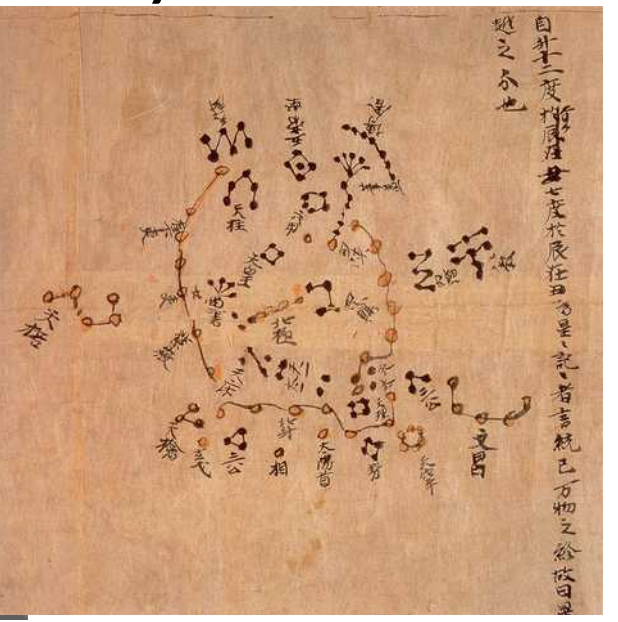
Megaconstellations are about to ruin stargazing for everyone

(and what you can do about it)

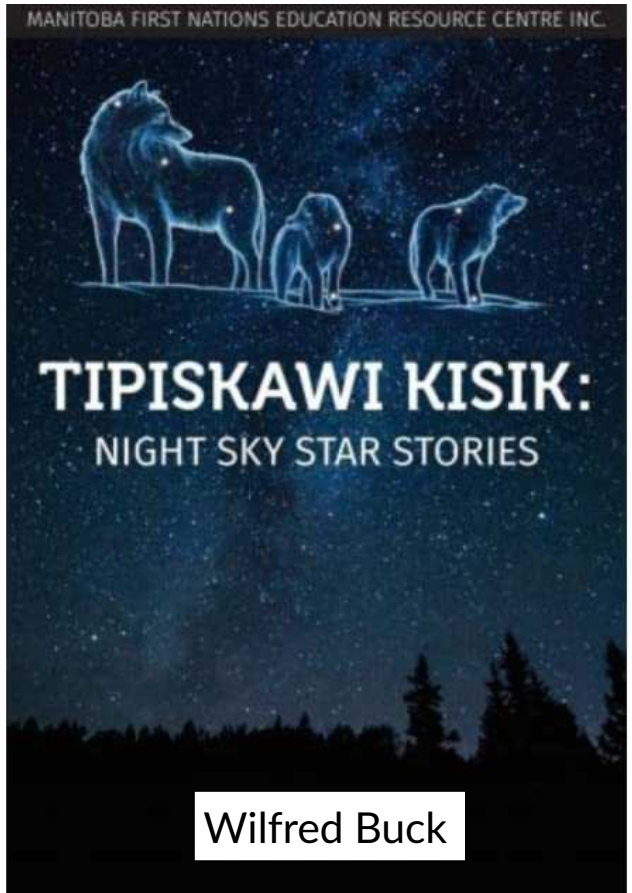
Samantha Lawler
Campion College and the Department of Physics
University of Regina, Saskatchewan

The ancient science of astronomy

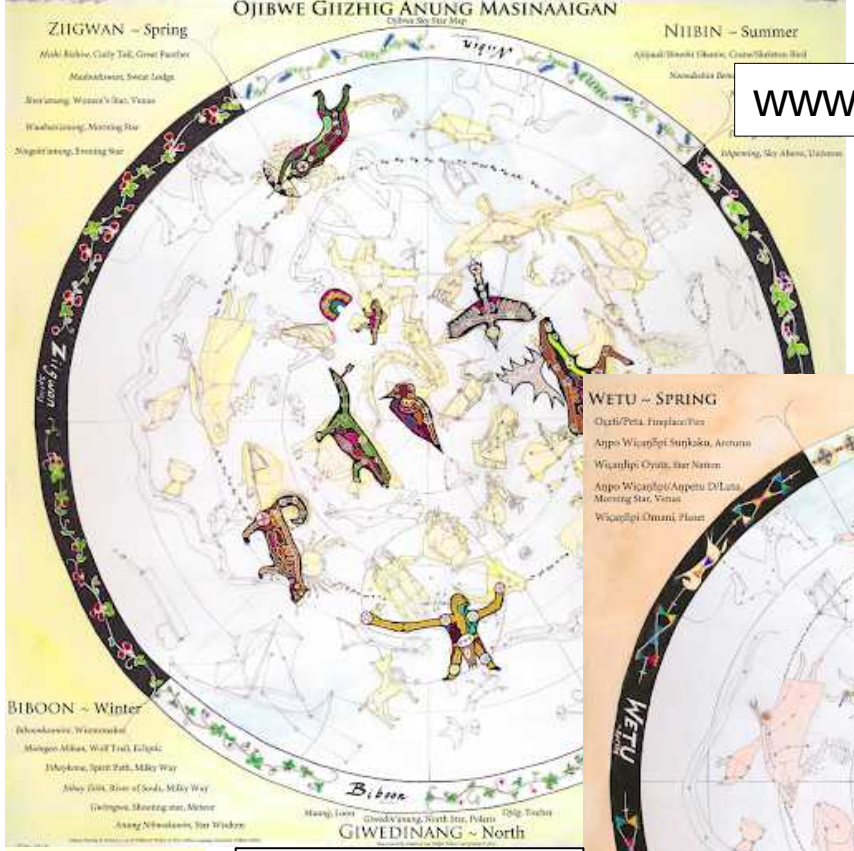


People have been looking up at the sky, noticing patterns, and making predictions for thousands of years – this is part of what makes us human

Indigenous people in North America have cultural heritage and active cultural practice associated with constellations and stargazing.



Wilfred Buck

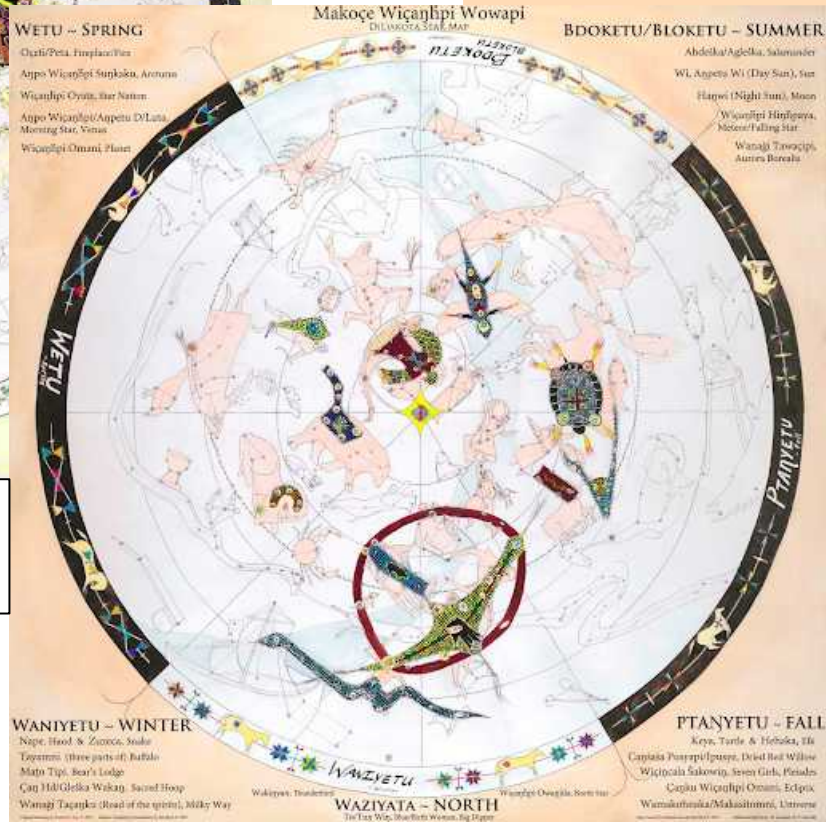


Ojibwe

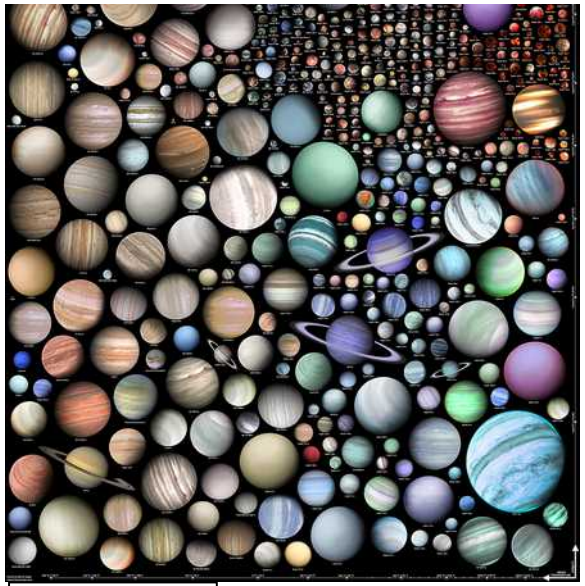
Credit: Annette S. Lee, William P. Wilson, Carl Gawboy

www.nativeskywatchers.com

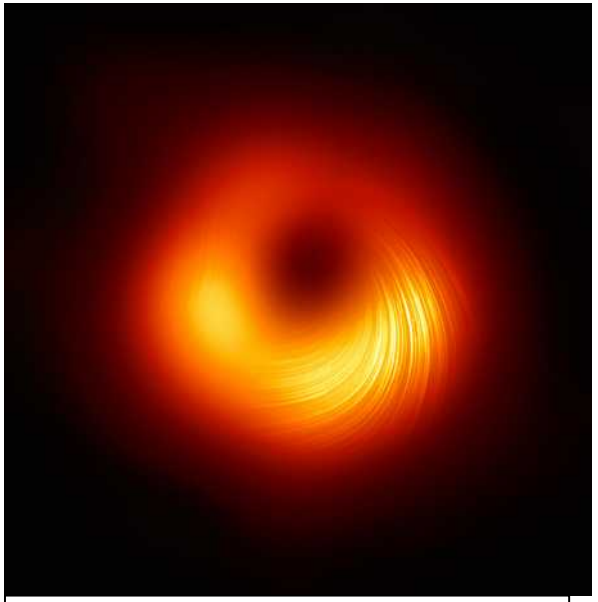
Dakota/Lakota



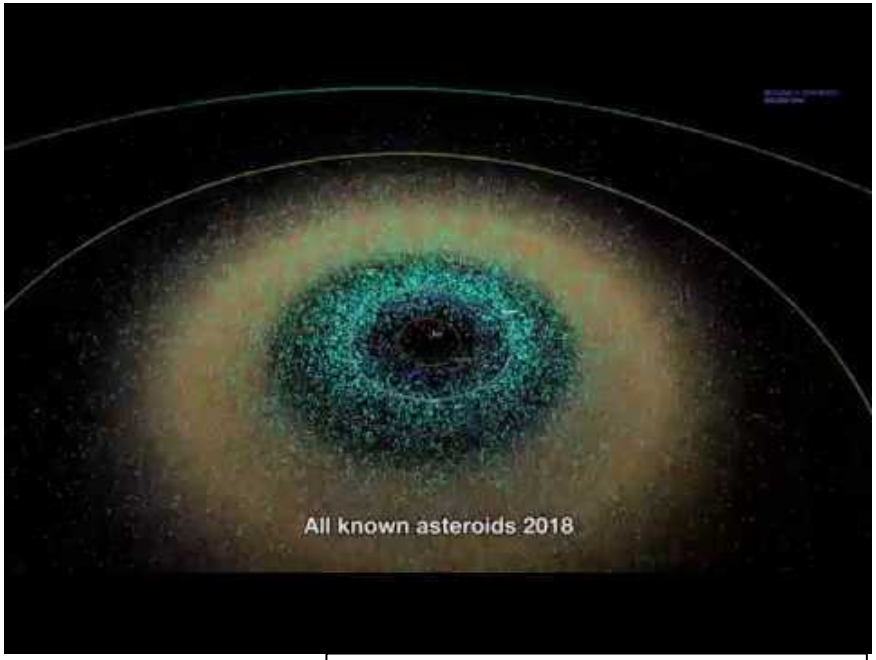
Patterns in the sky



Martin Vargic



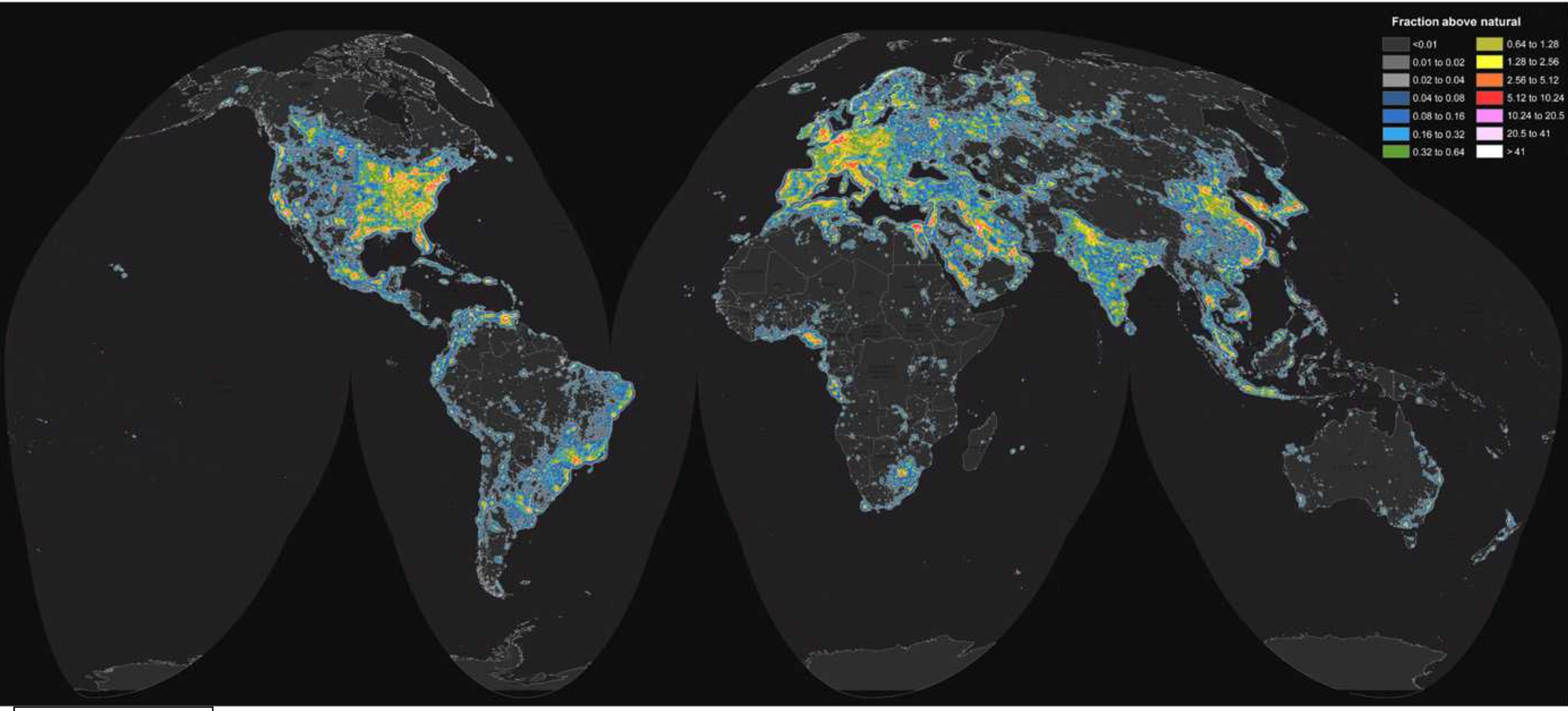
Event Horizon Telescope Collaboration



NASA/Jet Propulsion Laboratory

Our tools now are more sophisticated than in the past, but we still have the same goals: look for patterns, make predictions, avoid catastrophe.

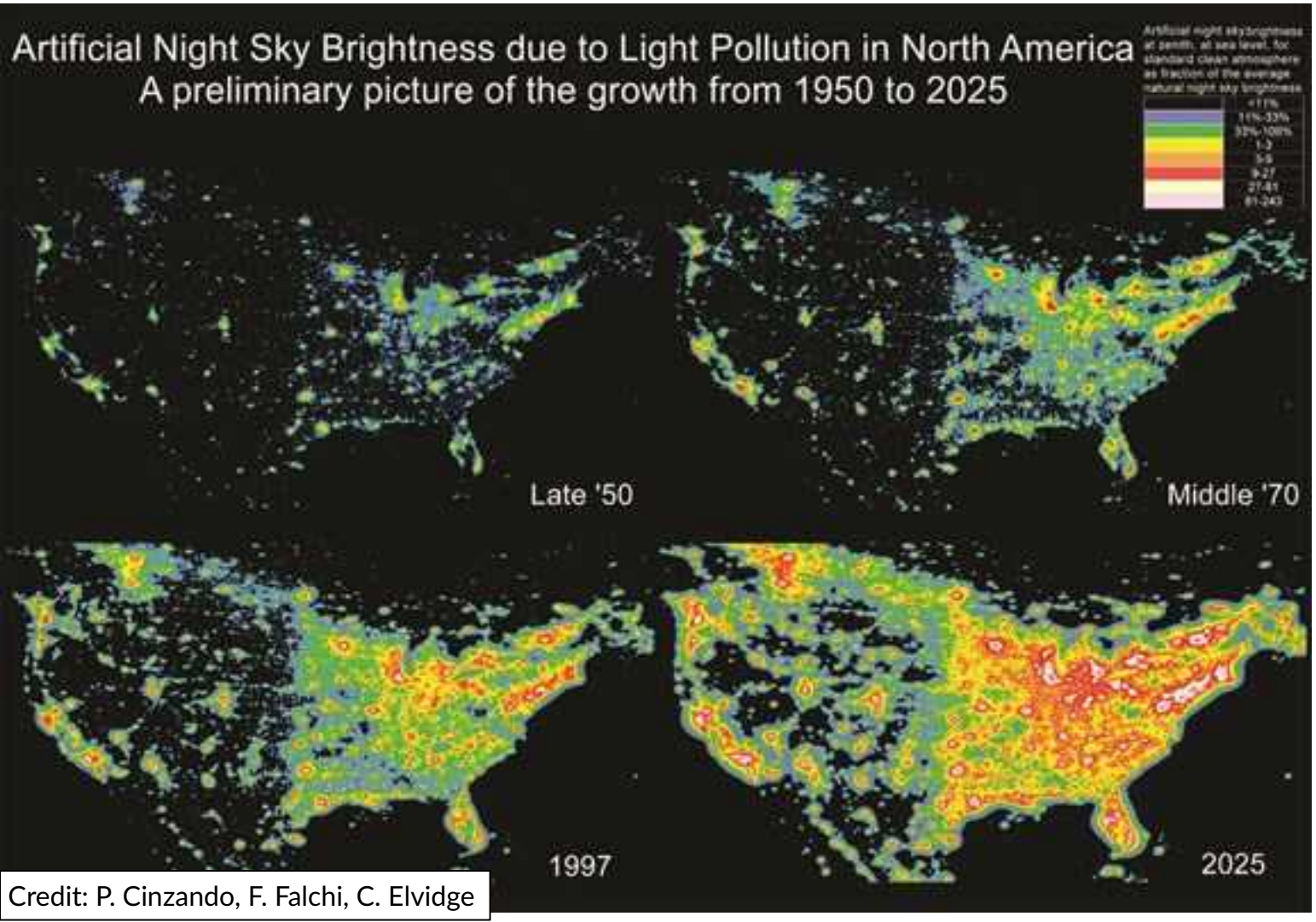
Urban light pollution is already destroying acess to the night sky



Falchi et al. 2016

99% of people in US and Europe live under light-polluted skies,
80% of North Americans can't see the Milky Way

Urban light pollution is already destroying acess to the night sky



Credit: P. Cinzando, F. Falchi, C. Elvidge

But there are many groups fighting! (ex: International Dark Sky Association)

LEDs (a sudden leap in technology access) took these groups by surprise

LEDs are good – use less energy for more light. But are massively over-used because they're cheap.

Urban light pollution is escapable

https://www.michigan.org/darksky

10 TIPS FOR ENJOYING MICHIGAN'S DARK SKIES

Michigan is surrounded by the Great Lakes, which shroud the state in near-total darkness. This makes it the perfect destination for some of the best stargazing in the nation. To be well prepared for your night of stargazing, follow these ten tips.

READ MORE →

THE MOST STELLAR PLACES FOR STARGAZING IN MICHIGAN

The night sky has perhaps never been a bigger tourist attraction, and there are few better spots for its viewing than along long, rural stretches of Pure Michigan sandy beach where the rhythm of Great Lakes waves serves as a stargazing soundtrack.

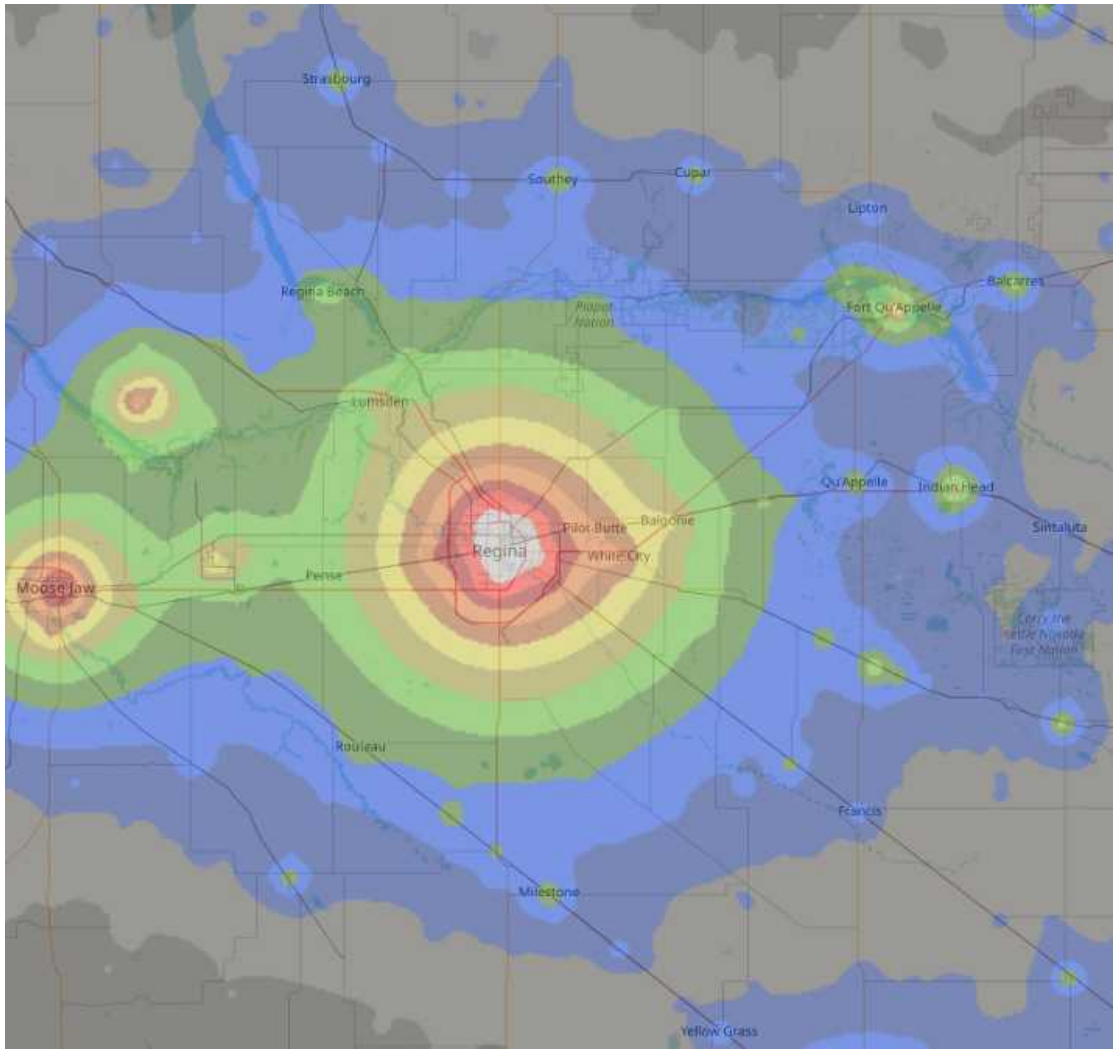
READ MORE →

MAGICAL DESTINATIONS TO CHASE THE NORTHERN LIGHTS IN PURE MICHIGAN

Michigan is home to more than 300 waterfalls, 2,500 miles of trails and 11,000 inland lakes, but did you know it's also one of the best places in the world to view the northern lights?

