

 @merrdiff

 @mrawls

[arxiv.org/abs/2006.12417](https://arxiv.org/abs/2006.12417)

# Comparing SpaceX's DarkSat to brighter Starlink siblings in *g*-band with DECam

Meredith Rawls

SATCON1 • June 29, 2020





# Why observe low-earth-orbit satellites?

- Tens of thousands will be launched in the next ~decade
- Even with mitigations, they will land in our data

Nov 18, 2019  
*DECam DELVE Survey/  
CTIO/AURA/NSF*





# Why observe low-earth-orbit satellites?

Rubin  
Observatory

Nov 18, 2019  
*DECam DELVE Survey/  
CTIO/AURA/NSF*

- Tens of thousands will be launched in the next ~decade
- Even with mitigations, they will land in our data
- Predict their impact on astronomy now
  - Wide-field ground-based optical surveys in particular
  - Rubin Observatory's LSST (Legacy Survey of Space and Time) ~2023





# CTIO/AURA/NSF

- 
- A circular diagram representing the Hawaiian Islands. The names of the islands are written in Hawaiian script around the perimeter of a circle. Starting from the top and moving clockwise, the names are: 'ĀKAU, Haka, Nā Leo, Nālanī, Manu, Noio, 'Āina, Lā, KOMOHANA, Lā, 'Āina, Noio, Manu, Nālanī, Nā Leo, Haka, HEMA, Haka, Nā Leo, Nālanī, Manu, Noio, 'Āina, Lā, HIKINA, Lā, 'Āina, Noio, Manu, Nālanī, Nā Leo, Haka, HEMA, Haka, Nā Leo, Nālanī, Manu, Noio, 'Āina, Lā. In the center of the circle is a stylized illustration of a bird in flight, facing left. The background is a solid dark blue color.

Meredith Rawls • SATCON1 • June 29, 2020

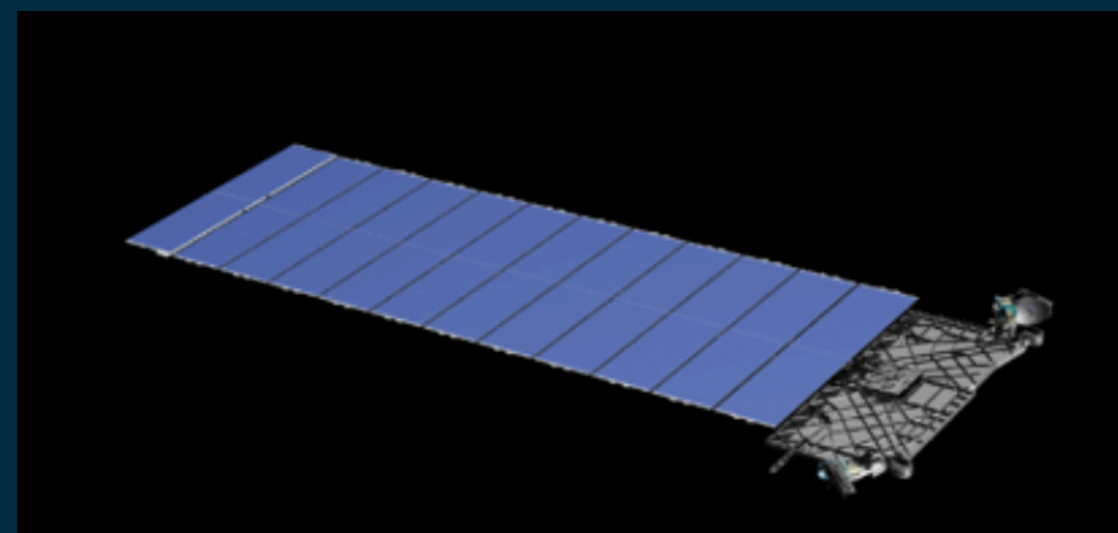


# Low-earth-orbit satellite life cycle 101

*For my astronomy colleagues who are learning this for the first time*

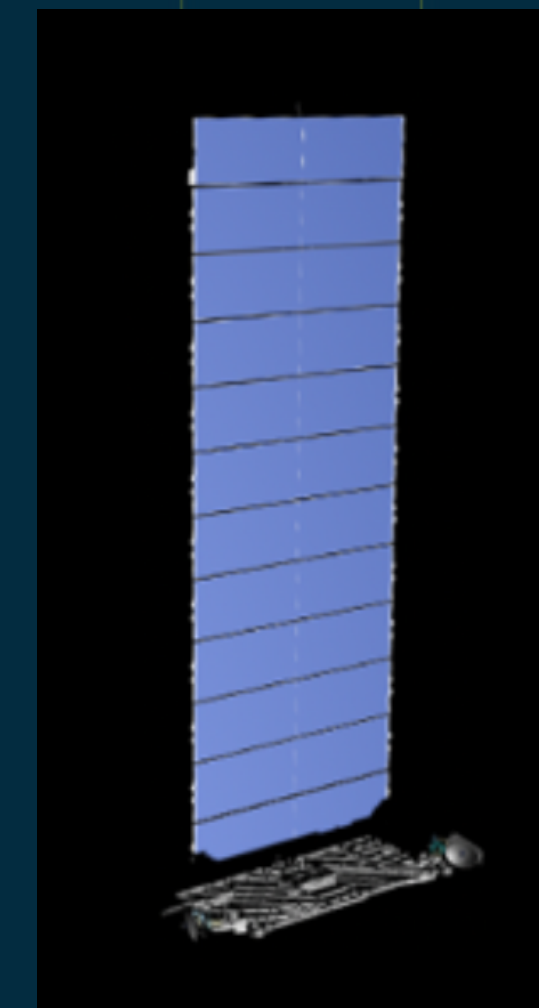
- SpaceX's Starlink is the first example of a megaconstellation
- Satellite life cycles should be ~similar for other operators

Orbit Raise (months)



*SpaceX images*

**On Station** (~550 km, years)



*Not shown:  
Launch, insertion,  
parking orbit, de-orbit*

C ← → D



# Data from wide-field ground-based optical surveys (like Rubin Observatory's LSST)

Rubin  
Observatory

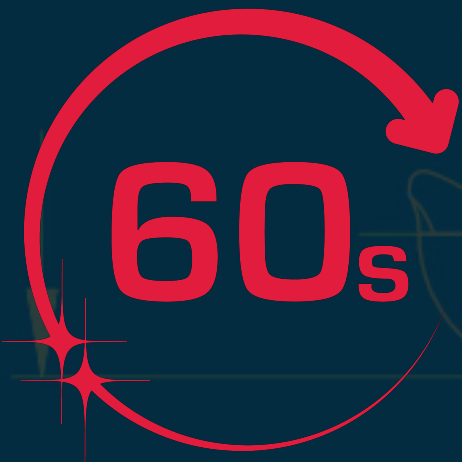
June 9, 2020  
Rubin Observatory  
Cerro Pachón, Chile





# Data from wide-field ground-based optical surveys (like Rubin Observatory's LSST)

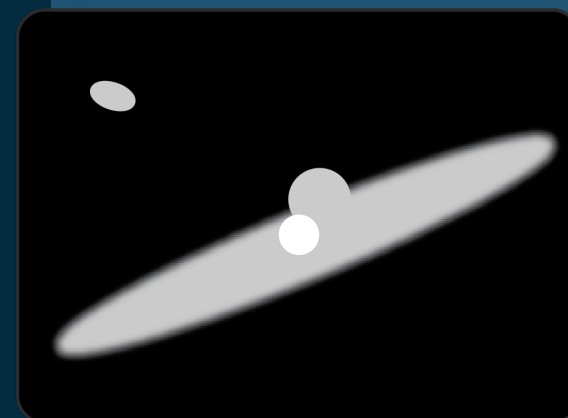
## Prompt



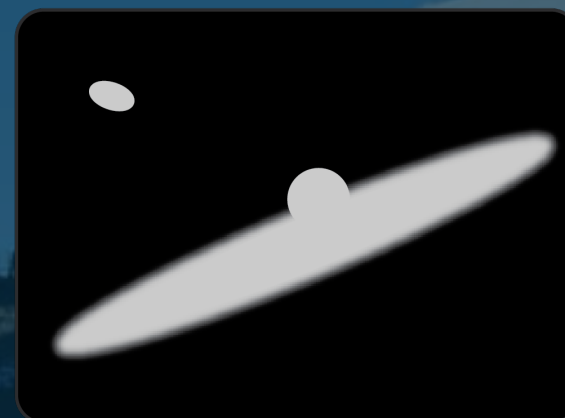
Real-time  
alerts



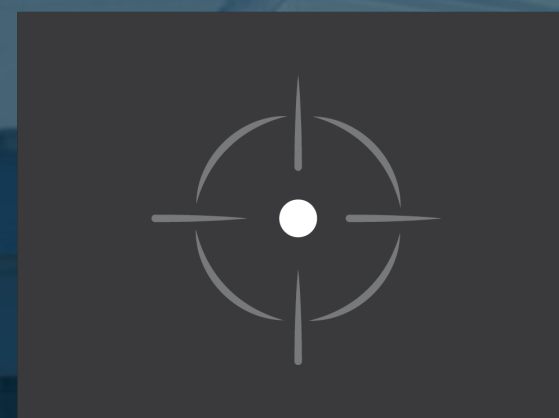
Prompt products database  
with forced photometry



new image



template



difference image

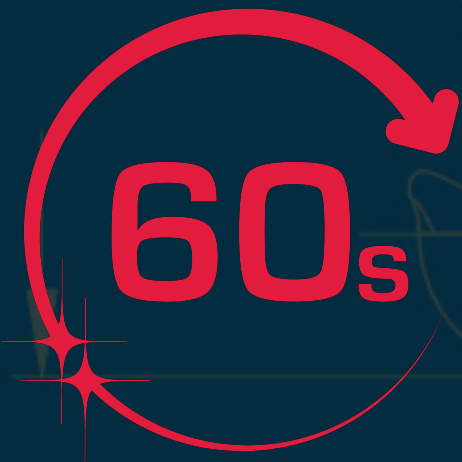




# Data from wide-field ground-based optical surveys (like Rubin Observatory's LSST)

## Prompt

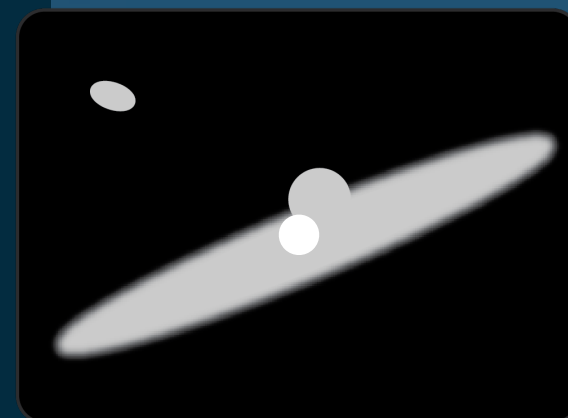
## Data Release



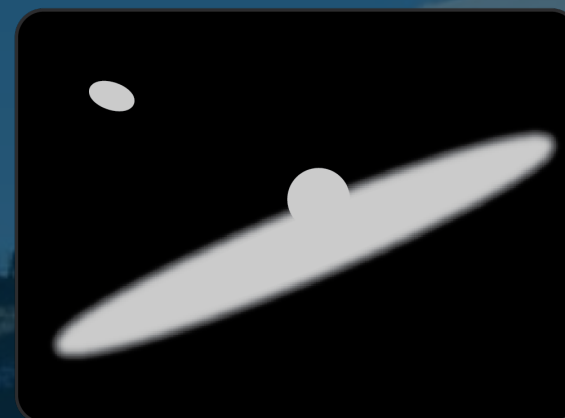
Real-time  
alerts



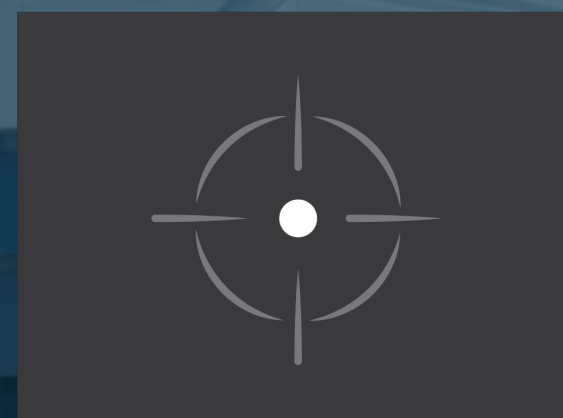
Prompt products database  
with forced photometry



