



清华大学
Tsinghua University

A Networking Perspective on Starlink's Self-Driving LEO Mega-Constellation

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Jianping Wu, Qian Wu, Jun Liu, Zeqi Lai, Han Qiu

Low Earth Orbit (LEO) Mega-Constellation



42,000
SATELLITES

High-speed Internet for the “unconnected” 2.7B users

LEO Satellites in **Harsh, Congested** Space



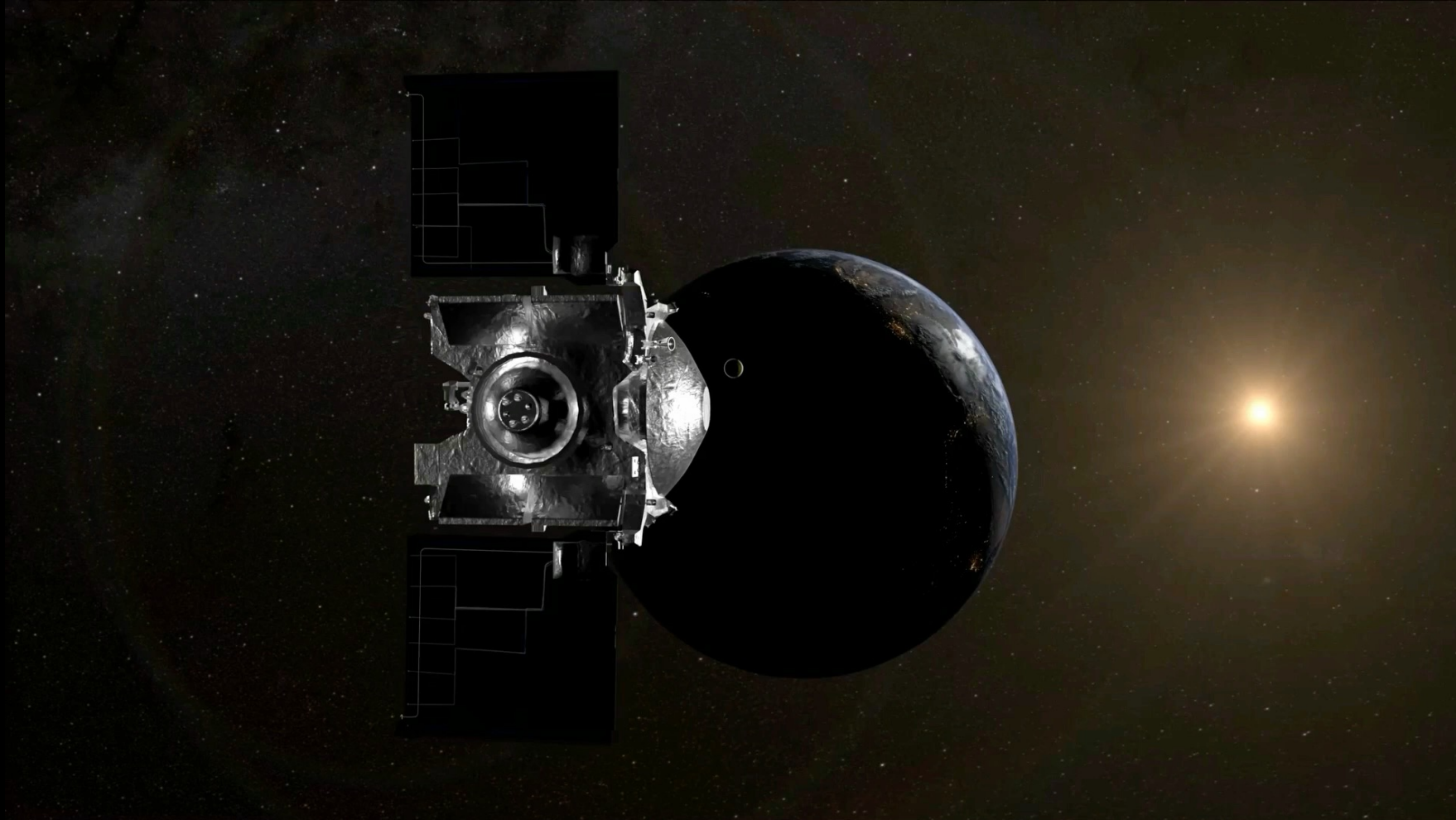
Altitude (Km) :
19 121

LEO Satellites in **Harsh, Congested** Space



Safety threat: **collision** with debris and satellites

Orbital Maneuvers for Space Safety



Calibrate and adjust the satellite's orbits for safety

Today: **Manual** Orbital Maneuvers



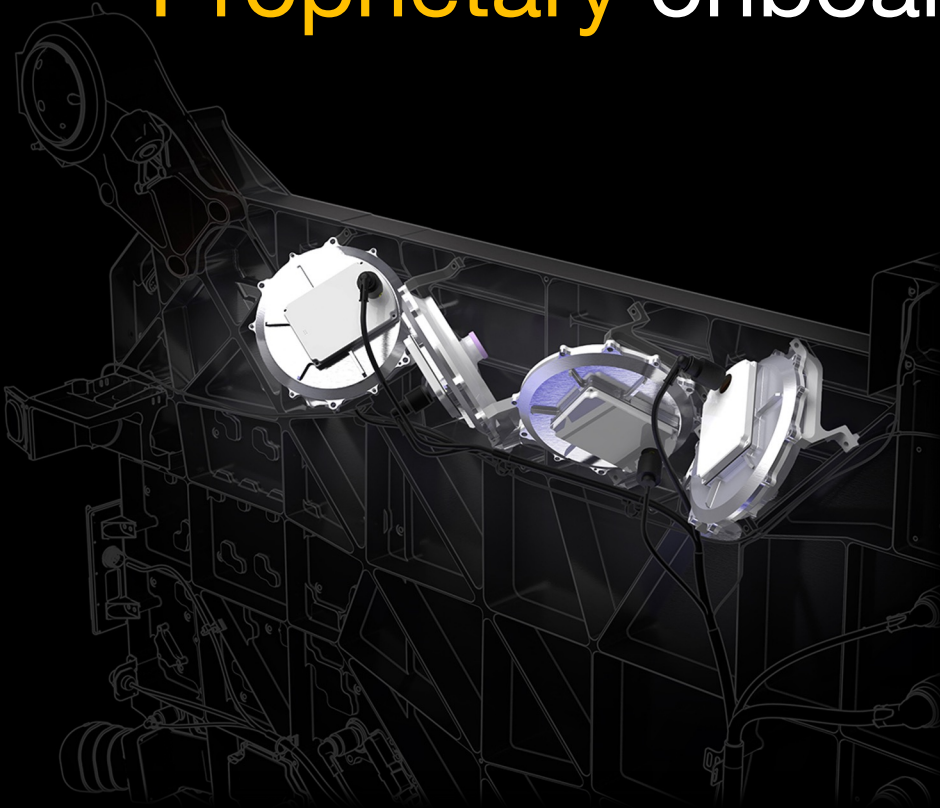
Today: **Manual** Orbital Maneuvers

Not scalable, responsive, or accurate
for LEO satellite **mega-constellations**



Starlink's **Self-Driving** LEO Satellites

Proprietary onboard **automatic** maneuver system

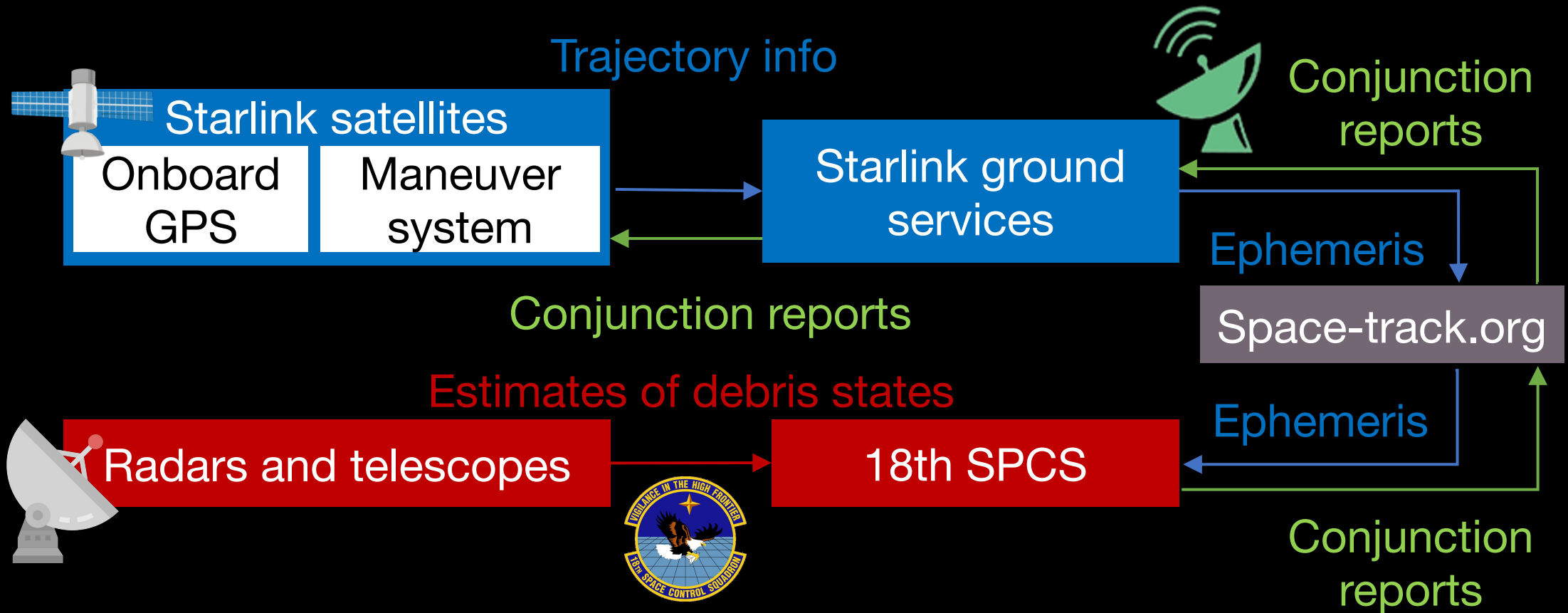


AUTONOMOUS COLLISION AVOIDANCE

Starlink satellites autonomously maneuver to avoid collisions with orbital debris and other spacecraft. This capability reduces human error and provides exceptional reliability, exceeding the industry standard by an order of magnitude.

Starlink's **Self-Driving** LEO Satellites

Proprietary onboard **automatic** maneuver system



Starlink's **Self-Driving** LEO Satellites

Proprietary onboard **automatic** maneuver system



Excellent for each individual satellite.

