34th Annual INCOSE international symposium

hybrid event

Dublin, Ireland
July 2 - 6, 2024

Application of Systems Engineering Methods to Expand and Enhance an Earth-sized Telescope

Black Hole Cinema

Outline

- Very brief primer on black holes & VLBI
- What's next for the EHT?
- Unique systems challenge
- Highlighted SE Process & Tools
  - System context diagram
  - Design process flow
  - Science traceability matrix
  - Tradespace model
  - Parameter space visualizations
  - System model, requirements, traceability

About me...

Garret Fitzpatrick
ngEHT Project Engineer
Smithsonian Astrophysical Observatory

B.S. Engineering Mechanics and Astronautics, University of Wisconsin-Madison

University College Cork, Ireland

Moscow International University, Russia

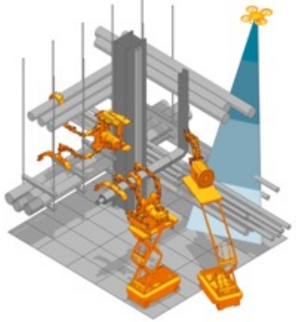
Crew Survival Systems Engineer, NASA Johnson Space Center

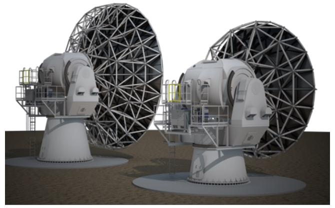
M.S. Science Writing, Massachusetts Institute of Technology

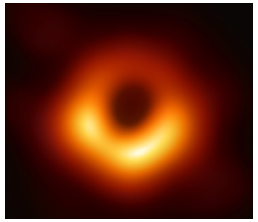
Indian Institute of Science, Bangalore, India

Lead Project Engineer, NASA Ames Research Center

Head of Products, Shell TechWorks



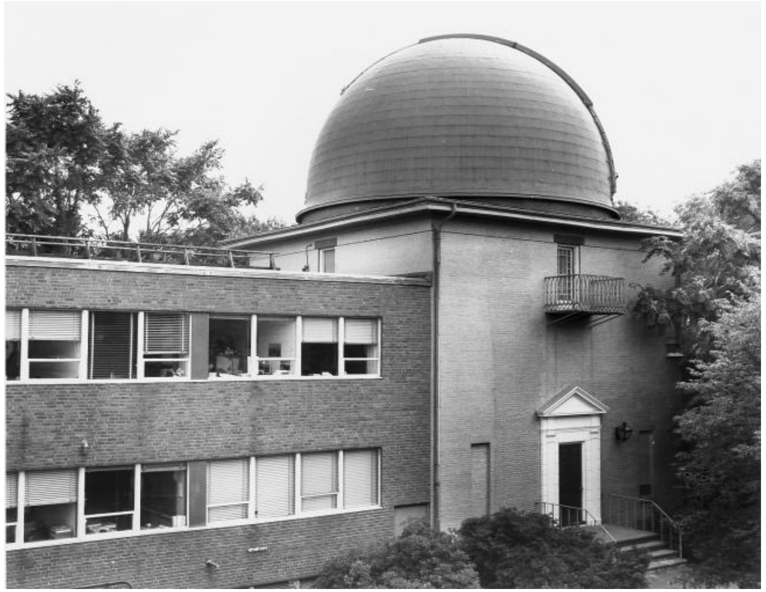




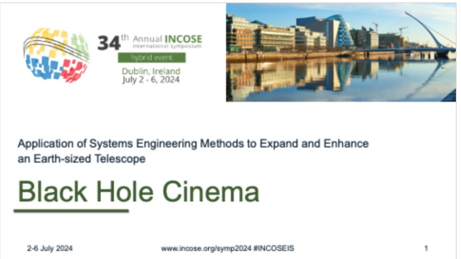
Project Engineer, Next Generation Event Horizon Telescope

Smithsonian Astrophysical Observatory

- Established in 1890 as a research unit of the Smithsonian Institution
- Formalized collaboration with Harvard University in 1973 as the Center for Astrophysics | Harvard & Smithsonian (CfA)
- Today one of the largest, most diverse astrophysical institutions in the world with key research areas in exoplanets, the sun and solar weather, **black holes**, pulsars, supernovae, white dwarfs, neutron stars and magnetars
- Facilities: Fred Lawrence Whipple Observatory (FLWO); Submillimeter Array Telescope (SMA) on Mauna Kea, Hawaii; Chandra X-ray Observatory



CENTER FOR
ASTROPHYSICS
HARVARD & SMITHSONIAN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2-6 July 2024
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1


M87 – 2019


What's the encore?
Goals
COMING SOON


Challenges
Everything seems simple
until you think about it.


System Context

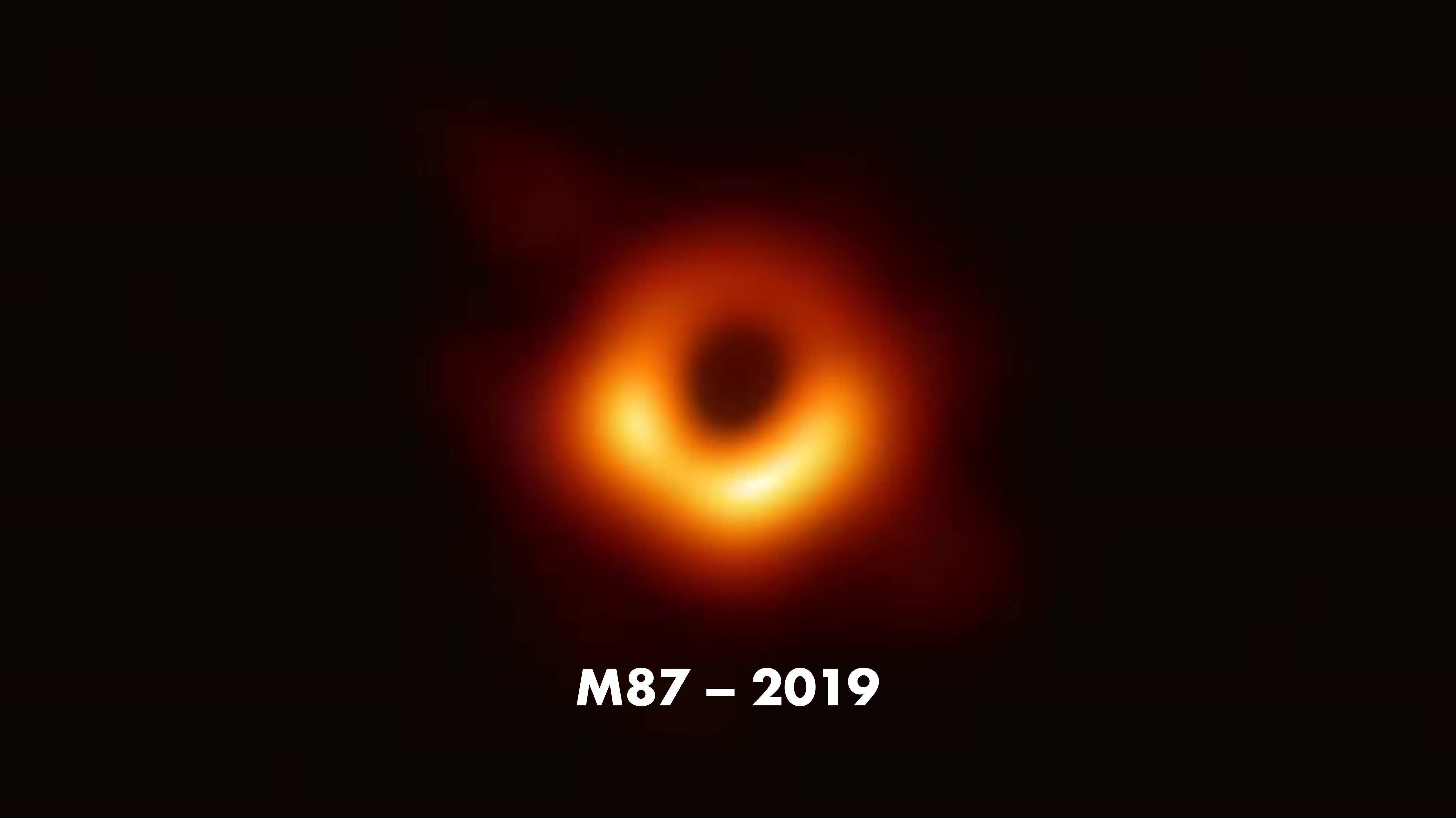

Design Process Flow


Tradespace Model
Tradespace Model


Ryan Chaves
Systems Engineer & Software Architect

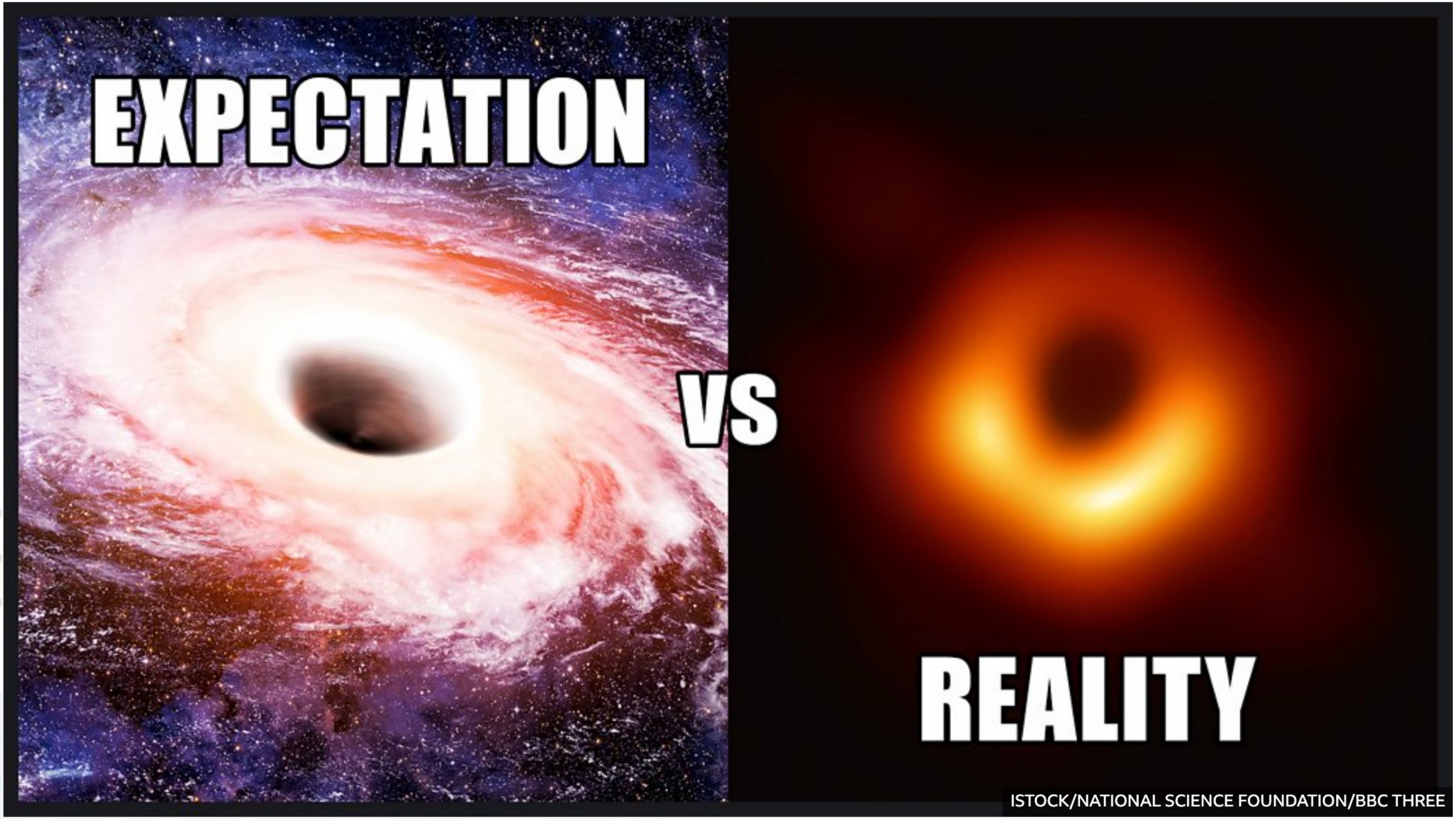

Summary


Backup



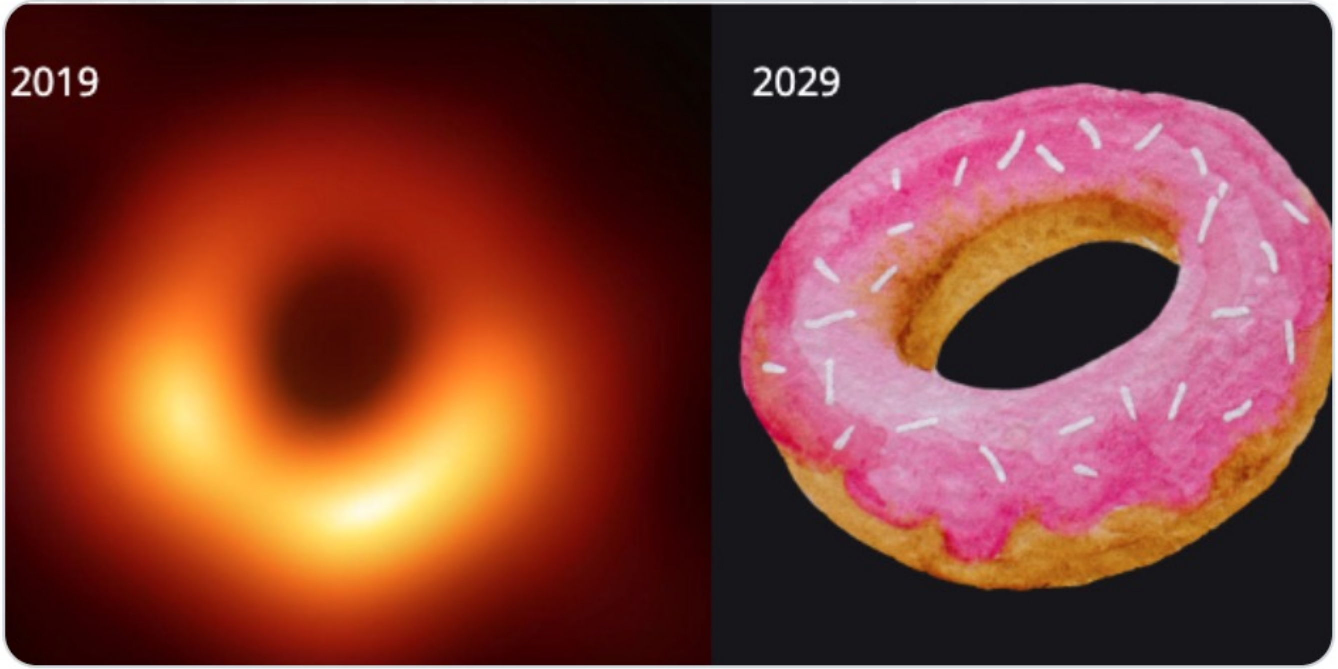
M87 – 2019

The first image of a black hole appeared on the front page of most major newspapers all over the world


EXPECTATION
VS
REALITY
ISTOCK/NATIONAL SCIENCE FOUNDATION/BBC THREE

Fakhar Khalid
@FakharKhalid

I am sure the spatial resolution of the #blackhole images will get better in future.



9:39 AM · Apr 10, 2019

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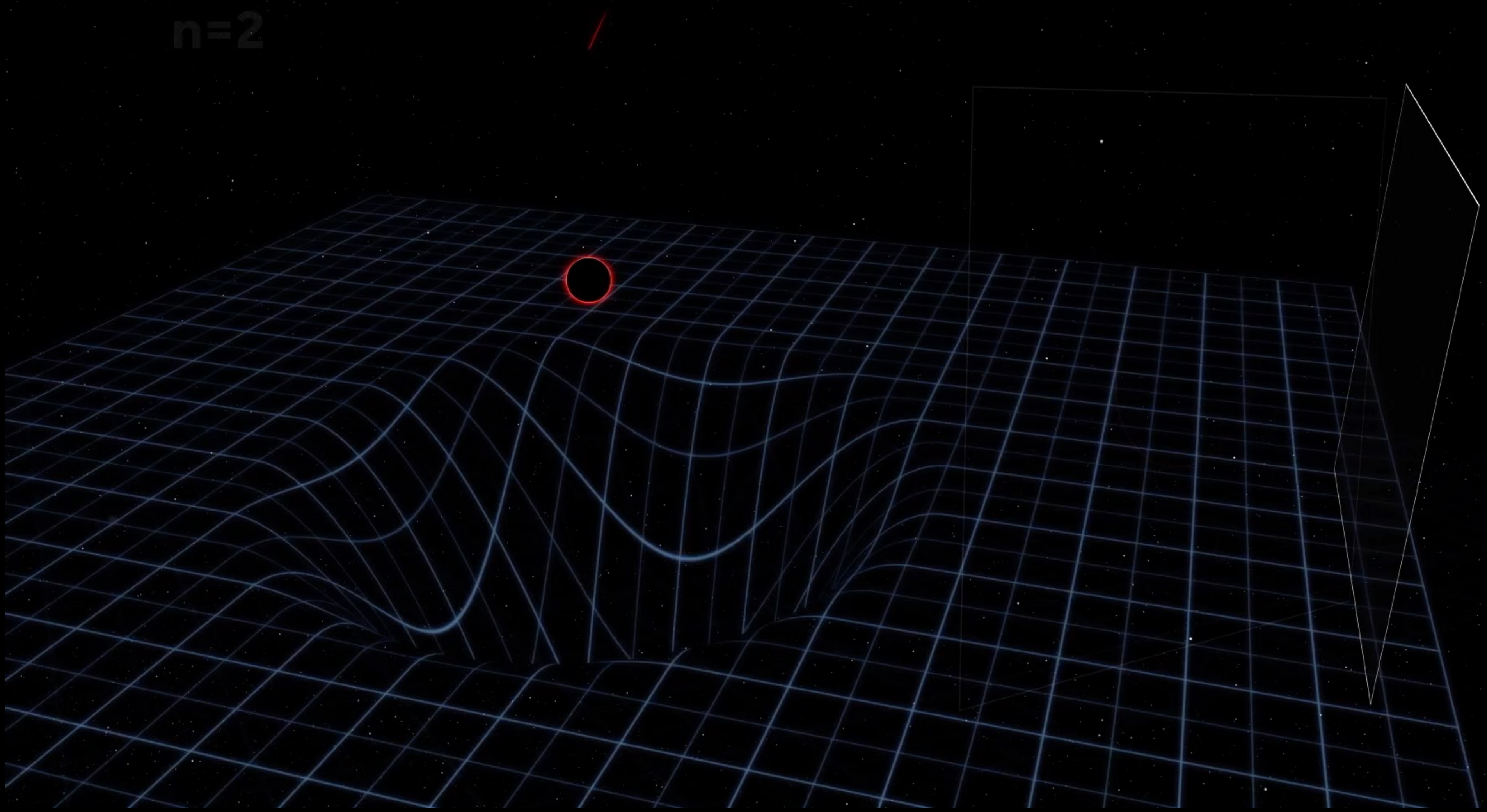
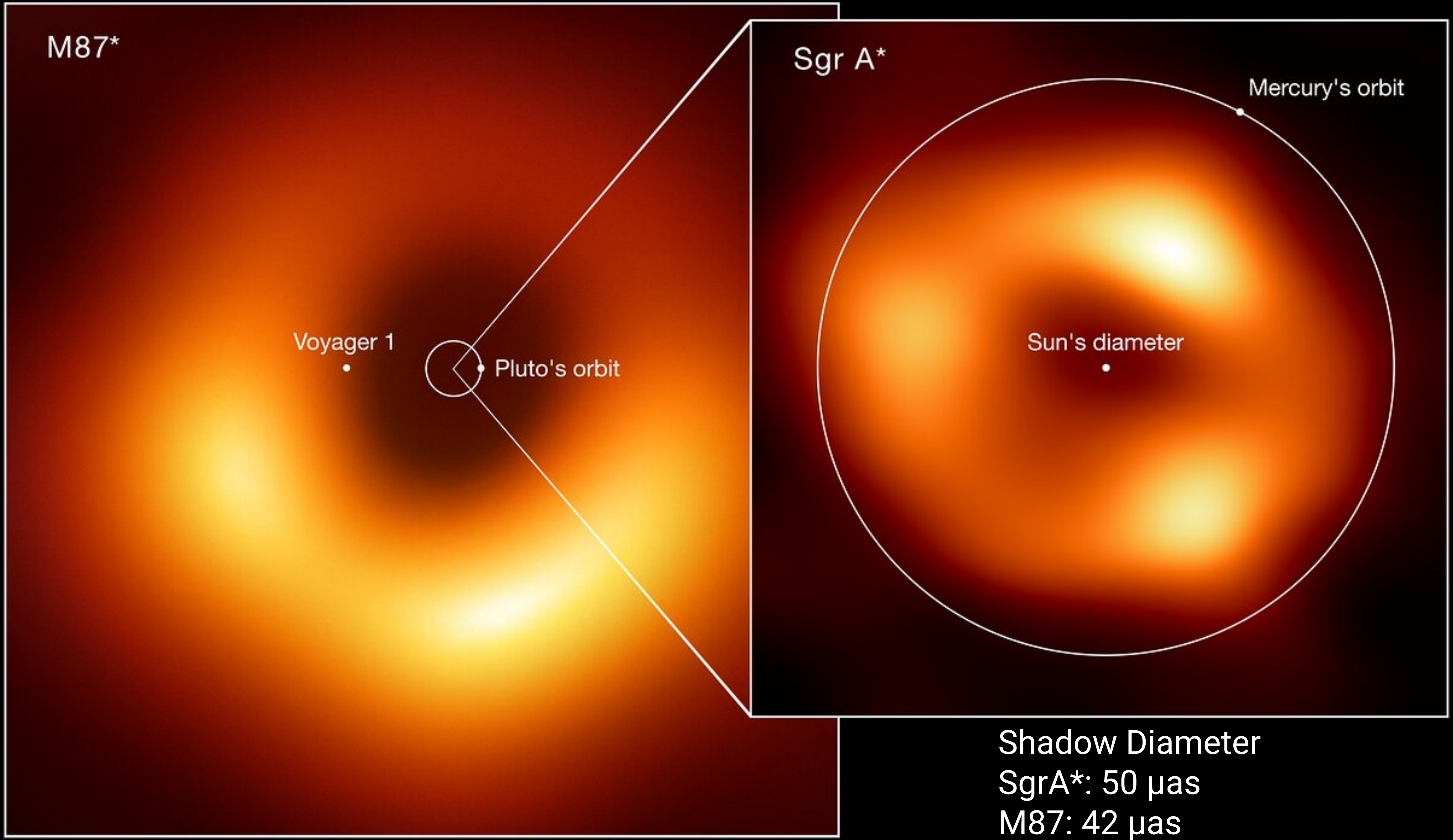
Why was it such a breakthrough?

- Light can't escape a black hole… so how do you see it?
- A whole new laboratory – and a whole new field – for astrophysics
- Highest angular resolution of any astronomical facility
- It took a telescope the size of the Earth to make it happen!

How do you see the unseeable?
A quick primer on black holes & Very Long Baseline Interferometry!

