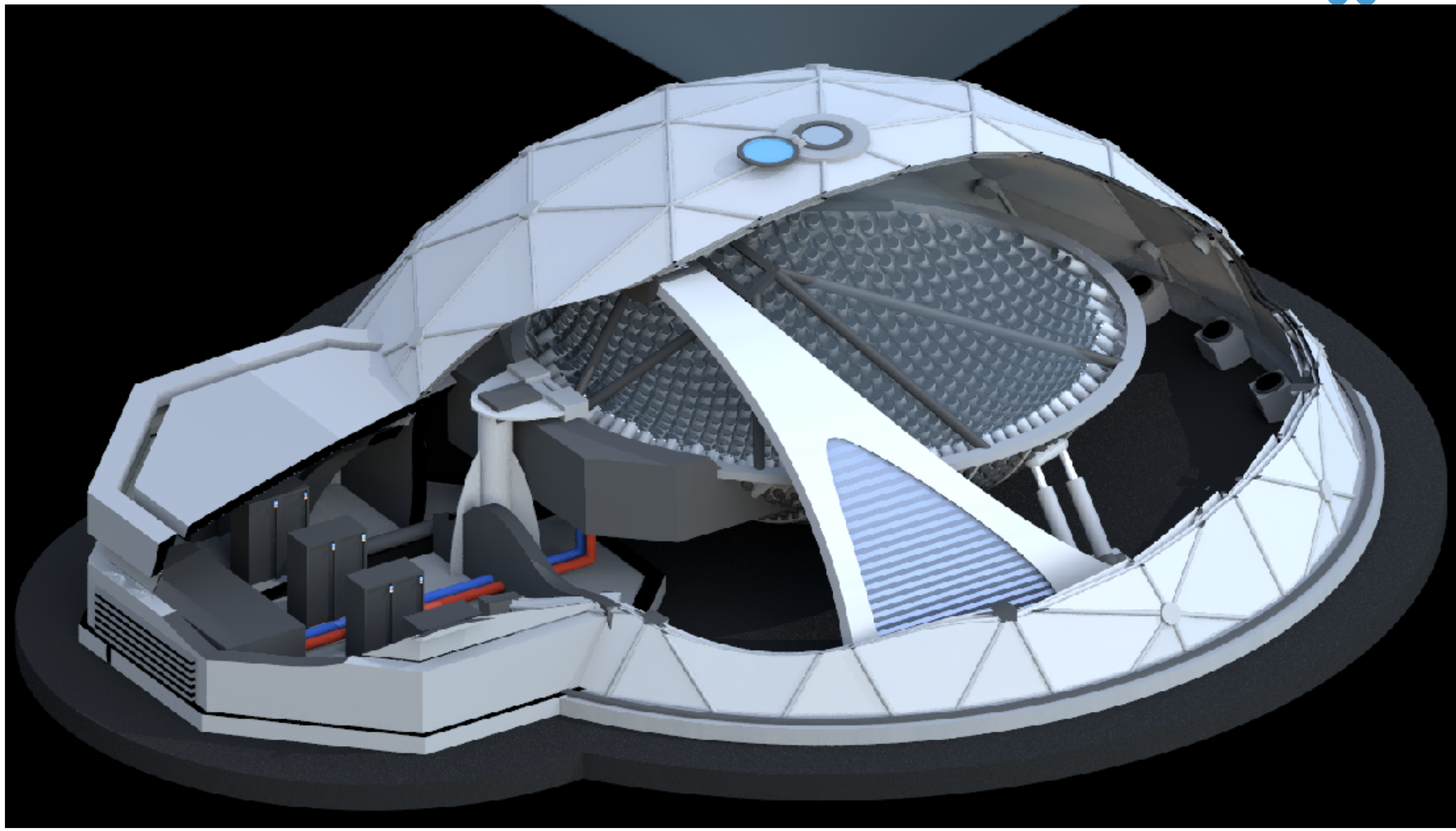
Argus Array

Low-cost Access to the Deep, High-Cadence Sky:

The Argus Optical Array



Hank Corbett

3 Jun 2023

SCHMIDT FUTURES

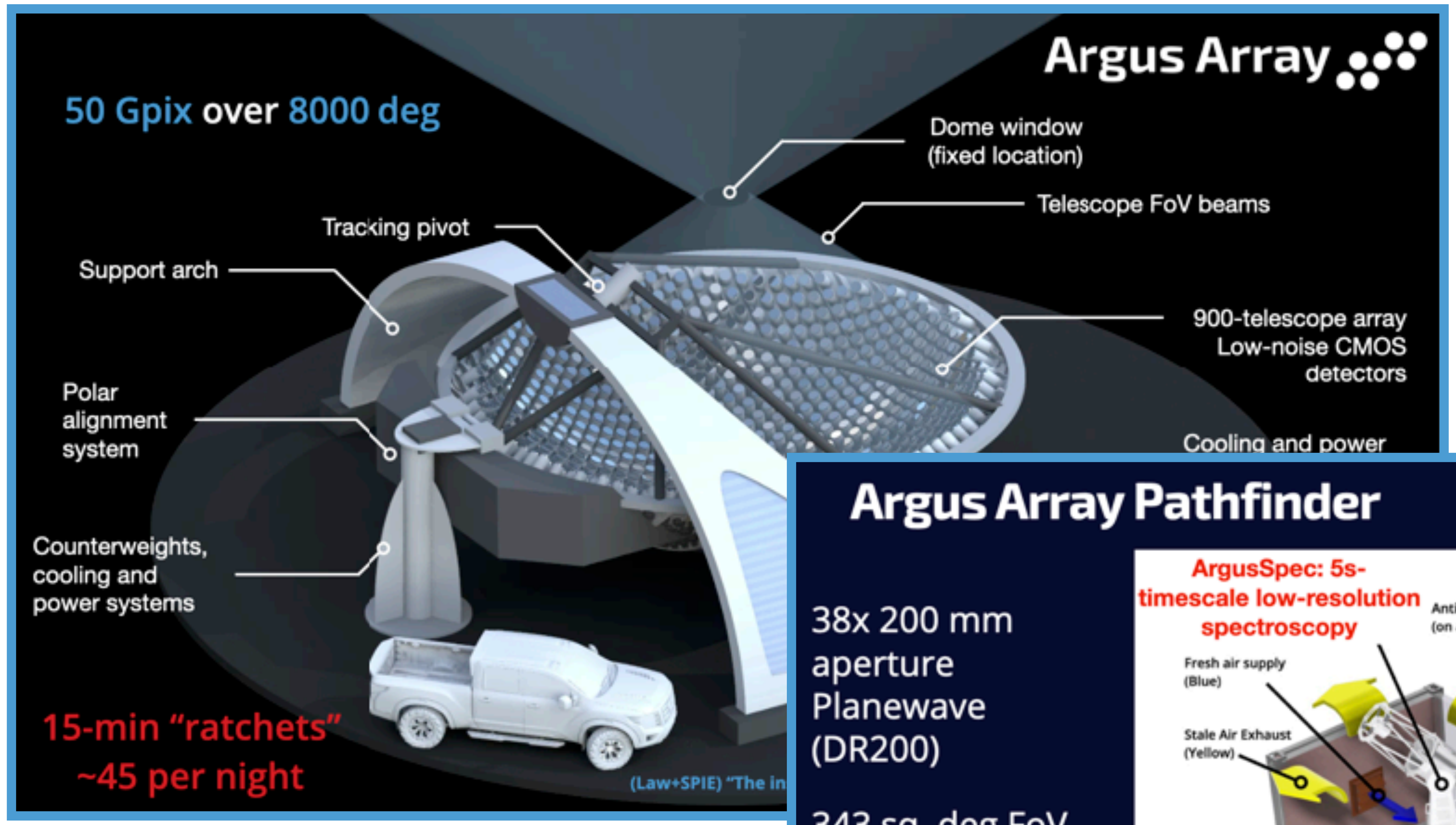
THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

