NATIONAL RADIO ASTRONOMY OBSERVATORY

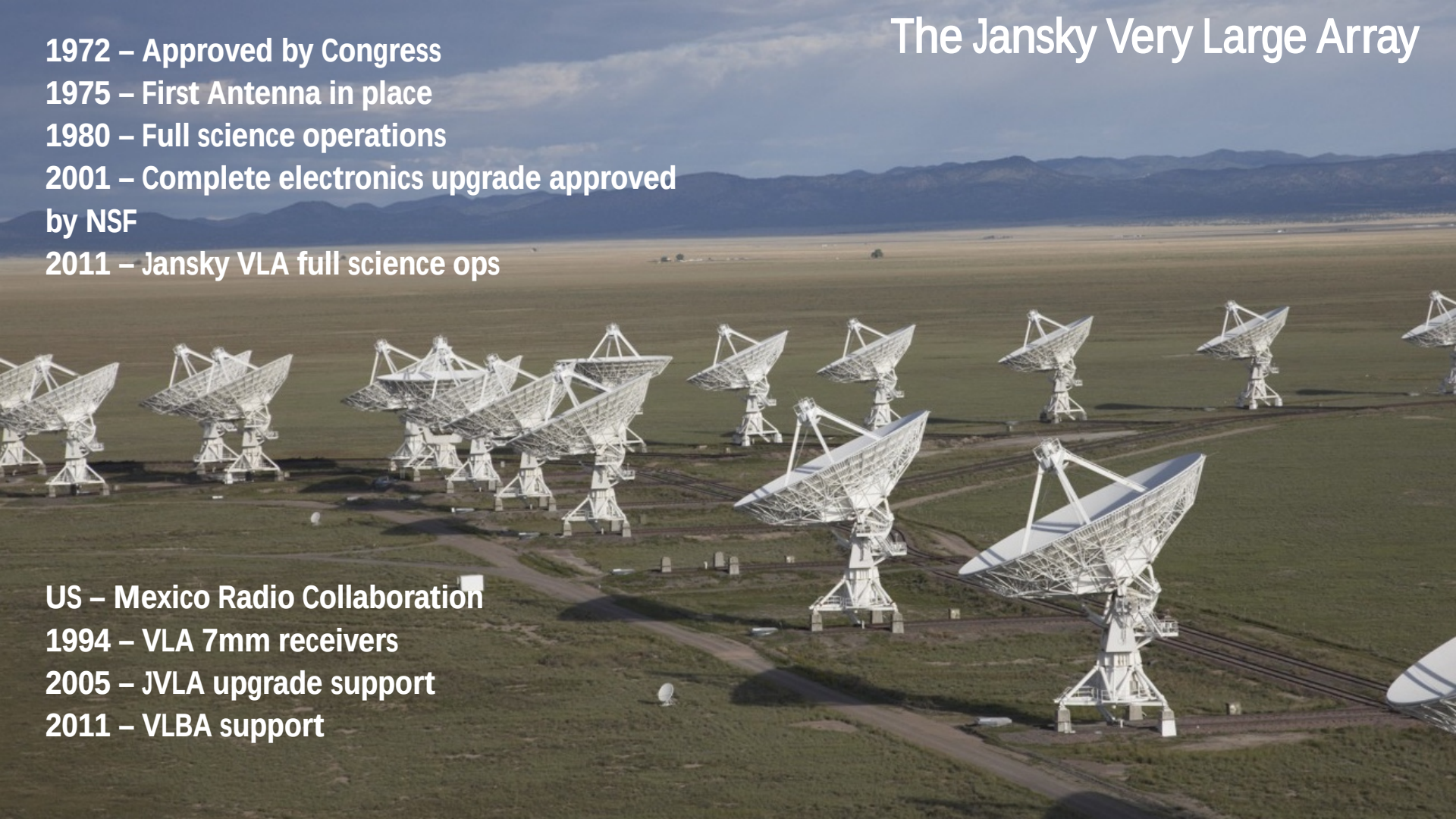
Next-generation Very Large Array

Tony Beasley, NRAO

ngvla

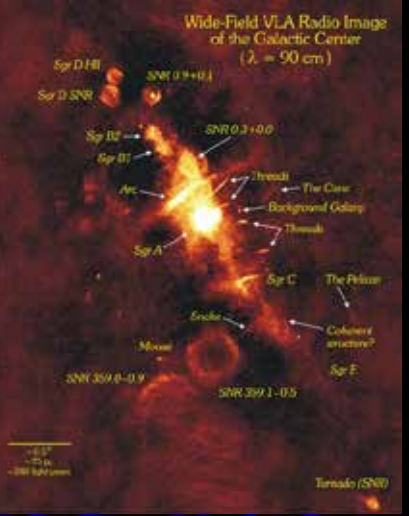
Next Generation Very Large Array

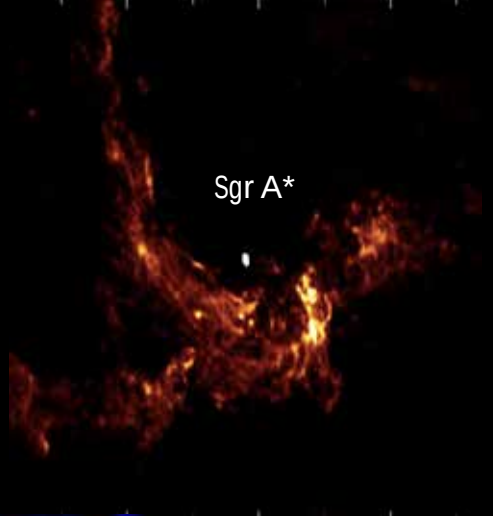
The Jansky Very Large Array

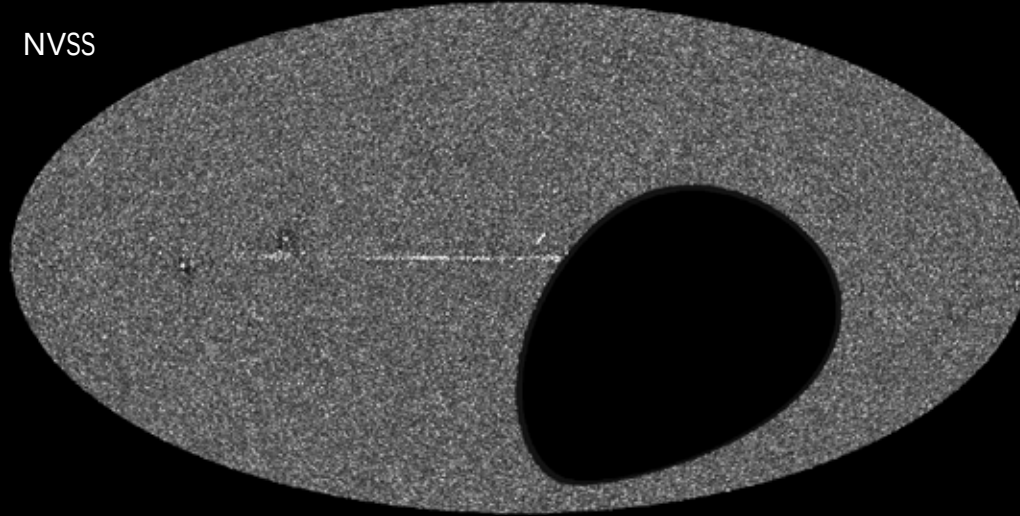


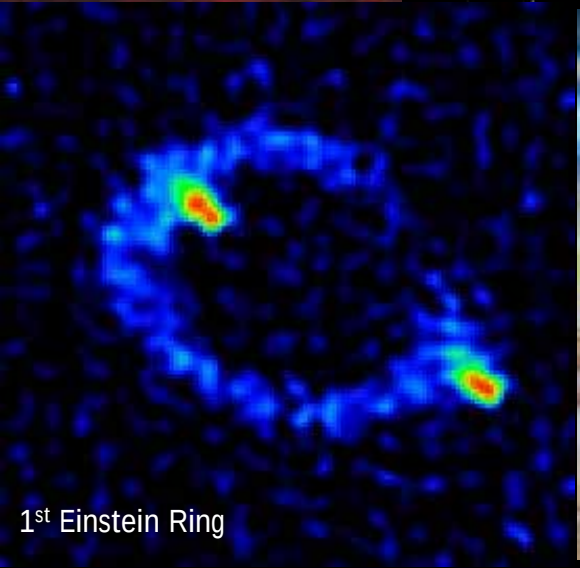
1972 – Approved by Congress
1975 – First Antenna in place
1980 – Full science operations
2001 – Complete electronics upgrade approved by NSF
2011 – Jansky VLA full science ops

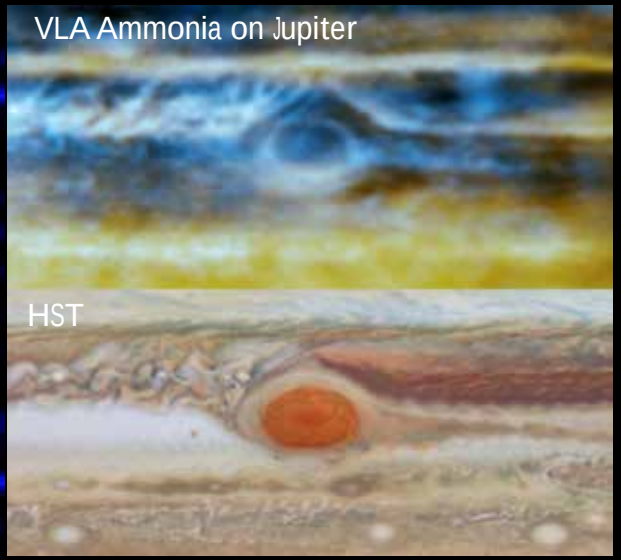
US – Mexico Radio Collaboration
1994 – VLA 7mm receivers
2005 – JVLA upgrade support
2011 – VLBA support

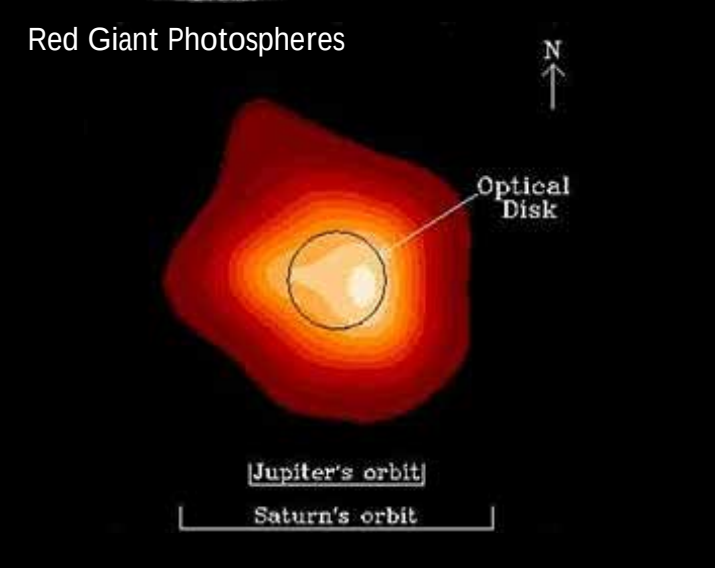

Wide-Field VLA Radio Image
of the Galactic Center
(λ = 90 cm)
Sgr D HII
Sgr D SNR
SNR 0.3+0.0
Sgr B2
Sgr B1
Threads
Arc
The Cane
Background Galaxy
Threads
Sgr A*
Sgr C
The Pelican
Snake
Coherent structure?
Mouse
Sgr E
SNR 359.0–0.9
SNR 359.1–0.5
Tornado (SNR)


