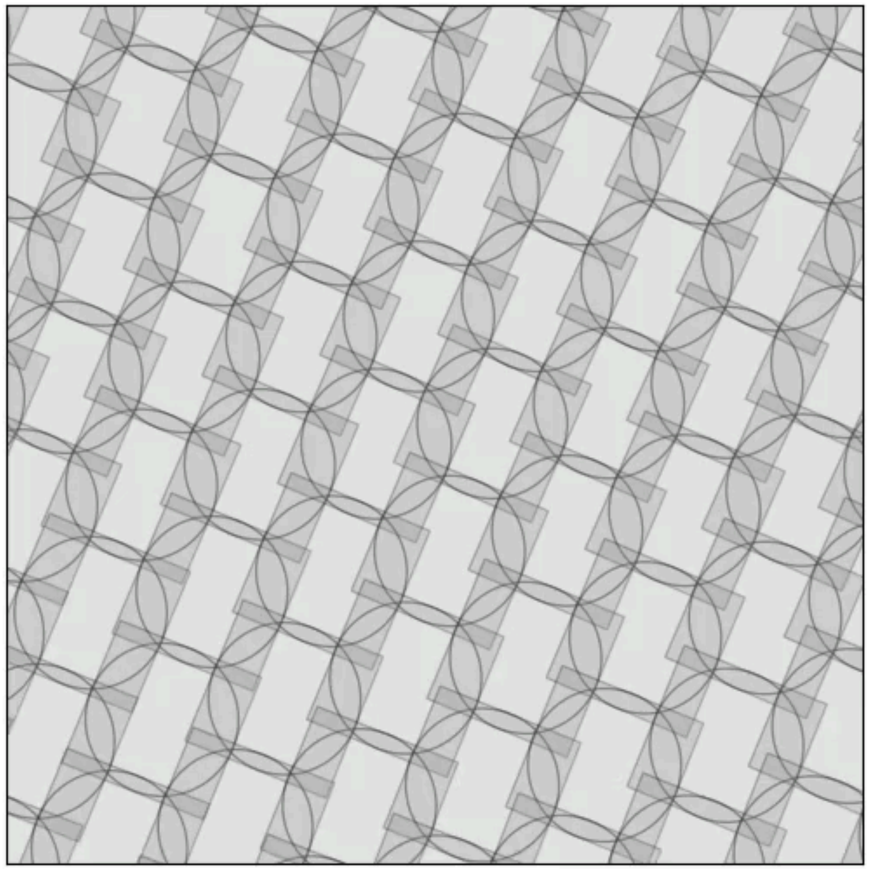
The spacecraft must always observe at a **nominal roll angle** that is set by the position of the target and the time of the observation.

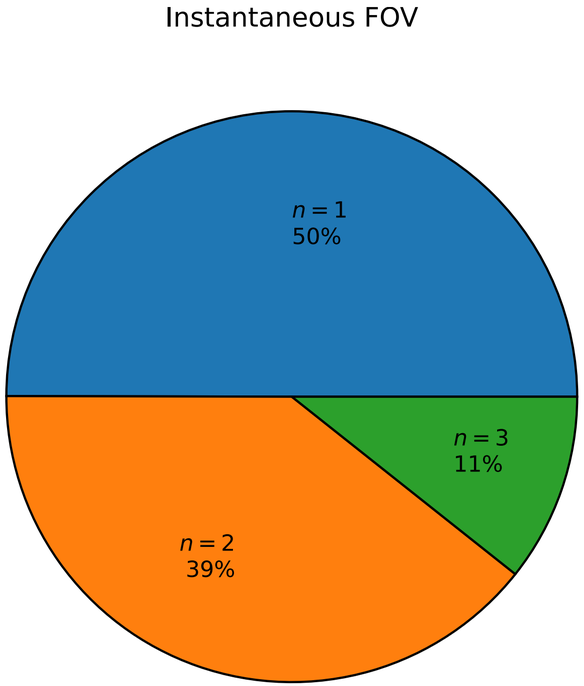
Coordinate system:
$+x$ axis along telescope bore sight
$+y$ axis along solar array axis
$+z$ axis to spacecraft's cold side

