# Going Beyond Mono-Mission Earth Observation: Using the Multi-Agent Paradigm to Federate Multiple Missions

## MASSpace'24

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# Earth Observation Ecosystems Evolution

- More advanced instruments and satellites
- Growing needs for higher responsiveness [EUSPA, 2022]
- E.g. order surveillance, maritime monitoring, and disaster response
- From mono- to multi-missions
- Ground Segment as a Service (GSaaS)

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# Case Study: Reactive Large Area Acquisition

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- Optimize acquisition time of large areas
- Optimize download time of acquisitions

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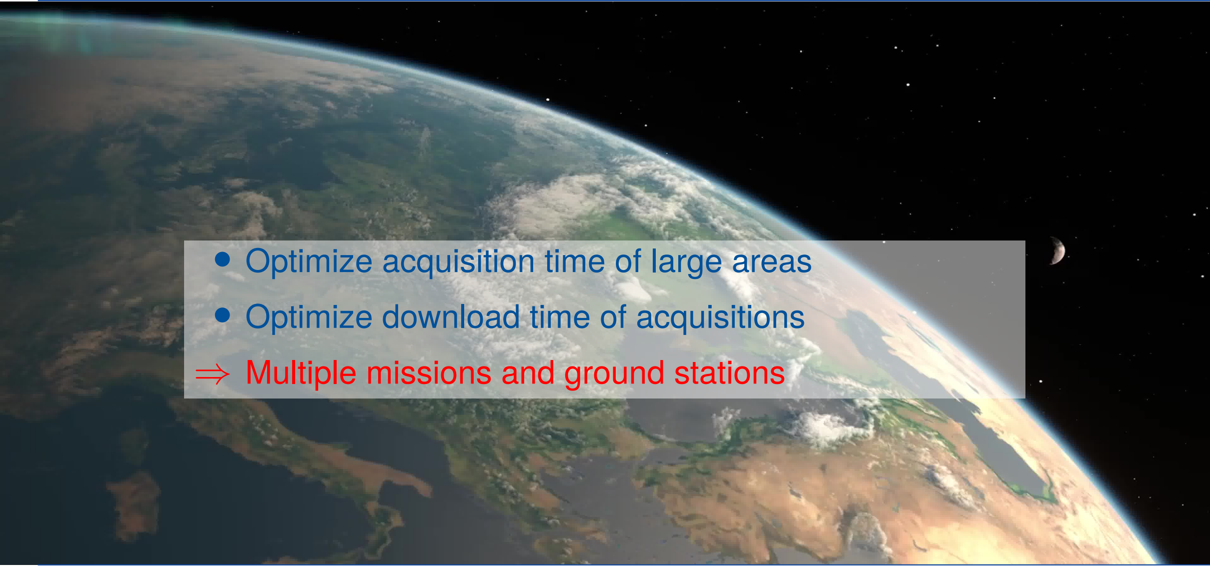
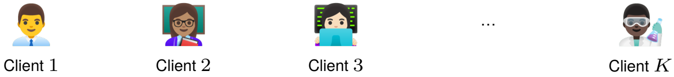


- Optimize acquisition time of large areas
- Optimize download time of acquisitions

⇒ Multiple missions and ground stations

# Conventional Approach for Requesting EO Services



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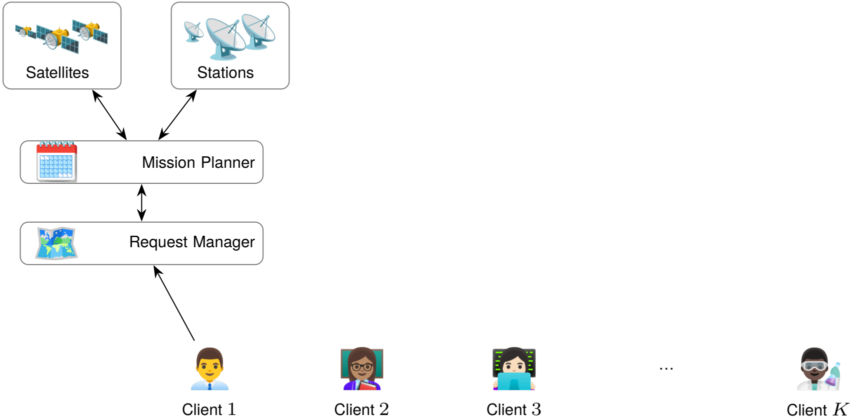

