



 @merrdiff

 @mrawls

Satellite constellations, astronomy, and the future of our sky

Meredith Rawls | Steward + NOIRLab Colloquium | November 4, 2021





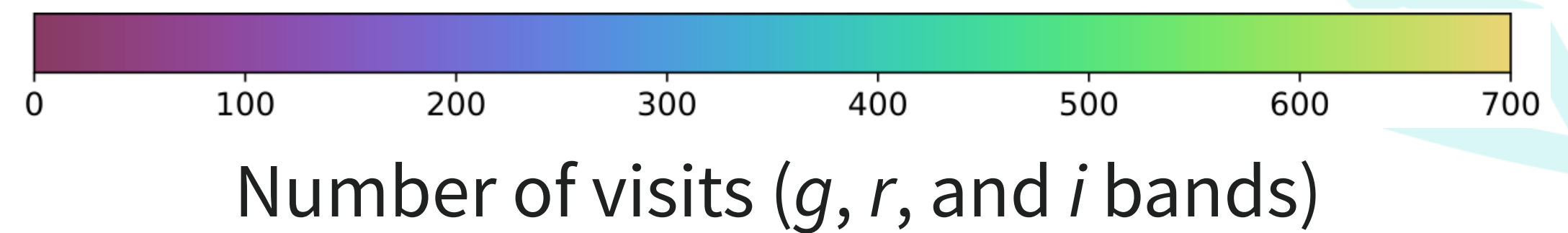
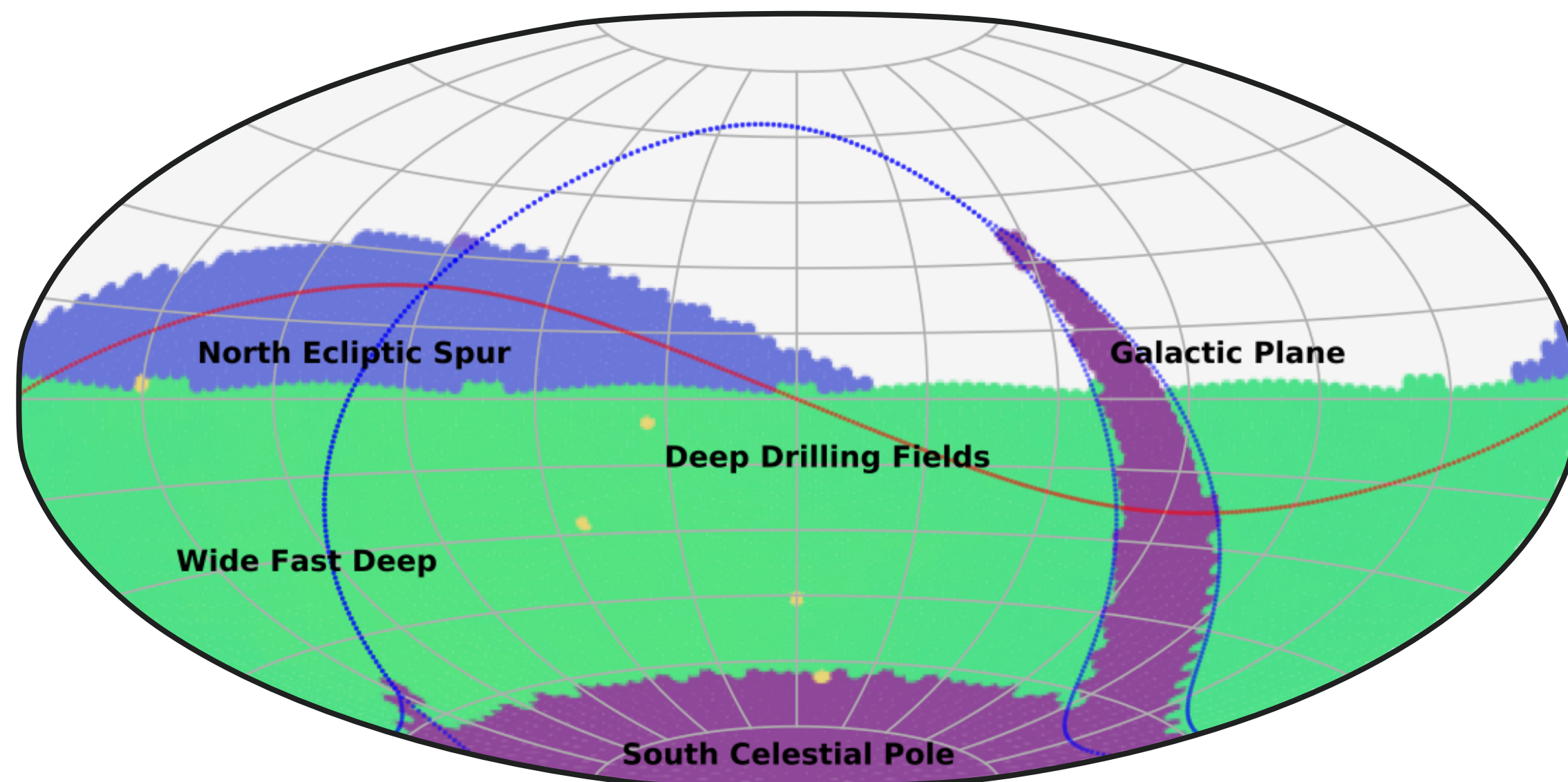
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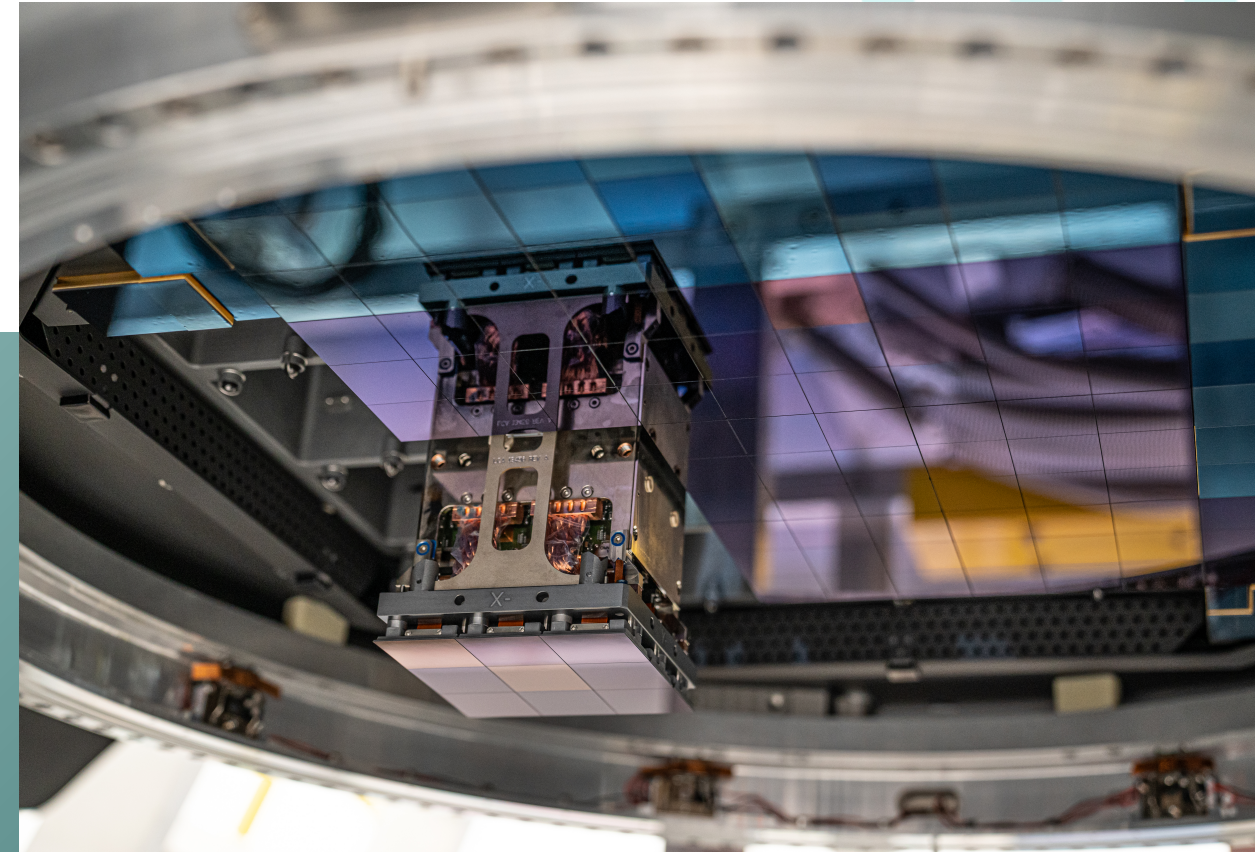
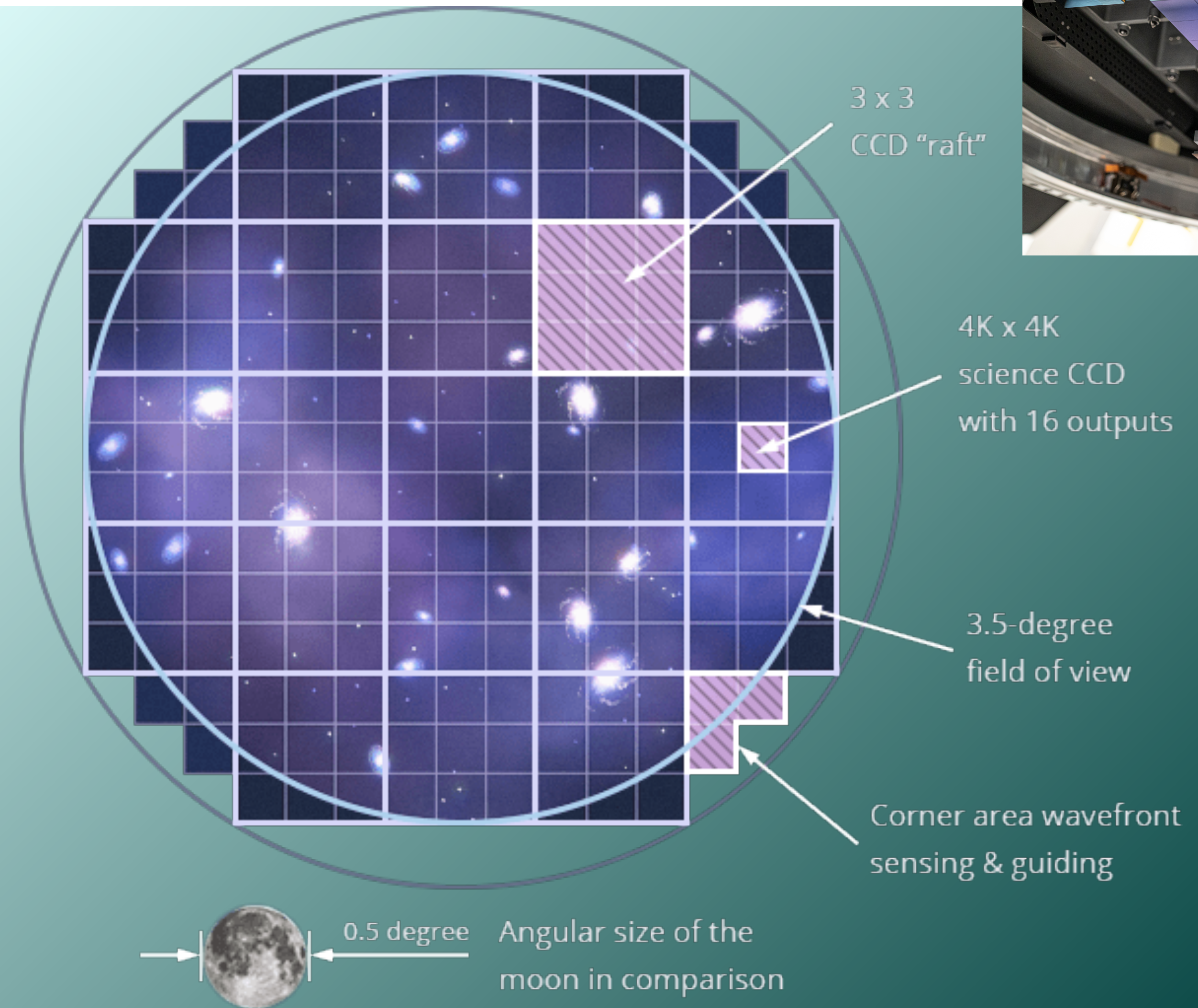
Lopez Island, October 2021

The Legacy Survey of Space and Time

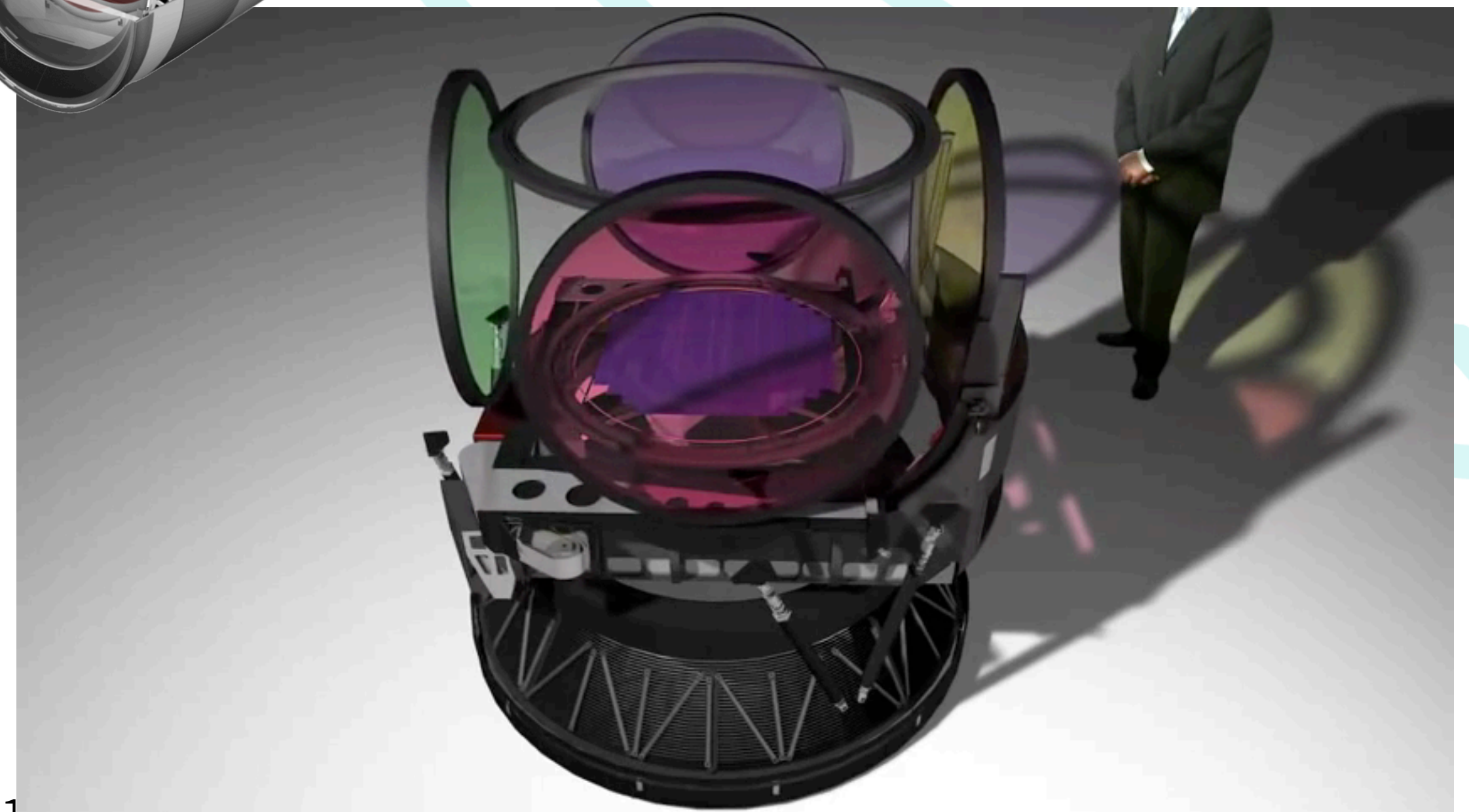
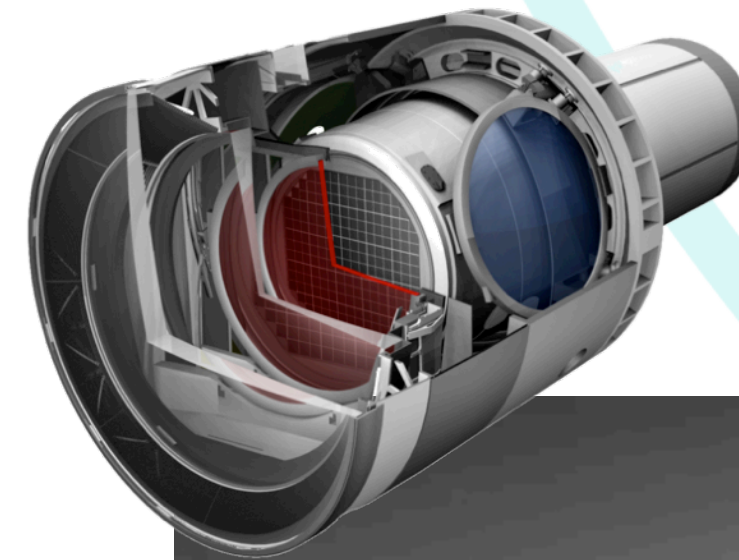
- The 10-year survey from Rubin Observatory
- Six bandpasses (*ugrizy*) for full color
- Uniform map of southern sky every three days
- Data and software for the community
- Science from solar system to dark energy



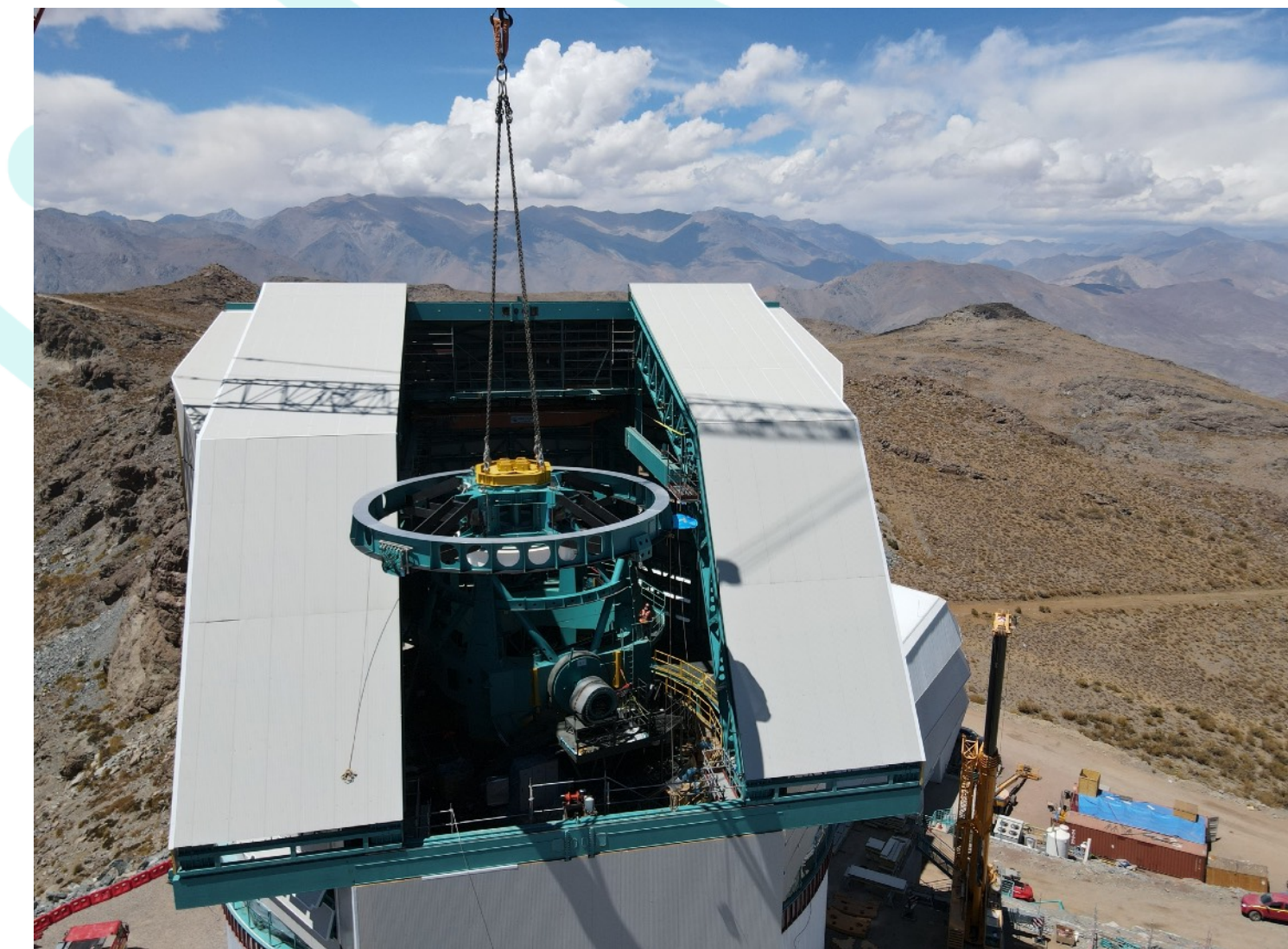
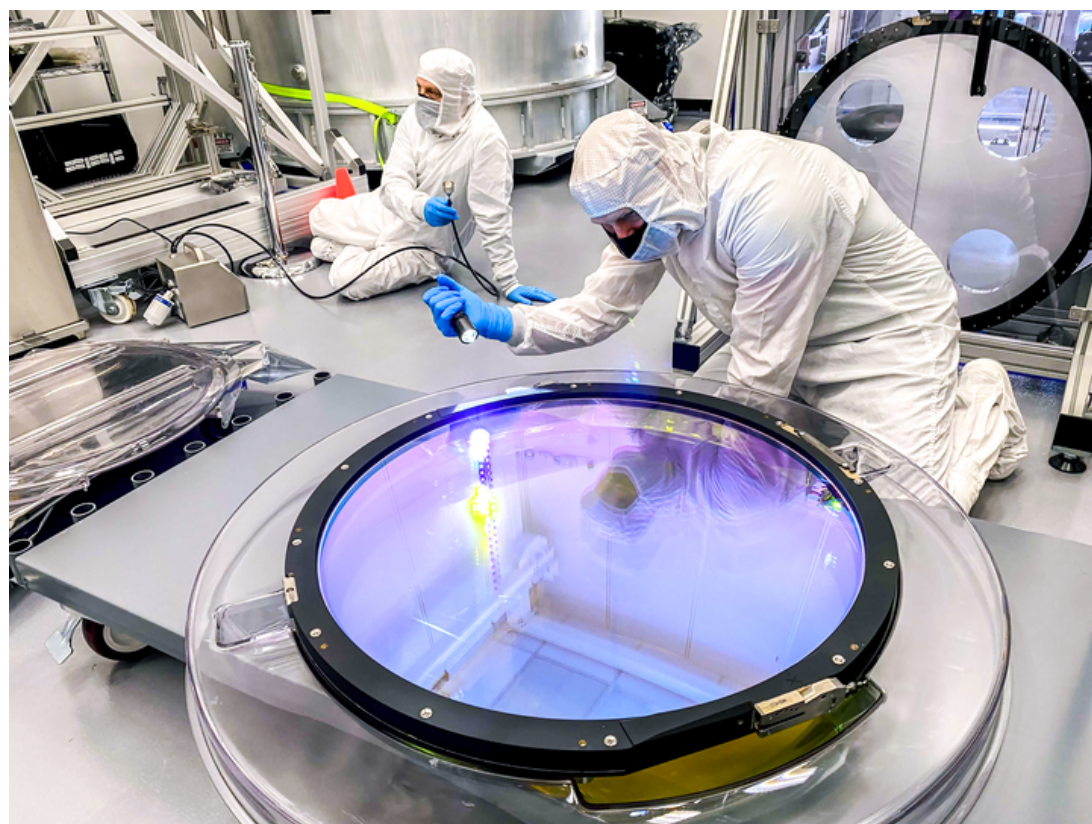
3.2-gigapixel camera!



