LEO Spacecraft Proliferation and its Impact on O/IR Astronomy Observations (Dark Skies)

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We need remote internet connectivity…

Credit: By NASA - https://eol.jsc.nasa.gov/, Public Domain

- Weather
- Disaster Comms
- Telemedicine
- Climate change

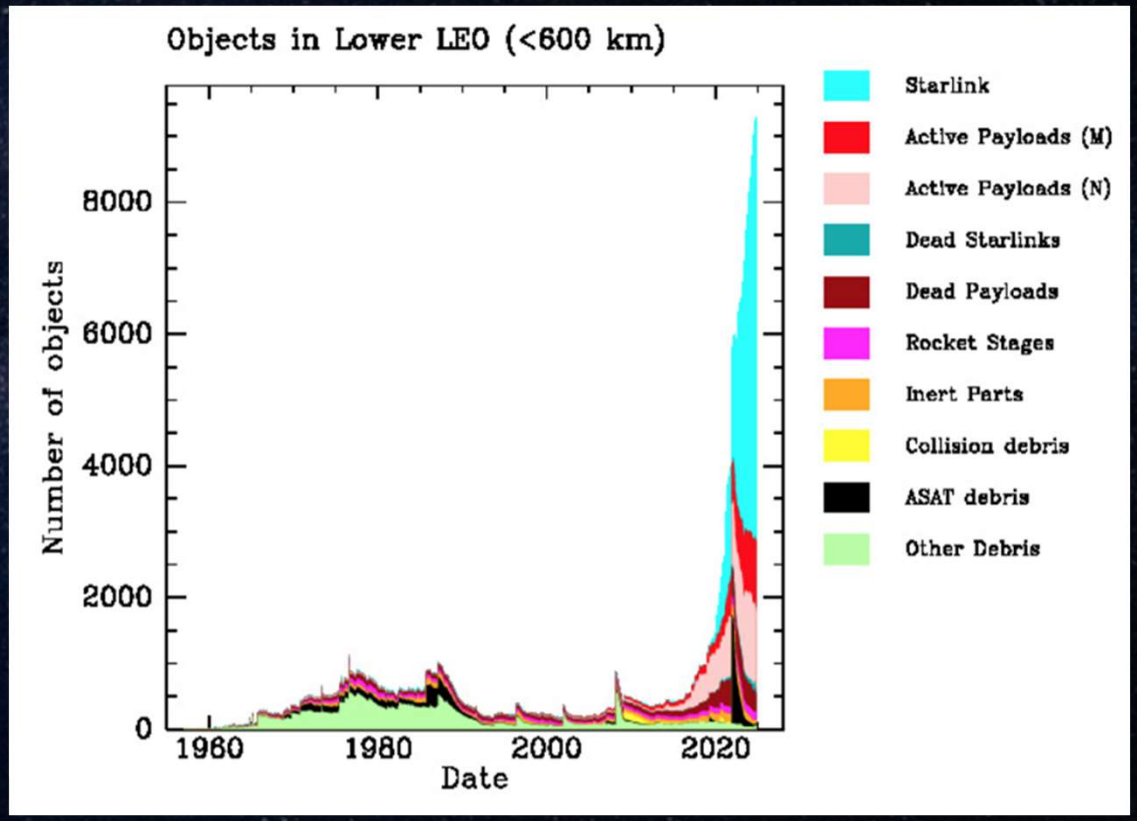
Hurricane Ian viewed by the Expedition 67 crew on the International Space Station on September 28

Overview

- The **numbers** and **brightness**
- **Impact** on the science of O/IR astronomy and its observatories
- A stellar example: the **Rubin** Observatory
  - Addressing streaks and glints
  - Small debris de-focussed?
- **Mitigations** by the astronomical community and satellite operators
- The Center for the Protection of the Dark & Quiet Sky from Satellite Constellation Interference (**CPS**)
  - International cooperation among software engineers, observers, astronomers, satellite industry folk, policy experts, space lawyers, government officials
  - Their success stories through the CPS Hubs (nationally & internationally)

CHALLENGES

Exponential Growth in the Number of LEO Satellites



Active Satellites in LEO

2019 Sept: ~2,200

2024 15 Nov: > 8,800 (<600km)

> 9,600 (<1200km)

Active+Inactive Satellites in LEO

>11,600 (<1200km)

Total Planned LEO sats in constellations

> 555,000 (in reality: 100K to 200K)

[J. McDowell, planet4589.org]

CHALLENGES

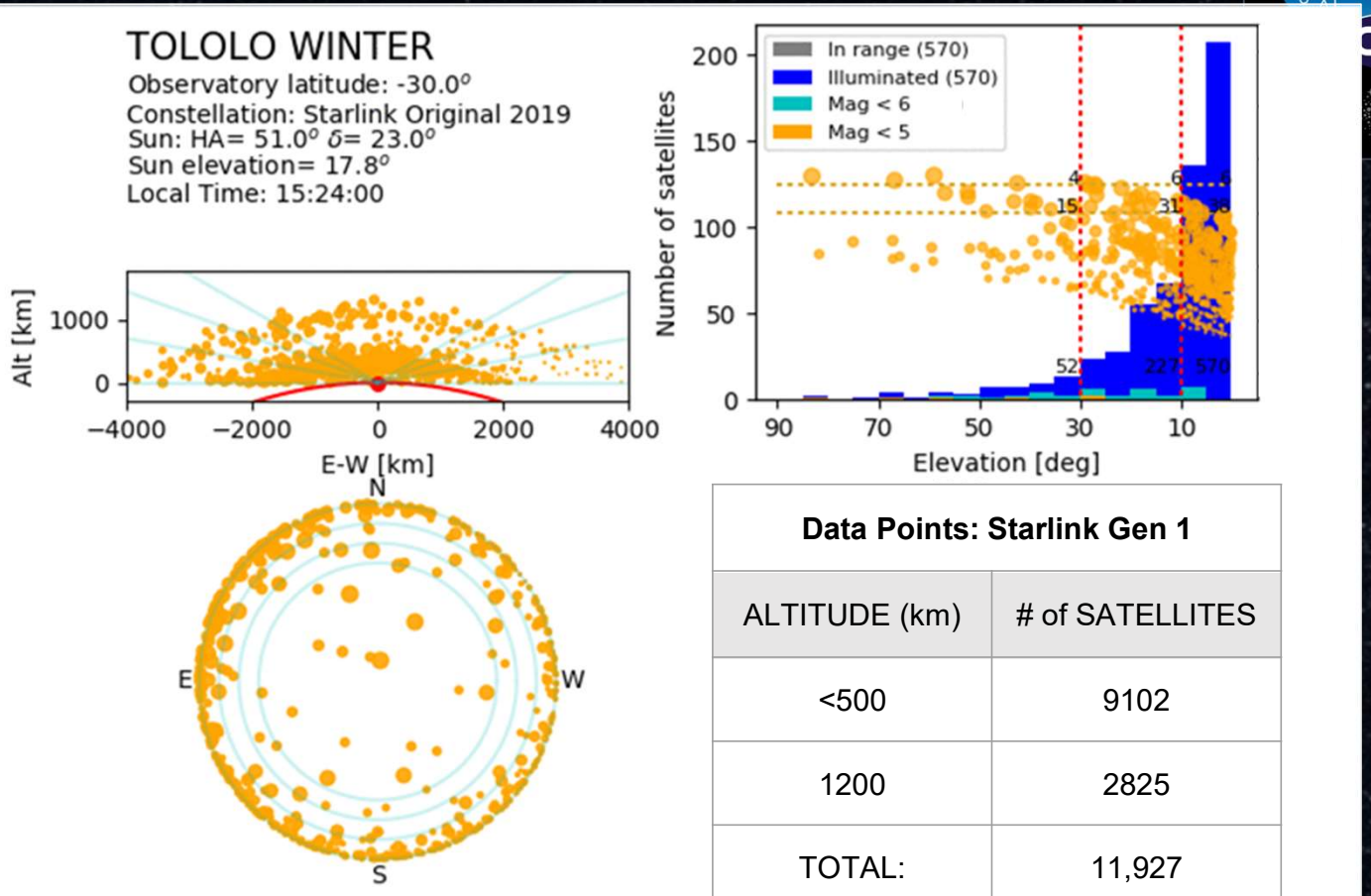
Satellite Visibility & Brightness

- Illuminated
- Shadow

View from Space

View from Earth

Credit: O. Hainaut, ESO (https://www.eso.org/~ohainaut/satellites/plots.html#compare)

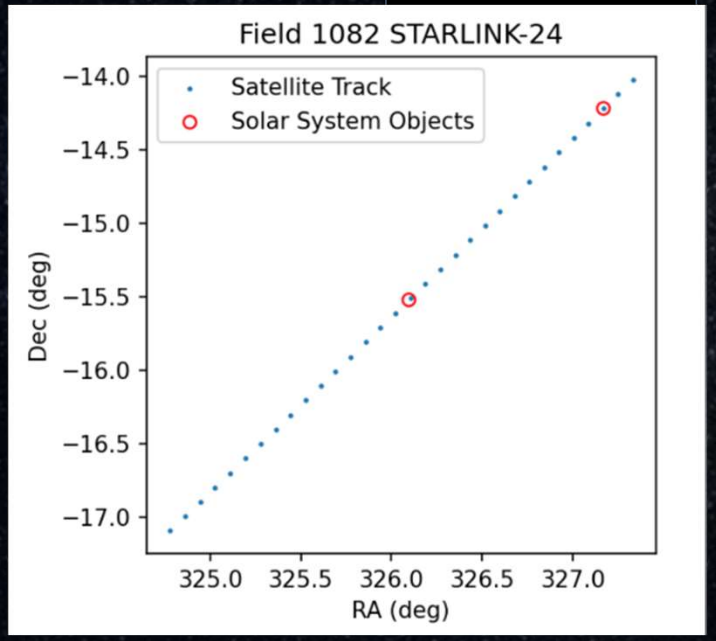


Data Points: Starlink Gen 1	
ALTITUDE (km)	# of SATELLITES
<500	9102
1200	2825
TOTAL:	11,927

CHALLENGES

Impact on Optical Astronomy

- A satellite streak makes a small part of an image unusable (lost data), and may distort other areas of the image too
- Impacts to science (and society) include:
  - **Loss of orbit recovery of Potentially Hazardous Asteroids**
  - Loss of time series for variable stars in nearby galaxies
  - Confusion with subtle distortions in the shape of distant galaxies by Dark Matter weak lensing
  - For spectroscopy, contamination of faint object spectroscopic measurements by reflected sunlight



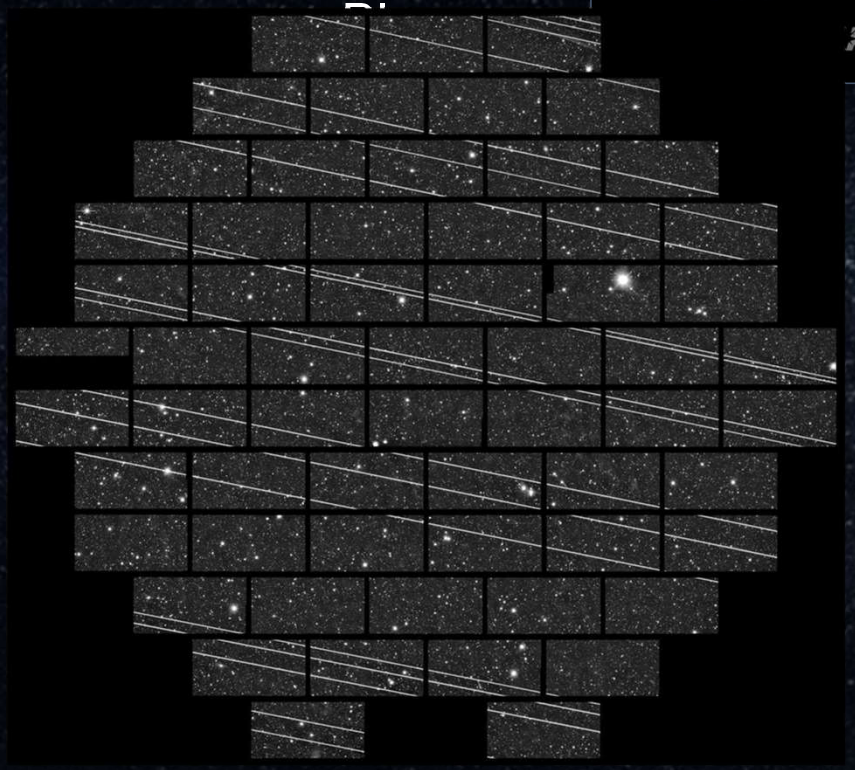
Credit: S. Eggl (UIUC)

CHALLENGES

Impact on Optical Observatories

Based on 40,000 satellites (Hu et al 2022)