NSF

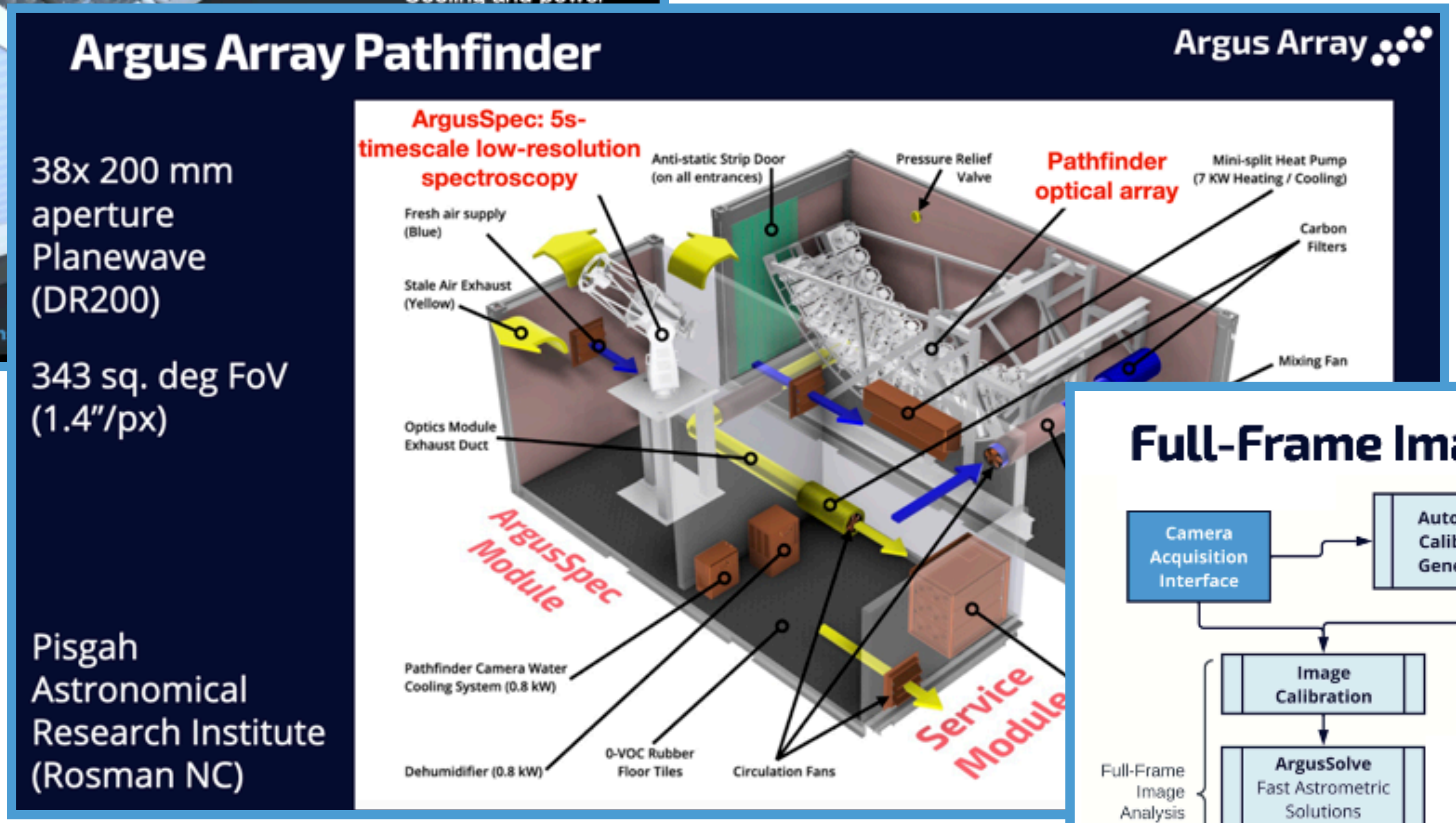
AAS 242: Small Ground and Space Telescopes in the New Era of Big Telescope Surveys

