Network topology design at 27,000 km/hr

Debopam Bhattacherjee, ETH Zürich

IETF -109

Network topology design at 27,000 km/hr

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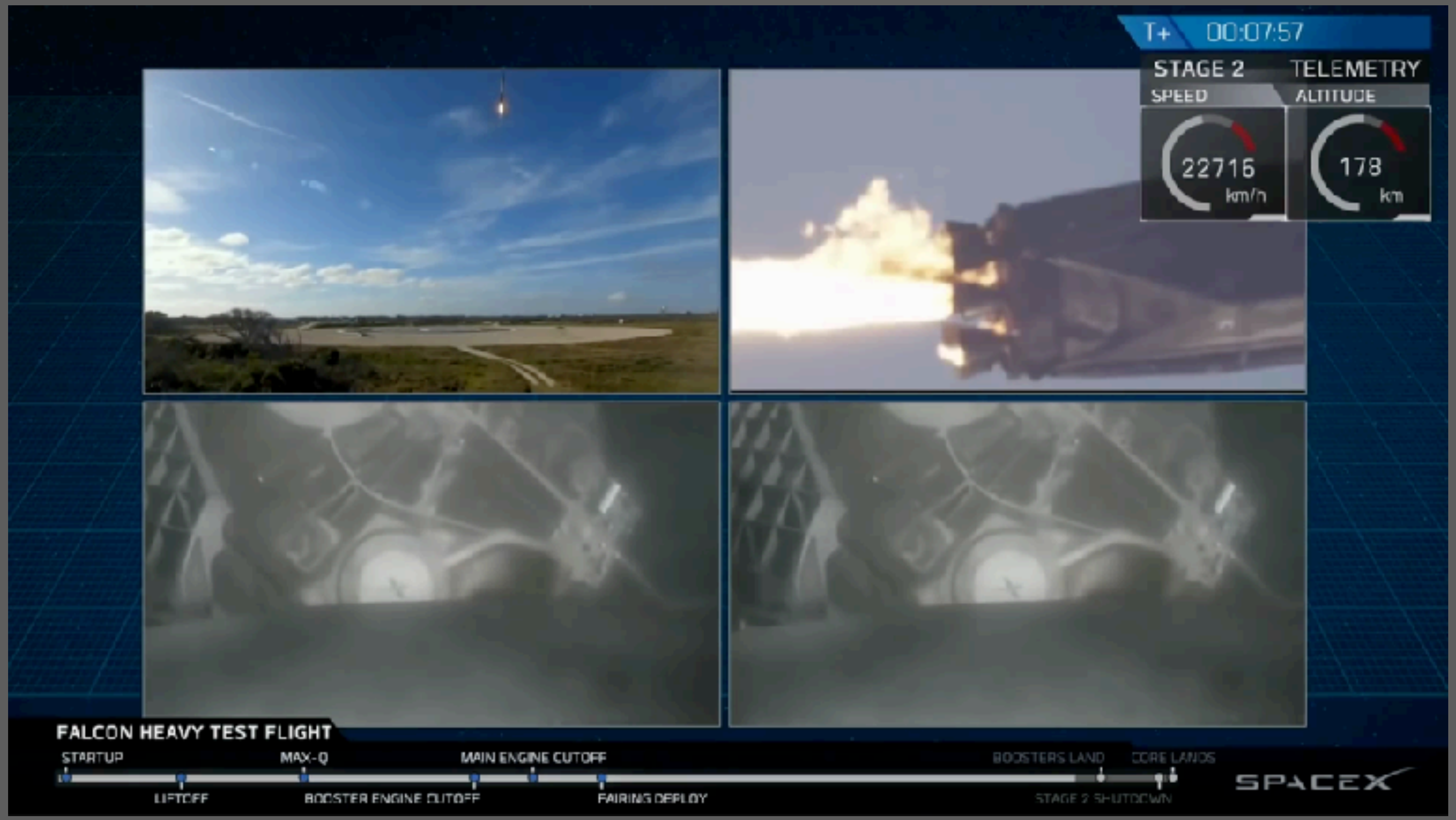
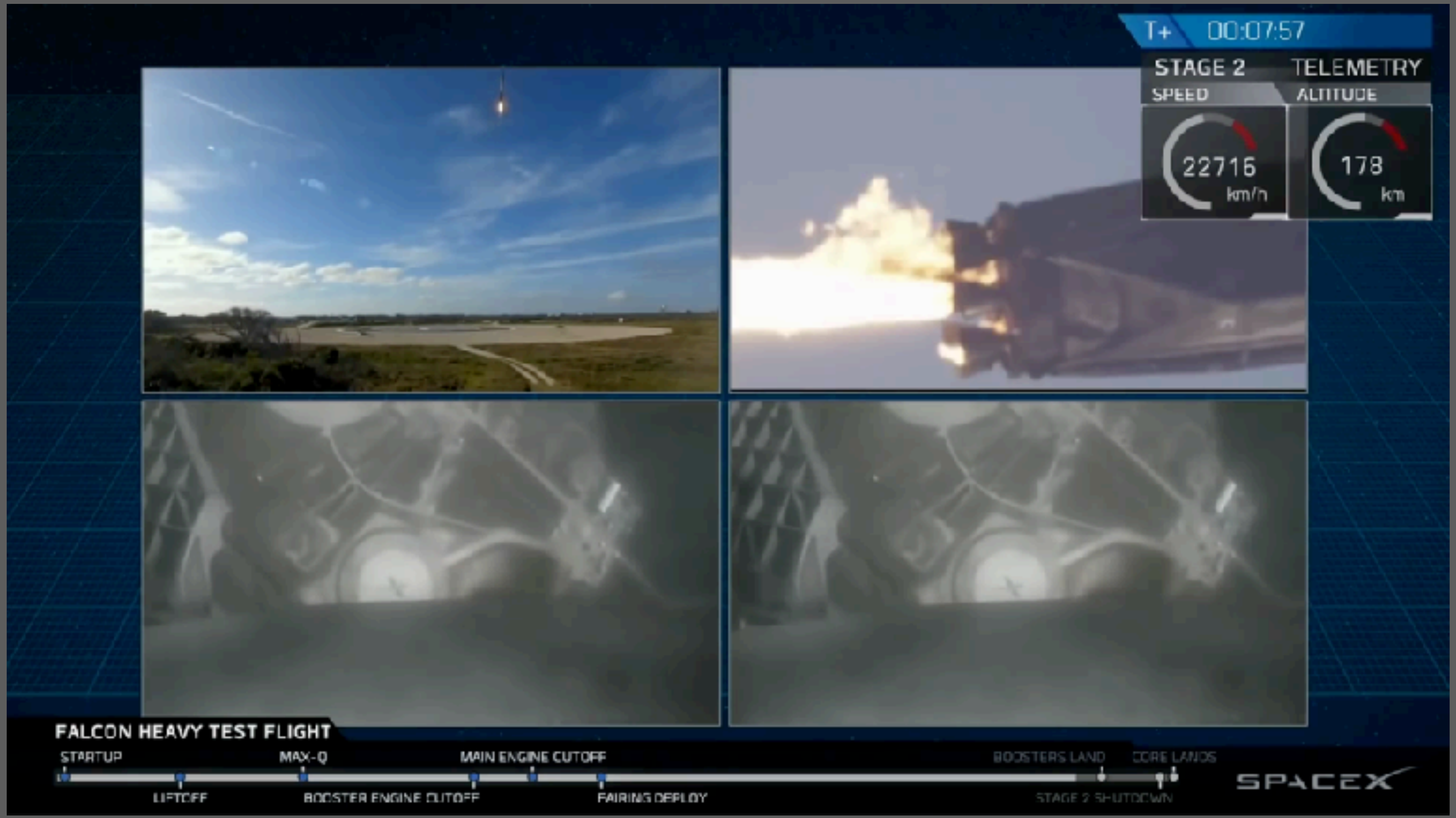
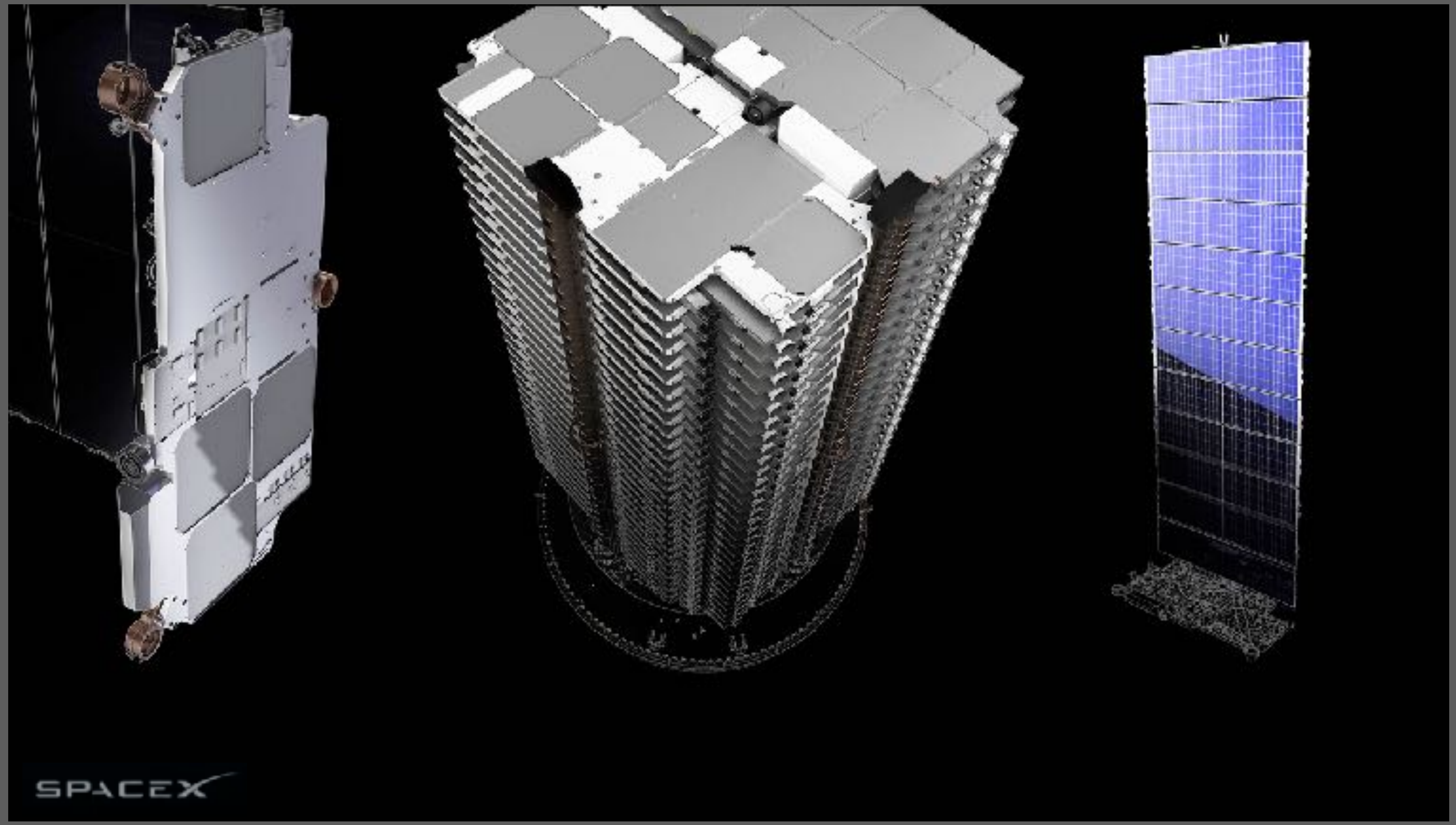
Recent advances

Recent advances



Recent advances





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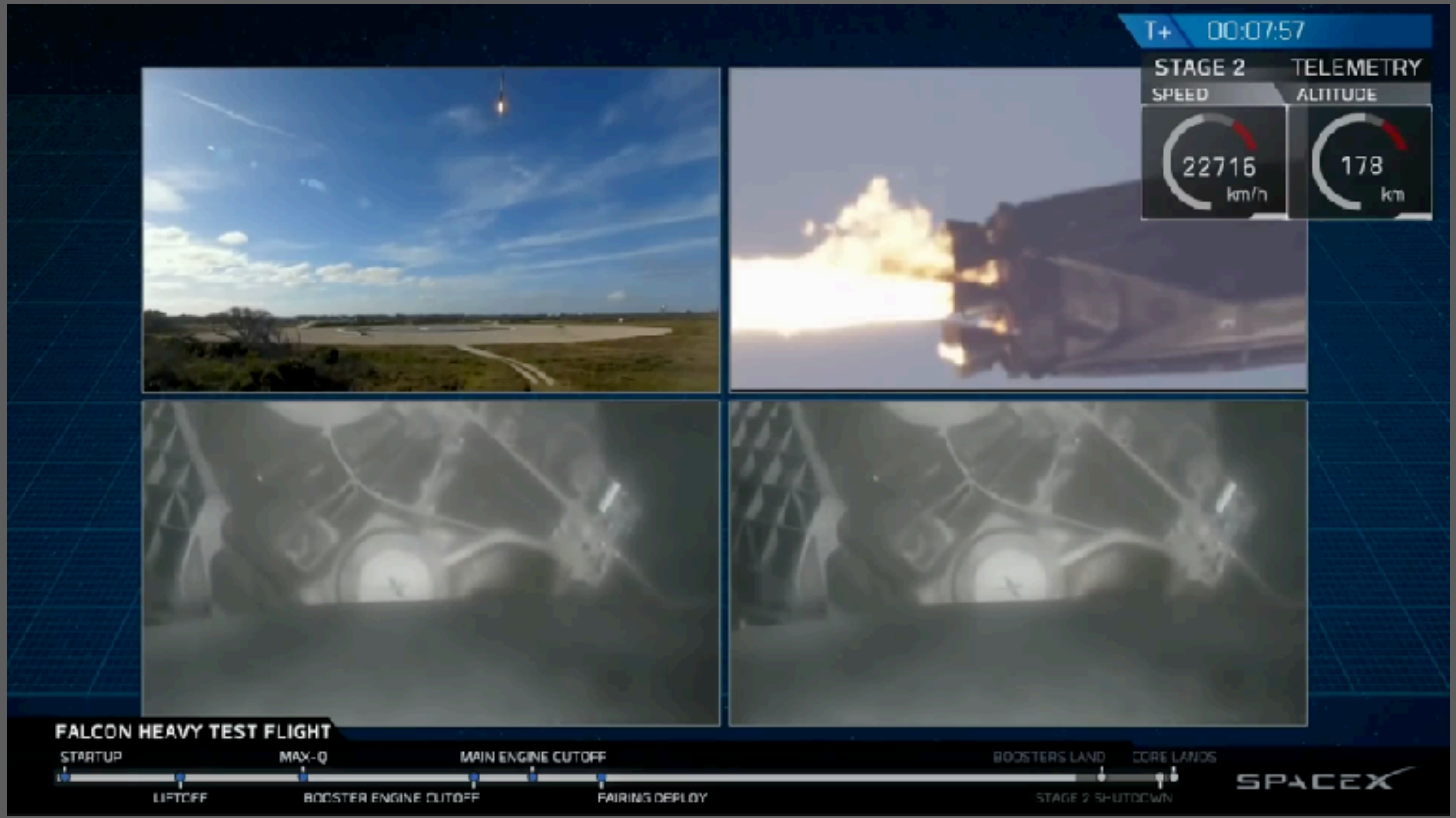

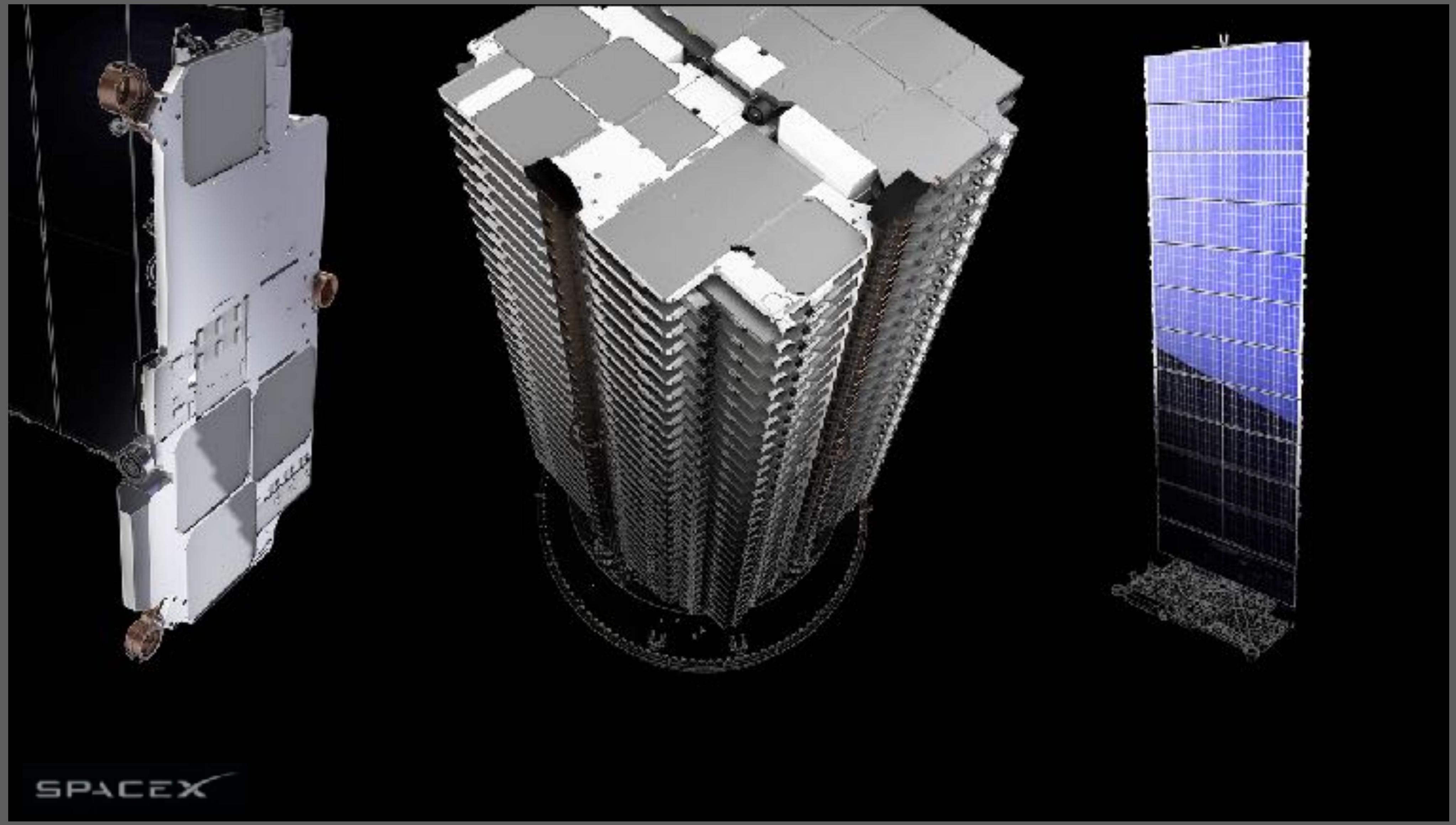

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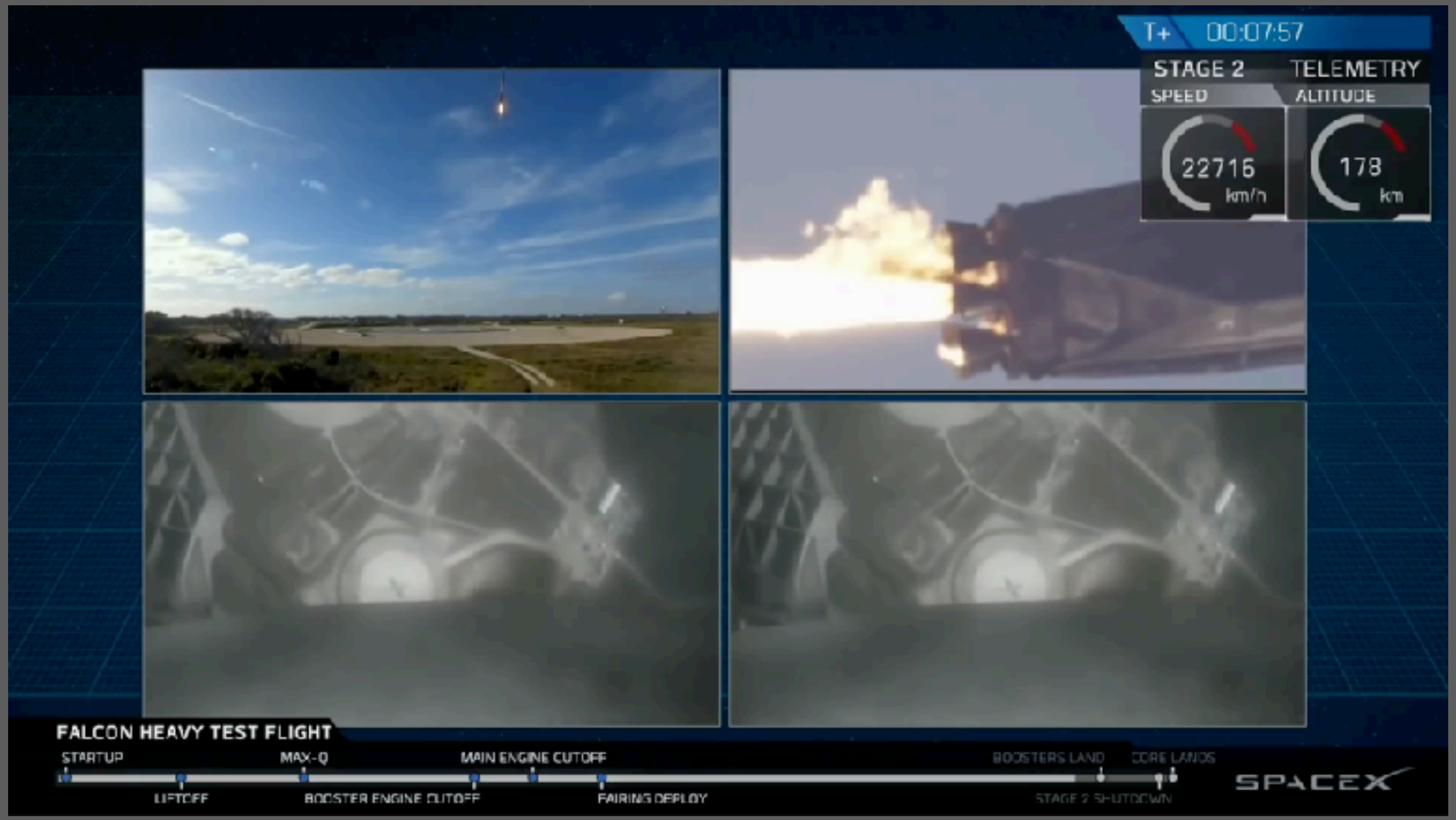

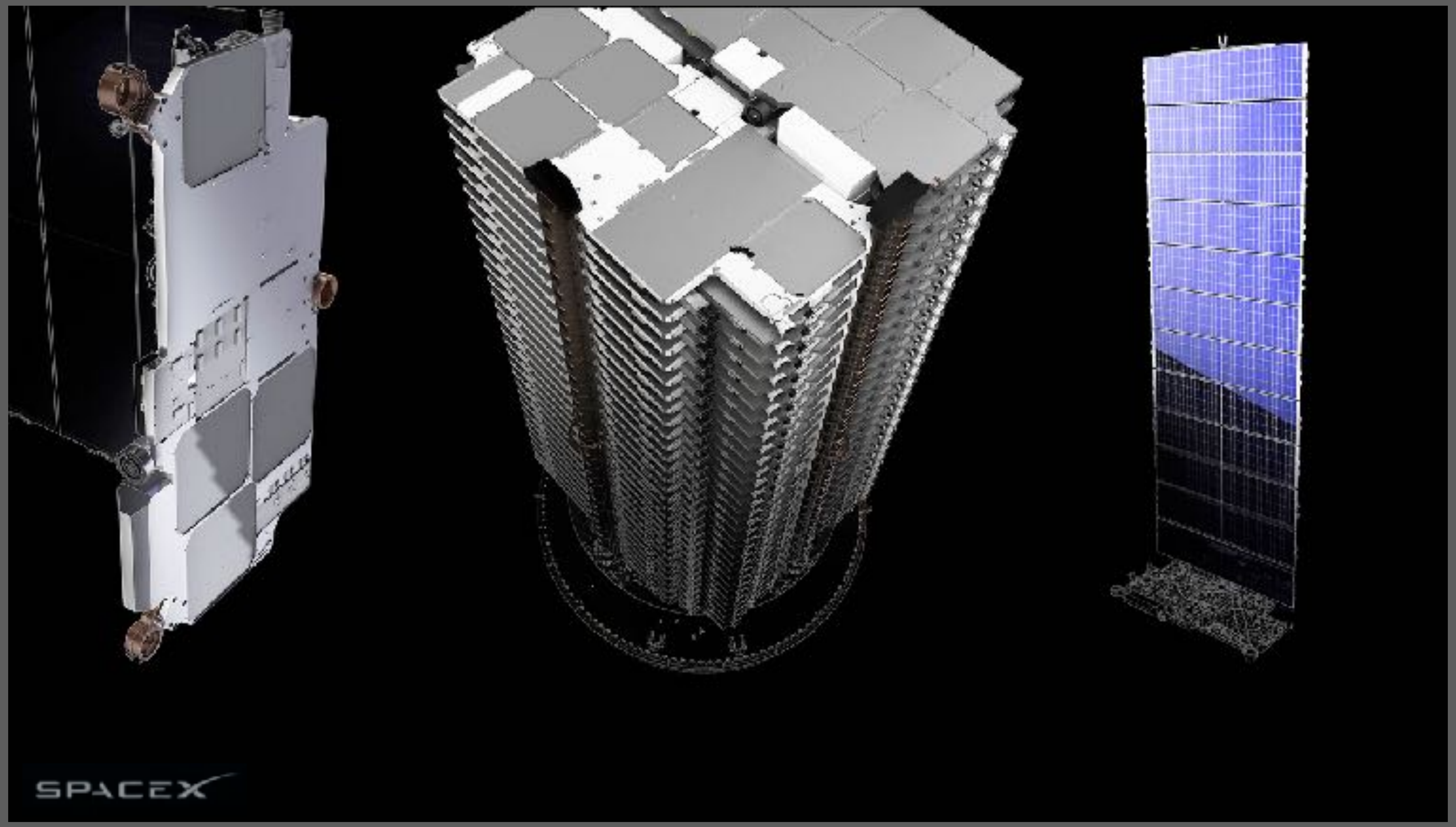

10-20G / up to 8000 km

Tens of seconds for link setup

Global low-latency Internet coverage

SpaceX Starlink

1,600 satellites initially

42,000 planned

SpaceX Starlink

1,600 satellites initially

42,000 planned

Amazon Kuiper

3,200 planned
in 3 phases

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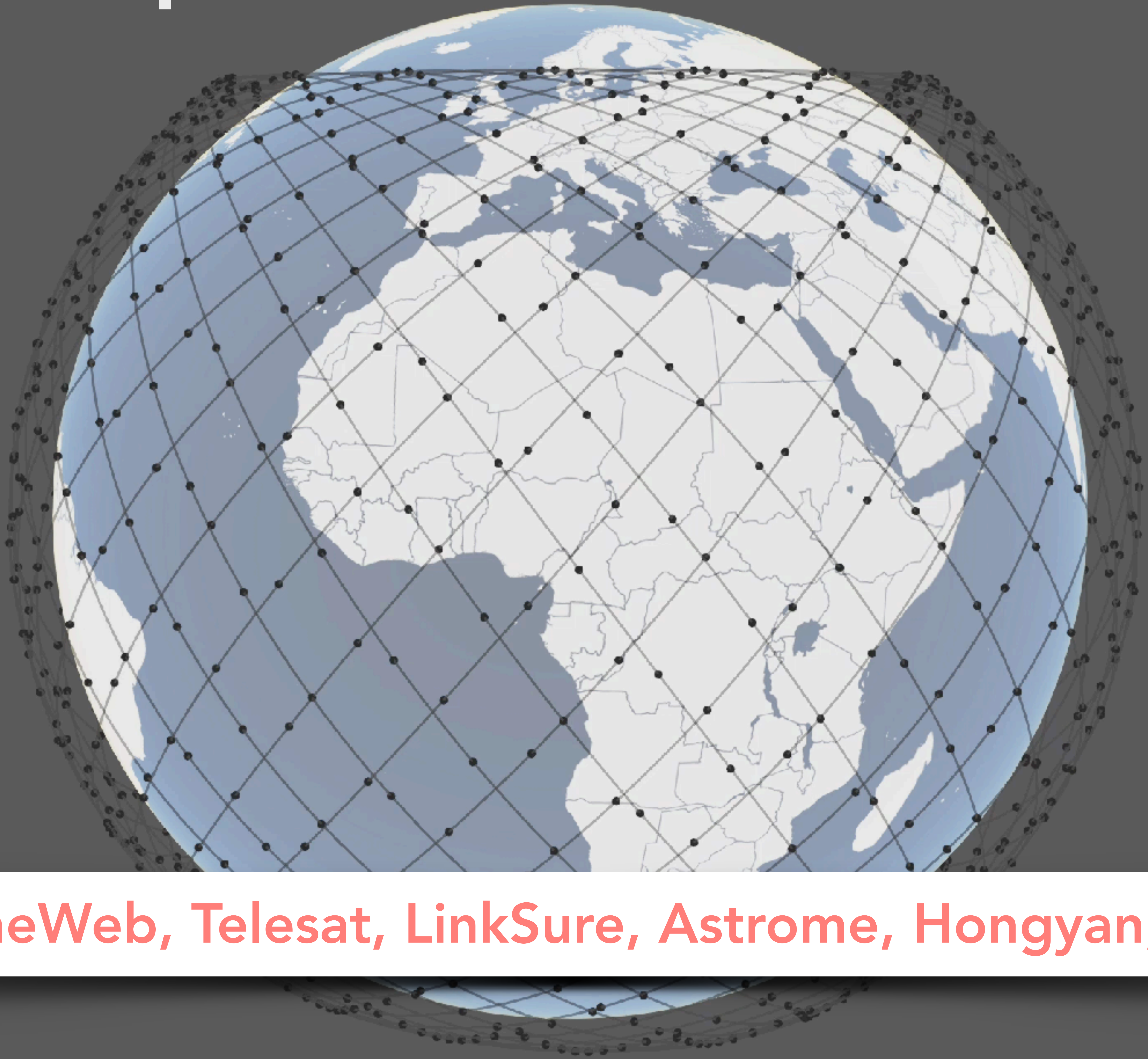


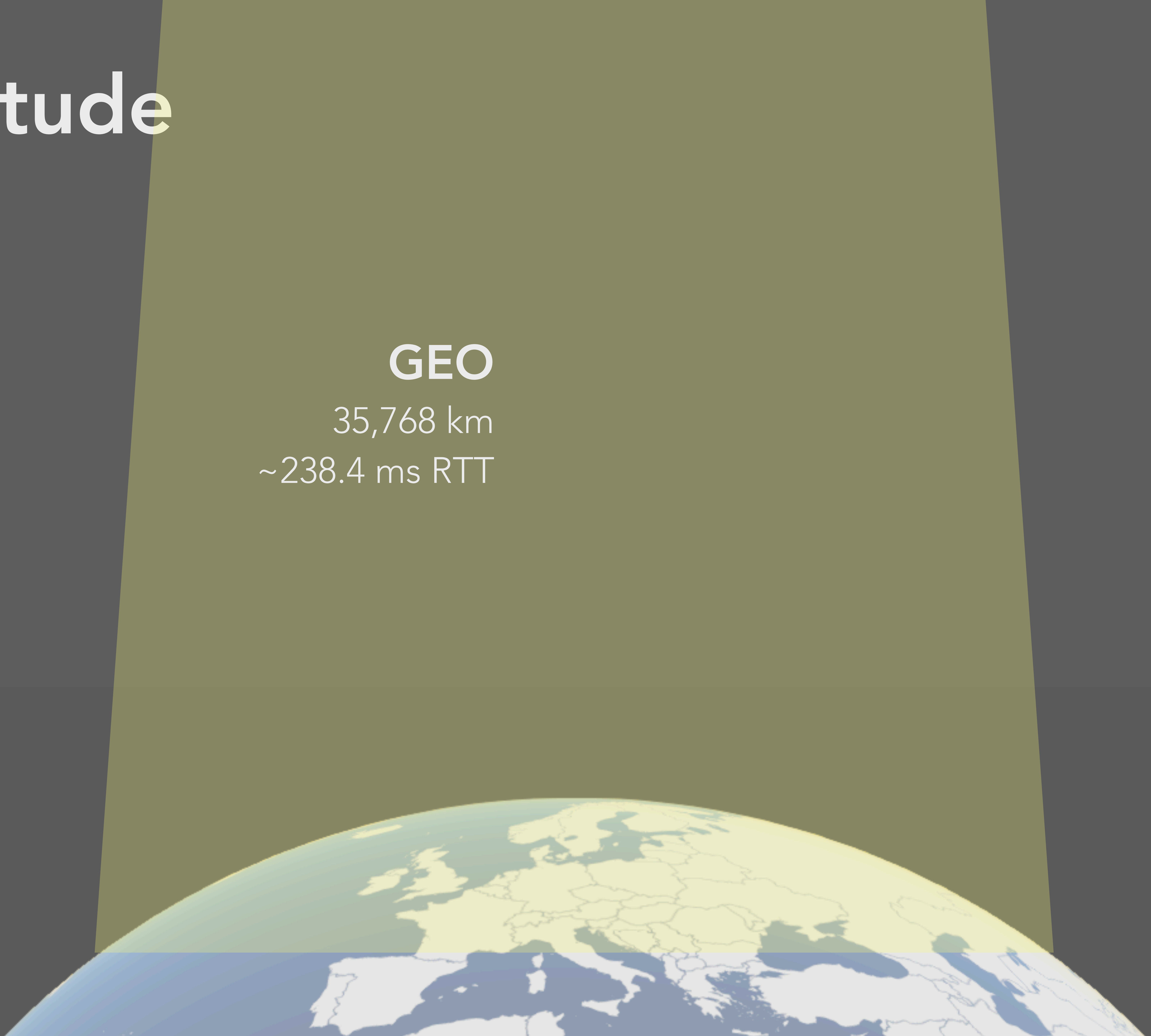
OneWeb, Telesat, LinkSure, Astrome, Hongyan, ...

How do we connect satellites?

