Impact on Science at Today's Large-FoV Telescopes

Increasing number of trails detected in the Zwicky Transient Facility science images

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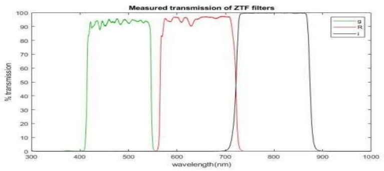
Goals

- Report on the evidence of the increasing number of satellite trails detected on astronomical images (from a large field-of-view facility, the Zwicky Transient Facility)
- Statistical results on:
  - Increasing number of satellite trails detected
  - Satellites brightness as a function of:
    - Range (distance from the satellite to the observer)
    - Wavelength (selected astronomical spectral bands)
    - Angular distance of satellite to the Sun

The Zwicky Transient Facility (ZTF)

- Study astrophysical phenomena in the time domain
- Based on a 48-inch aperture (~1.25 m), Schmidt-type design Samuel Oschin telescope.
- Location, Palomar Observatory in Southern California
- **FOV, 47 square-degree**
- CCD, mosaic science camera
  - 16 Detectors
  - 6144 x 6160 pixels each detector
  - Arranged into 4 quadrants
- **Plate scale 1.01 arcsecs/pixel**
- Supported with an aspheric corrector optics and a robotic bandpass filter (**ZTF-g, ZTF-r, ZTF-i**)
- Science exposures of 30 seconds, overheads < 10 seconds
- Assisted by a Robotic Operations Software.
  - The regular observations starts as the Sun reaches -12 degrees below the horizon
- **ZTF carries out a ’twilight’ survey each morning and evening at large zenith angles and relatively small solar angles.**



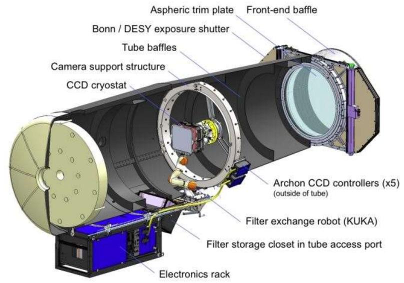
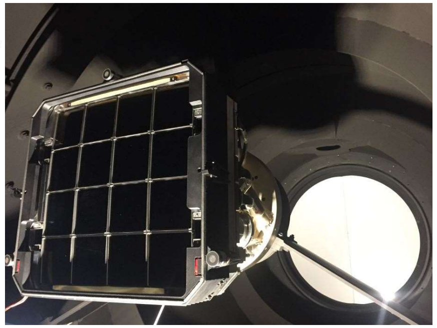


Figure 1. Cutaway view of the Samuel Oschin Telescope highlighting new ZTF subsystems.



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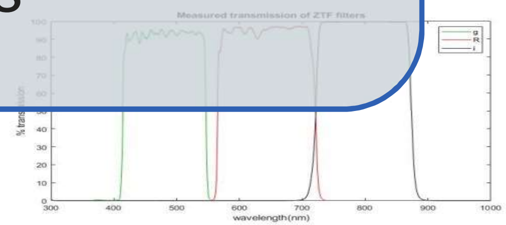
These characteristics make the ZTF and ideal telescope/camera setup for the detection, characterization and statistical analysis of LEO satellite trails



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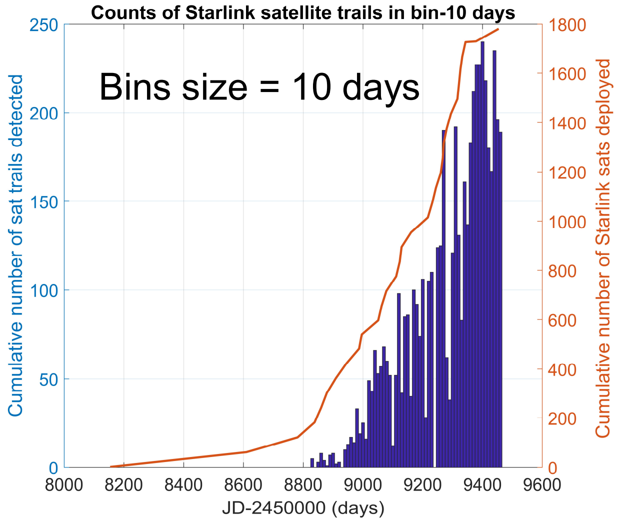
Characterizing the increasing number of ***Starlink satellite trails*** on astronomical images with the ZFT