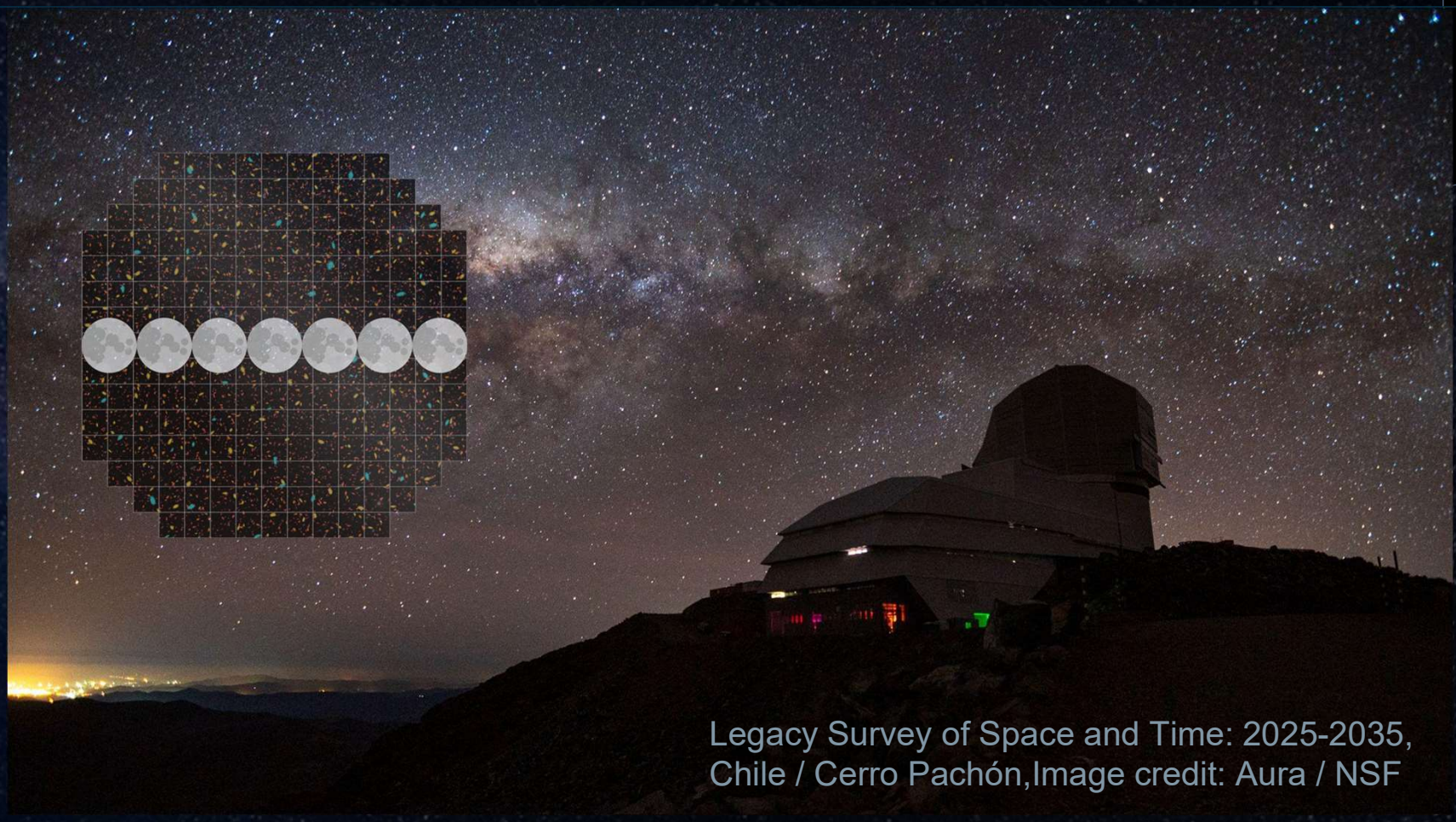
- **Narrow field** (Gemini, Keck, ESO's VLT, ELT): **~10% of frames** (end of ast. twilight)
- **Wide-field** (Blanco, VST): **50% of frames** (twilight)
- **Super-Wide-field:** (Rubin Observatory)
  - ➤ **~ all image frames** (twilight)
  - ➤ Many frames — during whole nights



Credit: CTIO/NOIRLab/NSF/AURA/Decam DELVE Survey, 2019

OPPORTUNITY

The Vera C. Rubin Observatory / LSST

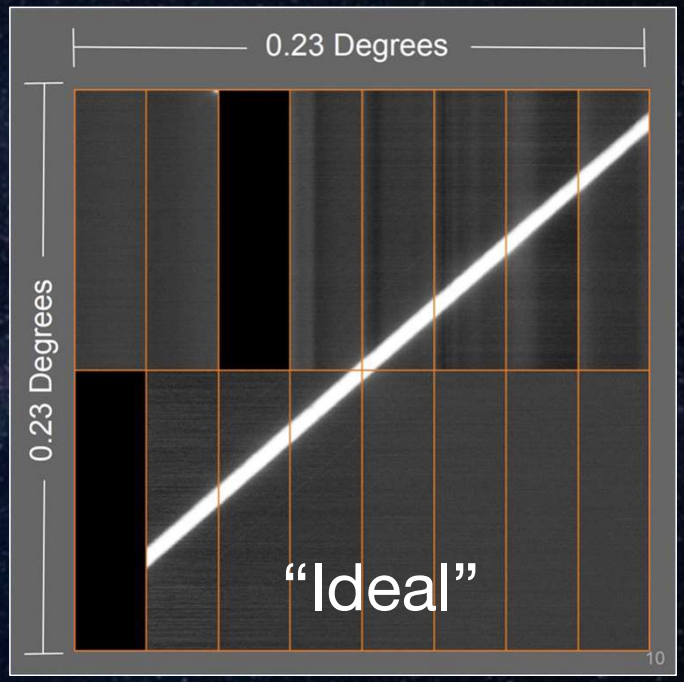


Legacy Survey of Space and Time: 2025-2035, Chile / Cerro Pachón,Image credit: Aura / NSF

CHALLENGES

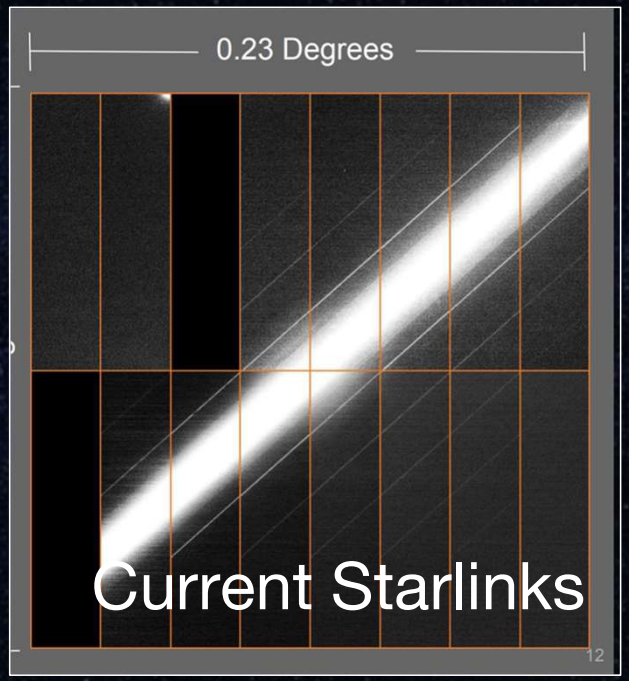
Rubin Observatory LSSTCam detectors

IAU CPS maximum recommended brightness



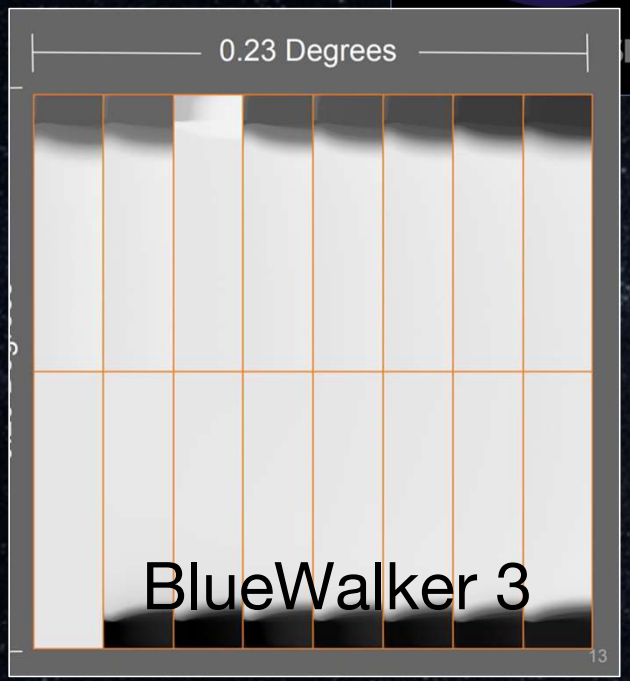
~7 mag, largely correctable
Affects some faint object science

Starlink Direct To Cell



4–5 mag, correctable with larger error bars
Affects most science

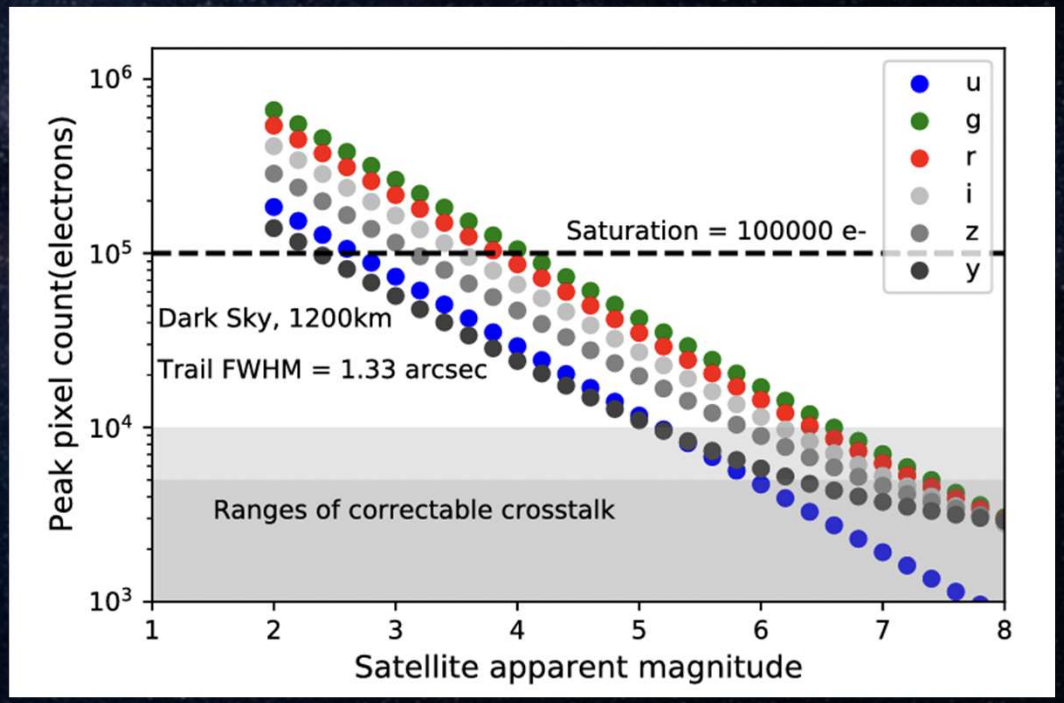
Larger Direct To Cell

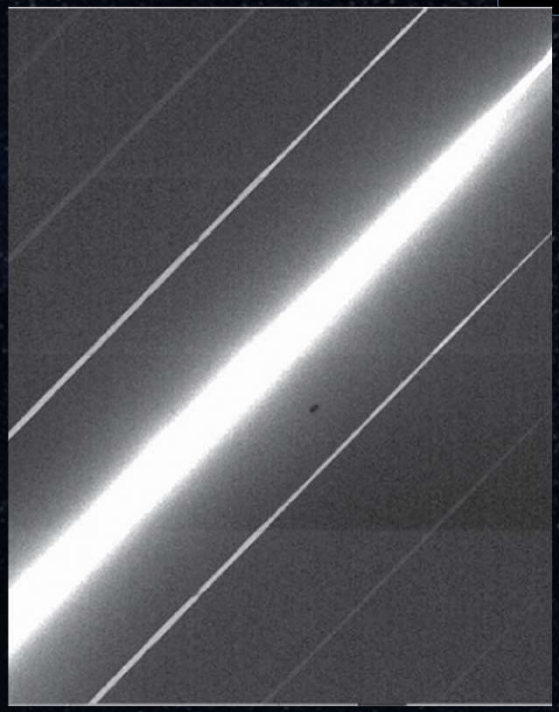


0–1 mag, not correctable
Rubin will need to sacrifice observing time to avoid these

