Analytical simulations of the effect of satellite constellations on astronomical observations

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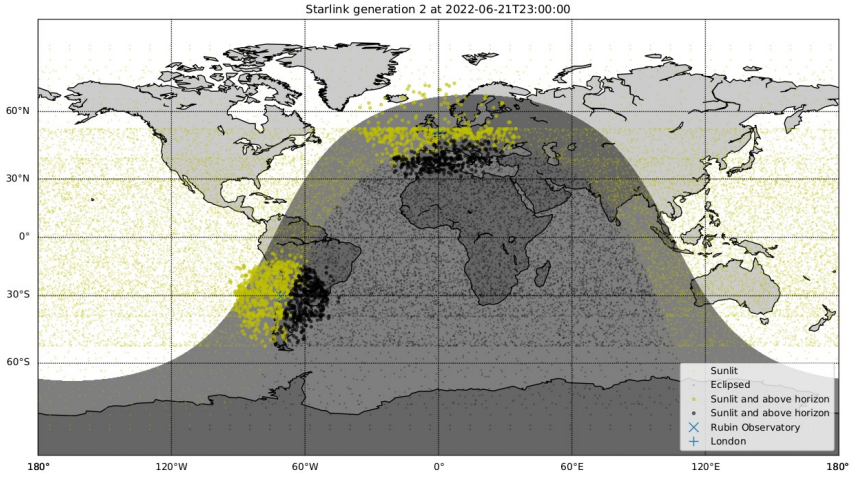
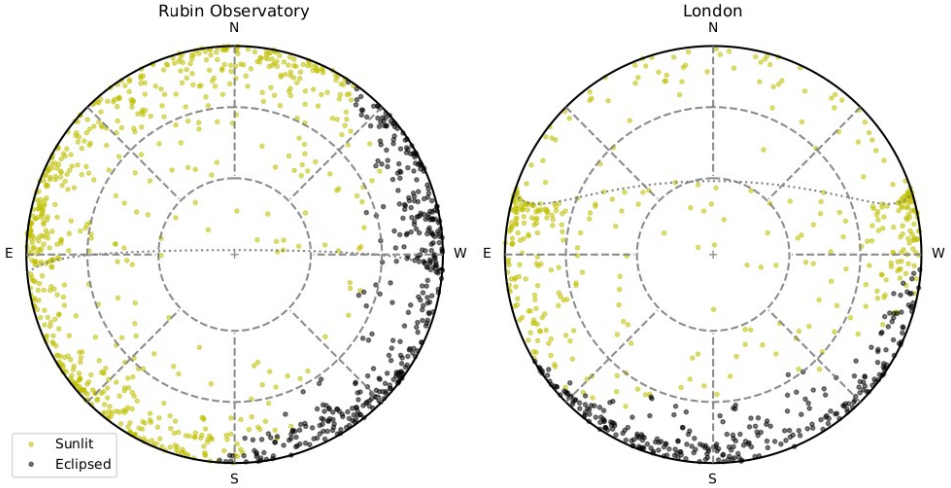
See afternoon talk by Olivier Hainaut!

@cgbassa

Based on https://arXiv.org/abs/2108.12335

Discrete simulations of all-sky impact





- Constellation/satellite properties
- Observatory latitude

- Solar declination (time of year)
- Solar elevation (time of day)

See McDowell (2020), Hainaut & Williams (2020), Lawler et al. (2021)

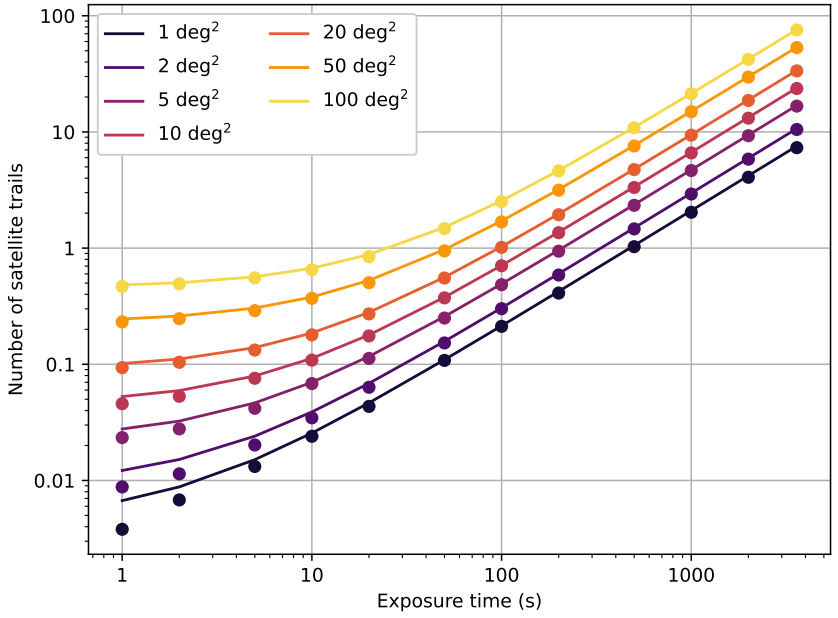
Discrete simulations of observational impact