Primer on constellations

1. Altitude

1. Altitude



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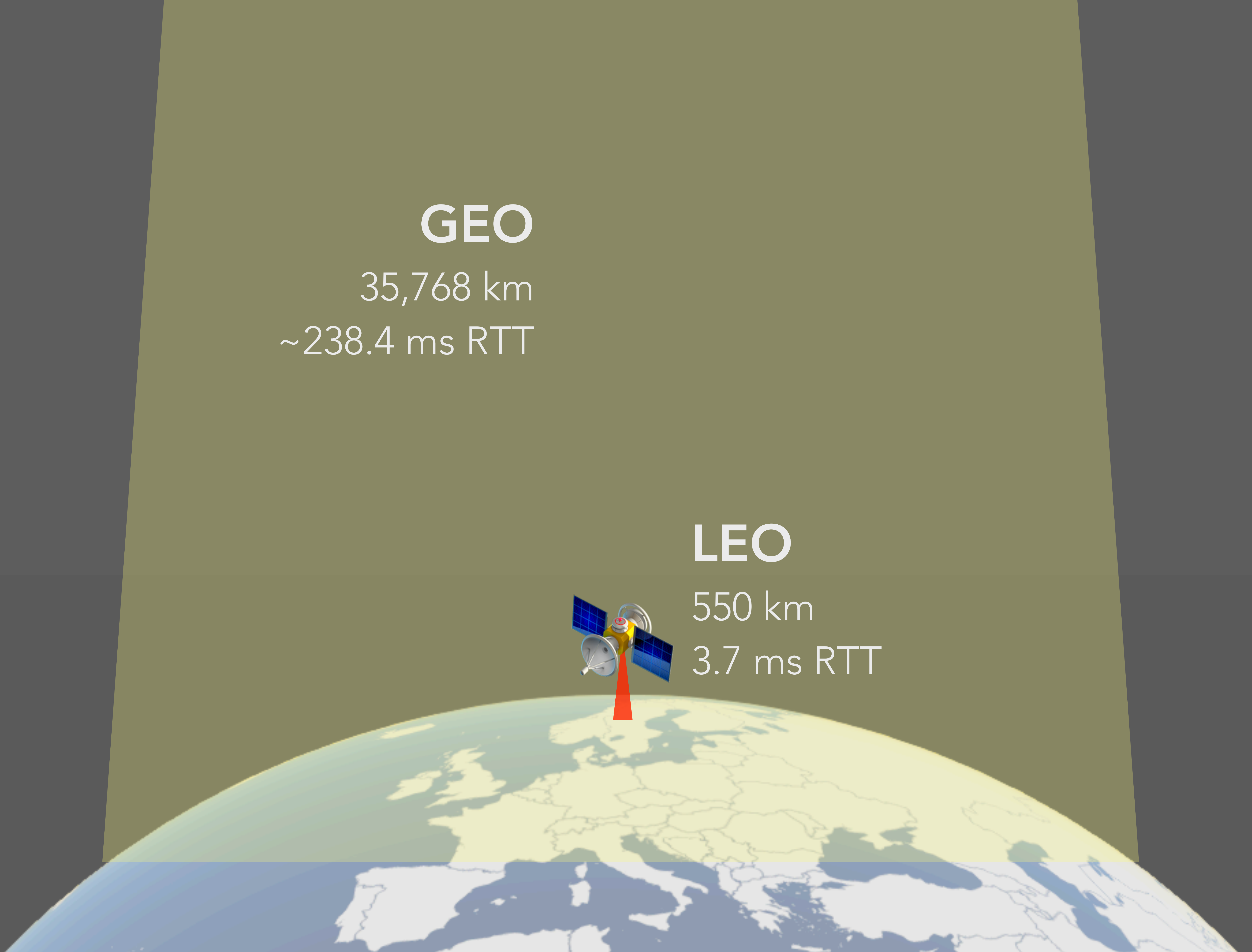
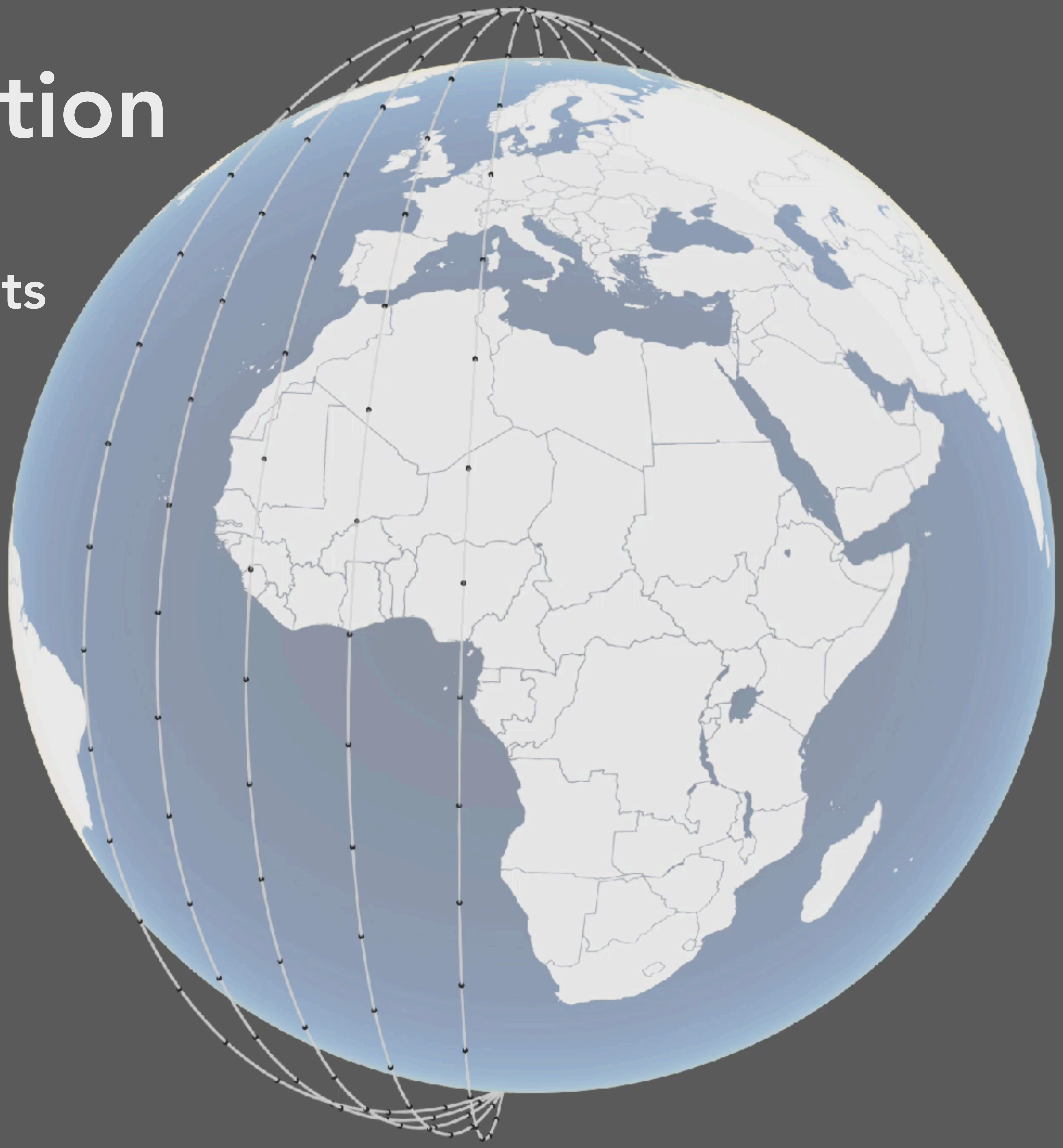


2. Inclination

Polar orbits



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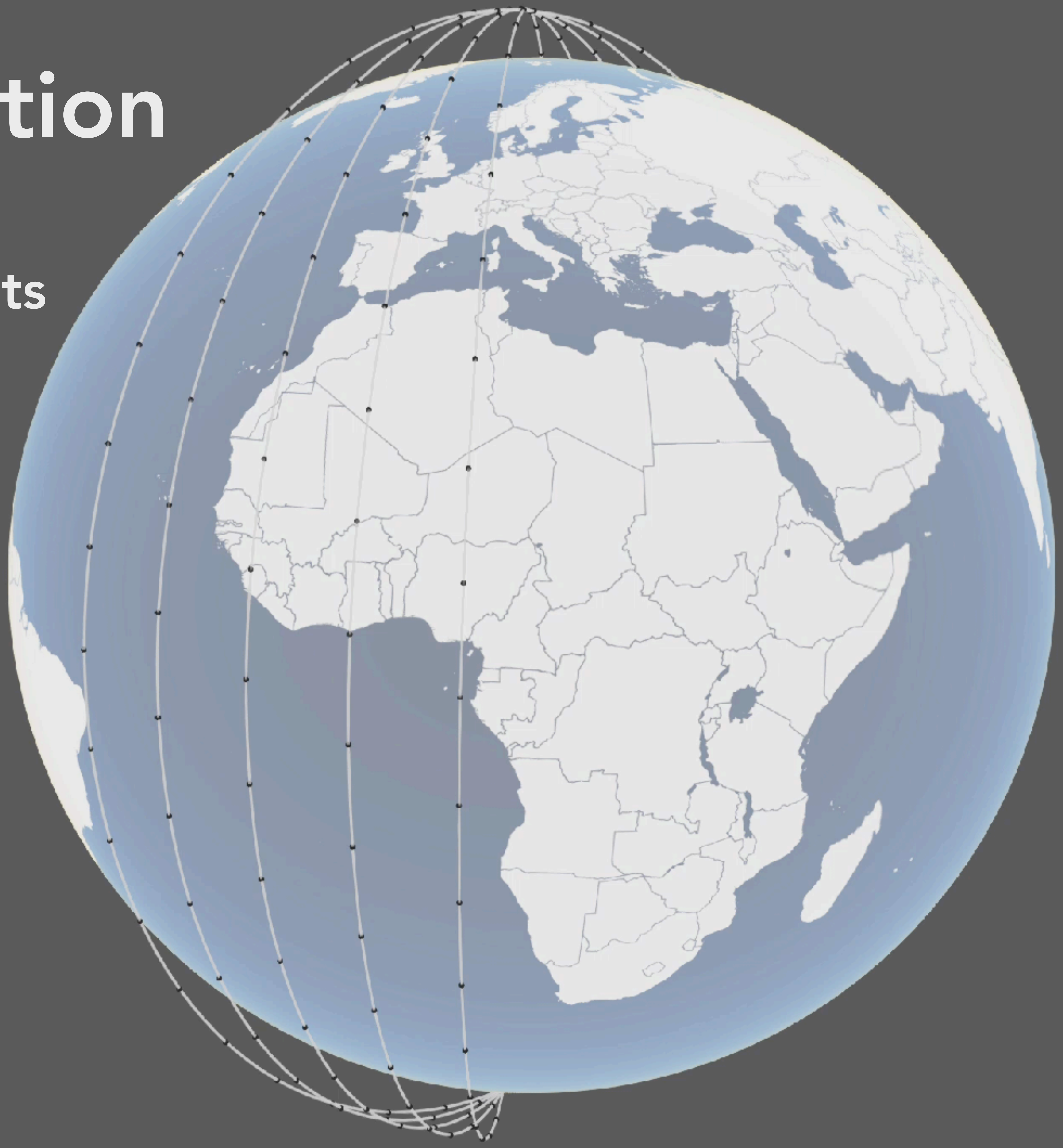
Polar orbits



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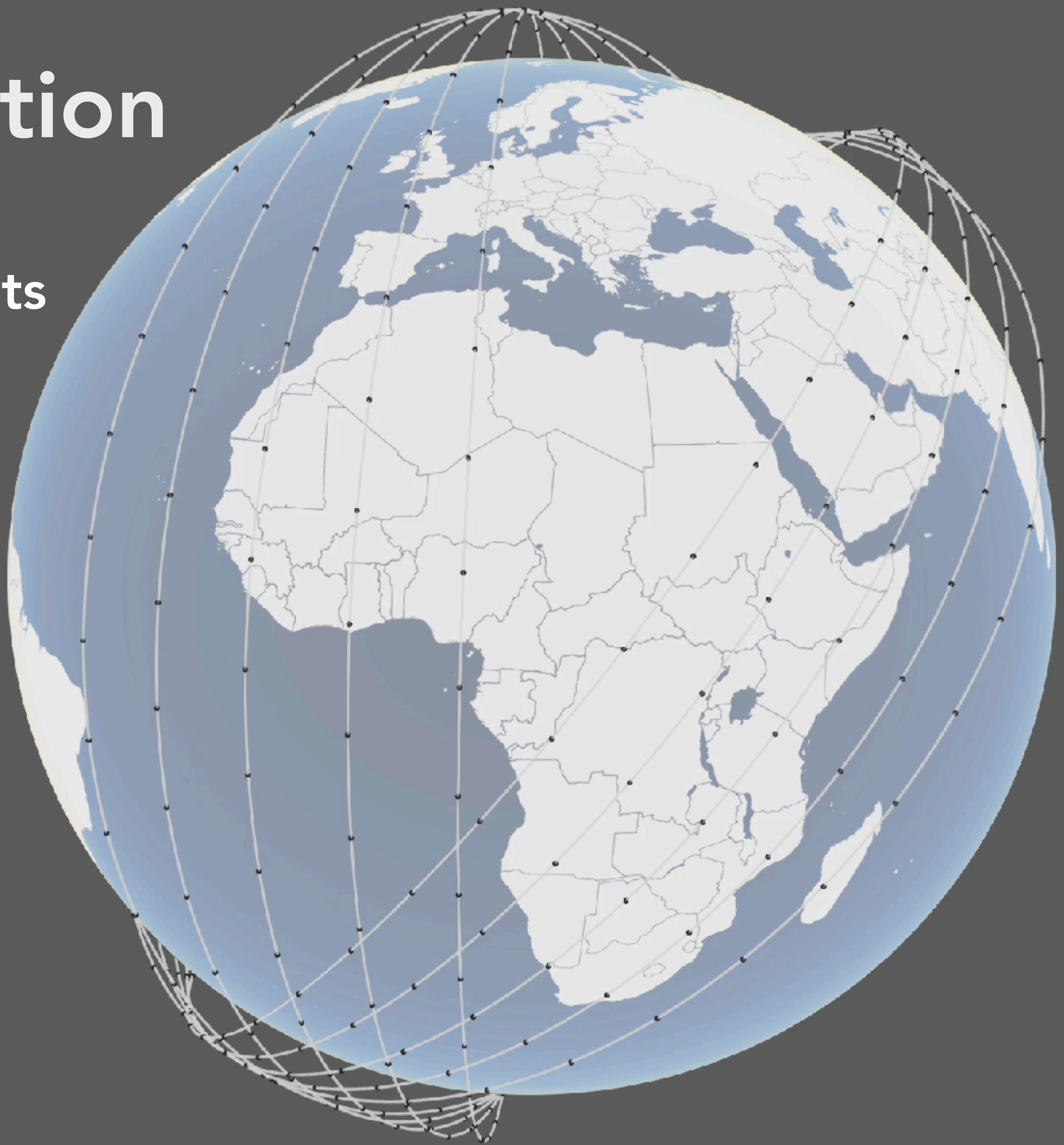
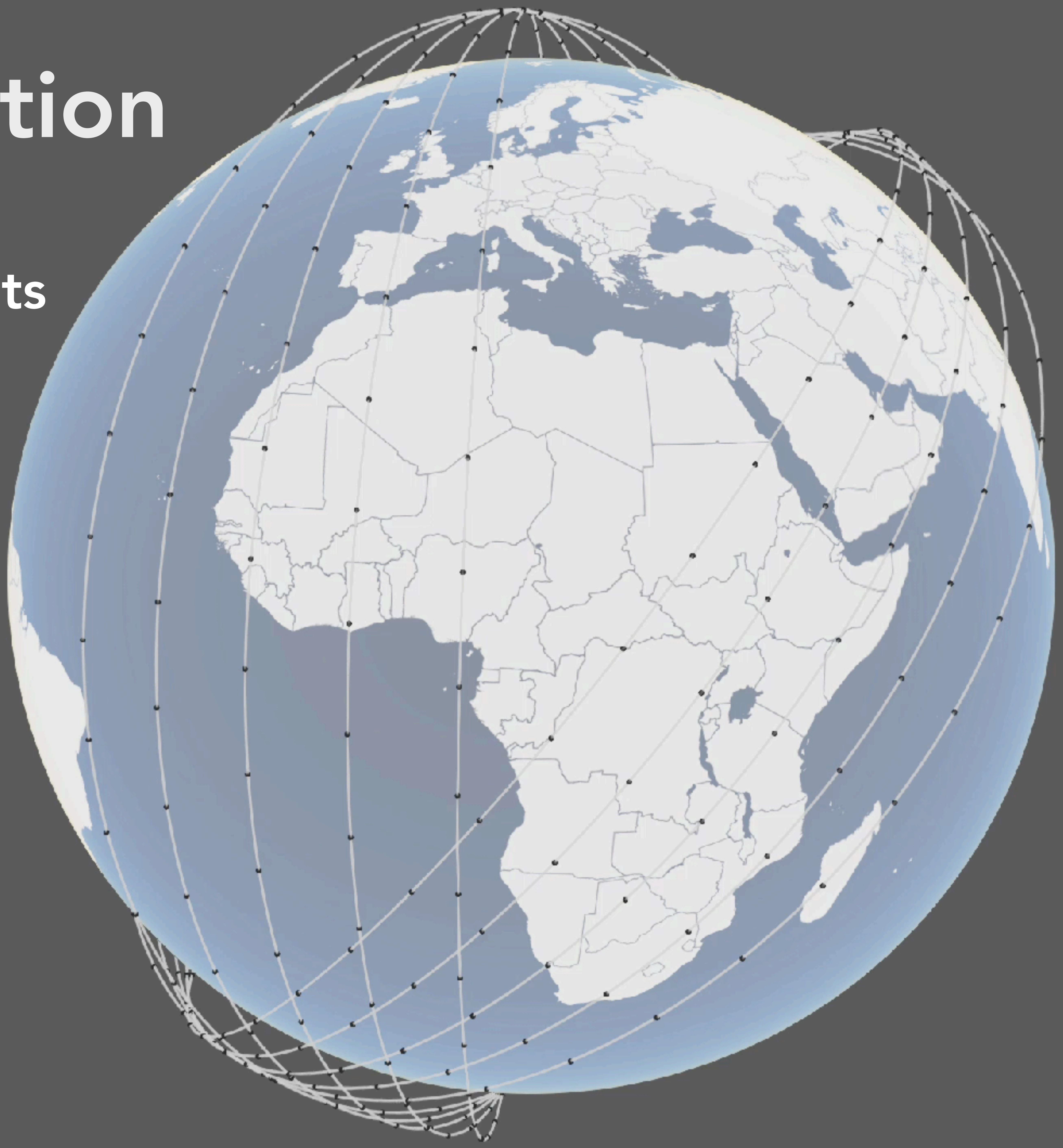
Polar orbits



Inclined orbits

2. Inclination



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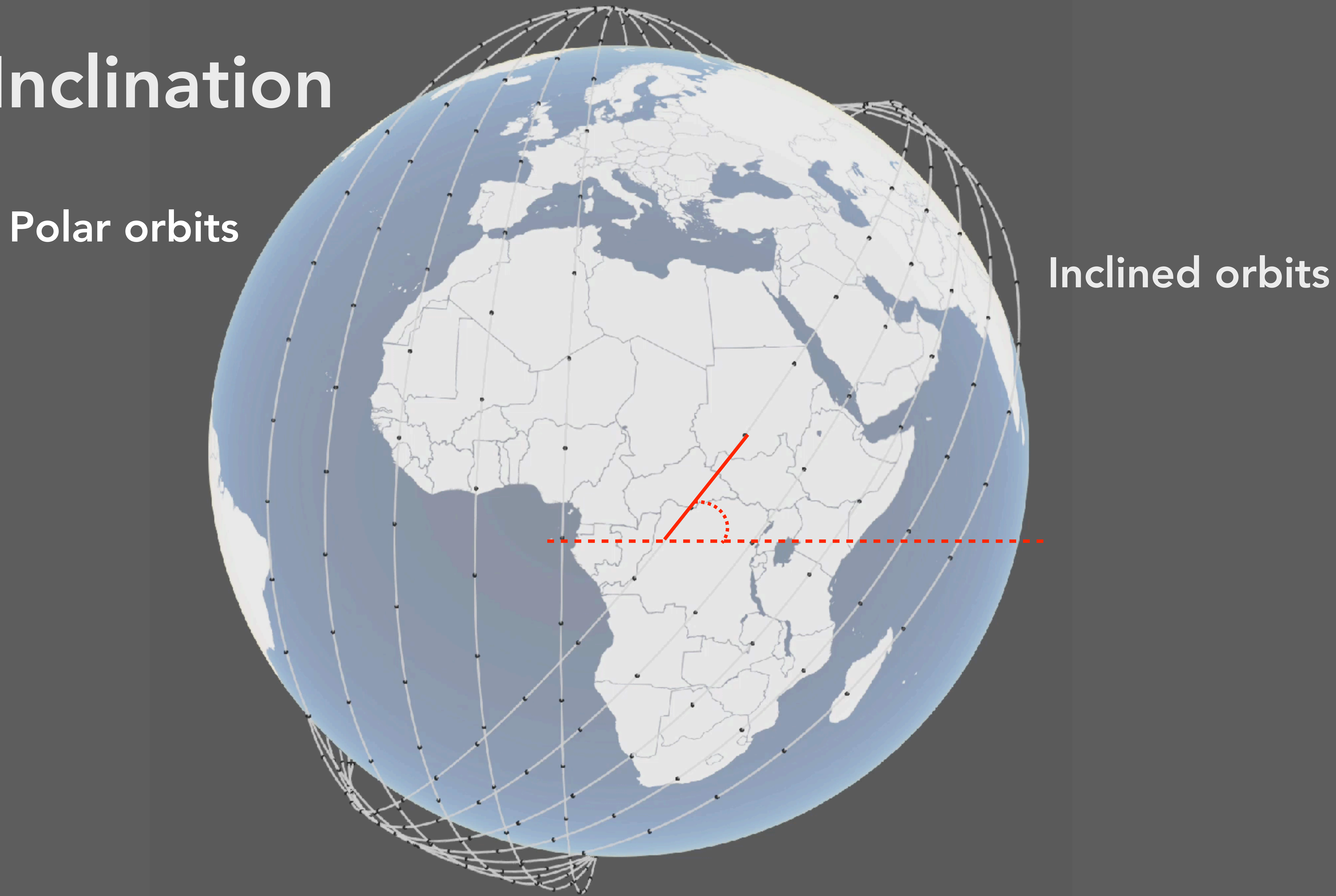

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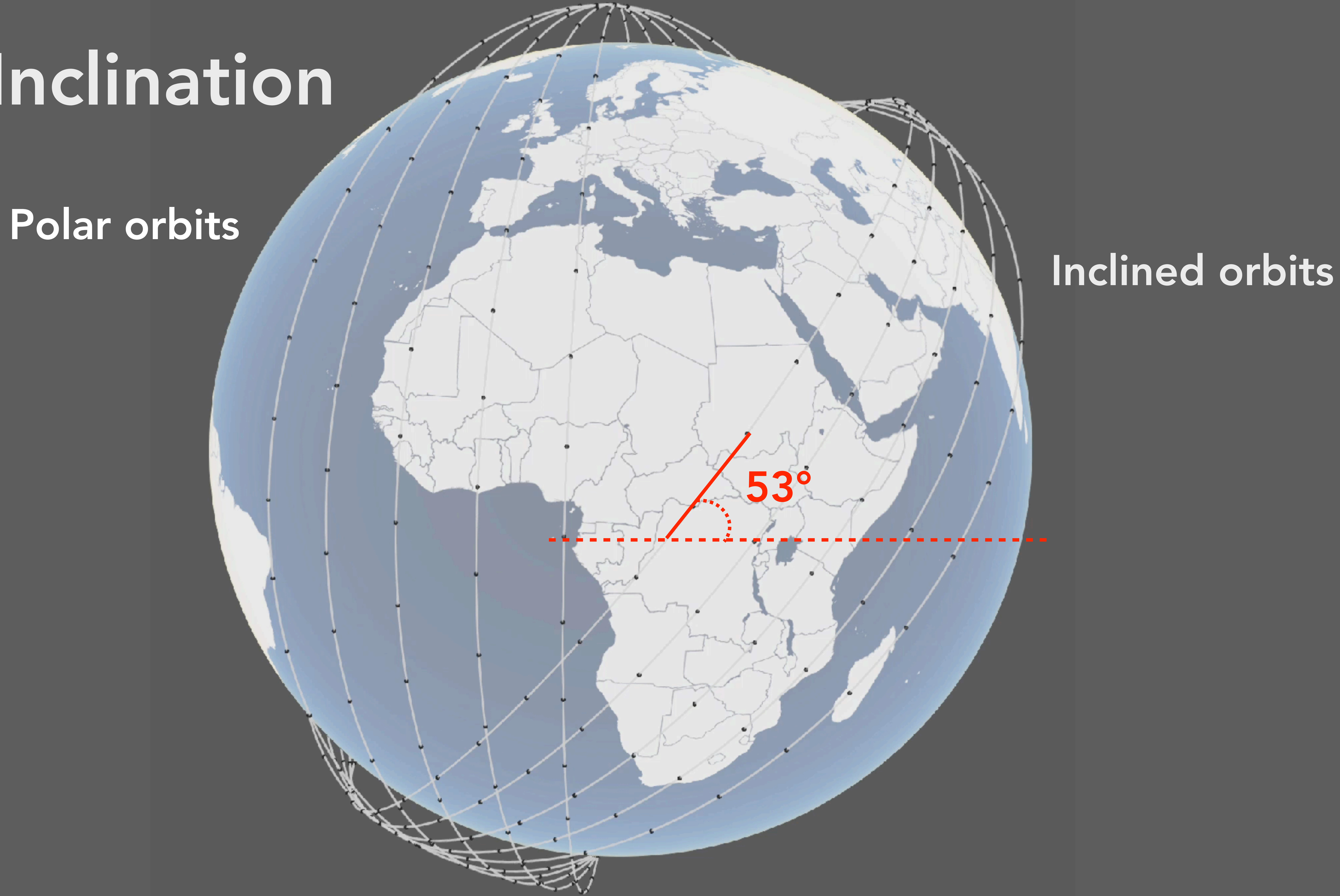

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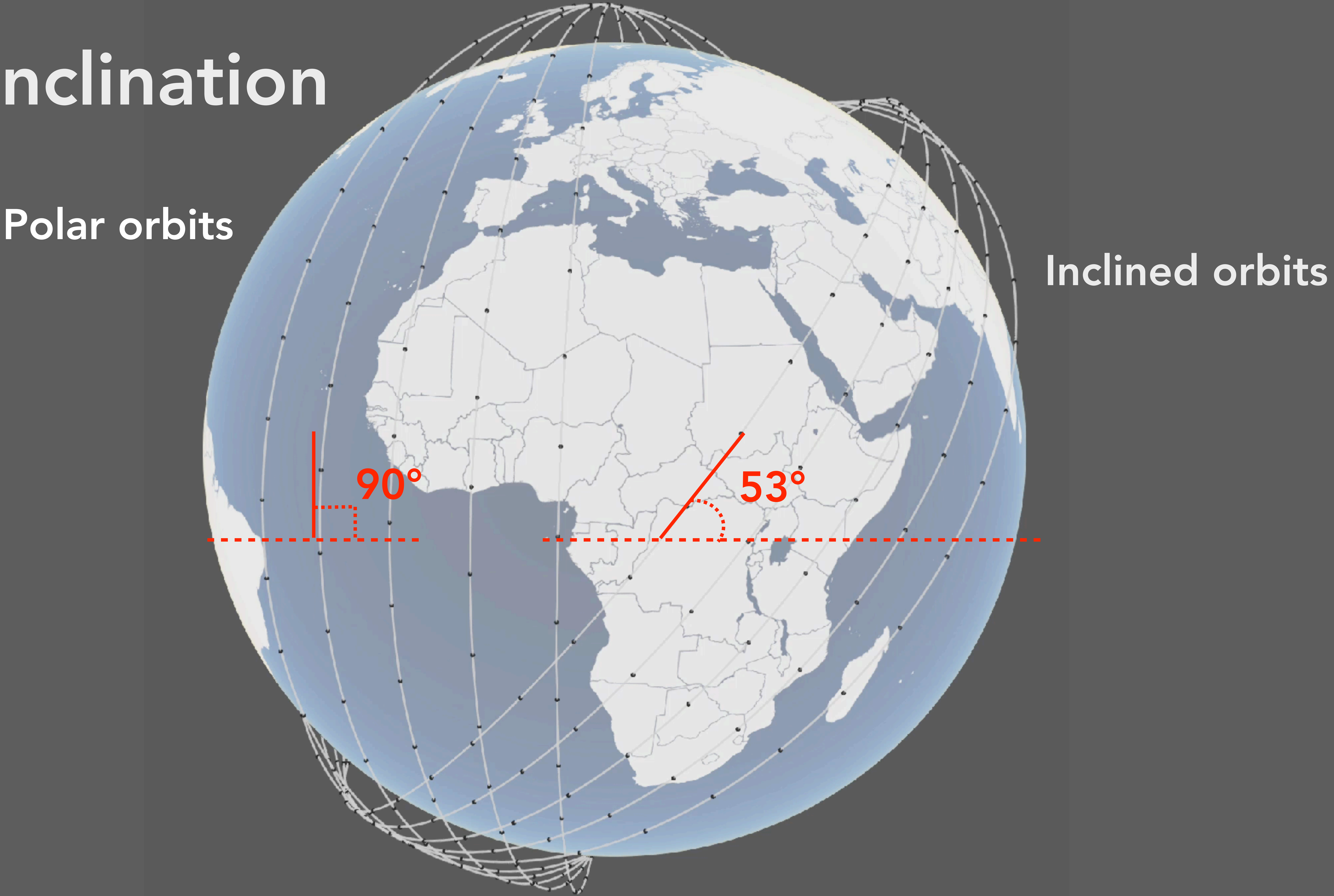
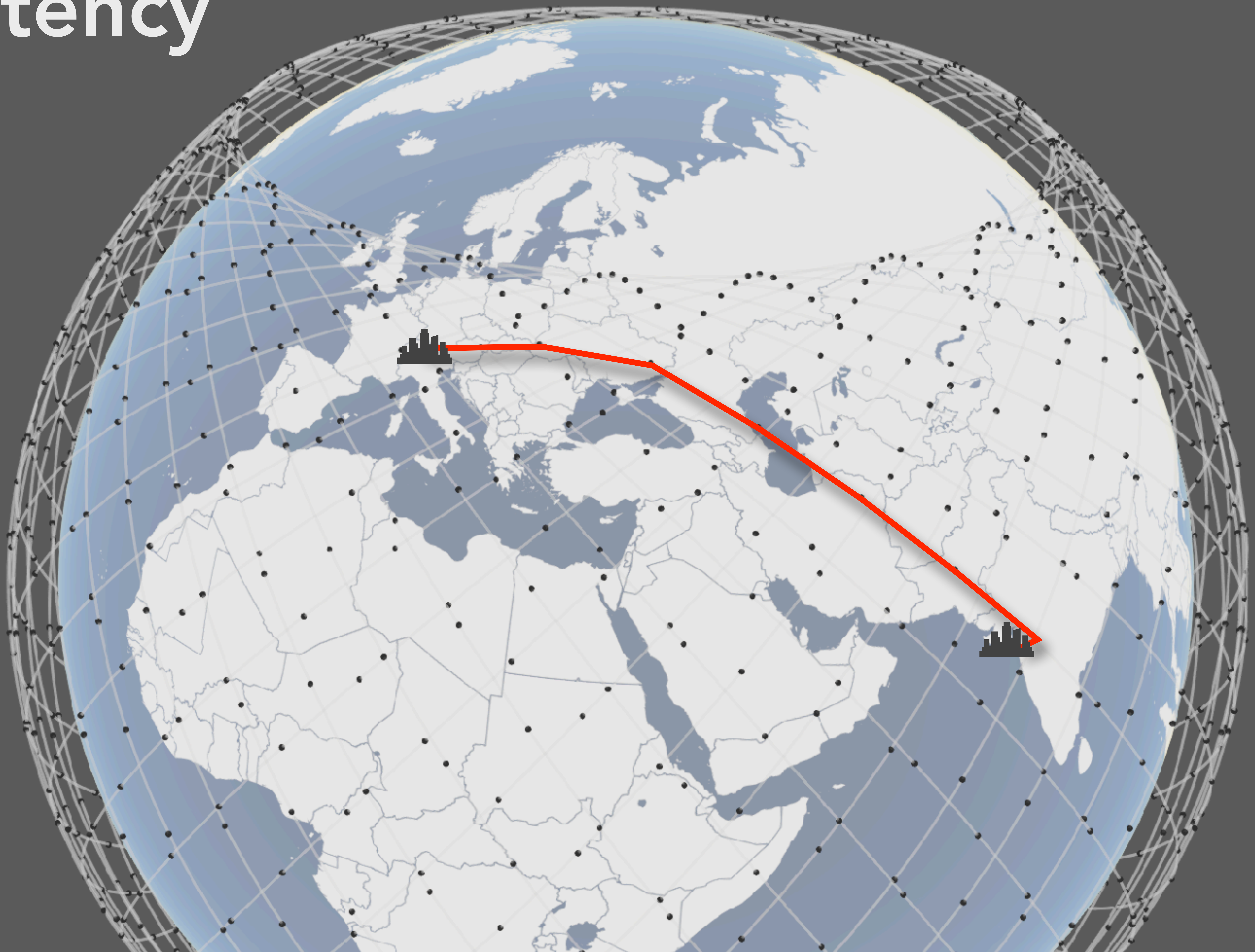


3. Connectivity

+Grid

4. Latency

4. Latency



4. Latency

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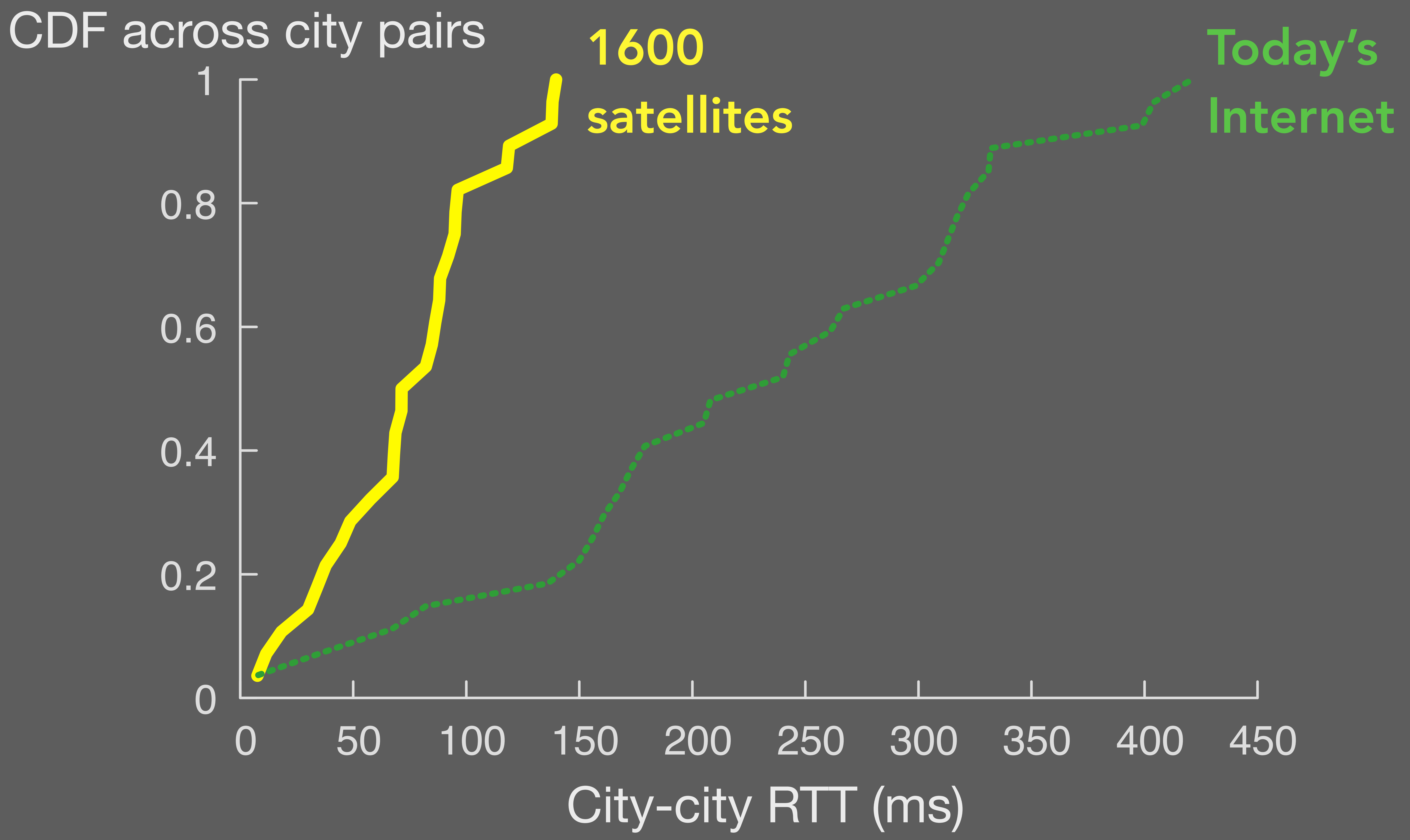
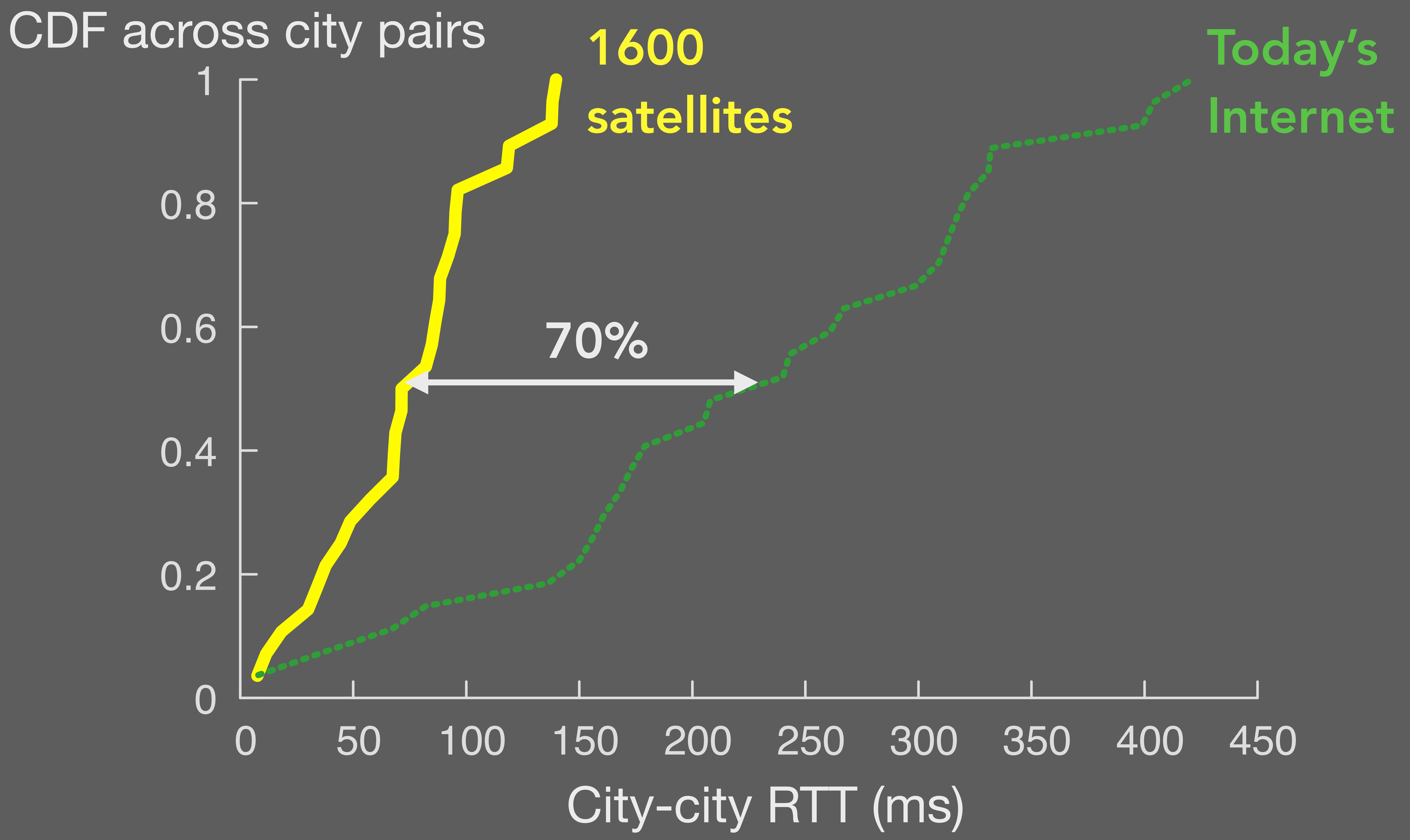