SLAC



Rubin Observatory under construction

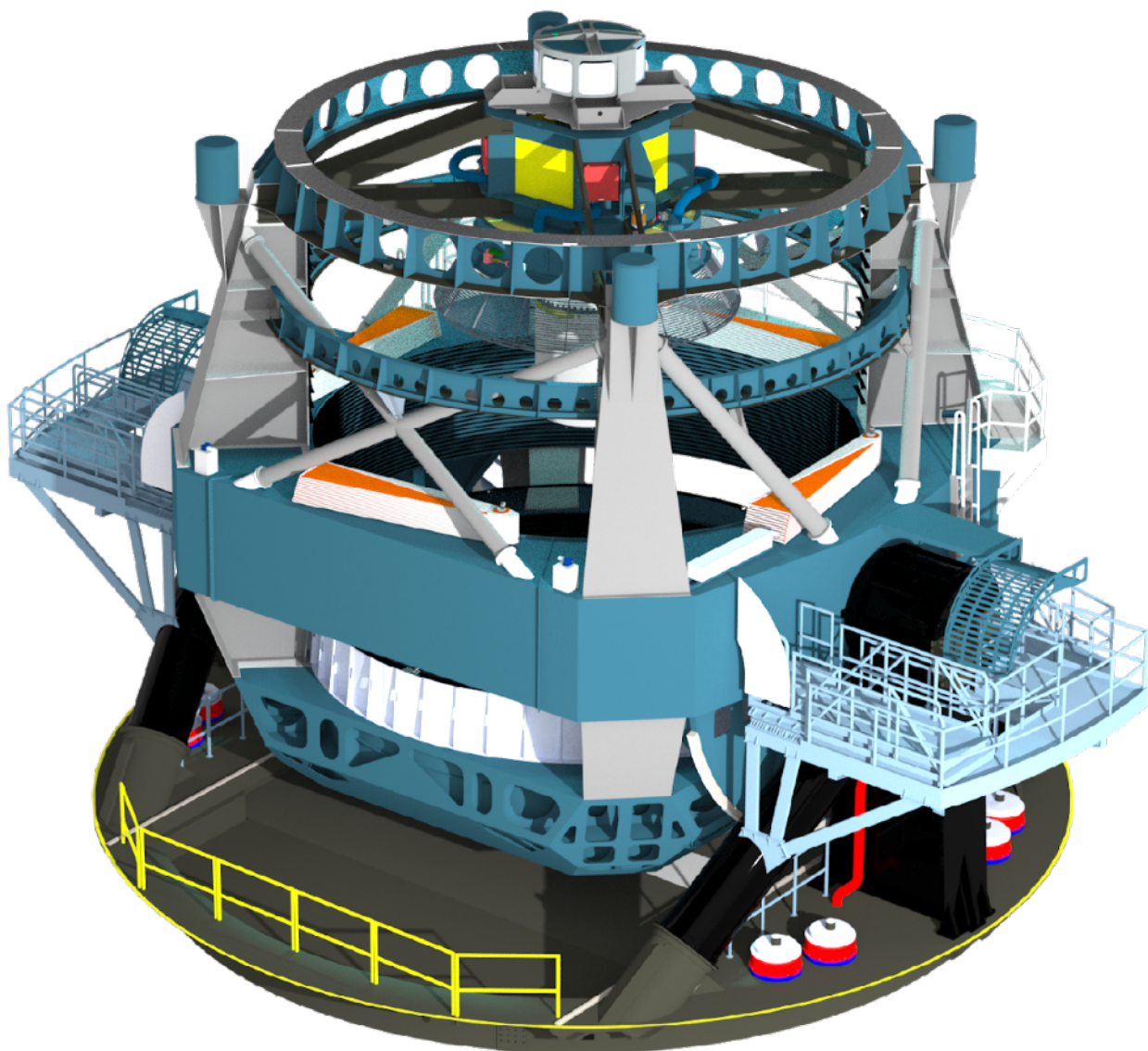


Data Management System

Raw Data: 20TB/night



Sequential 30s images covering the entire visible sky every few days



Prompt Data Products

Alerts: up to 10 million per night

Results of Difference Image Analysis (DIA): transient and variable sources

Solar System Objects: ~ 6 million

Data Release Data Products

Final 10yr Data Release: Michitaro Koike

- Images: 5.5 million x 3.2 Gpx
- Catalog: 15PB, 37 billion objects



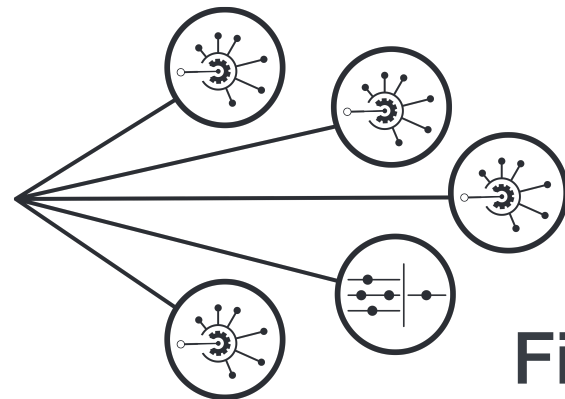
via nightly alert streams



via Prompt Products Database



via Data Releases



Community Brokers

LSST Alert Filtering Service

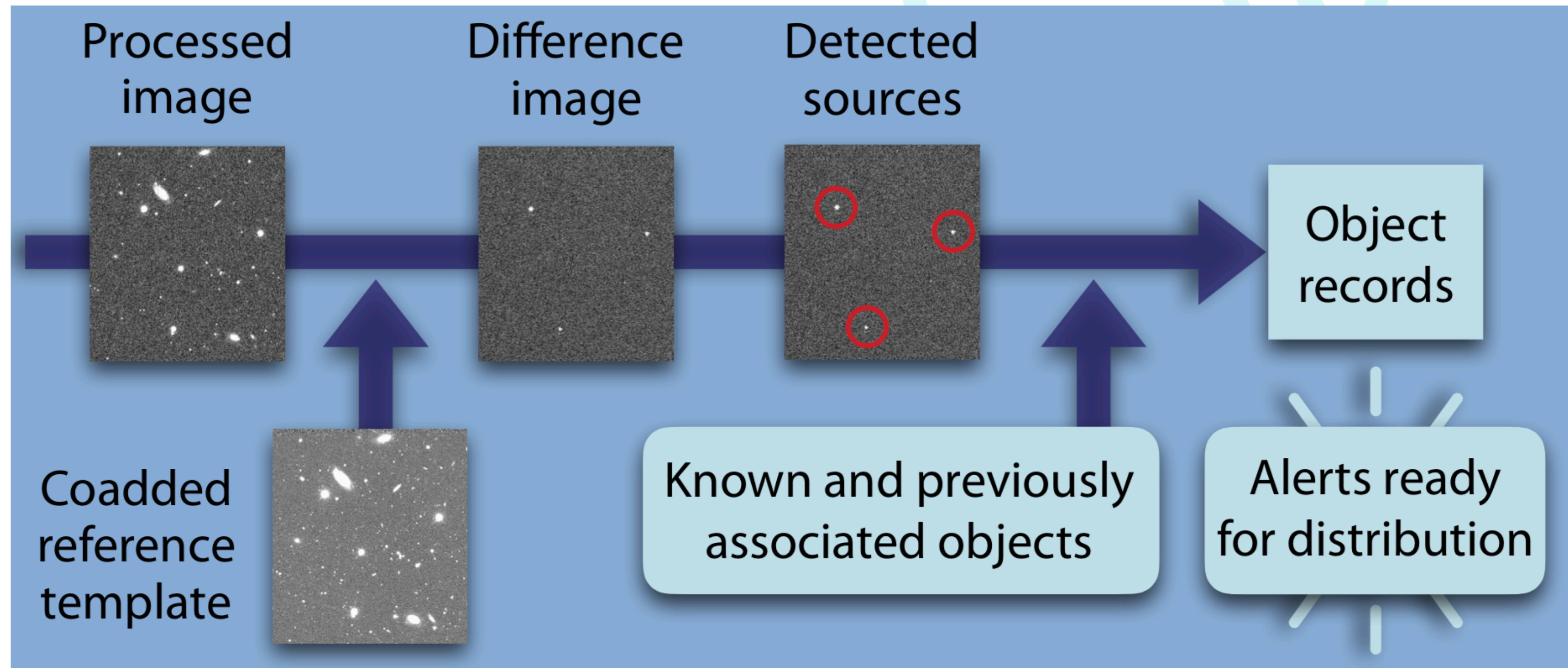
LSST DACs (Chile & NCSA)

Independent DACs (iDACs)

The software is at least as important as the science

Building software for prompt data products

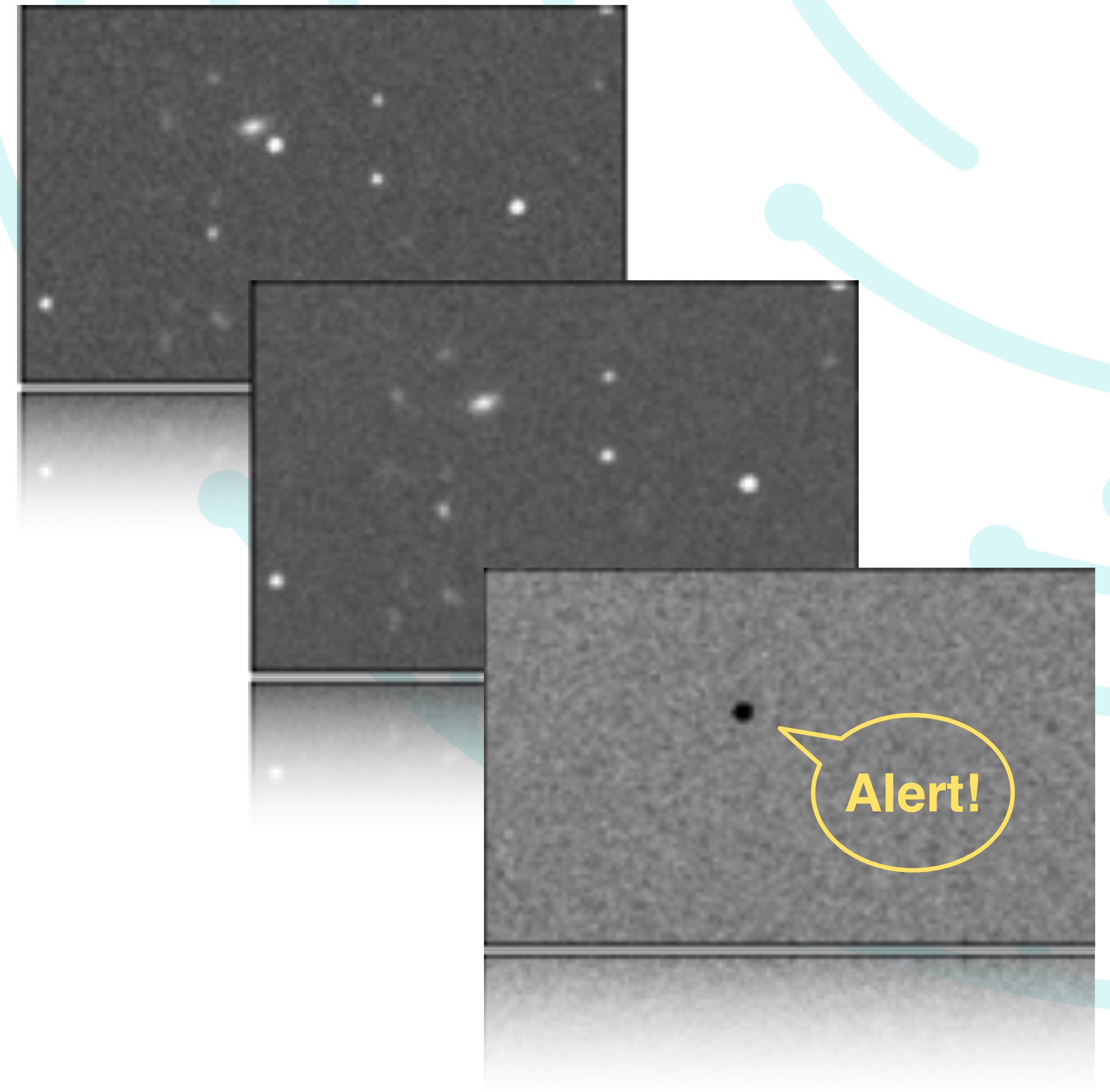
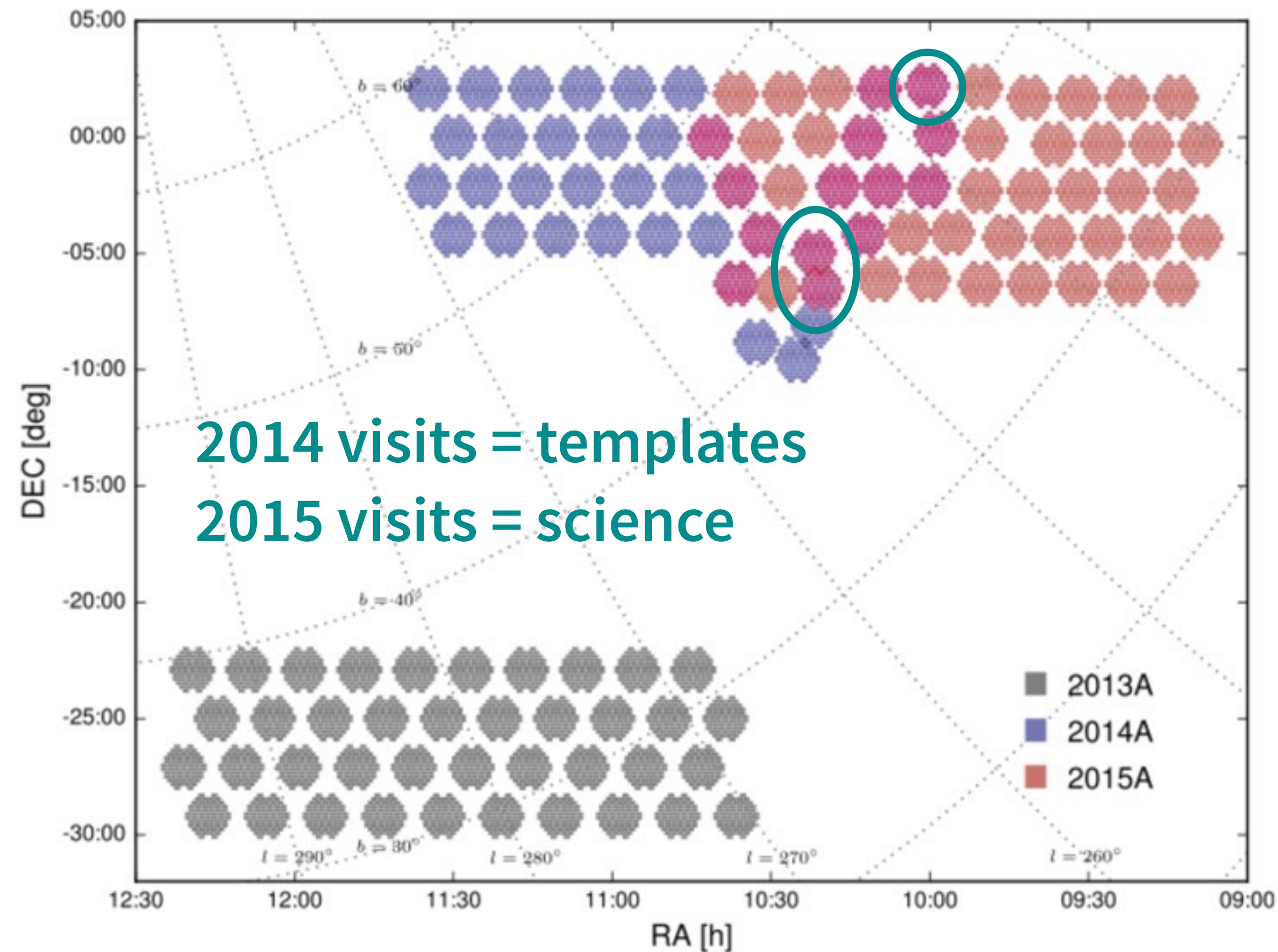
- The team I work with at UW focuses on **difference imaging** and **alert production**



W



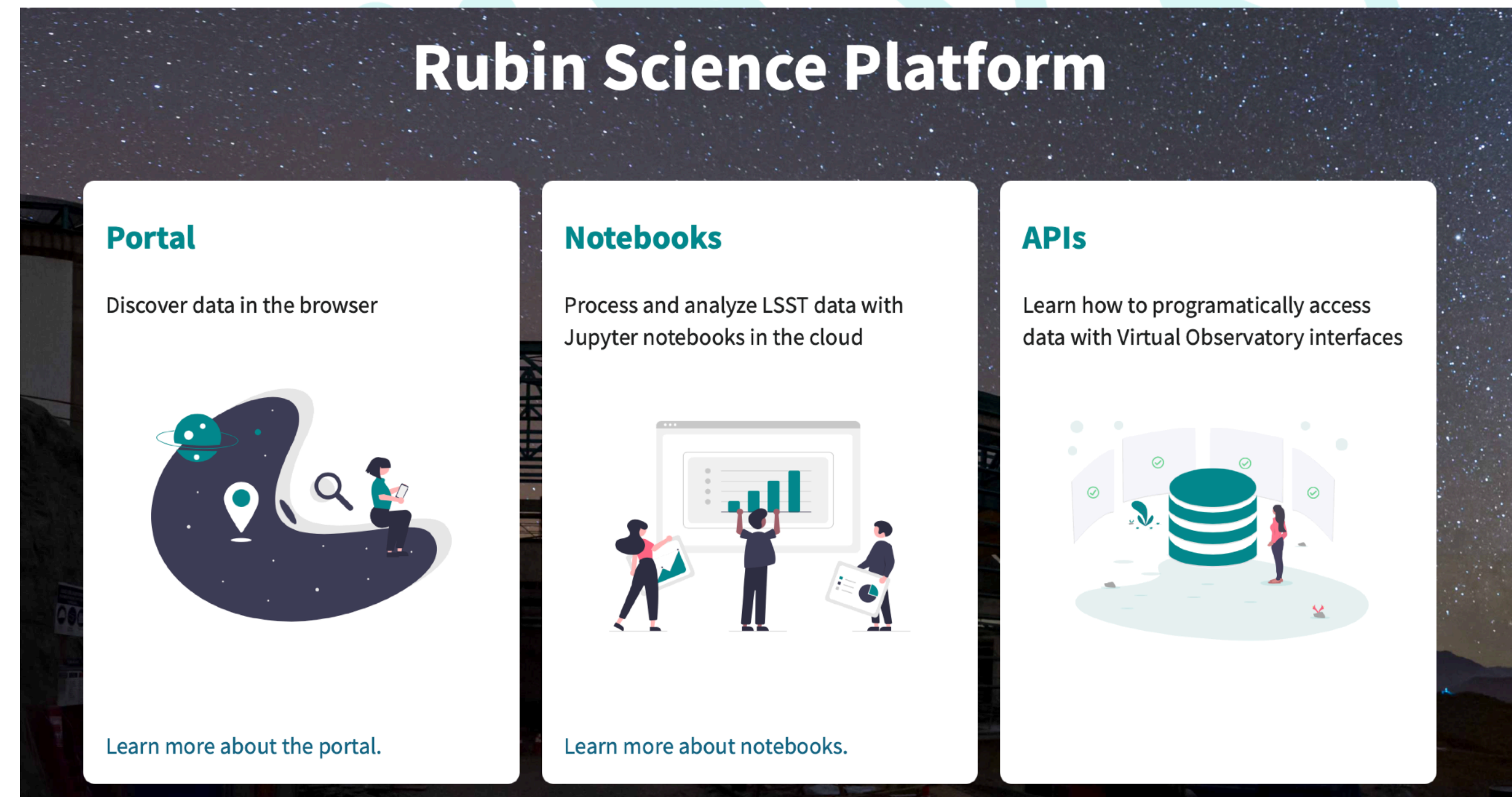
Running Rubin software on precursor data