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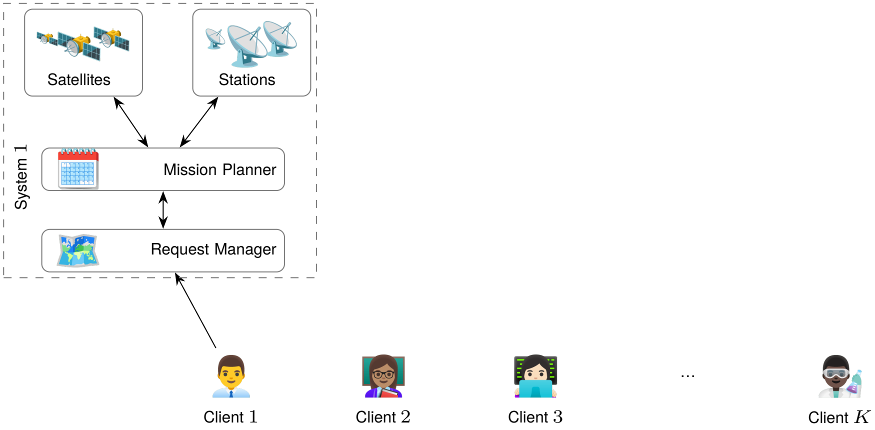

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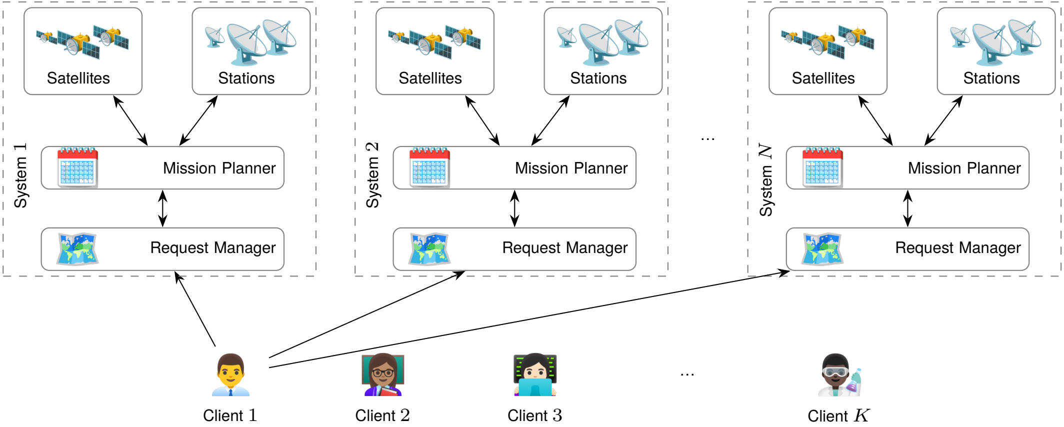

