NATIONAL RADIO ASTRONOMY OBSERVATORY



Project Summary

Eric J. Murphy, ngVLA Project Scientist

Associated Universities, Inc.

ngVLA

The 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

A next generation VLA

- Scientific Frontier: Thermal imaging at milli-arcsecond scale resolution
- Core Design Requirements
  - *10x effective collecting area of JVLA and ALMA*
  - *10x resolution of JVLA and ALMA*
  - *Frequency range: 1.2 –116 GHz*
- Located in Southwest U.S. (NM+TX+?) & Mexico, building from JVLA site
- Baseline design remains under continuous development
- Low technical risk (reasonable step beyond current state of the art)

https://science.nrao.edu/futures/ngvla



Developing the ngVLA Science Case

Community-Driven, Growing, and Evolving

- Numerous Science and Technical meetings, starting from Jan 2015 AAS
- Initial Science Working Group reports covering 4 broad areas, Nov .2015 (*http://library.nrao.edu/ngvla.shtml*)
  - ***Cradle of Life: CoL*** *(Isella et al):* Terrestrial-zone planet formation, Massive Stars, etc.
  - ***Galaxy Ecosystems: GEco*** *(Leroy et al):* wide field, high resolution/sensitive imaging
  - ***Galaxy Formation: GFor*** *(Casey et al):* *Dense gas history of the Universe*
  - ***Time domain, Cosmology, and Physics: TdCP*** *(Bower et al):* Plasma physics, Exo-space weather, Strong Lensing



- 26 Community Design Studies in progress, partially funded by NRAO (*https://science.nrao.edu/futures/ngvla/ngvla-community-studies-approved-programs)*
- 75 Community-Led Science Use Cases Submitted for ‘Reqs to Specs’ process (ngVLA memo # 18)

- ***All gathered to report out and build toward a consensus vision last week of June in Socorro***

Community-Led Advisory Councils

ngVLA Science Advisory Council

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

Alberto Bolatto (University of Maryland: **co-Chair**)
Andrea Isella (Rice University : **co-Chair**)
Brenda Matthews (NRC-Victoria: **SWG1 Chair**)
Cornelia Lang (University of Iowa: **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:
  - Antennas, low-noise receiver systems, cryogenics, data transmission, correlators, and data processing

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



Developing the ngVLA Science Program Workshop

Socorro, NM, USA | 26 - 29 June, 2017



- ~ 150 attendees (capped with waitlist)
- 24 talks on innovative science allowed by the ngVLA
- Followed by SAC face-to-face meeting

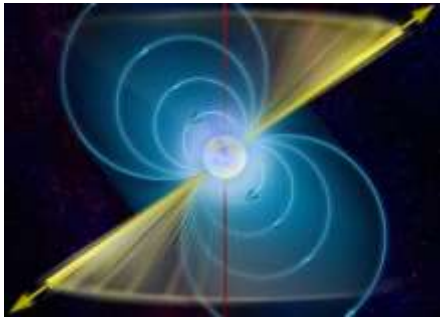
Main outcomes:

- ngVLA preliminary telescope design

- Definition of the Key Science Goals for the ngVLA

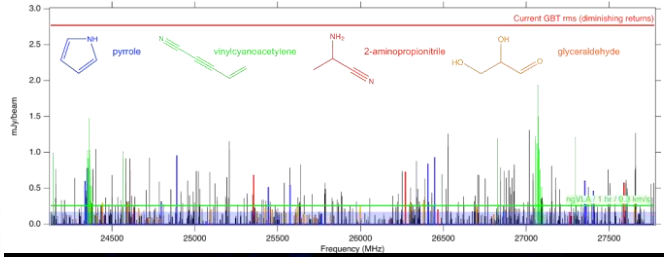
ngVLA Key Science Mission

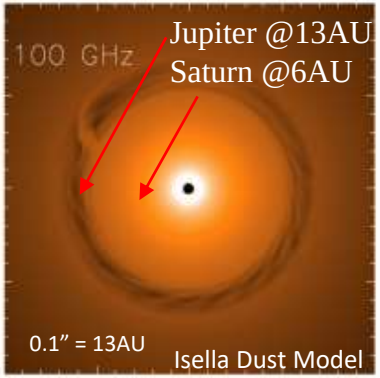
(ngVLA memo #19)