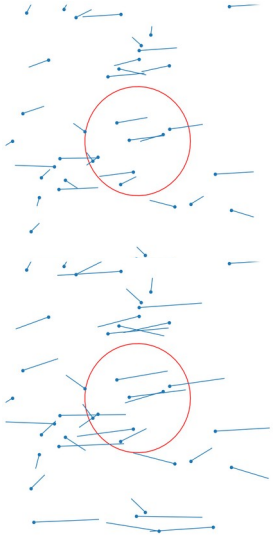
Count trails per exposure:

- Exposure time (t_{exp})
- Field-of-view (A_{fov} and L_{fov})
- Satellite density (ρ_{sat})
- Angular velocity (ω_{sat})

$$N_{\text{trail}} = \rho_{\text{sat}}(A_{\text{fov}} + L_{\text{fov}}\omega_{\text{sat}}t_{\text{exp}})$$

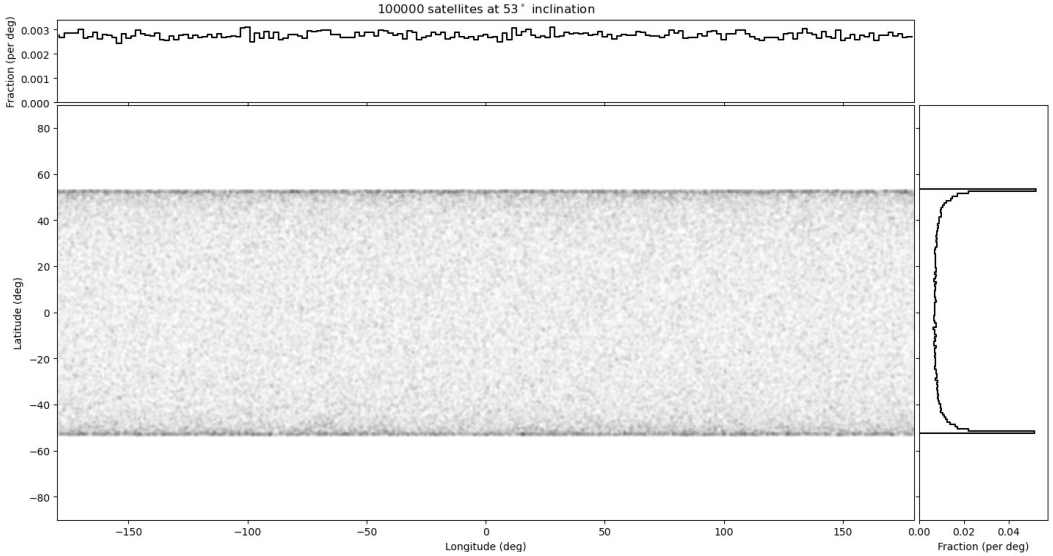
Average over many discrete constellation realizations
(slow for 65000 satellites!)