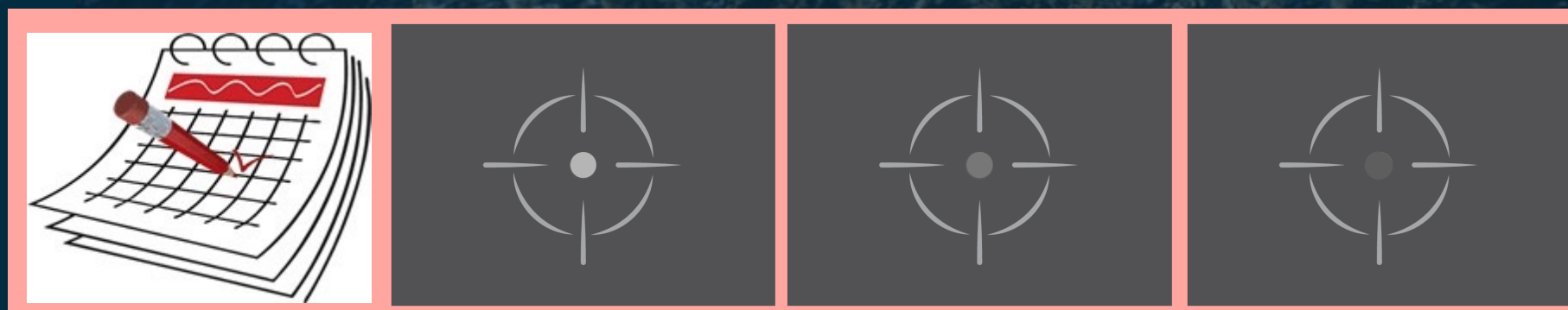
new image



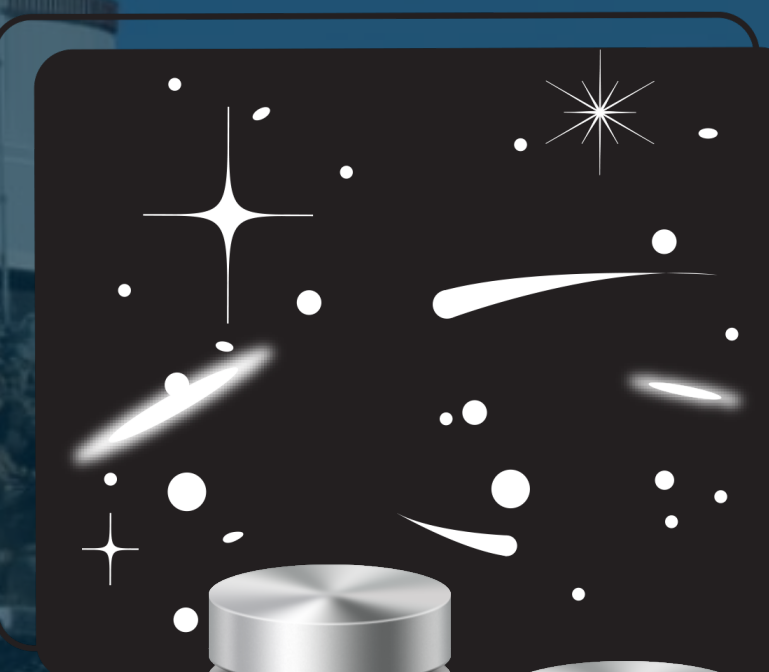
template



difference image



Annual reprocessing  
with stacked images





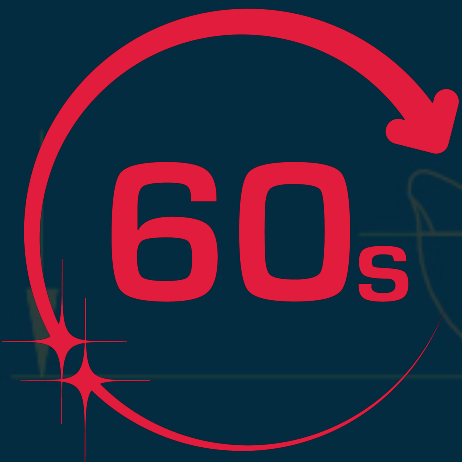
# Data from wide-field ground-based optical surveys (like Rubin Observatory's LSST)

Rubin  
Observatory

**Prompt**

**Data Release**

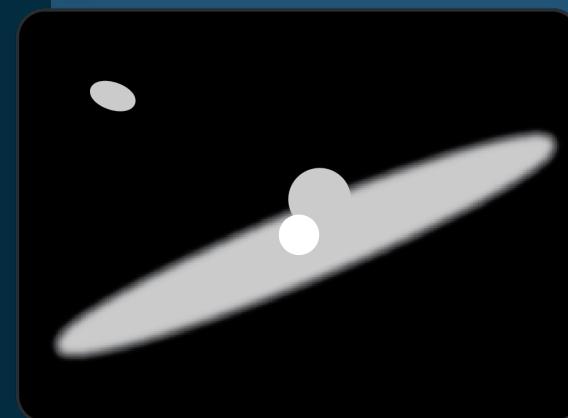
**User  
Generated**



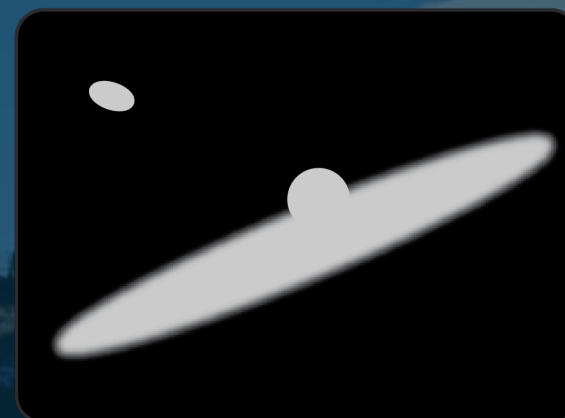
Real-time  
alerts



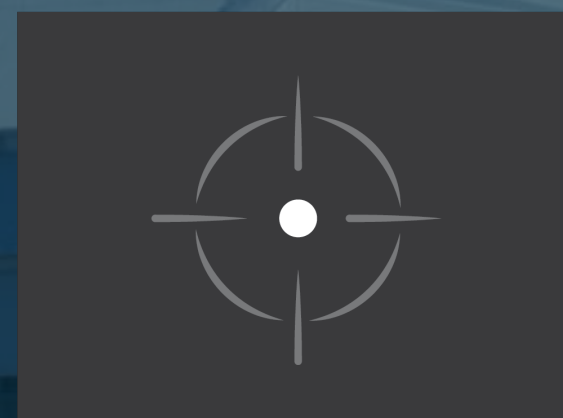
Prompt products database  
with forced photometry



new image



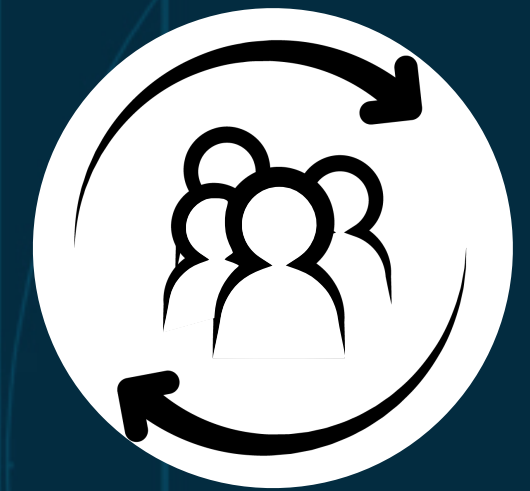
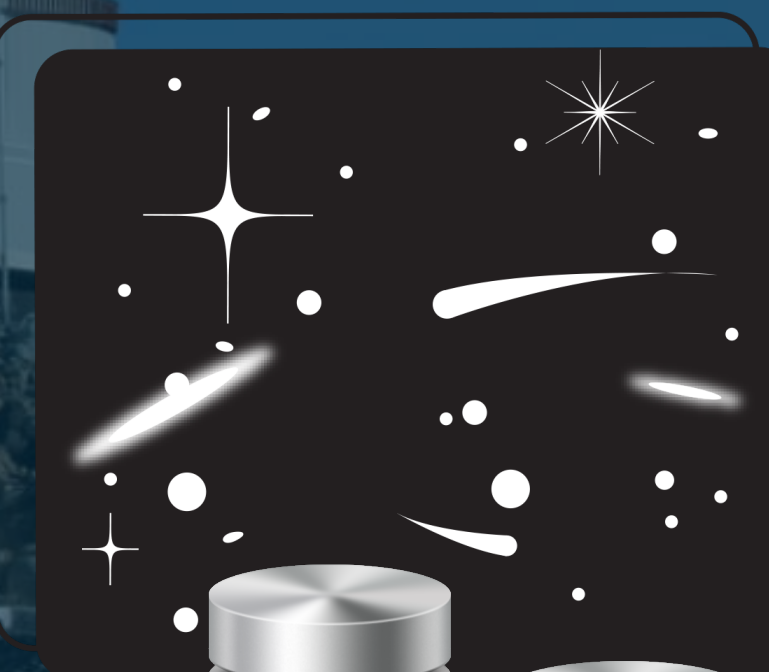
template