Argus Array

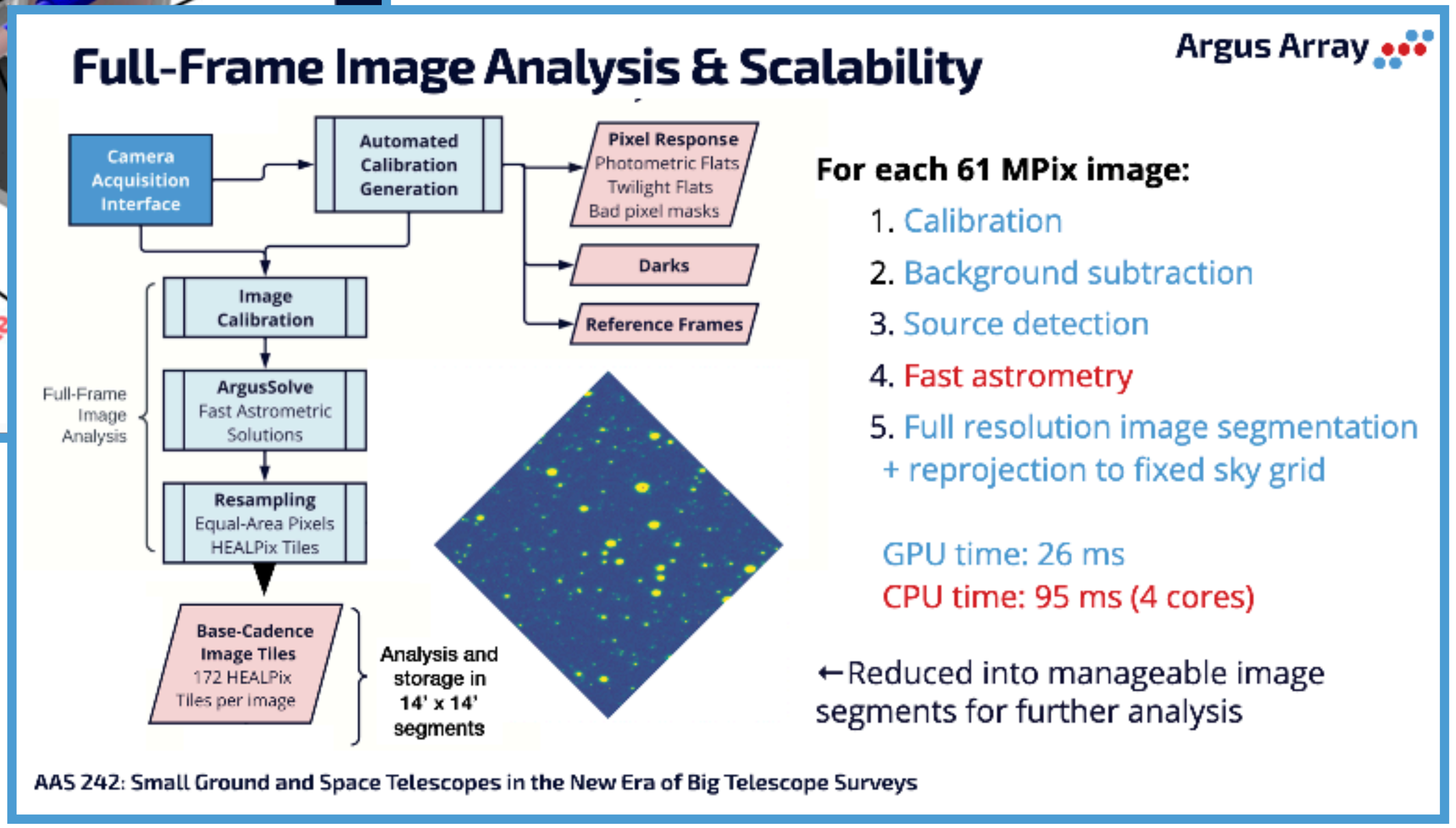
1. Instrument Description



2. Implementation and Prototypes

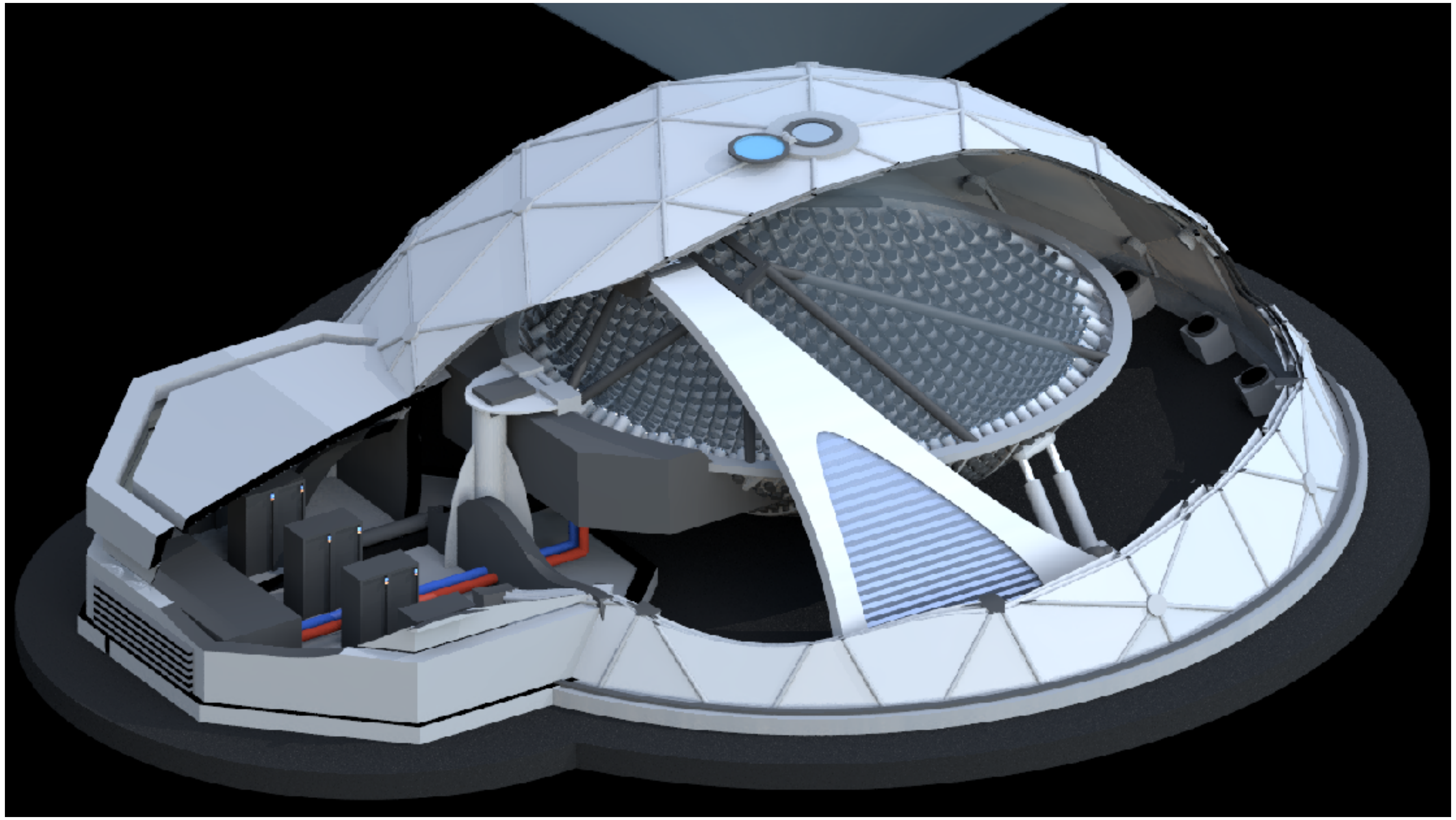


3. Data Products and Pipelines



The Argus Optical Array

Argus Array



5m-class collecting area

50 GPix mosaic camera

8,000 sq. deg. FoV

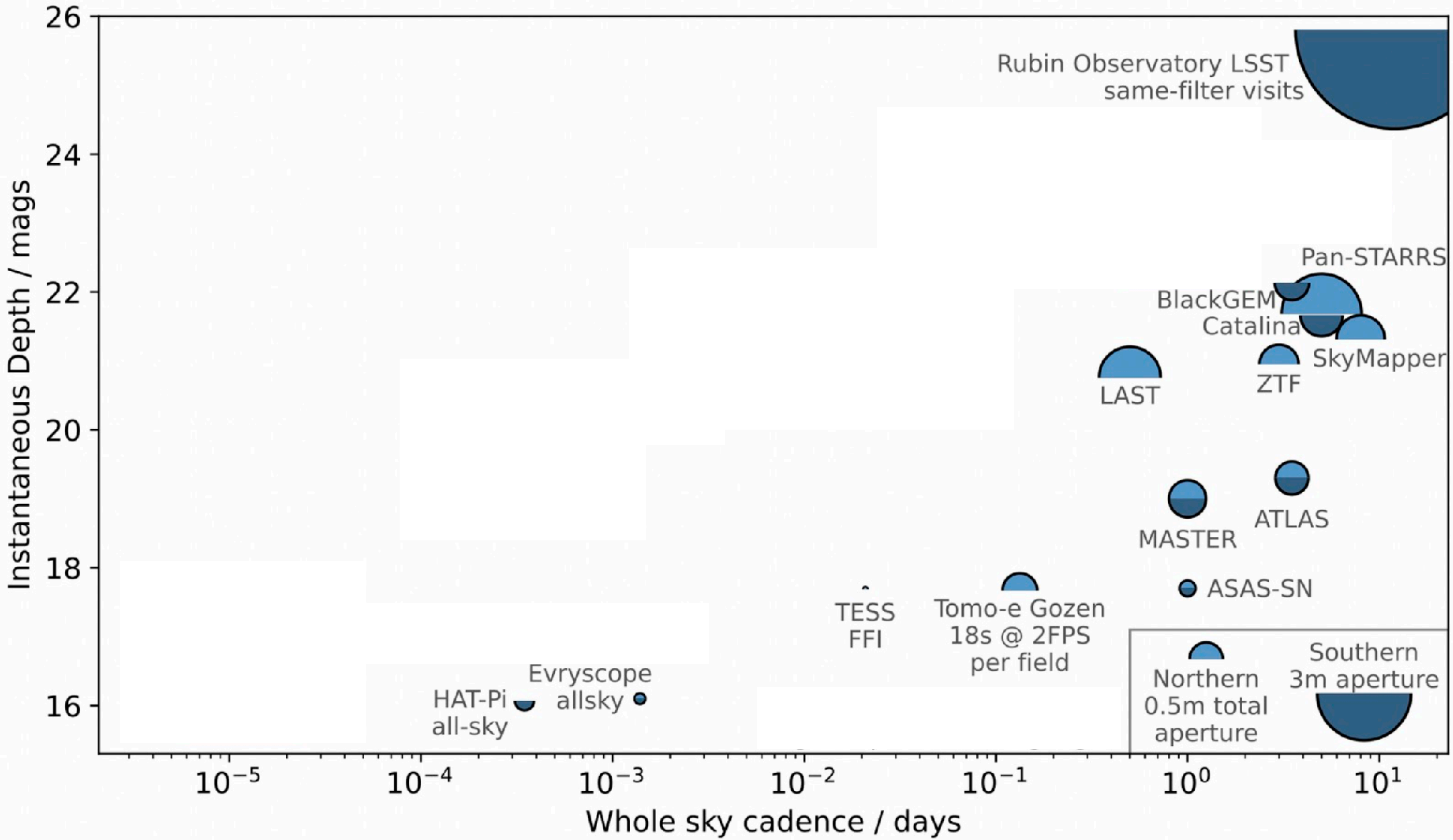
1.4 arcsec per pixel

m_g~16.0 (1s cadence)

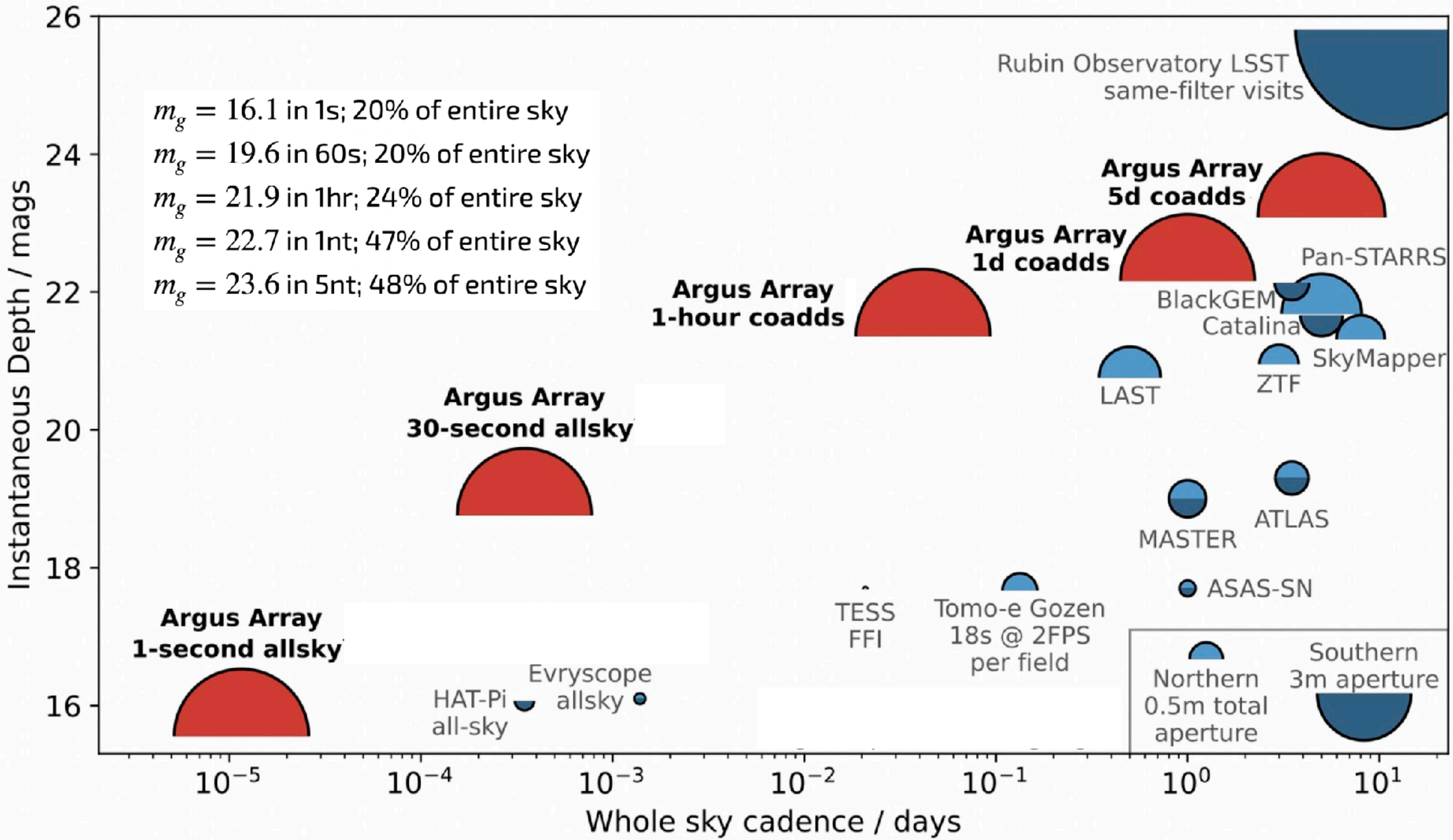
m_g~19.1 (30s cadence)