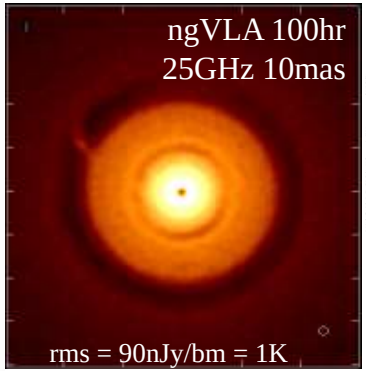


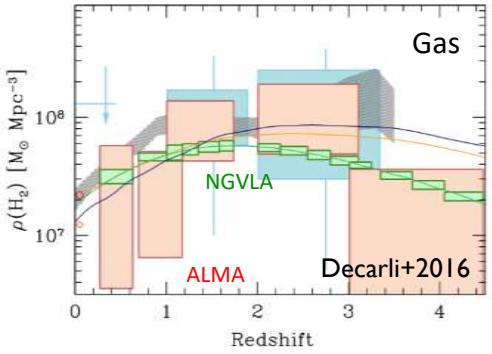
- ***Unveiling the Formation of Solar System Analogues***
- ***Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry***
- ***Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time***
- ***Using Pulsars in the Galactic Center as Fundamental Tests of Gravity***
- ***Understanding the Formation and Evolution of Stellar and Supermassive BH's in the Era of Multi-Messenger Astronomy***

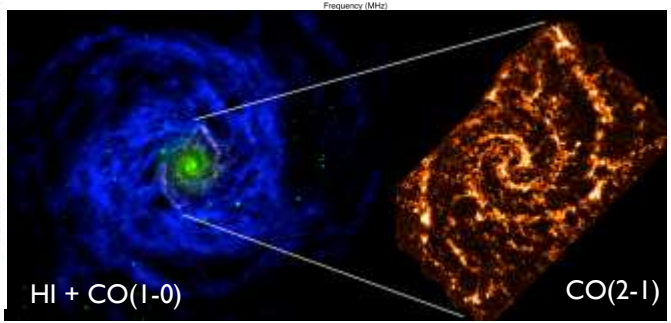
Highly synergistic with next-generation ground-based OIR and NASA missions.











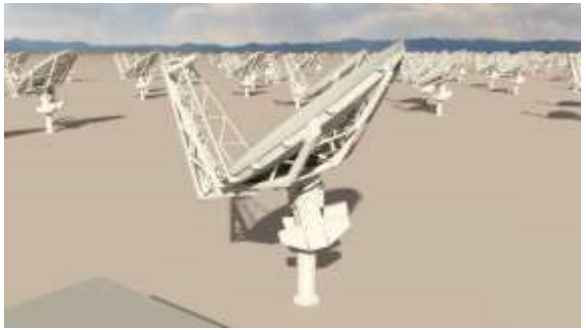


Current Reference Design Specifications

(ngVLA Memo #17)

- 214 18m offset Gregorian (feed-low) Antennas
  - Supported by internal cost-performance analysis
- Fixed antenna locations across NM, TX, MX
  - ~1000 km baselines being explored
- 1.2 – 50.5 GHz; 70 – 116 GHz
  - Single-pixel feeds
  - 6 feeds / 2 dewar package
- Short-spacing/total power array under consideration

- Continuum Sensitivity: ~0.1uJy/bm @ 1cm, 10mas, 10hr => T_B ~ 1.75K
- Line sensitivity: ~14uJy @ 1cm/bm, 10 km/s, 1” => T_B ~ 215K



Receiver Configuration

Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.55	3.9	3.25	2.7
2	B	3.9	8.25	12.6	3.23	8.7
3	B	12.6	16.8	21.0	1.67	8.4
4	B	21.0	28.0	35.0	1.67	14.0
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0



The ‘Southwest Array’

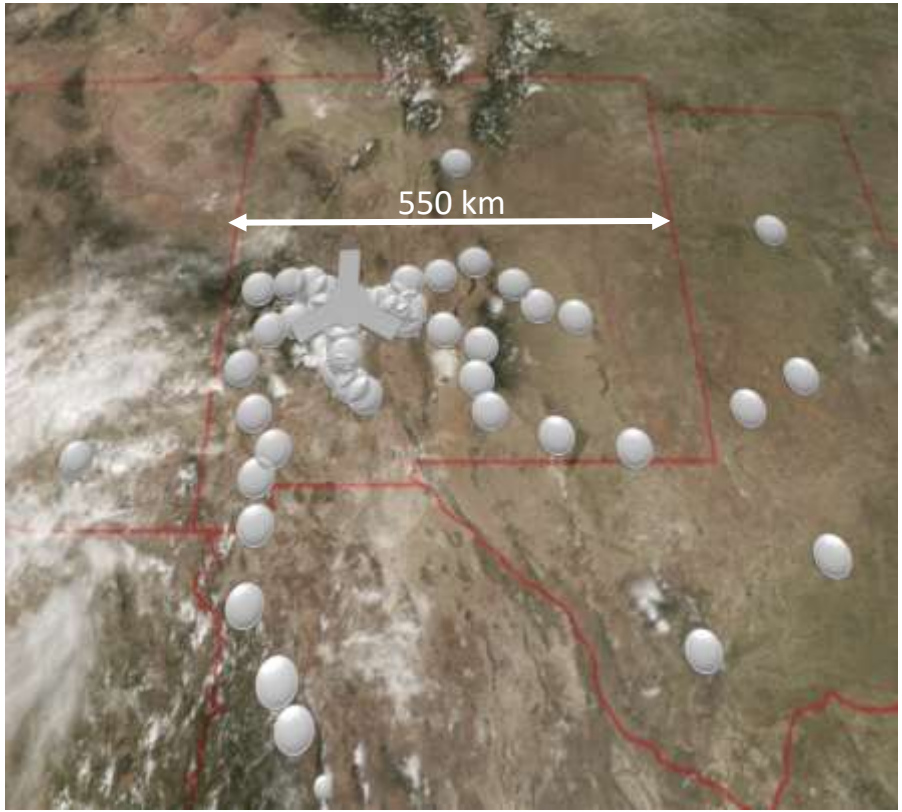
- Location: U.S. Southwest, Mexico
- Homogeneous array 214 x 18m, off-axis antennas
- 50% to core: b < 3 km => 1” at 30GHz
- 80% to mid: b < 30 km => 0.1”
- 100% to long: b < 1000 km => 0.003”