How about the **holistic constellation/network?**

This Work

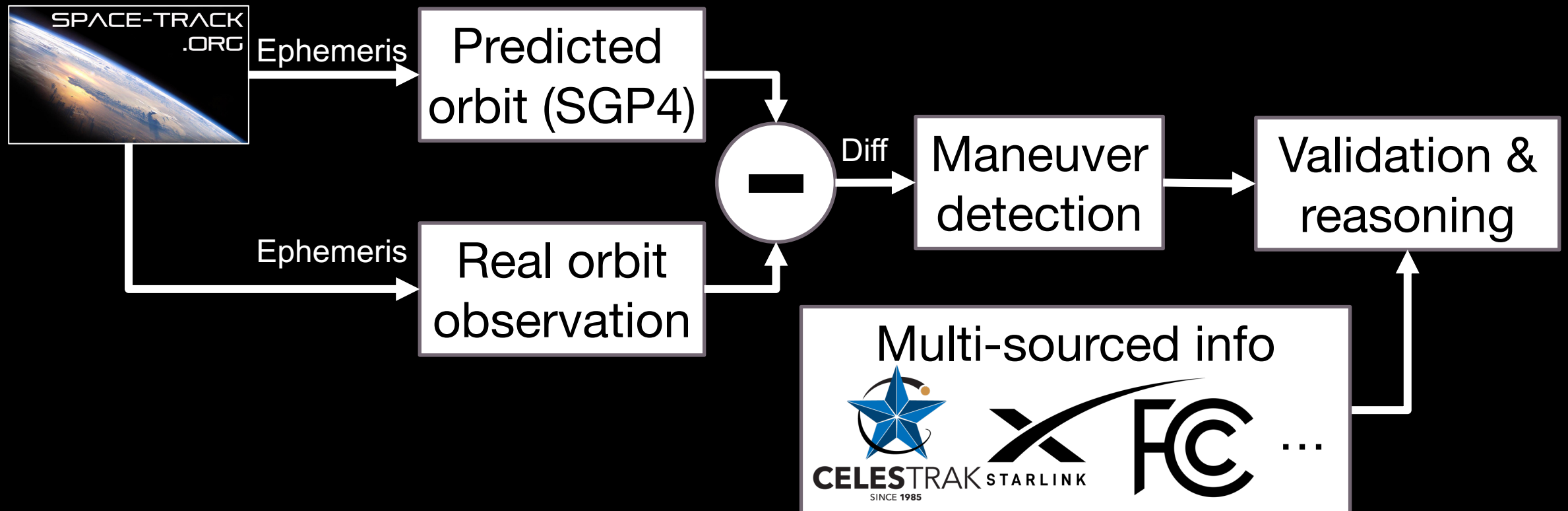
- Demystify Starlink's "black box" maneuvers
- Diagnose Starlink's maneuvers from
 - The individual satellite view
 - The mega-constellation view
 - The networking view
- Implications for networking-maneuver co-design

This Work

- **Demystify Starlink's "black box" maneuvers**
- Diagnose Starlink's maneuvers from
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Demystify Starlink's **Black Box** Maneuvers

Idea: maneuvers cause **observable orbit changes** that **differ from predicted orbits** *without* maneuvers.

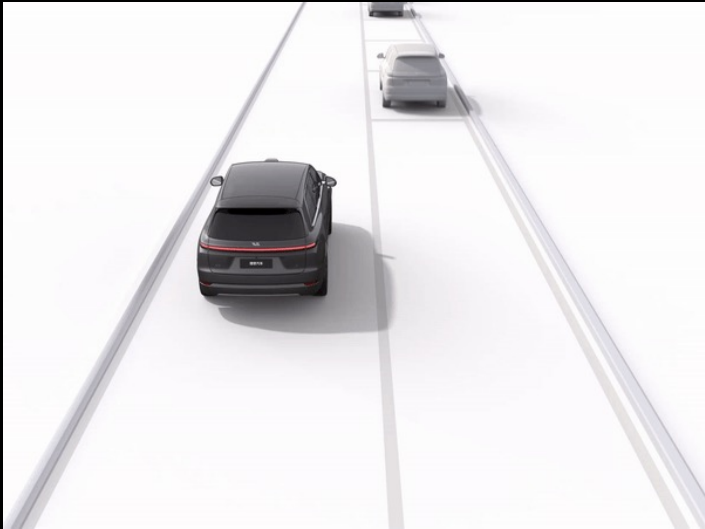


This Work

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Analogy: Terrestrial Driving

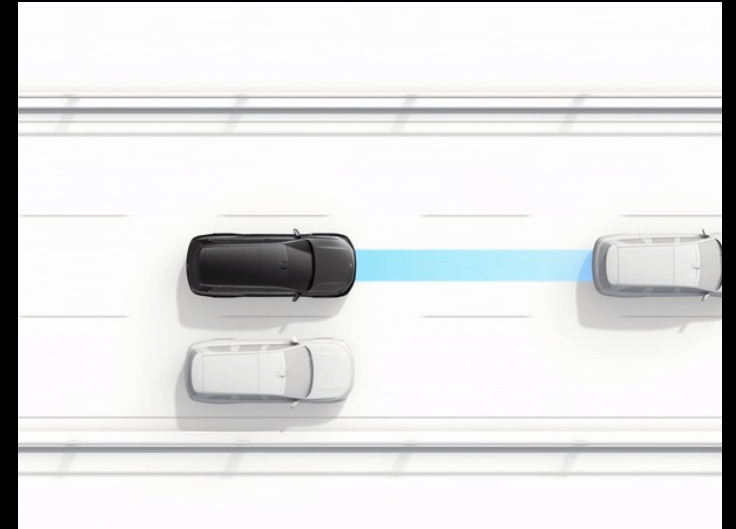
Three categories of common self-driving behaviors



Lane keeping



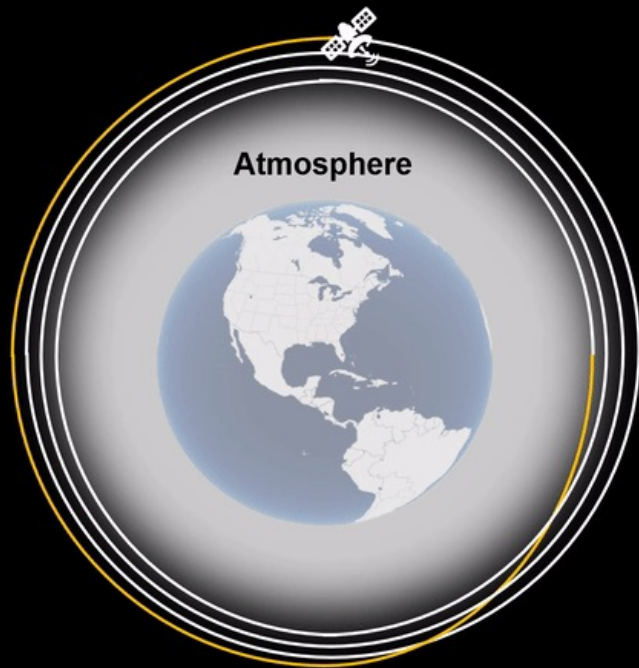
Collision avoidance



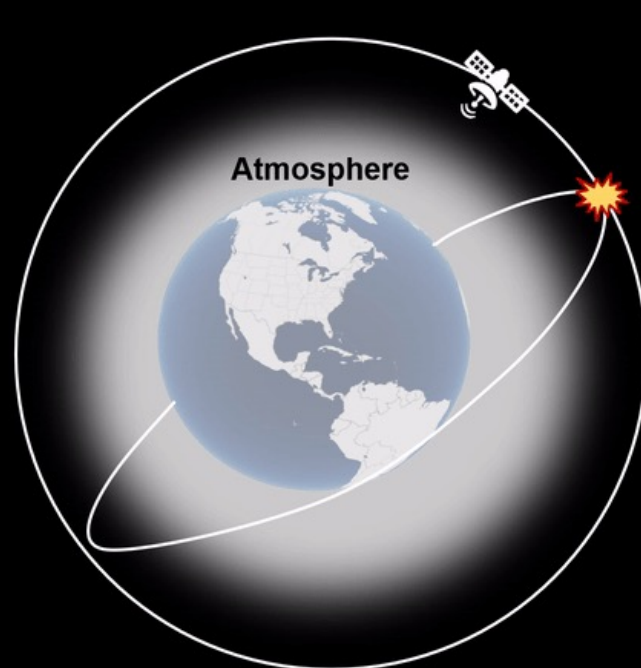
Lane change

Starlink's Self-Driving LEO Constellation

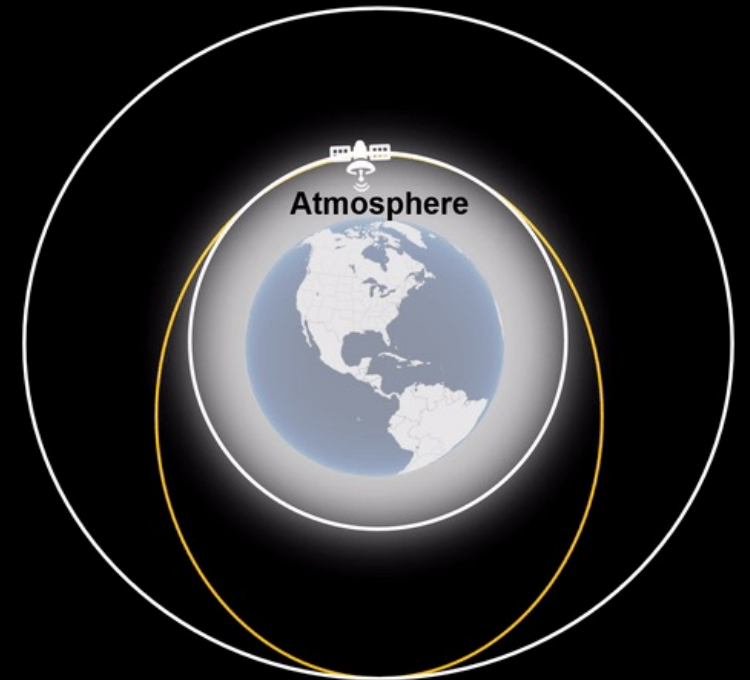
Three categories of common self-driving behaviors



