Computer Architecture In Space: Computational Nanosatellite Constellations

Brandon Lucia, Professor, Carnegie Mellon University ECE
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Carnegie Mellon University

CMU's NSF CPS Frontiers Center on Software-Defined Nanosatellite Constellations

Goals of our Center on Software-defined Nanosatellite Constellations

Satellite Autonomy:

Sensing, ML, computing, communication, actuation w/o manual human interaction

Satellite Software-definition:

Ability to support many applications on a single constellation with reconfiguration and adaptability

Constellation Efficiency & Scale:

Capability to compute on orbit & communicate efficiently minimizing ground cost & amplifying scale

Space Democratization & Access:

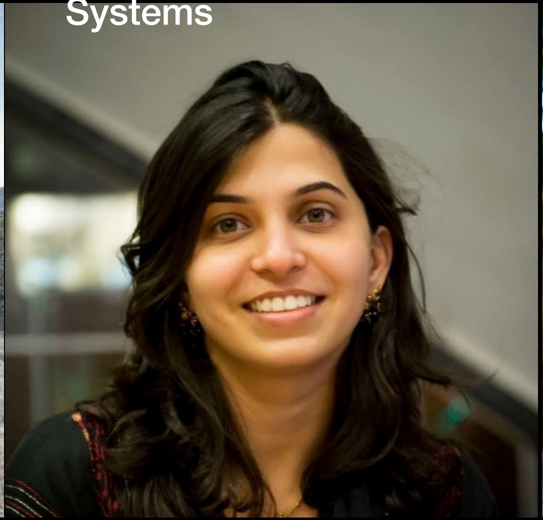
Software definition gives space access to all CPS applications without costly bespoke launch infra.

Highly Inter-disciplinary Computer Systems Expertise to Softwa defined Nanosatellite Constellations

Computer Arch. & systems,
Intermittent Computing

Brandon Lucia, Professor,
Dept. of Elec. & Comp. Eng.

Federated & Distributed
ML Algorithms &
Systems



Gauri Joshi, Asst. Prof.
Dept. of Elec. & Comp. Eng.

Distributed Controls &
Space SW/HW Systems

Zac Manchester, Asst. Prof.
Robotics Institute.

Ultra-low-power wireless
systems & networking

Swarun Kumar, Assoc. Prof.
Dept. of Elec. & Comp. Eng.

Networked distributed
systems & security

Vyas Sekar, Professor
Dept. of Elec. & Comp. Eng.

Egress area unobstructed
Last observed: 5 minutes ago
Risk level: *low*

Unexpected vehicle in fire lane
Duration: 15 minutes
Last observed: seconds ago
Risk level: *medium*
Action: Continuously re-identify object, query event parking authorities

Crowd/field egress unobstructed
Last observed: 5 minutes ago
Risk level: *low*

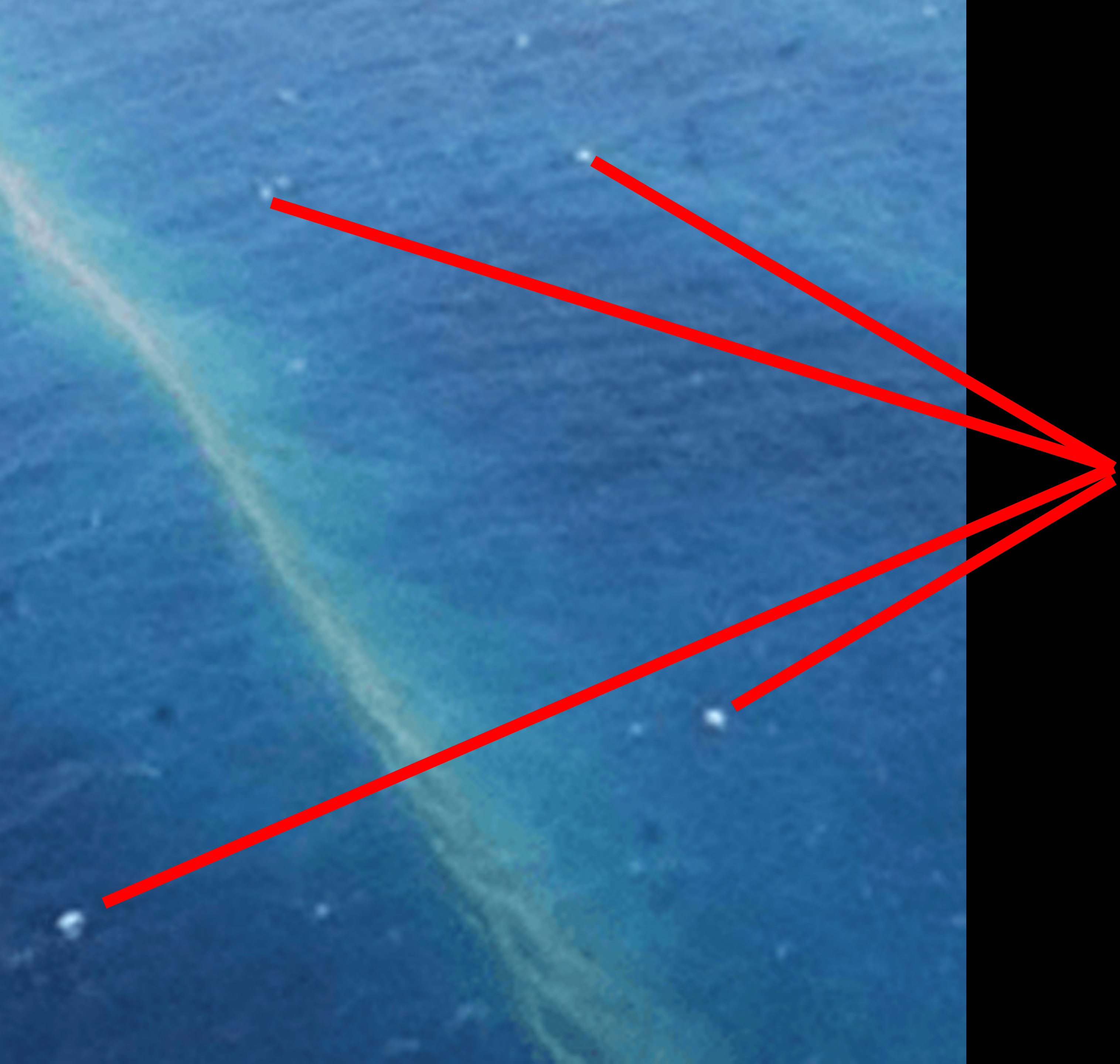
Unidentified object in crowd entry area
Last observed: seconds ago
Risk level: unknown / high
Action: Focus sensing on object, alert authorities

Debris along pipeline
Last observed: 15 minutes ago
Leak risk: medium
Action: Focus sensing on debris area, request heat/IR signature, alert work crew

Pipeline IR Signature Abnormal
Last observed: 15 minutes ago
Leak risk: high
Action: Alert leak mitigation team

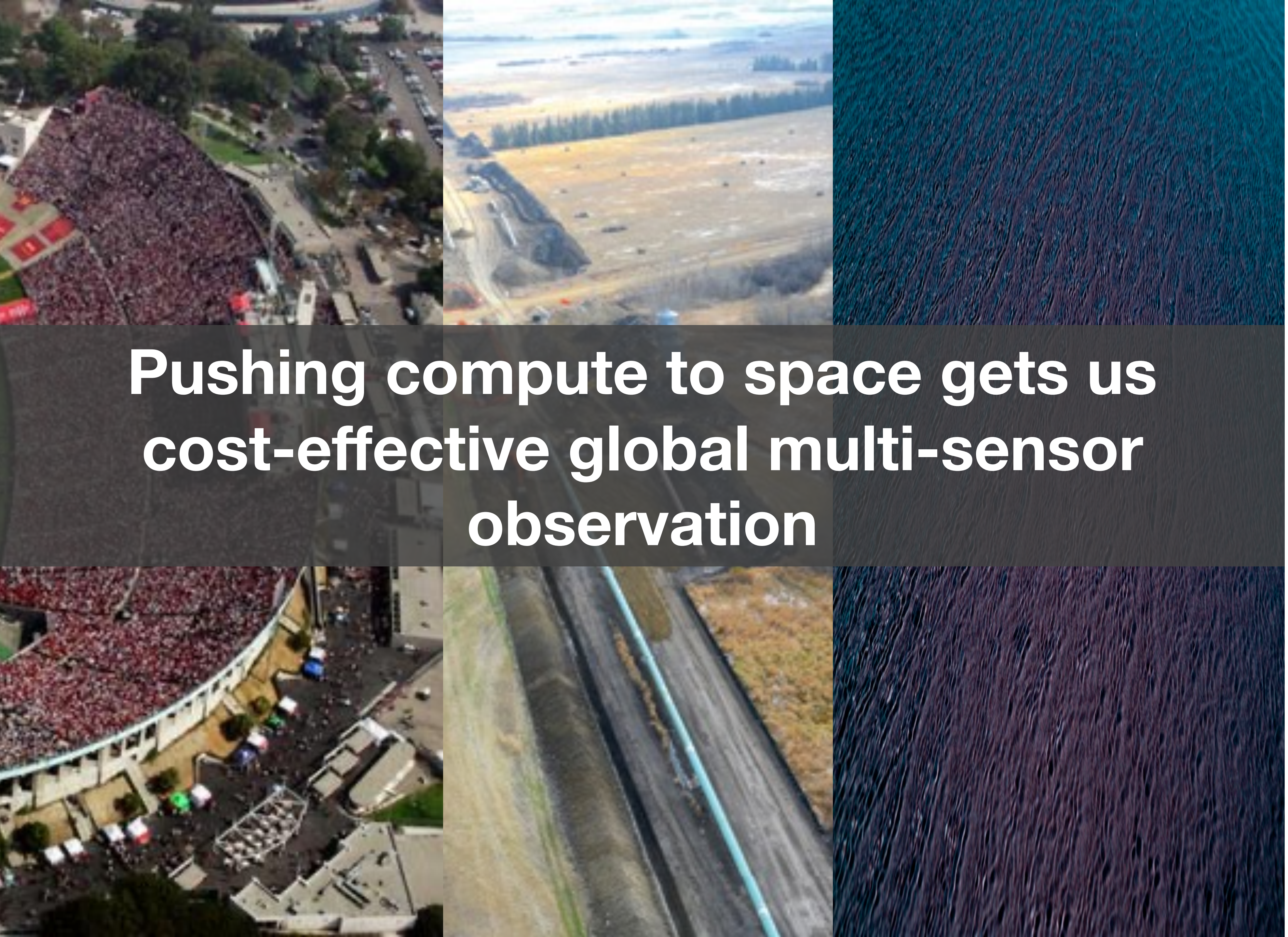
Pothole in driving lane
Last observed: 5 minutes ago
Leak risk: medium
Action: Focus sensing, compute depth & moisture map of surrounding area

Safely Driving Car
Last observed: 5 minutes ago
Speed: 45mph, Heading: stable



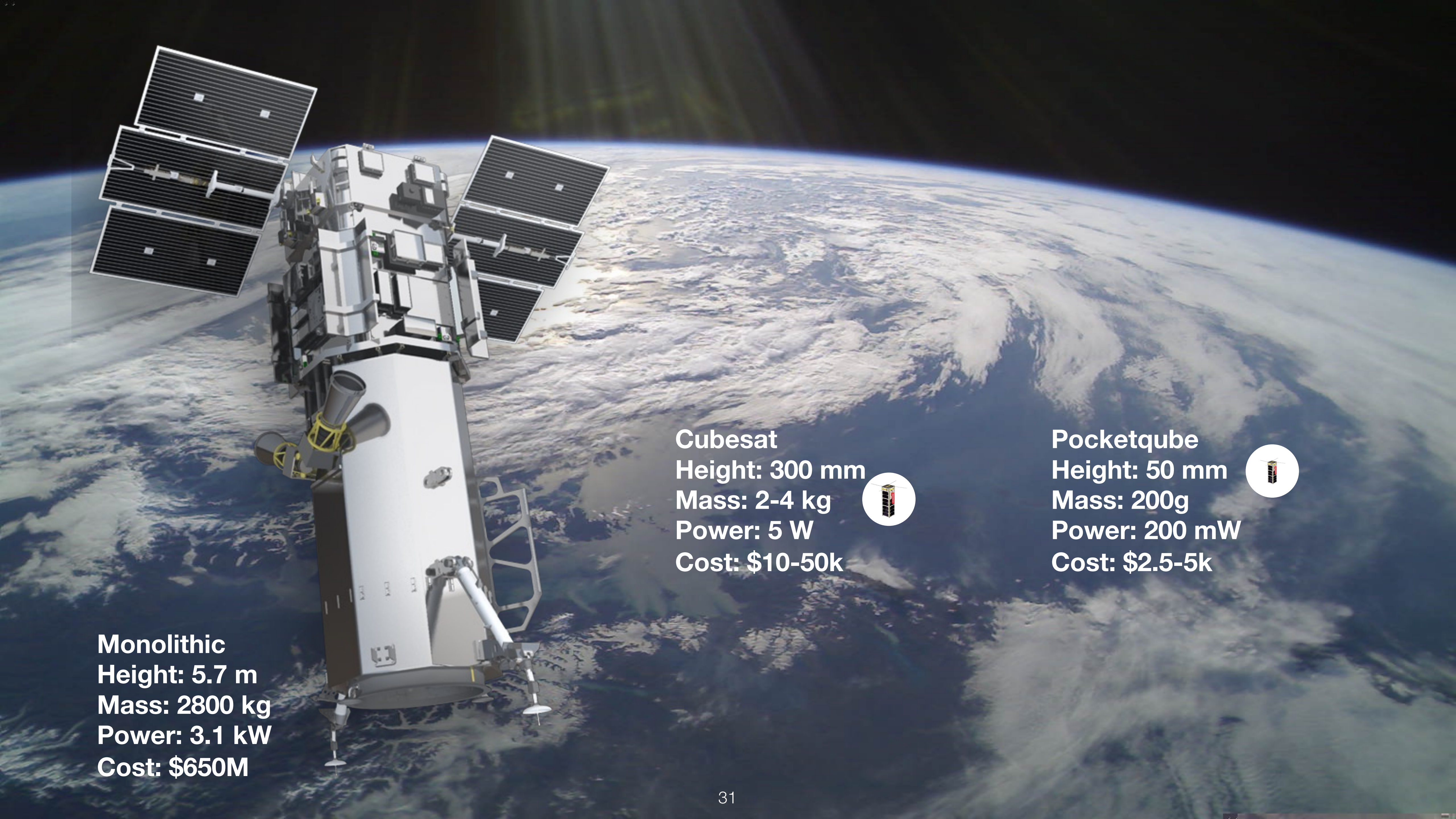
Abnormal ocean debris drifting
Last observed: 15 minutes ago
Safety risk: unknown
Action: Focus sensors on debris field, build IR & hyperspectral chemical signature map, search for signs of life, alert authorities.

Pushing compute to space gets us cost-effective global multi-sensor observation



Why now?