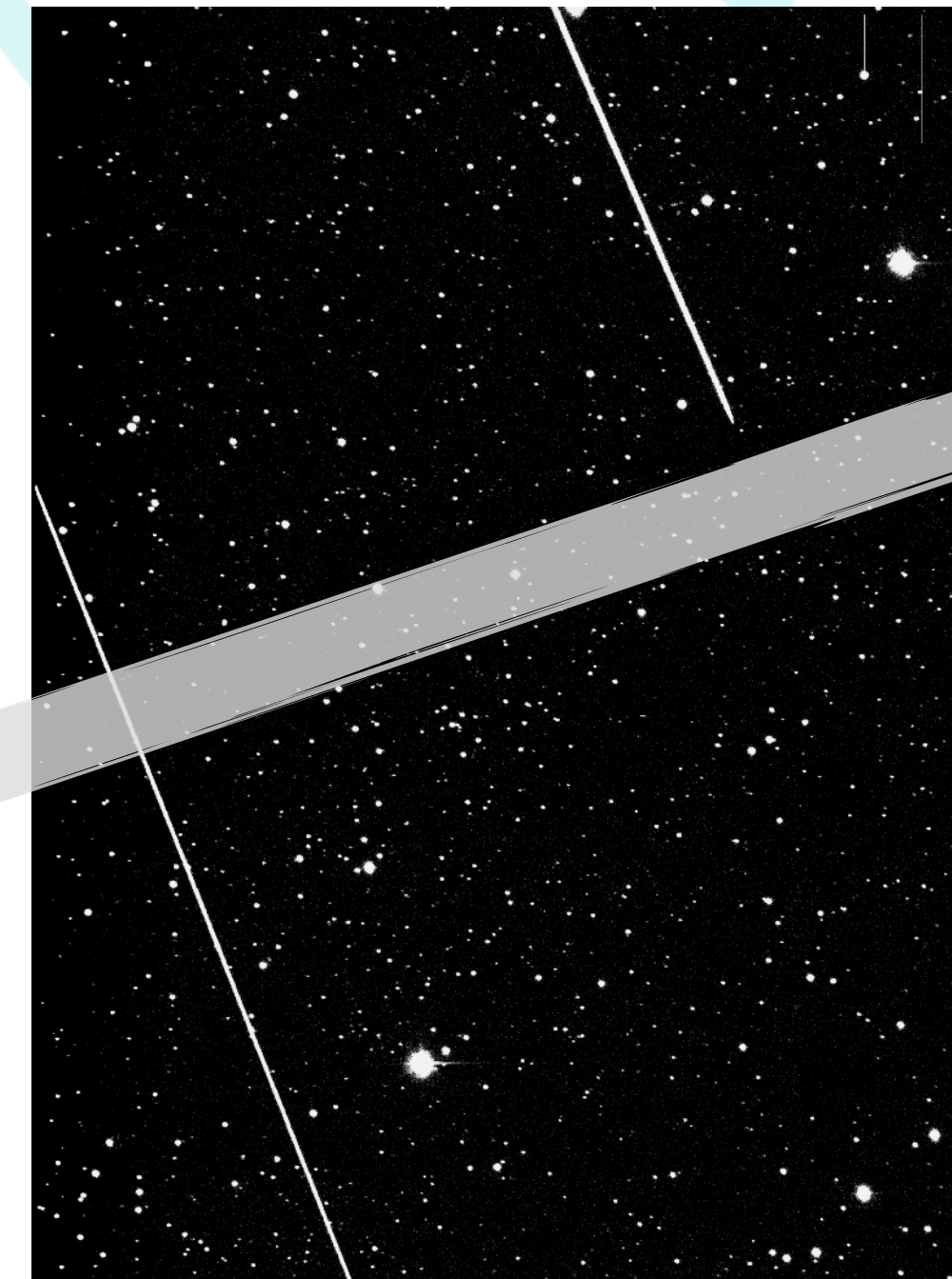
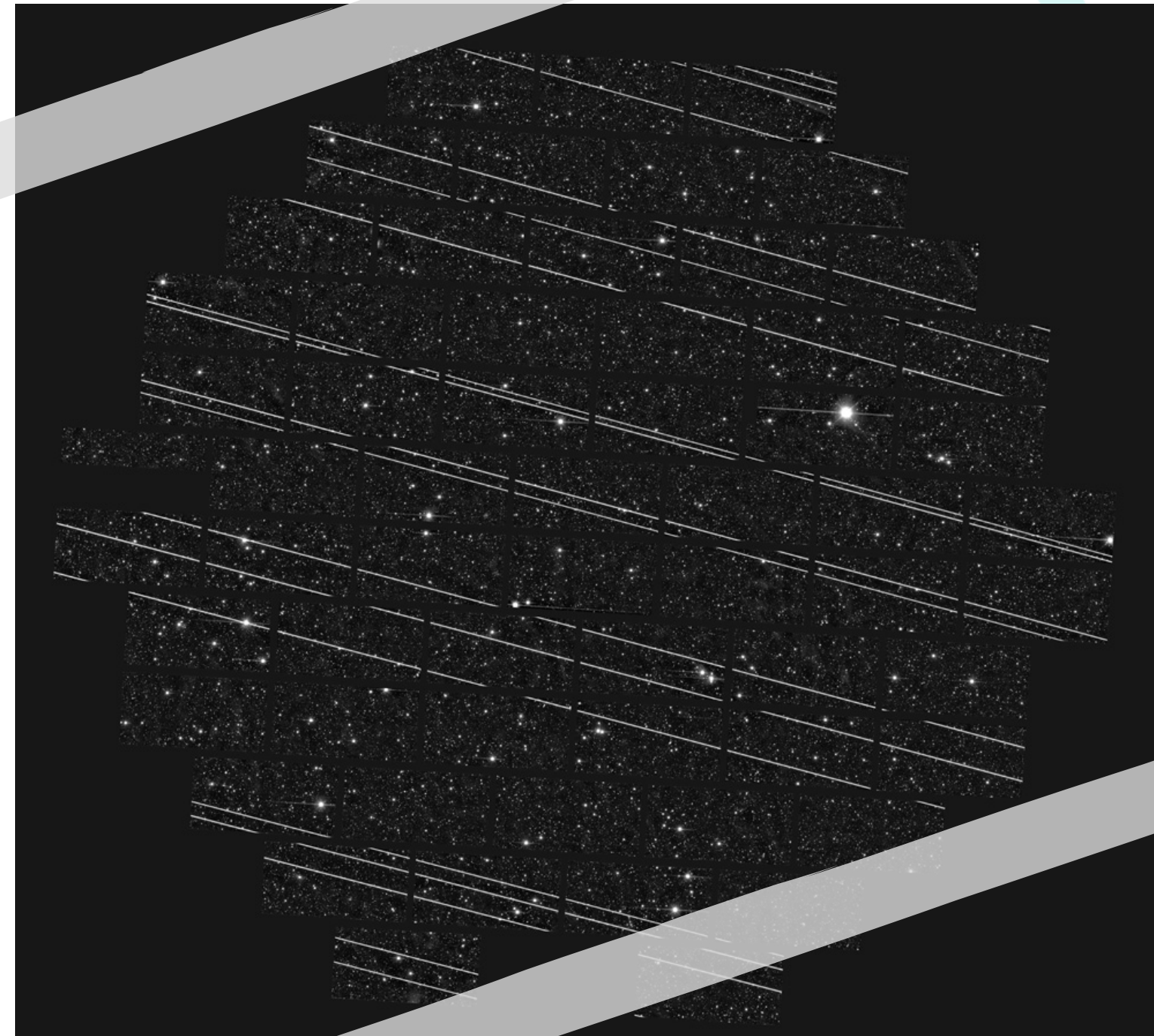
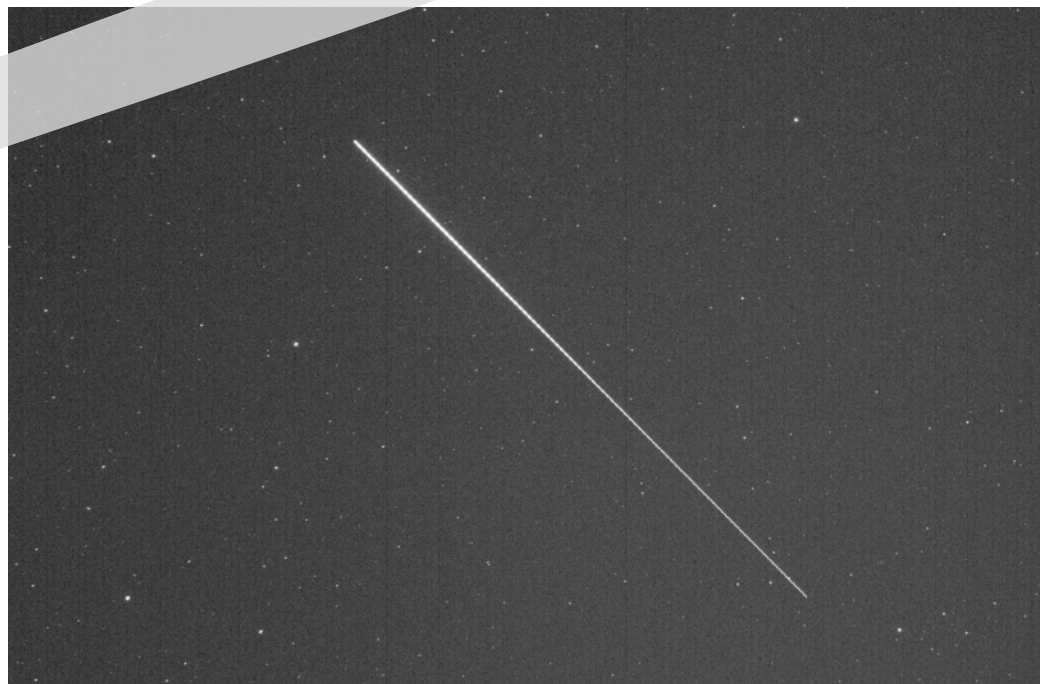
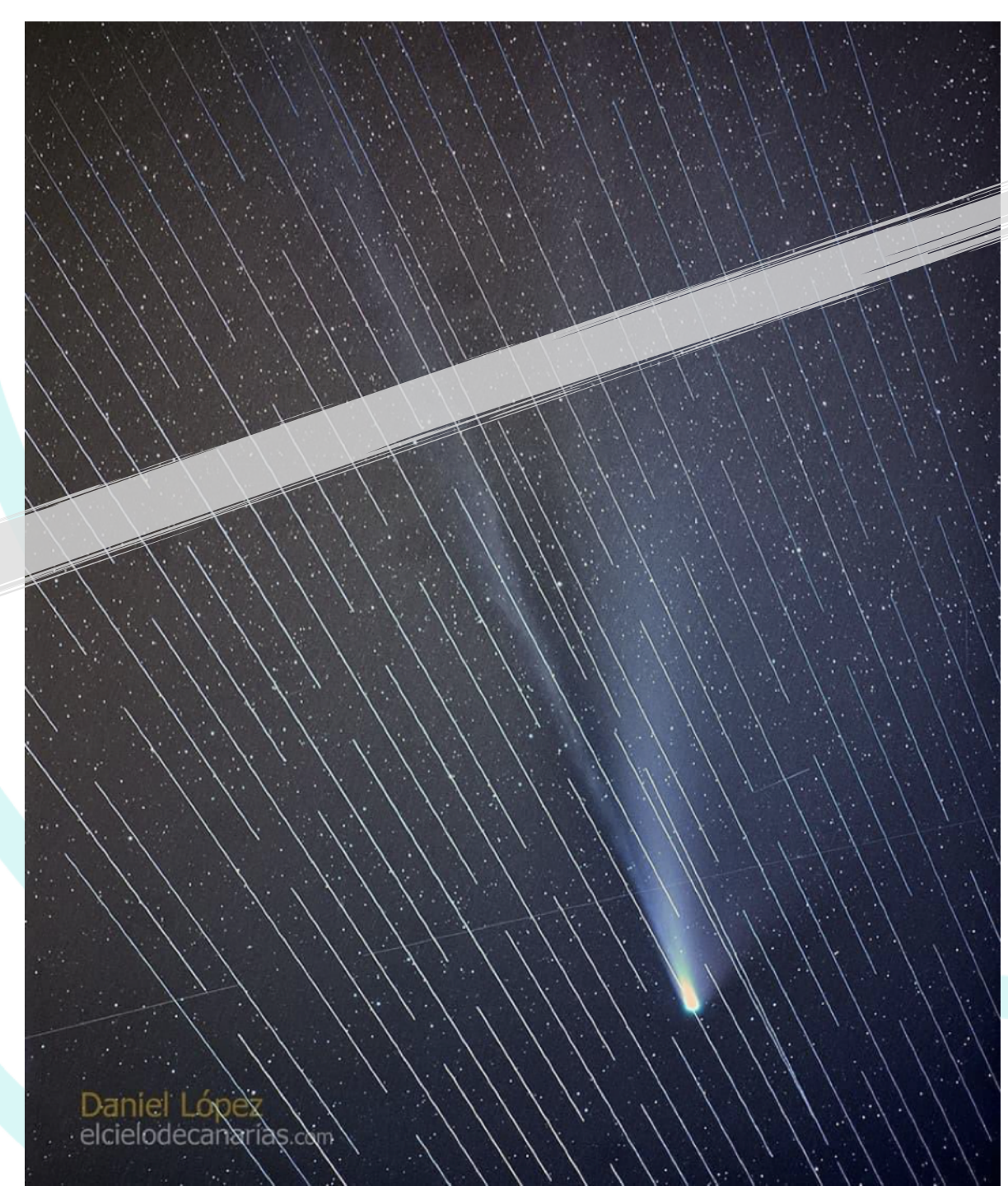
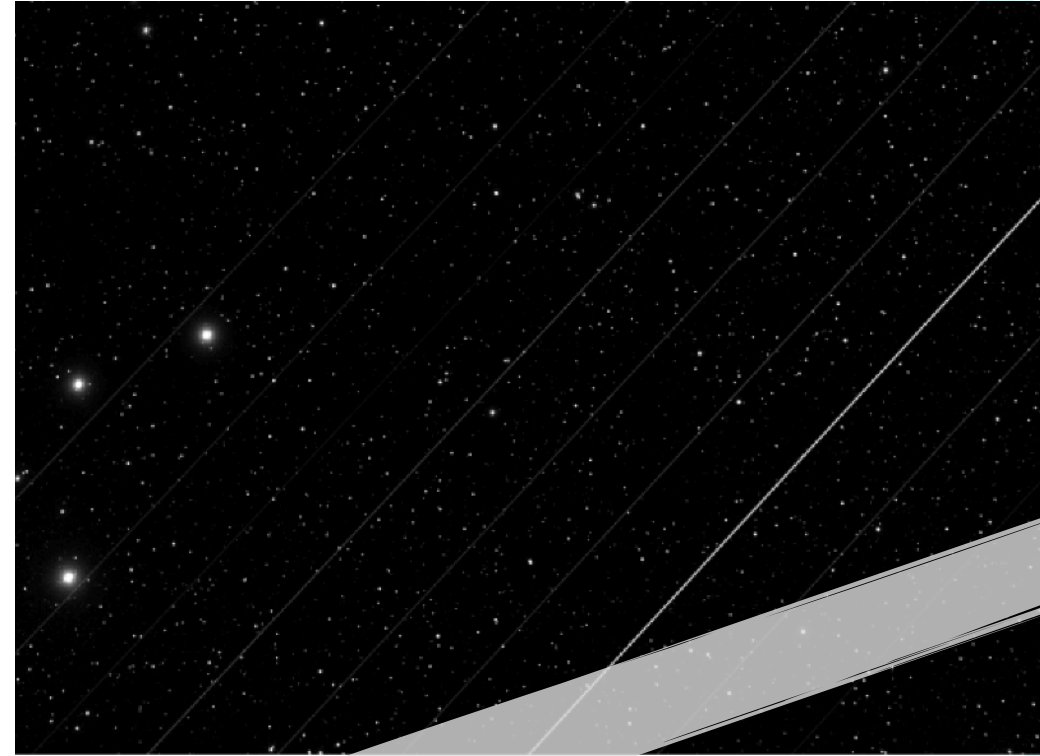
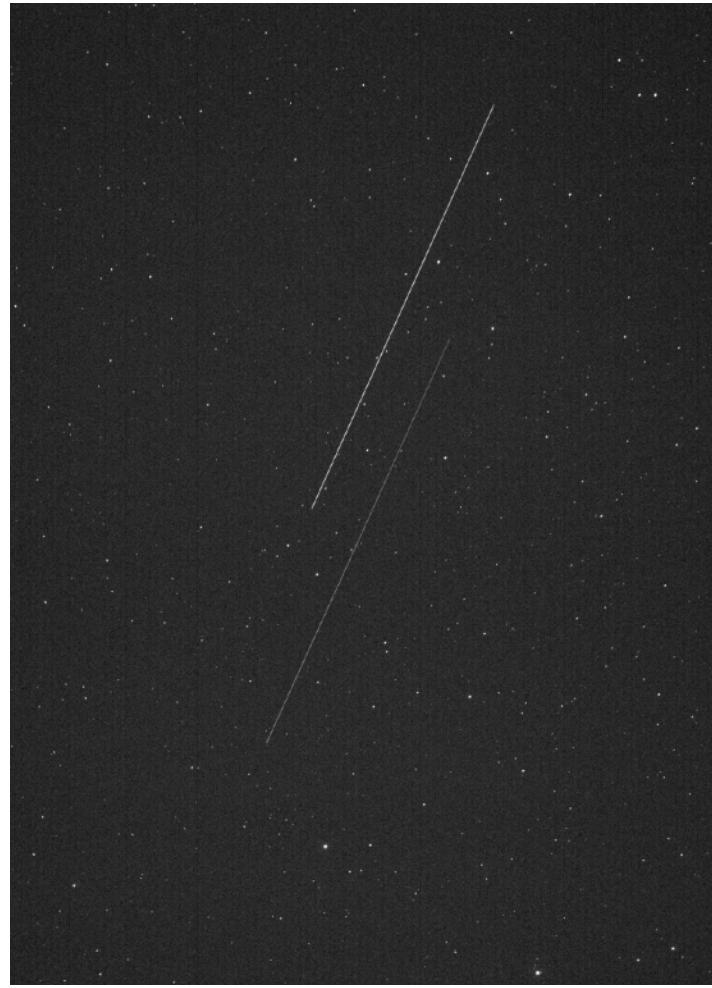
Blanco DECam HiTS Survey (Förster+ 2016)

Rubin's Data Preview 0 (DP0) is underway

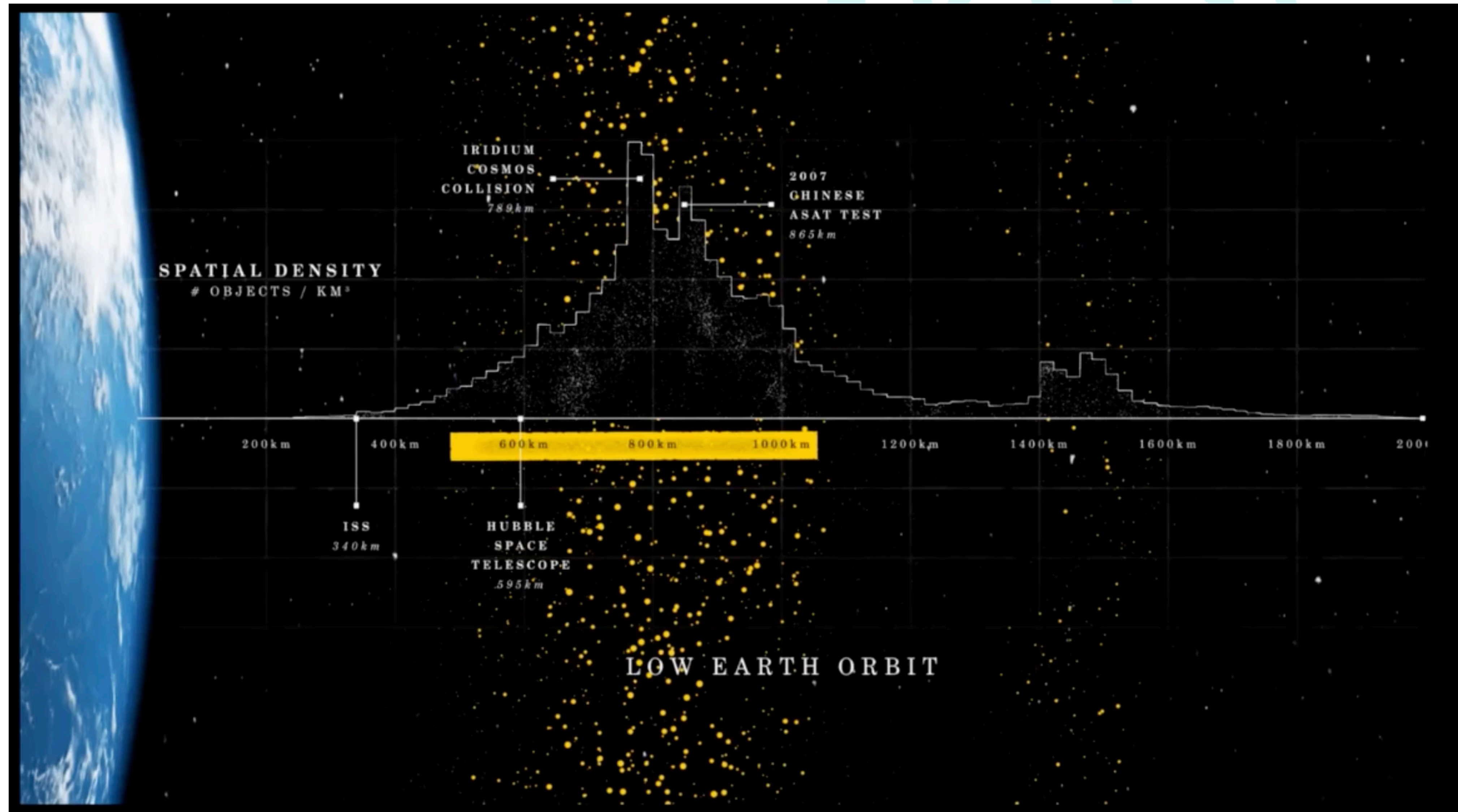
- Simulated “LSST-like” data products in the Rubin Science Platform
 - Based on the LSST Dark Energy Science Collaboration “DC2” *Simulated* Sky Survey
- Available to 300 scientists initially — including students (began June 2021)
- **Applications will open again in early 2022**
- No expert knowledge prerequisites!
- DP1 and DP2 will use *real* imaging data from commissioning in the future
- More: community.lsst.org/tag/dp0



There's just one problem



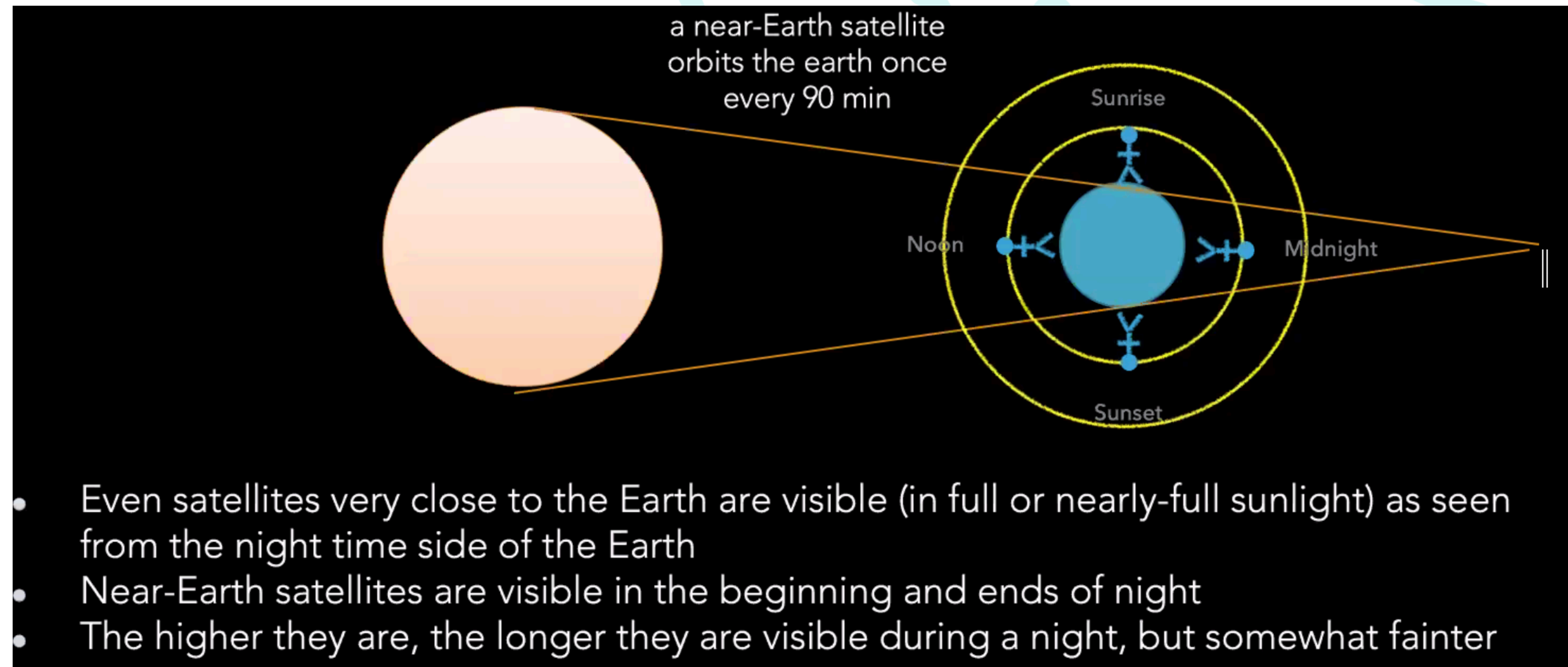
What's happening in low-Earth orbit?

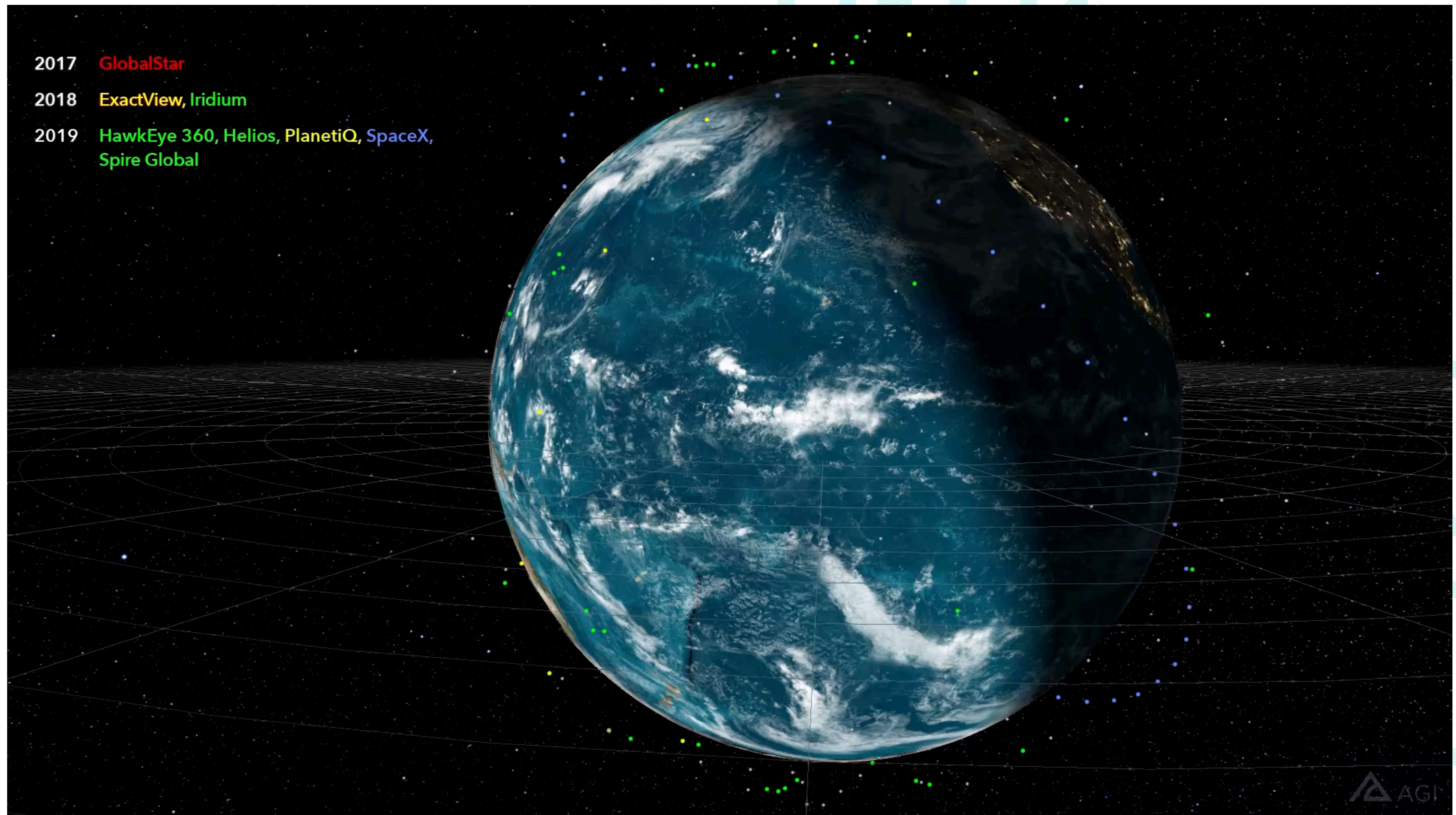


What's happening in low-Earth orbit?

- Starlink is the first, largest example of a LEO constellation (thousands at < 2000 km altitude)
- Satellite life cycles should be ~similar for other operators

- Launch
- Insertion
- Orbit raise (weeks)
- Parking orbit?
- On-station (years)
- De-orbit



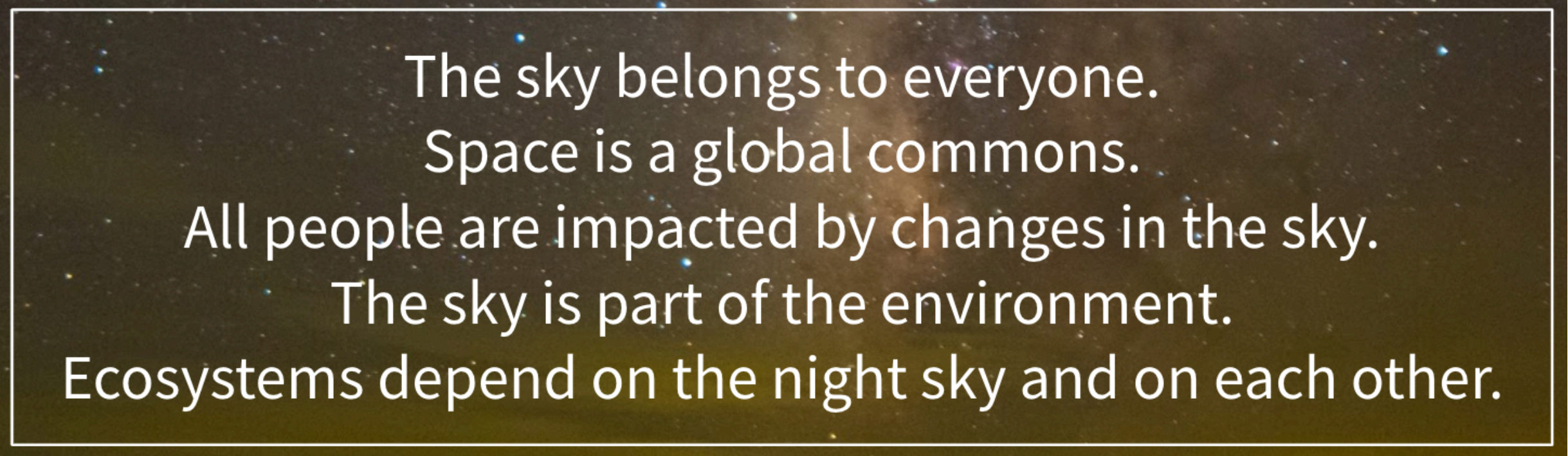


2017 **GlobalStar**
2018 **ExactView, Iridium**
2019 **HawkEye 360, Helios, PlanetiQ, SpaceX, Spire Global**

Why should you care about this?