- **Observations of LEO satellite trails in the period December 2019 until September 2021**
- The ZTF data reduction pipeline can identify and mask satellite trails
- **A code produced by Przemek Mróz helps to ID the satellites in the ZTF images**
- The ZTF camera has 16 detectors, each detector is divided into 4 quadrants
  - A satellite trail may be detected on multiple quadrants. **The reported magnitude is the average (with outlier rejection) of many measurements**
  - The reported magnitude **uncertainty is the standard error of the mean**
  - **The accuracy of calibrations is about 0.01 mag** (to be added in quadrature)

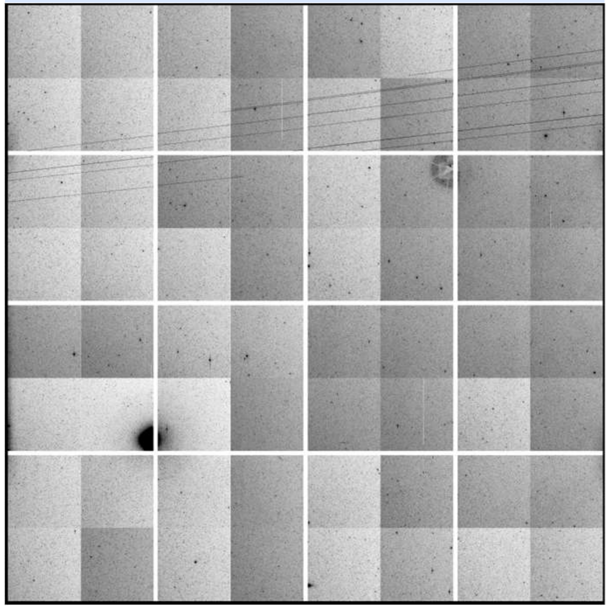
Results: **Number of sat trails detected**

- The ZTF observes about 5000 images/month, while the Sun is between -12 and -30 degrees below the horizon. ➔ **1500 images in a 10 days period**.
- Currently, in a 10 days period we have **about 230 trails detection**. ➔ up to 15% of the images could be polluted by a trail (at the rate of 1 trail/image).
- If number of satellites increases to 40000 ➔ there will be 25x more satellites than currently in orbit.

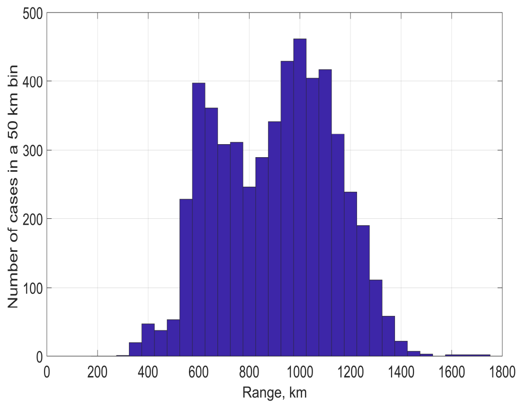


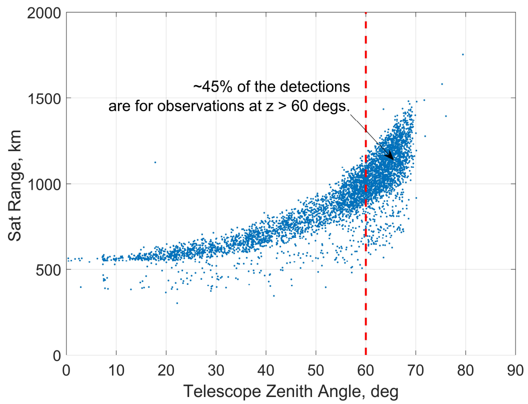
This plot shows that the relation between satellite trails detected in a 10-days period is about 8-10% of the total number of satellites in the Starlink constellation.