difference image



Annual reprocessing  
with stacked images



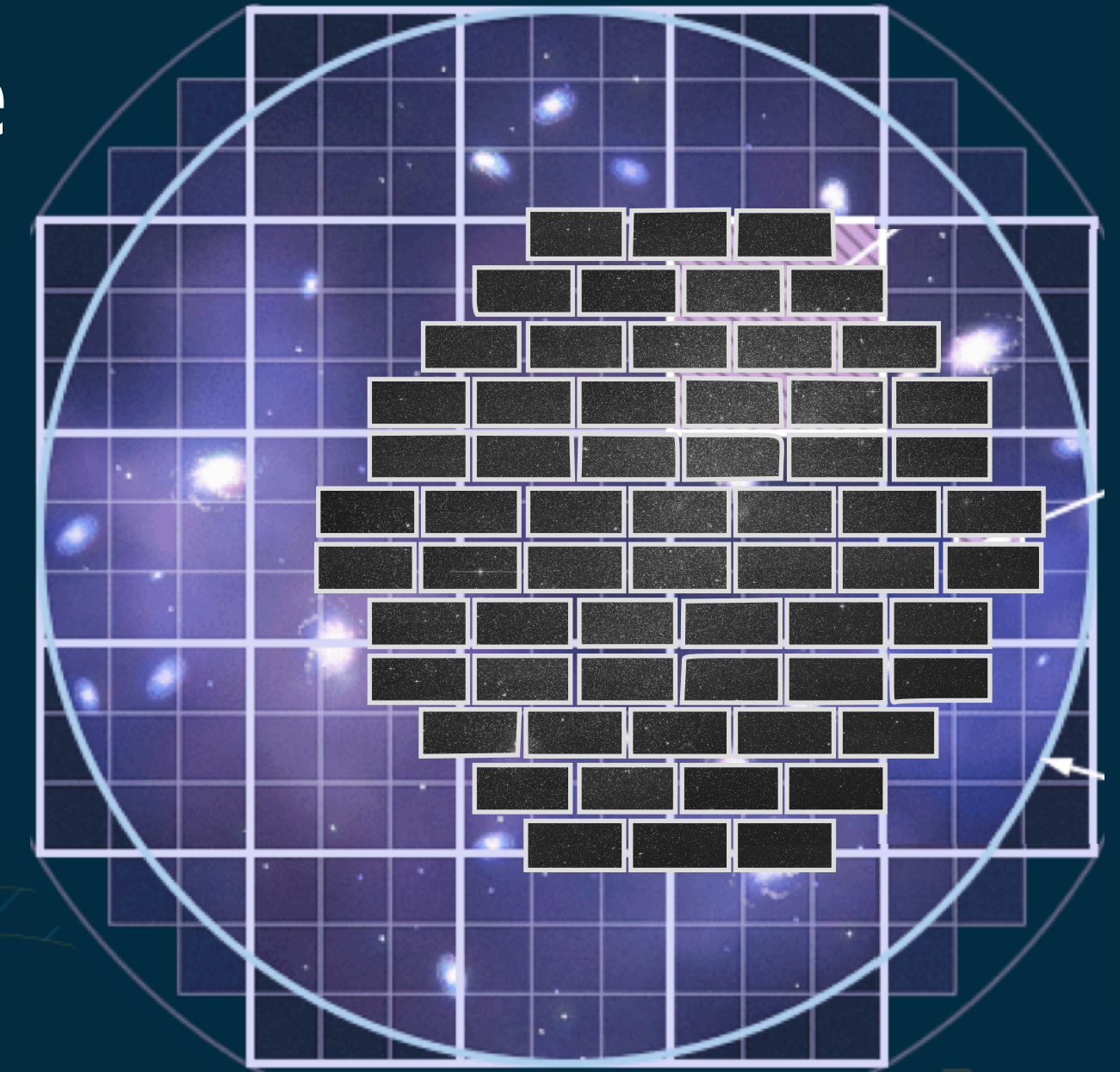
DIY scripts





# Processing raw telescope images

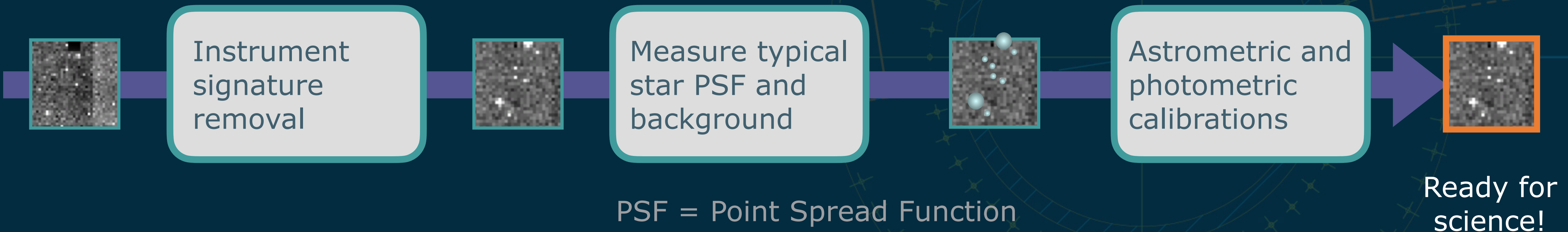
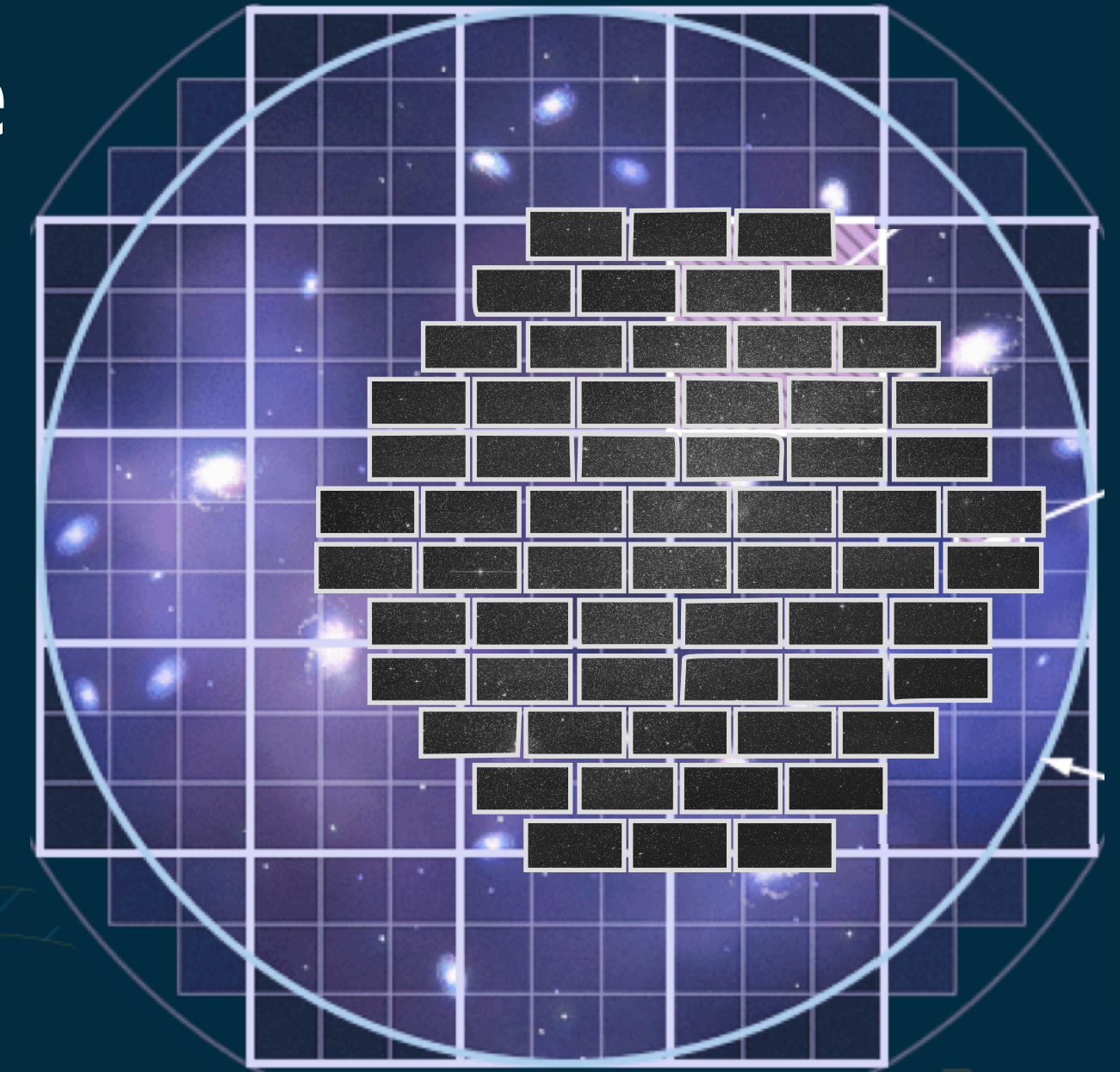
- Many steps before data products are ready for science
- LSST Science Pipelines: open source software for this (and much more!)
  - [pipelines.lsst.io](https://pipelines.lsst.io)
  - Bosch et al. 2019 [arxiv.org/abs/1812.03248](https://arxiv.org/abs/1812.03248)
- Blanco 4-m DECam (Dark Energy Camera) is a precursor to Rubin Observatory 8.4-m LSSTCam





