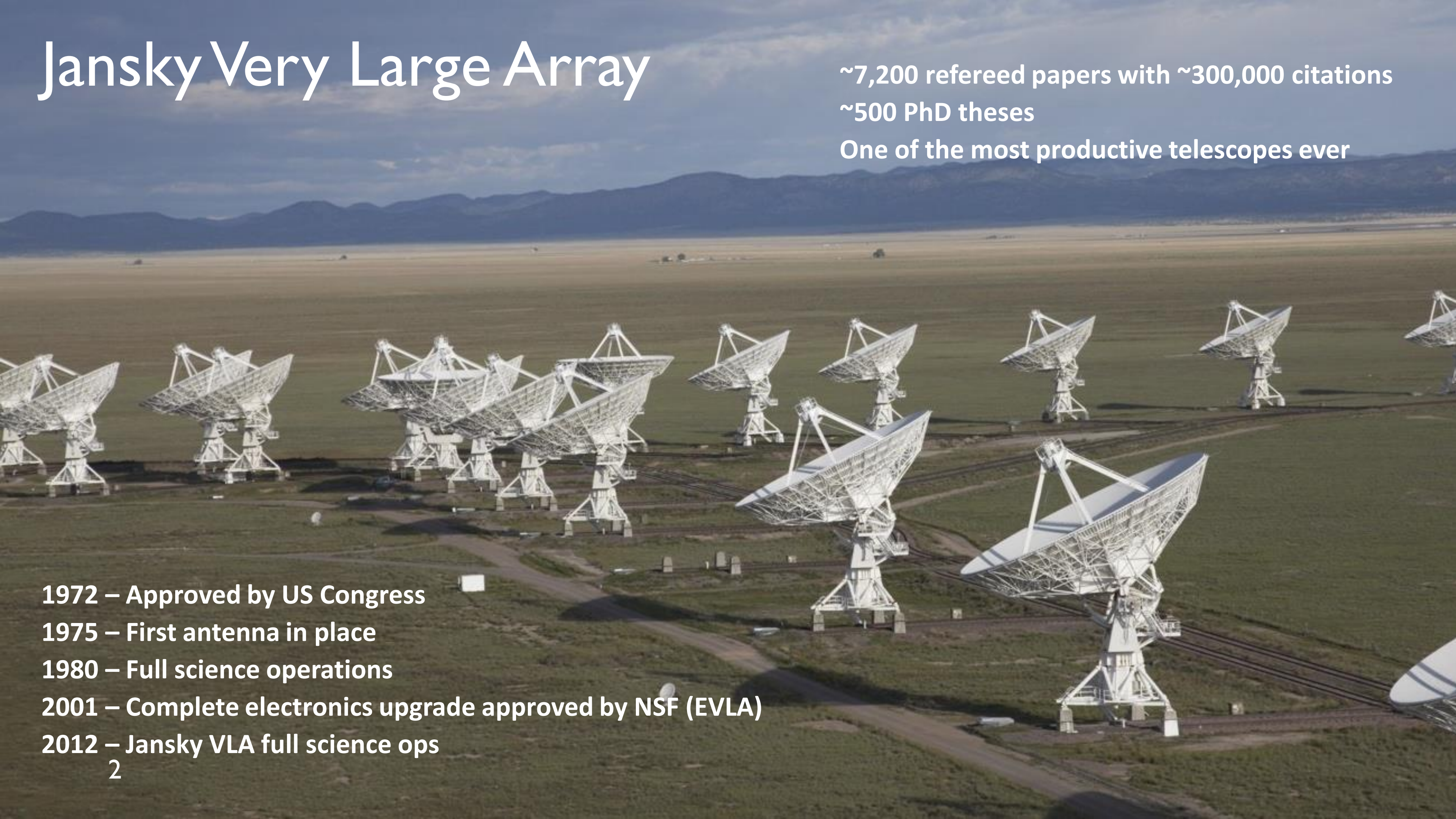
ngvla
Next Generation Very Large Array

Project Overview

ngVLA Project Team (NRAO)

Jansky Very Large Array



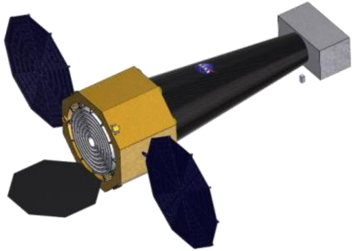
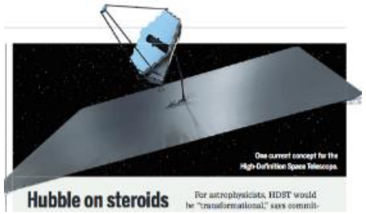
~7,200 refereed papers with ~300,000 citations
~500 PhD theses
One of the most productive telescopes ever

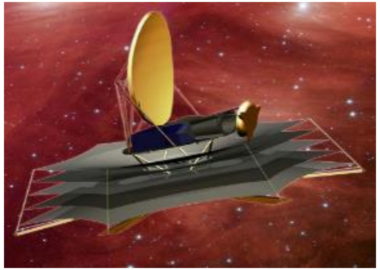
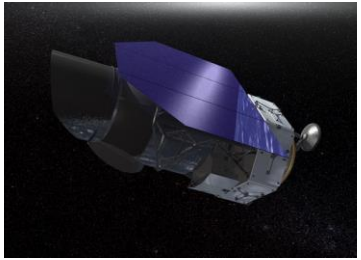
1972 – Approved by US Congress
1975 – First antenna in place
1980 – Full science operations
2001 – Complete electronics upgrade approved by NSF (EVLA)
2012 – Jansky VLA full science ops

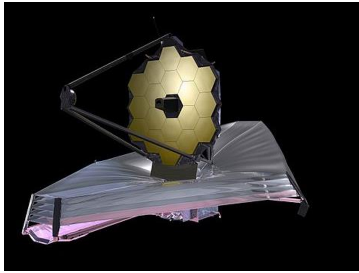
Highly Synergistic with Other 2020s Facilities

- SKA/Lynx
  - Atomic/non-thermal
  - *Molecular/thermal*
- ALMA
  - Warm/star-forming
  - *Cold/dense fuel for SF*
- LUVOIR/HabEx
  - Image earth-like planets
  - *Image terrestrial-zone planets forming*
- OST (FIR surveyor)
  - C/WNM & WIM
  - *Cold Molecular Medium*
- TMT/GMT
  - *Stellar Mass and Unobscured SF*
  - *Dense Gas and Obscured SF*
- JWST/WFIRST
  - *Continuing its legacy in many areas of astrophysics*



Concept Development

- Kavli science meetings: 2015-2017 – Radio Futures Series
- ngVLA Science Meetings: 2017-2020 – concept iteration.
- Sep 2016: Science Advisory Council (SAC) formed
- Nov 2016: Launched ngVLA Community Studies Program
    - 38 studies over 2 rounds, financially supported by NRAO
    - Community-led Science Use Cases: 80 submitted for 'Reqs to Specs' process (ngVLA memo # 18)
- Feb 2017: Technical Advisory Councils (TAC) formed
- Science case development by Science Working Groups (SWGs)

Community Participation

Successful 2018 & 2019 ngVLA Science Meetings

Broad Participation Largely Dominated by Early Career Astronomers

http://go.nrao.edu/ngVLA18

http://go.nrao.edu/ngVLA19

First Internationally-Led Science Meeting!

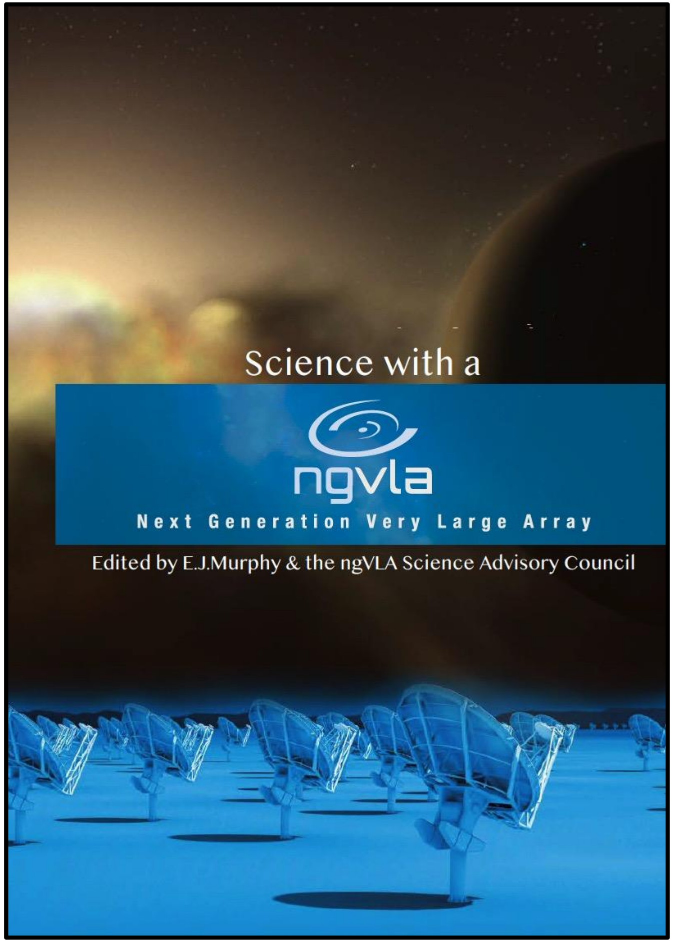
Broad Participation Largely Dominated by Early Career Astronomers

- NAOJ-ngVLA Science Meeting: September 16-20, 2019 in Mitaka, Japan ***~100 Participants!***
- Forward looking talks covering broad scientific interests.

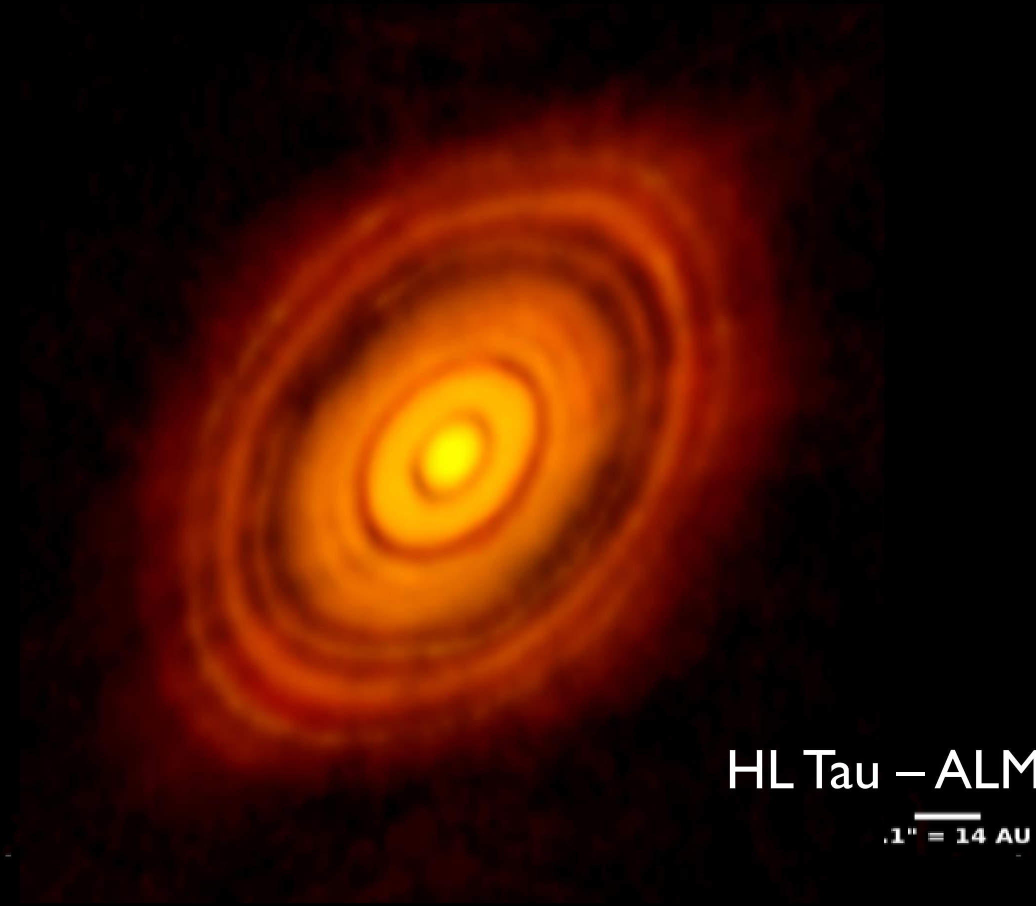
ngVLA Science Book

- Released in January 2019
  - 88 peer-reviewed contributions received
  - 286 unique authors (comp: *LSST* Science Book had 245)
  - **https://ngvla.nrao.edu/page/projdoc**

- ngVLA science cases developed over a generation: 10 yrs beyond the Northern Hemisphere Array, 15 years after SKA Phase 3, 20 yrs from EVLA Phase 2.