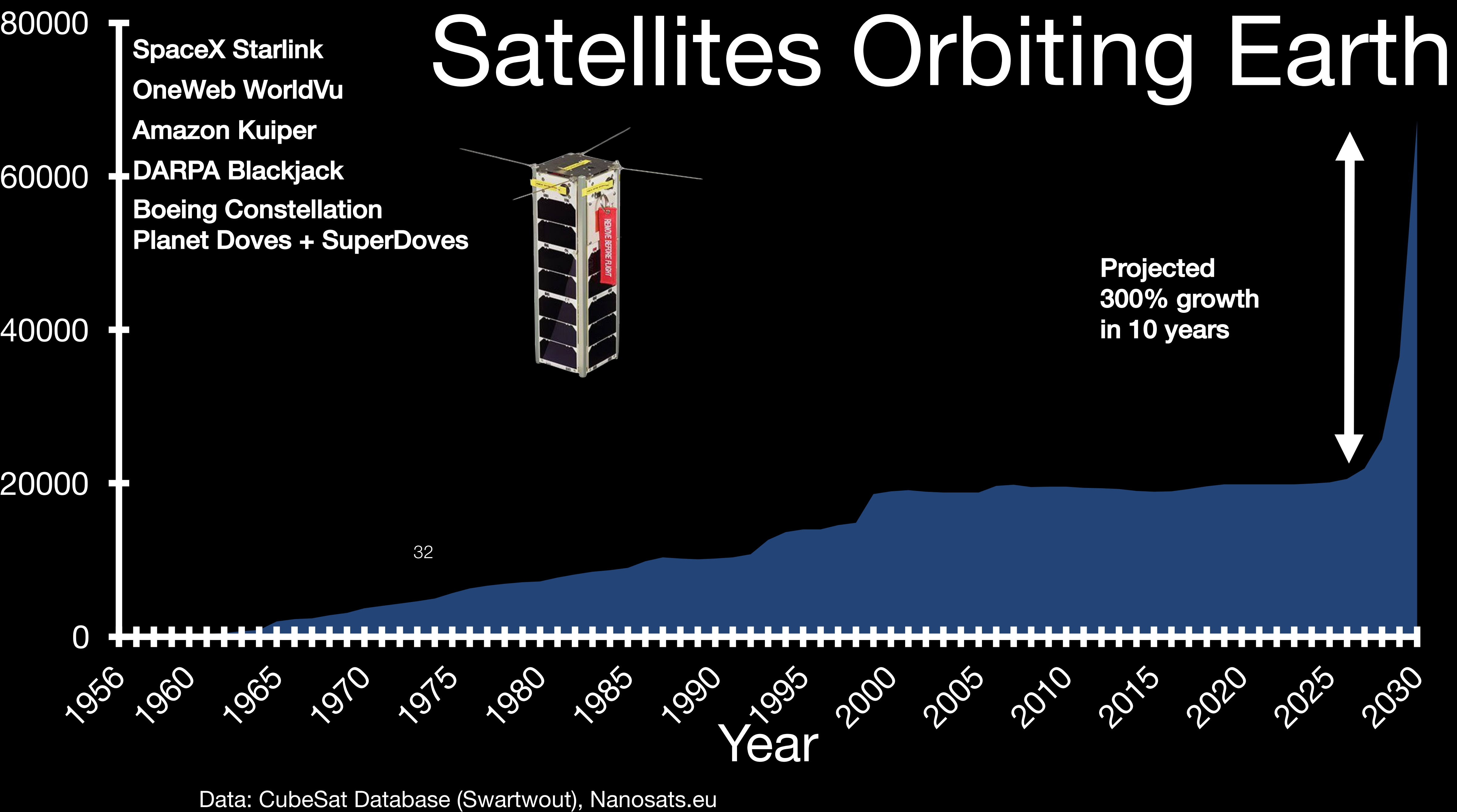
Explosive Space Sector Growth & Opportunity for Paradigm Shift



Cubesat
Height: 300 mm
Mass: 2-4 kg
Power: 5 W
Cost: $10-50k

Pocketqube
Height: 50 mm
Mass: 200g
Power: 200 mW
Cost: $2.5-5k

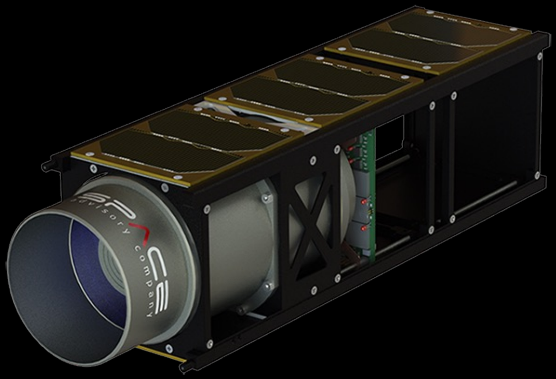
Monolithic
Height: 5.7 m
Mass: 2800 kg
Power: 3.1 kW
Cost: $650M


Satellites Orbiting Earth
SpaceX Starlink
OneWeb WorldVu
Amazon Kuiper
DARPA Blackjack
Boeing Constellation
Planet Doves + SuperDoves
REMOVE BEFORE FLIGHT
Projected
300% growth
in 10 years
80000
60000
40000
20000
0
32
1956
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year
Data: CubeSat Database (Swartwout), Nanosats.eu

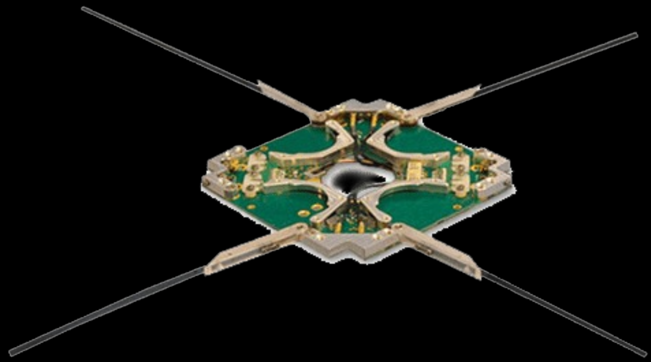
Nanosatellite constellations are an enabling CPS technology

100s of nanosats feasible *today*.

Nanosatellite constellations are an enabling CPS technology



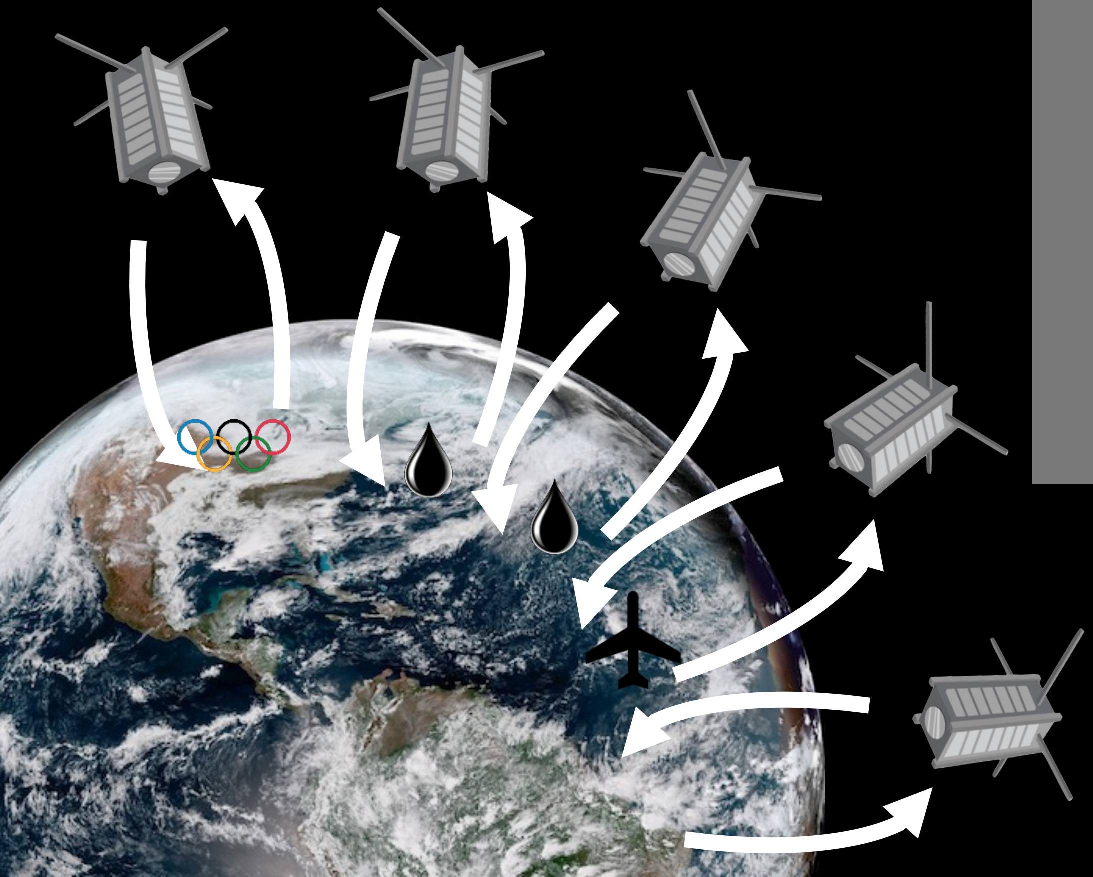
Imager &
hyperspectral sensor



Radio transceiver

Constellation == Collection of remote sensor devices

Constellations limited by centralized manual control



"Dumb" remote control sensors.

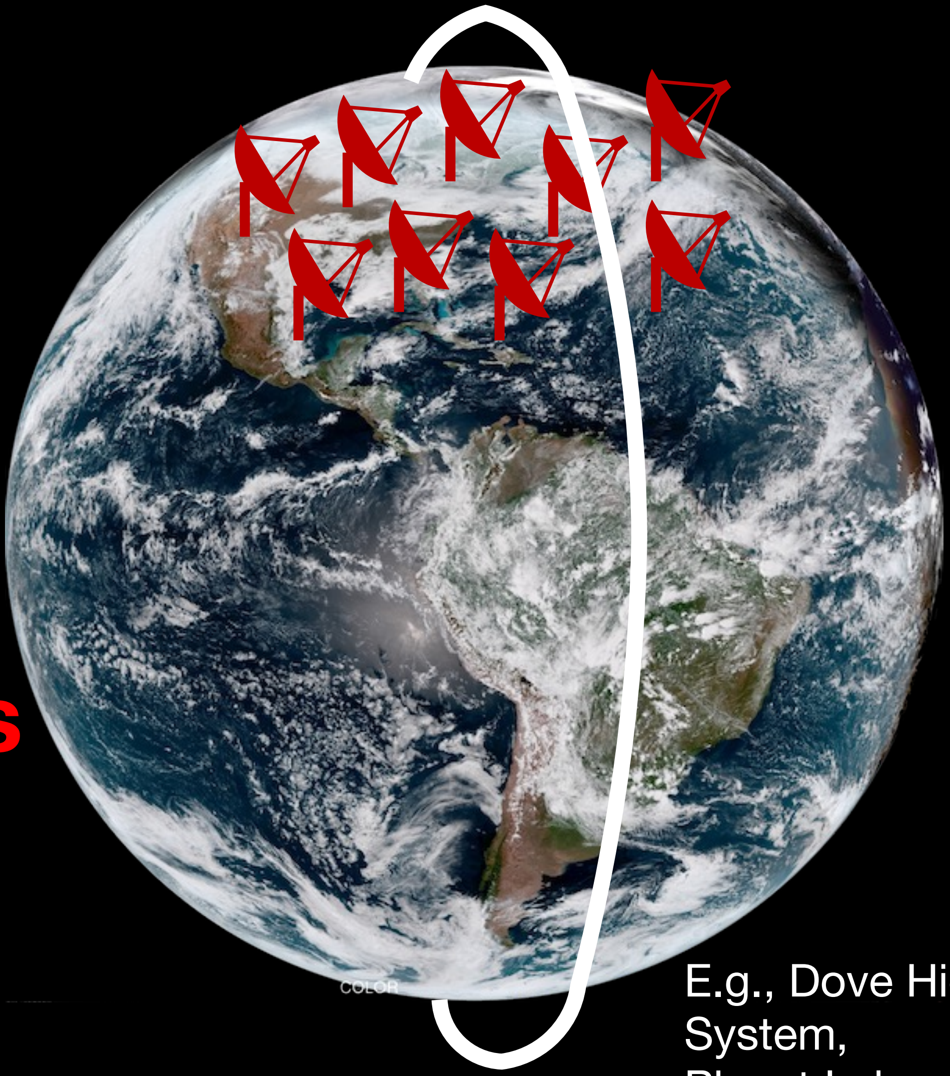
Manual per-sat control.

Commands up, data down.

Key Challenge: Data Backhaul Downlink Does Not Scale

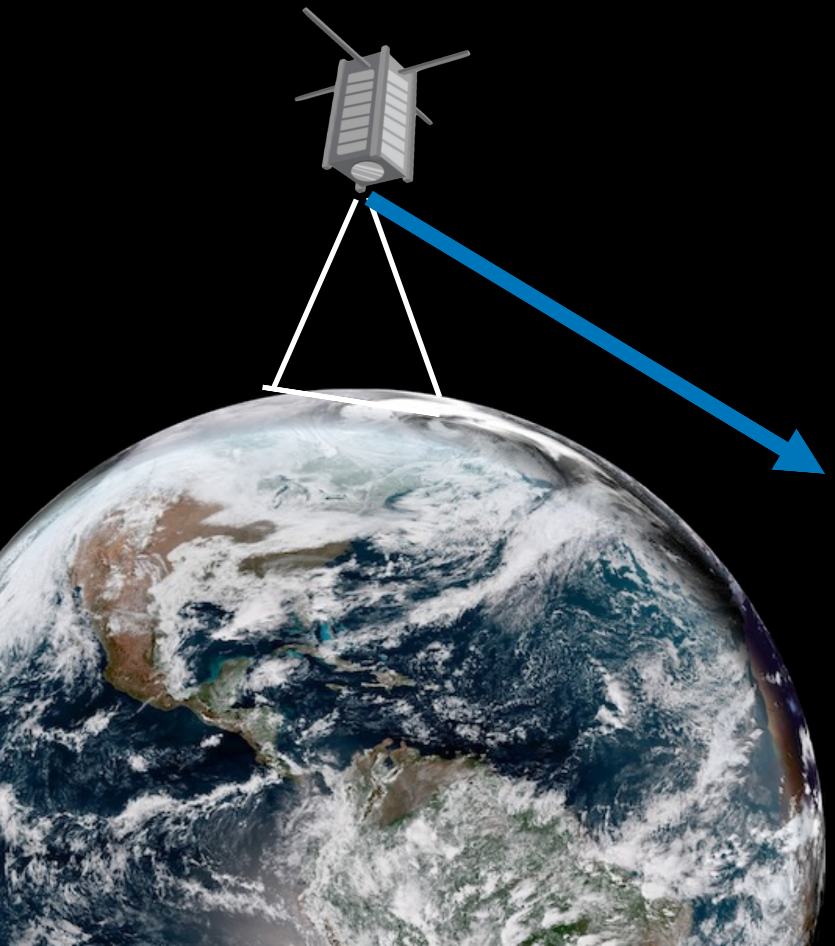
Optimistic Comms. Scenario:
Polar Orbit, Polar Ground Stations
Downlink: 1Gbps, Duration: ~5 min.