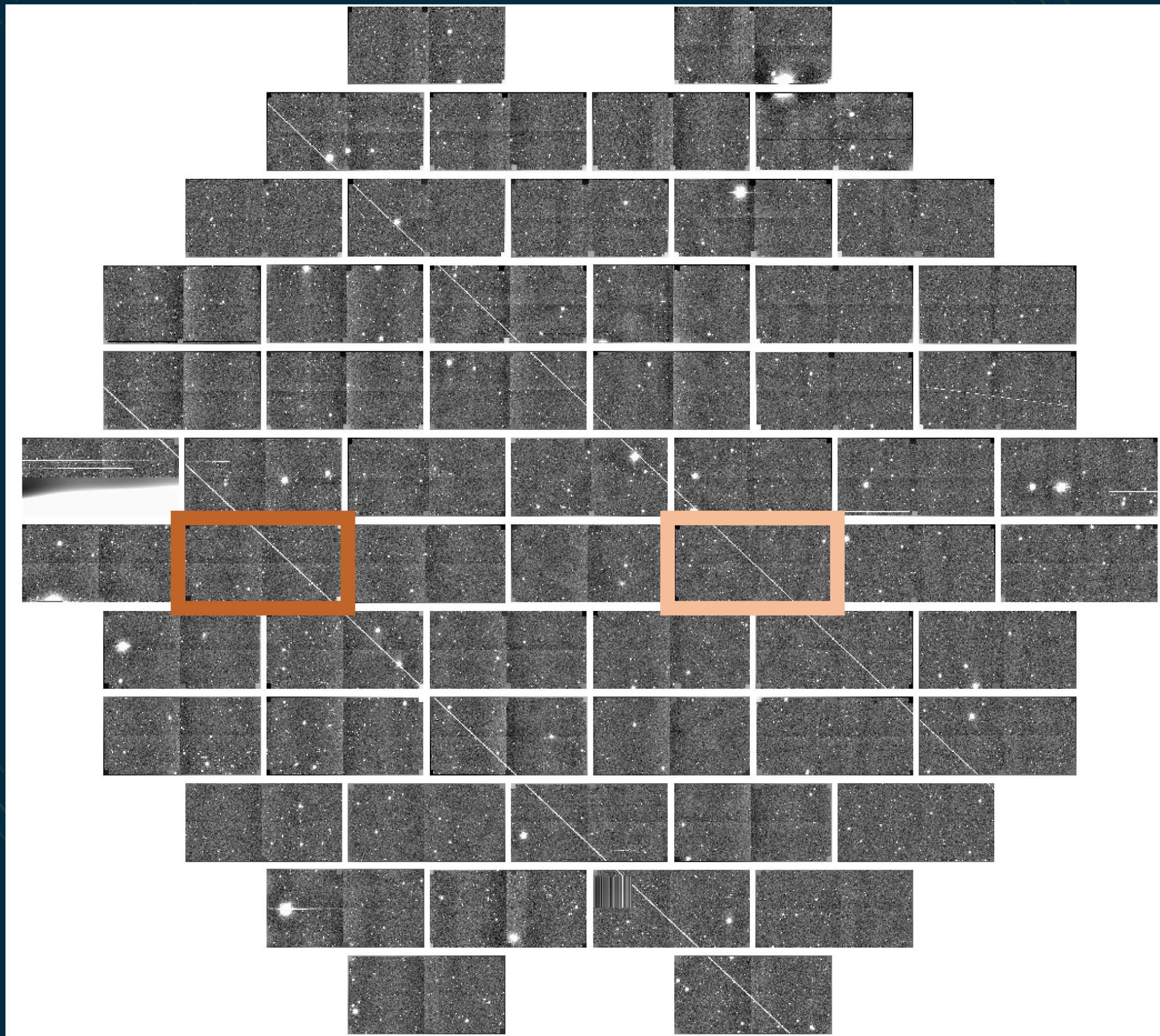
# Processing raw telescope images

- Many steps before data products are ready for science
- LSST Science Pipelines: open source software for this (and much more!)
  - [pipelines.lsst.io](https://pipelines.lsst.io)
  - Bosch et al. 2019 [arxiv.org/abs/1812.03248](https://arxiv.org/abs/1812.03248)
- Blanco 4-m DECam (Dark Energy Camera) is a precursor to Rubin Observatory 8.4-m LSSTCam





# Two Starlinks in 1 of 4 DECam visits



**Starlink-1112**



Blanco 4-m  
*David Walker*

Observations courtesy of DELVE (Alex Drlica-Wagner)

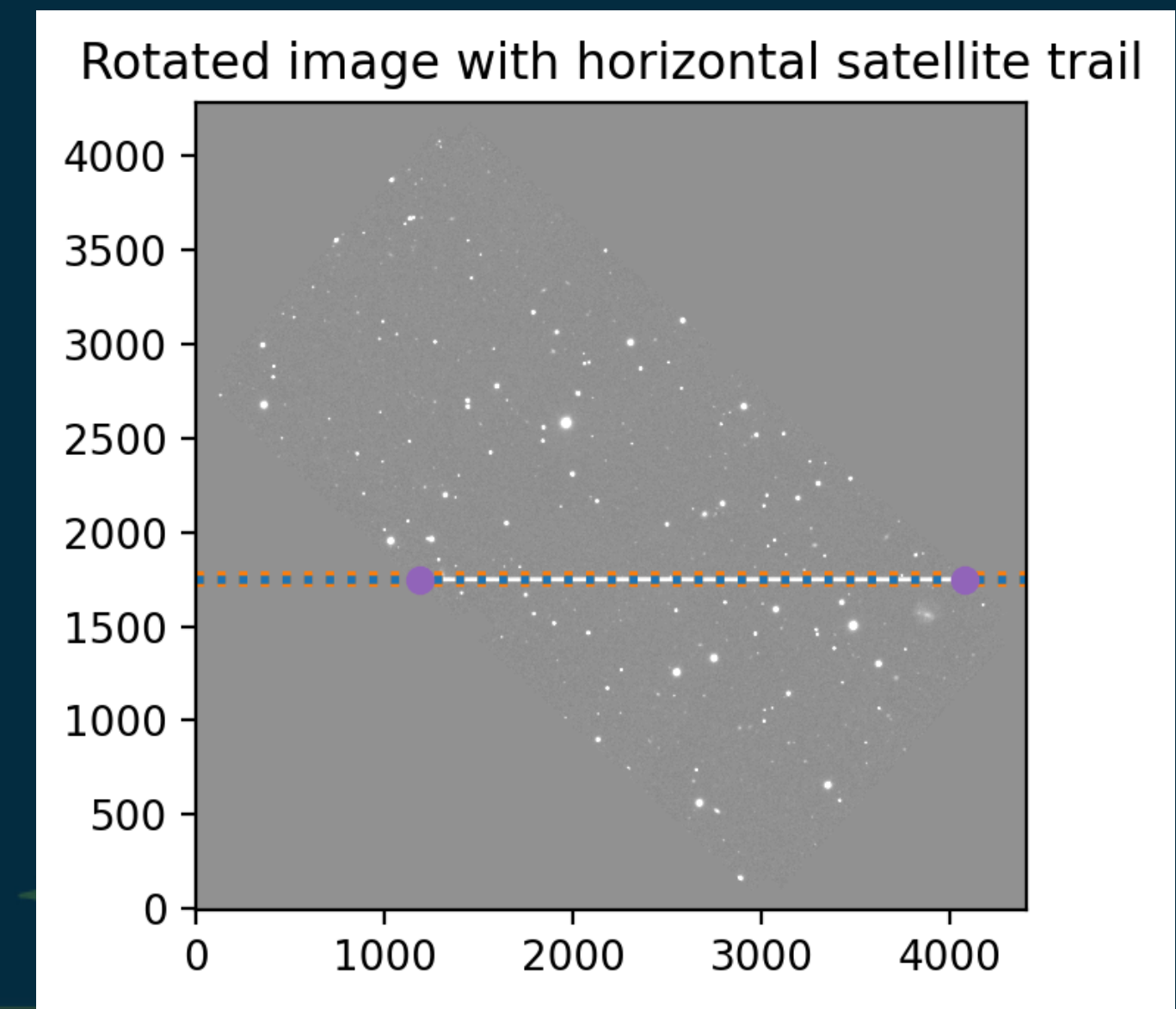
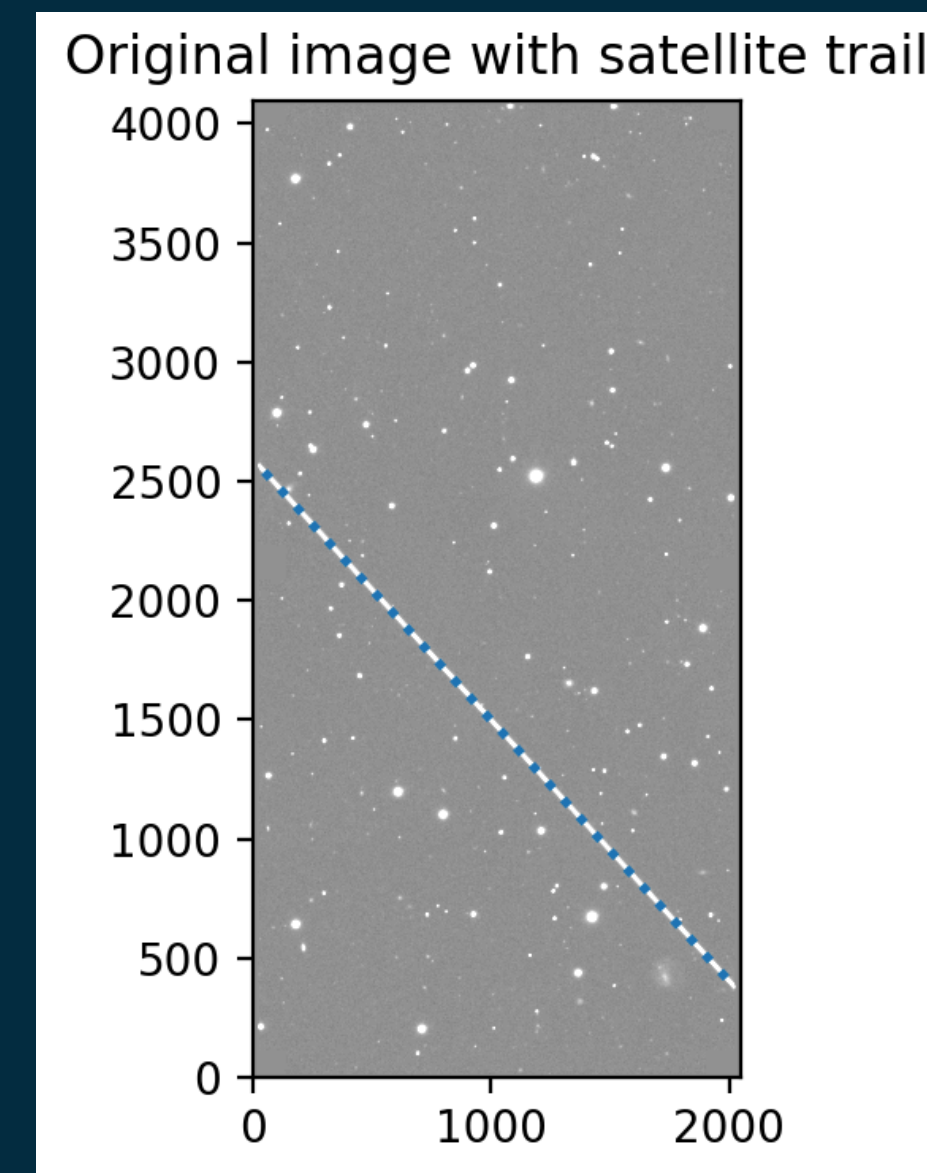
**DarkSat**

Full analysis: Tyson et al. 2020  
[arxiv.org/abs/2006.12417](https://arxiv.org/abs/2006.12417)



# Analyzing processed DECam images with python

- Load processed image data
- 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