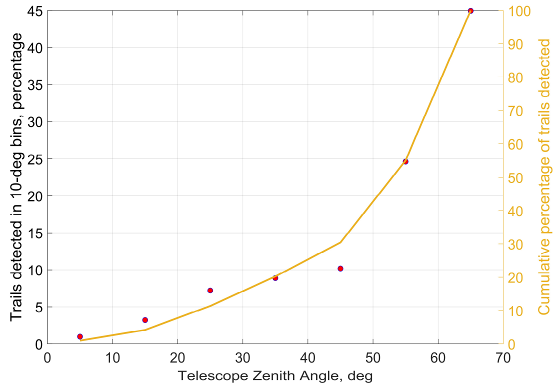
ZTF Image affected by with LEO satellites
30 seconds exposure, 16 detectors show satellite trails



Results: **Sat range (at detection)**

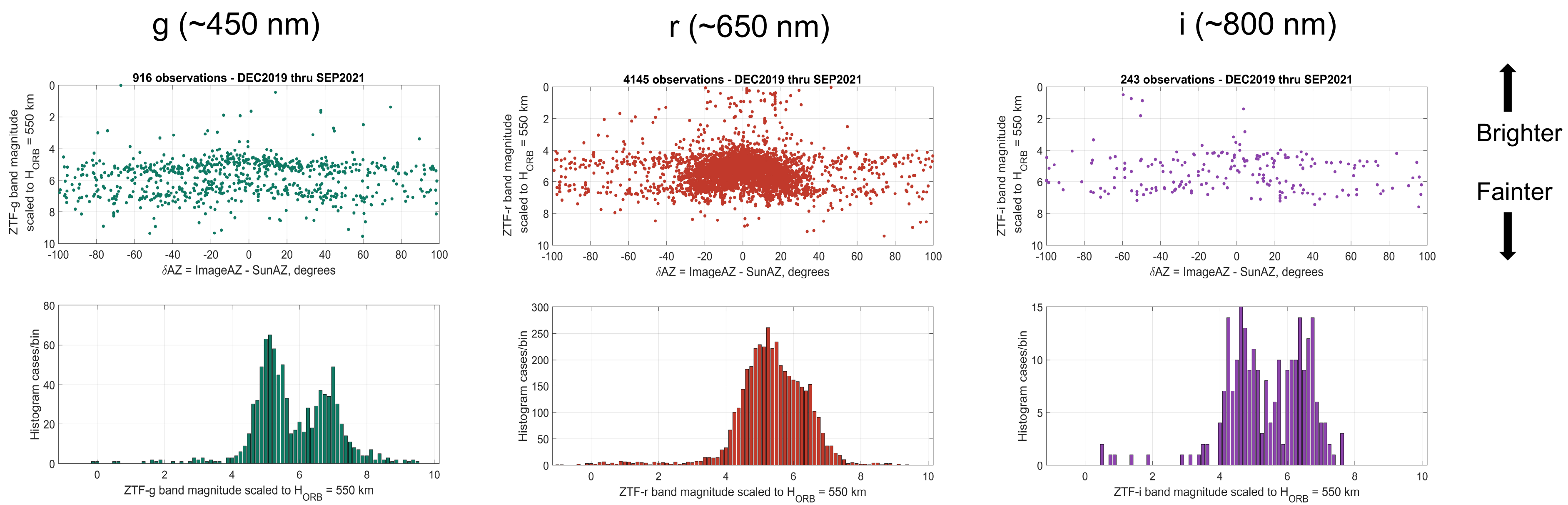






- ~45% of satellite trails detected at zenith angles > 60 degrees
- This is of particular importance for facilities interested in the high zenith angle ranges, such as, Solar system science (comets, asteroids, potentially Interstellar objects objects detection and their characterization, etc…)