Lane keeping



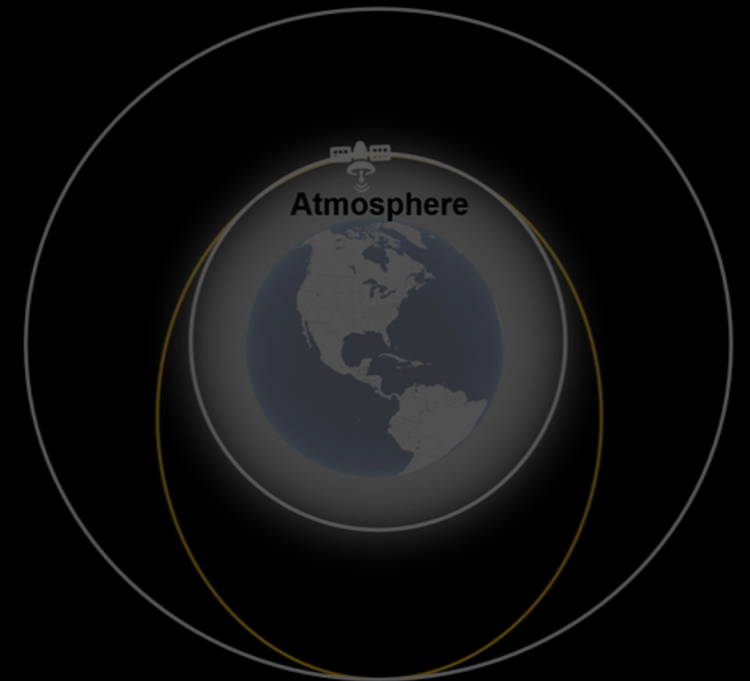
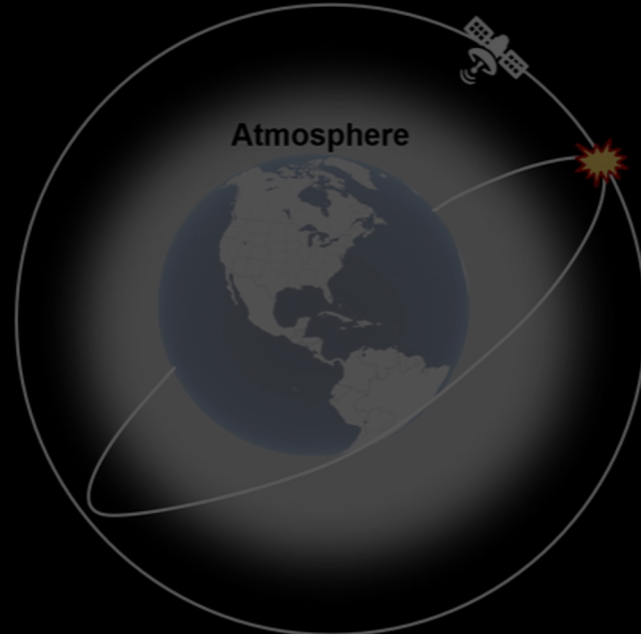
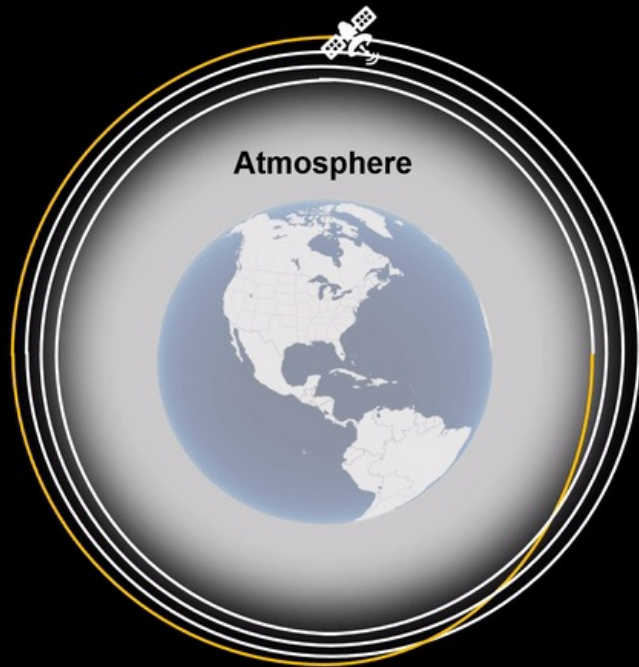
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Lane change

Starlink's Self-Driving LEO Constellation

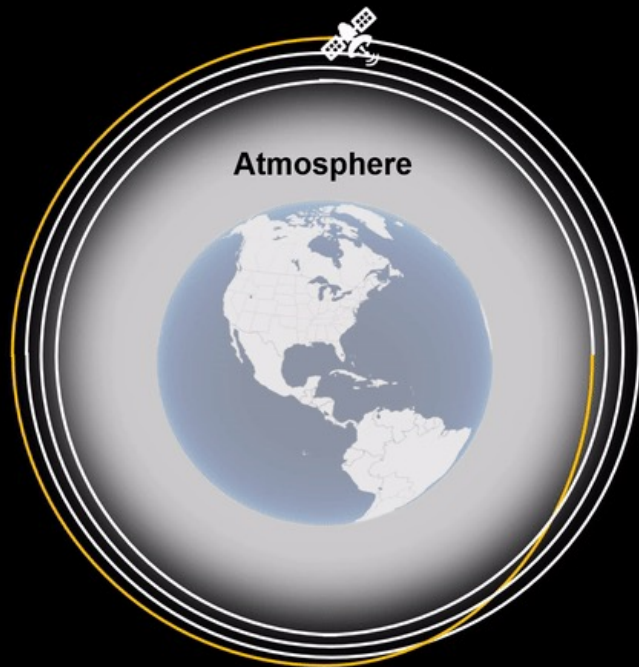
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Orbit maintenance Collision avoidance Inter-shell maneuver

Orbit Maintenance

Compensate for atmospheric decays via maneuvers



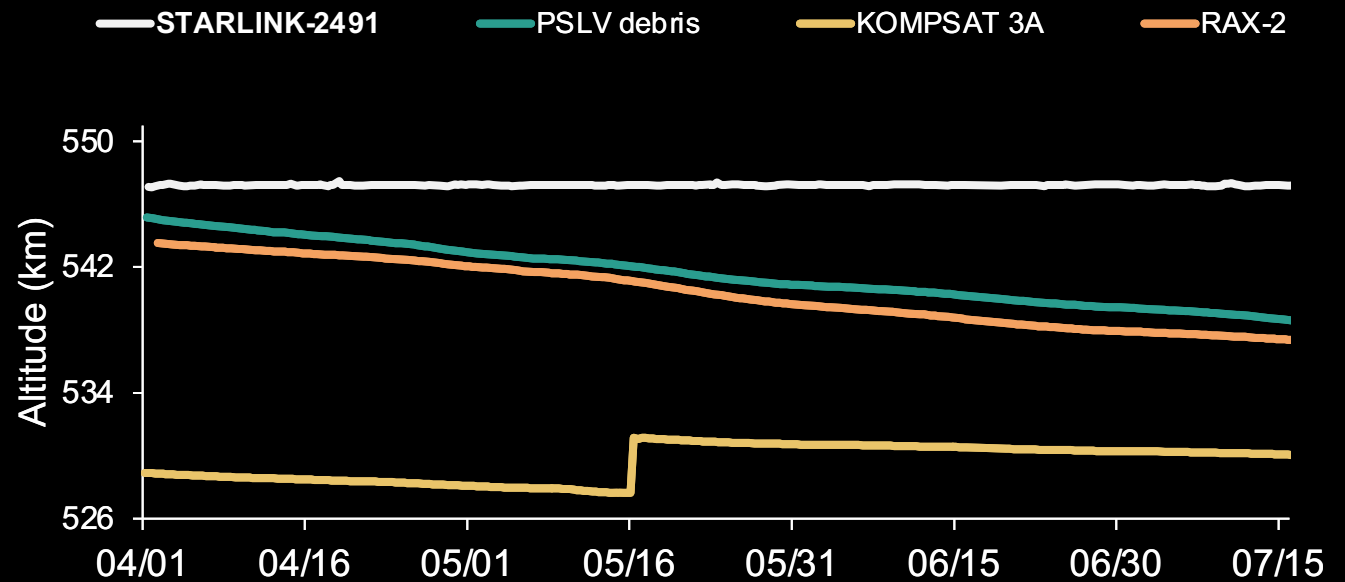
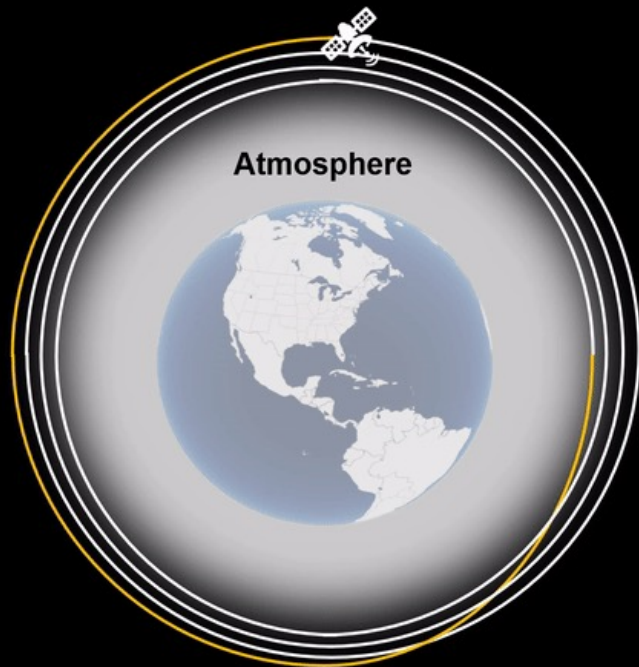
Single Satellite view