$A_{fov}=L_{fov}^2$
$A_{fov}=\pi(L_{fov}/2)^2$

Analytical simulations of observational impact



$$P(\phi, i, h_{\mathrm{sat}}) = \frac{1}{2\pi^2 (R_\oplus + h_{\mathrm{sat}})^2 \sqrt{(\sin i + \sin\phi)(\sin i - \sin\phi)}}.$$

Satellite density is uniform with longitude but strongly peaked with latitude (arcsine distribution)

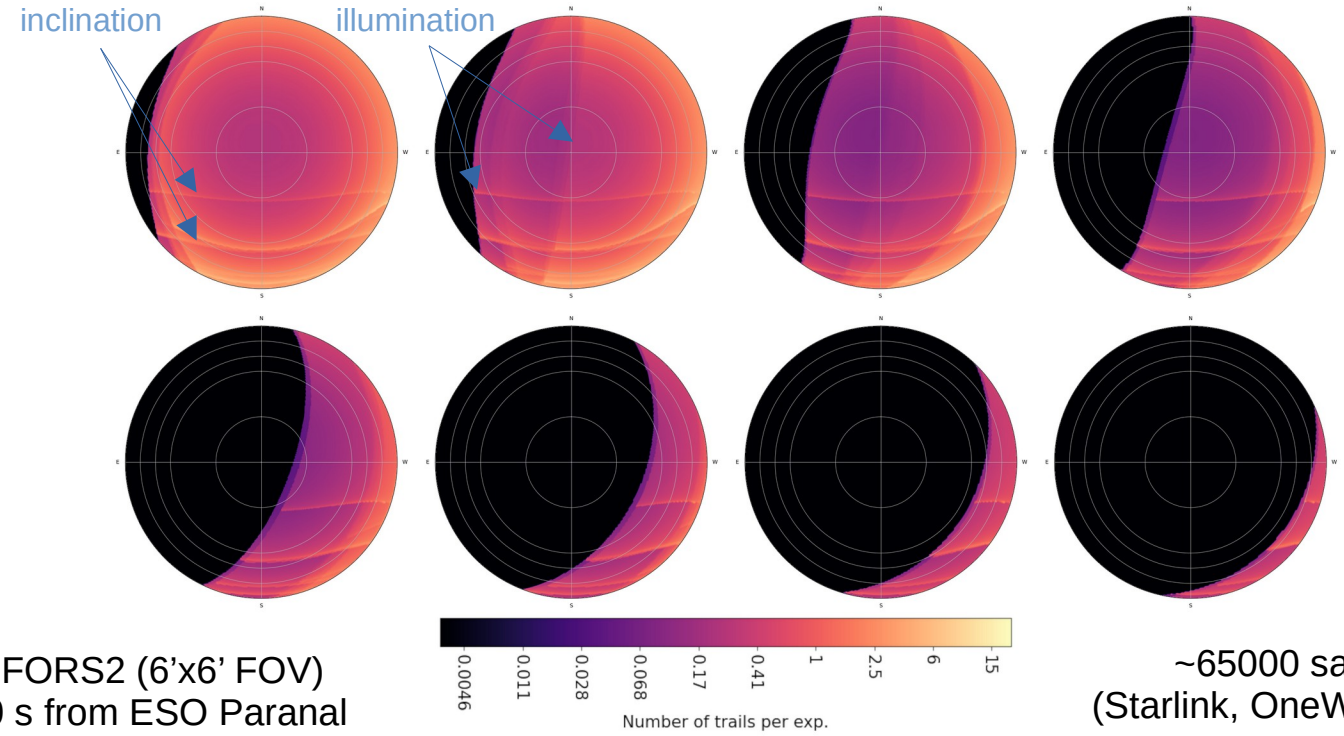
Use analytical probability density to define orbital shell density (n_{sat}/km^2)

Transform to sky density ρ_{sat} (n_{sat}/deg^2) for sight line at distance d, impact angle α, field-of-view A, and N_{sat} objects in orbital shell

$$\rho_{\mathrm{sat}} = N_{\mathrm{sat}} P(\phi, i, h_{\mathrm{sat}}) \frac{d^2 A}{\cos\alpha}$$

Applicable to fully populated shells

Trails per exposure



FORS2 (6'x6' FOV)
300 s from ESO Paranal

~65000 satellites
(Starlink, OneWeb, Kuiper)

Simple photometric modelling

- Apparent magnitude:

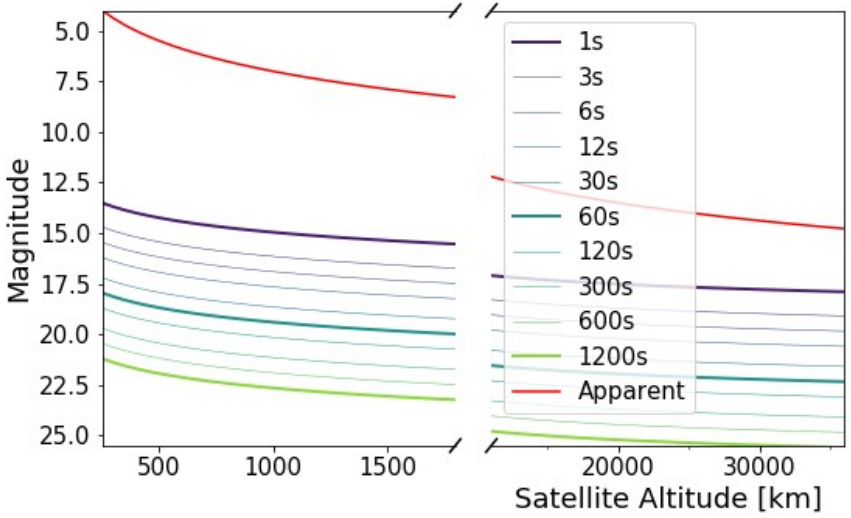
$$m_{\mathrm{sat}} = m_{1000\mathrm{km}} + 5\log_{10}(d_{\mathrm{sat}}/1000) + kd_{\mathrm{sat}}/h_{\mathrm{sat}}$$

Depends on distance d_{sat}, altitude h_{sat} and extinction k
(m_{1000km}~7 for Starlink and OneWeb)

- Effective magnitude:

$$m_{\mathrm{eff}} = m_{\mathrm{sat}} - 2.5\log_{10}\frac{t_{\mathrm{eff}}}{t_{\mathrm{exP}}} = m_{\mathrm{sat}} - 2.5\log_{10}\frac{r}{\omega_{\mathrm{sat}} t_{\mathrm{exp}}}$$

Depends on instrument resolution r, exposure time t_{exp} and angular velocity ω_{sat}



See afternoon talk by Olivier Hainaut!

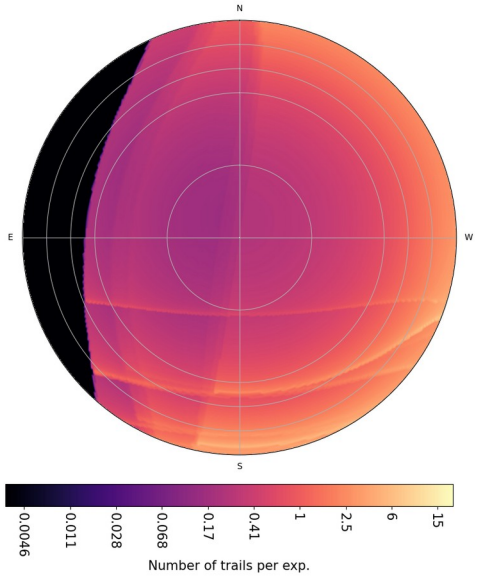
Effect on observations

Definition:

- m_{eff} < 1σ detection limit: no effect
- otherwise, area of 5 arcsec wide trail lost from detector or slit
- if m_{eff} > heavy saturation limit, entire observation lost

Check of all orbital shells, all constellations.

Fraction lost is the fraction of observations or pixels in observation lost due to satellite trails