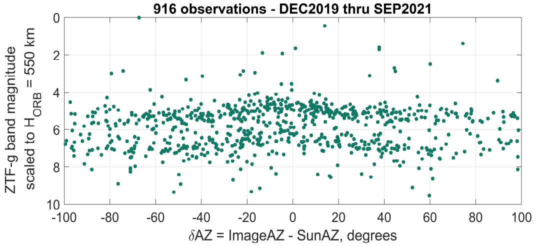
Results: Magnitude Brightness at 3 spectral bands (5000+ obs)



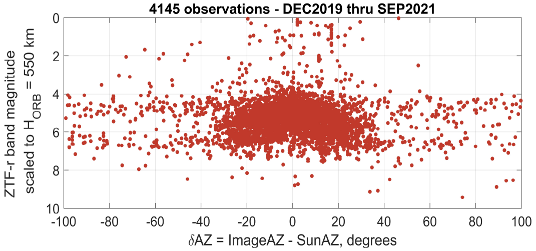
Results: Magnitude Brightness at 3 spectral bands (5000+ obs)

The data shows two distinct groups

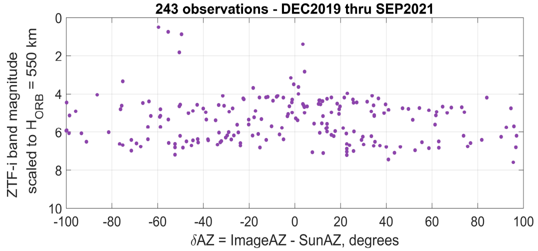
g (~450 nm)



r (~650 nm)

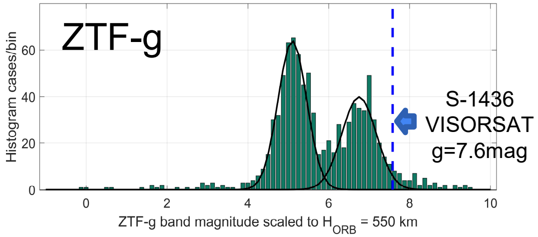


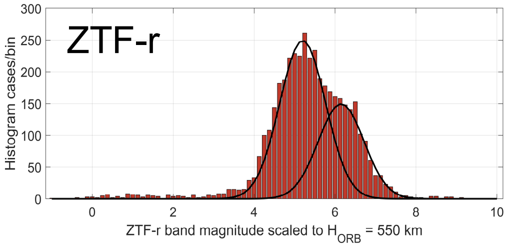
i (~800 nm)