CDF across city pairs
1600 satellites
Today's Internet
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
City-city RTT (ms)

4. Latency


CDF across city pairs
1
0.8
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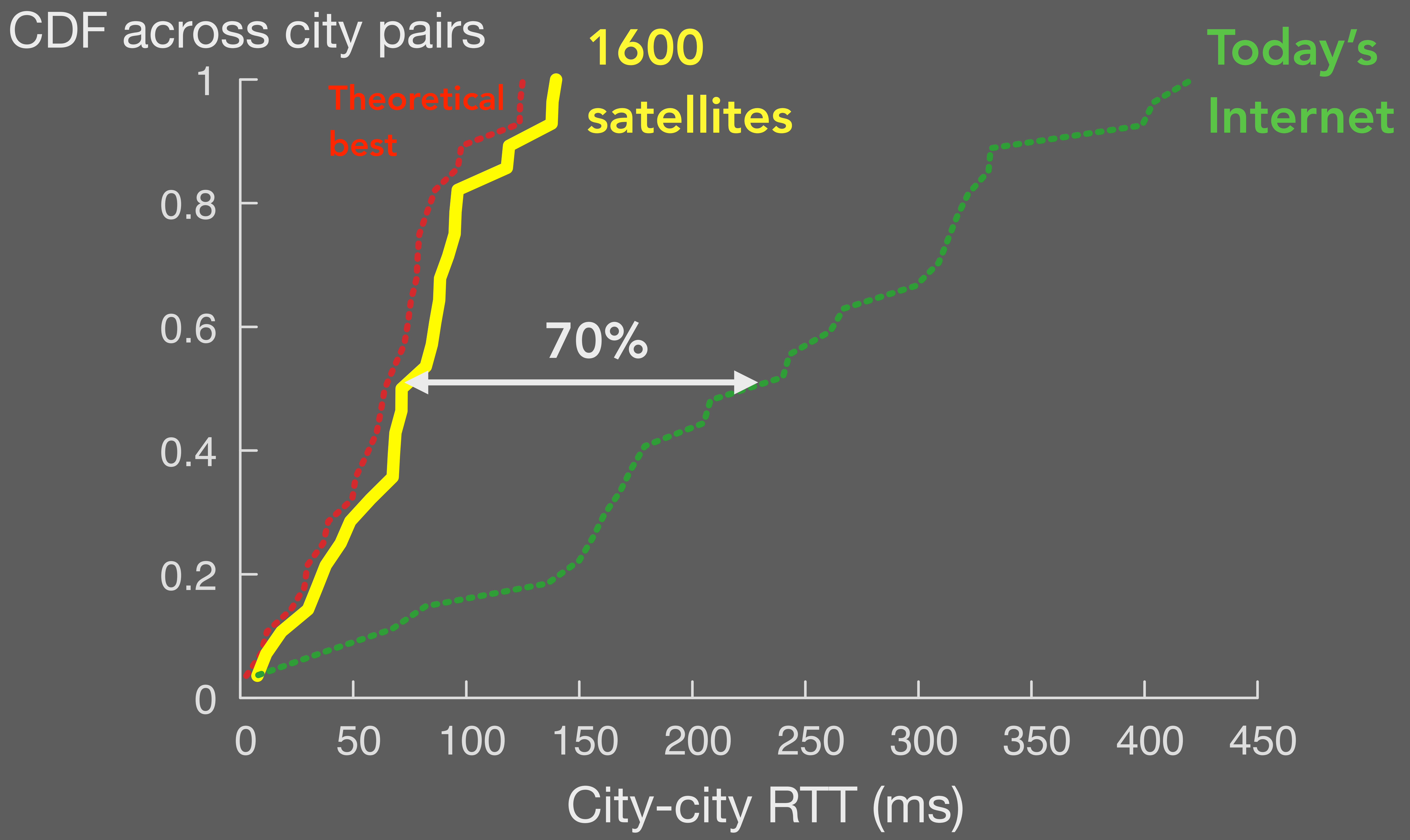
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
City-city RTT (ms)
1600
satellites
Today's
Internet
70%

4. Latency


CDF across city pairs
1
0.8
0.6
0.4
0.2
0
Theoretical
best
1600
satellites
Today's
Internet
70%
0
50
100
150
200
250
300
350
400
450
City-city RTT (ms)

5. System dynamics

5. System dynamics

Challenges

Challenges

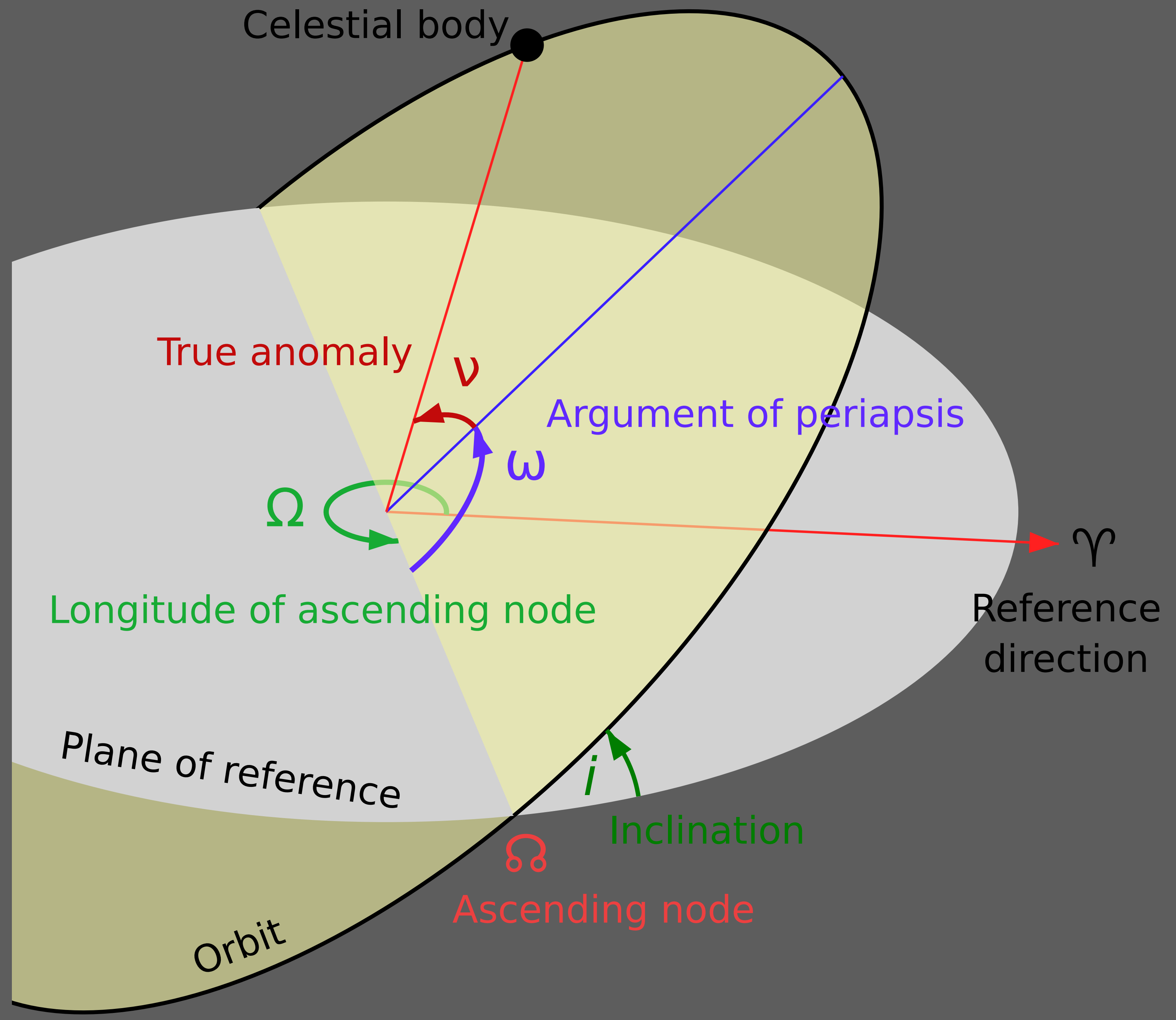
Gearing up for the 21st century space race

Debopam Bhattacherjee[1], Waqar Aqeel[2], Ilker Nadi Bozkurt[2], Anthony Aguirre[3], Balakrishnan Chandrasekaran[4], P. Brighten Godfrey[5], Gregory Laughlin[6], Bruce Maggs[2,7], Ankit Singla[1]

[1]ETH Zürich, [2]Duke, [3]UCSC, [4]MPI-INF, [5]UIUC, [6]Yale, [7]Akamai Technologies

Topology design problem

Topology design problem



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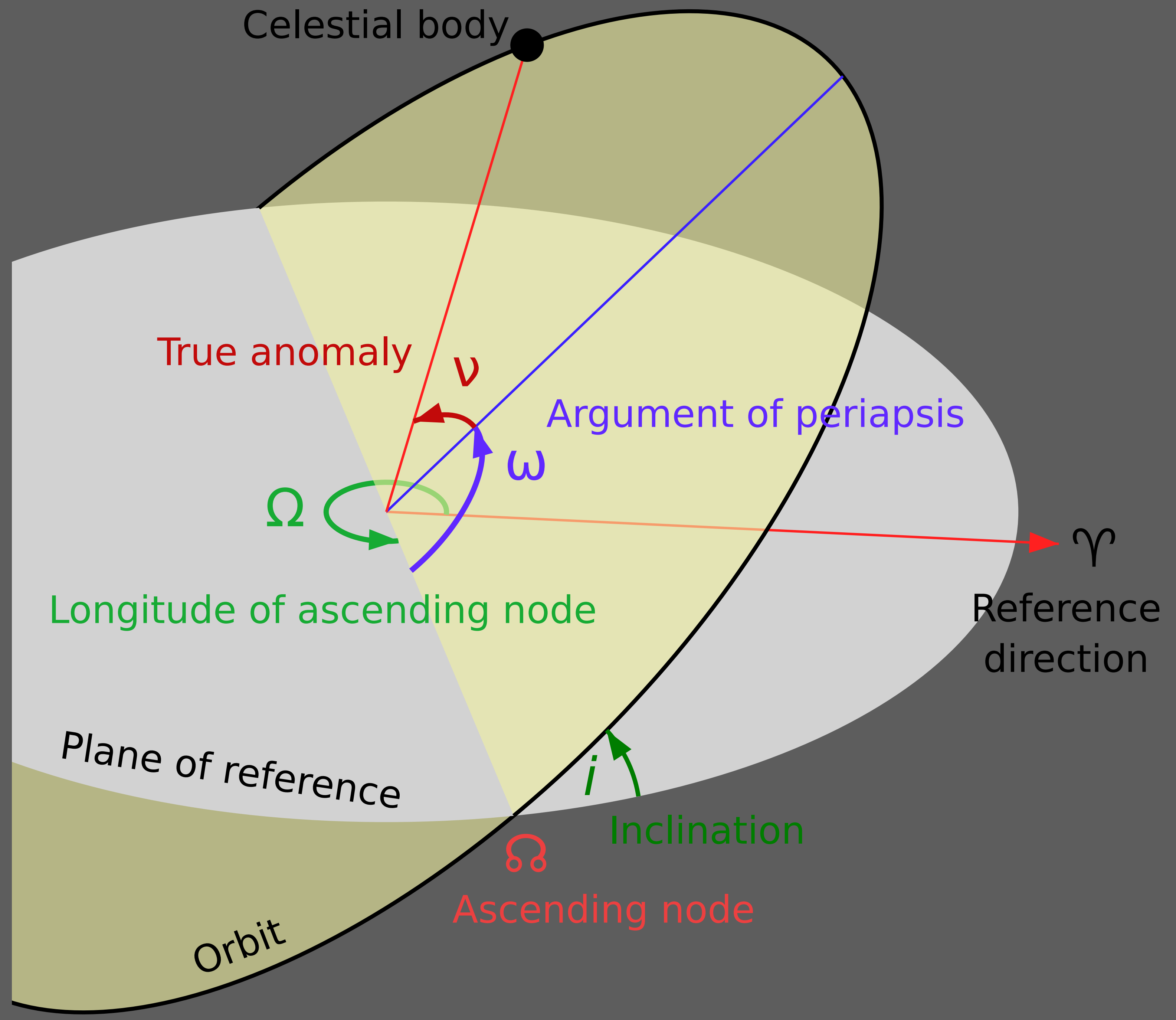
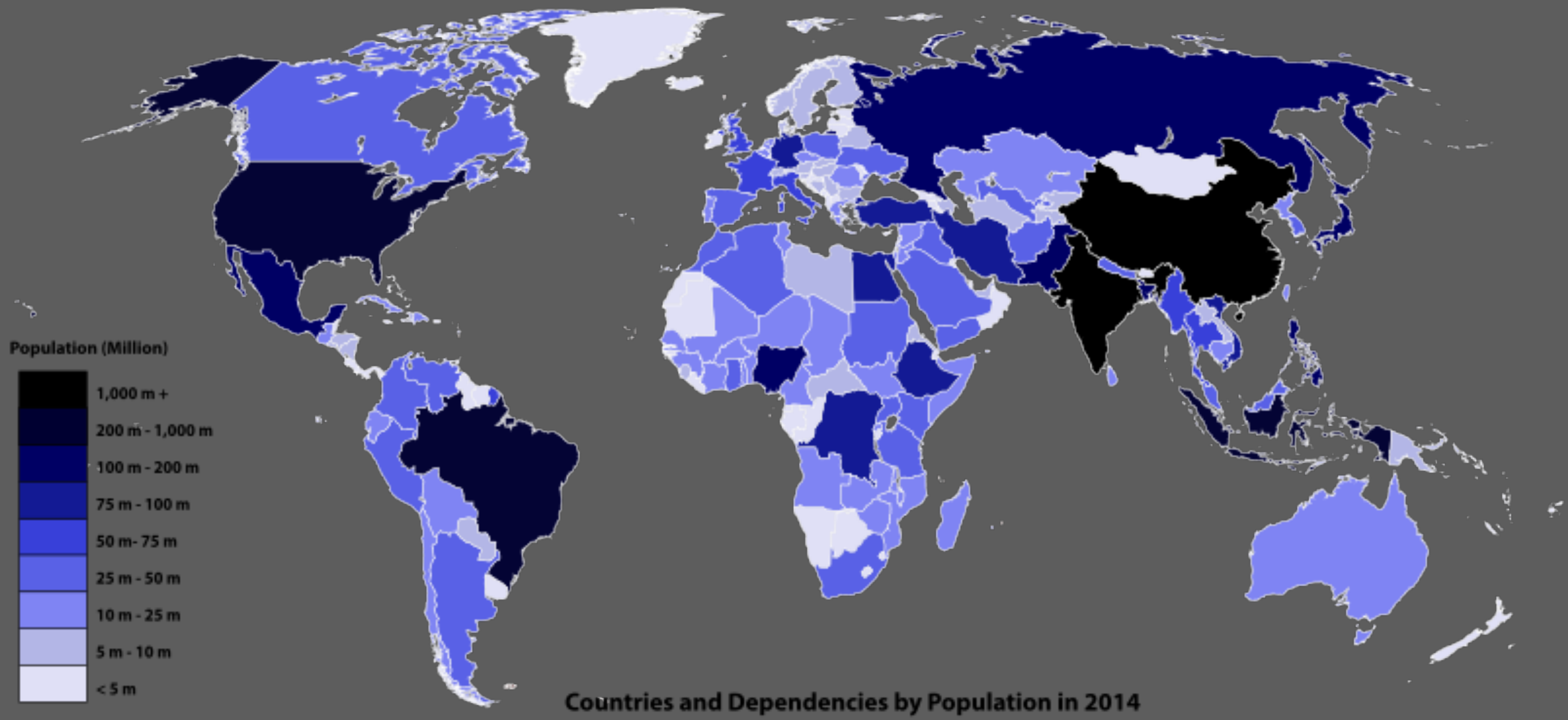
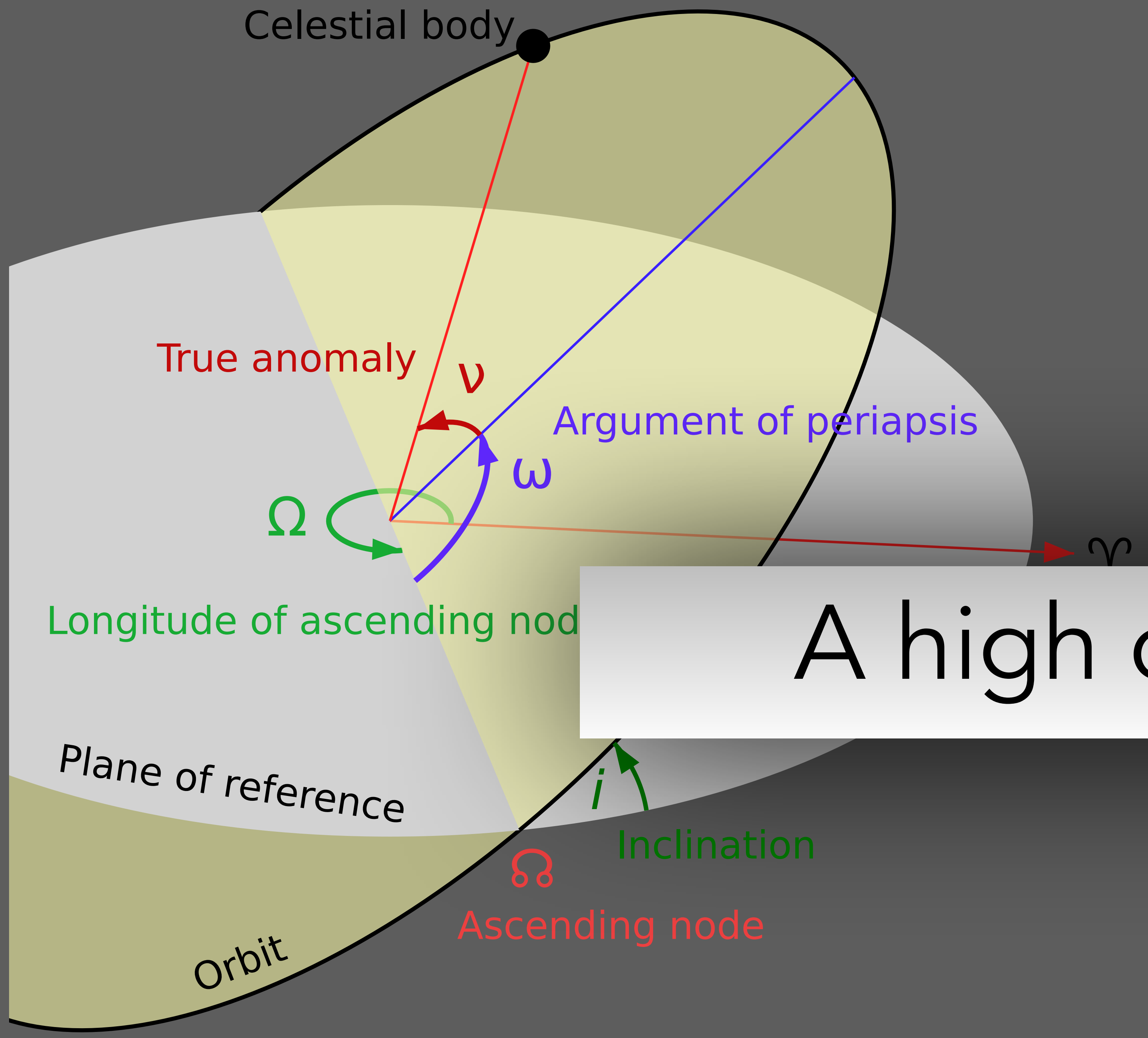


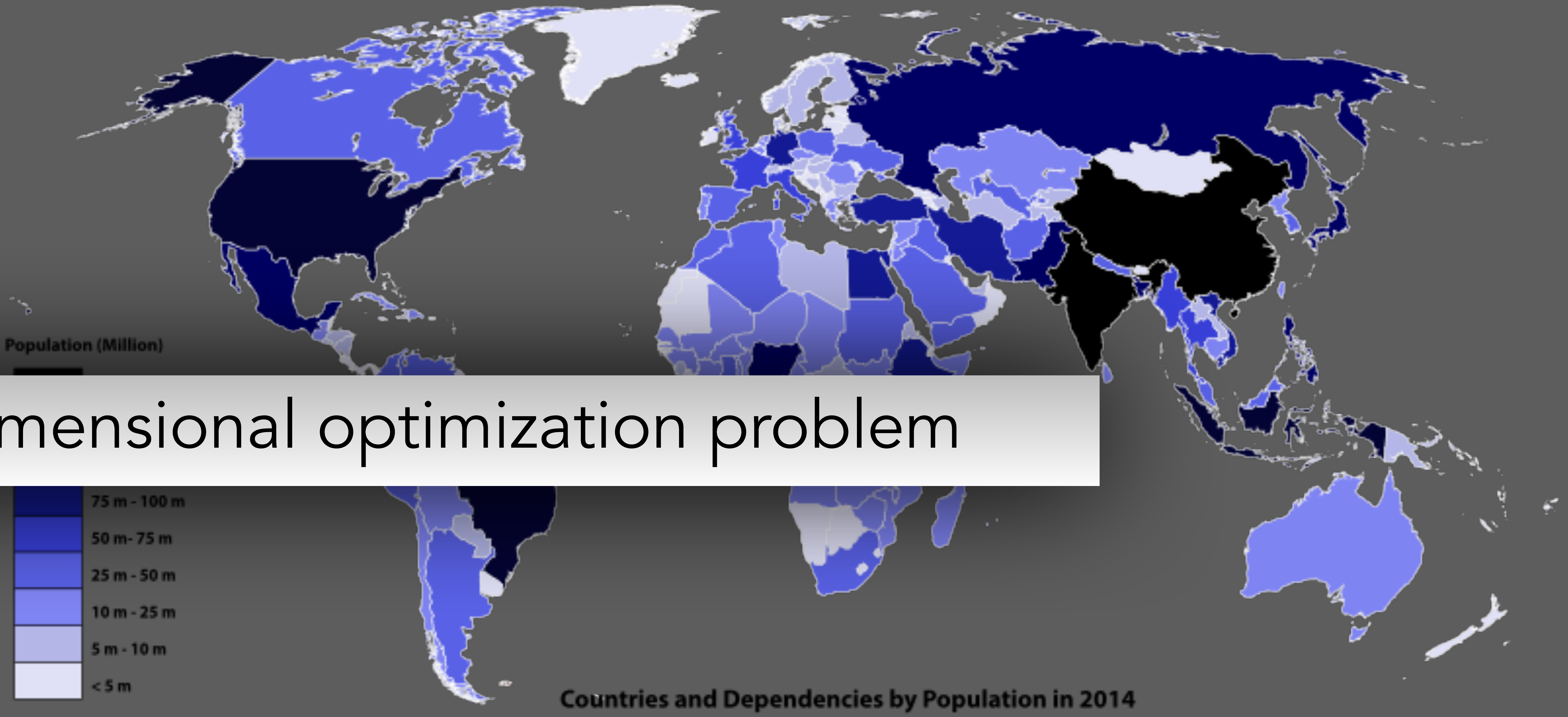


Taken from Wikipedia

Topology design problem



A high dimensional optimization problem



Taken from Wikipedia

Challenge for BGP?

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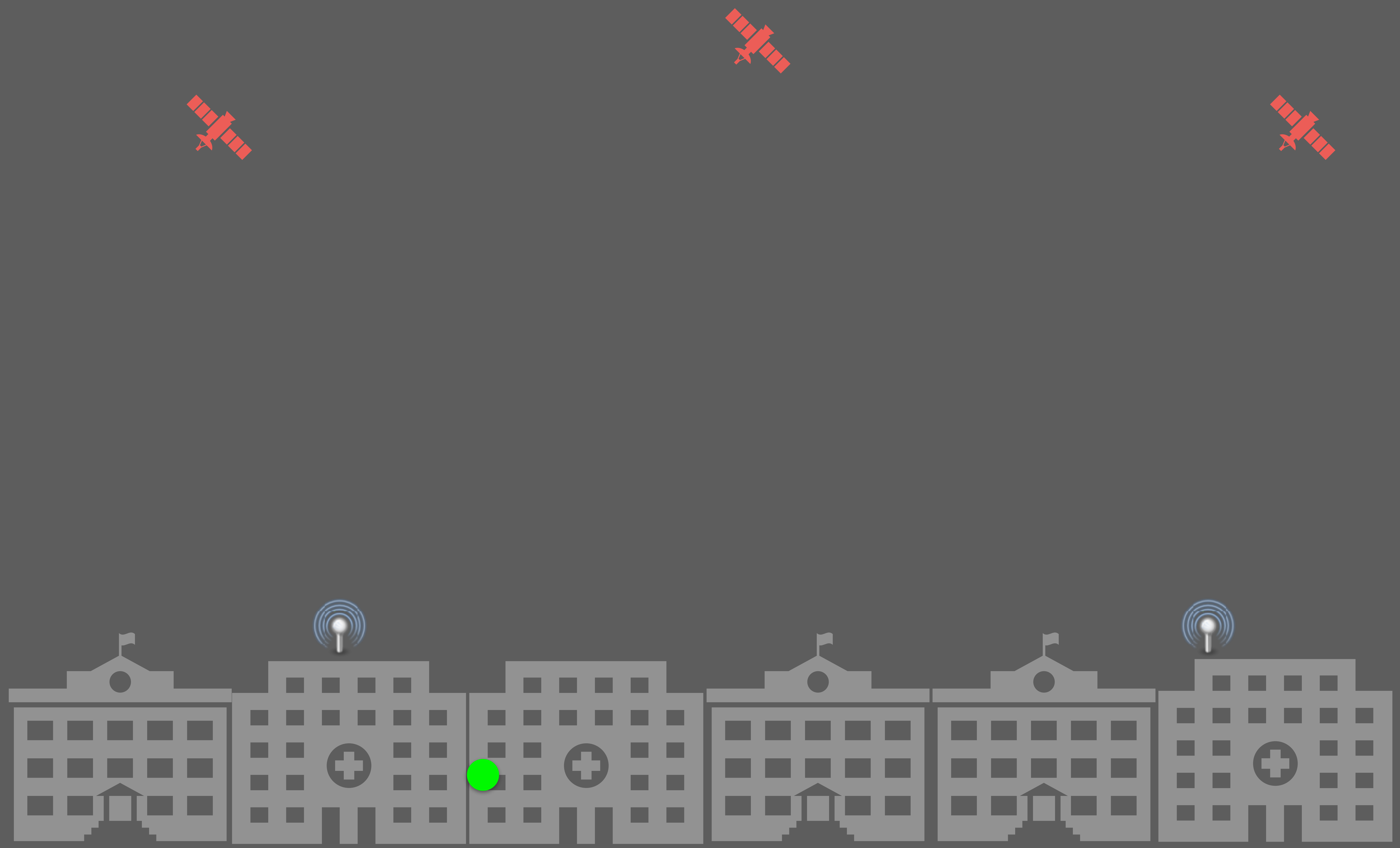
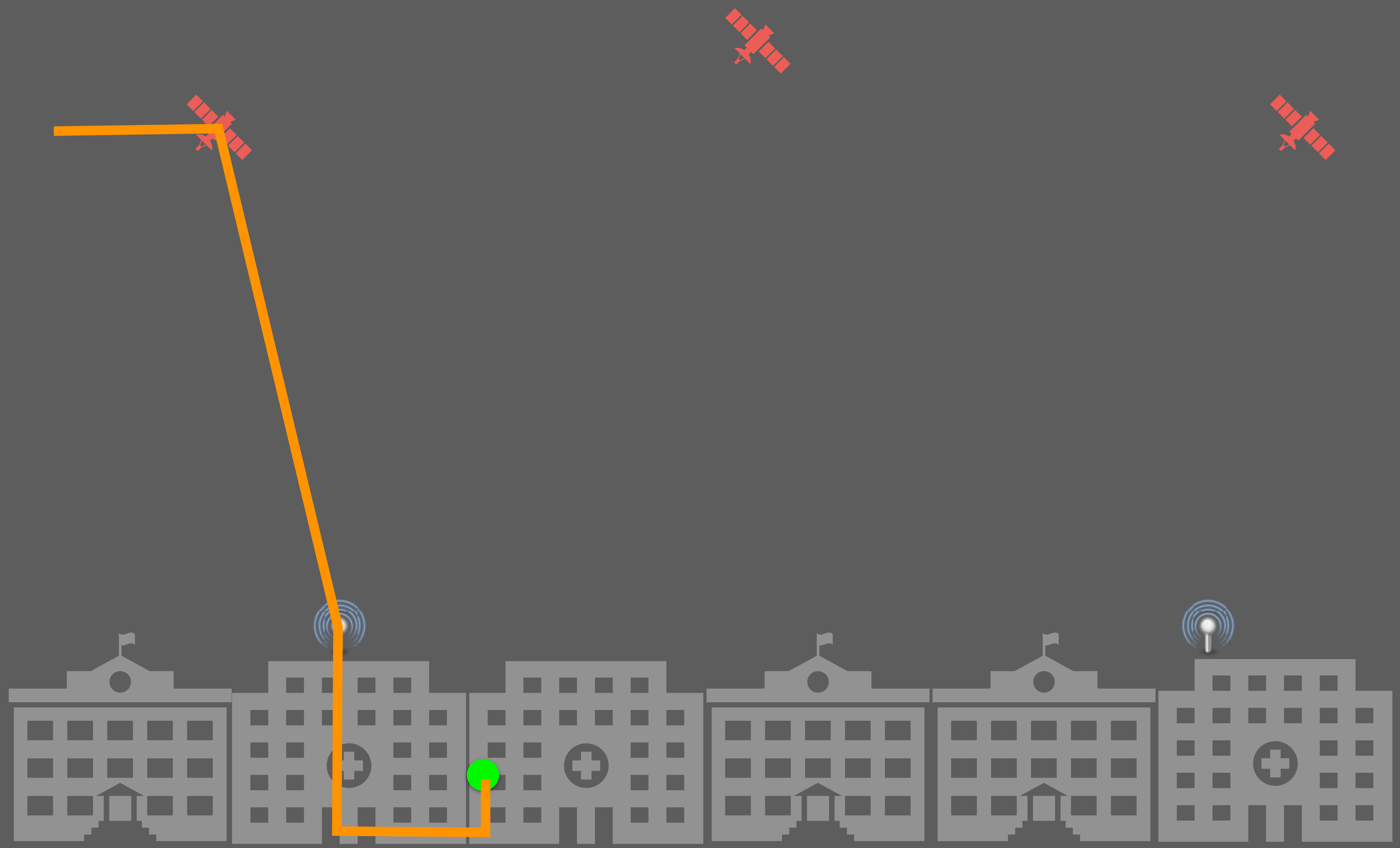
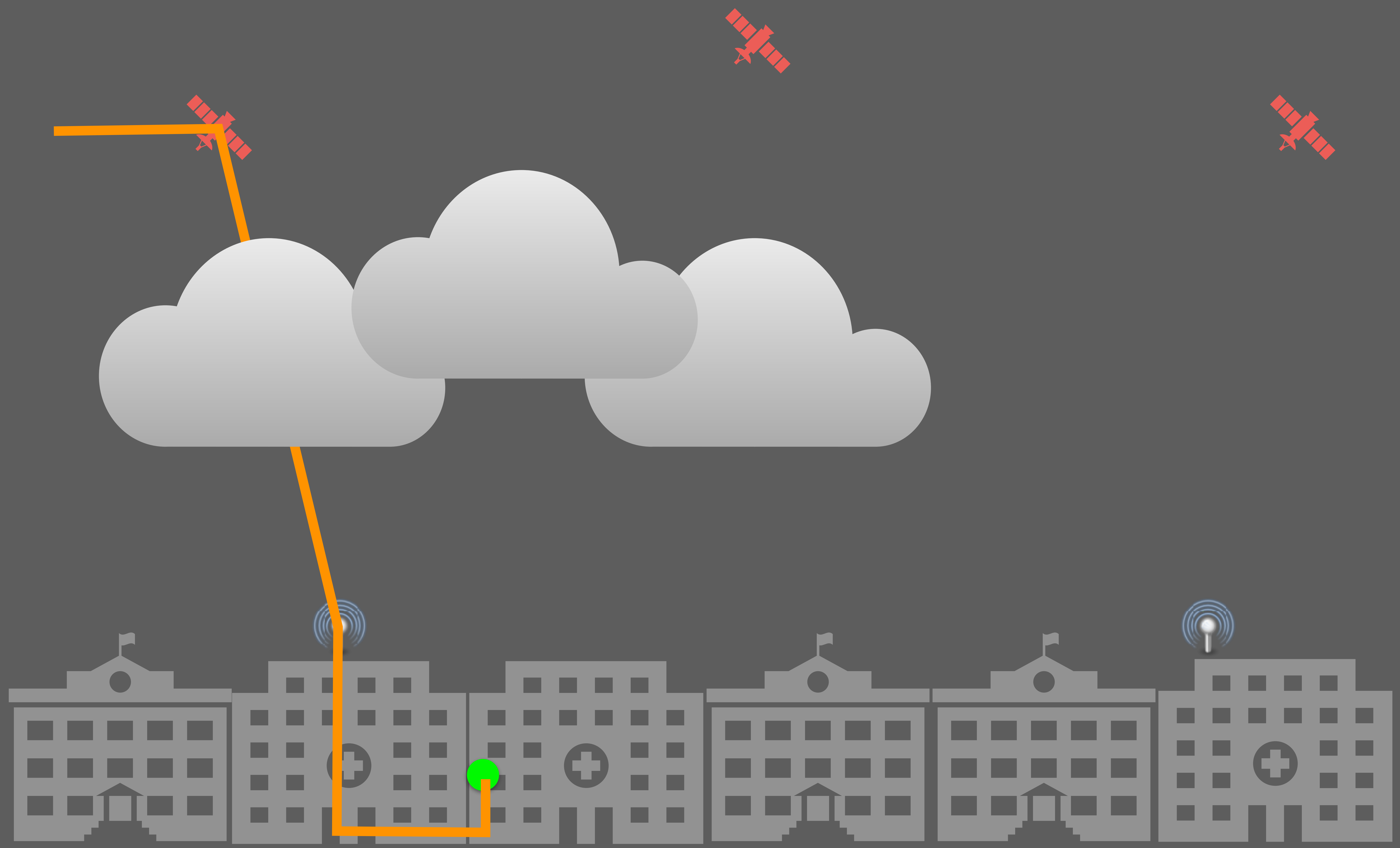
Weather awareness