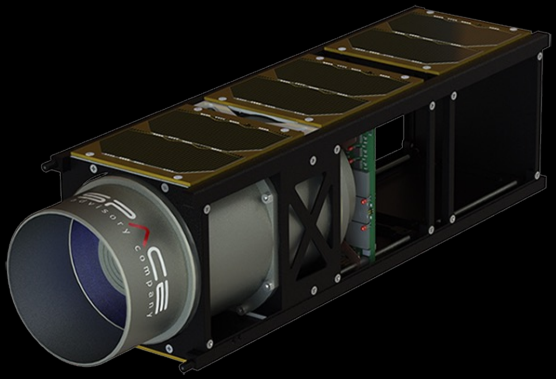
37.5GB downlink capacity per pass



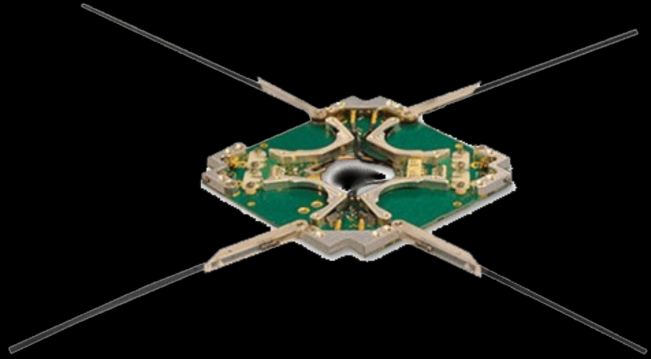
E.g., Dove High Speed Downlink System,
Planet Labs, SmallSat 2017

Nanosatellites collect more imagery than they can downlink





Imager &
hyperspectral sensor

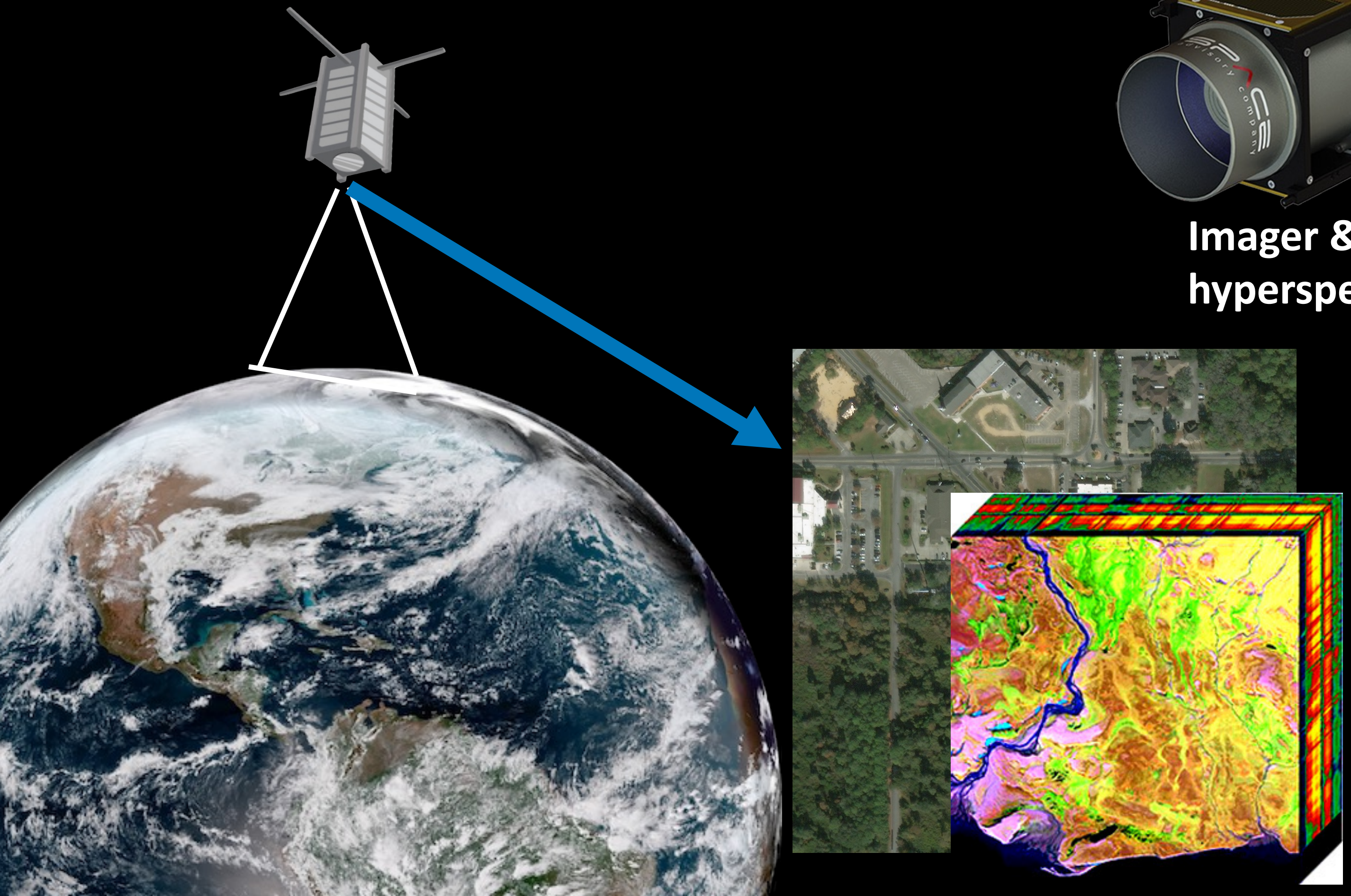


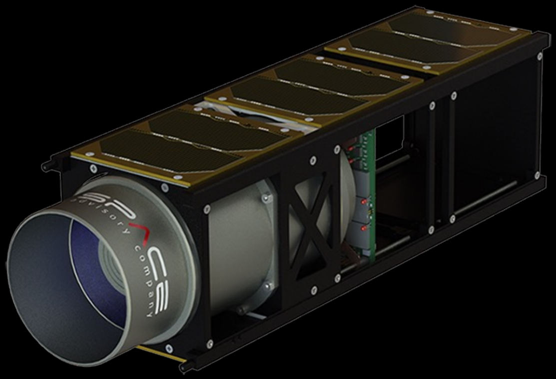
Radio transceiver

Image quality: 8K raw = 200MB
New frame every 1.7s, 90 min btw comm sessions

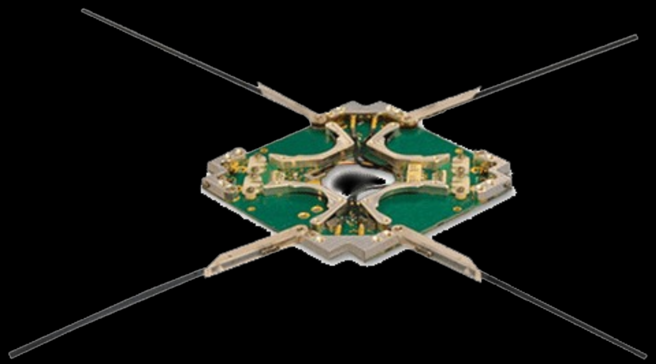
634GB per satellite
per orbital period!

Hyperspectral sensing generates *even more* data than imagery





Imager &
hyperspectral sensor



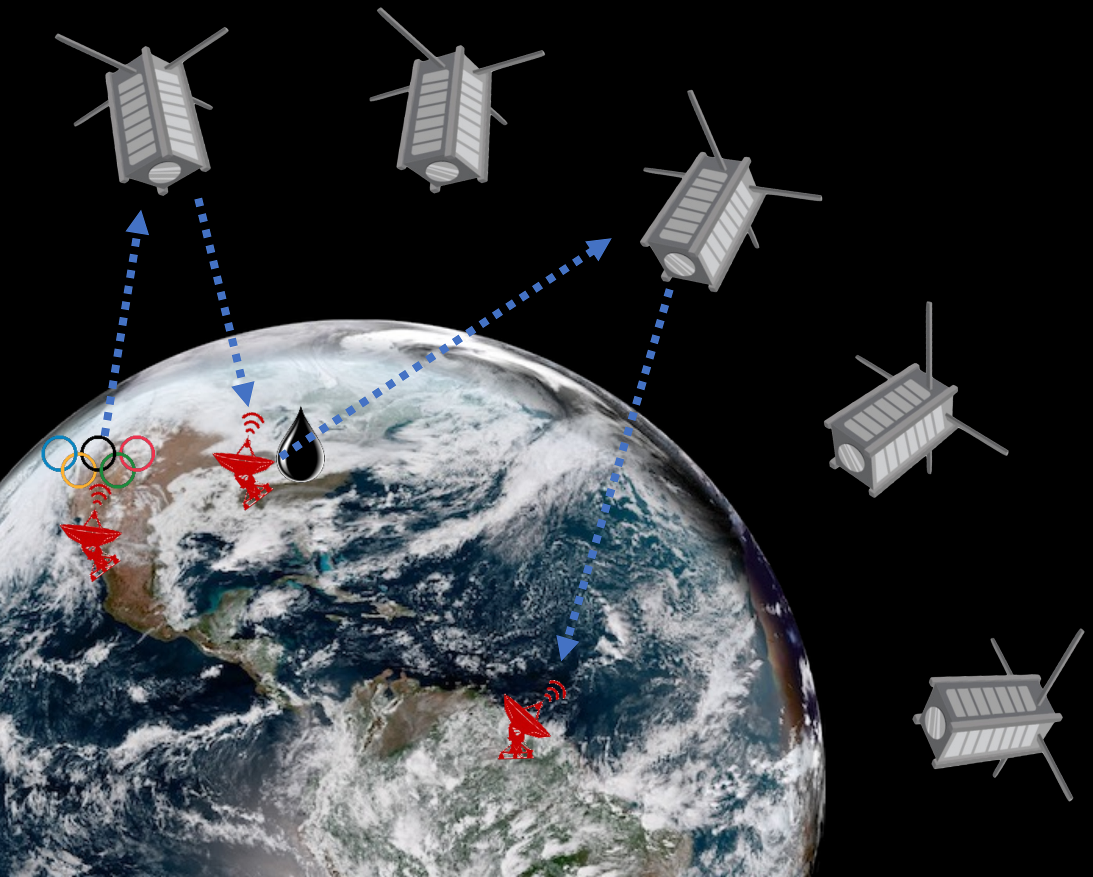
Radio transceiver

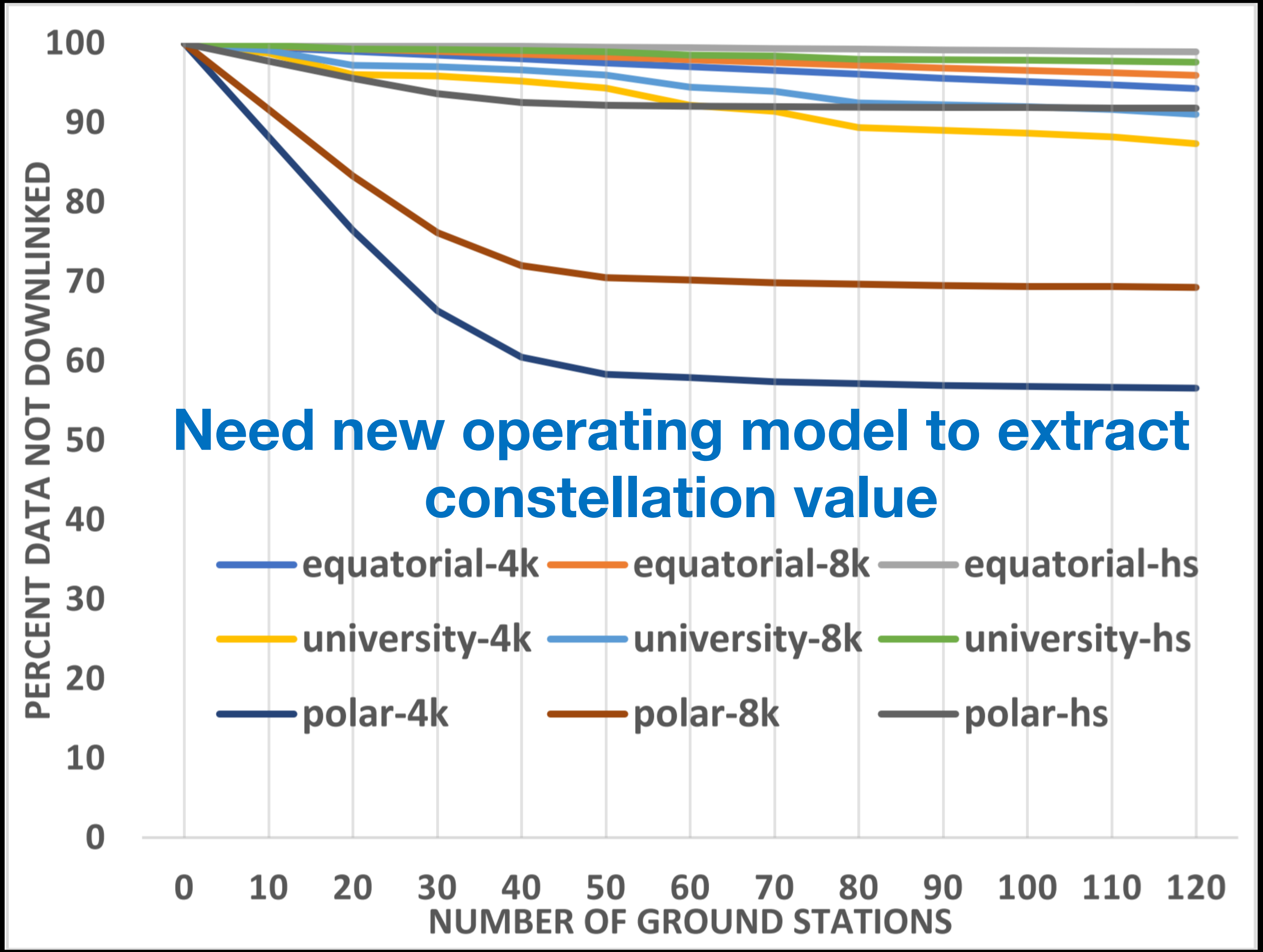
Image quality: 8K+hyperspectral = ~400MB