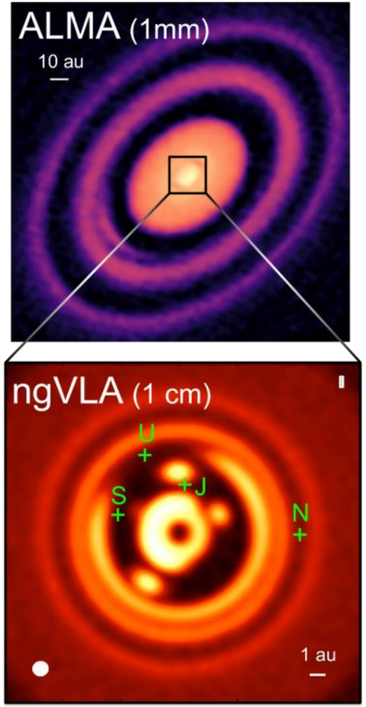
Thermal Imaging on Milliarcsecond Scales

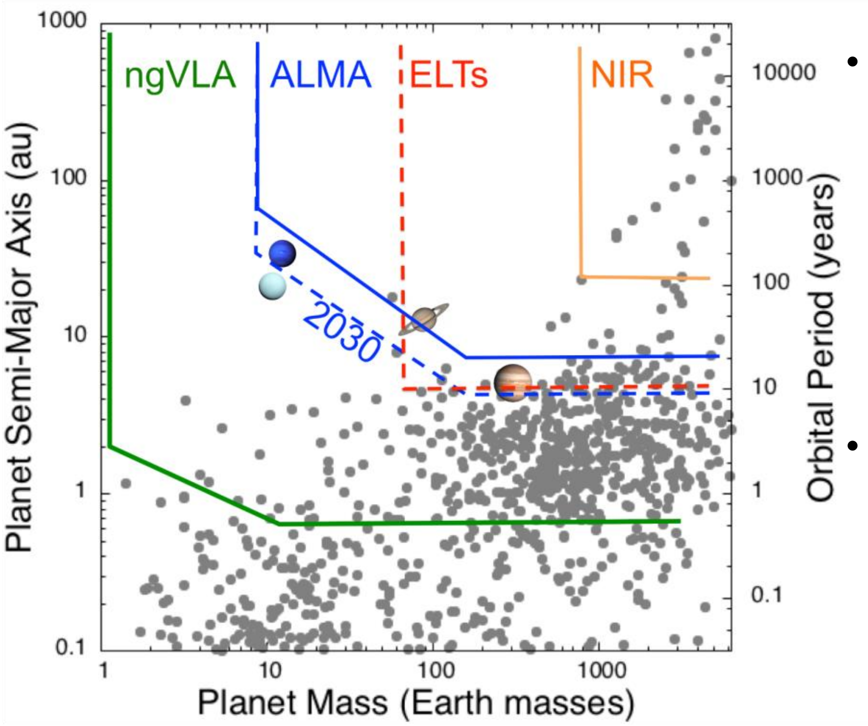


HL Tau – ALMA B6

KSG1: Unveiling the Formation of Solar System Analogues

The ngVLA will measure the planet IMF down to ~1.5 Earth masses and unveil the formation of planetary systems similar to our own Solar System.

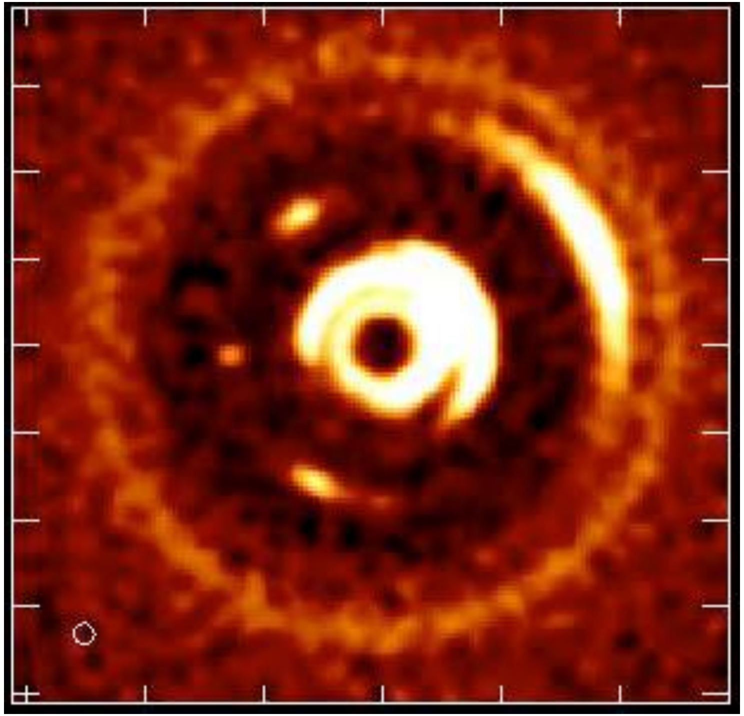




- ALMA observation of HD163296 at 1mm along with a simulated 1 cm ngVLA observations (Ricci et al. 2019) of the innermost 24 au region at 1 au resolution for Jupiter-, Saturn-, and Neptune-like planets.
- The distribution of exoplanets and young planets embedded in circumstellar disks: Then ngVLA will discover many hundreds of planets with orbital periods <10 yr.

KSG1: Unveiling the Formation of Solar System Analogues

The ngVLA will measure the orbital motion of planets and related features on monthly timescales.



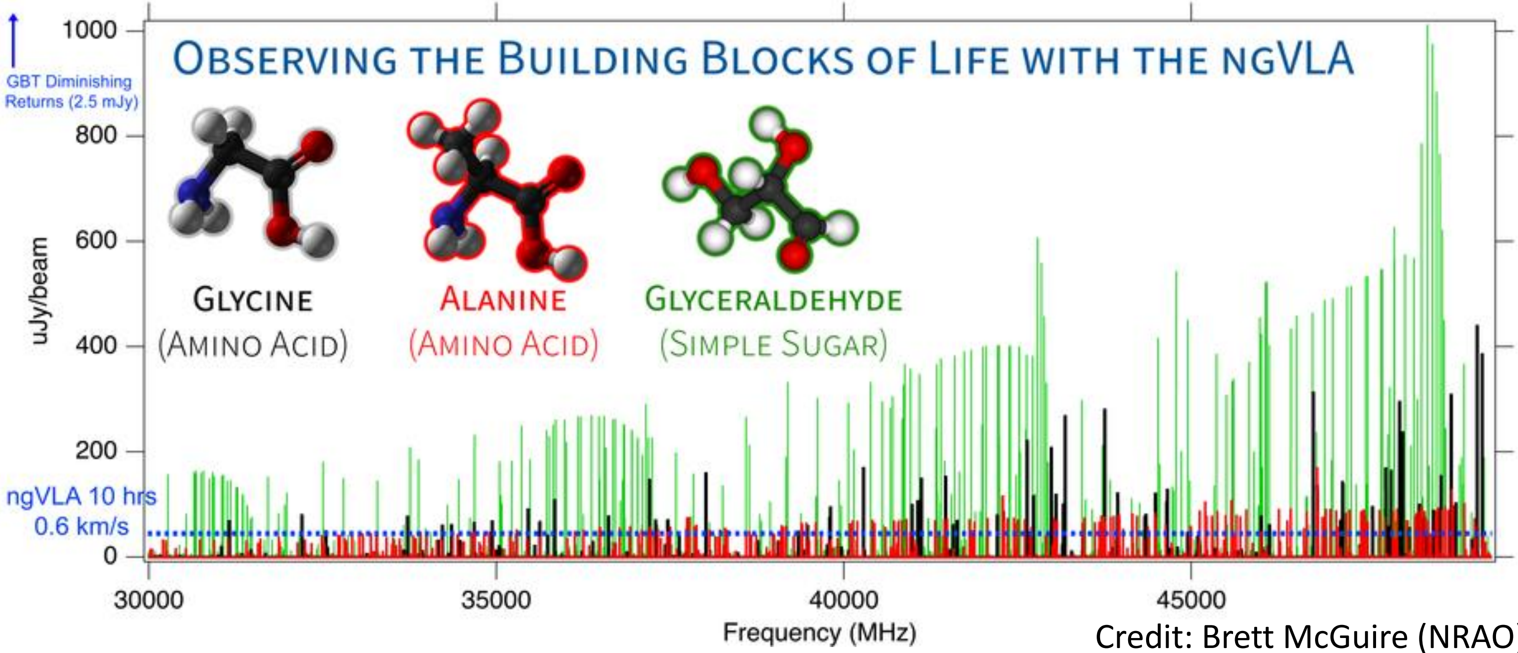
The ngVLA will measure the planet IMF down to ~5-10 Earth masses and unveil the formation of planetary systems similar to our own Solar System.

Simulated 100 GHz ngVLA observations of a newborn planetary system comprising a Jupiter analogue orbiting at 5 AU from a Solar type star.