(did you not WATCH the video?)

- Your research relies on observational astronomy
 - ***We won't know what we don't discover***
- You have stood in awe while watching the night sky
- This is ground-based astronomy's light pollution moment of truth, much like radio astronomy before radio spectrum allocation
- The sky is more than science waiting to happen or a shiny resource to be utilized or exploited
- Choices today set precedents for how we use low-Earth orbit



The sky belongs to everyone.
Space is a global commons.
All people are impacted by changes in the sky.
The sky is part of the environment.
Ecosystems depend on the night sky and on each other.

J. Lowenthal, A. Venkatesan, & SATCON2 Community Engagement Working Group

If 100,000 low-Earth orbit satellites are deployed,
“...no combination of mitigations can fully avoid the impacts of the satellite trails on the science programs of current and planned [...] astronomy facilities.” —SATCON1 Report, 2020

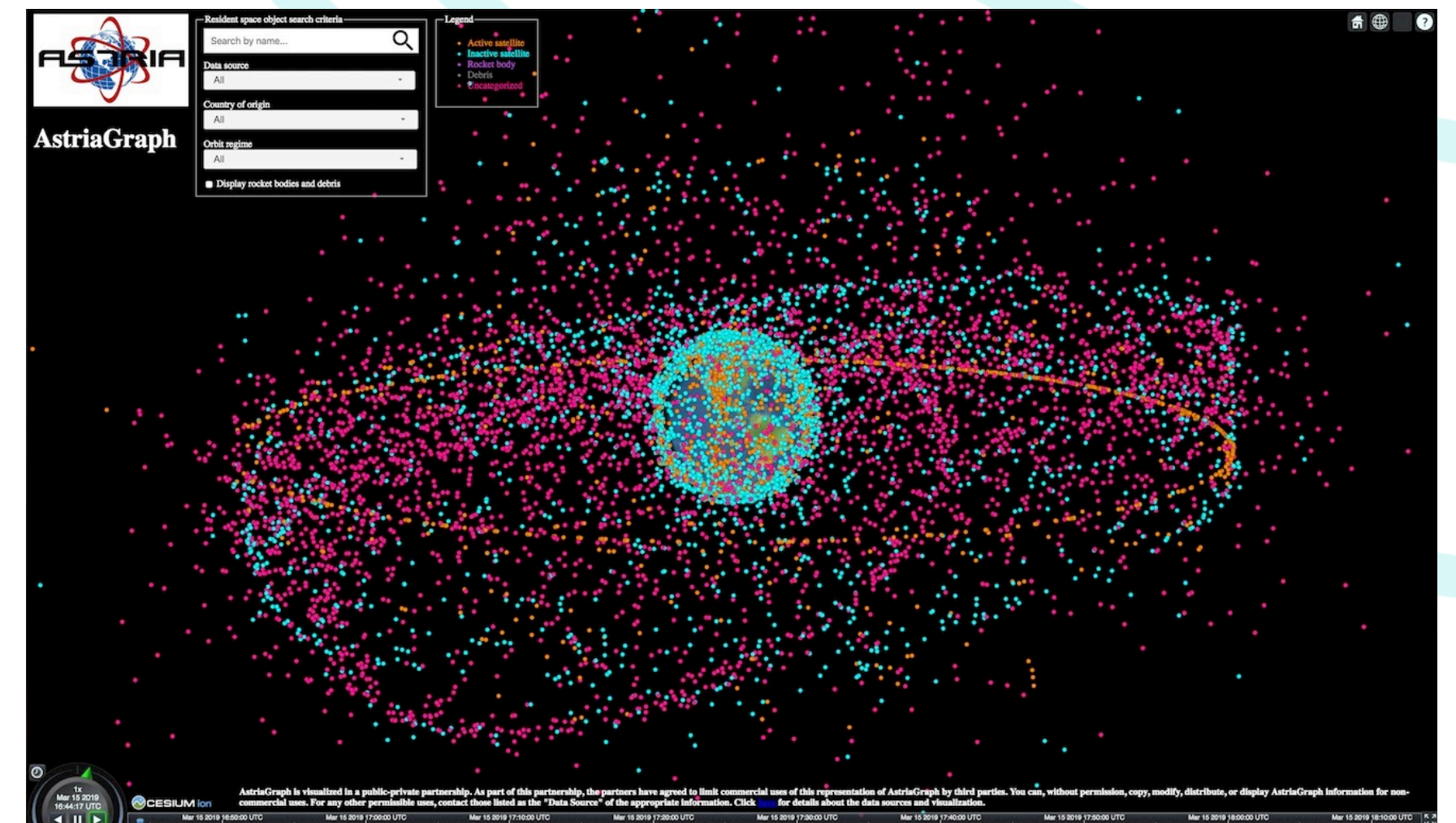
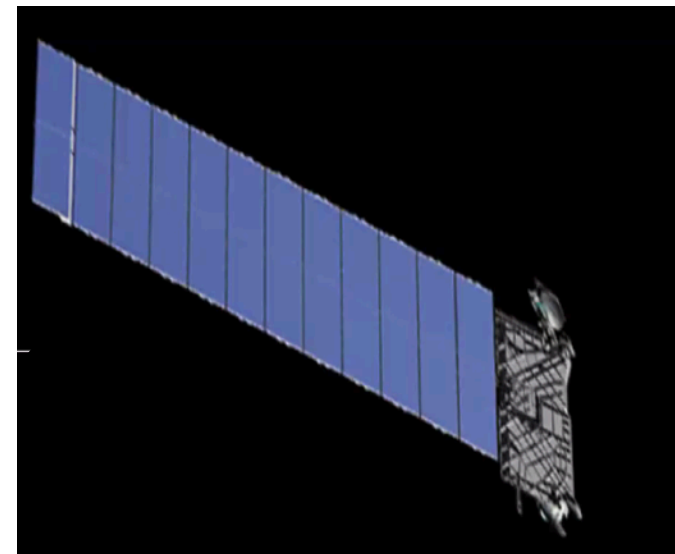


Hugely increasing rate of new LEO satellites

- Most prevalent near twilight, but some illuminated all night long
- Impacts are worst for large wide-field ground-based facilities
- New satellites launching and old ones de-orbiting

- **Key recommendations:**

- Design to 7th mag or dimmer
- Keep satellites at low altitudes
- Share timely, accurate, and precise trajectories
- Darken in all phases of satellite life cycle
- Sharp bandpass filters on transmitters
- End-to-end simulations of impacts



What are we doing about it?

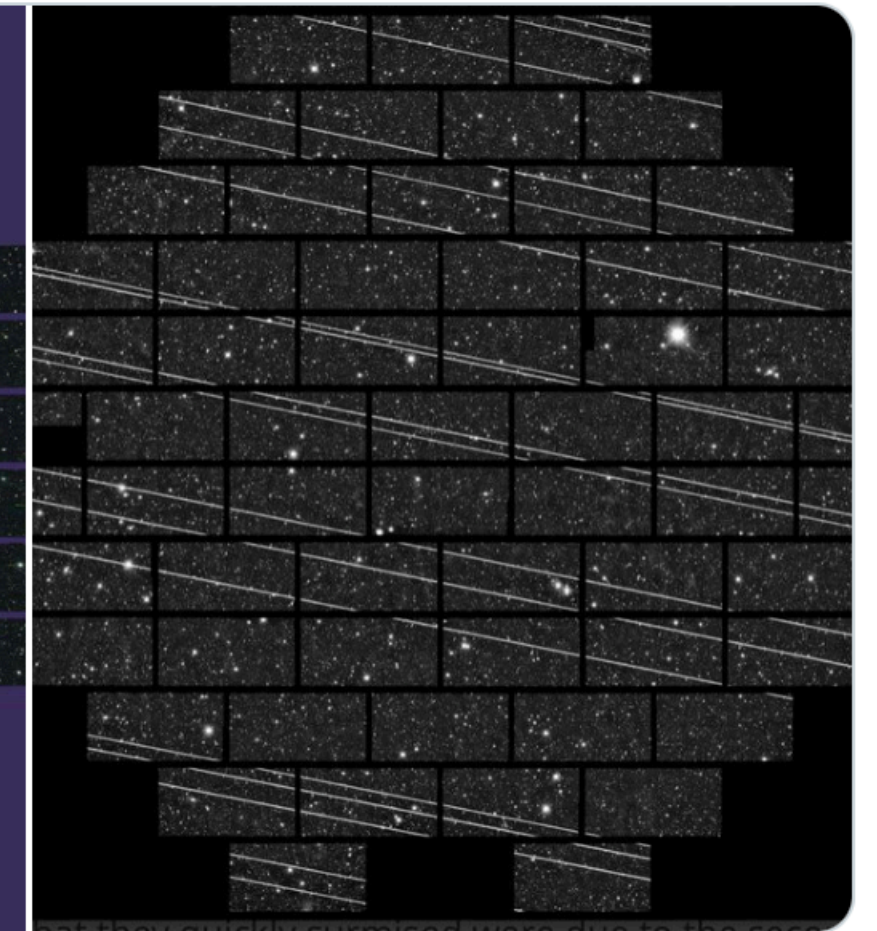
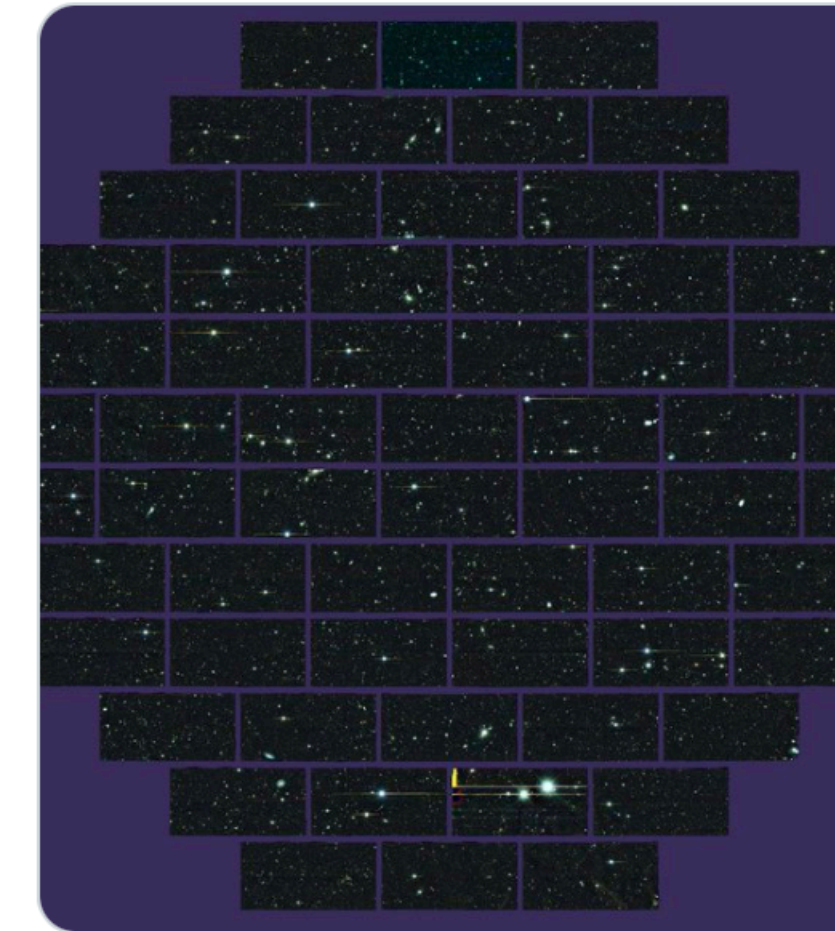
- Measuring satellite brightnesses
- Studying science impacts
- Talking to satellite operators
- Tweeting ruined images
- Writing long reports
- Listening to other stakeholders
- Forming an IAU Centre



Meredith Rawls
@merrdiff

How it started:

How it's going:



6:56 PM · Oct 17, 2020



5.8K



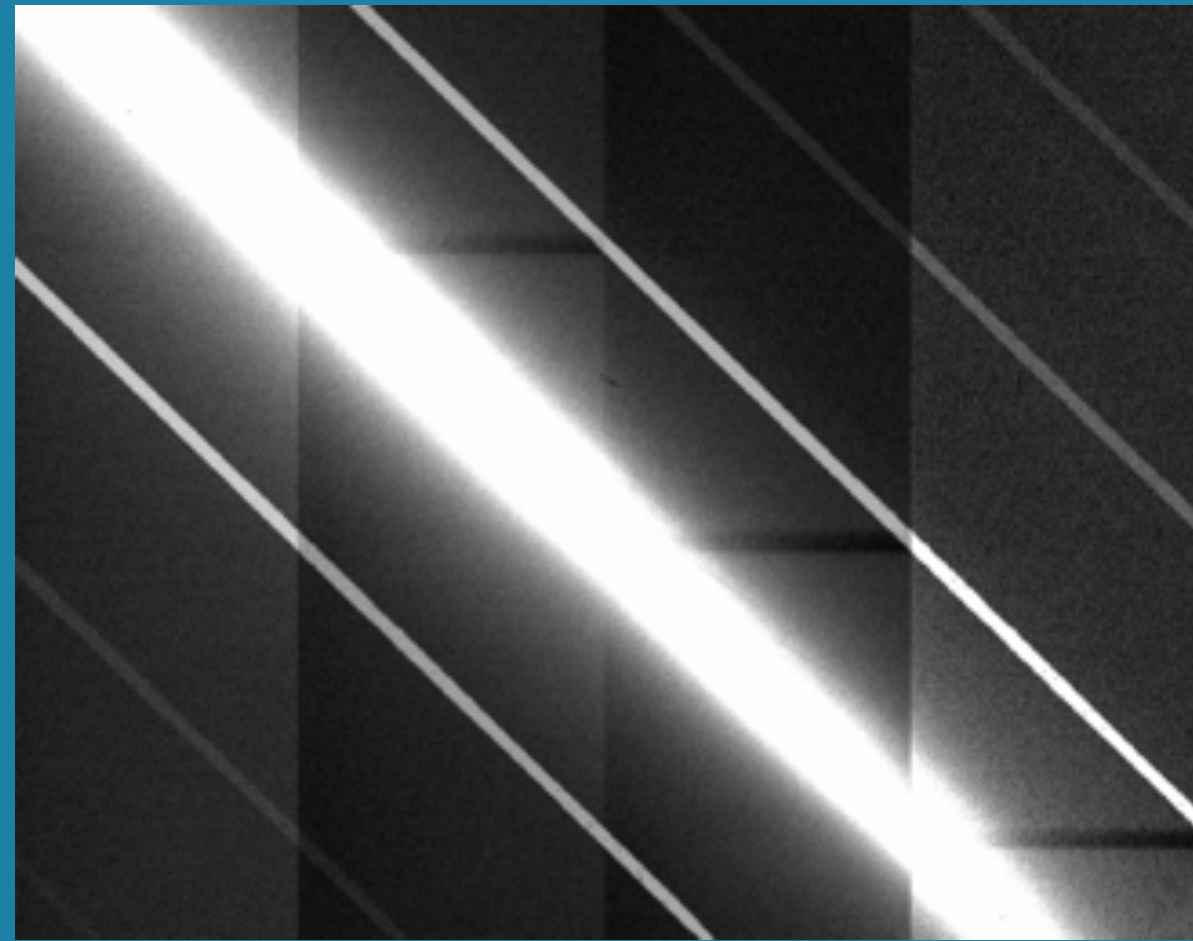
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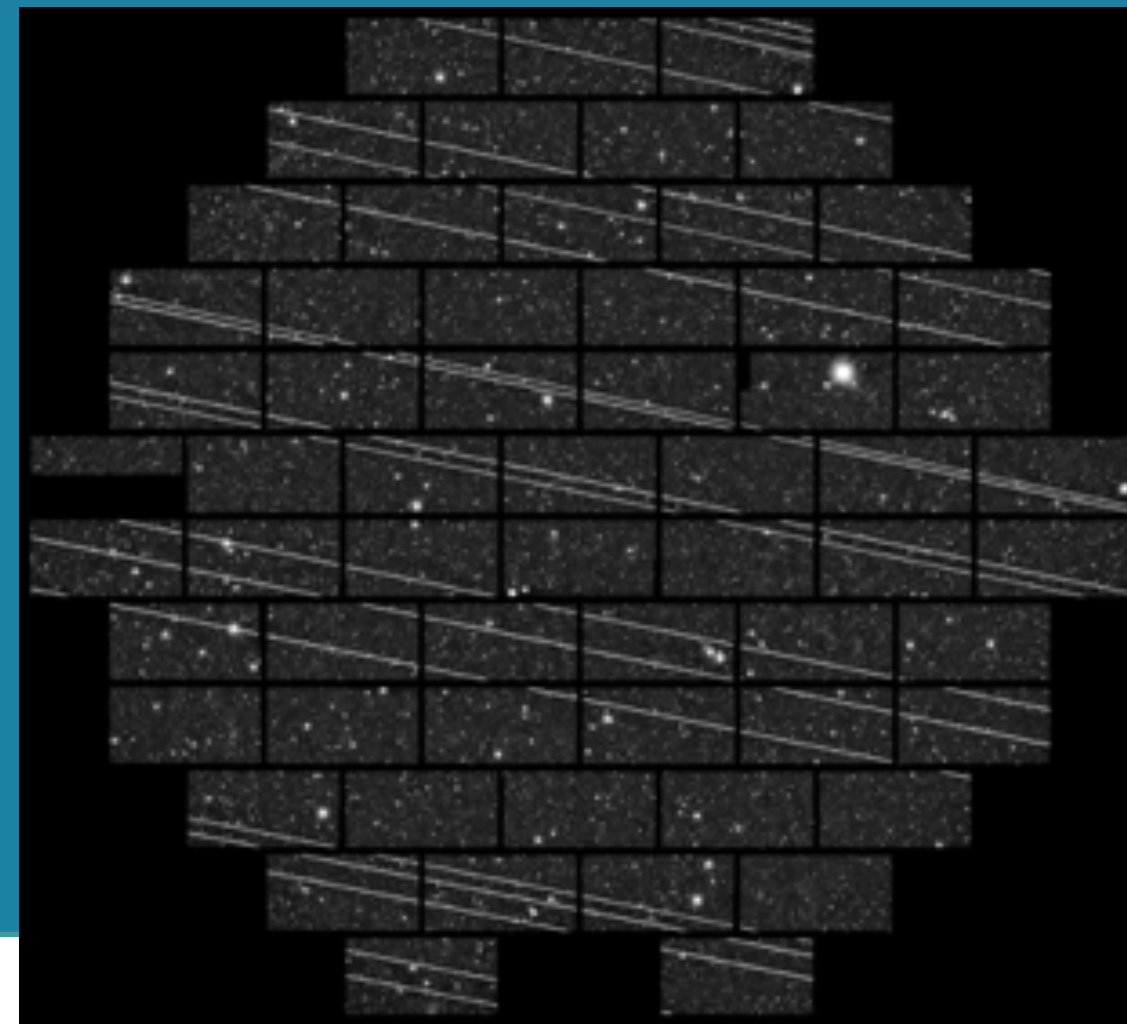
Share this Tweet



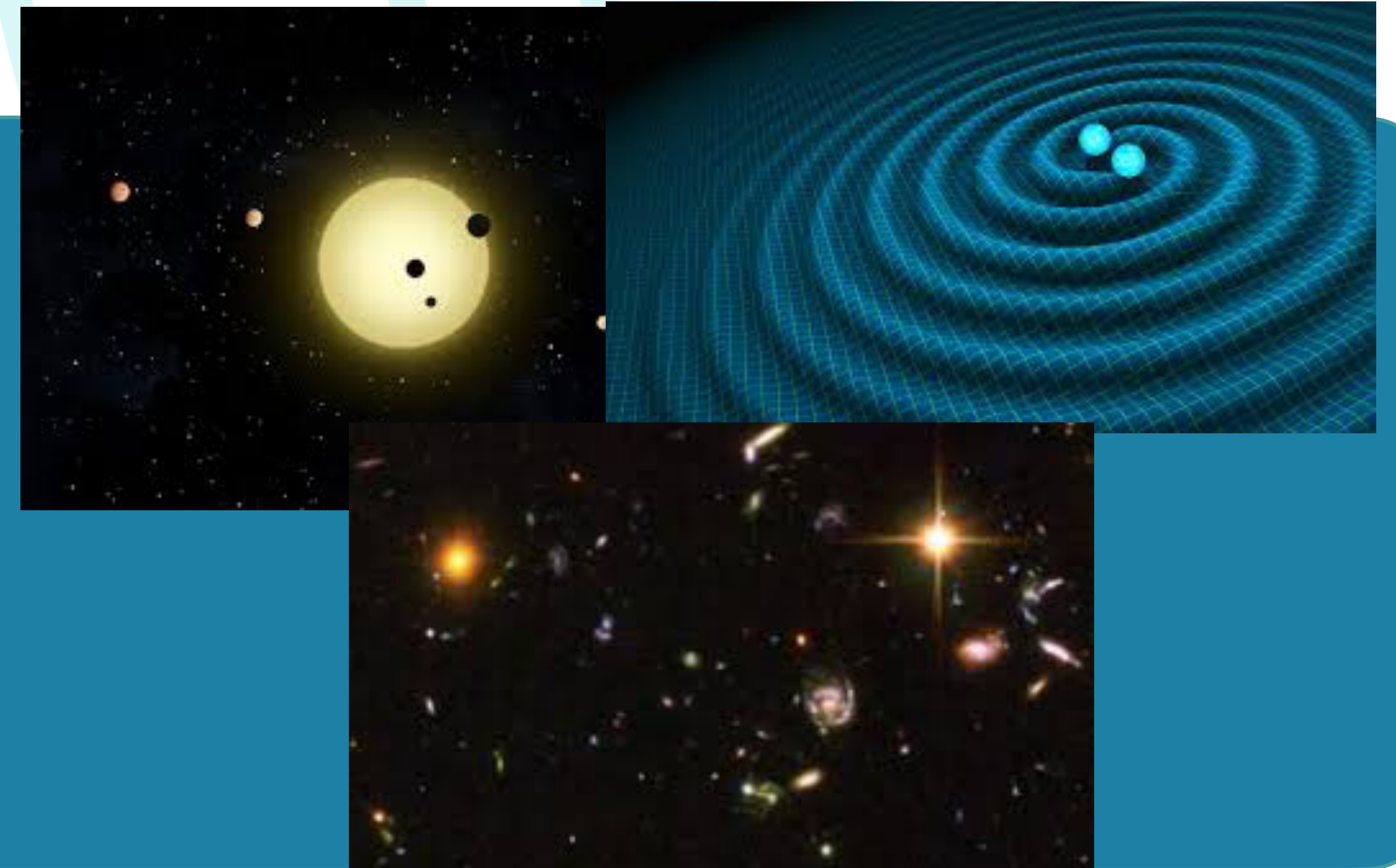
Quantifying the satellite problem



How bad is it?



How often does it happen?



What is the cost to science?

What are the science impacts?

- **Vera C. Rubin Observatory:** the most severely impacted NIR facility; Tyson et al. 2020 recommends satellites be $> 7^{\text{th}}$ V mag & < 600 km
- **Weak lensing:** spatially correlated noise from removed trails
- **Near-Earth asteroids:** fewer discoveries and orbit determinations
- **Other:** ??? depends on your program and the satellite population
- **Spectroscopy:** solar spectrum contamination you might not notice without simultaneous imaging to rule out satellite photobombs
- **Radio Astronomy:** 🤔🤔🤔 ...