Sgr A*

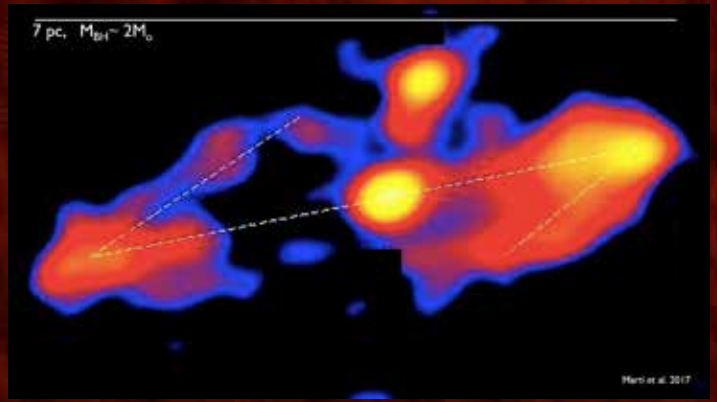

NVSS


1st Einstein Ring


VLA Ammonia on Jupiter
HST

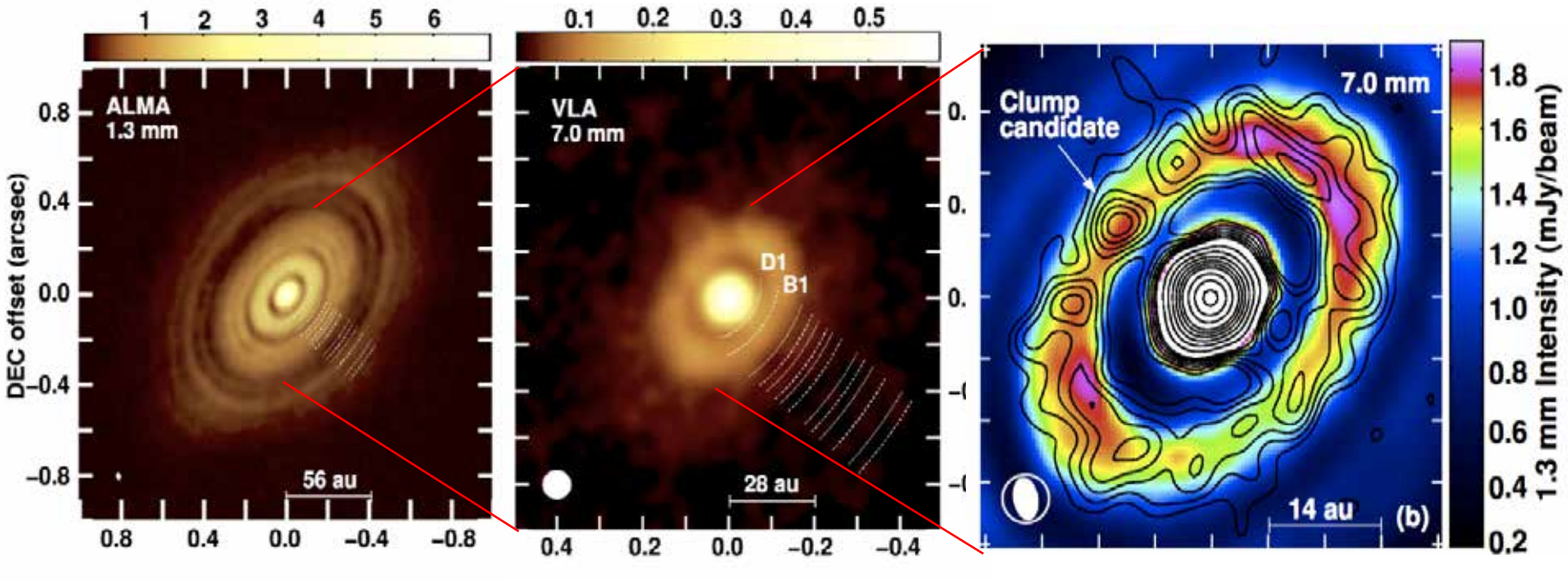

Red Giant Photospheres
N
Optical Disk
Jupiter's orbit
Saturn's orbit

120 kpc, $M_{BH} \sim 10^{10} M_o$



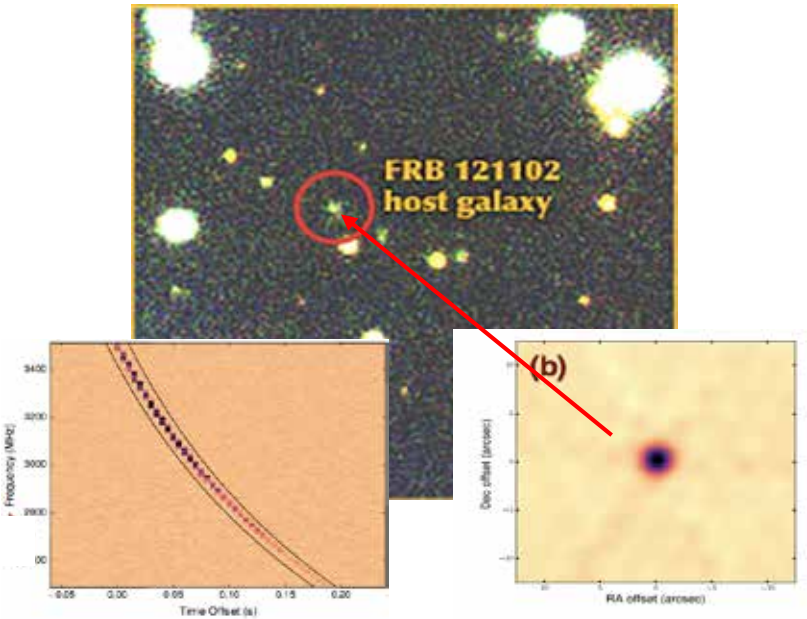
Perley et al. 1984

Star and Planet Formation: seeing through the natal dust

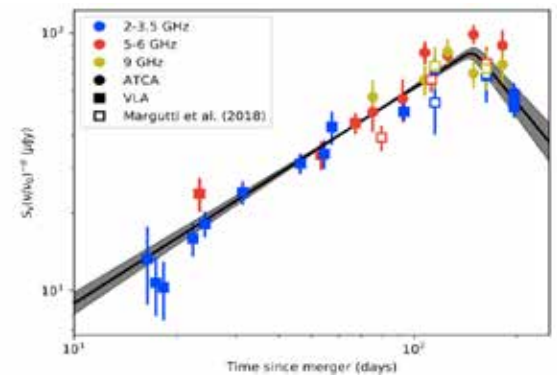


ALMA 1.3mm, JVLA 7mm, and overlay (7mm contours at 40mas res; Carrasco-Gonzales ea. 2016

The Explosive Universe - Transients



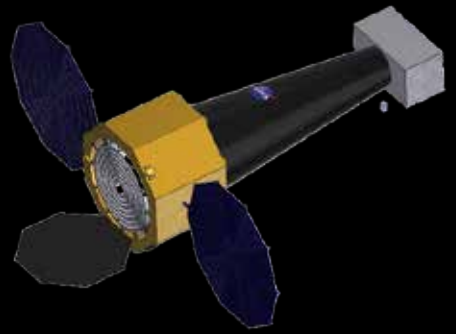
VLA localization of an FRB to a z=0.2 galaxy (Chatterjee ea. 2017)

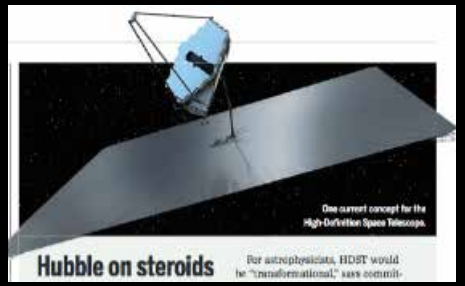


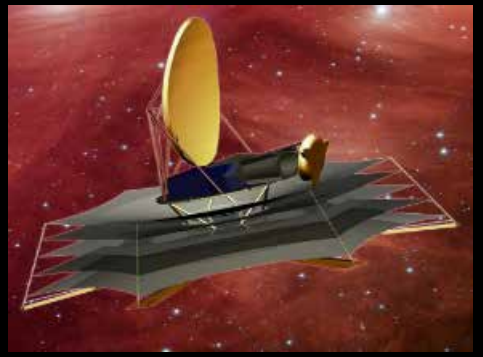
The radio light curve of GW170817 and a schematic of the model for the EM counterpart to GW sources: a wide angle jet which is trapped by the explosion debris (Dobie ea. 2018)

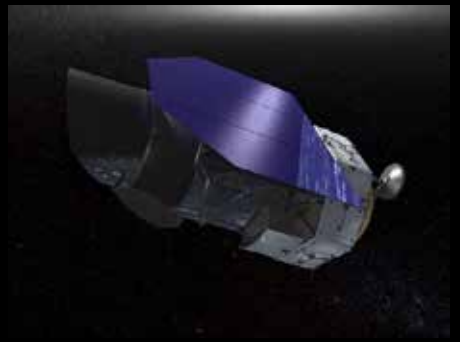
VLA + VLBA ® Combination of sensitive Wide Field of view + High-angular resolution at cm wavelengths.

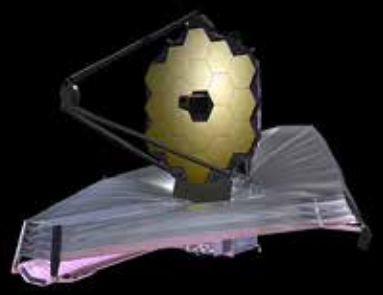
2020s




One current concept for the High-Definition Space Telescope.
Hubble on steroids
For astrophysicists, HDST would be "transformational," says commit-







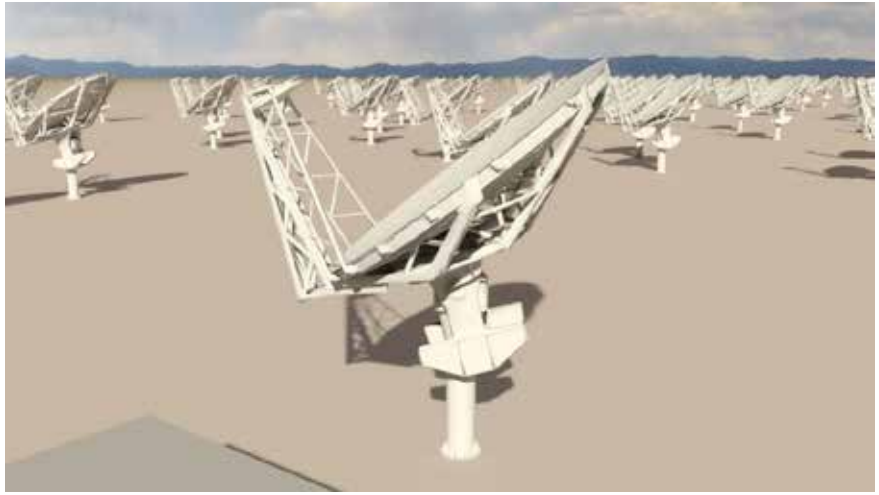
A Next-generation Very Large Array

- Scientific Frontier: Thermal imaging at milliarcsecond-scale resolution
- Key principle: Scientifically-compelling instrument for 2020s.
- Core Design Requirements
  - ***10x sensitivity of JVLA and ALMA***
  - ***10x resolution of JVLA and ALMA + Long Baselines***
  - ***Frequency range: 1.2 –116 GHz***
- Located in Southwest U.S. (NM+TX) & Mexico, building from JVLA site
- Reference design remains under continuous development
- Low technical risk (measured step beyond current state of the art)
- Stand-alone, multi-wavelength & multi-messenger scientific roles.

https://ngvla.nrao.edu

ngVLA Reference Design

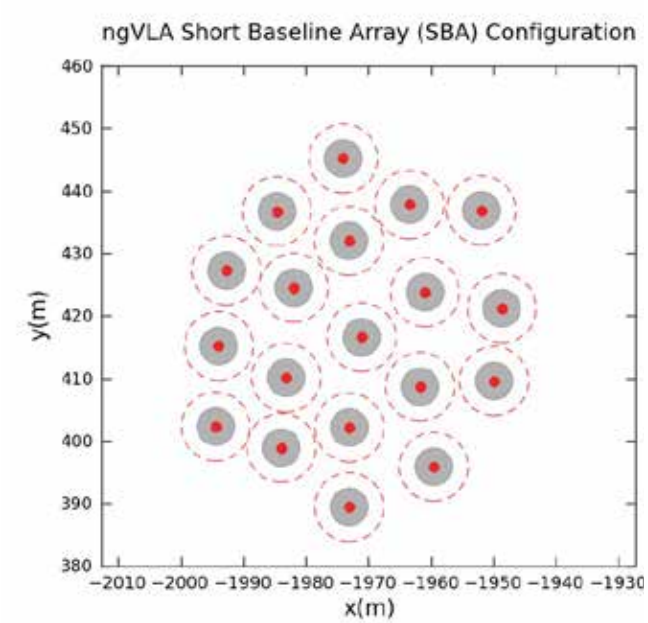
- Goal: A baseline design with known cost and low technical risk. Technical & cost basis of the Decadal proposal.
- 1.2 - 116 GHz Frequency Coverage. Src-driven.
- **Main Array**: 214 x 18m offset Gregorian Antennas.
  - Fixed antenna locations across NM, TX, AZ, MX.
- **Short Baseline Array**: 19 x 6m offset Gregorian antennas
  - 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 8000km.
  - Designed for both integrated and subarray use.