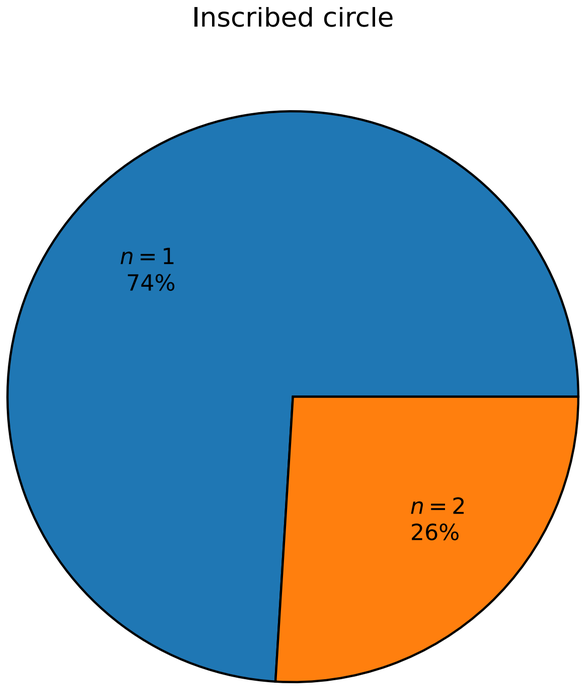




Overlap fraction



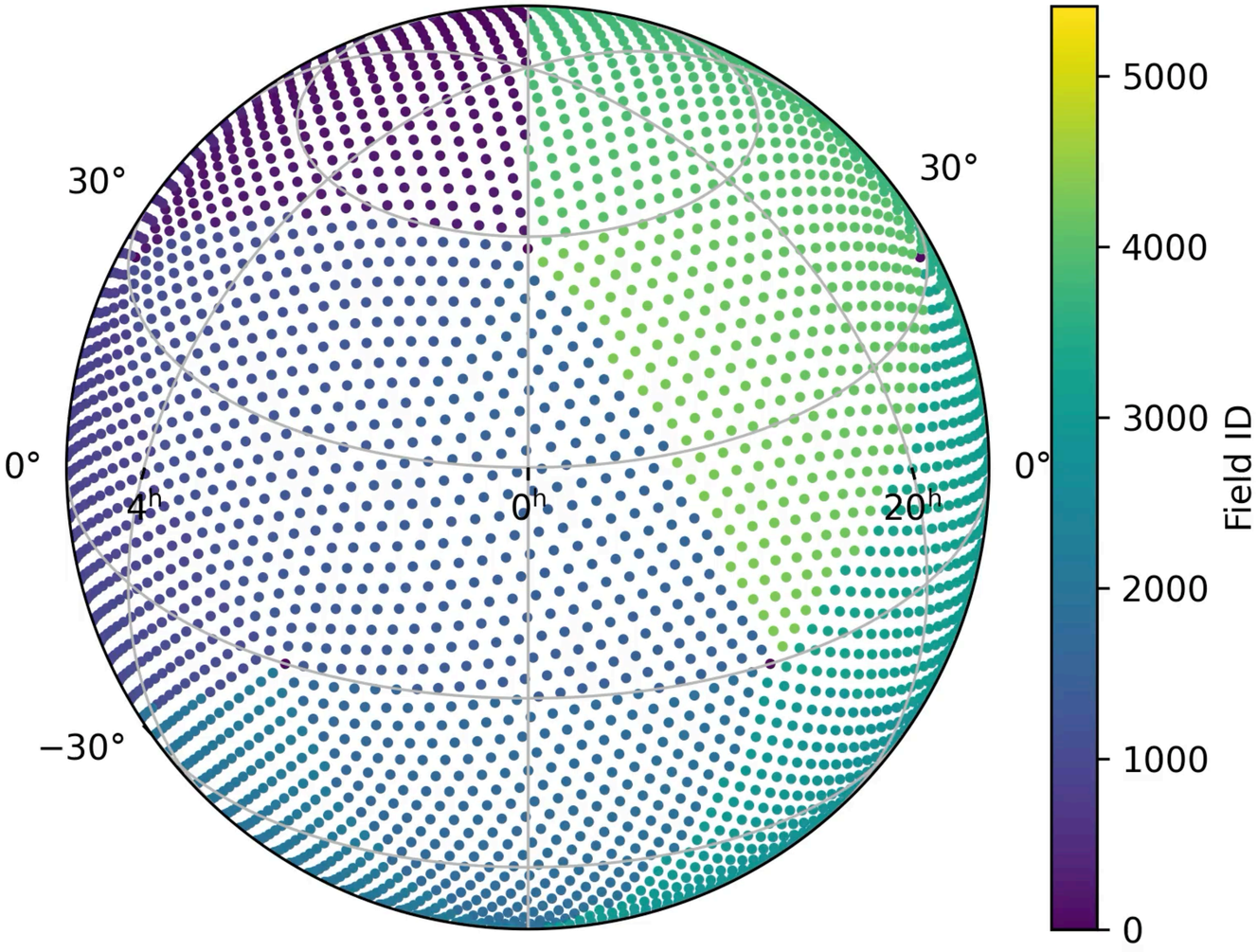


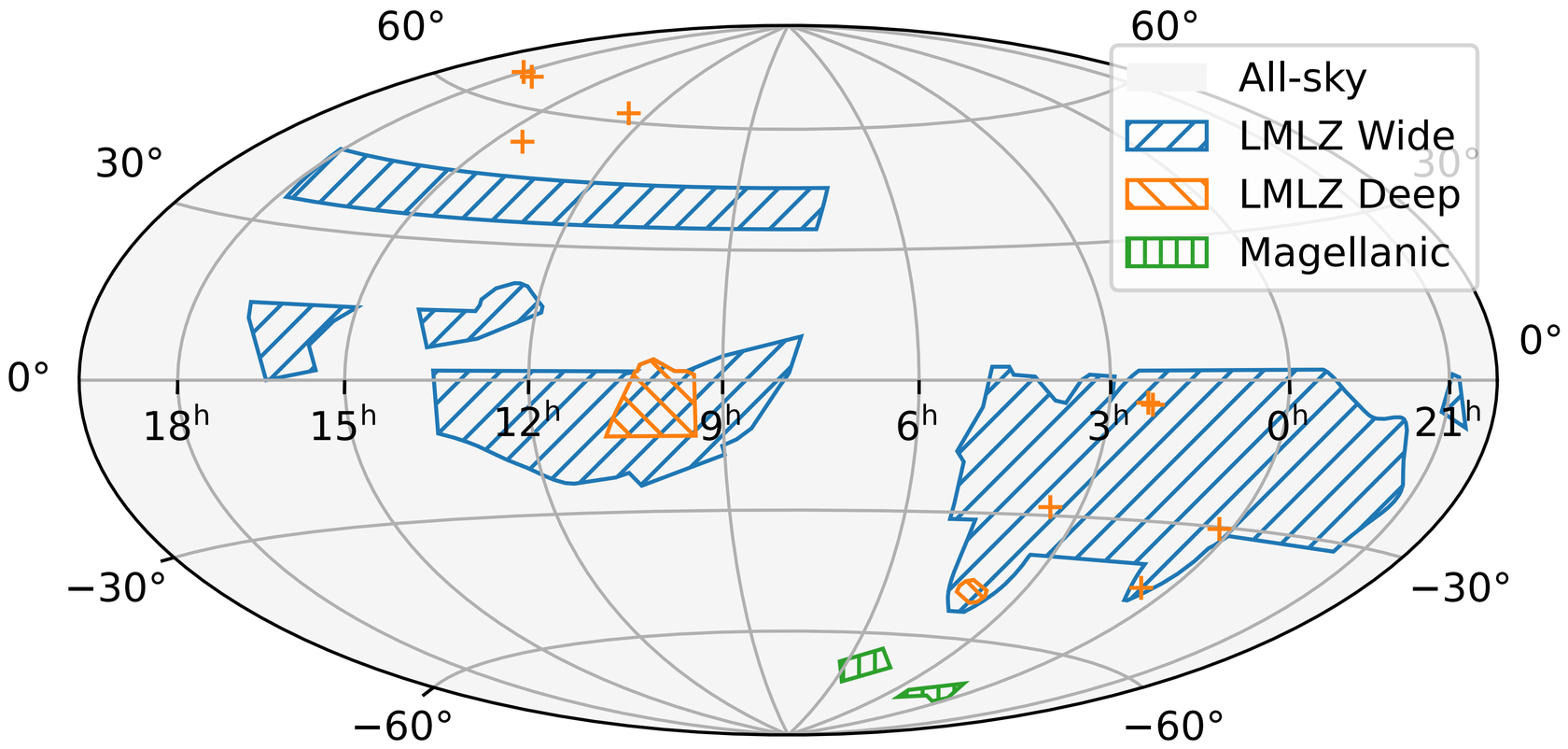


Fraction of sky covered by grid *n* times

Current survey grid design

- The survey grid is **fixed in ICRS (celestial) coordinates**.
- It consists of the **5,412 vertices** of a $\{3,5+\}_{21,4}$ geodesic polyhedron.
- This design **completely covers the sky** with nearly as few as possible circles of diameter 3.5°.
- You can get it in Python as **m4opt.missions.uvex.skygrid**.




60°
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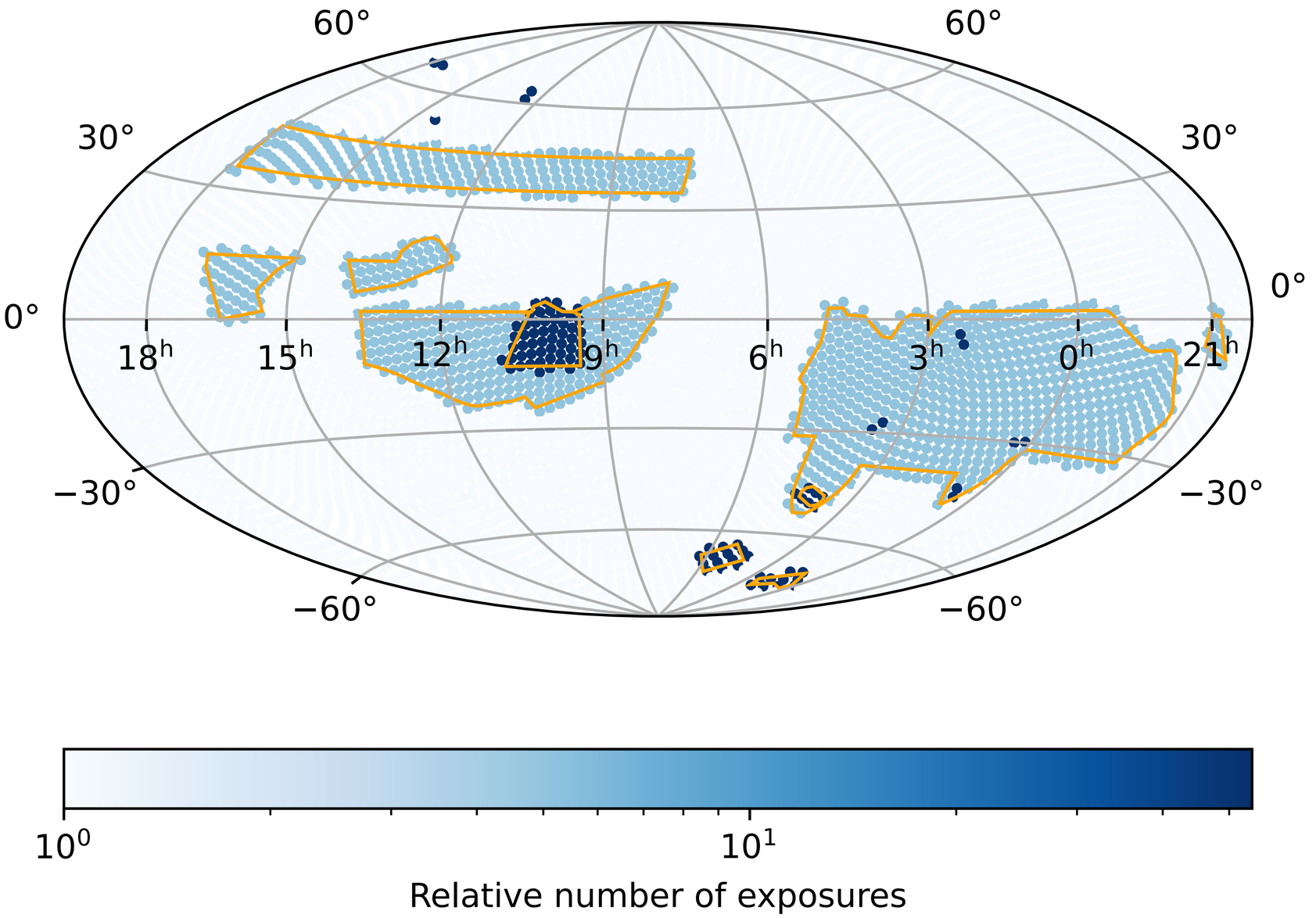
−60°
18h
15h
12h
9h
6h
3h
0h
21h
All-sky
LMLZ Wide
LMLZ Deep
Magellanic