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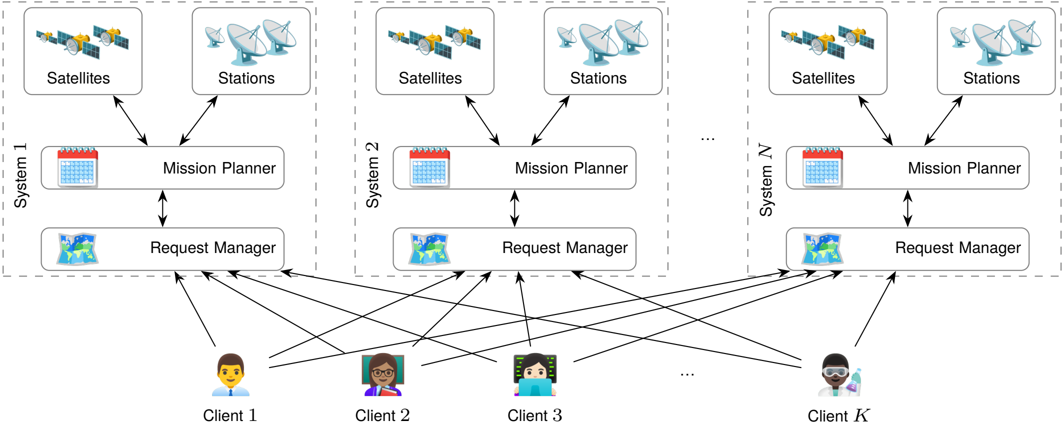
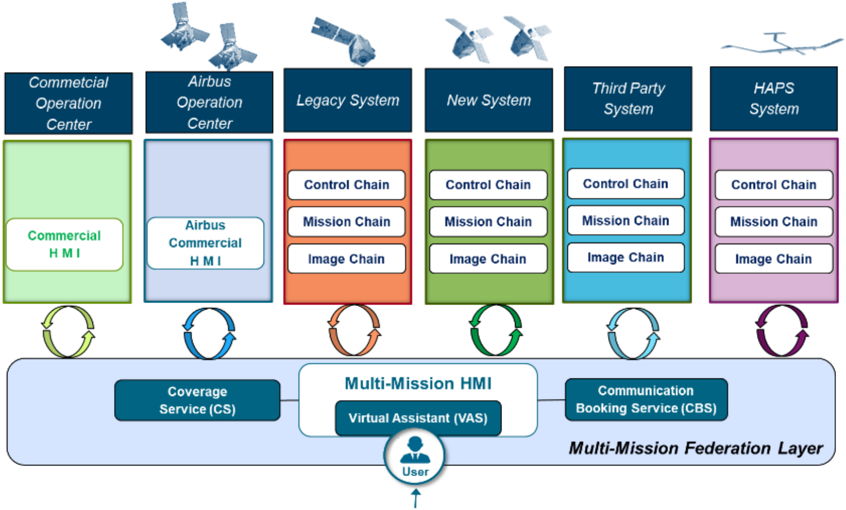