FORS2 (6'x6' FOV)
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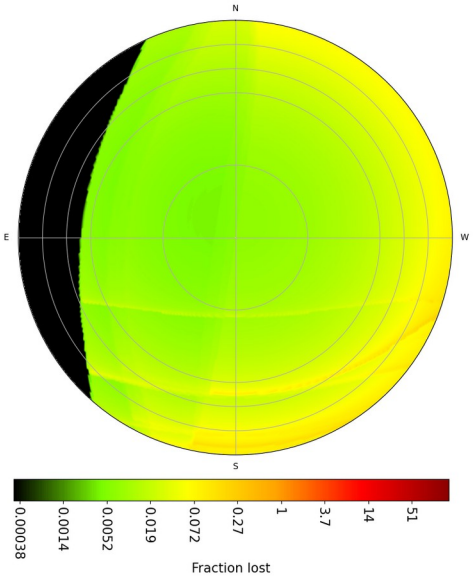
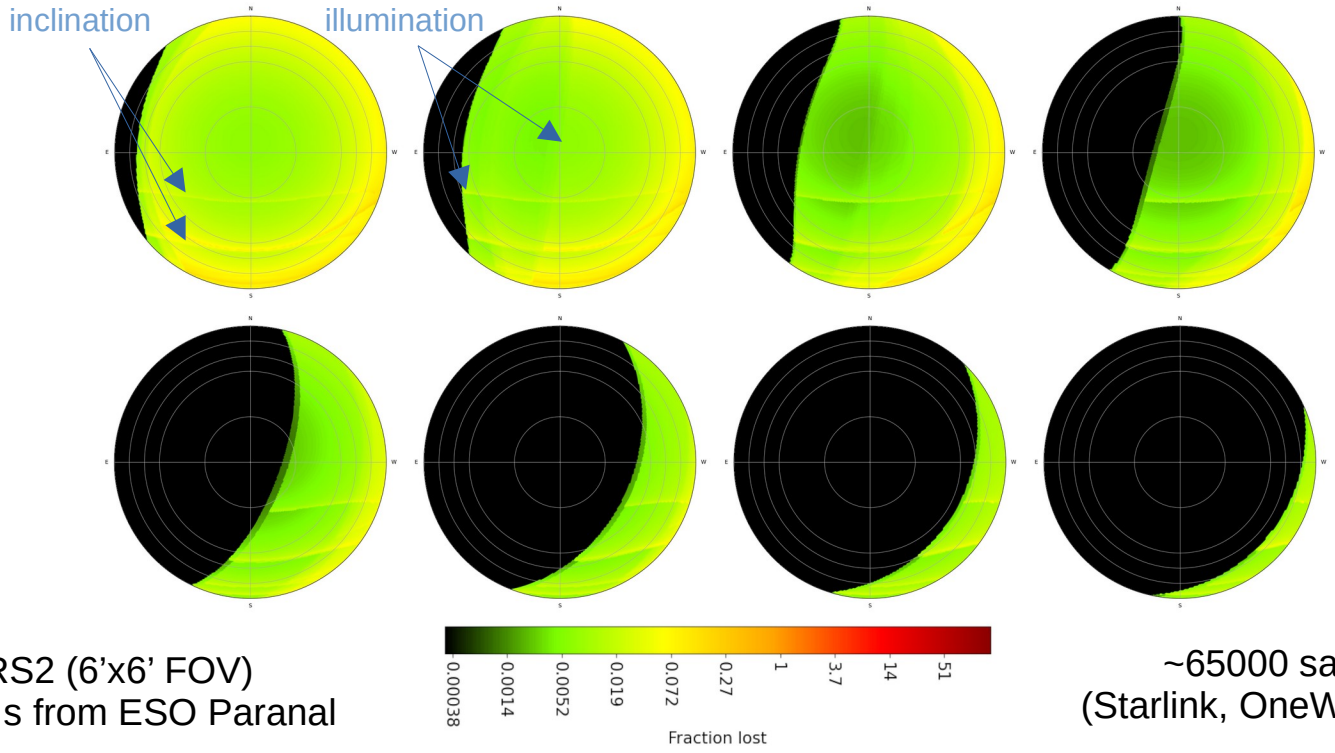


~65000 satellites
(Starlink, OneWeb, Kuiper)

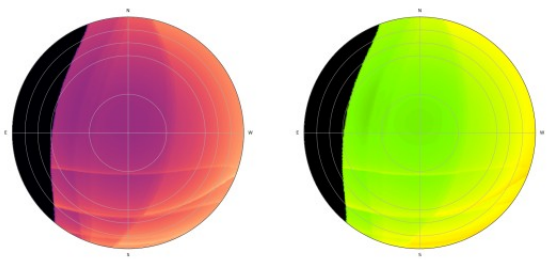
Fraction of lost observations



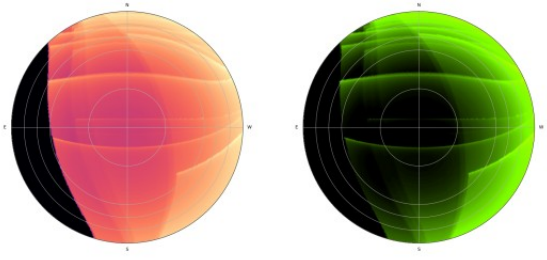
FORS2 (6'x6' FOV)
300 s from ESO Paranal

~65000 satellites
(Starlink, OneWeb, Kuiper)