60°
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0°
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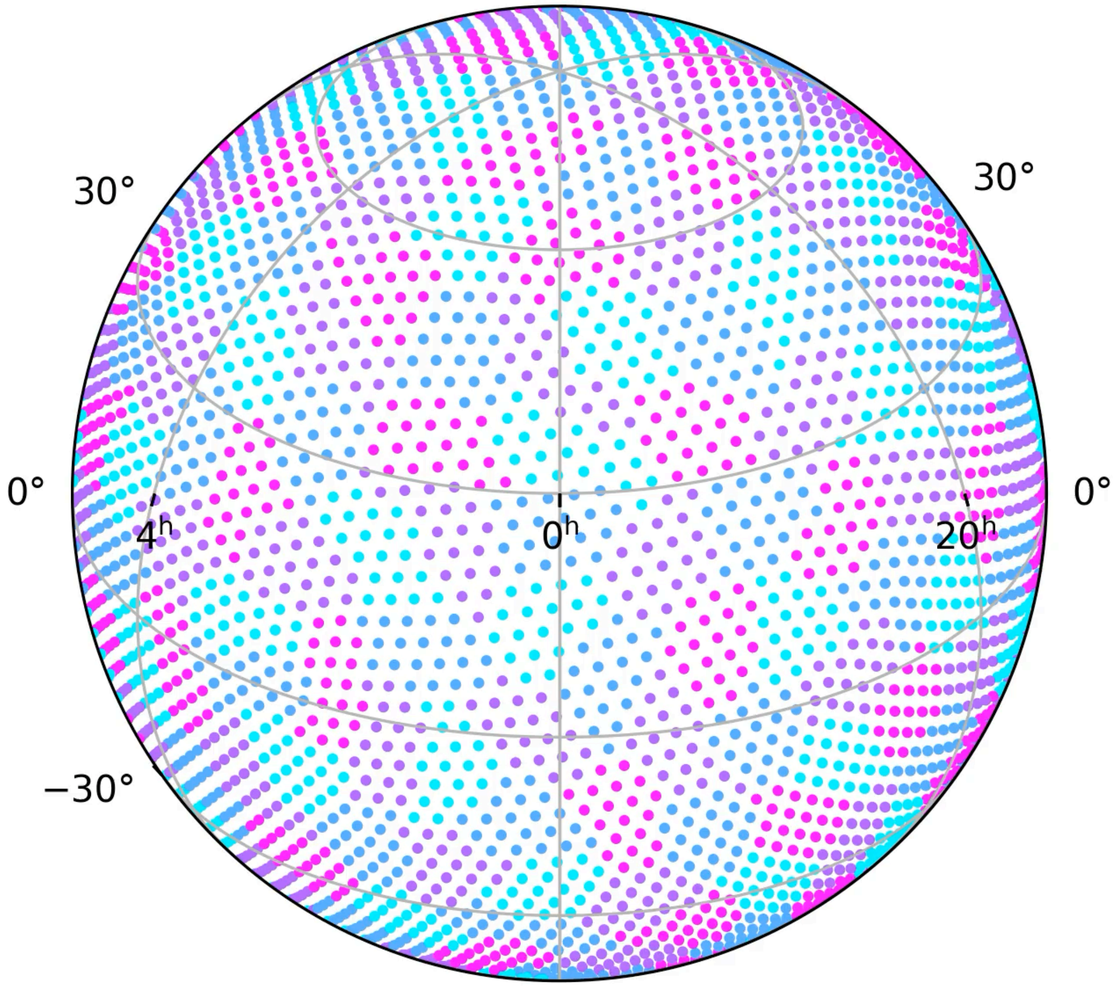
−30°
−60°
−60°
18h
15h
12h
9h
6h
3h
0h
21h
10^0
10^1
Relative number of exposures

Schedule blocks ↔ sky blocks

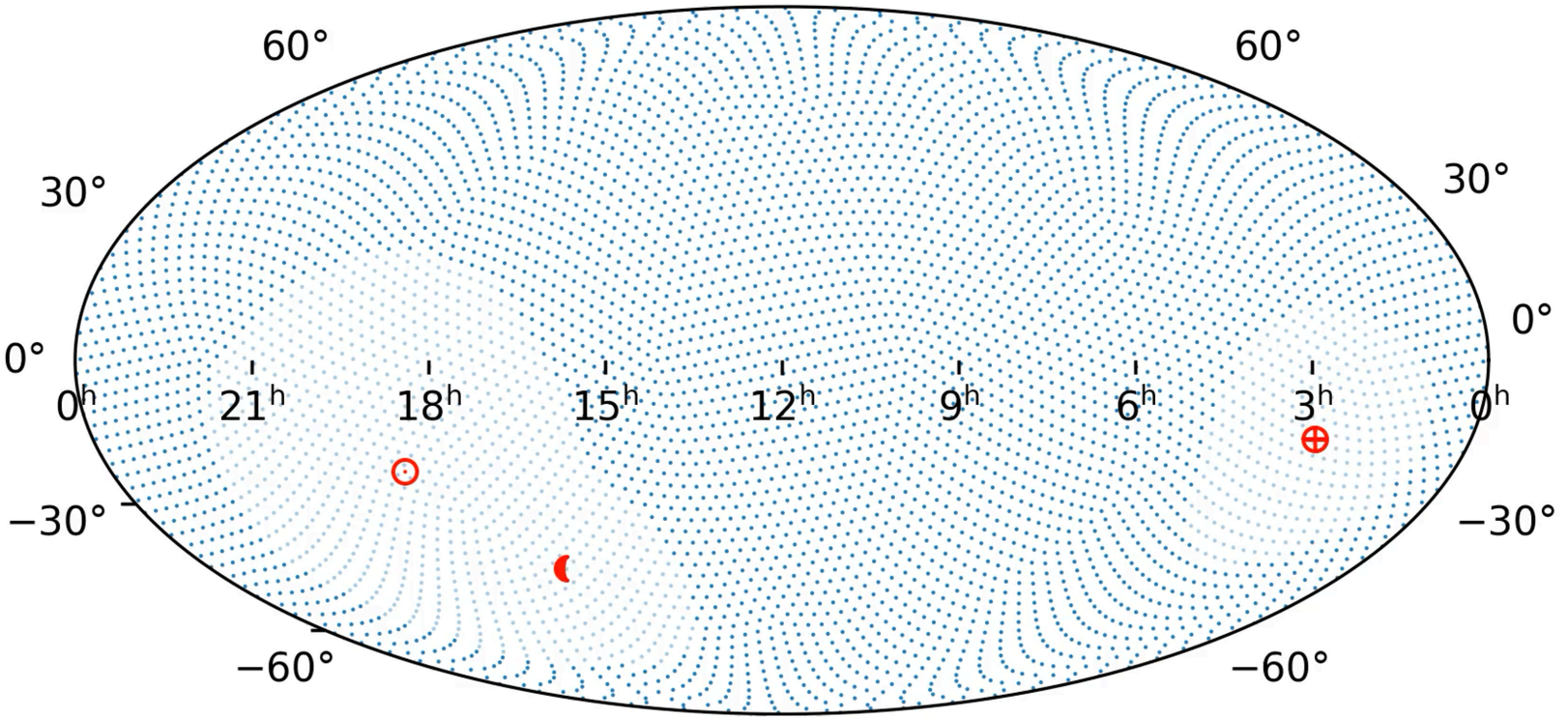
- We use an algorithm called **METIS** to partition the survey grid into **276 groups** of up to 20 adjacent fields.
- These groups are called **sky blocks** because we observe one **sky block** per **schedule block**.
- The blocks have **nonuniform shapes**. We can apply weights to control the shapes:
  - Narrow in RA and tall in Dec for easier shadowing by ground-based telescopes?
  - Define regions of interest that we want to keep contiguous and observe to the same depth