Ricci et al. (2018)

KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

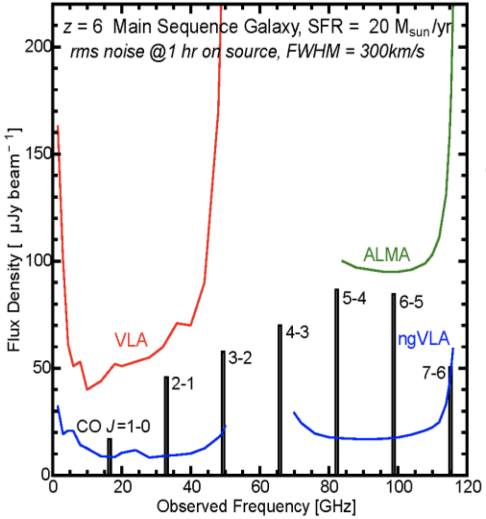
The ngVLA can detect complex pre-biotic molecules and provide the chemical initial conditions in forming solar systems and individual planets

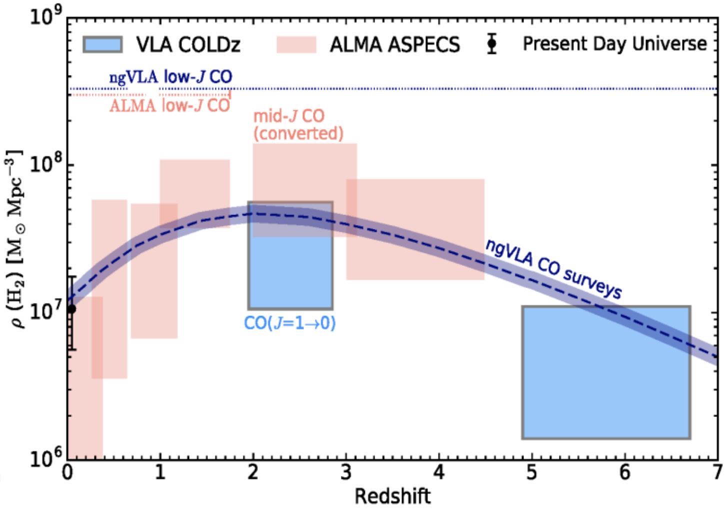


Credit: Brett McGuire (NRAO)

KSG3: Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time

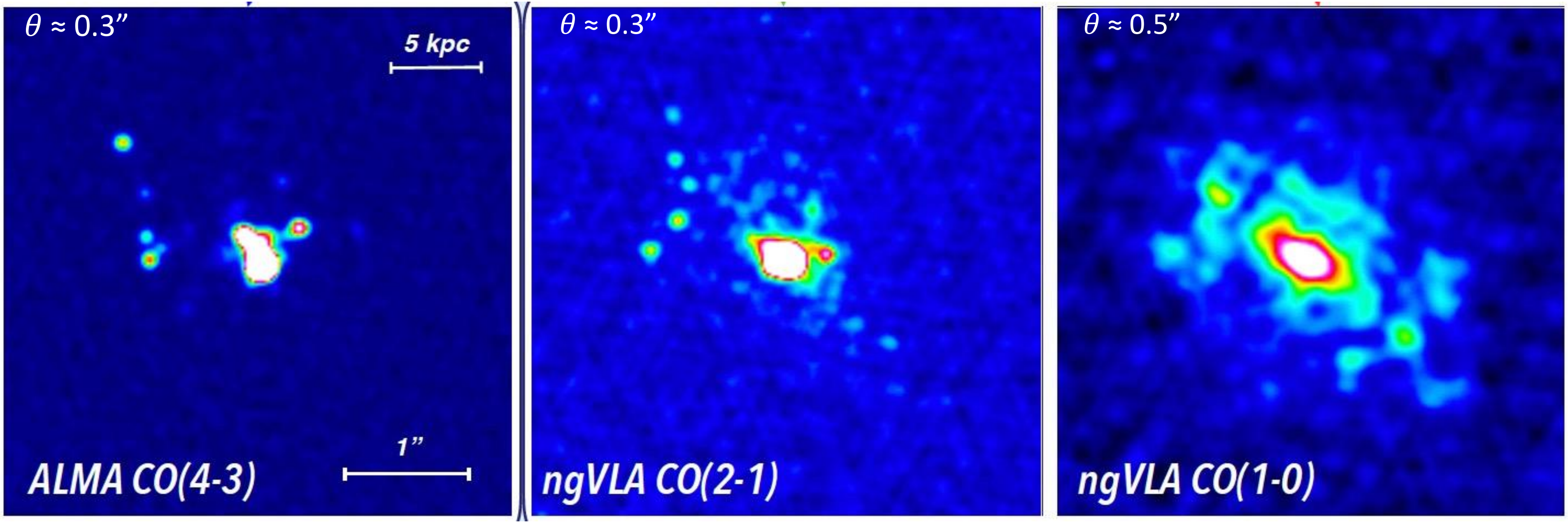
- Improve by 10x the depth and area of cold gas surveys to early cosmic epochs
  - Low-*J* lines inaccessible to ALMA
  - Constrain molecular gas evolution similar to SF and Stellar Mass
- Routinely image that cold gas at sub-kiloparsec resolution
- For nearby galaxies, show how they accrete, expel and transform their atomic and molecular gas





Credit: Dominik Riechers, Cornell U

KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billions Years to the Present

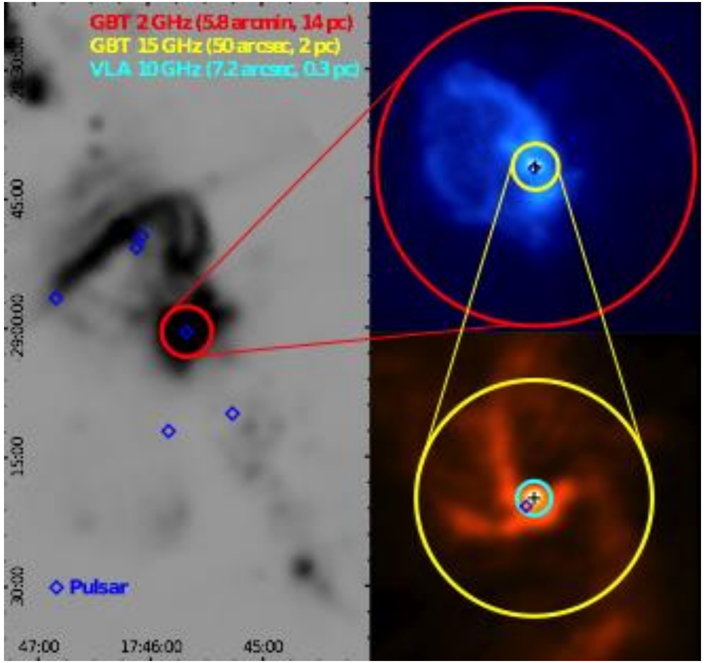


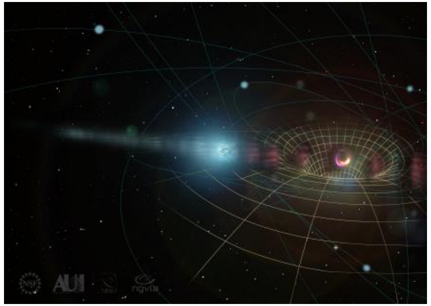
SMG at z = 4.4; SFR ≈ 400 $M_\odot$ /yr
Total molecular gas content largely missed by high-J lines

Credit: Caitlin Casey (UT Austin)

KSG4: Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

- Search for the predicted but not-yet-observed population of pulsars in the Galactic Center
  - Estimates are as high as 1,000 PSRs. Only known example is PSR J1745-2900 magnetar – extremely rare (<1%)
- Use pulsars (clocks) moving in the spacetime potential of Sgr A*, a supermassive black hole, to make precise tests of theories of gravity
- Use the population of pulsars in the Galactic Center to constrain its
  - Star formation history
  - Stellar dynamics
  - Stellar evolution
  - Magnetoionic medium

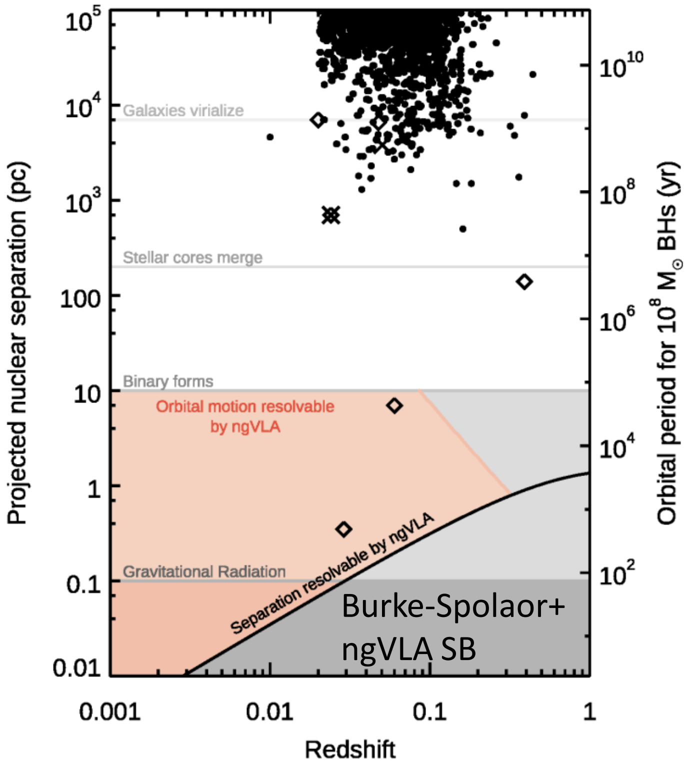




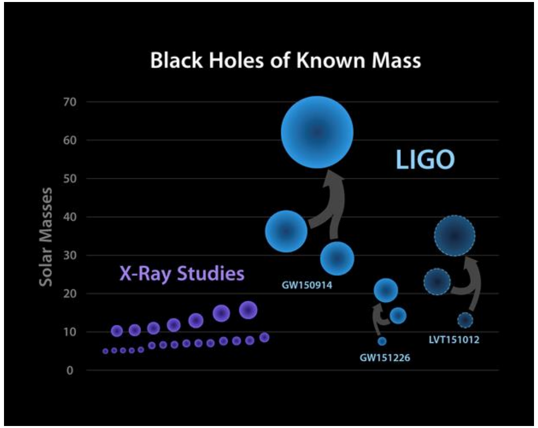
Credit: R. Wharton

KSG5: Understanding the Formation and Evolution of Black Holes in the Era of *Multi-Messenger Astronomy*

- Unaffected by dust obscuration, the ngVLA's sensitivity and angular resolution will be able to:
  - resolve dual AGN and BH binaries.
  - Measure proper motions over 5 year periods (orange shaded region), including sources detect by GWs



- Search for BHs across all masses, including weakly accreting BHs in the MW via proper motions



In its first 10 years, the ngVLA will:

- *Movies of planets*: Map hundreds of PP disks within 500pc on scales as small as 0.1 au with enough sensitivity to constrain the orbital motions Earth-mass planets (KSG1).
- *Origins of Life*: Measure the spatial and temporal evolution of the complex organic chemistry in the mid-planes of 100's of PP disks (KSG2).
- *Origins of Galaxies*: Image the cold molecular gas (fuel for star formation) down to GMC scales in galaxies back to cosmic reionization and the first galaxies, by detecting their fundamental low-*J* CO emission (KSG3).
- *GR beyond Einstein*: Detect hundreds of millisecond pulsars near the Galactic Center (if they exist) to test GR with unprecedented precision (KSG4).
- *Precision GW physics/Multi-messenger science*: Detect nearly all EM counterparts from next-generation GW facilities, enabling time-series imaging of astrophysical jets on sub-mas scales (KSG5).