LSST Science Pipelines



astropy-powered  
astropy.org

- All publicly available: <https://github.com/dirac-institute/starlink>



# Measuring satellite trail brightness

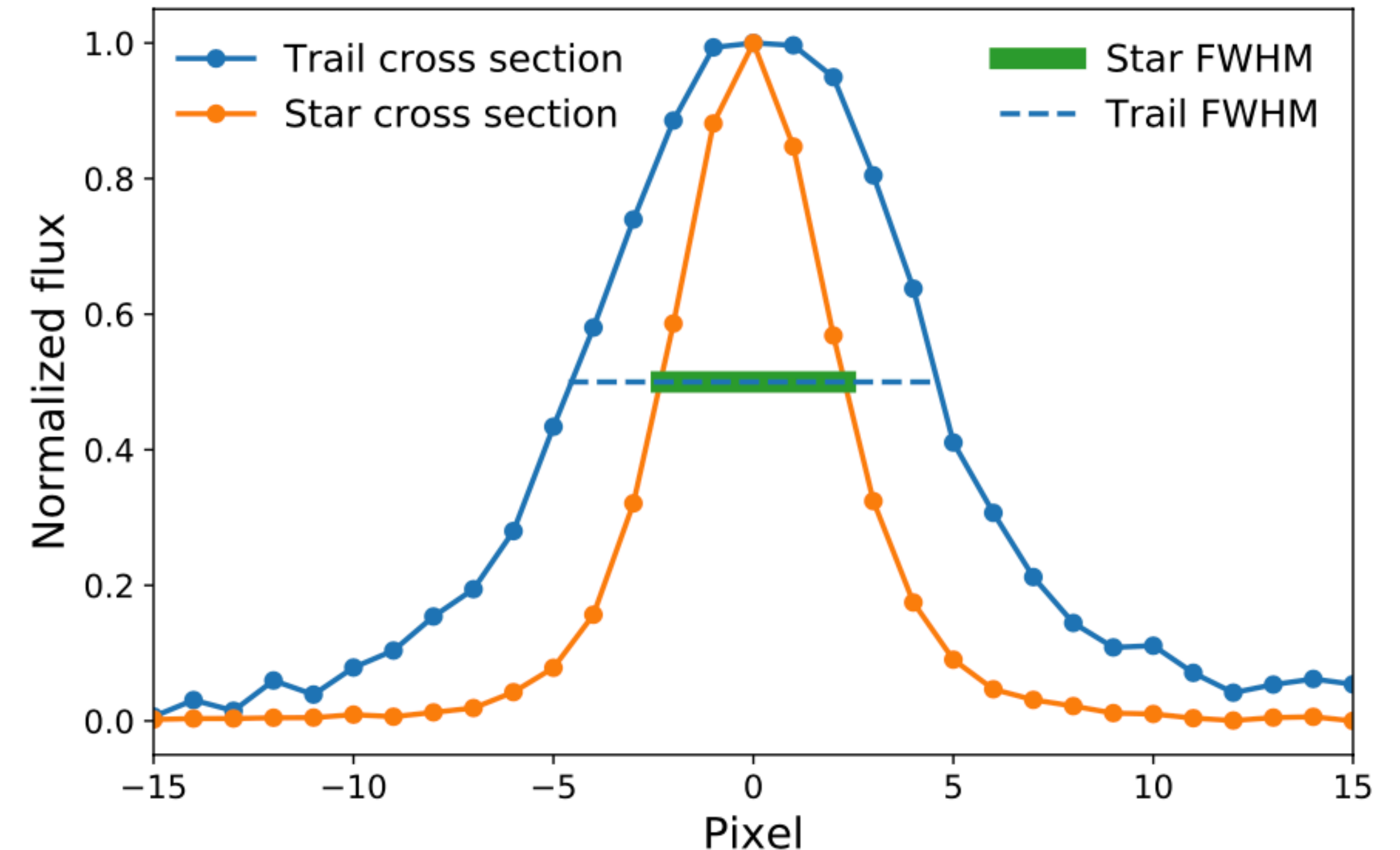
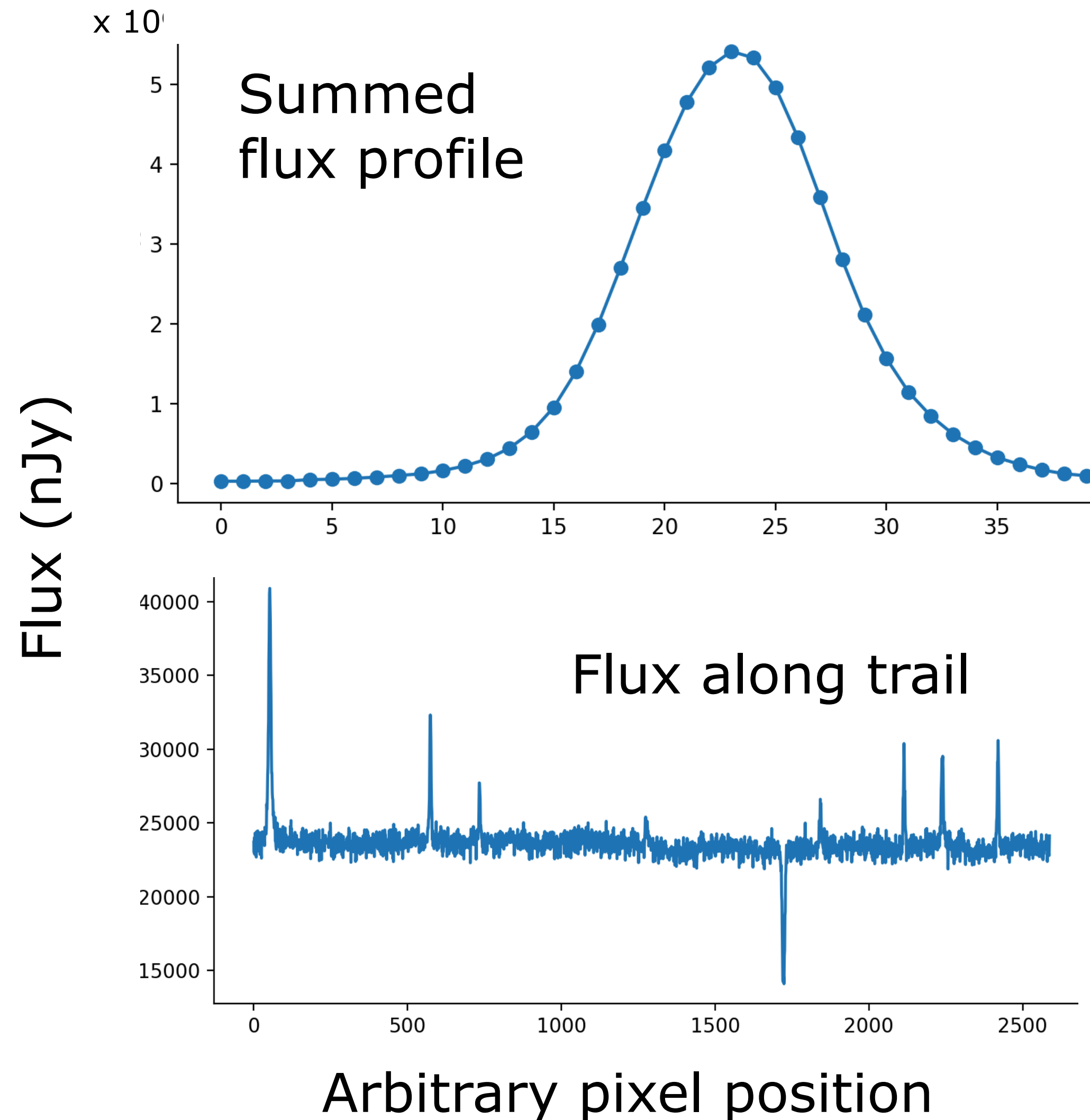


Fig. 9, Tyson et al. 2020 [arxiv.org/abs/2006.12417](https://arxiv.org/abs/2006.12417)

- Images are background-subtracted
- Pixel values are calibrated (nJy)
- Trail width is a function of telescope size



# DarkSat is 1.1 mag darker than its siblings in *g*-band

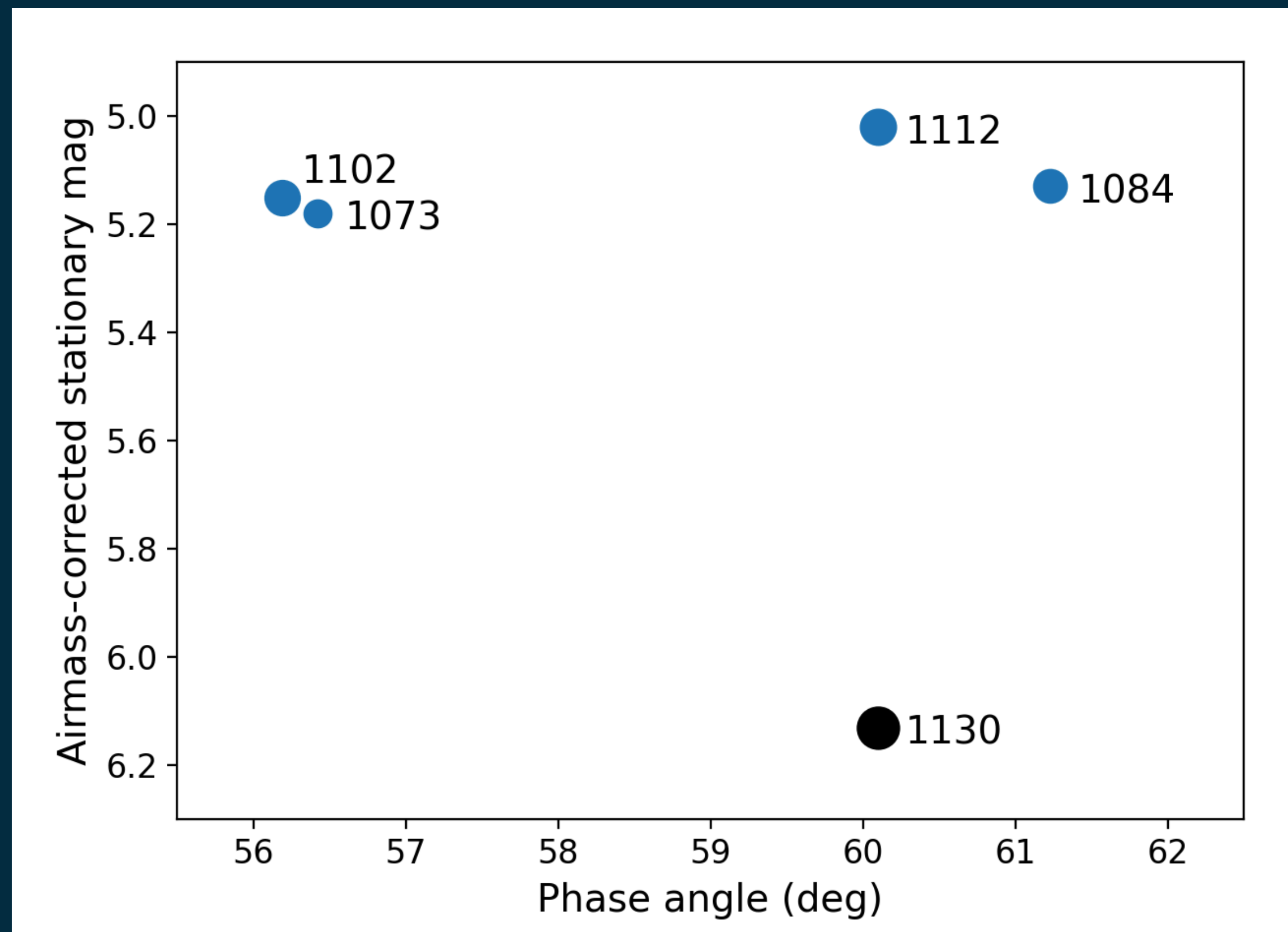
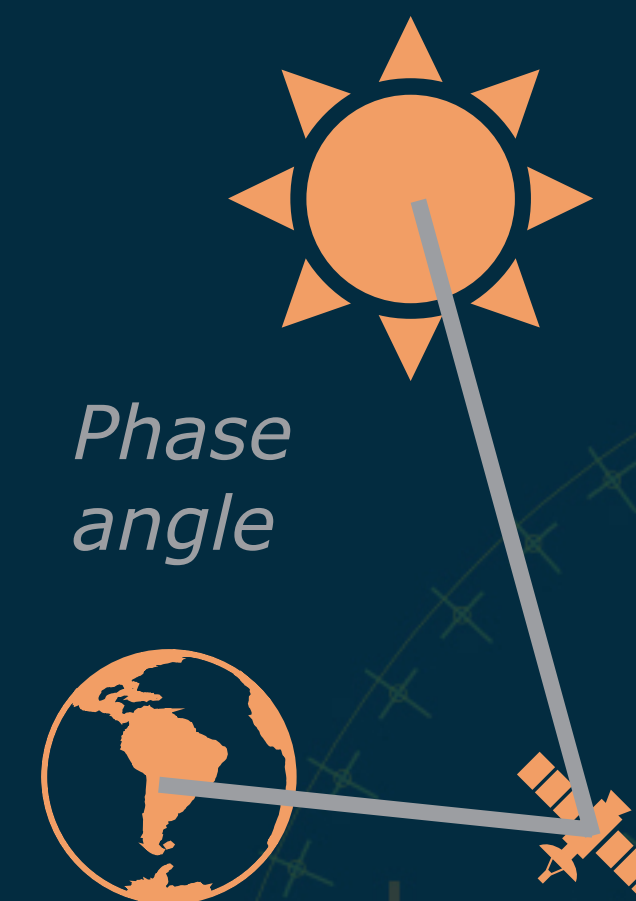
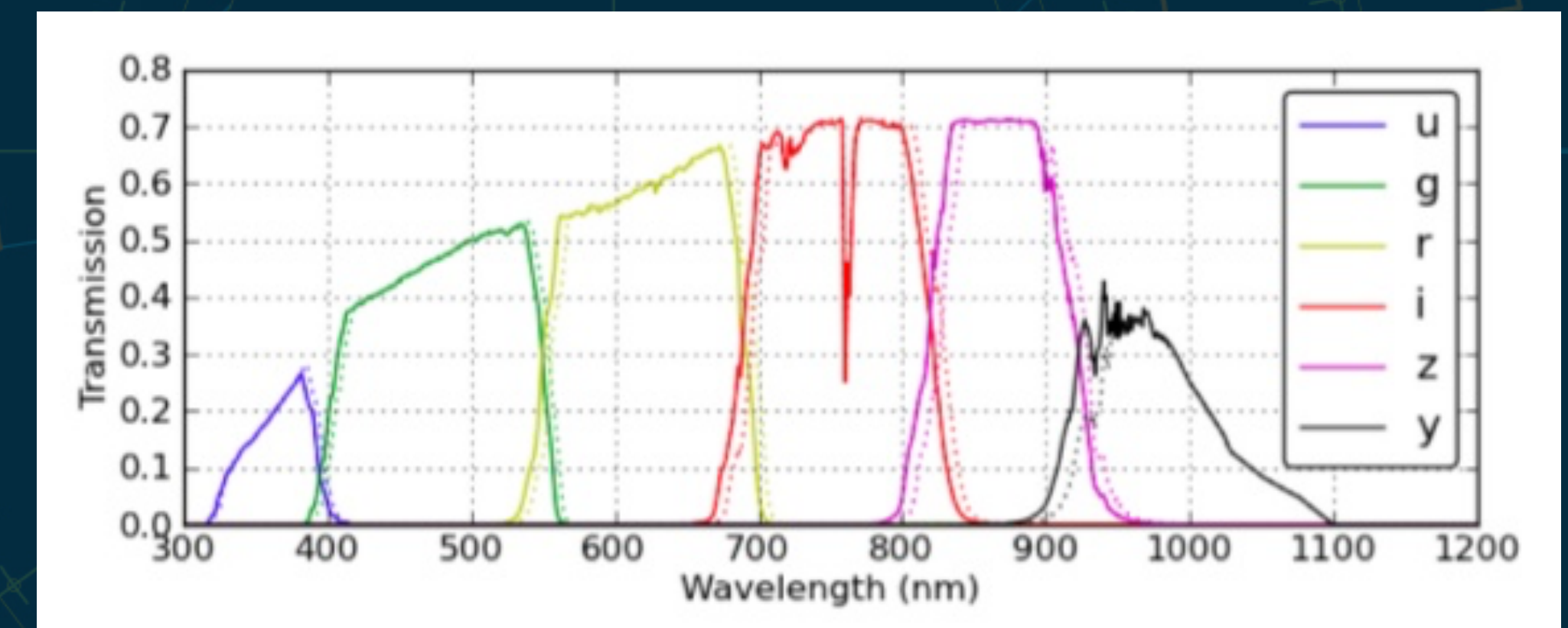