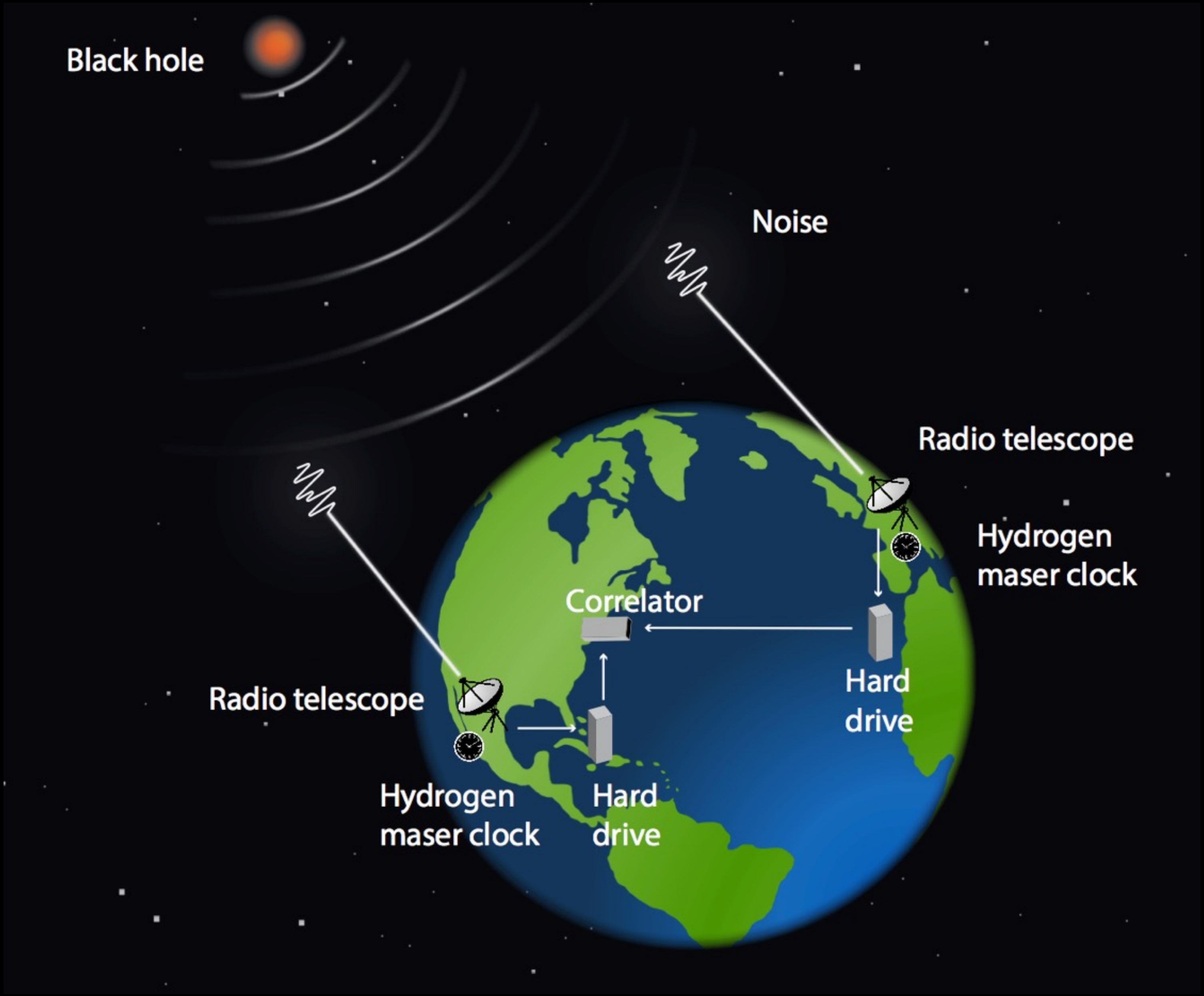




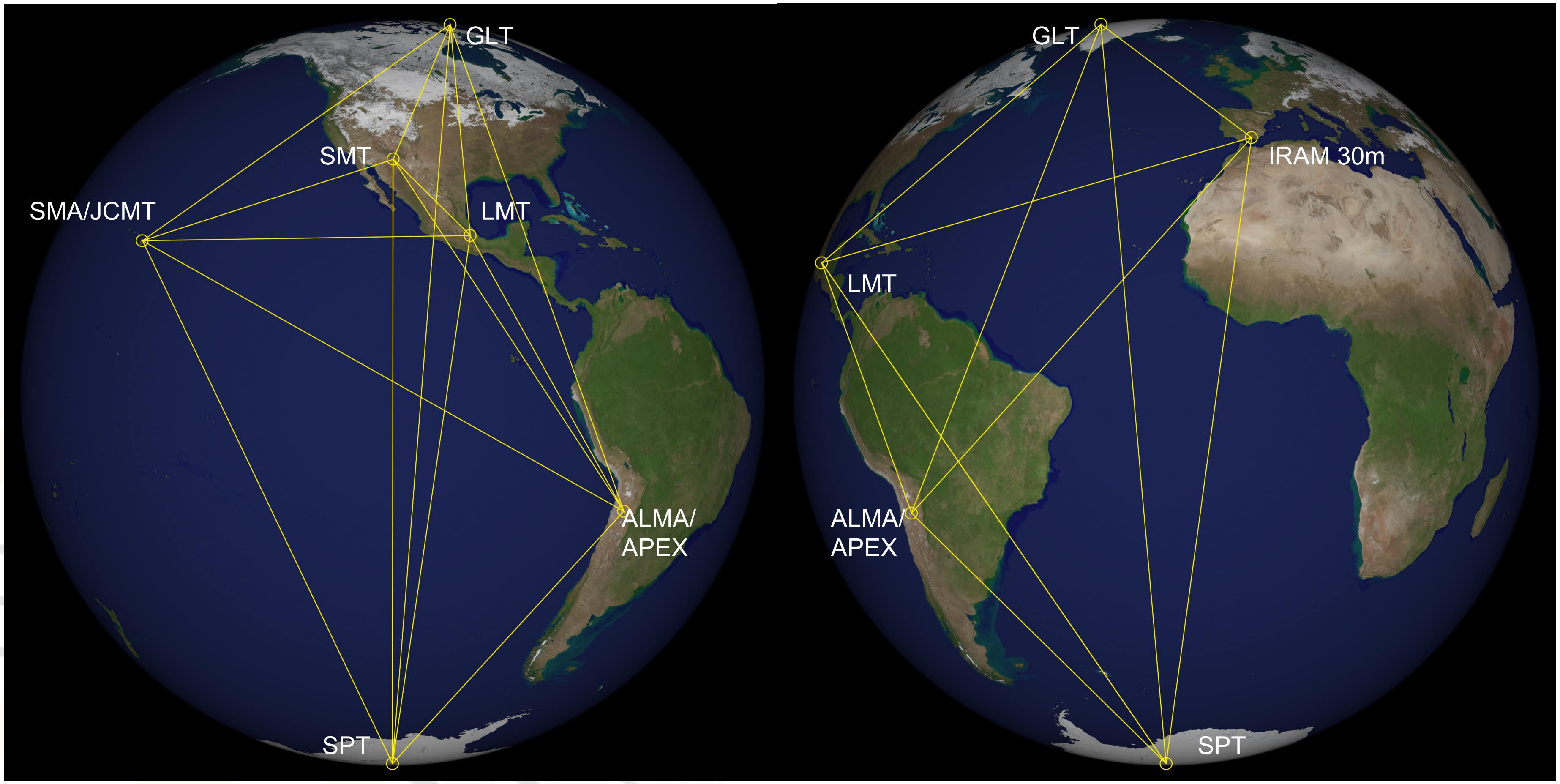
Shadow Diameter
SgrA*: 50 μas
M87: 42 μas

Angular Resolution $\approx \frac{\lambda}{D}$

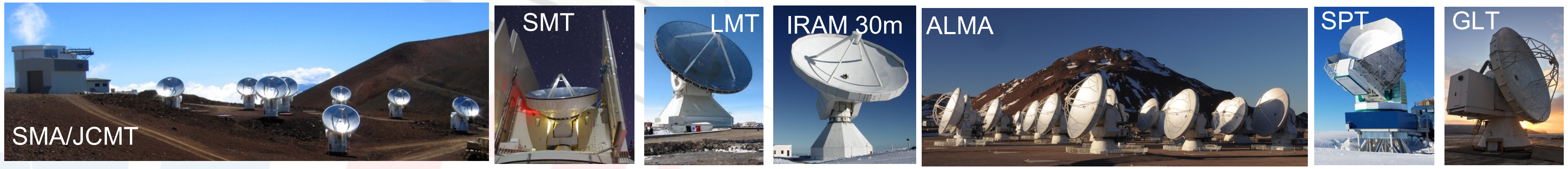
- Seeing to the event horizon requires a wavelength of λ ~ 1mm to see through all the clouds of dust and gas
- Need angular resolution of ~20 μas to resolve the biggest supermassive black holes, which means the diameter of your telescope needs to be ~ 10,000km
- Luckily, there's a technique for this: Very Long Baseline Interferometry (VLBI)



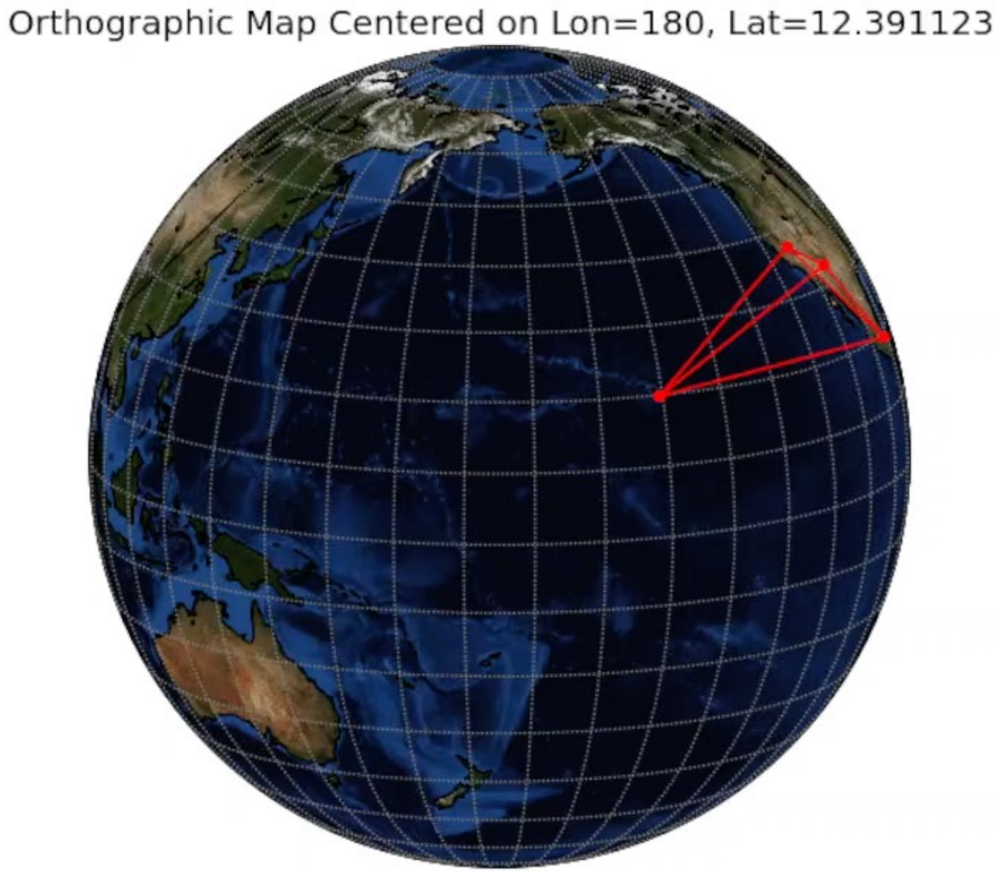
Event Horizon Telescope in 2018

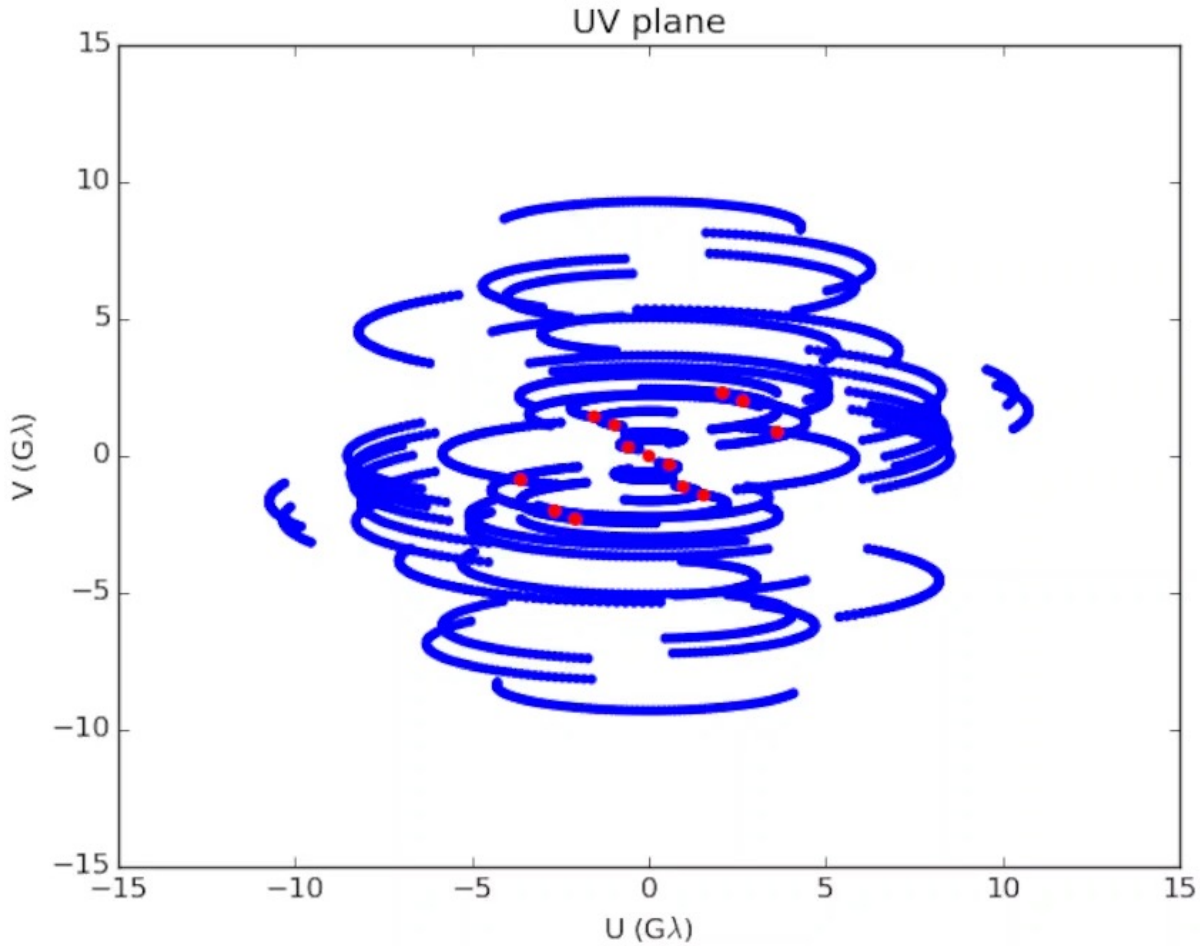


D. Marrone/UofA



We use the rotation of the Earth and the combination of pairs of telescopes to collect data that can be used to piece together an image





What's the encore?

Goals

- First ever black hole cinema!
- New science goals beyond the horizon

Current EHT Limitations

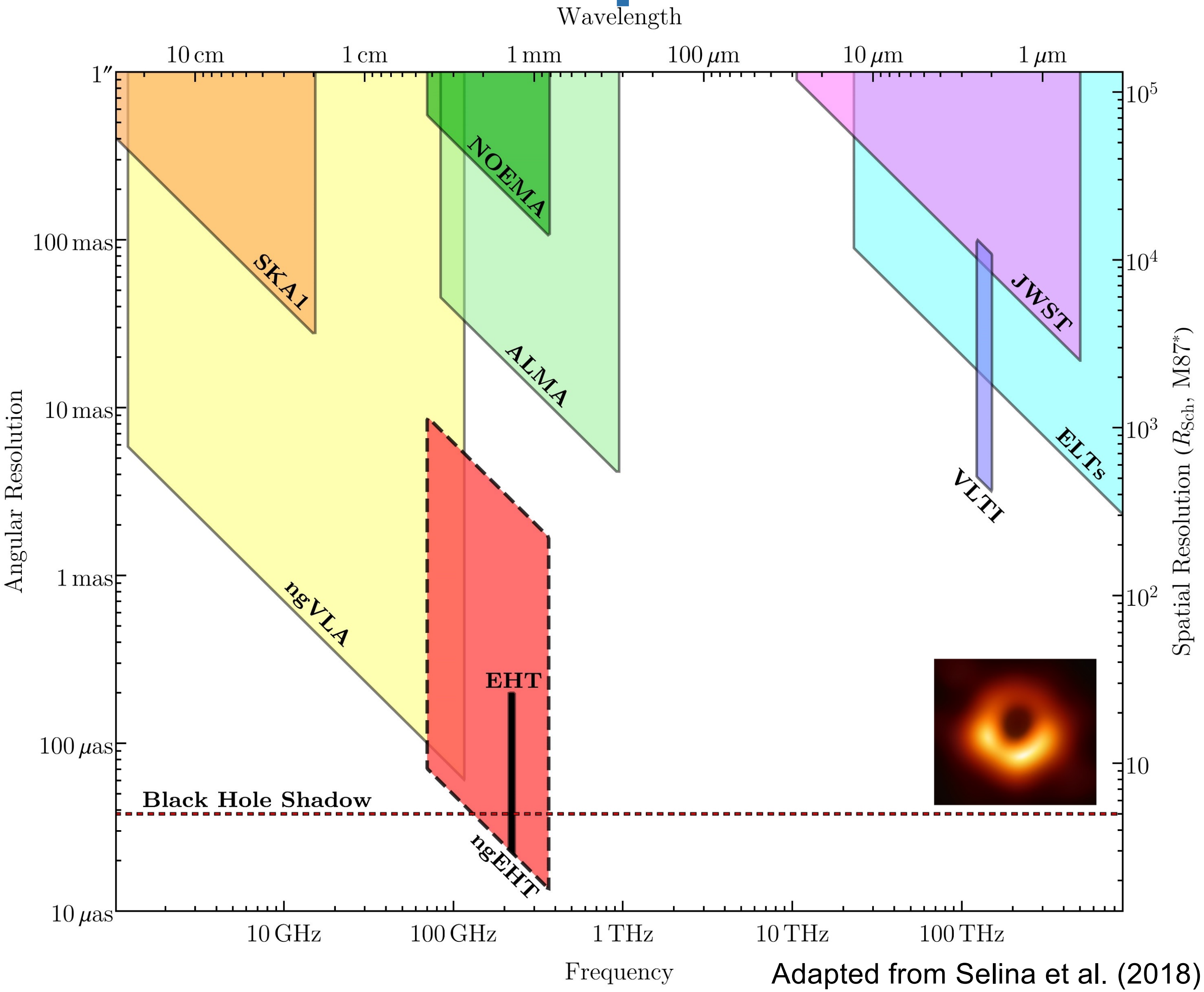
- Imaging capabilities (resolution, field of view, dynamic range)
- Range of accessible timescales (both long and short)
- Sensitivity to persistent structures (e.g., gravitational features)
- Number of observable sources

Next Generation Array Concept

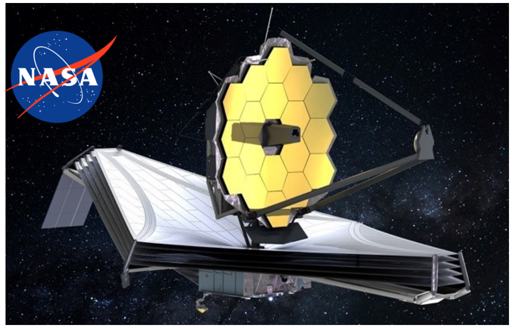
- **New dishes:** new antennas to the array at optimized geographic locations
- **Multi-frequency:** simultaneous multi-frequency observations across the 86/230/345 GHz bands (i.e. new receiver subsystems)
- **Wider bandwidth:** increasing the recorded data rates across the array to capture wide bandwidths (16 GHz per polarization) (i.e. new backend subsystems)
- **Multi-epoch:** opening a new "monitoring" operating mode and associated data pipeline that will enable observations to be carried out for multiple months of the year (i.e. new operating modes and data pipeline)

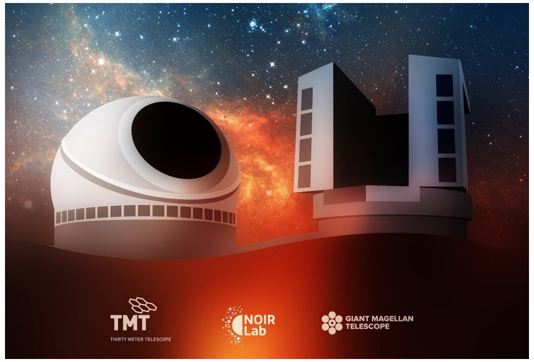
Collectively, these upgrades will double the instantaneous sensitivity per baseline, triple the frequency coverage of the array, increase the effective number of baselines by a factor of ~5, and expand the range of accessible timescales by multiple orders of magnitude compared to optimal EHT capabilities as of 2024

Next Generation Telescopes

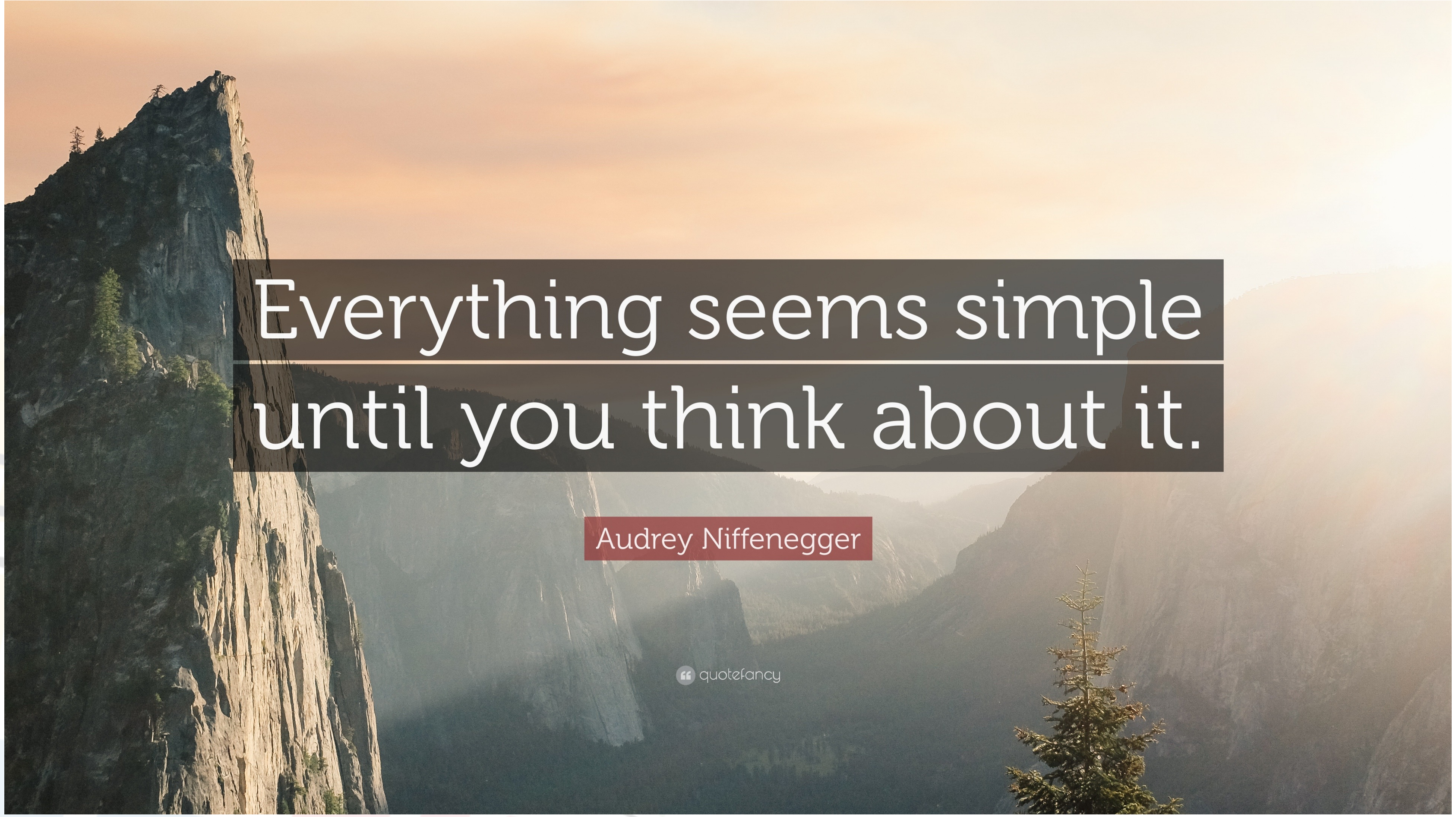


Adapted from Selina et al. (2018)