Mega-Constellation view

Networking view

Orbit Maintenance

Compensate for atmospheric decays via maneuvers



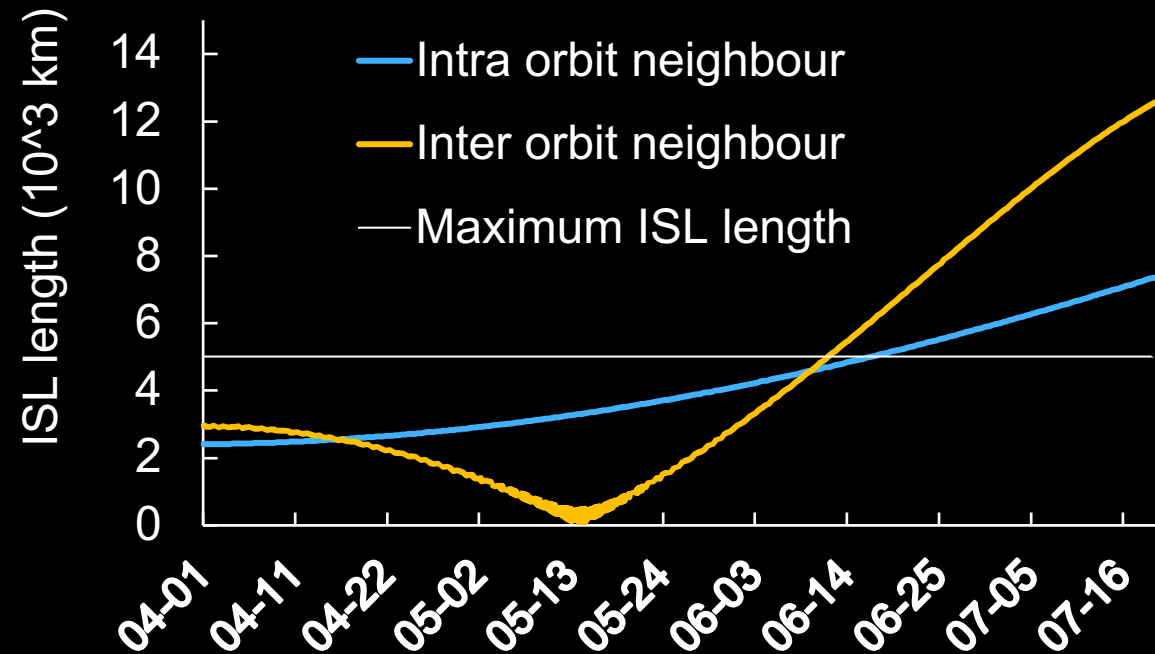
Single Satellite view

Mega-Constellation view

Networking view

Orbit Maintenance

Retain **uniform** constellation w/o **heterogeneous decays**



Without orbit maintenance

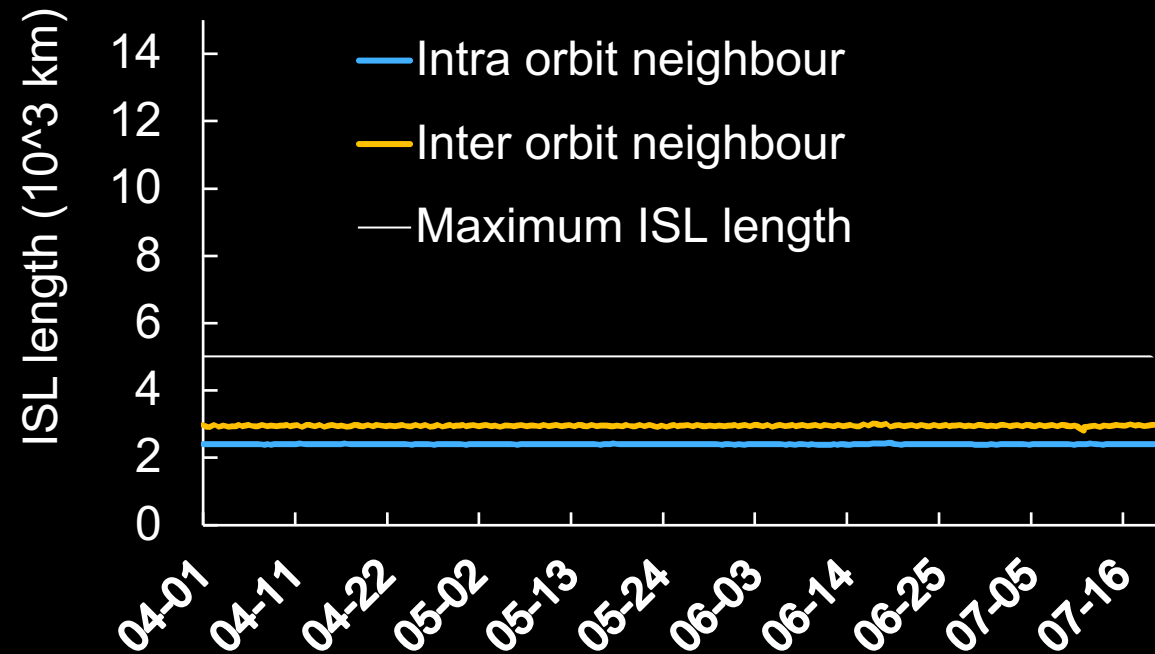
Single Satellite view

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Networking view

Orbit Maintenance

Retain **uniform** constellation w/o **heterogeneous decays**



With orbit maintenance

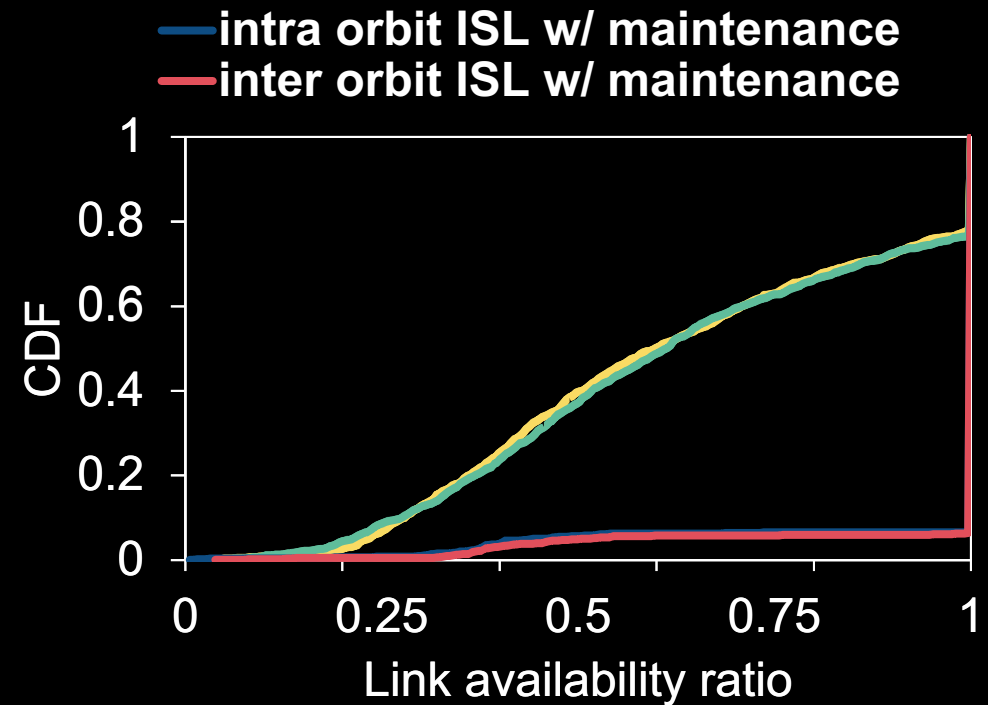
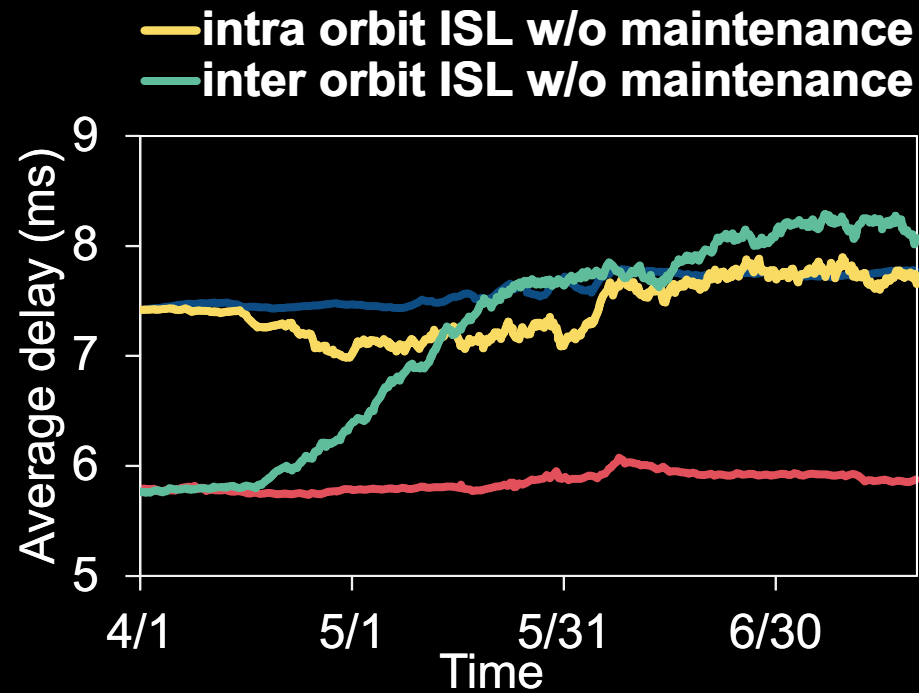
Single Satellite view

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Orbit Maintenance

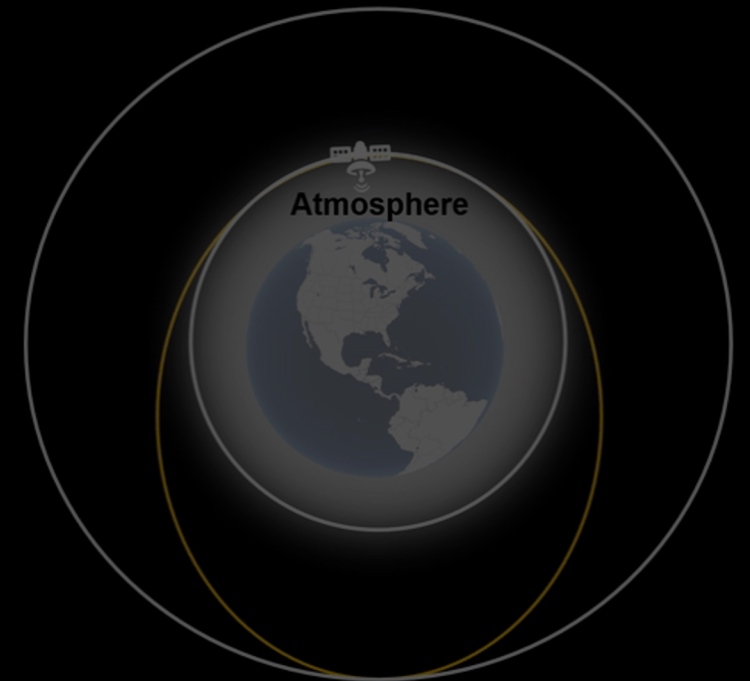
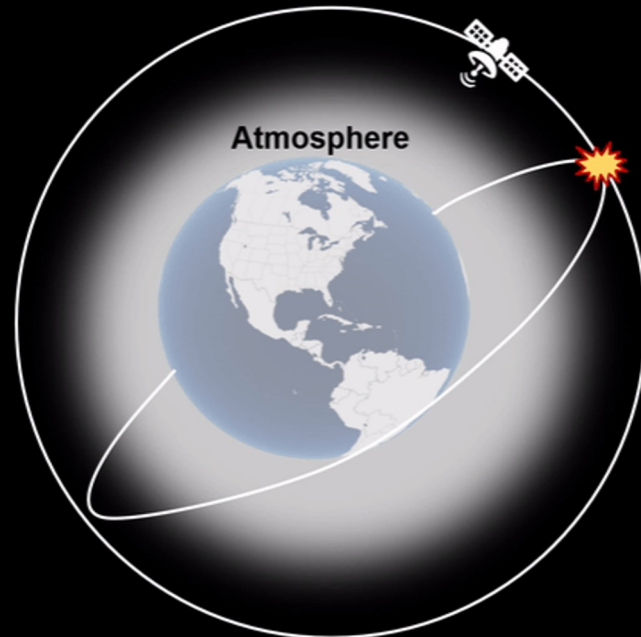
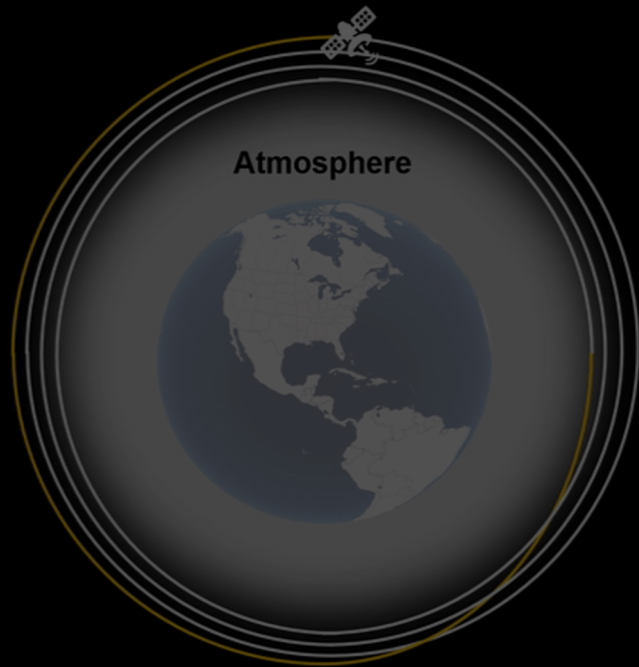
Uniform satellite distribution → **Stable network topology**