Next Generation VLA

- **New frontiers: thermal imaging on milliarcsecond scales, transients, astrochemistry, local and high-redshift molecular spectroscopy,….**
- Design Goals
  - Enhanced frequency coverage
  - 10x sensitivity of VLA: 244 x 18-m antennas + 19 x 6-m
  - 10x sensitivity on all angular scales possible on the ground
- Frequency range: 1.2-116GHz.
- Locate in southwest US (AZ, NM, & TX) and MX, centered on VLA site.
- Low technical risk, minimize operations costs.
- Design & development in 2020-2024; construction in 2025-2034.

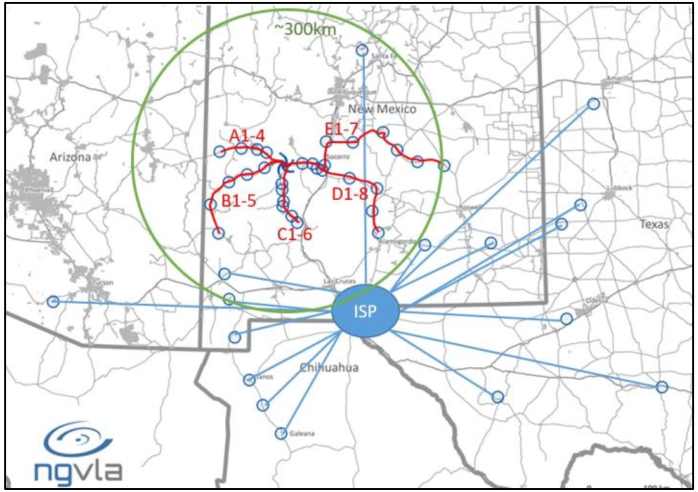
Components:

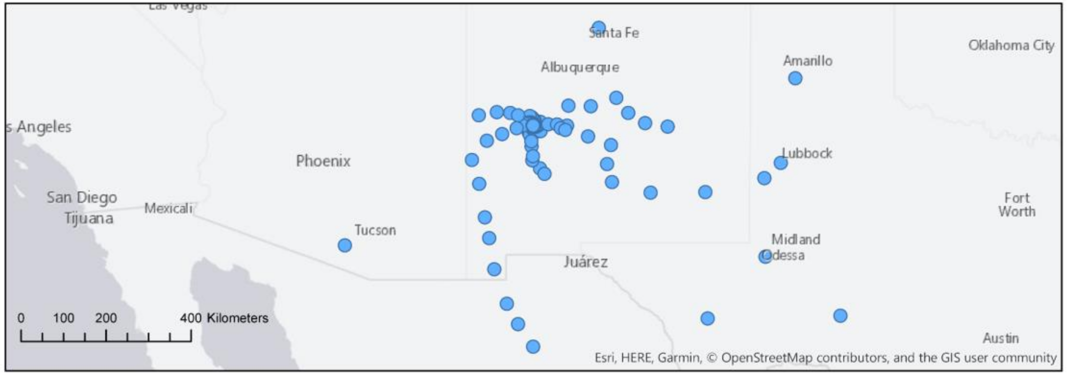
- **Main Array**: 214 x 18m offset Gregorian Antennas
  - Fixed antenna locations across NM, TX, AZ, MX.
- **Short Baseline Array**: 19 x 6m offset Greg. Antenna
  - Use 4 x 18m in TP mode to fill in (*u, v*) hole
- **Long Baseline Array**: 30 x 18m antennas located across continent for baselines up to 8860km

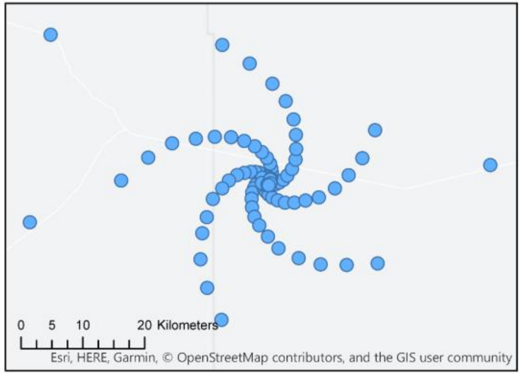
Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.35	3.5	2.91	2.3
2	B	3.5	7.90	12.3	3.51	8.8
3	B	12.3	16.4	20.5	1.67	8.2
4	B	20.5	27.3	34.0	1.66	13.5
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0

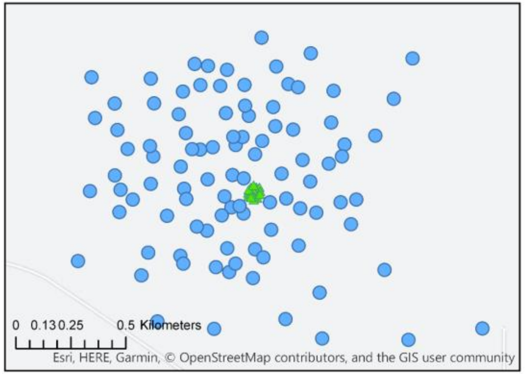
Main Array (MA) Configuration

Radius	Collecting Area Fraction
0 km < R < 1.3 km	44%
1.3 km < R < 36 km	35%
36 km < R < 1000 km	21%



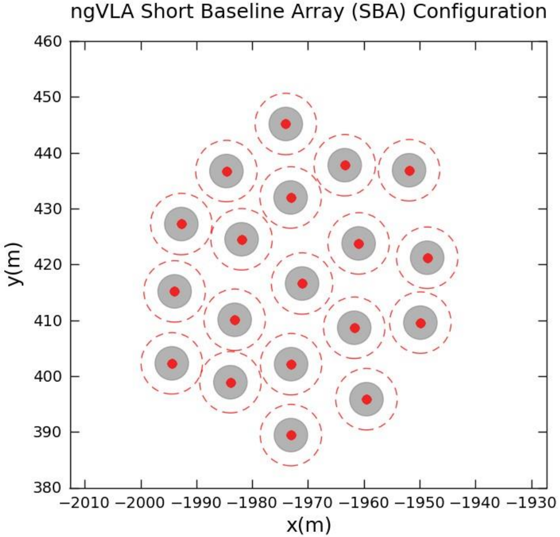


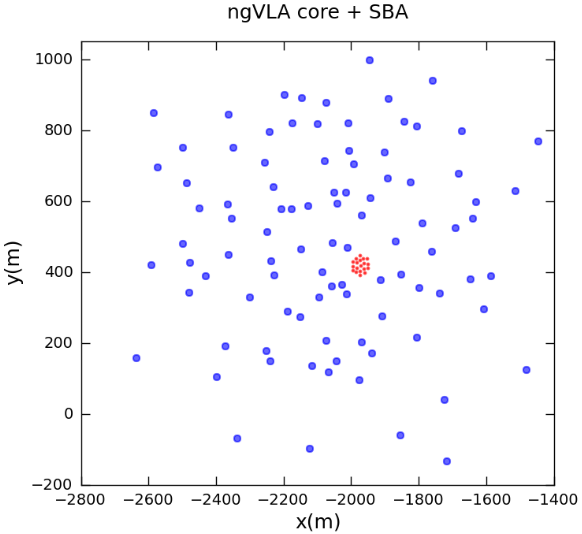


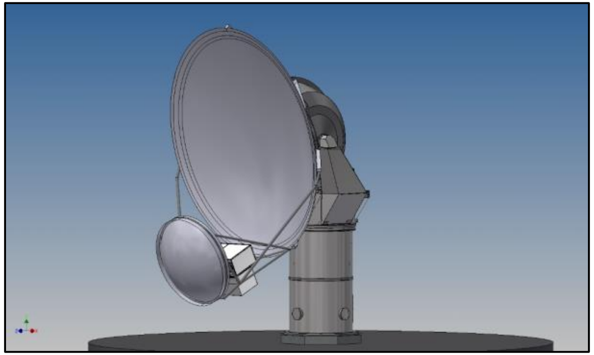


Short Baseline Array (SBA)

- Array of 19 x 6 m antennas
- Total Power Array of 4 x 18m (included as part of the 214 ant main array component)