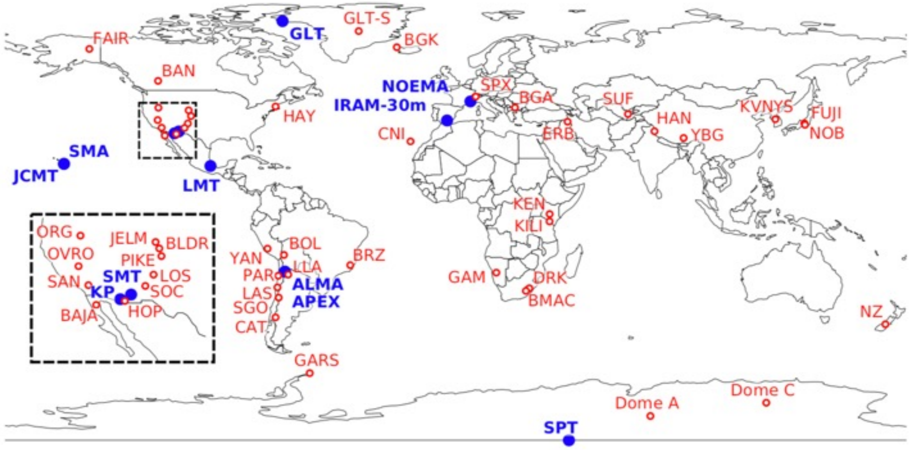


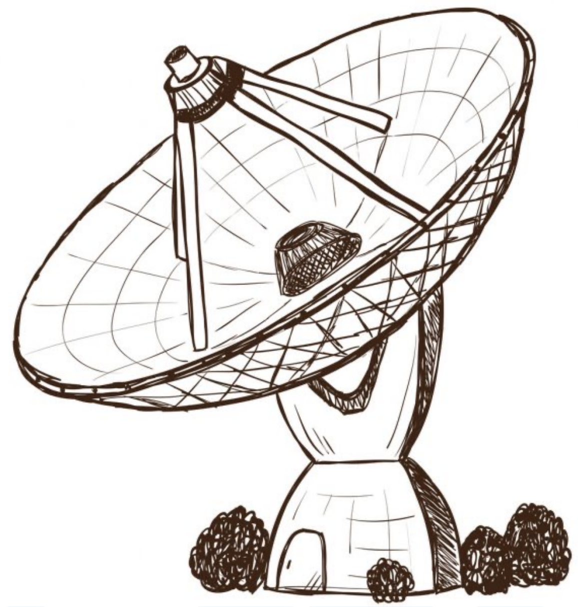


Challenges


Everything seems simple
until you think about it.
Audrey Niffenegger
quotefancy

Getting from Here to There

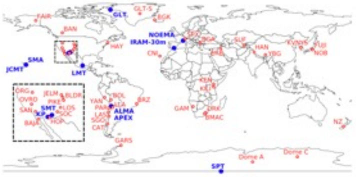


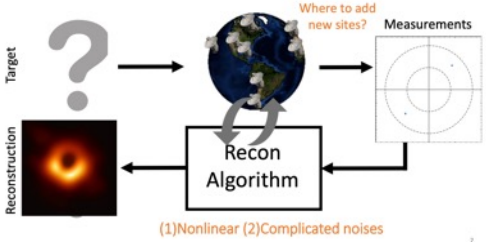


Getting from Here to There

Science Traceability Matrix

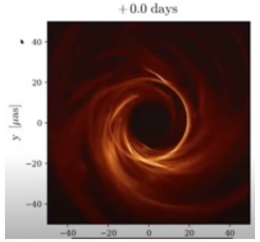
Array Optimization

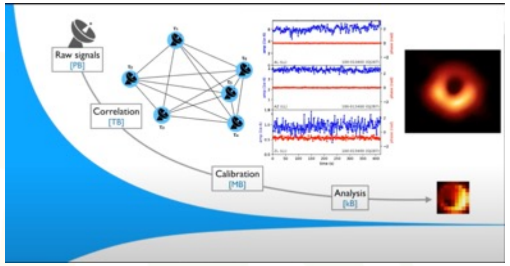




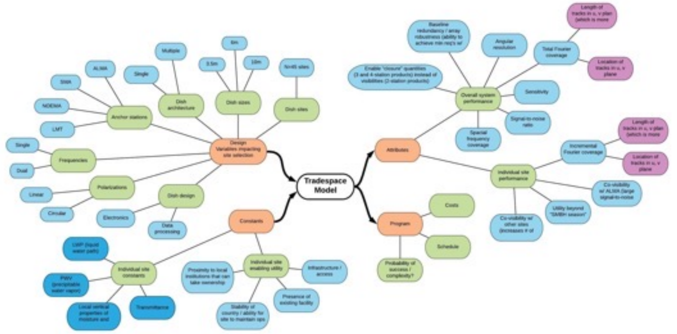
Imaging Reconstruction

Modeling & Simulations



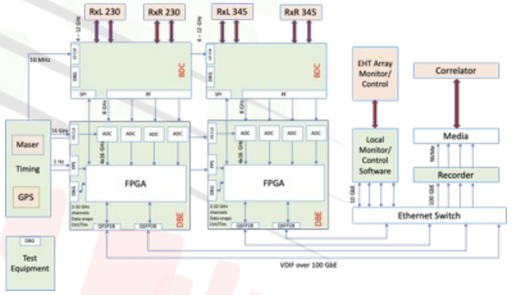


Data & Calibration Pathway



Tradespace Exploration

Cost Model

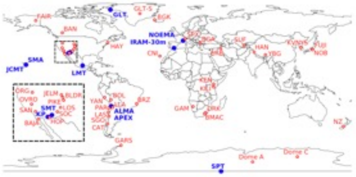


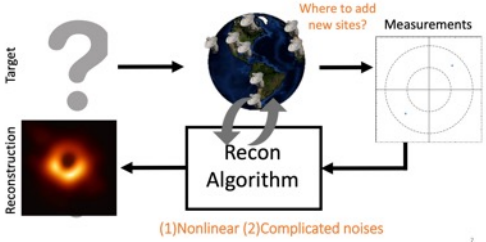
Instrumentation

Getting from Here to There

Science Traceability Matrix

Array Optimization





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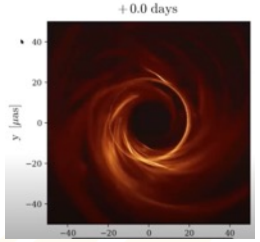
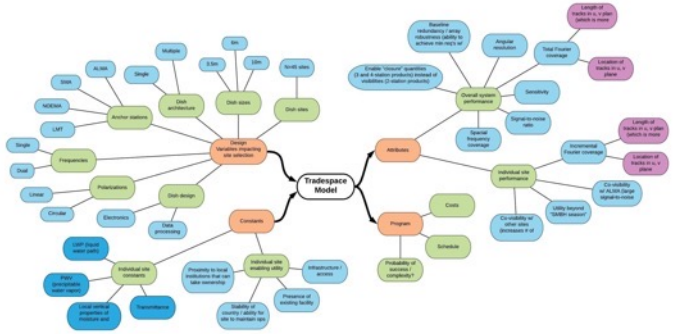
Modeling & Simulations





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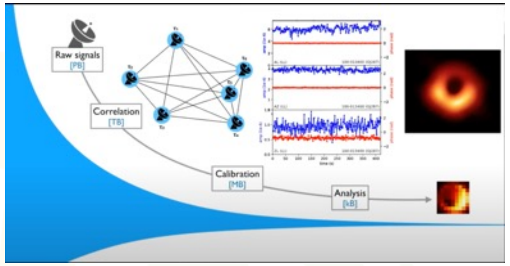

Data & Calibration Pathway

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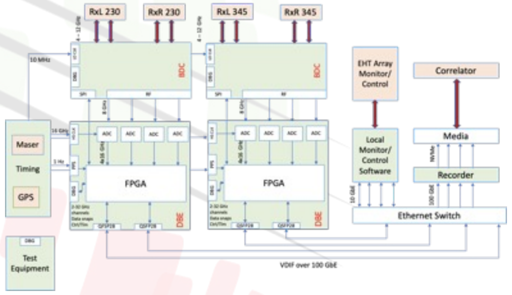


Instrumentation





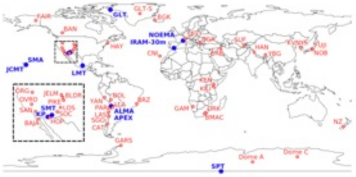


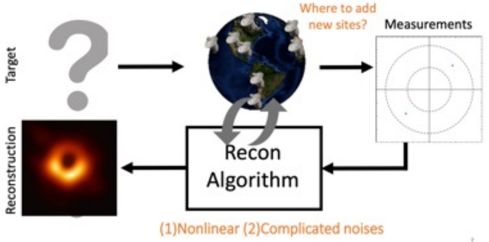



Getting from Here to There

Science Traceability Matrix

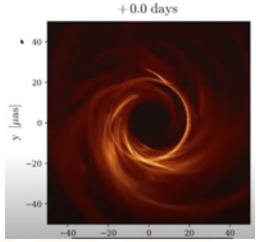
Array Optimization

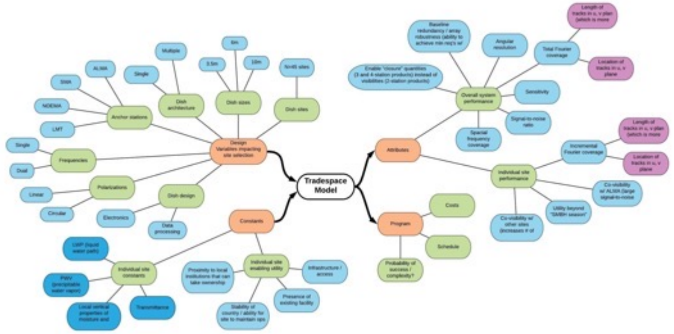




Imaging Reconstruction

Modeling & Simulations





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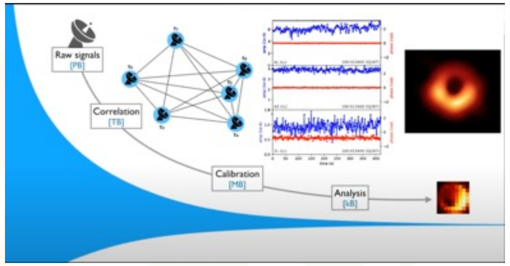
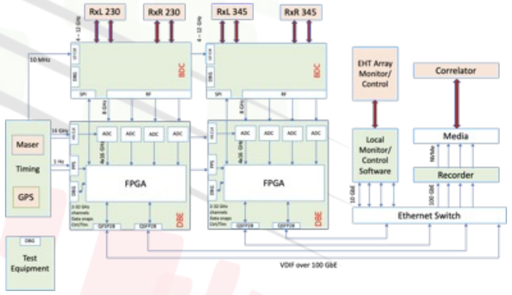


Data & Calibration Pathway

Cost Model

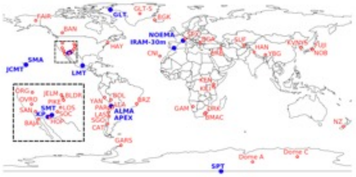


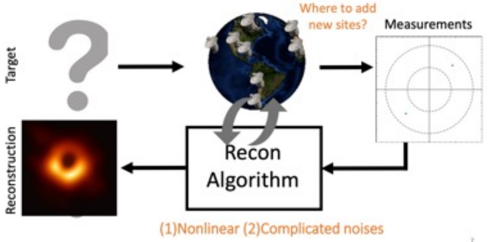
Instrumentation

Getting from Here to There

Science Traceability Matrix

Array Optimization





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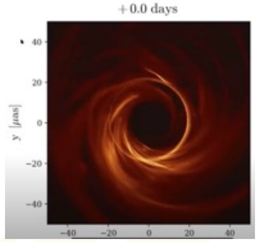
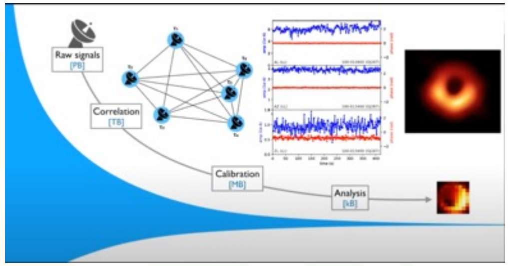
Modeling & Simulations





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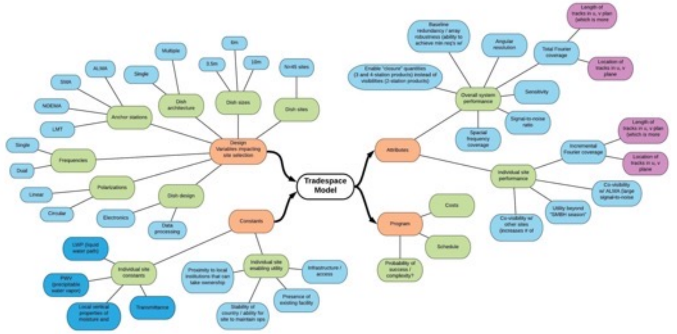
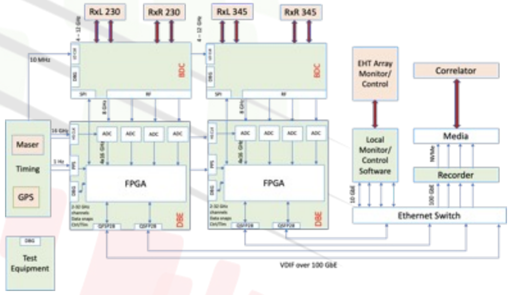


Tradespace Exploration

Cost Model



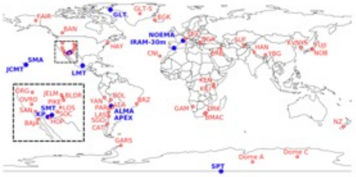
Instrumentation

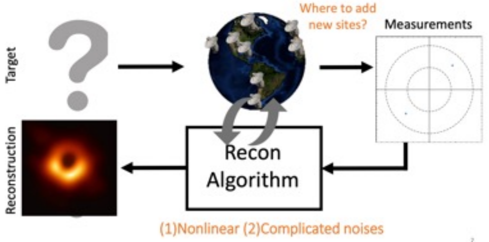
Time

Getting from Here to There

Science Traceability Matrix

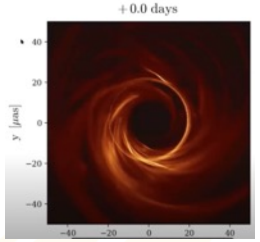
Array Optimization

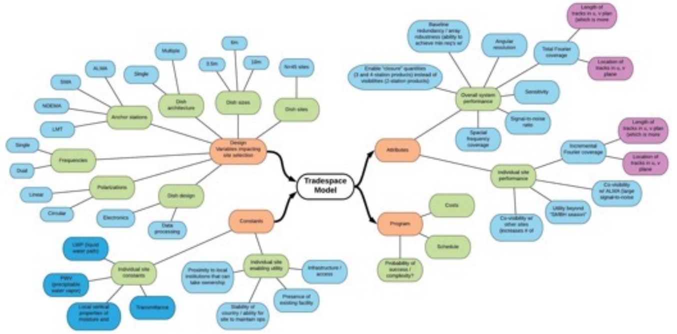




Imaging Reconstruction

Modeling & Simulations





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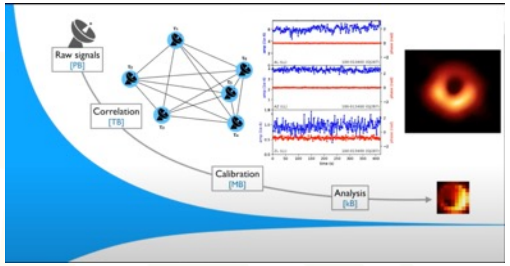
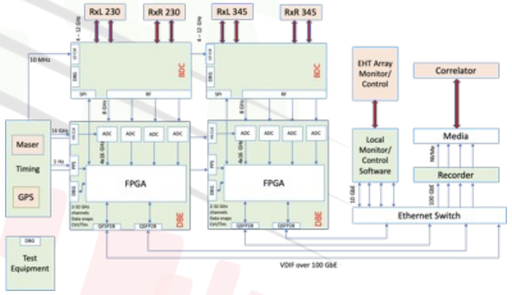
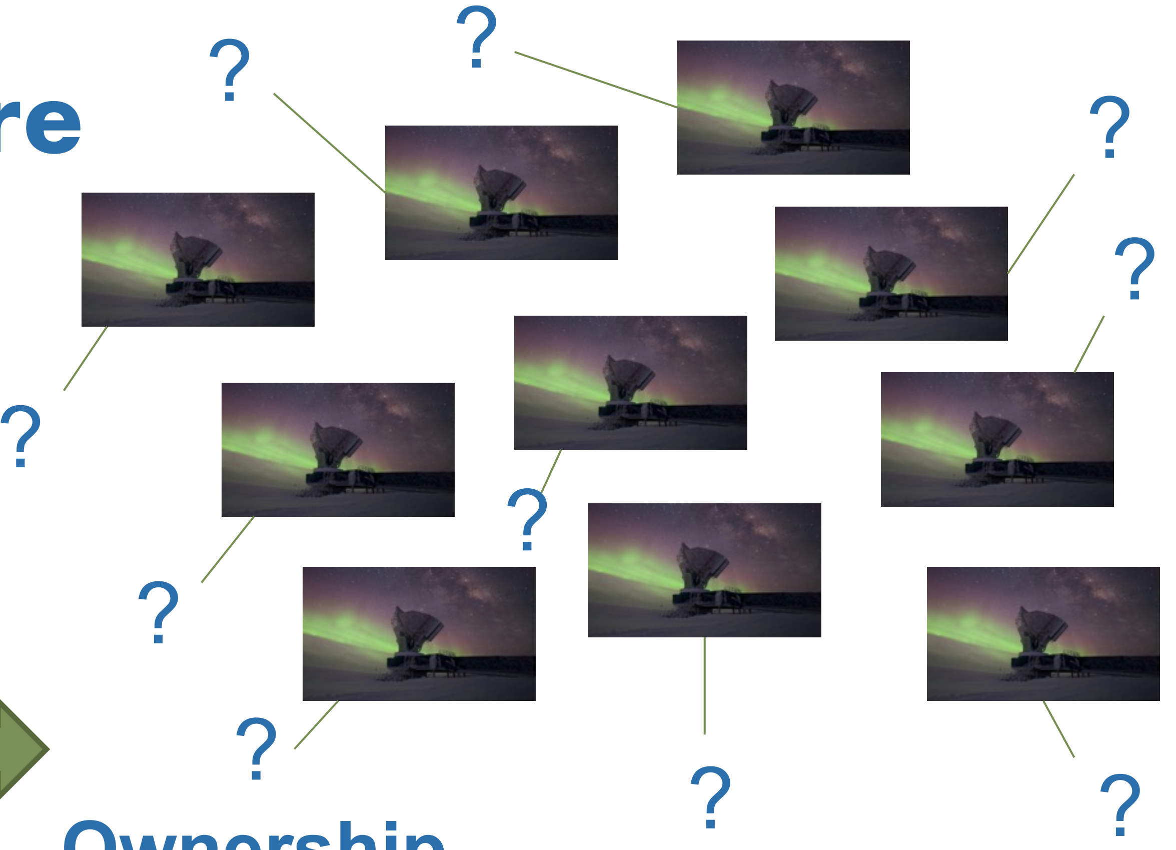


Data & Calibration Pathway

Cost Model



Instrumentation



Ownership

Getting from Here to There

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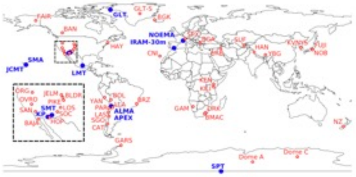
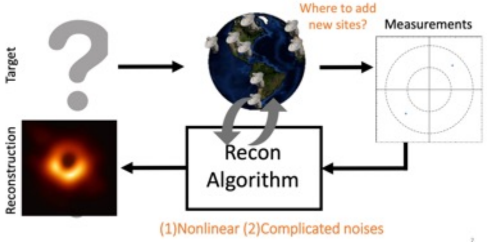
Array Optimization





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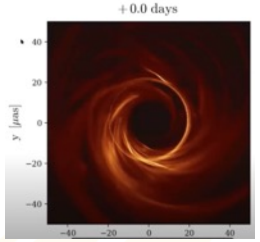
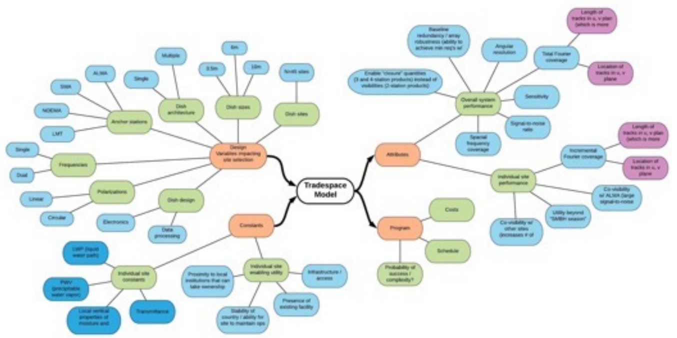
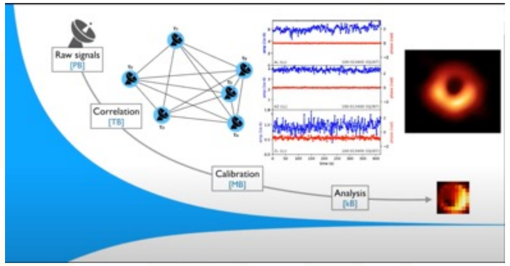
Modeling & Simulations



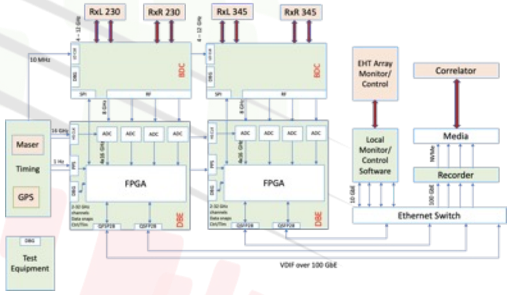


Tradespace Exploration



Data & Calibration Pathway

Cost Model



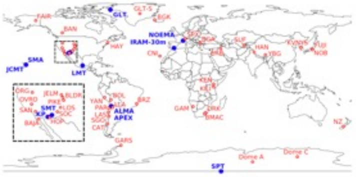
Instrumentation

Technical

- Unconstrained system boundaries
- Complex system optimization problem
- Simultaneous tri-band observing
- 4x increase in observing time
- 4x increase in recording bandwidth
- 10x increase in data throughput
- Bottlenecks in existing data pipeline
- Interoperability with legacy systems
- Robustness over longer durations to the loss of any given station throughout an observation
- System of systems (system of array as a whole + system of each individual station)

Getting from Here to There

Science Traceability Matrix



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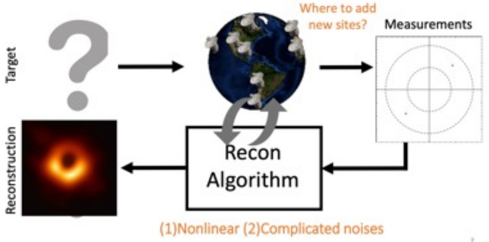

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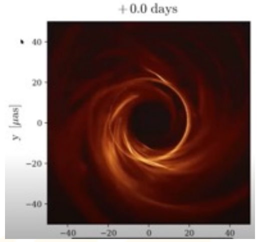
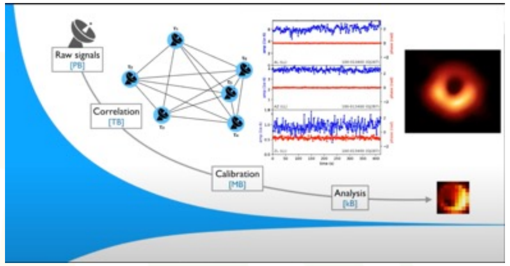
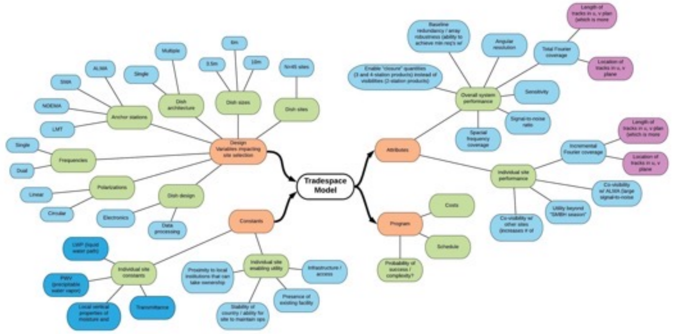