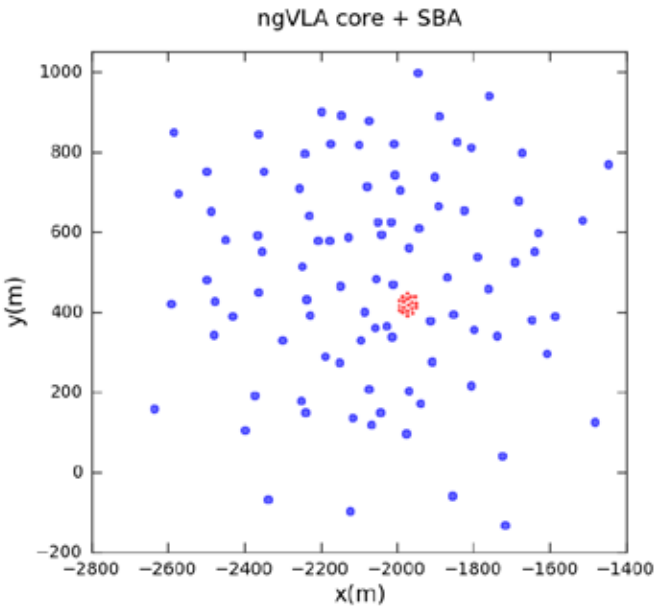


Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.35	3.5	2.91	2.3
2	B	3.5	7.90	12.3	3.51	8.8
3	B	12.3	16.4	20.5	1.67	8.2
4	B	20.5	27.3	34.0	1.66	13.5
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0

Short Baseline Array (SBA) And Total Power

- Short Baseline Array of 19 x 6 m (shortest baseline = 11 m)
- Total Power Array of 4 x 18 m (included as part of the 214 main array).

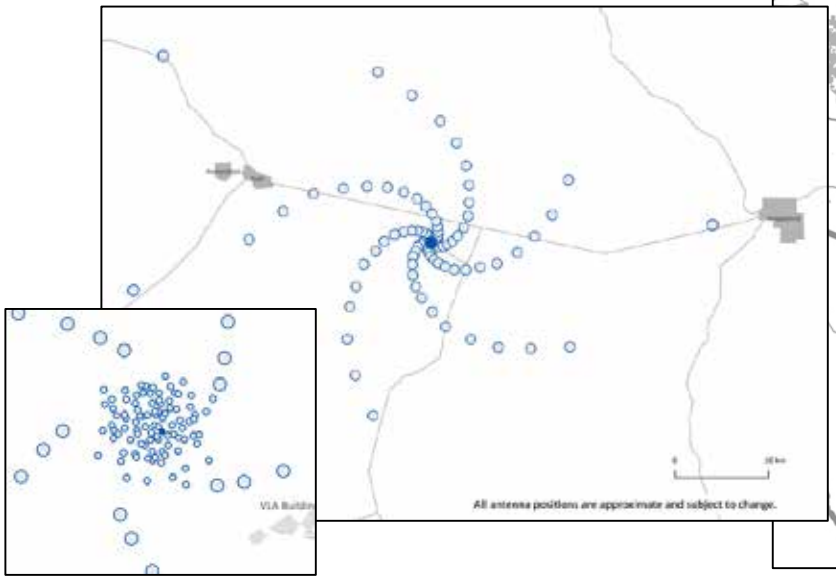


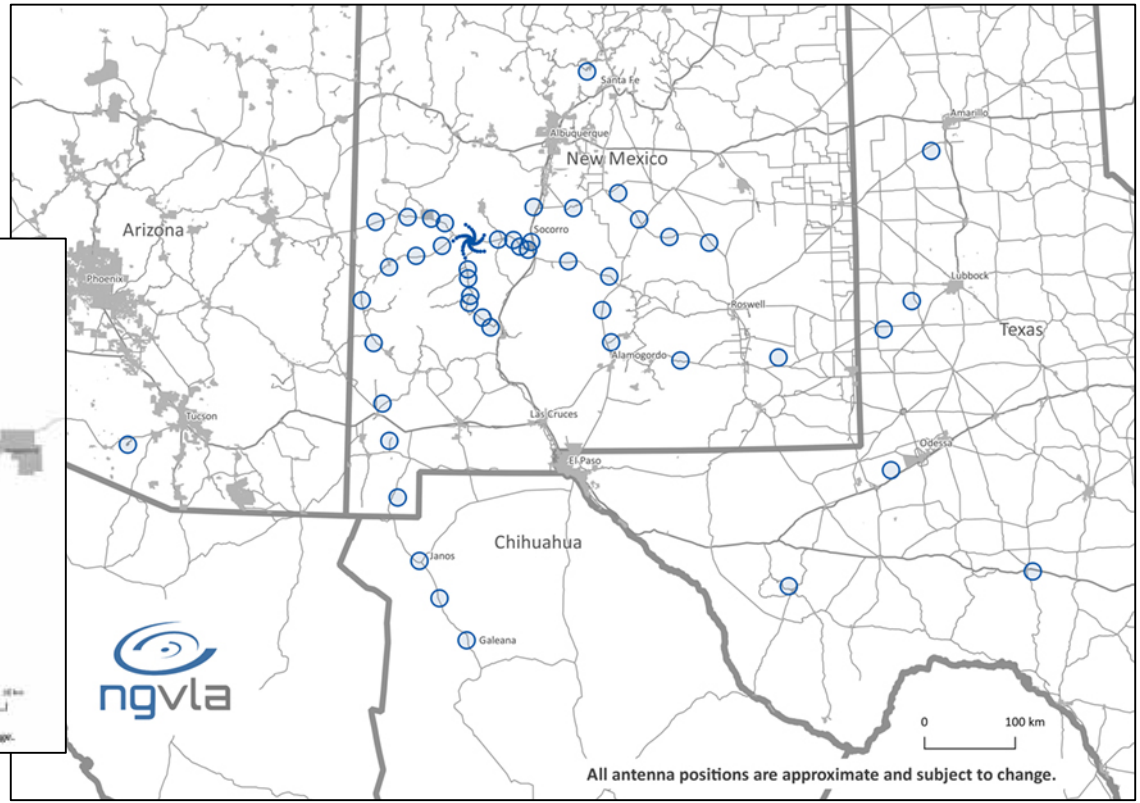


Reference Design Document

The Main Array Configuration

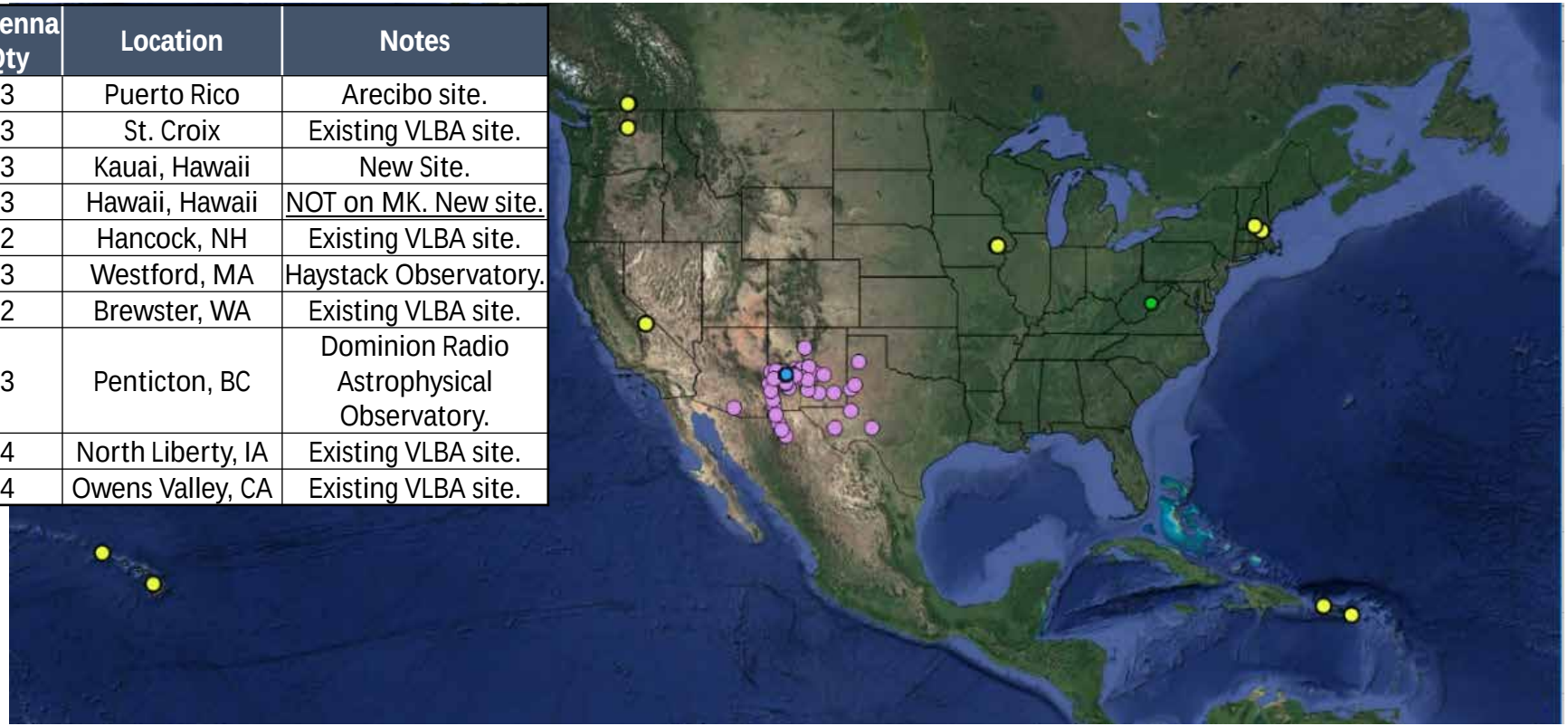
- Array of 214 x 18m off-axis antennas
- 44% core: b < 1.3 km => 1.5” at 30GHz
- 79% mid: b < 37 km => 0.6”
- 100% to long: b < 1000 km => 0.002”