Nominal 18m homogeneous array

- Consensus design
- Challenge of tri-scale-array: Sensitivity vs. resolution

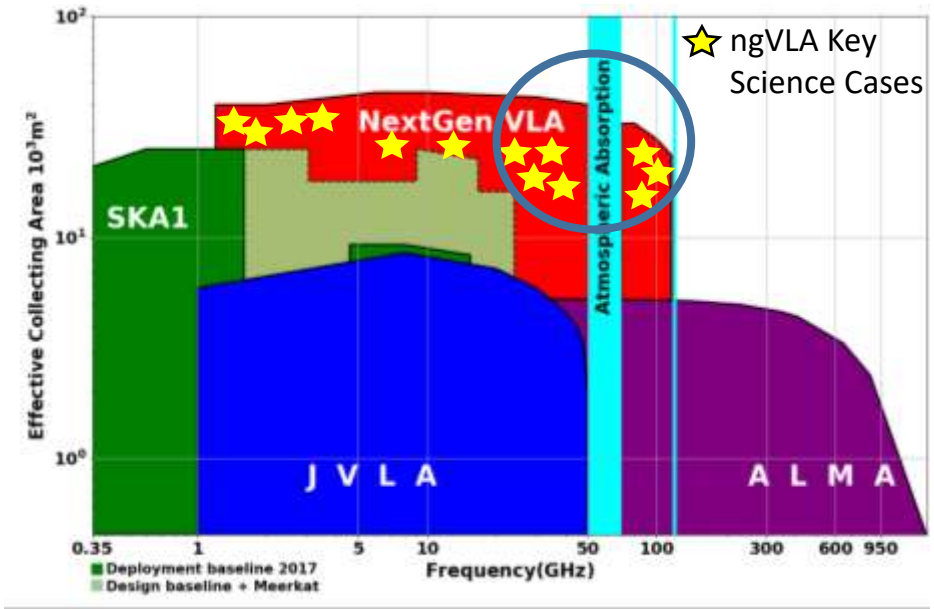
Options

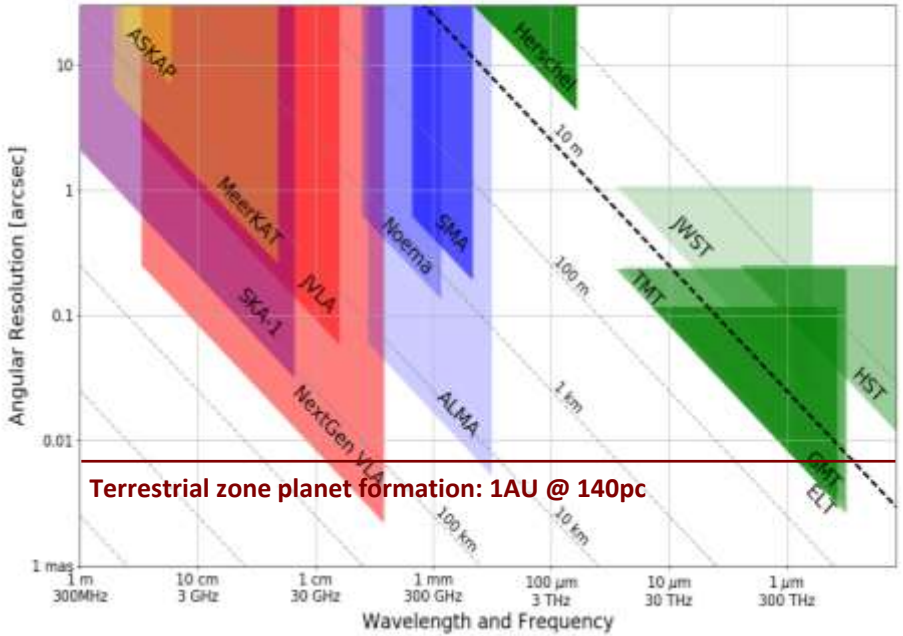
- Reconfiguration: not at loss of 18m antennas
- Long baselines: continental VLBI
- Short baselines: [45m dish + FPA] or [6m array + 18m total power]