Fig. 8, Tyson et al. 2020 [arxiv.org/abs/2006.12417](https://arxiv.org/abs/2006.12417)



- Magnitudes are corrected for satellite speed and airmass
- Marker size indicates derived satellite size and  $\sim$ mag error
- Brightness not measured for phase angles far from  $60^\circ$





# Measurements of 5 Starlinks launched in Jan 2020

| Starlink | Time  | Phase angle | Airmass | PSF FWHM | Background               | Trail FWHM |
|----------|-------|-------------|---------|----------|--------------------------|------------|
|          | UTC   | deg         |         | arcsec   | mag arcsec <sup>-2</sup> | arcsec     |
| 1102     | 00:05 | 56.2        | 1.03    | 1.35     | 19.0                     | 2.43       |
| 1073     | 00:15 | 56.4        | 1.15    | 1.35     | 19.2                     | 2.04       |
| 1130     | 00:30 | 60.1        | 1.55    | 1.20     | 18.9                     | 2.12       |
| 1112     | 00:30 | 60.1        | 1.55    | 1.18     | 19.0                     | 1.87       |
| 1084     | 00:35 | 61.2        | 1.71    | 1.33     | 18.8                     | 1.82       |

- Night of March 5-6, 2020
- ~1 hour after sunset
- Four visits within 30 min
- All exposures 120 sec

| Starlink | Raw trail                | Corrected trail          | Speed               | Stationary | Zenith | <i>d</i> | Size |
|----------|--------------------------|--------------------------|---------------------|------------|--------|----------|------|
|          | mag arcsec <sup>-2</sup> | mag arcsec <sup>-2</sup> | deg s <sup>-1</sup> | mag        | mag    | km       | m    |
| 1102     | 19.98                    | 14.78                    | 0.77                | 5.21       | 5.15   | 565      | 3.84 |
| 1073     | 19.96                    | 14.76                    | 0.70                | 5.49       | 5.18   | 625      | 2.34 |
| 1130     | 21.31                    | 16.11                    | 0.54                | 7.08       | 6.13   | 810      | 5.58 |
| 1112     | 20.06                    | 14.86                    | 0.54                | 5.97       | 5.02   | 810      | 4.02 |
| 1084     | 20.27                    | 15.07                    | 0.50                | 6.29       | 5.13   | 878      | 3.47 |



# Measurements of 5 Starlinks launched in Jan 2020

| Starlink | Time  | Phase angle | Airmass | PSF FWHM | Background               | Trail FWHM |
|----------|-------|-------------|---------|----------|--------------------------|------------|
|          | UTC   | deg         |         | arcsec   | mag arcsec <sup>-2</sup> | arcsec     |
| 1102     | 00:05 | 56.2        | 1.03    | 1.35     | 19.0                     | 2.43       |
| 1073     | 00:15 | 56.4        | 1.15    | 1.35     | 19.2                     | 2.04       |
| 1130     | 00:30 | 60.1        | 1.55    | 1.20     | 18.9                     | 2.12       |
| 1112     | 00:30 | 60.1        | 1.55    | 1.18     | 19.0                     | 1.87       |
| 1084     | 00:35 | 61.2        | 1.71    | 1.33     | 18.8                     | 1.82       |

- Night of March 5-6, 2020
- ~1 hour after sunset
- Four visits within 30 min
- All exposures 120 sec
- Near full moon

| Starlink | Raw trail                | Corrected trail          | Speed               | Stationary | Zenith | <i>d</i> | Size |
|----------|--------------------------|--------------------------|---------------------|------------|--------|----------|------|
|          | mag arcsec <sup>-2</sup> | mag arcsec <sup>-2</sup> | deg s <sup>-1</sup> | mag        | mag    | km       | m    |
| 1102     | 19.98                    | 14.78                    | 0.77                | 5.21       | 5.15   | 565      | 3.84 |
| 1073     | 19.96                    | 14.76                    | 0.70                | 5.49       | 5.18   | 625      | 2.34 |
| 1130     | 21.31                    | 16.11                    | 0.54                | 7.08       | 6.13   | 810      | 5.58 |
| 1112     | 20.06                    | 14.86                    | 0.54                | 5.97       | 5.02   | 810      | 4.02 |
| 1084     | 20.27                    | 15.07                    | 0.50                | 6.29       | 5.13   | 878      | 3.47 |



# Measurements of 5 Starlinks launched in Jan 2020

| Starlink | Time  | Phase angle | Airmass | PSF FWHM | Background               | Trail FWHM |
|----------|-------|-------------|---------|----------|--------------------------|------------|
|          | UTC   | deg         |         | arcsec   | mag arcsec <sup>-2</sup> | arcsec     |
| 1102     | 00:05 | 56.2        | 1.03    | 1.35     | 19.0                     | 2.43       |
| 1073     | 00:15 | 56.4        | 1.15    | 1.35     | 19.2                     | 2.04       |
| 1130     | 00:30 | 60.1        | 1.55    | 1.20     | 18.9                     | 2.12       |
| 1112     | 00:30 | 60.1        | 1.55    | 1.18     | 19.0                     | 1.87       |
| 1084     | 00:35 | 61.2        | 1.71    | 1.33     | 18.8                     | 1.82       |

- Night of March 5-6, 2020
- ~1 hour after sunset
- Four visits within 30 min
- All exposures 120 sec
- Near full moon
- Speeds assume 550 km altitude circular orbit

| Starlink | Raw trail                | Corrected trail          | Speed               | Stationary | Zenith | <i>d</i> | Size |
|----------|--------------------------|--------------------------|---------------------|------------|--------|----------|------|
|          | mag arcsec <sup>-2</sup> | mag arcsec <sup>-2</sup> | deg s <sup>-1</sup> | mag        | mag    | km       | m    |
| 1102     | 19.98                    | 14.78                    | 0.77                | 5.21       | 5.15   | 565      | 3.84 |
| 1073     | 19.96                    | 14.76                    | 0.70                | 5.49       | 5.18   | 625      | 2.34 |
| 1130     | 21.31                    | 16.11                    | 0.54                | 7.08       | 6.13   | 810      | 5.58 |
| 1112     | 20.06                    | 14.86                    | 0.54                | 5.97       | 5.02   | 810      | 4.02 |
| 1084     | 20.27                    | 15.07                    | 0.50                | 6.29       | 5.13   | 878      | 3.47 |



# Measurements of 5 Starlinks launched in Jan 2020

| Starlink | Time  | Phase angle | Airmass | PSF FWHM | Background               | Trail FWHM |
|----------|-------|-------------|---------|----------|--------------------------|------------|
|          | UTC   | deg         |         | arcsec   | mag arcsec <sup>-2</sup> | arcsec     |
| 1102     | 00:05 | 56.2        | 1.03    | 1.35     | 19.0                     | 2.43       |
| 1073     | 00:15 | 56.4        | 1.15    | 1.35     | 19.2                     | 2.04       |
| 1130     | 00:30 | 60.1        | 1.55    | 1.20     | 18.9                     | 2.12       |
| 1112     | 00:30 | 60.1        | 1.55    | 1.18     | 19.0                     | 1.87       |
| 1084     | 00:35 | 61.2        | 1.71    | 1.33     | 18.8                     | 1.82       |