SOLUTIONS

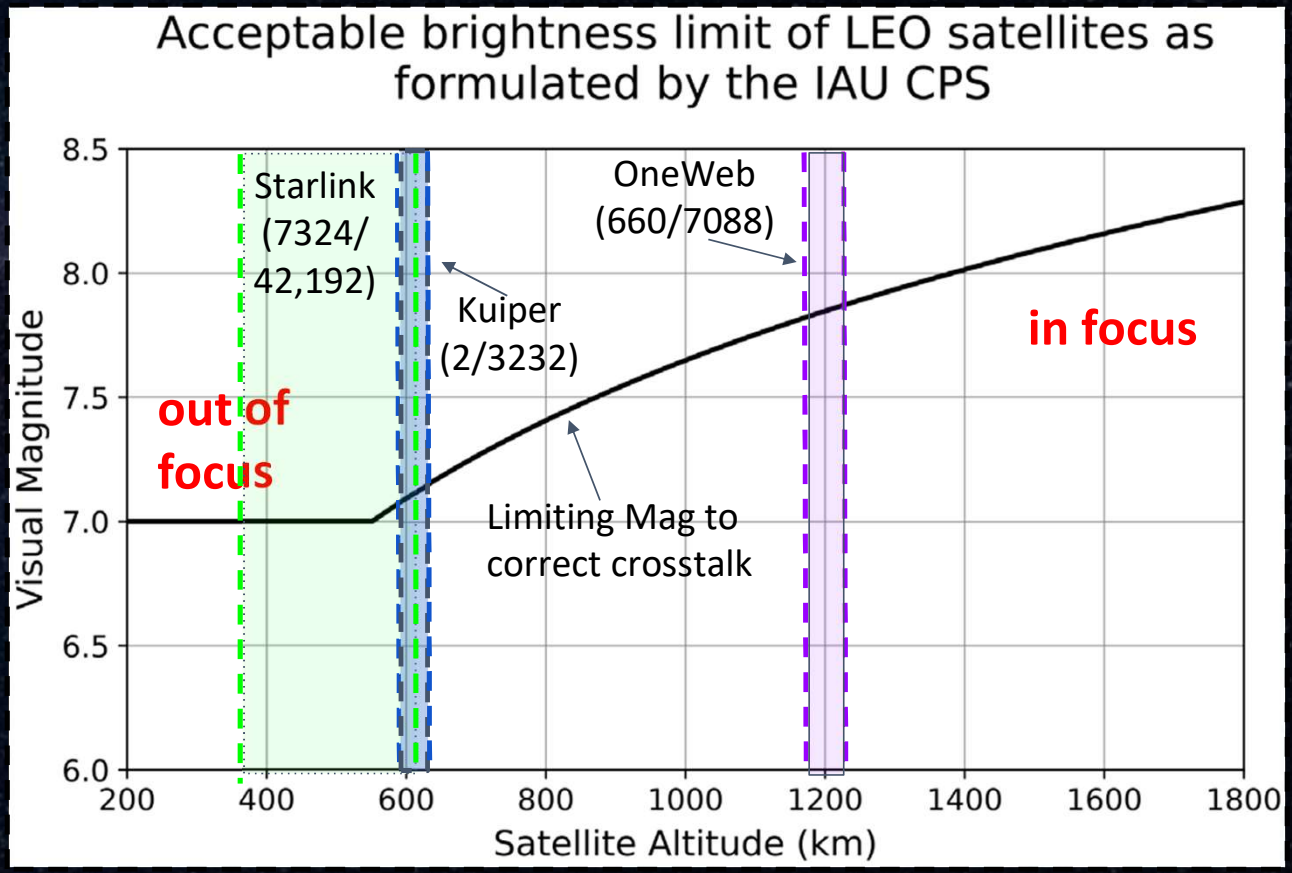
Is crosstalk correctable for the LSST? Yes, if less than 6.5 or 7th mag…





CHALLENGES

IAU recommendation: Do no harm to current facilities

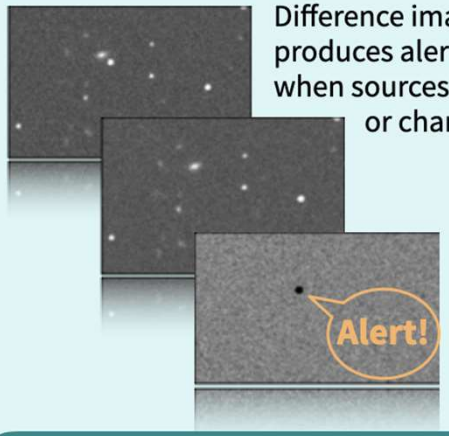


SOLUTIONS

Rubin and satellites

1

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



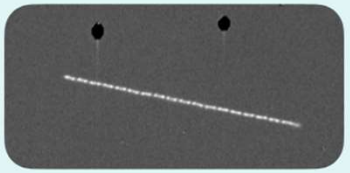
Difference imaging produces alerts when sources move or change

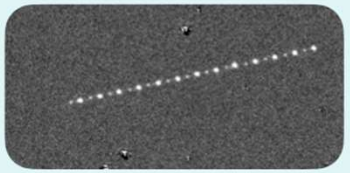
Wide, fast, deep imaging survey will produce 10 million nightly alerts from 2025 as the population of low-Earth orbit (LEO) satellites and debris continues to increase

Mitigations we control include identifying glints and streaks in difference images and an option for avoidance

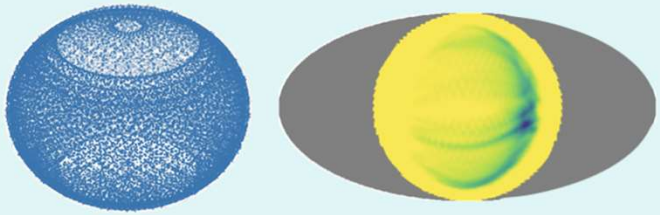
The LSST Science Pipelines will find and label streaks and glints in difference images — without discarding any pixel data — to help distinguish satellites and debris from astrophysical sources

Avoidance uses observing time, and is probably only worthwhile for the brightest satellites





Model Starlink Gen2 satellite population and corresponding sky regions to potentially **avoid** with the scheduler — Hu+2022



Prototype **glint** detection works on ATLAS data — A. Heinze

Portion of Ivezić & Rawls IAU GA 2024 poster

Slide 12

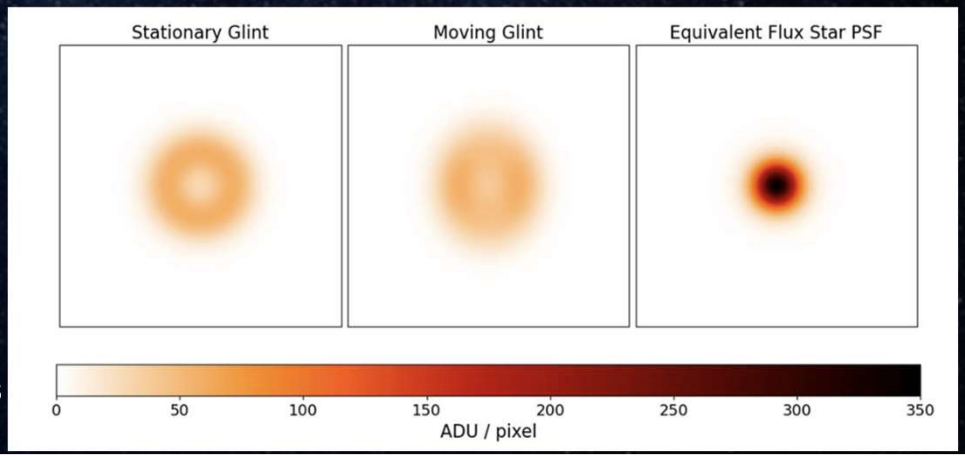
1 @pat.mccarthy@noirlab.edu @mrawls@uw.edu Should this slide be here or before slide 9?
Connie Walker, 11/17/2024

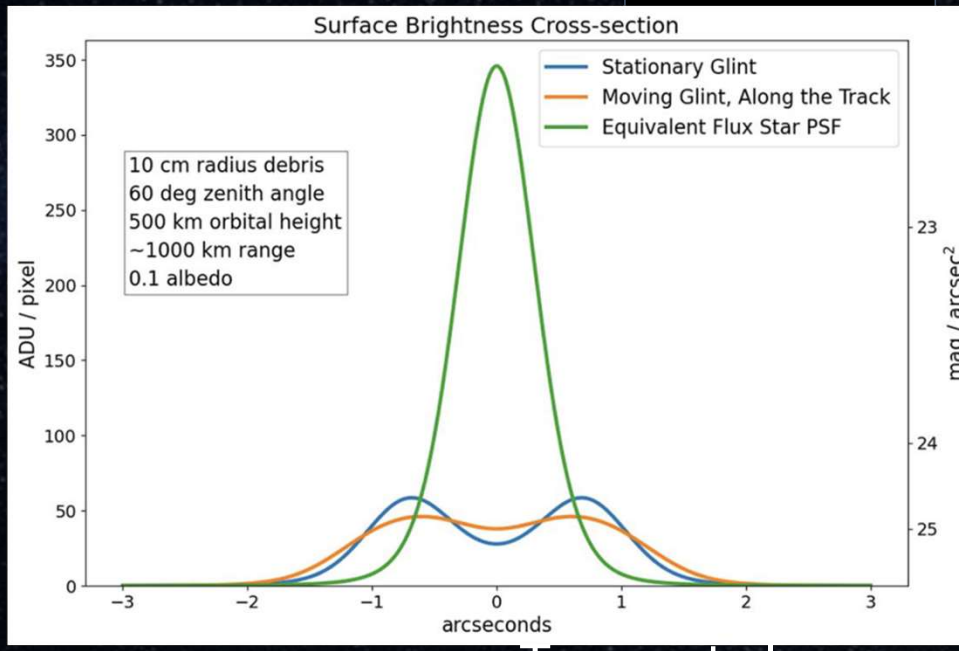
SOLUTIONS

Debris and LSST

- 10 cm and smaller debris should not typically* be detected or cause prob
- Need to account for defocus (primary effect) and motion (secondary effect)
- Still a problem: **gradually increasing sky background brightness** from growing population of very small debris

$$\theta_{\mathrm{eff}}^2 = \theta_{\mathrm{atm}}^2 + \frac{D_{\mathrm{satellite}}^2 + D_{\mathrm{mirror}}^2}{d^2}$$



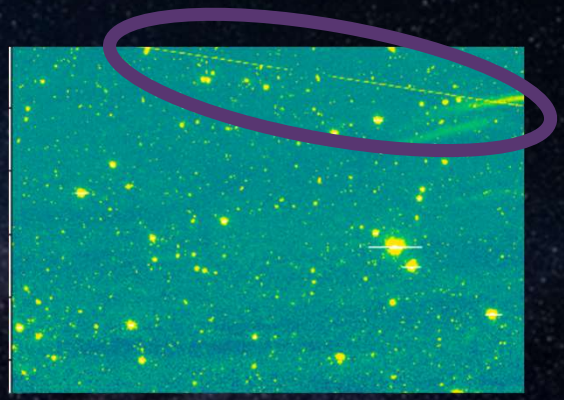


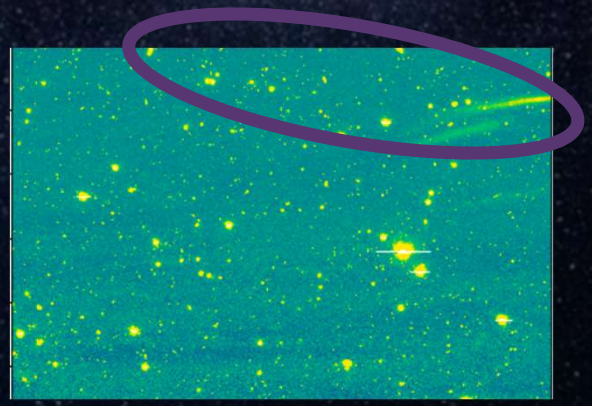
Tyson et al. 2024

*unless it's super shiny

SOLUTIONS

Mitigations by the Astronomy Community

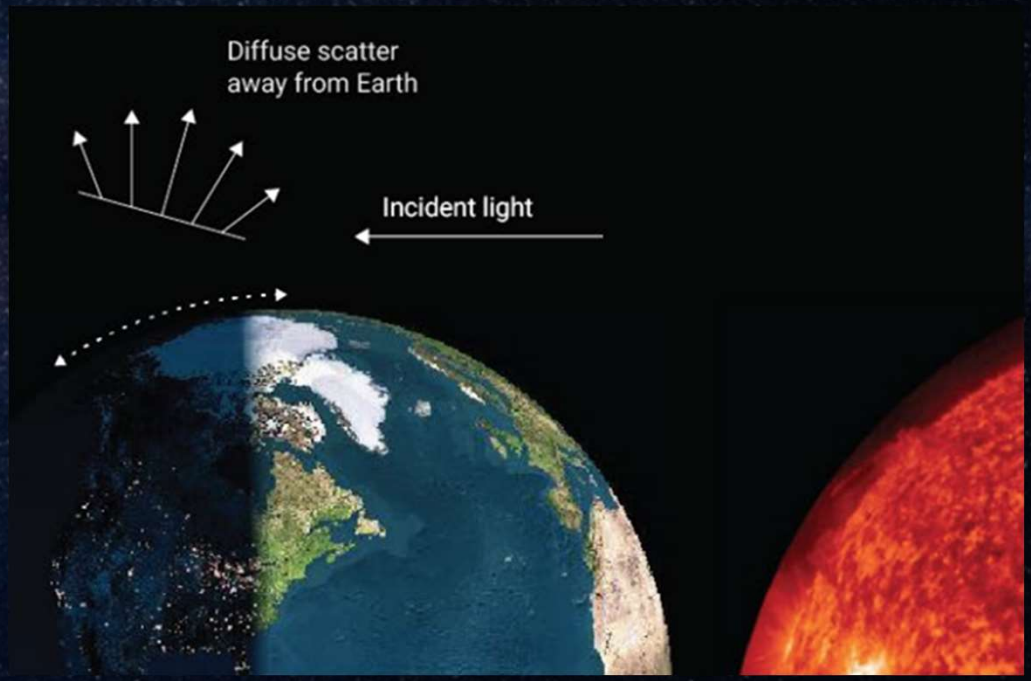




- Modelling / Simulations
- Software to avoid satellites
- Observations to verify mitigations
- Closing telescope shutter when satellite overhead
- Redoing observations
- Post processing of data (masking)