Initial full-sky survey

Science timeline for the first 3 months of UVEX

- We want to **initially survey the entire sky as quickly as possible** so that we have reference images everywhere.
- Neglecting field of regard constraints, it would take **69 days to visit all 276 blocks**.
- The initial survey must take at least **1/4 year** due to the 45° sun avoidance angle.
- This animation shows a science timeline for the initial survey, taking **102 days**.
- It includes **downlinks**, **slews**, and **all field of regard constraints**.



EM-GW Strategy

First two published UVEX science papers:

EM Follow-up to GW Events with UVEX. *PASP*, 2025. https://doi.org/10.3847/1538-4357/ad2704

Optimal Follow-Up of GW Events with UVEX. *PASP*, 2025. https://doi.org/10.1088/1538-3873/adcfc6

Early Career

Sydney Leggio
Graduate Student
USC

Alexander Criswell
Postdoctoral Fellow
Vanderbilt+Fisk

Weizmann Kiendrebeogo
Graduate Student
Observatoire de la Côte d'Azur

Michael Coughlin
U. of Minnesota

Leo Singer
NASA Goddard

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

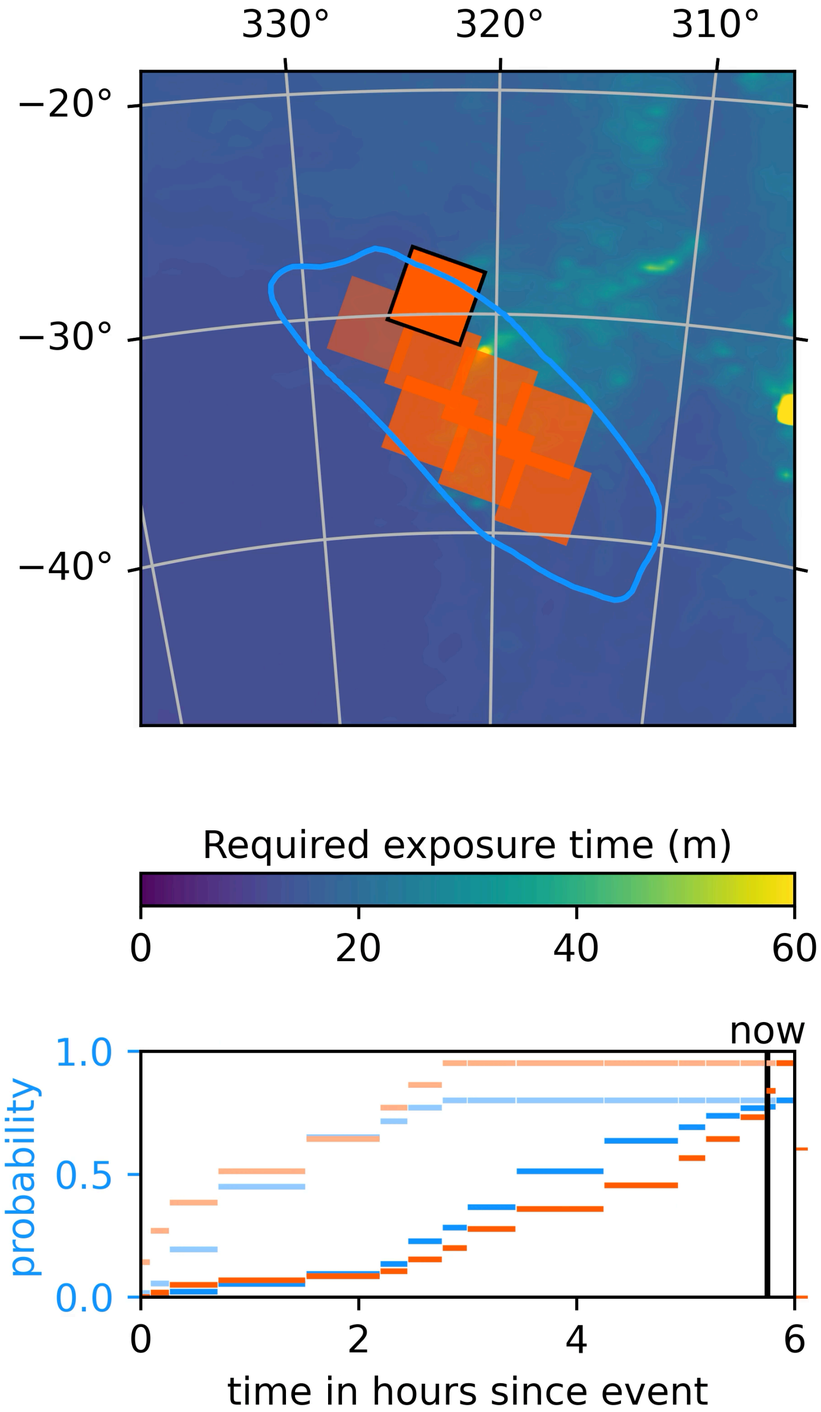
Cadence: minimum time between revisits of a field

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



Three guiding principles

- **Simulatable**: We use the same code to simulate and operate the mission.
- **Engaged**: We need deep engagement with the science teams to ensure that the scheduler will deliver the data that they want. Work with science teams to develop figures of merit for rapid data-driven iteration.
- **Open source**: The scheduler is free and open source. It is part of the science user tools. Any team or community member can download it, install it on their computer, and make changes to it.

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.