1.2TB per satellite per orbit

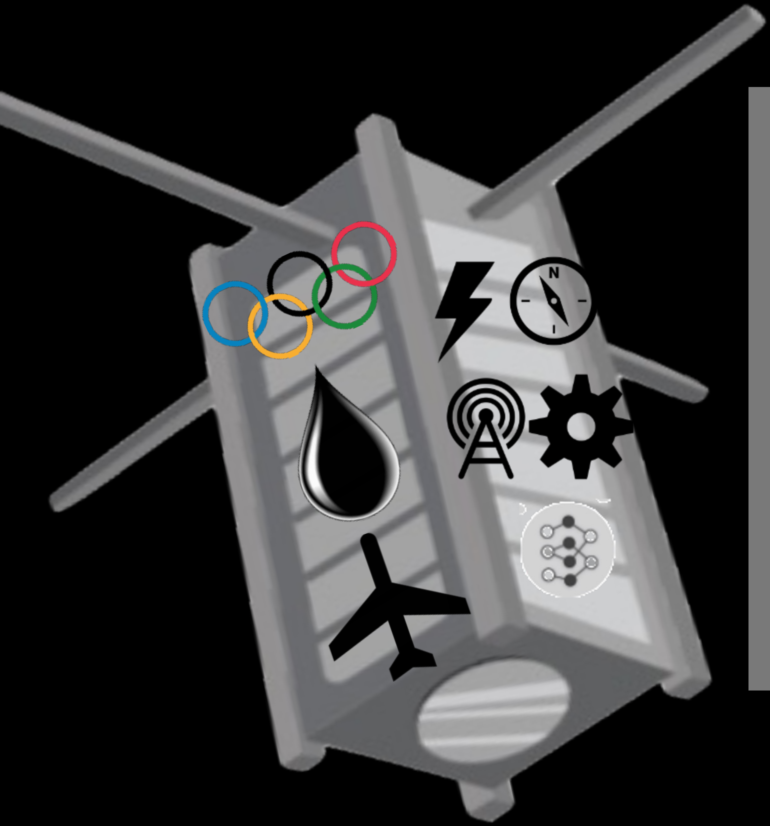
More/denser hyperspectral data increases size

Constellations are limited by constellation architecture

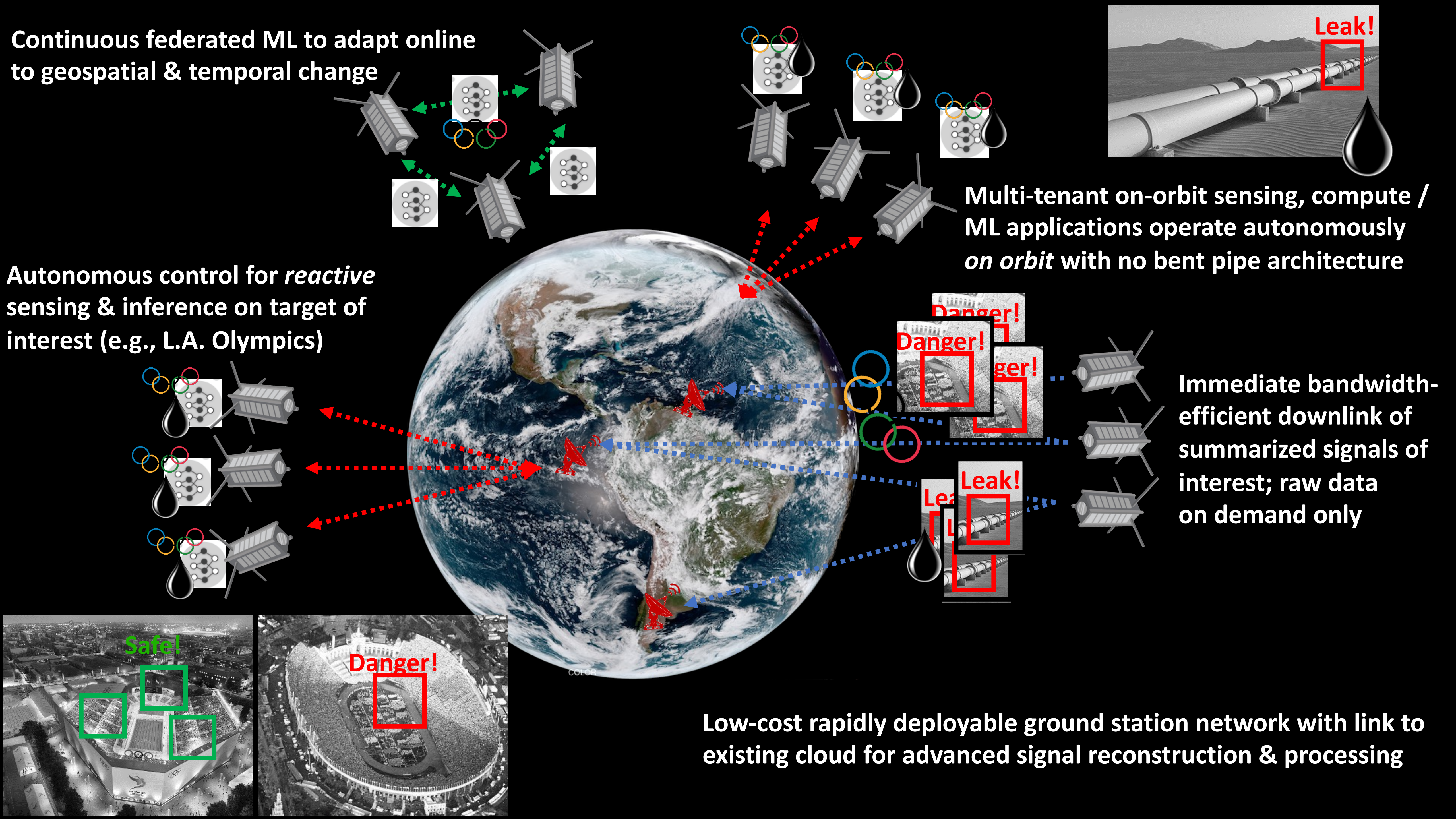


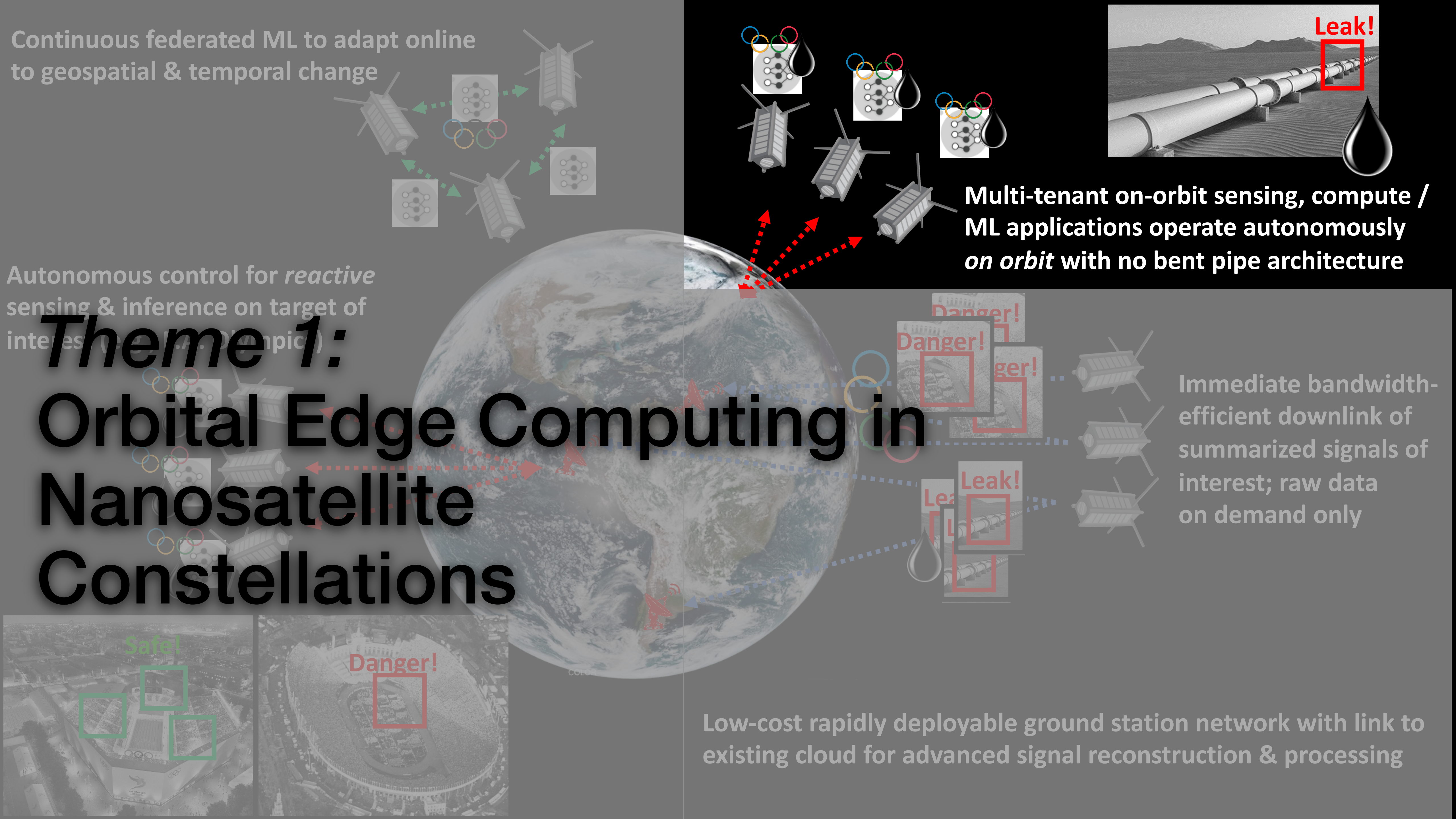


What is a
Software-Defined Nanosatellite



A **software-defined nanosatellite** is a programmable cyber-physical space system sensing, computing, actuating, and communicating autonomously to support multi-tenant ML apps.


Continuous federated ML to adapt online to geospatial & temporal change
Leak!
Multi-tenant on-orbit sensing, compute / ML applications operate autonomously *on orbit* with no bent pipe architecture
Autonomous control for *reactive* sensing & inference on target of interest (e.g., L.A. Olympics)
Danger!
Immediate bandwidth-efficient downlink of summarized signals of interest; raw data on demand only
Leak!
Safe!
Danger!
Low-cost rapidly deployable ground station network with link to existing cloud for advanced signal reconstruction & processing