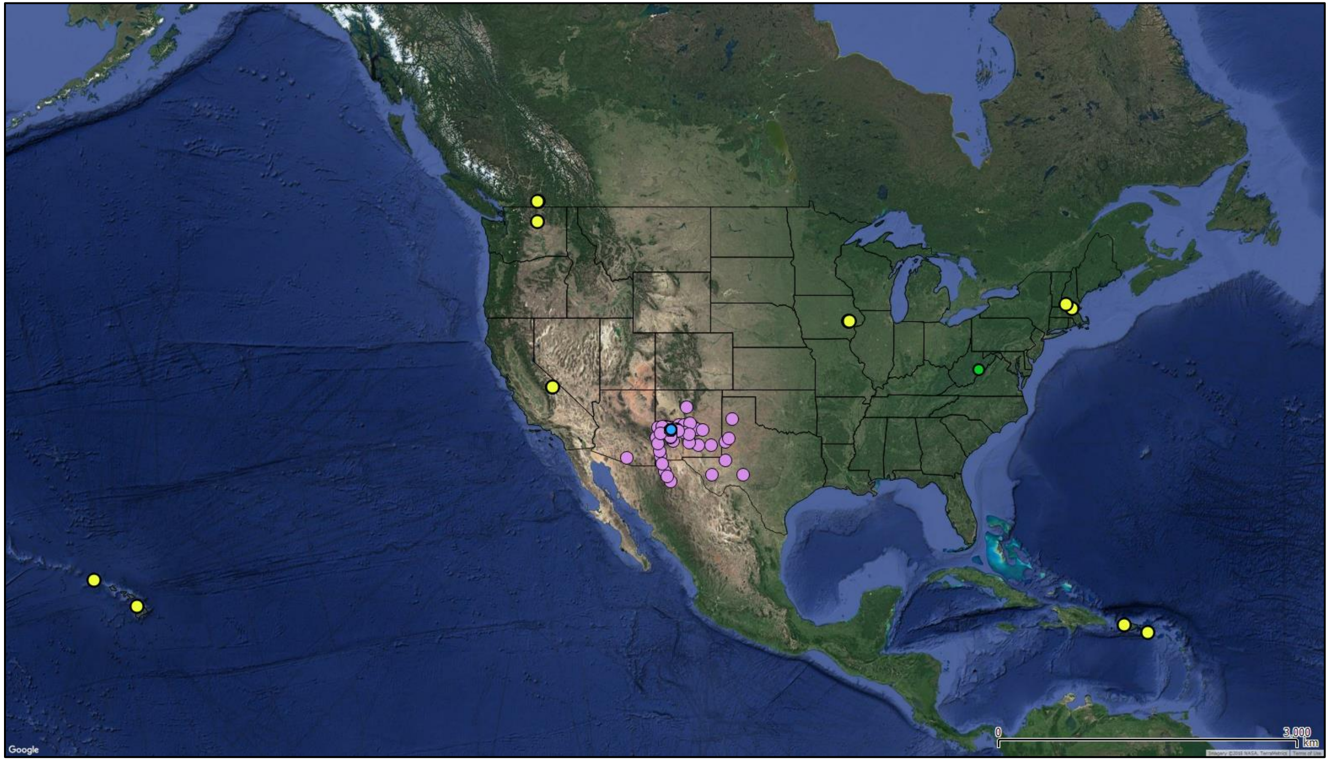


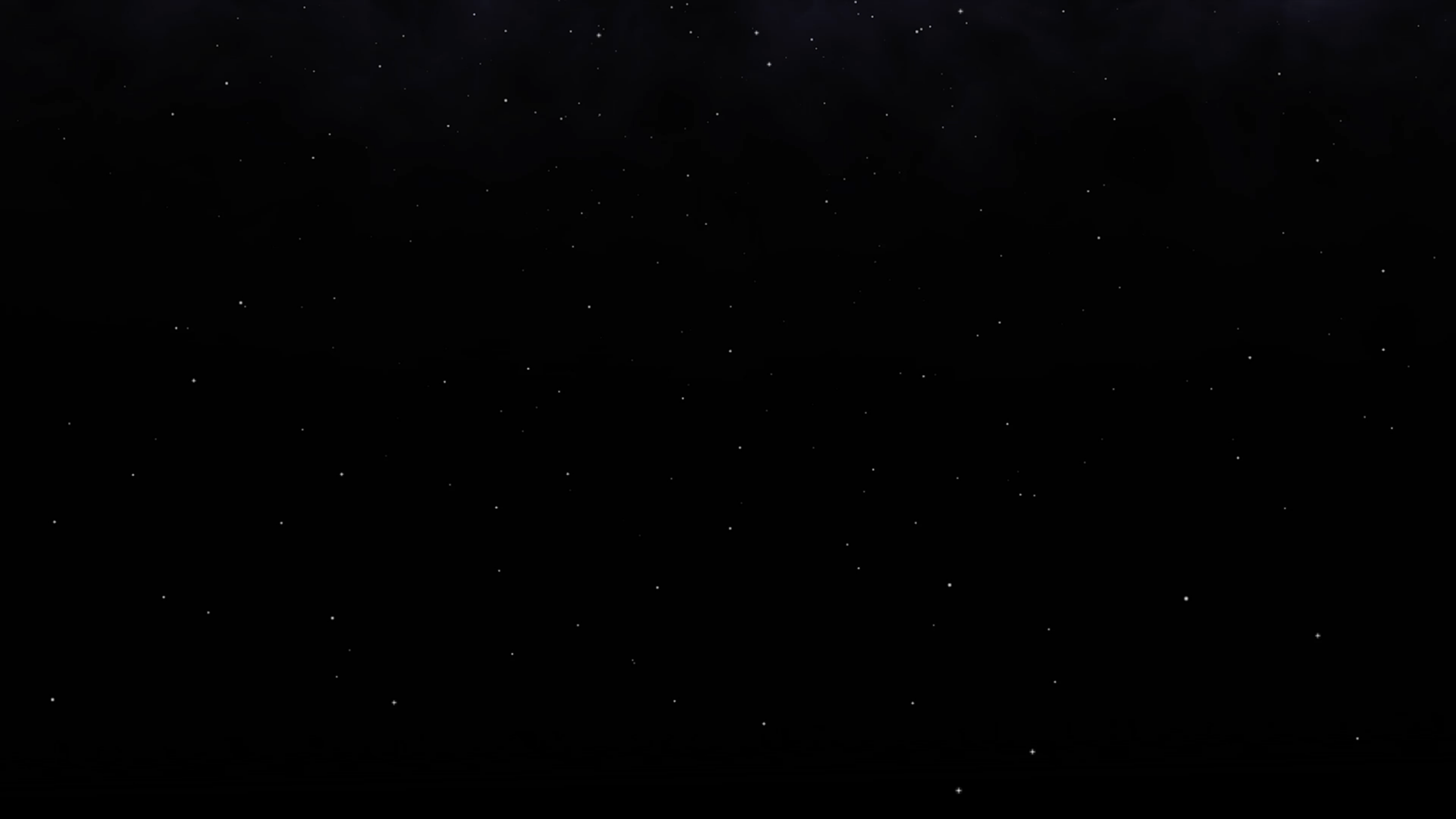


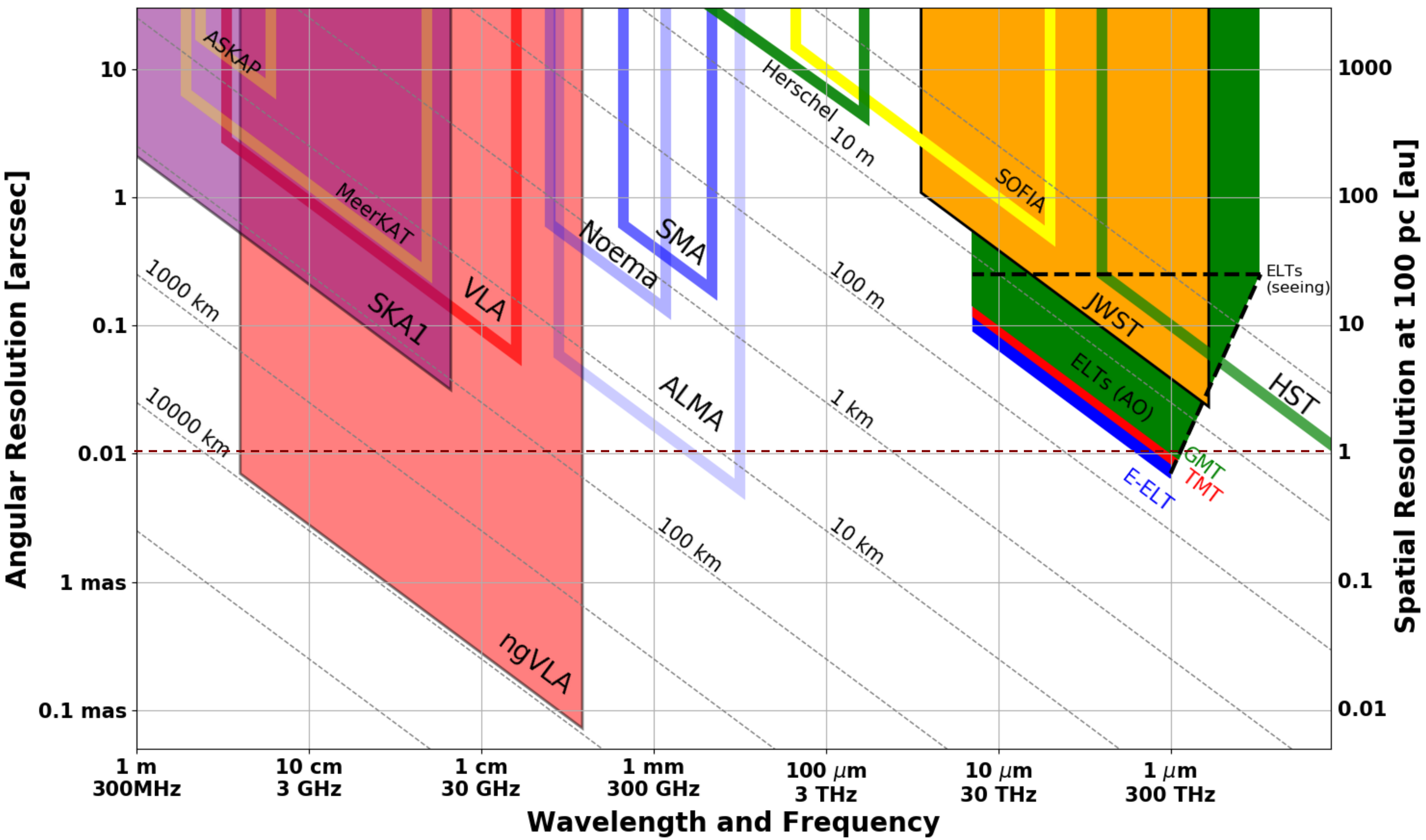
Long Baseline Array (LBA)

- 30 x 18m Antennas at 10 sites
- Astrometry, Imaging & Information Use Cases
- Sensitivity gain x 5-15

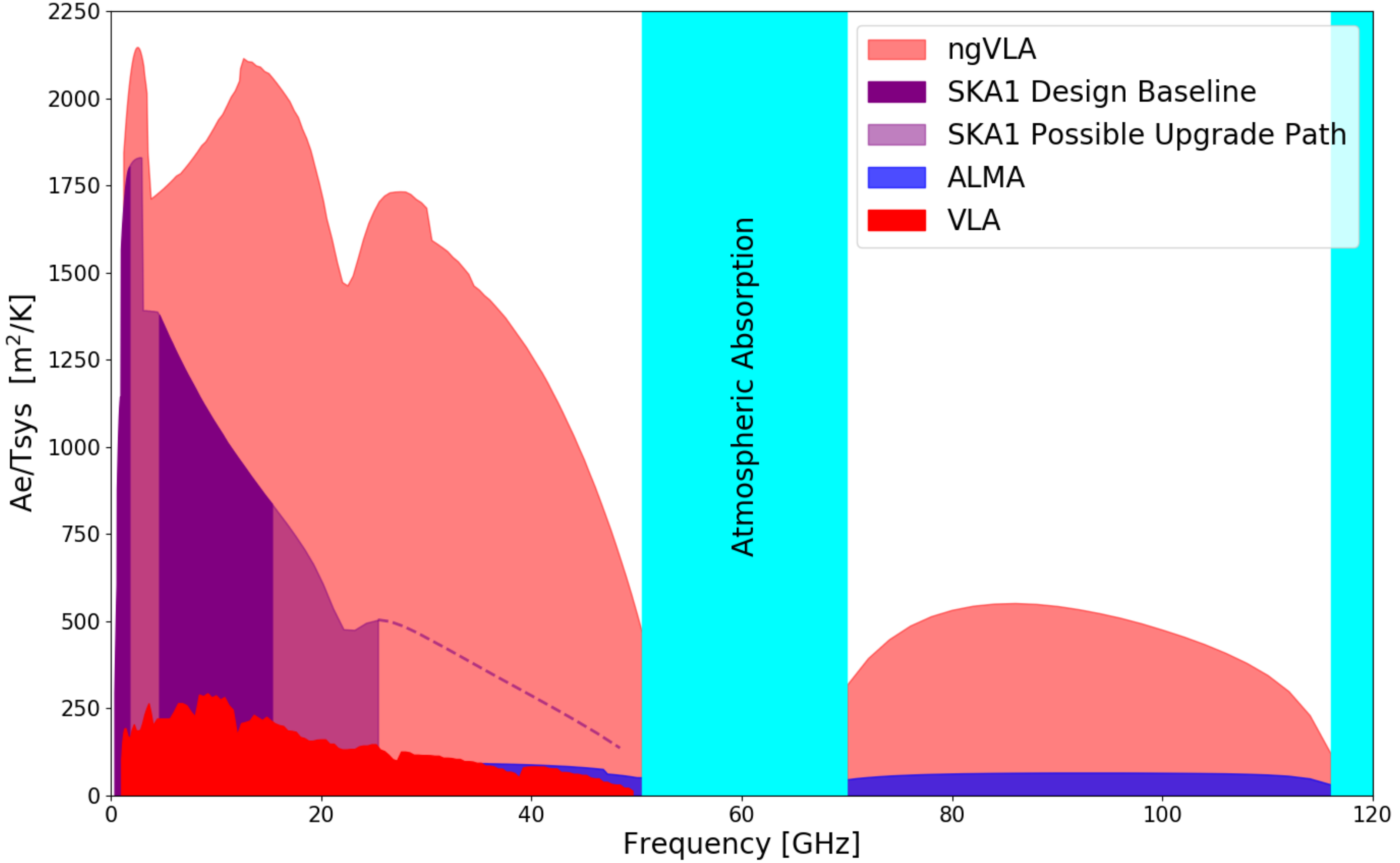
Qty	Location	*Possible* Site
3	Puerto Rico	Arecibo Site
3	St. Croix, US VA	VLBA Site
3	Kauai, HI	Kokee Park Geo. Obs.
3	Hawaii, HI	New Site (off MK)
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack
2	Brewster, WA	VLBA Site
3	Penticton, BC, CA	DRAO
4	North Liberty, IA	VLBA site
4	Owens Valley, CA	OVRO