Bridging SKA & ALMA Scientifically

Thermal Imaging on mas Scales at λ ~ 0.3cm to 3cm



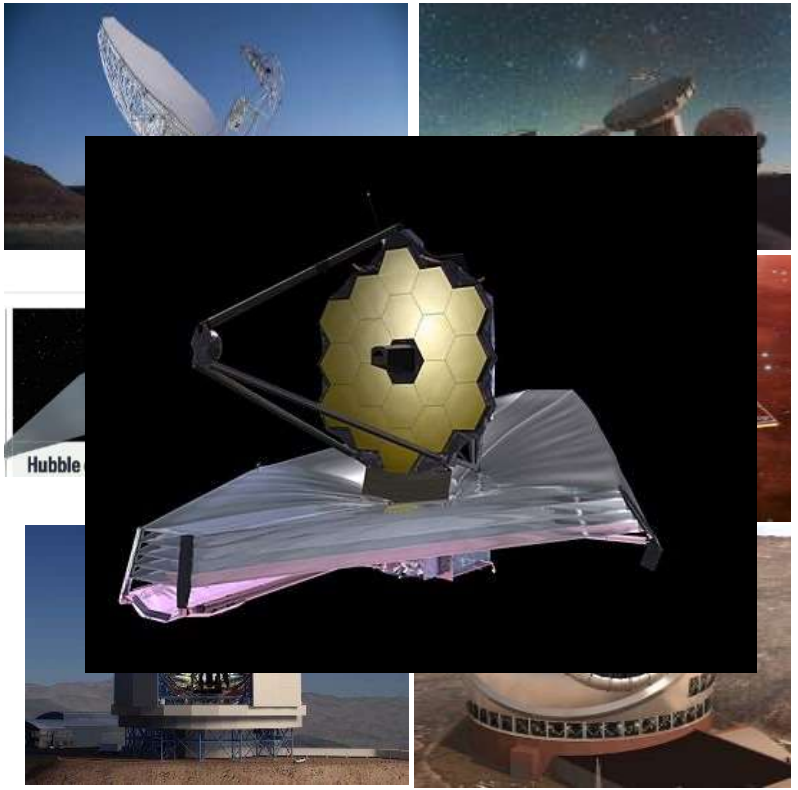


Complementary suite from cm to submm arrays for the mid-21st century

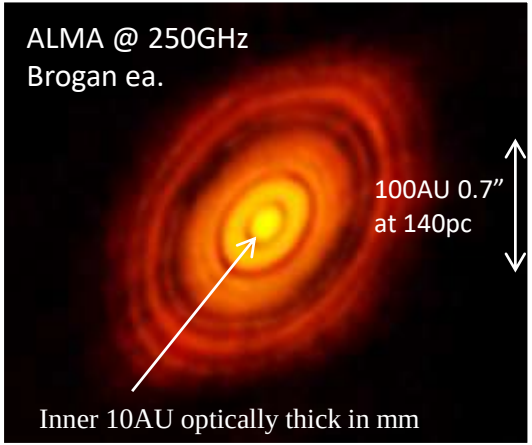
- **< 0.3cm:** ALMA 2030 superb for chemistry, dust, fine structure lines
- **0.3 to 3cm: ngVLA** ngVLA superb for terrestrial planet formation, dense gas history, baryon cycling
- **> 3cm:** SKA superb for pulsars, reionization, HI + continuum surveys

Highly Synergistic with Other Facilities on Similar Timescales

- SKA
  - 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
  - *Continuing its legacy in many areas of astrophysics*