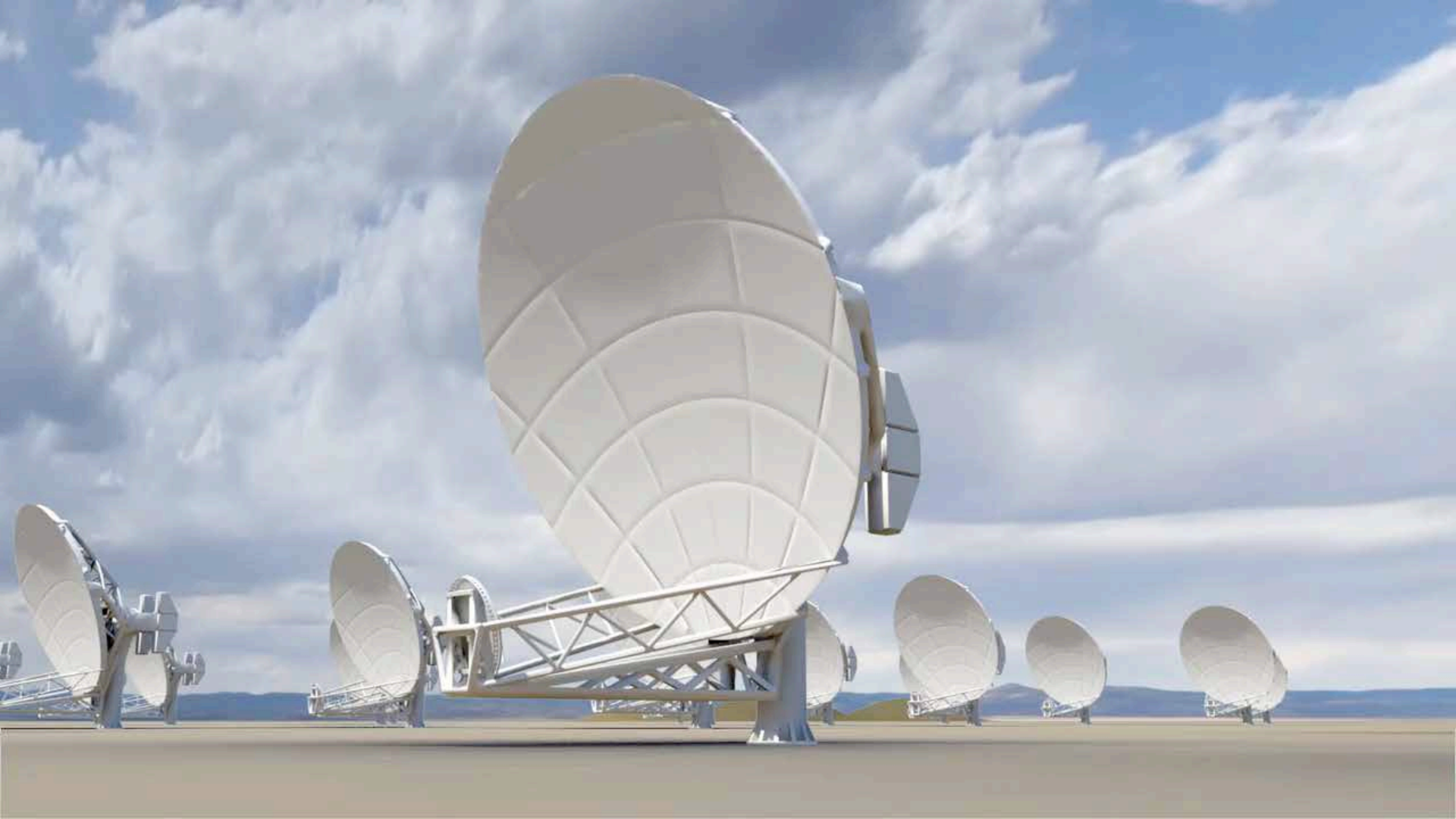


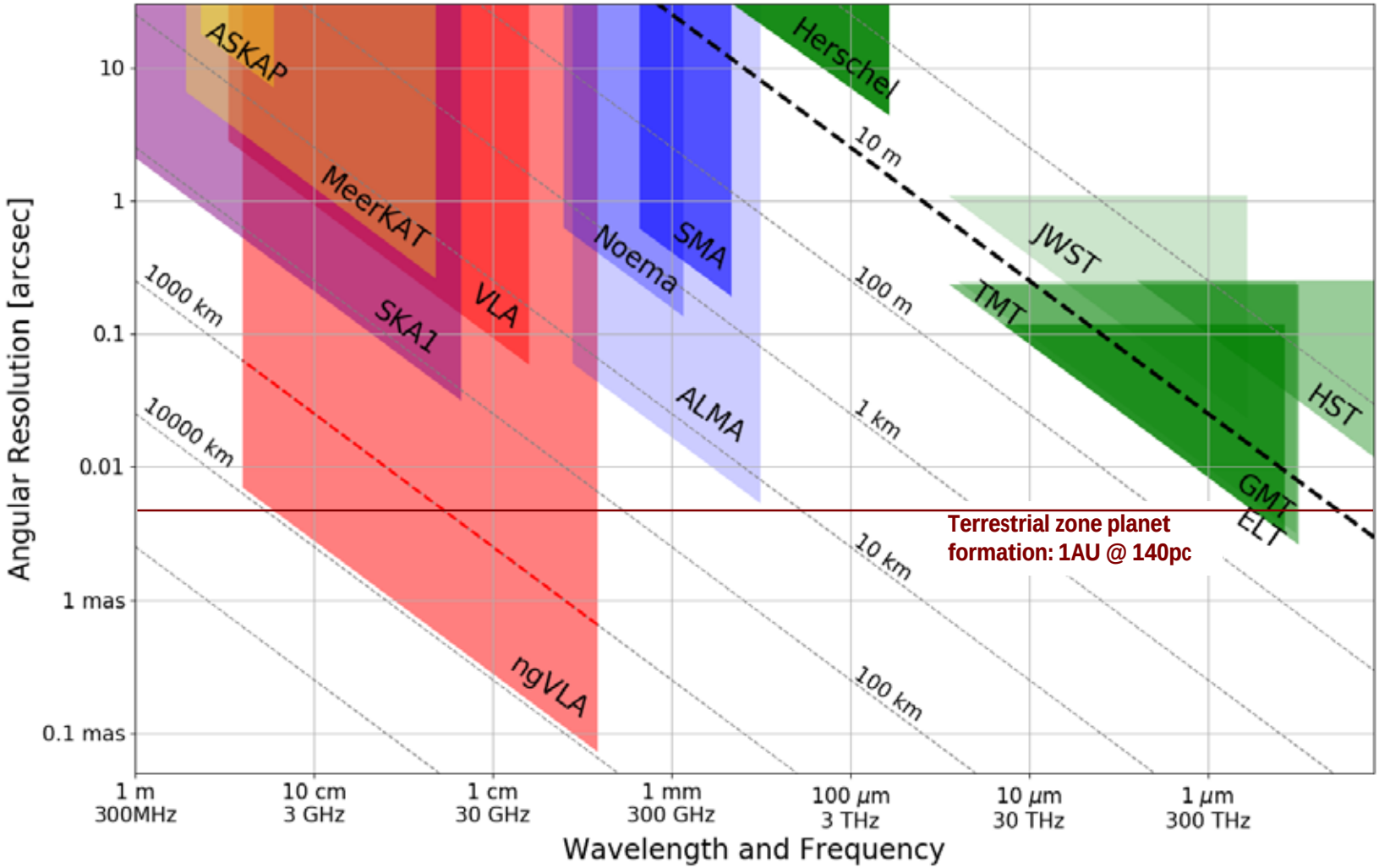


Long Baseline Array

Antenna Qty	Location	Notes
3	Puerto Rico	Arecibo site.
3	St. Croix	Existing VLBA site.
3	Kauai, Hawaii	New Site.
3	Hawaii, Hawaii	NOT on MK. New site.
2	Hancock, NH	Existing VLBA site.
3	Westford, MA	Haystack Observatory.
2	Brewster, WA	Existing VLBA site.
3	Penticton, BC	Dominion Radio Astrophysical Observatory.
4	North Liberty, IA	Existing VLBA site.
4	Owens Valley, CA	Existing VLBA site.






ASKAP
MeerKAT
SKA1
VLA
ngVLA
Noema
SMA
ALMA
Herschel
JWST
TMT
GMT
ELT
HST
10 m
100 m
1 km
10 km
100 km
1000 km
10000 km
Terrestrial zone planet formation: 1AU @ 140pc
Angular Resolution [arcsec]
10
1
0.1
0.01
1 mas
0.1 mas
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
Wavelength and Frequency

Five Key Science Goals for the ngVLA

Unveiling the Formation of Solar System Analogues

Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

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

Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

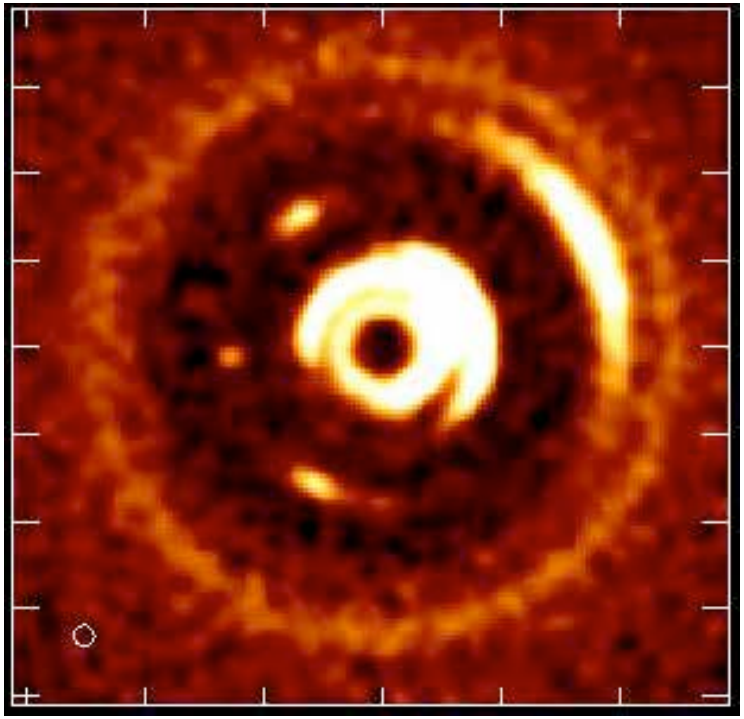
http://library.nrao.edu/public/memos/ngvla/NGVLA_19.pdf

Thermal Imaging on Milliarcsecond Scales

HL Tau – ALMA B6

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.

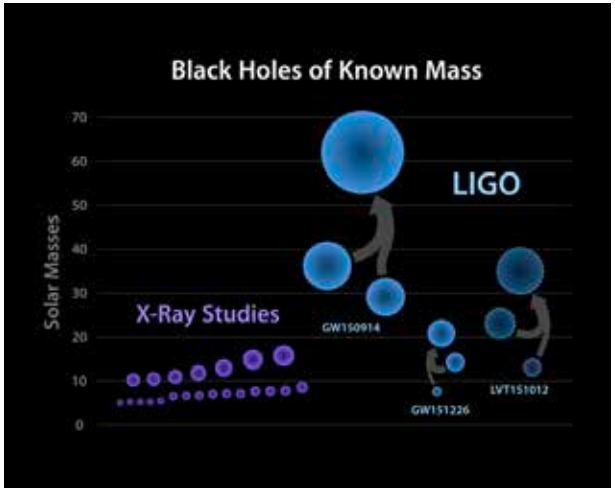
Simulated 100 GHz ngVLA observations of a newborn planetary system comprising a Jupiter analogue orbiting at 5 AU from a Solar type star.

Ricci et al. (2018)

Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

- Unaffected by dust obscuration and with the angular resolution to separate Galactic sources from background objects using proper motions, the ngVLA will enable a search for accreting black holes across the entire Galaxy.

- Key to understanding GW discoveries

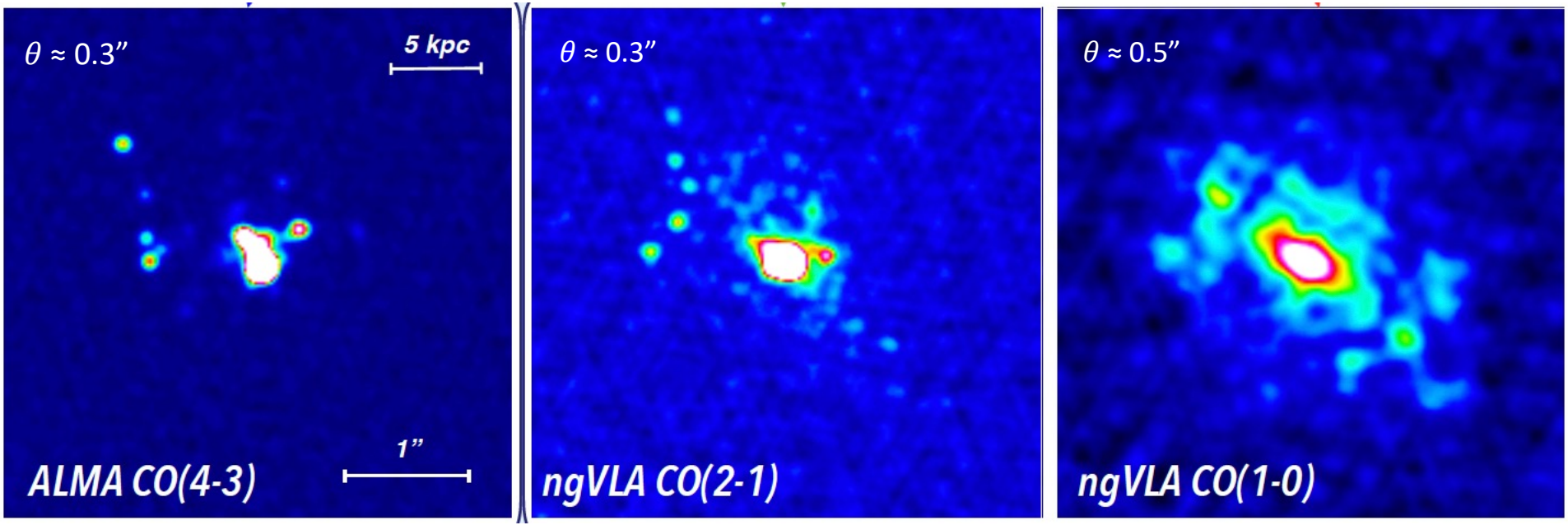


Long Baselines & high sensitivity enable studies of low-luminosity low mass AGN across Universe