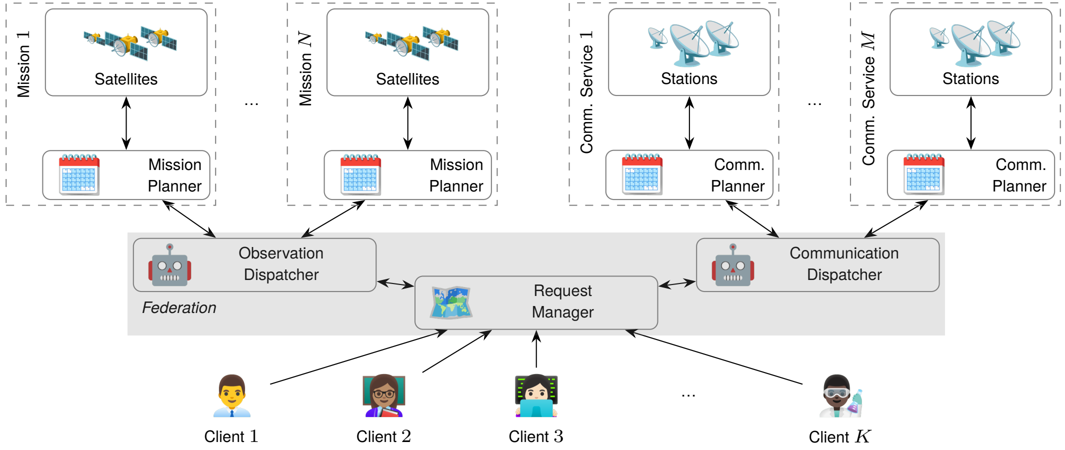
# DOMINO-E Approach

## Add a Federation Layer to Coordinate Multiple Systems



# DOMINO-E Approach (cont.)

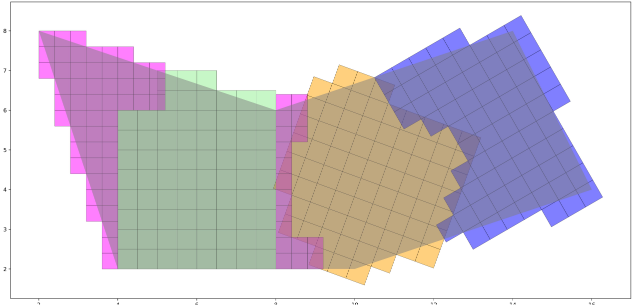
## Add a Federation Layer to Coordinate Multiple Systems



1. What are EOS Federations?
2. Federated Observations
3. Federated Communications
4. Wrap-up

# Federated Observations

*"How to divide a large area and to assign these subdivisions to different missions in order to minimize time of acquisition and maximize the quality of the images, even though we do not know the future workload of missions?"*



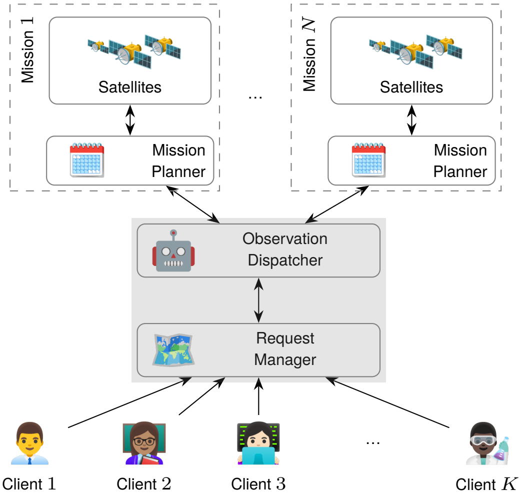
# Federated Observations

## System Composition

- $K$ end-users, referred to as *clients*, who request images over large areas on the Earth's surface
- $N$ observation agents, referred to as *missions* with own *planners*
- Objective = complete the observations requested by the $K$ clients using the $N$ observation missions available

$\rightarrow$ Dispatch observation tasks to missions than merge results

- Seamless access to numerous resources without having to care about details



# Federated Observations

## Multi-agent Decisions and Interactions

### Multi-agent negotiation [Kraus, 2001]

- Send queries for sub-areas to missions (that could accept or reject)
- Each sub-area is allocated to a specific mission

⚠️ The response time of a mission is high during the negotiation part

⇒ Surrogate model to assess the impact of including obs into mission schedules [Tuli et al., 2022]

### Combinatorial auctions [Cramton et al., 2006]

- Limit the number of interactions between the agents
- First phase: the missions to bid on possible observation sub-areas
- Second phase: observation tasks are dispatched given the bids received

⚠️ bidding system for each mission is time-consuming

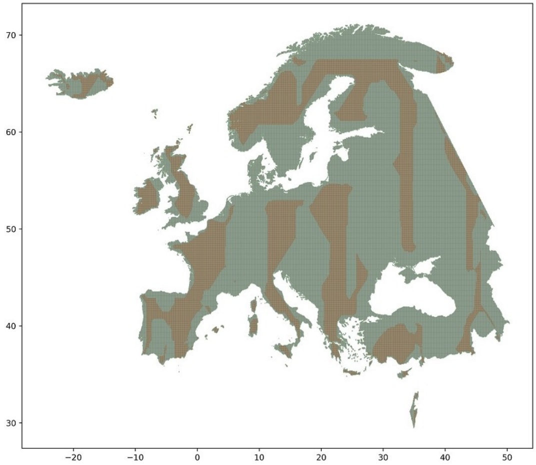
⇒ The federation skips the bidding phase and directly allocates observation tasks based on its current knowledge of the capacity and load of each mission (a surrogate model)