Cradle of Life
Terrestrial-Zone Planet Formation

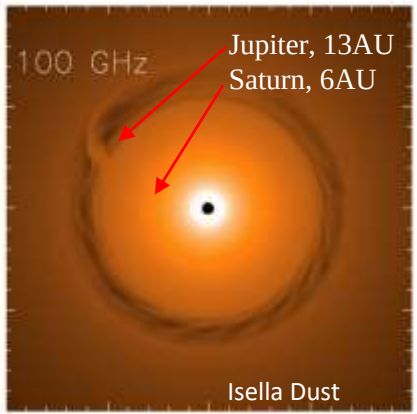


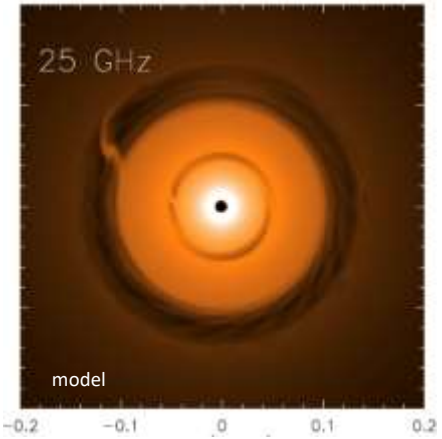
HL tau: Rosetta-stone of planet formation

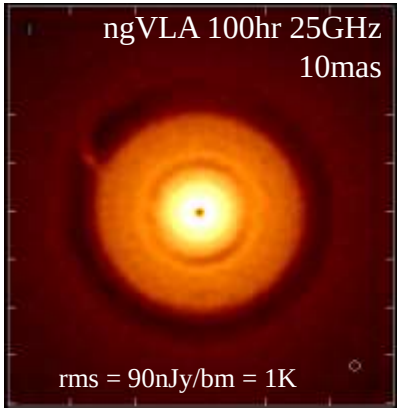
- Distance = 140pc
- 1Myr old protostar ~ 1 M_o + 0.1 M_o dusty disk
- *Inner few AU disk optically thick in mm/submm*

ngVLA requirements

- Frequency: low tau on AU-scales => 30GHz
- Resolution: 1AU at 140pc => 10mas
- Sensitivity: 1K at 10mas resolution => 10x VLA, ALMA
- *Movies of planet formation: Image gaps, accretion onto planets, and annual variations*