ngvla

NRAO NSF AUI

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

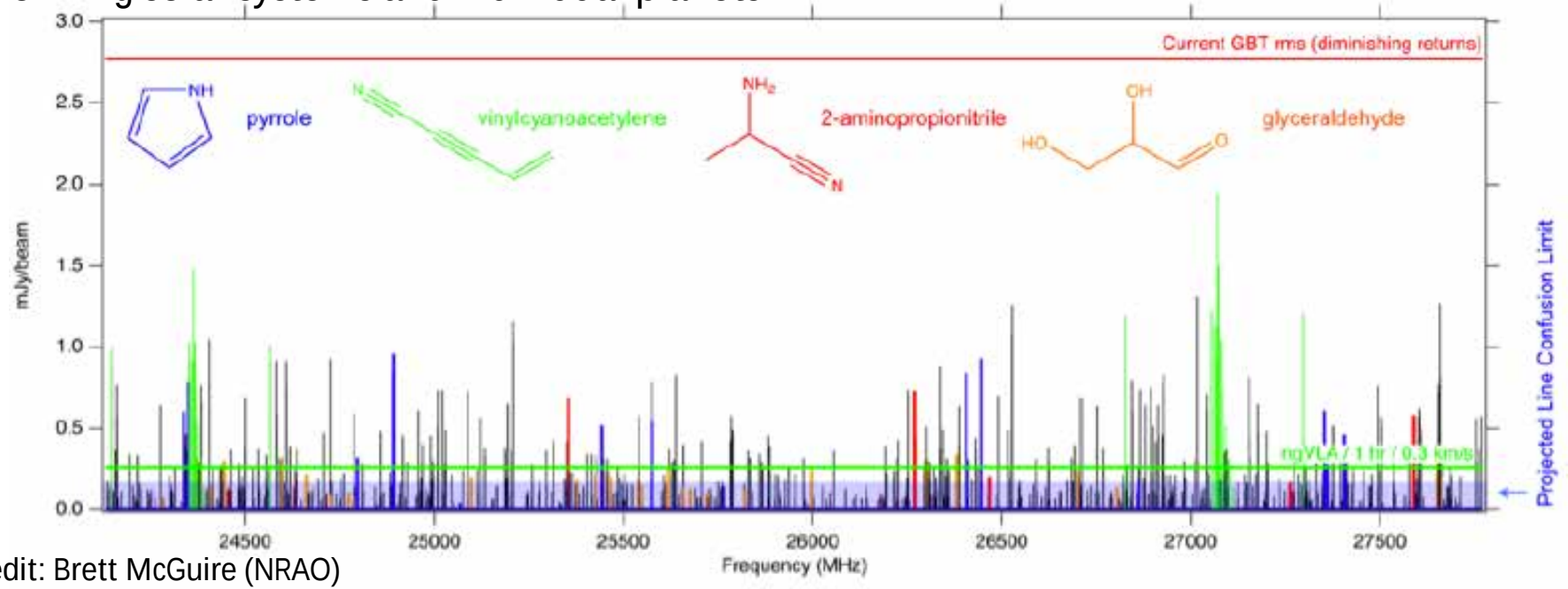


SMG at z = 4.4; SFR ≈ 400 $M_\odot$ /yr
Total molecular gas content largely missed by high-J lines

Credit: Caitlin Casey (UT Austin)

Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

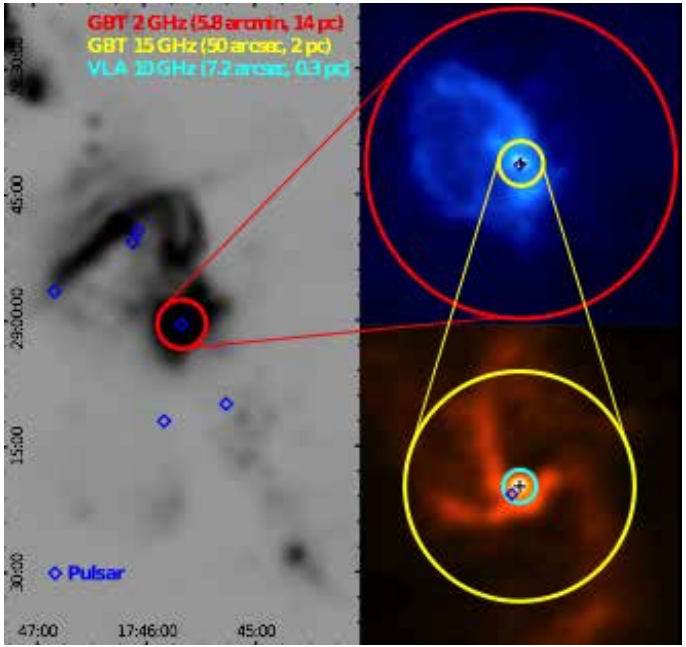
The ngVLA can detect complex pre-biotic molecules and provide the chemical initial conditions in forming solar systems and individual planets



Credit: Brett McGuire (NRAO)

Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

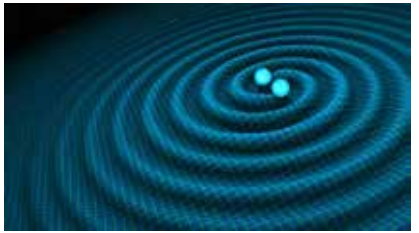
- The ngVLA sensitivity and frequency coverage will probe deeper than currently possible into the GC area looking for pulsars, which are moving clocks in the space-time potential of Sgr A*
- New tests of theories of gravity, constraints on exotic binaries, SF history, stellar dynamics and evolution, and ISM at the GC
- Estimates are as high as 1,000 PSRs. Only known example is PSR J1745-2900 magnetar, which are extremely rare (<1%)



Credit: R. Wharton

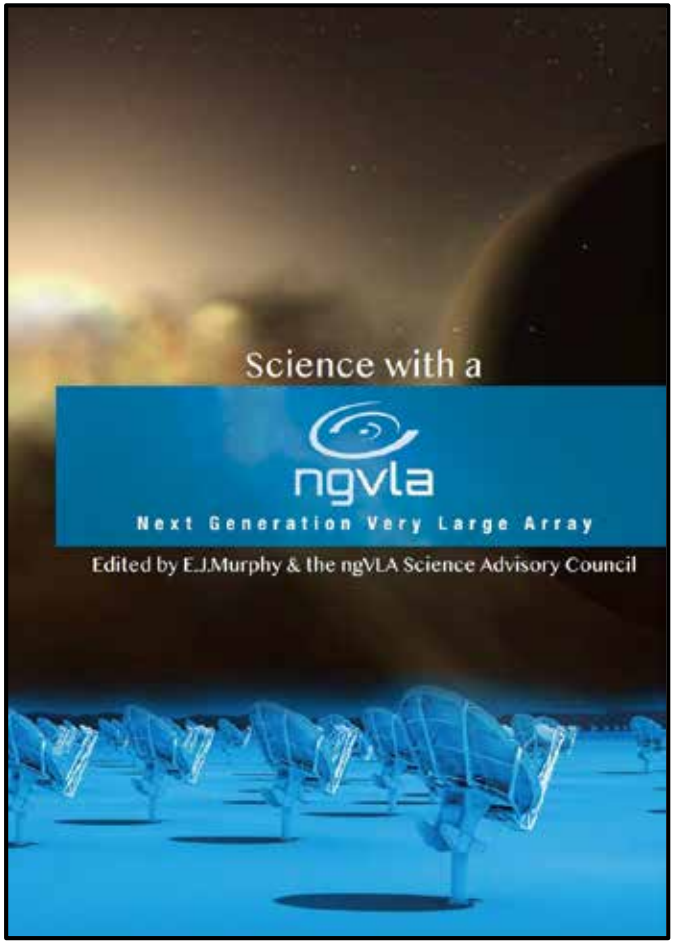
Versatility: Remarkable breadth of Science Enabled by the ngVLA

- Extrasolar Space Weather
- Bursting universe (FRB, GRB, TDE…)
- Low surface brightness HI, CO
- Obscured Black Hole Growth and AGN Physics
- Quasar-Mode Feedback and the SZ Effect
- Black hole masses and H_0 with Mega-Masers
- μas Astrometry: ICRF, Galactic structure…
- Solar system remote sensing: passive and active radar
- Spacecraft telemetry, tracking: *movies from Mars*



ngVLA Science Book

- First draft of Science Book released in June 2018
  - 57 (refereed) contributions received
  - ~200 unique authors
  - 6 contributions known to be in preparation, more expected
  - Volume is culmination of numerous science/technical meetings, beginning with Jan 2015 AAS
- 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)
- Related: Kavli science meeting series: 2016-2017
- Science Book to be published by ASP
    - Distribute at 2019 Winter AAS Meeting

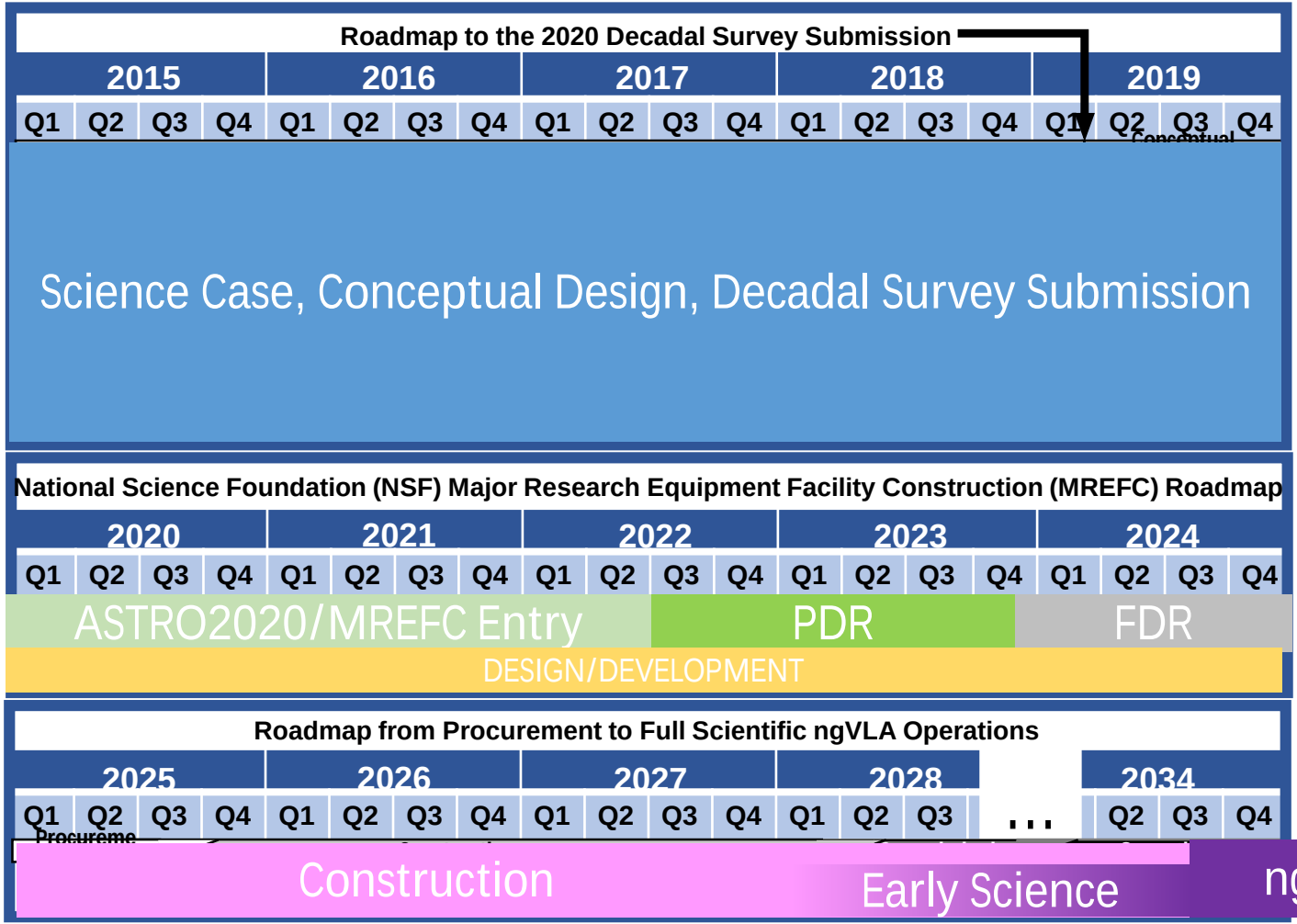


Cost Estimates

- Most recent cost estimate for construction: **in 2018 base-year dollars**
- Target operations budget: **(3x current VLA) + VLBA Ops (approx. $M/yr)**
  - Operations, maintenance, computing, archiving, etc.: optimize as part of design.
  - Anticipate changes to Observatory-wide operations model.

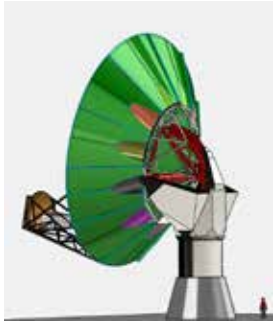
- Scope changes and cost data refinement have adjusted the initial estimate, examples of scope adjustments include:
  - ***Short Baseline Array (19 six-meter antennas)***
  - ***Long Baseline Array (30 eighteen-meter antennas)***
- Also under consideration: Green Bank Array
- All ngVLA components/data will be reviewed as part of ASTRO2020 process.