READ MORE →

My personal connection to the sky



I moved to a farm with Bortle 4 skies in 2019.

For the first time in my life, I could see the Milky Way from my back door!

...But I could also see a noticeably growing number of satellites in the sky.

cleardarksky.com

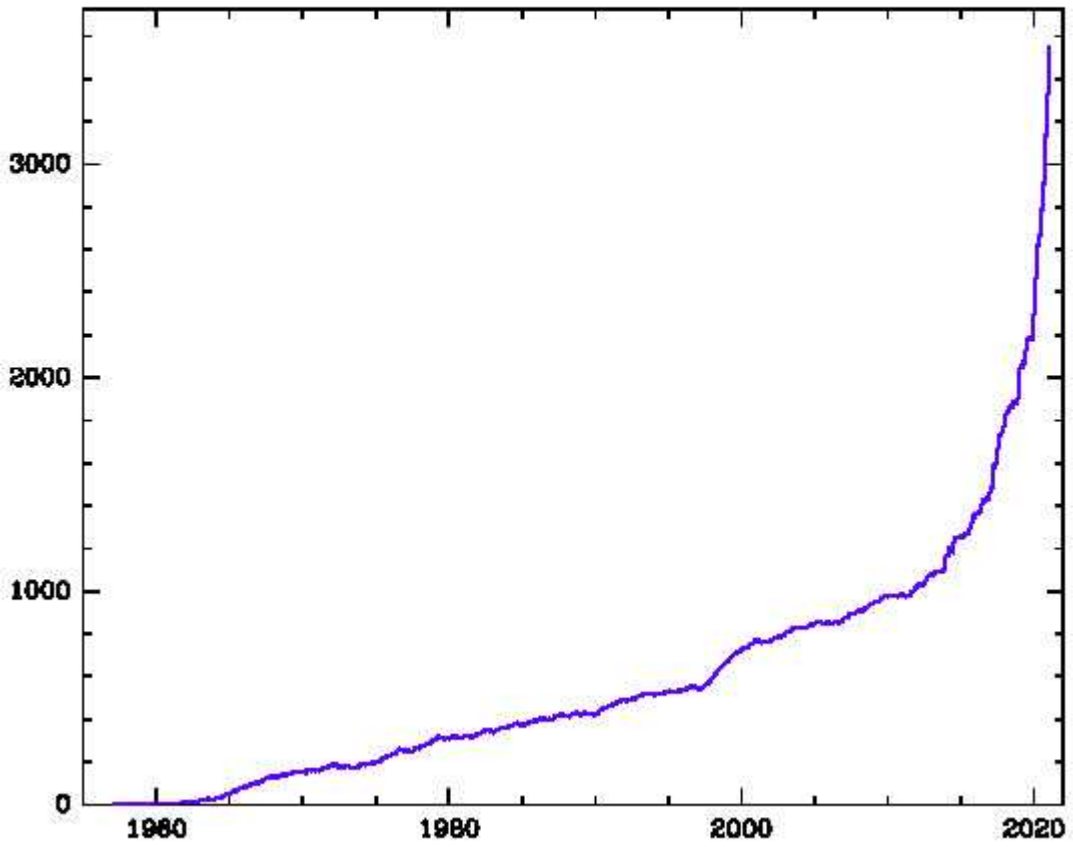
What is happening to my sky??

American private company SpaceX is launching batches of 60 satellites into low-Earth orbit **every 2-3 weeks**.

There are currently 1,637 Starlink satellites in orbit (out of 1740 so far launched)

[Numbers from Jonathan McDowell's Starlink Statistics Page]

What is happening to my sky??



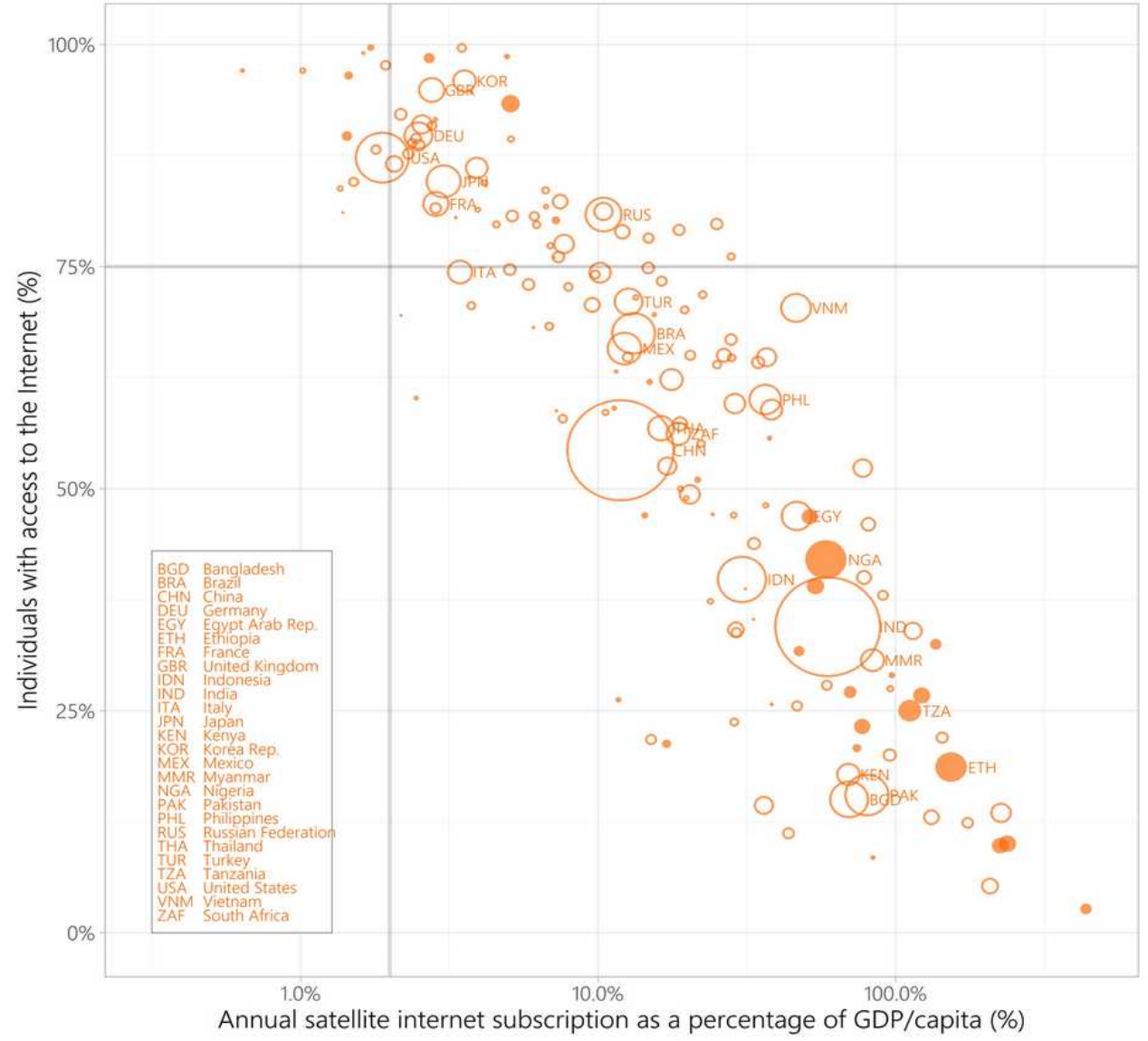
Credit: Jonathan McDowell

1637 active Starlink satellites: almost **50% of active satellites** (3,500 total).

By the end of 2021, SpaceX will own **more than half of all active satellites**.

SpaceX has provisional permission from the FCC to operate **42,000**

These satcons are to provide global internet



Internet satellite access

- Unaffordable and/or not needed

Current Internet cost

- Cheaper than satellite
- More expensive than satellite

Population (in millions)

- 1
- 3
- 10
- 30
- 100
- 300
- 1000

Who benefits?

Rawls et al. 2020

Many other companies are building megaconstellations

- SpaceX - Starlink - 42,000 satellites (provisionally approved)
- Amazon - Kuiper - 3,236 satellites
- OneWeb - 6,372 satellites
- Chinese automotive company Geely - ramping up to build 500 satellites per year by 2025.
- Chinese Hongyun constellation - 864 satellites
- Chinese Hongyan constellation - 320 satellites
- Russian Sfera - 600 satellites.
- France and India signed a deal to cooperate on a marine tracking satellite constellation.
- Laser Light Communications (US) - 12 satellites
- Viasat (US) - 20 satellites
- Germany's Kleo Connect - 300 satellites
- Canada's Telesat - 298 satellites

Why is this a problem?

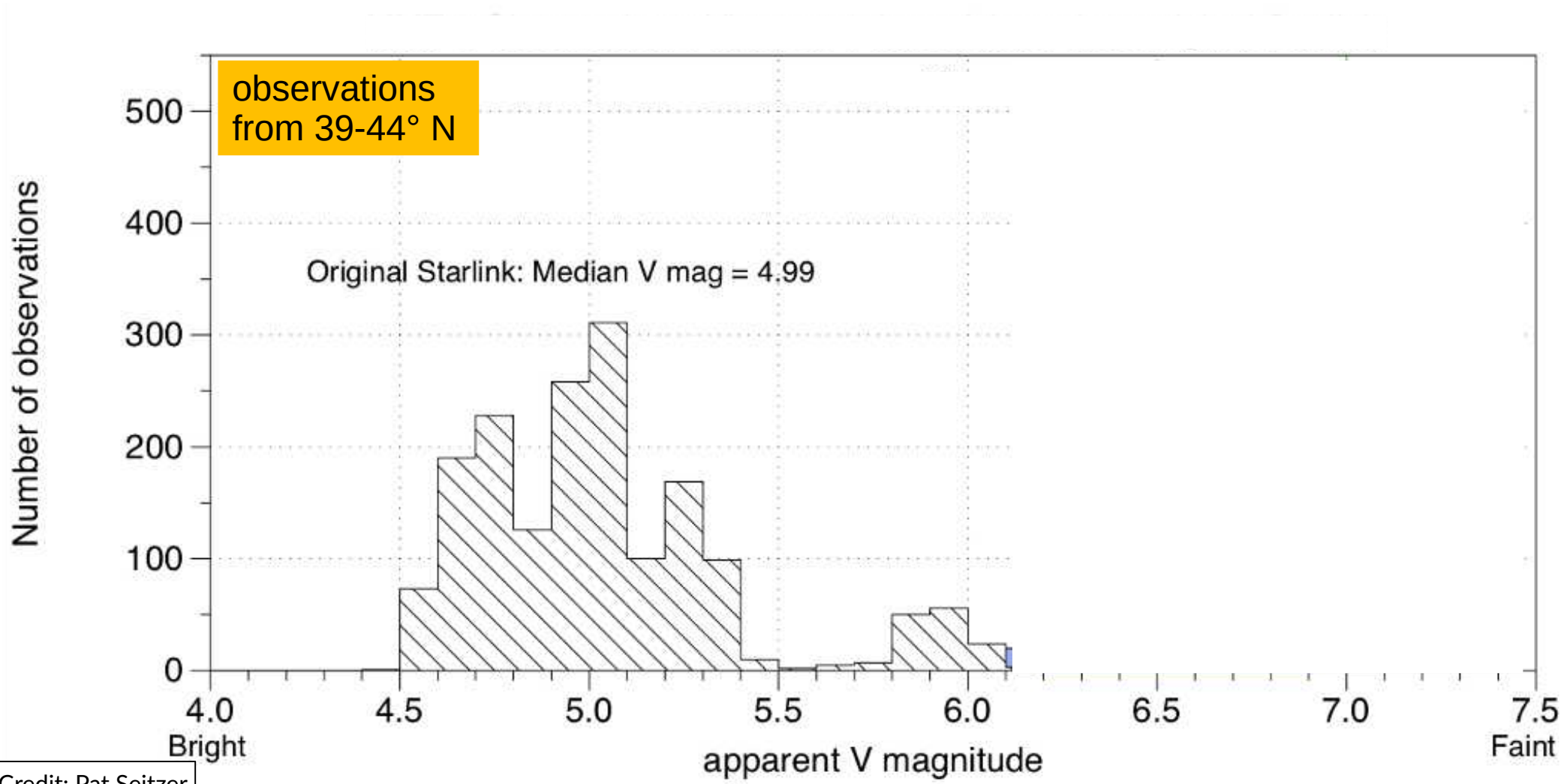
The problem for astronomy: these satellites are very reflective

We are at a transition point: it used to be interesting and exciting to see a satellite pass over.

Now the night sky will become a mundane highway of crawling light pollution.

There are no rules about satellite brightnesses (or orbits, or launches, or really much of anything…) so engineers have almost no effort into making them fainter.

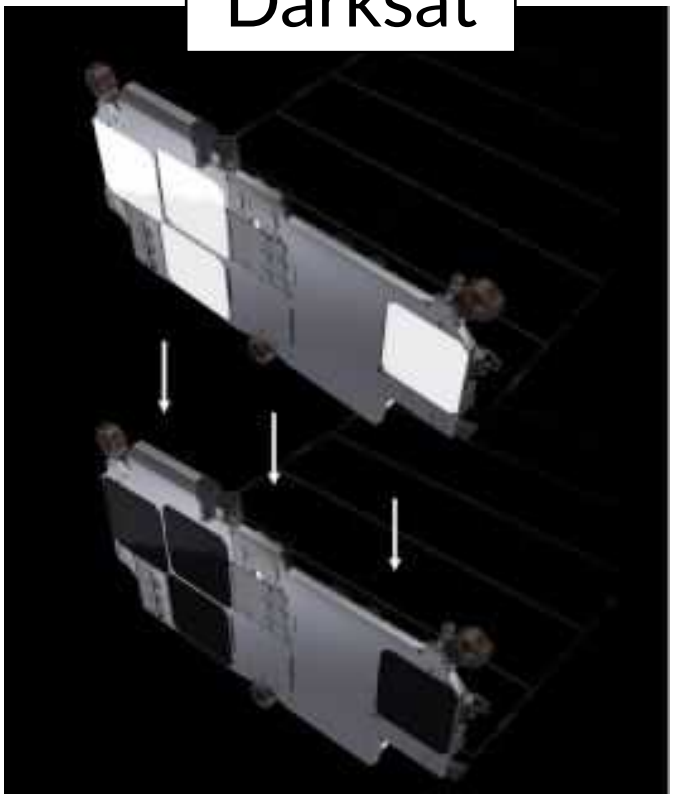
How bright are they?



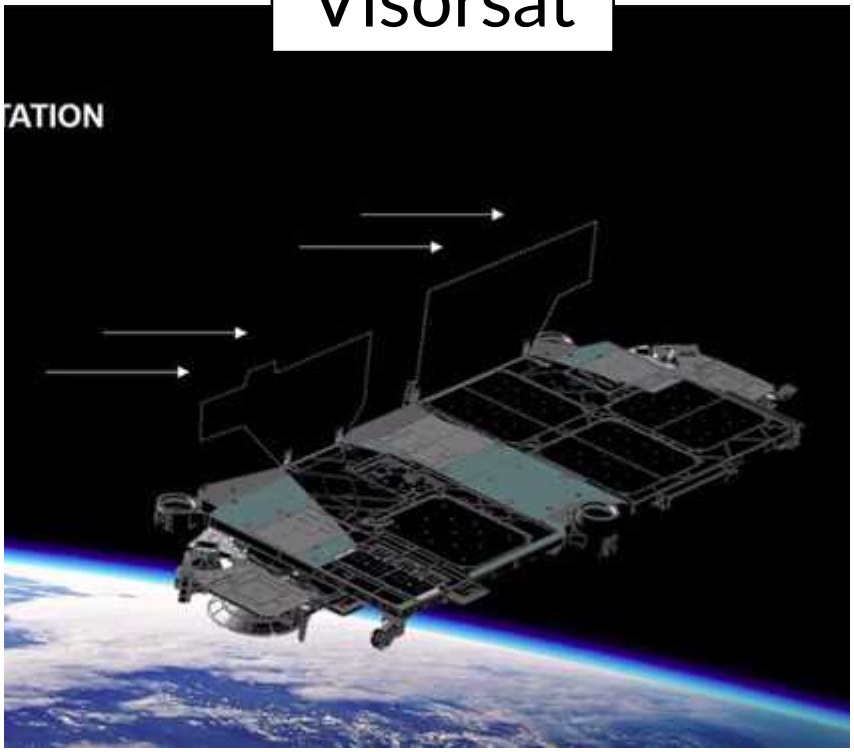
Credit: Pat Seitzer

First attempts at mitigation by SpaceX

"Darksat"

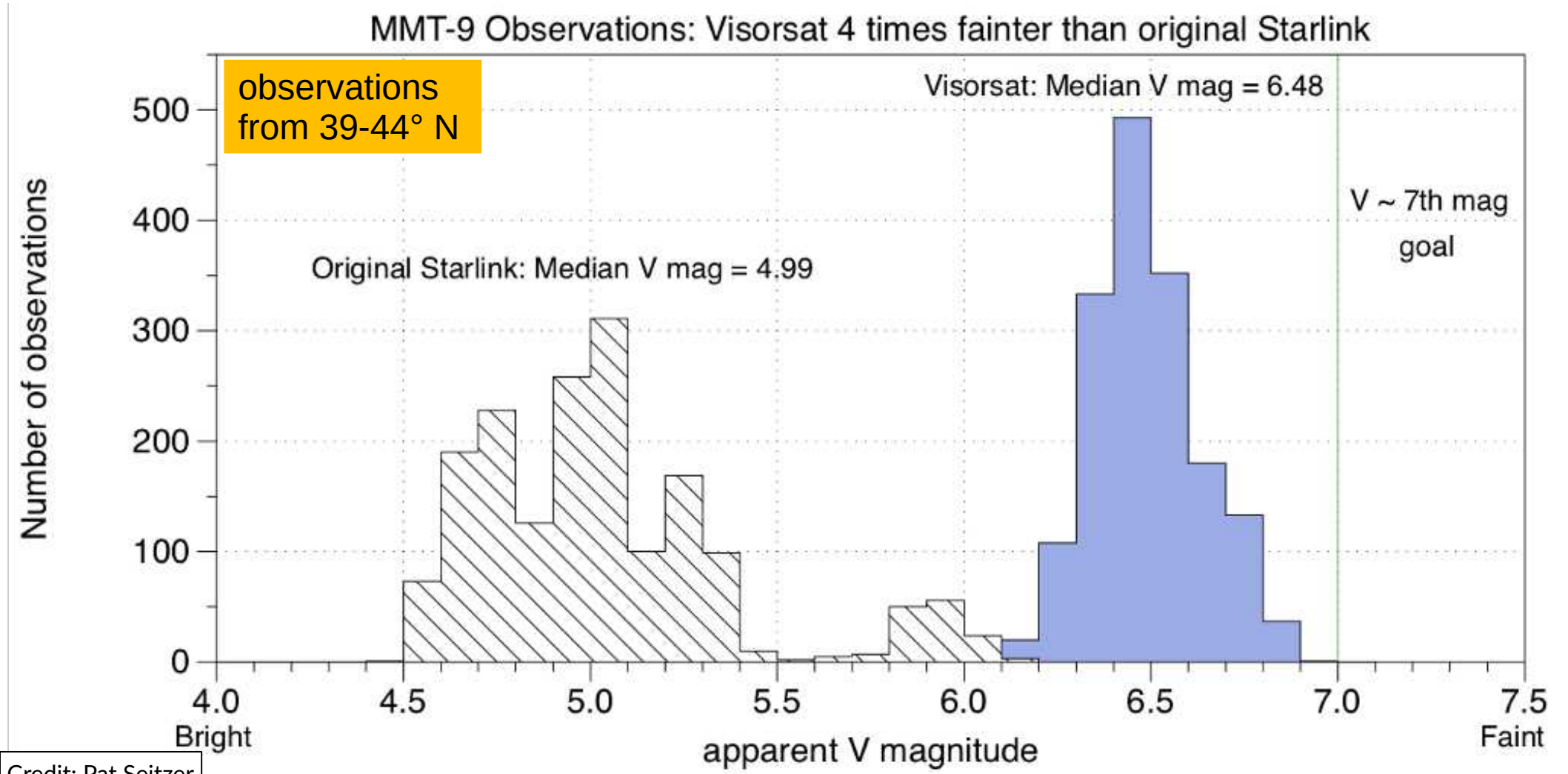


"Visorsat"



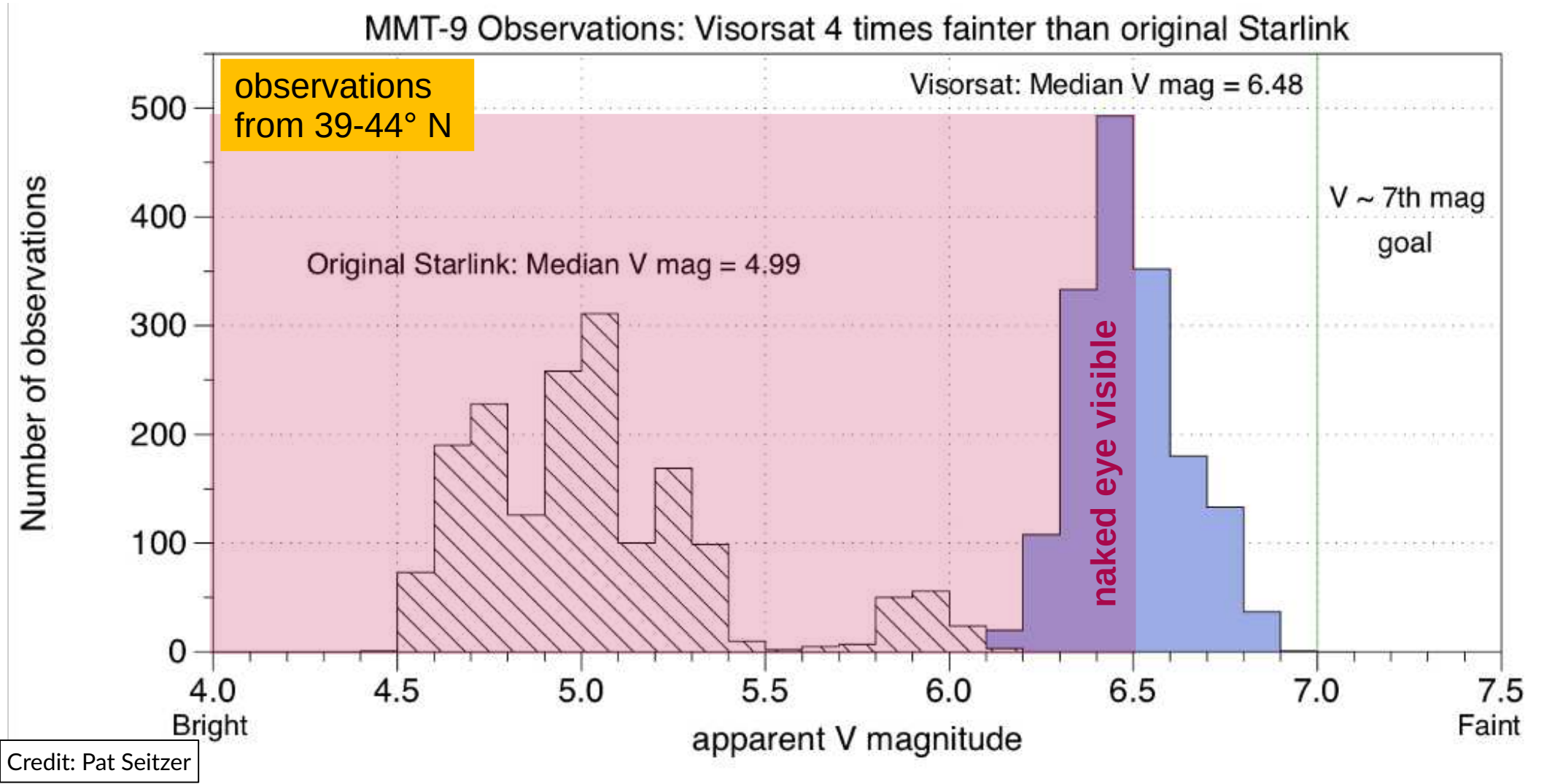
Complaining loudly actually worked! SpaceX listened!
All new Starlinks are Visorsats