Weather awareness



Weather awareness



Weather awareness

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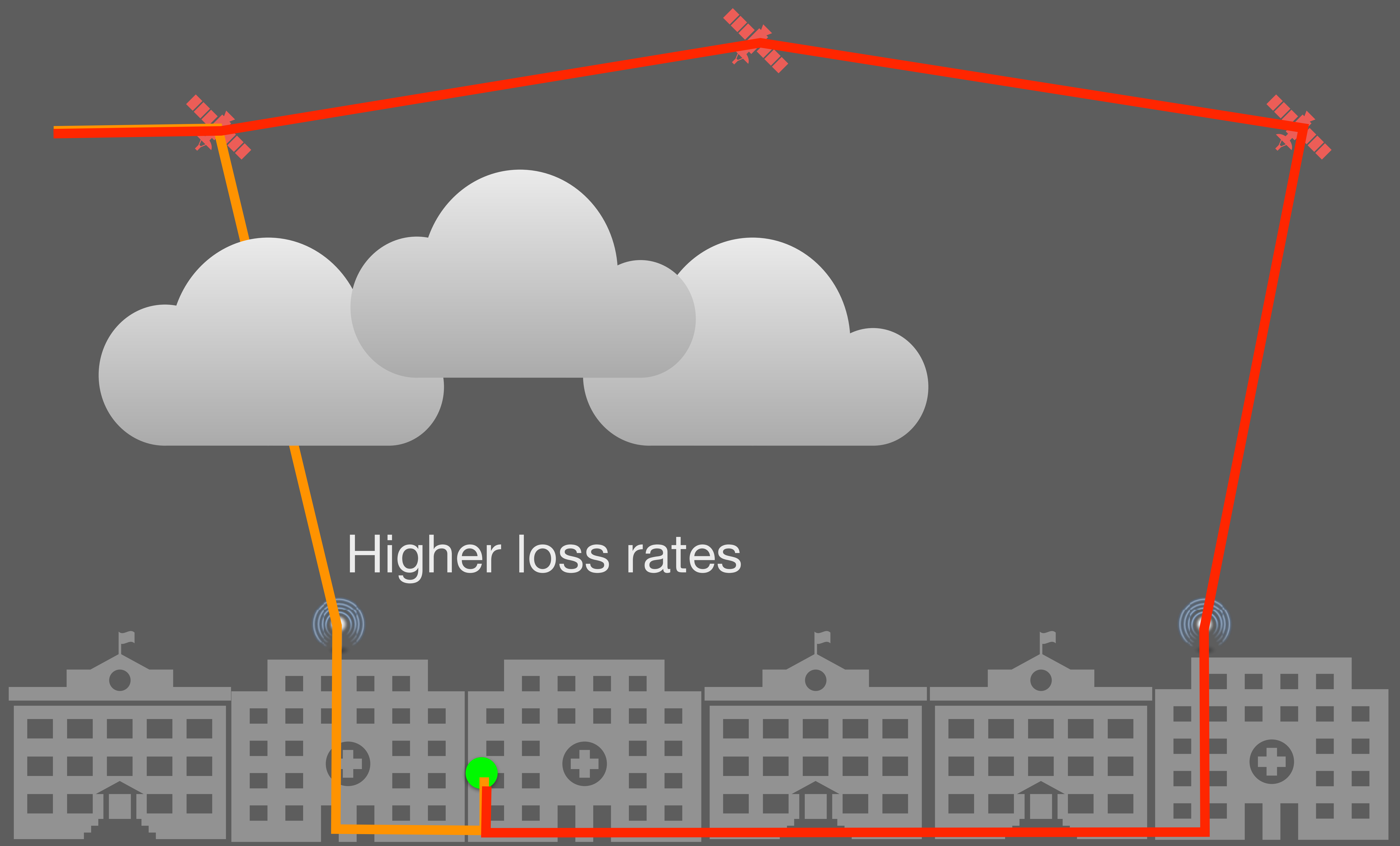

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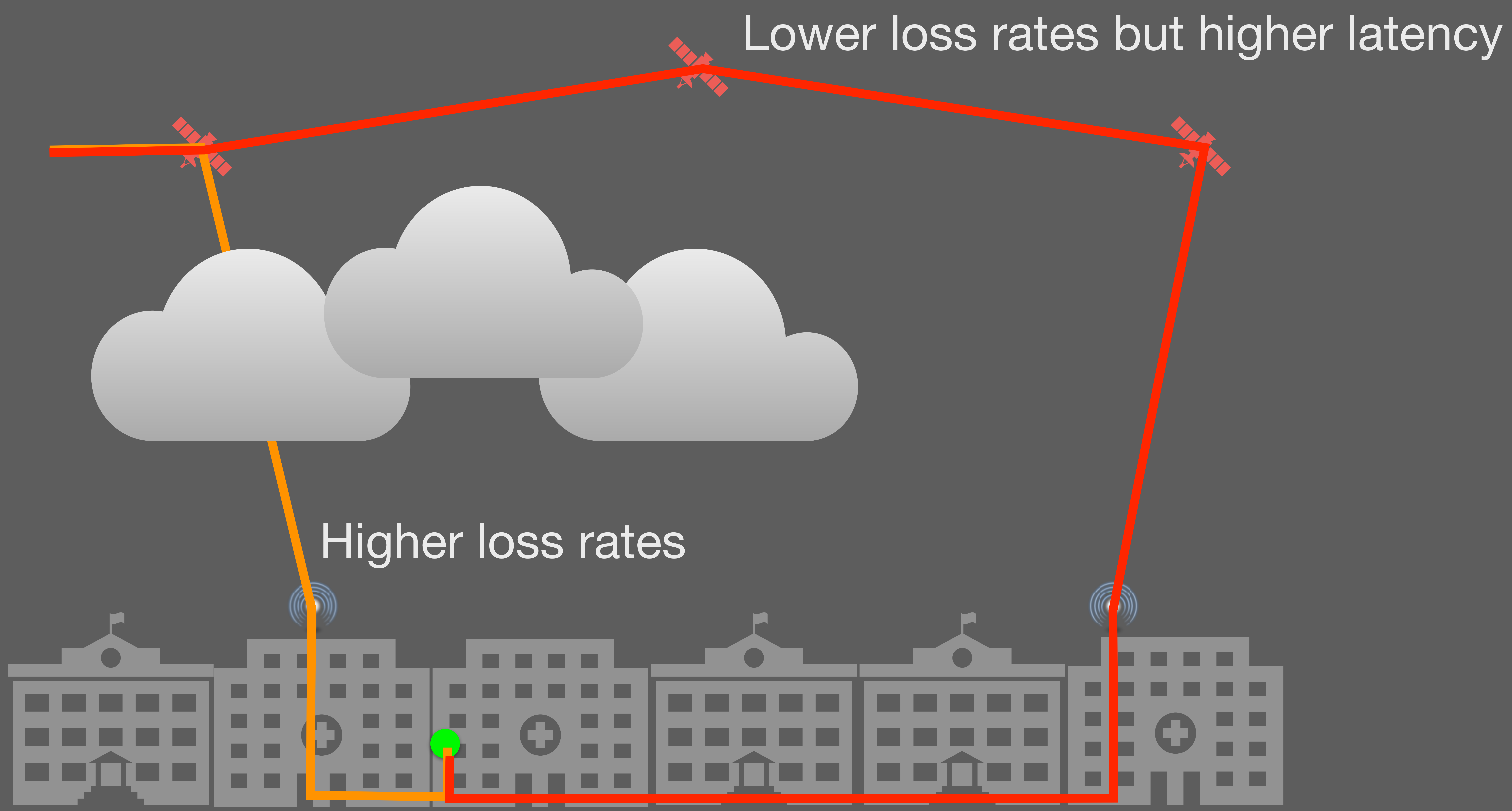
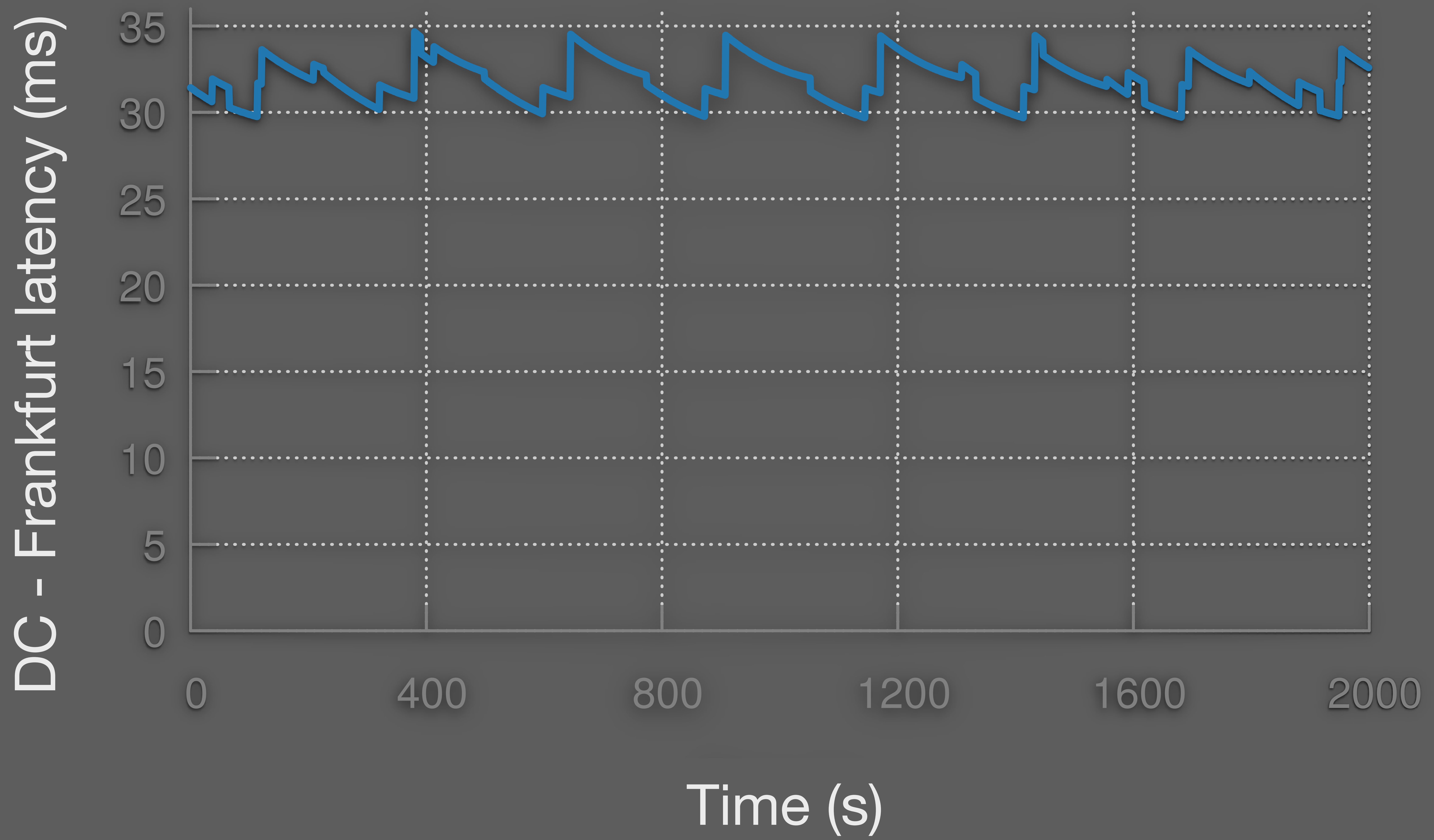


Challenges for congestion control



Challenges for congestion control

Delay-based congestion control schemes do not fare well

Utility of ISLs

“Internet from Space” without Inter-satellite Links?

Yannick Hauri, Debopam Bhattacherjee, Manuel Grossmann, Ankit Singla
ETH Zürich

FCC specification

presumptively acceptable risk and encourage "design for demise," i.e. designing spacecraft so that they burn up completely upon re-entry into the Earth's atmosphere,[450] but maintain the possibility for approval

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- No mention of silicon carbide components

FCC specification

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- No mention of silicon carbide components
- Constellation under deployment does not have ISLs

Bent-pipe connectivity (BP)

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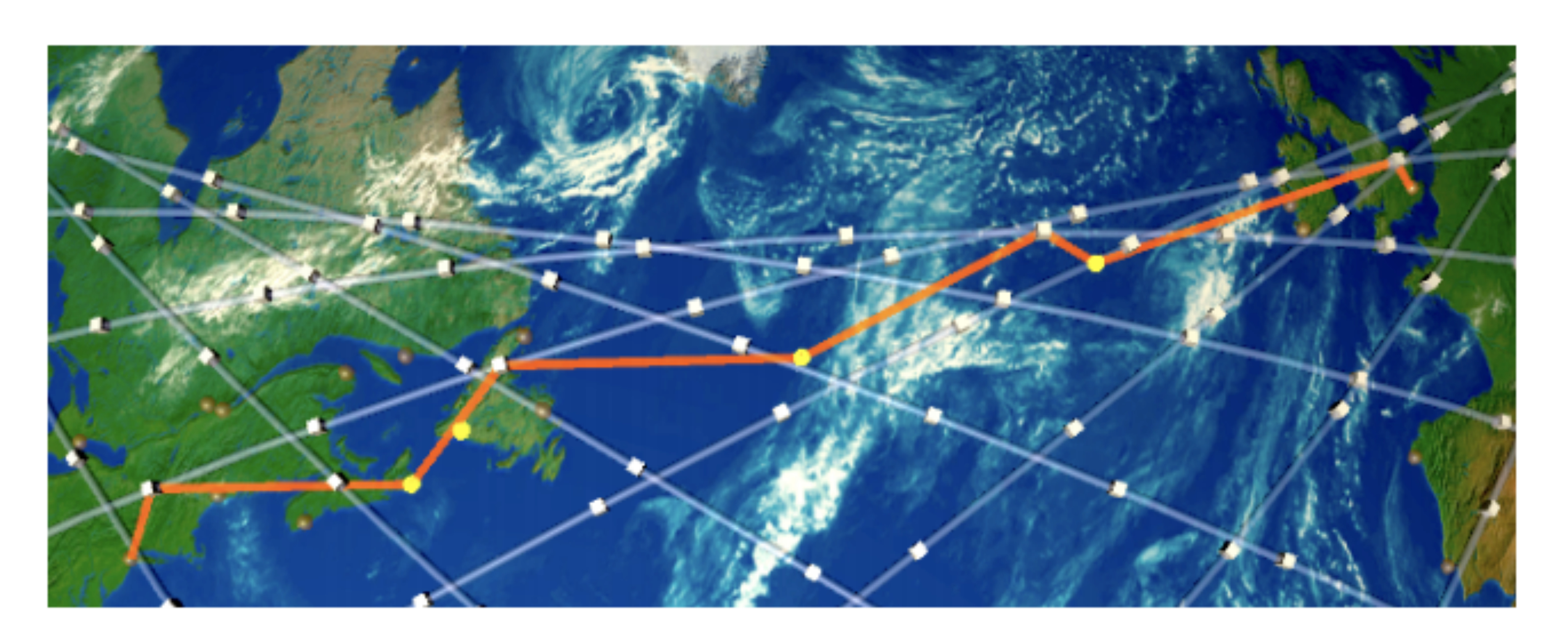
Bent-pipe connectivity (BP)

HotNets 2019

Using ground relays for low-latency wide-area routing in megaconstellations

Mark Handley, University College London



ISL versus BP

ISL versus BP

- Latencies and **variations** thereof

ISL versus BP

- Latencies and **variations** thereof
- Impact on network-wide **throughput**

ISL versus BP

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"Internet from Space" without Inter-satellite Links?

Yannick Hauri, Debopam Bhattacherjee, Manuel Grossmann, Ankit Singla
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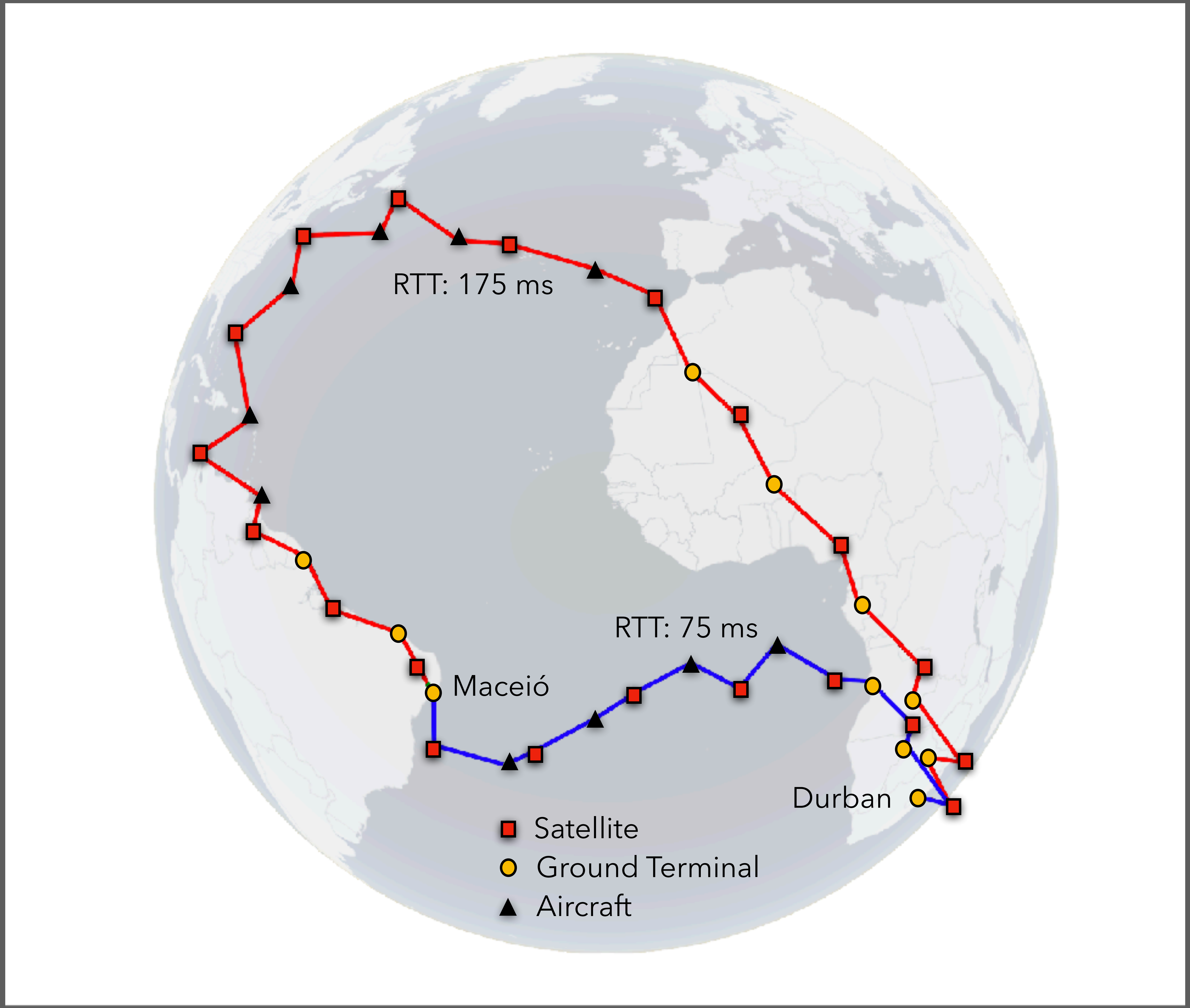
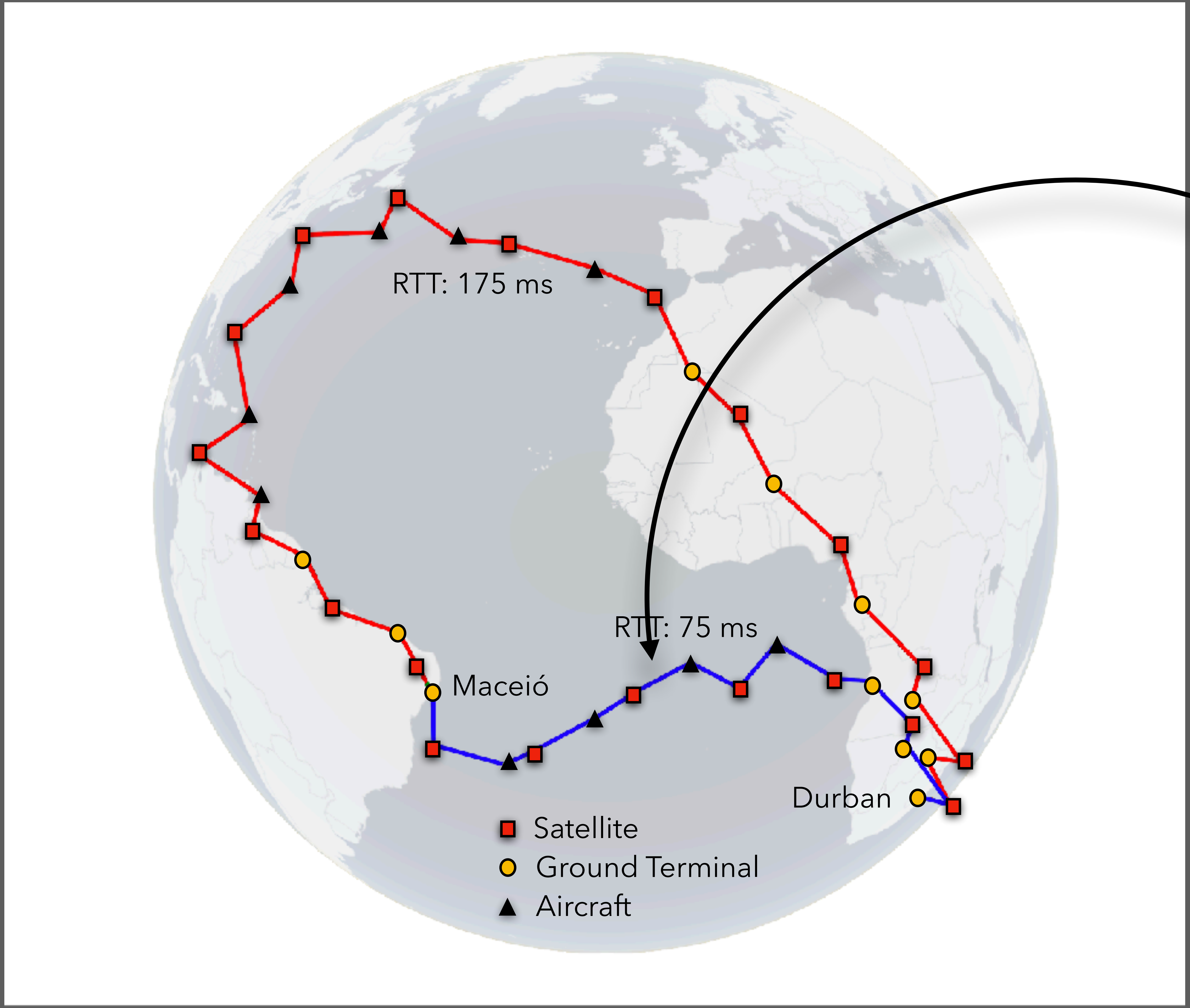
HotNets 2020

High latency variations in BP

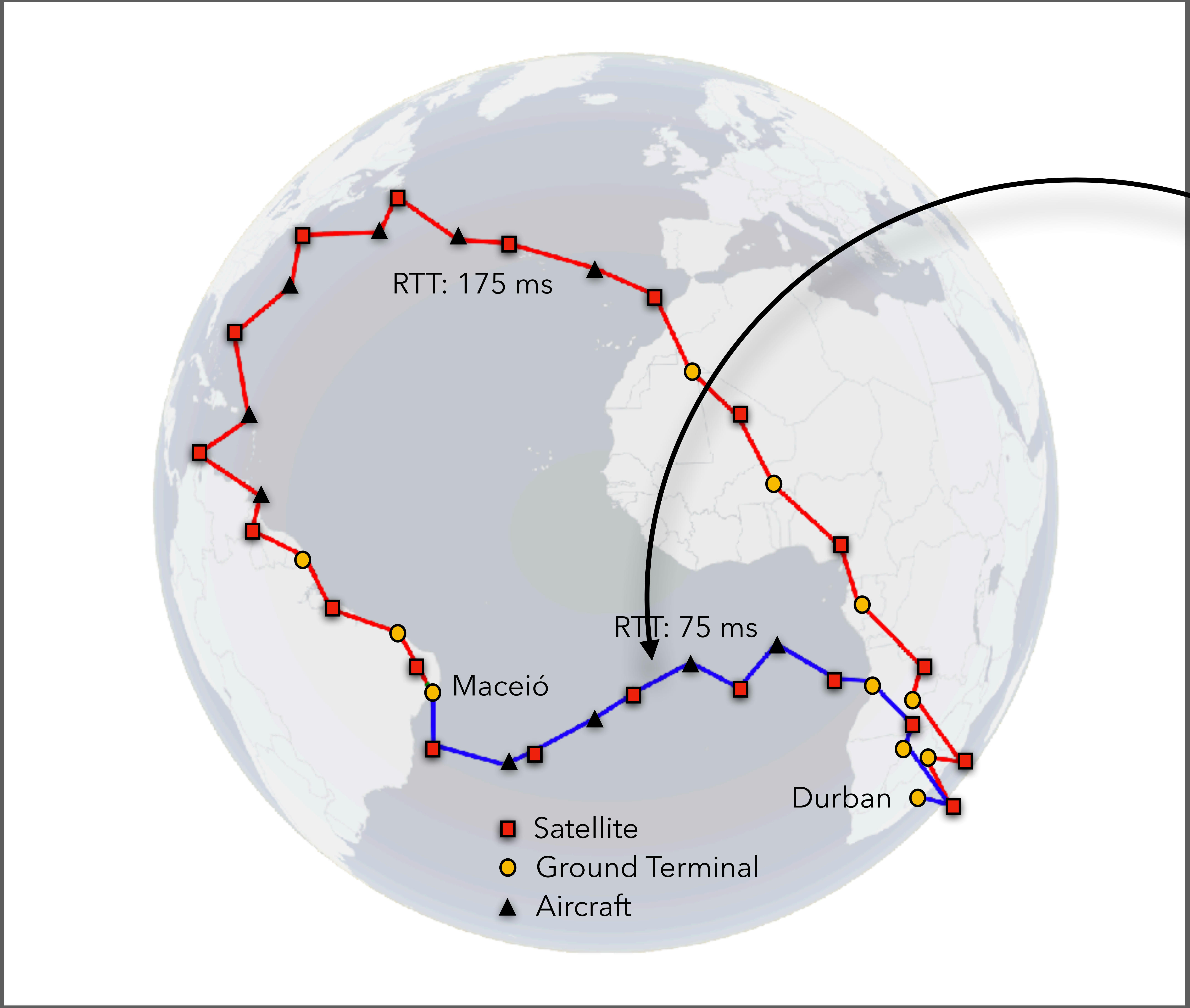


High latency variations in BP



Sparser air traffic over South Atlantic

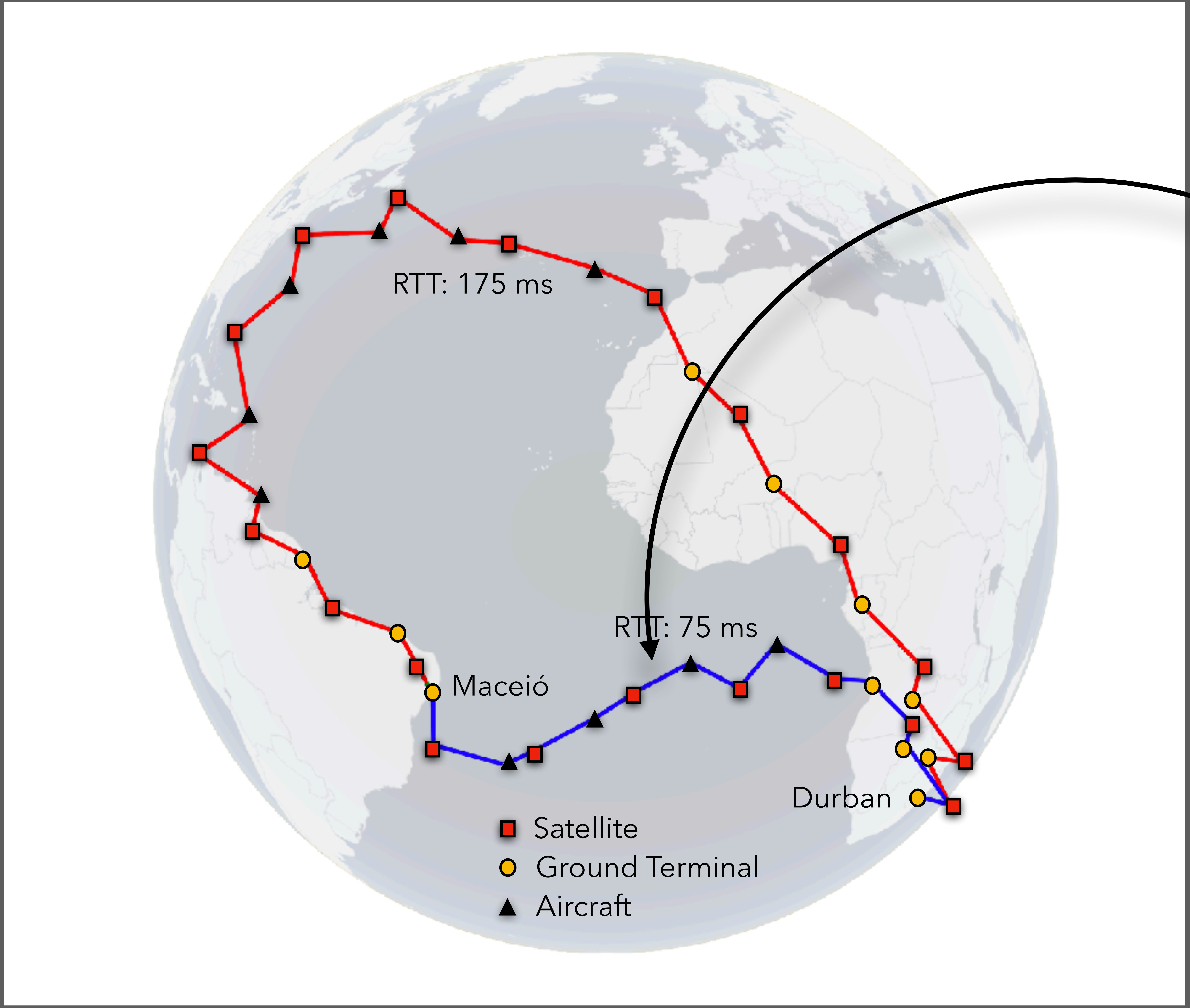
High latency variations in BP



Sparser air traffic over South Atlantic

- Inflation of ~100 ms

High latency variations in BP



Sparser air traffic over South Atlantic

- Inflation of ~100 ms
- North Atlantic paths get congested

Impact of weather

Impact of weather

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Other benefits of ISLs

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- Crossing unfriendly territory

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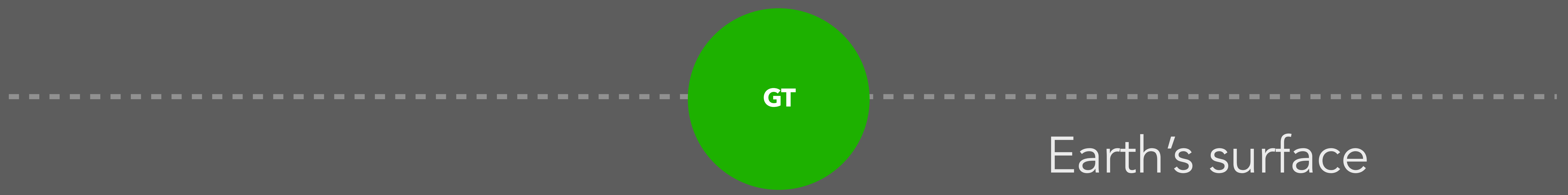
- Crossing unfriendly territory
- Spectrum efficiency
- GSO arc avoidance



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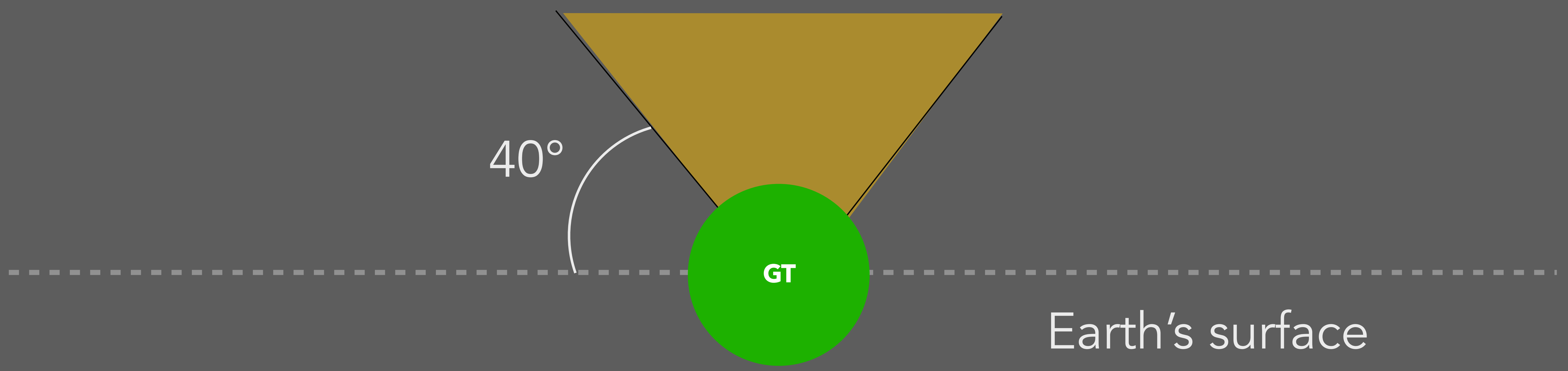

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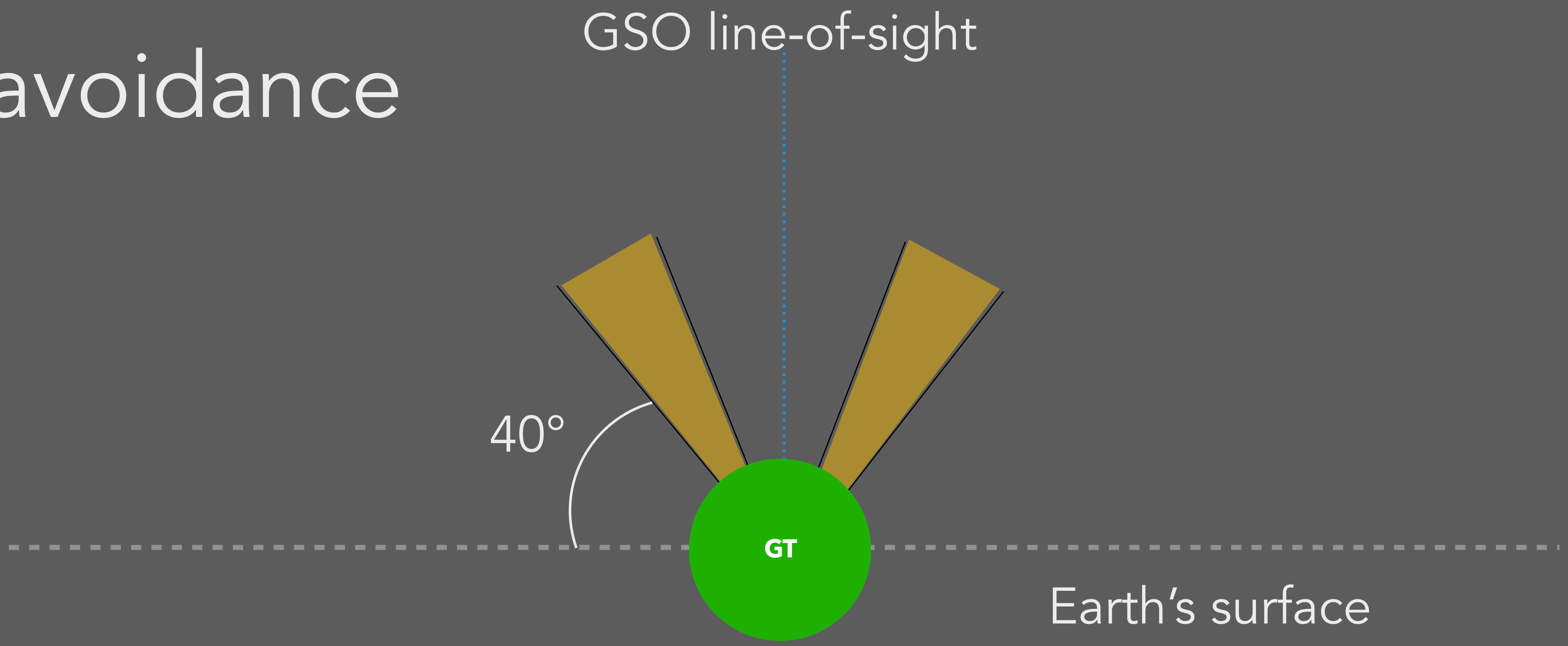

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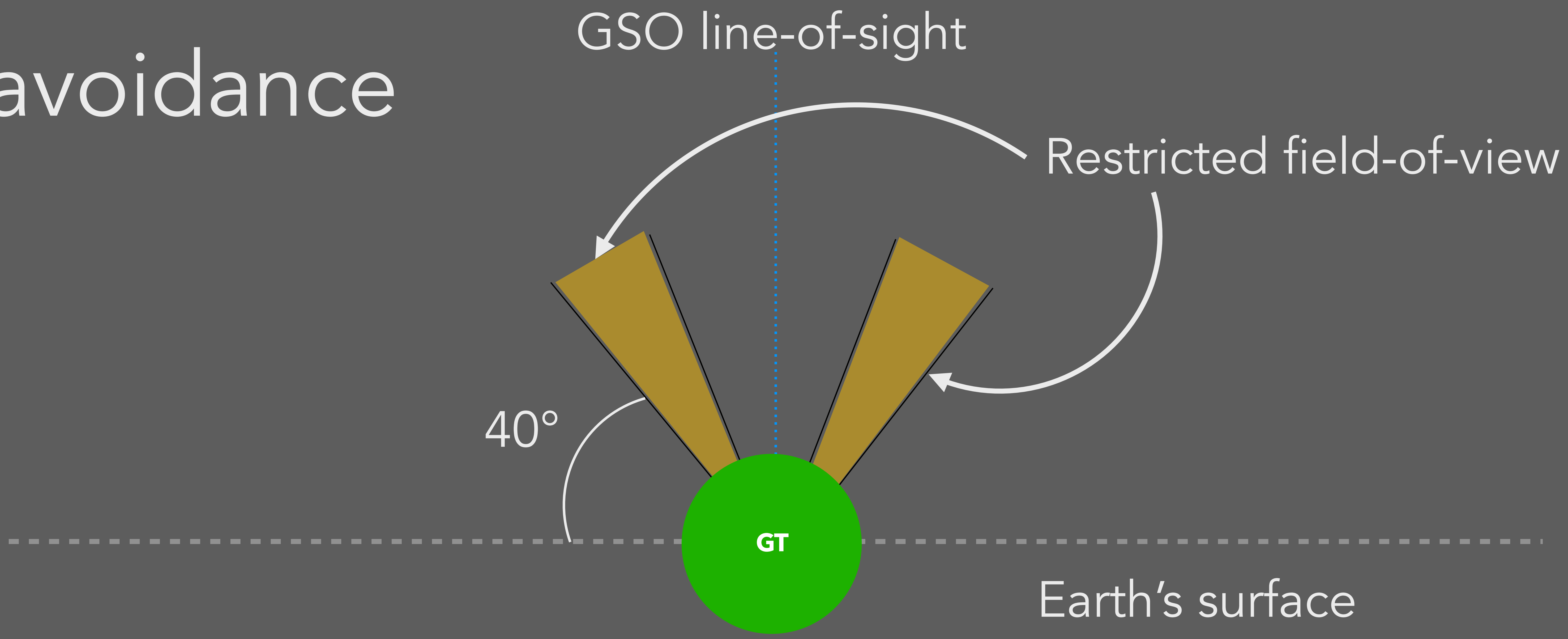

Recent news

- SpaceX September 3 launch video

  “Recently as the Starlink team completed a test of two satellites in orbit that are equipped with our inter-satellite links which we call space lasers. With these space lasers, the Starlink satellites were able to transfer hundreds of gigabytes of data.”