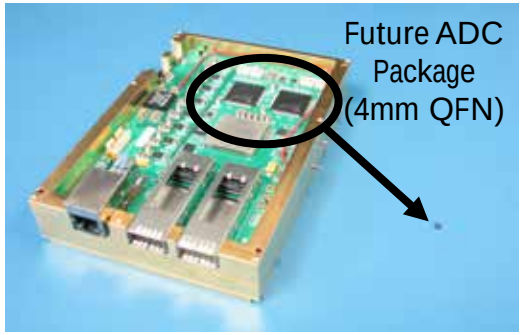
Next Generation Very Large Array (ngVLA) Project Timeline



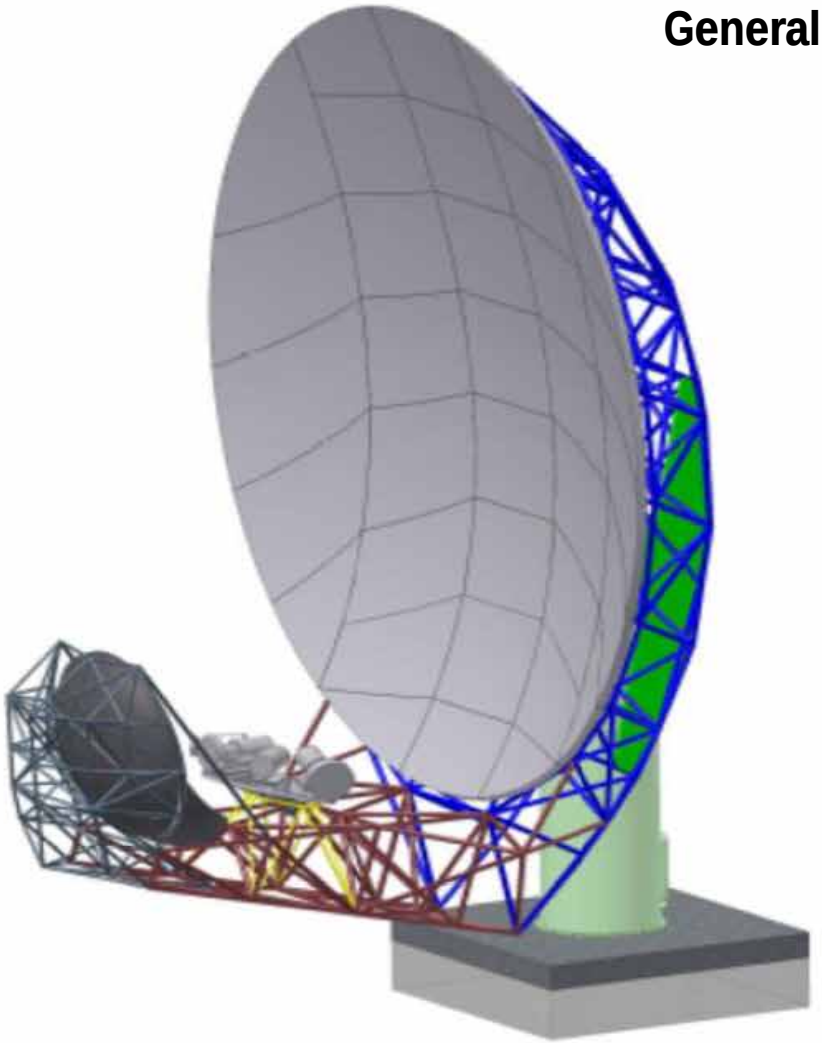
Design Development Risk Reduction

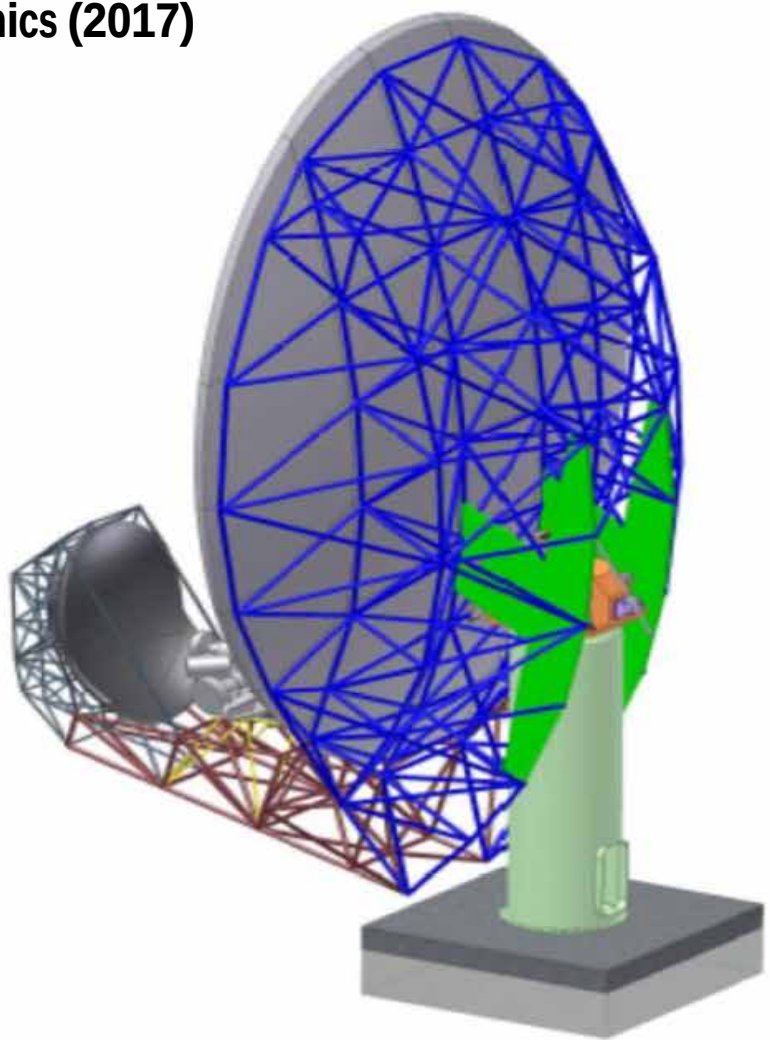
- Highest priorities:
  - **Antenna conceptual design and prototype**
    - Fund though CoDR. Options for PDR, Prototype, FDR.
  - **Production digitizer-serializer ASIC development**
    - Demonstration underway. Next: Full-Specification ASIC. Game changer.
  - **Band 6 axially corrugated feed horn prototype**
    - Retire mfg. risk that could impact antenna design.





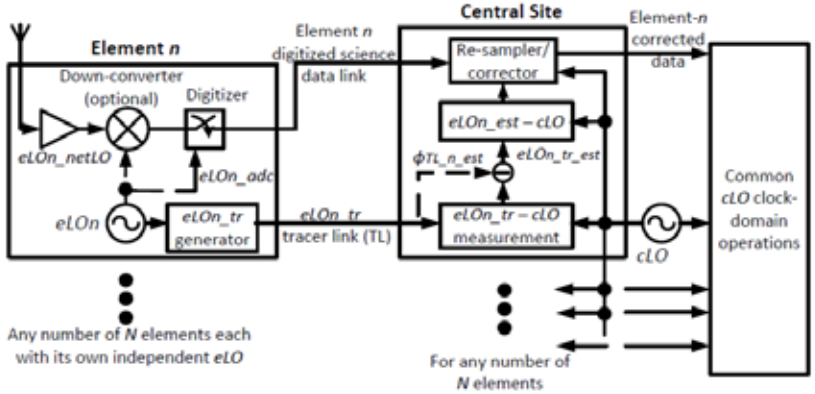
General Dynamics (2017)





Design Development Risk Reduction

- **PT link and incoherent clocking time transfer**.
  - Opportunity to replace expensive analog RF components with affordable COTS telecom equipment.
- **Cryogenically-cooled, dielectrically-loaded, low frequency feeds**.
  - Eliminate performance risks for Band 1 and Band 2 (<12 GHz)
- **Chip-scale atomic clock and frequency reference study.**
  - Opportunity to eliminate active hydrogen masers at sites 300km+ from ngVLA core.



Moving Forward

- Received $11M support from NSF for initial Design/Development. Next section of Design/Development – beginning FY2020.
- Transition model for JVLA® ngVLA to be discussed with NSF, community (options under consideration: 0-100% overlap).
- Complete science case, reference design for instrument components.
- ASTRO2020 – prepare information, present to community...
- Post Design: Begin technology development, Prototyping (Antennas, FEs, Computing).
- Partnership Development – 25% goal...

Partnerships (Science, Technical, Manufacturing)

- Strong International Partnership critical for success:
  - Current International Involvement in SAC/TAC/Community Studies:
  - Canada, Mexico, Japan, Germany, Netherlands, Taiwan
- Current Industrial Involvement through Community Studies:
  - General Dynamics, REhnu Inc., Minex Engineering Corp, LaserLaB, Quantum Design
- Possible U.S. Multiagency Interest (including long baseline option)
  - ICRF – DOD/Navy, Air Force
  - Spacecraft tracking/imaging, `burst-telemetry' (mission-critical events) – NASA, DOD, Space situational awareness – DOD

Community Participation

ngvla

NRAO NSF AUI

Community-Led Advisory Councils

ngVLA Science Advisory Council

- Interface between the science community & NRAO
- Recent/Current Activities:
  - Ø Science working groups: science use cases à telescope requirements
  - Ø SOC for science meeting in June 2017/2018
  - Ø Winter 2018 AAS Special Session
  - Ø Lead Science case development à 'science book' & DS2020 White Papers

Alberto Bolatto (University of Maryland: **co-Chair**)
Andrea Isella (Rice University : **co-Chair**)
Brenda Matthews (NRC-Victoria: **SWG1 Chair**)
Danny Dale (University of Wyoming: **SWG2 Chair**)
Dominik Riechers (Cornell: **SWG3 Chair**)
Joseph Lazio (JPL: **SWG4 Chair**)

ngVLA Technical Advisory Council

- Interface between the engineering & computing community and NRAO
- Membership covers a broad range of expertise in relevant technical areas including:
  - Ø Antennas, low-noise receiver systems, cryogenics, data transmission, correlators, and data processing

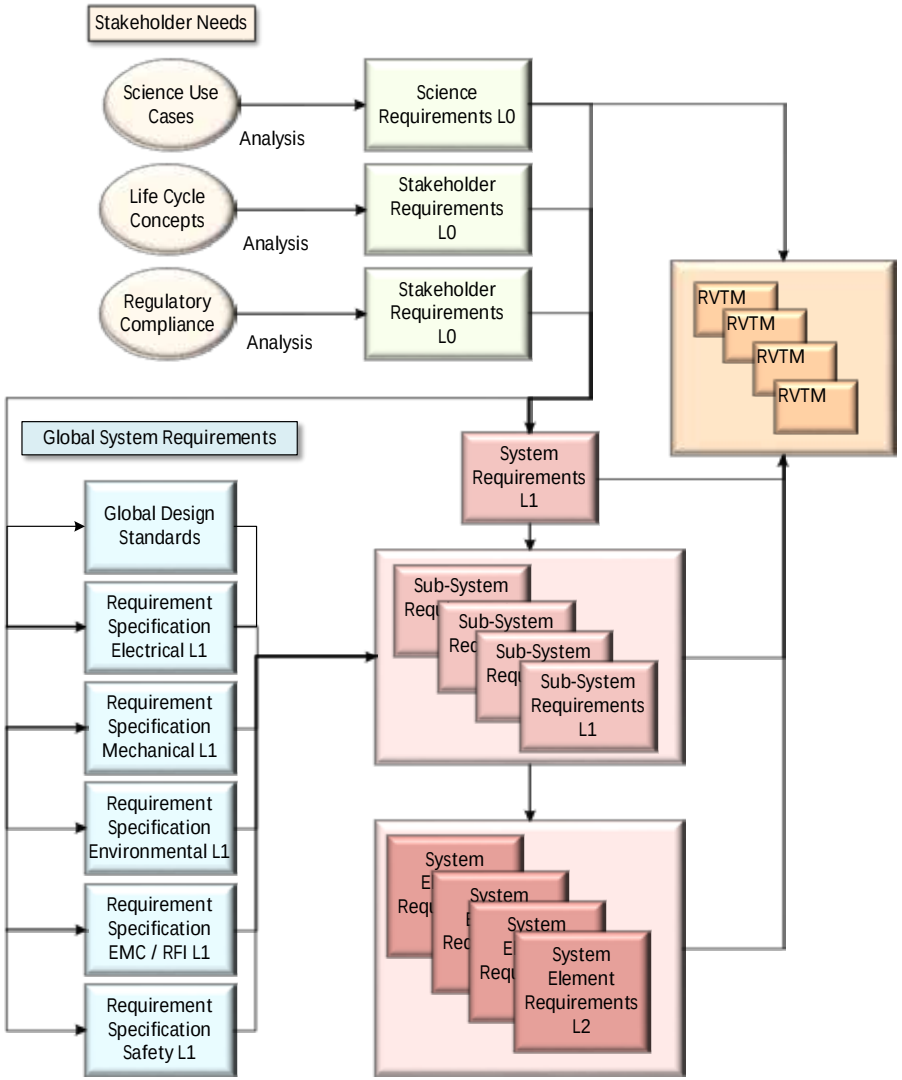
James Lamb (Caltech : **co-Chair**)
Melissa Soriano (JPL : **co-Chair**)

ngVLA 2018 Science Meeting

- Meeting was science-focused and wavelength agnostic
  - Brought together a broad cross-section of community
- 3 Parallel Sessions:
  - Origins of Exoplanets and Protoplanetary Disks
  - Mechanisms of Galaxy Evolution
  - Black Holes and Transient Phenomena
- Over 200 registrants and **70+ students**!
  - ***Creating the next-generation of users!***

System Flow-Down

- Begins with Science Use Cases (>80)
  - Distilled into ~200 unique observations
- Prioritization by SAC
  - 5 Key Science Goals with born out of various driving/supporting use cases
- Converted into Level 0 Science Requirements
  - 34 Requirements to support KSGs
    - 18 Telescope Reqs.
    - 16 Performance Reqs.
- Translated into Level 1 Technical Requirements
  - 122 System Level Reqs.