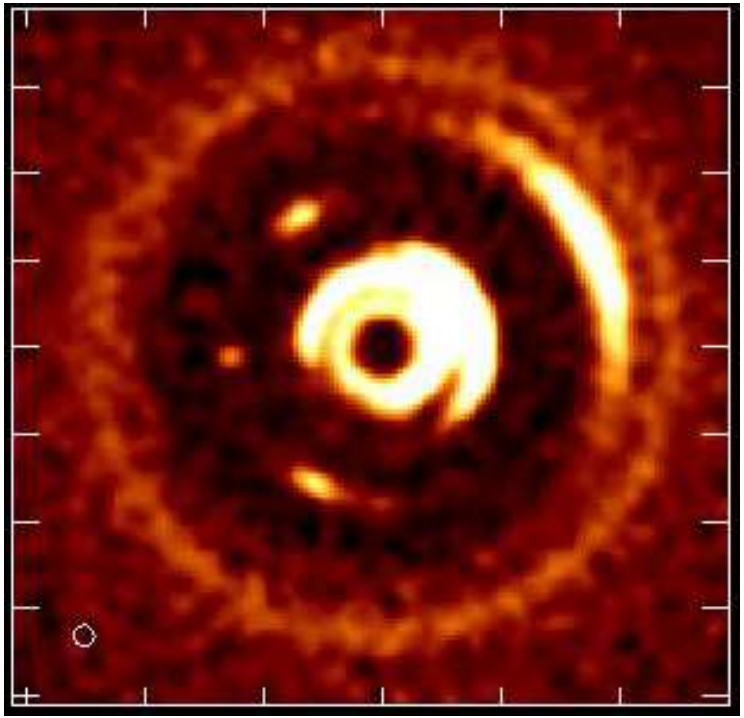






Unveiling the Formation of Solar System Analogues

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

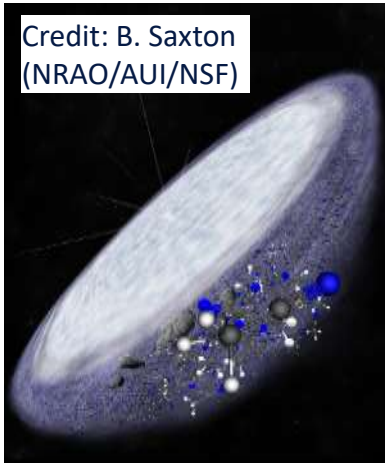


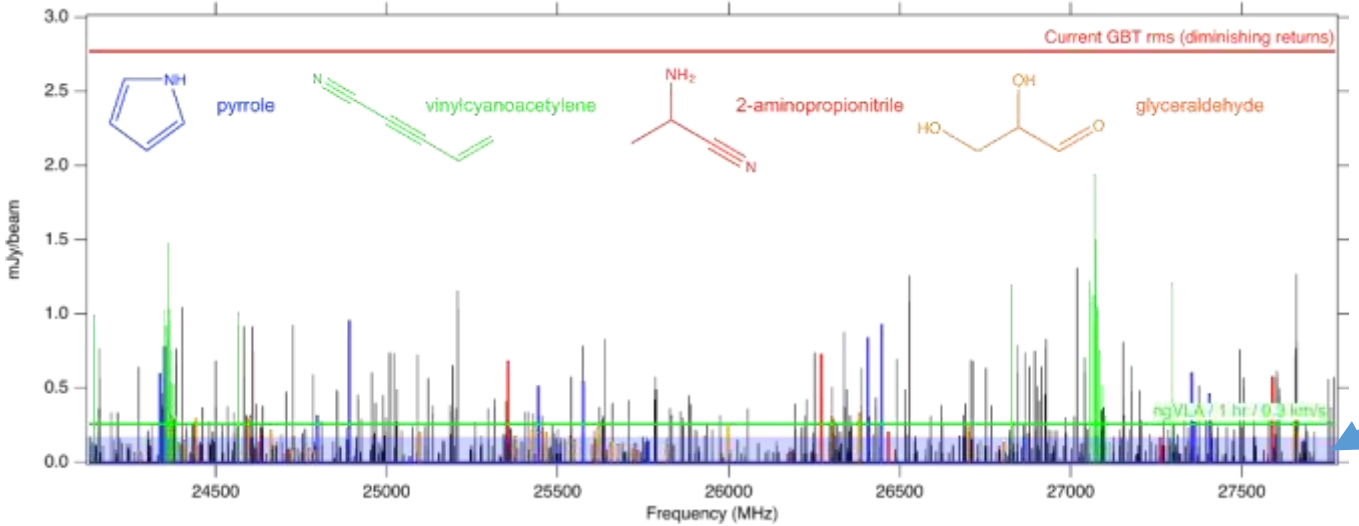
Simulated 100 GHz ngVLA observations of a newborn planetary system comprising a Jupiter analogue orbiting at 5 AU from a Solar type star.

Luca Ricci et al. (in preparation)

Tracing Chemistry from Hot Cores to Protoplanetary Disks

- Complex organic molecules are the building blocks of life
- Line blending is a killer in the submm; for cold sources, 0.3 – 1cm ideal
- ngVLA will provide access to a wealth of new molecular detections
- ngVLA will hit line confusion in ~10hr for molecular rich sources like these



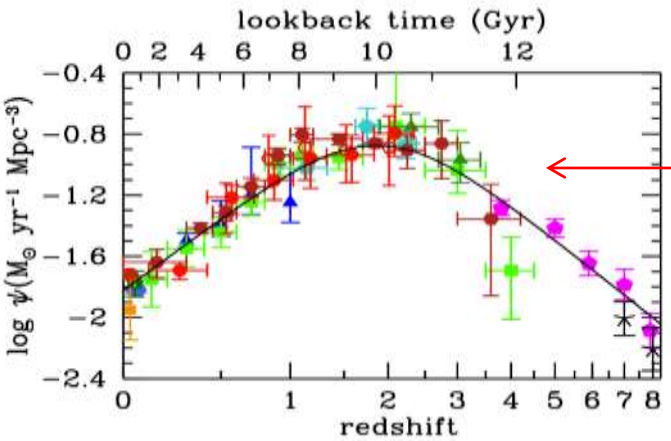


Projected Line Confusion Limit

B. McGuire

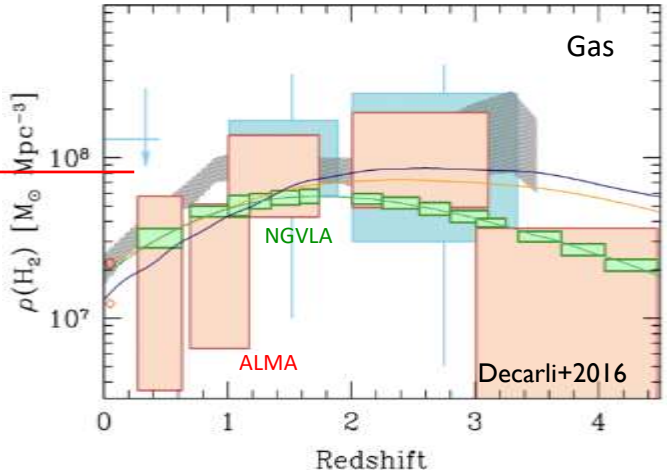
Synergy: Cosmic Cycle of Gas to Stars

'Precision Galaxy Formation'