Orbit maintenance strives for **predictable & stable** LEO networking

Starlink's Self-Driving LEO Constellation

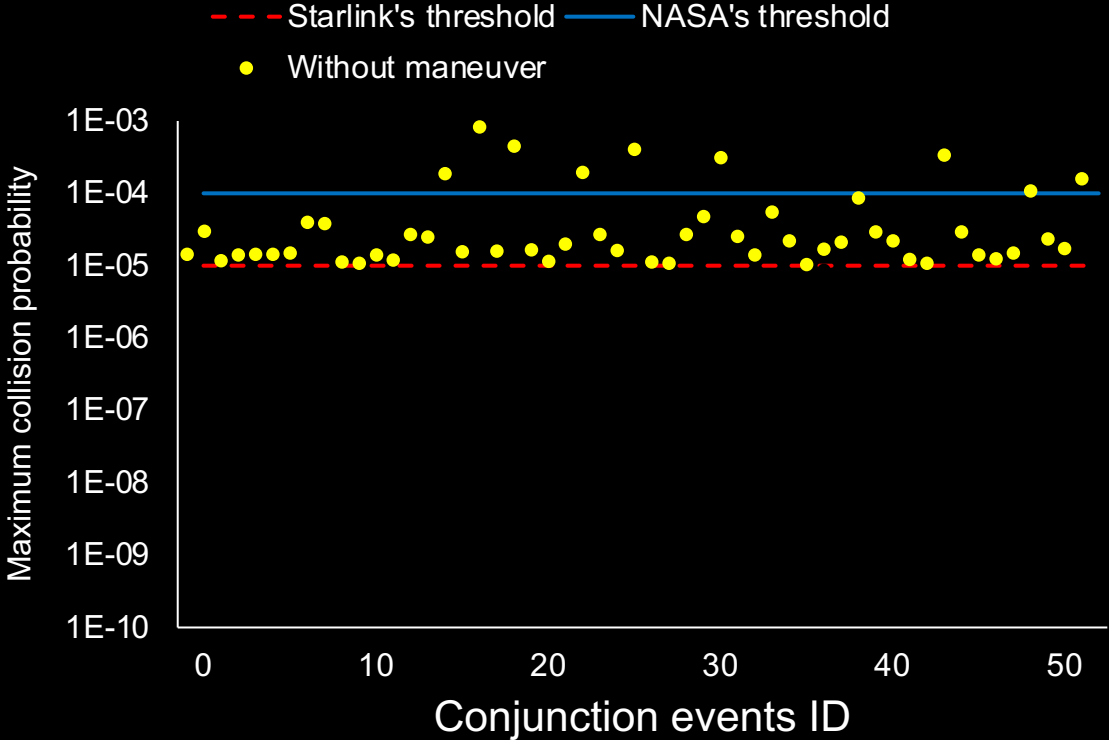
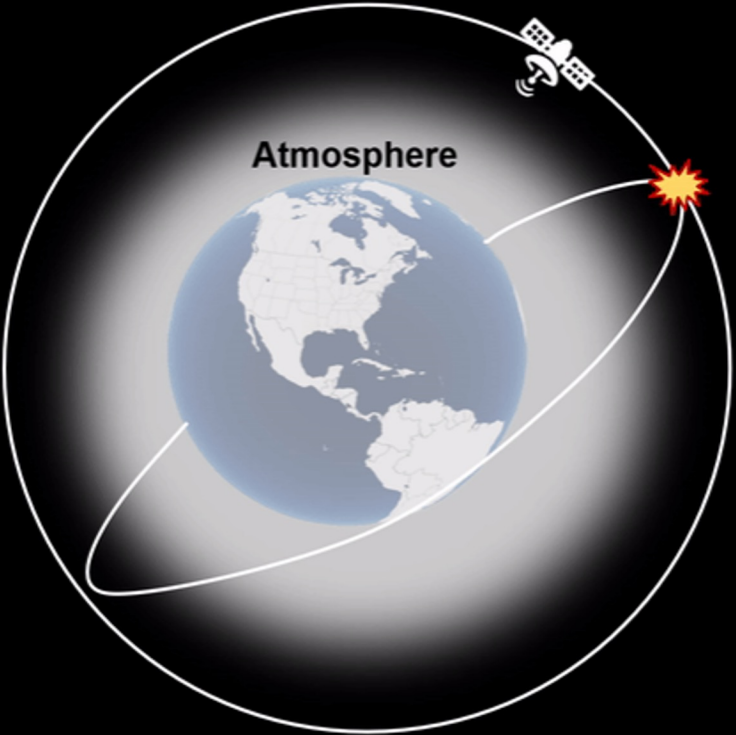
Three categories of common self-driving behaviors



Orbit maintenance **Collision avoidance** **Inter-shell maneuver**

Collision Avoidance

Starlink excels in lowering collision risks in most cases



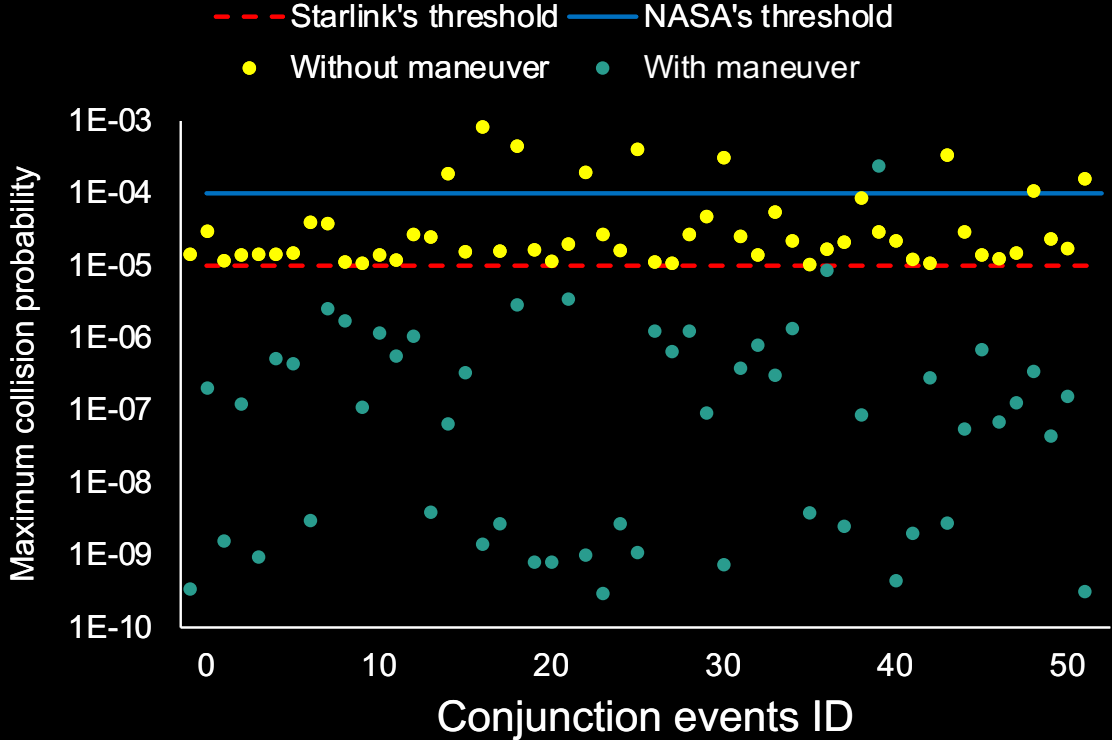
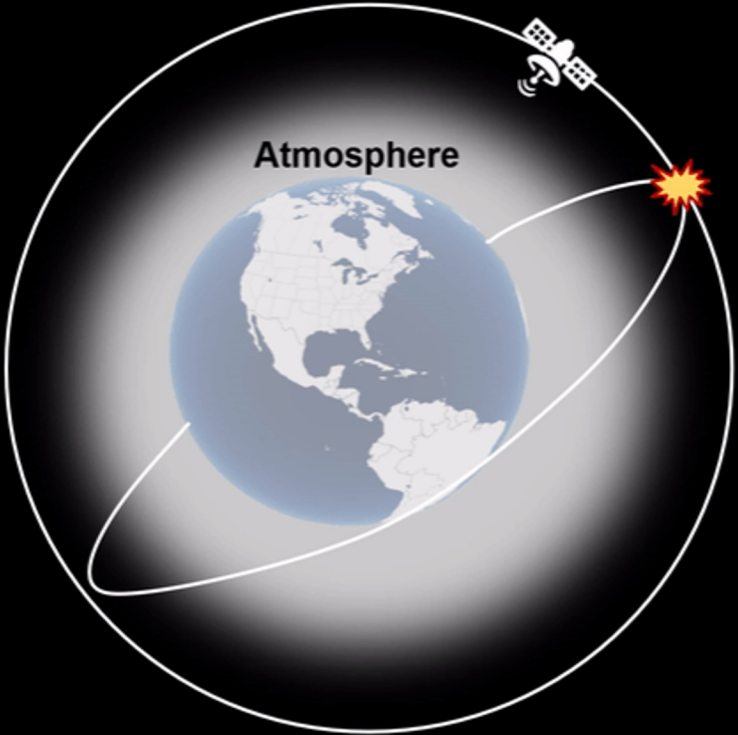
Single Satellite view