Modeling & Simulations

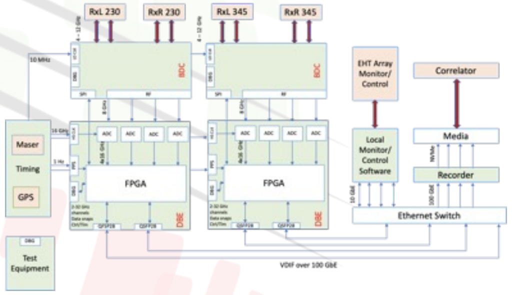


Data & Calibration Pathway



Tradespace Exploration

Cost Model



Instrumentation

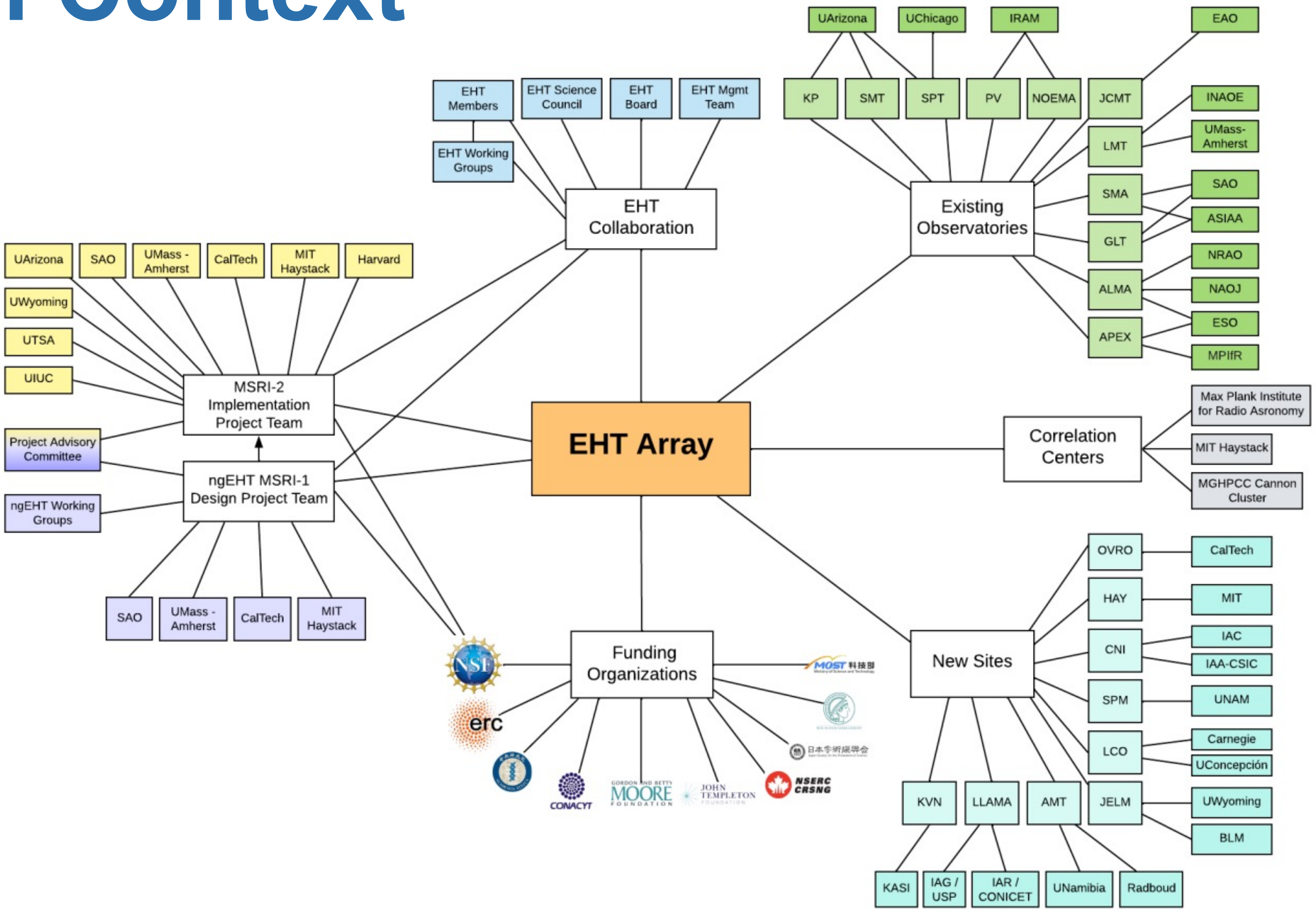
Non-Technical

- Managing an engineering design and construction project within an academic environment
- Coordinating construction and logistics in multiple countries simultaneously
- Structure of international collaboration and operating model
- Complex stakeholder landscape
- Desire to take advantage of the "splash" momentum of the first black hole image
- Politics…

It all adds up to…

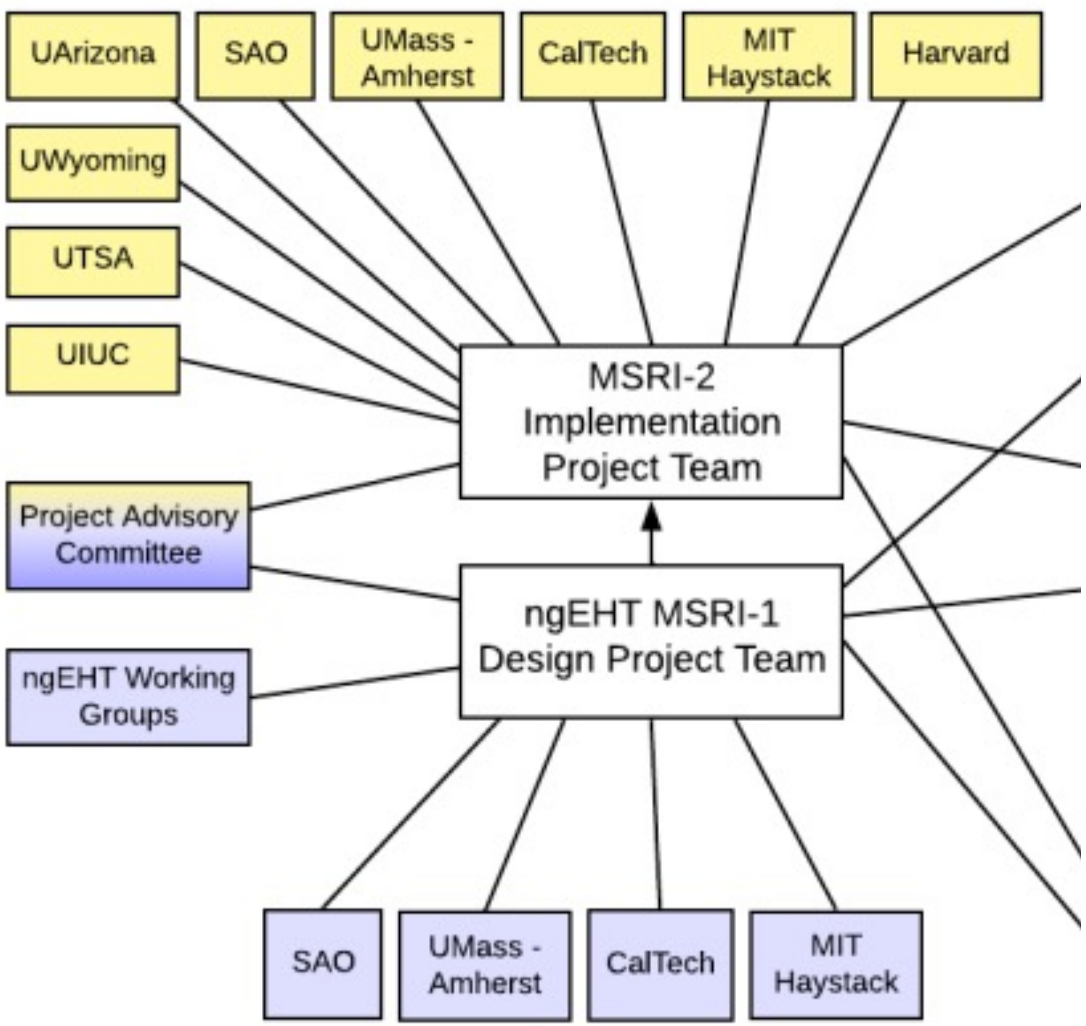
… an amazingly interesting systems challenge!

System Context

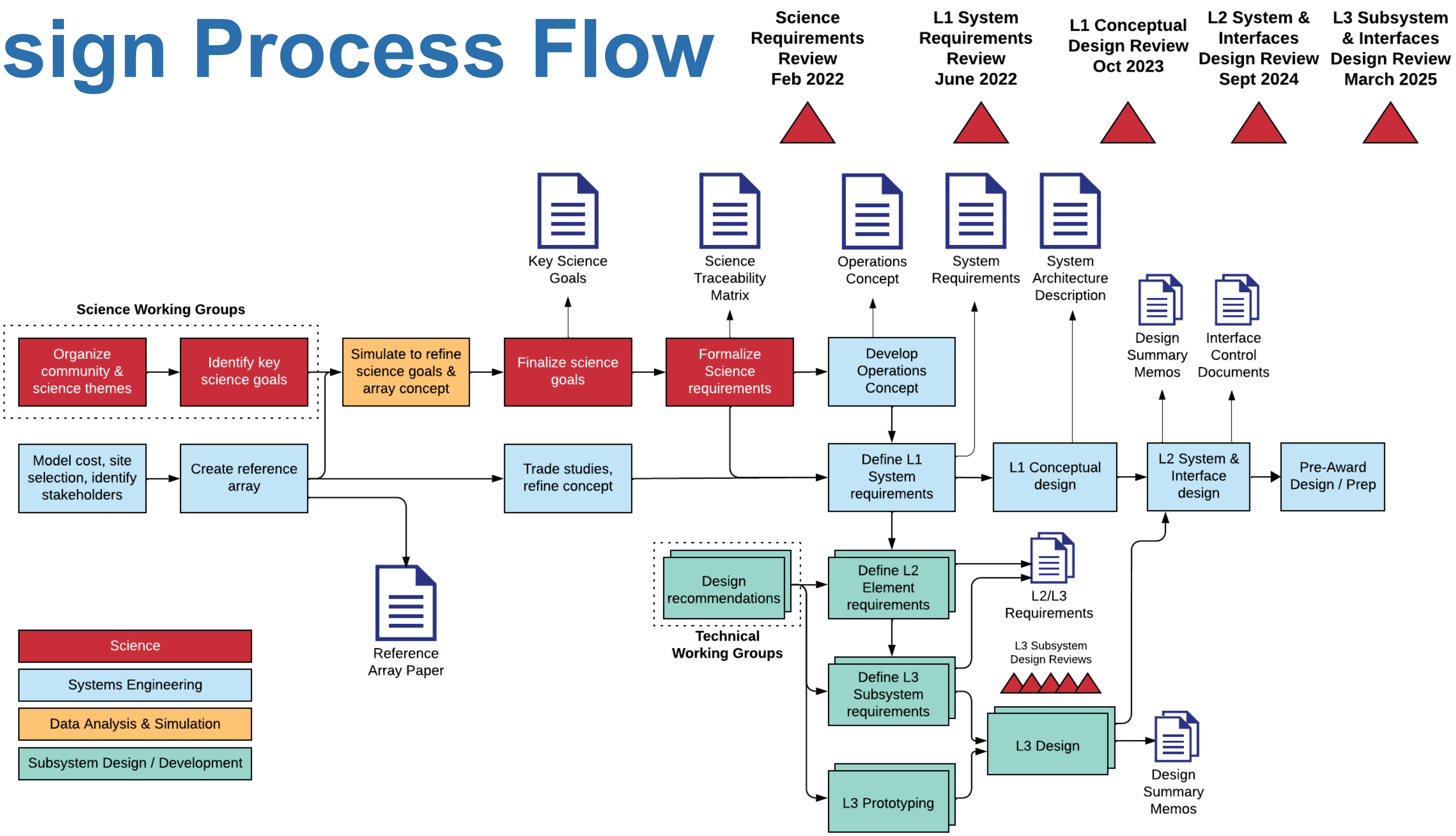


System Context

- US-driven upgrade with multiple partners for separate design and implementation projects
- Stakeholders include:
  - Funding organizations
  - EHT Collaboration Board, Management Team, members
  - Existing observatories and their funding / operating institutions
  - New sites and their local and national construction / environmental permitting agencies
  - Correlation centers

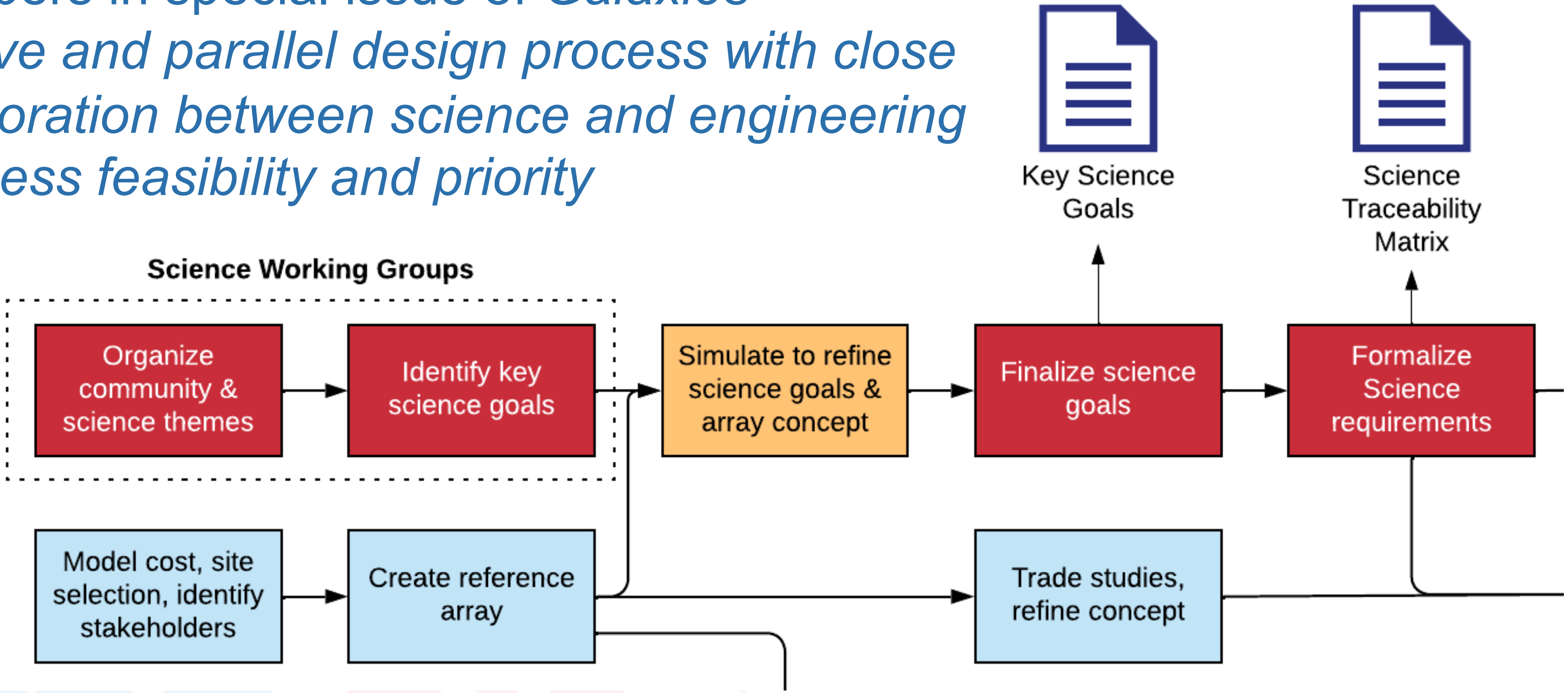


Design Process Flow

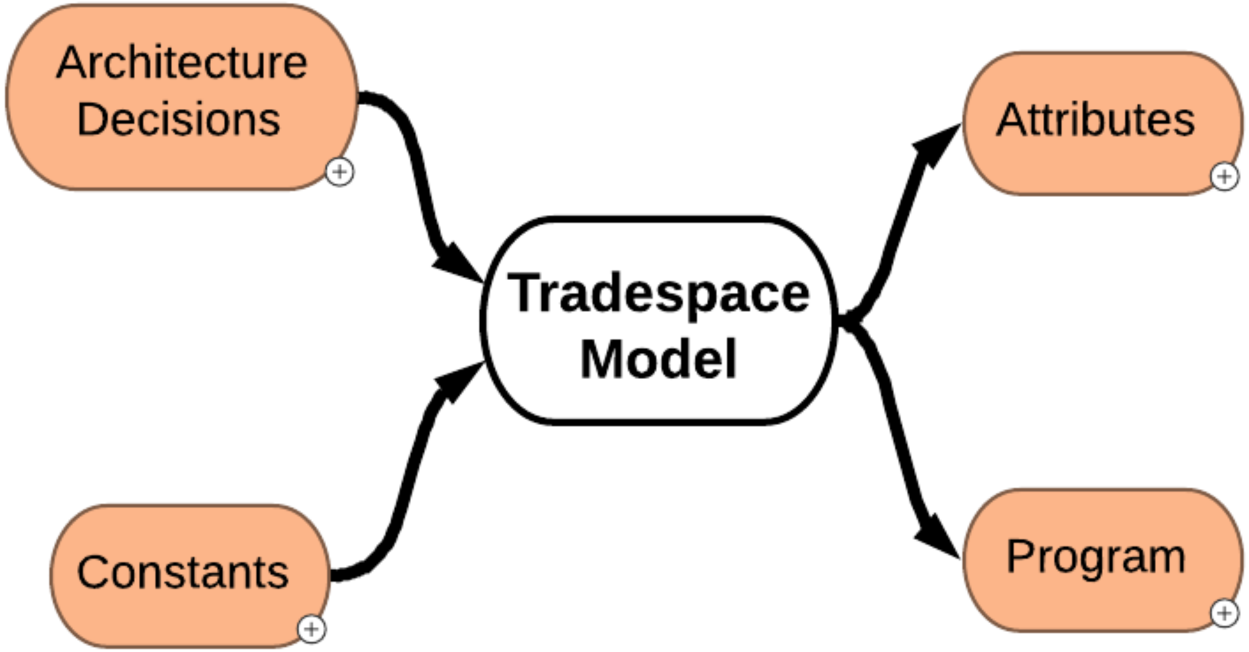


Design Process Flow

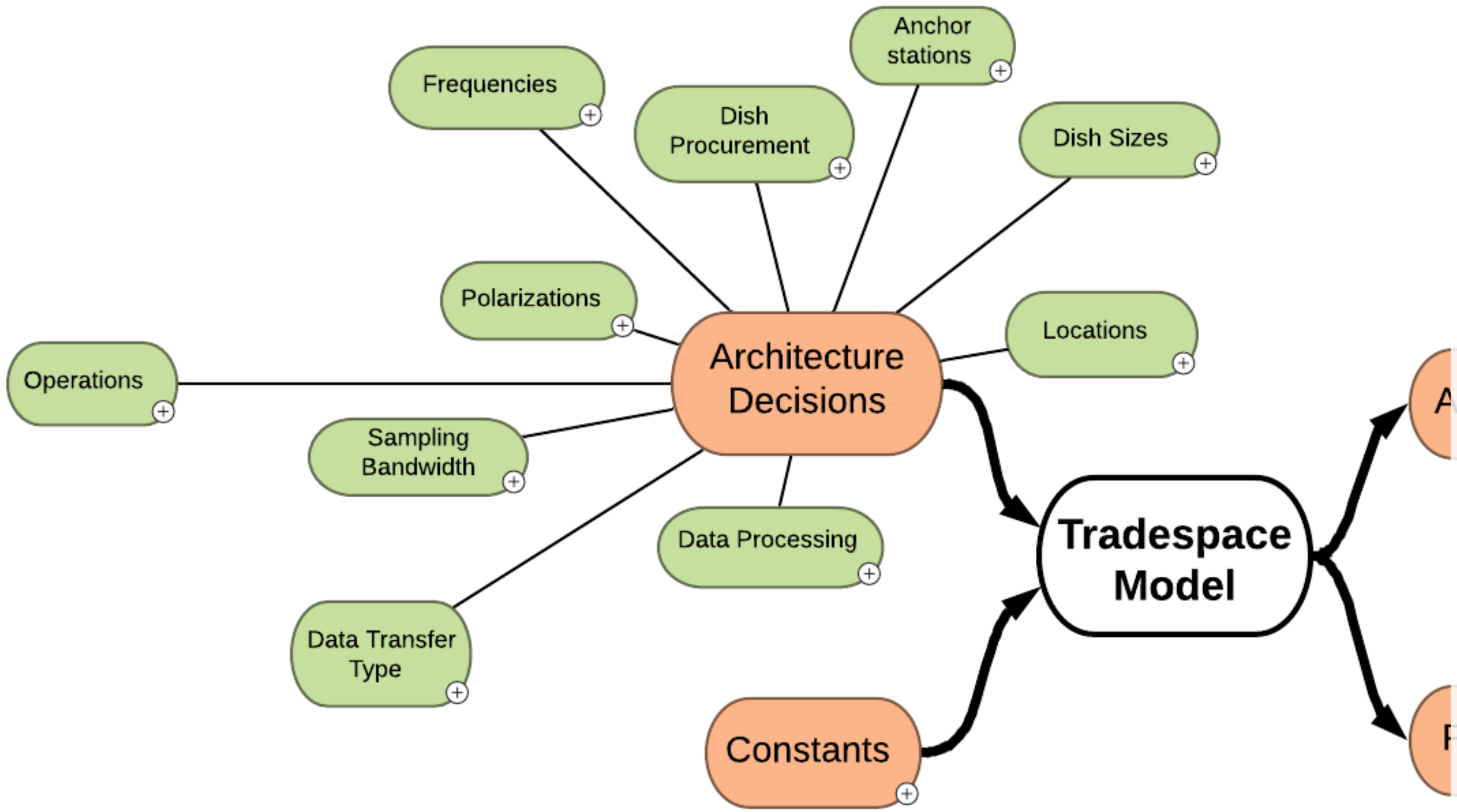
- 8 international science working groups
- 3 ngEHT collaboration meetings
- 25 papers in special issue of *Galaxies*
- *Iterative and parallel design process with close collaboration between science and engineering to assess feasibility and priority*



Tradespace Model



Tradespace Model



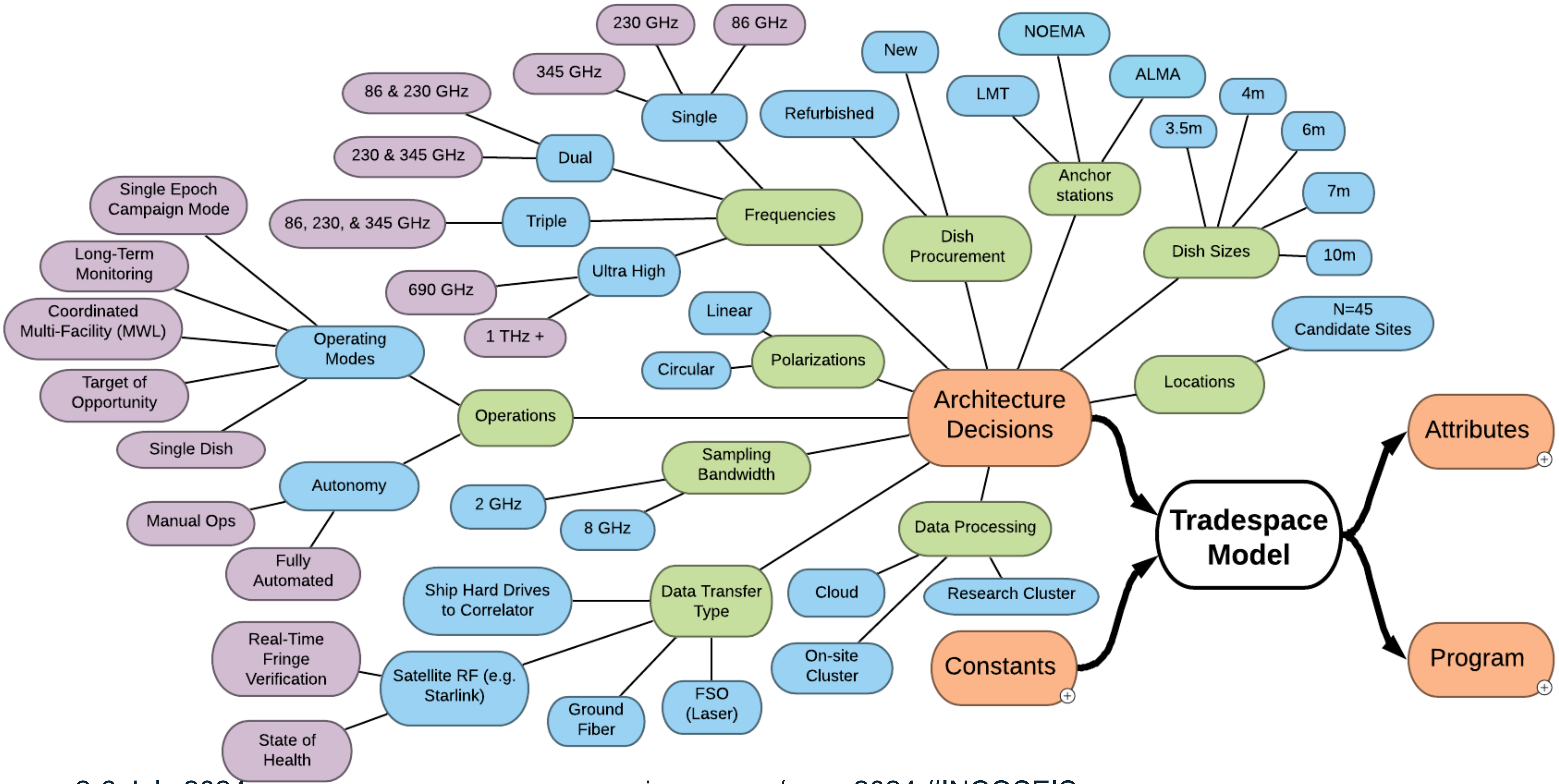
Key Performance Requirements:

- Bandwidth Expansion: 256 Gb/s (4x)
- Tri-Band Observing: 3.0/1.3/0.87mm
- Data Volumes: 10-100 PB
- Data Processing: 16x computational load