4.3 PB per night

(only 145 TB at 30s cadence)



Rubin Observatory LSST
same-filter visits
Pan-STARRS
BlackGEM
Catalina
SkyMapper
ZTF
LAST
ATLAS
MASTER
ASAS-SN
TESS
FFI
Tomo-e Gozen
18s @ 2FPS
per field
Evryscope
allsky
HAT-Pi
all-sky
Northern
0.5m total
aperture
Southern
3m aperture
Instantaneous Depth / mags
Whole sky cadence / days
26
24
22
20
18
16
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



$m_g = 16.1$ in 1s; 20% of entire sky
$m_g = 19.6$ in 60s; 20% of entire sky
$m_g = 21.9$ in 1hr; 24% of entire sky
$m_g = 22.7$ in 1nt; 47% of entire sky
$m_g = 23.6$ in 5nt; 48% of entire sky
Rubin Observatory LSST same-filter visits
Argus Array 5d coadds
Argus Array 1d coadds
Argus Array 1-hour coadds
Argus Array 30-second allsky
Argus Array 1-second allsky
Pan-STARRS
BlackGEM
Catalina
SkyMapper
LAST
ZTF
ATLAS
MASTER
ASAS-SN
TESS FFI
Tomo-e Gozen 18s @ 2FPS per field
HAT-Pi all-sky
Evryscope allsky
Northern 0.5m total aperture
Southern 3m aperture
Instantaneous Depth / mags
Whole sky cadence / days
26
24
22
20
18
16
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Science Cases

The Argus Optical Array is designed for the priority areas identified by the Astro2020 Decadal Survey

- Worlds and Suns in Context
- New Messengers and New Physics
- New Midscale Time-Domain Astrophysics Surveys

Multimessenger Time-Domain Astronomy

• How do kilonova GW-counterpart sources evolve in the minutes following the gravitational wave emission?
•By how much can the LIGO significant-detection event rate, and resultant astrophysical leverage, be increased with high-cadence optical monitoring of the entire sky for simultaneous optical counterparts?
•Do non-repeating fast radio bursts (FRBs) have optical counterparts? *
•Will simultaneous entire-sky high-cadence monitoring reveal new counterparts to neutrino, gamma-ray, radio and other sources from non-optical all-sky surveys?

Exoplanets

• What is the population of low-mass icy worlds around nearby stars, revealed by the first deep, all-sky high-cadence microlensing survey? *
• What is the population of circumbinary planets, revealed by monitoring the timing variations of 10^7 eclipsing binaries at minute cadence for years?
• What is the population of white-dwarf exoplanet-debris disks, revealed by high-cadence monitoring of 125,000 white dwarfs, an order of magnitude more than any previous survey? *
• With a deep high-cadence survey of all accessible young stars simultaneously, can we identify transient events associated with planetary collisions around young stars? *
• What are the long-term stellar activity effects for the habitability of planets around nearby brown dwarfs?
• Can long-term, high-precision, high-cadence monitoring of all active stars identify light echoes from planets being impacted by the largest and rarest stellar flares? *
• Can star-planet interactions drive periodic stellar activity, and even be used to detect exoplanets?

Stellar Astrophysics

• Is our theoretical understanding of the stellar mass-radius relation (especially at the low-mass end) matched by long-term, high-cadence photometric observations of 10^7 eclipsing binaries?

Stellar Astrophysics (cont.)

• How do flare rates correlate with the long-term activity cycles of nearby exoplanet host stars, and what are the implications for habitability of the planets around them?
• Can we characterize the population of ancient galactic transients via long-term light-echo searches?
• What are the rotation rates and RV-false-positive implications for slowly-rotating stars (exoplanet hosts or other important sources) that cannot be measured with shorter-term surveys?
• What is the rate of faint galactic stellar mergers due in-spiraling eclipsing binaries like V1309 Sco? Can we find and predict these events before they happen and use them to constrain stellar interior models?
• What are the rates and general properties of dust-disk drop-out events across 10^8 stars?
• How common are the most massive, potentially civilization-ending stellar flares, among stars like our Sun? *

General Transient Events

• What is the very-early-time evolution of supernovae? What does the shock-breakout regime look like for the likely-to-be best-studied supernova events?
• What is the chemical makeup of stellar winds just before supernova explosions?
• How common are stellar outbursts just before supernova events?
• What is the early-time behavior of nearby SN-1a events used for supernova cosmology?
• Are there short-timescale extragalactic transient events rejected as asteroids in longer-cadence surveys? *

Solar System Science

• What is the comprehensive distribution of shapes, rotation rates and thus strengths of main-belt and Kuiper-belt objects, as determined from 10^5-10^6 epoch multicolor light curves?
• What is the (upper-limit-to-the) population of large bodies in the Oort cloud, as determined by a years-long occultation survey of 10^8 stars? *
• How many main-belt objects and KBOs have eclipsing moons, and what are their mass distributions?
• Are outbursts the source of anomalous acceleration for interstellar asteroids?
• What are the detailed shapes, rotation rates and strengths of interstellar asteroids?
• How much do the surfaces of interstellar asteroids vary, spatially and during their solar system passages?

** Science Cases for which the Argus Pathfinder prototype system will produce useful data*

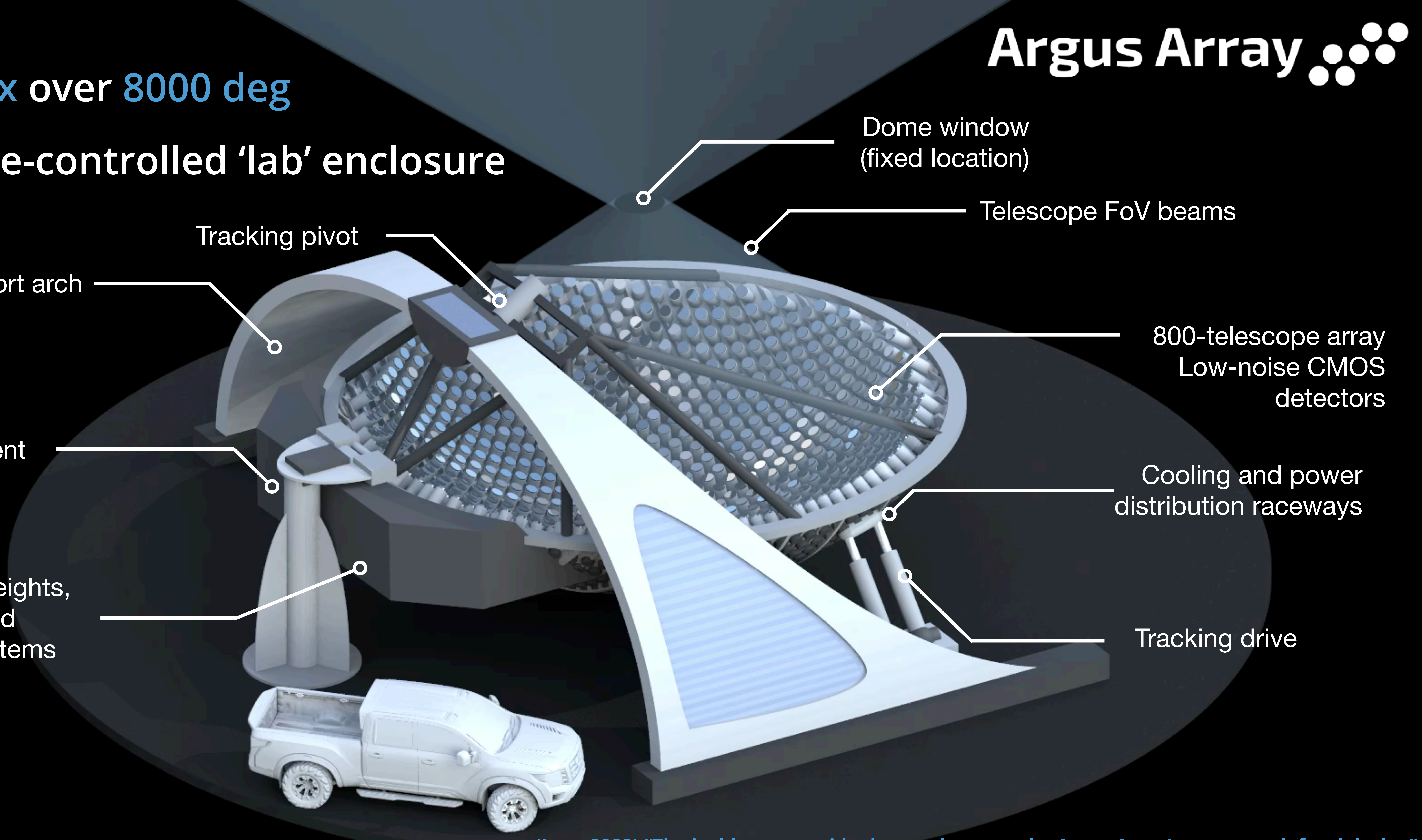
Argus Array

- Early-time discovery of transients
- Simultaneous coverage for 20% of the sky before and after GW, ν, γ, radio events
- Light curves for entire Gaia catalog (10^6 epochs for 10^7 stars)
- Light curves for 40K asteroids