Mega-Constellation view

Networking view

Collision Avoidance

Starlink excels in lowering collision risks in most cases



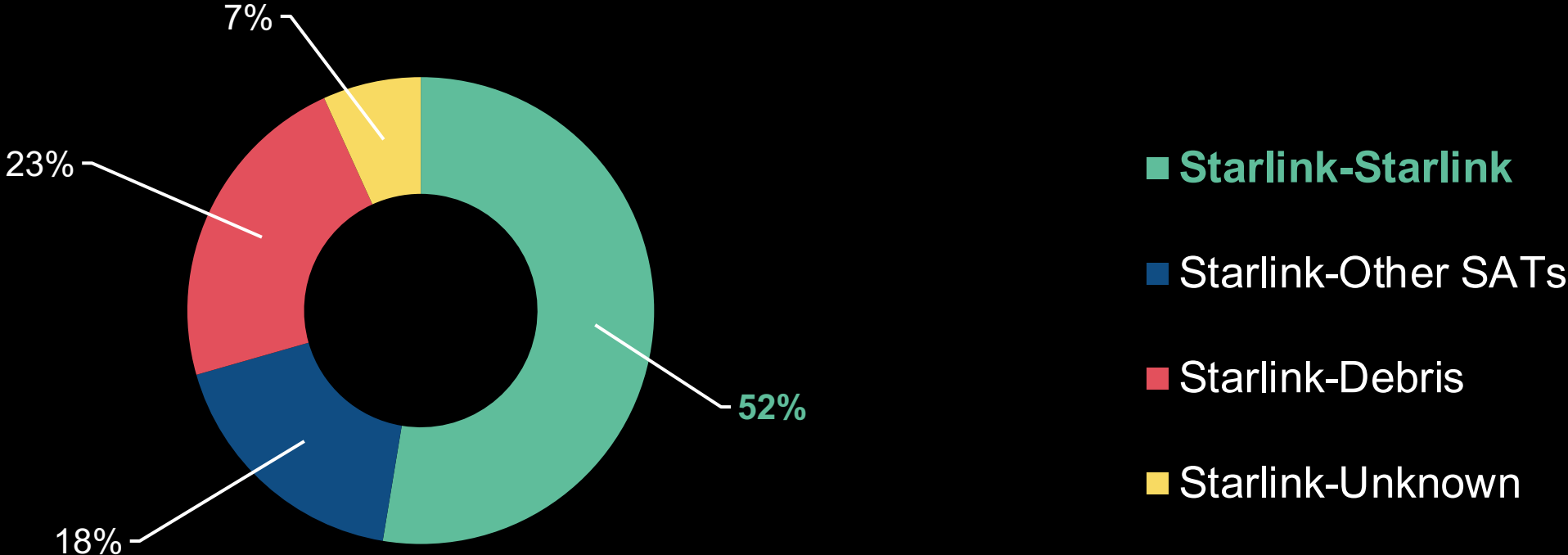
Single Satellite view

Mega-Constellation view

Networking view

Collision Avoidance

Non-negligible collision risks **among Starlink satellites**



Distribution of satellite conjunctions (2022/04-2022/08)

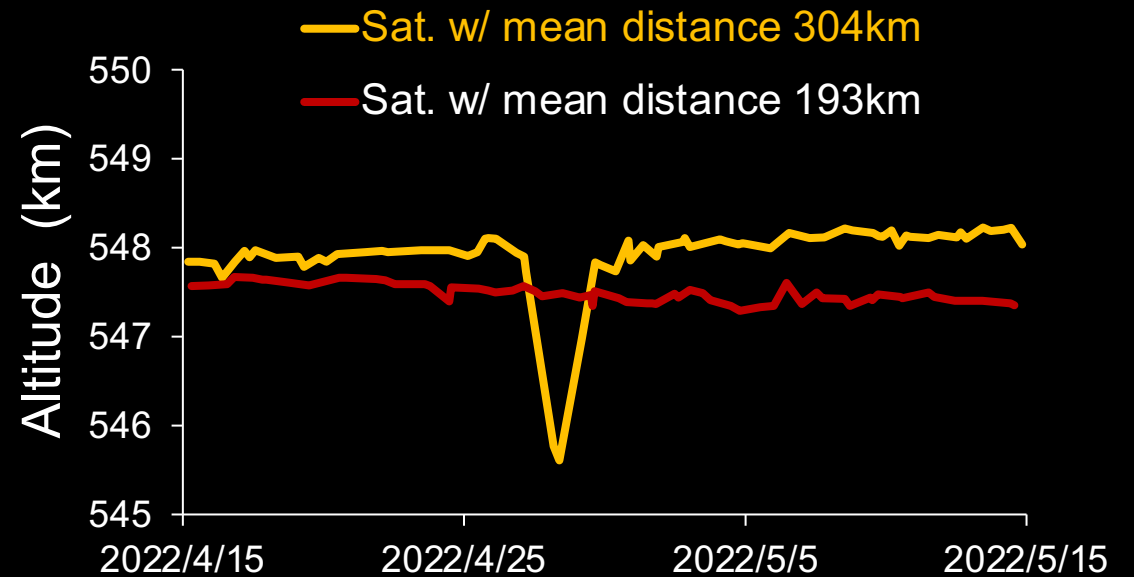
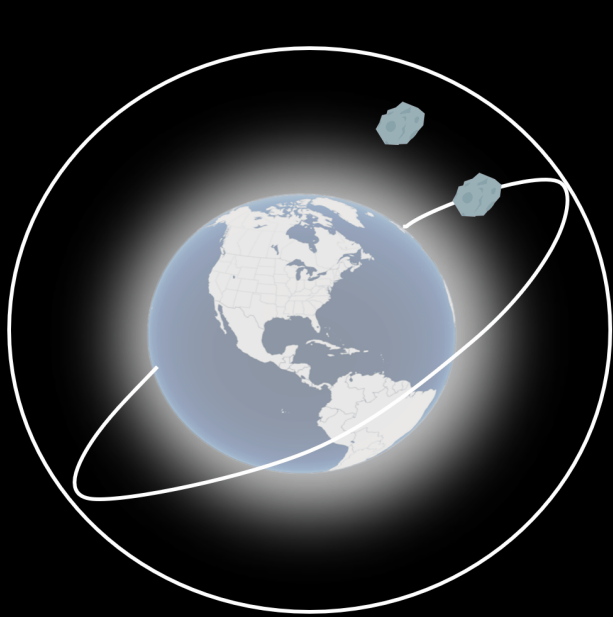
Single Satellite view

Mega-Constellation view

Networking view

Collision Avoidance

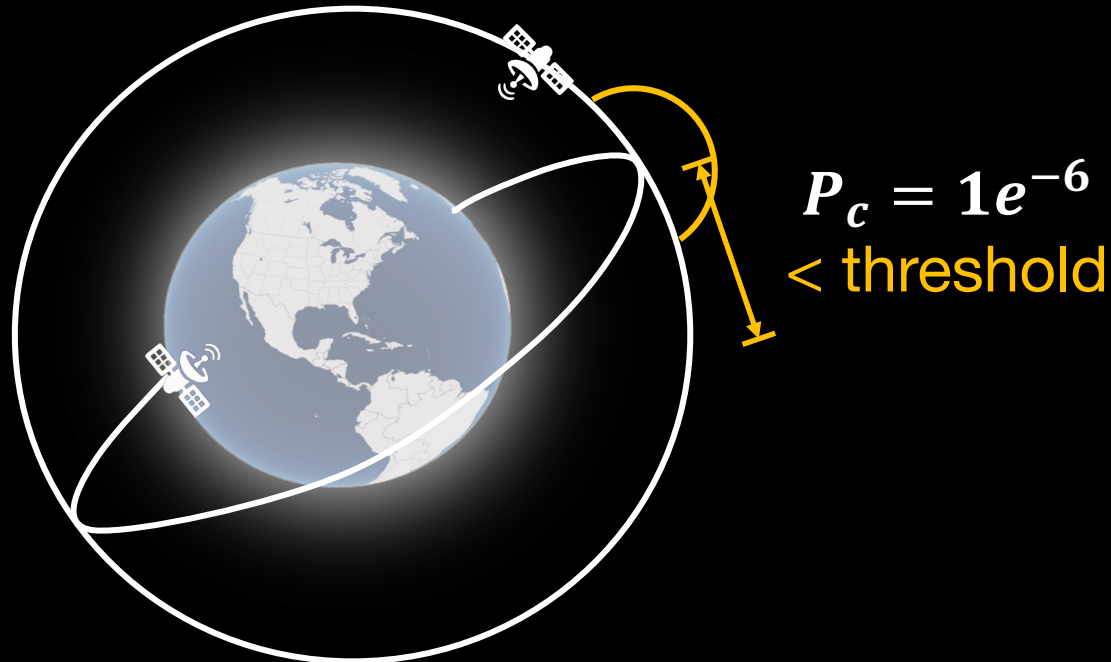
Cooperative collision avoidance inside Starlink