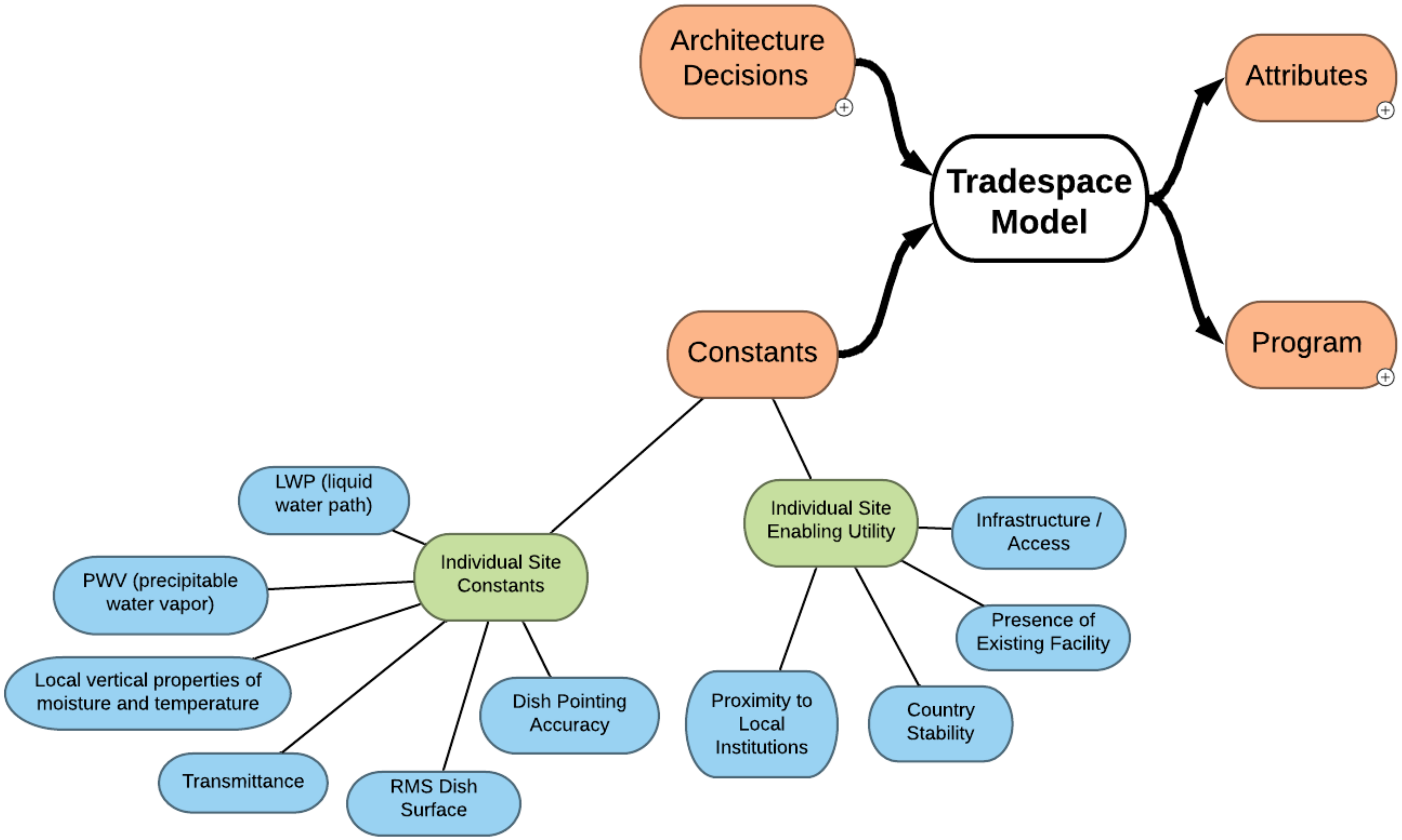
Key Cost Drivers:

- Location (environment, access, existing infrastructure, logistics)
- Dish Size
- Operating Mode
- Autonomy of Array Monitoring & Control
- Data Transfer

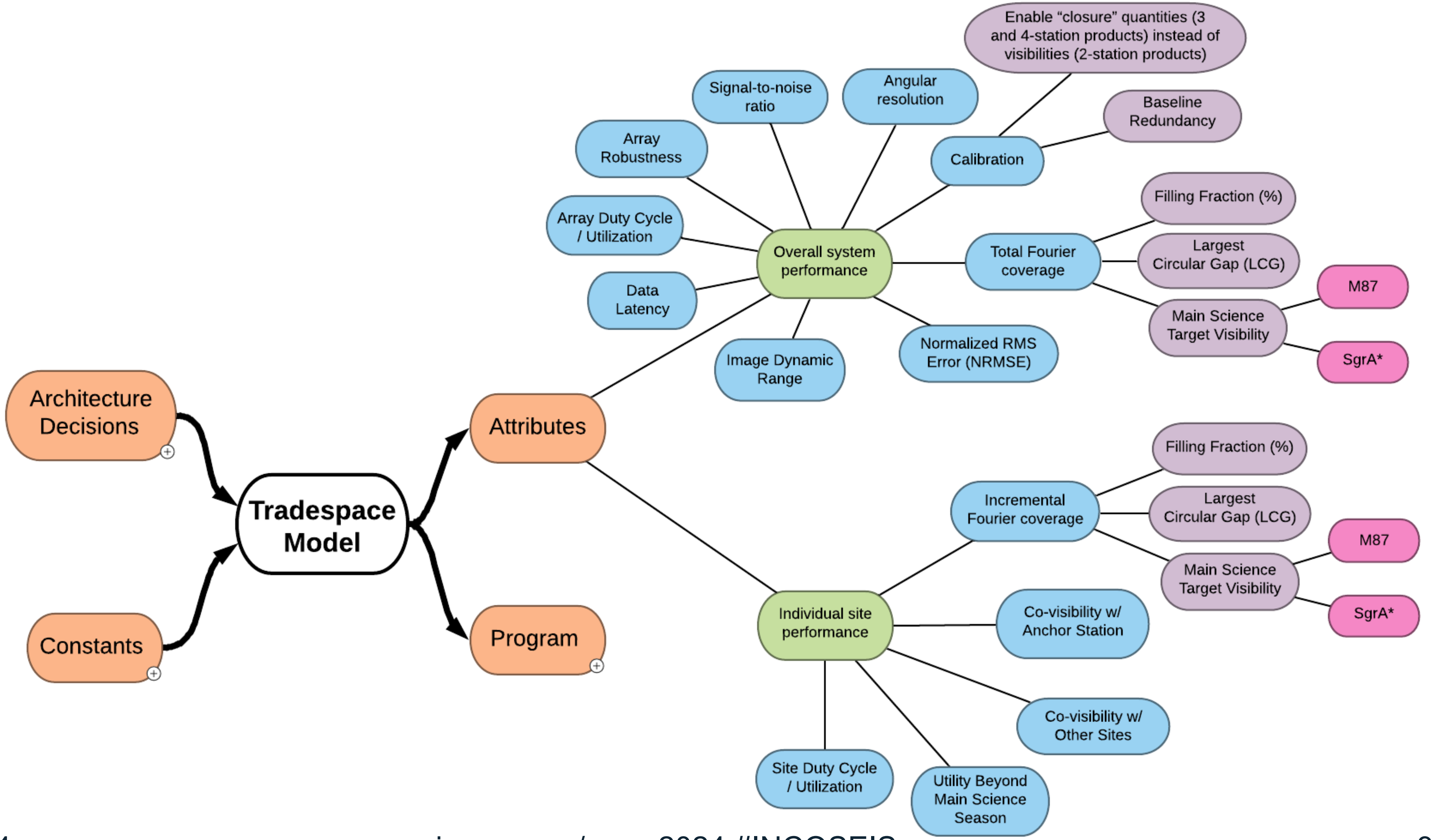
Tradespace Model



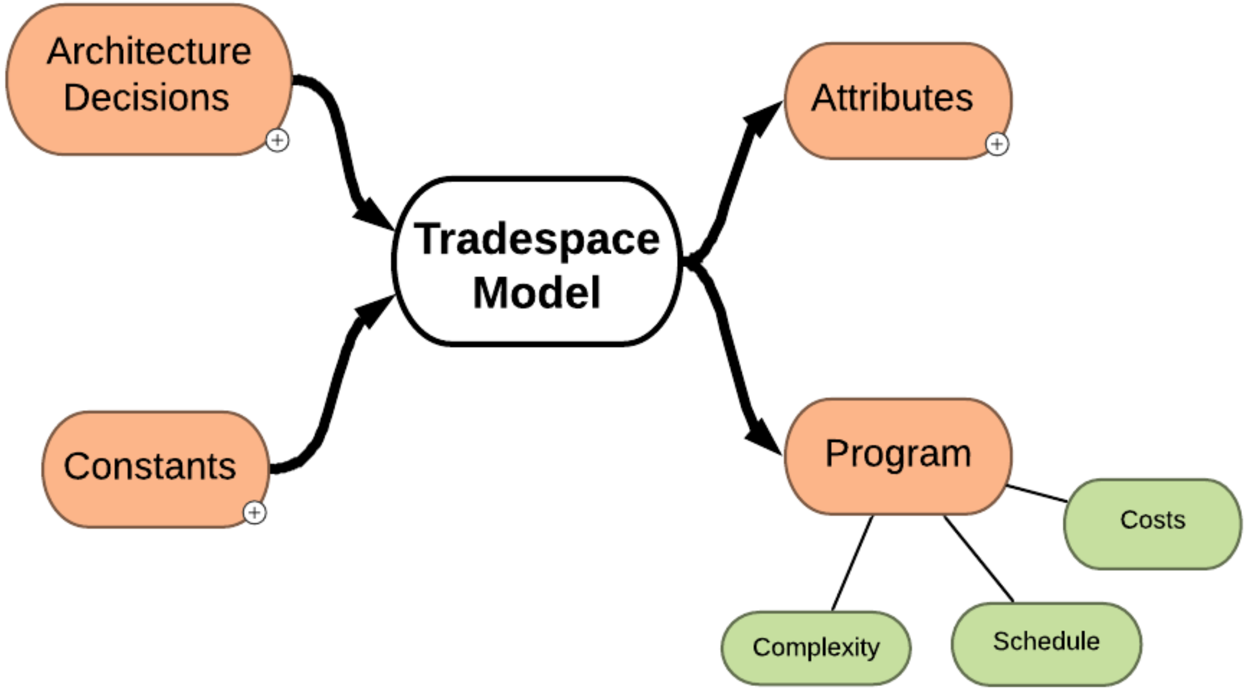
Tradespace Model



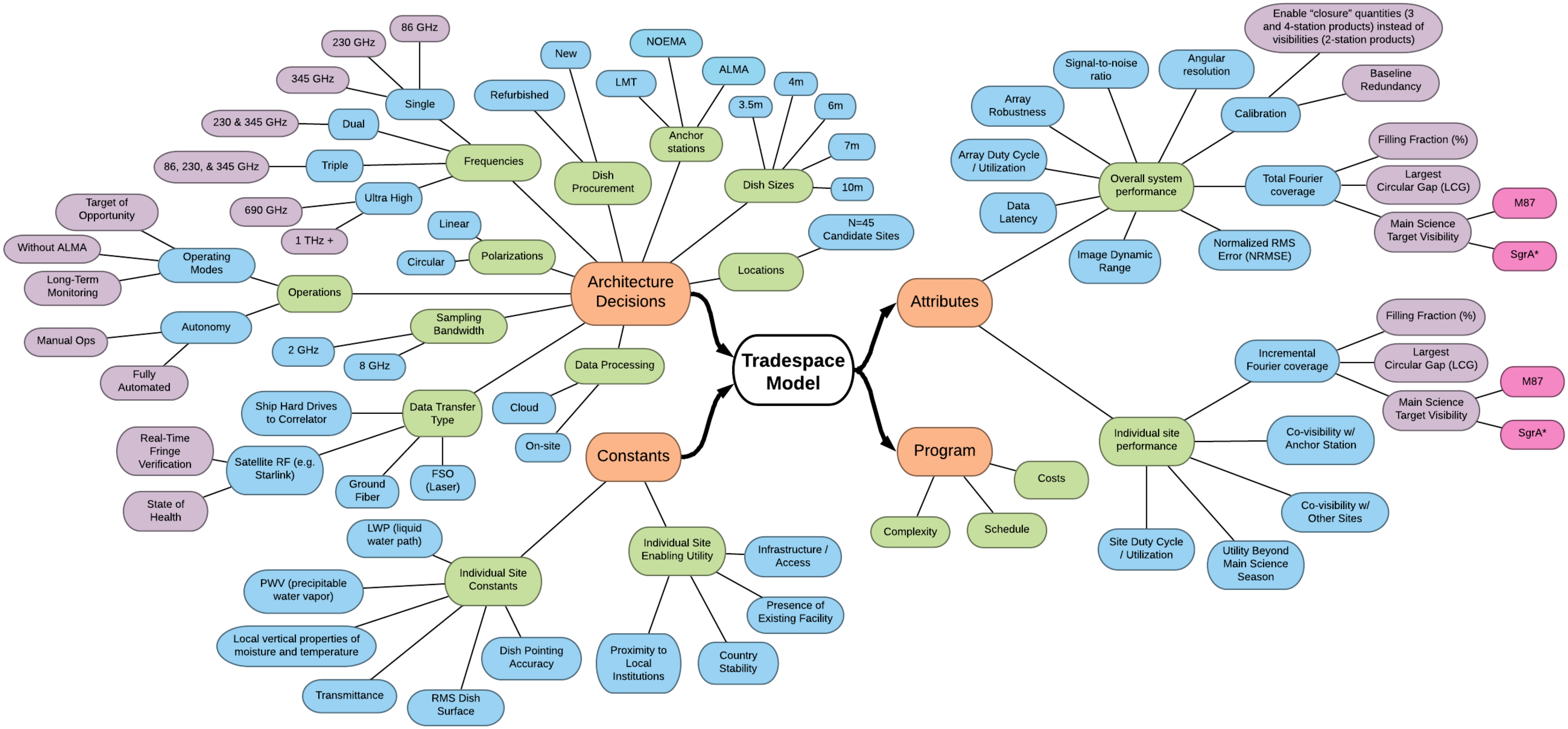
Tradespace Model



Tradespace Model



Tradespace Model



Ryan Chaves
Systems Engineer & Software Architect

Education

- B.S. Computer Engineering – Georgia Institute of Technology
- M.S. Electrical Engineering – Northeastern University

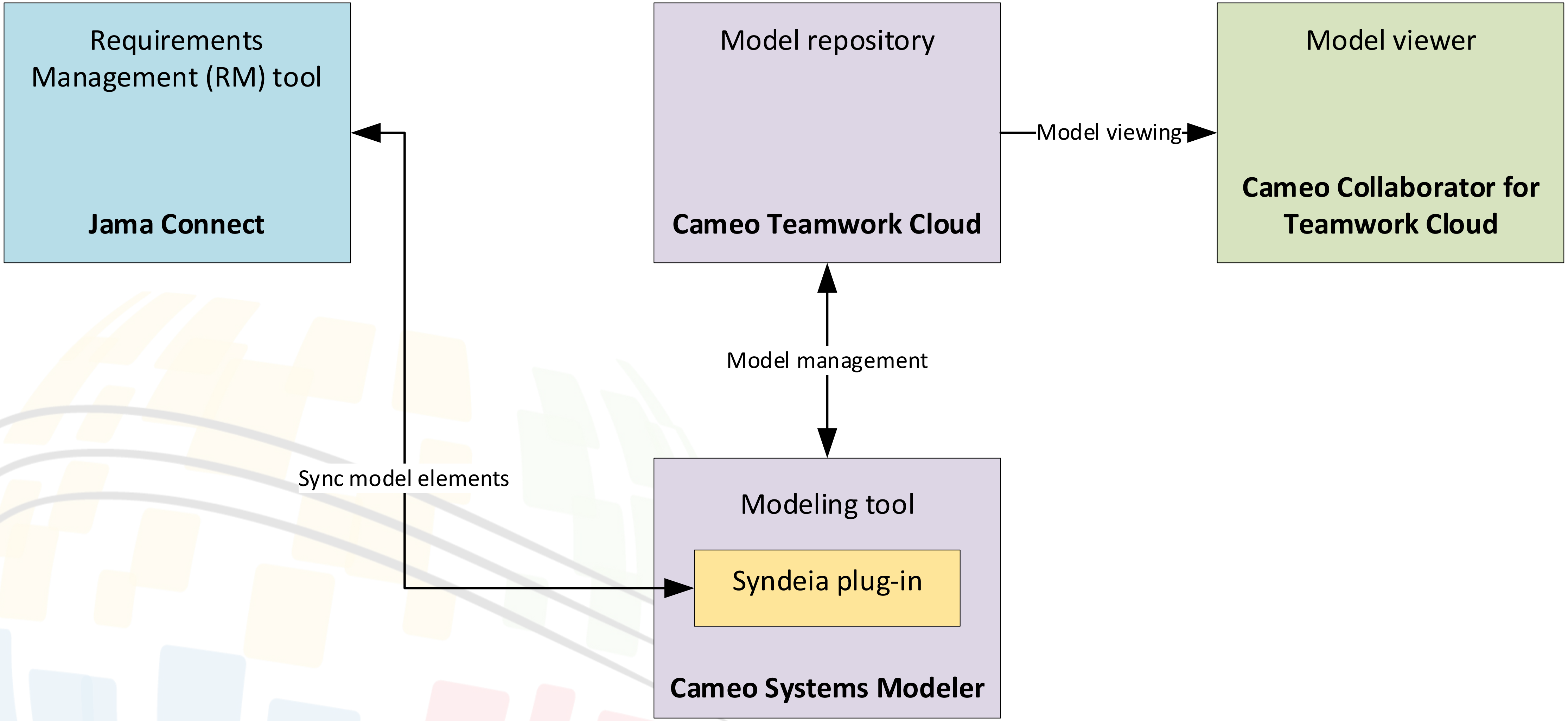
Experience

- Joined the CfA and the ngEHT project in 2021
- 22 years of experience developing novel, complex products in the medical, automotive, and consumer industries
- On the ngEHT Project, responsible for the overall requirements and system architecture as well as leading the Monitoring & Control subsystem
- Staunch advocate and practitioner of MBSE and modern systems & software engineering best practices with a proven record of delivering high-quality, standards-compliant software

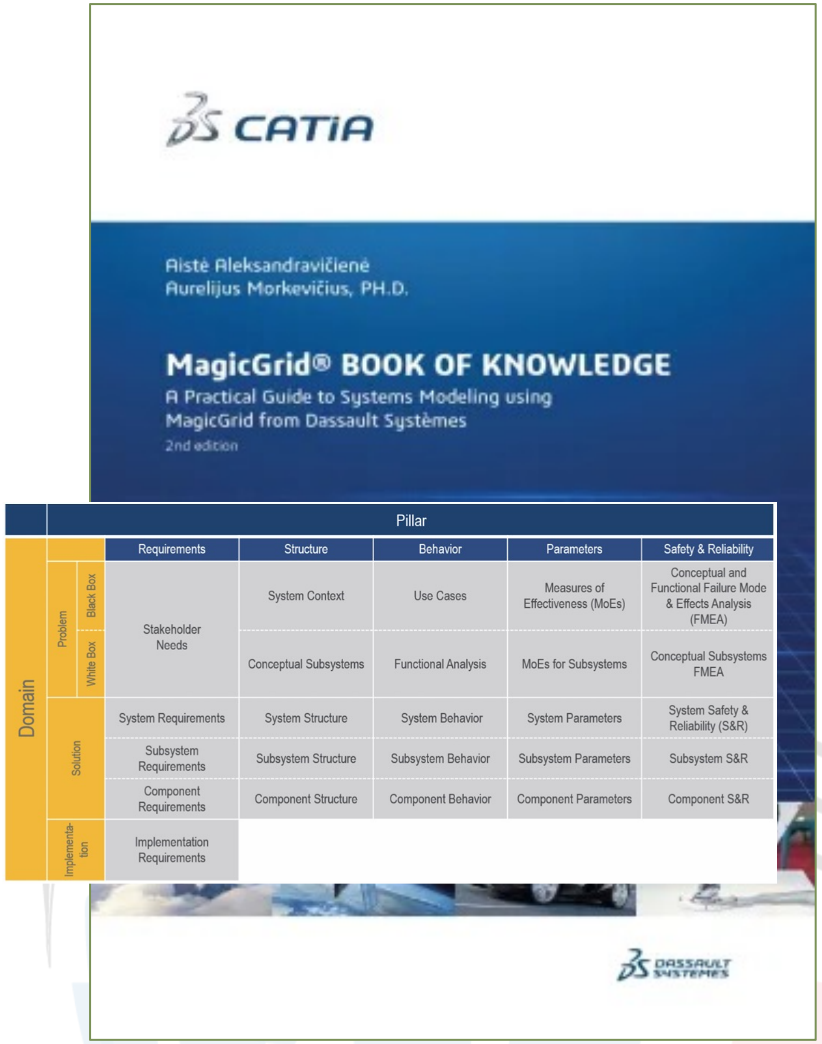
System modeling goals

- Provide Authoritative Source of Truth (ASoT) for project that objectively demonstrates a science-based rationale for technical designs and decisions
- Right-size MBSE approach to
  - Ensure value-add and avoid “over-modeling”
  - Facilitate document generation

MBSE toolchain



Methodology – MagicGrid (Dassault Systèmes)

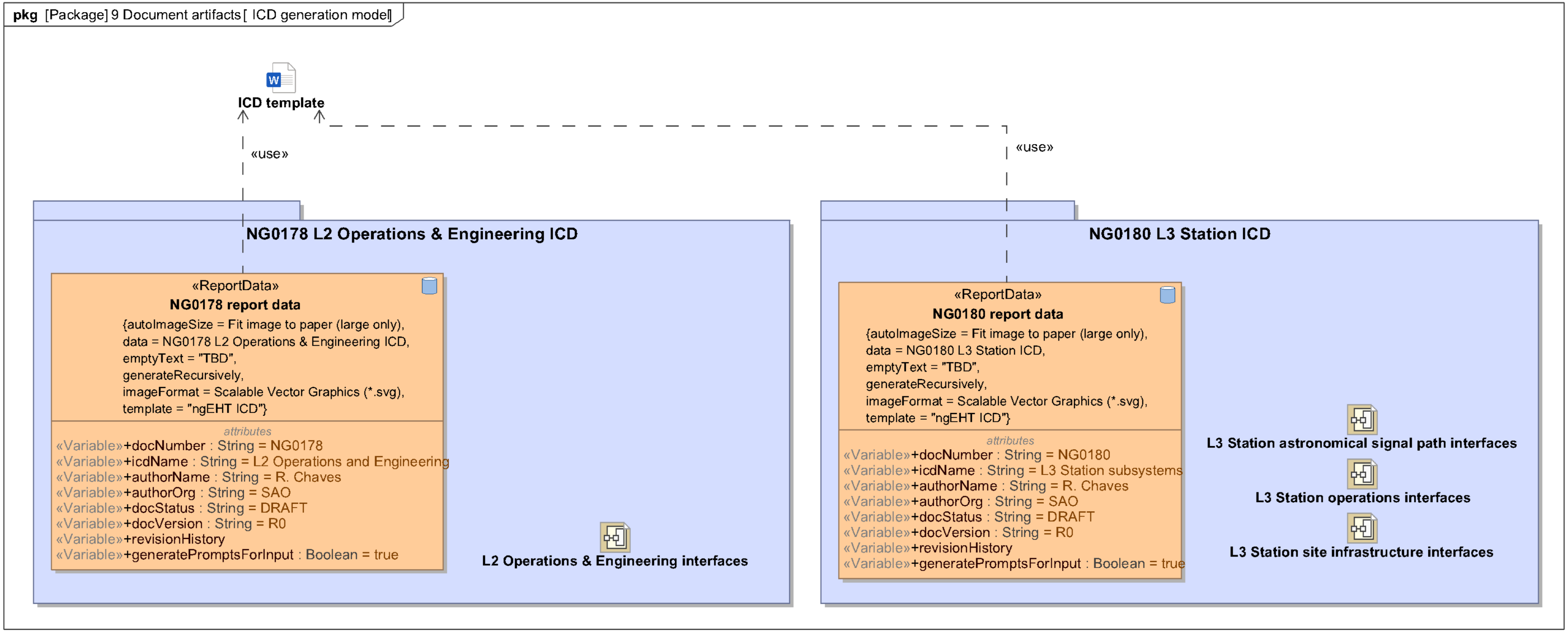


Pillar / Activity	Implemented?	Comments
Requirements	Yes	Discussed next
Structure	Yes	Discussed next
Behavior	Partially	Functional analysis currently a mix of diagrams (**uc** & **act**) and written scenarios. Desire is to model key functions such that allocations to subsystems are traceable
Parameters	Minimally	Key moes are captured as properties, but very few modeled with **par**ametric diagram. Most parametric analysis is done with custom simulation tools https://github.com/Smithsonian/ngeht-arrayperformance-sims
Safety & Reliability	No	Relevant requirements captured but analyses not integrated into model