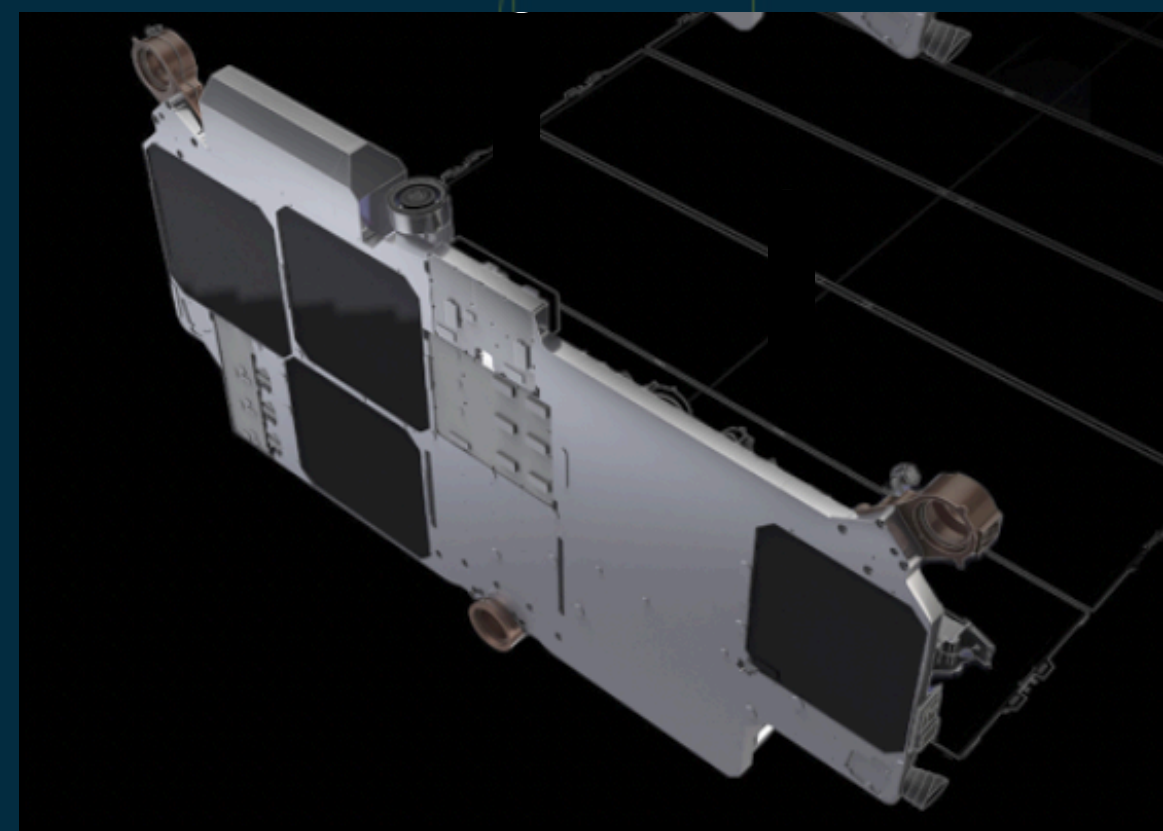
| Starlink | Raw trail                | Corrected trail          | Speed               | Stationary | Zenith | <i>d</i> | Size |
|----------|--------------------------|--------------------------|---------------------|------------|--------|----------|------|
|          | mag arcsec <sup>-2</sup> | mag arcsec <sup>-2</sup> | deg s <sup>-1</sup> | mag        | mag    | km       | m    |
| 1102     | 19.98                    | 14.78                    | 0.77                | 5.21       | 5.15   | 565      | 3.84 |
| 1073     | 19.96                    | 14.76                    | 0.70                | 5.49       | 5.18   | 625      | 2.34 |
| 1130     | 21.31                    | 16.11                    | 0.54                | 7.08       | 6.13   | 810      | 5.58 |
| 1112     | 20.06                    | 14.86                    | 0.54                | 5.97       | 5.02   | 810      | 4.02 |
| 1084     | 20.27                    | 15.07                    | 0.50                | 6.29       | 5.13   | 878      | 3.47 |

- Night of March 5-6, 2020
- ~1 hour after sunset
- Four visits within 30 min
- All exposures 120 sec
- Near full moon
- Speeds assume 550 km altitude circular orbit
- *d* is derived distance from observer to satellite
- Size is derived satellite size from trail width, stellar PSF, and mirror

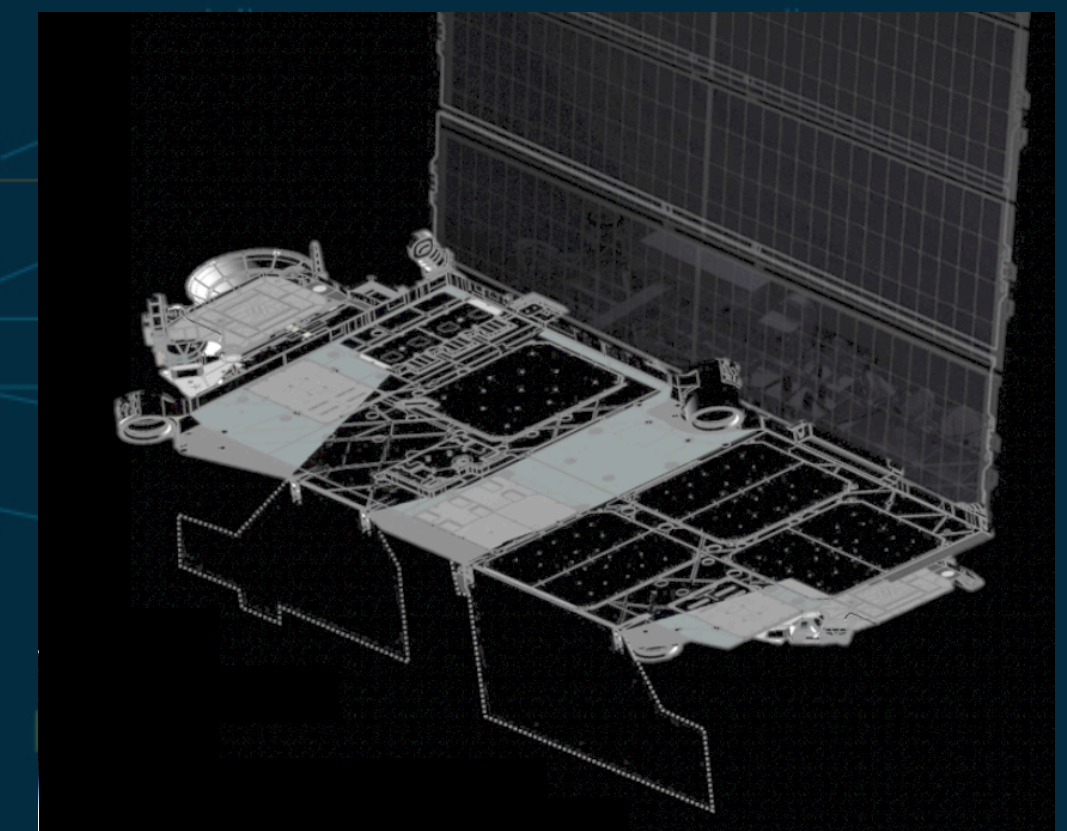


# DarkSat is $\sim 6$ th mag, but we really need $\sim 7$ th mag

- Would enable image artifact correction for Rubin Obs/LSST
- Trails that remain will likely impact science in other ways



DarkSat (SpaceX)

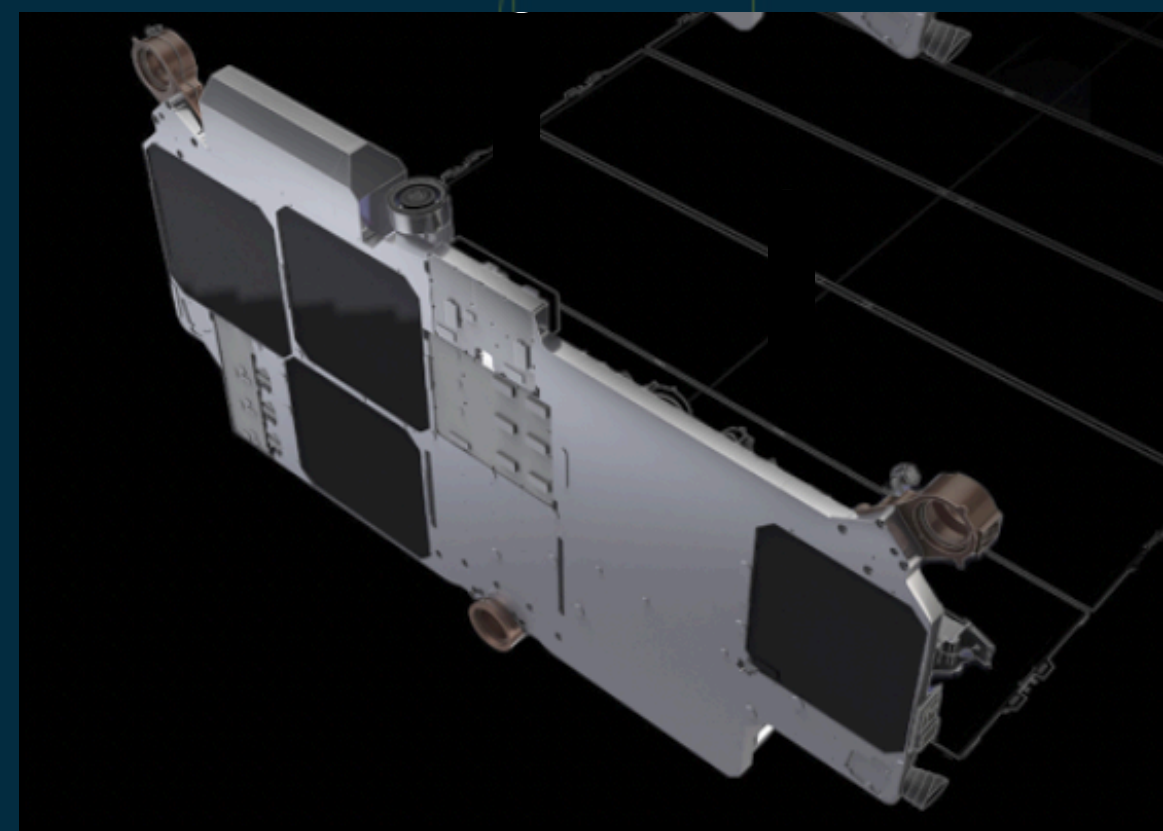


VisorSat (SpaceX)