Recent news

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- ISL capacities?

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- ISL capacities?
- Pointing

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- ISL capacities?
- Pointing
- Topology

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- ISL capacities?
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- Topology
- OneWeb's no-ISL design

Network topology design at 27,000 km/hour

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How do we connect satellites?

How do we connect satellites?

How do we connect satellites?

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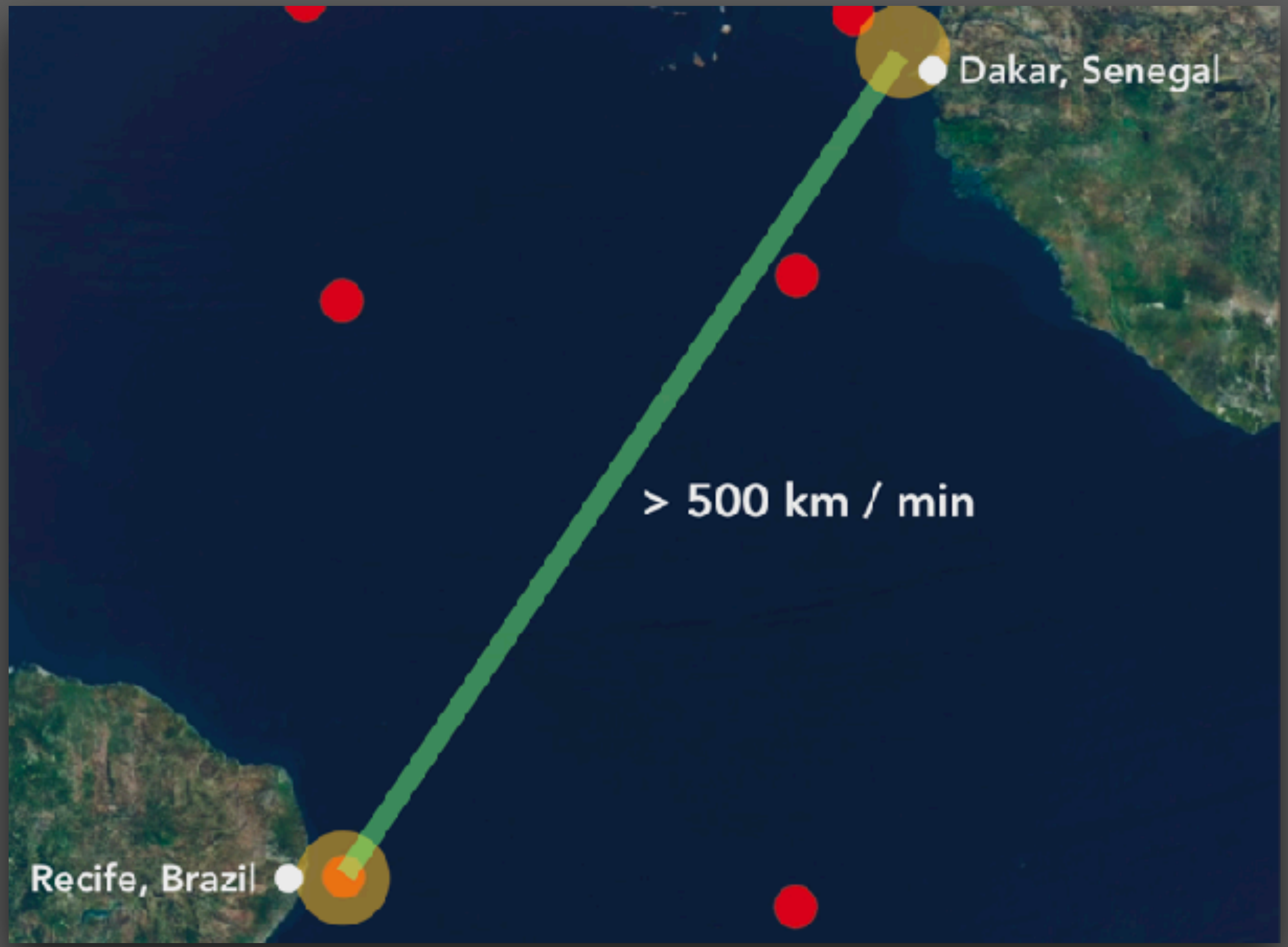
CoNEXT 2019

Key constraints

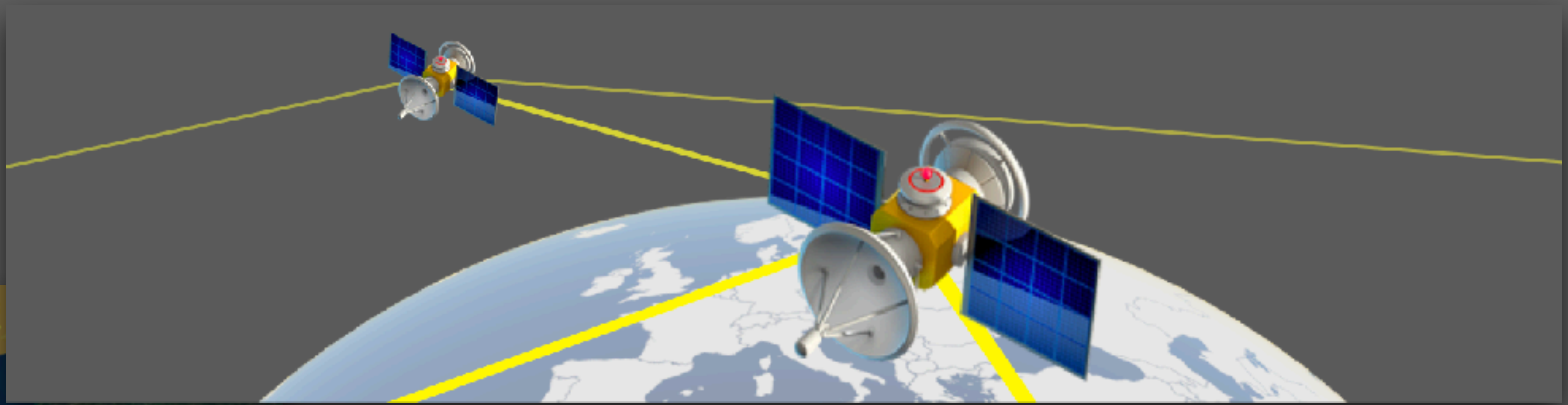
Key constraints

System dynamics

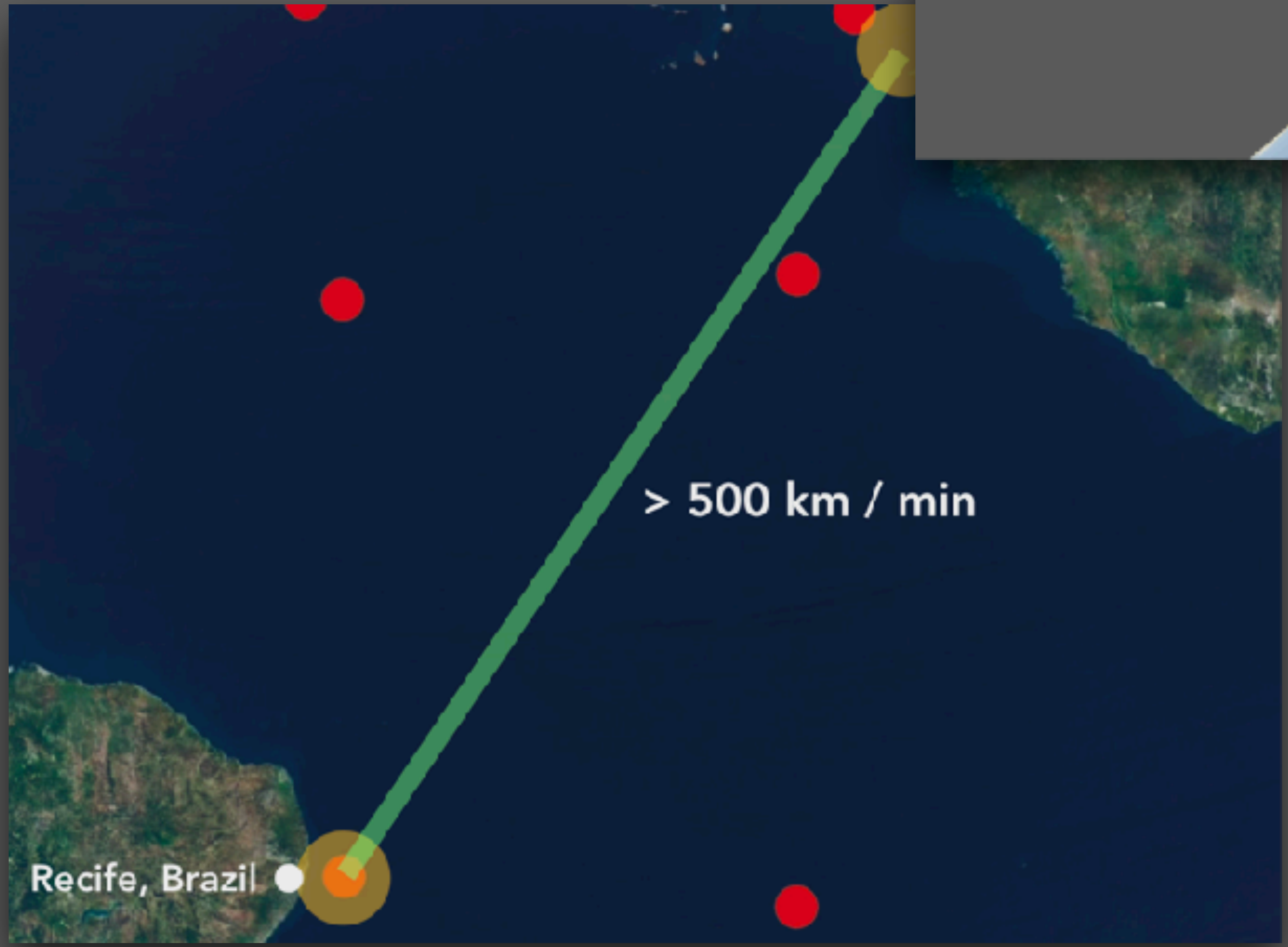


Key constraints

Link setup times



System dynamics



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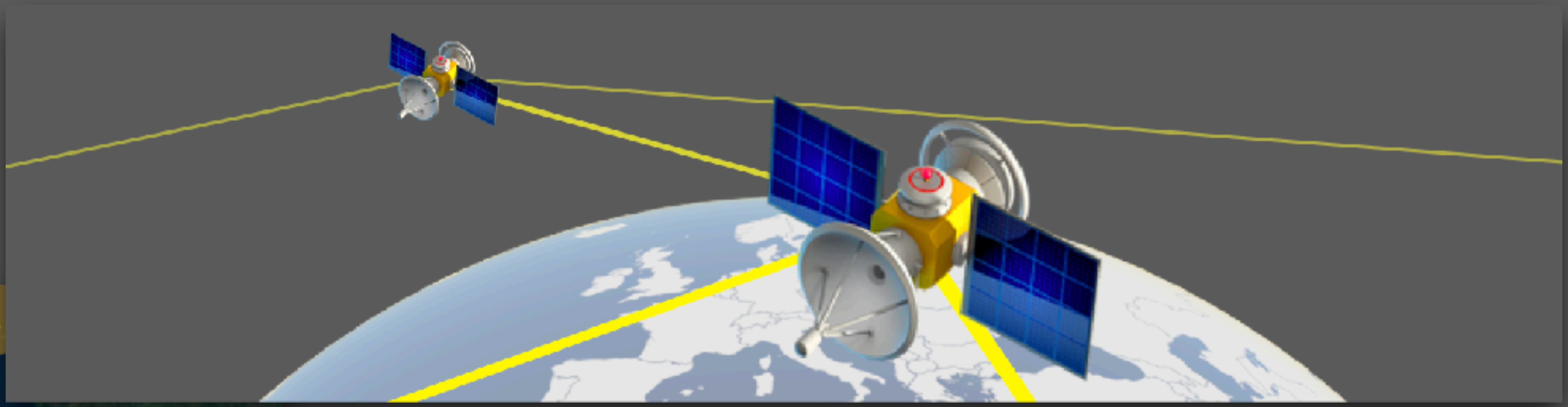
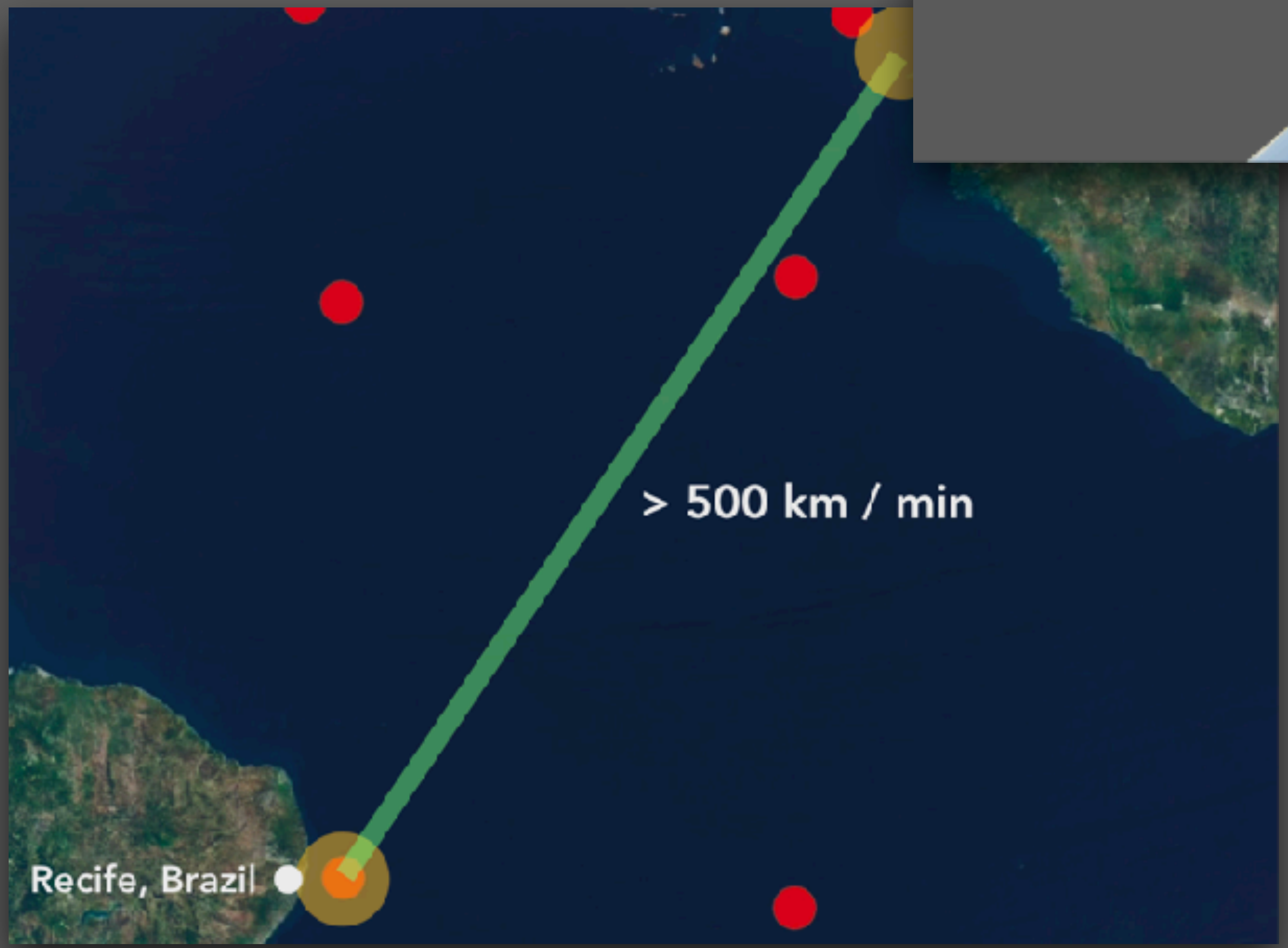
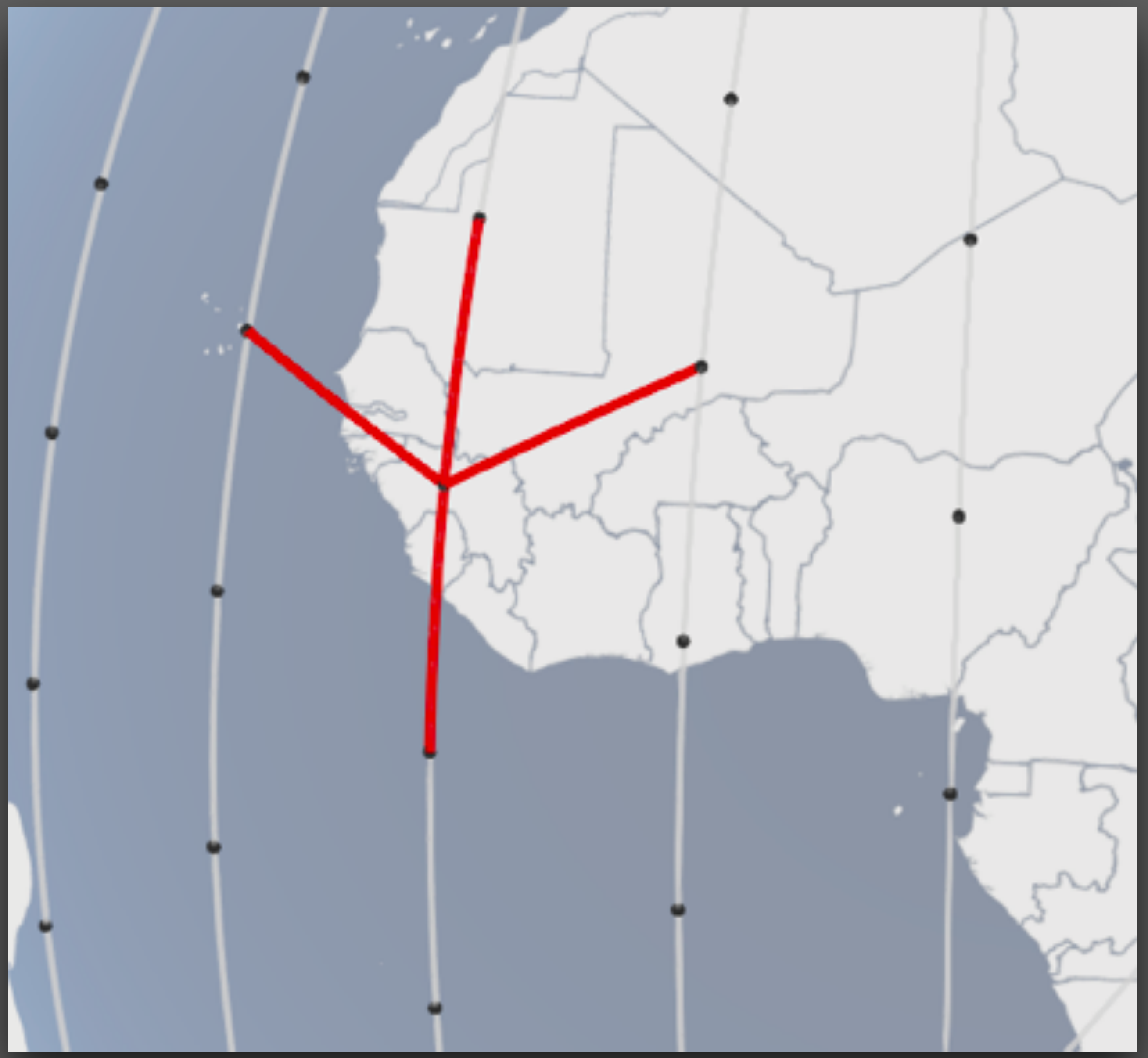


System dynamics





Max. no of links per satellite

Assumptions

Assumptions

- Given satellite trajectories

Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition

Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
- Ground-satellite connectivity is range-bounded

Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
- Ground-satellite connectivity is range-bounded
- +Grid is the baseline