Courtesy Genoveva Micheva

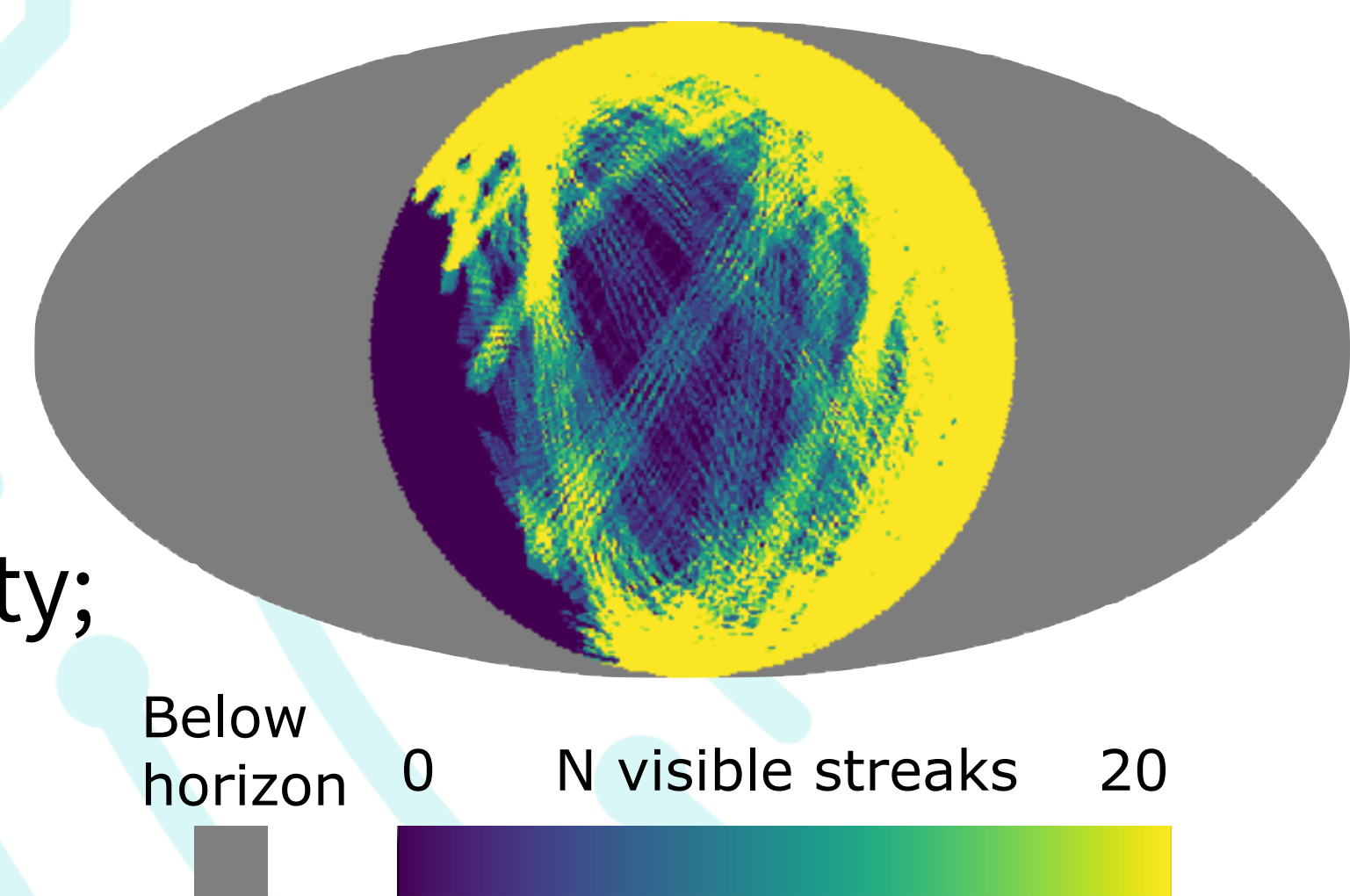
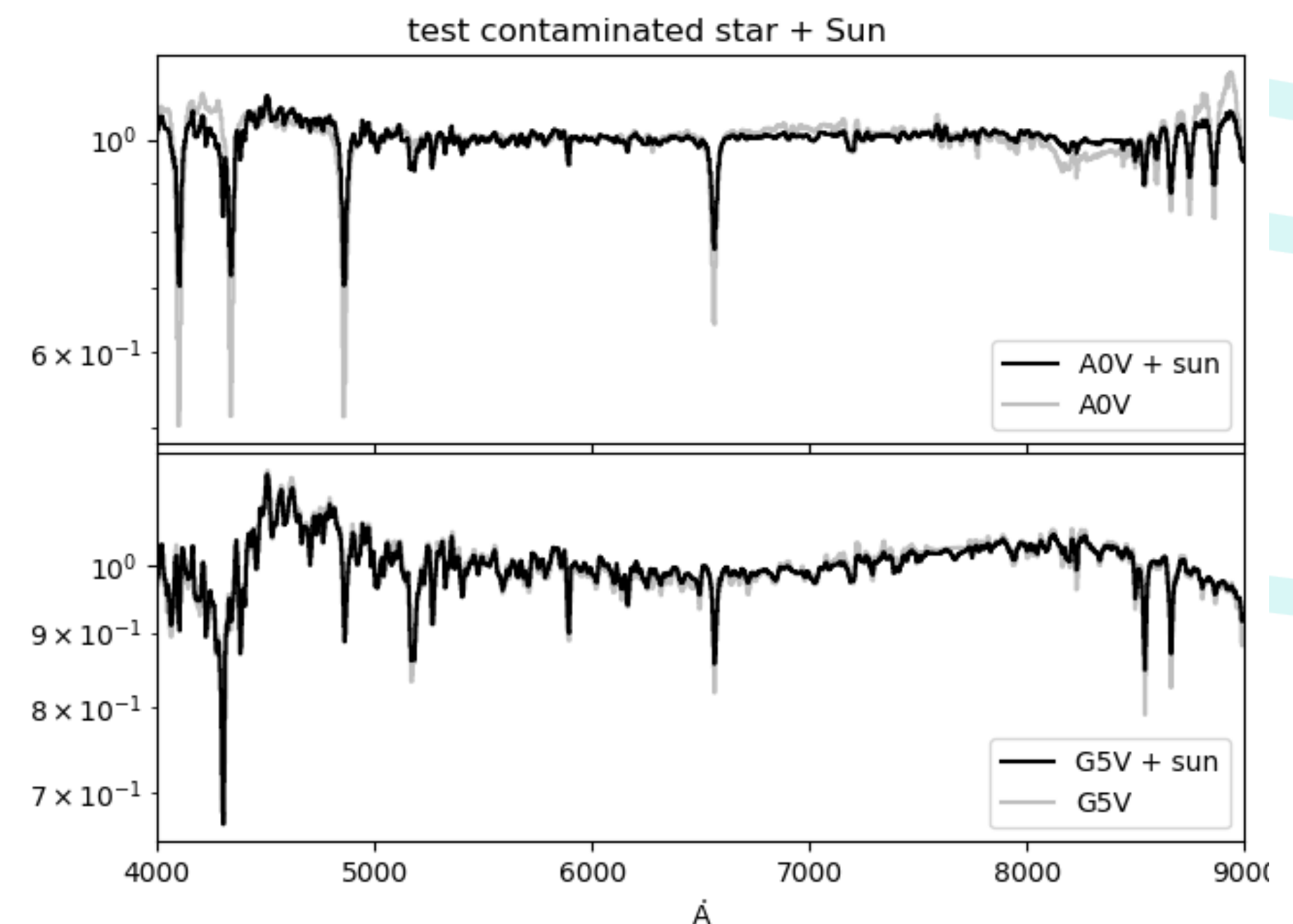


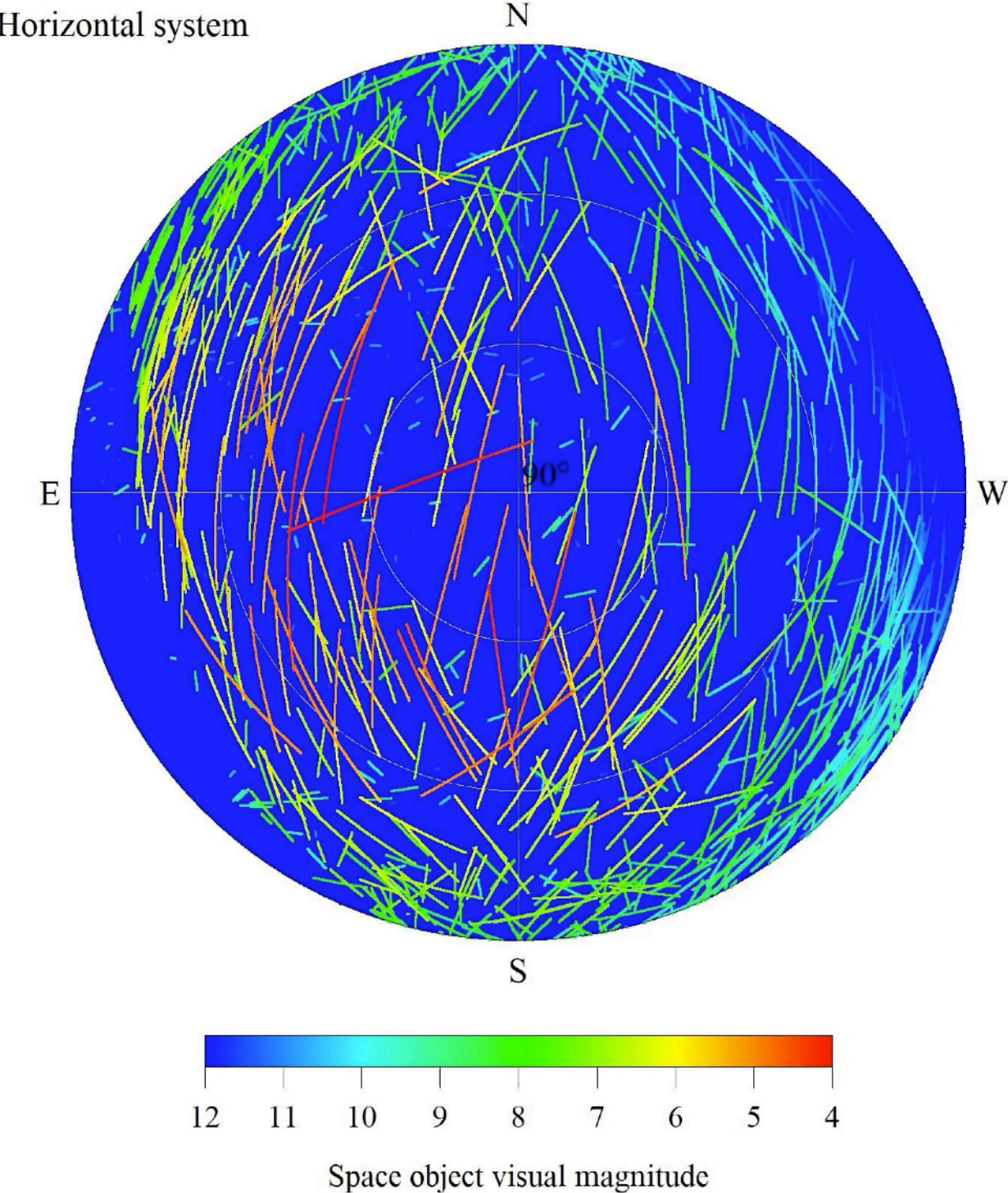
Fig 1, Tyson et al. 2020,
by Peter Yoachim



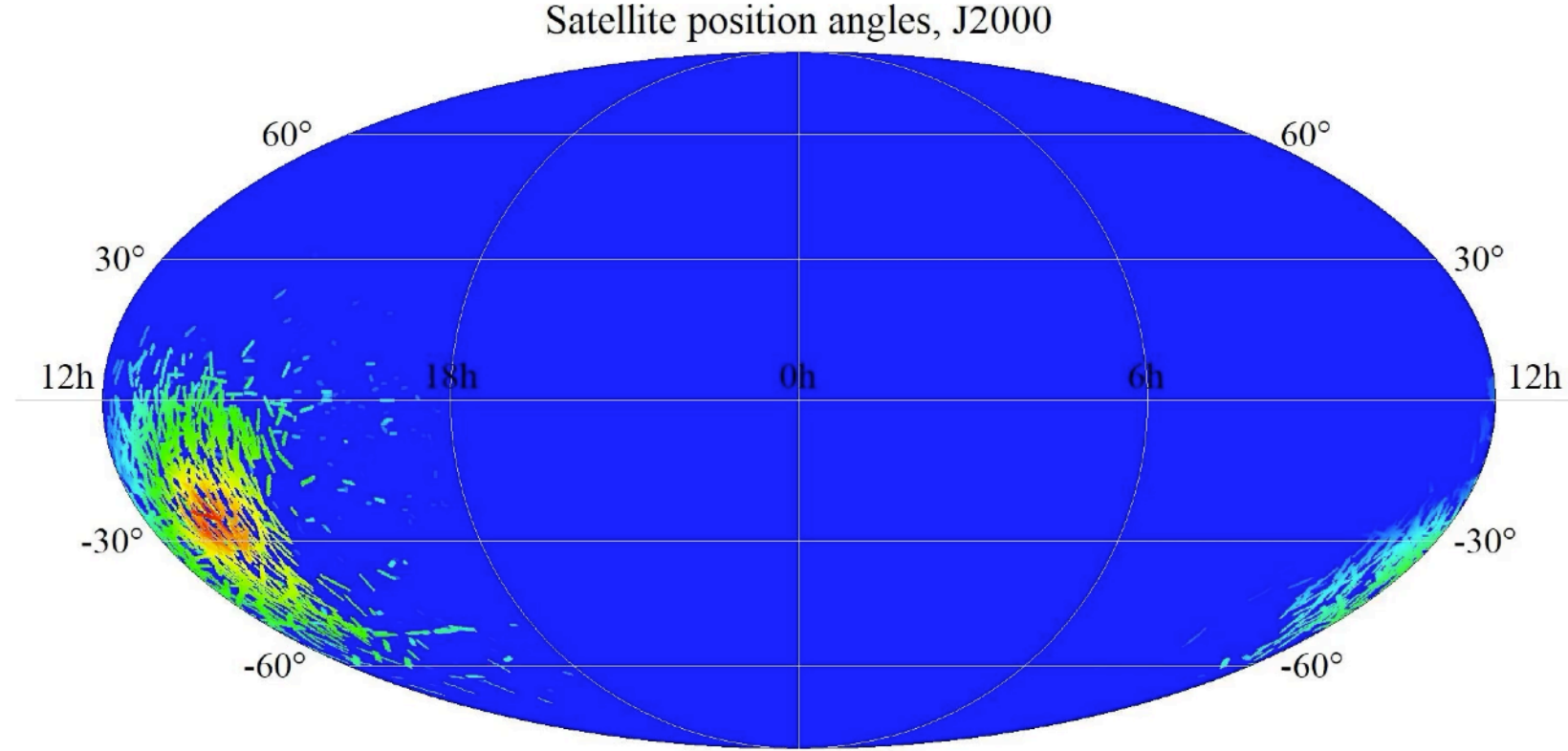
Rubin's potential for discovery is also its vulnerability to LEO satellites

1 July, 2020, 22:57 UTC, Space Object Light Pollution, VST

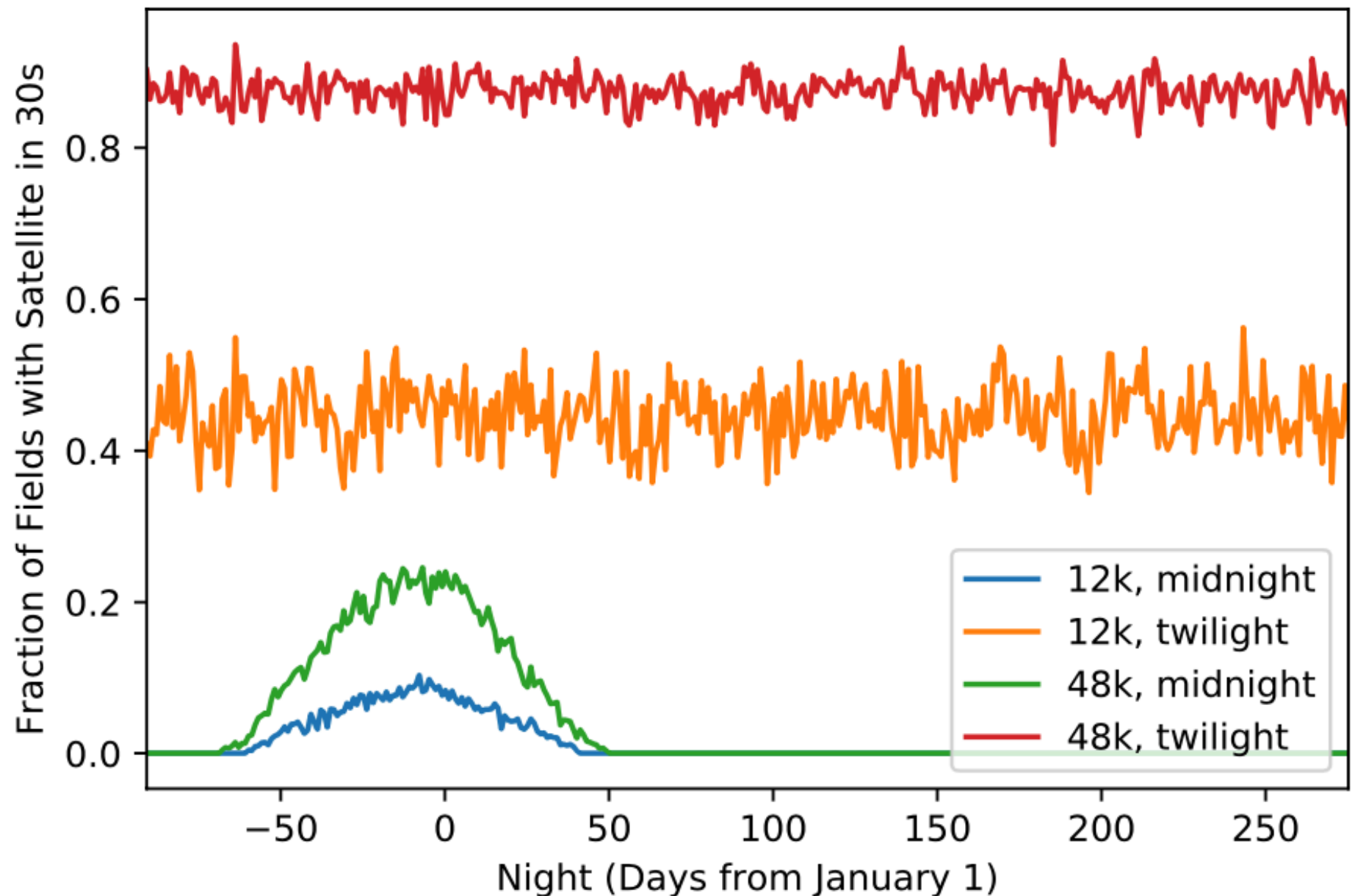
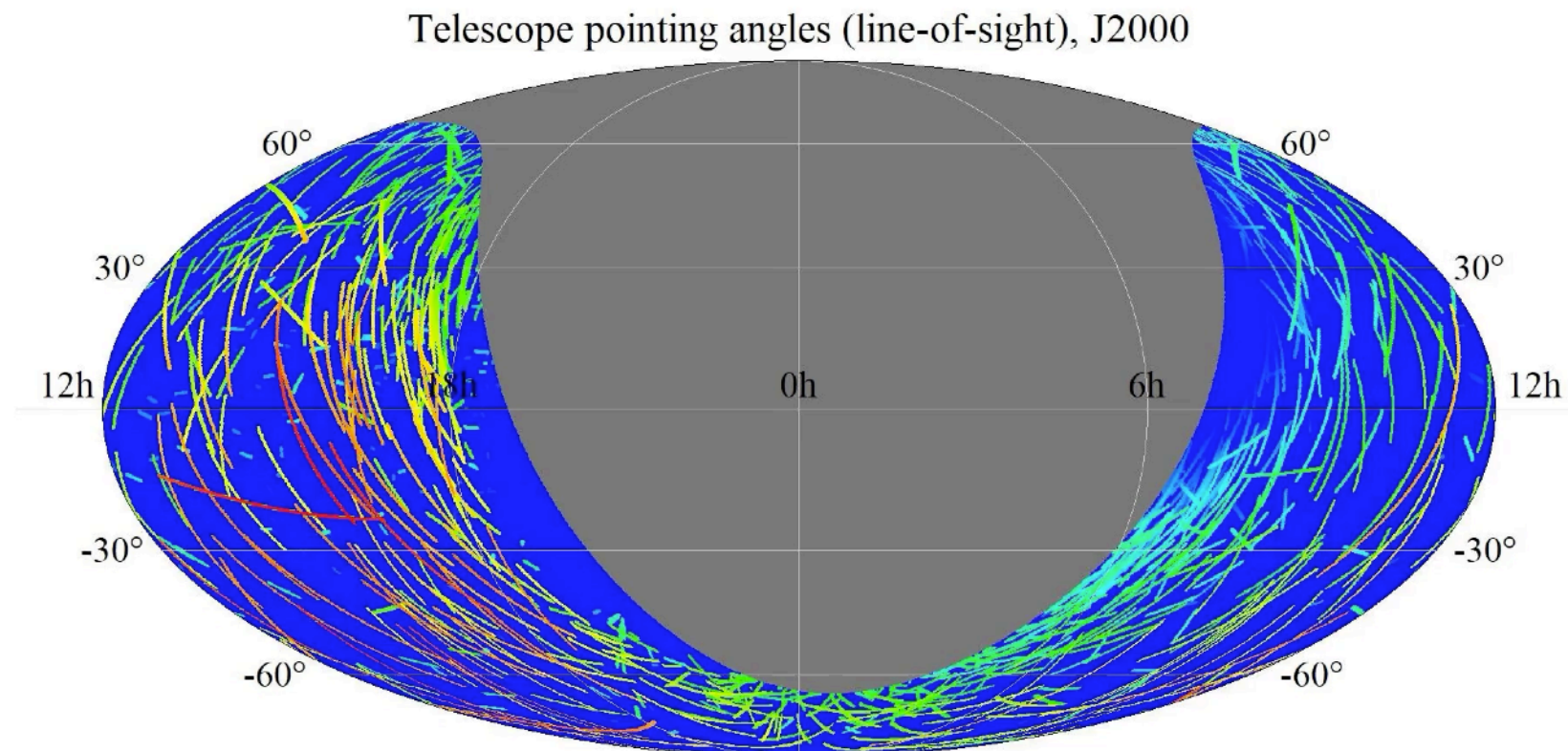
Horizontal system



Satellite position angles, J2000



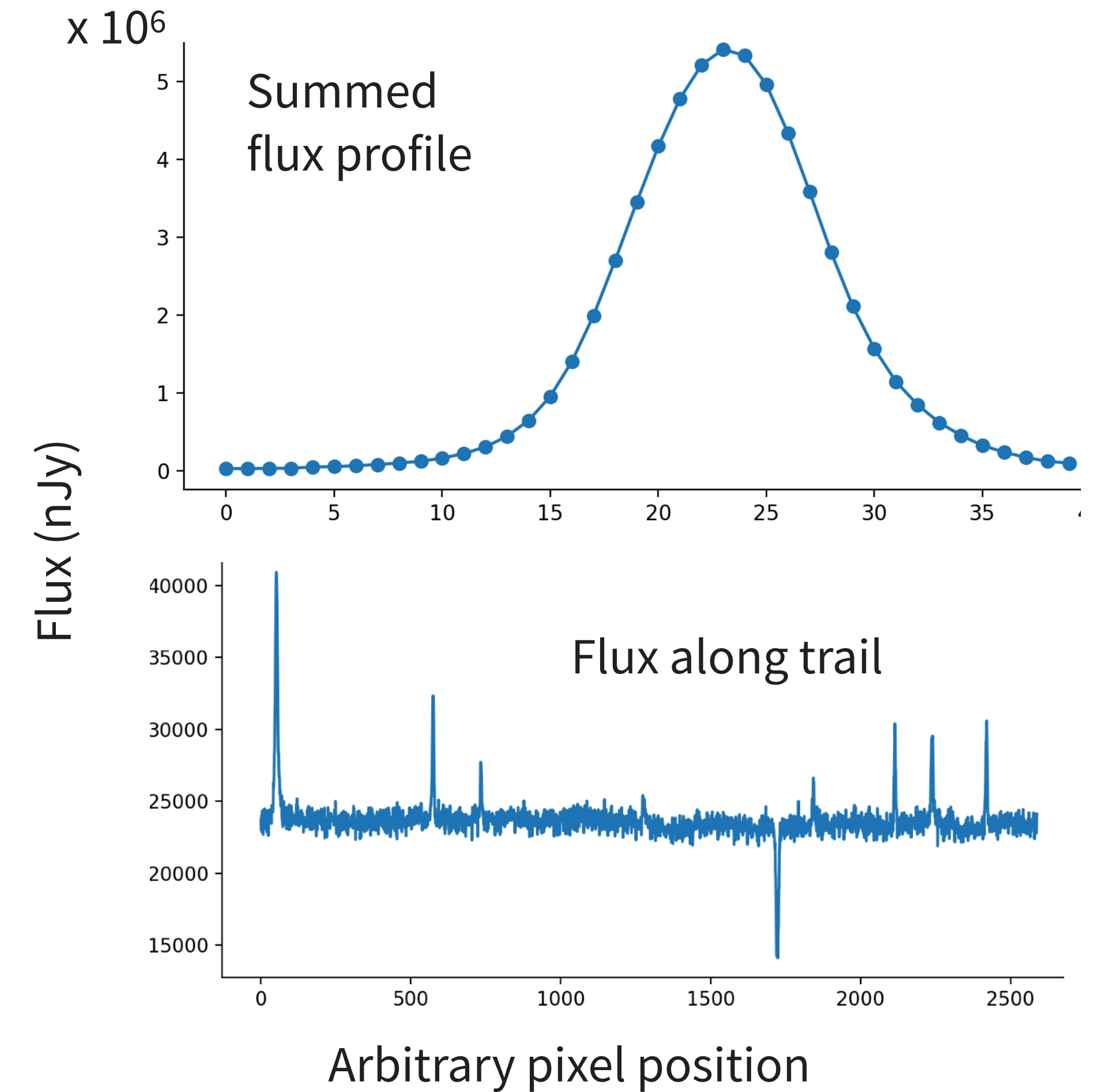
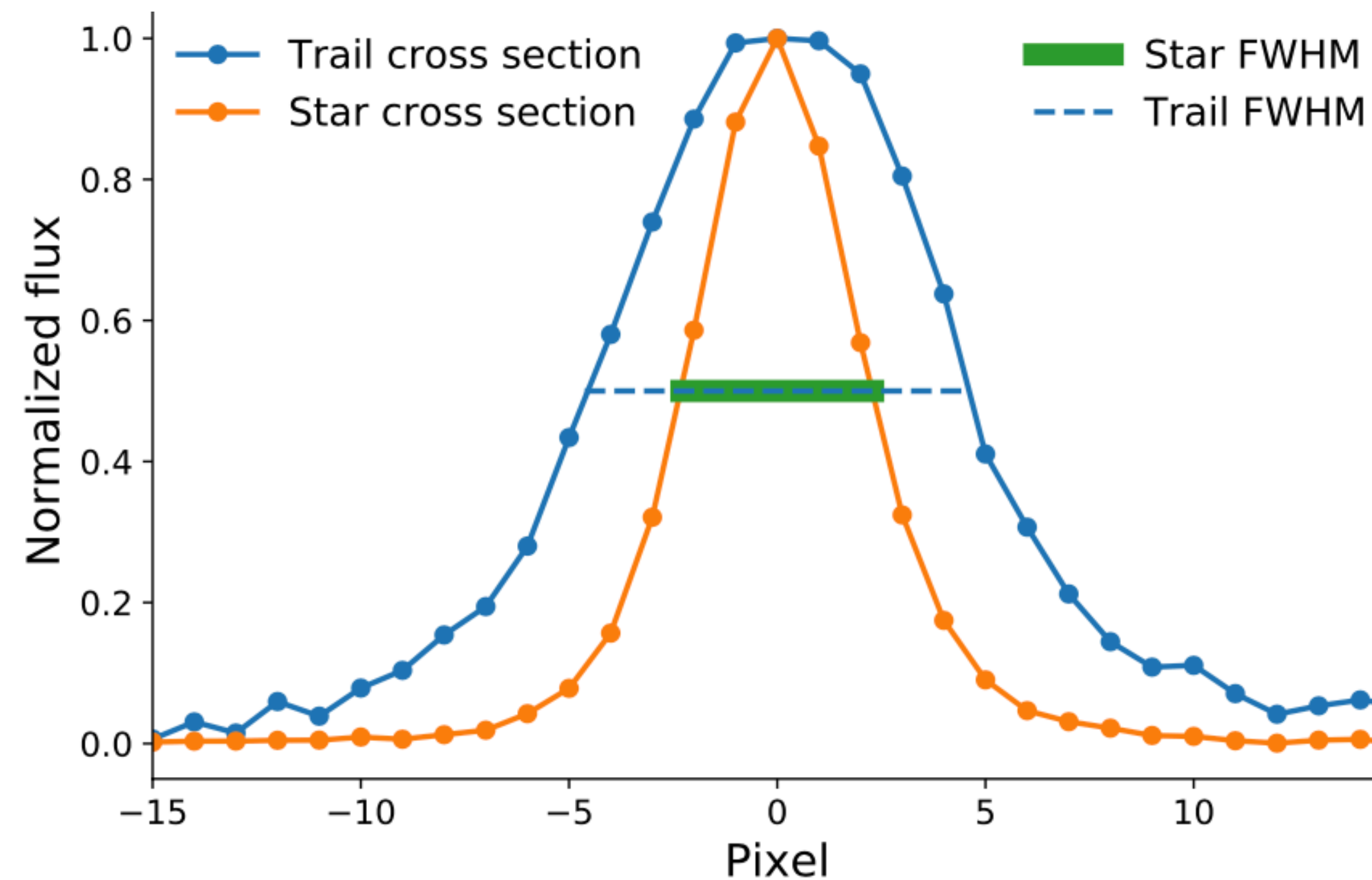
Telescope pointing angles (line-of-sight), J2000