SOLUTIONS

Mitigations by the Satellite Operators



- ~~Fewer satellites~~
- Lower satellites
- Darker materials — Sun visors
- Directionally reflective coatings
- Attitude adjustment
- Sharing position data

SOLUTIONS

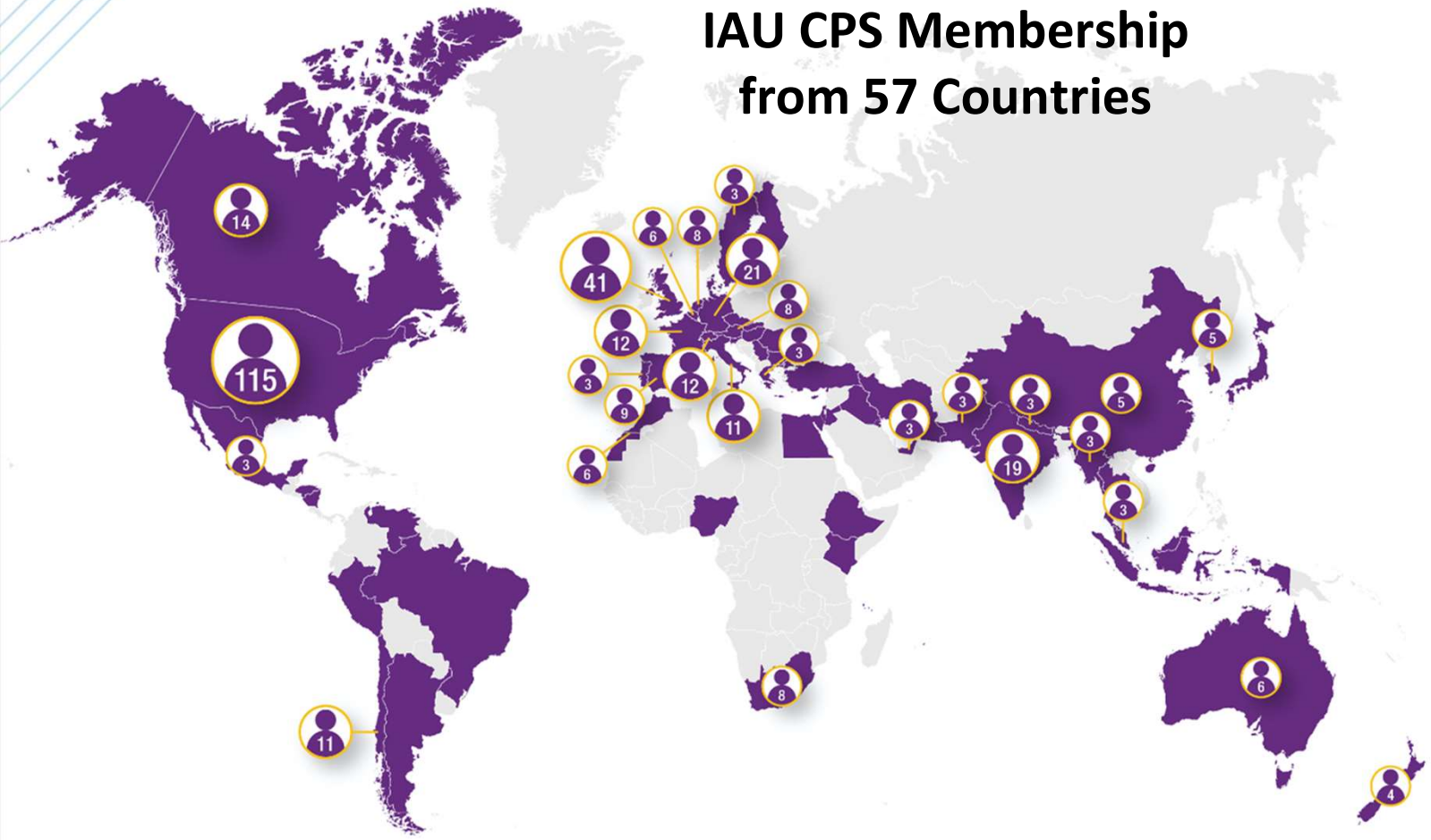
IAU Center for the Protection of the Dark & Quiet Sky from Satellite Constellation Interference (CPS)

The Center's **mission** is to

- Research the impact of satellite constellations
- Collect, produce, and disseminate information
- Bring together different communities
- **~400 members** (astronomers, sky observers, space lawyers, industry staff, etc)
- **4 Hubs** (Community Engagement, SatHub, Policy, and Industry & Technology,)

https://cps.iau.org

IAU CPS Membership from 57 Countries

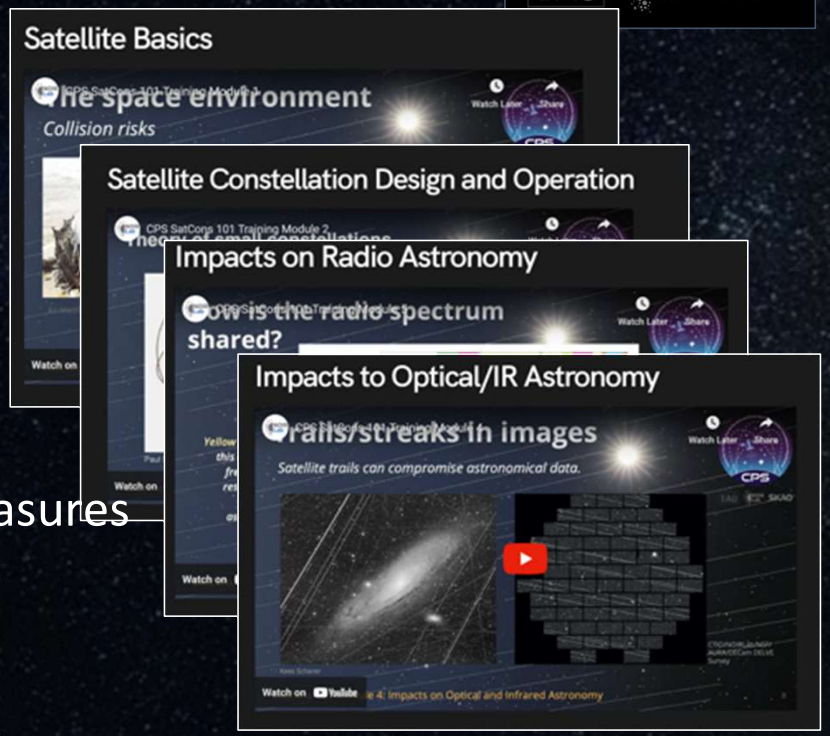


Argentina	2	Malaysia	3
Australia	11	Malta	1
Austria	6	Mexico	3
Bangladesh	3	Morocco	6
Belgium	6	Nepal	3
Brazil	2	Netherlands	8
Bulgaria	1	New Zealand	4
Canada	14	Nicaragua	1
Chile	11	Nigeria	2
China	5	Pakistan	3
Cyprus	2	Peru	1
Czech Republic	2	Portugal	3
Denmark	2	Romania	2
Egypt	2	Serbia	1
Ethiopia	2	Singapore	1
Finland	2	Slovakia	1
France	12	Slovenia	2
Germany	21	South Africa	8
Greece	3	South Korea	6
Honduras	1	Spain	9
Hungary	2	Sweden	3
India	19	Switzerland	12
Indonesia	1	Thailand	1
Iran	1	Türkiye	3
Iraq	2	UK	41
Italy	11	UAE	3
Japan	2	USA	115
Jordan	1	Venezuela	1
Kenya	2		

SOLUTIONS

CPS Hubs: International Cooperation

- **Community Engagement Hub**
  - ➤ Community forums - for unheard voices
  - ➤ Outreach as with SatCon 101 videos
- **SatHub**
  - ➤ Software tools for observation planning, predictions, and processing affected data
  - ➤ Working toward brightness modeling
  - ➤ International observing network & campaigns
- **Policy Hub**
  - ➤ Recommendations for policy & regulatory measures
- **Industry Hub**
  - ➤ Outreach to satellite companies
  - ➤ Astronomy guides partnered with companies
  - ➤ Development of best practices



SOLUTIONS

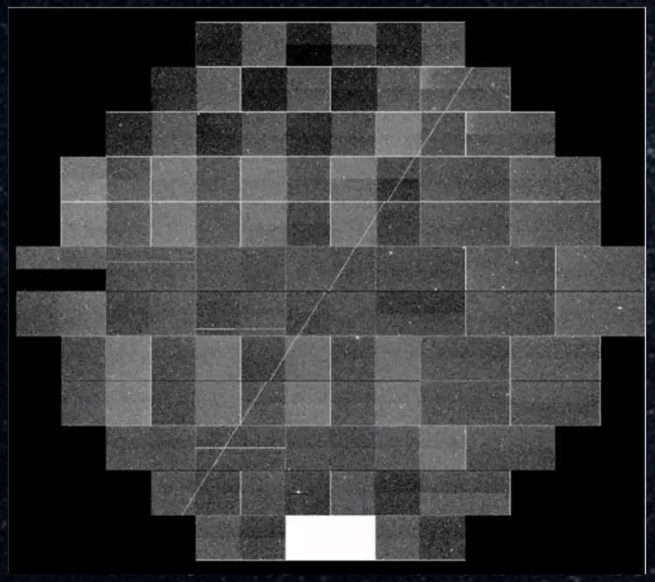
SatHub Software Tools & Brightness Models

NSF SWIFT-SAT award: NOIRLab + U. Illinois totaling $750K over 3 years

Main Goal: Expand web-based software tools to develop satellite position and brightness forecasting tools.

Utilizing:

- SatChecker (pass forecasts) and SCORE (Satellite Constellation Observation Repository)
- Database of accurate satellite orbits cleared by the US government through Aerospace Corp
- Fankhauser et al. 2023 detailed brightness model (presently possible for Starlink satellites)

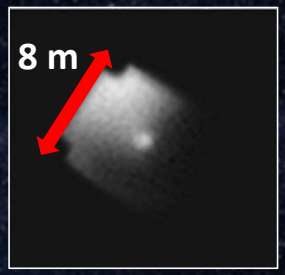


Validation of the SatChecker tool using DECam instrument on 4m Blanco, Chile

SOLUTIONS

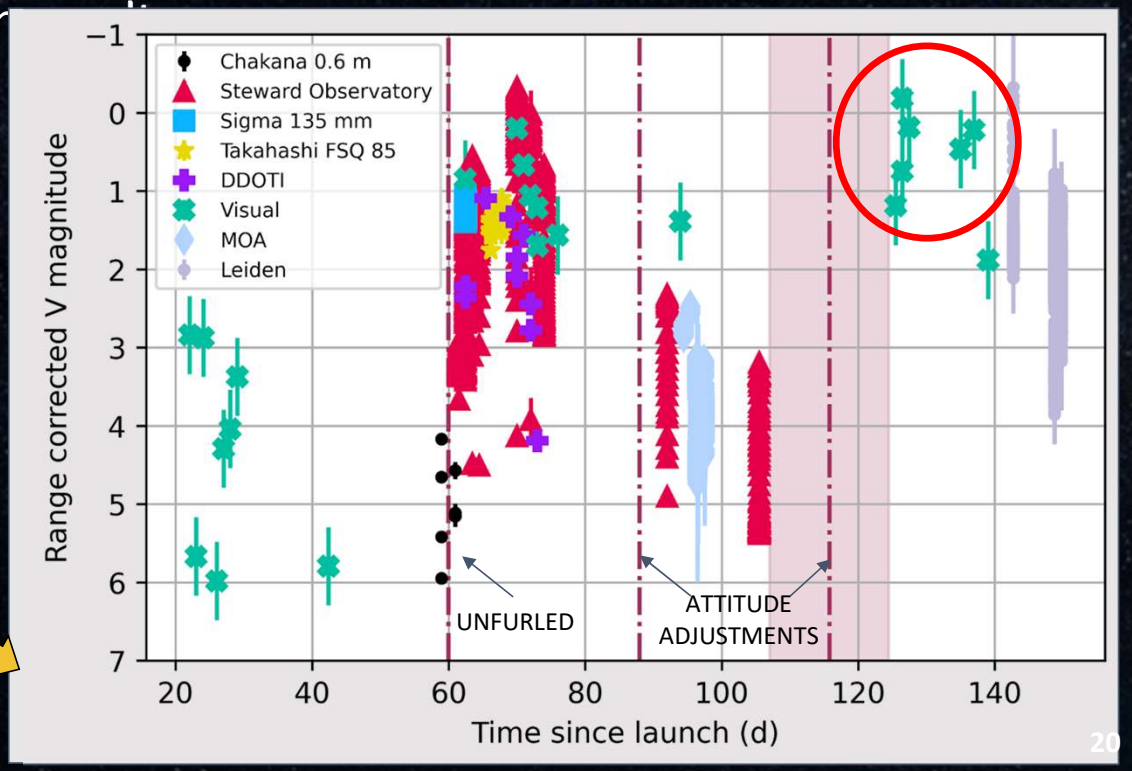
SatHub Observations Network

Main Goal: Volunteer-led observation campaigns to measure streak brightnesses, study flare/glint properties, assess mitigation efficacy, measure science impacts, and publish



BlueWalker 3
(M. Tzukran)

Nandakumar et al. 2023



SOLUTIONS

Policy Hub: Ensuring Dark & Quiet Skies is included in…

- ESA's Zero Debris Charter
- A new IAU GA 2024 **resolution passed** as an IAU mandate
- A Dark & Quiet Skies Act in the US Senate
- **Policy outlook – U.S. regulatory authority**
- **NSF's coordination agreements as a condition of FCC licensing**
- **A new 5-year agenda item at the UN**

United Nations Agrees to Address Impact of Satellite Constellations on Astronomy

SOLUTIONS

UN Committee on the Peaceful Use of Outer Space (COPUOS)

- 5 year-agenda item "Dark and Quiet Skies, Astronomy and Large Constellations: addressing emerging issues and challenges"
- Many sponsors behind this achievement
- The US State Department has been a prominent participant
- **NEXT:** developing input on the topic for the Feb 2025 meeting.