Visorsats are fainter



Credit: Pat Seitzer

Visorsats are fainter...but not yet faint enough



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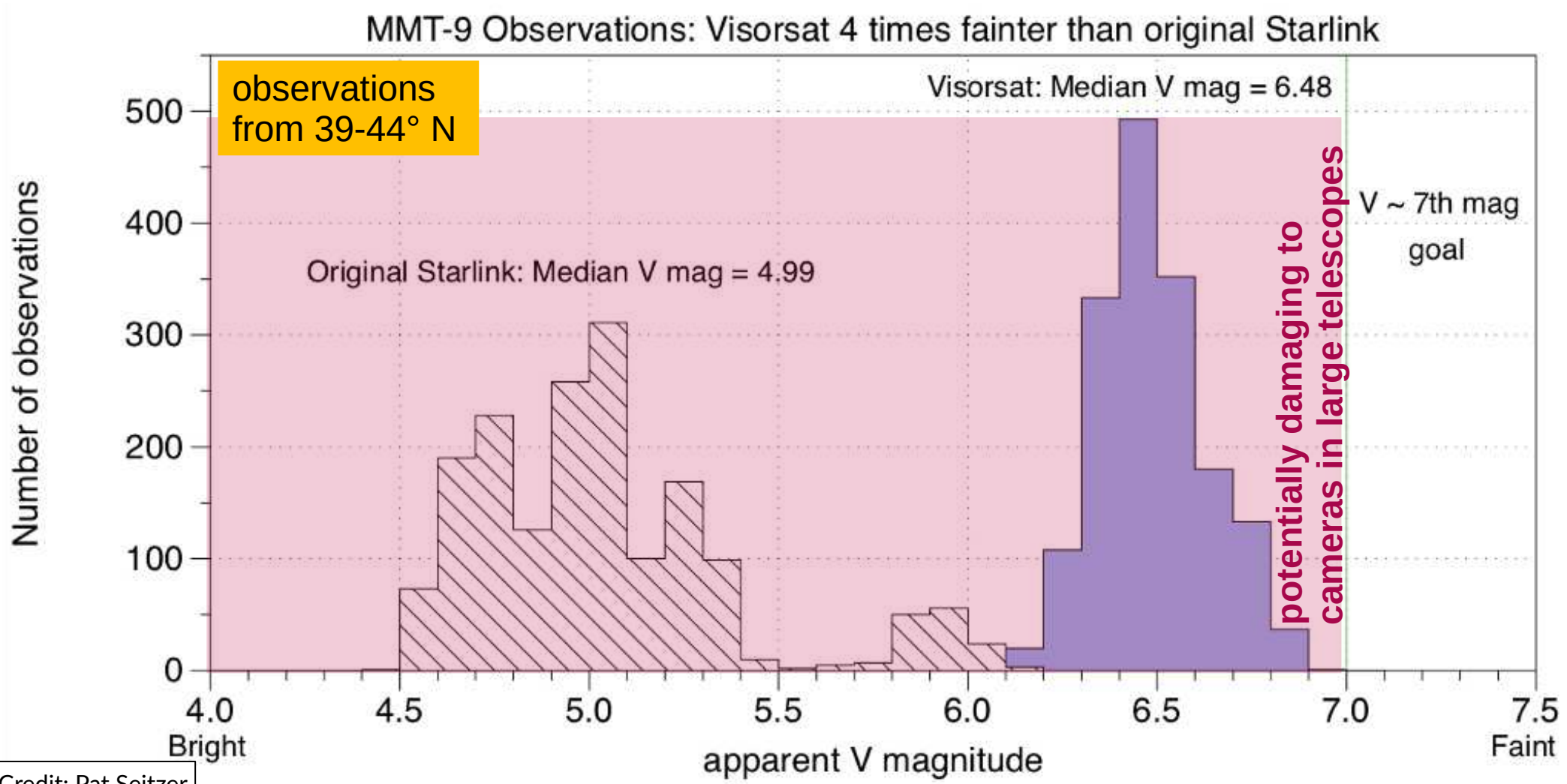
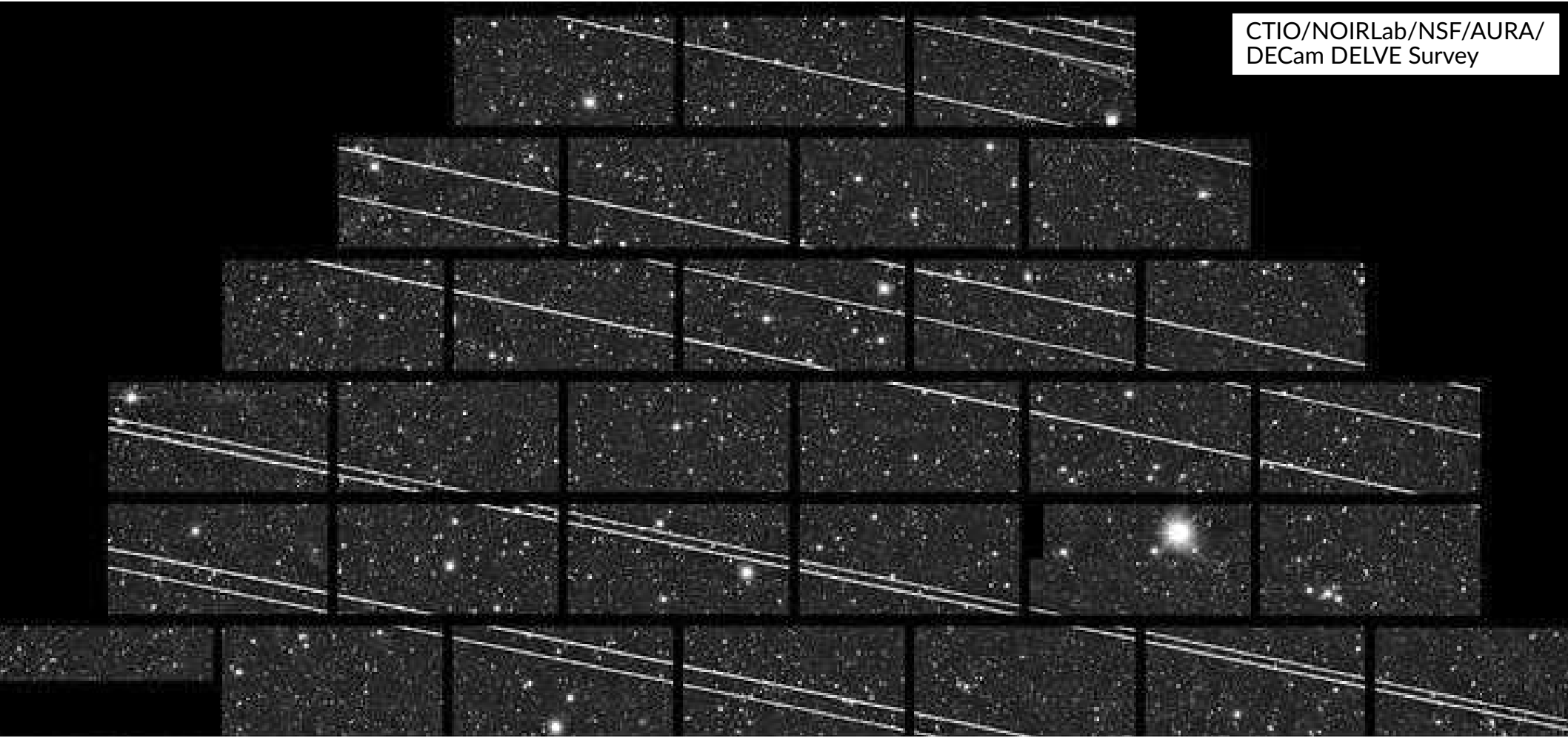


Credit: Pat Seitzer

These satellites “photobomb” long time exposure astrophotos

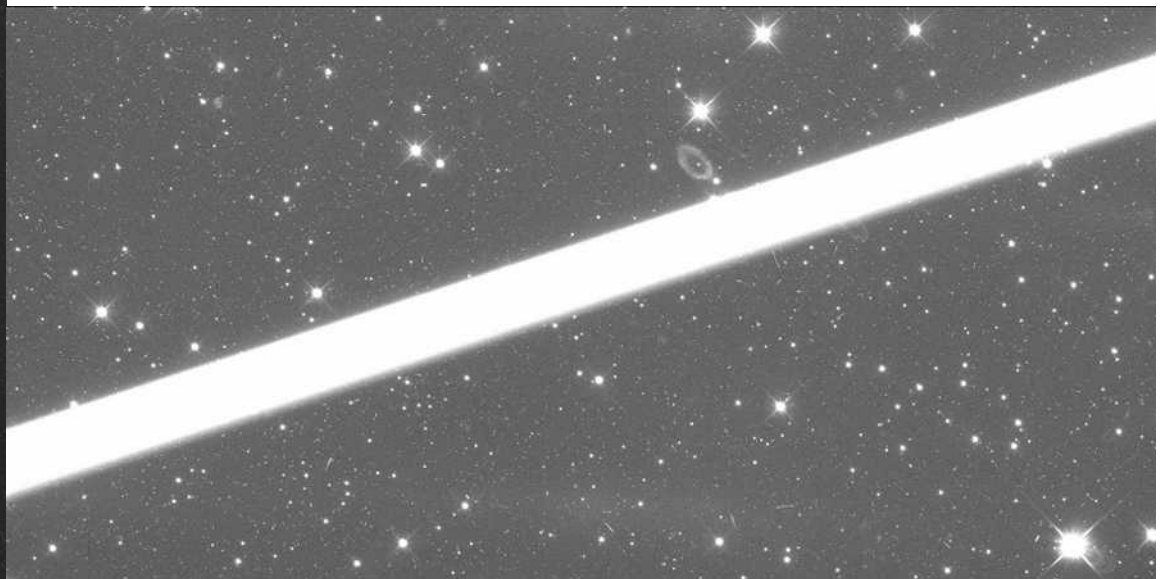
@zdenek_bardon

These satellites “photobomb” long time exposure astrophotos, and research images also



These satellites “photobomb” long time exposure astrophotos, and research images also. Even in space!

@SpaceGeck



@AscendingNode & @planet4589

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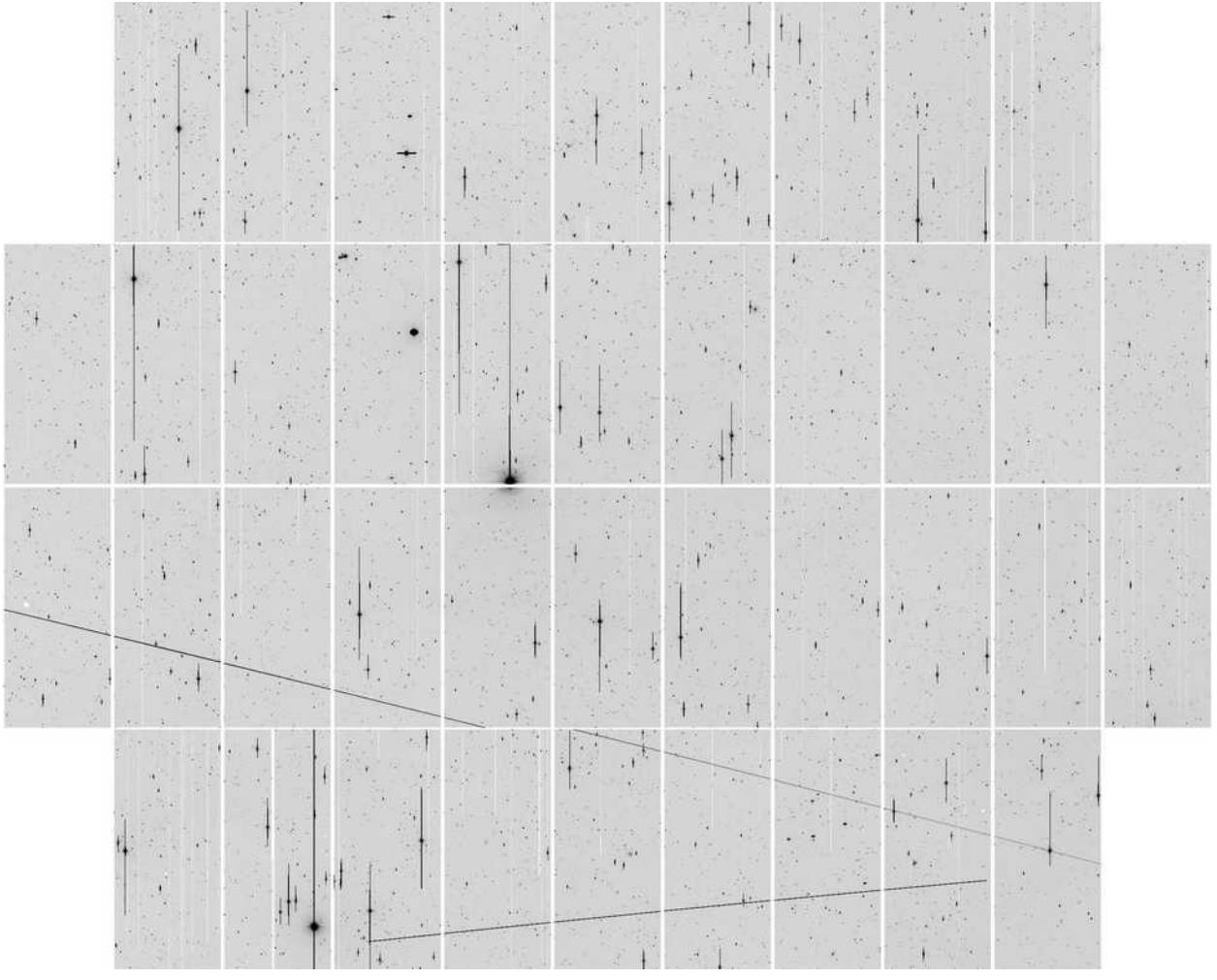

My research: trying to discover new Kuiper Belt Objects to learn about how the Solar System formed.

The typical KBOs we search for are g-mag~25, **15 million times fainter** than a typical Starlink

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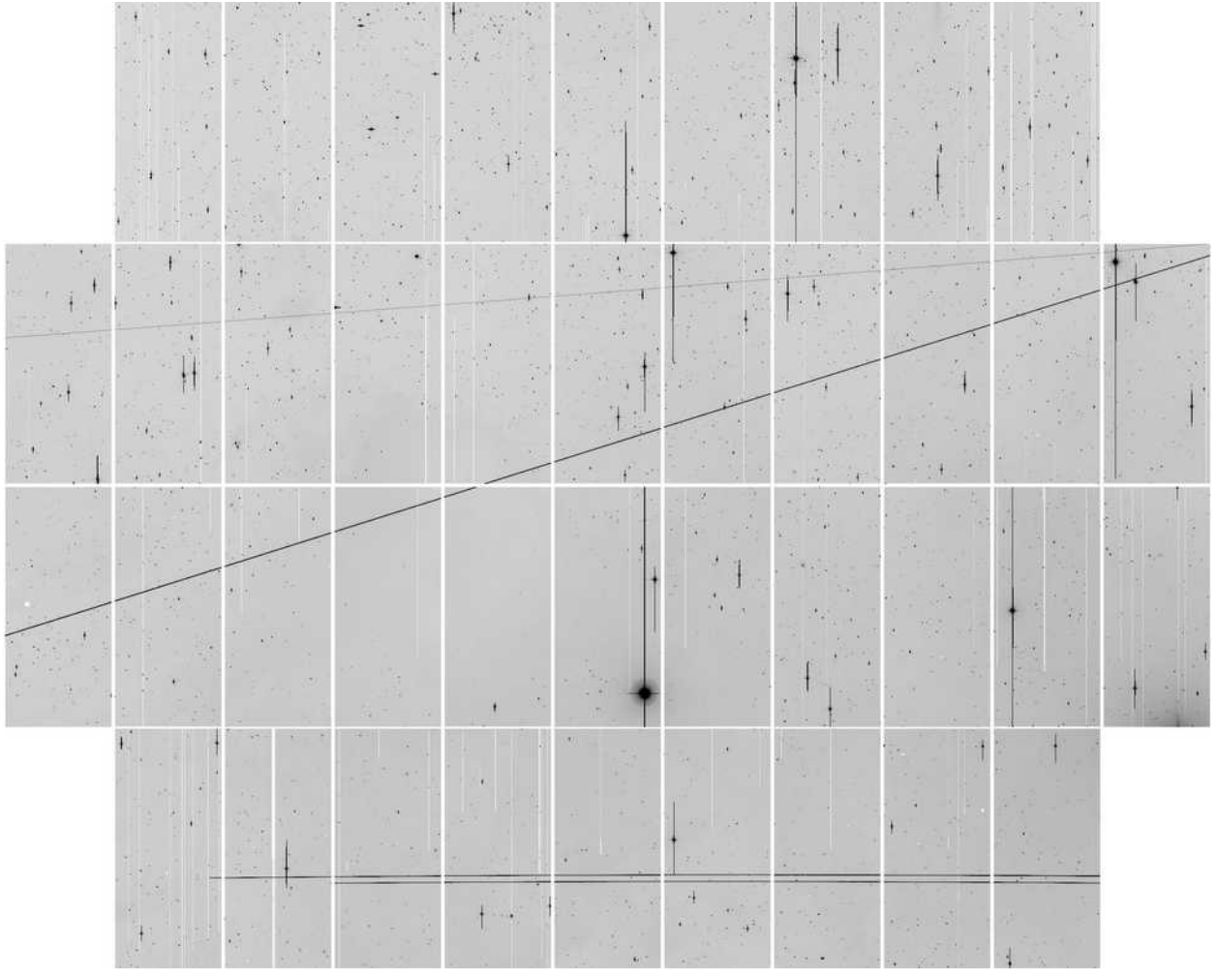

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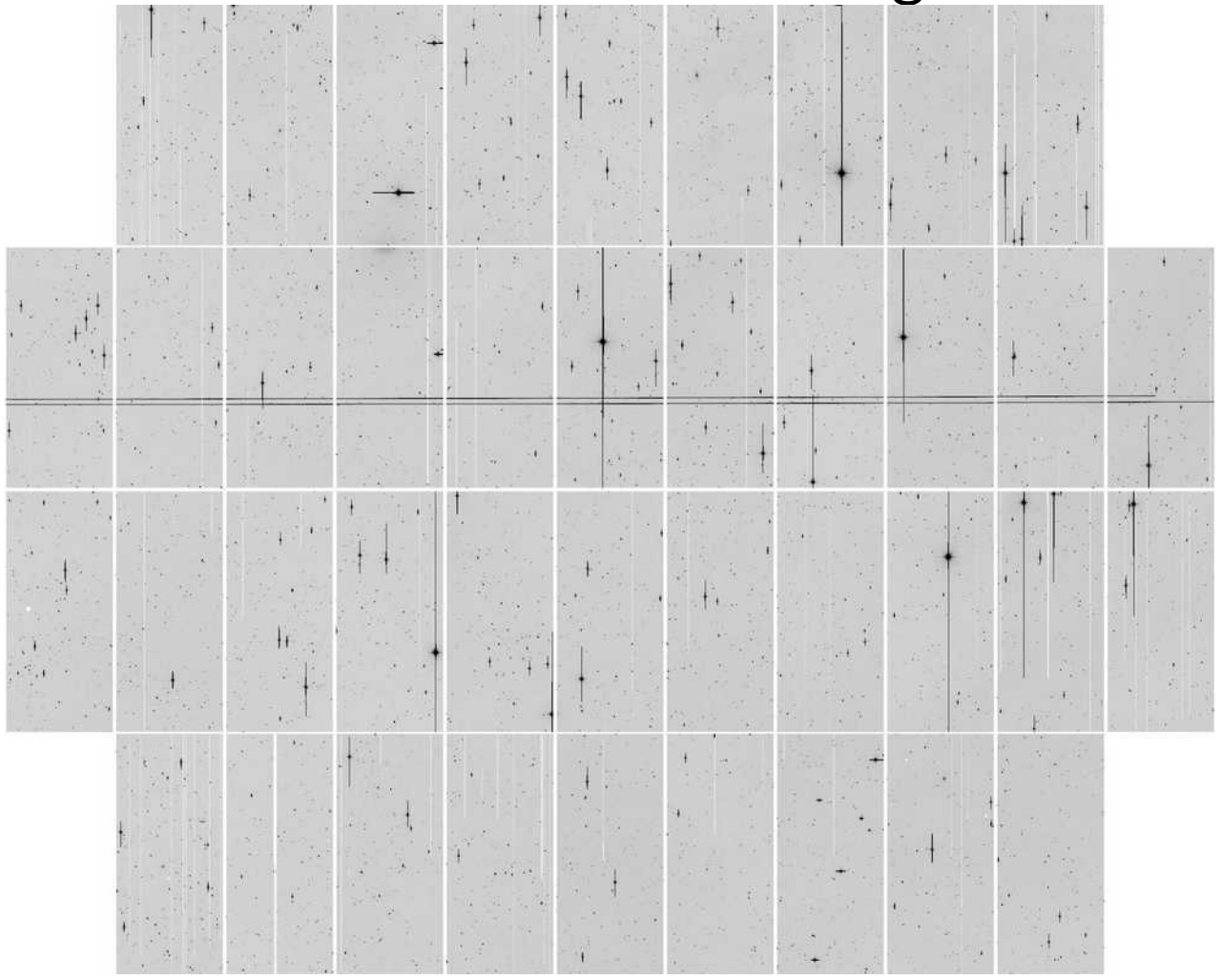