Theme 1:
Orbital Edge Computing in Nanosatellite Constellations
Continuous federated ML to adapt online to geospatial & temporal change
Autonomous control for *reactive* sensing & inference on target of
Multi-tenant on-orbit sensing, compute / ML applications operate autonomously *on orbit* with no bent pipe architecture
Leak!
Danger!
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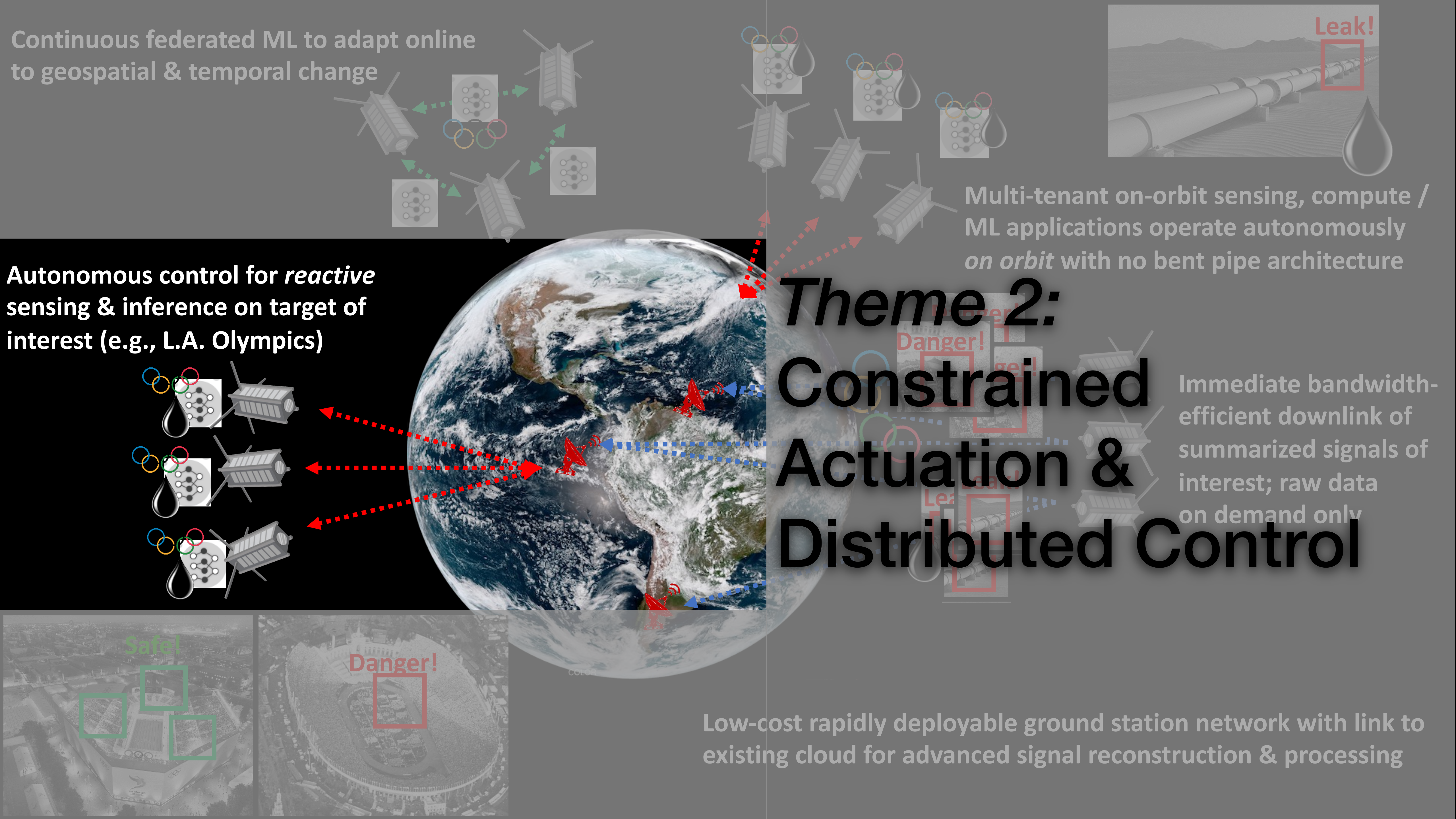
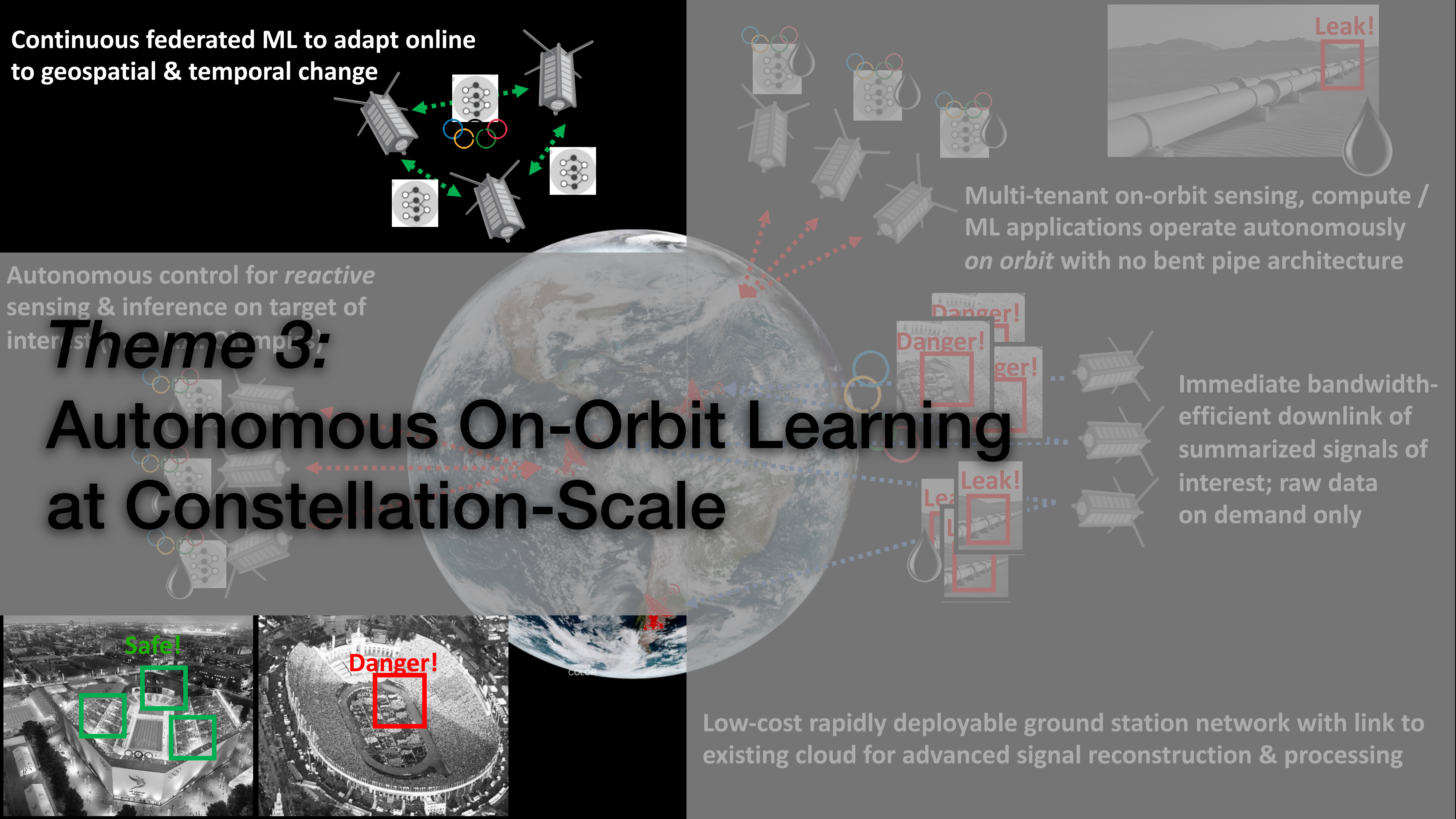
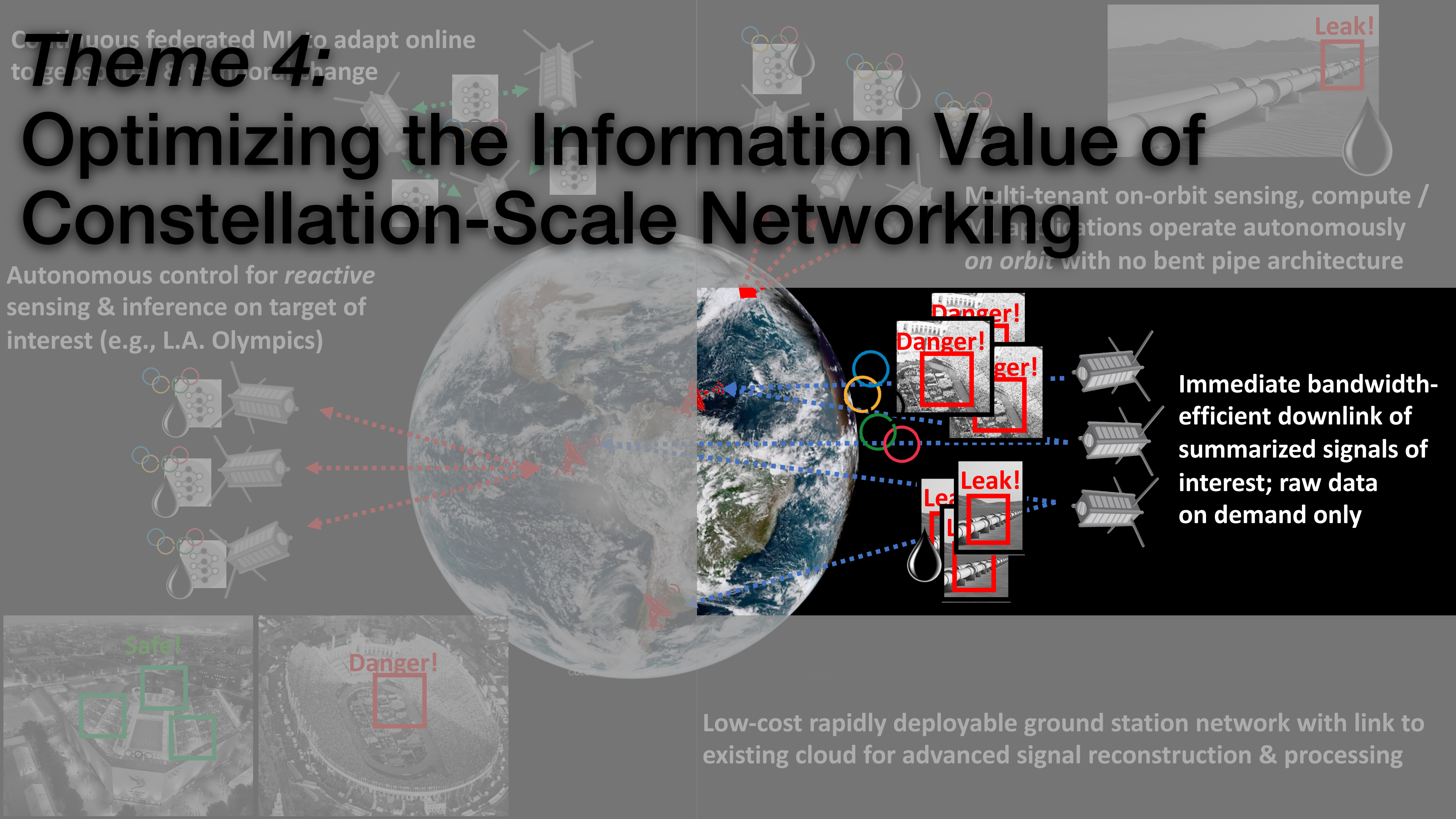
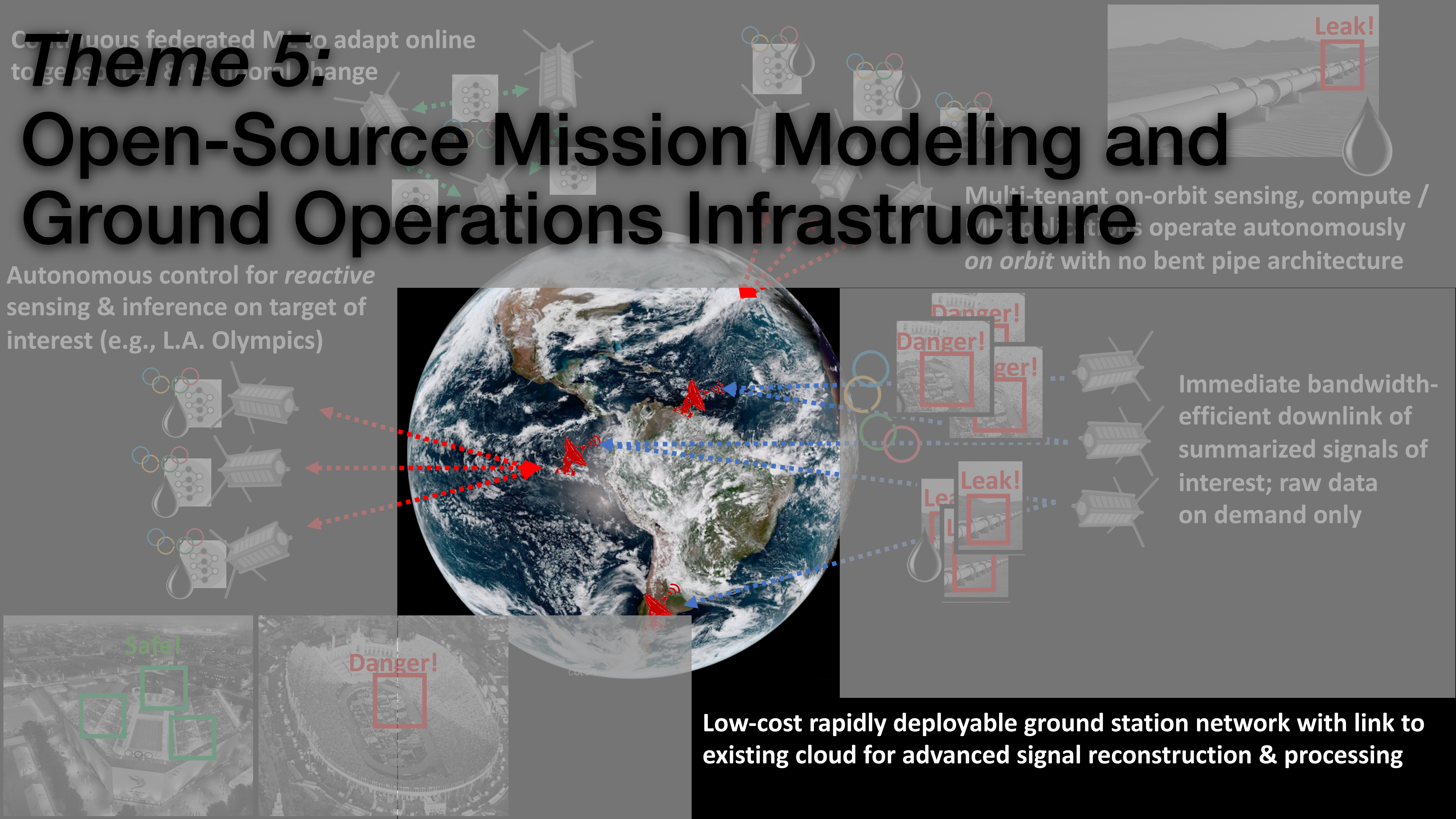


Continuous federated ML to adapt online to geospatial & temporal change
Leak!
Multi-tenant on-orbit sensing, compute / ML applications operate autonomously *on orbit* with no bent pipe architecture
Autonomous control for *reactive* sensing & inference on target of interest (e.g., L.A. Olympics)
Theme 2: Constrained Actuation & Distributed Control
Danger!
Immediate bandwidth-efficient downlink of summarized signals of interest; raw data on demand only
Safe!
Danger!
Low-cost rapidly deployable ground station network with link to existing cloud for advanced signal reconstruction & processing

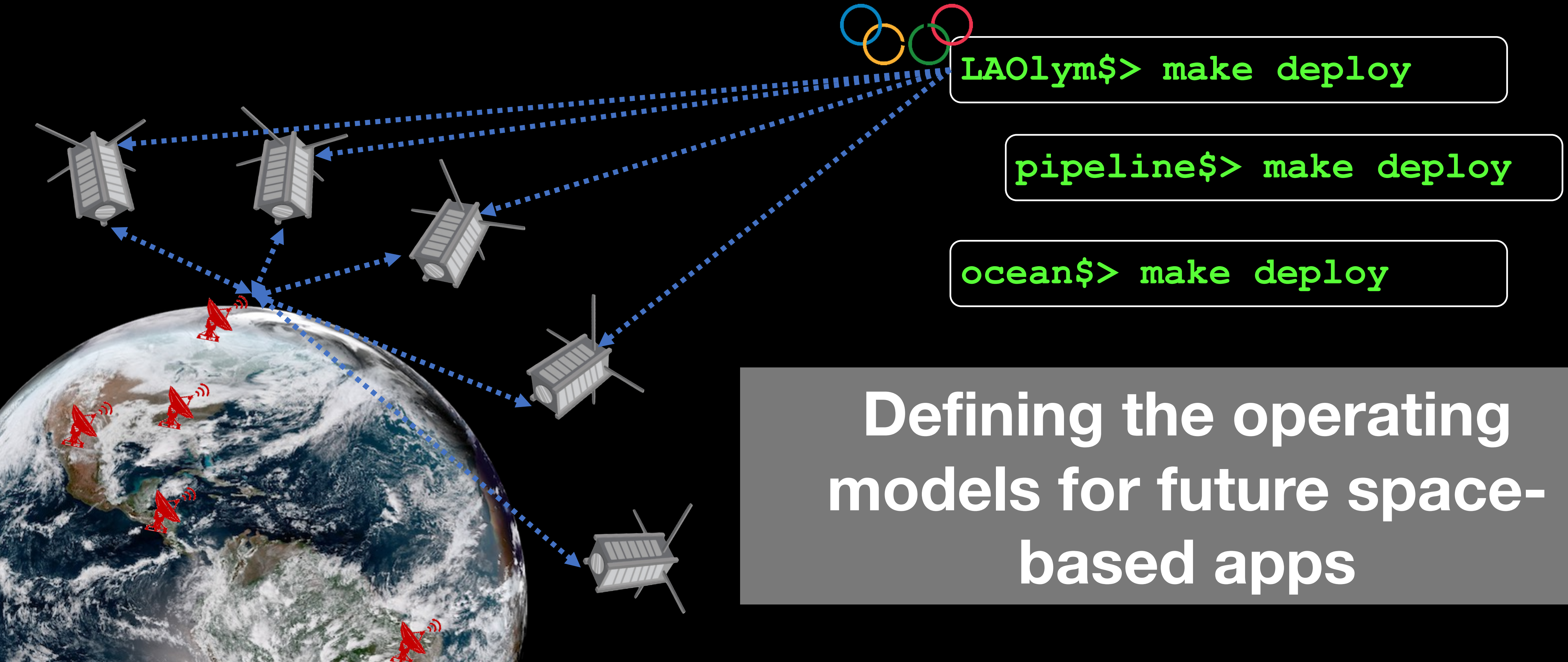

Theme 3:
Autonomous On-Orbit Learning at Constellation-Scale
Continuous federated ML to adapt online to geospatial & temporal change
Autonomous control for *reactive* sensing & inference on target of
Multi-tenant on-orbit sensing, compute / ML applications operate autonomously *on orbit* with no bent pipe architecture
Leak!
Danger!
Immediate bandwidth-efficient downlink of summarized signals of interest; raw data on demand only
Leak!
Safe!
Danger!
Low-cost rapidly deployable ground station network with link to existing cloud for advanced signal reconstruction & processing

Theme 4:
Optimizing the Information Value of Constellation-Scale Networking




Theme 5:
Open-Source Mission Modeling and Ground Operations Infrastructure
Continuous federated ML to adapt online to geospatial & temporal change
Multi-tenant on-orbit sensing, compute / ML applications operate autonomously *on orbit* with no bent pipe architecture
Autonomous control for *reactive* sensing & inference on target of interest (e.g., L.A. Olympics)
Immediate bandwidth-efficient downlink of summarized signals of interest; raw data on demand only
Leak!
Danger!
Safe!
Low-cost rapidly deployable ground station network with link to existing cloud for advanced signal reconstruction & processing