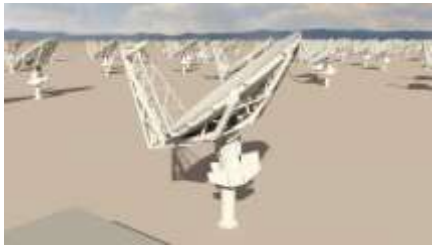


JWST/ELT: stars and star formation





ngVLA: cold gas fueling cosmic star formation

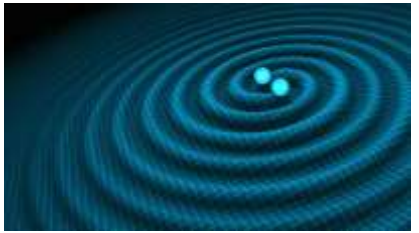




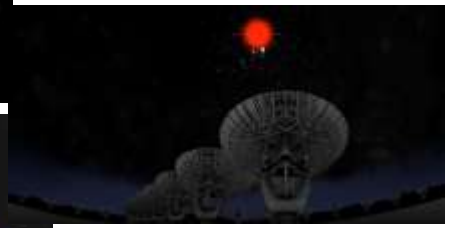
Versatility: Remarkable breadth of Science Enabled by the ngVLA

- Galactic Center pulsars: *testing GR*
- Gravitational Wave EM Follow-up
- 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_o with Mega-Masers
- µas Astrometry: ICRF, Galactic structure…
- Solar system remote sensing: passive and active radar
- Spacecraft telemetry, tracking: *movies from Mars*











Estimated Price Tag

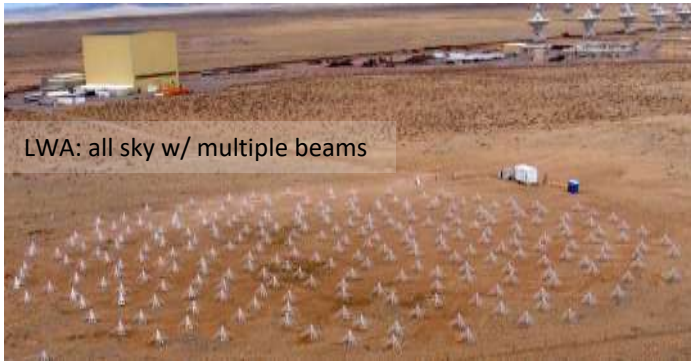
(Internal Preliminary Costing Exercise)

- Target construction baseline budget **~ (2016) $1.5B**
- Target operations budget of **< (2016) $75M** (< 3x current VLA)
  - Operations, maintenance, computing, archiving, etc.: optimize as part of design
- Partnerships
  - Possible U.S. Multiagency Interest [including VLBI option]
    - ICRF – DOD/Navy, Air Force
    - Spacecraft tracking/imaging, `burst-telemetry' (mission-critical events) – NASA, DOD
    - Space situational awareness – DOD
  - ***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:
    - REhnu Inc., Minex Engineering Corp, LaserLaB, Quantum Design

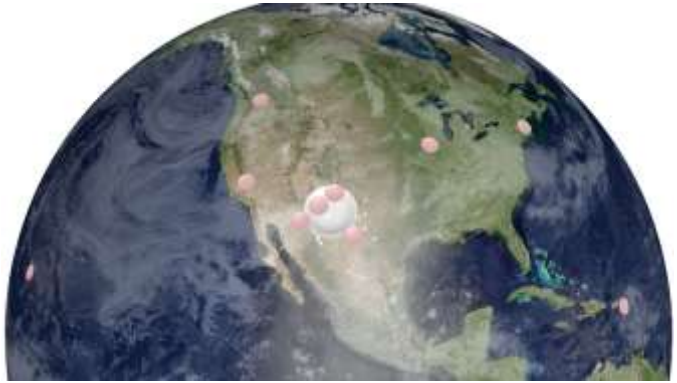


Science Options

- Commensal Low Frequency Science
  - Leverage ngVLA infrastructure (land/fiber/power) for commensal LF capabilities (ngLOBO)
  - 5 – 150 MHz: multi-beam dipole arrays alongside ngVLA long-baseline stations (e.g., LWA style).
  - 150 – 800 MHz commensal prime focus feeds on ngVLA antennas (e.g., VLITE style)



- U.S. VLBI Expansion of Capabilities
  - Replace existing VLBA antennas/infrastructure with ngVLA technology
  - Introduce new ~1000 km baseline stations to bridge gap between ngVLA & existing VLBA baselines
  - Cross correlate VLBI antennas with phased ngVLA



ngVLA Long Baselines

- Core ngVLA plans exclude baselines > 1000km
  - Excluded from budget and scope
- Long baselines kept as “Major Option”
  - Funding to be pursued independently
- Timescale
  - Lag core ngVLA by approx. 5 years
  - Reference concept complete in time for detailed core ngVLA configuration design (2020?)
  - Deployment on heels of core ngVLA, during period 2030-2040