Angular Resolution [arcsec]
Spatial Resolution at 100 pc [au]
Wavelength and Frequency
10
1
0.1
0.01
1 mas
0.1 mas
1000
100
10
1
0.1
0.01
1 m
300MHz
10 cm
3 GHz
1 cm
30 GHz
1 mm
300 GHz
100 μm
3 THz
10 μm
30 THz
1 μm
300 THz
ASKAP
MeerKAT
SKA1
VLA
ngVLA
Noema
SMA
ALMA
Herschel
SOFIA
JWST
HST
ELTs (AO)
ELTs
(seeing)
GMT
TMT
E-ELT
10 m
100 m
1 km
10 km
100 km
1000 km
10000 km



2250
2000
1750
1500
1250
1000
750
500
250
0
Ae/Tsys [m²/K]
0
20
40
60
80
100
120
Frequency [GHz]
Atmospheric Absorption
ngVLA
SKA1 Design Baseline
SKA1 Possible Upgrade Path
ALMA
VLA

Recent Highlights

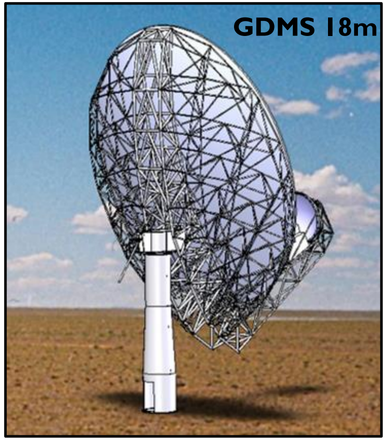
- ngVLA Reference Design Concept review, Docs completed (Aug 2019) – ASTRO2020
  - https://ngvla.nrao.edu/page/refdesign

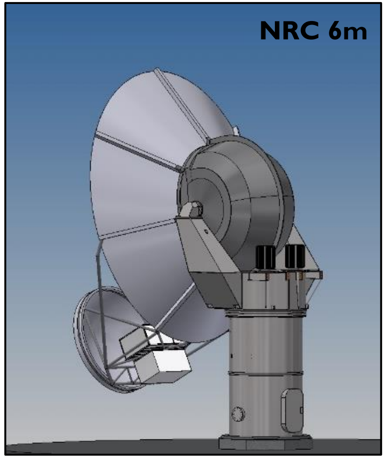
- Significant NSF Design/Development funding in 2017/2020, Partner contributions at 5-10%.
- Project Independent Cost Review (2019)
- International Partners Meeting (2019)
- Antenna Concepts contracts released.

Antenna Concept

- **Feed Low**: Maintenance requirements favor a receiver feed arm on the low side of the reflector.
- **Mount concept**: Leaning towards pedestal concepts for life-cycle cost. W/T under evaluation.
- **Drives:** All motor-gearbox; gearbox and linear drives; all direct drive, etc.
- **Materials:** Traditional Al panels & steel BUS; composite reflector and mix of steel and carbon BUS.

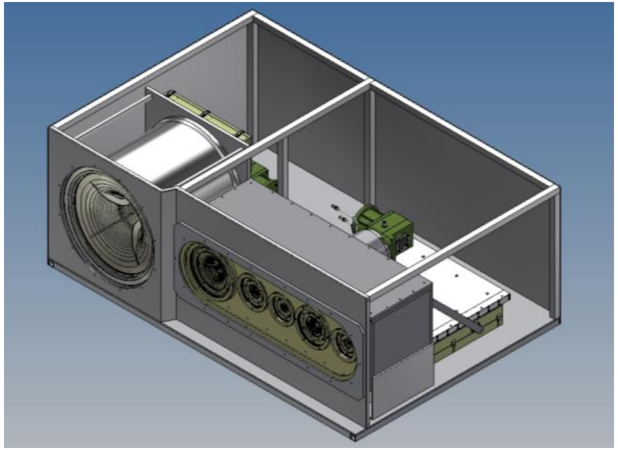
Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	4° Slew & Settle in 10 sec
Surface: 160 µm rms	Referenced Pointing: 3” rms

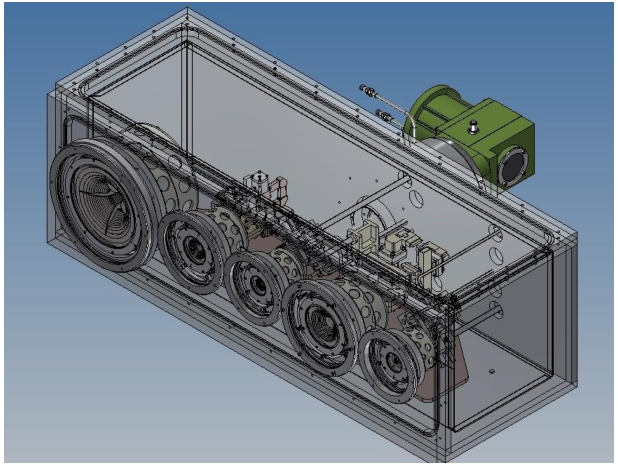




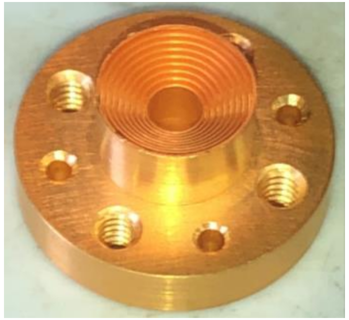
Electronics – Front End

- 6 Receivers in 2 Cryogenic Dewars
- Highly integrated analog electronics package
- Fiber optic interface to front end
- Designed with performance and operating costs (total lifecycle costs) as drivers
- 400 Gb Ethernet links back to central signal processor
- Receive remote time and frequency reference signals from central electronics facility

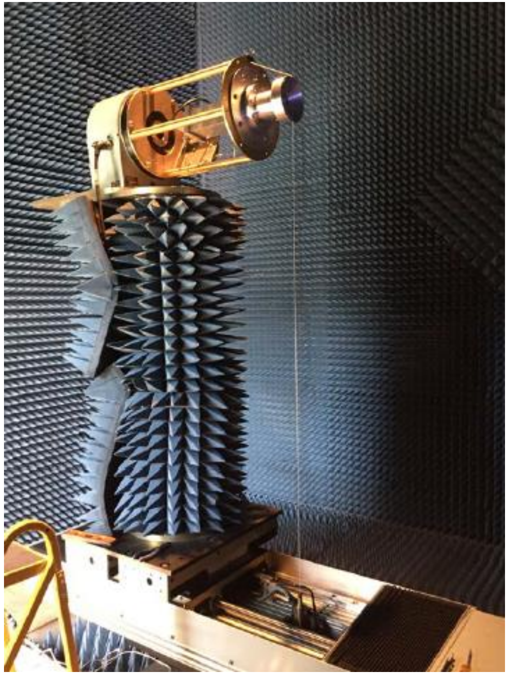


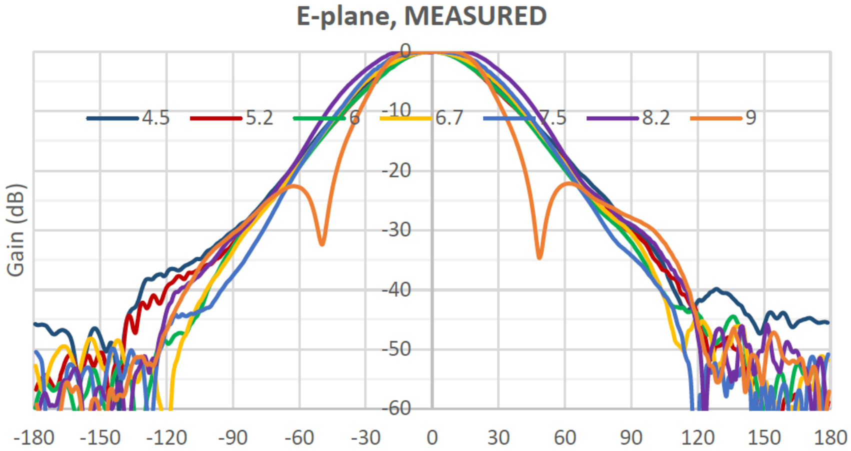


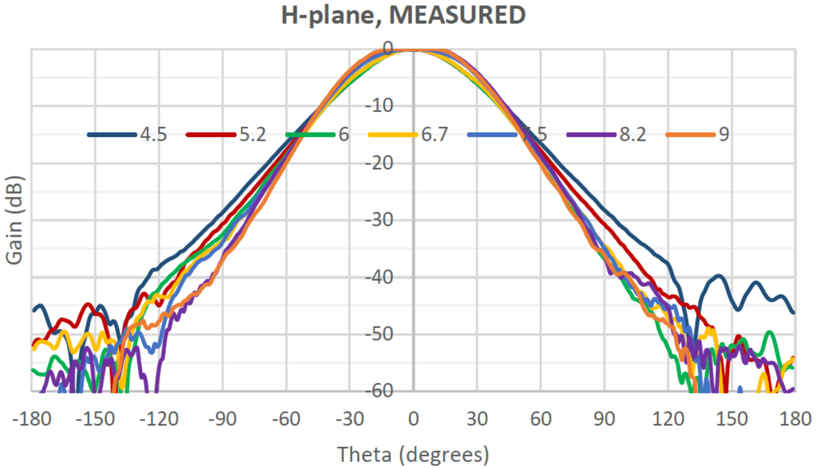
Feed Development


(courtesy S. Srikanth, NRAO CDL)


(courtesy R. Lehmensiek, EMSS)