# Federated Observations

## Challenges

### Highly combinatorial problems

- Hundreds or thousands of requests, tens or hundreds of satellites, numerous ways to partition the area of each request into a set of sub-areas, etc.
- Study both coarse-grain dispatching strategies and fine-grain dispatching strategies
- Multiple objectives
- Compatibility between the requirements associated with each request and the capabilities of the missions



# Federated Observations (cont.)

## Challenges

*How to assess the load of each mission?*
*How to predict a mission response?*

### Need for a model of the other agents

- The federation must handle a model of the current capabilities of each mission
- Can be imprecise, especially for *external missions*
- Even for the *legacy missions*, the federation layer does not have a full control

⇒ *Learn a high-level model of the capabilities*

- Exploiting a model of the density of the high-priority requests

# Federated Observations (cont.)

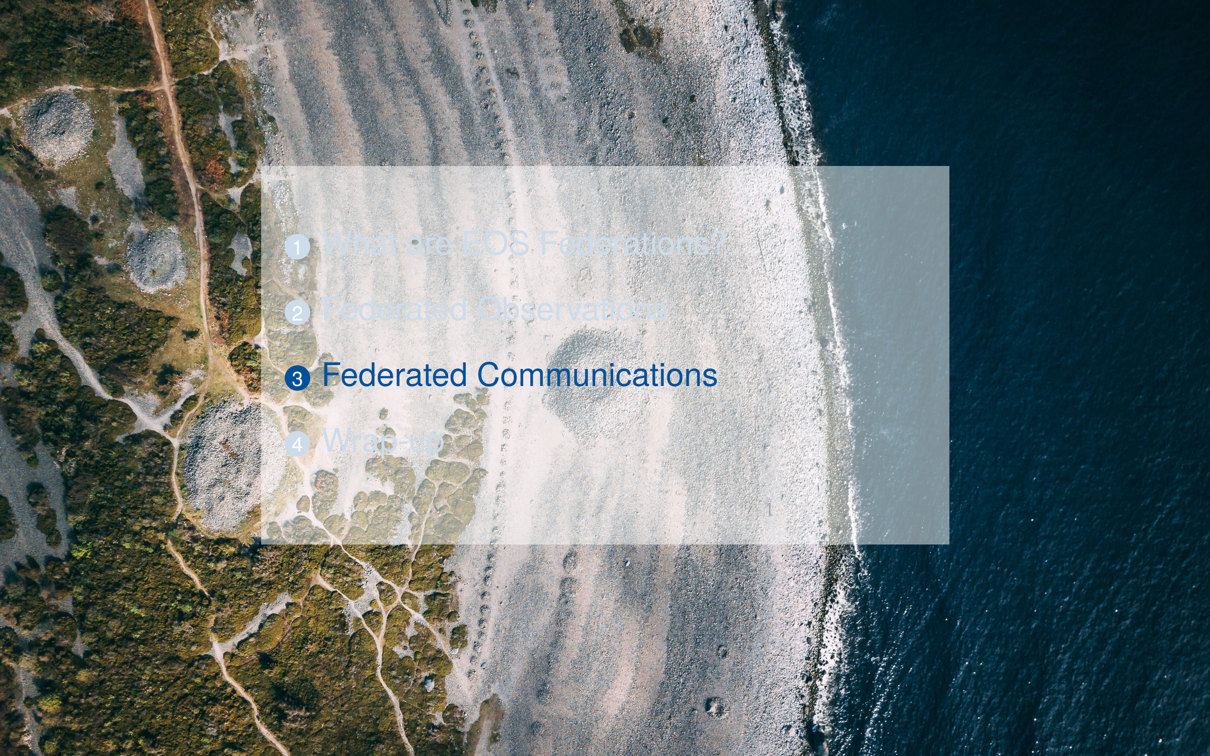
## Challenges

### Uncertainty management

- Various sources of uncertainty
- e.g. Clouds lead to failed images (approx. 50%) [Hadj-Salah et al., 2019]
- How to exploit short-term meteorological forecast
- How to exploit historical weather data

⇒ Learn a model of the *long-term reward* provided by a dispatching decision

⇒ Re-dispatch online to automatically update the coverage strategy based on the actual execution status