In **98%** cases, satellite with **sparser surrounding** runs the maneuver

Collision Avoidance

Non-negligible link failures by **unnecessary maneuvers**

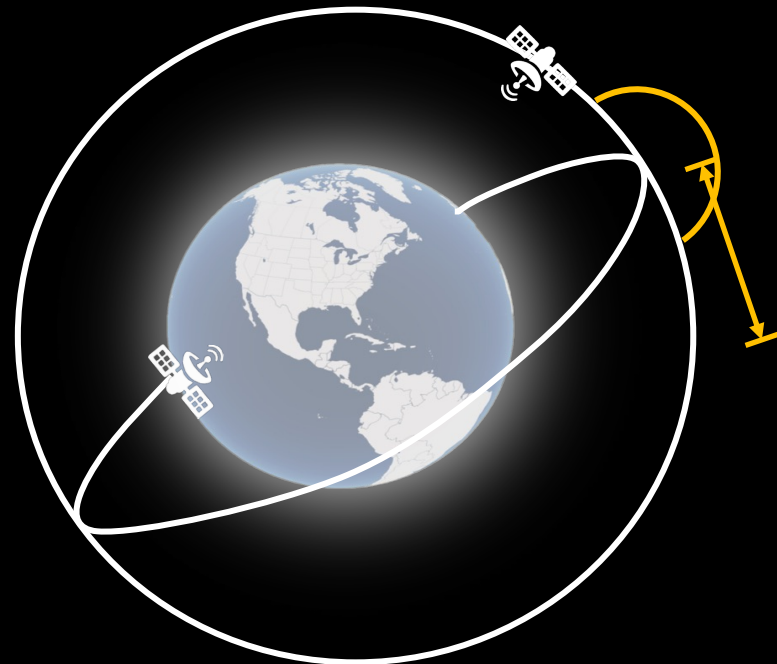


Unnecessary collision avoidances

Still room for Starlink to **safely stabilize** its LEO network topology

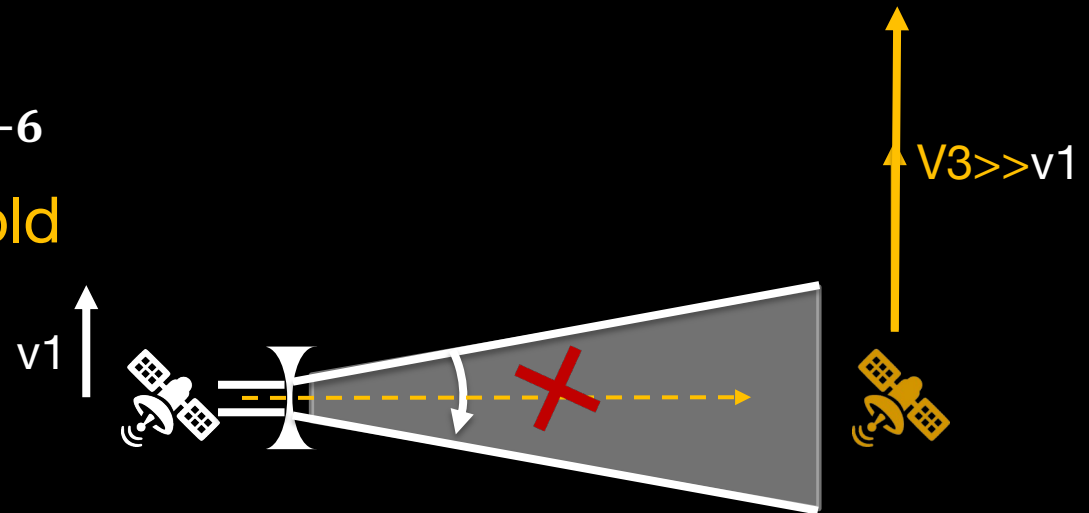
Collision Avoidance

Non-negligible link failures by **unnecessary maneuvers**



$$P_c = 1e^{-6} < \text{threshold}$$

Unnecessary collision avoidances

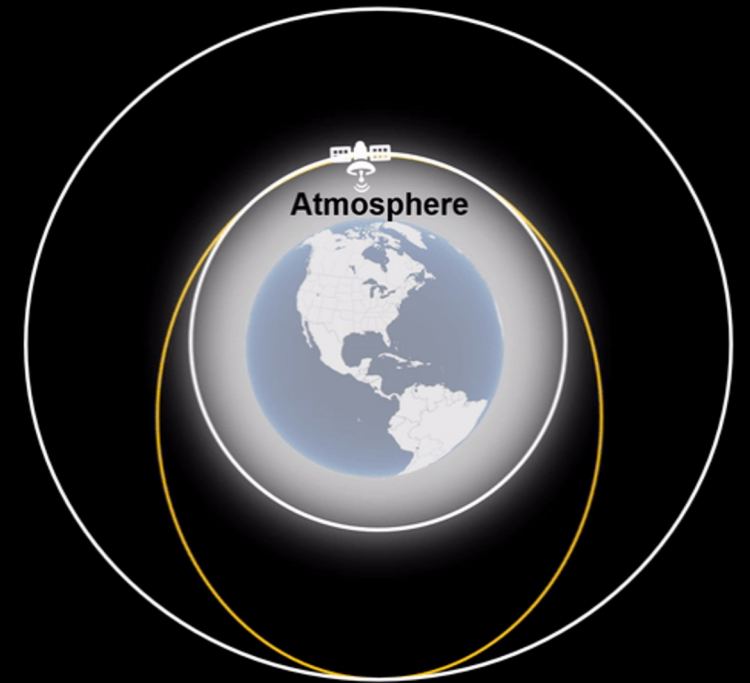
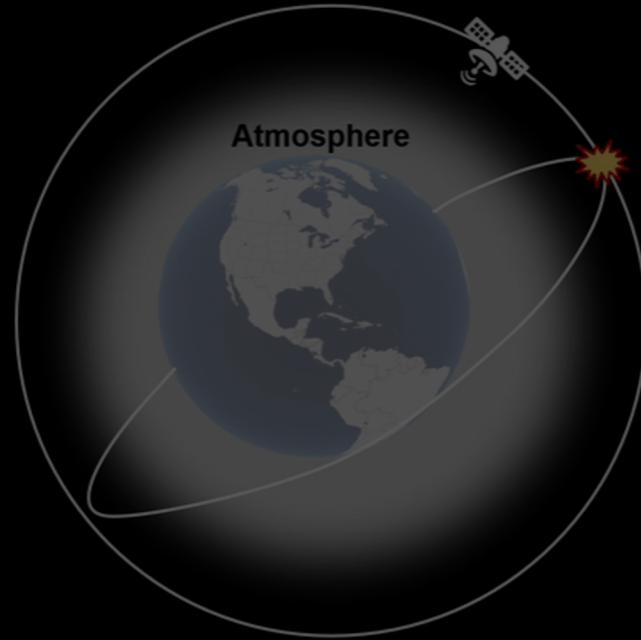
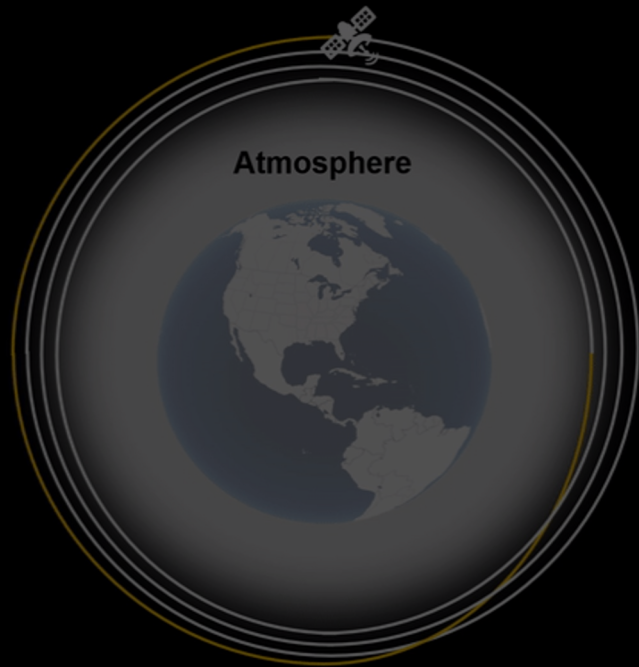


ISL interruption

Still room for Starlink to **safely stabilize** its LEO network topology

Starlink's Self-Driving LEO Constellation

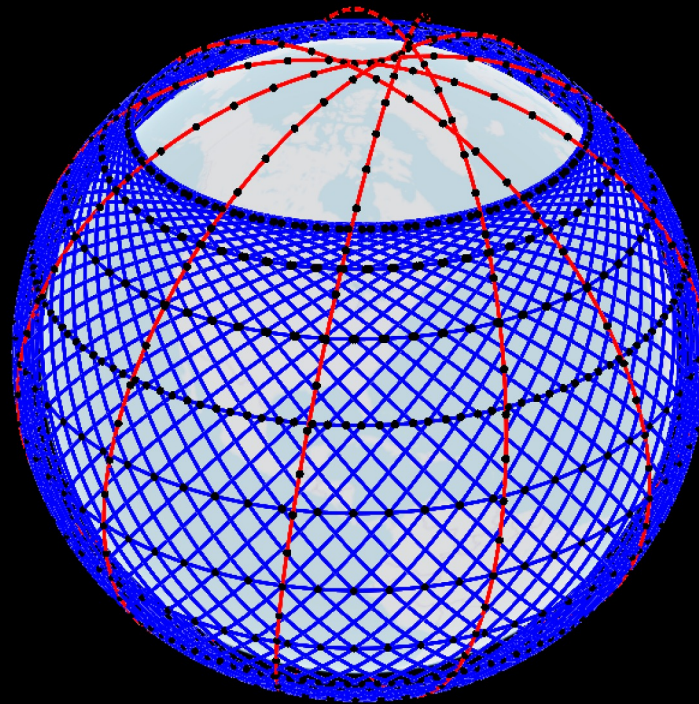
Three categories of common self-driving behaviors