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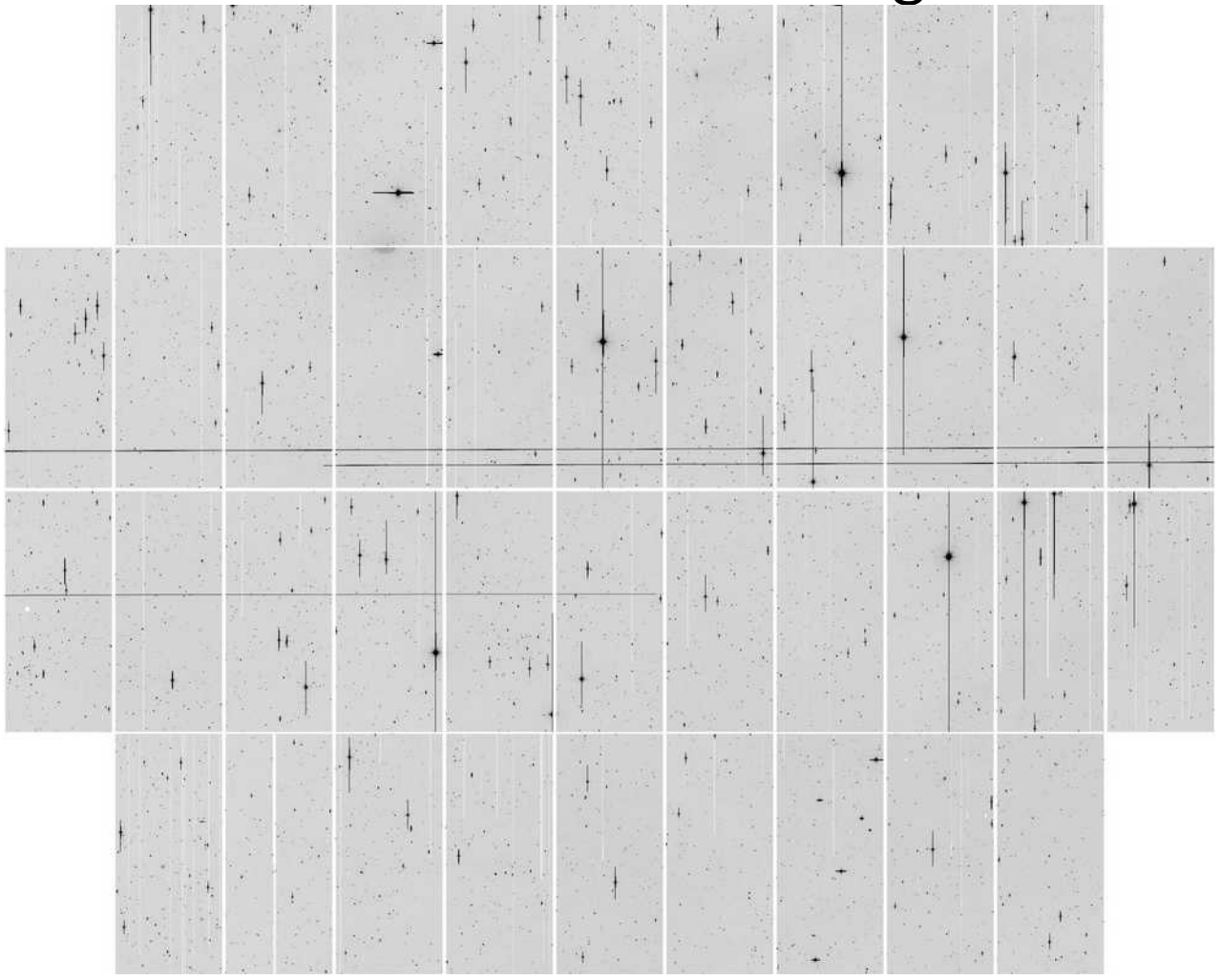

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They are extremely bright and weird-looking when in their initial parking orbit: Starlink “trains”

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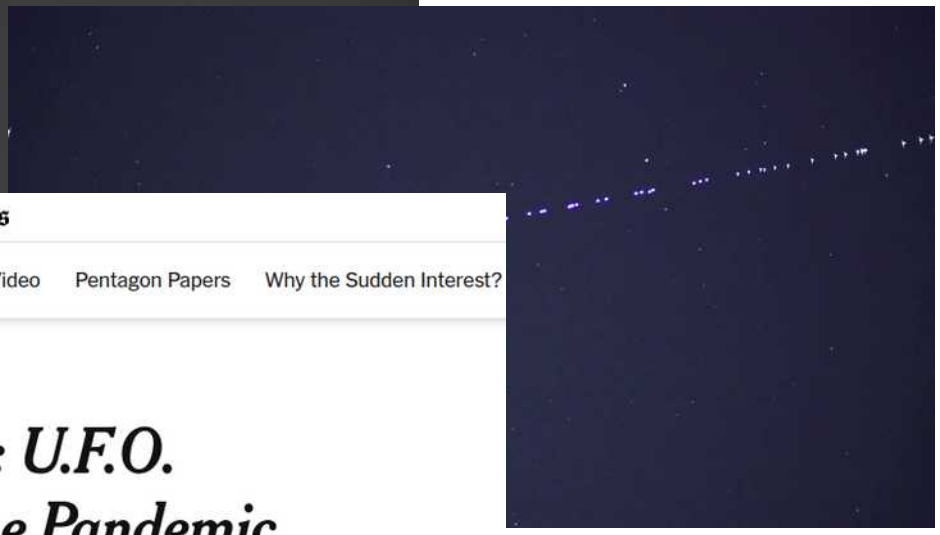


The New York Times

Report on U.F.O. Sightings | Government Report | Watch the U.S. Navy Video | Pentagon Papers | Why the Sudden Interest?

They Are Not Alone: U.F.O. Reports Surged in the Pandemic

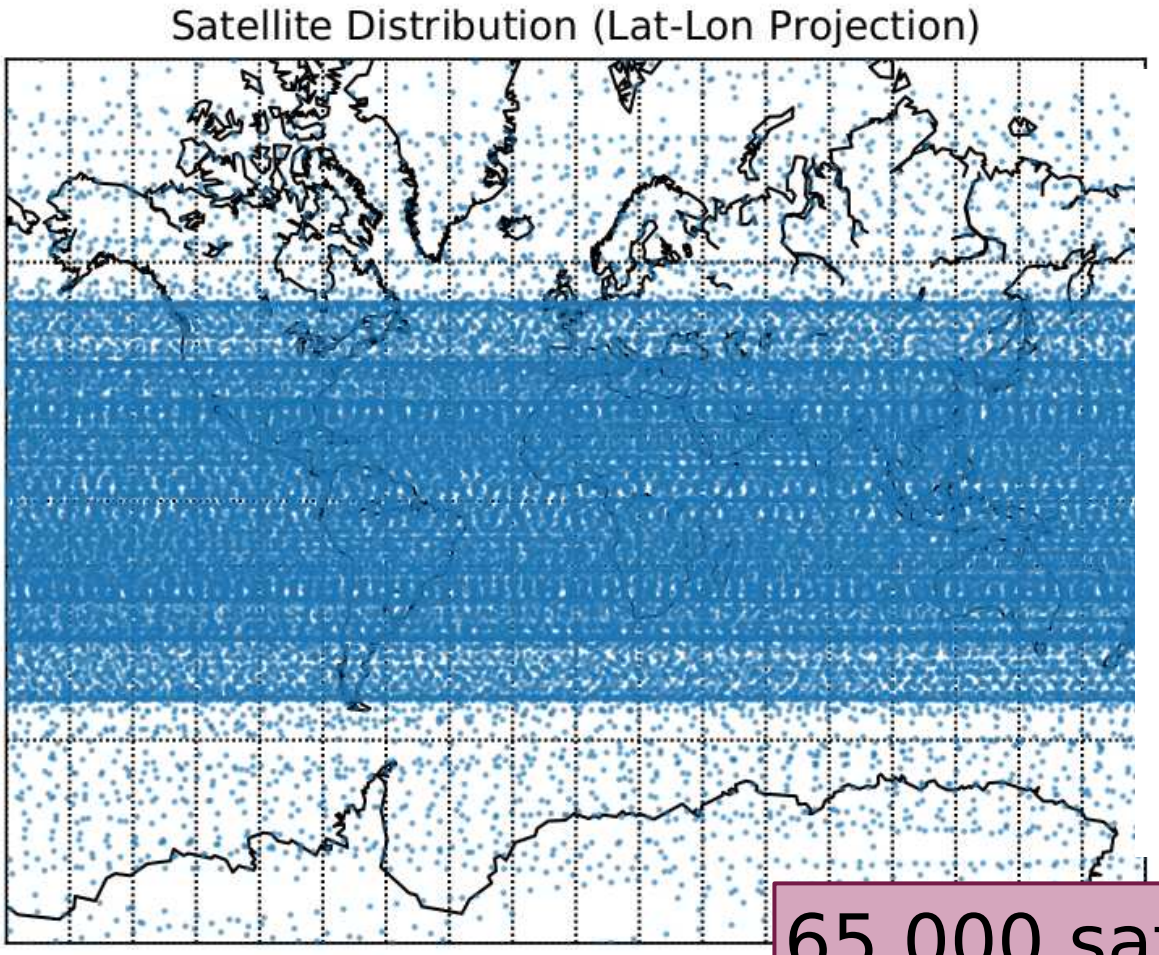
With skies lacking light pollution and most nights free, New Yorkers reported nearly twice as many mysterious sightings last year.

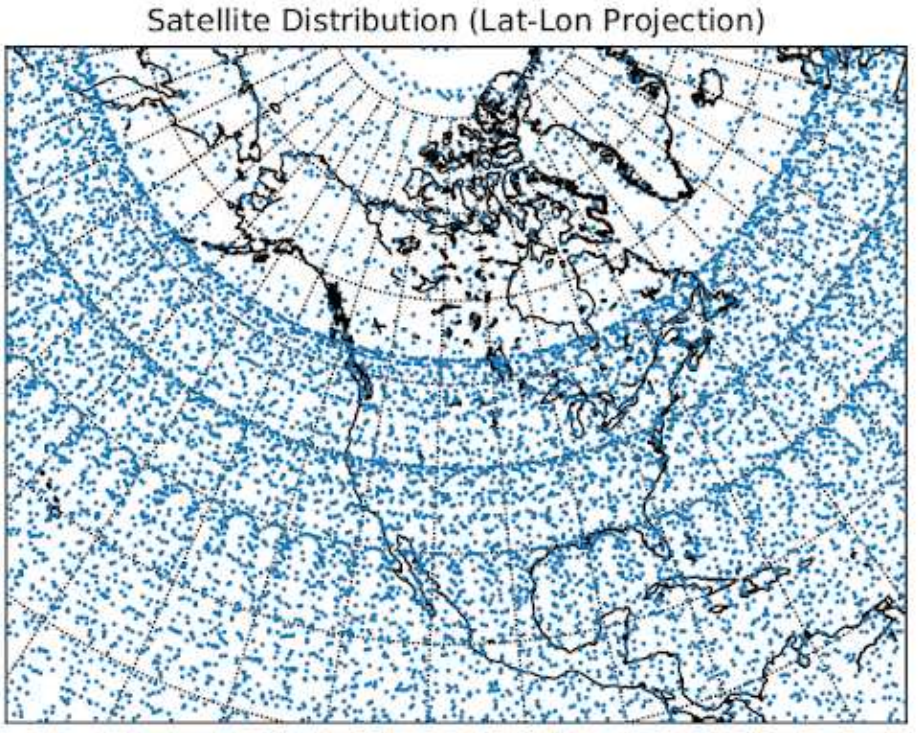
How bad could it get?

SpaceX Starlink + Amazon Kuiper + UK’s OneWeb + China’s Starnet/GW =

65,000 satellites

How bad could it get?





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Lawler, Boley & Rein (subm.)

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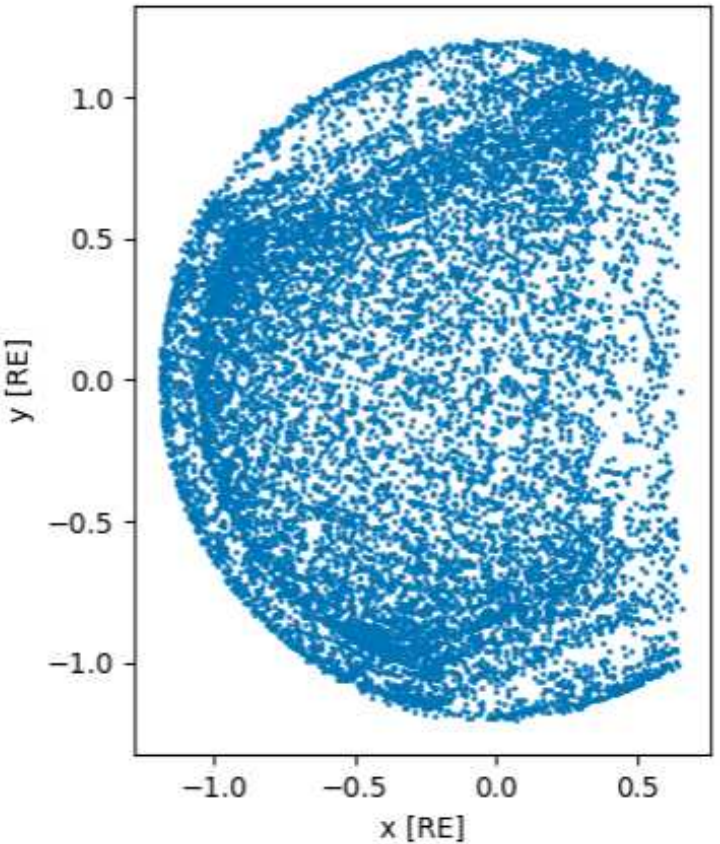

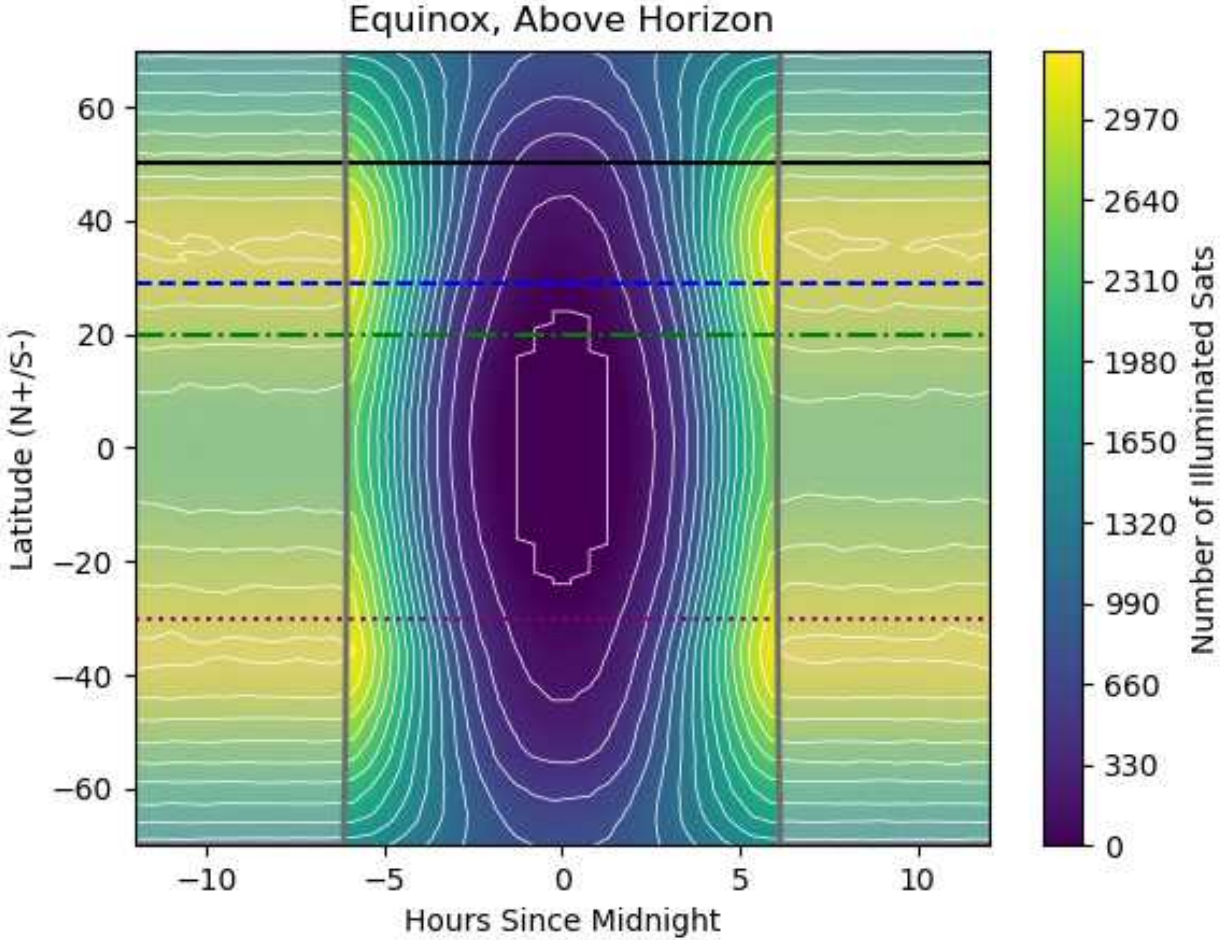

How many satellites are illuminated depends on geometry:
Observer latitude & time of night, season, satellite altitude

Lawler, Boley & Rein (subm.)

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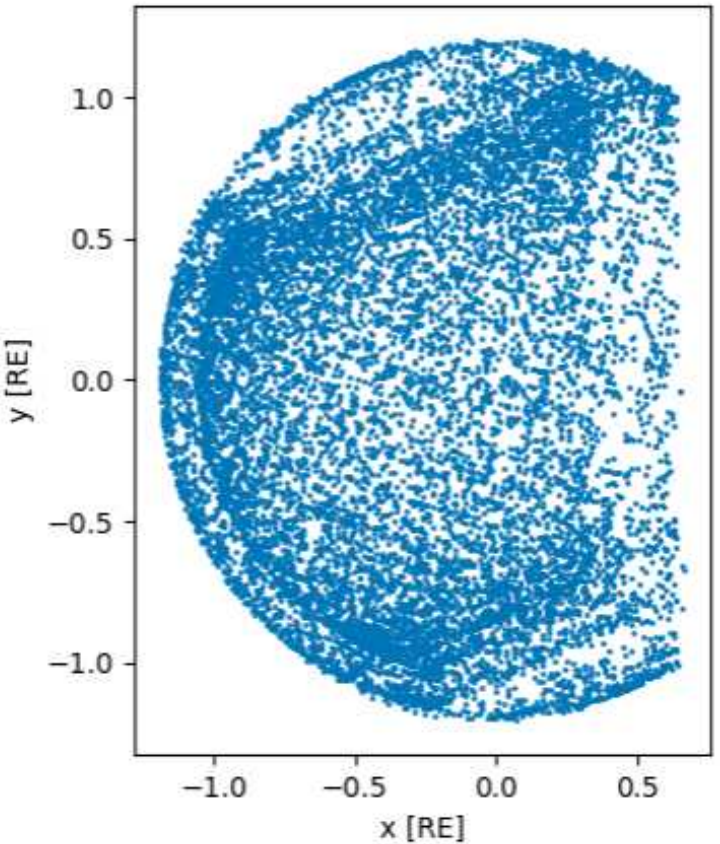

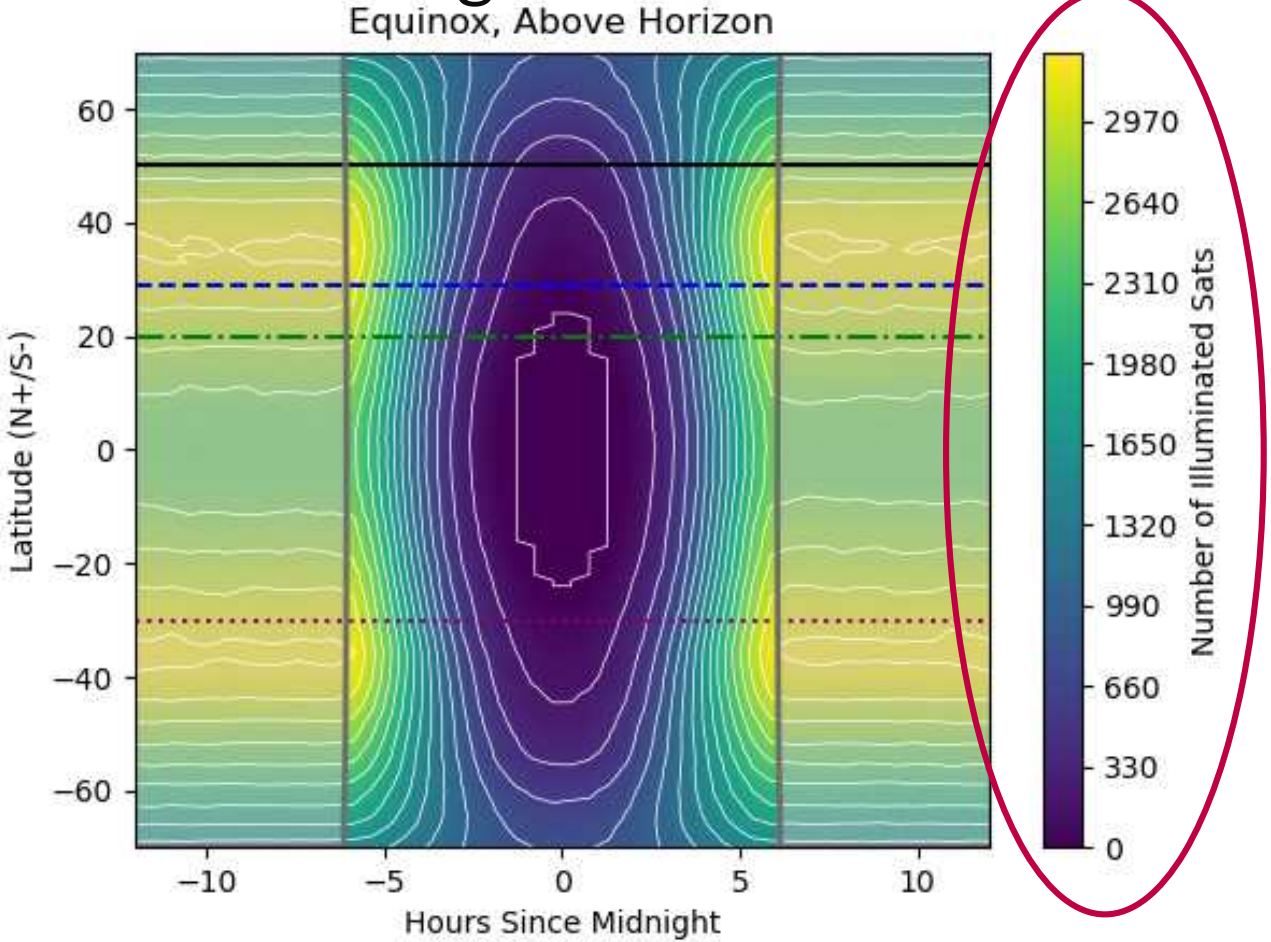

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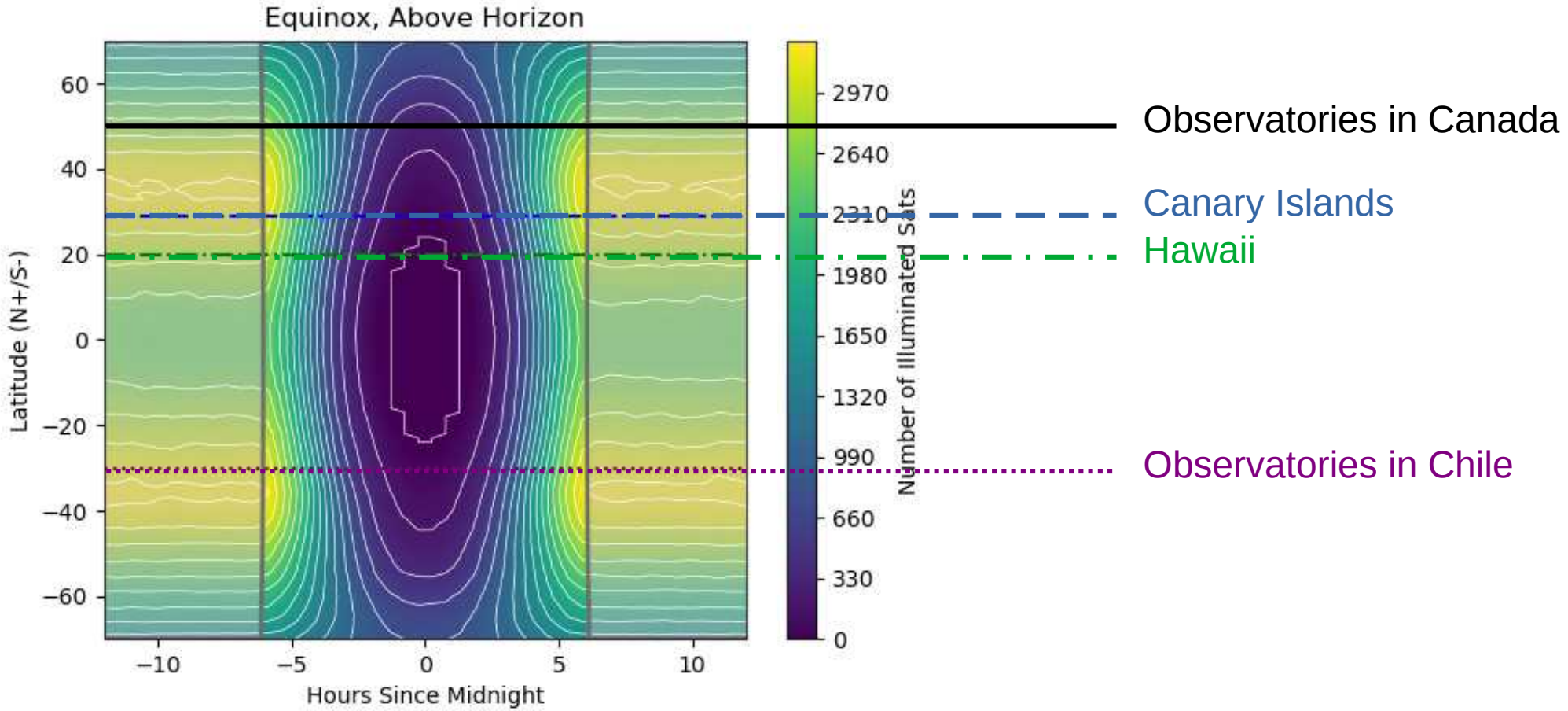