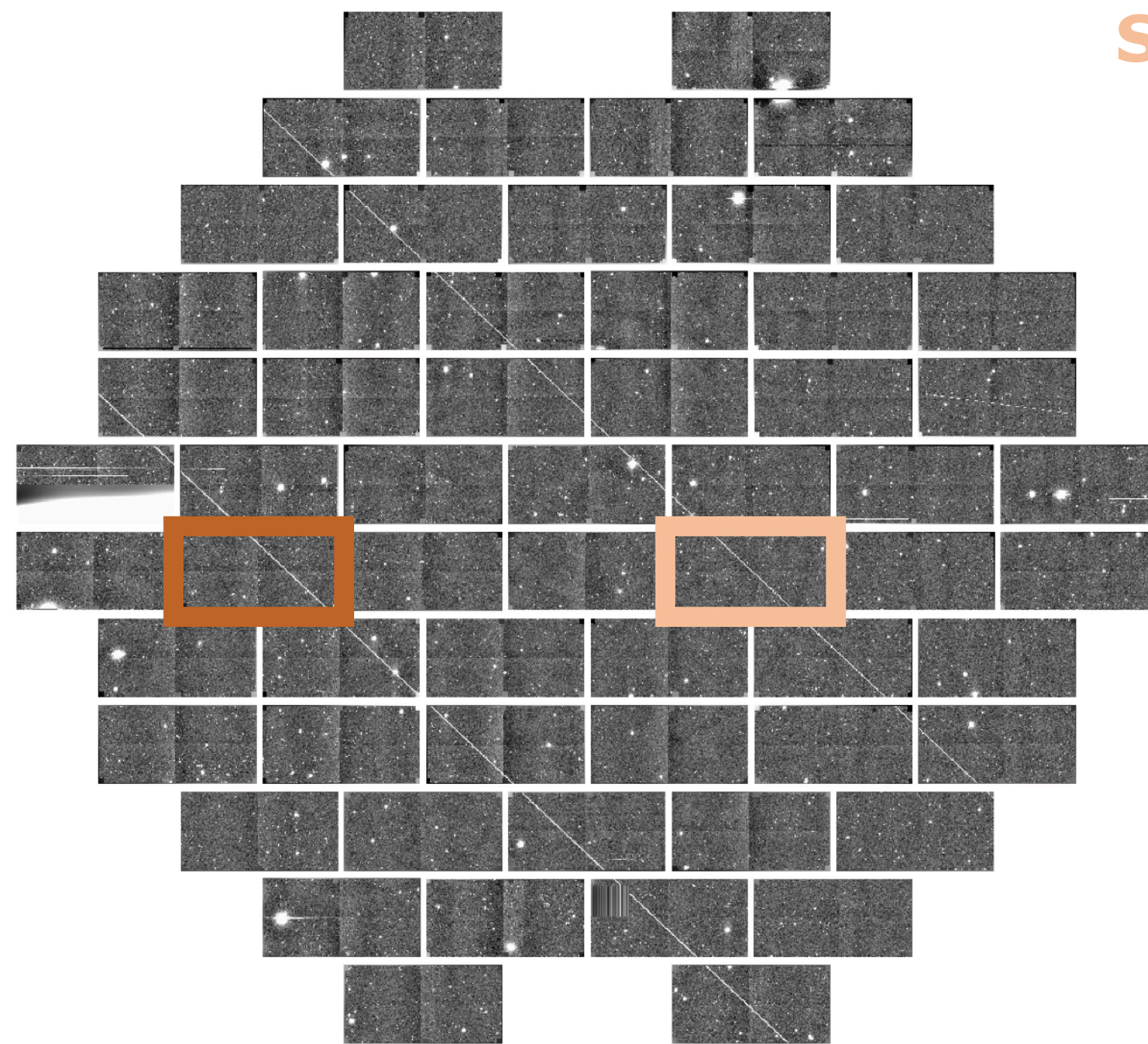
Simulation by Moriba Jah

Lower satellites have lower peak brightness

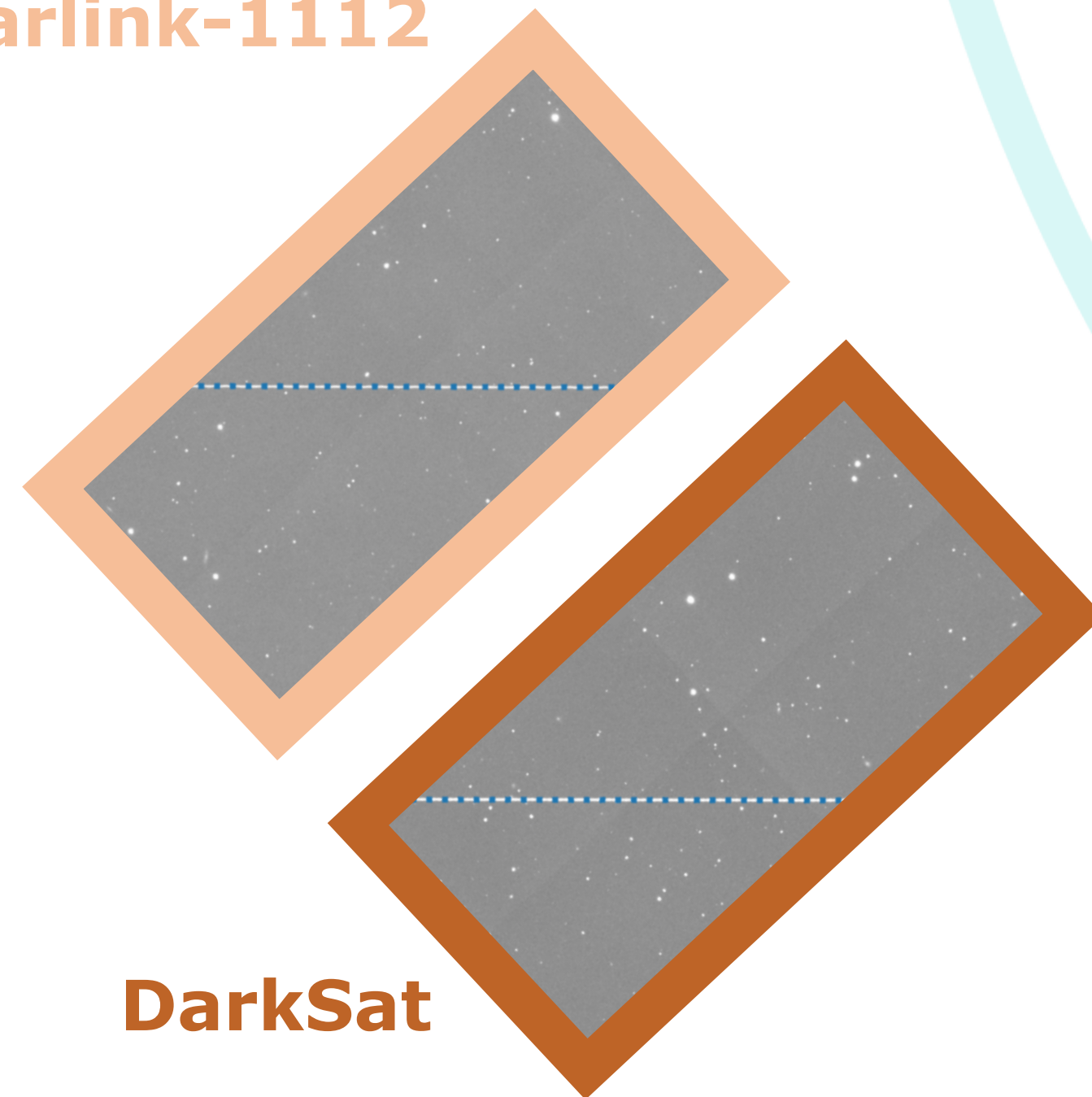
- Higher satellites, > 600 km altitude, are generally worse!
- **Slower speed + sharper focus = more time on each pixel**
- Most bright streaks don't saturate detectors, but subtle effects like non-linear crosstalk can still affect science



DarkSat analysis from mid-2020 (Tyson et al.)



Starlink-1112



DarkSat

- Reduce and calibrate raw images
- Get Sun location and phase angle
- Rotate image so trail is horizontal
- Measure trail brightness
- Account for exposure time
- Account for satellite speed
- Estimate distance to satellite
- Estimate satellite size

DarkSat analysis from mid-2020 (Tyson et al.)

DarkSat is ~1 mag fainter than its siblings in *g*-band

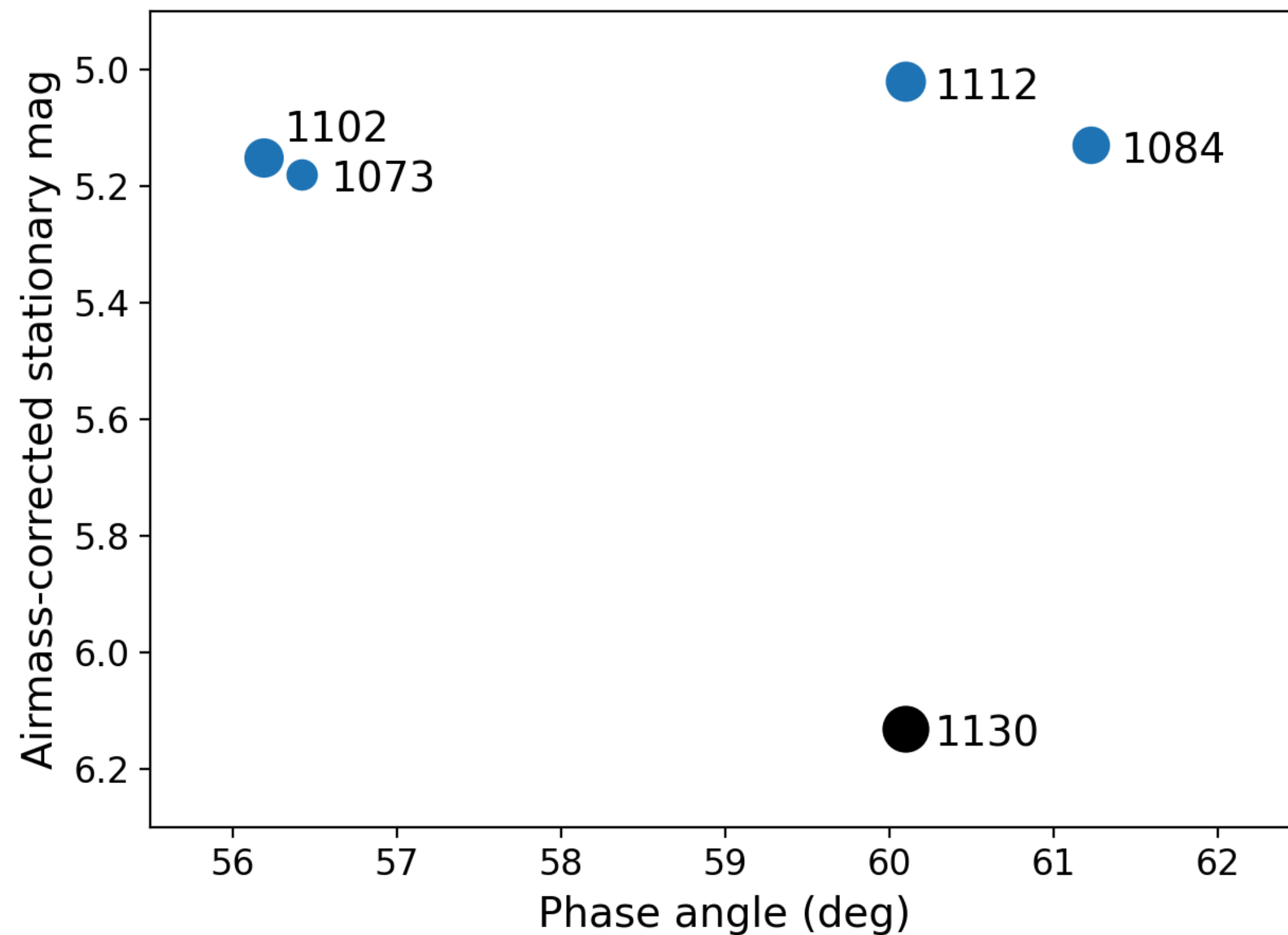
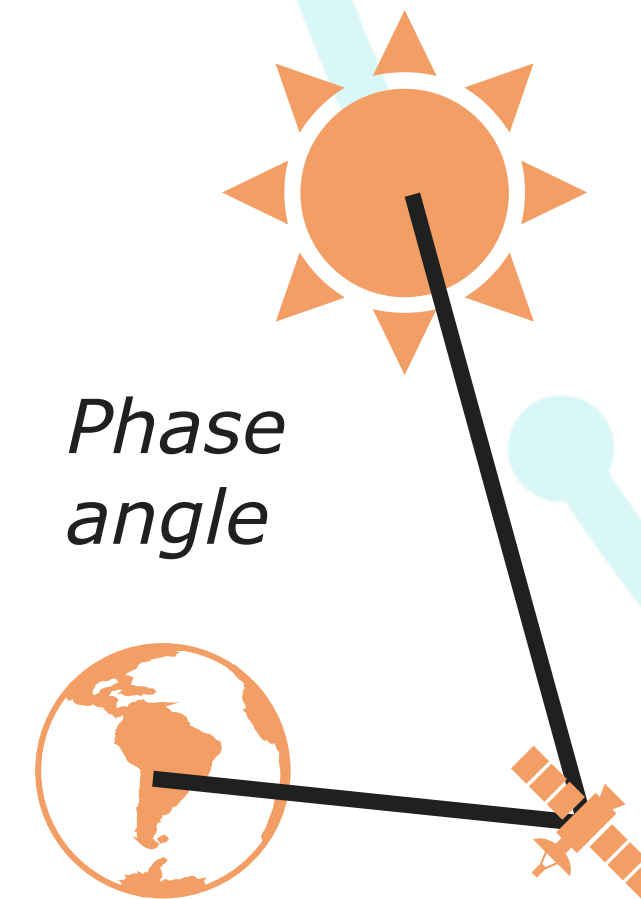
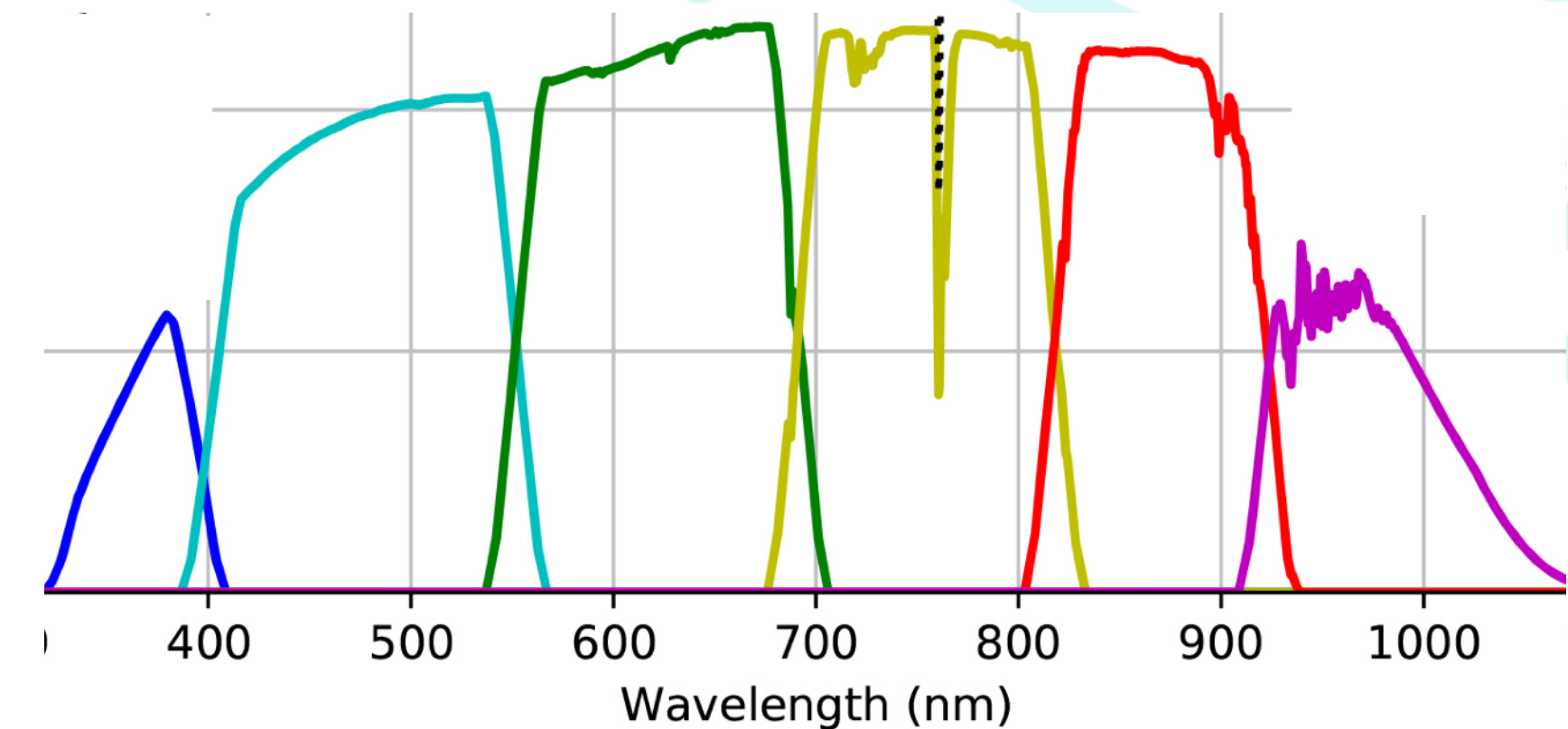


Fig. 8, Tyson et al. 2020, by me

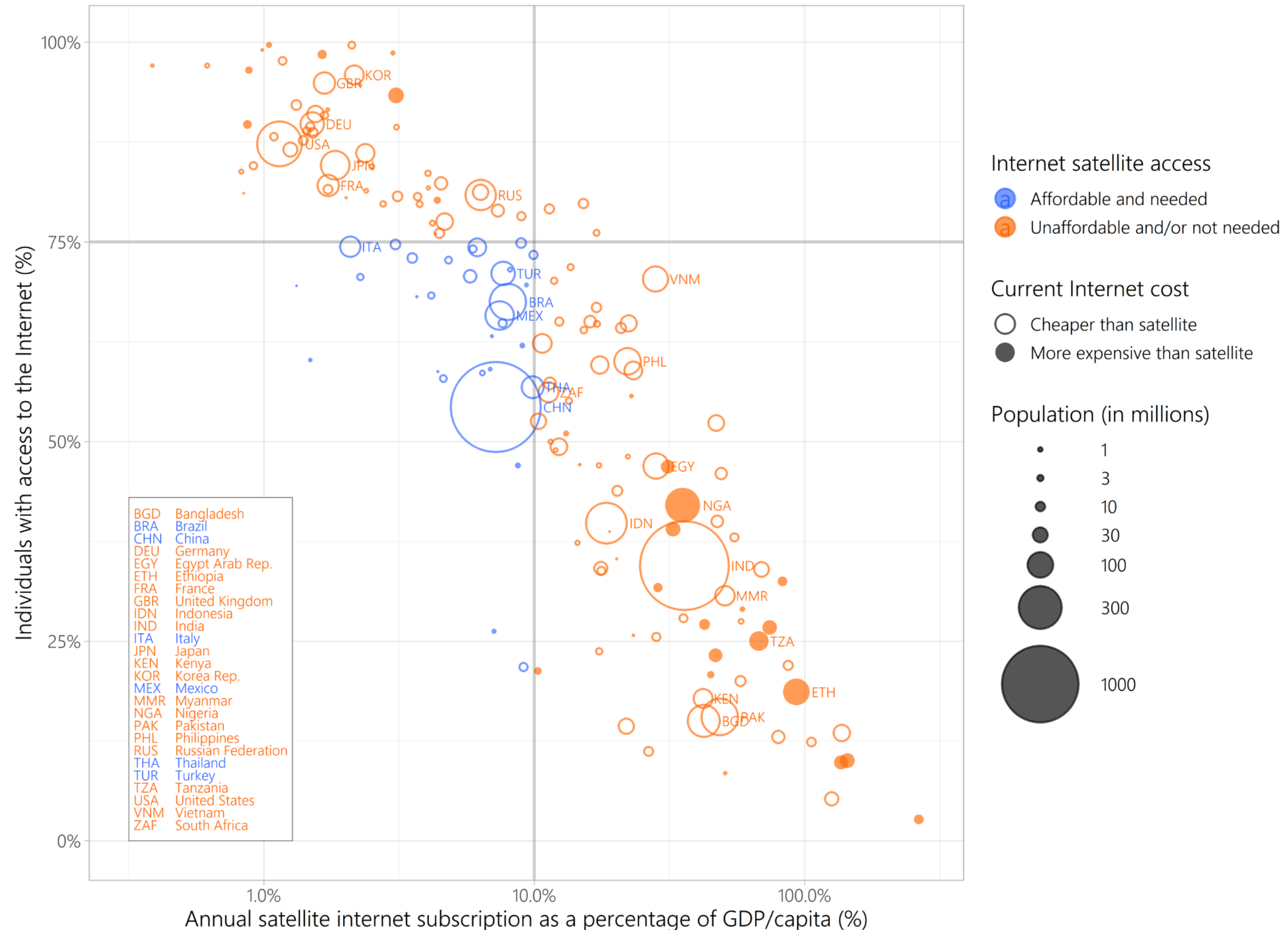


- Magnitudes are corrected for satellite speed and airmass
- Marker size indicates derived satellite size and ~mag error
- Brightness not measured for phase angles far from 60°