Infrastructure to Make Space Easy

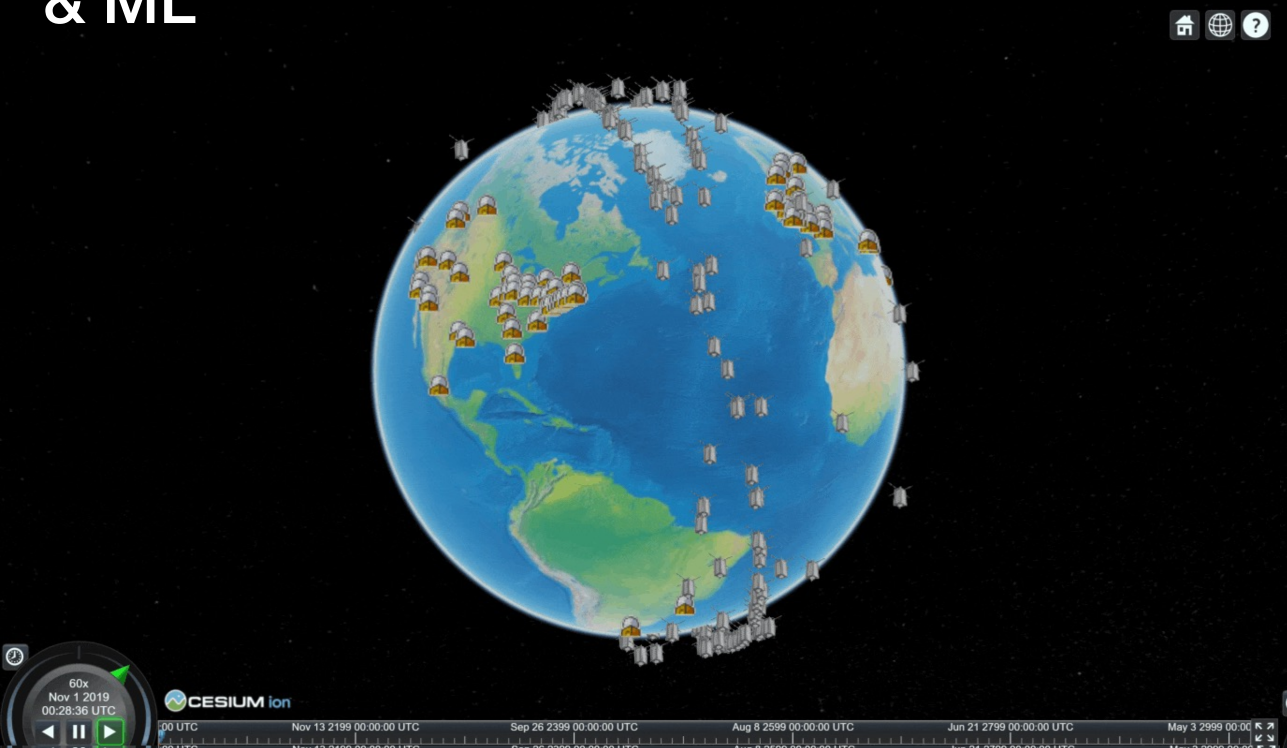


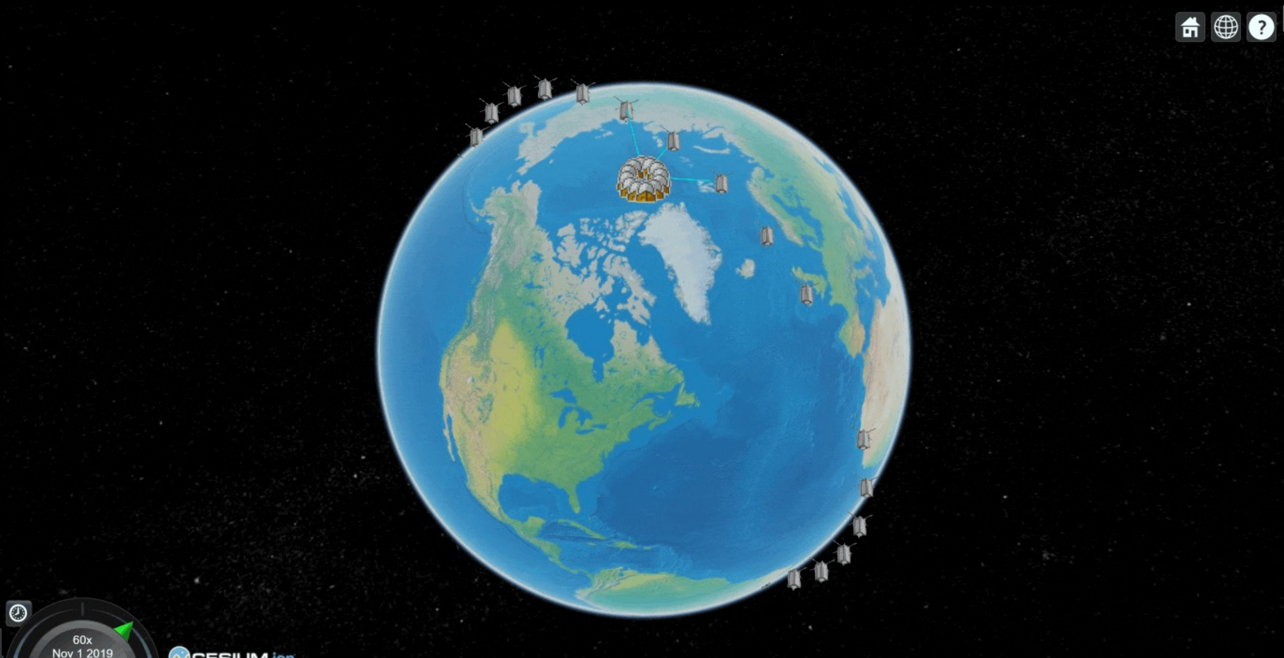
Defining the operating models for future space-based apps

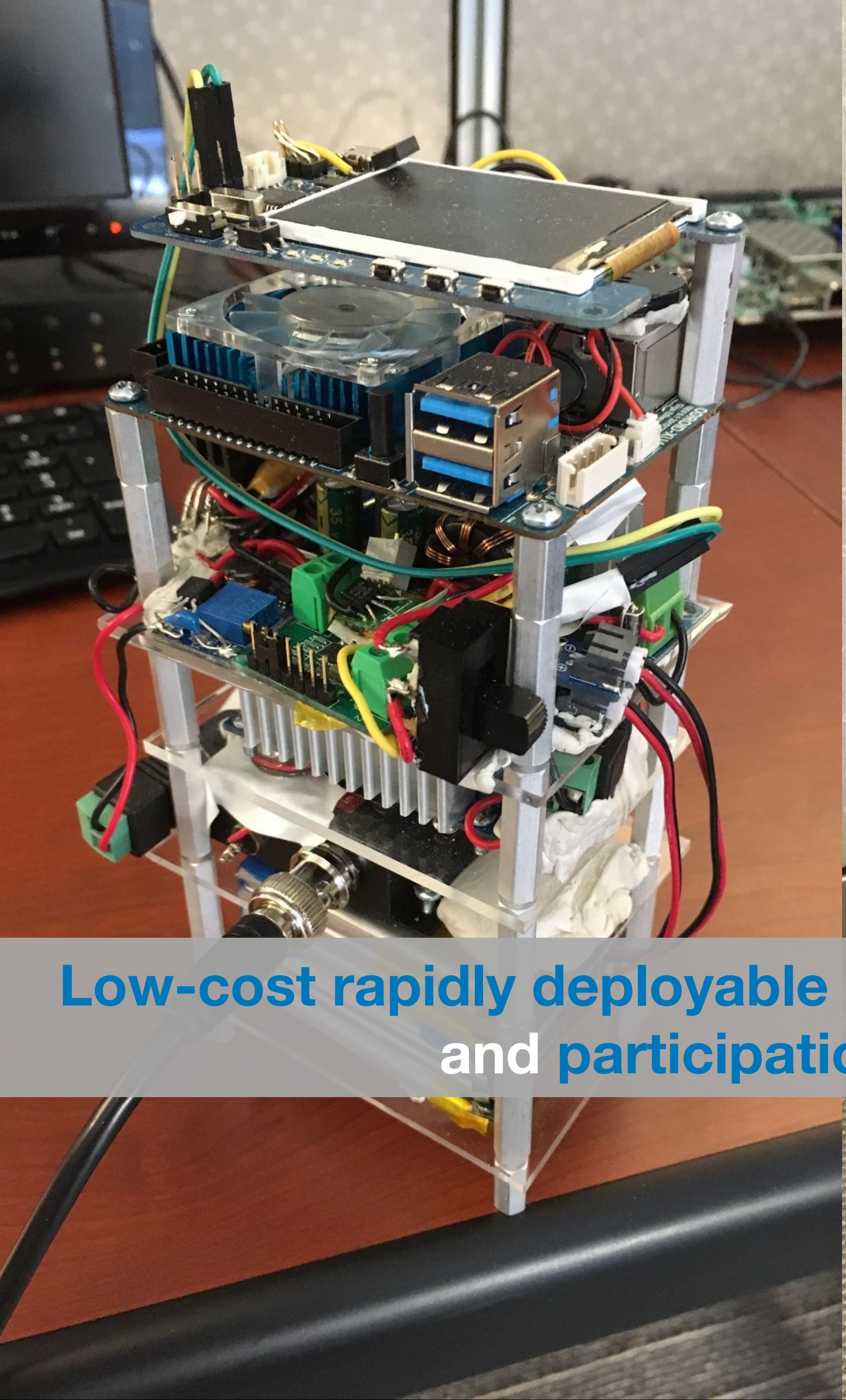
Pre-launch modeling tools & post-launch autonomy

Key Challenge:
Existing tools for modeling and autonomy do not consider constellation-scale, computing HW, controls, energy collection, & ML

Preliminary Prototype:
Our Cote simulator models orbits, comm., energy, & basic CPUs.



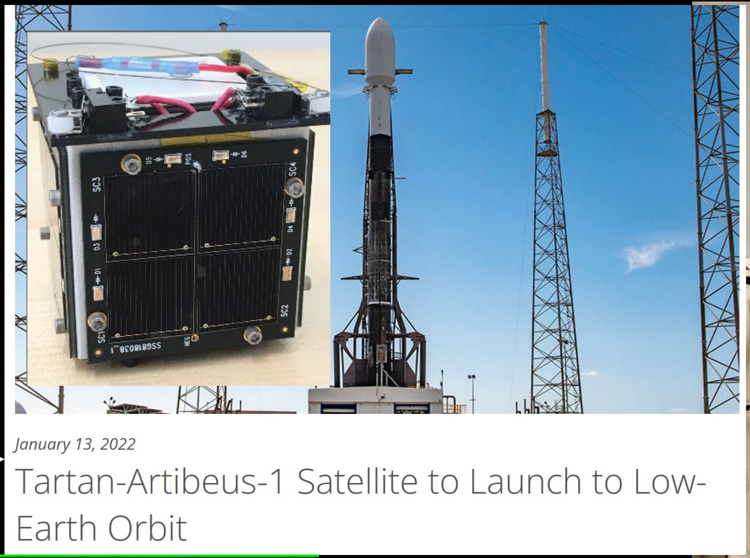


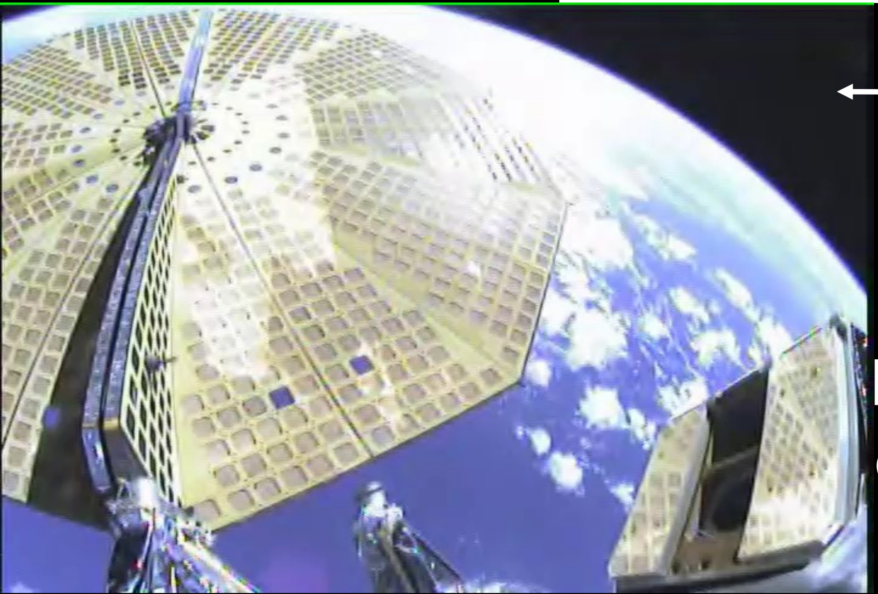


Low-cost rapidly deployable ground station equipment enables **widespread distribution** and **participation** from the research community and beyond

Launching your research to orbit is possible (Talk to me if you're interested in what we are doing about real launches)

January 13, 2022: CMU TA-1 Launch to LEO via Alba on SpaceX Transporter-3





March 2019: CMU/Stanford KickSat-2 Launch to LEO, deploying >100 chipsats

CPS: Frontier: Collaborative Research: Software-Defined Nanosatellite Constellations: The Foundation of Future Space-Based Cyber-Physical Systems