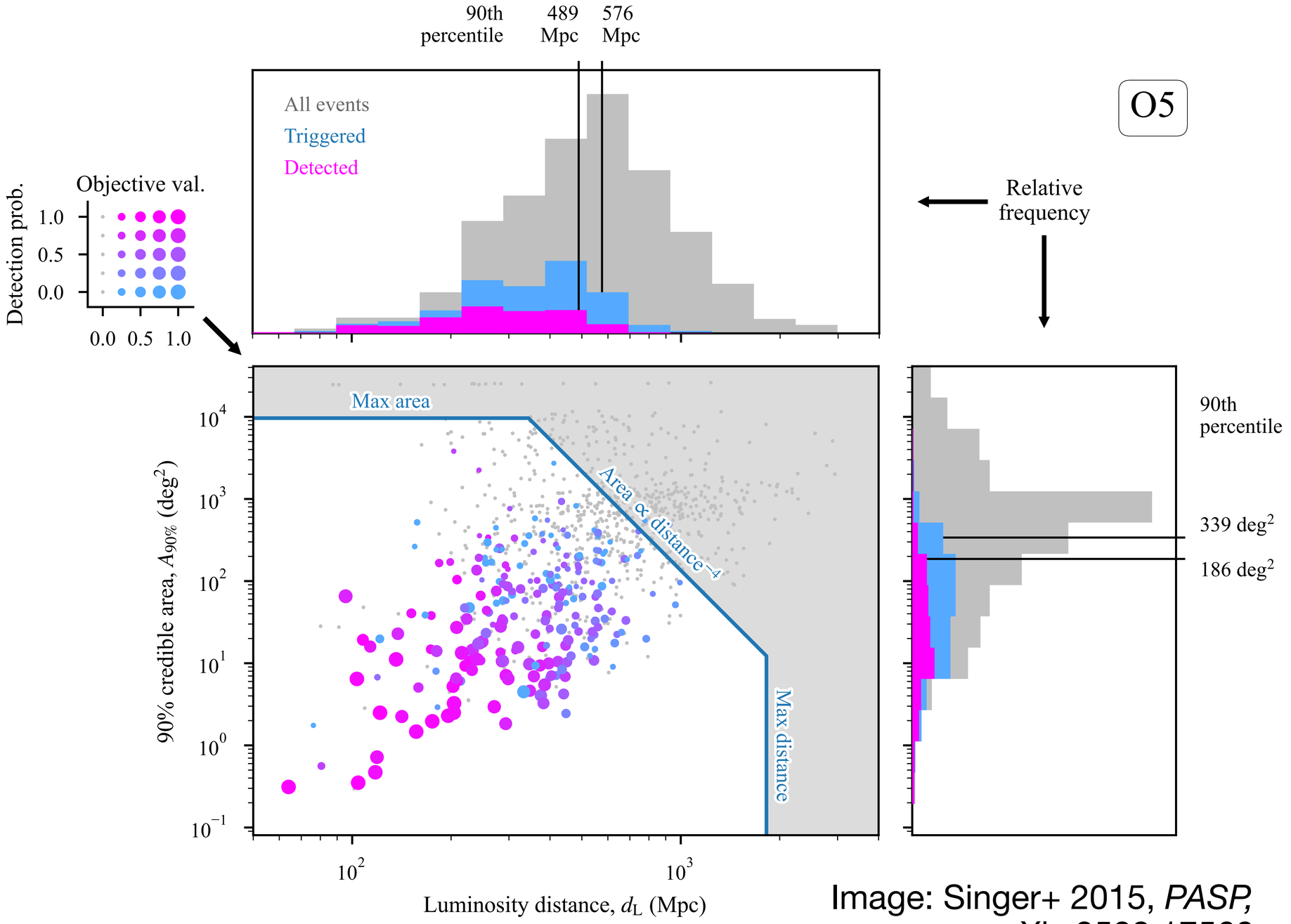
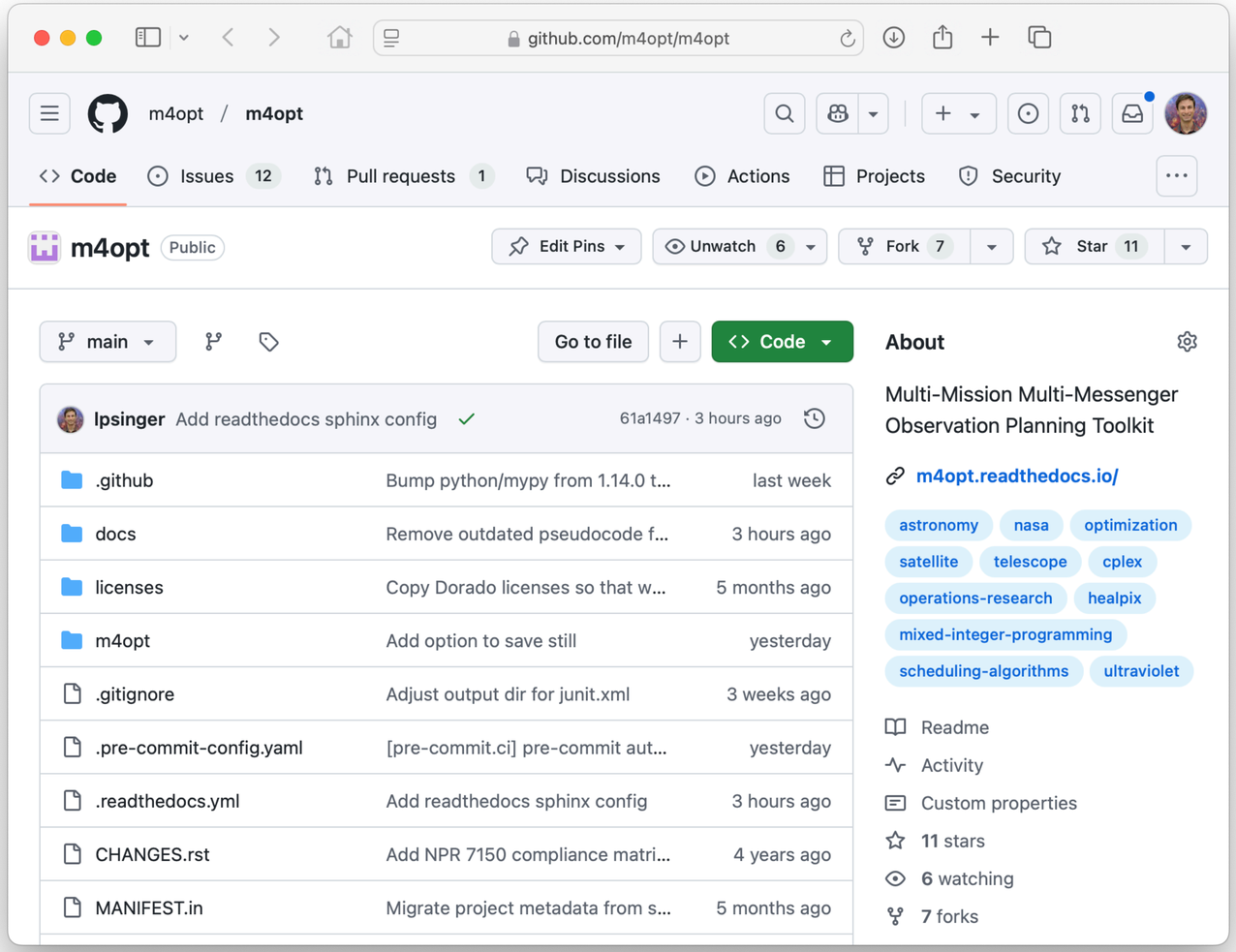