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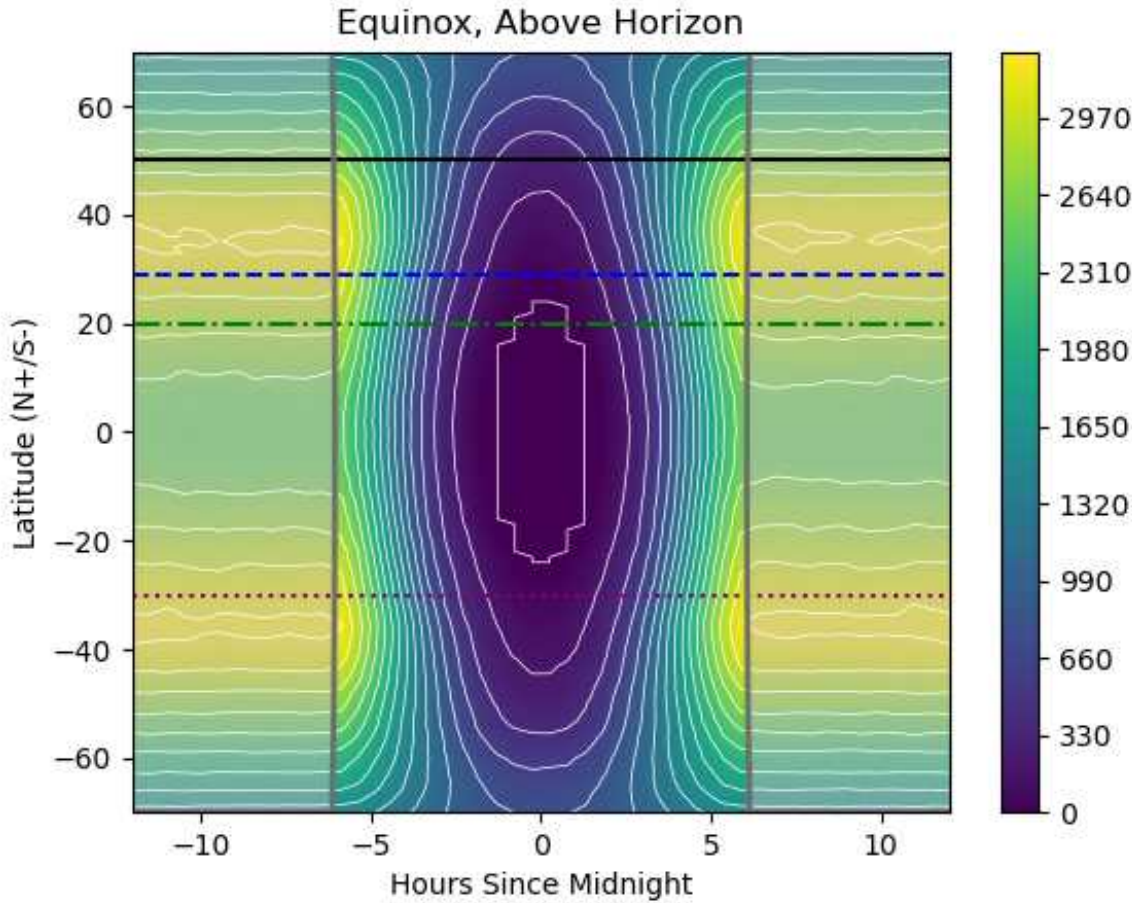

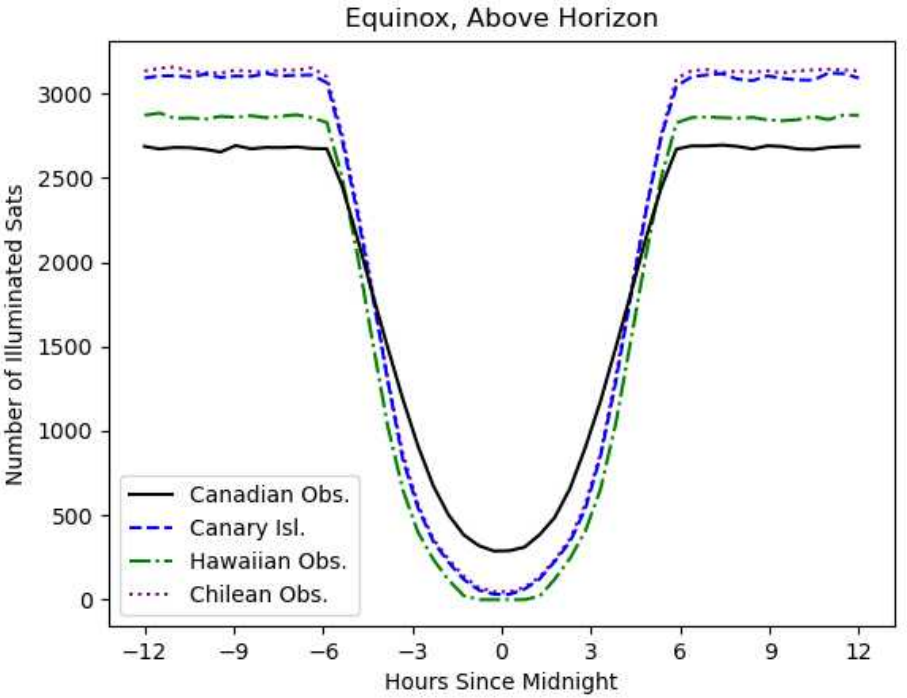

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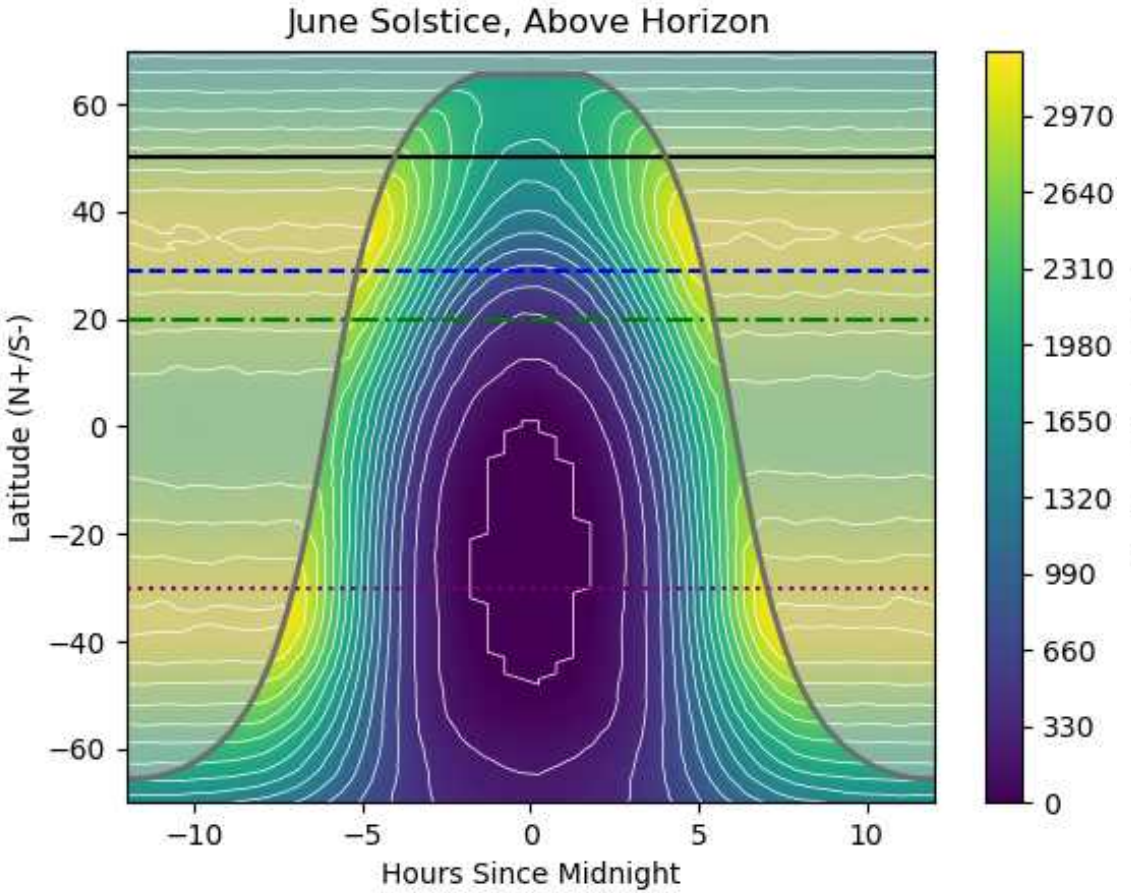
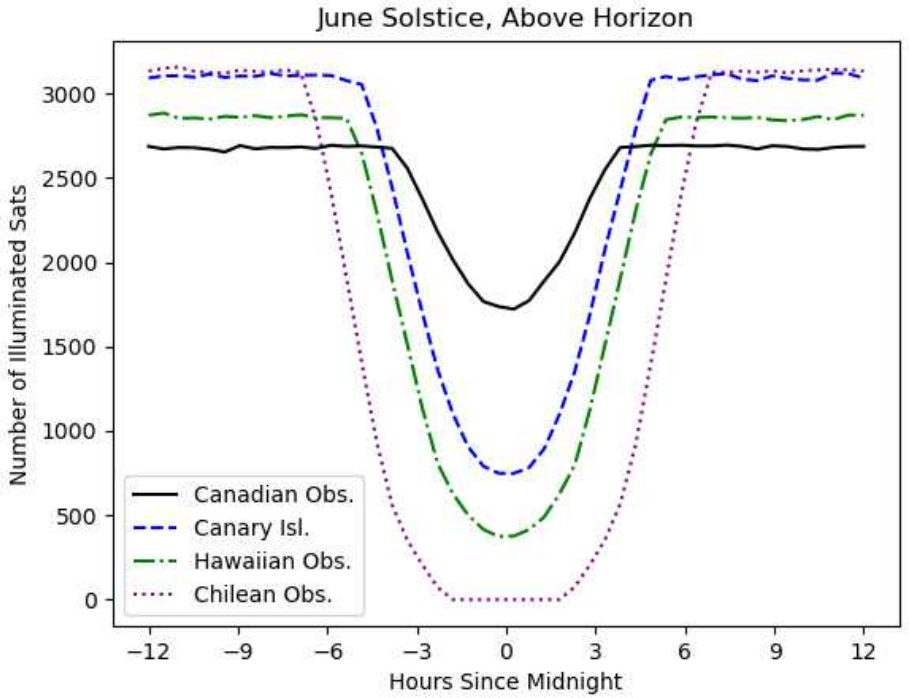




How many satellites are illuminated depends on geometry:
Observer latitude & time of night, season, satellite altitude

Lawler, Boley & Rein (subm.)

How bad could it get?

How bright the satellites are when illuminated in orbit depends entirely on unknown engineering.

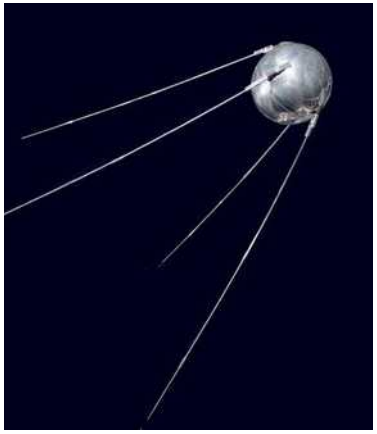
How bad could it get?

We use a diffuse Lambertian sphere model:

$$m_v = m_{\mathrm{Sun}} - 2.5 \log \left(\frac{2}{3\pi^2} A\rho[(\pi - \phi)\cos\phi + \sin\phi] \right) + 5 \log R$$

Pradhan et al. (2019)

≠



(We know this is a TERRIBLE model for satellites: there is nothing spherical about them. But more complicated models did not do a better job fitting real data, so we're sticking with this simple model for now)

How bad could it get?

We use a diffuse Lambertian sphere model:

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Apparent mag. of Sun
(V = -26.77, g' = -26.47)

Phase angle:
observer to sat. to Sun

Distance between
observer and sat.

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Now we need to calibrate our model to real satellites

How bad will it get up here? Canadian modelling and data

Plaskett Telescope

Aaron Boley,
UBC

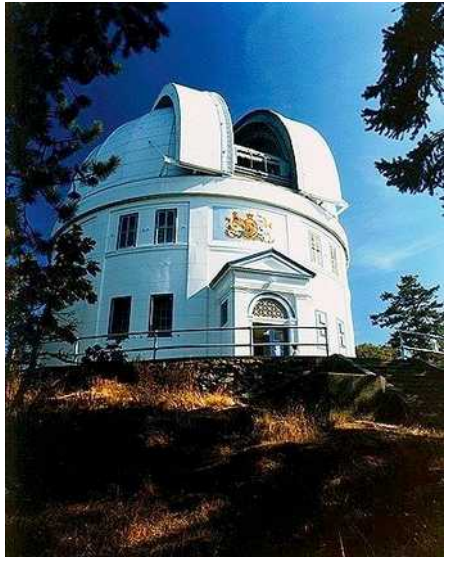
me,
U. of Regina

Hanno Rein,
U. of Toronto

How bad will it get up here? Canadian modelling and data

observations from 49° N, July 2021, within ±1.5 hr of midnight

Boley et al. (in prep.)



Plaskett Telescope, Victoria, BC

Note: we tried to only use Visorsats, because all Starlinks launched after Aug. 2020 are equipped with visors (“Visorsats”).

But there is no information anywhere about whether visors are actually deployed on all Visorsats (and inconsistencies in the data lead us to think that they are not uniformly deployed – work in progress)

Lawler, Boley & Rein (subm.)

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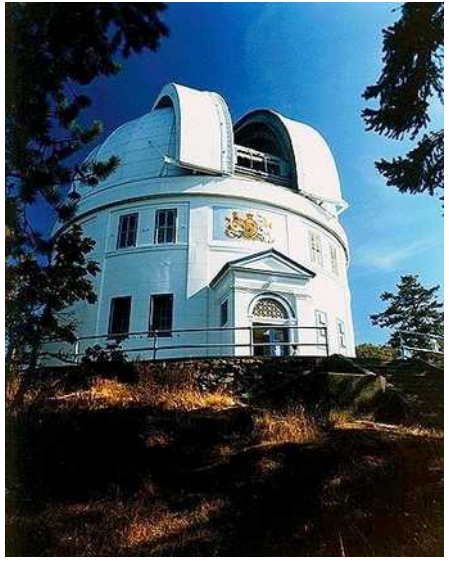

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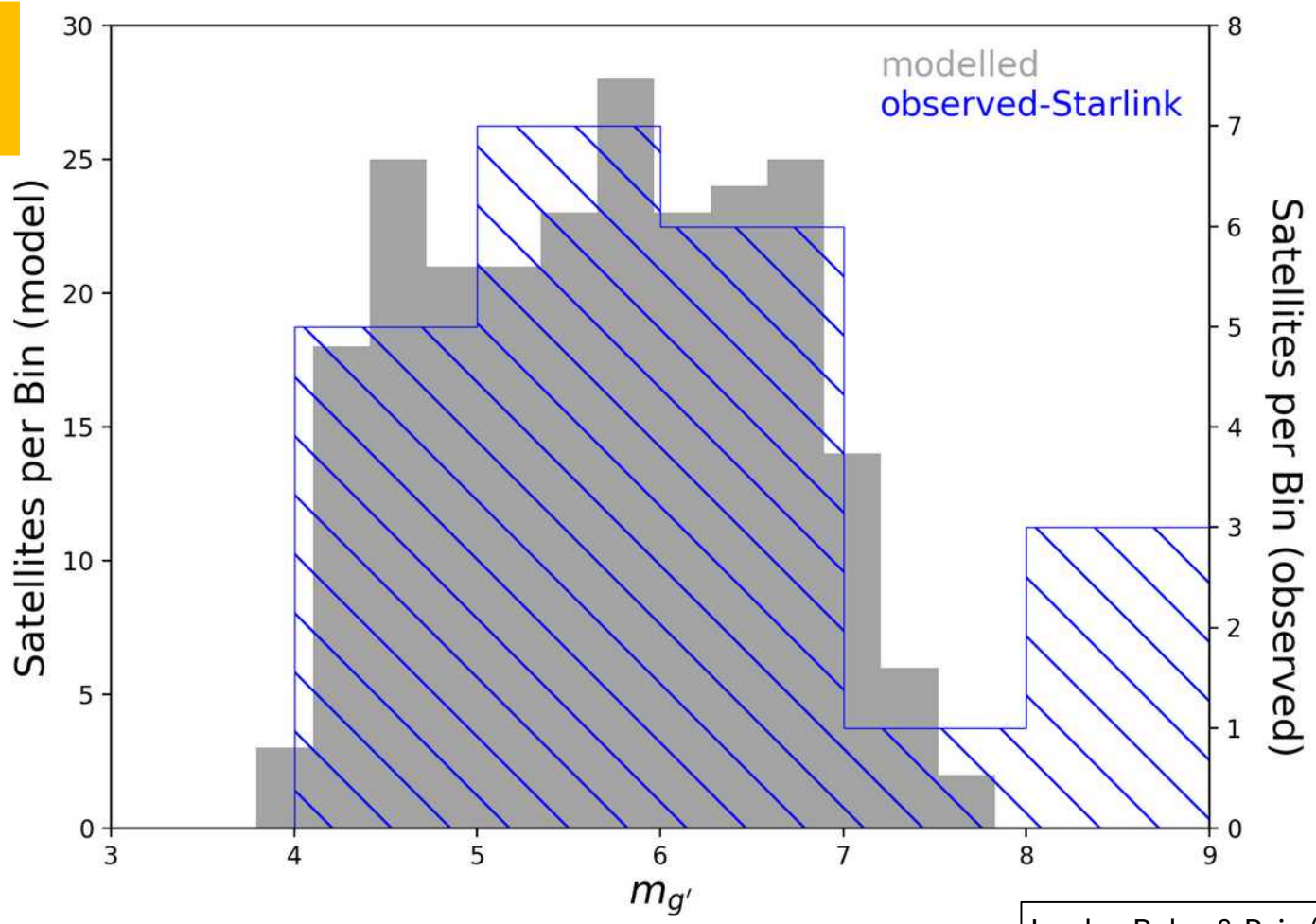
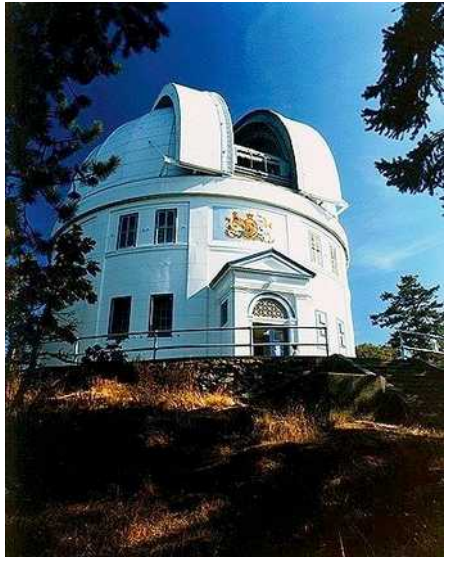


Lawler, Boley & Rein (subm.)

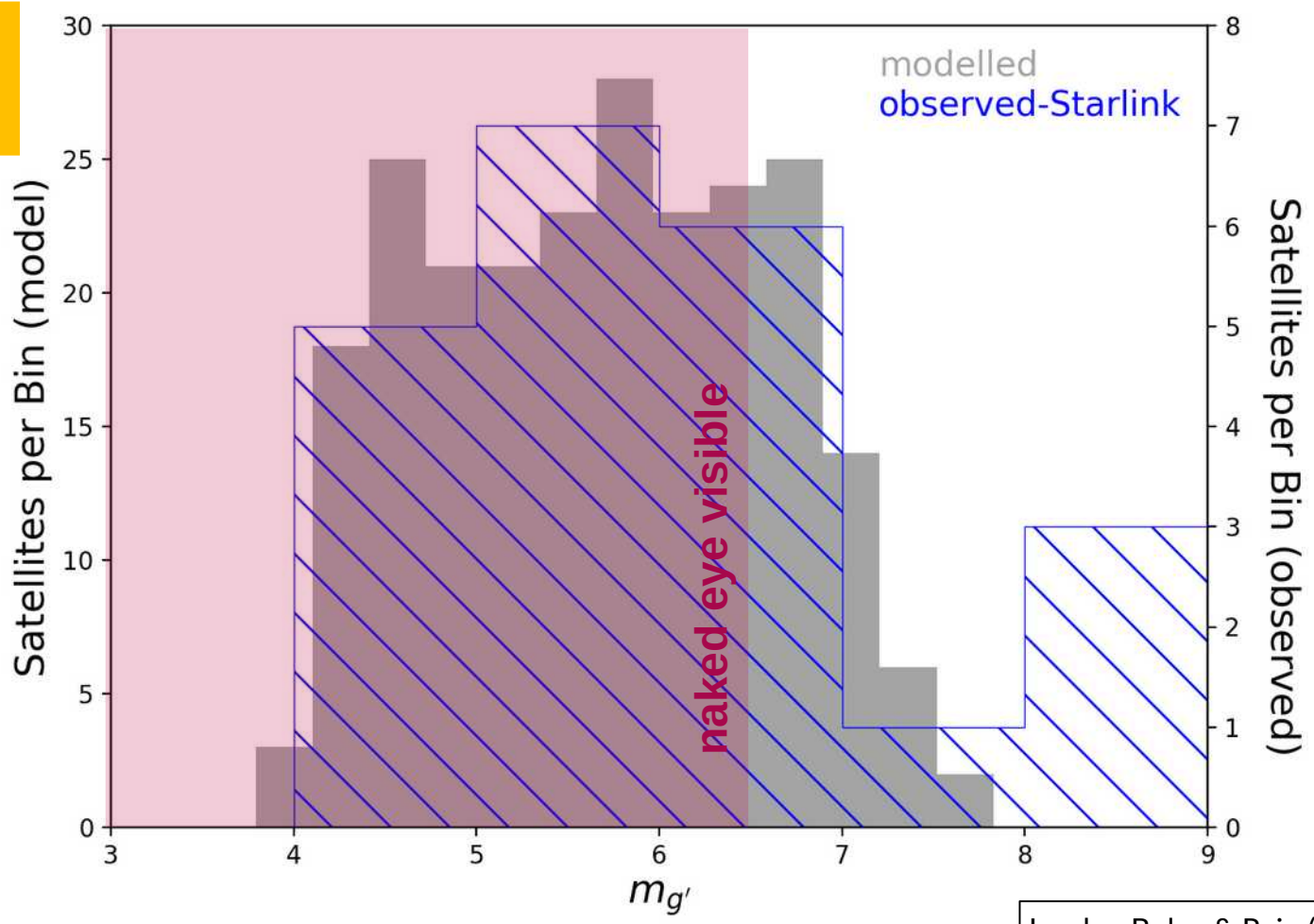
How bad will it get up here? Canadian modelling and data

observations from 49° N, July 2021, within ±1.5 hr of midnight

Boley et al. (in prep.)