Photo: C. Walker

Slide courtesy: R. Green

SOLUTIONS

Establishment of Group of Friends of D&QS

- UN COPUOS Delegations and Observers:
  - Belgium, Bulgaria, Chile, Colombia, Germany, Italy, Luxembourg, Mexico, New Zealand, Romania, Slovakia, South Africa, Spain, Switzerland, UK, USA
  - COSPAR, EAS, ESO, IAA, IAU, SKAO

- Aims of the Group of Friends (GoF):
  - Promote awareness
  - Support/Review best practices and mitigation recommendations
  - Discuss the overall implications of the adoption of mitigating measures
  - Discuss approaches for coordination between the various stakeholders

- GoF webpage: https://cps.iau.org/group-of-friends/

Courtesy: R. Green

SOLUTIONS

Satellite-Astronomy Coordination – Optical

FCC licenses commercial satellite operators and imposes conditions:

From NSF's Coordination Agreement with SpaceX (other companies in similar discussions):

- Limit brightness to ~7th magnitude at altitude of 550 km
- Limit orbits to ~700 km so satellites de-orbit on human timescales
- Orient satellites to not reflect sunlight directly at Earth
- Provide precise orbital telemetry to inform telescope observations

SOLUTIONS

Policy Outlook – U.S. Regulatory Authority

"Mission authorization" - A system to provide oversight of commercial space activities, under Outer Space Treaty obligations.

House Proposal (Commercial Space Act of 2023)	White House Proposal (Novel Space Activities Authorization and Supervision Framework)
Only Department of Commerce	Split between Commerce and Transportation
Only requires space debris mitigation plan	Includes broader "space sustainability" considerations.
Automatic approval if not approved/denied within 60 days.	No deadline for consideration.

Both proposals still require FAA licenses for launch and reentry and FCC license for spectrum use.

With the new administration and Congress, some version of the House bill may pass – it is not clear whether the FCC will still be able to regulate light pollution, e.g. through coordination agreements.

SOLUTIONS

Industry & Technology Hub: Engaging Satellite Stakeholders

For the 16 satellite constellation operators & manufacturers to date, I&T

- Provides background and updates for astronomers
- Synthesized recommendations and best practices for stakeholder
- Created directory of available mitigation technologies and tools
- Launched “Astronomer Guides” to pair I&T Hub members with astronomers
- Advocates for additional R&D on viable/affordable solutions

OPPOTUNITY

More Satellites are Coming

- **The large number of constellation satellites will**
  - ➢ Impact the quantity and quality of science possible from ground-based facilities.
  - ➢ Potentially change the appearance of the night sky.
- **Reduction of satellite brightness and good software are integral to sustainable use of outer space for the benefit of**
  - ➢ Astronomy, space science, and all sky observers
  - ➢ Cultural Heritage of Humanity
- **We are working to reduce the impact on astronomy with industry stakeholder and governmental bodies worldwide.**

Questions the NAS organizers want answered

What does the future look like in this context?

We are not going to make the problem go away. We will have to live with it, but we take steps to minimize the impact to astronomy.

- Satellites can be made less reflective.
- Accurate positions can allow for the apparent position of the satellites to be accurately predicted for avoidance during scheduling.

To accomplish these,

- A strong collaboration with the satellites industries and private companies is needed.
- Best practices have to be identified and voluntarily implemented.
- After becoming more aware of astronomers' concerns, companies are more amenable to implement changes in the early phase of design.

The IAU CPS is working along these lines with promising results.

Questions the NAS organizers want answered

- ***Is there a chance that ground-based observations will take precedence over providing bandwidth to underserved communities globally?***

  No.

- ***Do innovations in image processing or changes to spacecraft reflection have a significant positive impact, or are these effects minimal?***

  Yes, they are impactful but in the case of Rubin, you still have 97% to 99% of the pixels that are unimpacted in the remaining portion of the image.

- ***What is the status of governing conventions (say from COSPAR) and possible rules in the US and elsewhere?***

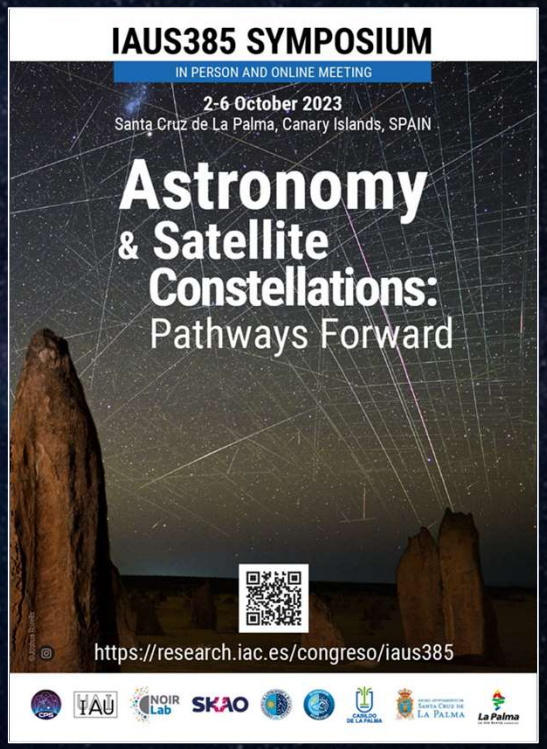
  UN Observers like COSPAR and other organizations as well as UN Delegates from various countries are engaged now with the UN COPUOS Group of Friends and discussions are moving forward.

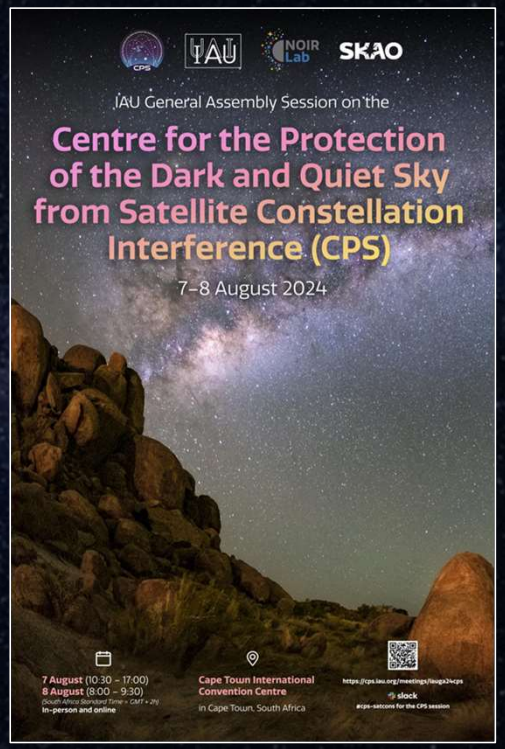
ADDITIONAL SLIDES

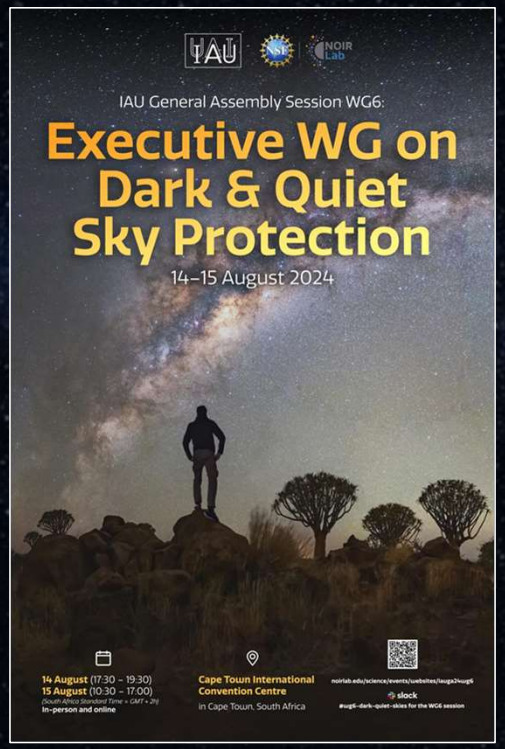
OPPORTUNITY

More information available…

Visit cps.iau.org and compasse.aas.org







CPS Resources:

https://bit.ly/Resources4DSProtection

Contact Information

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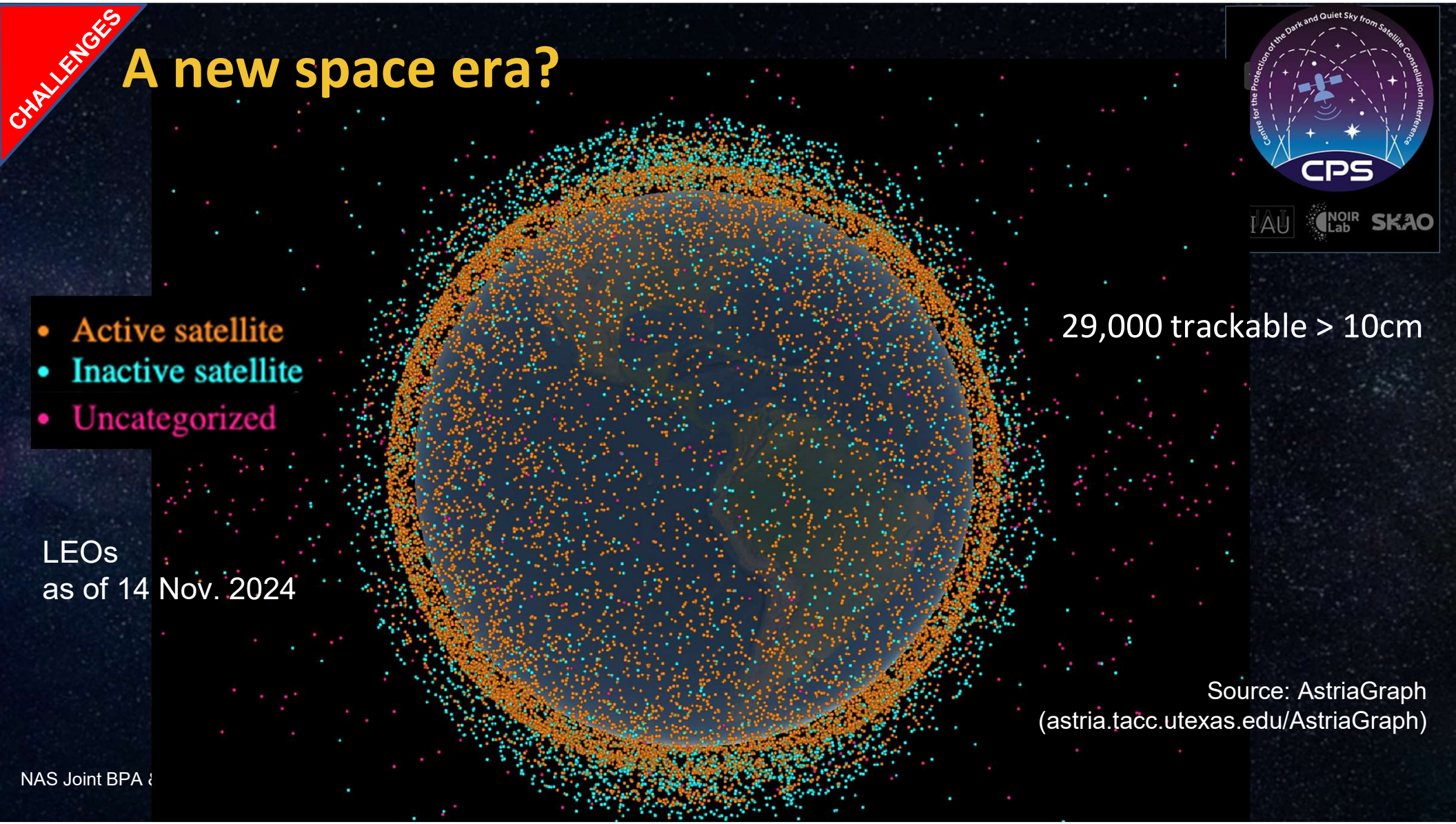
CHALLENGES

A new space era?