Image: Singer+ 2015, *PASP*, arXiv:2502.17560

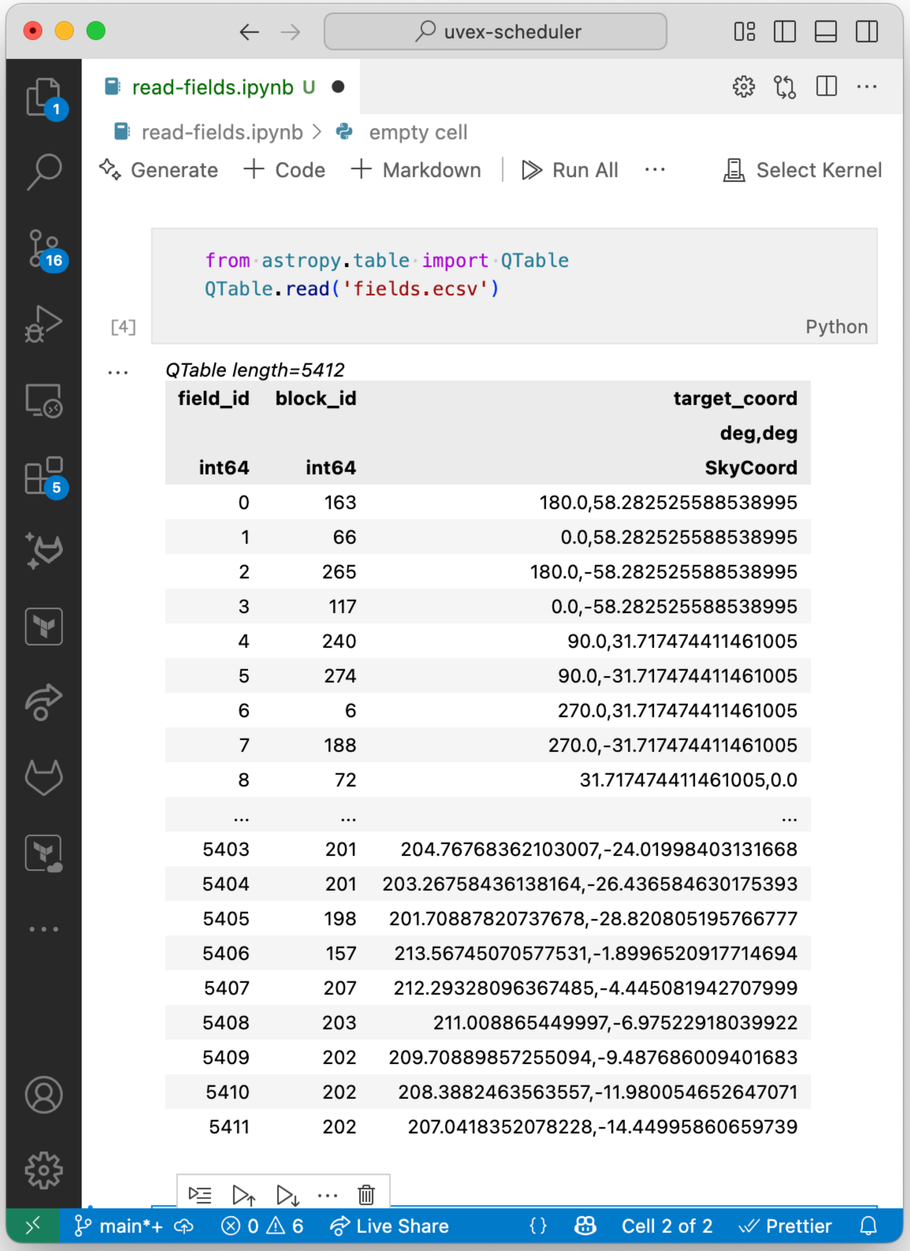
Tools and Data Products

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

https://github.com/m4opt/m4opt



uvex-scheduler

https://github.com/m4opt/uvex-scheduler

main.ipynb: Notebook to generate most of the plots in this presentation as well as the data products below

fields.ecsv: Working field grid and block definitions

initial-survey.ecsv: Reference science timeline for first 100 days

fov.ds9: Region file for camera footprint

Extra Slides

What tools do we need/will we provide?

In Progress

Offline Scheduler: The simplest conceivable software framework to generate a feasible science timeline for the whole mission while meeting all science requirements.

Reference Science Timelines: Pre-generated, version-controlled, simulated science timelines and related data products for selected points in design space (baseline, CBE).

High Performance ETC: A scalable synthetic photometry package that emulates a versioned snapshot of the UVEX instrument simulator, suitable for ETC-driven scheduling and for modeling for billions of sources per second over an entire science timeline.

Survey Analytics Framework: Software to tabulate, plot, and report figures of merit for each science goal of a given reference science timeline and point in design space.

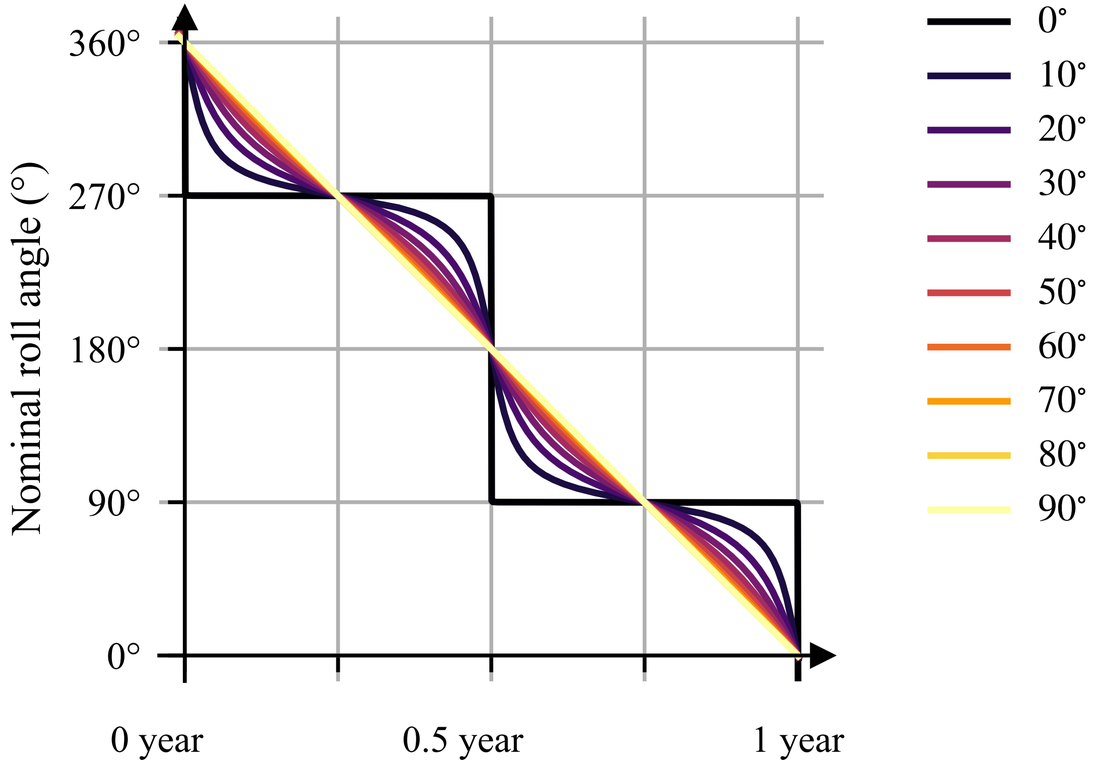
Online Scheduler: A real-time scheduling software framework that accepts new ToO inputs and replans in real time.

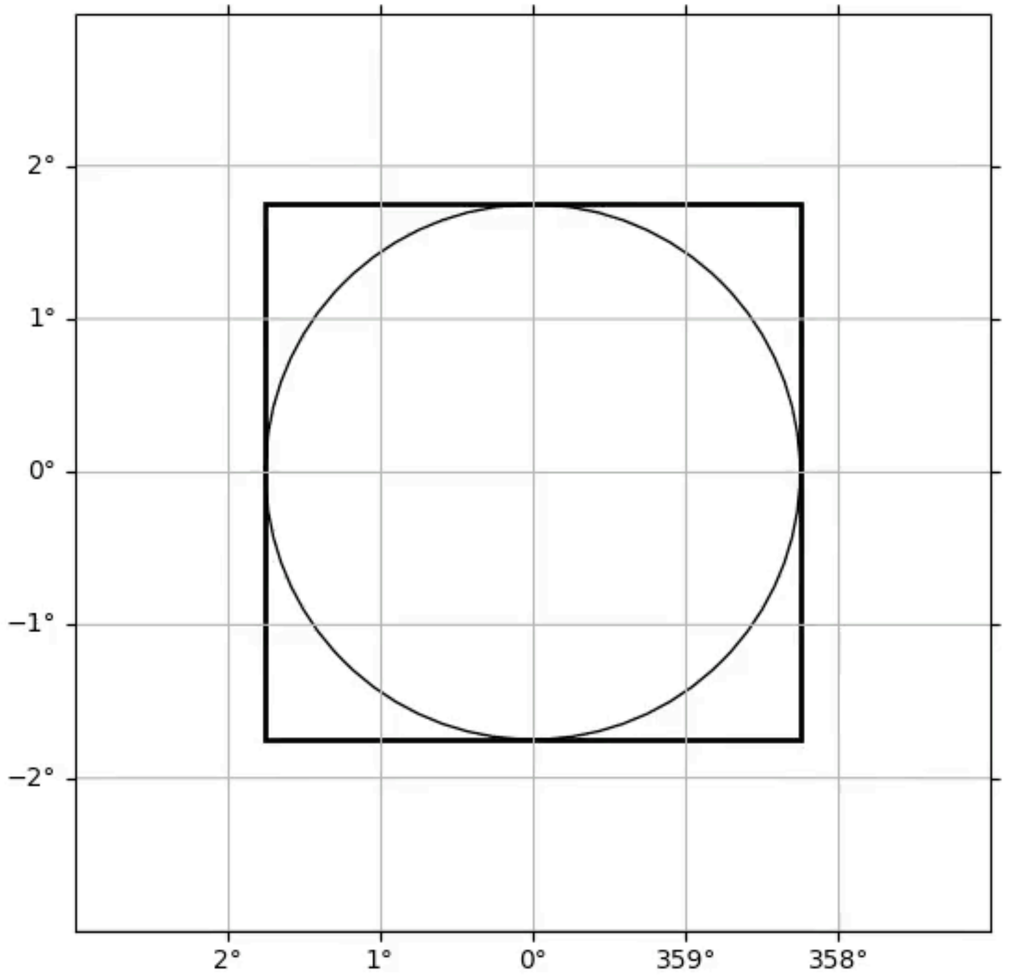
Scheduler Dashboard and APIs: Live web tools for team and community members to interact with the scheduler.