Plaskett Telescope, Victoria, BC



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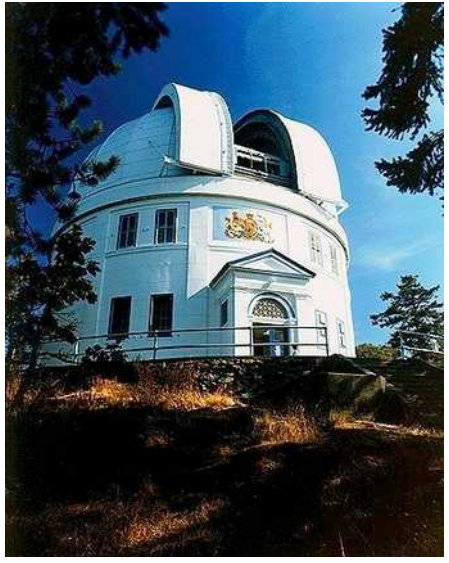

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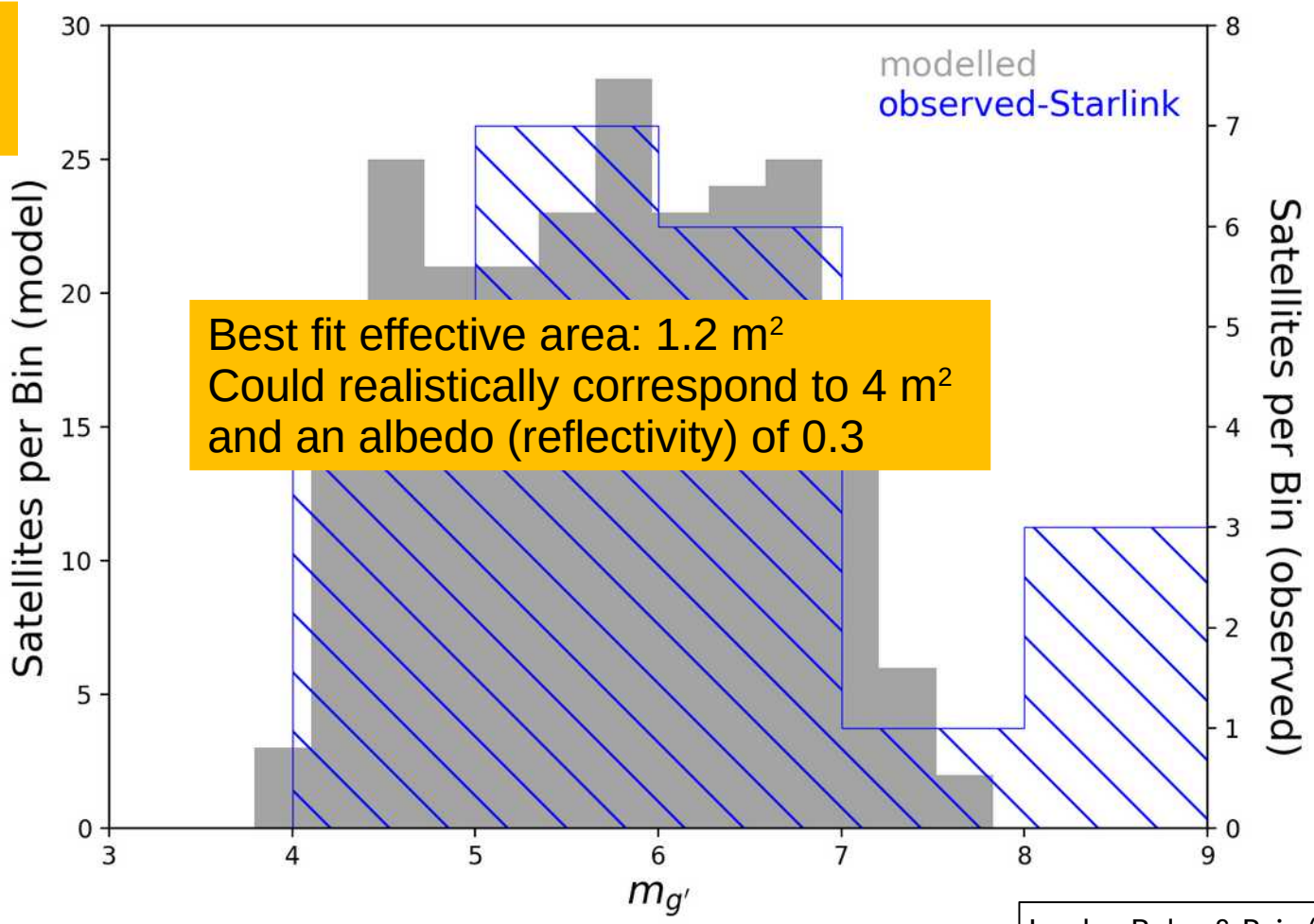


Best fit effective area: 1.2 m^2
Could realistically correspond to 4 m^2 and an albedo (reflectivity) of 0.3

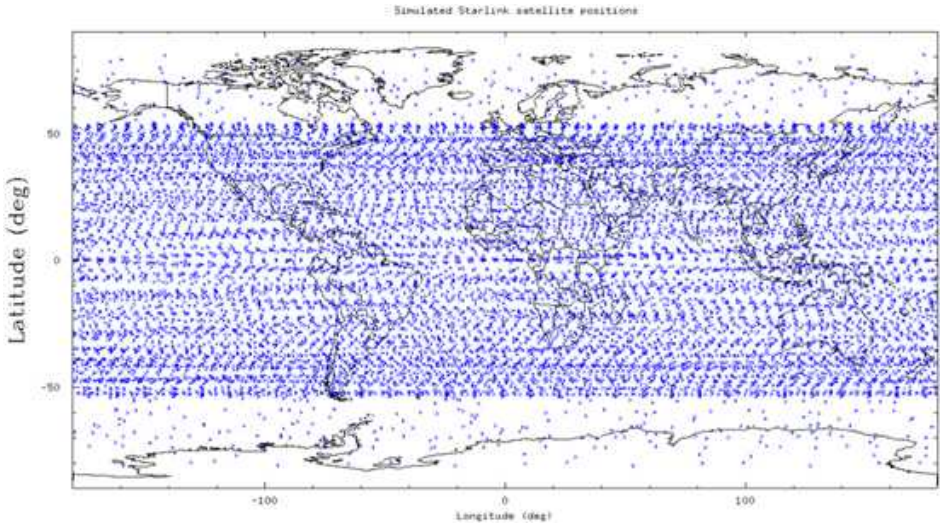
Lawler, Boley & Rein (subm.)

How bad will it get all over the world?

Situation is changing SO FAST! Papers from 1 year ago are already out of date.

My goal: how badly affected will the night sky be in different parts of the world?

Building on previous work:



McDowell (2020): 12,000 sats

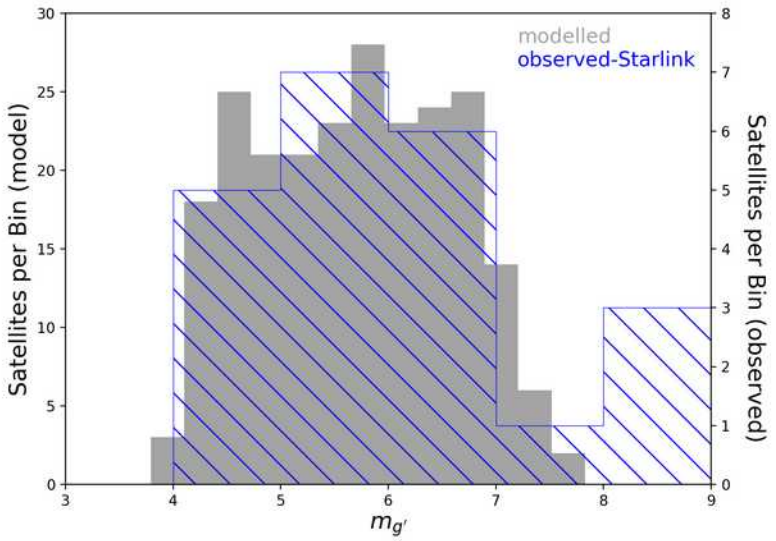
Effect of satellite trail

Observing Tecnique	Instrument	Field of view diametre [arcmin]	Exposure Time [s]	Altitude of the sun [deg] 0 Daylight	-6 Civil Twilight	-12 Nautic Twilight	-18 Astron. Twilight	-24	-30	-36	-42	-48	-54	-60	-66	-72	-78	-84
				Astronomical night														
Number of low illuminated satellites visible above Zdmax				14	11	7	3	0	0	0	0	0	0	0	0	0	0	0
Number of high satellites illuminated visible above zMax				244	213	183	153	123	93	67	41	24	11	0	0	0	0	0
Contaminated fraction of the observable sky																		
Wide field Imaging	LSST	200'	30			48.9%	39.2%	29.9%	22.6%	16.2%	10.1%	5.8%	2.7%	0.0%	0.0%	0.0%	0.0%	0.0%
Wide field Imaging	OMEGACAM	60'	100			8.5%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Imaging	FORS	6'	100			0.5%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Long-slit Spectro	FORS	6'	1000				2.0%	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Short-slit Spectro	UVES	0.2'	1000				1.3%	1.0%	0.8%	0.5%	0.3%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Fibre	HARPS	2 arcsec	1000				0.2%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Multi-fibre spectro	QMOST	up to 30 fibres	1000				6.5%	5.0%	3.8%	2.7%	1.7%	1.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%

Hainaut & Williams (2020): 26,000 sats

How bad will it get all over the world?

We assume this same Starlink brightness profile for all satellites



(Is this an optimistic or pessimistic assumption? We do not know...)

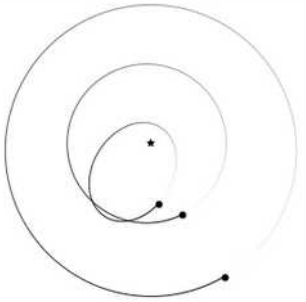
+

65,000 satellites on filed or predicted orbits:

operator	N_{Sat}	inclination [°]	Altitude [km]
Starlink[a]	7178	30	328
(USA)	7178	40	334
	7178	53	345
	2000	96.9	360
	1998	75	373
	4000	53	499
	144	148	604
	324	115.7	614
	2547	53	346
	2478	48	341
	2493	42	336
	1600	53	550
	1584	53.2	540
	720	70	570
	348	97.6	560
	172	97.6	560
OneWeb[b]	720	87.9	1200
(UK)	1764	87.9	1200
	2304	40	1200
	2304	55	1200
StarNet/GW[c]	480	85	590
(China)	2000	50	600
	3600	55	508
	1728	30	1145
	1728	40	1145
	1728	50	1145
	1728	60	1145
Kuiper[d]	1156	51.9	630
(USA)	1296	42	610
	784	33	509

+

REBOUND open-source N-body integrator



github.com/hannorein/rebound

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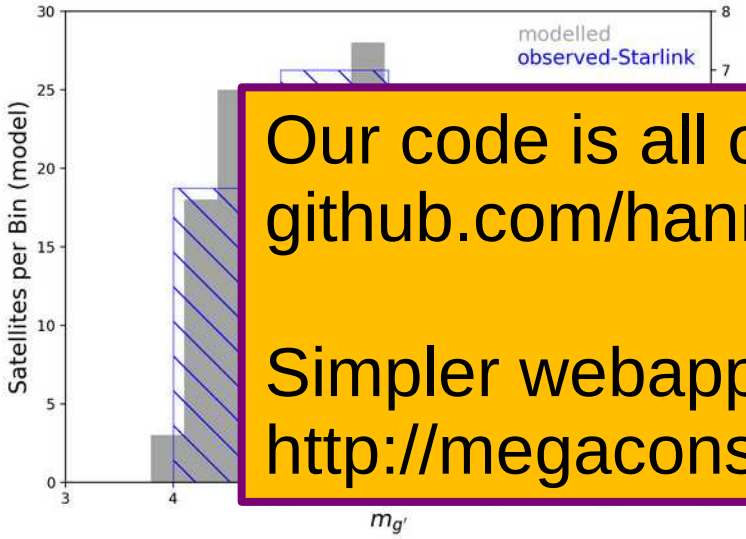

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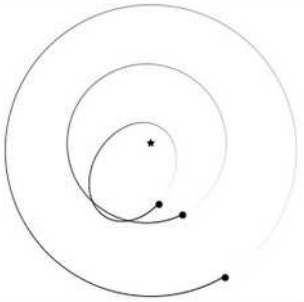
Our code is all open-source!
github.com/hannorein/megaconstellations

Simpler webapp here:
http://megaconstellations.hanno-rein.de/

REBOUND
pen-source N-
ody integrator



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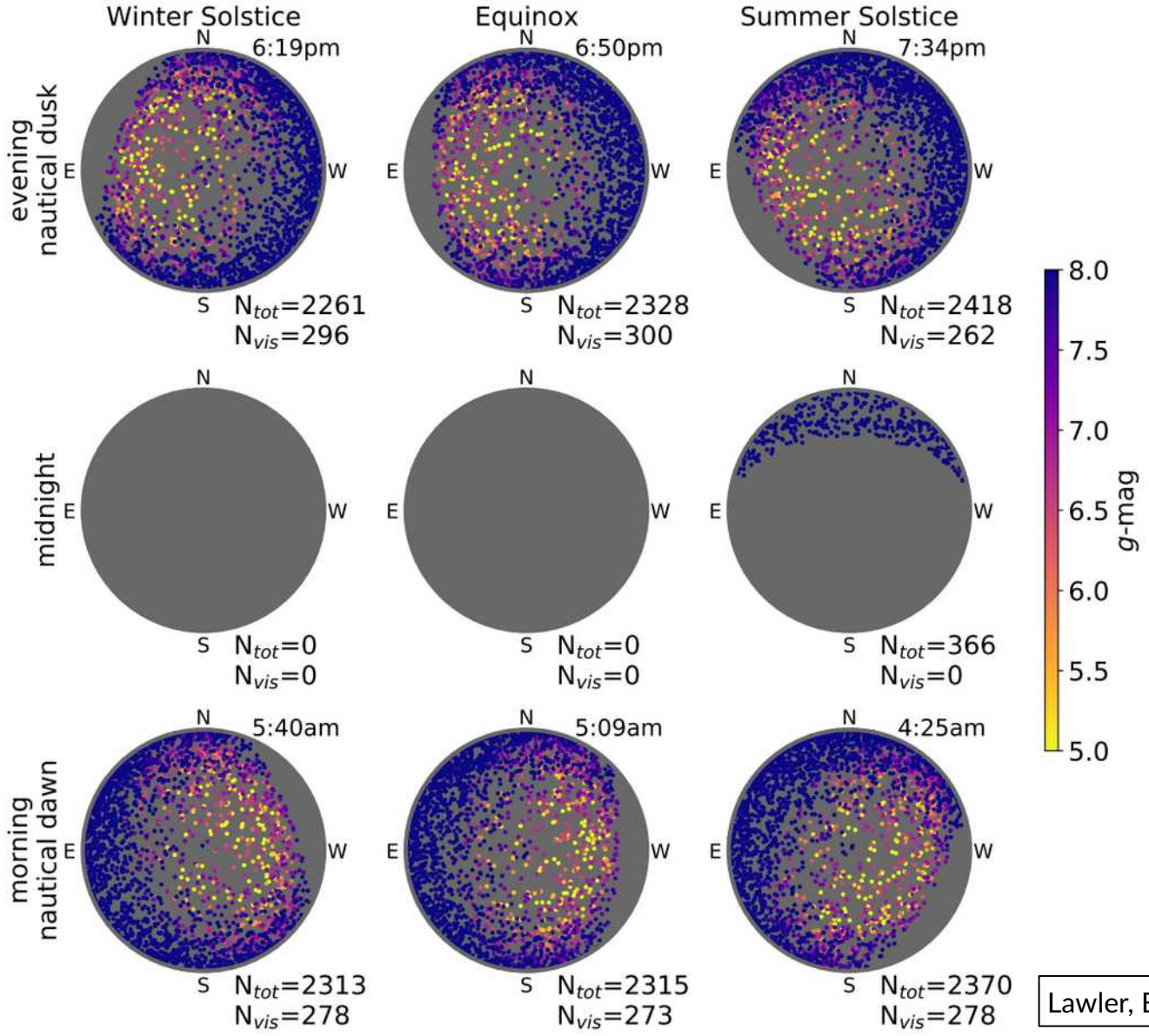
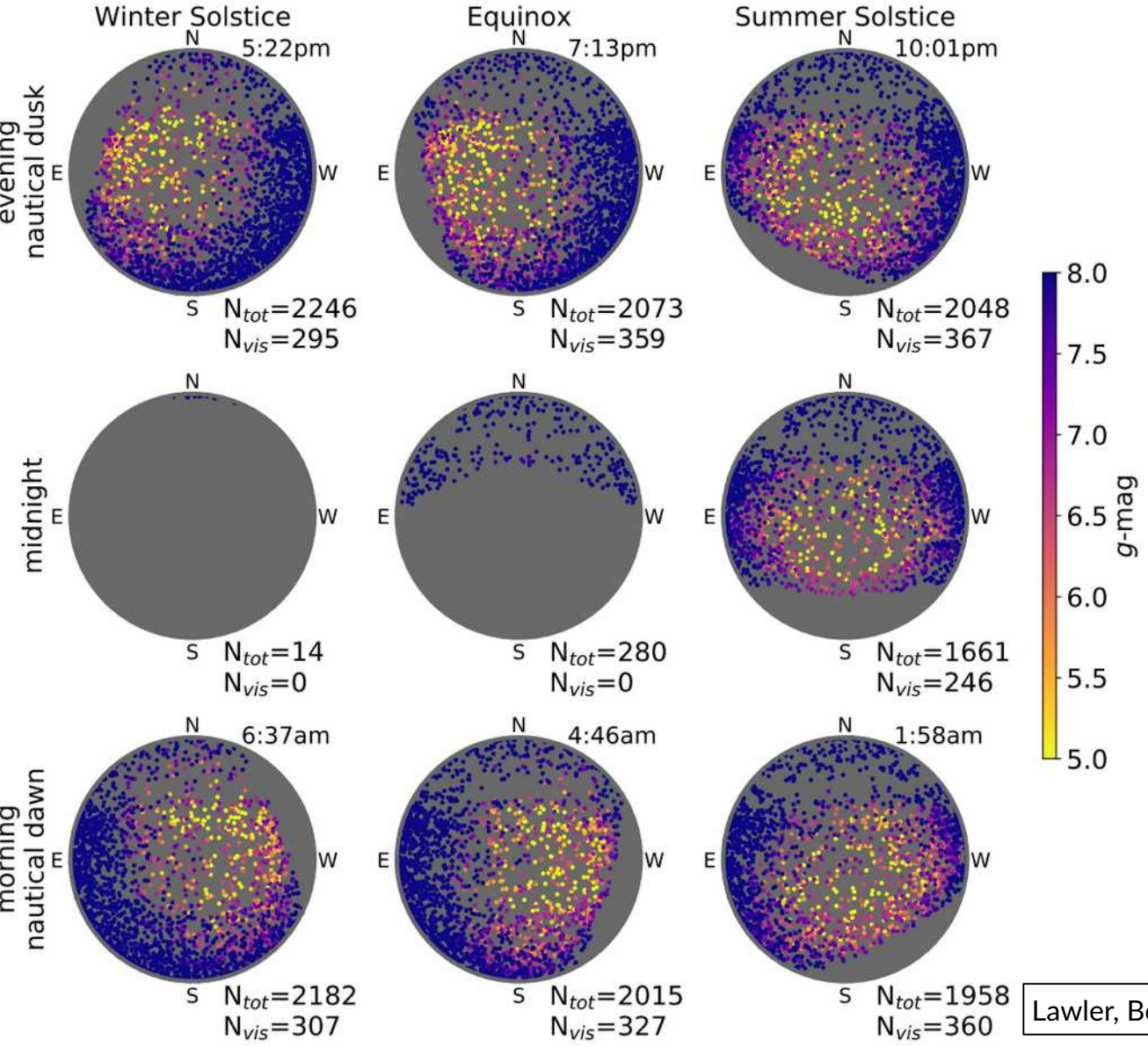


The view from Hawaii.

Bad close to twilight, then the number of bright sats drops rapidly. Mostly very faint satellites close to the horizon and won't interfere significantly with most observing.

Hawaii, Summer Solstice

Lawler, Boley & Rein (subm.)

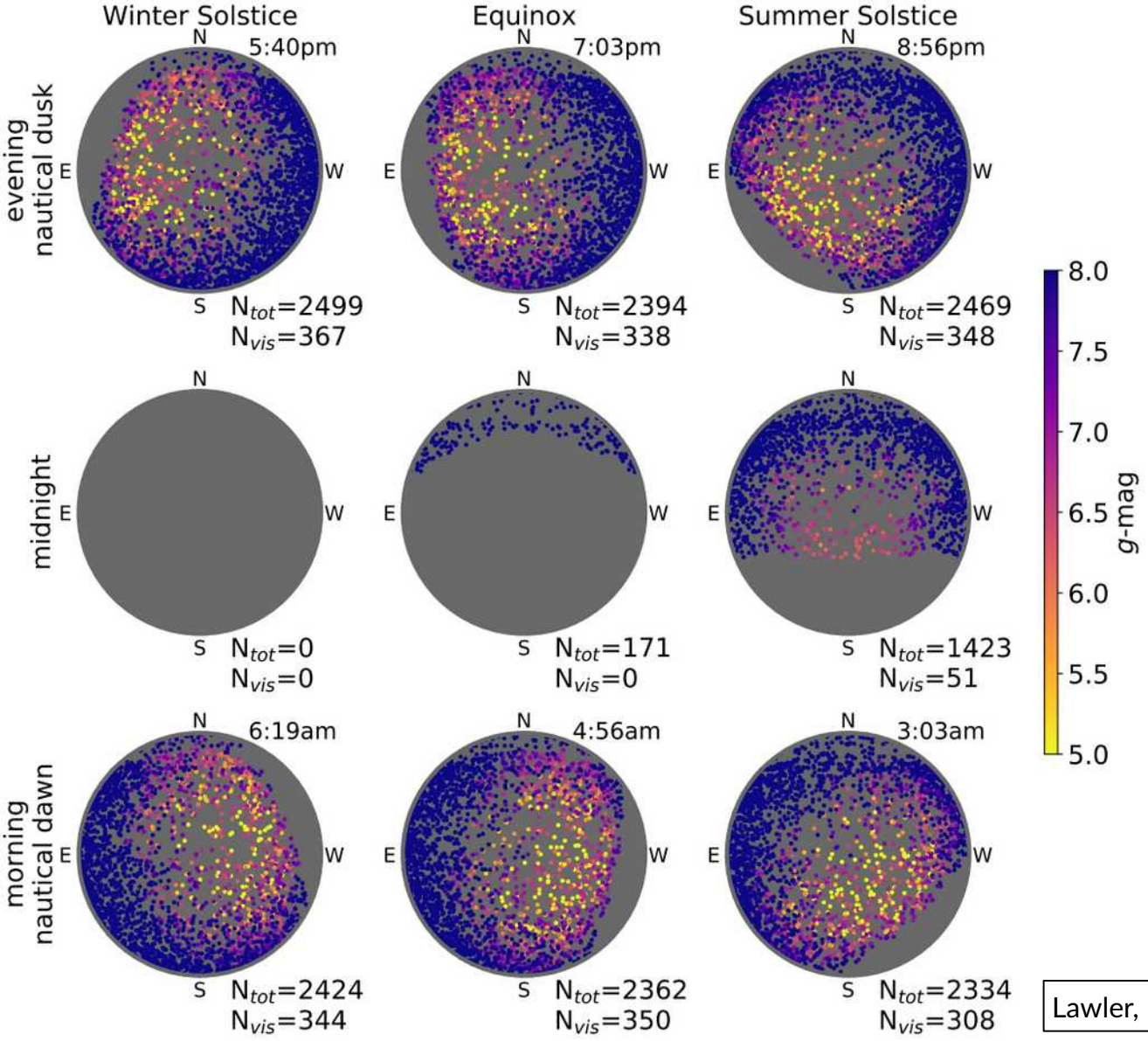


The view from Canada.

This is really terrible. HUNDREDS of naked-eye satellites visible all night long on the Summer Solstice, and dozens visible close to sunrise and sunset near the equinox (winter isn't too bad though)

Summer Sky

Lawler, Boley & Rein (subm.)



The view from Michigan (latitude 42 N).

Not quite as bad as latitude 50N, but still pretty bad.