New Messengers and New Physics	Fast / early-time transients	Hank Corbett	UNC Chapel Hill
		Alan Vasquez	UNC Chapel Hill
		Jeff Cooke	Swinburne University
		Takashi Moriya	National Astro. Obs. of Japan
		Allesandro Pappito	National Inst. of Astro., Italy
		Robert Quimby	San Diego State University
		Dan Scolnic	Duke University
		Andrew Howell	Los Cumbres Global Observatory
		Giacomo Terreran	Los Cumbres Global Observatory
		Curtis McCully	Los Cumbres Global Observatory
		Doug Leonard	SDSU
	Gravitational-wave events	Igor Andreoni	University of Maryland
		Stephen Eikenberry	University of Central Florida
		Mansi Kasliwal	Caltech
		Dan Reichart	UNC Chapel Hill
Worlds and Suns in Context	Exoplanet detection	Andrew Vanderburg	MIT
		Rachel Street	Los Cumbres Global Observatory
		Nicholas Law	UNC Chapel Hill
		Josh Pepper	NASA-SMD / Lehigh University
	Stellar characterization	Bill Welsh	SDSU
		Marcel Agueros	Columbia University
		Brad Barlow	High Point University
		Christopher Clemens	UNC Chapel Hill
		JJ Hermes	Boston University
		Andrew Mann	UNC Chapel Hill
	Stellar flares	Eric Sandquist	SDSU
		Ward Howard	CU Boulder
Other areas	Solar system	David Trilling	Northern Arizona University
		Chengxing Zhai	JPL
		Andrew McNeil	Northern Arizona University
	High-energy astrophysics	Tom Maccarone	Texas Tech University
		Eric Stein	Caltech
		Eric Burns	Louisiana State University
		Jerry Orosz	SDSU

50 Gpix over 8000 deg

Climate-controlled 'lab' enclosure



(Law+2022) "The inside-out, upside-down telescope: the Argus Array's new pseudofocal design"

Enabling Technologies and Scalability

- COTS astrographic telescopes
  - Celestron 8” f/2 Rowe-Ackermann Schmidt Astrograph (RASA)
  - 200-mm f/2.8 from PlaneWave Instruments
- Back-side illuminated CMOS sensors (Sony IMX 455 -based from Atik and QHYCCD)

Planewave Delta Rho 200 with Argus Focuser cage

Phased Prototyping of the Argus Array

Argus Array

Evryscope

24x 61cm
DSLR lenses

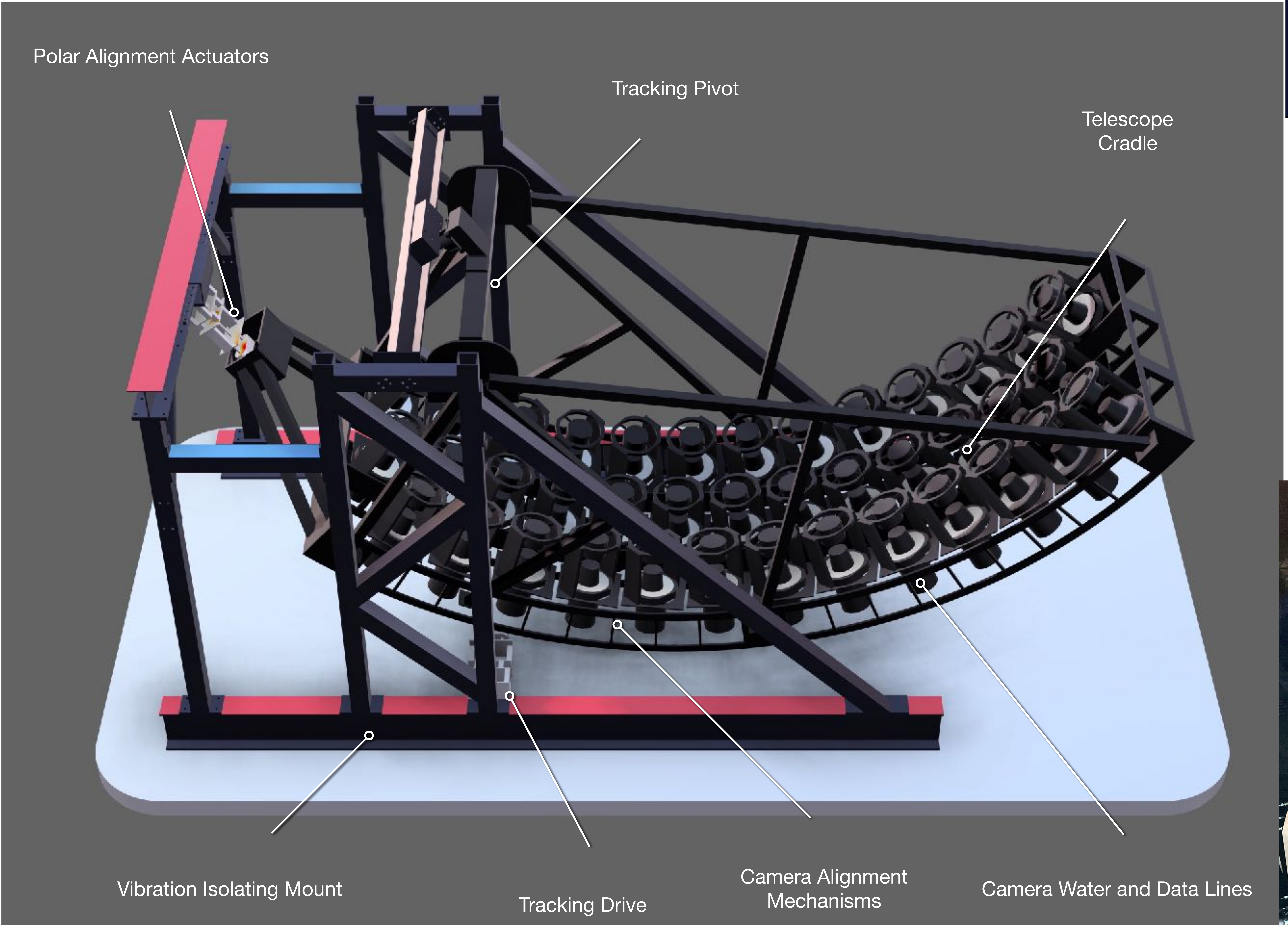
Argus Pathfinder
38x Planewave Argus-8
Commissioning now
PARI, NC