Mexico & ngVLA

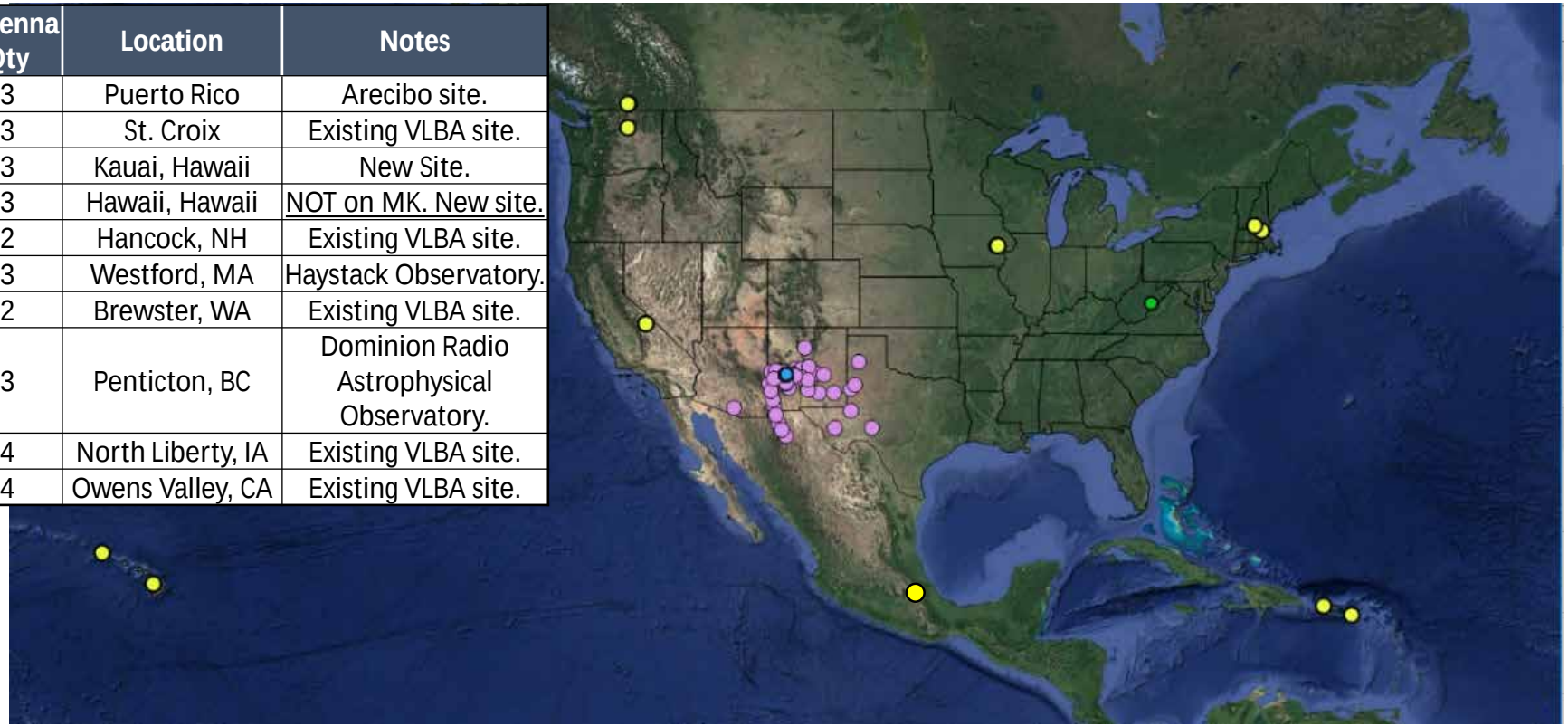
- Long tradition of US-Mexico collaboration in radio astronomy.
- Strong connection to ALMA/ngVLA science themes in Mx.
- ngVLA: critical N/S baselines, possible long baseline LMT addition.
- Opportunity: Science & Technology development, manufacturing roles.
- Apr 2018 – support letter from CONACYT – Dr Enrique Cabrero Mendoza
- Different levels of participation possible…


Los Angeles
Palm Springs
San Diego
Mexicali
Yuma
DESERT
Phoenix
SONORAN
Mesa
Tonto National Forest
Prescott
Tucson
Douglas
NEW MEXICO
LLANO
Roswell
ESTACADO
Lubbock
Alamogordo
Las Cruces
Carlsbad
(STAKED PLAIN)
El Paso
Odessa
Abilene
San Angelo
TEXAS
Waco
Fort Worth
Garland
Dallas
Tyler
Wichita Falls
Lawton
Little Rock
ARKANSAS
Texarkana
Shreveport
LOUISIANA
Monroe
Jackson
MISSISSIPPI
Greenville
Tupelo
ALABA
Montg
Lufkin
Alexandria
Baton Rouge
Lafayette
Mobile
New Orleans
Houston
Galveston
Austin
San Antonio
Del Rio
Victoria
Corpus Christi
Laredo
McAllen
Brownsville
Monterrey
Saltillo
Hermosillo
Chihuahua
Culiacan
La Paz
Durango
Mazatlan
MEXICO
Zacatecas
San Luis Potosi
Aguascalientes
Tepic
Guadalajara
Queretaro
Morelia
Colima
Tolnca
México City
Cuernavaca
Pachuca
Puebla
Jalapa
Veracruz
Tampico
Ciudad Victoria
Merida
Campeche
Villahermosa
Belmopan
Acapulco
Oaxaca
Gulf of Mexico
Gulf of California
SIERRA MADRE OCCIDENTAL
SIERRA MADRE ORIENTAL
SIERRA MADRE DEL SUR
0
125
250
500 Kilometers
Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS


Los Angeles
Palm Springs
San Diego
Mexicali
Yuma
DESERT
Phoenix
SONORAN
Mesa
Tonto National Forest
Prescott
Tucson
Douglas
NEW MEXICO
LLANO
ESTACADO
Roswell
Alamogordo
Las Cruces
Carlsbad
(STAKED PLAIN)
Lubbock
El Paso
Odessa
TEXAS
Abilene
San Angelo
Waco
Fort Worth
Dallas
Garland
Wichita Falls
Lawton
Little Rock
ARKANSAS
Texarkana
Tupelo
MISSISSIPPI
Greenville
Birmingham
ALABAMA
Montgomery
Shreveport
Monroe
Jackson
LOUISIANA
Lufkin
Alexandria
Baton Rouge
Lafayette
Mobile
New Orleans
Houston
Galveston
Austin
San Antonio
Del Rio
Victoria
Corpus Christi
Laredo
McAllen
Brownsville
Monterrey
Saltillo
Hermosillo
Chihuahua
Culiacan
La Paz
Durango
Mazatlan
MEXICO
Zacatecas
San Luis Potosi
Aguascalientes
Tepic
Guadalajara
Queretaro
Morelia
Colima
Toluca
México City
Cuernavaca
Pachuca
Puebla
Jalapa
Veracruz
Tampico
Ciudad Victoria
Merida
Campeche
Villahermosa
Oaxaca
Acapulco
Gulf of California
Gulf of Mexico
SIERRA MADRE OCCIDENTAL
SIERRA MADRE ORIENTAL
SIERRA MADRE DEL SUR
0
125
250
500 Kilometers
Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Long Baseline Array + LMT

Antenna Qty	Location	Notes
3	Puerto Rico	Arecibo site.
3	St. Croix	Existing VLBA site.
3	Kauai, Hawaii	New Site.
3	Hawaii, Hawaii	NOT on MK. New site.
2	Hancock, NH	Existing VLBA site.
3	Westford, MA	Haystack Observatory.
2	Brewster, WA	Existing VLBA site.
3	Penticton, BC	Dominion Radio Astrophysical Observatory.
4	North Liberty, IA	Existing VLBA site.
4	Owens Valley, CA	Existing VLBA site.



Summary

- The ngVLA is being designed to tap into the astronomical community's intellectual curiosity and enable a broad range of scientific discovery (e.g., planet formation, signatures of pre-biotic molecules, cosmic cycling of cool gas in galaxies, massive star formation in the Galaxy etc.)
- Major Challenges: No major technological risks identified, but continually looking to take advantage of major engineering advancements seeking performance and operations optimizations.
- Next Steps: Continue Design/Development research; refine the ngVLA science mission and instrument specifications/performance via detailed science book and reference design studies. Transition to prototyping within next two years, in particular – antenna, electronics.
- Partnerships important – critical role to be played by Mexico (5-10% partner?)

Many Thanks to:

- The ngVLA Science and Technical Advisory committees.
- All ngVLA Science Working Group Participants, White Paper Authors.
- ngVLA Community Studies Participants.
- National Science Foundation.