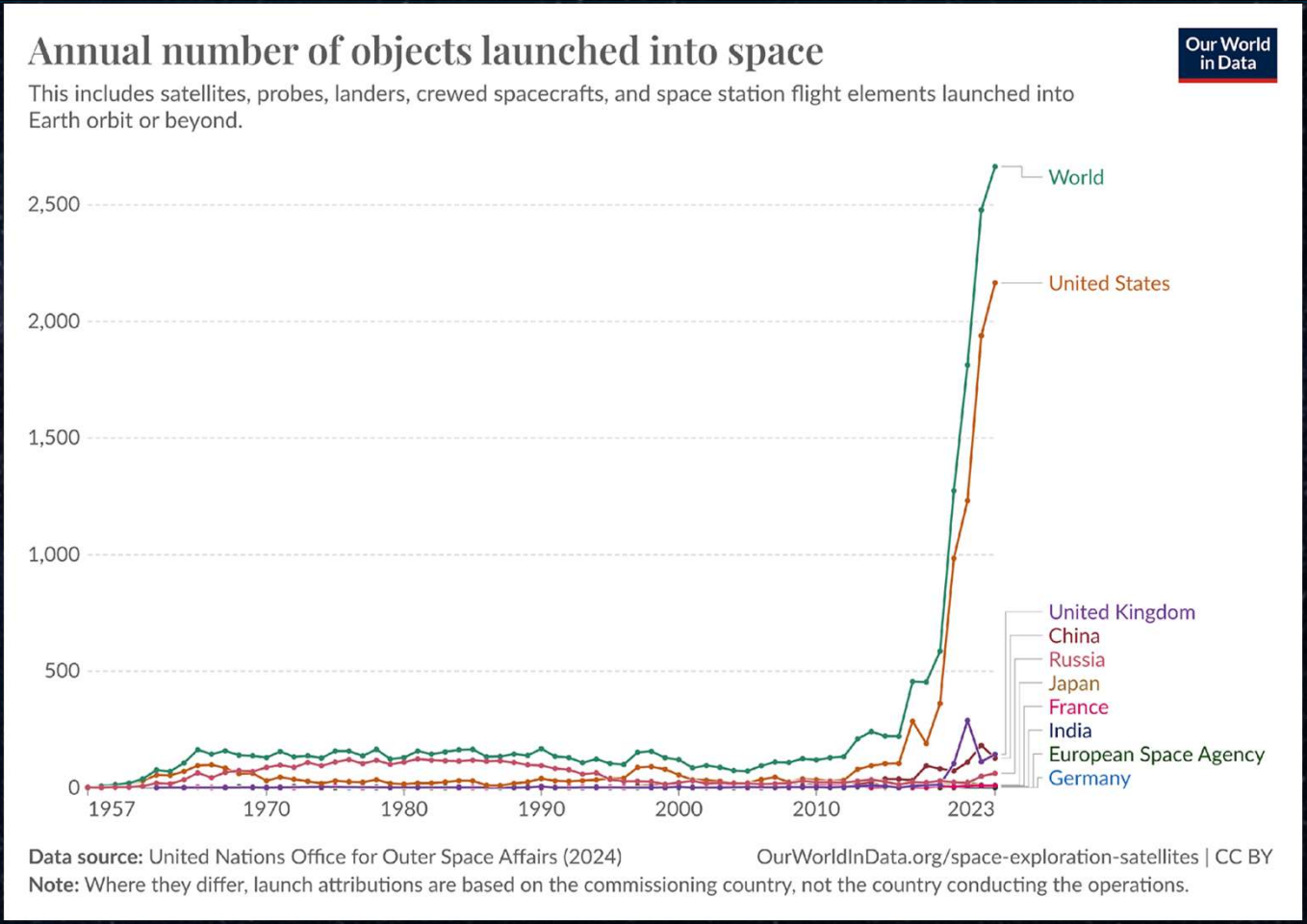
29,000 trackable > 10cm

LEOs
as of 14 Nov. 2024

Source: AstriaGraph
(astria.tacc.utexas.edu/AstriaGraph)

CHALLENGES

Annual number of launched spacecraft

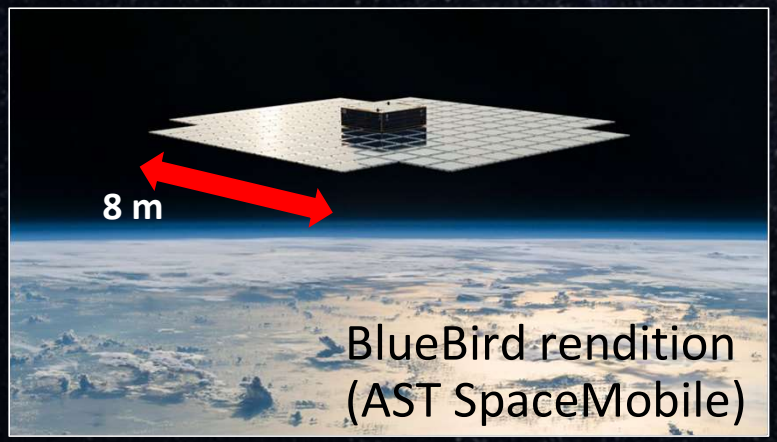


CHALLENGES

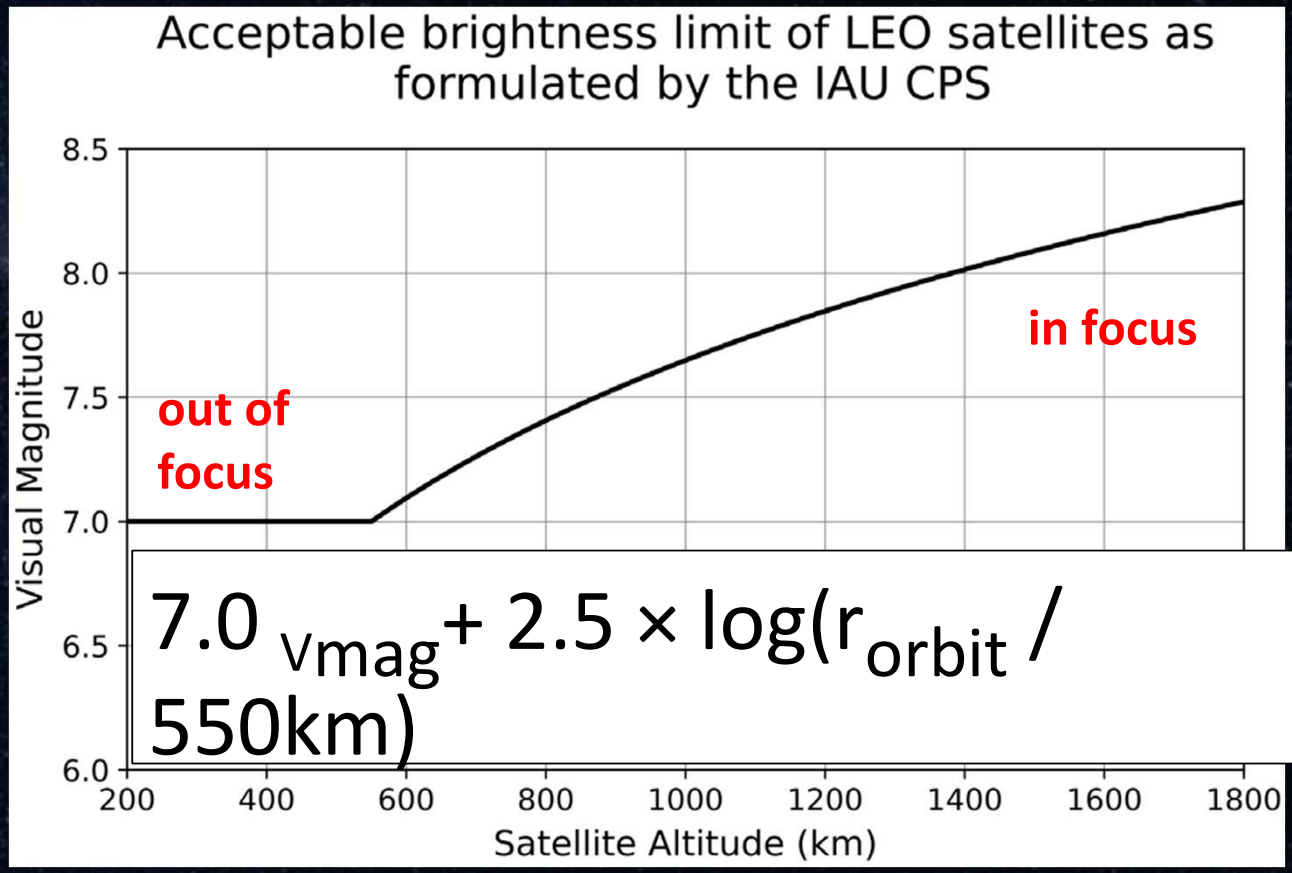
SatHub Observations - Direct to Cell

- **Starlink:** direct-to-cell, lower altitude and larger, about 5x brighter than previous version
- **AST SpaceMobile:** 5 BlueBirds launched Sep 2024, recently unfurled, comparable to BlueWalker 3
- **NASA:** solar sail demo launched Aug 2024, tumbling, oscillates in brightness from below human vision to as bright as Vega

Starlink V2.0 direct-to-cell (Tom Williams)



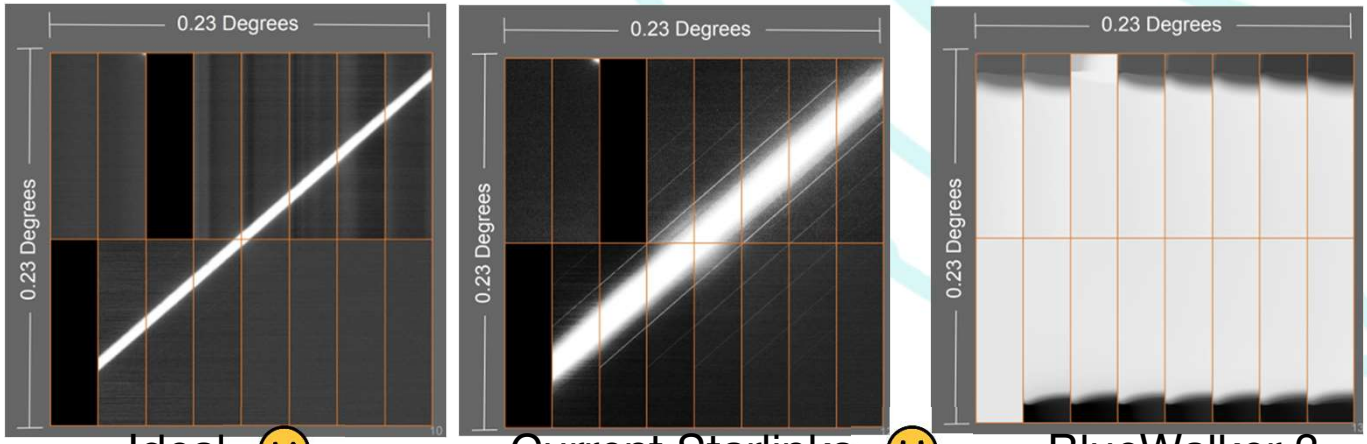
IAU recommendation: Do no harm to current facilities



What will LSSTCam actually see?

- Depends on **satellite population**: number, orbits, brightness (out of our immediate control)
- LSST observing **scheduler** can avoid 1000 bright satellites, but not 50,000.

It is becoming an "industry best practice" to reduce brightness to ~7 V mag (sometimes)

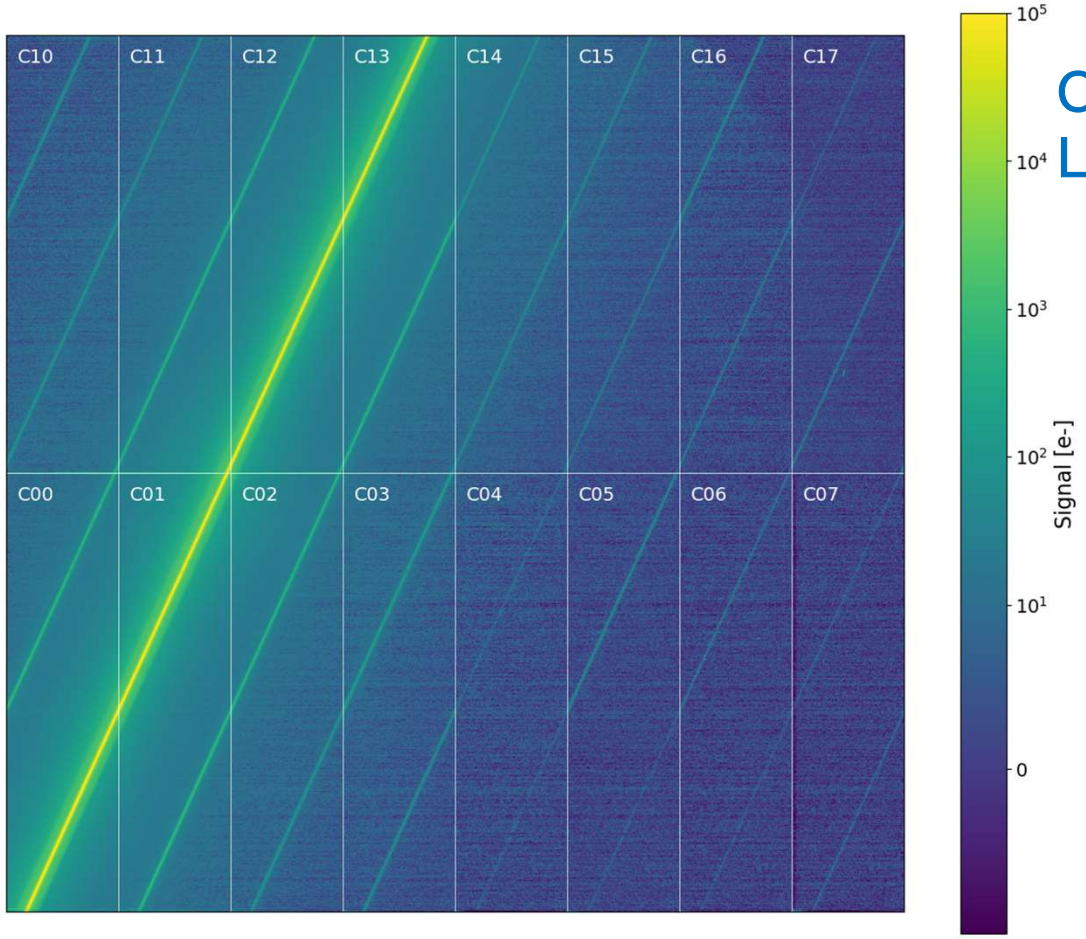


Ideal 😐 Current Starlinks 😬 BlueWalker 3 😭

Courtesy: T. Tyson

Ghosts of a satellite streak on CCDs

- LSST camera CCDs are spit into 16 segments, each with its own output amplifier.
- There is some crosstalk between channels during readout.
- This causes “ghosts” of the main satellite trail.
- For satellites fainter than 7th mag, we can correct for this in data reduction.