Michigan, equinox

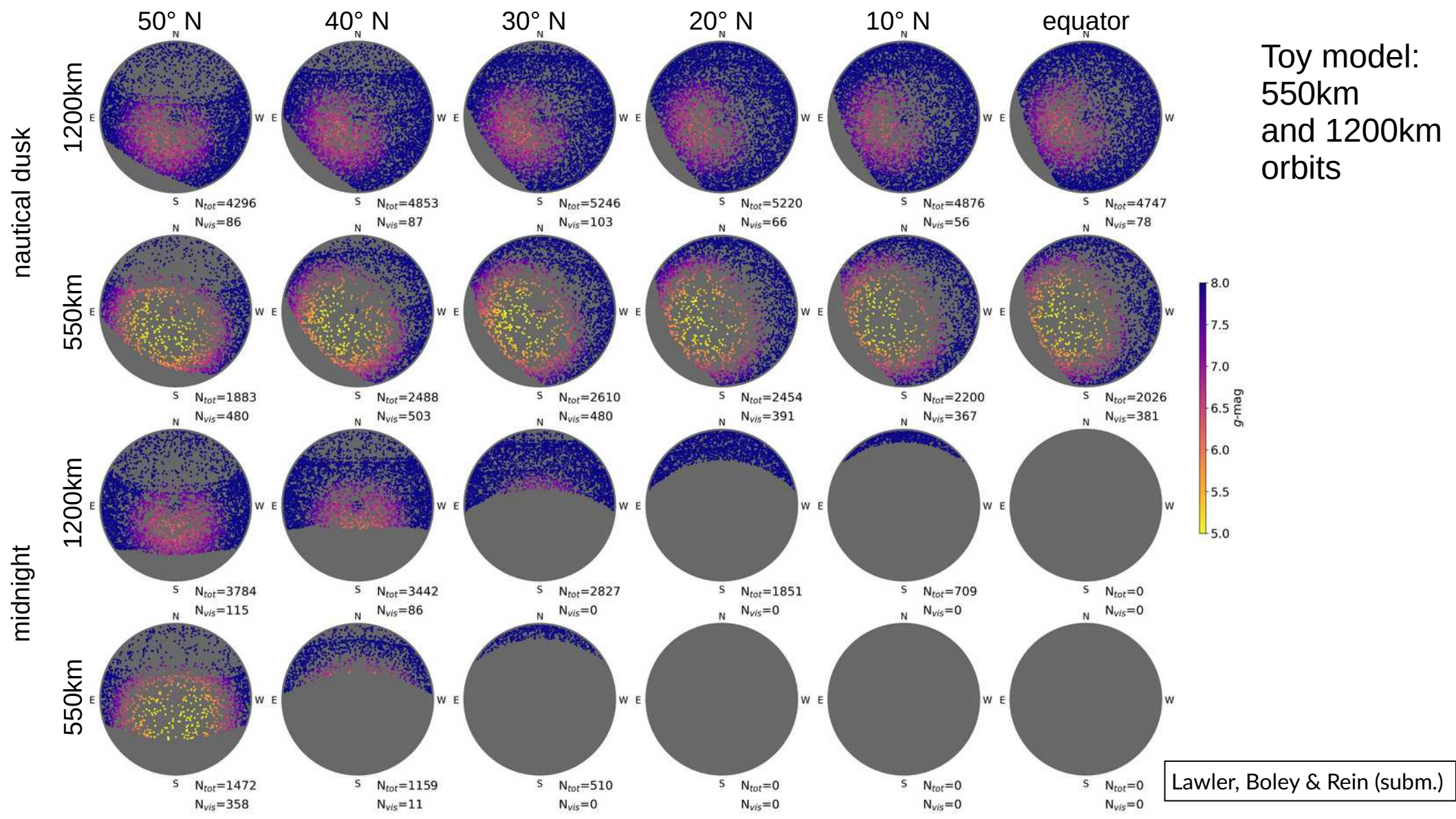
Michigan, summer

Lawler, Boley & Rein (subm.)

The SATCON1 and SATCON2 reports recommend lower altitude orbits for satellites

This makes satellites brighter, but they move across a field of view faster
(But this likely means that satcon operators will want more satellites...)

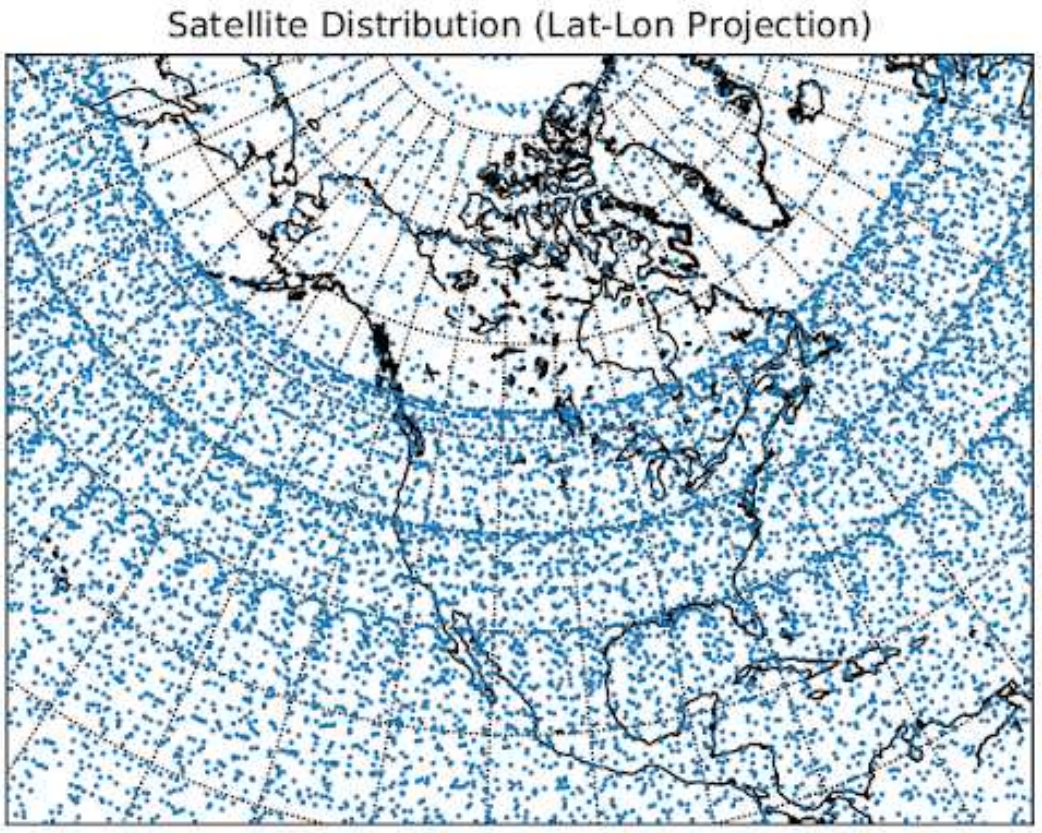
Do lower altitude orbits actually make things better?



Toy model:
550km
and 1200km
orbits

Lawler, Boley & Rein (subm.)

Latitude 50N and S are most severely affected by satellite light pollution



Most of Canada's population is in the latitude range with the worst satellite light pollution:
This is because of Earth's axial tilt combined with the chosen distribution of orbits.

This means that Canada will also experience the worst of another negative from megaconstellations:

Space junk

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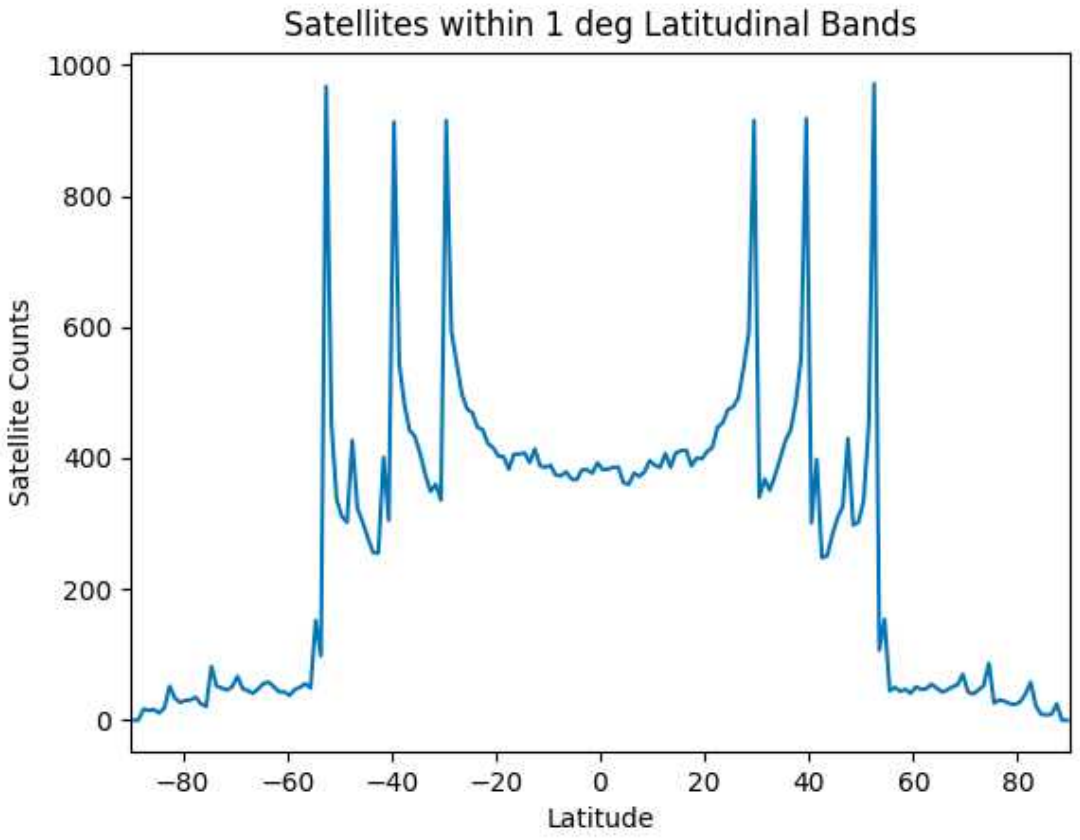

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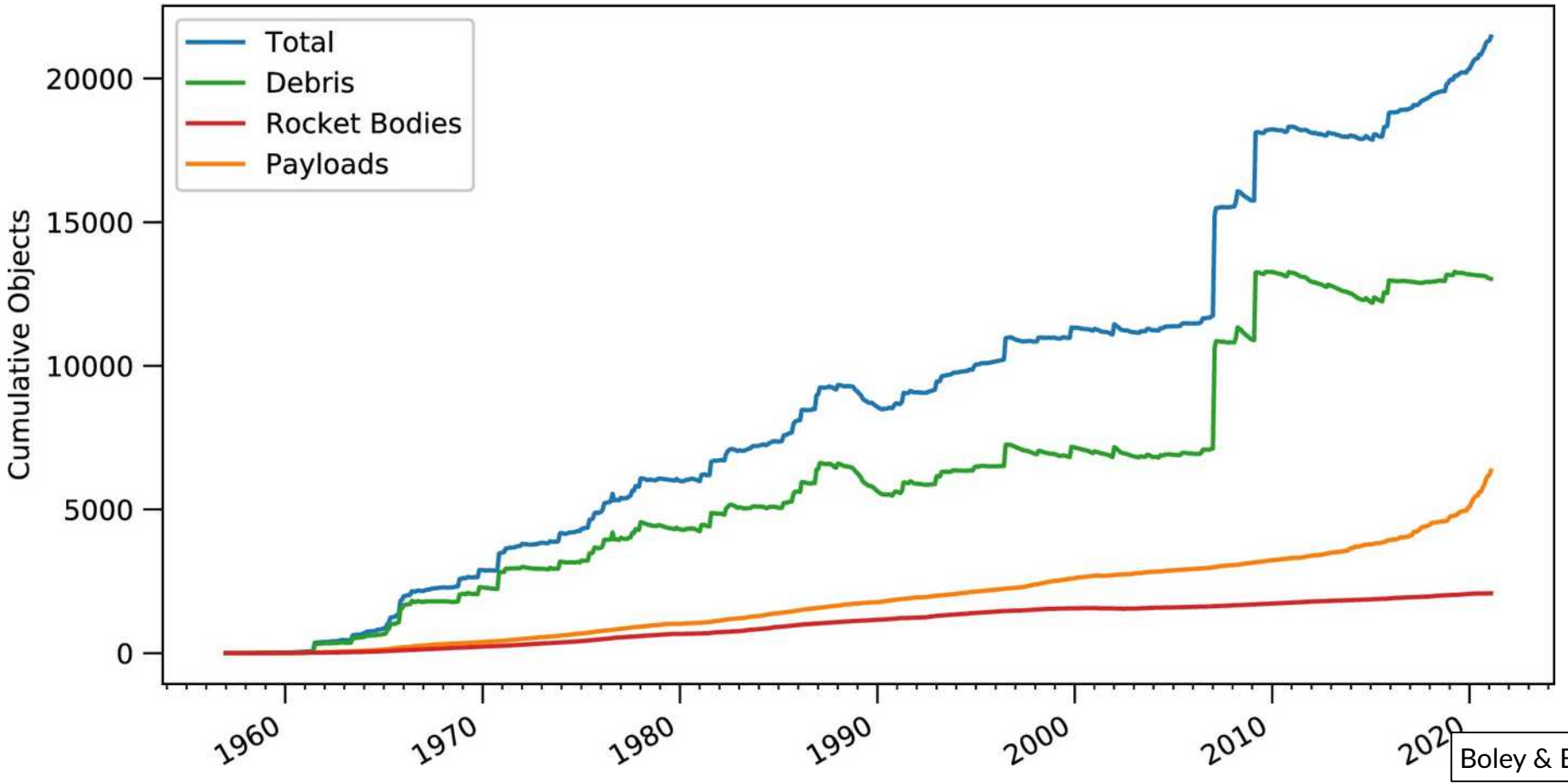
Another problem: Low Earth Orbit is getting crowded



Boley & Byers 2021

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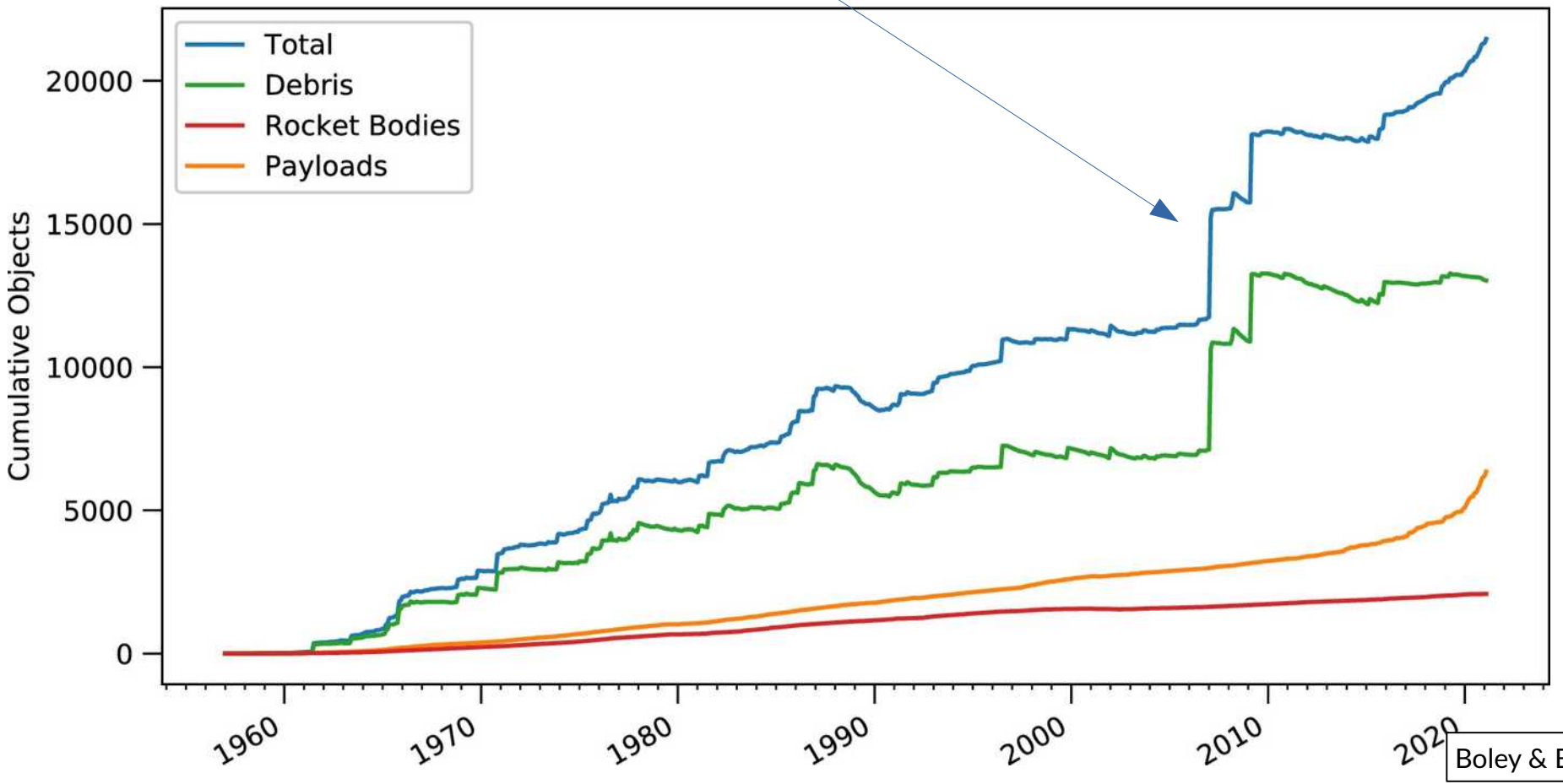

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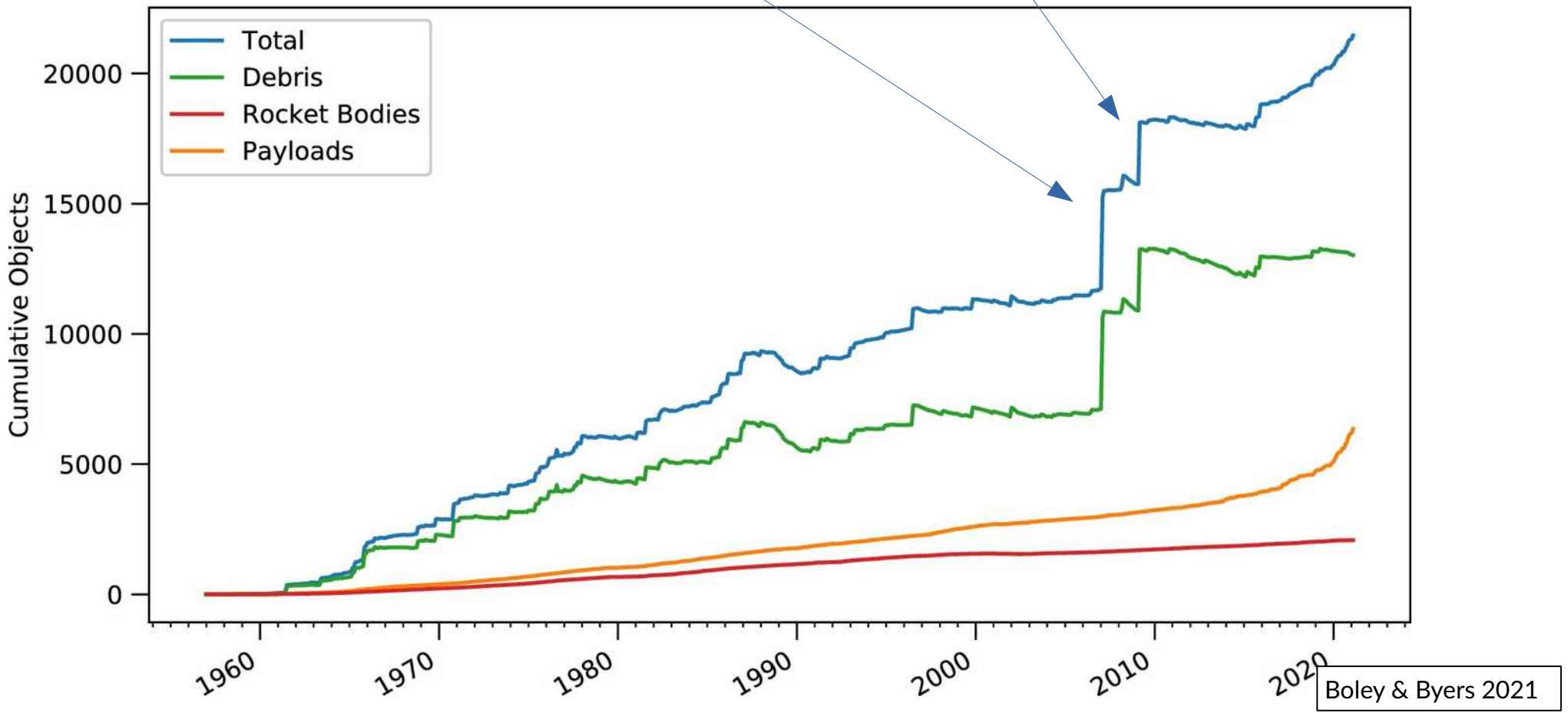

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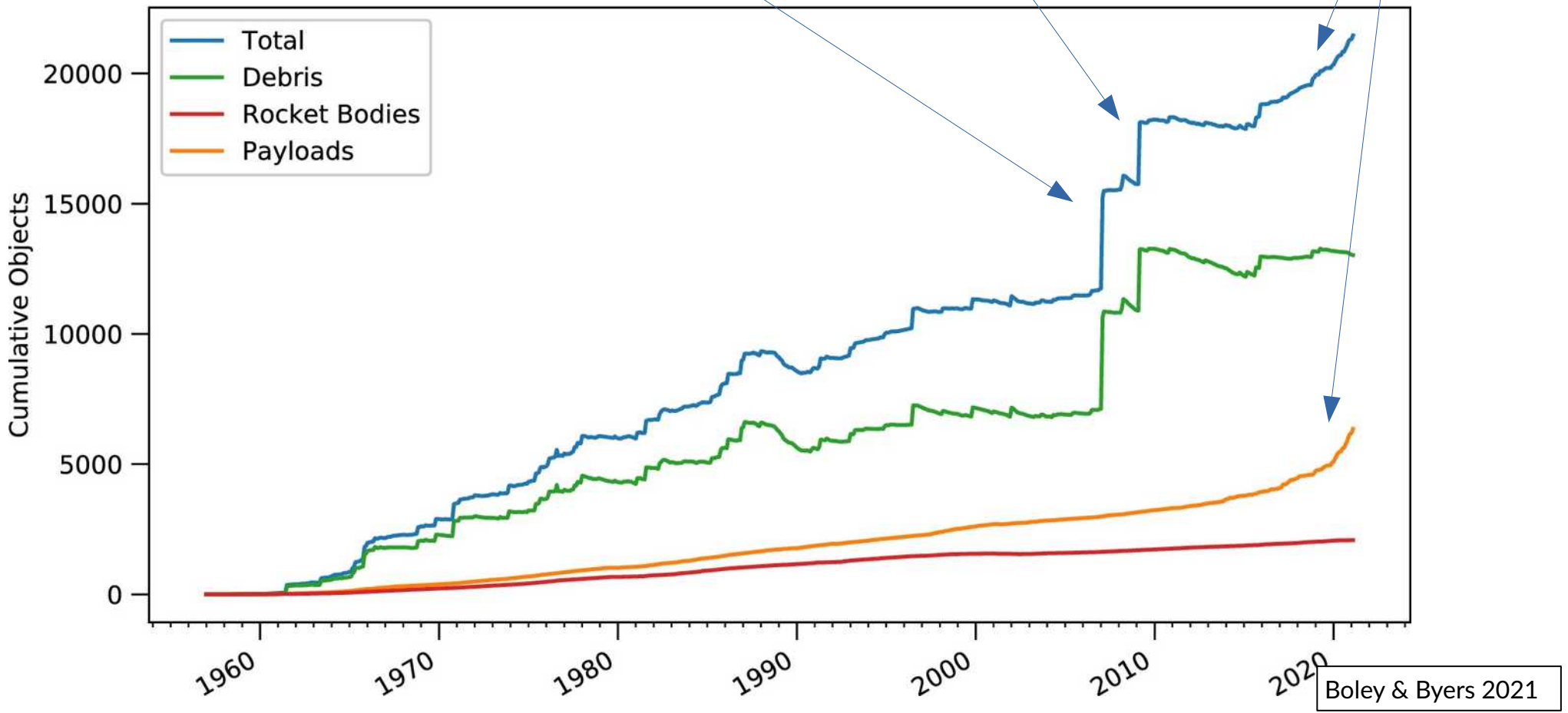