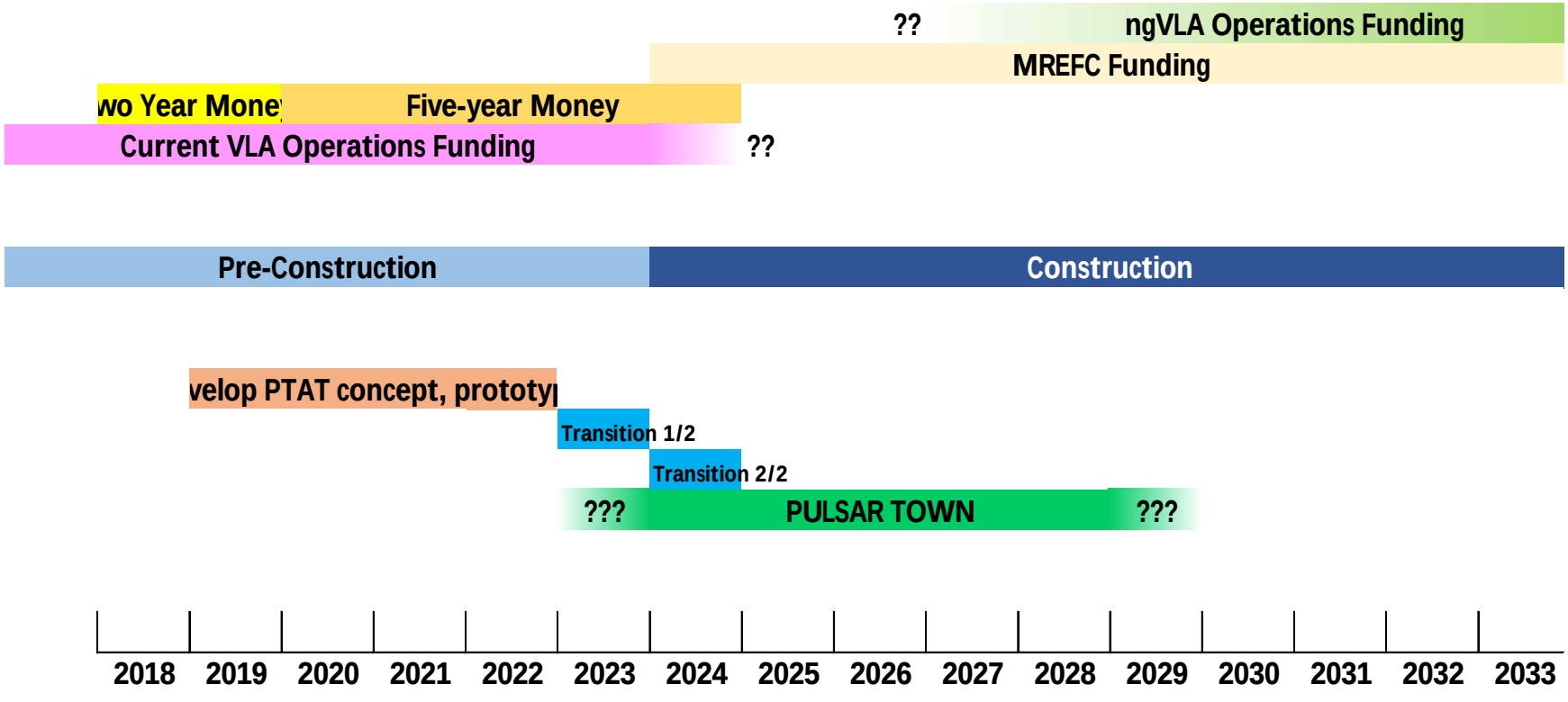
ngvla.nrao.edu

www.nrao.edu
science.nrao.edu
public.nrao.edu

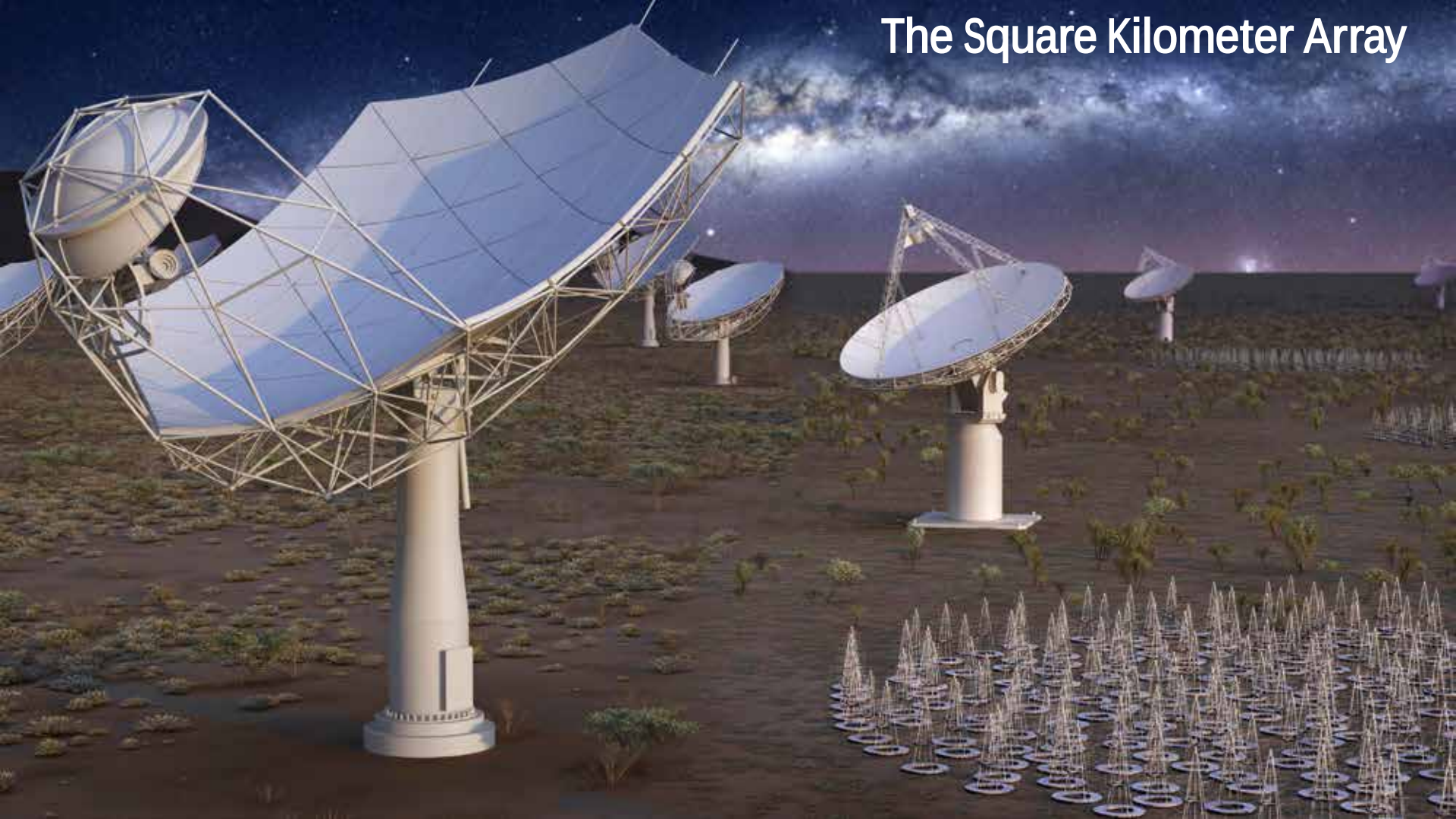
The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Transition

- Analysis underway about plans for JVLA hardware/infrastructure during ngVLA D/D and construction periods.
- Multiple options: turn off JVLA asap ($) through full steam ahead ($$$$)
- Science issue – key moment in transient astronomy science (LSST, LIGO) to be off the air….
- Under discussion: “Pulsar-town”, “Minimum Ops”, …
- Funding AND human capital issue…. tough competition with ngVLA needs.
- Transition - TBD


??
ngVLA Operations Funding
MREFC Funding
wo Year Mone
Five-year Money
Current VLA Operations Funding
??
Pre-Construction
Construction
velop PTAT concept, prototy
Transition 1/2
Transition 2/2
???
PULSAR TOWN
???
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033

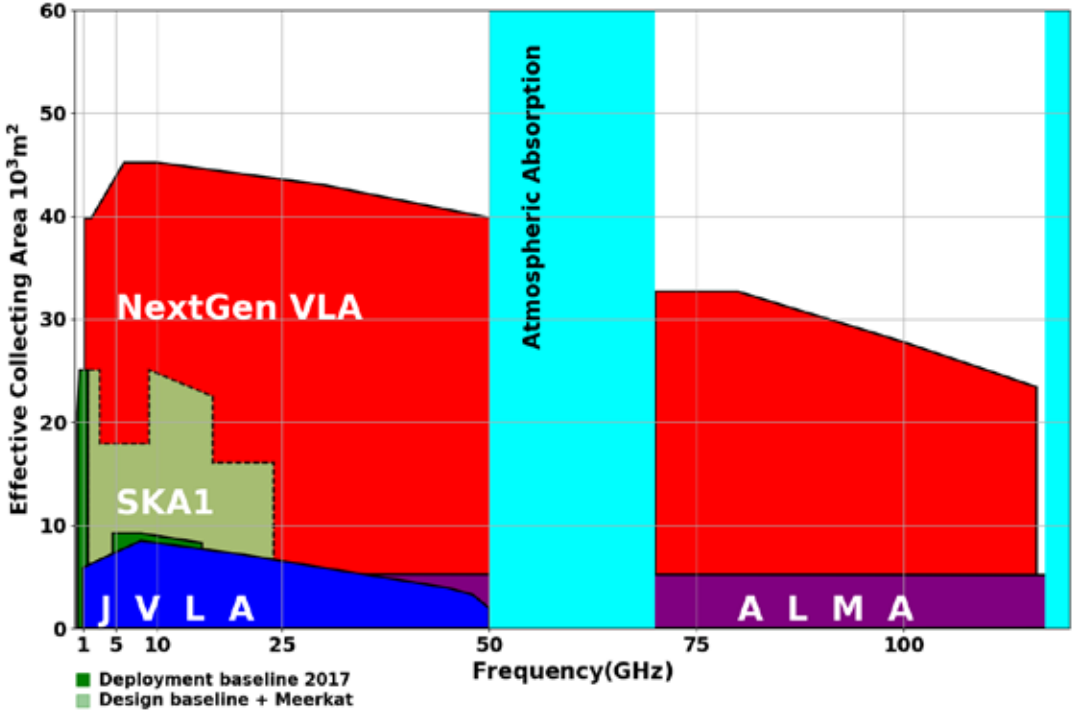
SKA


The Square Kilometer Array

- Long history together… parted ways ~2010.
- Currently: external participation in SKAPO, ongoing CASA initiative, some technology investments benefits going both ways.
- CASA software will be integral part of SKA.
- No obvious path to SKA1 participation for US community.
- US science environment, culture… different drivers, expectations.

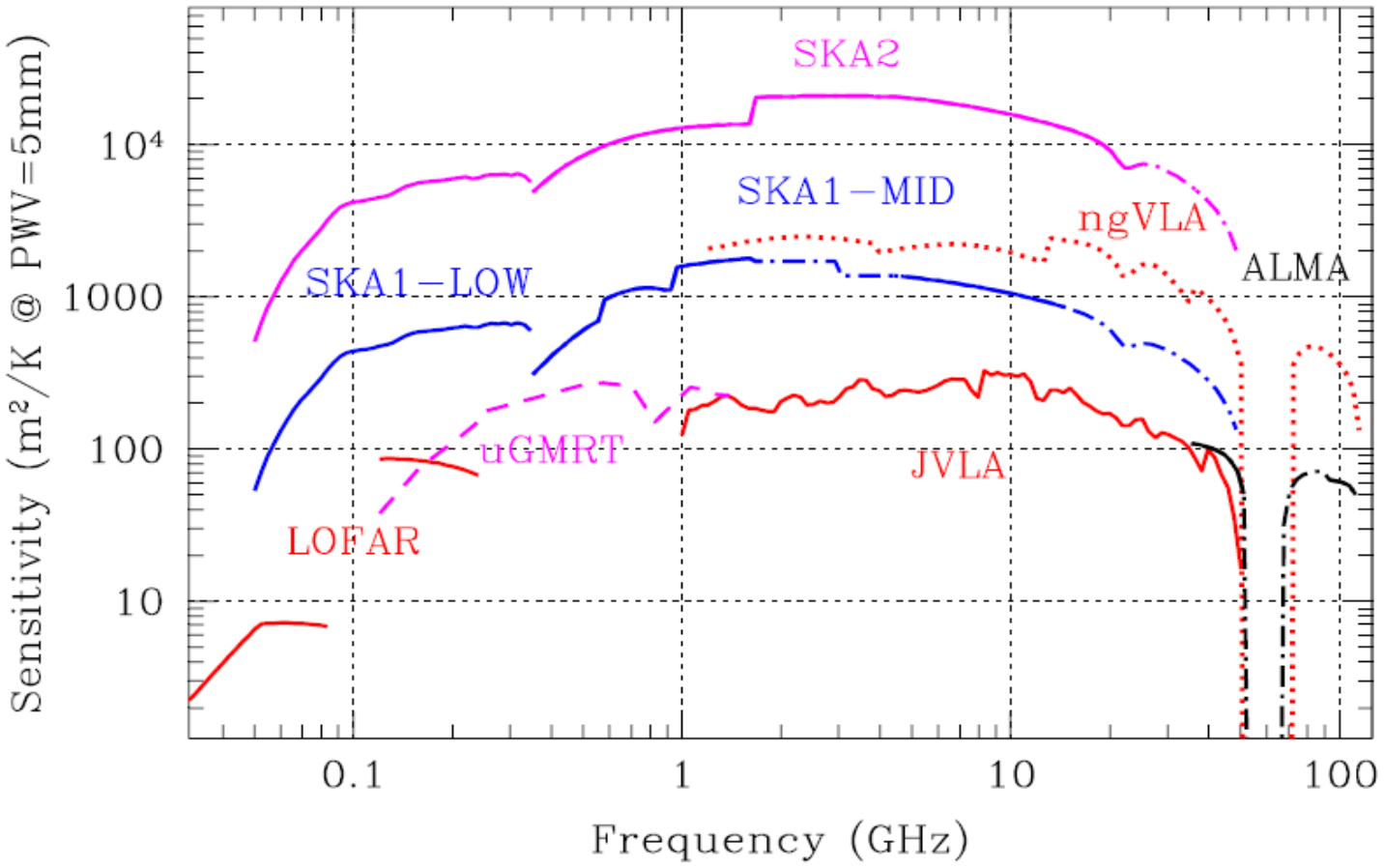
- Can ngVLA be thought of as SKA2-HIGH? (…yes)

Global Radio Astronomy 2020-2040?



Complementary suite from cm to submm arrays for the mid-21st century

- **< 0.3cm:** ALMA 2030 superb for chemistry, dust, fine structure lines
- **0.3 to 3cm: ngVLA ngVLA superb for terrestrial planet formation, dense gas history, baryon cycling**
- **> 3cm:** SKA superb for pulsars, reionization, HI + continuum surveys


SKA2
SKA1−MID
ngVLA
ALMA
SKA1−LOW
uGMRT
JVLA
LOFAR
Sensitivity (m²/K @ PWV=5mm)
10⁴
1000
100
10
0.1
1
10
100
Frequency (GHz)

- SKA1 & ngVLA/ALMA - a “Global Science Alliance” ?
  - **Provide US community & ngVLA partners access to SKA infrastructure.**
  - Provide SKA countries access to US infrastructure. (Quid pro quo: Open Skies)
  - Enable technology transfer, software collaboration.
  - US funding spent in US, partners; control remains in ngVLA.

- Further discussion with science community, partners, NSF required.

25 Years of US Leadership in Radio Astronomy