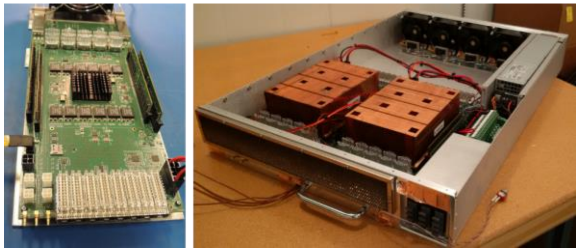


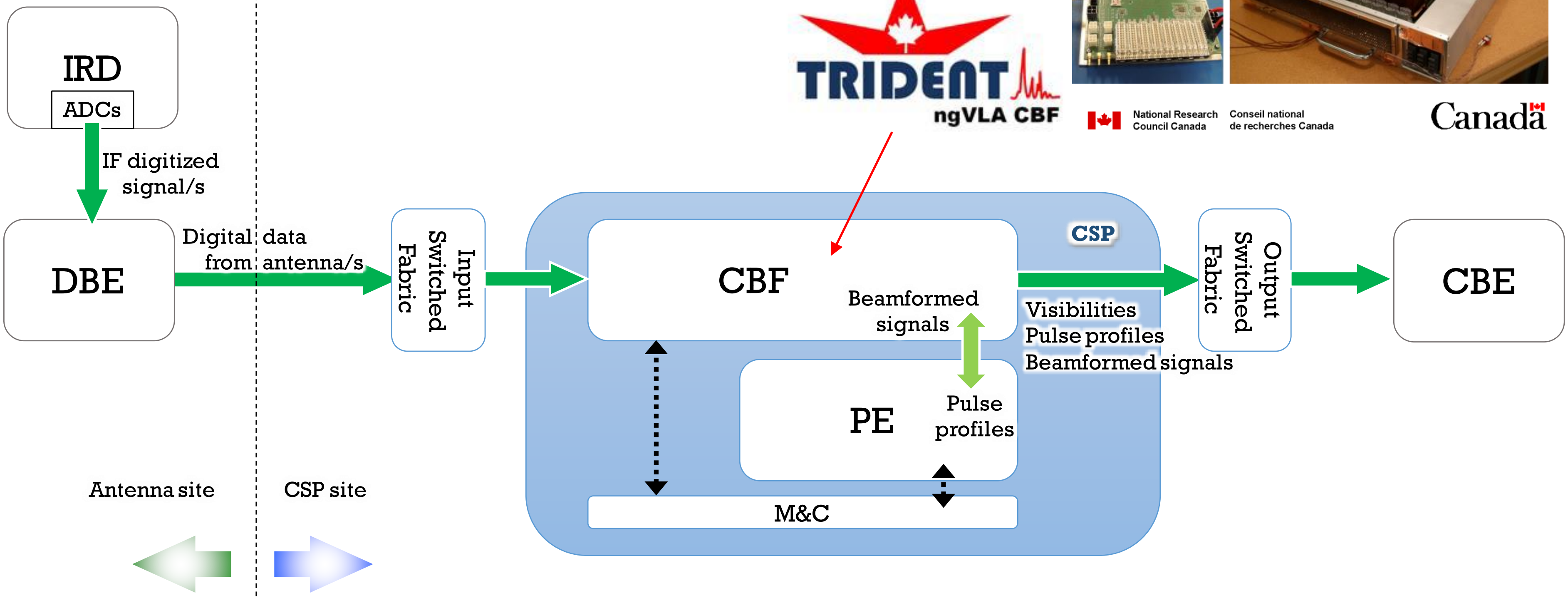


ASU/Caltech Band 1 Prototype Cryostat

(Credit: Sander Weinreb, Caltech & Hamdi Mani, ASU)

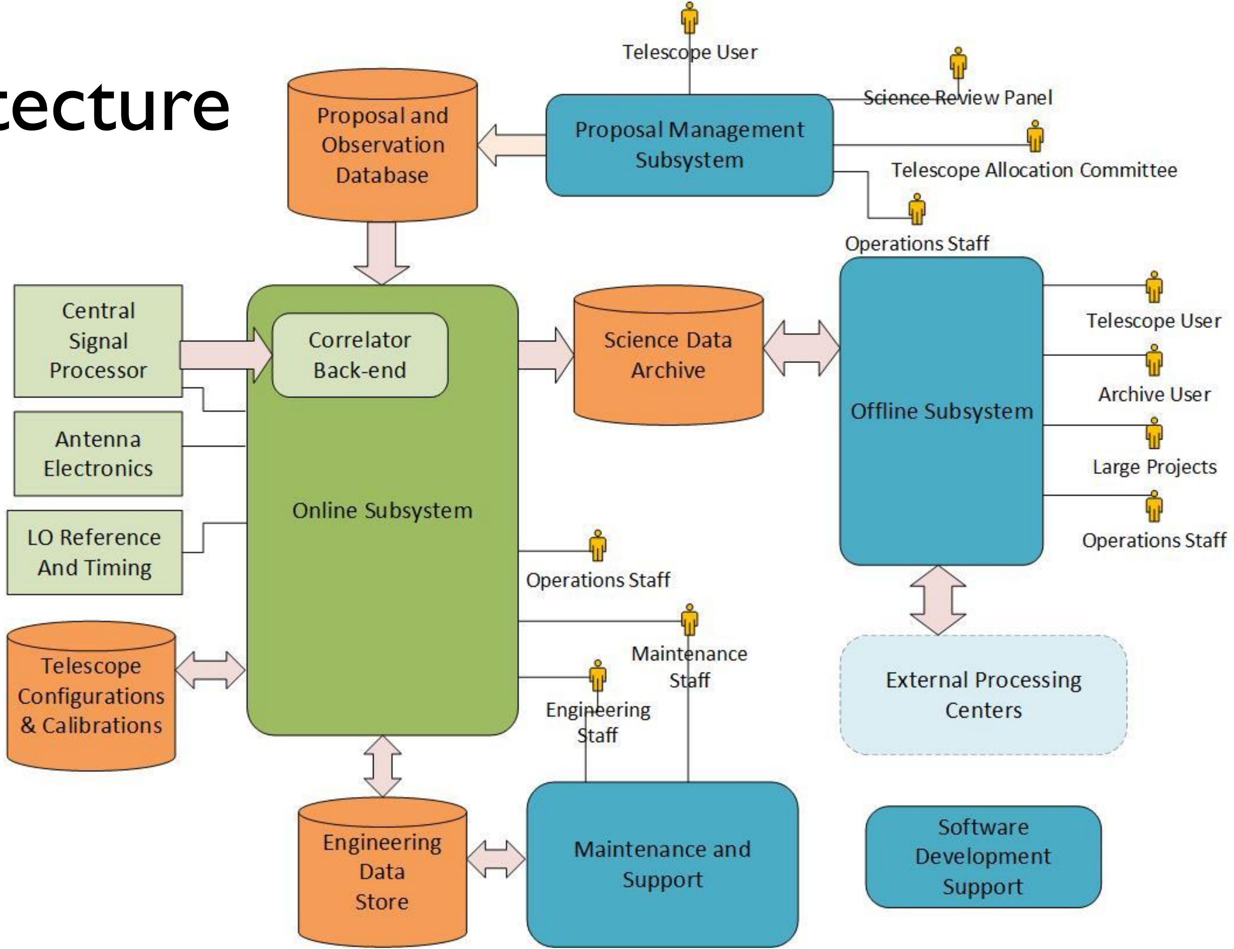
Central Signal Processor





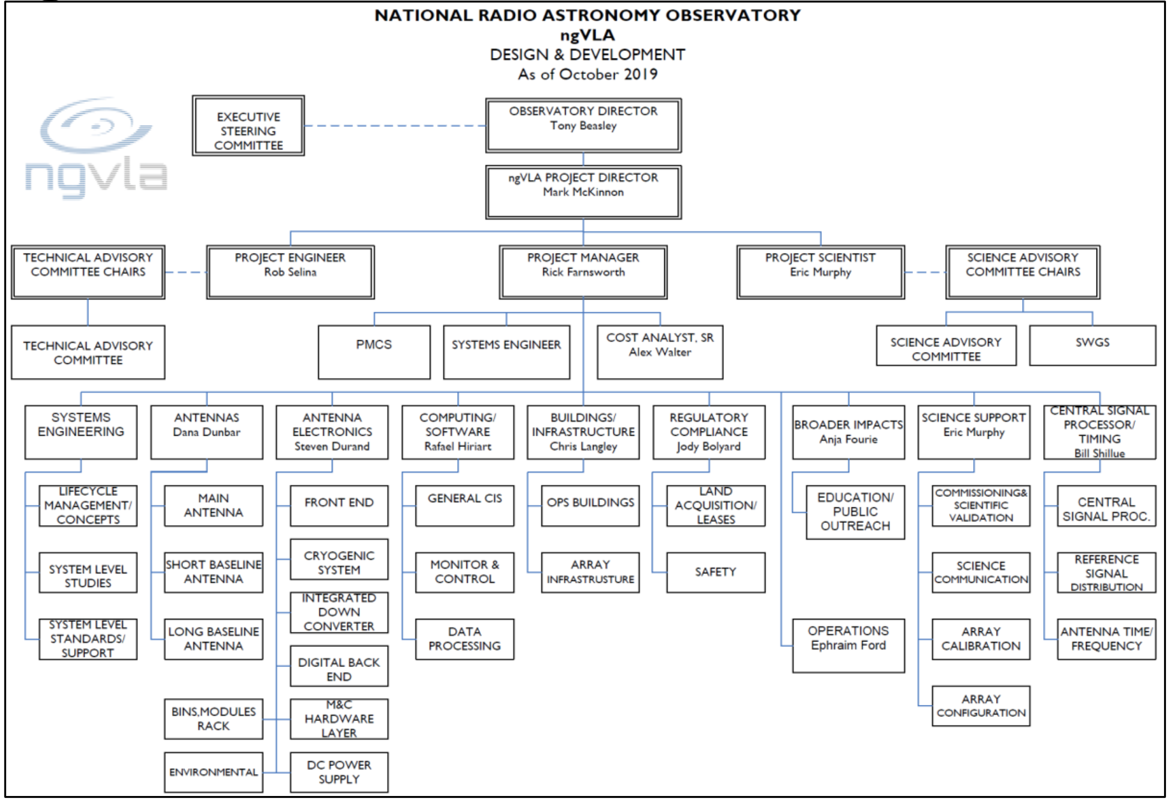
S/W Architecture

- Evolution of ALMA & VLA Architectures
- Builds on ALMA & VLA code base
- Significant reuse (~50%); leverages active R&D
- **Science-Ready Data Products – 2030!**



Project Organization

- 10 Integrated Product Teams (IPTs)
- MREFC-style project definition
- Actively-engaged science and technical advisory councils
- System/subsystem PDRs - 2020/2021.



Cost Estimate

- Current Cost Estimate for Construction
  - $2.3B in 2018 risk-adjusted, base-year dollars
    - Seeking ~25% International Partner Contributions (discussions underway)

      ⇒ ***2018$1.75B U.S. Contribution to ngVLA***

- Current Operations estimate: 2018$92M/year total.