Orbit maintenance Collision avoidance **Inter-shell maneuver**

Inter-Shell Maneuver

Multi-layer orbital shell for coverage optimization



— Orbital shell 1
— Orbital shell 2

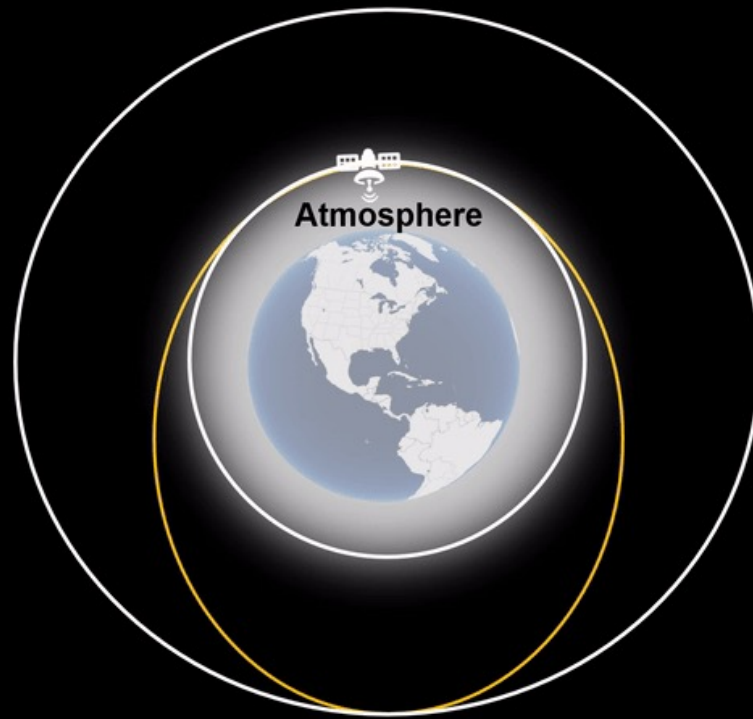
Single Satellite view

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Networking view

Inter-Shell Maneuver

Protracted maneuver between orbital shells



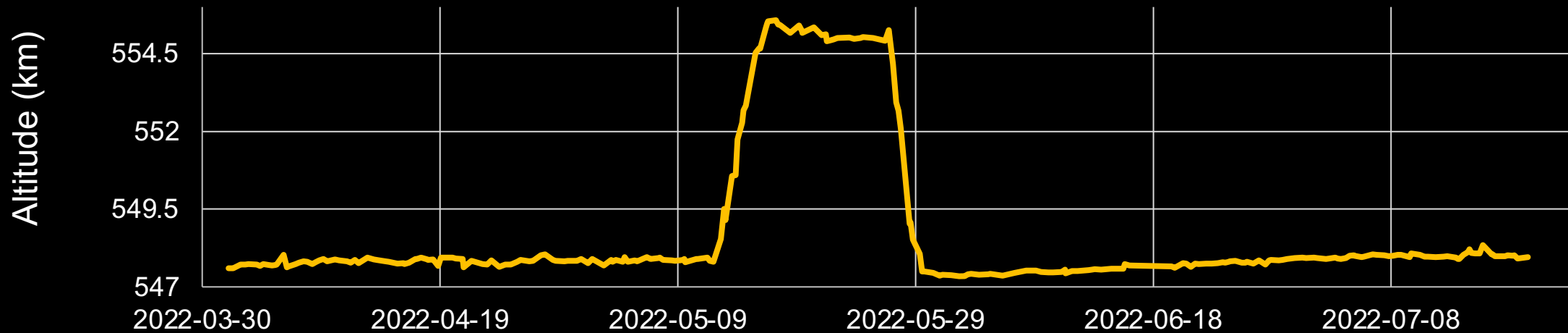
Single Satellite view

Mega-Constellation view

Networking view

Inter-Shell Maneuver

Protracted maneuver between orbital shells



Single Satellite view

Mega-Constellation view

Networking view

Inter-Shell Maneuver

Accumulative inter-satellite neighborhood changes

Kepler 3rd law

Constant gravitational parameter

$$v = \sqrt{\frac{\mu}{a^3}}$$

Velocity $\rightarrow v$ \leftarrow Altitude a^3

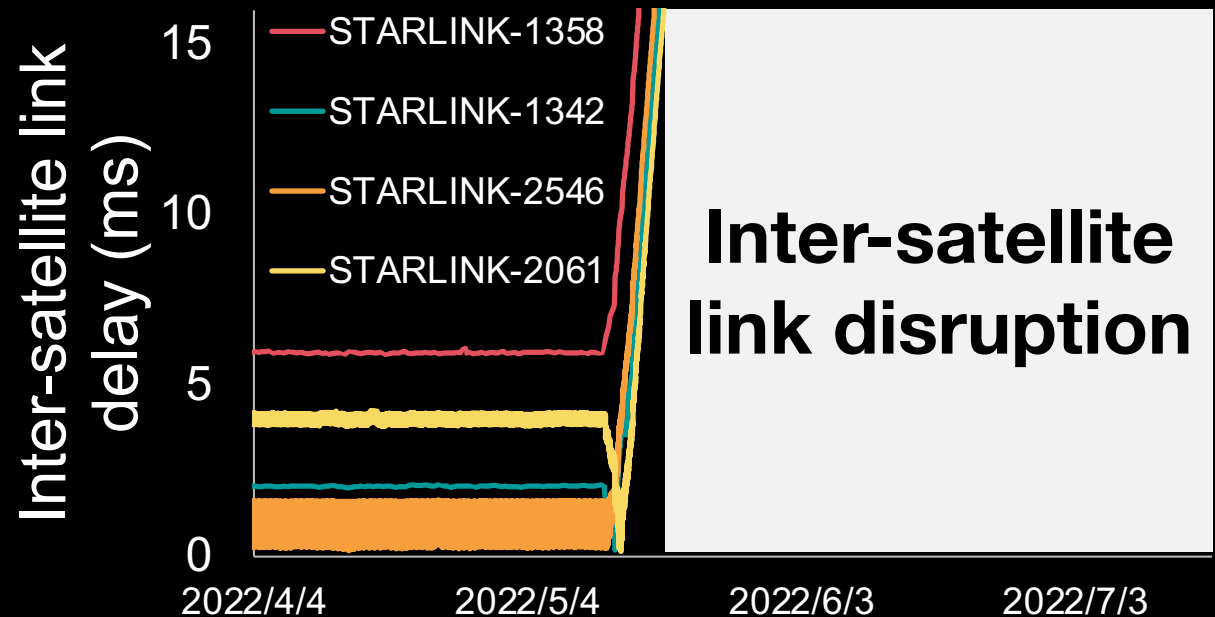
Single Satellite view

Mega-Constellation view

Networking view

Inter-Shell Maneuver

Accumulative inter-satellite neighborhood changes



Single Satellite view

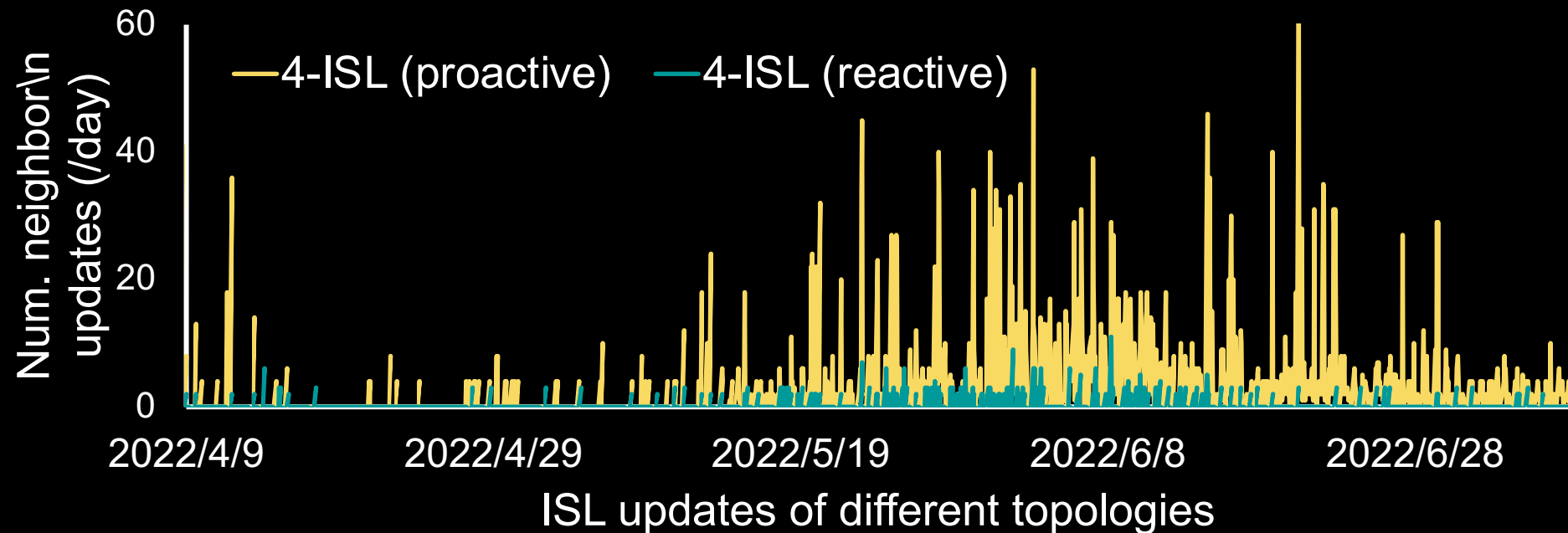
Mega-Constellation view

Networking view

Inter-Shell Maneuver

Accumulative inter-satellite neighborhood changes

→ Network topology and link changes



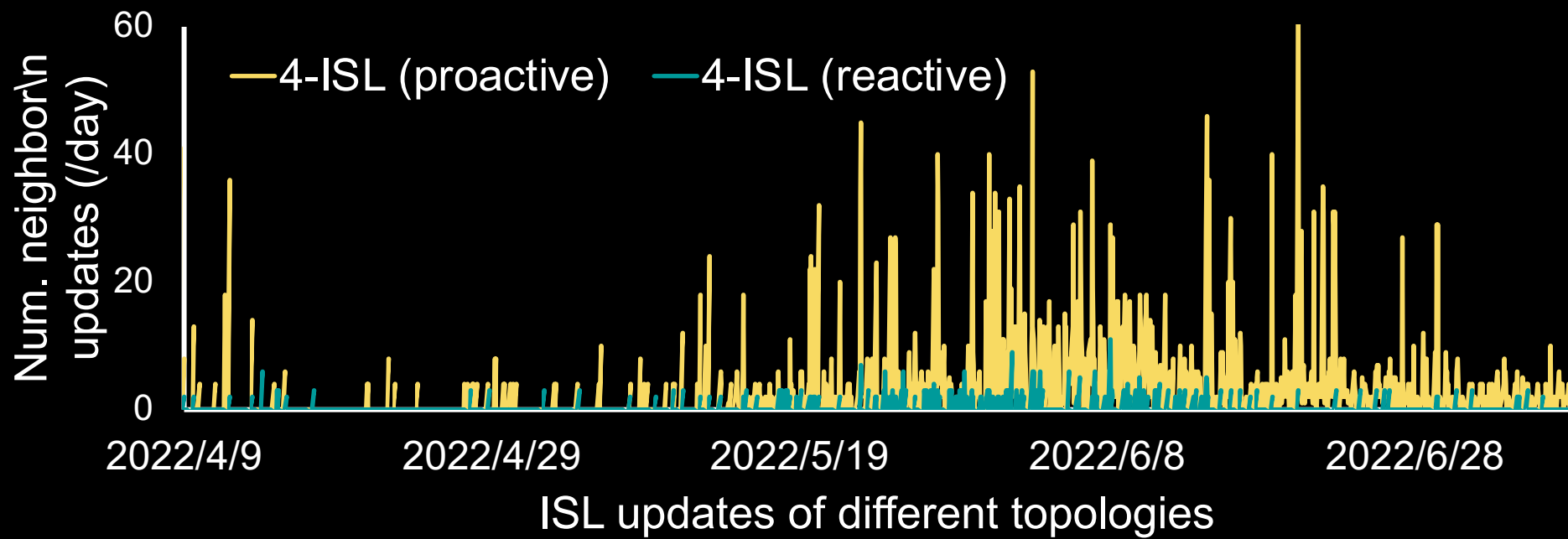
Protracted inter-shell maneuvers threaten LEO network stability

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- **Implications for networking-maneuver co-design**

Maneuver-Aware Networking

- Safety is first priority → Maneuvers are must-have
- Upper-layer networks should **tolerate maneuvers**
 - Orbit prediction is great, but **shouldn't be over-relied on!**



Networking-Aware Maneuver

A First Look at Networking-Aware LEO Maneuvers

Wei Zhao, Yuanjie Li, Hewu Li, Yimei Chen



清華大學
Tsinghua University

Join us at LEO-NET'23, October 6, 15:05-15:15

Conclusion

- From manual to **self-driving** LEO mega-constellations
 - Safe, sustainable, and scalable use of space for Internet
- **This work:** demystify Starlink's self-driving LEO
 - Orbital maneuvers have **mixed impacts** on networking
- Toward maneuver-networking **co-design**
 - Call for inter-disciplinary collaboration among communities



Thank you!