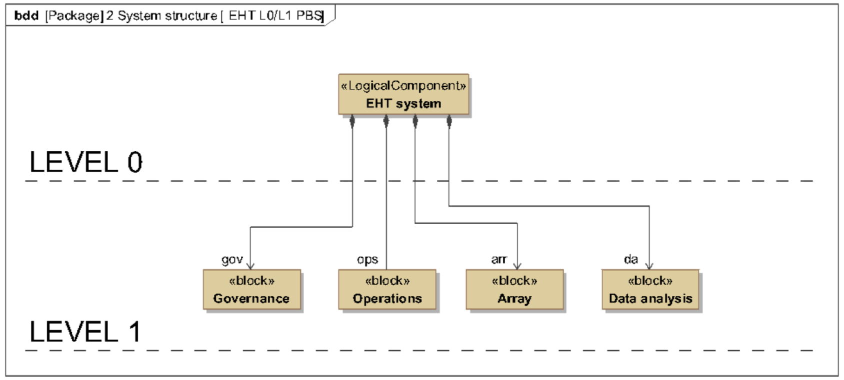
From model to documents

Document type	Source data	Tool generated?	Comments
Requirements specification	Jama	Yes	Basic reports, not Velocity-based
Architecture / Design specification	Teamwork Cloud	No	Diagrams manually imported as needed from Cameo Systems Modeler
Interface Control Document (ICD)	Teamwork Cloud	Yes	Report Wizard and custom Velocity template
Other (risk register, schedule, etc.)	n/a	No	Not modeled

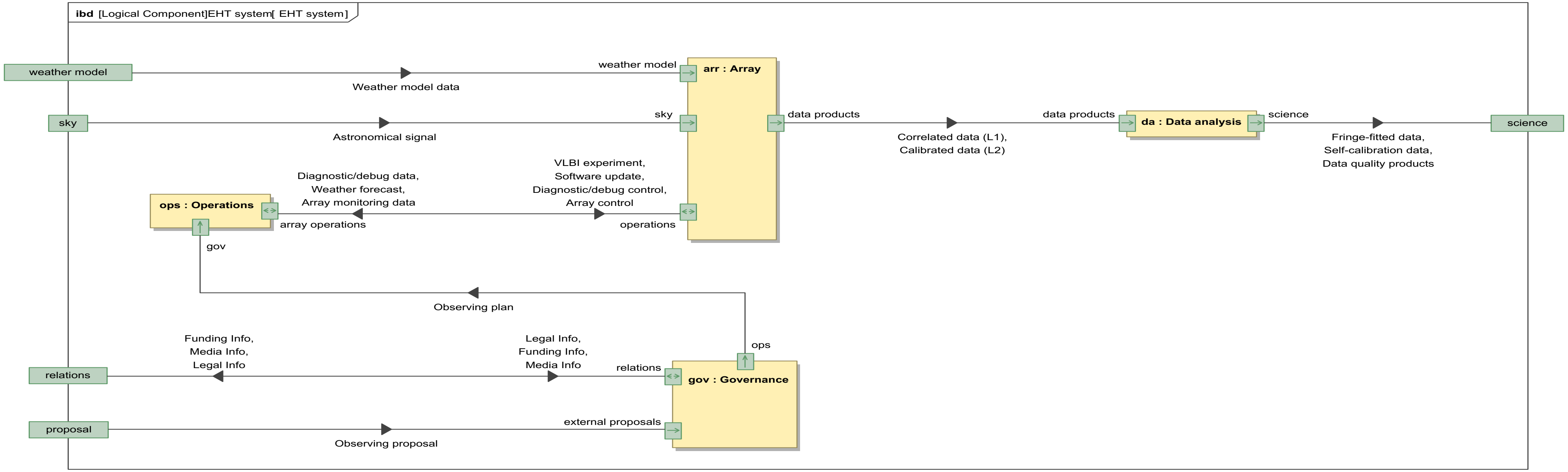
ICD generation overview



Top-level system-of-systems model



- The Array is one of four L1 systems within the EHT SoS
- Allows scope of Array development effort to be precisely defined in large stakeholder landscape



Science requirements modeling

«requirement»
«Jama_Requirement»
Observation Frequency (Fundamental Physics)

«requirement»
«Jama_Requirement»
Brightness Temperature Sensitivity (Fundamental Physics)

«requirement»
«Jama_Requirement»
Inverse shortest projected non-intrasite baseline (Fundamental Physics)

«requirement»
«Jama_Requirement»
Polarization (Fundamental Physics)

«requirement»
«Jama_Requirement»
Observation Targets (Fundamental Physics)

«requirement»
«Jama_Requirement»
Operational Configuration (Fundamental Physics)

«requirement»
«Jama_Requirement»
Frequency Phase Transfer (Fundamental Physics)

«requirement»
«Jama_Requirement»
Inverse longest projected baseline (Fundamental Physics)

«requirement»
«Jama_Requirement»
Minimum baseline RMS noise (Fundamental Physics)

«requirement»
«Jama_Requirement»
L0 - Science Requirements

«requirement»
«Jama_Requirement»
Fundamental Physics

«requirement»
«Jama_Requirement»
Black Holes and their Cosmic Context

«requirement»
«Jama_Requirement»
Black Hole Accretion

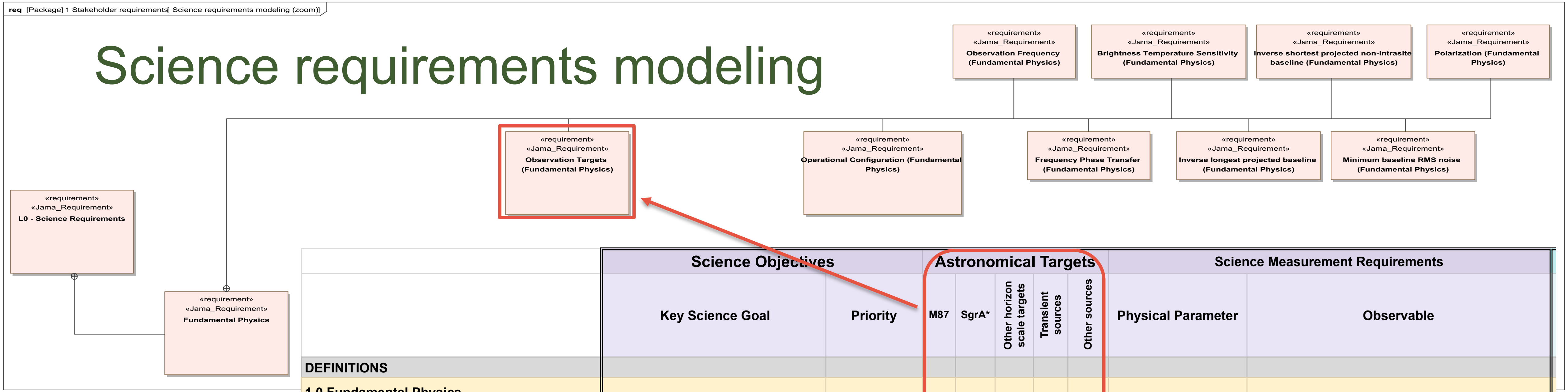
«requirement»
«Jama_Requirement»
Jet Launching

«requirement»
«Jama_Requirement»
Transients

«requirement»
«Jama_Requirement»
New Horizons

Version 7	Science Objectives		Astronomical Targets					Science Measurement Requirements		Operational Configuration						EHT Array Required Specifications							
	Key Science Goal	Priority	M87	SgrA*	Other horizon scale targets	Transient sources	Other sources	Physical Parameter	Observable	ngEHT Phase	Array Configuration	Observation Mode	Cadence	Duration	External Dependencies	Observation Freq (GHz)	Frequency Phase Transfer	Brightness Temperature Sensitivity (K)	Inverse longest projected baseline (µas)	Inverse shortest projected non-intrasite baseline (µas)	Minimum baseline RMS noise (mJy)	Point Source Sensitivity (mJy)	Polarization
DEFINITIONS																							
1.0 Fundamental Physics																							
1a.1 Black hole horizons (M87*)	Establish the existence and properties of black hole horizons	Threshold	X					Lensed image of the horizon	Measure brightness and shape of the dimmest region of the apparent shadow	1	Full	Single Observation	Once	Full track	None	230+345	Yes	5×10^8	20	80 µas (20 M/D to capture both n = 0 and n = 1)	N/A	N/A	Stokes I
1a.2 Black hole horizons (SgrA*)		Threshold		X						2	Full	Single Observation	Once	Full track	None	230+345	Yes	5×10^8	25	100 µas (20 M/D to capture both n = 0 and n = 1)	N/A	N/A	Stokes I
1b.1 SMBH spin measurement (M87*)	Measure the spin of a SMBH	Threshold	X					SMBH spin	Average polarization spiral (beta_2 phase) over 10 epochs at 230 and 345 GHz.	2	Full	Multiple Observations	At least matches photon ring detection goal, but requires more independent epochs (precise cadence is insignificant)	Full track	None	230+345	No	N/A	N/A	80 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I
1b.2 SMBH spin measurement (SgrA*)		Threshold		X						2	Full	Multiple Observations		Full track	None	230+345	Yes	N/A	N/A	100 µas (20 M/D to capture both n = 0 and n = 1)	10 mJy on longest baselines	N/A	Stokes I
1c.1 Photon ring (M87)	Constrain the properties of a black hole's photon ring	Objective	X					Photon ring	Statistically significant detection of persistent thin ring feature Statistically significant = 3 sigma Persistent = >1000M (~1 year) Thin = <1M (~4 µas)	1	Full	Multiple Observations	Minimum cadence: At least 3 observations separated by >1 month.	Full track	None	230+345	Yes	N/A	N/A	80 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I
1c.2 Photon ring (SgrA*)		Objective		X						2	Full	Multiple Observations	At least 2 epochs of single 2-week campaigns over 2 years	Full track	None	230+345	Yes	N/A	N/A	100 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I, Q, U
1d. Axions	Constrain ultralight boson fields	Objective	X	X				Superradiance from clouds of sub-eV ultralight bosonic	Polarization angle oscillation along the photon ring and spin measurement	1	Full	Multiple Observations	Sequence of 3 observations within 20 days (expected oscillation period)	Full track	None	230+345	No	5×10^8	20	50	10	N/A	Stokes I, Q, U
2.0 Black Holes & their Cosmic Context																							
2a. SMBH assembly	Reveal Black Hole-Galaxy Formation, Growth and Coevolution	Threshold	X	X	X			SMBH masses and indirect estimates of their spins	SMBH emission ring and its polarized structure in a sample of >10 sources	1	Full	Multiple Observations	One observation (~one night) per target, repeated twice	Full track is ideal	Candidates identified by ETHER survey	230	No	N/A	N/A	N/A	1	1	Stokes I, Q, U
2b. SMBH binaries	Determine how SMBHs merge through observations of sub-parsec binaries	Objective					X	SMBH binary orbit, masses, (and indirect estimates of spins)	SMBH spatial separation & evolution of that spatial separation	1	Full	Periodic Monitoring	Several measurements taken over at least half of the orbital period (~months to years). Examples: 1) 6-month period = observations monthly. 2) 5-year period = observations every year.	Full track is ideal	None	230	No	N/A	N/A	1000	1	1	Stokes I
2c. MWL/MM Studies of BH and Jets	Connect SMBHs to high-energy and neutrino events within their jets	Objective	X		X	X	X	Neutrinos produced in regions with PeV protons	Mapping of the jet (imaging), neutrino emission location	1	Partial	Multiple Observations	~Monthly observations of >20 bright blazars and those with neutrino triggers	Full track is ideal	None	86+230+345	Yes	5×10^8	20	1000	10	N/A	Full Stokes polarization
3.0 Black Hole Accretion																							
3a.1. Accretion (M87*)	Reveal how black holes accrete material using resolved movies on event horizon scales	Threshold	X					Accreting plasma onto M87*	Surface brightness and spectral index of the direct image near the photon ring	1	Partial	Periodic Monitoring	Every 3 days for 3 months (250M)	Full track	None	86+230+345	Yes	10^9	20	100	10	N/A	Stokes I
3a.2. Accretion (SgrA*)		Threshold		X				Accreting plasma onto Sgr A*	Surface brightness and spectral index of the direct image near the photon ring	2	Full	Multiple Observations	One full night at least 3 times	Full track	None	230+345	Yes	10^9	20	100	10	N/A	Stokes I
3b.1. Electron heating (M87*)	Observe localized heating and acceleration of relativistic electrons on astrophysical scales	Threshold	X					Time-dependent temperature, magnetic field strength, and density	Spatially and time-resolved compact flaring structures in sub-mm movies	1	Partial	Periodic Monitoring	Every 3 days for 3 months (250M)	Full track	None	86+230+345	Yes	10^9	20	200	10	N/A	Full Stokes polarization
3b.2. Electron heating (SgrA*)		Threshold		X				Time-dependent temperature, magnetic field strength, and density	Spatially and time-resolved compact flaring structures in sub-mm movies	2	Full	Multiple Observations	One full night at least 3 times	Full track	None	230+345	Yes	10^9	20	200	10	N/A	Full Stokes polarization
3c.1. Frame dragging (M87*)	Detect frame dragging within the ergosphere of a rotating black hole	Objective	X					Sign of accretion flow angular velocity on scales of a few to 10M	Radial evolution of resolved polarization structure and dynamics on scales of a few to 10M	2	Partial	Periodic Monitoring	Every 3 days for 3 months (250M)	Full track	None	86+230+345	Yes	5×10^8	20	100	10	N/A	Stokes I, Q, U
3c.2. Frame dragging (SgrA*)		Objective		X				Sign of accretion flow angular velocity on scales of a few to 10M	Radial evolution of resolved polarization structure and dynamics on scales of a few to 10M	2	Full	Multiple Observations	One full night at least 3 times	Full track	None	230+345	Yes	5×10^8	20	100	10	N/A	Stokes I, Q, U
4.0 Jet Launching																							
4a. Energy extraction	Determine whether relativistic jets are powered by energy extraction from rotating black holes	Threshold	X					Magnetic flux threading BH, spin, and kinetic jet power	Polarized, multi-frequency images on horizon scales and SMBH spin estimate	2	Partial	Periodic Monitoring	Every 3 days for 3 months (250GM/c³)	Full track	None	86+230+345	Yes	5×10^8	20	500	10	N/A	Full Stokes
4b.1 Jet formation (M87*)	Determine the physical conditions and launching mechanisms for relativistic jets	Threshold	X					Jet/counter-jet composition, B-field structure, and velocity field on scales of 5-100M	Full polarization, multi-frequency movies with spectral index and rotation measure	1	Partial	Periodic Monitoring	One full night at least 3 times	Full track	None	86+230+345	Yes	5×10^8	20	500	10	N/A	Stokes I, Q, U
4b.2 Jet formation (SgrA*)		Threshold		X						1	Full	Multiple Observations	Every 3 days for 3 months (250M)	Full track	None	230+345	Yes	5×10^8	20	500	10	N/A	Stokes I, Q, U
5.0 Transients																							
5a. XRB dynamics	Measure the inner jet structure and dynamics in black hole X-ray binaries	Objective				X	X	Jet collimation profile and velocity at 10^5-10^8M	Motion, brightness, and size of ejected components during flares	1	Partial	Target of Opportunity	2-3 targets per year. Single long observation for tracking of features (could be resolved out on ~9 hour time scales). Ideally will be one night-long triggered observation with 1-2 follow ups on ~days timescale if there is continued activity.	Full track, response within ~10 to 60 minutes is ideal	concurrent observations (e.g., VLBI, single-dish) monitoring at <100 GHz would be beneficial	86+230	Yes	N/A	50	1000	10	1	Full Stokes
5b. Extragalactic transients	Detect the kinetic power, physical structure, and velocity in extragalactic transients	Objective				X	X	Kinetic power, physical structure, and velocity of transient outflows	Temporally and spatially resolved morphology of transient outflows	1	Full	Target of Opportunity	2-3 targets per year with ~monthly observations following initial detection for 1-2 years (though this is target-dependent: GRBs = days, TDEs = years)	Full track	concurrent observations (e.g., VLBI, single-dish) monitoring at <100 GHz would be beneficial	86+230	Yes	N/A	25	1000	10	1	Stokes I
6.0 New Horizons																							
6a. AGN astrometry	Detect proper motions and secular (CMB) parallaxes of AGN up to ~80 Mpc distances	Objective					X	Proper motions Secular (CMB) parallaxes	Multi-year tracking of many sources across the sky with 1ps (~5 µas) delay fidelity Requires access to suitable subset of array to revisit sources at different sky locations multiple times per year	2	Partial	Multiple Observations	Multiple observations spread over >3 years per source for >10 sources	2 hours per night	None	86+230	Yes	N/A	25	N/A	100	10	Stokes I
6b. Megamasers	Leverage AGN accretion disk megamasers to measure their AGN host properties	Objective					X	- Black hole masses - Geometric distances - Hubble constant - Physical conditions (temperature, density) in AGN accretion disks	Spectral lines of megamasers	1	Partial	Multiple Observations	- Masses: Single observation per source - Distances: For each source, must observe ~monthly for one year (exact separation is source dependent) -Hubble Constant: Typical distance uncertainties are ~10%, so an accuracy of 3% for H0 requires ~10 sources observed monthly -Physical Conditions: Single observation per source, but requires simultaneous multi-frequency observations	2 hours per night	Coordinated observations of 22 GHz maser lines will help constrain the physical conditions (within ~1 week)	Covering a redshift range from 0-0.05 requires a frequency coverage of 300-325 GHz	No	N/A	N/A	N/A	10 mJy per 1 MHz channel	10 mJy per 1 MHz channel	Stokes I

Science requirements modeling



	Science Objectives		Astronomical Targets					Science Measurement Requirements	
	Key Science Goal	Priority	M87	SgrA*	Other horizon scale targets	Transient sources	Other sources	Physical Parameter	Observable
DEFINITIONS									
1.0 Fundamental Physics									
1a.1 Event horizons (M87*)	Establish the existence and properties of black hole horizons	Threshold	X					Lensed image of the horizon	Measure brightness and shape of the dimmest region of the apparent shadow
1a.2 Event horizons (SgrA*)		Threshold		X					
1b.1 SMBH spin measurement (M87*)	Measure the spin of a SMBH	Threshold	X					SMBH spin	Average polarization spiral (beta_2 phase) over 10 epochs at 230 and 345 GHz.
1b.2 SMBH spin measurement (SgrA*)		Threshold		X					
1c.1 Photon ring (M87)	Constrain the properties of a black hole's photon ring	Objective	X					Photon ring	Statistically significant detection of persistent thin ring feature Statistically significant = 3 sigma Persistent = >1000M (~1 year) Thin = <1M (~4 μas)
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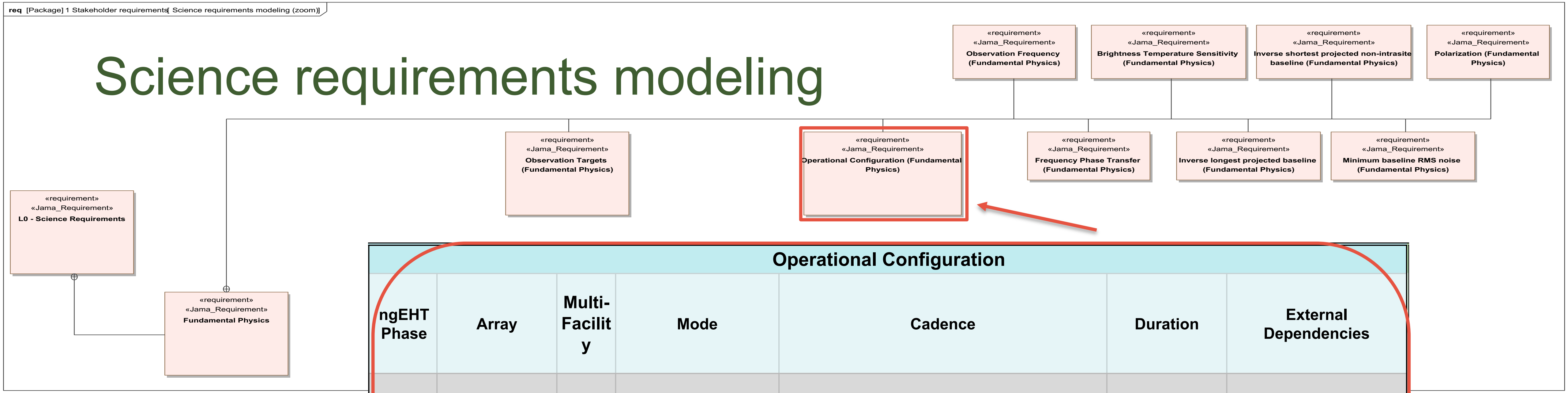
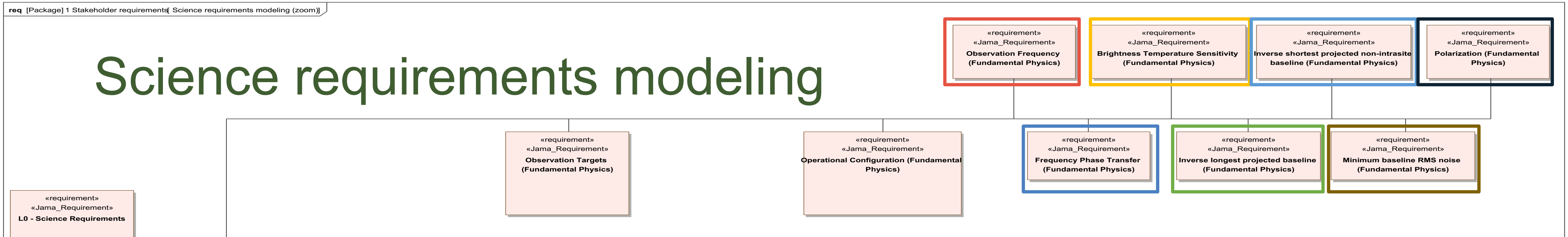
Science requirements modeling



Operational Configuration

ngEHT Phase	Array	Multi-Facility	Mode	Cadence	Duration	External Dependencies
1	Full	No	Single Observation	Once	Full track	None
2	Full	No	Single Observation	Once	Full track	None
2	Full	No	Multiple Observations	At least matches photon ring detection goal, but requires more independent epochs (precise cadence is insignificant)	Full track	None
2	Full	No	Multiple Observations		Full track	None
1	Full	No	Multiple Observations	Minimum cadence: At least 3 observations separated by >1 month.	Full track	None
2	Full	No	Multiple Observations	At least 2 epochs of single 2-week campaigns over 2 years	Full track	None
1	Full	No	Multiple Observations	Sequence of 3 observations within 20 days (expected oscillation period)	Full track	None