  ⇒ ***2018$69M U.S. Contribution to Ops (~3 x VLA+VLBA)***

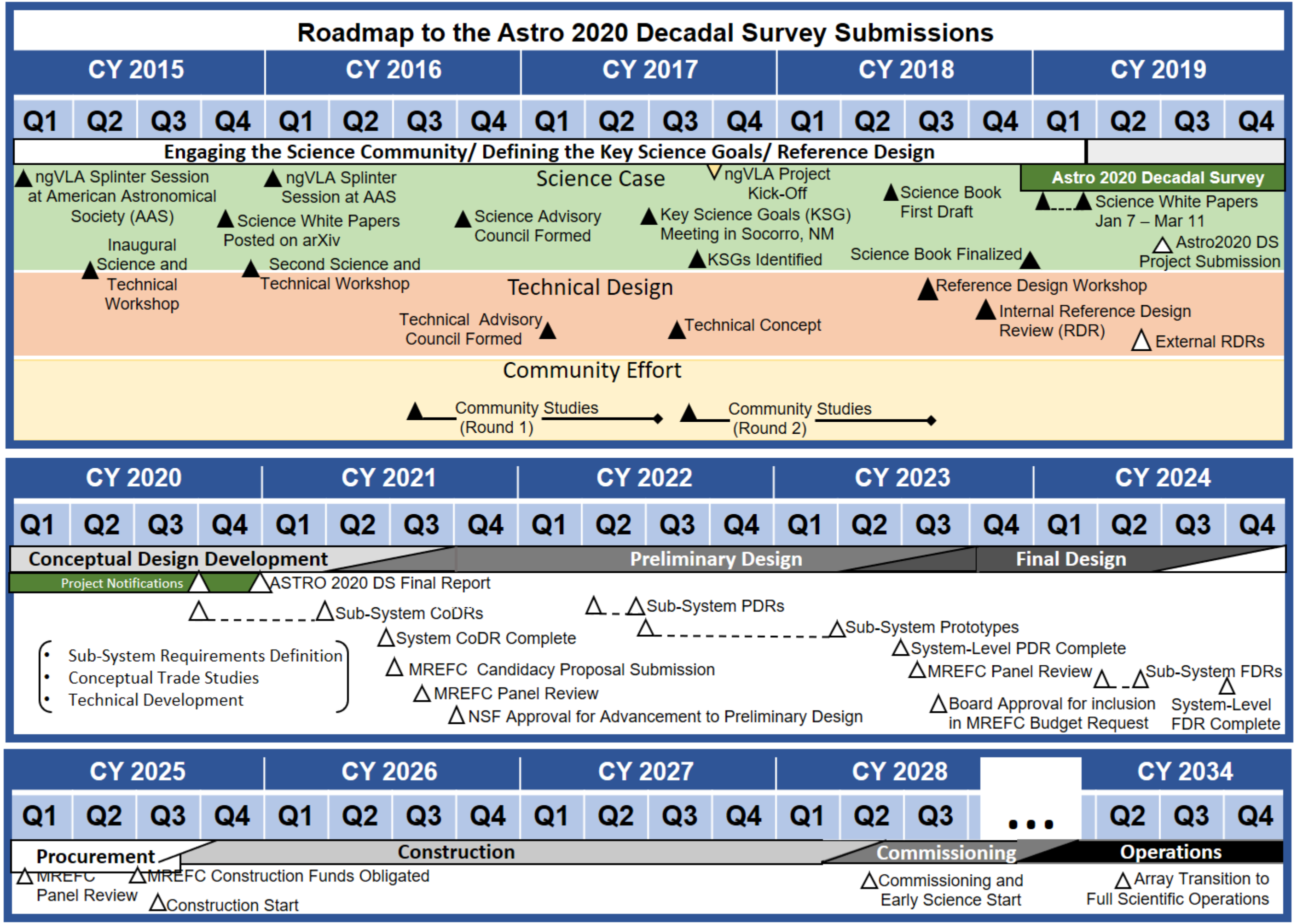
- Design/Dev: $15M committed to date; project total ~2018$119M (2017-2025).
- Ops, maintenance, computing, archiving, etc.: optimize as part of design.
- Drive major changes to NRAO administration & science operations models.

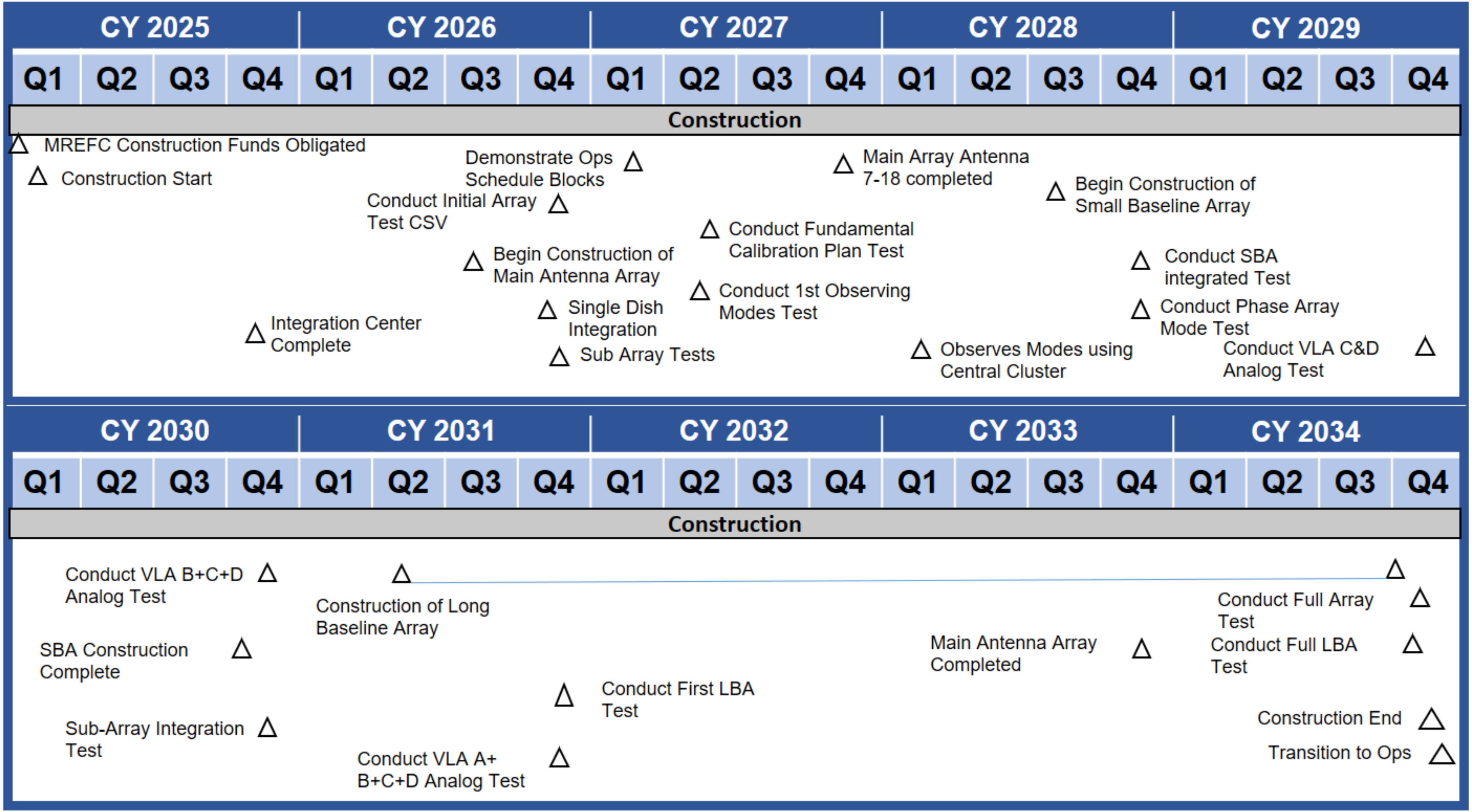
Next Generation Very Large Array (ngVLA) Project Timeline

As of 4/20/2019

NAS DS2020 Roadmap

NSF MREFC Roadmap




CY 2025
CY 2026
CY 2027
CY 2028
CY 2029
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Construction
MREFC Construction Funds Obligated
Construction Start
Demonstrate Ops Schedule Blocks
Conduct Initial Array Test CSV
Main Array Antenna 7-18 completed
Begin Construction of Small Baseline Array
Conduct Fundamental Calibration Plan Test
Begin Construction of Main Antenna Array
Conduct SBA integrated Test
Conduct 1st Observing Modes Test
Single Dish Integration
Conduct Phase Array Mode Test
Integration Center Complete
Sub Array Tests
Observes Modes using Central Cluster
Conduct VLA C&D Analog Test
CY 2030
CY 2031
CY 2032
CY 2033
CY 2034
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Construction
Conduct VLA B+C+D Analog Test
Construction of Long Baseline Array
Conduct Full Array Test
SBA Construction Complete
Main Antenna Array Completed
Conduct Full LBA Test
Conduct First LBA Test
Sub-Array Integration Test
Construction End
Conduct VLA A+ B+C+D Analog Test
Transition to Ops

Risks

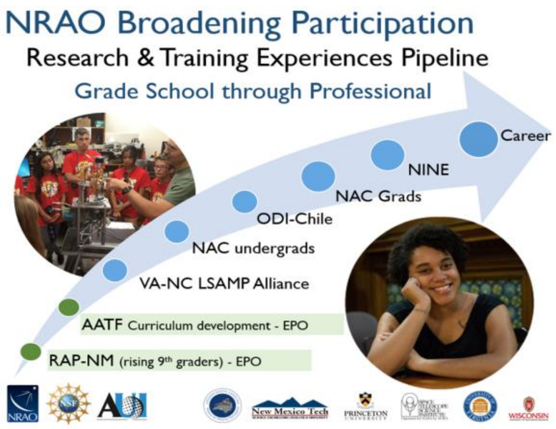
- Technical
  - Data rates & Compute Capacity
  - Evolution of RFI environment (responsive technologies).
  - LO/time distribution (default sol'n – maser fleet - unappealing).
  - Moore's law assumptions (compute/network/storage).
- Programmatic
  - Affordability
  - Development Schedule / funding profile
  - Partner interaction/coordination.
  - Major contractor performance (e.g. antennas).
  - Recruiting & retention – pan-Project.
  - Site selection, permitting, regulatory.

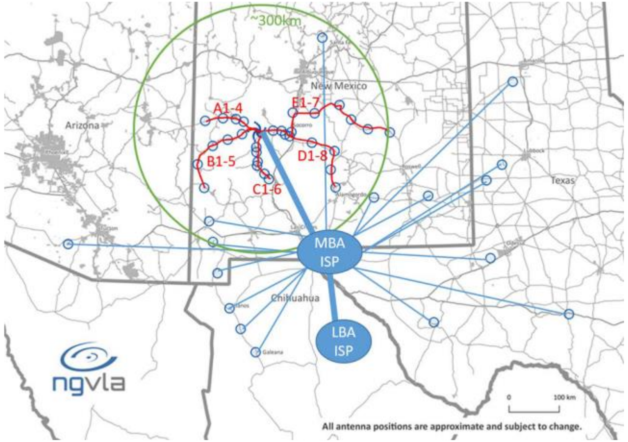
International Partnerships

- International involvement via SAC, TAC, Community Studies
  - Canada, Mexico, Japan, Germany, Netherlands, Taiwan
- Inaugural international development meeting, Socorro (May 2019)
  - Provided project overview; possible distribution of work packages
- ngVLA-SKA *Future Large Radio Telescope Alliance* meeting in Reykjavik, Iceland (Jun 2019)
  - Purpose: investigate process and possibility of a scientific alliance between SKA and ngVLA
- NAOJ-ngVLA workshop, Mitaka (Sep 2019)

Broader Impacts

- Open Skies Science
- Education and Public Outreach Campaign.
- Technology Transfer
- Economic Impacts – several sectors
- Broadening Participation
- Building University, Industrial and International Partnerships
- Fostering Broader Impacts to the Community (e.g. Rural Broadband thru ngVLA fiber install)
- Supporting other agency missions (DoD, NASA) via information services.





Summary

- ngVLA is being designed to tap into the astronomy community's intellectual curiosity and to enable a broad range of scientific discovery.
- Key Science Goals, Use Cases, and Science Book continue to grow.
- The ngVLA Reference Design, a credibly-costed and low-technical risk concept, was prepared for the Astro2020 Decadal Survey.
- System-level design (requirements, architecture) will be baselined in 2020 to enable sub-system conceptual design down-selects.
- Major Challenges: No major technological blockers. Challenges in cost-performance optimizations, manufacturability and reliability.

NRAO/AUI are proud to present ngVLA on behalf of the U.S. community.

ngvla

Next Generation Very Large Array

ngvla.nrao.edu

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