+Grid

+Grid

Can use much longer links

Can use much longer links

Can use much longer links

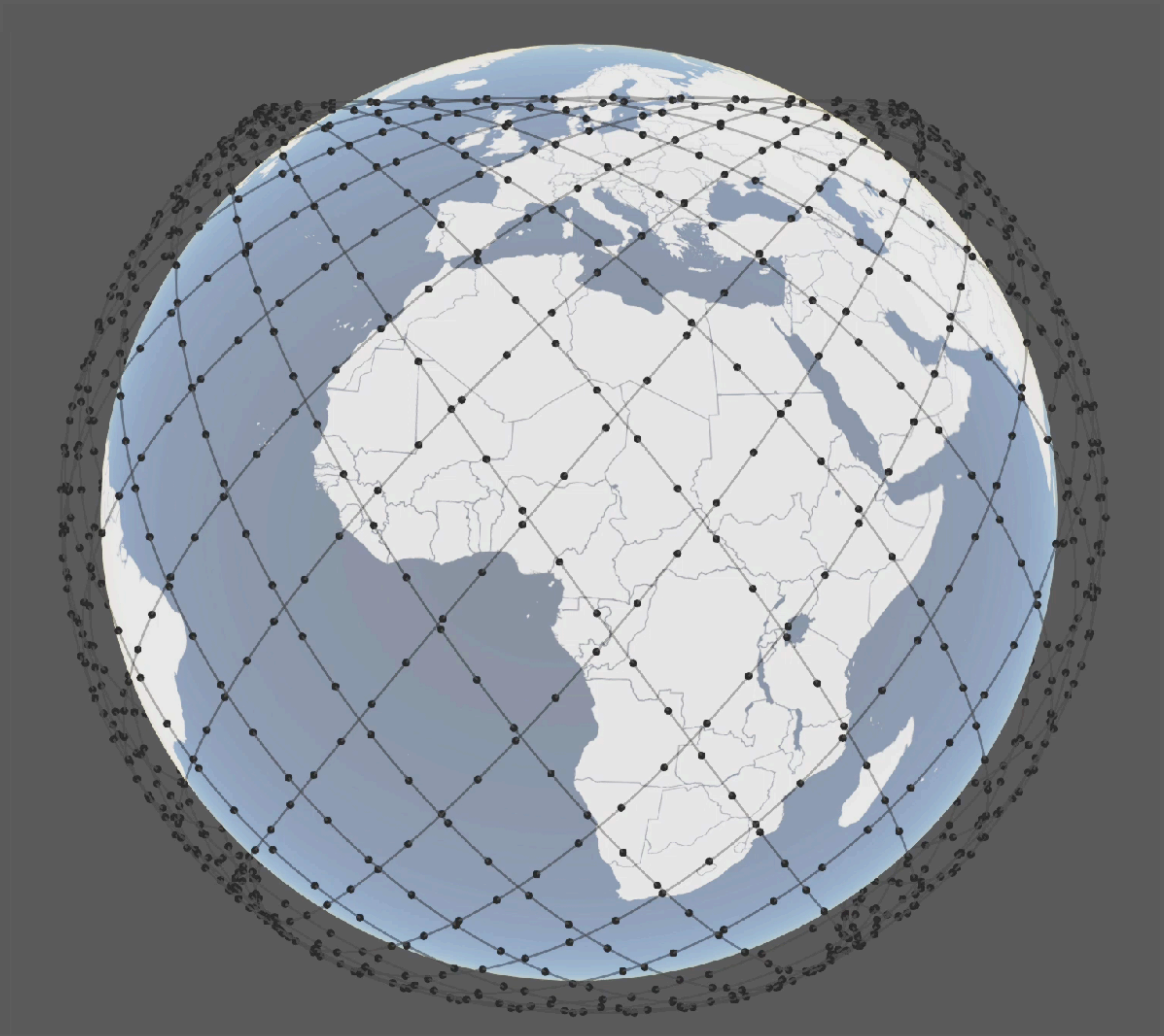
Can use much longer links

Can use much longer links

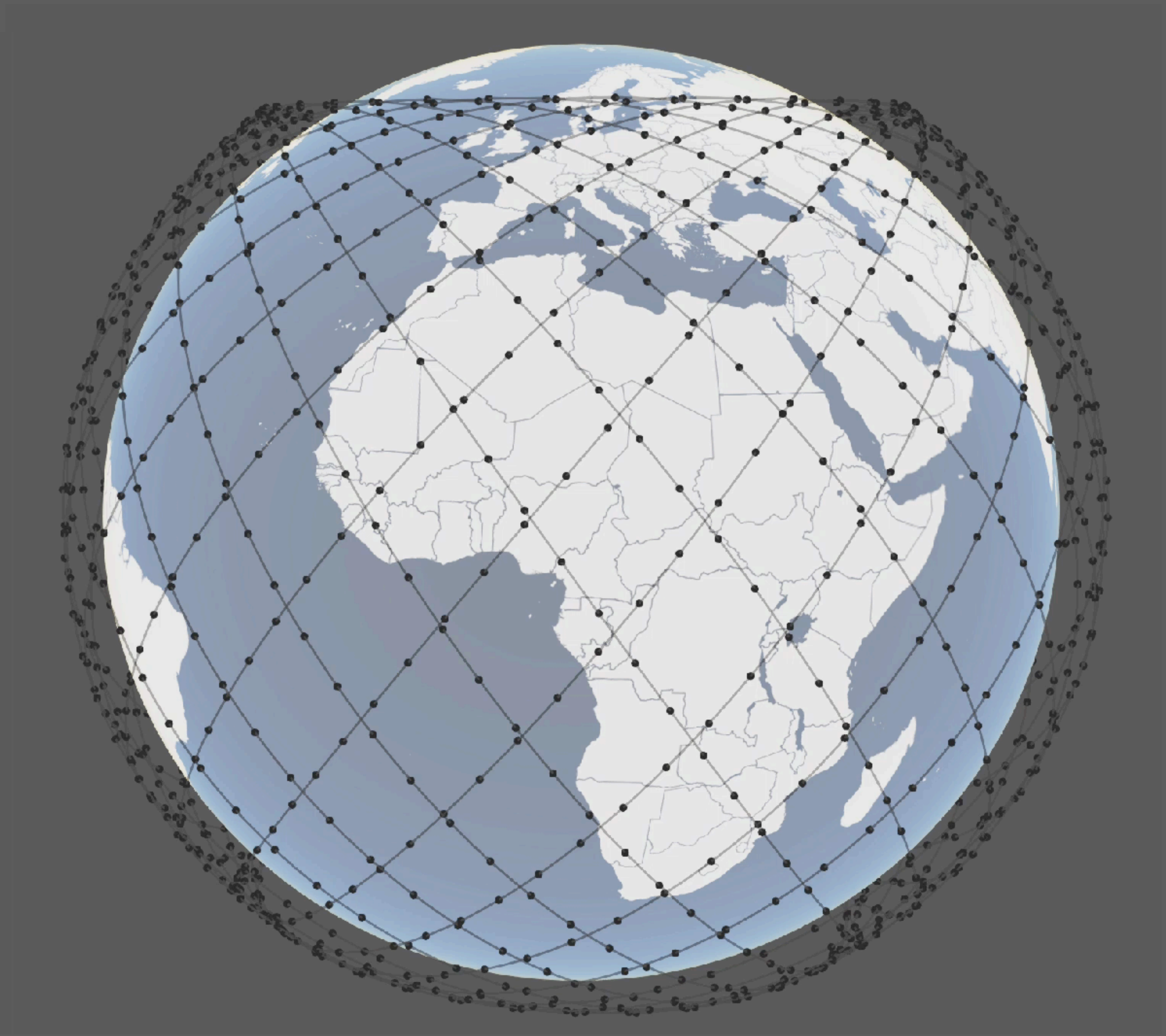
Can use much longer links

Can use much longer links

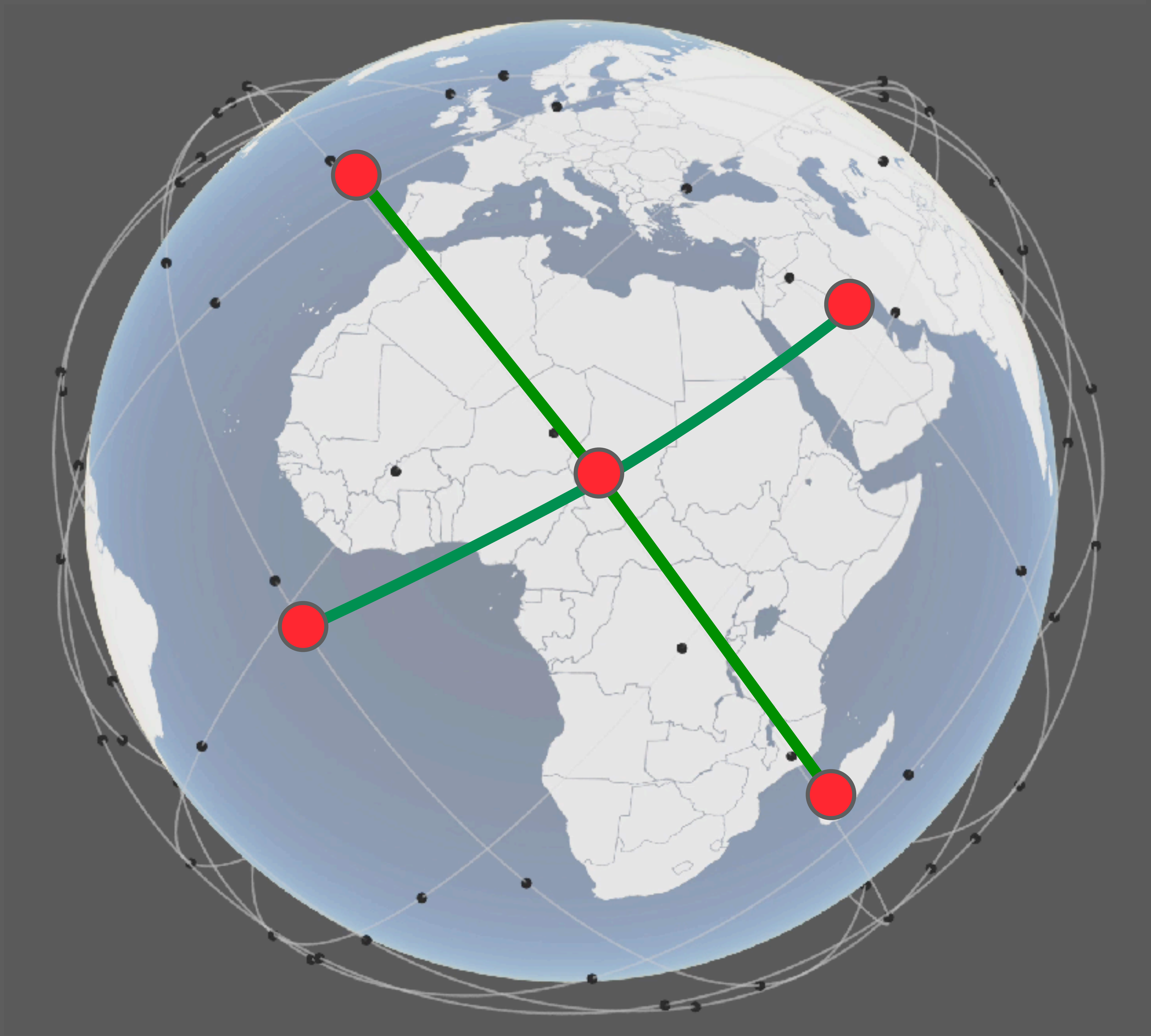
Much larger design space

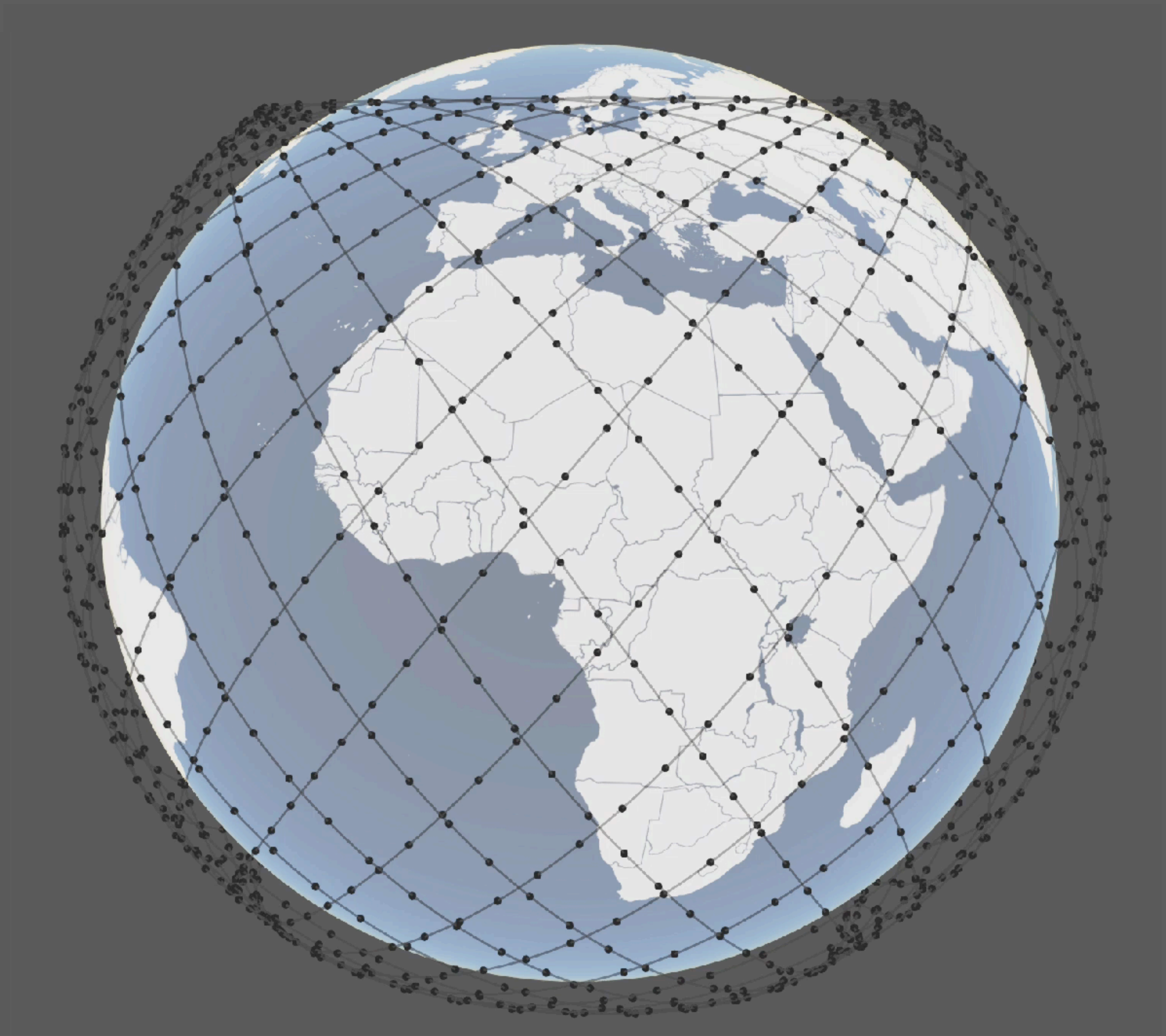


Much larger design space

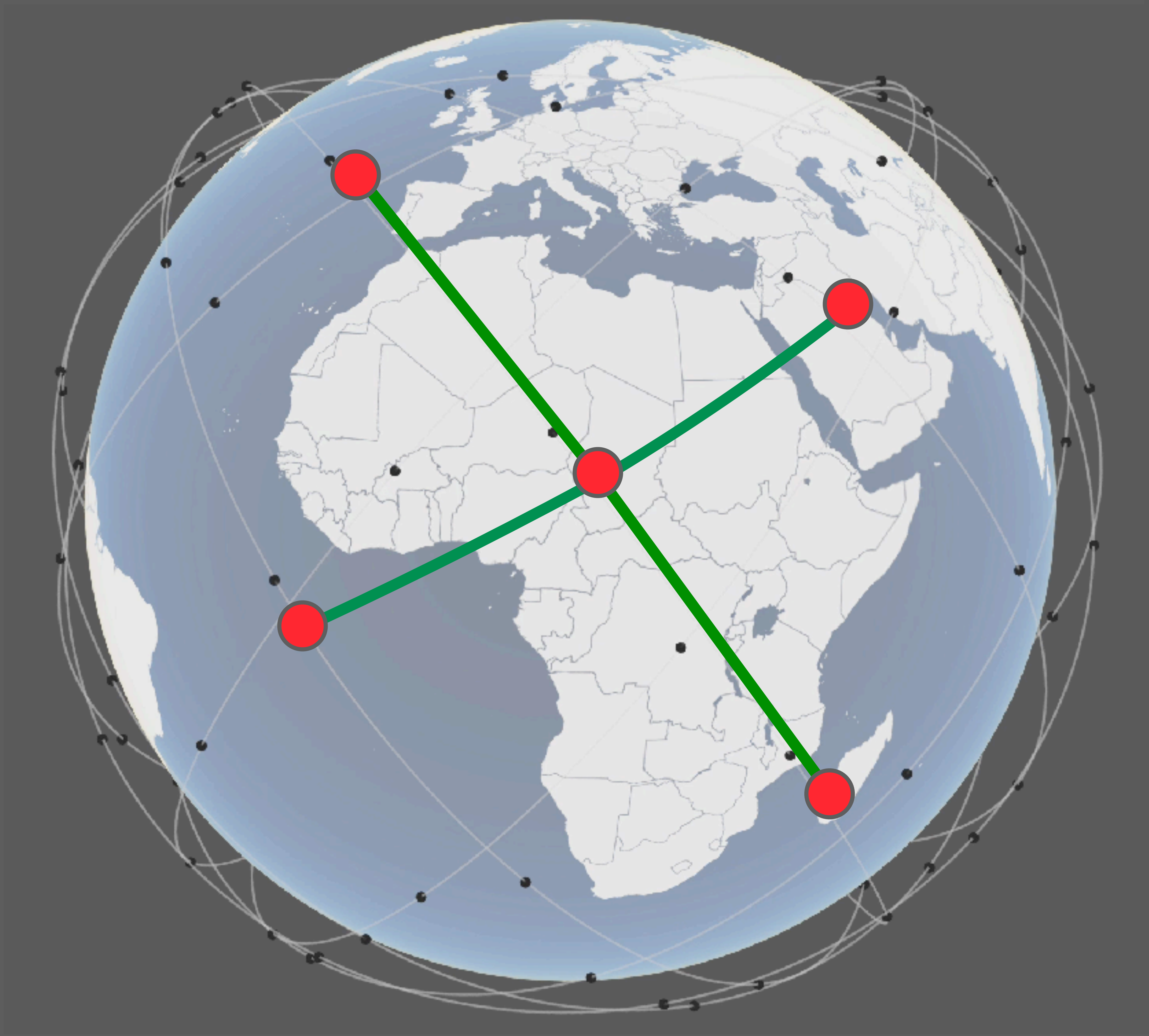


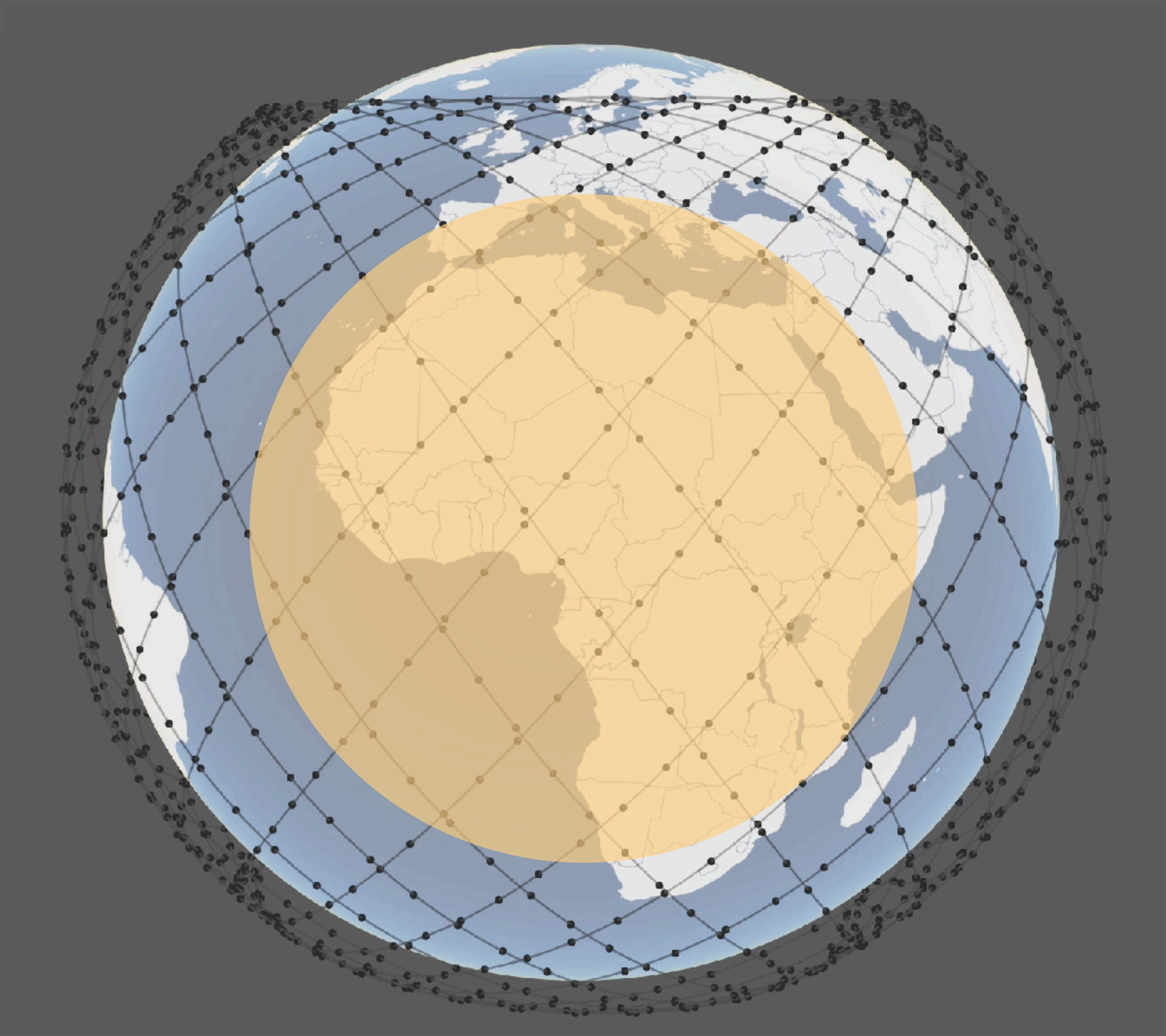
Much larger design space





Much larger design space



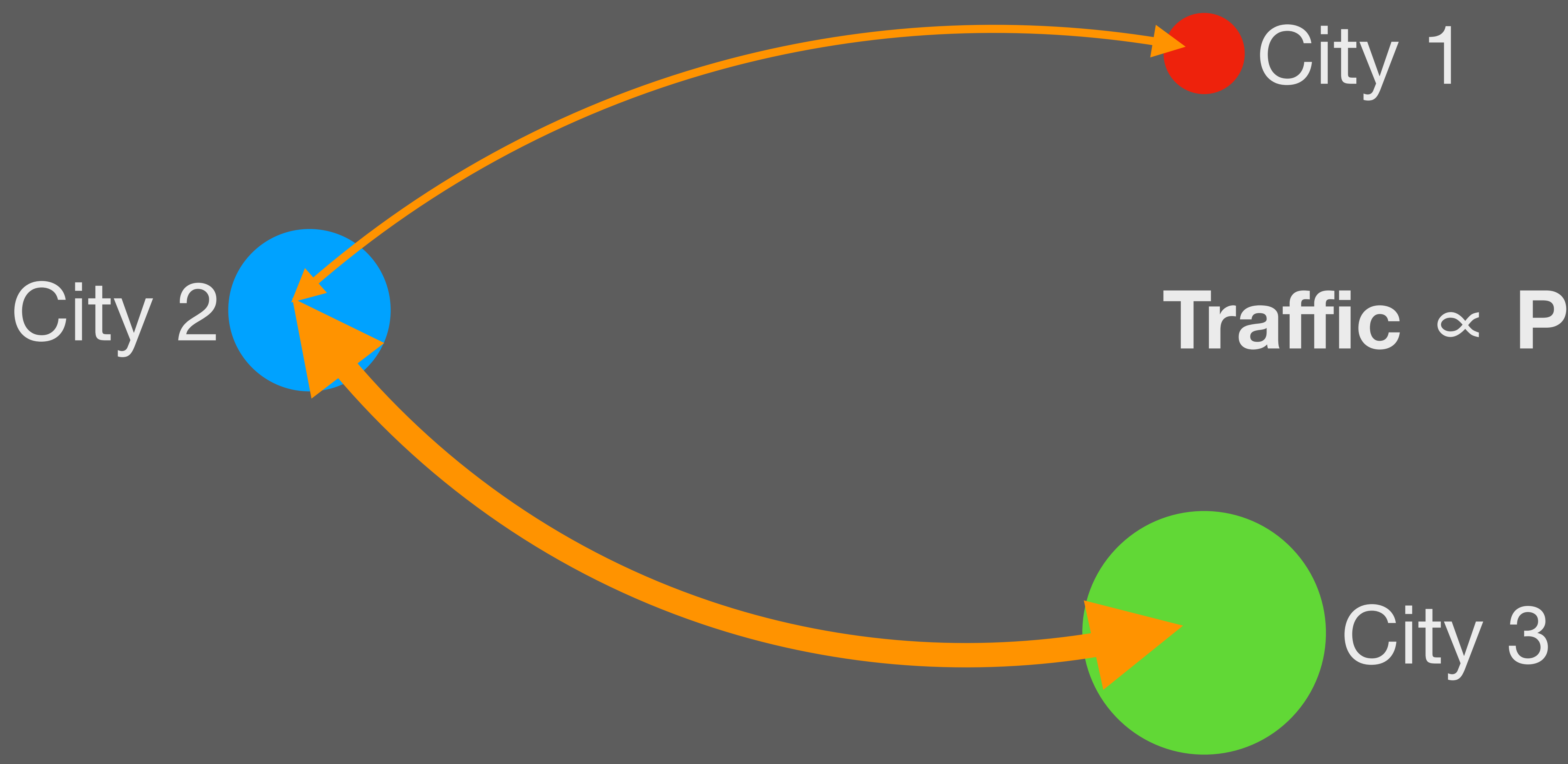


What do we optimize for?

Traffic matrix

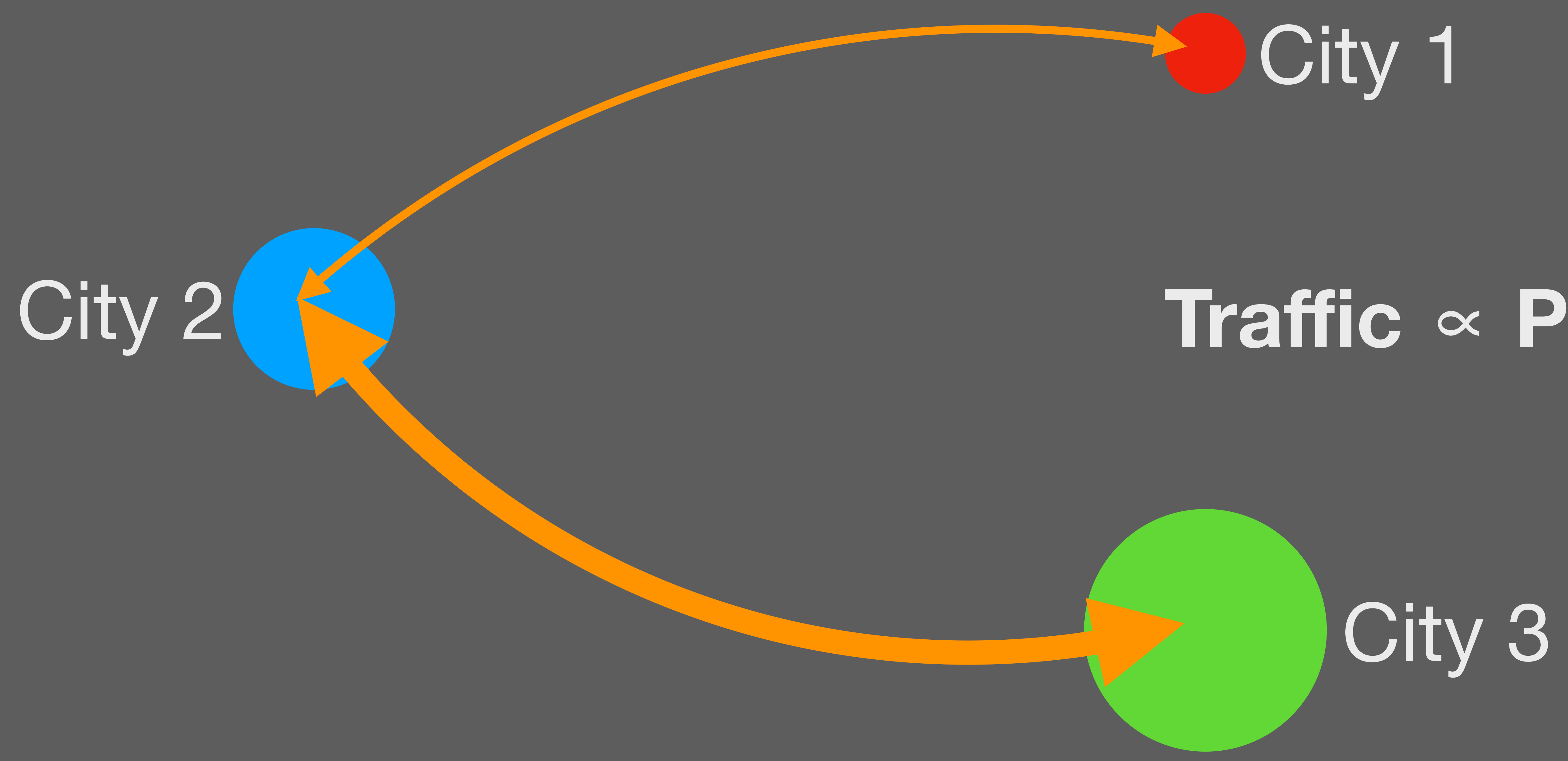
Traffic matrix

Traffic matrix



Traffic $\propto$ Population product

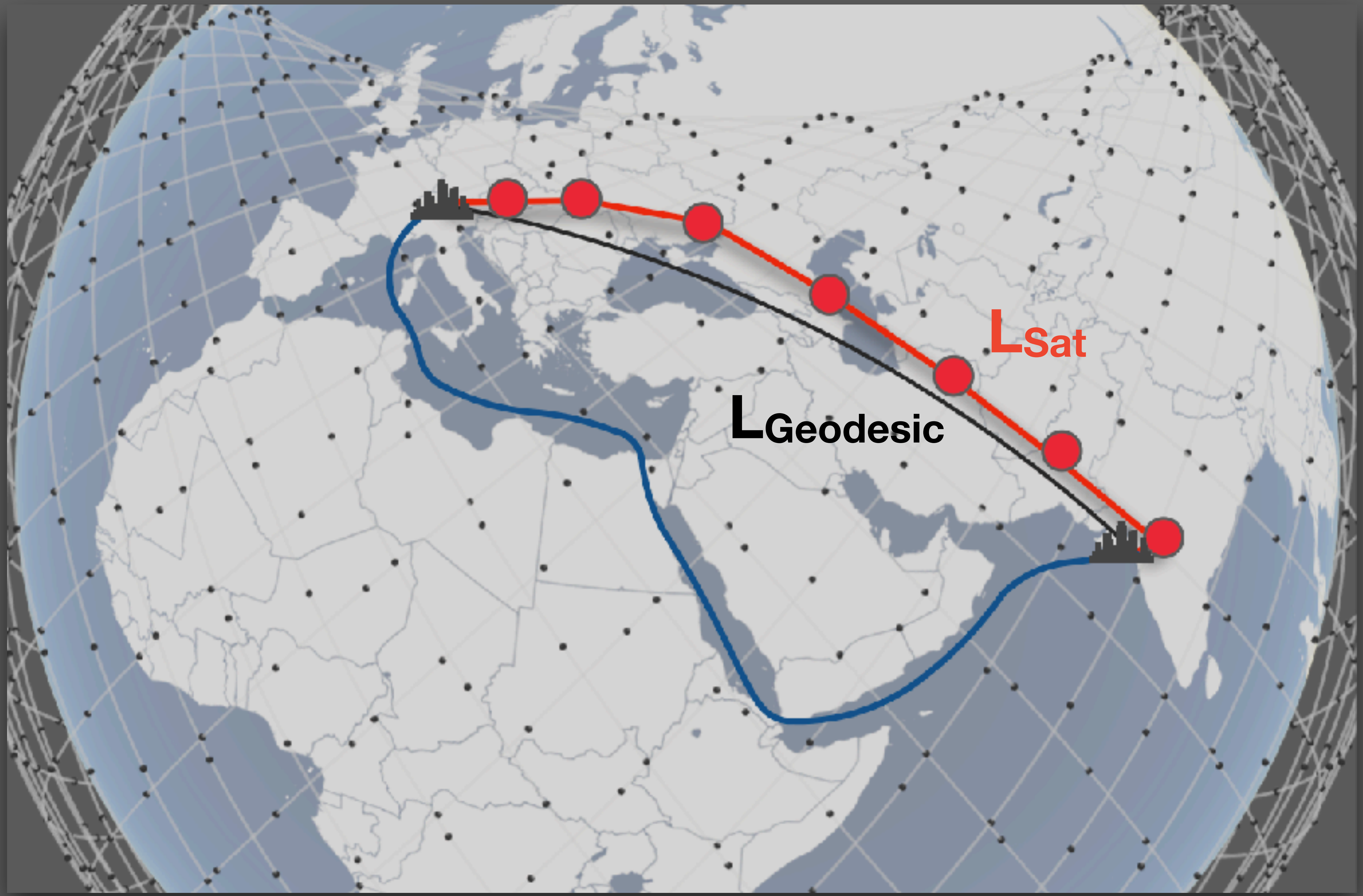
Traffic matrix



Traffic ∝ ~~Population~~ product

GDP

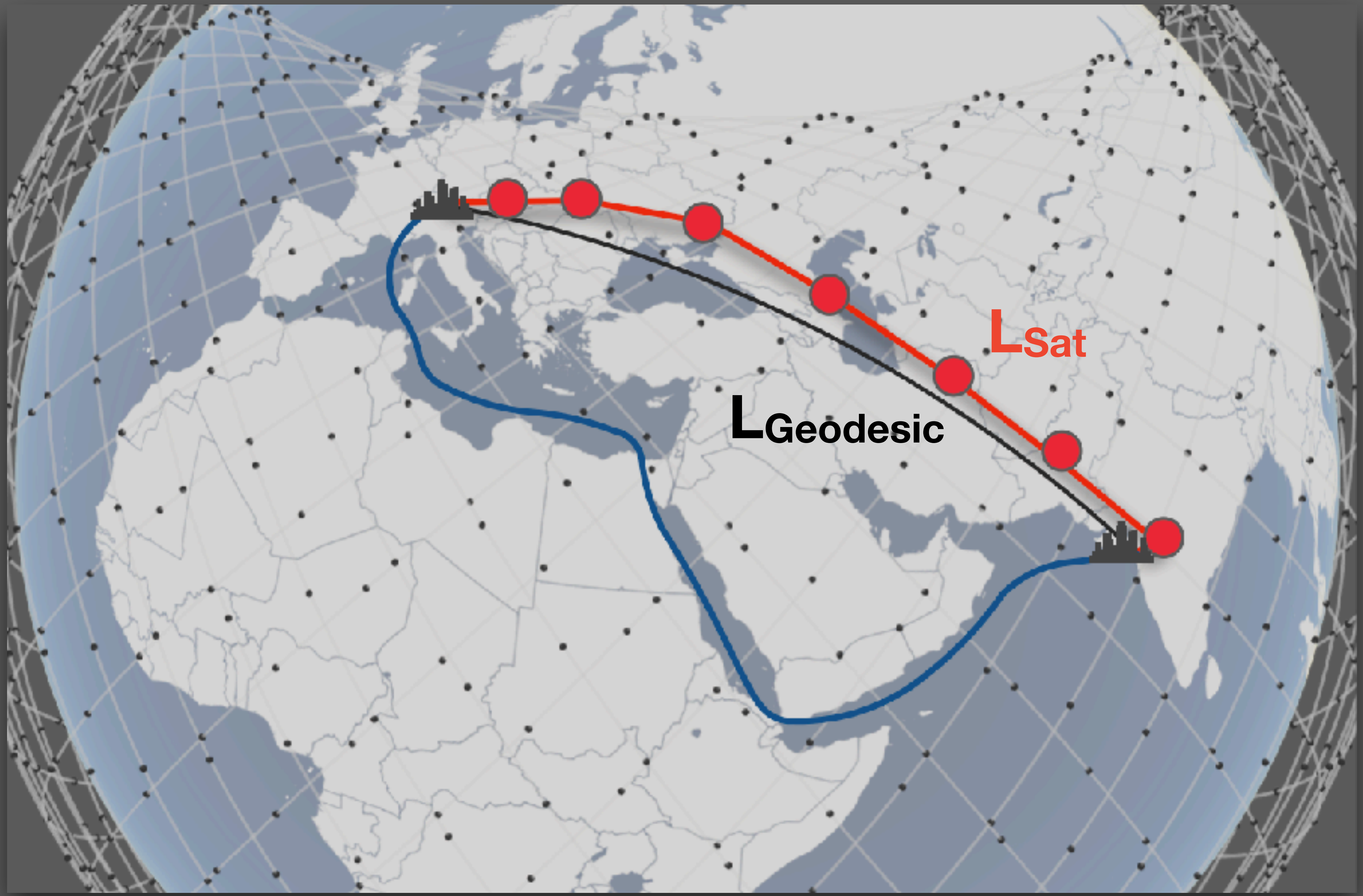
Metrics



$$\text{Stretch} = \frac{L_{Sat}}{L_{Geodesic}}$$

Hop count

Metrics



$$\text{Stretch} = \frac{L_{Sat}}{L_{Geodesic}}$$

Hop count

$$M = \alpha\ \text{Stretch} + \text{Hop count}$$

Why aren’t obvious / traditional methods enough?

Why not use Integer programming?

Why not use Integer programming?

For 1000 cities, would take $\sim 10^{29}$ days

Why not use Integer programming?

For 1000 cities, would take ~10^{29} days

One minute apart ~91% links are different

Why not use random graphs?

Why not use random graphs?

In 5 mins, 19% of links become infeasible

Why not use random graphs?

In 5 mins, 19% of links become infeasible

Cannot optimize for arbitrary objectives

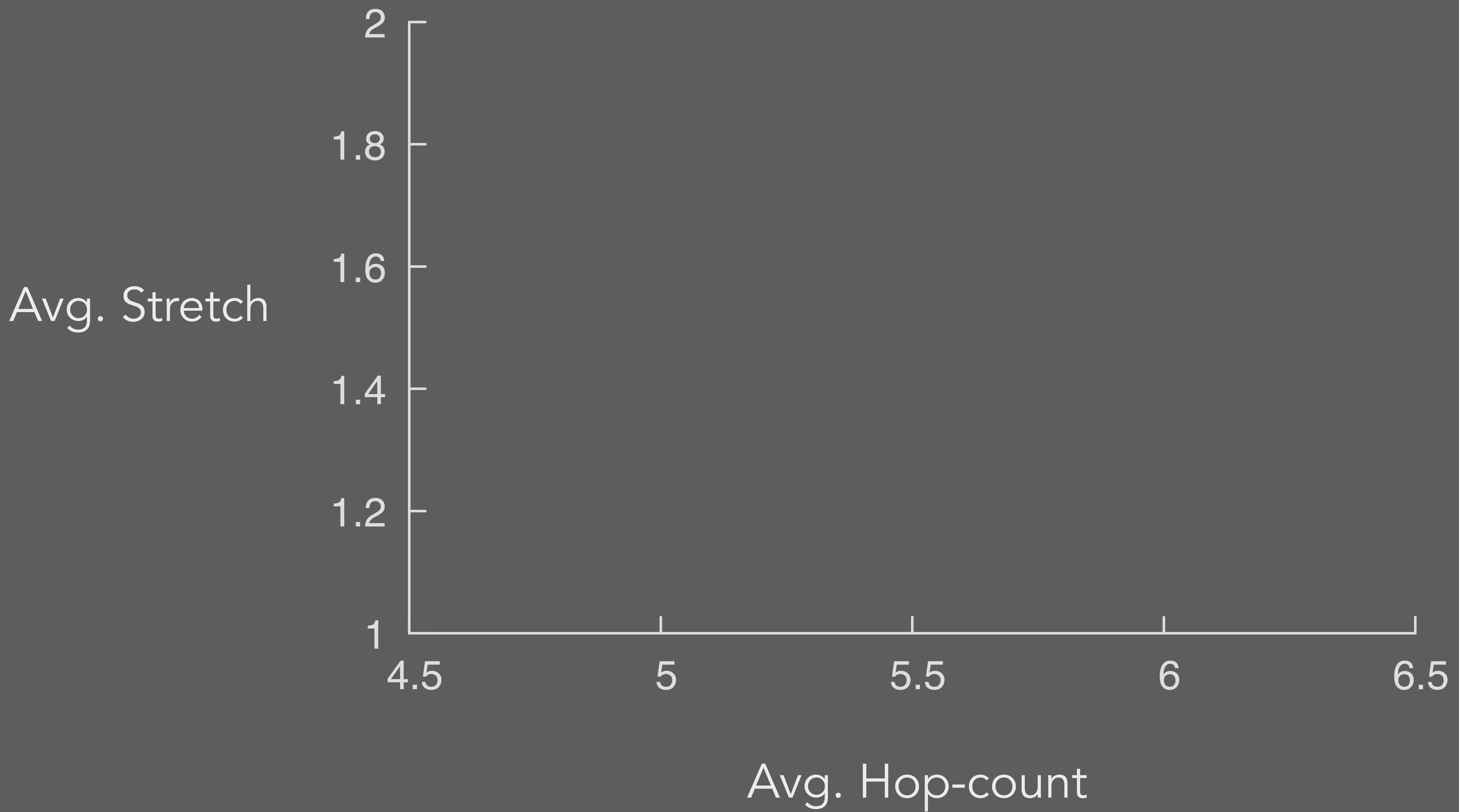
Our approach


pexels.com

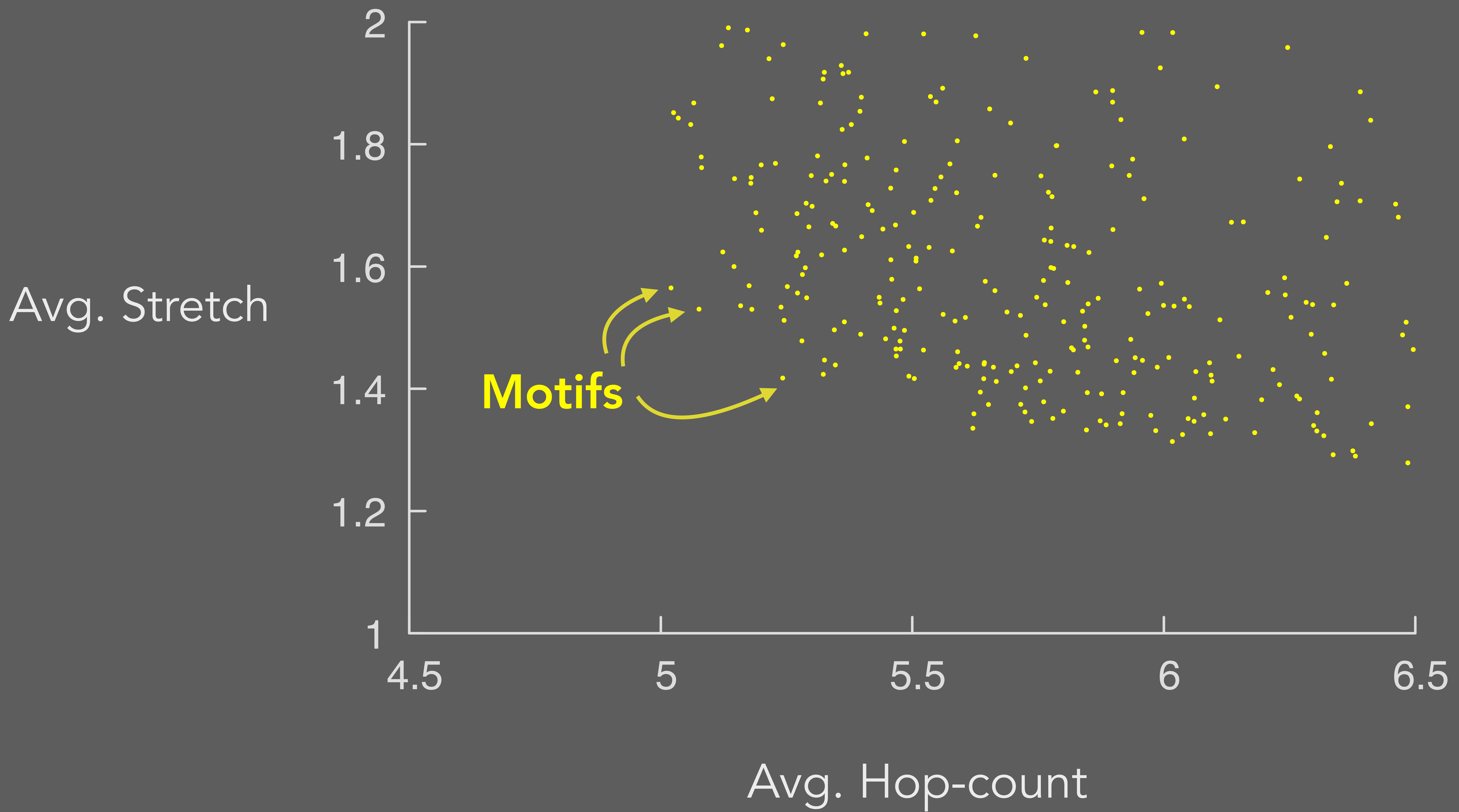
Constellations explored

- Uniform 40x40 (40^2) 53° inclination, 550 km altitude
- SpaceX **Starlink** Phase 1 (24x66, 53°, 550 km) [Configuration changed recently]
- Amazon **Kuiper** Phase 1 (34^2, 51.9°, 630 km)