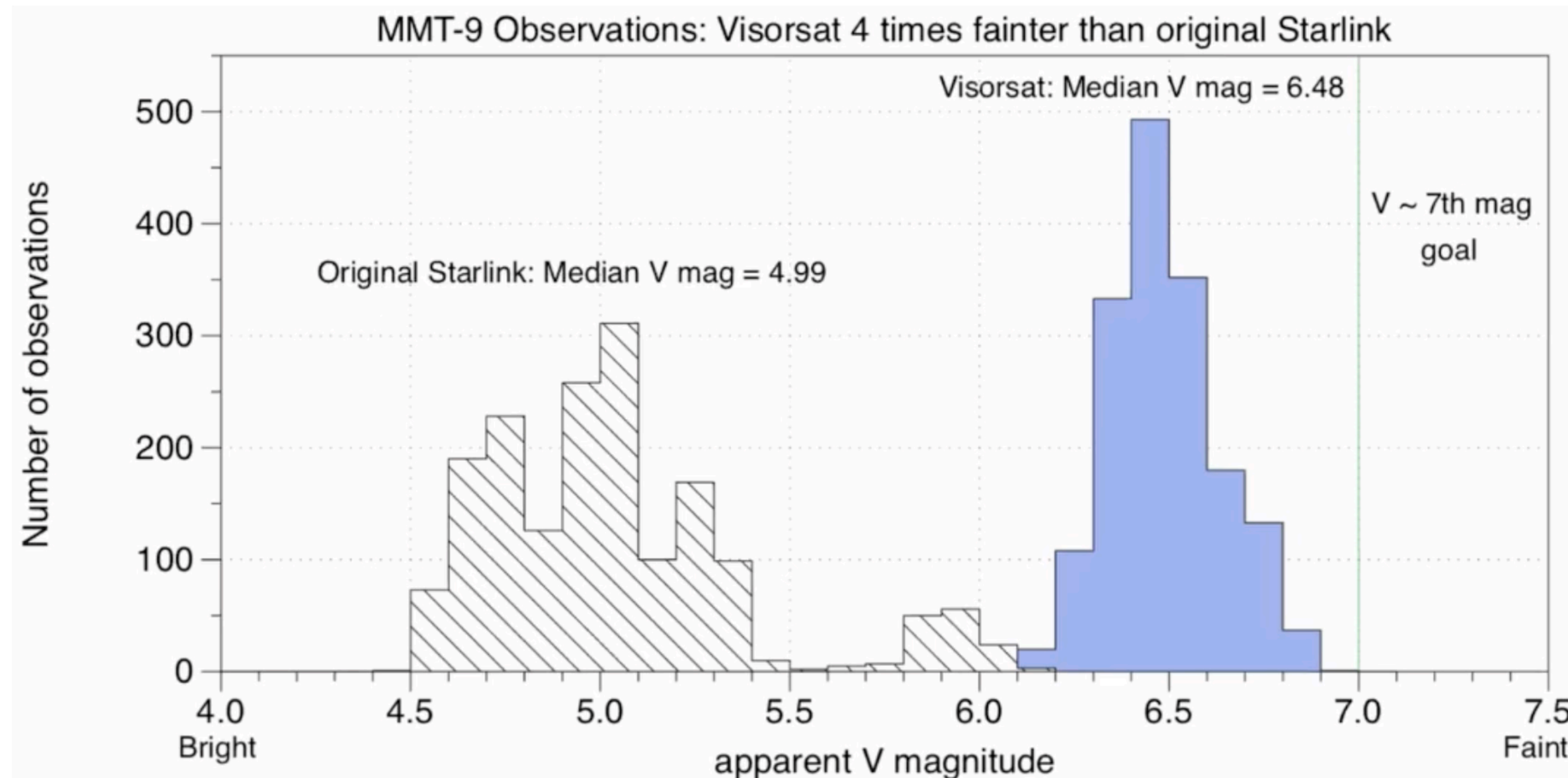


A quick foray into the *point* of satellite constellations

- Many aim to provide worldwide broadband internet services, which is a real need...
- ... but commercial satellite operators are not humanitarian missions, and large + bright swarms will harm astronomy and the orbital environment
- Satellite internet remains unaffordable to the groups that are most in need of it
- Rawls et al. 2020 (research note)

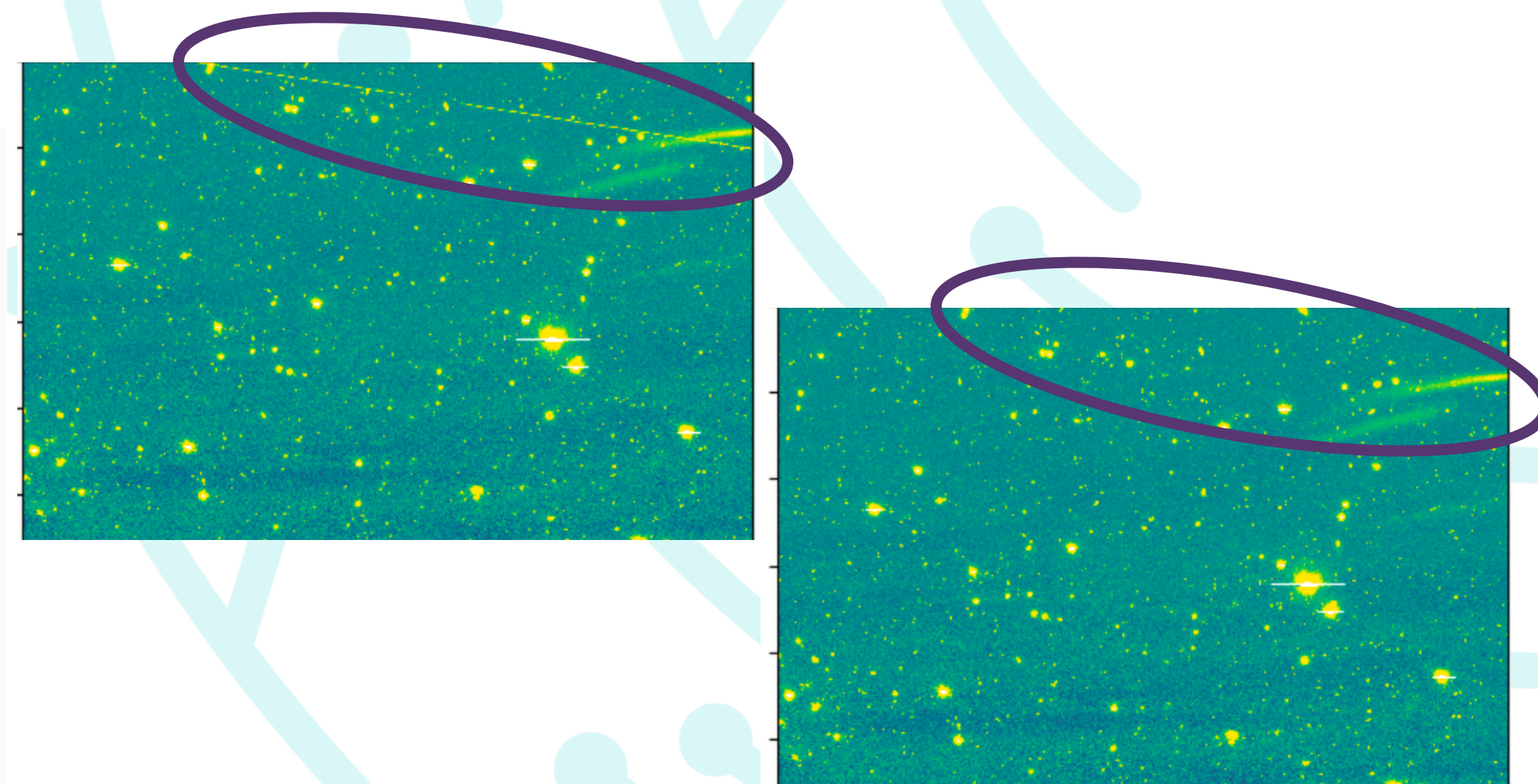


Operator mitigations and software masking



VisorSat: better than DarkSat, but not dark enough

Figure courtesy Pat Seitzer

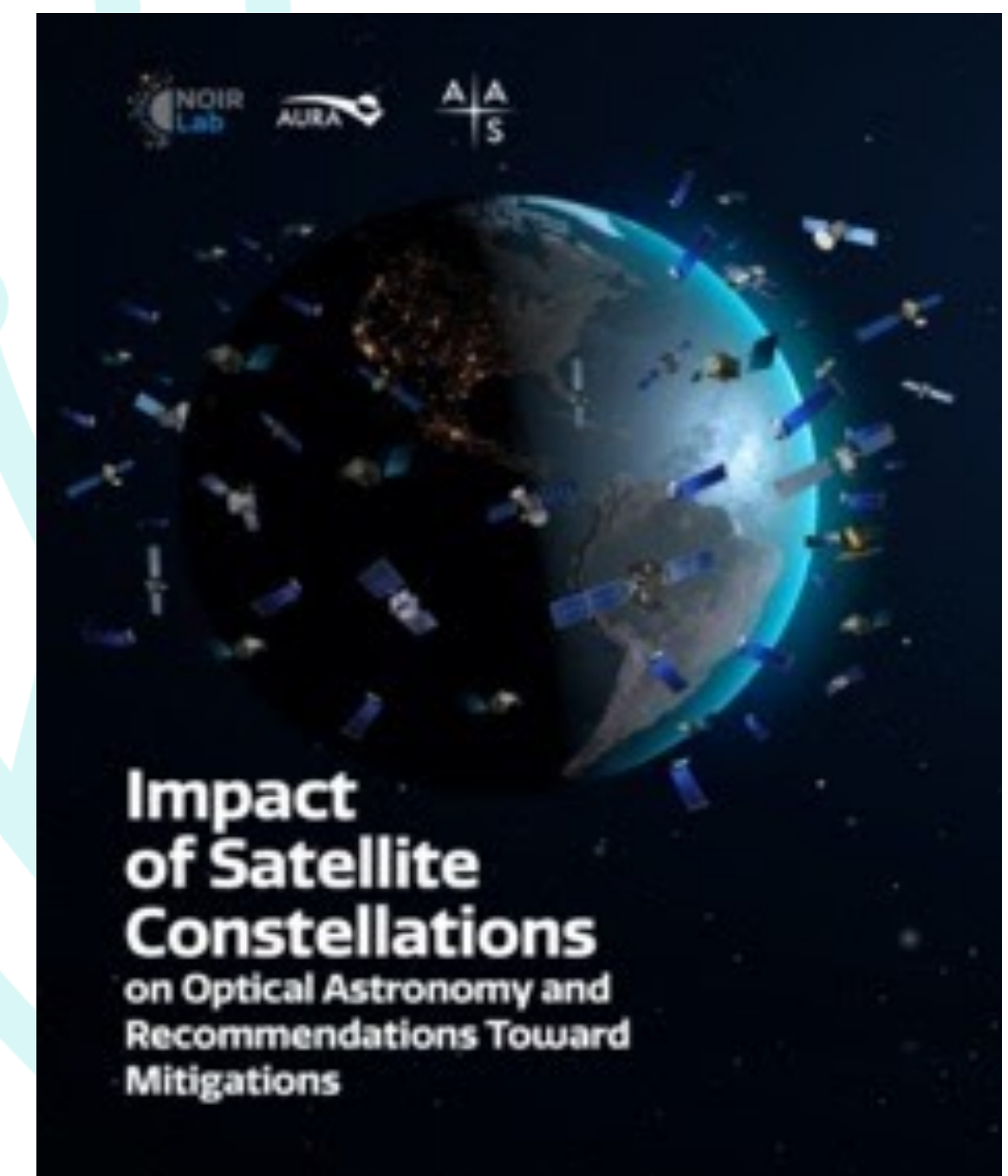


Rubin Science Pipelines can remove satellite trails from stacked images

Figure courtesy Clare Saunders

Addressing the impact of satellite constellations on astronomy

- **2020:** Identify issues, formulate recommendations for mitigation
 - SATCON1, Dark & Quiet Skies I
- **2021:** Identify pathways to implement the recommendations
 - SATCON2, Dark & Quiet Skies II
- **2022:** Begin taking pathways to implement recommendations
 - IAU Centre for the Protection of the Dark Sky from Satellite Constellation Interference to be established
 - *Voluntary* mitigations from satellite industry operators
 - Discussions with US and other governments to make progress toward regulations and funding sources for this crucial work



Astro2020! Maybe you've heard of it?

- 122 instances of “satellite,” **half** of which refer to satellite constellations (not moons, observatories, galaxies, etc.)

Recommendation: The National Science Foundation should work with the appropriate federal regulatory agencies to develop and implement a regulatory framework to control the impacts of satellite constellations on astronomy and on the human experience of the night sky. All stakeholders (U.S. astronomers, federal agencies, Congress, satellite manufacturers/operators, and citizens who care about the night sky) should be involved in this process. This is an international issue; therefore, international coordination is also vital.

Last, just as spectrum management at radio frequencies has been a key NSF mission for many years, the time may have arrived for NSF to take a more active role in managing the use of the optical window. For decades, all major OIR observatories have faced challenges from background light generated by ground-based lights of various kinds. In the past 12 months, OIR astronomy is suddenly facing an almost existential challenge from mega-constellations of satellites in Low Earth Orbit (LEO). Federal action and support are needed immediately, or an entire scientific field may be crippled in an unrecoverable way.

nap.edu/resource/26141/interactive

Moderate optical interference from satellite constellations

Mega satellite constellations will more significantly affect work in astronomy and astrophysics in the future. The NSF should work with the appropriate federal regulatory agencies to develop and implement a regulatory framework to control the impacts of satellite constellations on astronomy.

Reduce radio-frequency interference

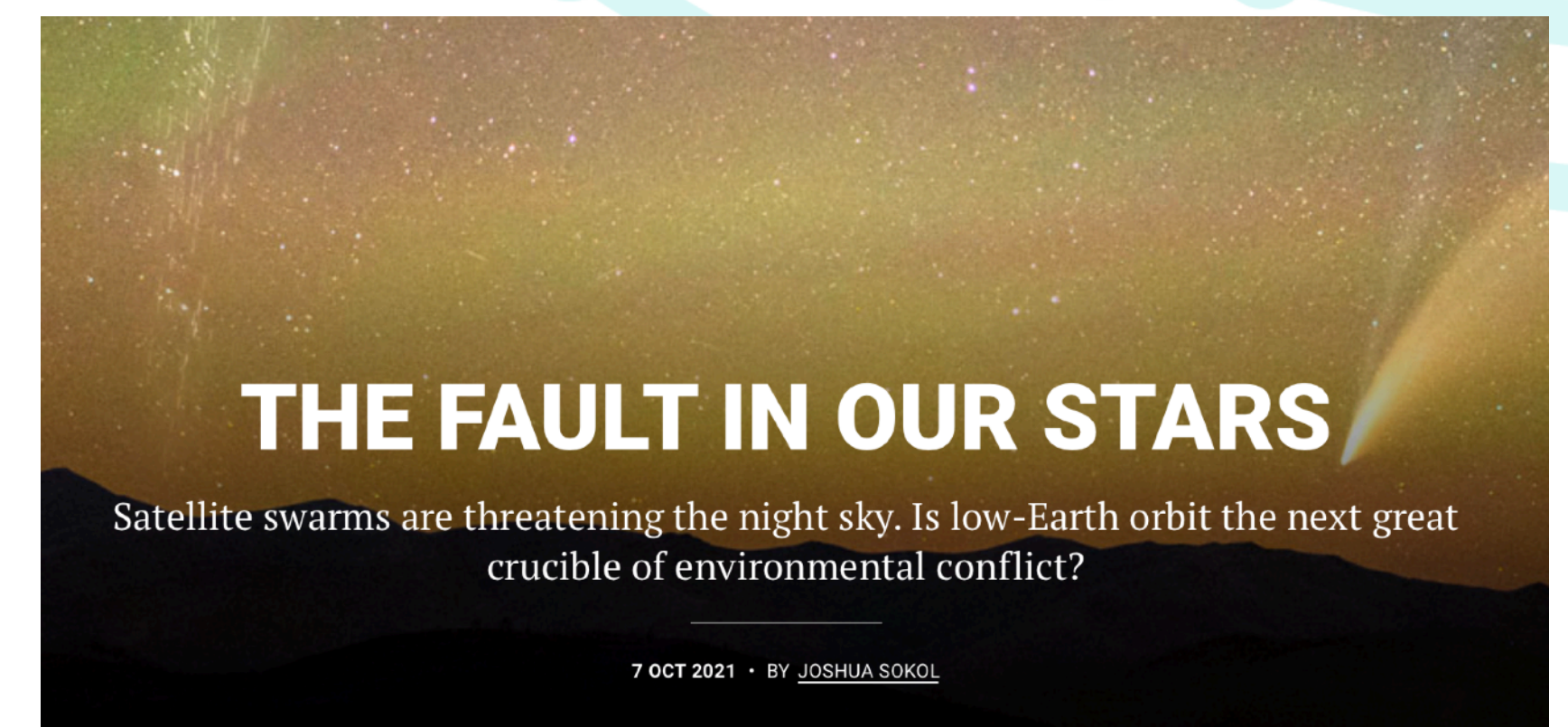
To ensure that the skies remain open to radio astronomy, NSF, in partnership with other agencies as appropriate, should support and fund a multi-faceted approach to the avoidance and mitigation of radio-frequency interference.

Climate change mitigation actions

Human-induced climate change will be one of the greatest challenges of this century. The astronomy community can minimize its impact on climate by reducing travel-related carbon emissions. Examples include remote observing, hybrid conferences, and virtual conferences.

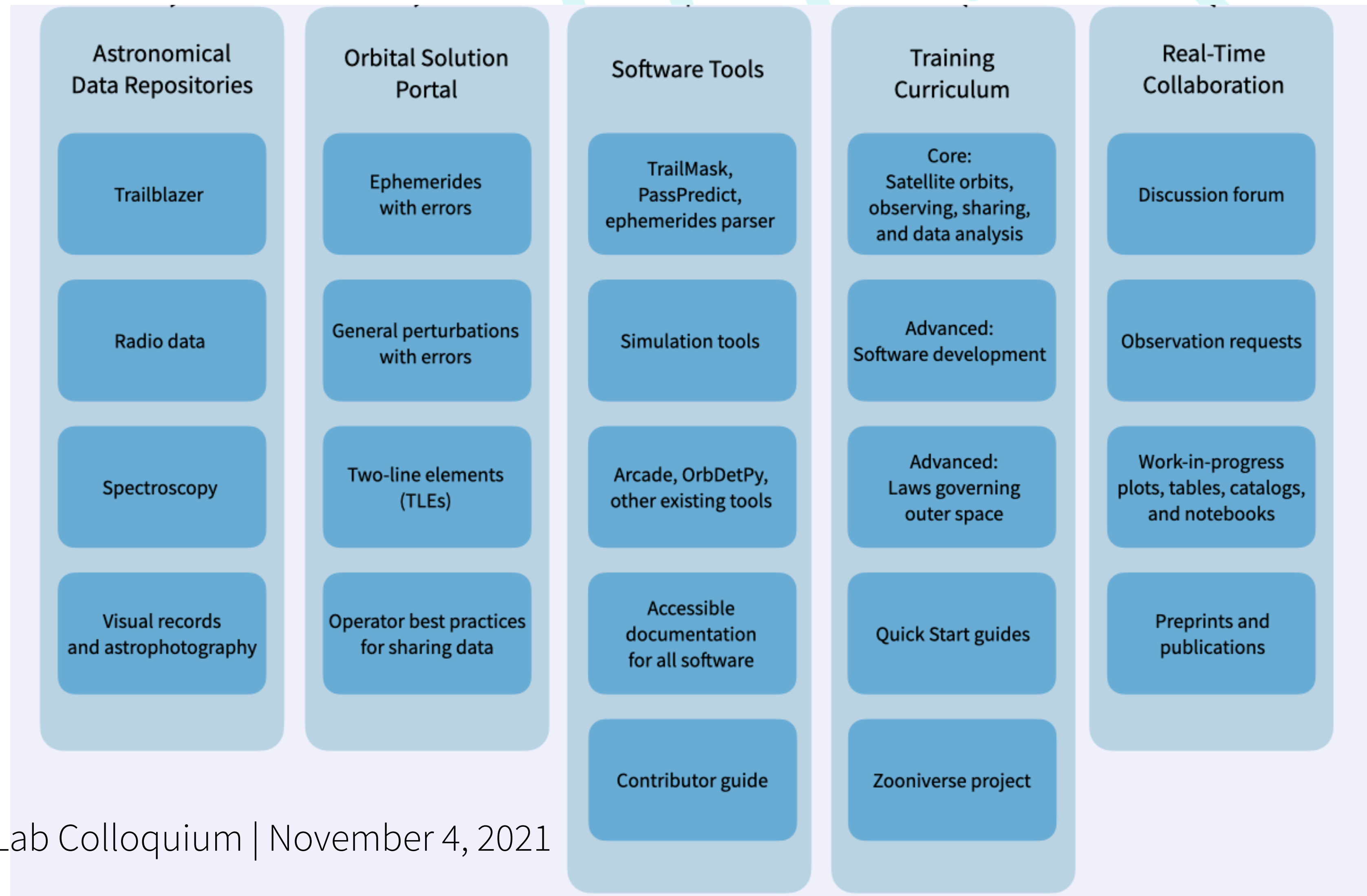
Also released in the last month: SATCON2 Reports

- **Read it:** noirlab.edu/science/events/websites/satcon2/publications
 - Observations Working Group (chaired by me!)
 - Algorithms Working Group
 - Policy Working Group
 - Community Engagement Working Group
- **Too technical?** Try: <https://www.science.org/content/article/satellite-swarms-are-threatening-night-sky-low-earth-orbit-next-great-crucible-environmental-conflict>



Observations — SatHub

- A “one-stop shop” for training, outreach, and collection & analysis of satellite observations



Observations — SatHub

- **Astronomical Data Repositories**

- Public, accessible, user-friendly, documented
- Trailblazer will be one of them! (early 2022)
- Also a need for spectra, space-based (e.g., Hubble), radio, DSLR photos, visual sightings...

- **Training Curriculum**

- A global observing campaign, data, and software are great — but insufficient
- *Core curriculum* (intro, observing satellites, reporting observations, image & data analysis)
- *Advanced modules* (software development, radio astronomy, space law)
- *Quick start recipes* (for different observer hardware scenarios)



Courtesy Annie Morris



Trailblazer (project in progress)

W



An open data repository for astronomical data products affected by satellites

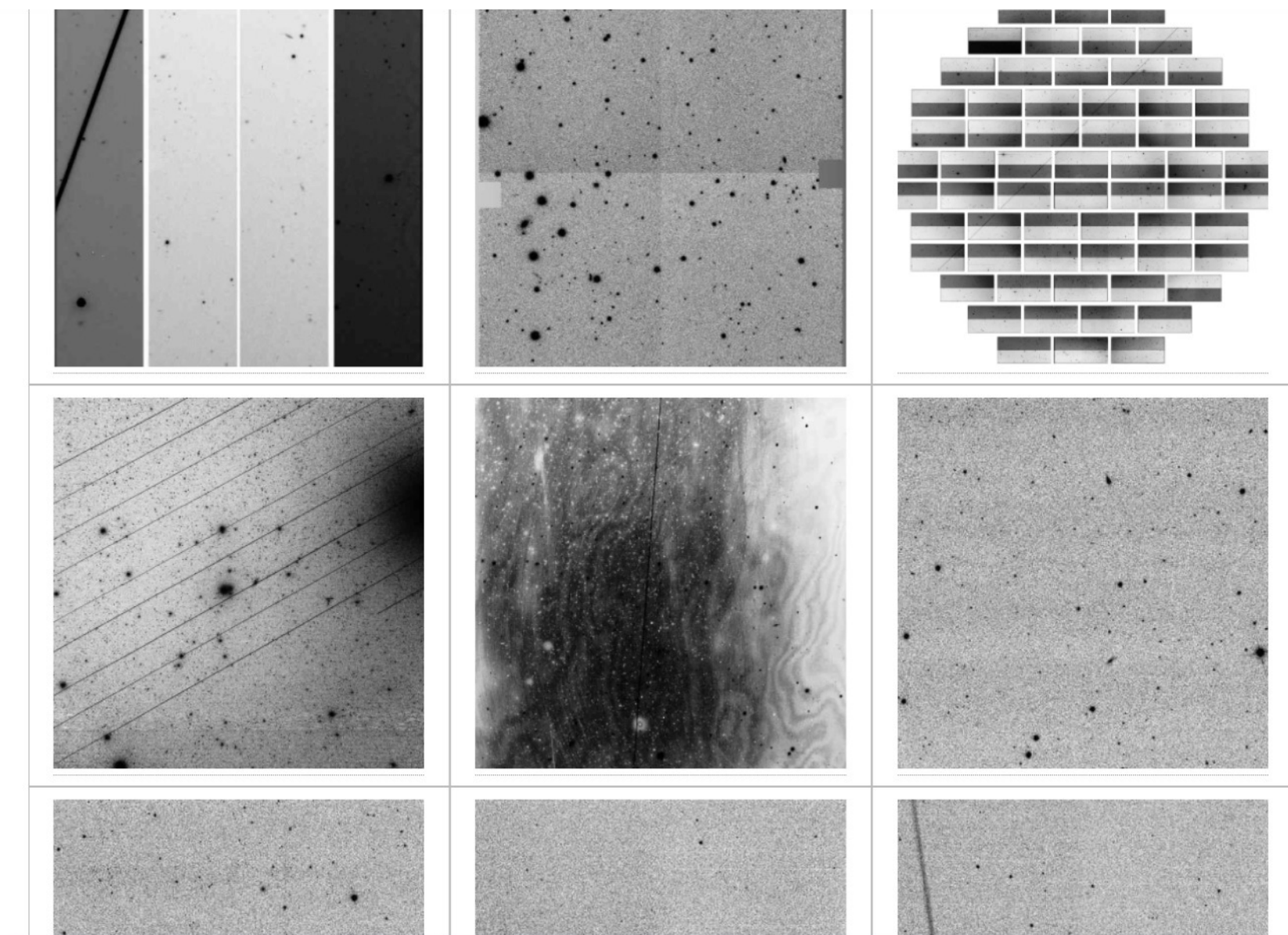
- Users can upload new data at any time (given vetted metadata)
- Users can access real representative data (FITS files) in minutes