One CCD, Log intensity

Courtesy: T. Tyson

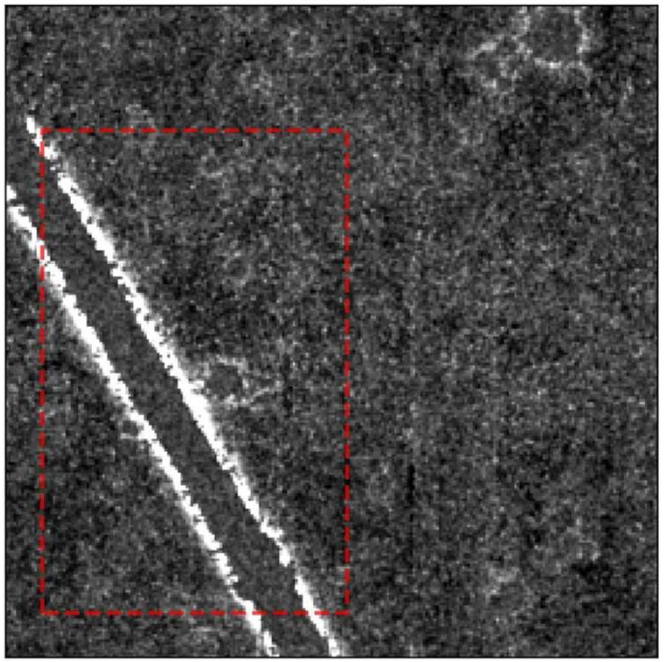
Attempts to Mask Satellite Trails

Then there is the trail itself

Incomplete masking of satellite trails can cause systematic effects in static sky and time-domain science:

- Residual spill-over light.
- Lines of “bogus galaxy detections”!
- Bogus alerts!

- Challenges: LEOsat trail brightness varies with time, and trail detection is not 100% complete.



Satellite trail in a Blanco DECam coadd image masked using a 40-arcsecond wide mask.

Hasan et al (2022)

Courtesy: T. Tyson

Impact on LSST transient data

- We find that only tumbling LEO debris larger than ~10 cm or with significantly greater reflectivity, **which give 1 millisecond glints**, will be detected.
- Satellites with multi-layer insulation (MLI) – and debris from them – can produce **very bright** glints.

- ***Impacts LSST discovery of the unexpected***

Expected Impact of Glints from Space Debris in the LSST
ApJ Letters 2024, 996, L38

Courtesy: T. Tyson

SOLUTIONS

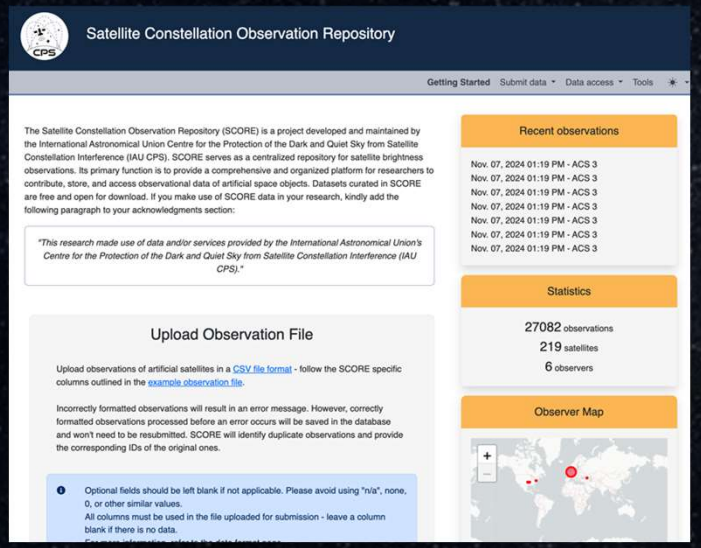
SatHub Software Tools & Brightness Models

SatChecker status:

- Single satellite position prediction
- Current/historical TLEs accessible
- Working on a preliminary FOV service (as a precursor to what will be done as part of the SWIFT-SAT work)

SCORE (Satellite Constellation Observation Repository) status:

- Supports upload of optical brightness and position measurements in a standardized data format
- Search/view/download observation data
- Alpha users have uploaded 27000 observation points for 200 satellites so far



SCORE main/upload page

Courtesy M. Dadighat, NOIRLab

SOLUTIONS

Policy updates: U.S. Dark & Quiet Skies Act of 2024 (S.4952)

- Introduced by Senators Hickenlooper (D-CO) and Crapo (R-ID) in August 2024.
- Would empower NIST to create a "center of excellence" to develop and promote voluntary best practices to reduce optical and radio interference.
- Would authorize $20 million of funding for five years of operations for the center
- Likely needs to be re-introduced in the next Congress.
- Endorsed by AAS, Slingshot Aerospace, DarkSky International and others.

Courtesy: R. Dalal

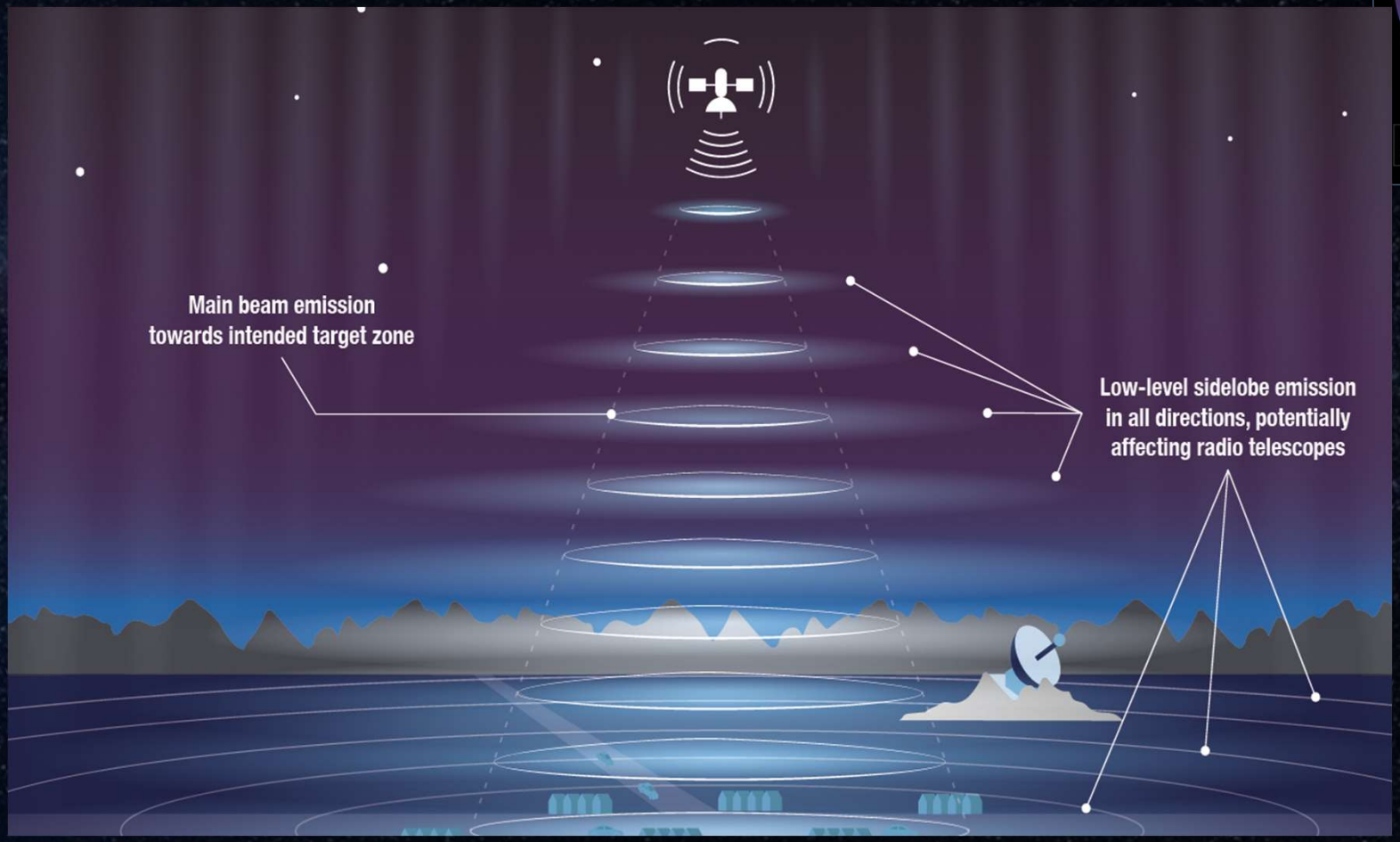
SOLUTIONS

Domestic Satellite - Astronomy Coordination

- Federal Communications Commission (FCC) licenses operations of commercial satellites
- To serve the public interest, the FCC has included conditions in several satellite licenses to address the impact of constellations on optical astronomy
- Satellite companies formally coordinate with NSF's Electromagnetic Spectrum Management office

CHALLENGES

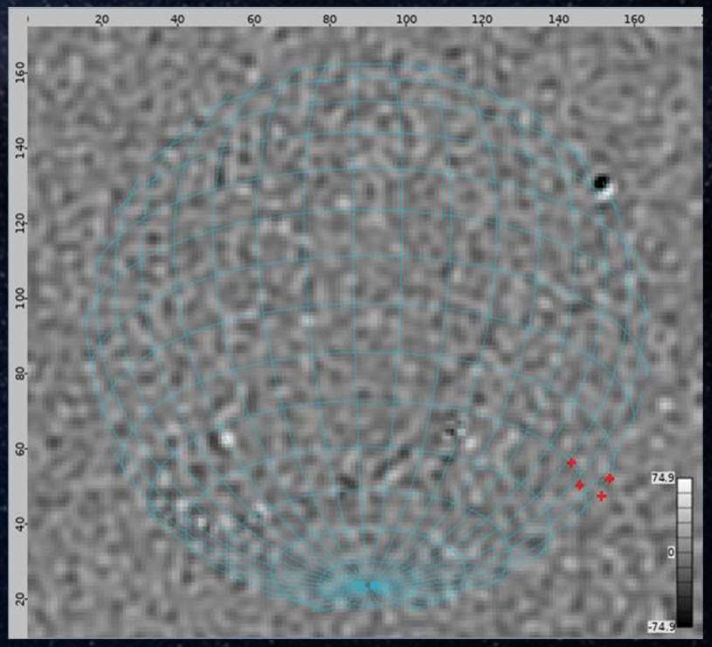
Impact on Radio Astronomy



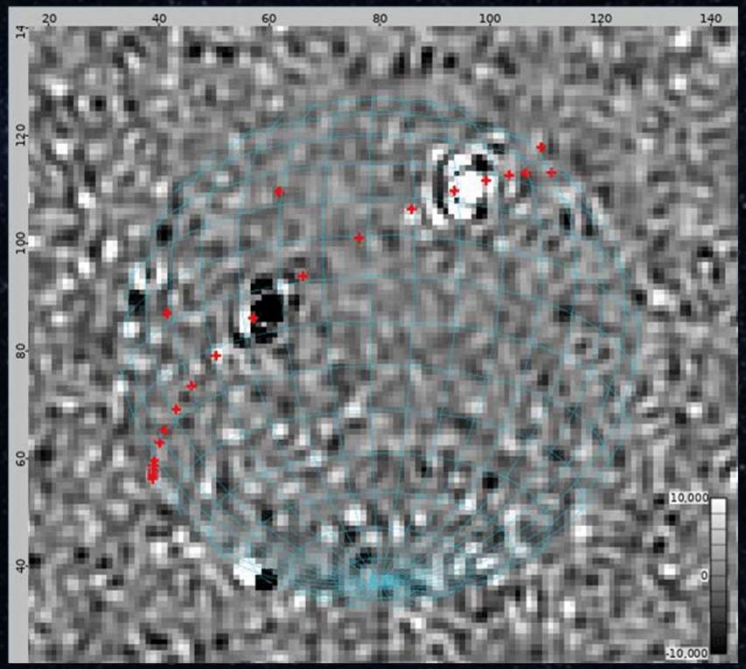
CHALLENGES

Impact on Radio Astronomy
(Starlink @ SKA Low Frequency)

160.4 MHz (Unintended Emission)
Intensities ~200 Jy/beam
(20% of the sun @ 20 MHz)



137.5 MHz (Downlink Frequency)
Intensities ~1,000,000 Jy/beam
(entire Milky Way @ 20MHz)



Grigg et al. (2023)

Courtesy of S. Eggl, UIUC

CHALLENGES

Are recommendations set in stone? No.