Science requirements modeling

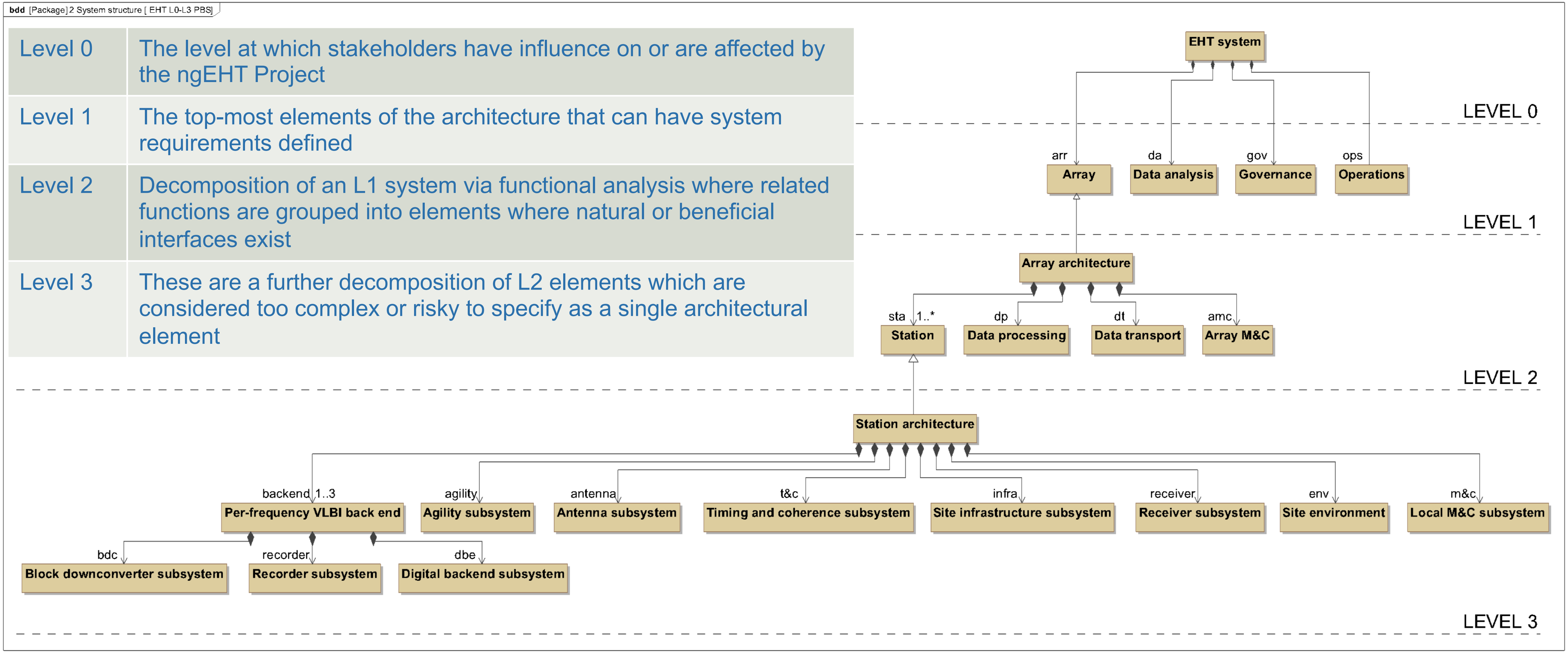


EHT Array Required Specifications

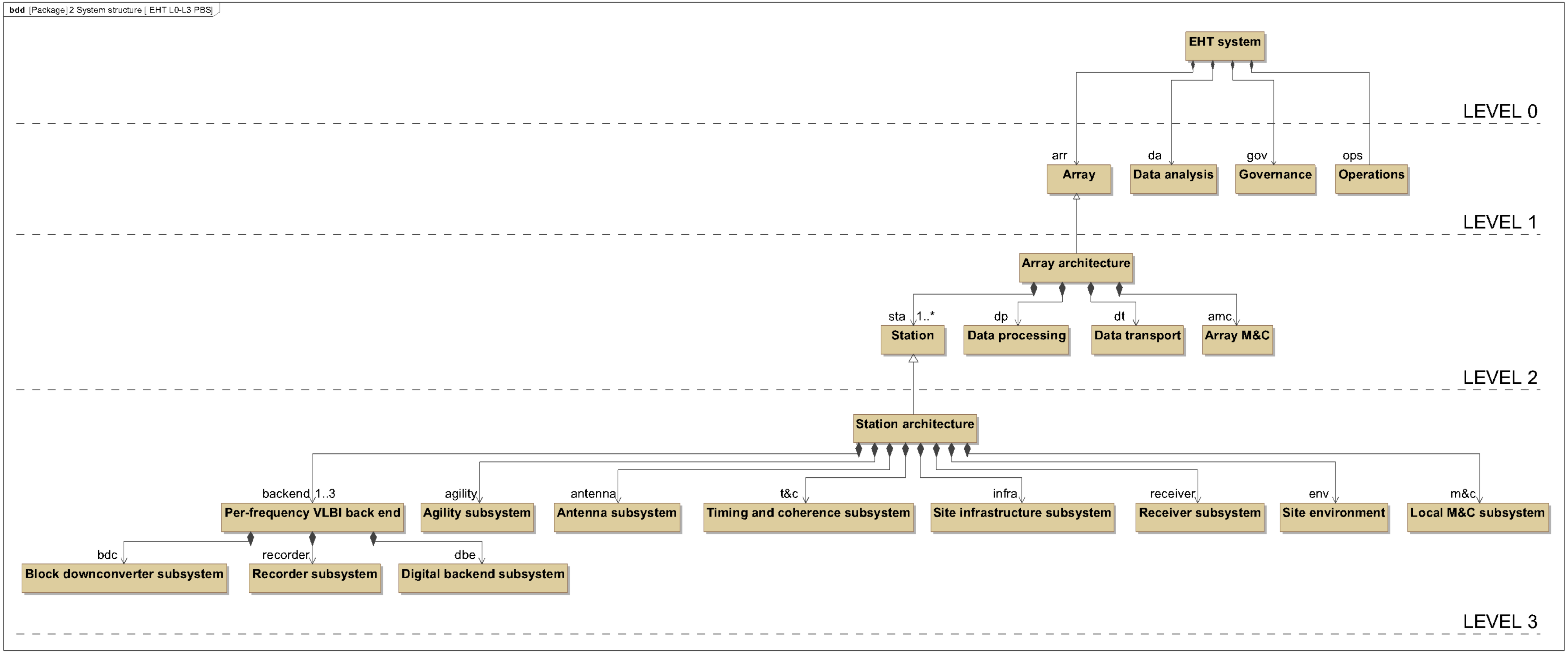
Observation Freq (GHz)	Frequency Phase Transfer	Brightness Temperature Sensitivity (K)	Inverse longest projected baseline (µas)	Inverse shortest projected non-intrasite baseline (µas)	Minimum baseline RMS noise (mJy)	Point Source Sensitivity (mJy)	Polarization
230+345	Yes	5×10^8	20	80 µas (20 M/D to capture both n = 0 and n = 1)	N/A	N/A	Stokes I
230+345	Yes	5×10^8	25	100 µas (20 M/D to capture both n = 0 and n = 1)	N/A	N/A	Stokes I
230+345	No	N/A	N/A	80 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I
230+345	Yes	N/A	N/A	100 µas (20 M/D to capture both n = 0 and n = 1)	10 mJy on longest baselines	N/A	Stokes I
230+345	Yes	N/A	N/A	80 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I
230+345	Yes	N/A	N/A	100 µas (20 M/D to capture both n = 0 and n = 1)	5 mJy on longest baselines	N/A	Stokes I, Q, U
230+345	No	5×10^8	20	50	10	N/A	Stokes I, Q, U

Overall logical structural model

Level 0	The level at which stakeholders have influence on or are affected by the ngEHT Project
Level 1	The top-most elements of the architecture that can have system requirements defined
Level 2	Decomposition of an L1 system via functional analysis where related functions are grouped into elements where natural or beneficial interfaces exist
Level 3	These are a further decomposition of L2 elements which are considered too complex or risky to specify as a single architectural element



Traceability to requirements



Traceability to requirements

Lower-level traceability & verification planning

- Shows direct and implied requirements satisfaction by logical architecture and physical system configuration
- Assists in verification planning

Legend
↙ Satisfy
⇠ Satisfy (Implied)

Requirement	2 Station structure	Station architecture	infra : Site infrastructure subsystem	antenna : Antenna subsystem	m&c : Local M&C subsystem	t&c : Timing and coherence subsystem	receiver : Receiver subsystem	backend : Per-frequency VLBI back end	agility : Agility subsystem	env : Site environment	quantization efficiency : Real	86+230 station	be86 : Per-frequency VLBI back end	be230 : Per-frequency VLBI back end	SEFD : spectral flux density[mJy] [2]	antenna : Antenna subsystem	dual-band rx : Receiver subsystem	86+230+345 station	be86 : Per-frequency VLBI back end	be230 : Per-frequency VLBI back end	be345 : Per-frequency VLBI back end	SEFD : spectral flux density[mJy] [3]	antenna : Antenna subsystem	tri-band rx : Receiver subsystem
ngEHT-SET-39 L2 - Station requirements																								
ngEHT-FLD-126 Functional requirements																								
ngEHT-L2R-13 Station Health and Status																								
ngEHT-L2R-17 Monitor site weather																								
ngEHT-L2R-305 Perform astronomical observations for simultaneous multi-band VLBI (dual-band station)	10											⇠	↙	↙		↙	↙	⇠	↙	↙			↙	↙
ngEHT-L2R-306 Perform astronomical observations for simultaneous multi-band VLBI (tri-band station)	6																	⇠	↙	↙	↙		↙	↙
ngEHT-L2R-307 Perform astronomical observations for single-band VLBI (tri-band)	7											⇠		↙				⇠		↙	↙		↙	↙
ngEHT-L2R-308 Perform astronomical observations for spectral line VLBI (goal)	4																	⇠			↙		↙	↙
ngEHT-L2R-309 Perform astronomical observations for single-band non-VLBI observations (dual-band)	6											⇠				↙	↙	⇠					↙	↙
ngEHT-L2R-310 Perform astronomical observations for single-band non-VLBI observations (tri-band)	3																	⇠					↙	↙
ngEHT-L2R-311 Test readiness to observe	10	⇠		↙	↙	↙	↙	↙	↙			⇠					↙	⇠						
ngEHT-L2R-312 Configure for VLBI observing	7	⇠		↙	↙	↙		↙				⇠						⇠						
ngEHT-L2R-313 Configure for non-VLBI observing	6	⇠		↙	↙			↙				⇠						⇠						
ngEHT-L2R-314 Capture metadata	4	⇠			↙							⇠						⇠						
ngEHT-L2R-315 E-transfer L0 data	5	⇠	↙					↙				⇠						⇠						
ngEHT-L2R-316 Monitor operating status	10	⇠	↙	↙	↙	↙	↙	↙	↙			⇠						⇠						
ngEHT-L2R-317 Test readiness for software update	4	⇠			↙							⇠						⇠						
ngEHT-L2R-318 Update station software	4	⇠			↙							⇠						⇠						

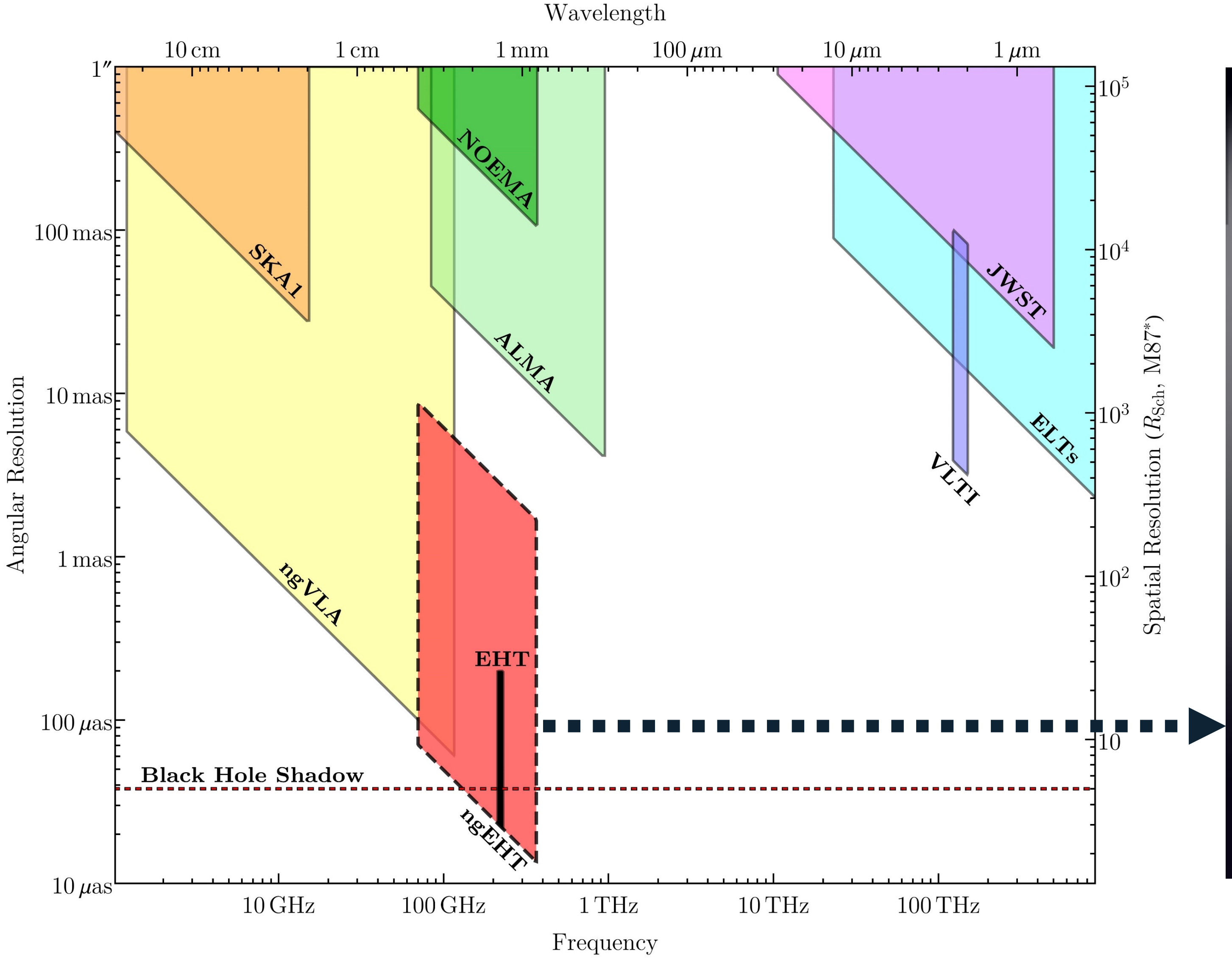
Requirement	4 Station configurations	0 Station archetypes	86+230 ngBackend station	86+230+345 ngBackend station	New station	1 MSRI-1	LMT (MSRI-1)	OVRO (MSRI-1)	2 MSRI-2	1 New stations	CNI	JELM	LCO	SPM	2 Upgraded stations	GLT	HAY	JCMT	KP	LMT (MSRI-2)	OVRO (MSRI-2)	SMA	SMT	SPT	9 Other stations	PV	AMT	APEX	NOEMA	ALMA	LLAMA	KVN
ngEHT-SET-39 L2 - Station requirements																																
ngEHT-FLD-126 Functional requirements																																
ngEHT-L2R-13 Station Health and Status																																
ngEHT-L2R-17 Monitor site weather																																
ngEHT-L2R-305 Perform astronomical observations for simultaneous multi-band VLBI (dual-band station)	16	3	1	1	1	1		1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-306 Perform astronomical observations for simultaneous multi-band VLBI (tri-band station)	11	2		1	1				9	4	1	1	1	1	5	1		1		1			1	1								
ngEHT-L2R-307 Perform astronomical observations for single-band VLBI (tri-band)	16	3	1	1	1	1		1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-308 Perform astronomical observations for spectral line VLBI (goal)	11	2		1	1				9	4	1	1	1	1	5	1		1		1			1	1								
ngEHT-L2R-309 Perform astronomical observations for single-band non-VLBI observations (dual-band)	16	3	1	1	1	1		1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-310 Perform astronomical observations for single-band non-VLBI observations (tri-band)	11	2		1	1				9	4	1	1	1	1	5	1		1		1			1	1								
ngEHT-L2R-311 Test readiness to observe	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-312 Configure for VLBI observing	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-313 Configure for non-VLBI observing	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-314 Capture metadata	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-315 E-transfer L0 data	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-316 Monitor operating status	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-317 Test readiness for software update	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								
ngEHT-L2R-318 Update station software	17	3	1	1	1	2	1	1	12	4	1	1	1	1	8	1	1	1	1	1	1		1	1								

How did we do?

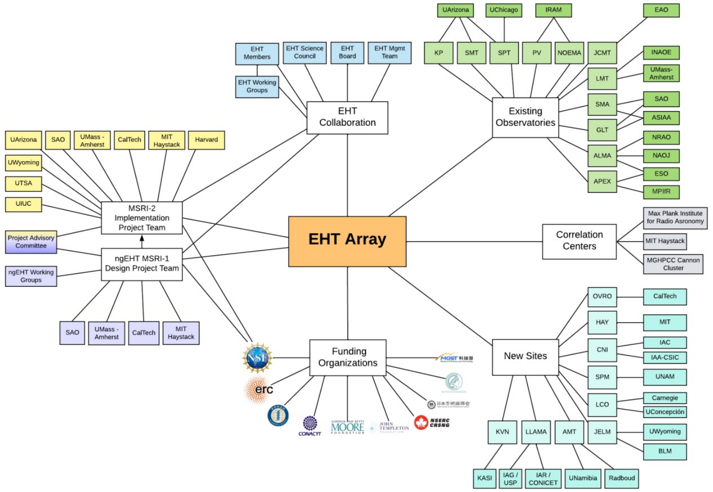
Goal	Evidence
Provide Authoritative Source of Truth (ASoT) for project that objectively demonstrates a science-based rationale for technical designs and decisions	Can answer the question "how is science affected if these aspects of requirements or design are changed?" and vice versa
Right-size MBSE approach to • Ensure value-add and avoid "over-modeling" • Facilitate document generation	• Limited use of some MagicGrid pillars & tool capabilities • Auto-generated requirements and interface specifications

Summary

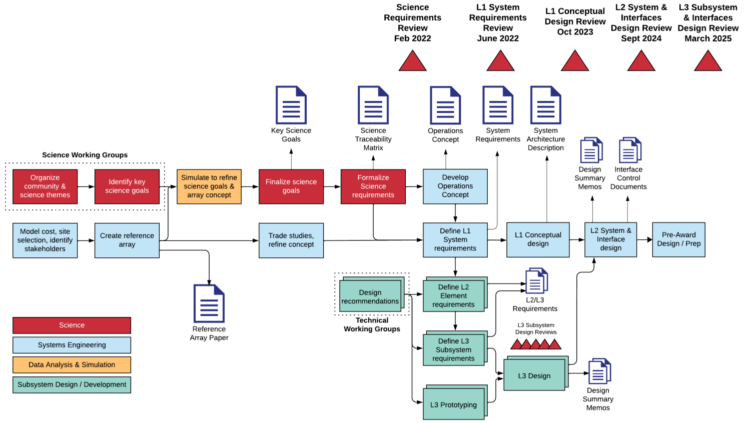
The next step for the EHT is a complex one



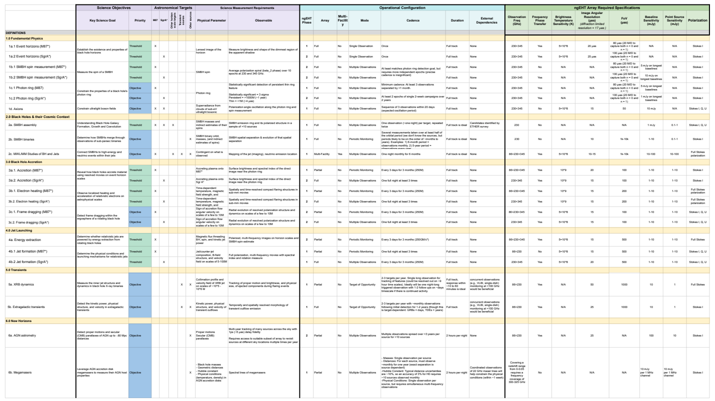
Systems engineering tools have helped manage complexity and align the team



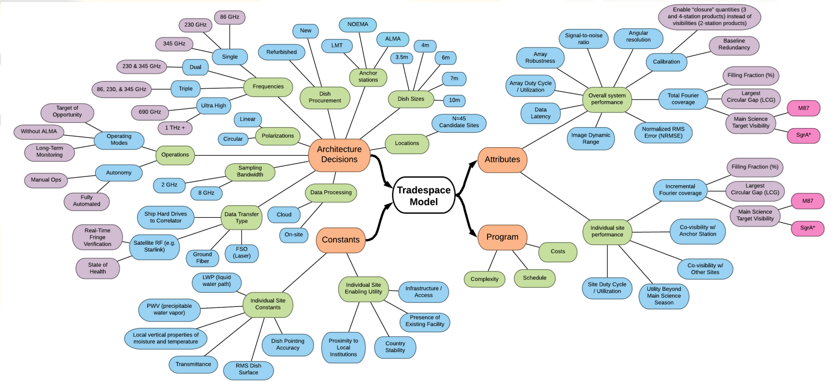
System Context



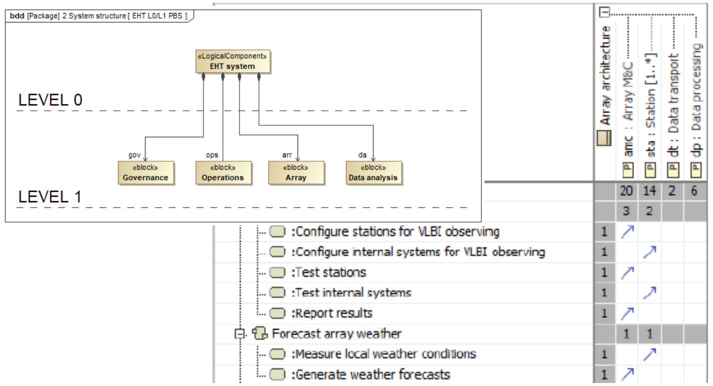
Design Process Flow



Science Traceability Matrix



Tradespace Model



System Model, Requirements & Traceability

Concluding Thoughts

- Scientists and engineers can often be at odds with different approaches and objectives
- When done properly, systems engineering can appeal on common grounds of logic, analysis, and rigor while allowing for experimentation, rapid iteration, and ambitious goals
- Complex science that pushes the limits of an exciting new field requires a system and processes to manage that complexity that is commensurate with the challenge at hand

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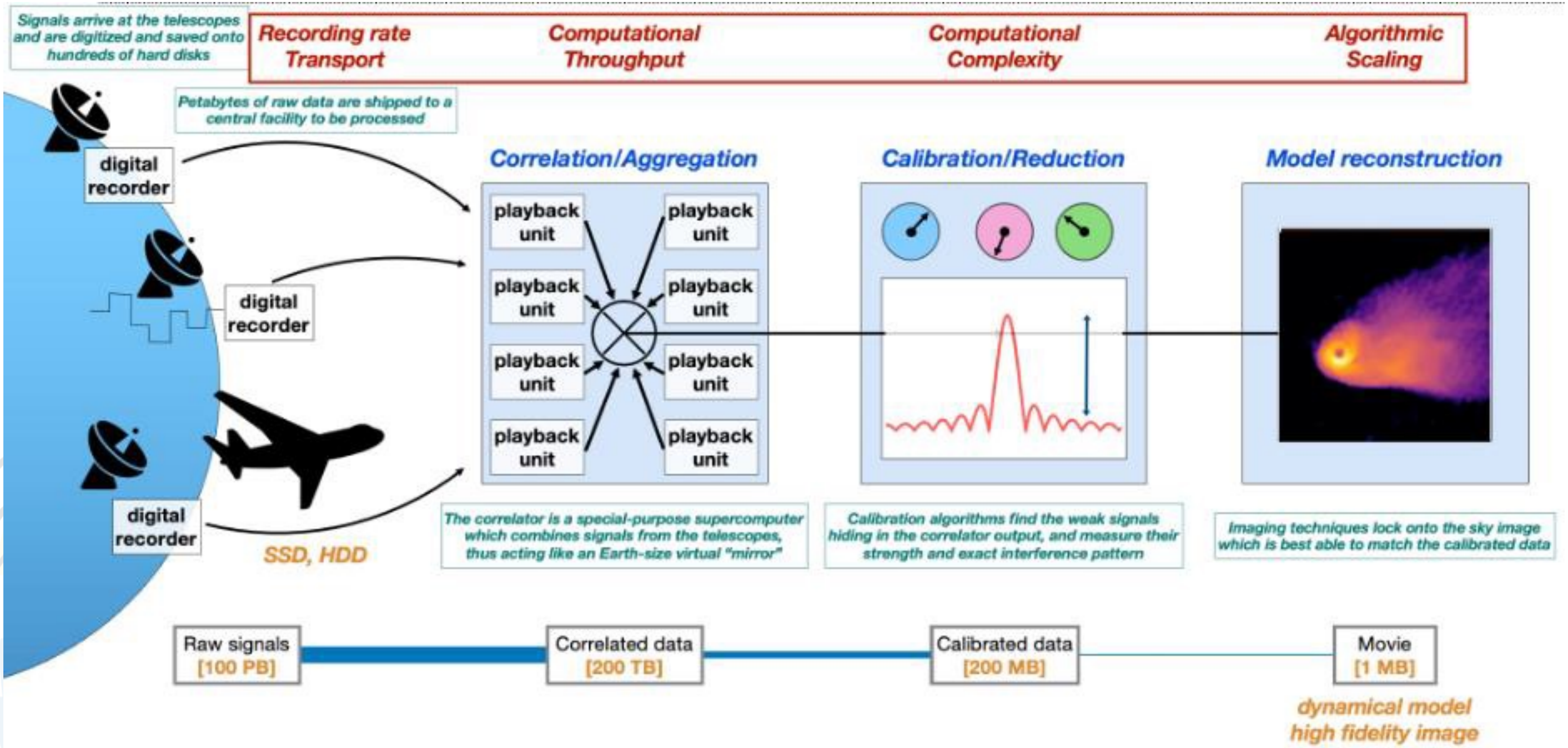
Backup

Data Pipeline Concept of Operations

Credit: Lindy Blackburn



What's happened since the first image?