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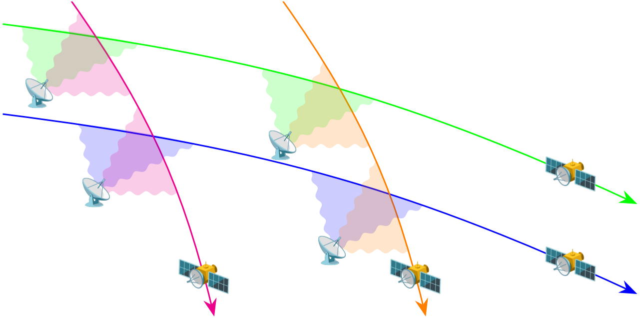
# Federated Communications

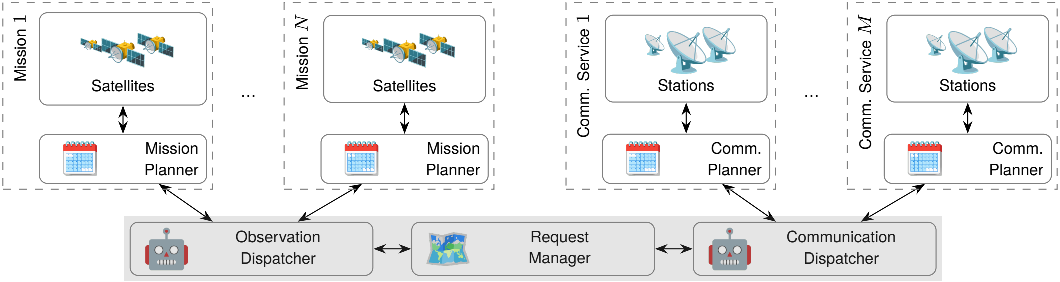
*”How to assign bundles of communication windows to satellites in order to meet data flow requirements, to minimize jamming, and to minimize costs induced by booking services?”*



# Federated Communications

## System Composition

- $N$ *satellites* (held by mission agents), seeking for communication windows for data transfer
- $M$ independent communication site agents, referred to as *sites*, implementing GSaaS interfaces
- Several *contacts* (communication opportunities) for each satellite-station pair
- Objective: allocating contacts to satellites of federated missions (optimizing costs and jamming)
- Pre-defined to respected when interacting with each GSaaS provider, based on an agreed SLA



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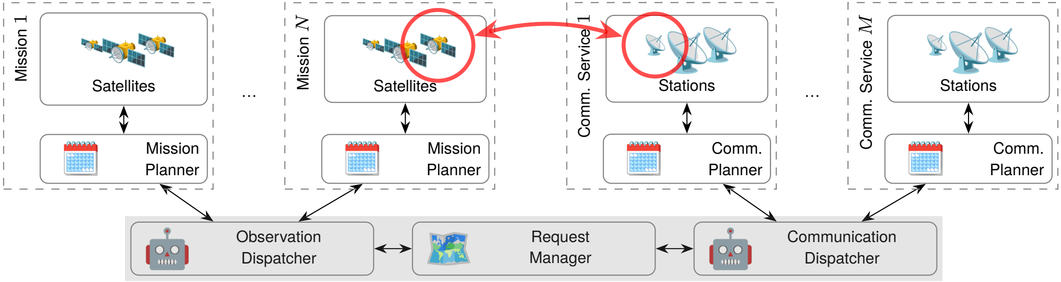

# Federated Communications

## Multi-agent Decisions

### Multi-Agent Resource Allocation [Chevaleyre et al., 2006]

- Allocating communication windows (contacts) to satellites for each request
- Each allocation generates non additive costs
- Each allocation generates non additive jamming

### Multi-Agent Planning [Shoham and Leyton-Brown, 2008]

- Planning satellites' communication activities
- Under visibility constraints
- Joint decisions may lead to jamming

⚠️ Jamming model is unknown (depends on external assets)

⚠️ Loads of some stations are unknown (GSaaS)