Argus
Technology
Demonstrator

9x Celestron
RASA8

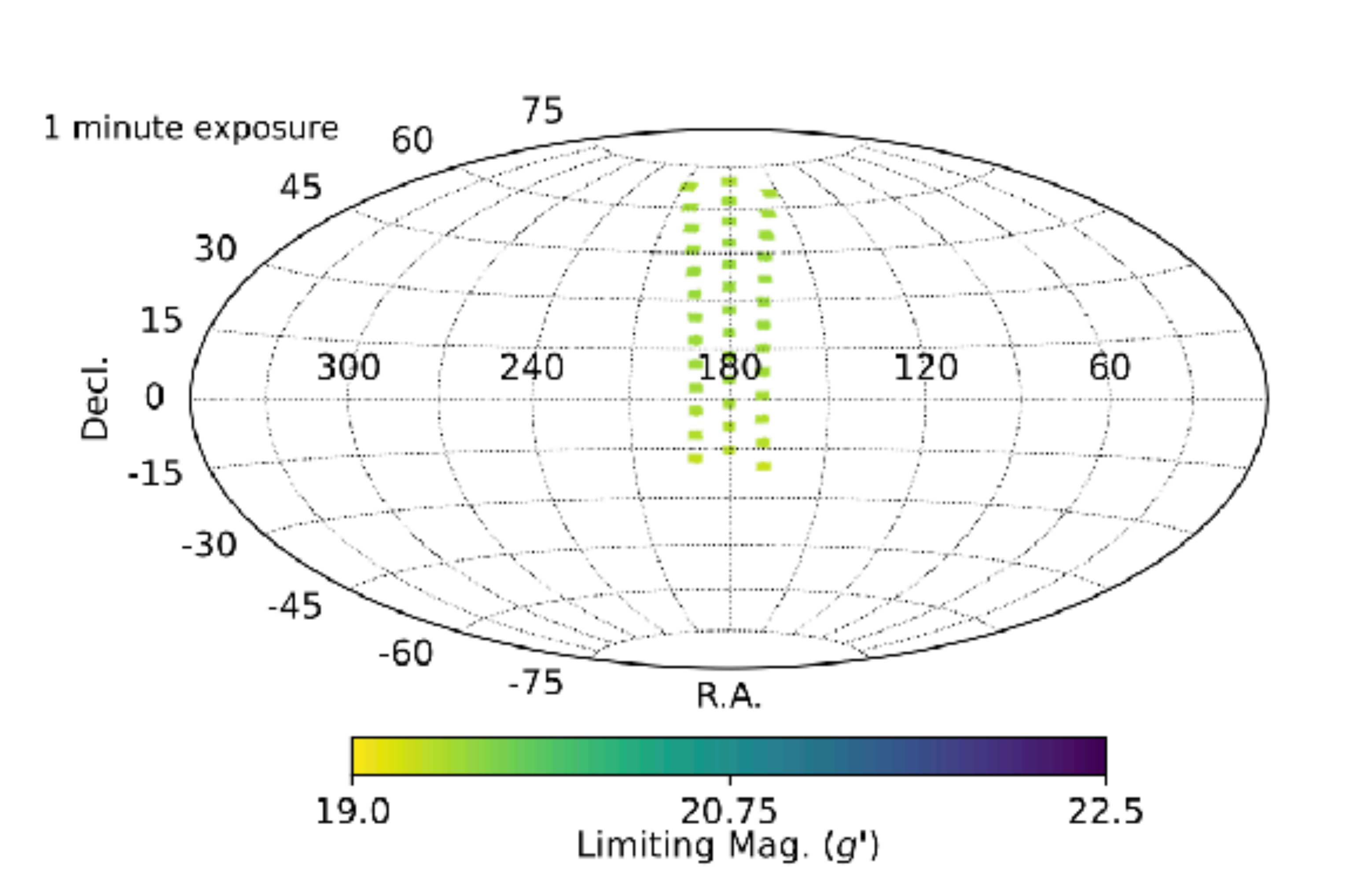
Argus Pathfinder

Argus Array



38x Planewave DR200s

2.3 Gpix + 343 deg² FoV

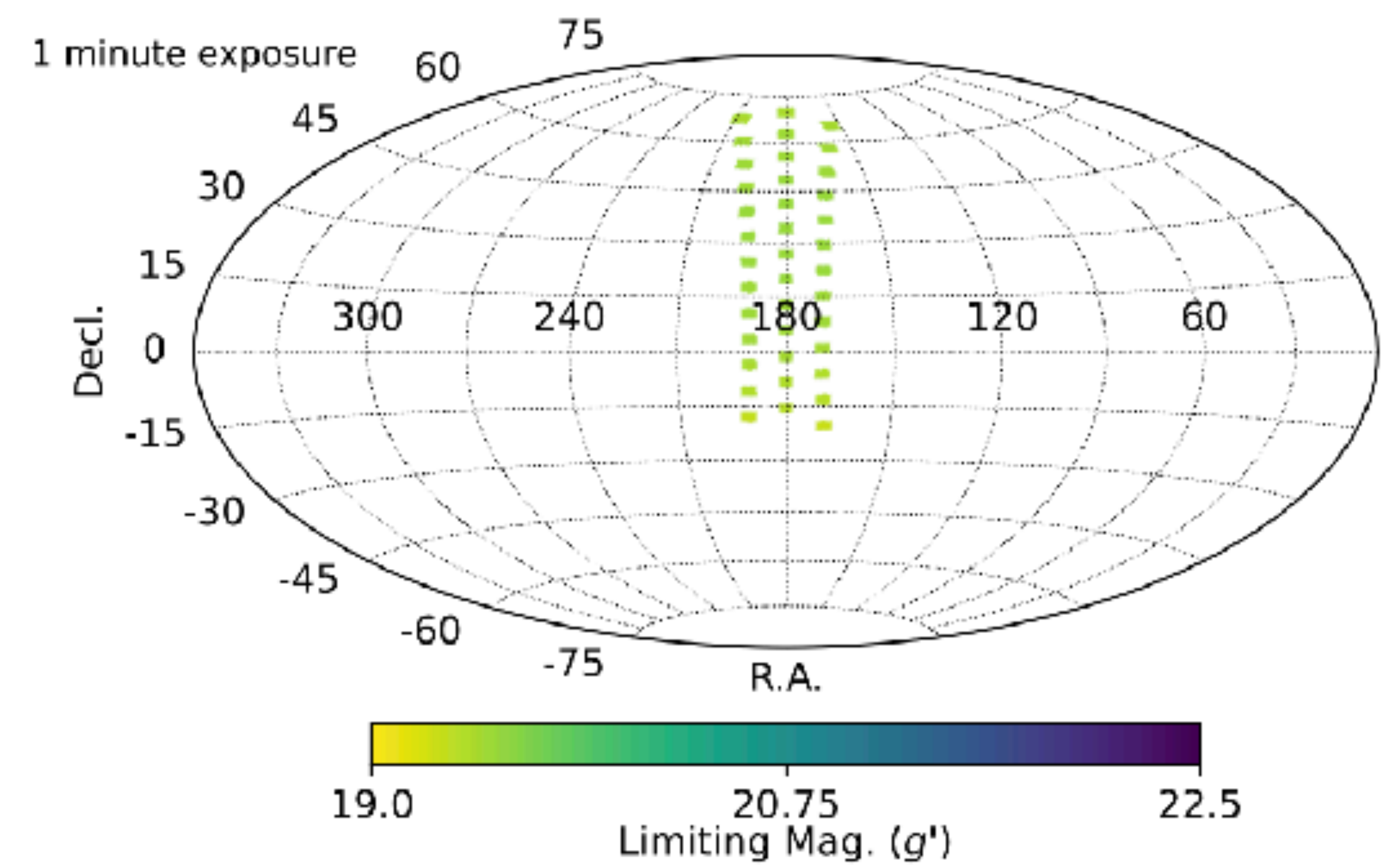


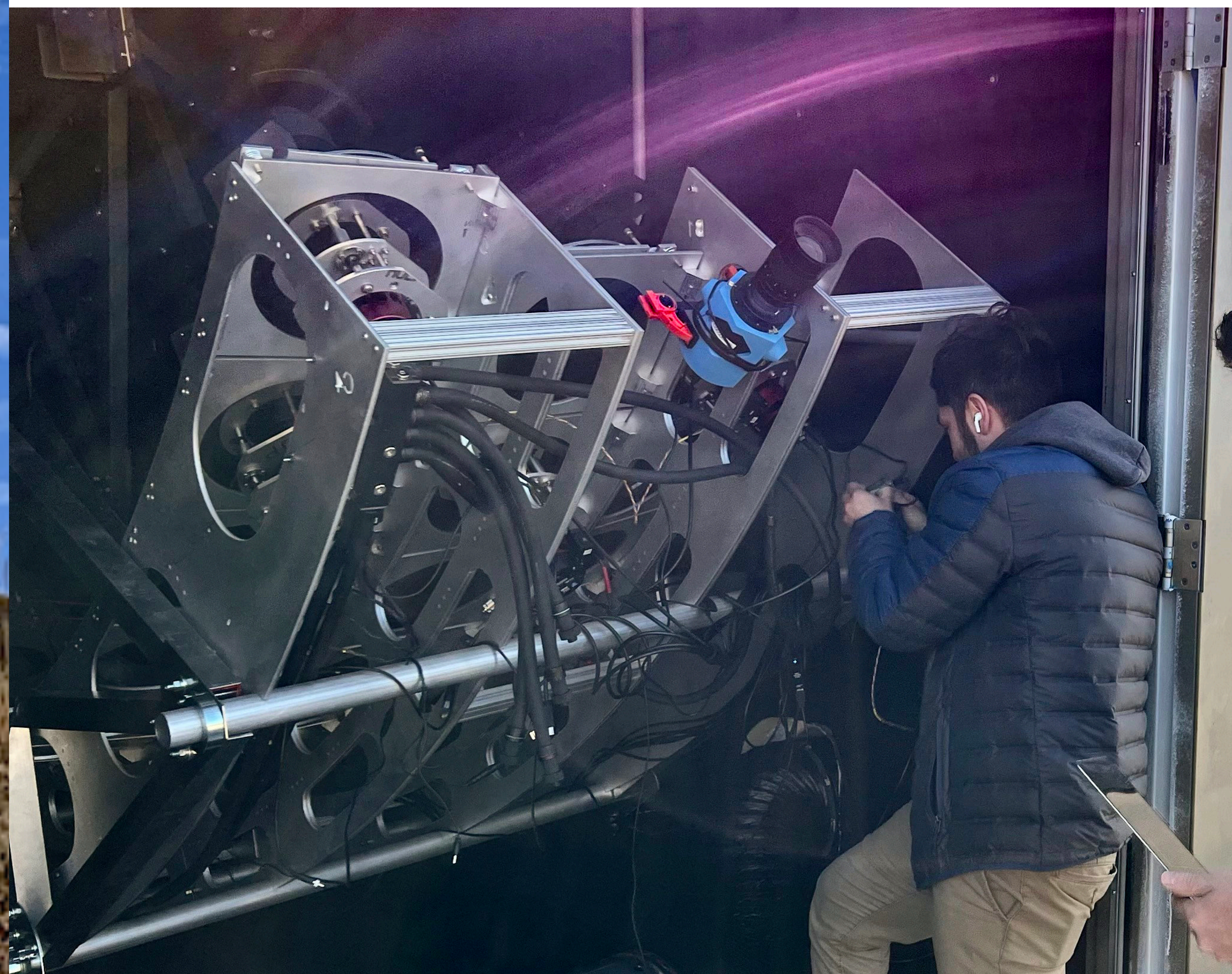
Argus Pathfinder

Argus Array

38x Planewave DR200s

2.3 Gpix + 343 deg² FoV





Data Rates & Storage requirements

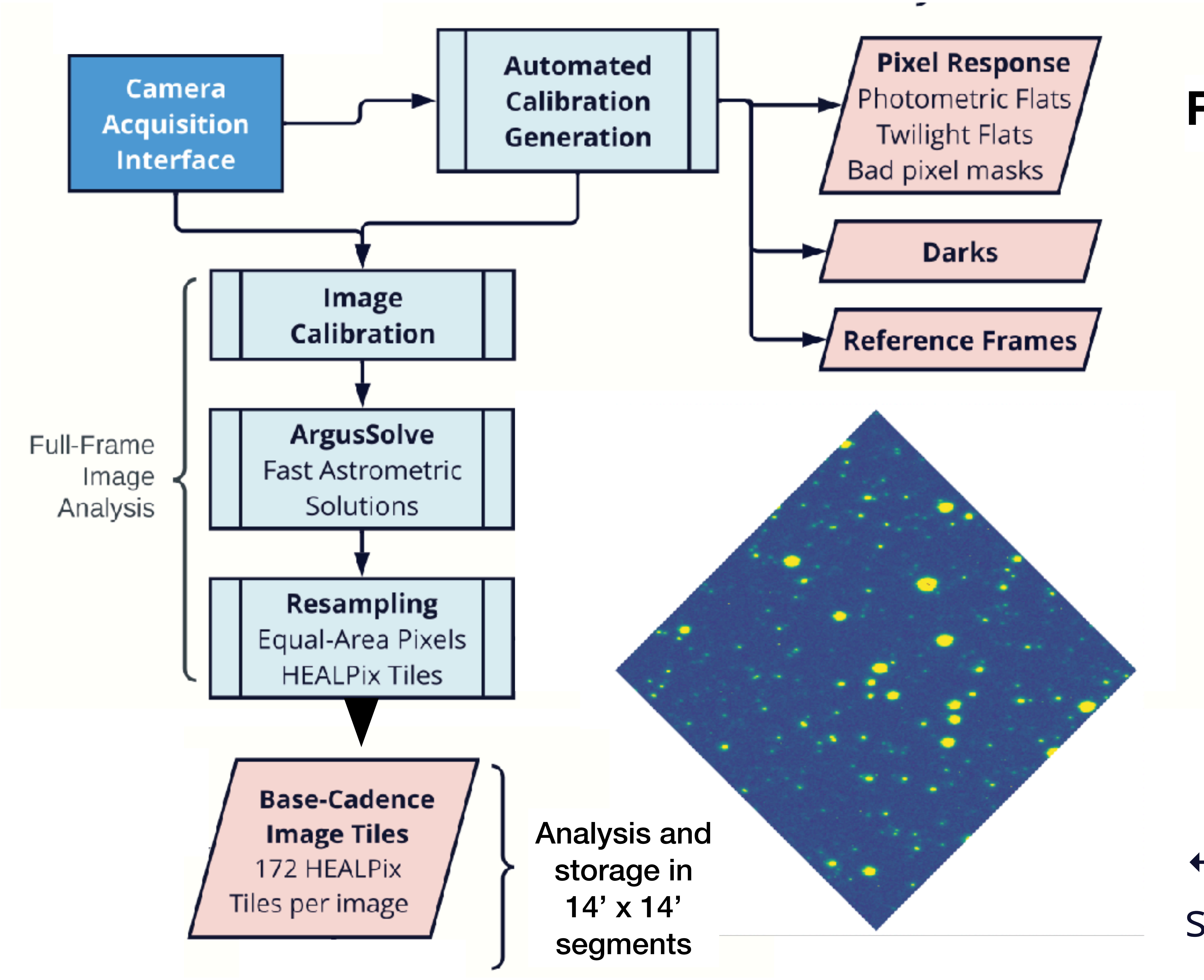
Argus Array

	Argus Array Technology Demonstrator (2021)	Argus Array Pathfinder (2022)	Argus Optical Array
Telescopes	9	38	900
Total Detector Size	550 MPix	2.3 GPix	54.9 GPix
1-second Cadence	110 Gbps (43 TB/ nt)	464 Gbps (180 TB/nt)	11 Tbps (4.3 PB/nt)
30-second Cadence	3.7 Gbps (710 GB)	15.5 Gbps (6 TB /nt)	367 Gbps (145 TB/ nt)