Brandon Lucia, Gauri Joshi, Swarun Kumar, Zac Manchester, Vyas Sekar

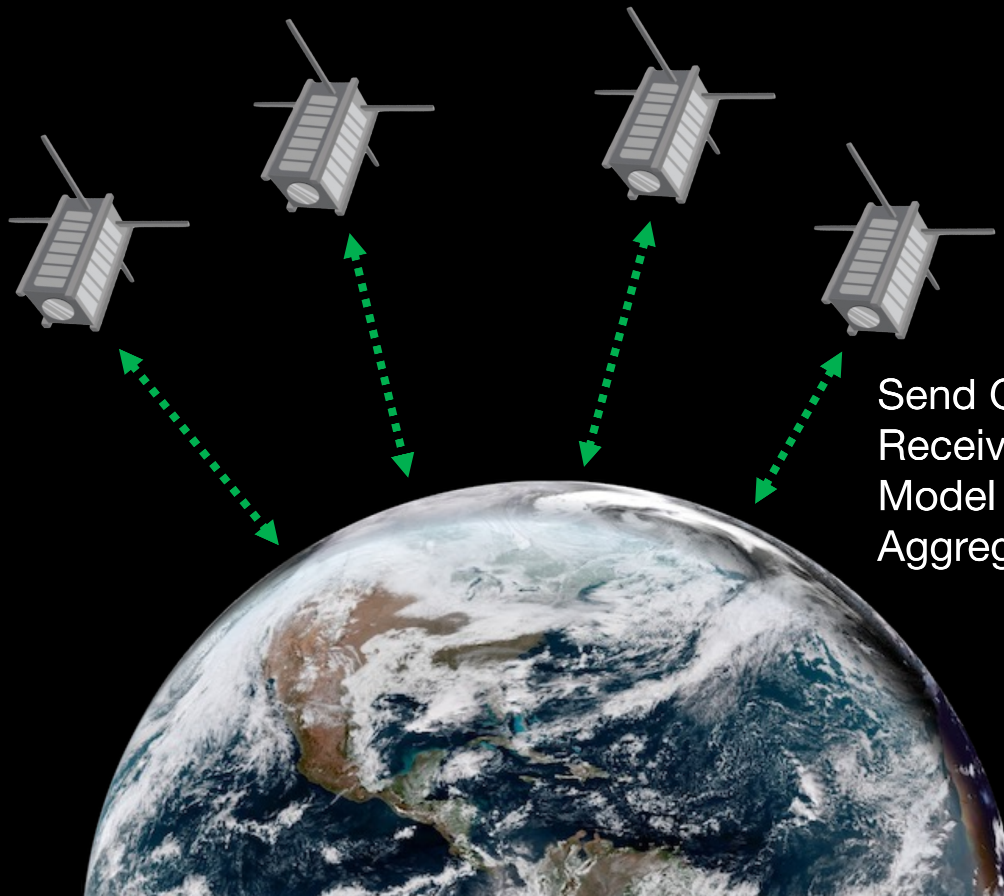
Carnegie Mellon University

National Science Foundation CPS Frontiers Reverse Site Visit – Jan. 18 2022

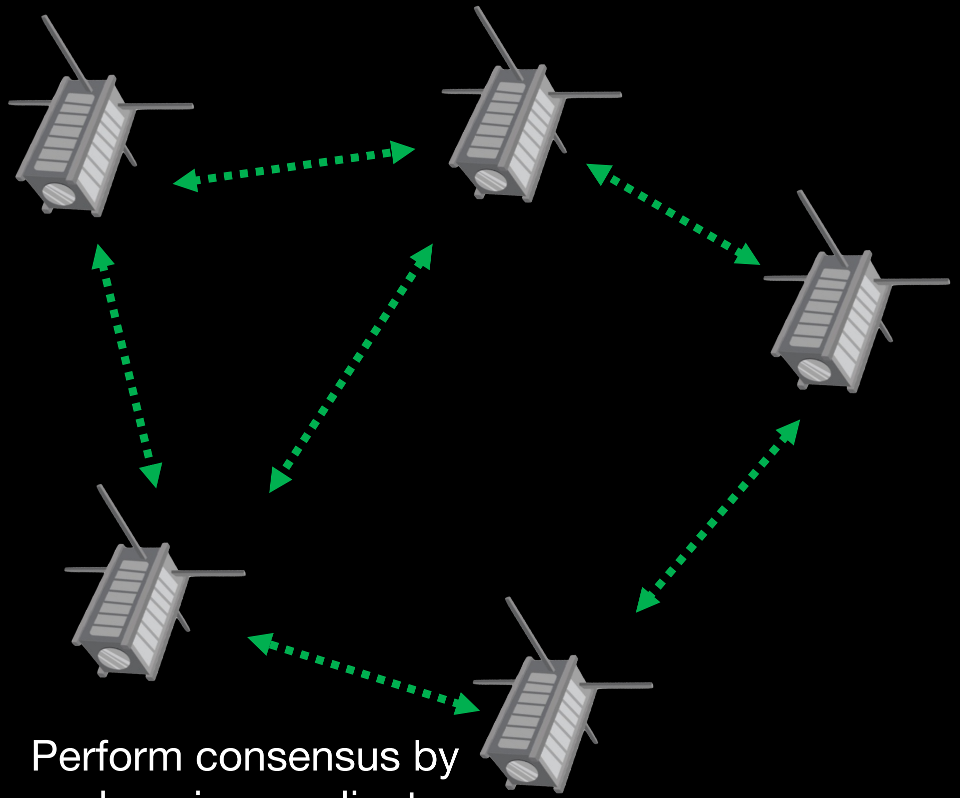
Backup

Minimizing Labeling Cost

- PROBLEM: Sending satellite images to the ground station for human-in-loop labeling is expensive
- SOLUTIONS: Mapping data to a low-dimensional latent space; using active learning for labeling

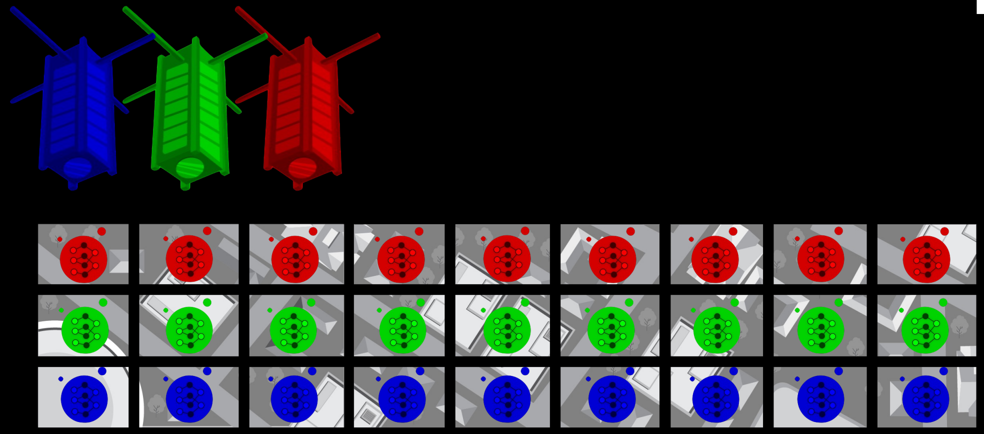


Send Gradients and Receive the Updated Model from Terrestrial Aggregator

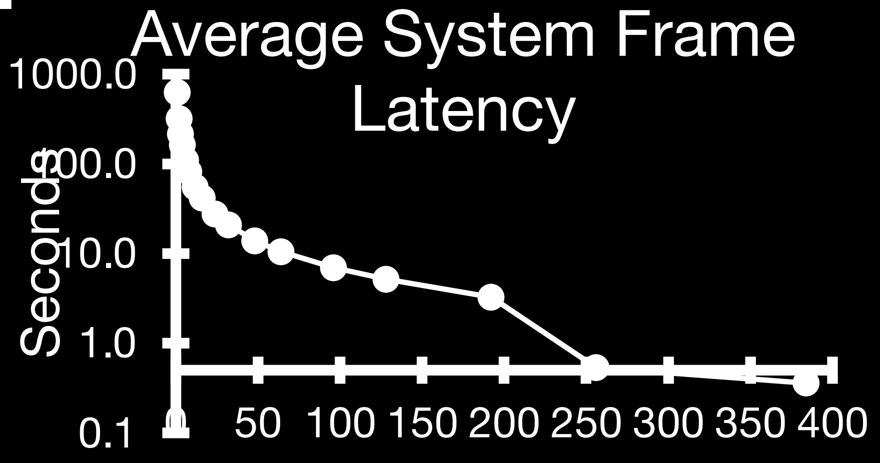


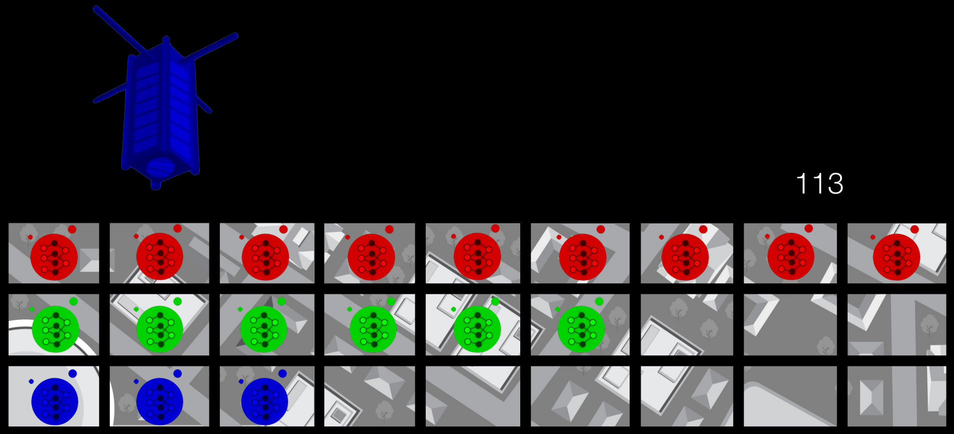
Perform consensus by exchanging gradients with neighbors

Tile-parallel: Close- vs Frame-spaced



Close-spaced, tile-parallel





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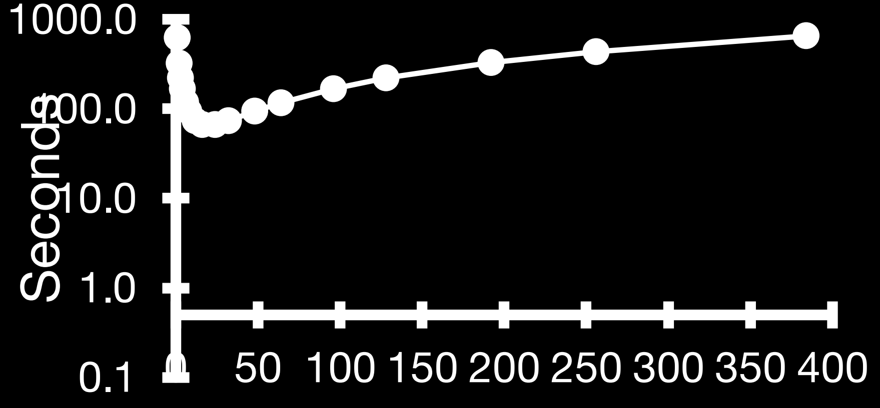
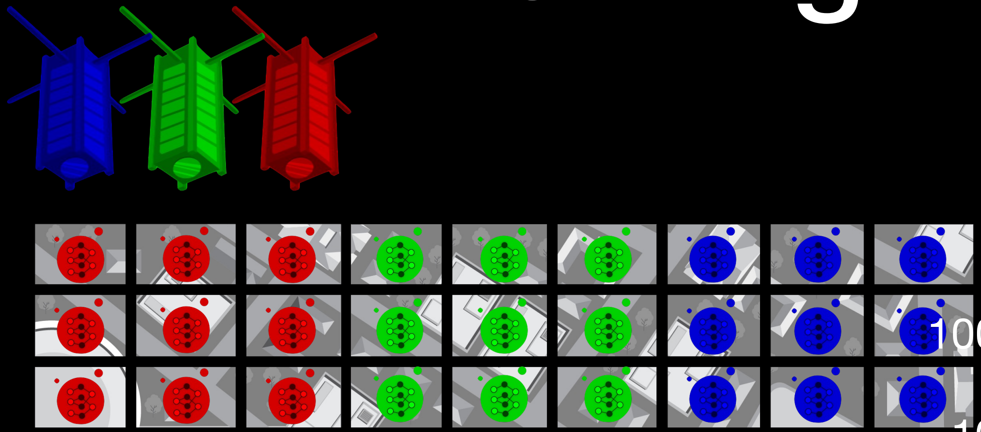
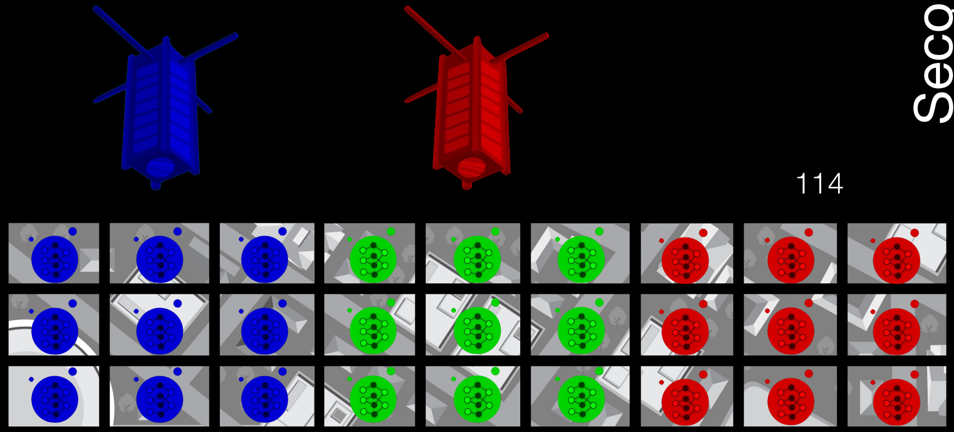
Frame-spaced, tile-parallel