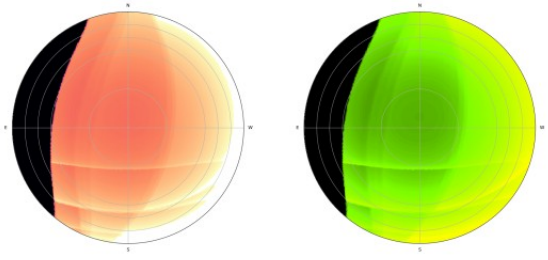
Imagers



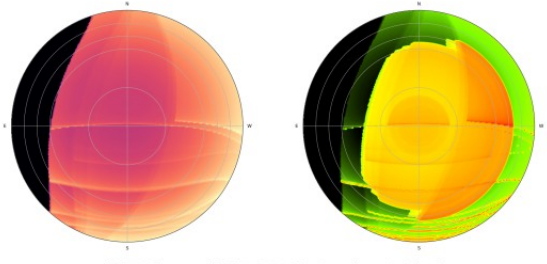
FORS (VLT, ESO, Paranal) 25.2
Average: 0.16 trail, 0.44% loss



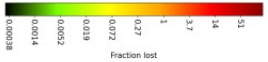
1.5m G96 (Catalina, U.AZ, Mt. Lemmon) 21.4,
0.47 trail, 0.030% loss



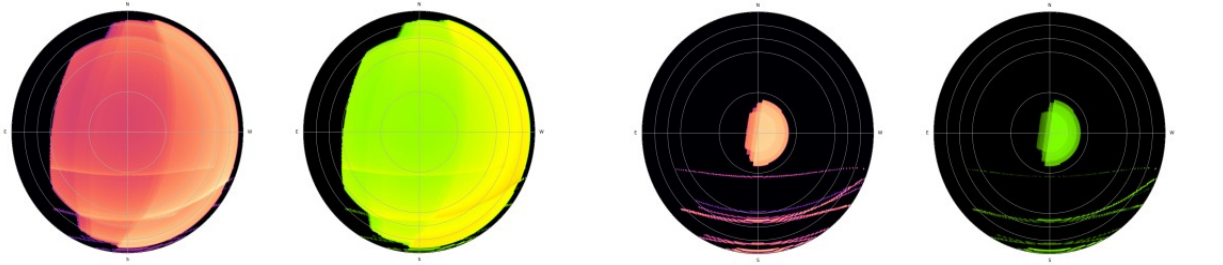
OmegaCam (VST, ESO, Paranal) 23.9,
1.60 trail, 0.22% loss