1-second cadence with Argus Pathfinder will enable testing pipelines up to the full Argus Optical Array base-cadence data rate

- Raw data storage requirements are prohibitive to store at the mid-scale funding level
- Even time averaged, terabit-scale transfer required for off-site analysis
- **Scope** control, pipeline **performance**, and **scaling** to full Array are essential

Full-Frame Image Analysis & Scalability



For each 61 MPix image:

1. Calibration
2. Background subtraction
3. Source detection
4. Fast astrometry
5. Full resolution image segmentation + reprojection to fixed sky grid

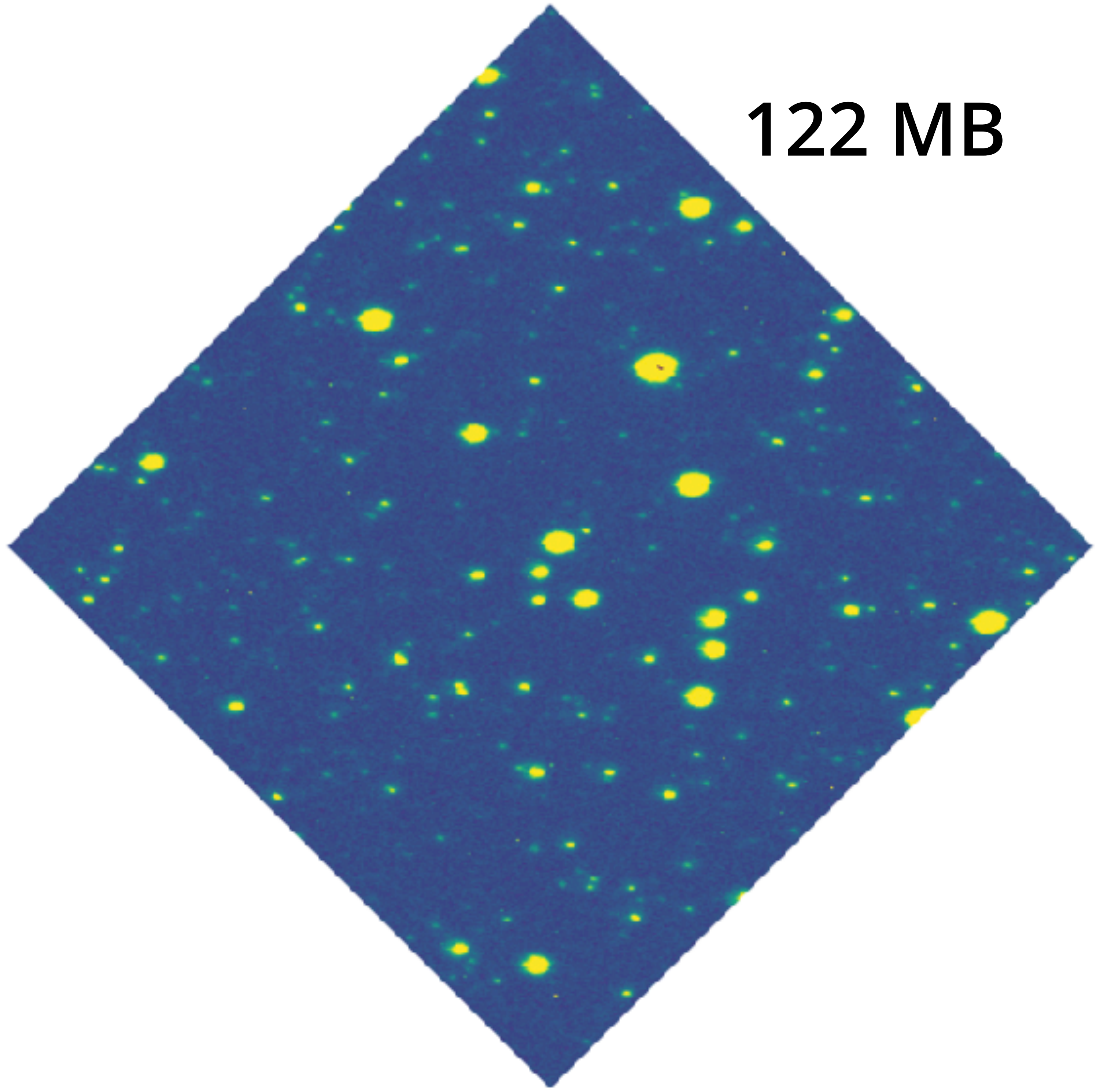
GPU time: 26 ms

CPU time: 95 ms (4 cores)