SgrA* – 2022

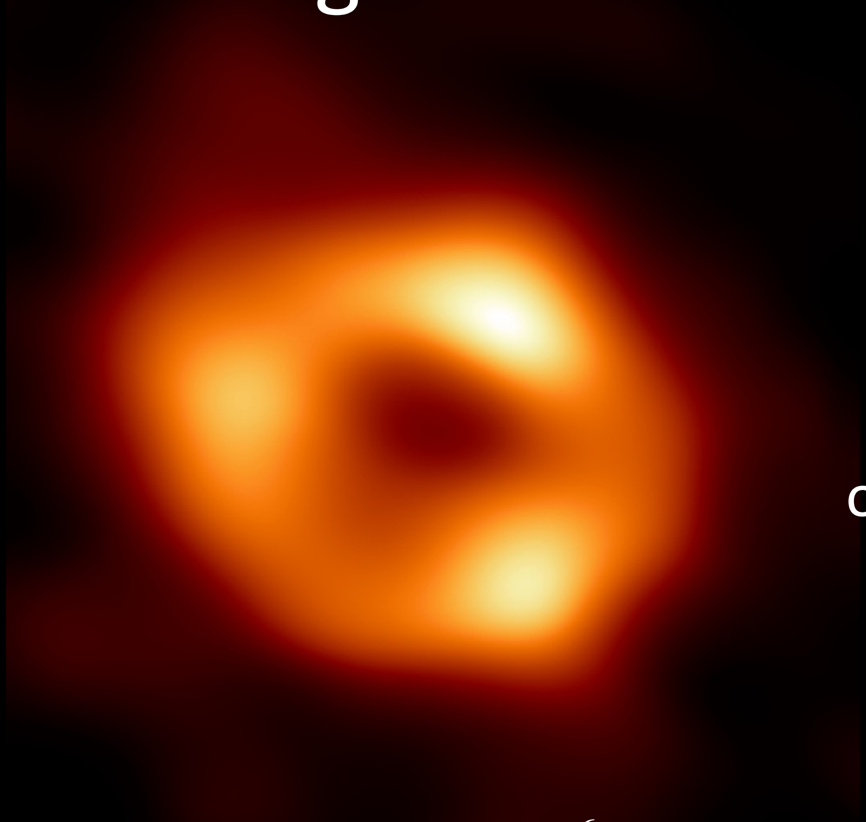
- Ring features match GR predictions
- Observed ordered magnetic fields seen in GRMHD jet/accretion simulations
- Two sources now conclusively confirm that we have access to the event horizon

M87*

About the size of our solar system, ~55 million light years away

$M \approx 6.5 \times 10^9\ M_\odot$
$D \approx 17$ Mpc
$d \approx 42\ \mu as$

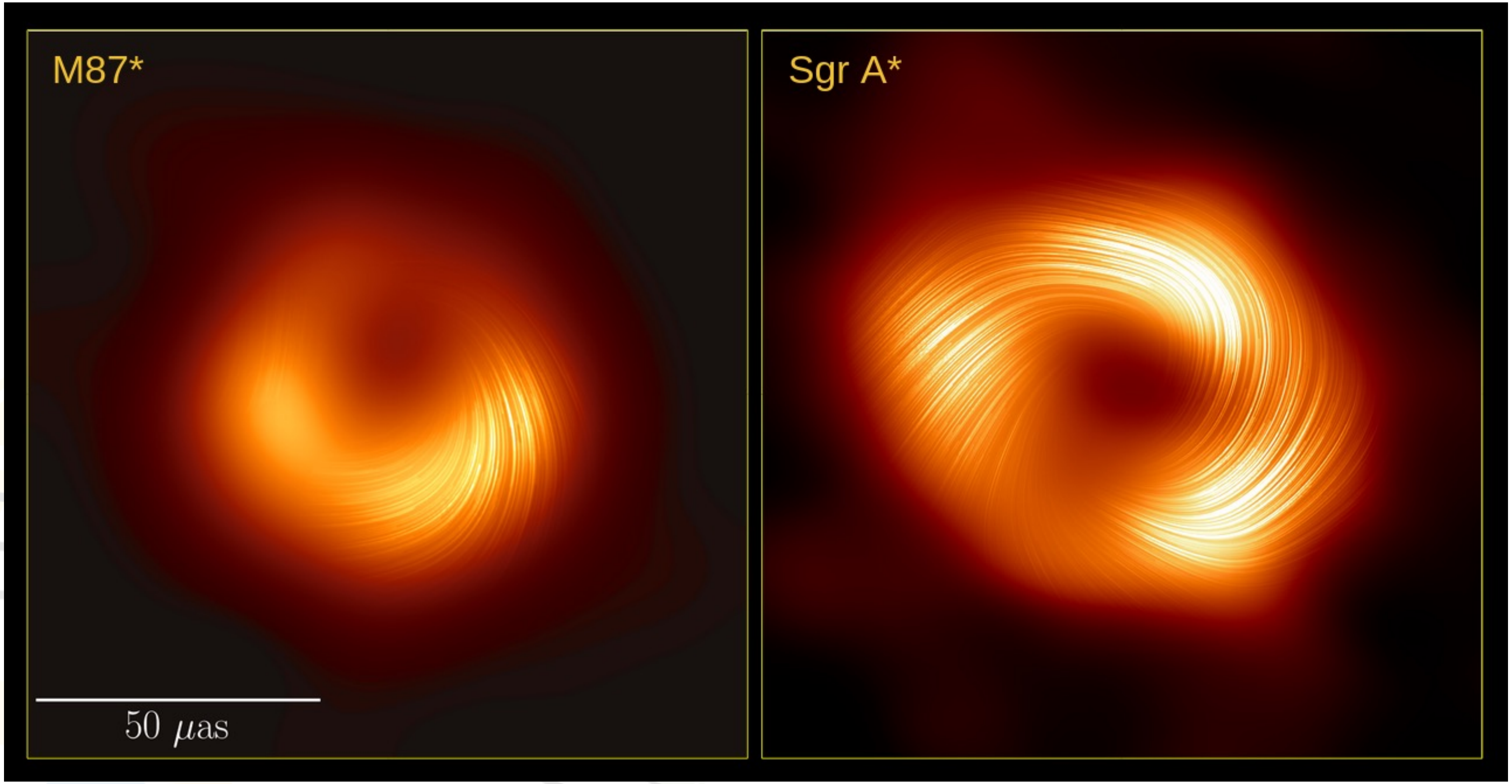
Sgr A*



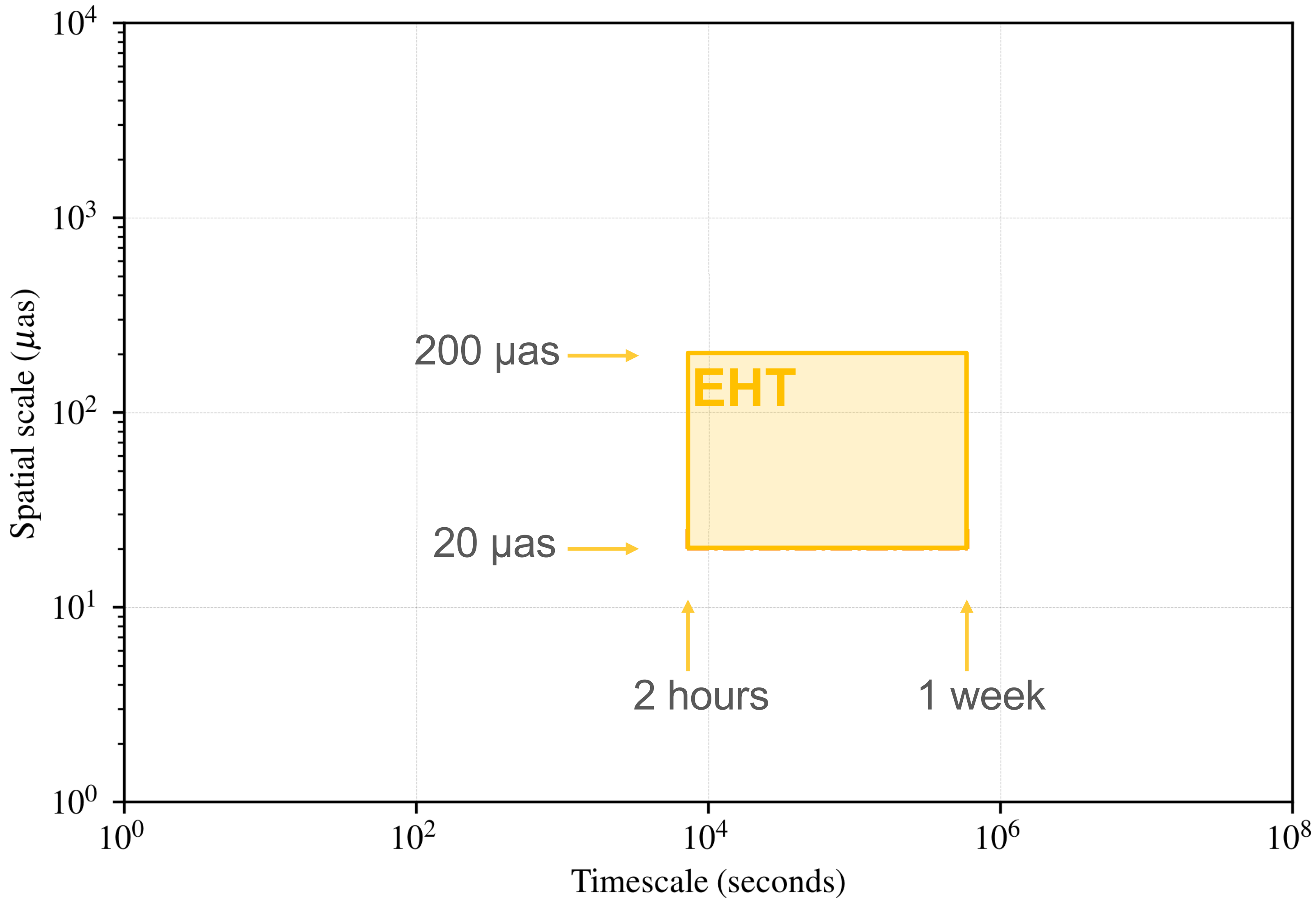
About the size of Mercury’s orbit, 27,000 light years away

$M \approx 4.0 \times 10^6\ M_\odot$
$D \approx 8.2$ kpc
$d \approx 52\ \mu as$

Recent Science Results: polarized images

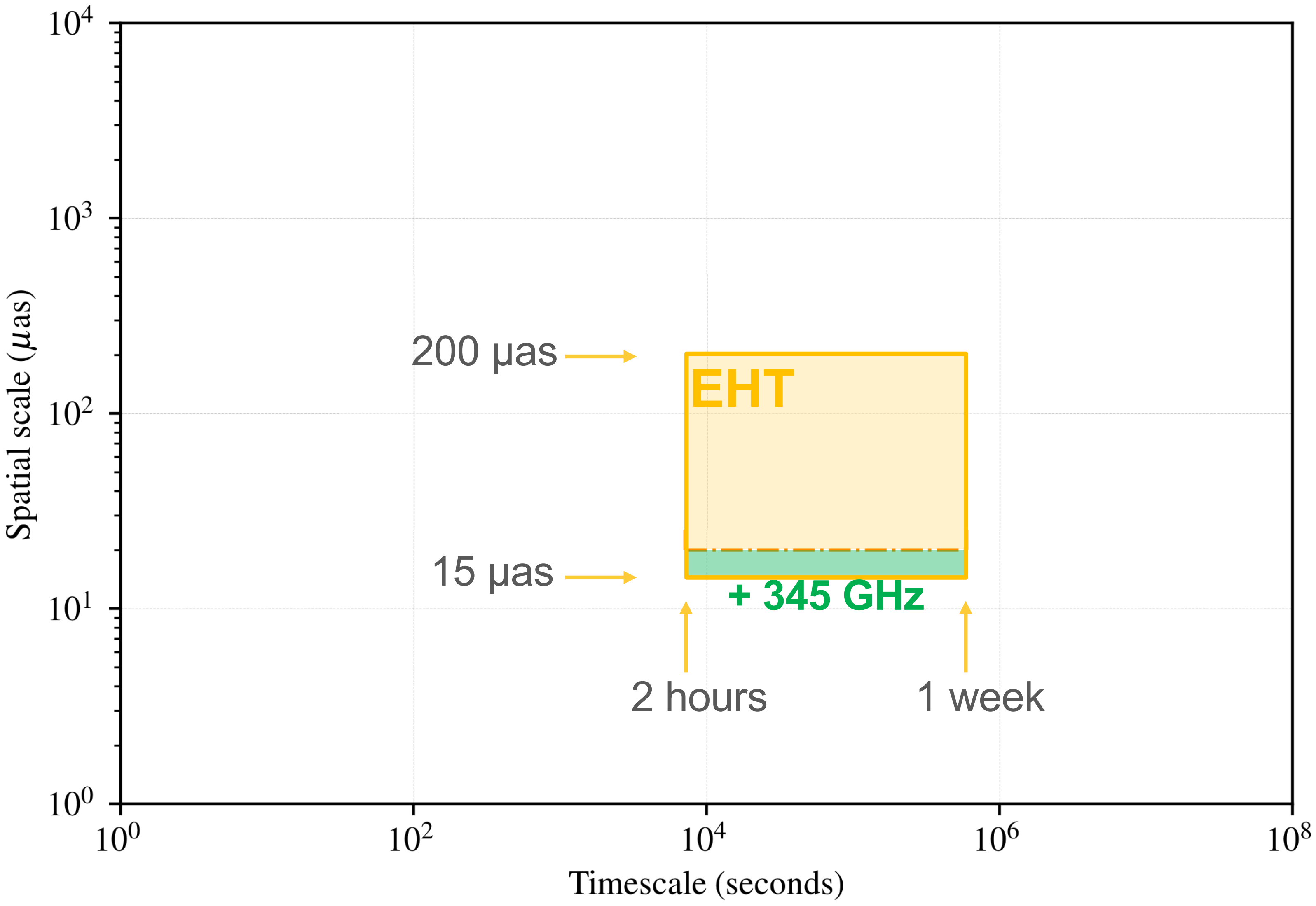


Parameter Space



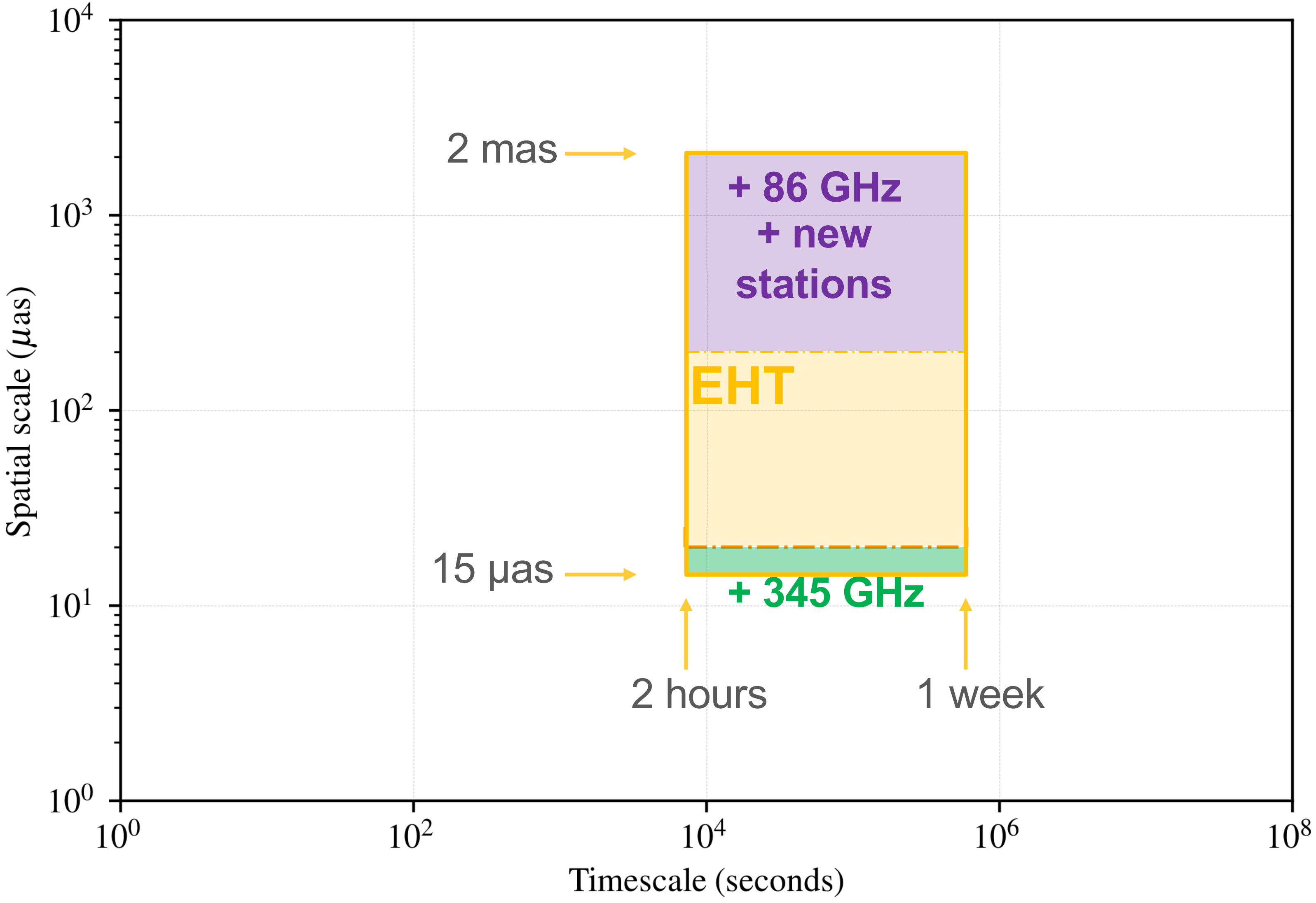
Credit: Dom Pesce

Parameter Space



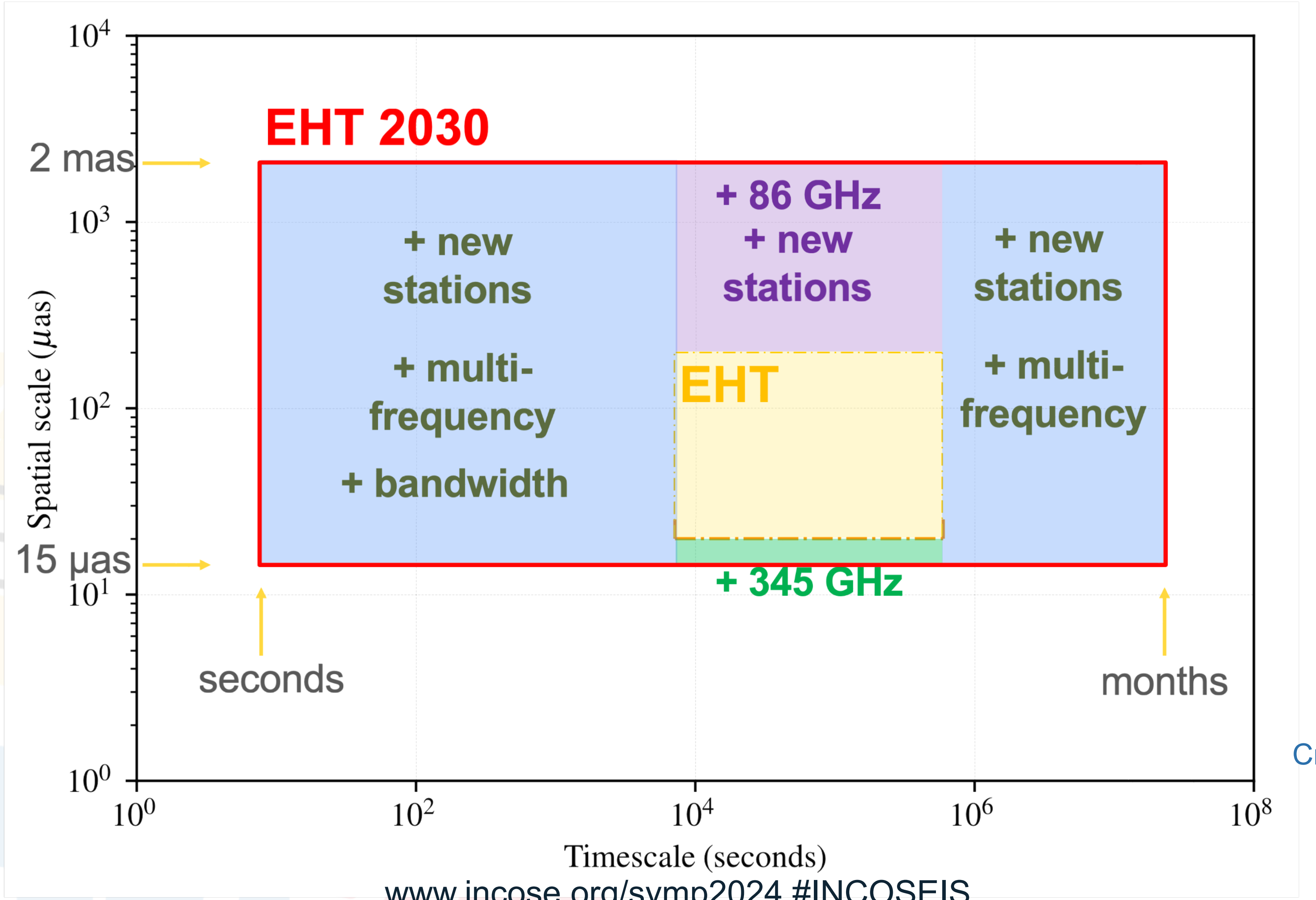
Credit: Dom Pesce

Parameter Space



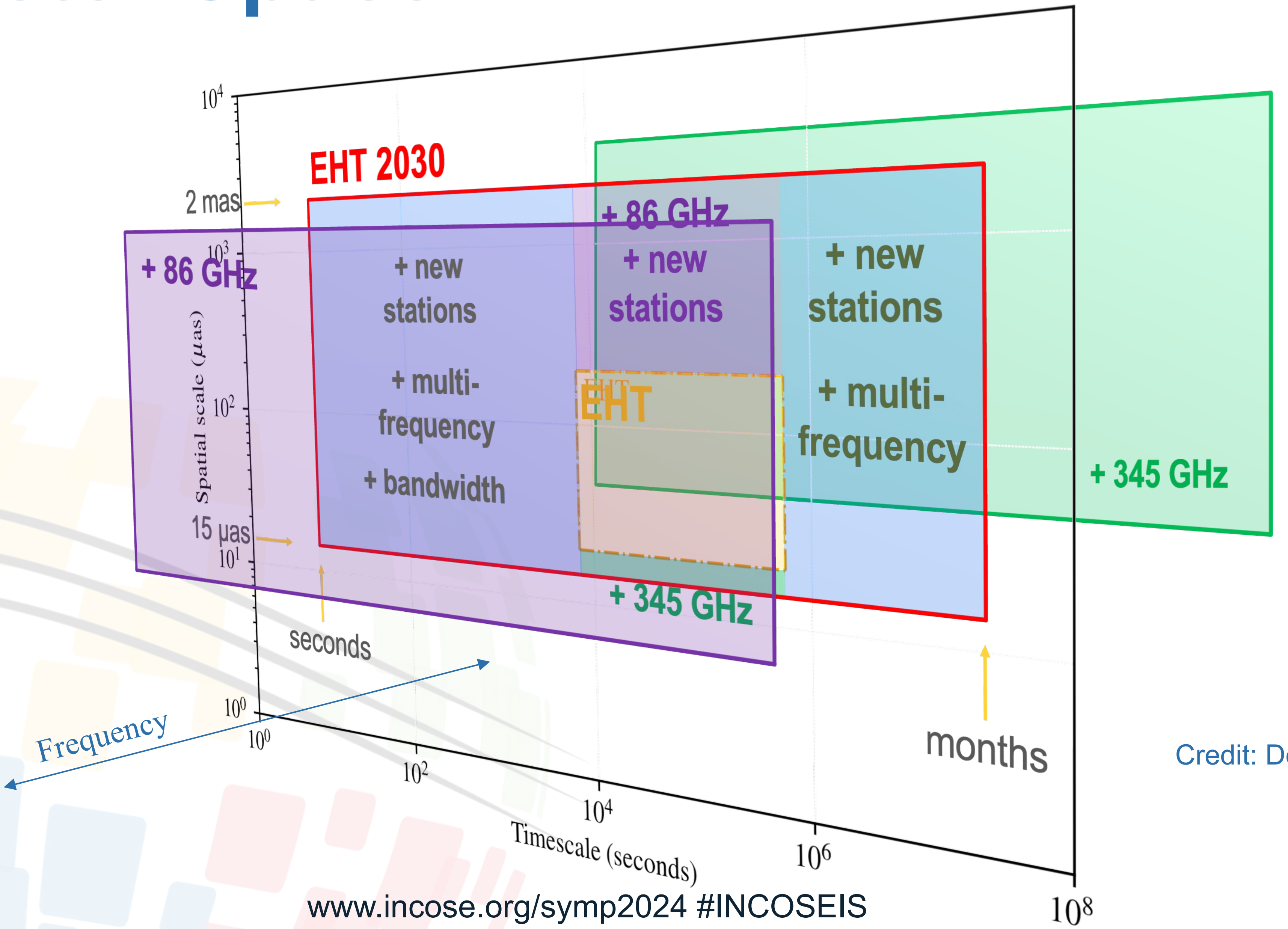
Credit: Dom Pesce

Parameter Space



Credit: Dom Pesce

Parameter Space



Credit: Dom Pesce