Boley & Byers 2021

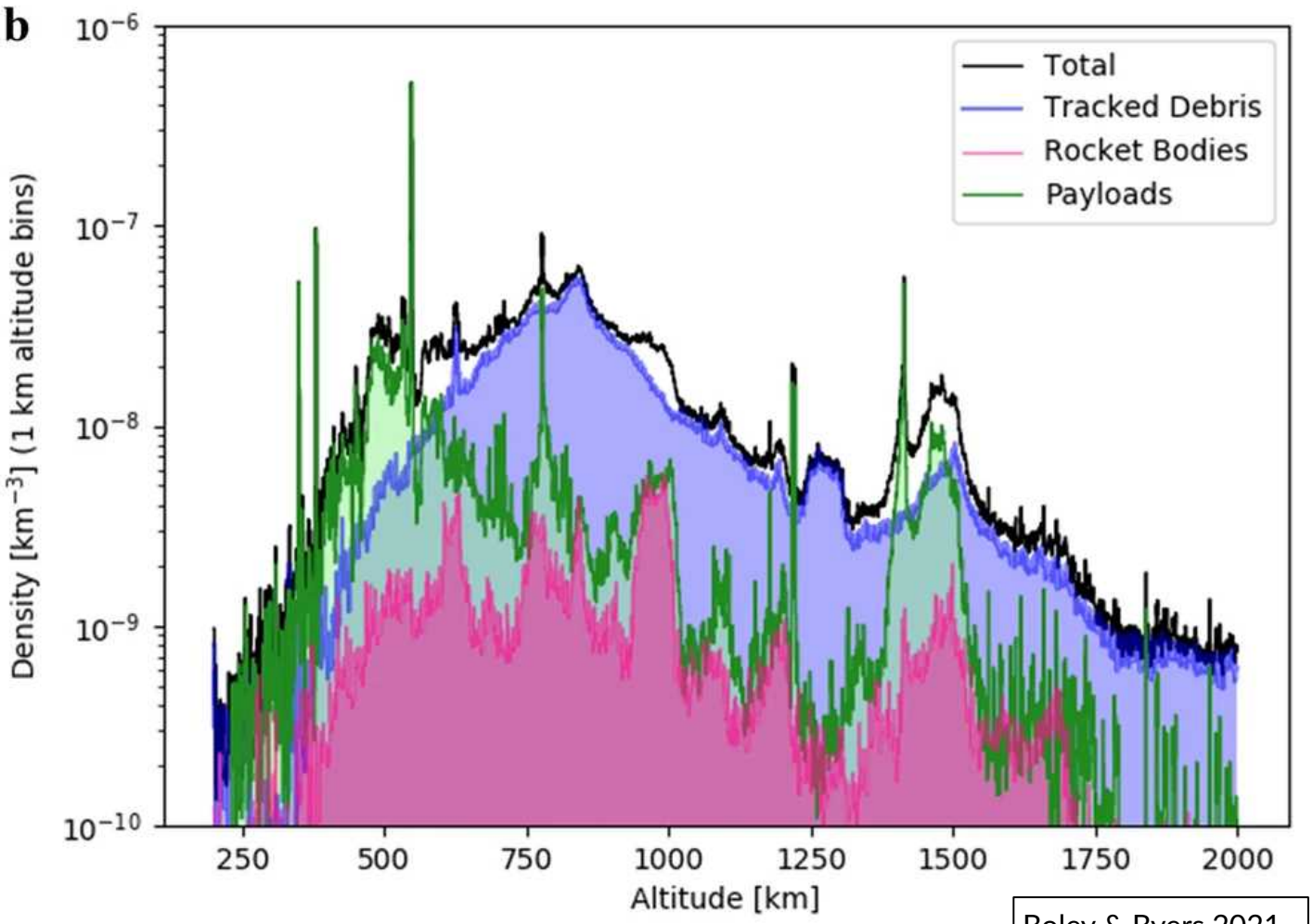
Another problem: Low Earth Orbit is getting crowded

Debris slowly spirals inwards.

A hockey puck travelling at orbital speeds (few km/sec) has the kinetic energy equivalent of 1 kg of TNT

We may already be in the early stages of **Kessler Syndrome**: even if launches stopped today, collisions would increase in LEO

Satcon orbital shells are already visible in this density plot.



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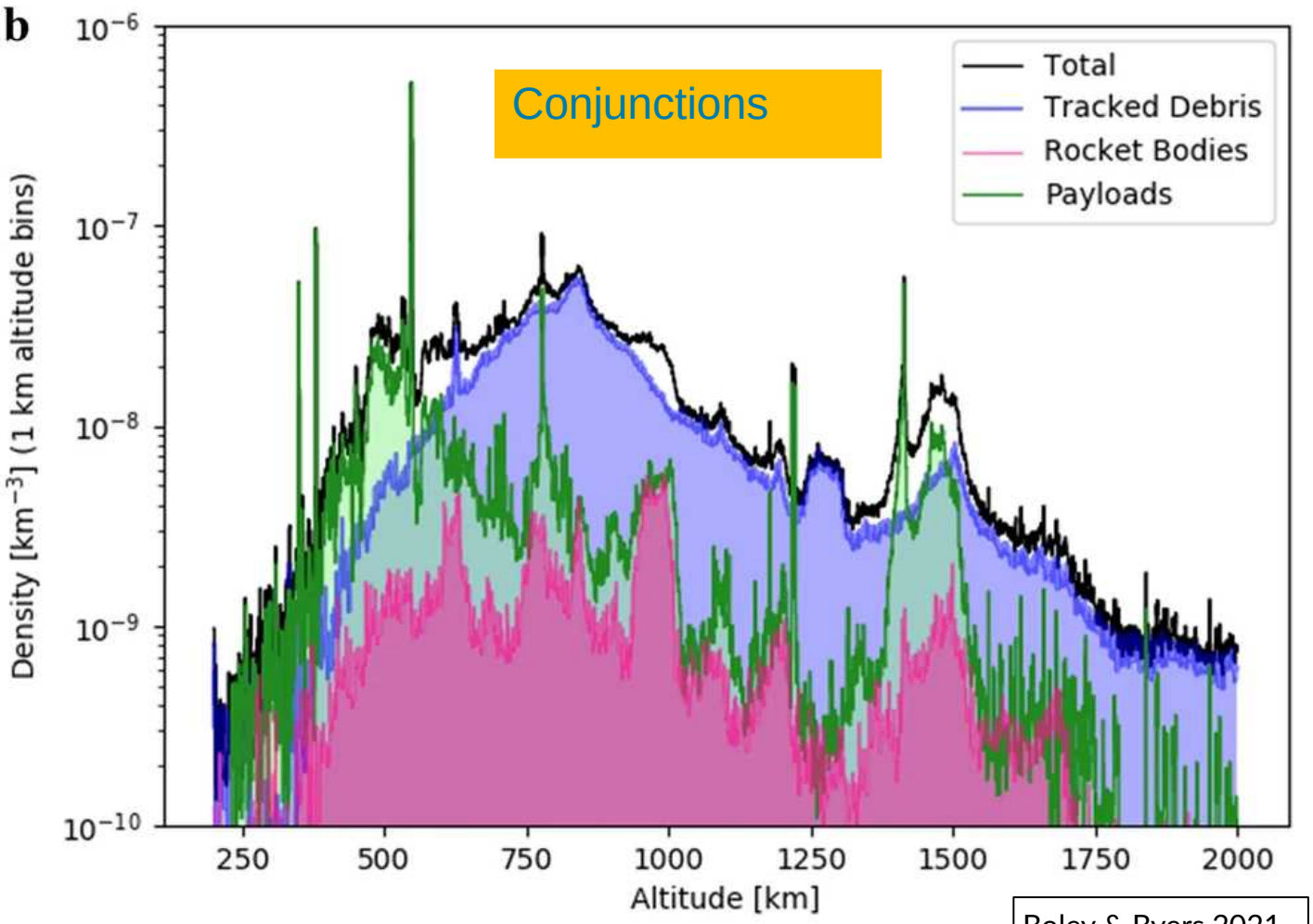


Boley & Byers 2021

Another problem: Low Earth Orbit is getting crowded

...and Solar max is coming (predicted 2024-25)

Satcons rely on active collision avoidance. What happens if a large number are damaged, broken, or put into safe mode for even a few hours?

Other problems: Atmospheric Pollution

NewSpace is applying the consumer electronics model to Space use

- Starlink and other mega-constellation satellite lifetimes are anticipated to be 5 years
- Allows for regular updates and upgrades
- Failures easily replaced

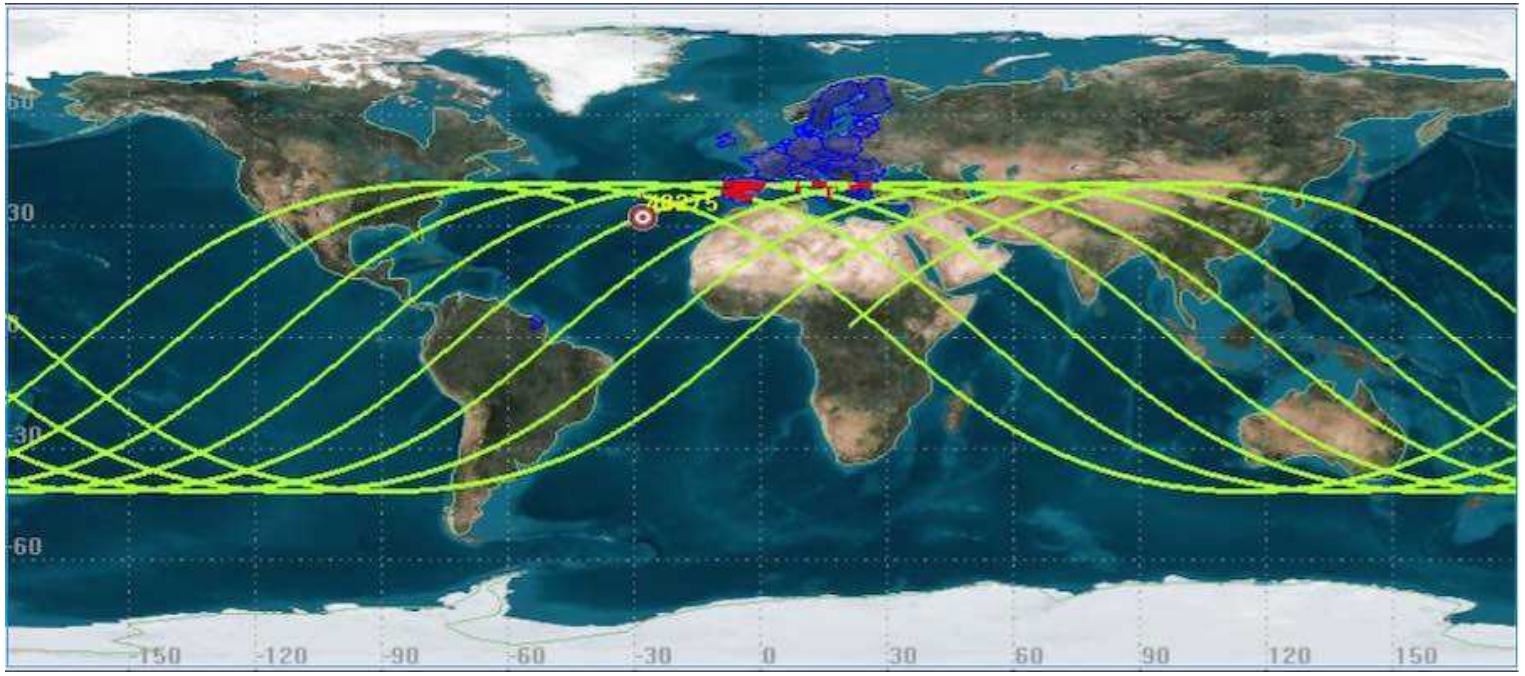
By the numbers:

- Starlink satellites are about 260 kg
- 42,000 satellites will be disposed every 5 years
- **6 tons** of satellites will be burned in the atmosphere **per day**

- Satellites have a large fraction of aluminum and other metals
- Meteoroids have an influx of about 54 tons per day
- Meteoroids are only about 1% aluminum
- Satellites will be the major contributor of metals (mainly aluminum) in the upper atmosphere (possibly creating alumina)

Canada will see a disproportionate number of uncontrolled re-entries

What happens if a rocket hits your house?



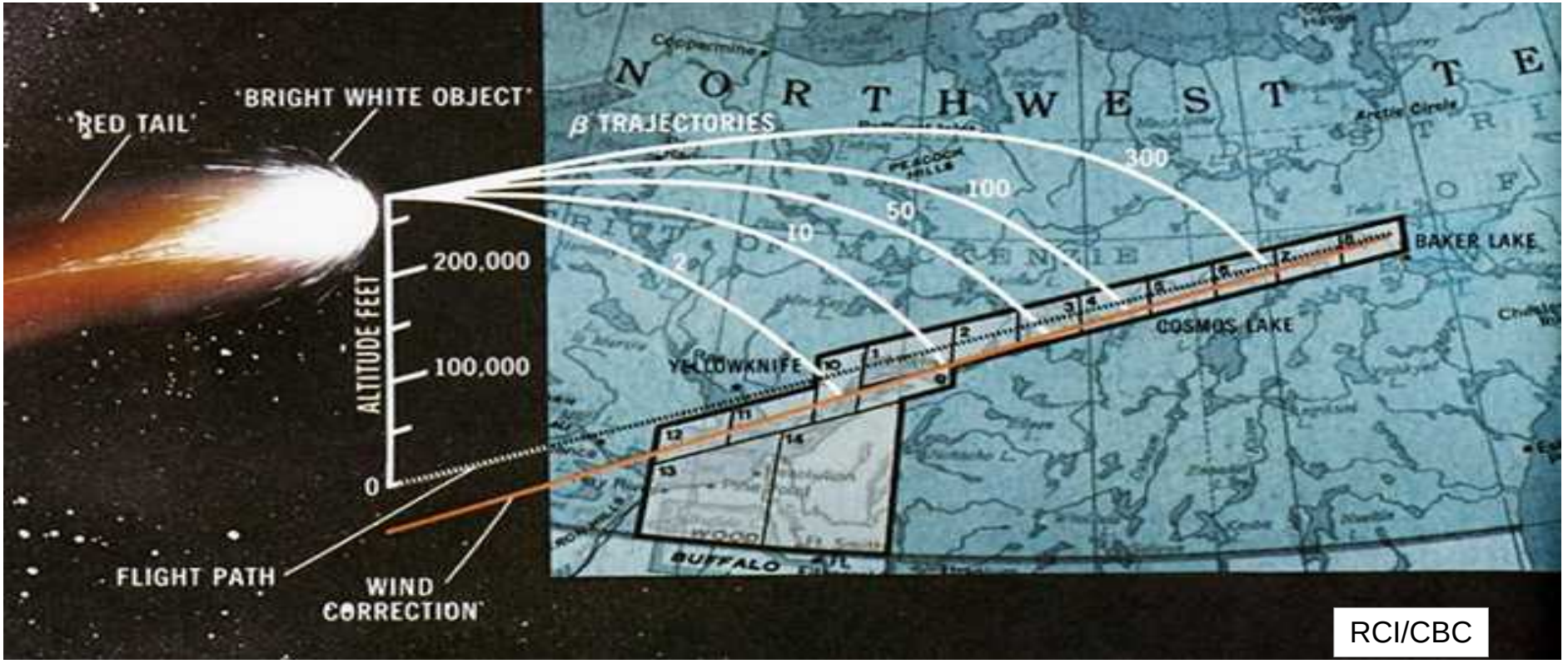
Long March 5B re-entry
(May 2021)

Falcon 9 reentry

@kaallori

SpaceX Falcon 9 helium tank recovered from a farm in Washington state (March 2021)

The only laws: the 1972 Liability Convention and 1968 Outer Space Treaty



USSR's Cosmos-954 exploded nuclear waste across Canada Jan. 24, 1978

The only laws: the 1972 Liability Convention and 1968 Outer Space Treaty

We need international regulation of satellites.

The only international laws are horribly outdated. Do they even apply to private companies?

What will we miss with no mitigation?

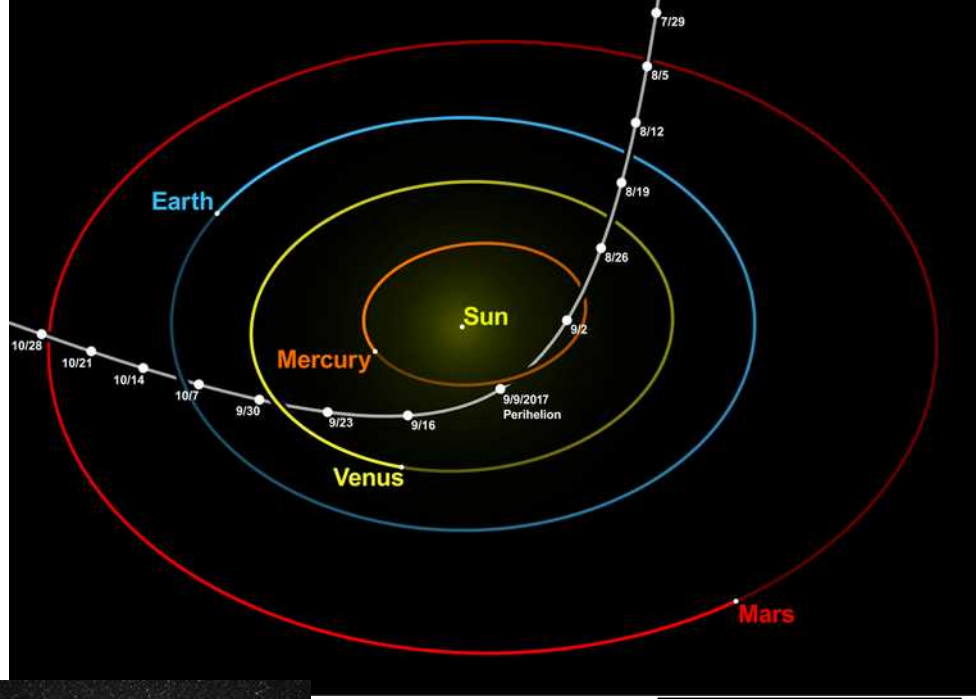
Dan Duriscoe/USNPS

The skies are changing right now.

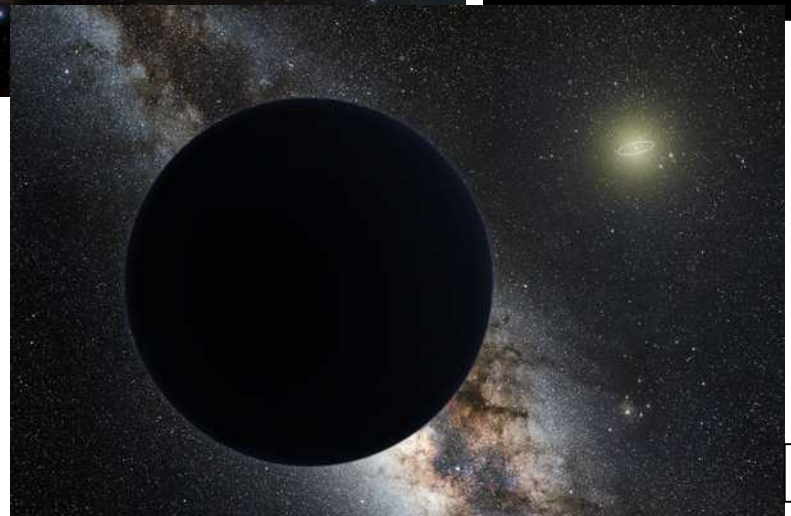
+60 new satellites every 2 weeks.

What will we miss?

NOIRLab/NSF/AURA/J. da Silva



Wikipedia/tomruen



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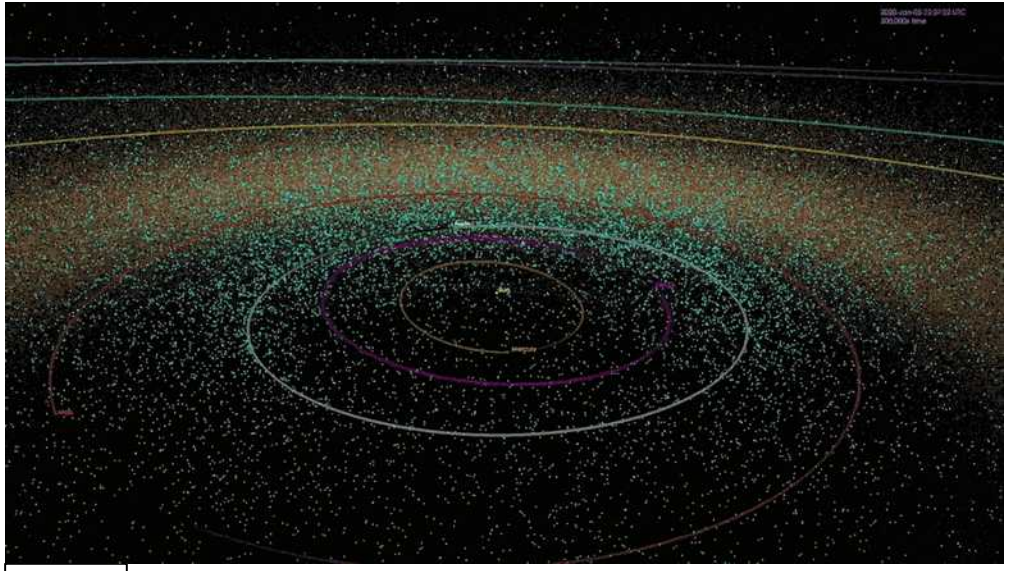
What will we miss?



NASA/JPL

Potentially hazardous asteroids

What are astronomers already doing about this?

- Astronomers are working on trail removal software (not perfect, like chemotherapy for your images)
- There are databases where you can look up satellite orbits and predict which ones are overhead at any given time – this is currently not very user friendly, but many astronomers/coders are working on better interfaces
- Purposeful observations of satellites: are they really as faint as companies claim? Do their positions/timing match predictions? Do their brightnesses vary?
- Continued respectful engagement with satellite operators, hoping that they will listen (so far, they have – but they don't have to)
- SATCON2 brought together astronomers (professional and amateur), space lawyers, satellite operators for discussions and a report of recommendations is forthcoming. Dark and Quiet Skies 2 meets in October to draft a UN report.
- The Canadian Space Agency held a public consultation, we wrote a report. Aaron Boley and I consulted with people from many branches of the Canadian government and told them our recommendations (will they listen? Maybe. Can one country's regulations actually make a difference? Unlikely.)

What can you do about this?

- Giant, powerful corporations like SpaceX will respond to only 2 things: legislation (which is very slow), and consumer pressure.
- If you have alternatives, don’t use satellite internet! (Especially not Starlink!)
- Talk to your friends and family about what is happening to the night sky – most people have no idea this huge change is coming
- Tell your local/state/federal government representatives upport alternative ways of accessing internet (cell towers, new fibreoptic lines)
- Use your skills and training to show many people the beautiful sky
- Go outside and enjoy the night sky as much as you can right now

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

We need to protect: culture/traditional knowledge, navigation, true darkness, science opportunties. Will be worldwide, without consent from most of the world's population.

There shouldn't have to be a choice between astronomy and global internet. With proper regulation, better engineering, and cooperation between satellite operators, maybe we can still have both.

github.com/hannorein/megaconstellations
http://megaconstellations.hanno-rein.de/

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