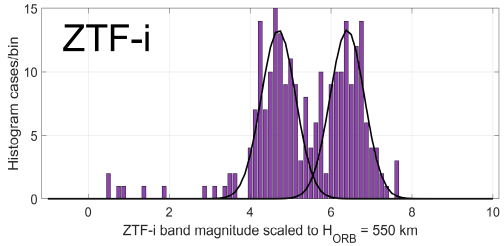


Brighter

Fainter

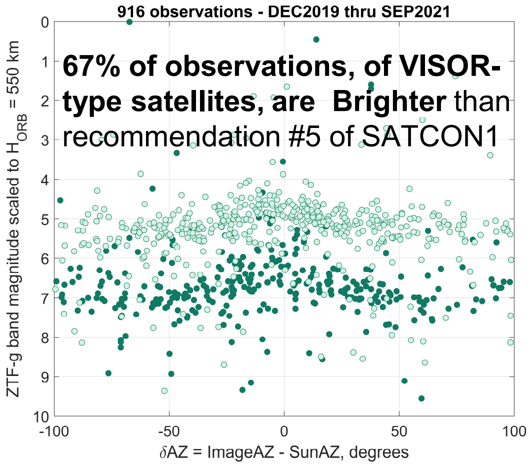


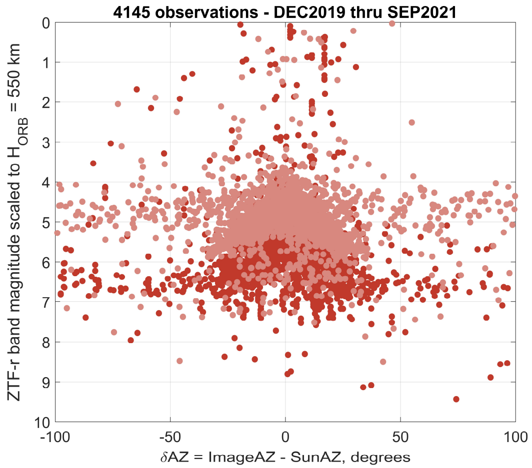


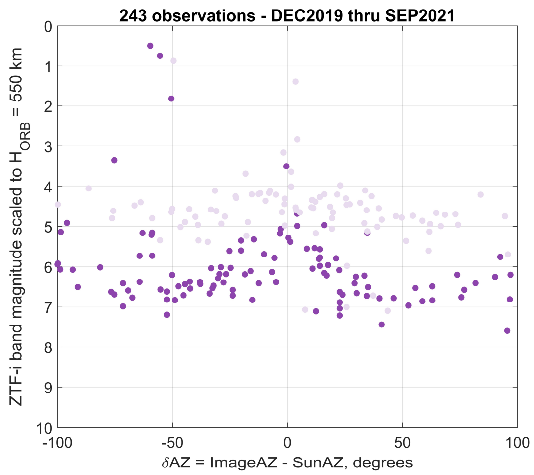


Results: Magnitude Brightness at 3 spectral bands (5000+ obs)

The dimmer satellites are clearly explained by VISOR-type (Starlink 1436, 1522 and onwards)







Brighter

Fainter

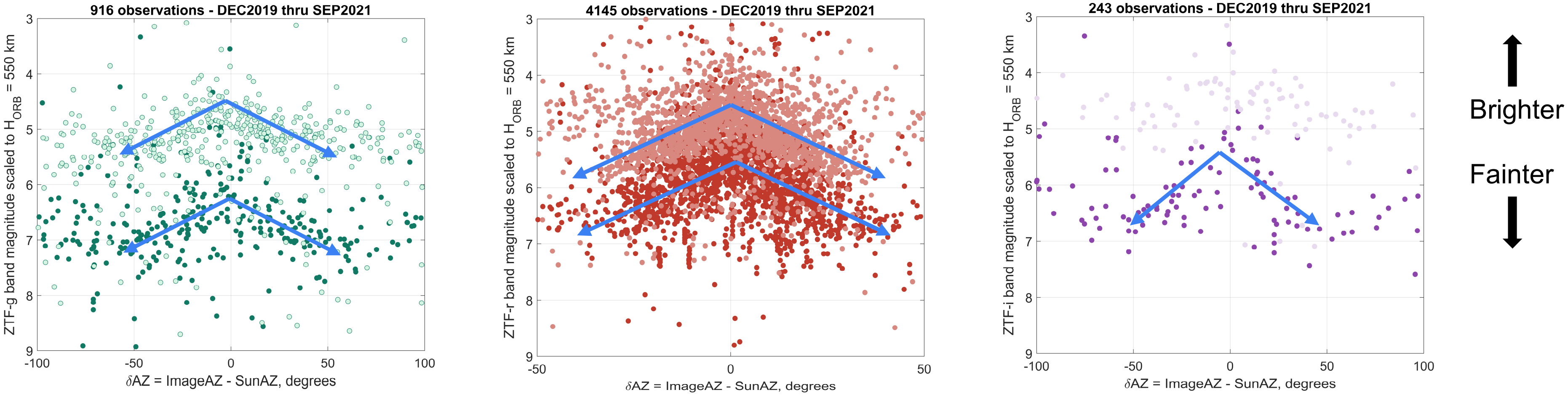
Non-Visors: 5.27 ± 0.07
Visors: 6.60 ± 0.08