←Reduced into manageable image segments for further analysis

Compression Rates from Stamping

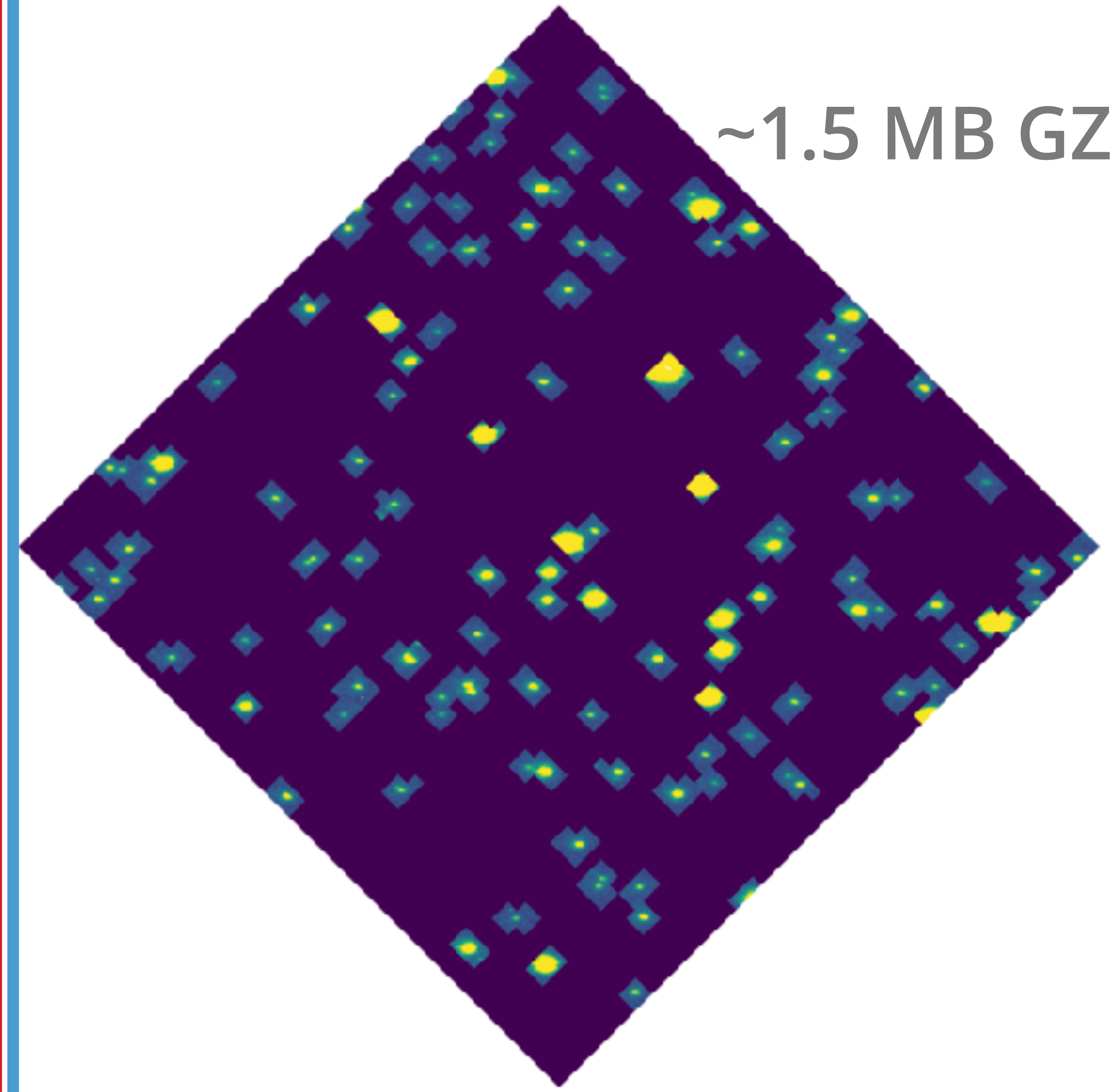
Segmented
Full-Resolution Image



122 MB

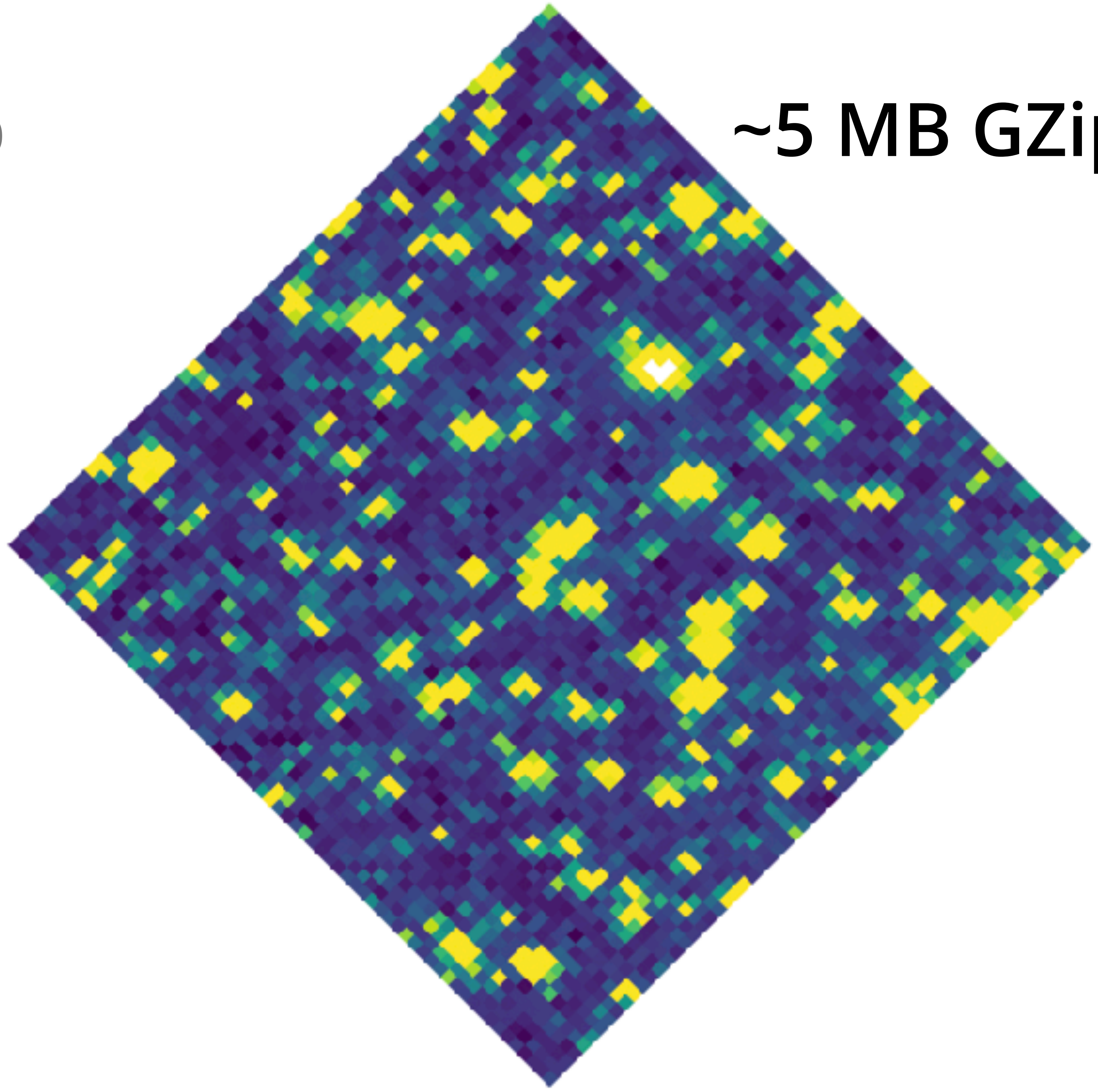
Local cache (~5 days)

Sparse
Full-Resolution Image



~1.5 MB GZip

Filled
Low-Resolution Image



~5 MB GZip

Long-term archiving and distribution

Low-res maps + sparse segments ➡ 95% reduction

Data Products for Argus Pathfinder

Argus Array

Images	Retention	Latency	Public Release (Pathfinder)
Full-resolution image segments	1-2 weeks	Real time	Tech-limited
Deep coadds 15 minutes 5 day	Long-term	<15 minutes	Yes
Sparse, contexual 'postage stamps' for 10^7 sources+transients	Long-term	Real time	Possible
Low-res segments (13.8 arcsec/px) resolution for full sky	Long-term	Real time	Possible
Transient Alerts	**Retention**	**Latency**	**Public Release (Pathfinder)**
From single images 1- and 30-second cadence	Long-term	Real time	Via Community Brokers After commissioning
Deep coadds 15 minutes 5 day	Long-term	<15 minutes	Via Community Brokers After commissioning
Photometric Light Curves	**Retention**	**Latency**	**Public Release (Pathfinder)**
Transient Sources From image subtraction	Long-term	Real time	Via Alerts to community brokers
Detrended long-term light curves for 10^7 input catalog sources	Long-term	Versioned data releases	Yes, scheduled data releases

Argus Array

Capabilities

- 8000 deg^2 FoV
- Northern Hemisphere
  - Mount Laguna, CA
- Limiting mag:
  - mg~19.1 @30s
  - mg=16.1@1s
- Images
  - Coadds out to 1 week
  - Sparse images at 30s cadence
  - Low-resolution + full resolution at 30s
- Transient Alerts
  - In-cadence
  - From coadds
  - Standard distribution channels
- Lightcurves
  - Input catalog of O(10M) sources
  - All transient sources

Limitations

- Limited color info:
  - SDSS g'
  - u+g+r wideband
- Ground-based, single-site
- ~30-35 deg airmass limit
- Resolution: 1.42"/pixel
- Minimal full-resolution image storage

Gaps

- No high-precision photometry (<1%)
- Astrometric RMS ≥ 250 mas
- No hosted analysis platform (like RSP)
- PSF modelling beyond limiting magnitude optimization (eg, for weak lensing)