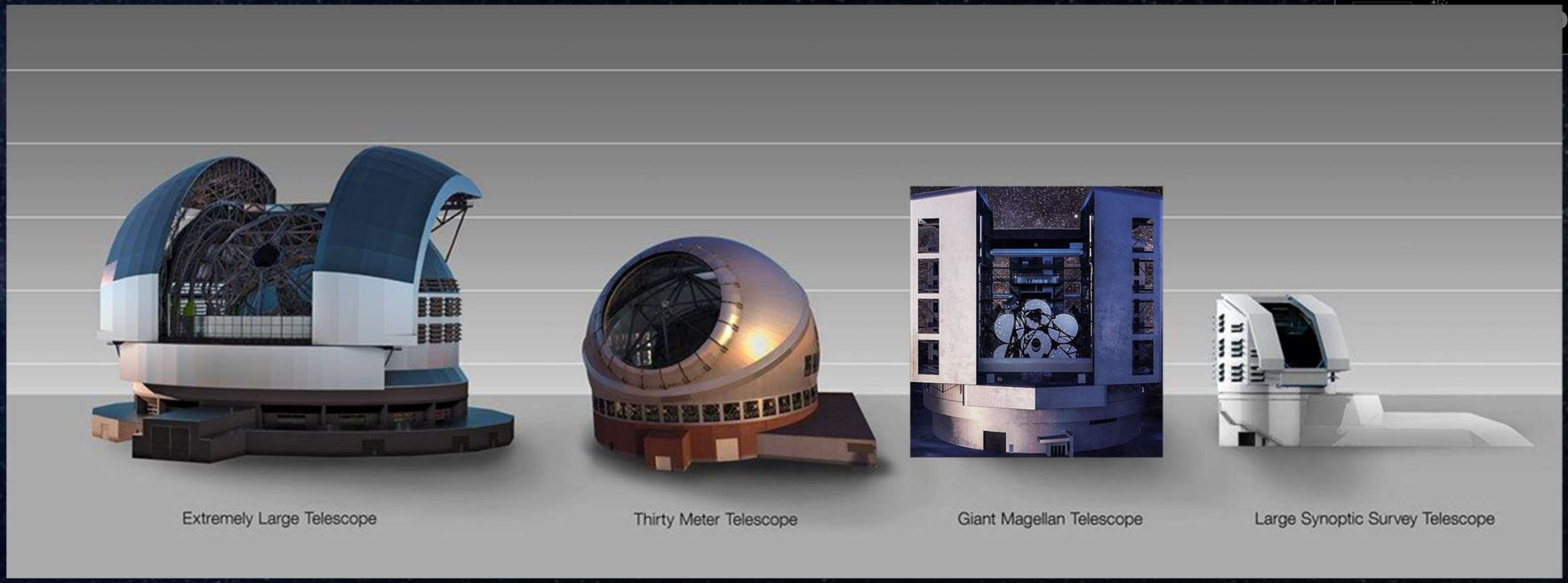
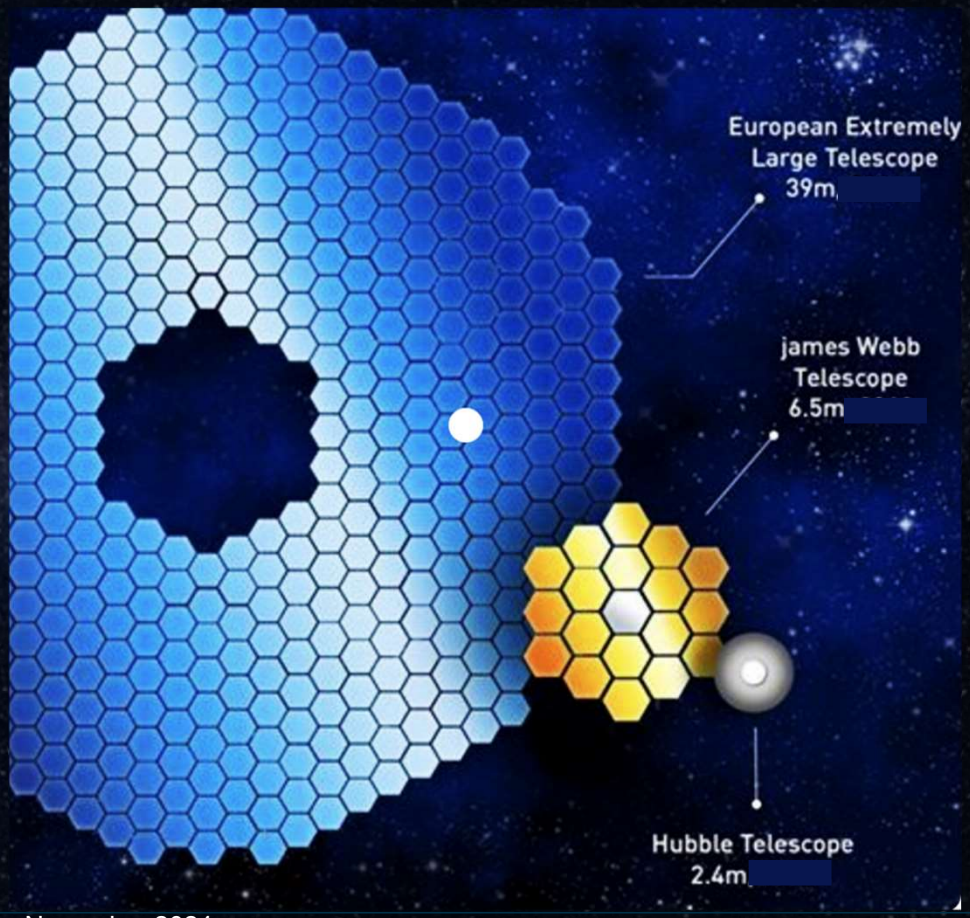
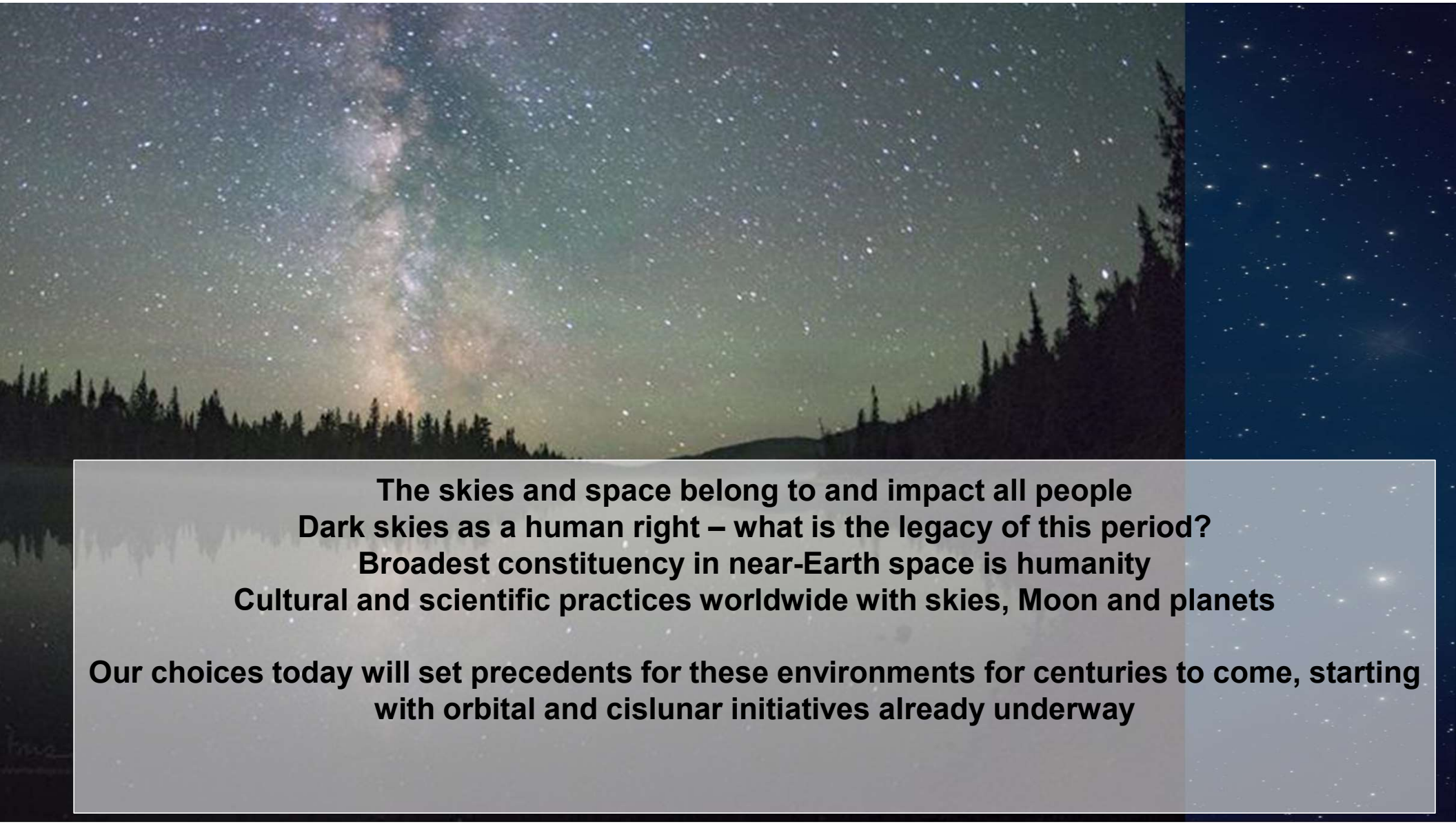


Image credit: ESO

SOLUTION?

Is space-based astronomy the solution?





The skies and space belong to and impact all people
Dark skies as a human right – what is the legacy of this period?
Broadest constituency in near-Earth space is humanity
Cultural and scientific practices worldwide with skies, Moon and planets

Our choices today will set precedents for these environments for centuries to come, starting with orbital and cislunar initiatives already underway

Potential Impact of space-based Light Pollution on Wayfinding (gratitude to ‘Ohana Wa‘a)

- SatCons are quite visible from ground, especially low in the sky, at dawn and dusk, or soon after launch. At later stages, they will be up all night at high altitudes
- Impacts real time observations of horizon and circumpolar skies that CANNOT be corrected with filters or software
- With predicted rise of global sky brightness from increasing orbital congestion, this affects not only the visibility of the brightest constellations, but also horizon markers and the web of guiding stars in non-instrument celestial navigation

Image credit:
Polynesian Voyaging Society,
Hokulea Star Compass

Public investment in private corporations, and what is owed communities in return

- Companies benefit from:

- Publicly funded research
- Taxpayer funded contracts from federal/state agencies
- Local/state/federal subsidies
- Many tax breaks

- Communities need benefits of space exploration to flow back to them in ways that maximize THEIR agency, innovation and security

What Astronomers Are Facing, and What The Outer Space Treaty (1967) Did Not Anticipate

- The sheer scale and pace of what is being launched
- No regulatory home for the myriad issues, and difficulty with enforcing the rules we do have
- The outsize role of private actors in space, and the reliance of governments on them.
- Threats of rogue actors and actions in space, including the return of nuclear threats in space

- Despite the rapidly growing numbers of space actors and orbital/cislunar initiatives, the world still looks to the US for examples and precedents of policy, regulation and collaboration

Barentine+2023 (Nature Astronomy, part of a Dark Skies collection)

- Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise
- Large objects (intact/defunct/functioning satellites) as well as smaller cm-sized objects make sizeable contributions to diffuse night sky brightness (NSB)
- Debris proliferation is a strong concern: since all log-decades in debris size contribute about the same amount of night sky radiance, debris-generating events lead potentially to a rapid rise in NSB.
- Unknown impact of satellite glints on time domain astronomy

Barentine+2023 (Nature Astronomy, part of a Dark Skies collection)

- Shrinking federal science budgets → even more competition for ground-based observing programs, loss of science opportunities, and greater institutional concentration of science programs

- Devaluing ground based assets and future workforce in a continuum of ground- and space-based observations that astronomy relies on; safety and security concerns (including humanmade, asteroid, cybersecurity), frequency interference

- This would be a planet-wide effect: loss of dark skies and visibility of Milky Way, meteor showers and more …. *everywhere for everyone*

Barentine+2023 (Nature Astronomy, part of a Dark Skies collection)

- High impact on ground-based observing: e.g. Vera Rubin Observatory estimates up to 30% of all LSST images would contain at least one satellite trail if 42,000 Starlink sats deployed
- For e.g. LSST to reach S/N ~ 10, increased observation time from aggregate effects of 12% (7.5%) from higher aggregate NSB (from individual sat streaks) or USD $34.8 ($21.8) million in additional project costs
- Additions from Meredith Rawls:
  - May be 8-10% images have a streak (more for higher SatCon #s)
  - LSST twilight near-Earth-object observing campaign: 50% with >1 streak
  - Glints! Current 10cm+ size debris population suggests 1 in 5 LSST exposures low on the sky during twilight might be affected. Smaller untrackable debris
  - Bright sat avoidance strategy with observations: loss of 10% of data