Roll angle over time

For any fixed target, the nominal roll angle **cycles through 360° per year**. Therefore only the **circle inscribed in the FOV** helps for reference image coverage for ToOs at any time of year.

Image: Singer+ 2015, *PASP,* in press. arXiv:2502.17560





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”)

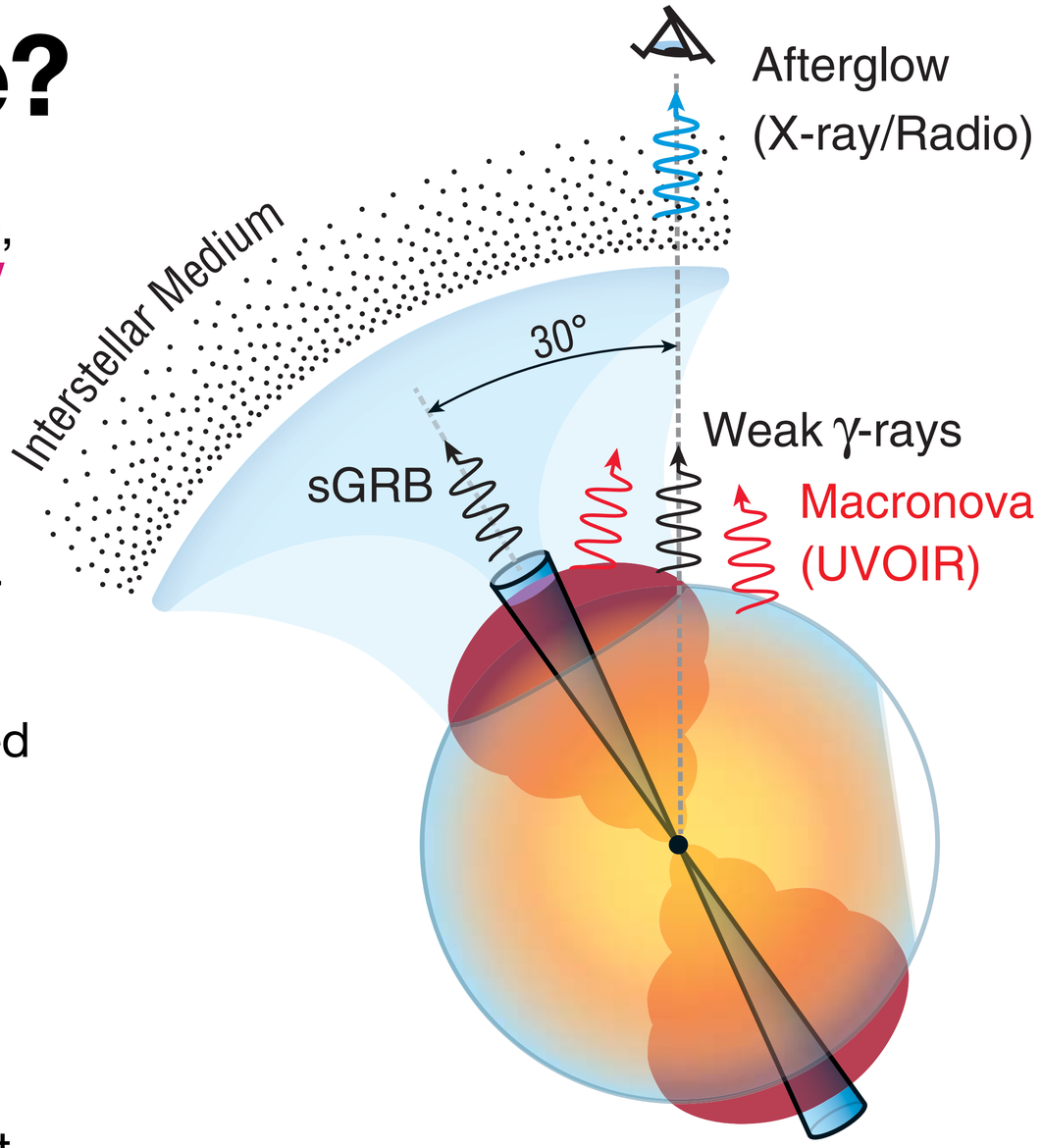
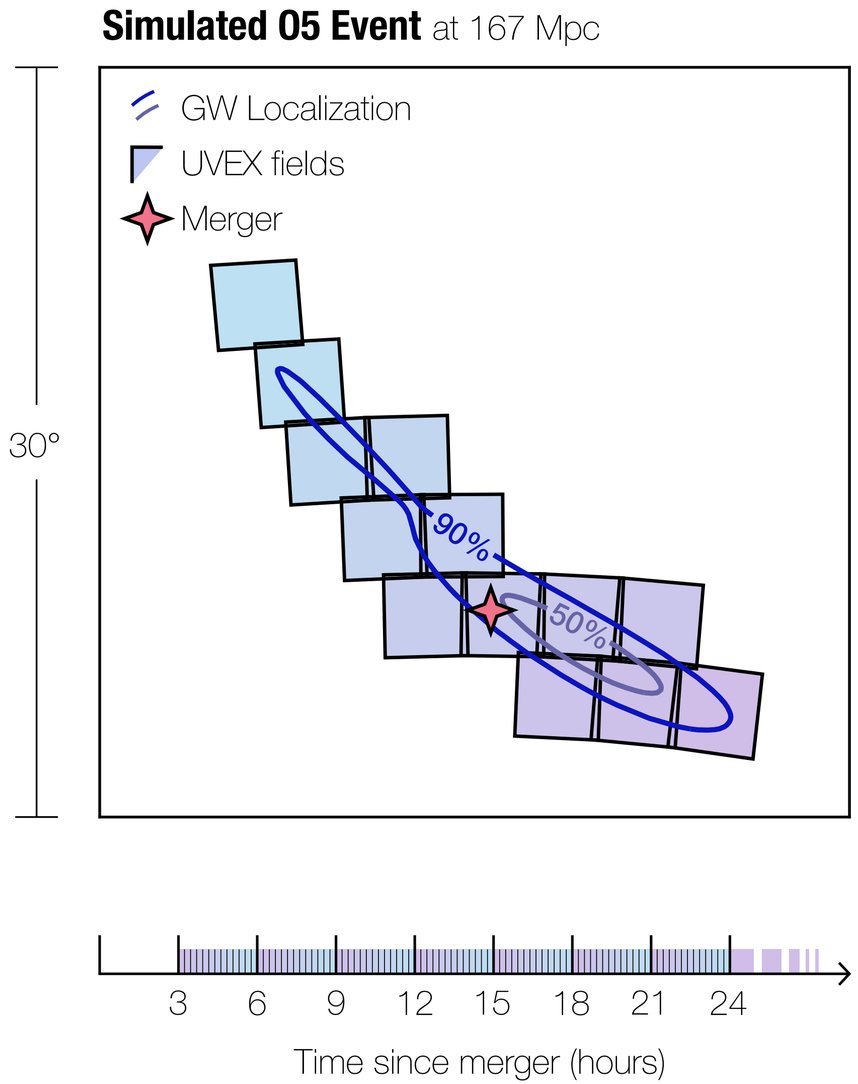
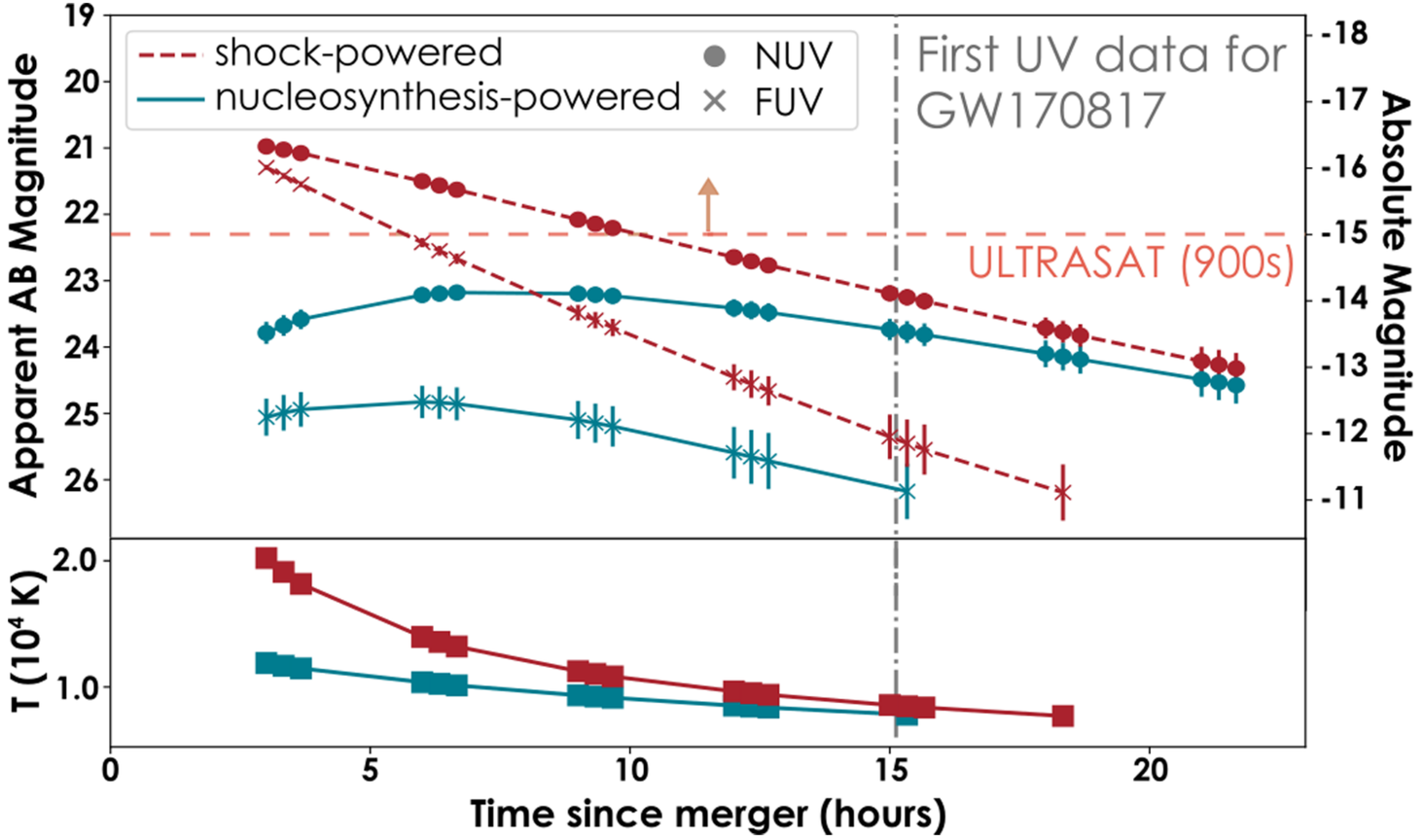