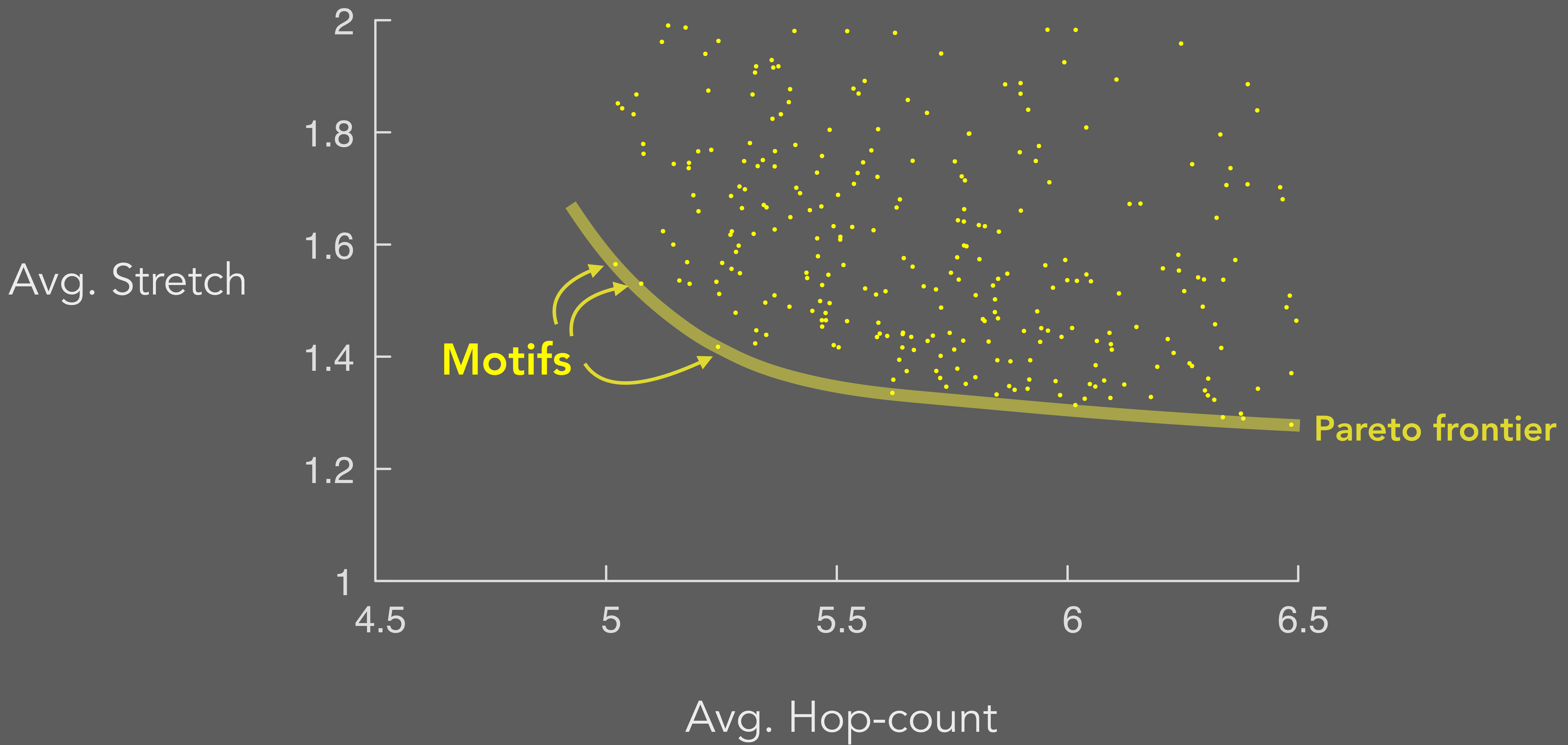
A large number of design points



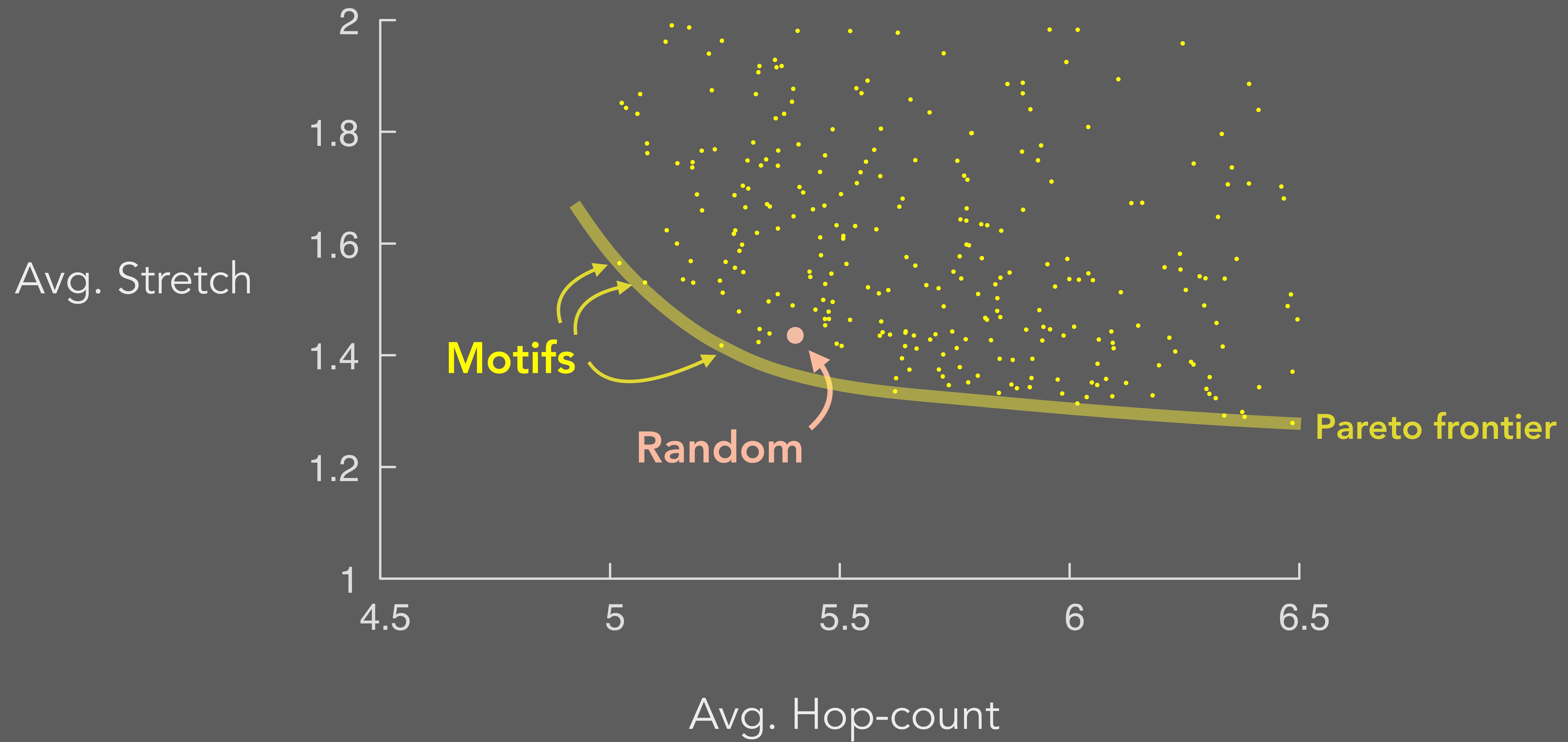
A large number of design points



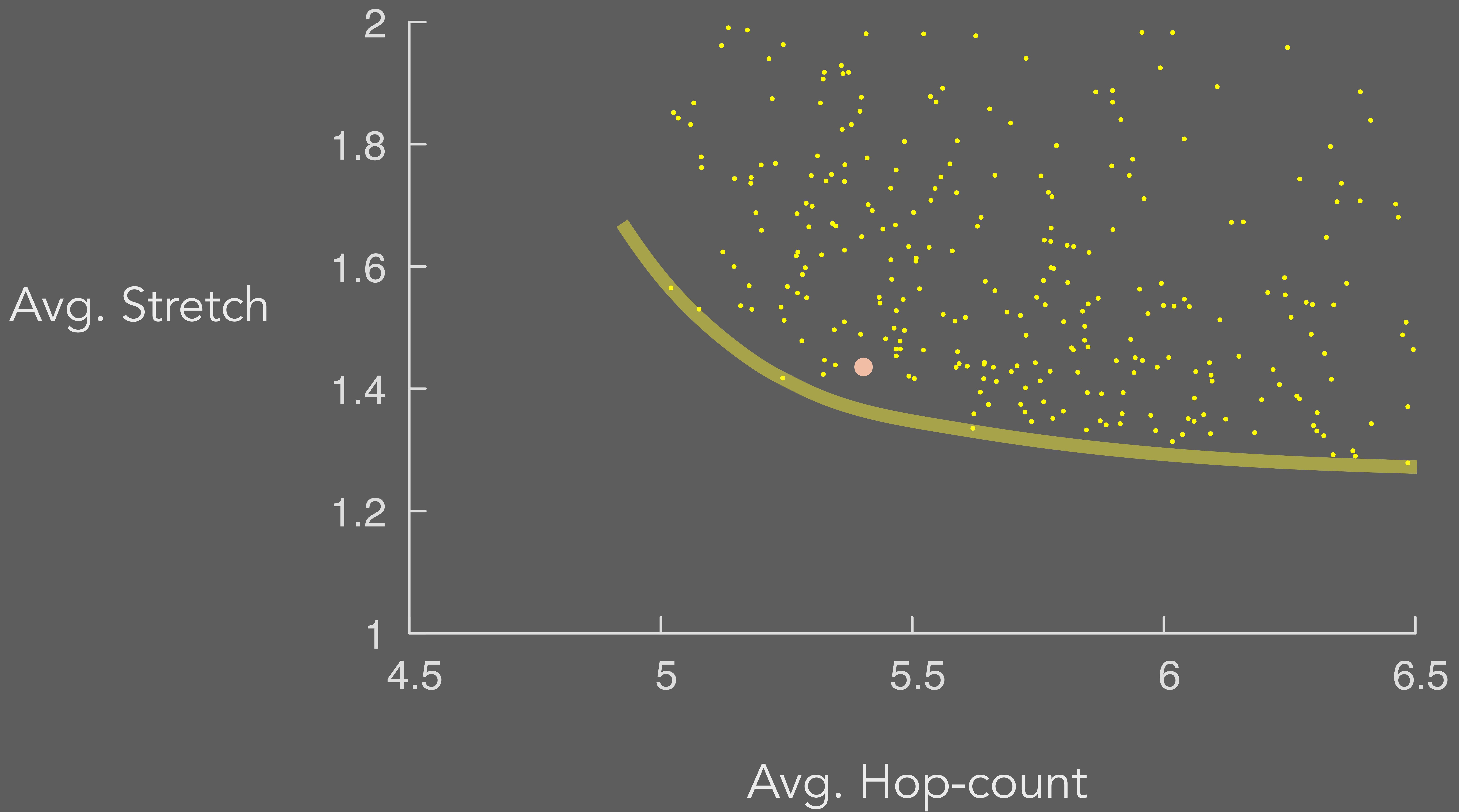
A large number of design points



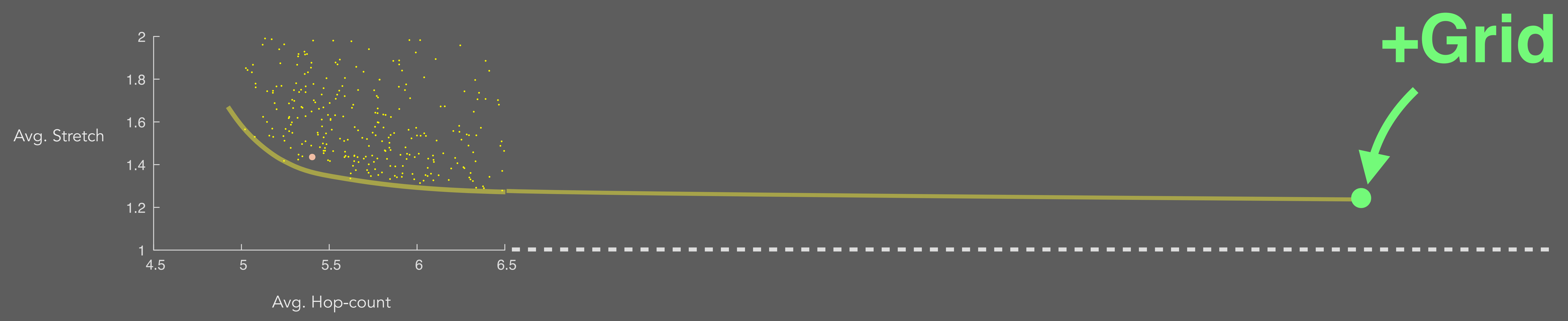
A large number of design points

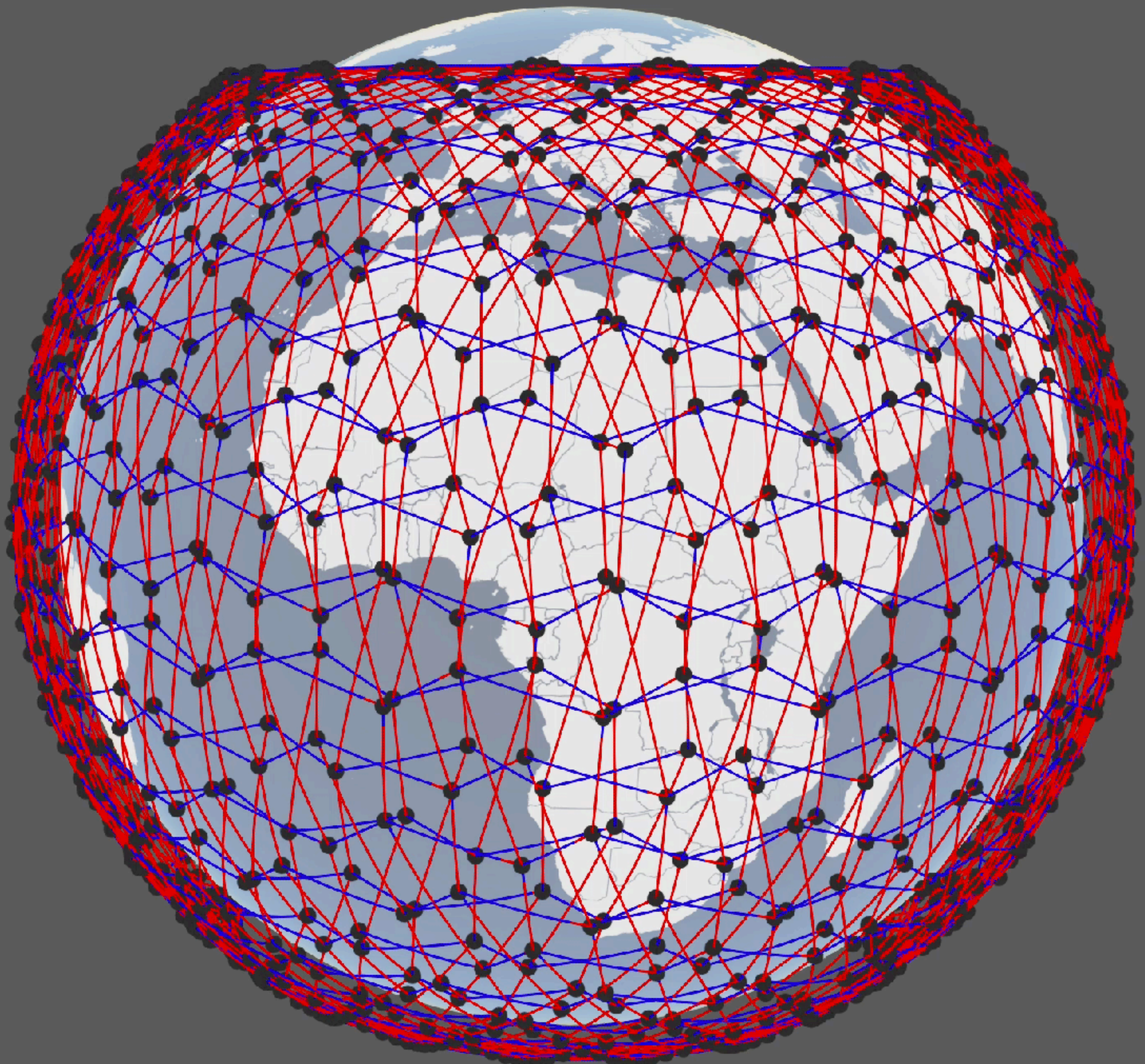


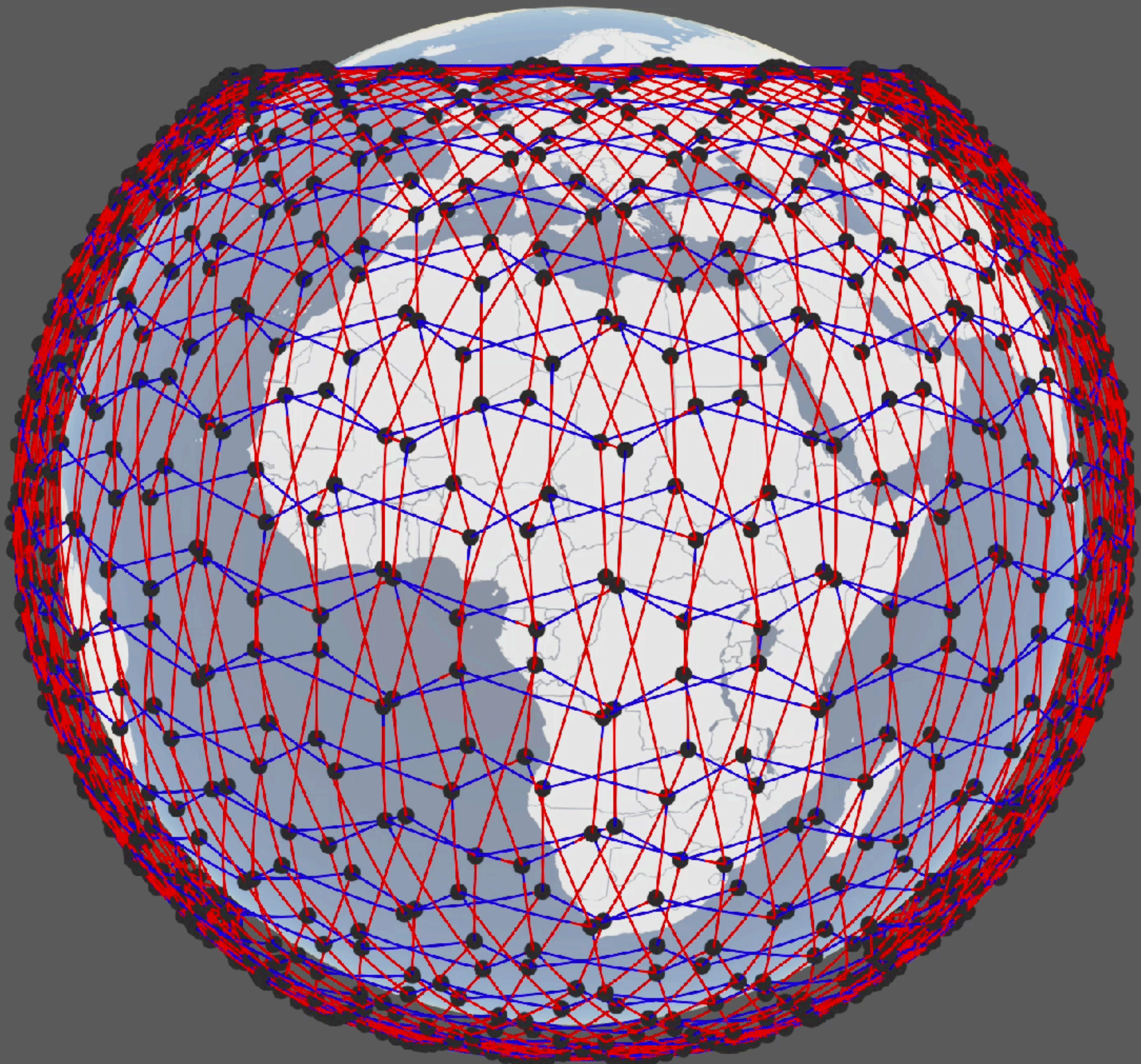
+Grid is a low-efficiency motif

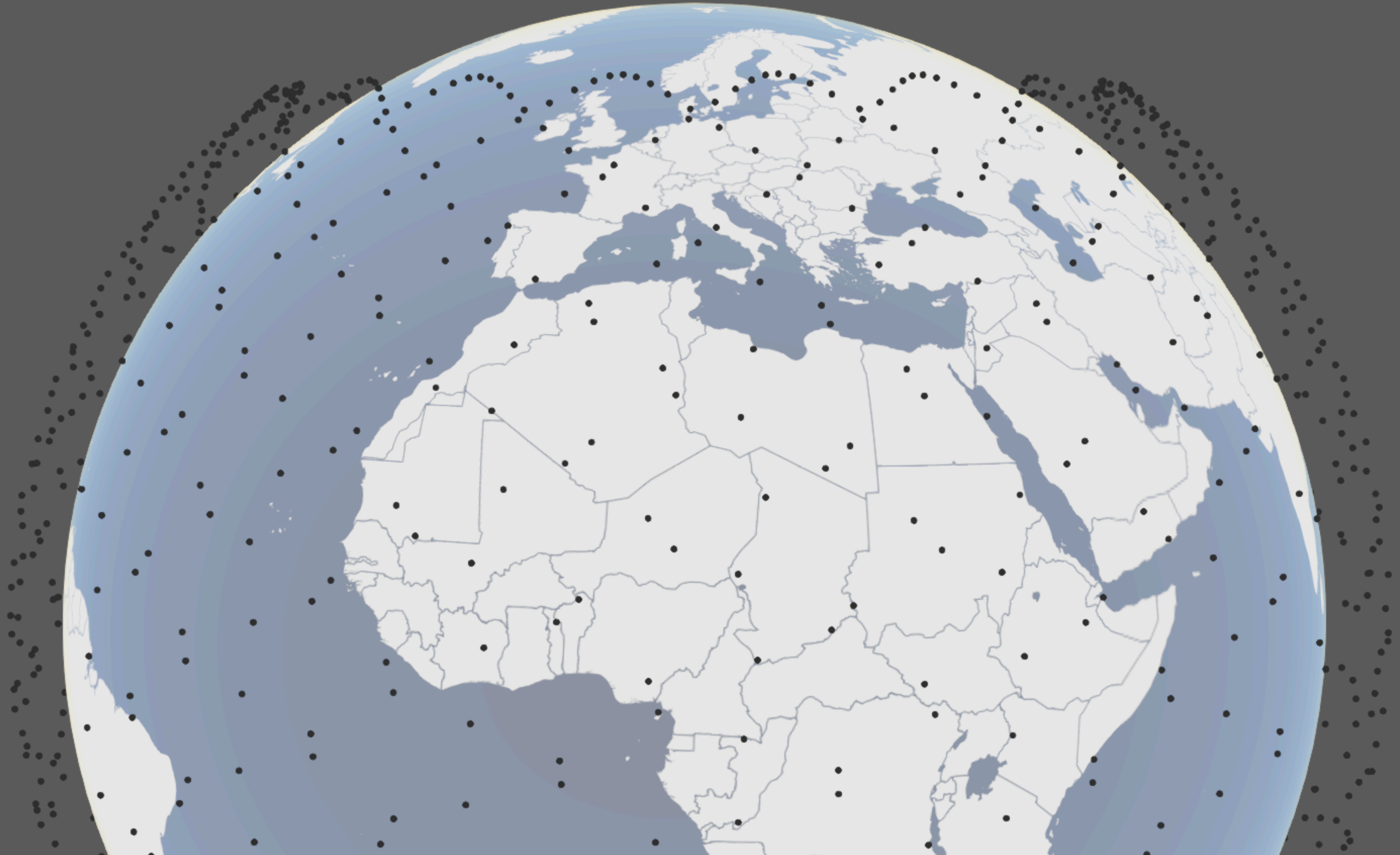


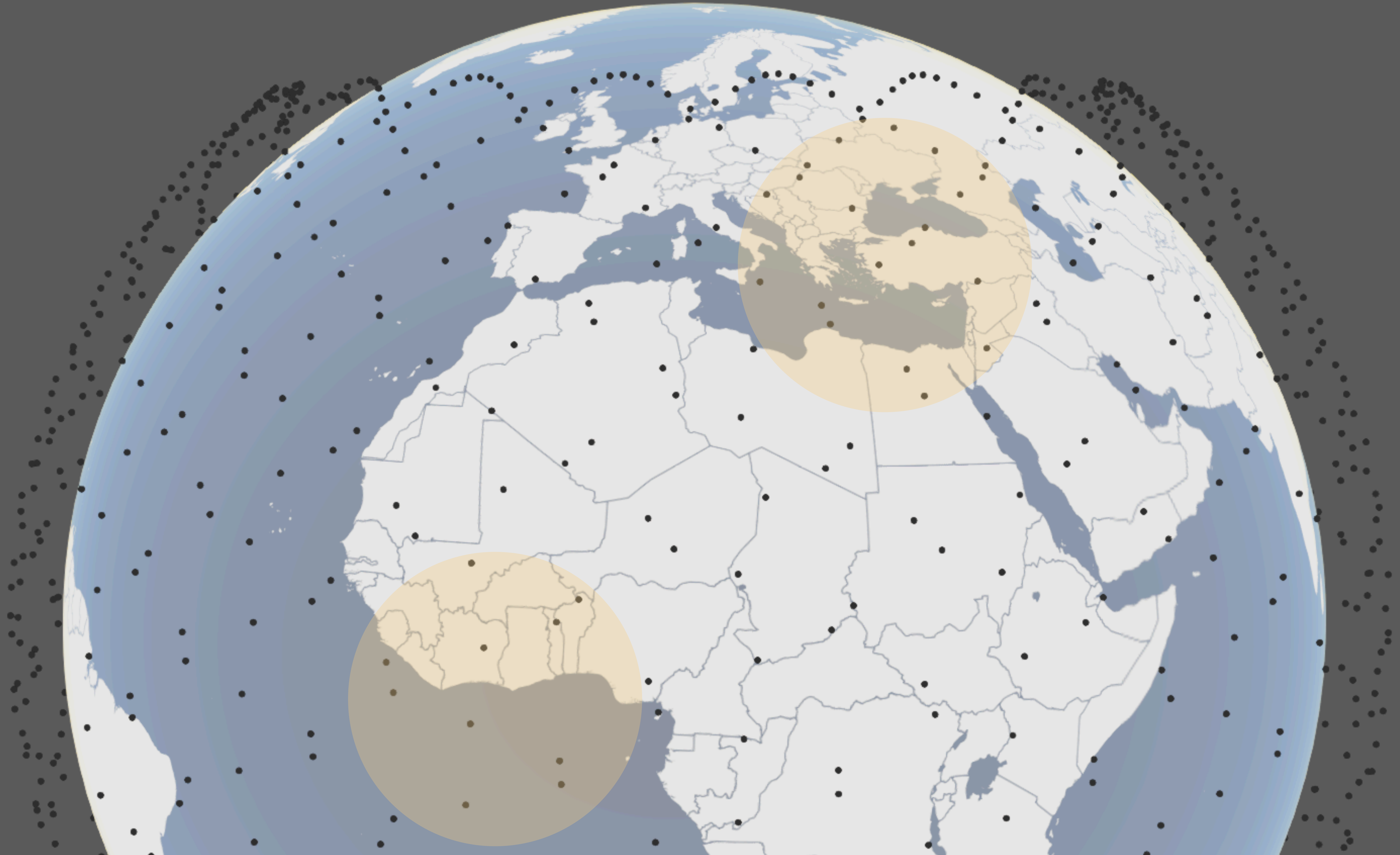
+Grid is a low-efficiency motif



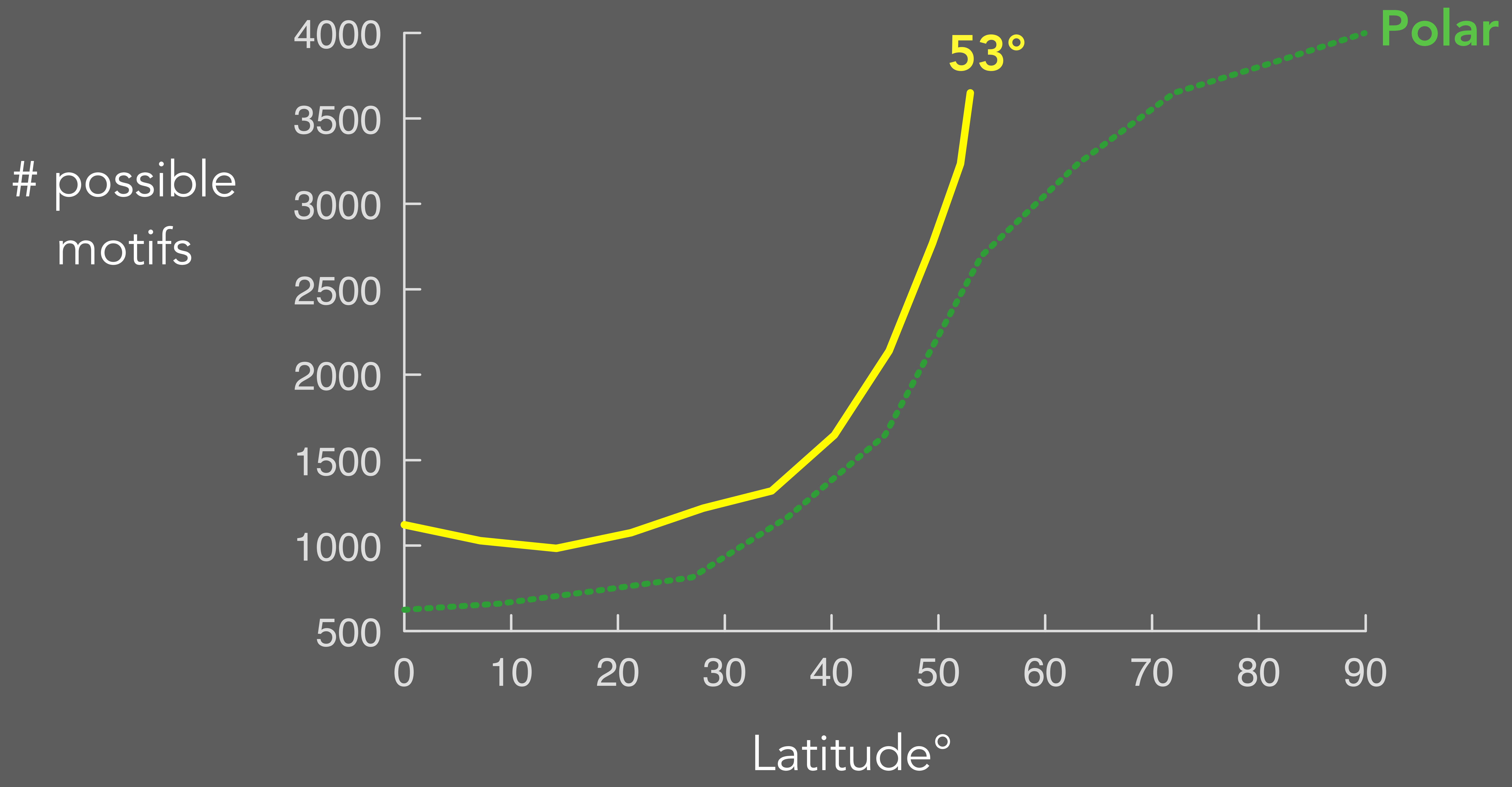


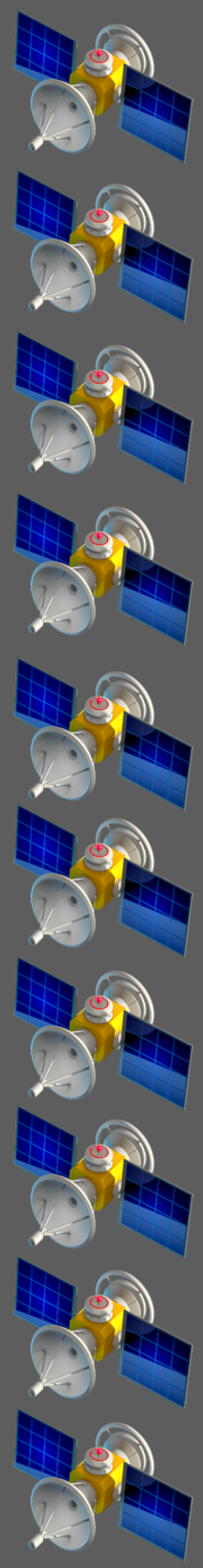


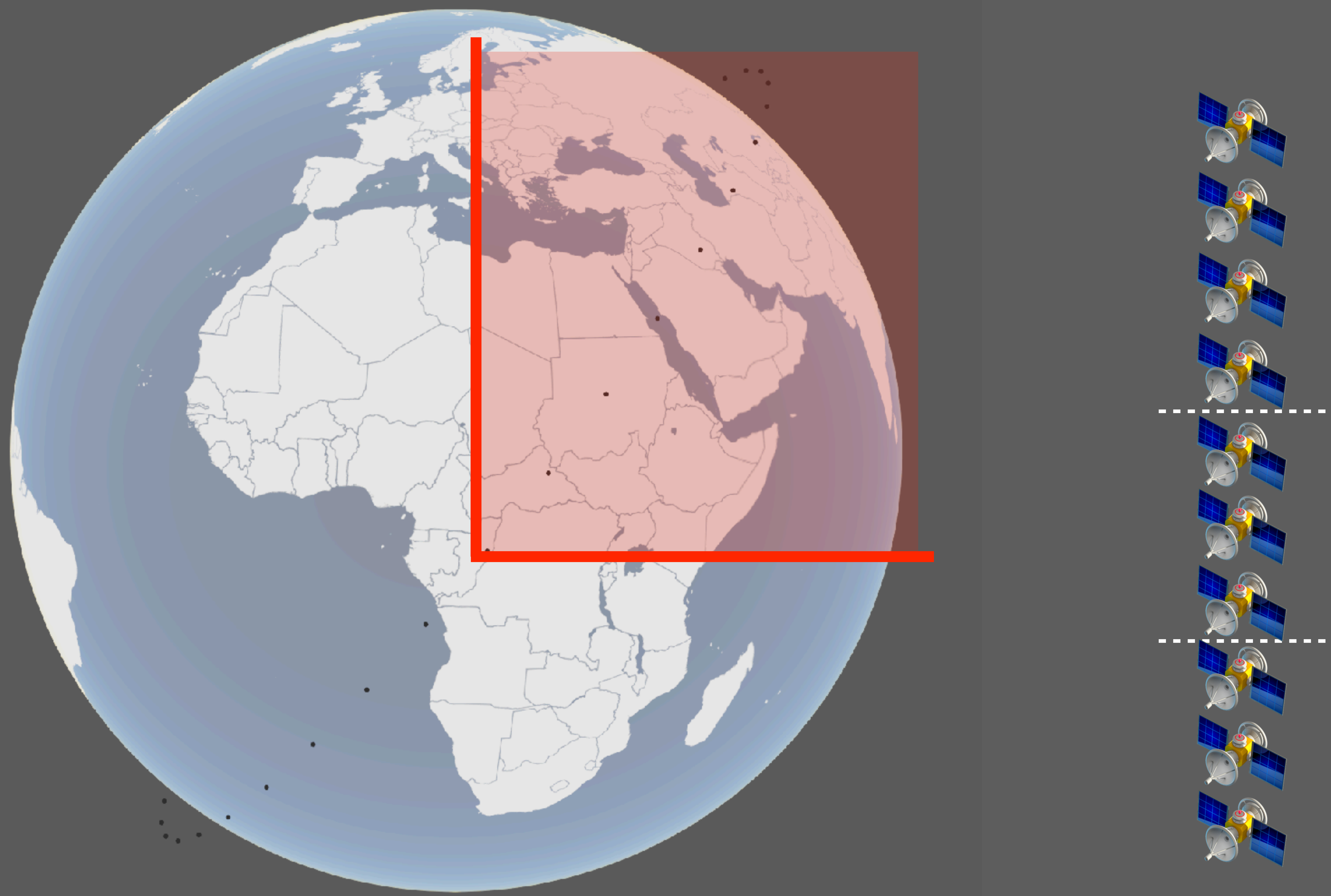


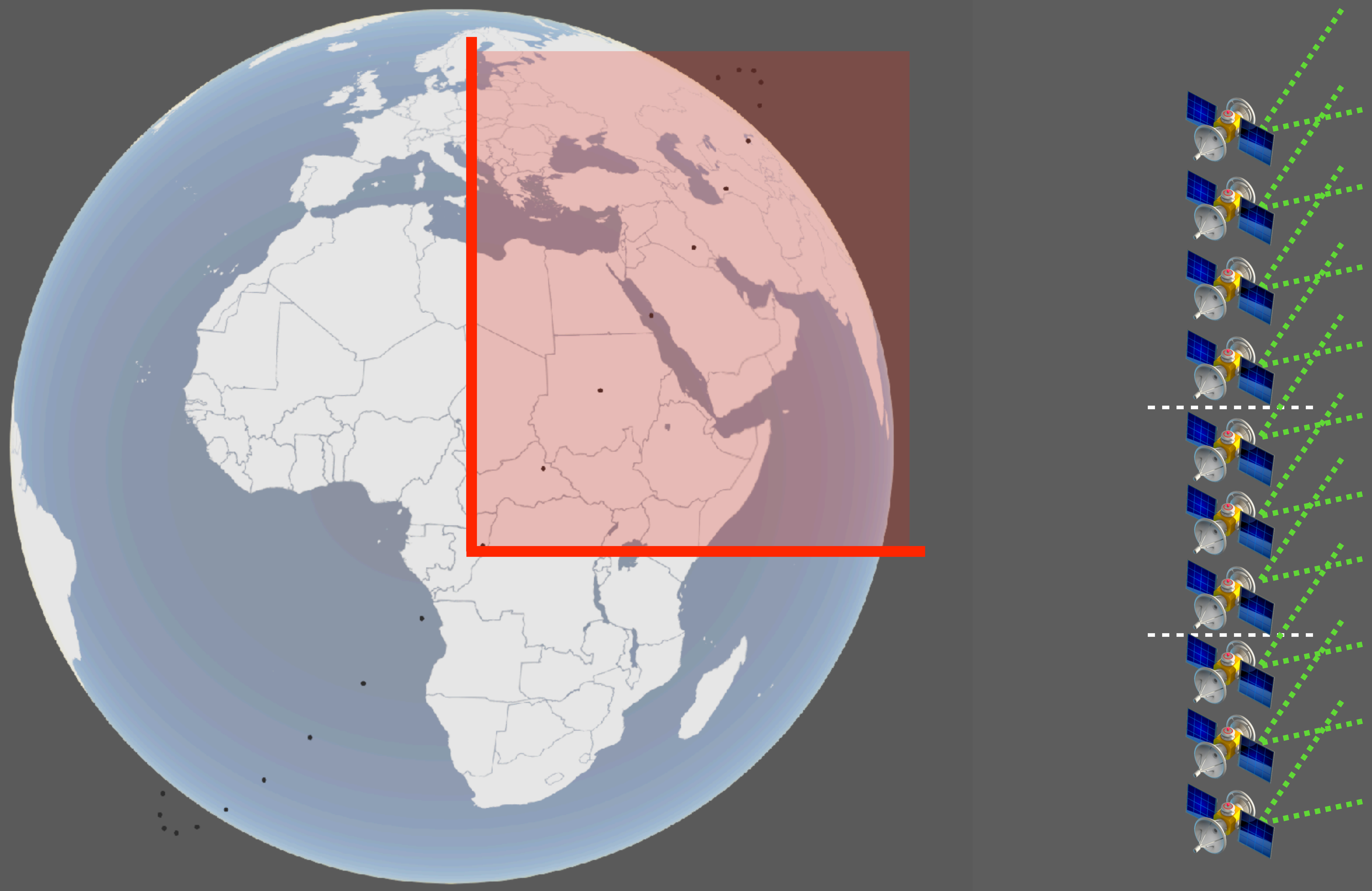


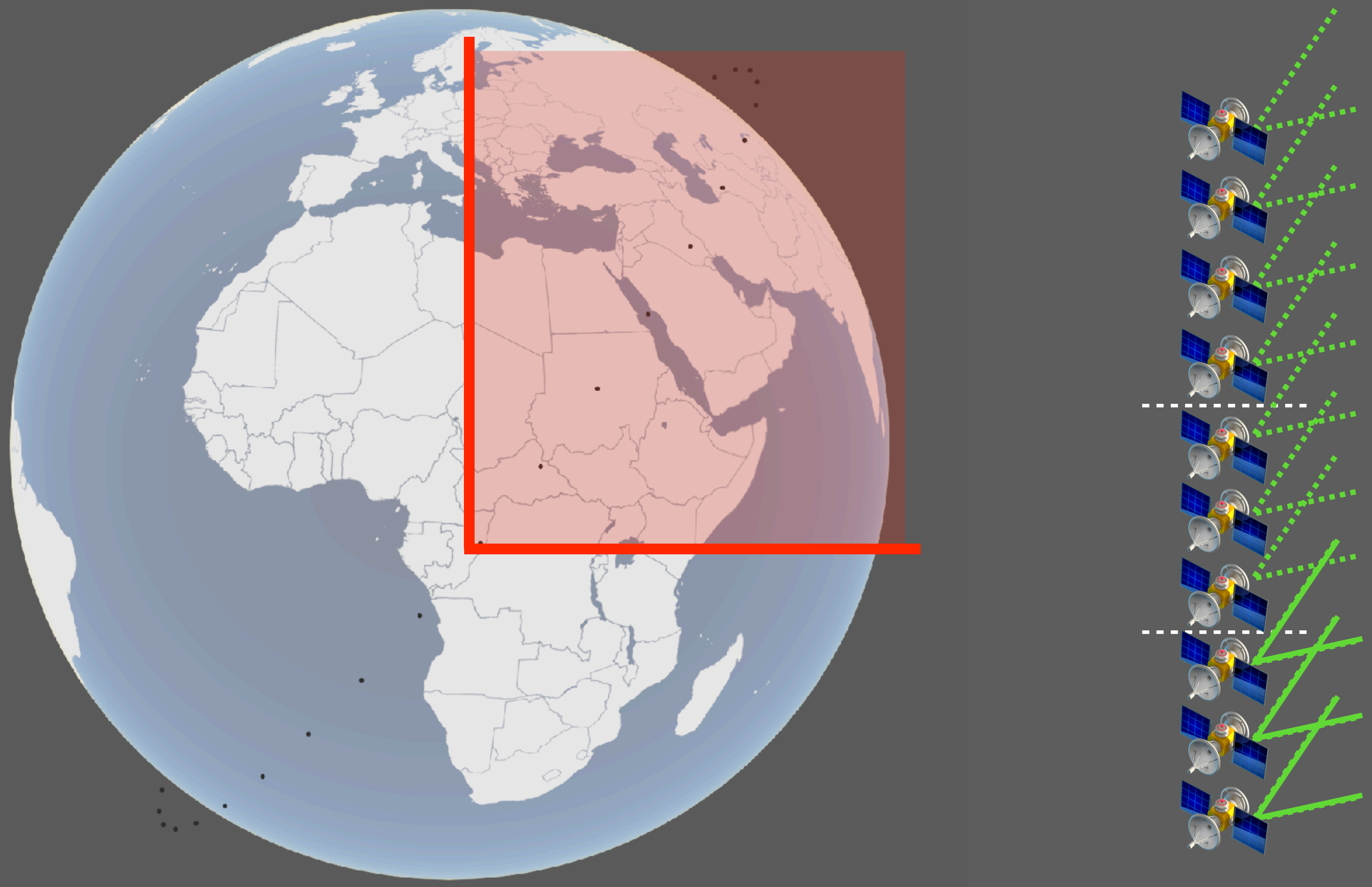
More options at higher latitudes

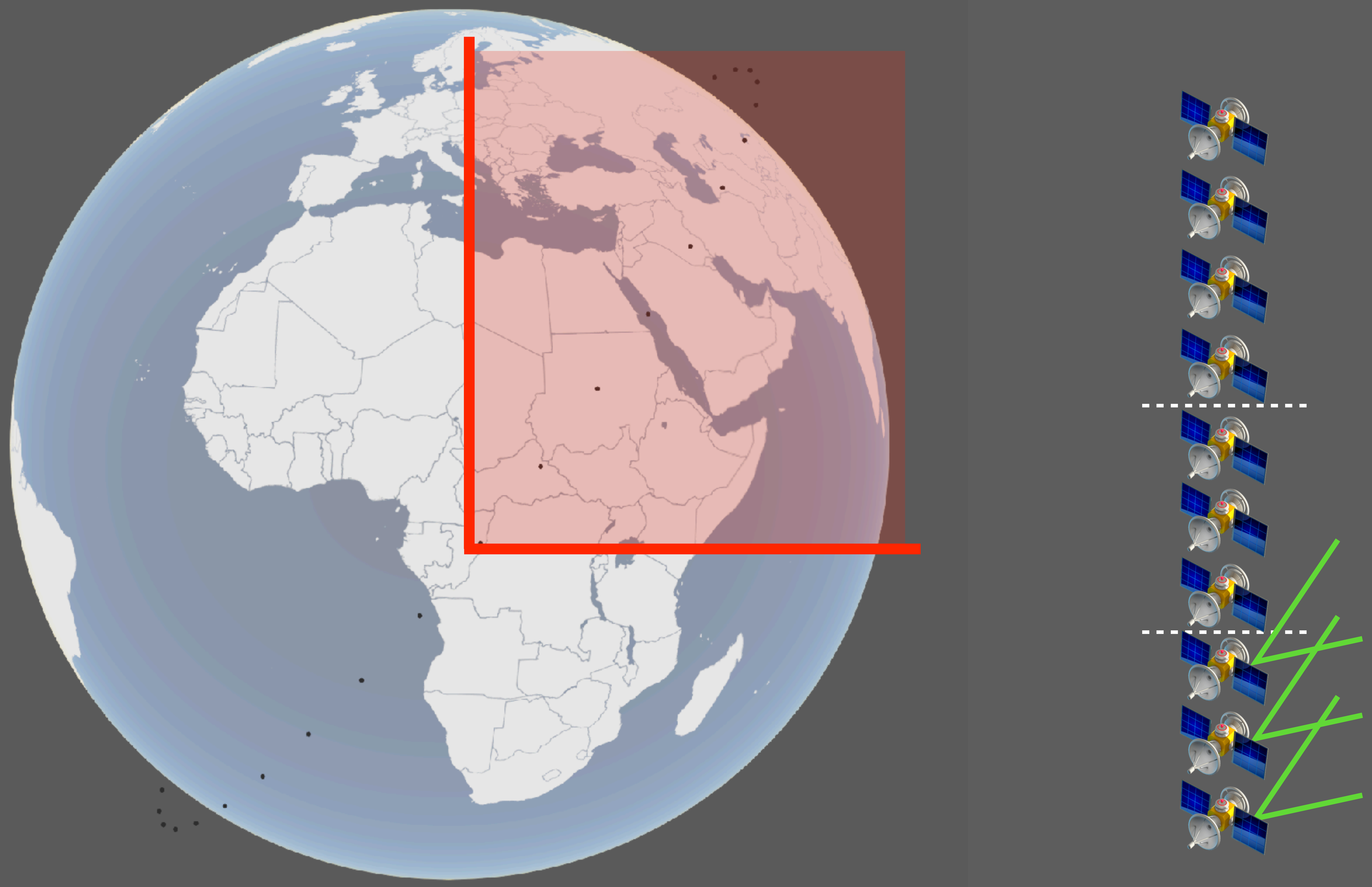


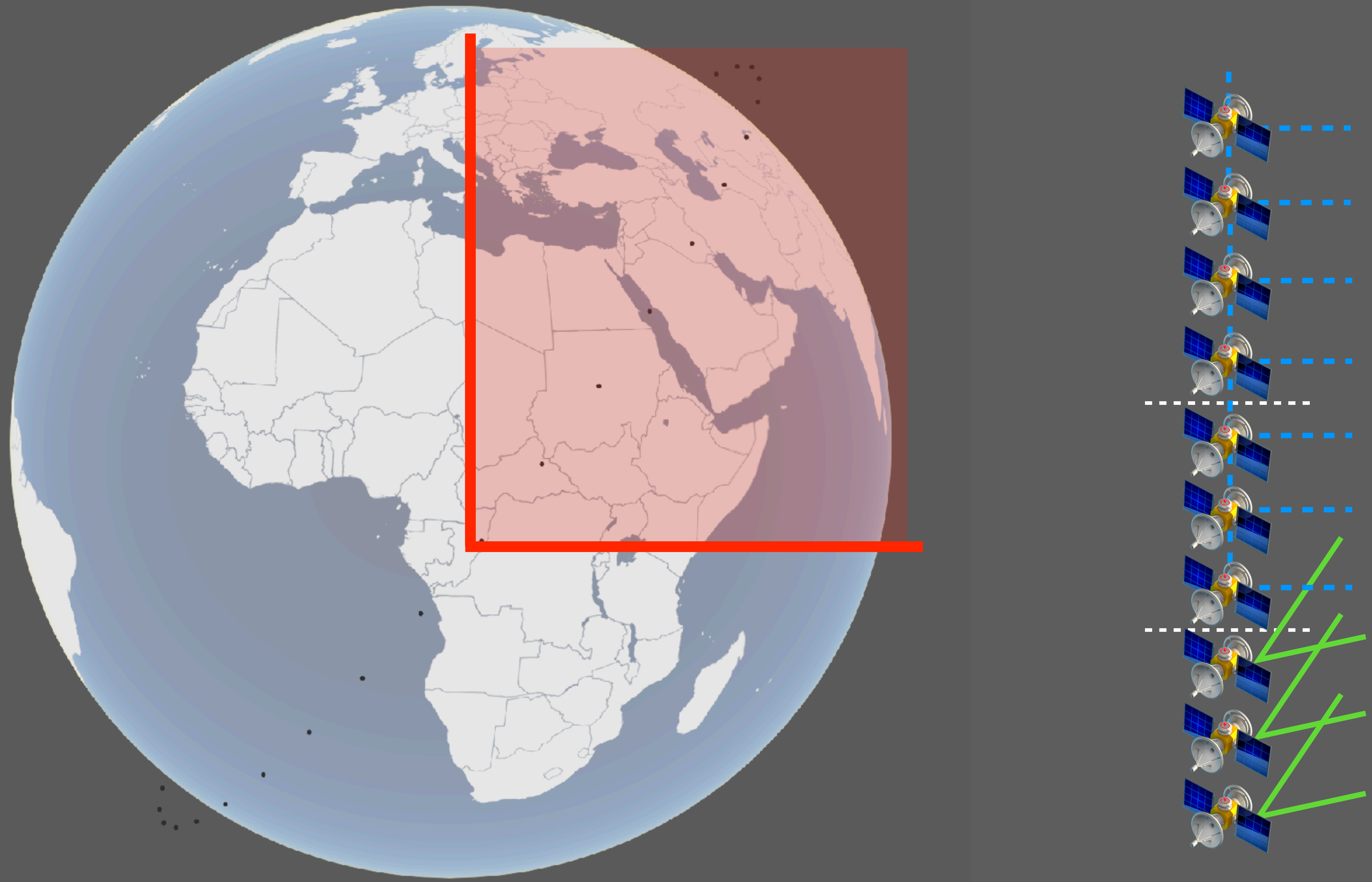



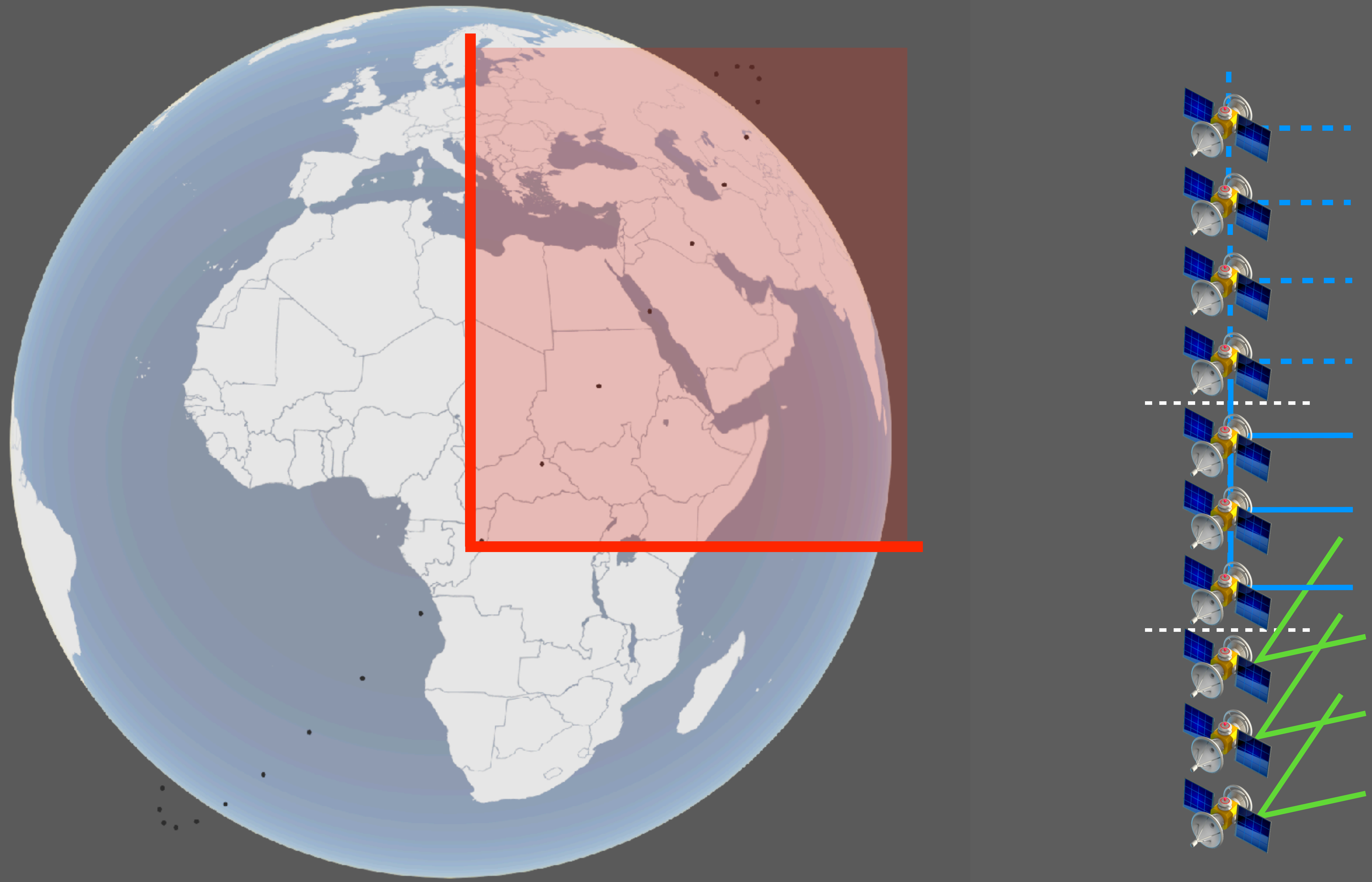


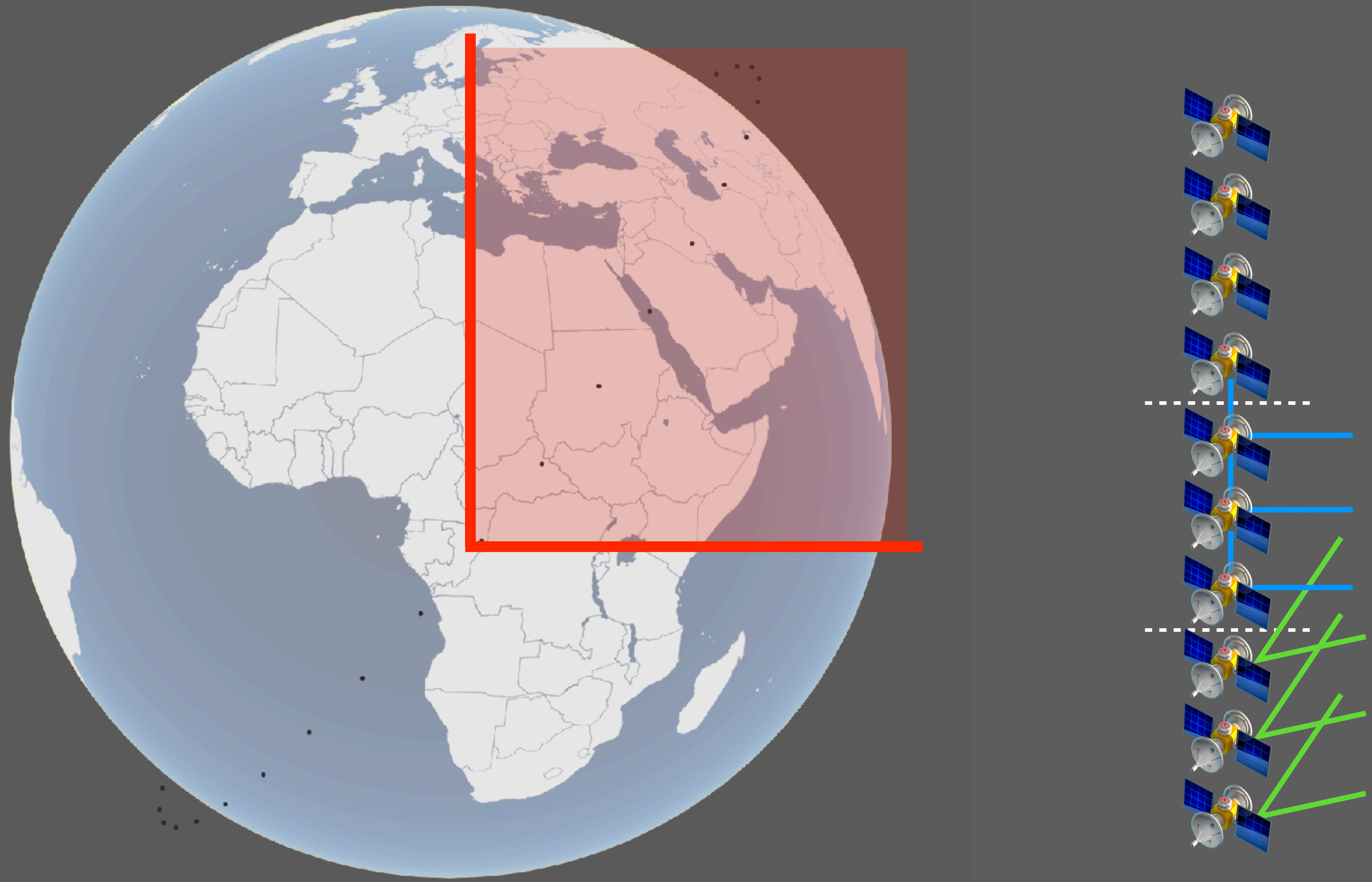


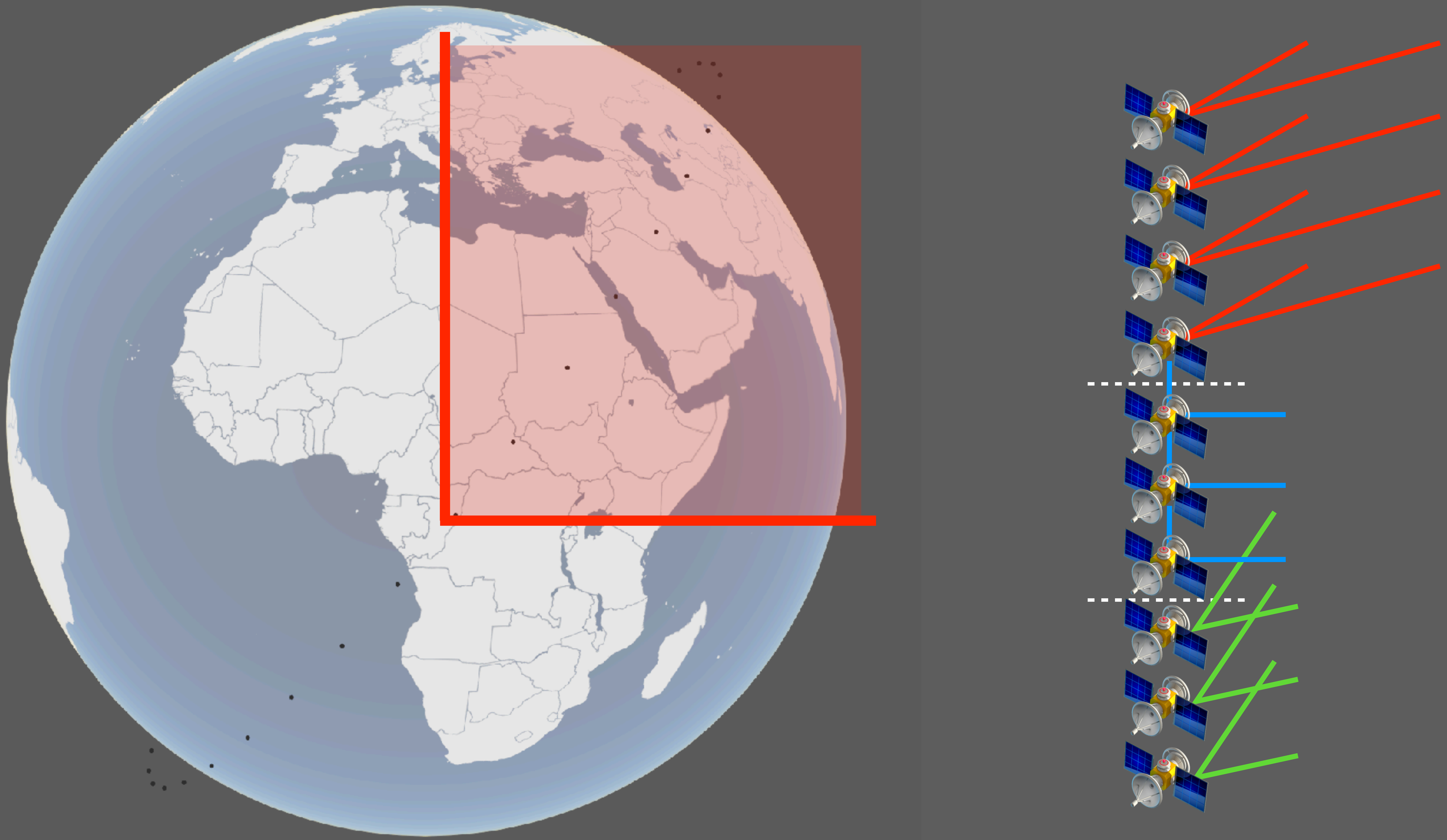


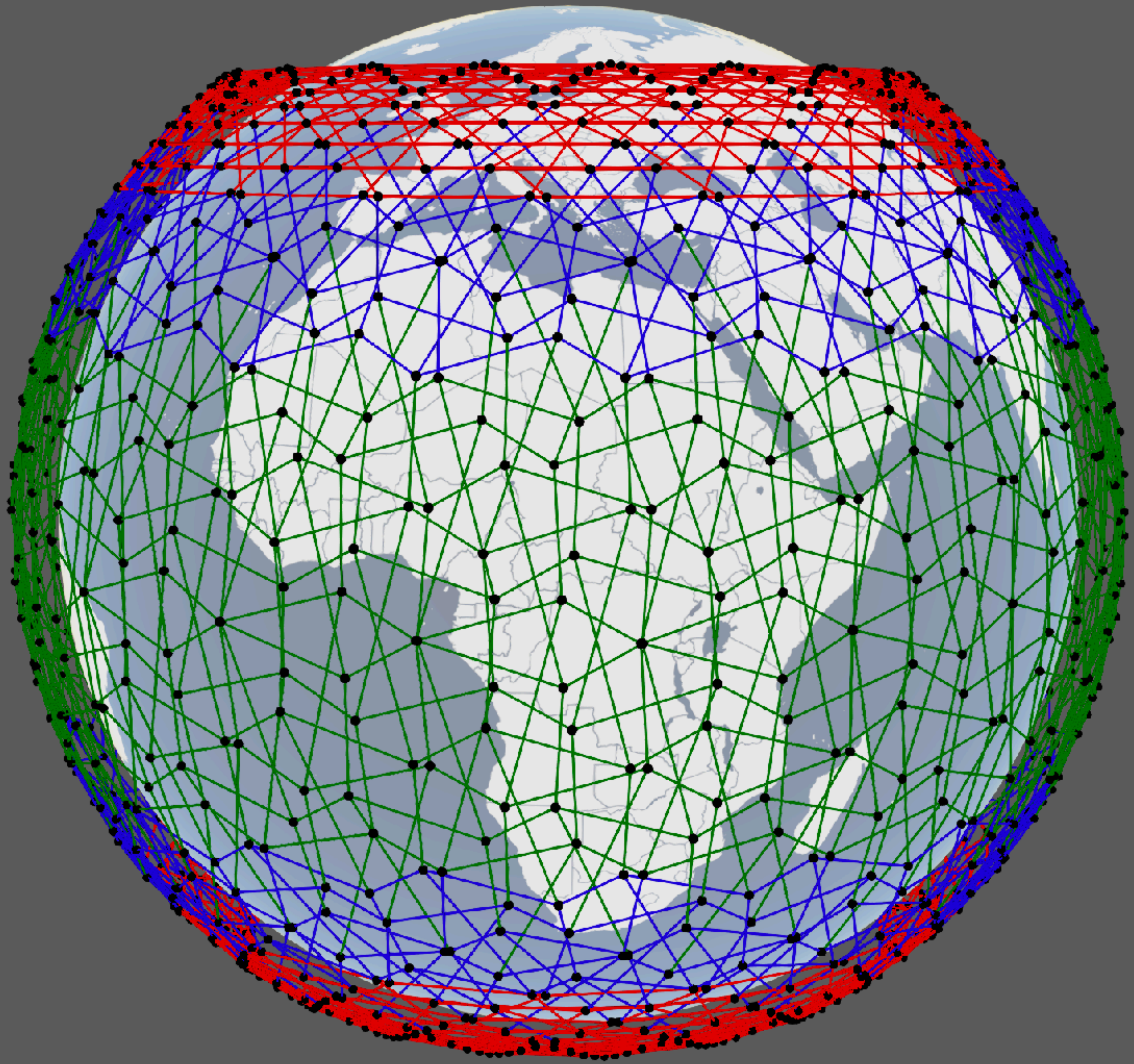