SST Cam. (SST, VRO, Pachon) 21.4,
0.41 trail, 22.0% loss

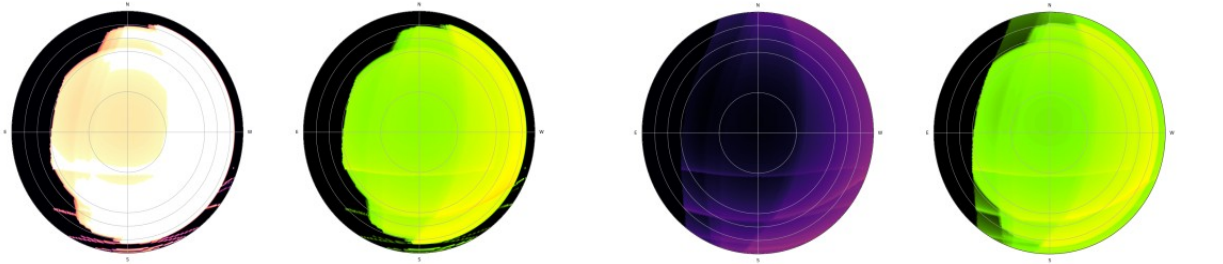


Spectrographs



FORS (VLT, ESO, Paranal) 25.2 Average: 0.64 trail, 8.8% loss

4MOST-HiRes (VISTA, ESO, Paranal), 0.33 trail, 0.018% loss



4MOST-LowRes (VISTA, ESO, Paranal), 14.7 trails, 0.78% loss

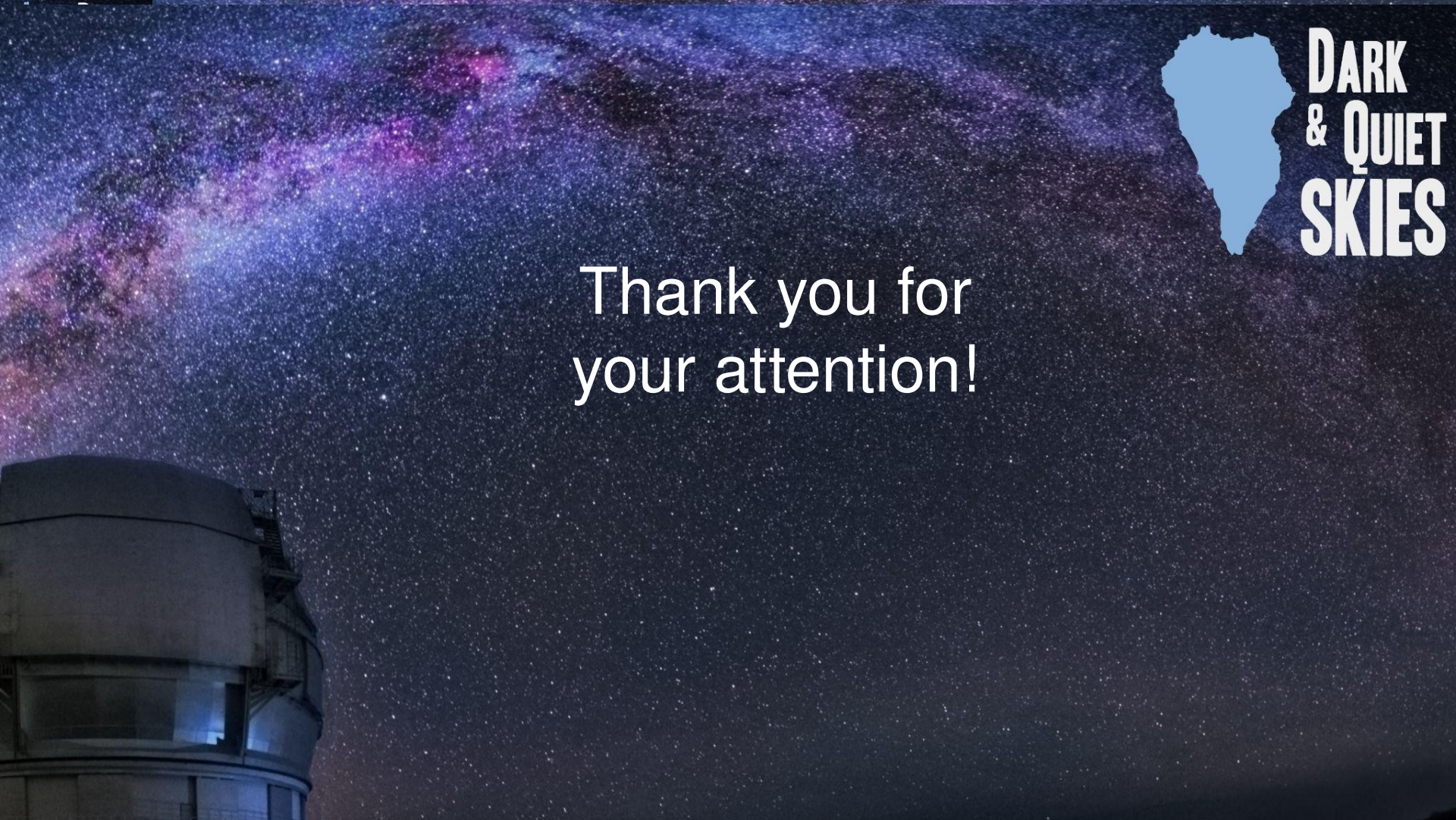
HARMONI (ELT, ESO, Armazones), 0.007 trail, 0.70% loss

Summary

- Derived analytical expressions to assess observational impact
- Analytical simulations allow for fast computation of observational impact for an observatory and satellite constellation(s)
- Impact on sky brightness: see afternoon talk by Olivier Hainaut
- Satellite trails will impact all observatories (both imagers and spectrographs)
- High sensitivity, large field-of-view instruments and/or long exposures are worst affected

Further information

- Paper: arxiv.org/abs/2108.12335 (A&A under review)
- Online simulator: www.eso.org/~ohainaut/satellites/simulators.html
- Github repository: github.com/cbassa/satconsim


DARK
& QUIET
SKIES
Thank you for
your attention!

Impact on observability of specific sources