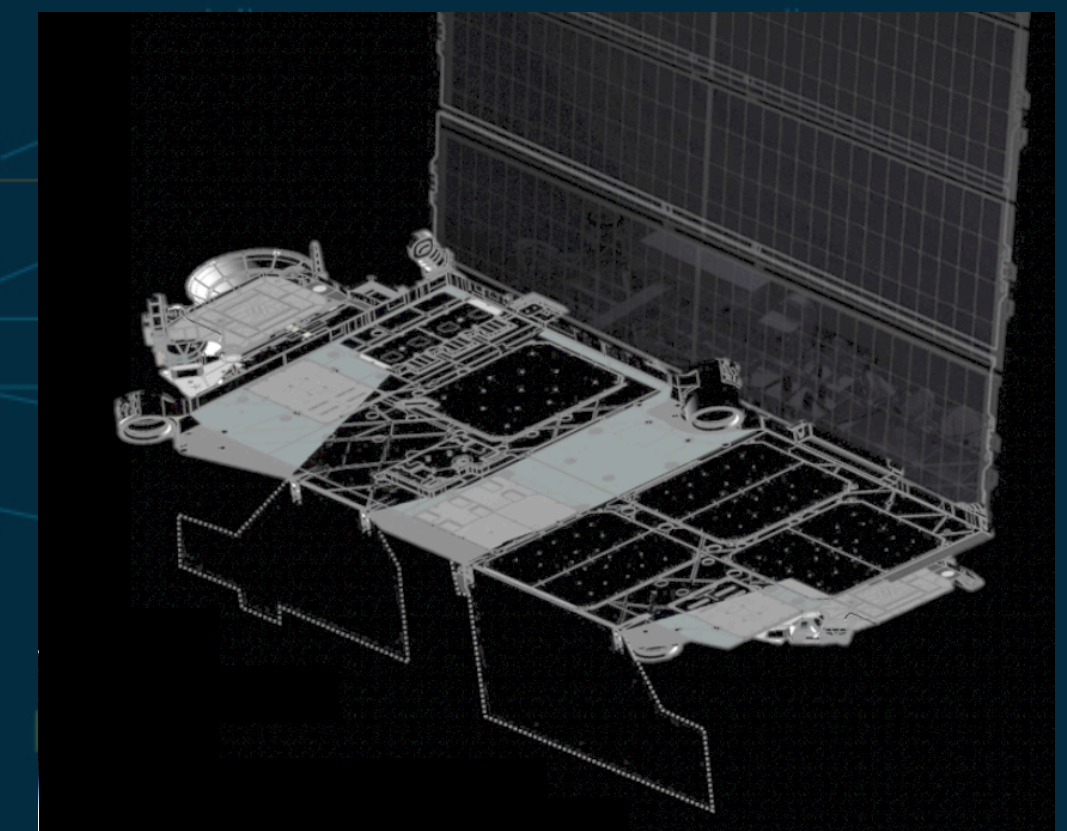


# DarkSat is $\sim 6$ th mag, but we really need $\sim 7$ th mag

- Would enable image artifact correction for Rubin Obs/LSST
- Trails that remain will likely impact science in other ways
- Would make satellites mostly invisible to unaided eye



DarkSat (SpaceX)

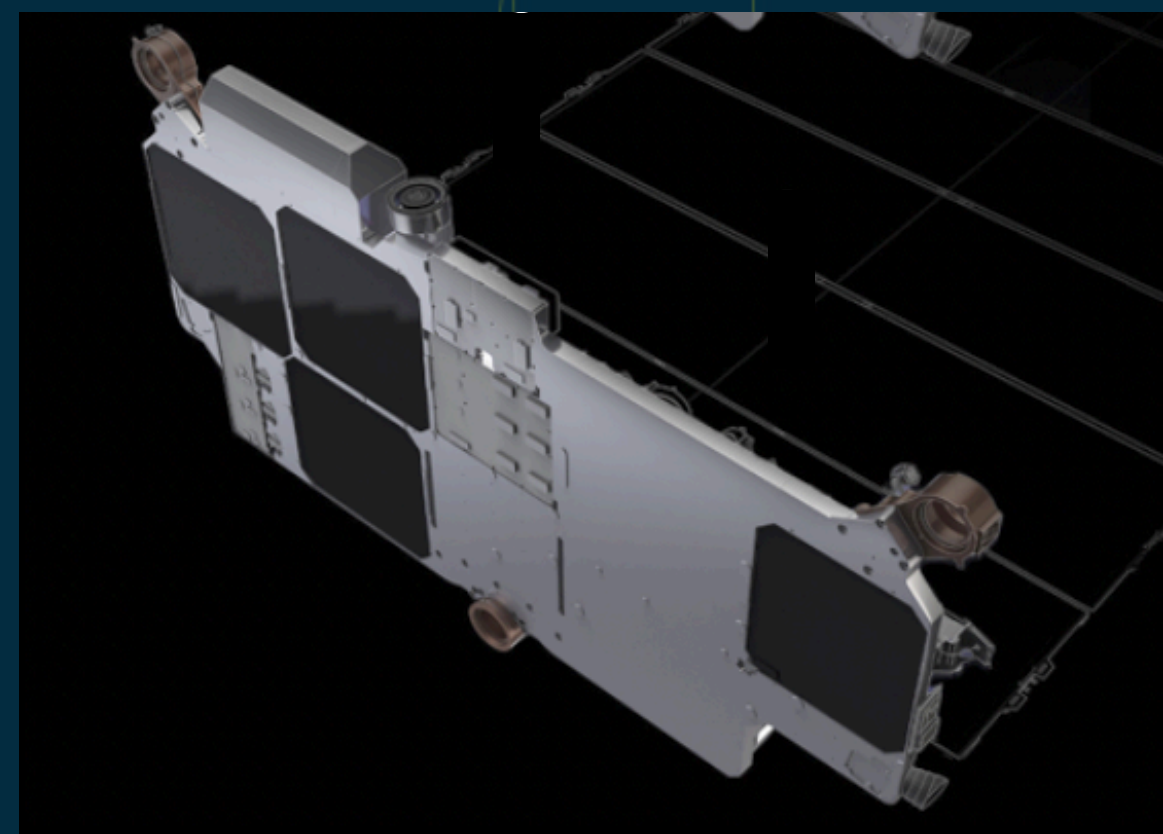


VisorSat (SpaceX)

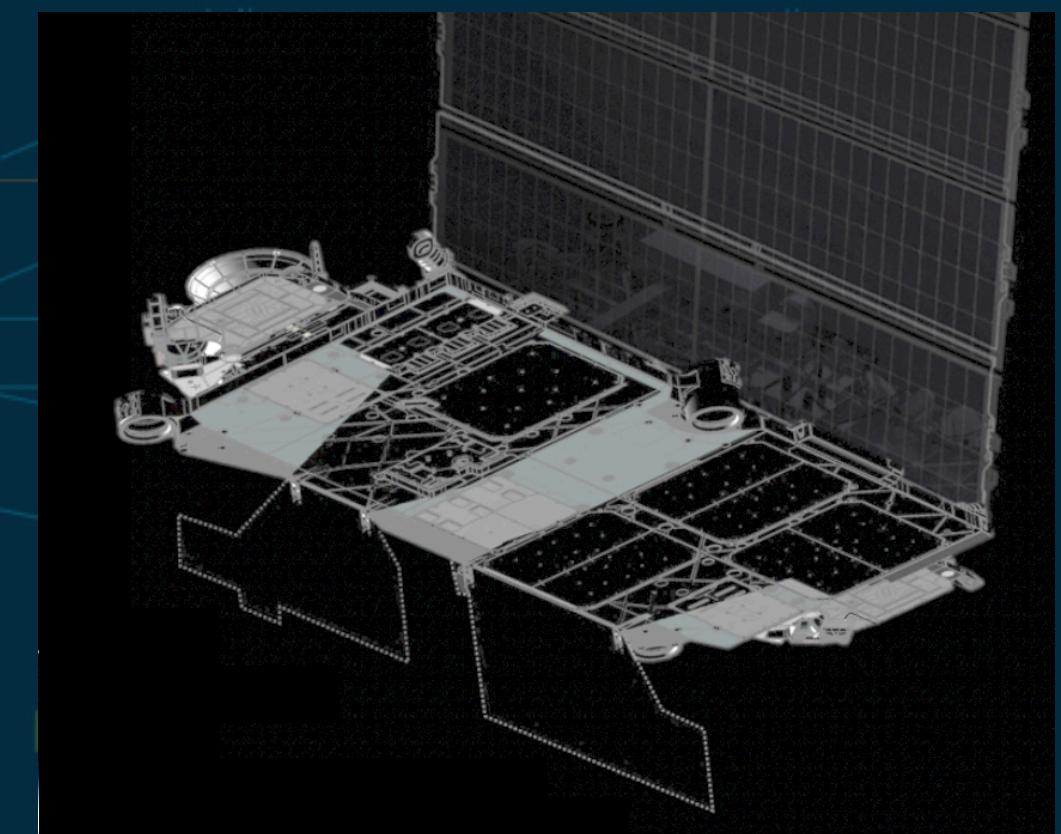


# DarkSat is ~6th mag, but we really need ~7th mag

- Would enable image artifact correction for Rubin Obs/LSST
- Trails that remain will likely impact science in other ways
- Would make satellites mostly invisible to unaided eye
- Reaching ~7th mag requires significant operator mitigations
- Satellite phases outside of "on station" still a problem



DarkSat (SpaceX)



VisorSat (SpaceX)



# Starlink mitigations are promising, but not everything

- Wide-field ground-based optical imaging surveys are most impacted by many bright low-earth-orbit satellites
- Jan 2020 Starlinks are  $\sim 5$ th mag, DarkSat is  $\sim 6$ th mag
- Mitigating the worst effects is possible for  $\sim 7$ th mag (VisorSat?)





# Starlink mitigations are promising, but not everything

- Wide-field ground-based optical imaging surveys are most impacted by many bright low-earth-orbit satellites
- Jan 2020 Starlinks are  $\sim 5$ th mag, DarkSat is  $\sim 6$ th mag
- Mitigating the worst effects is possible for  $\sim 7$ th mag (VisorSat?)
- Trail analysis tools: <https://github.com/dirac-institute/starlink>













# Starlink mitigations are promising, but not everything

- Wide-field ground-based optical imaging surveys are most impacted by many bright low-earth-orbit satellites
- Jan 2020 Starlinks are  $\sim 5$ th mag, DarkSat is  $\sim 6$ th mag
- Mitigating the worst effects is possible for  $\sim 7$ th mag (VisorSat?)
- Trail analysis tools: <https://github.com/dirac-institute/starlink>
- Unclear who will fund astronomers to do mitigation work
- Operator mitigations are voluntary, not legally required
- For more on Rubin Obs/LSST mitigations, read our paper

Tyson et al. 2020  
[arxiv.org/abs/2006.12417](https://arxiv.org/abs/2006.12417)

## Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST

J. ANTHONY TYSON <sup>1,2</sup> ŽELJKO IVEZIĆ <sup>3,4,2</sup> ANDREW BRADSHAW <sup>5</sup> MEREDITH L. RAWLS <sup>3,4</sup> BO XIN <sup>2</sup>  
PETER YOACHIM <sup>3,4</sup> JOHN PAREJKO,<sup>3,4</sup> JARED GREENE,<sup>6</sup> MICHAEL SHOLL <sup>7</sup> TIMOTHY M. C. ABBOTT <sup>8</sup> AND  
DANIEL POLIN<sup>1</sup>