# Federated Communications

## Challenges

### Highly combinatorial problems

- Large number of satellites and contacts
- Long planning horizon ($>$ week)
- Multi-objective
- Externalities: individual utility strongly depends on other agents' bundles

$\Rightarrow$ Dedicated solution methods have to be devised

# Federated Communications (cont.)

## Challenges

### Need for a model of the other agents

- The federation must handle a load model of each GSaaS
- The federation must handle a jamming model for each pair of satellites

⇒ *Learning the probability of a contact request being rejected*

⇒ *Learning the jamming model*

- Handle strategic behaviors
- *Multi-Agent Reinforcement Learning* (MARL) problem [Albrecht et al., 2024]

*How to assess the load of each GSaaS?*
*How to predict a GSaaS response?*
*How to assess jamming?*

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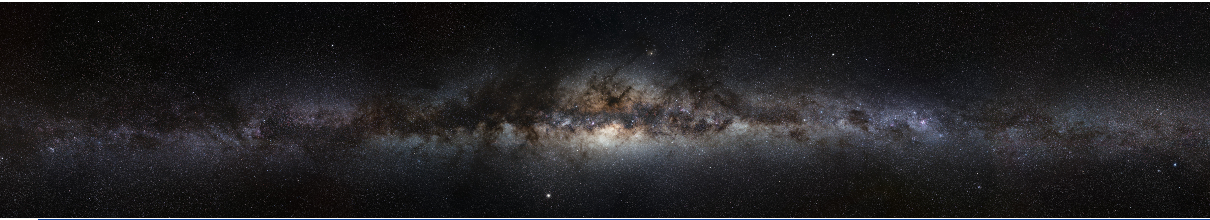
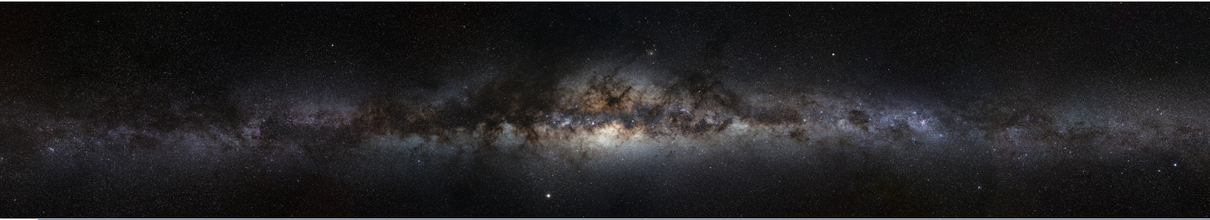
# Wrap-up

- Key terms for NewSpace: multi-asset, multi-user, multi-system...
- Asset sharing means **cost-efficiency**, but requires **automated coordination** and **privacy/sovereignity** preservation



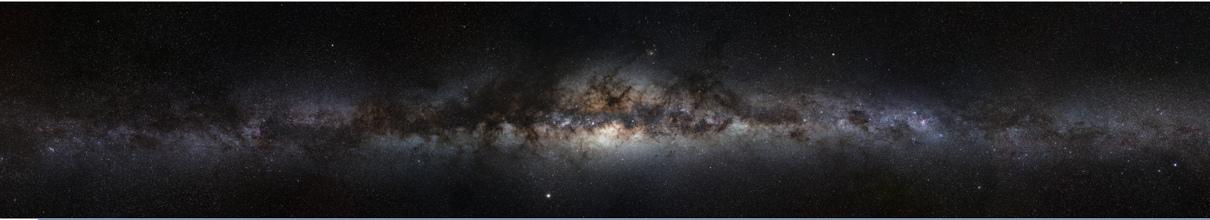
# Wrap-up(cont.)

- How to coordinate such composite systems?
  - Efficiency
  - Fairness
  - Explainability



# Wrap-up(cont.)

- How to coordinate such composite systems?
  - Efficiency
  - Fairness
  - Explainability
- Multi-agent Systems
  - Resource allocation and combinatorial auctions
  - Distributed optimization
  - Federated and multi-agent learning
  - …



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Thank you for your attention!

Any question?

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