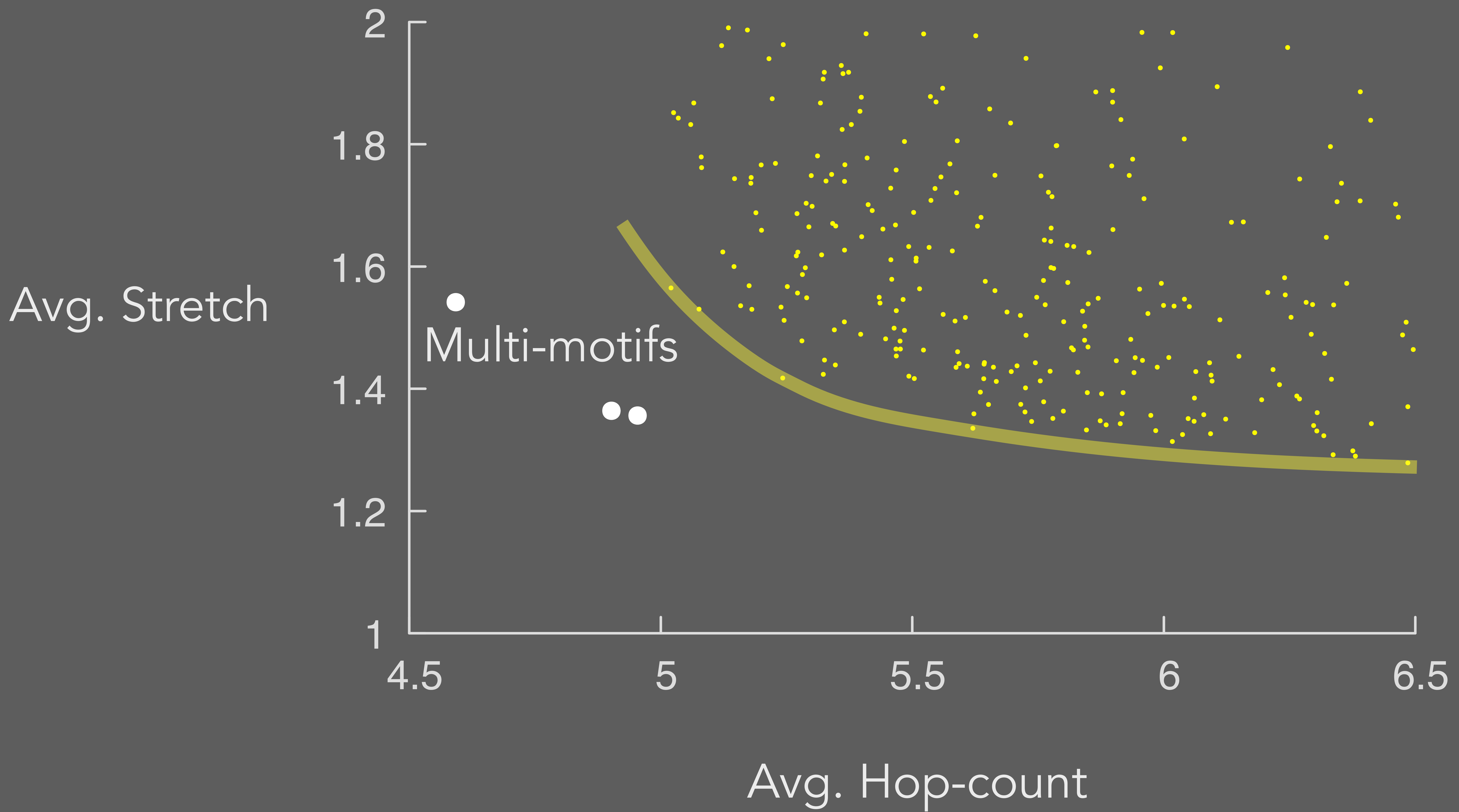




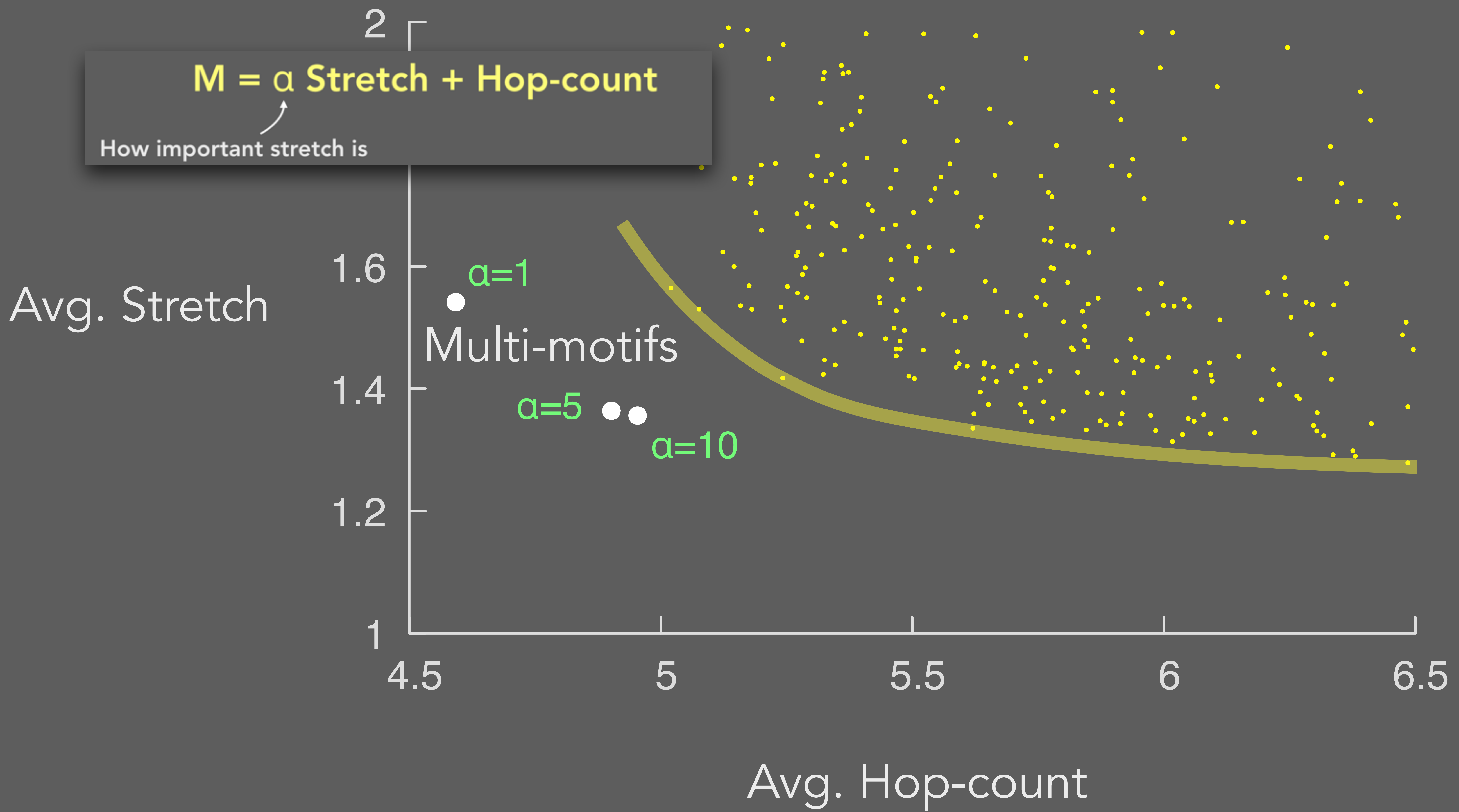




Beyond single motif frontier



Beyond single motif frontier



Performance improvements

Starlink	54%
Kuiper	45%
40^2	48%

Performance improvements

		Severely power-limited links
Starlink	54%	40%
Kuiper	45%	4%
40^2	48%	7%

Baking in our lab

Baking in our lab 

- Trajectory Design

Baking in our lab

- **Trajectory Design**
  - Multi-dimensional

Baking in our lab

- **Trajectory Design**
  - Multi-dimensional
- **Routing & Congestion Control**

Baking in our lab

- **Trajectory Design**
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- **Routing & Congestion Control**
- **Simulators**

Baking in our lab 

- **Trajectory Design**
  - Multi-dimensional
- **Routing & Congestion Control**
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  - Packet-level

Baking in our lab

- **Trajectory Design**
  - Multi-dimensional
- **Routing & Congestion Control**
- **Simulators**
  - Packet-level
  - Flow-level