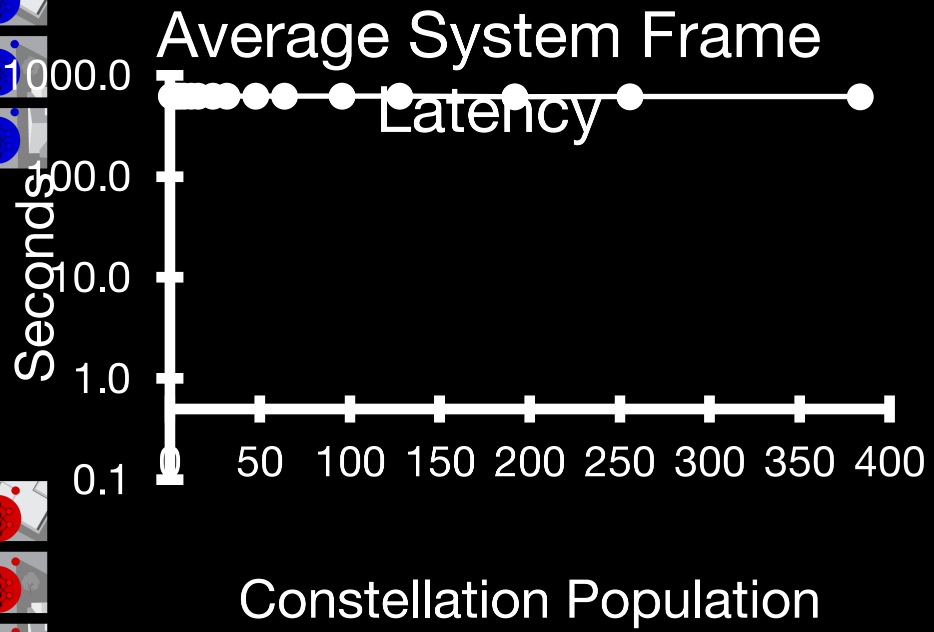
Frame Parallel Configurations



Close-spaced, frame-parallel

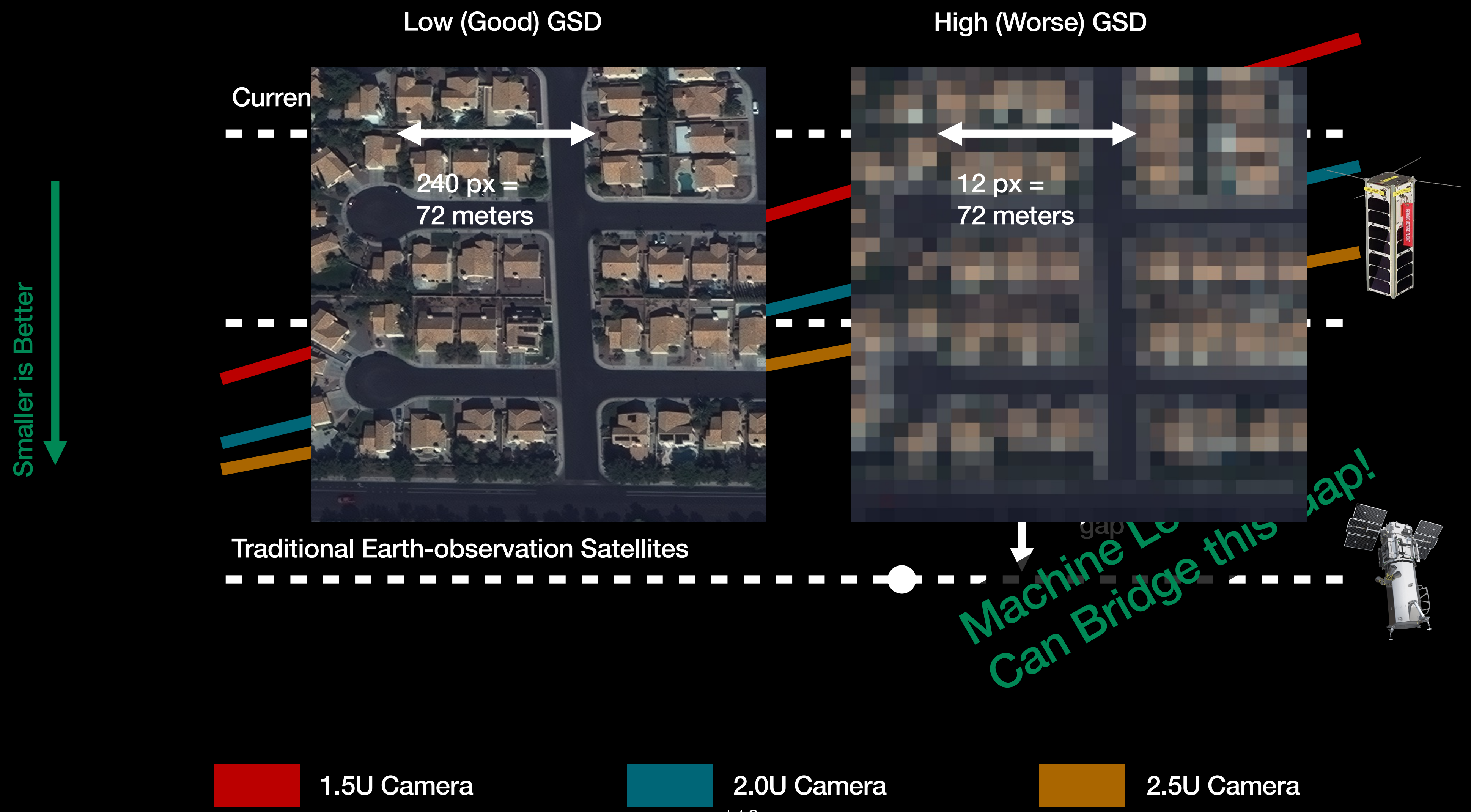


Frame-spaced, frame-parallel

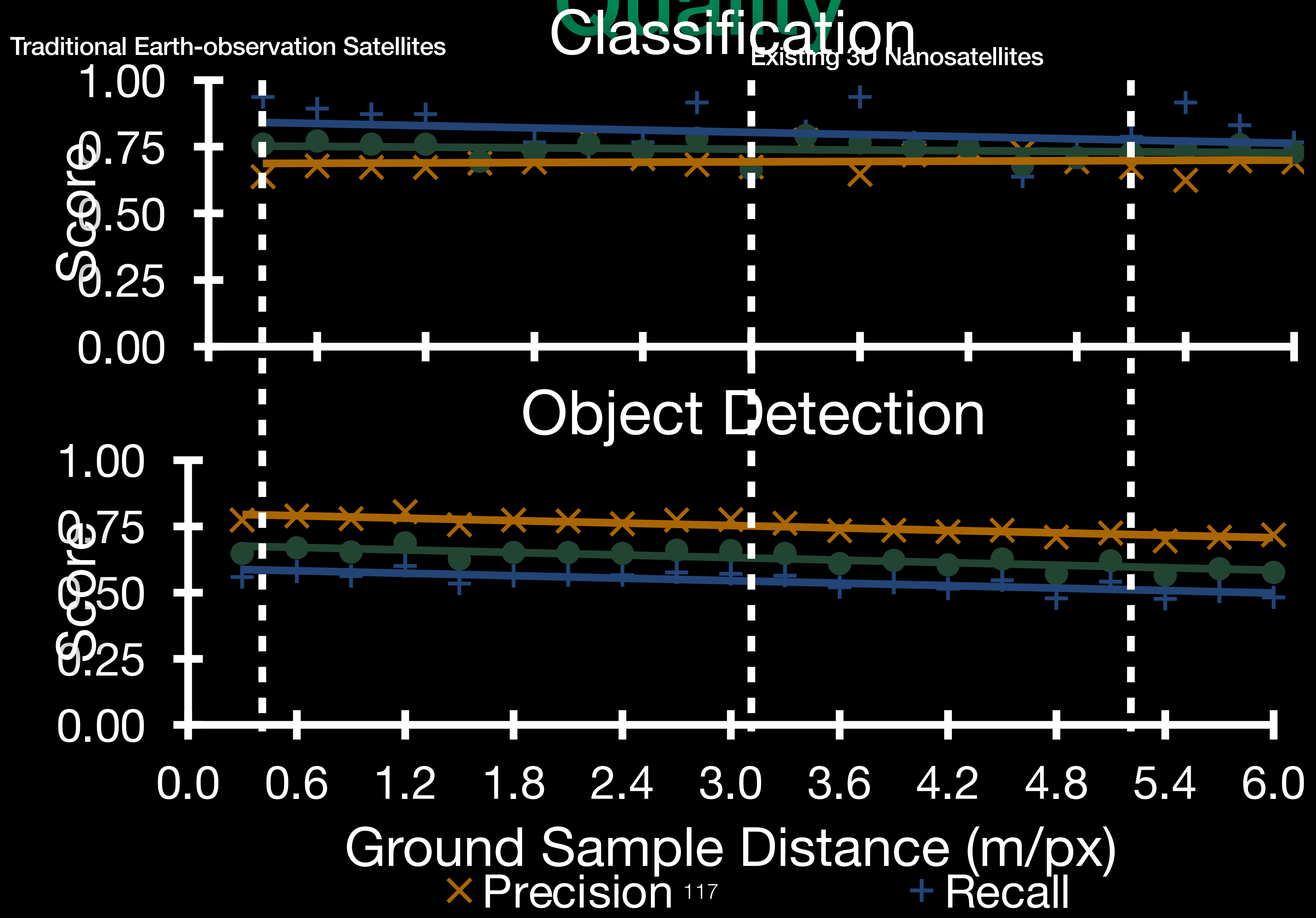


Ground Track Coverage

Designing for Maximum Data Quality



ML Tolerates Low Data Quality



Project Non-Goals:
What we do not intend to do

Project Non-goal:
Space Internet from LEO

"DARPA's Blackjack program aims to develop and demonstrate the critical elements for **a global high-speed network in low Earth orbit** (LEO) that provides the Department of Defense with highly connected, resilient, and persistent coverage."
-DARPA Blackjack Program Overview

"Starlink will deliver **high speed broadband** internet to locations where access has been unreliable, expensive, or completely unavailable"
-Starlink.com

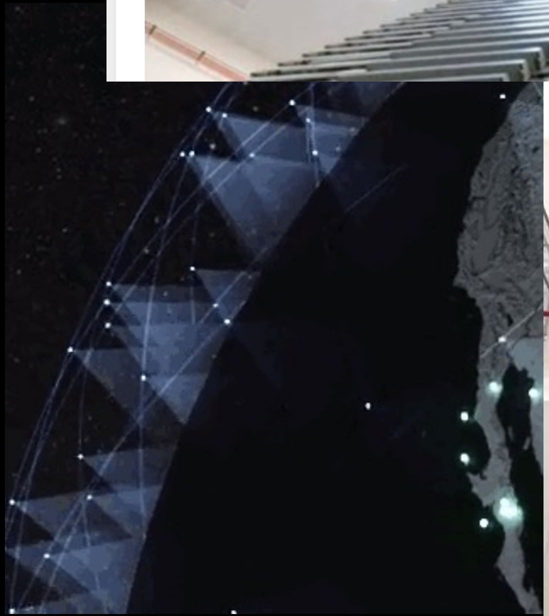
Project Non-goal:
Space Internet from LEO

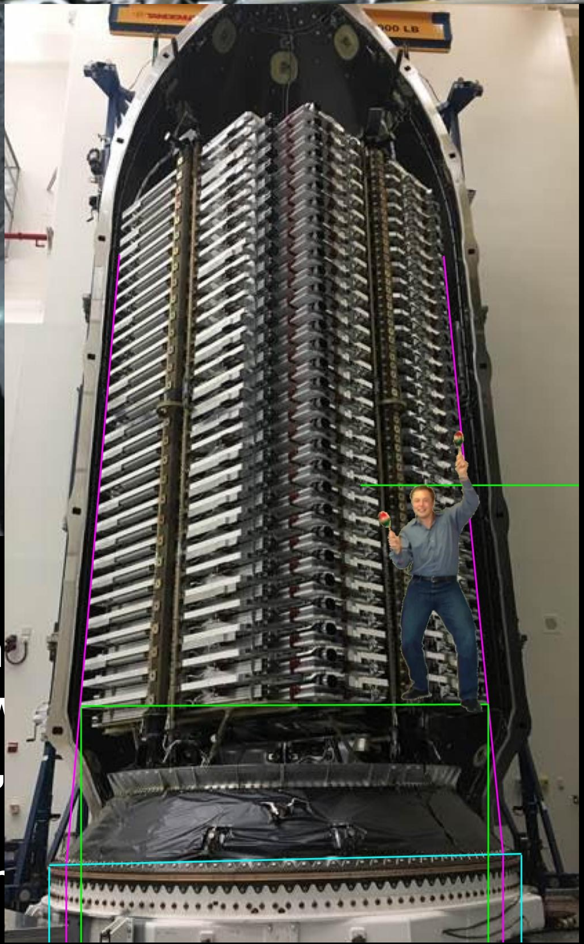
SpaceX Starlink Satellites Could Cost $250,000 Each and Falcon 9 Costs Less than $30 Million

Brian Wang | December 10, 2019

“DARPA’s Blackjack program aims to develop and demonstrate the critical elements for a global high-speed network in low Earth orbit (LEO) that provides the Department of Defense with highly connected, resilient, and persistent coverage.” … **“$2M dollars per payload”**

-DARPA Blackjack Program Overview





“Starlink will deliver **h** internet to locations w unreliable, expensive, unavailable”

-Starlink.com

Project Non-goal:
Fractionated Spacecraft (DARPA F6)

“functionality of a traditional “monolithic” spacecraft is delivered by a cluster of wirelessly-interconnected modules”
-System F6 Program Overview

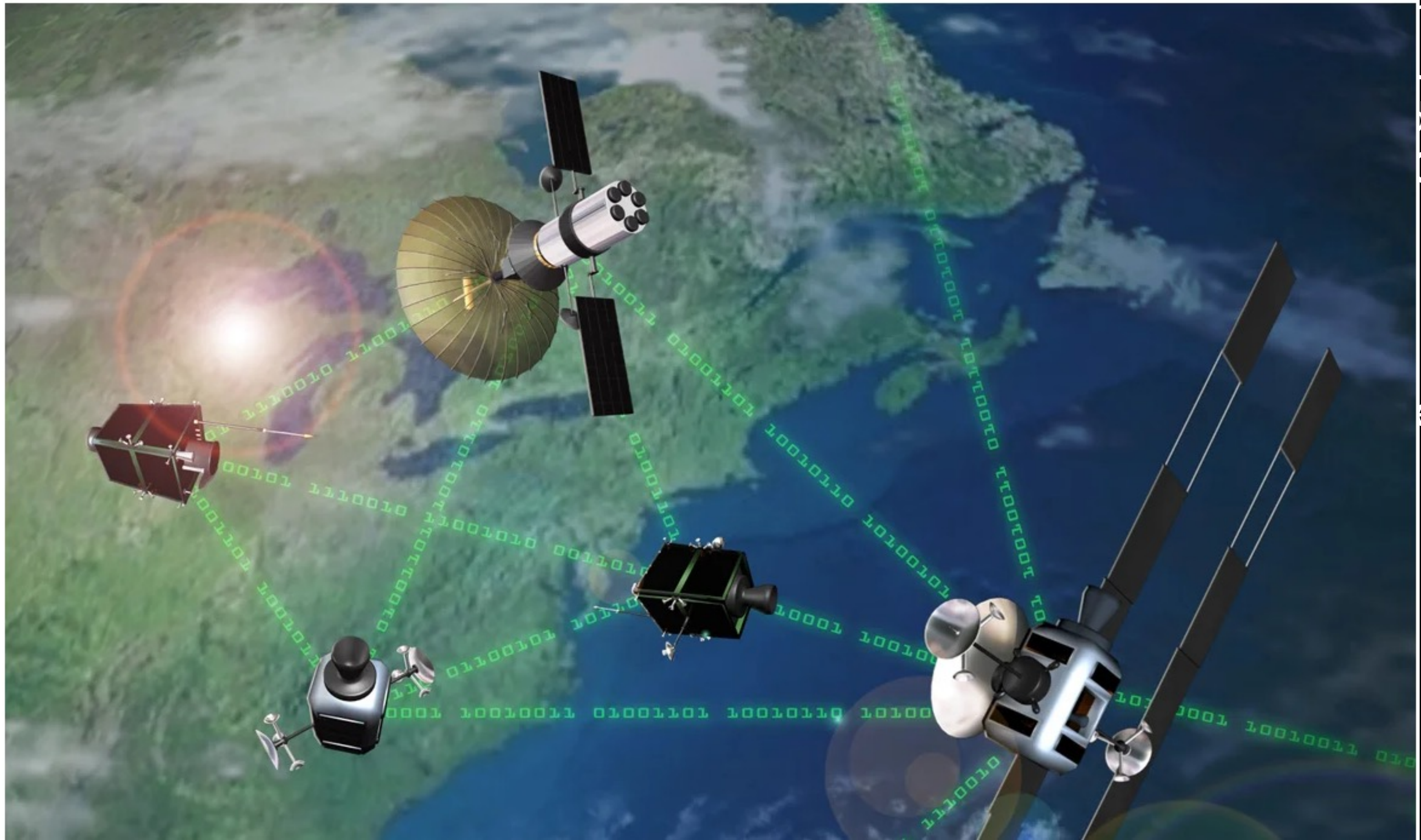
Emulating a **monolithic satellite** with a **tightly-coupled,** wirelessly connected heterogeneous collection of smaller satellites.

Project

Fractio[n] ... F6)

DAVID AXE 05.17.13 05:00 PM

After $200 Million, Darpa Gives Up on Formation-Flying Satellites



monolithic”
uster of
dules”
Overview

e with a tightly-
heterogeneous