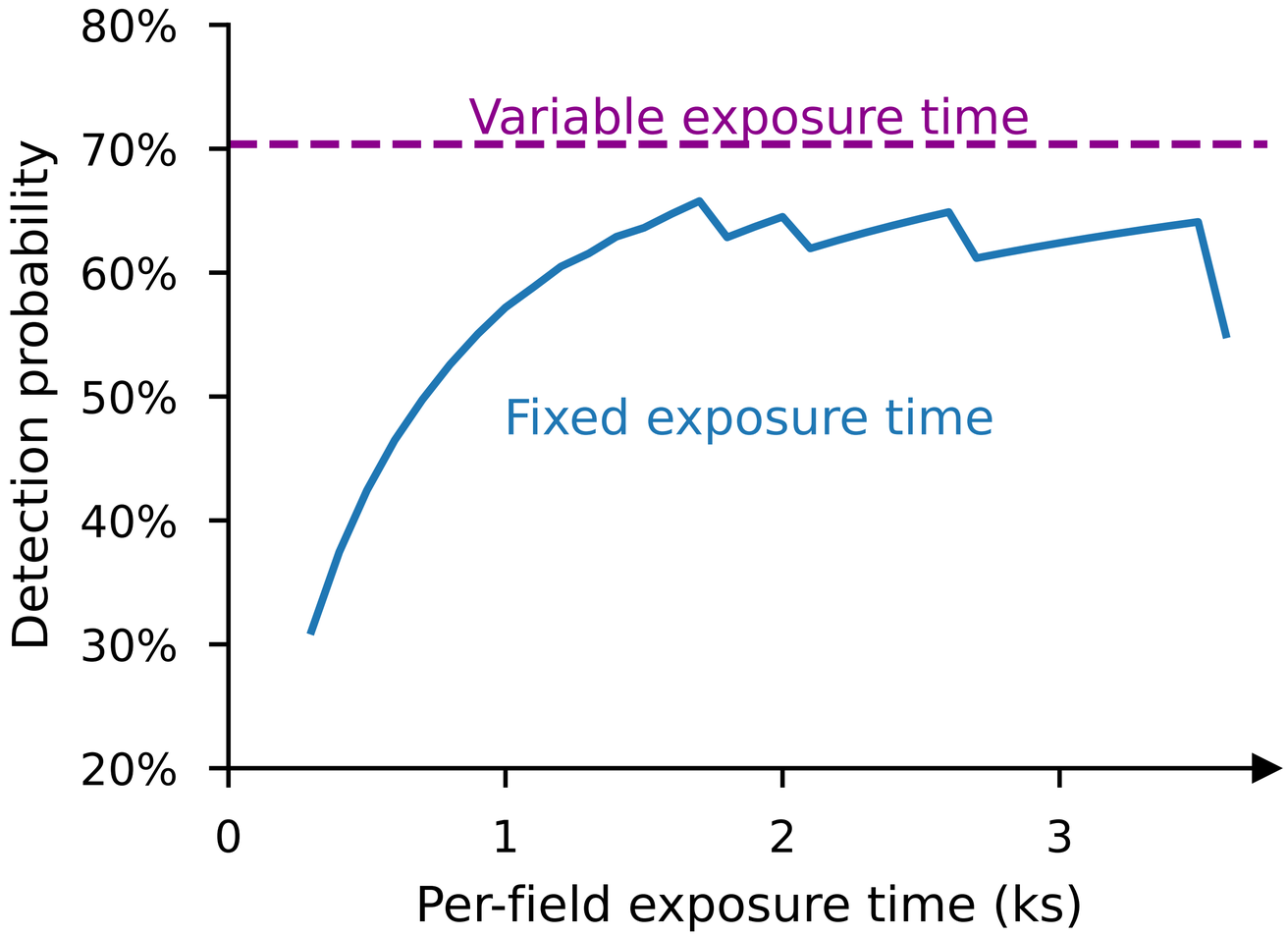
Image: Kasliwal, Nakar, Singer, et al. (2017), Science

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





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



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

Image: Singer+ 2015, *PASP*, arXiv:2502.17560