Non-Visors: 4.92 ± 0.08
Visors: 5.75 ± 0.11

Non-Visors: 4.59 ± 0.07
Visors: 5.99 ± 0.08

Results: Magnitude Brightness at 3 spectral bands (5000+ obs)

The observations help to show changes in brightness with relative orientation of the satellites to the Sun (dAZ shown)



- The decrease of brightness with Azimuth separation between Sun and Sat ~ 0.04 mag/degree
- The decrease in brightness levels off when reaching an AZ separation of about 25 degrees
- The satellites show up brighter when align with the Sun in Azimuth

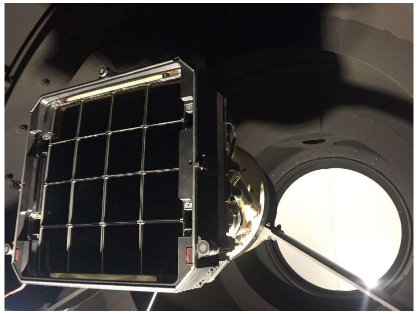
Summary

- The ZTF telescope/camera seems a great setup for the study on the effects of LEO mega constellation of satellites on wide field-of-view astronomy
- The number of observations, and the span in time, clearly shows the rate of increase of satellite trails in science fields as a function of increasing number of satellites being deployed in orbit
- The data illustrate the problem of larger number of images polluted with satellite trails at high zenith angles. This may be something to keep in mind, specially for Solar System observational astronomy. **However, to date, ZTF solar system observations have not been severely affected by satellite streaks, even at twilight.**
- The data clearly shows the VISOR satellites are dimmer. However, many of the observations are still brighter than stated in Recommendation #5 of the SatCON1 workshop. These data set shows that 67% of observations, of VISOR-type satellites, are brighter than recommendation #5 of SATCON1.
- The ZTF imaging, calibration and postprocessing produces magnitudes of very high accuracy (low uncertainty). This helps to show the change in brightness of satellites with angular separation from the Sun. The satellites are brighter when in the same observed with the same azimuth than the Sun.

How to move forward with the characterization efforts

- Keep an archive of astronomical images affected by satellite trails available/open for analysis
  - Facilities (ZTF, CSS, PanSTARR, ATLAS, MMT-9, etc), site coordinates, multi spectral band
- **Maintain an historical archive of TLEs for each satellite in each constellation of interest** (this will help with the identification of satellites trails in past observations)
- **Follow a common protocol for the processing of the satellite trails** (the goal is to provide satellite brightness magnitude data of high accuracy (low uncertainty)
- **For each satellite trail detection, keep a record of the following information**:
  - Sat ID
  - Calibrated brightness magnitude and estimate of its statistical uncertainty, specifying the spectral band used
  - Satellite Orbital Height (at the time of detection – helps understand if the satellite is still in deployment phase or already at its nominal orbital height)
  - Satellite range
  - Satellite's azimuth and altitude angles at the time of the observations
  - Satellite's angular velocity at the time of the observations
  - Latitude and longitude , on the surface, of the nadir point of the satellite at the time of observation
  - Sun azimuth and elevation at the time of the observations

Acknowledgments:



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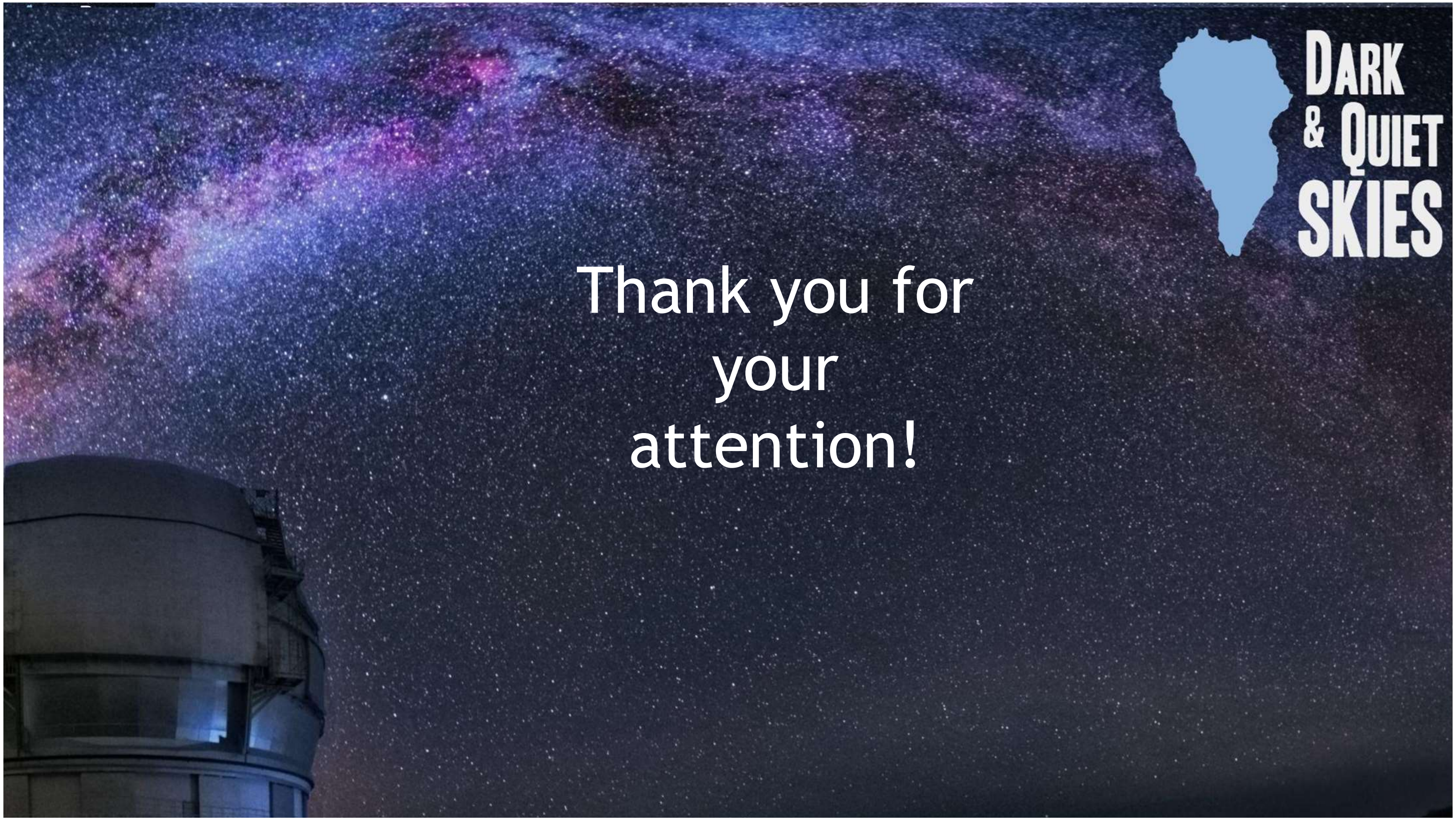
Przemek Mróz, Thomas (Tom) Prince and Matthew Graham (ZTF P.S.)
Zwicky Transient Facility Telescope (Funded in part by the US NSF and ZTF partner institutions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& QUIET
SKIES
Thank you for
your
attention!