Coming in 2022:

1. An astronomer can think, “my otherwise perfectly-good non-proprietary observations have these darn satellites in them; I'll submit them to trailblazer real quick so it's not a total loss”
2. Groups seeking to characterize the extent of the satellite streak problem have ready access to a dataset to quantify impacts to ground-based optical and NIR astronomy



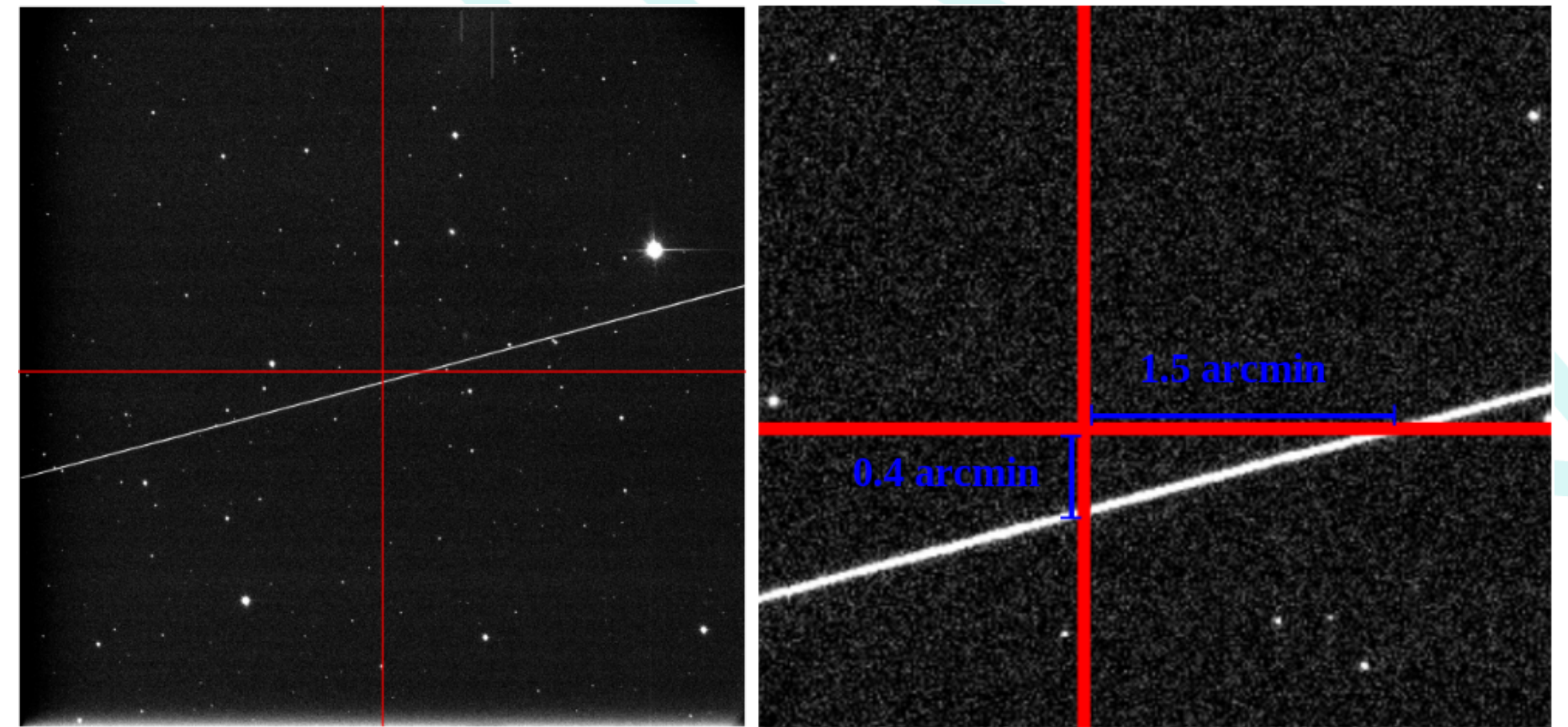
WELCOME TO THE GALLERY



Observations — SatHub

Standard requirements for present and future satellite operators to aid all sky observers

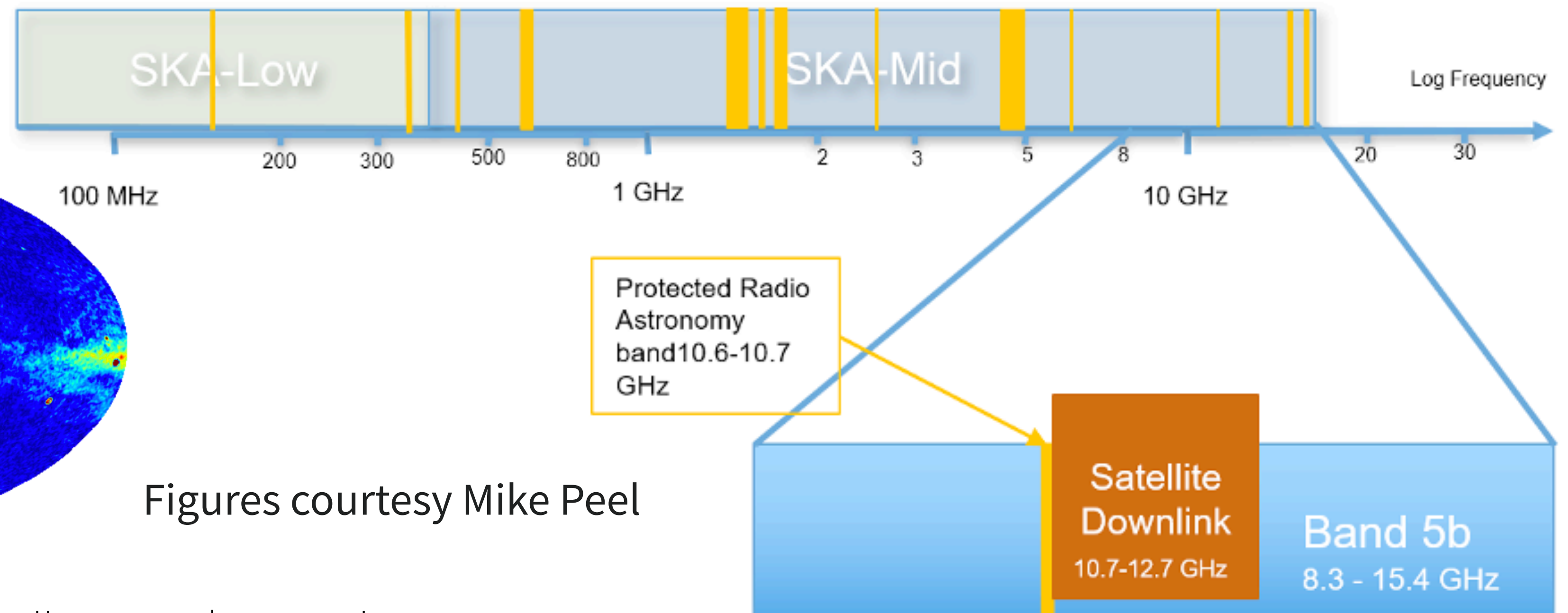
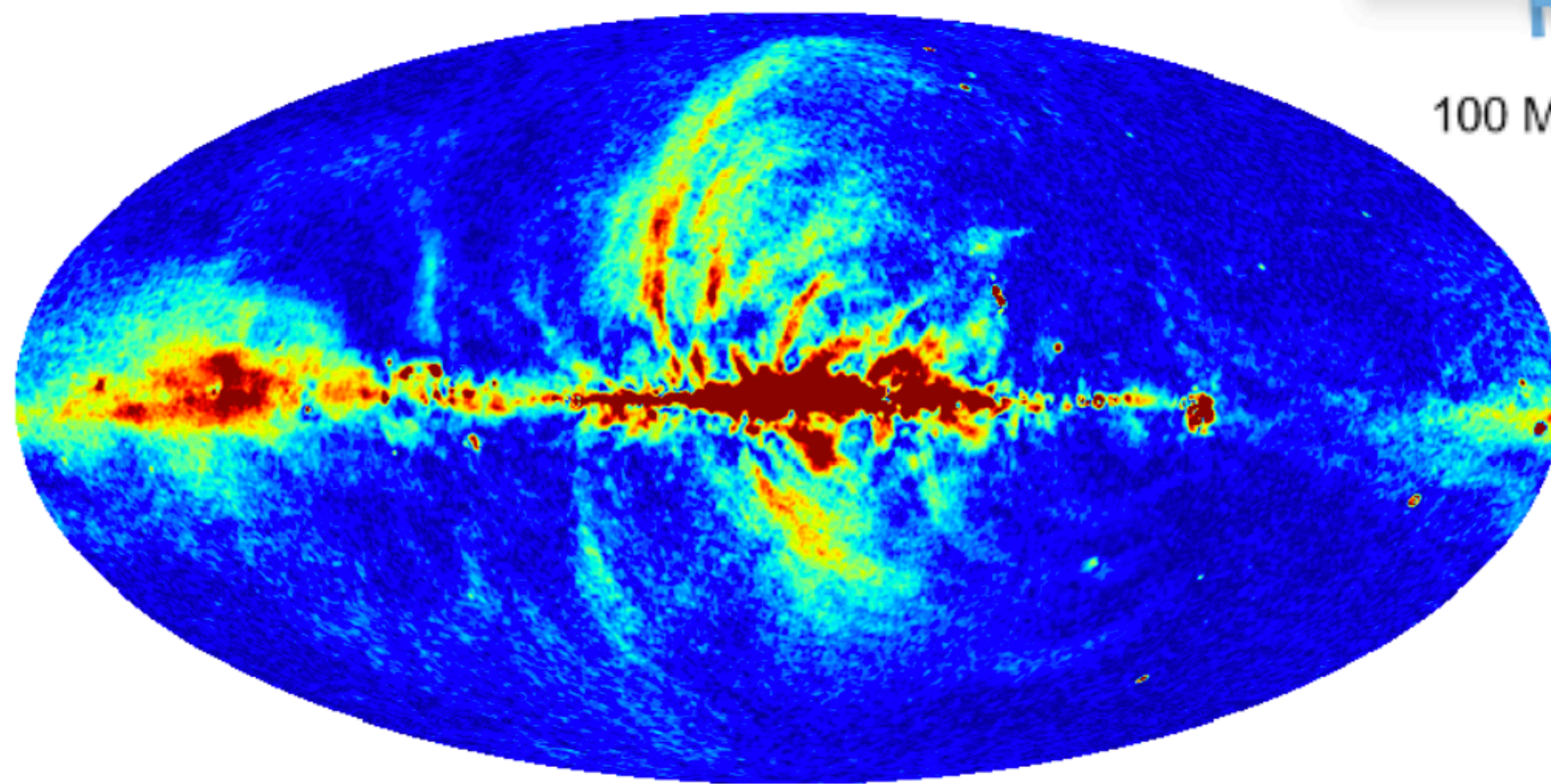
1. Publicly provide orbital solutions every 8 hours or immediately following a maneuver, whichever is first (and always include error bars!)
2. Publicly provide any other relevant metadata (e.g., reflective properties)
3. Adopt standard formats for the two types of orbital solutions
4. Financially support SatHub's Orbital Solution Portal



Courtesy Jeremy Tregloan-Reed

What about radio astronomy?

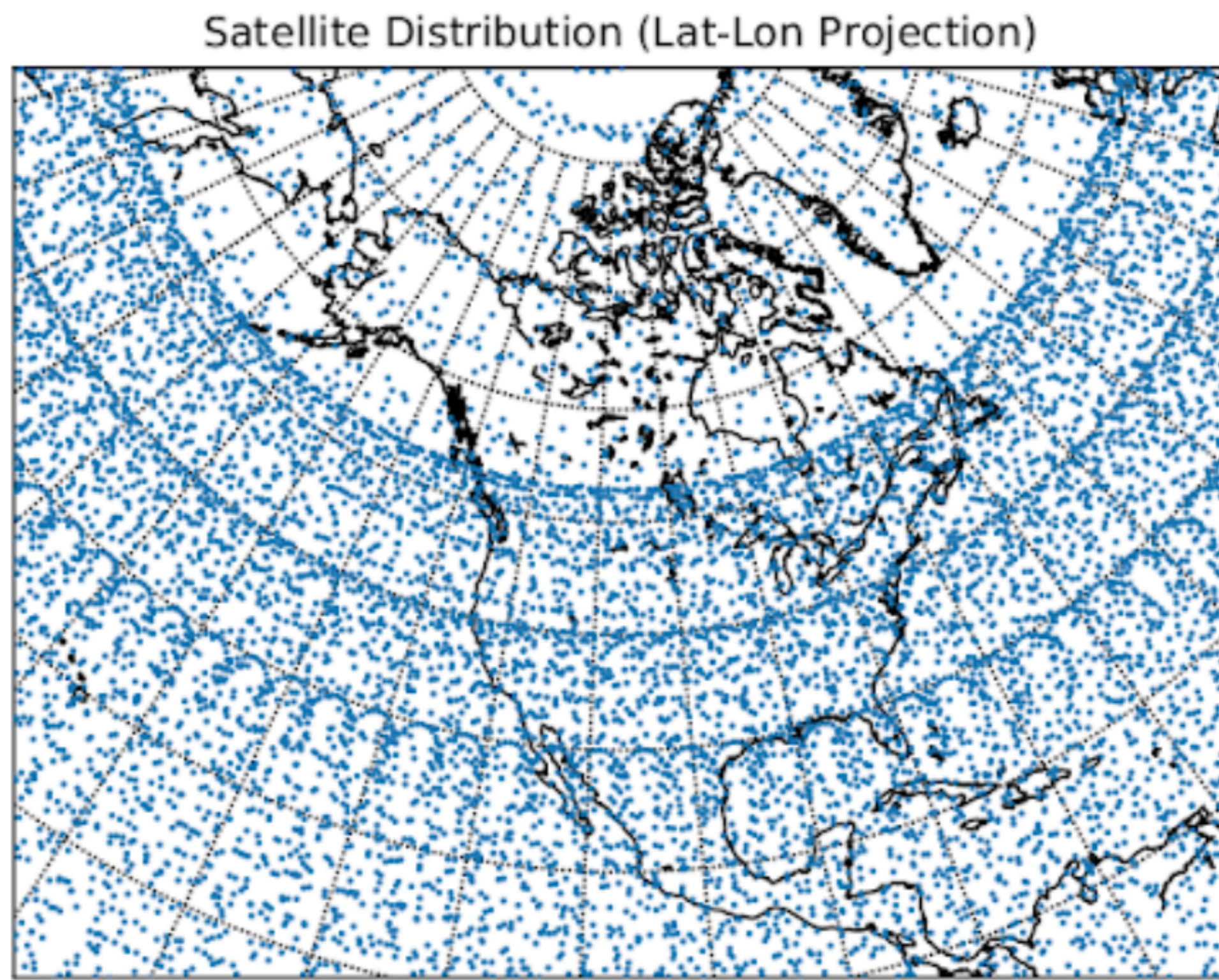
- Regulatory structure and existing protections exist, but are insufficient
- Radio astronomy has benefited from “quieter skies” thanks to geographic isolation
- More geographic quiet and coordination zones/“reserves” with more protections are needed
- Future research on radio frequency interference can help, but cannot solve all problems



Figures courtesy Mike Peel

Ongoing observer-operator dialogues are crucial

- Higher-latitude observatories (e.g., Canada) are affected by lower-altitude satellites more than mid-latitude sites (Lawler et al. 2021)

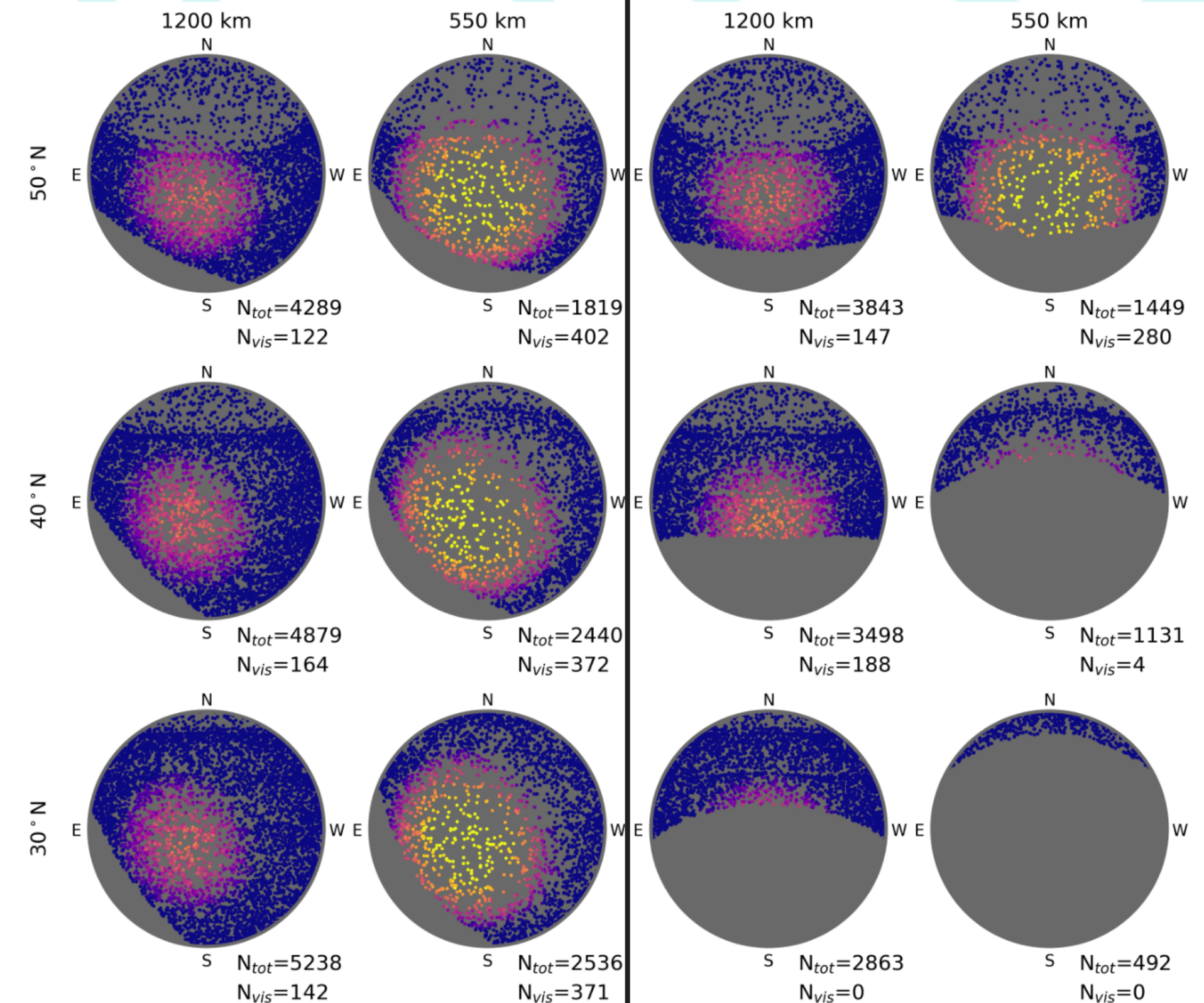


High
latitude

Mid
latitude

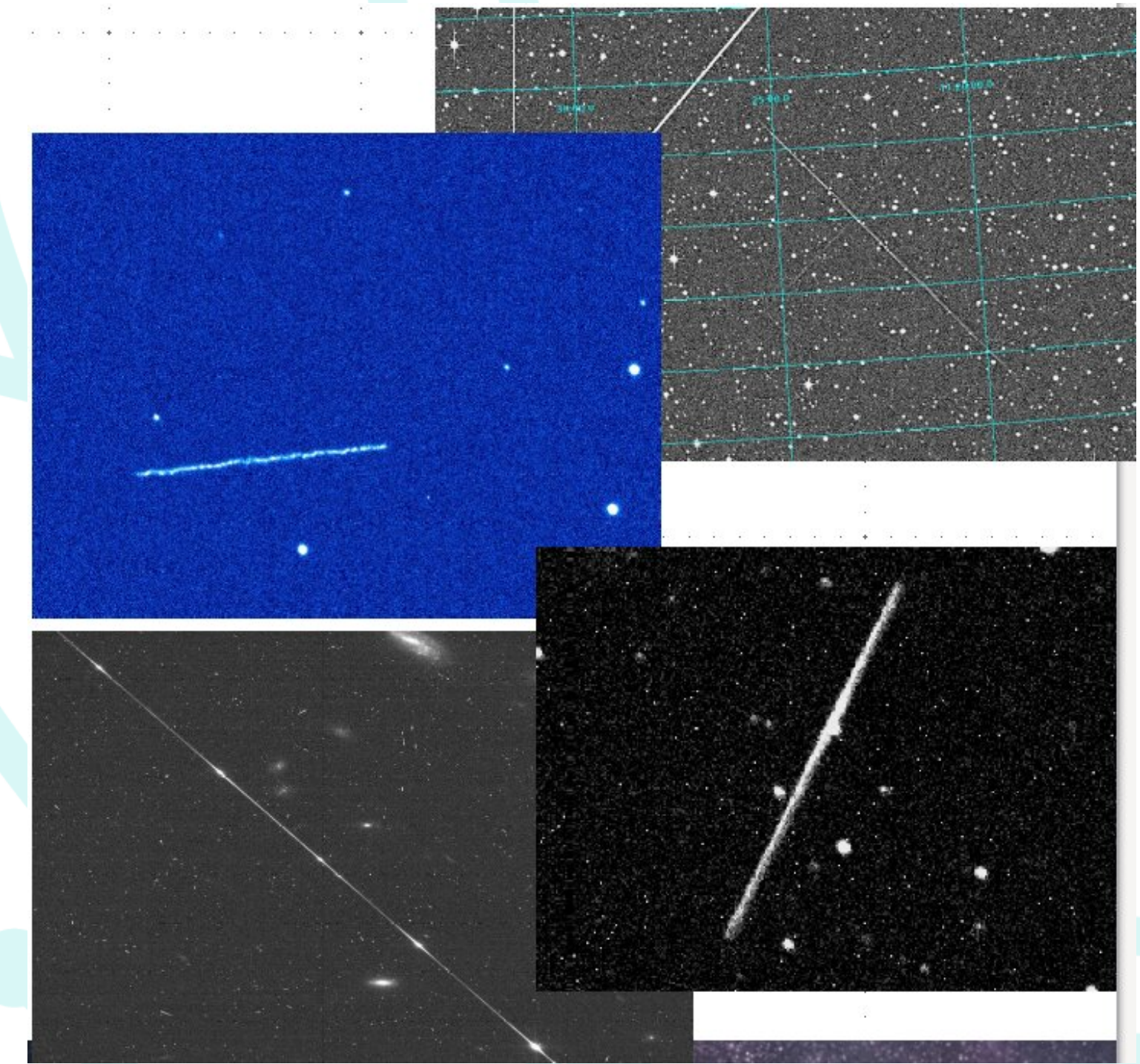
Twilight

Midnight



Algorithms (SATCON2 Working Group)

- Recommend developing satellite trail mitigation software ASAP
- Some tools exist, but lots of it isn't universally applicable
 - **PassPredict:** “Will my observations be affected?”
(plan observation timings)
 - **TrailMask:** “can I salvage useful science from affected data?”
(mask or remove streaks)
 - **Simulation and Modeling:** (assess overall impacts to determine any changes that could decrease those impacts)
- There is a timescale mismatch — we are already behind!
 - *Academic studies + software << Satellite industry design + launch << Regulatory changes*



Courtesy Jonathan McDowell

Policy (SATCON2 Working Group)

Courtesy Richard Green

- International law and treaties
 - Outer Space Treaty (1967) is the legal instrument binding 110 signatories
 - Work underway to identify international obligations and how they are implemented by different nations and policy mechanisms (esp international space law & international environmental law)
- US national law
 - American Astronomical Society (AAS) is engaged with various US government groups
 - Connections to light pollution laws, which are at the state/local level
- Orbit as environment
 - Low-Earth-orbit is not (yet) legally recognized as a human environment to preserve/protect
 - No environmental review currently required for satellite constellation launches
- Industry perspective

Community Engagement (SATCON2 Working Group)

Observations and Recommendations from CE Working Group

- Duty to Consult
- More Information/Communication (industry, astronomers, impacted communities)
- Engage with Industry
- Rebalance Power Structures
- Learn From the Past
- Science vs. Internet is a False Choice
- Better international regulation and globally coordinated oversight/enforcement

SATCON2 workshop was the beginning, rather than the endpoint, of a long overdue conversation that was prompted by SatCons, but extends to far broader issues of preserving space and the night sky as a scientific, environmental and cultural commons for humanity.

Courtesy Aparna Venkatesan & James Lowenthal

What to watch & how to shape the future of our sky

- Read the reports (SATCON1, Dark & Quiet Skies 1, SATCON2, Astro2020 are all freely available)!
- Start collecting your recent astronomical images with satellite streaks for Trailblazer
- Consider commenting on relevant FCC filings and talking to your congress members
- Stay tuned for announcements about a new IAU Centre and future Rubin/LSST data previews
- **The future of astronomy:** observations, measurements, algorithms, big data
- **But it is also:** who owns the sky? who profits? who decides?



*“Just put all your
telescopes in space”*

*“Global internet access
is more important”*



*“Dark skies are a human
right that connect us all”*

*“We need communities, not
colonies, in our shared skies”*