Long Baseline Options



- ngVLA integrated into a continental scale array: eVLBI, phasing of core…
- Replace existing VLBA antennas/infrastructure with ngVLA technology
- Operation: HSA/GMVA (‘campaign-mode’), or dedicated array
- Design and implementation depend on primary science drivers: astrometry vs. imaging vs. time domain…

Scope of Long-Baseline Option

- Very much TBD; *to be based on:*
  - Community input -- LBO (Walter Brisken) & ngVLA SAC + VLBI Community
  - Amount & source of funding – identifying other government agencies
  - Timescale of funding & development
- Some plausible constraints
  - ~20% of core ngVLA cost
  - 10-20% of core ngVLA collecting area
    - Perhaps 8 stations of 3 antennas?
    - ngVLA core to provide “short” (50-500 km) spacings
  - Use ngVLA antenna designs
  - Electronic transfer of data; full ngVLA bandwidth
  - Unmanned sites, periodically visited

Potential Performance

- Back of the envelope estimates from Walter Brisken:

- Sensitivity: 2x VLBA + ngVLA Core & 16 GHz of BW (dual pol.)
  - ~1 μJy/beam at 2 mas resolution in 1 hour at 30 GHz; Tb ~1,500K
  - ~4 μJy/beam at 0.7 mas resolution in 1 hour at 100 GHz; Tb ~6,000K

- Relative astrometry, in 3 hour observation, repeatable to:
  - 2μas at 10 GHz for compact sources > 4 mJy
  - 1μas at 30 GHz for compact sources > 2 mJy

- Absolute astrometry, 10 minutes over 24 hour observation, accurate to:
  - 100μas at 10 GHz for compact sources > 1 mJy
  - 50μas at 30 GHz for compact sources > 0.5 mJy

Exciting new possibilities

- Improvements in fundamental VLBI measurements across the board
  - Sub 1% H_0 measurement through megamasers
  - Factor of 10 improvement (to 3×10^{-5}) in GR γ parameter from light bending
  - Routine distance measurements across the Milky Way
- Many new possibilities
  - Image surfaces of 10s to 100s of stars
    - Strong synergy with optical interferometry
  - Deep (100 nJy) wide (2') surveys at mas resolution
  - Direct distances to and kinematics of globular clusters
  - Determine Virgo cluster proper motions



Unknowns

Could Benefit from Community Input

- Maximum baseline length
  - Restrict to continent, or extend to islands?
  - Improved North-South baseline length over VLBA?
- Calibration model
  - Antenna clusters may play large role
- Correlate all baselines?
  - Or phase clusters & core?
  - Separate correlator for long baselines?
- Full-field and/or multi-phase center correlator capability?
- Option for conventional VLBI via data recorders?
- Does VLBA get wholly replaced?
  - Or does it get retrofitted with ngVLA electronics & high-speed fiber optics?



Astrophysical Frontiers in the Next Decade:

Planets, Galaxies, Black Holes, & the Transient Universe

Workshop Boulder, CO USA June 26-29, 2018

Pre-Registration open: http://go.nrao.edu/ngVLA1

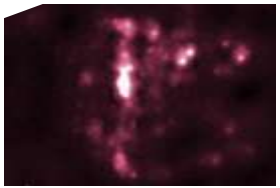
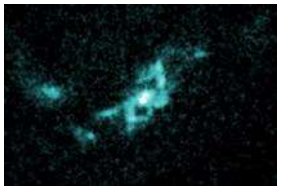
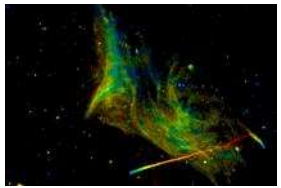
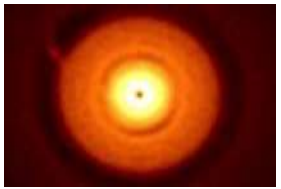
Very Important Announcement Regarding ngVLA Future Planning the Week of Sept. 17

New research facilities and the scientific vision outlined by New Worlds, New Horizons have m
the exploration of vast new discovery space, and astrophysics has seen extraordinary
past decade, opening new frontiers across many fields. Sponsored by the Nat omy
Observatory, this conference will bring together a substantial cro astronomical
community to discuss how to effectively address the highest pri questions of our time.
Plenary sessions will feature invited speakers, and thre or contributed presentations
will address (1) Exoplanet and Protoplanetary D laxy Evolution Mechanisms, and (3)
Black Holes & Transient Phenomena F anvas recent observational and theoretical
progress, address key unanswer notivate future research directions in the context of
next-generation facilitie he electromagnetic spectrum, including a Next Generation
Very Large Arr ptic Survey Telescope, 30m-class optical-infrared telescopes, the
Advanc eter Gravitational-Wave Observatory, and the Square Kilometre Array.

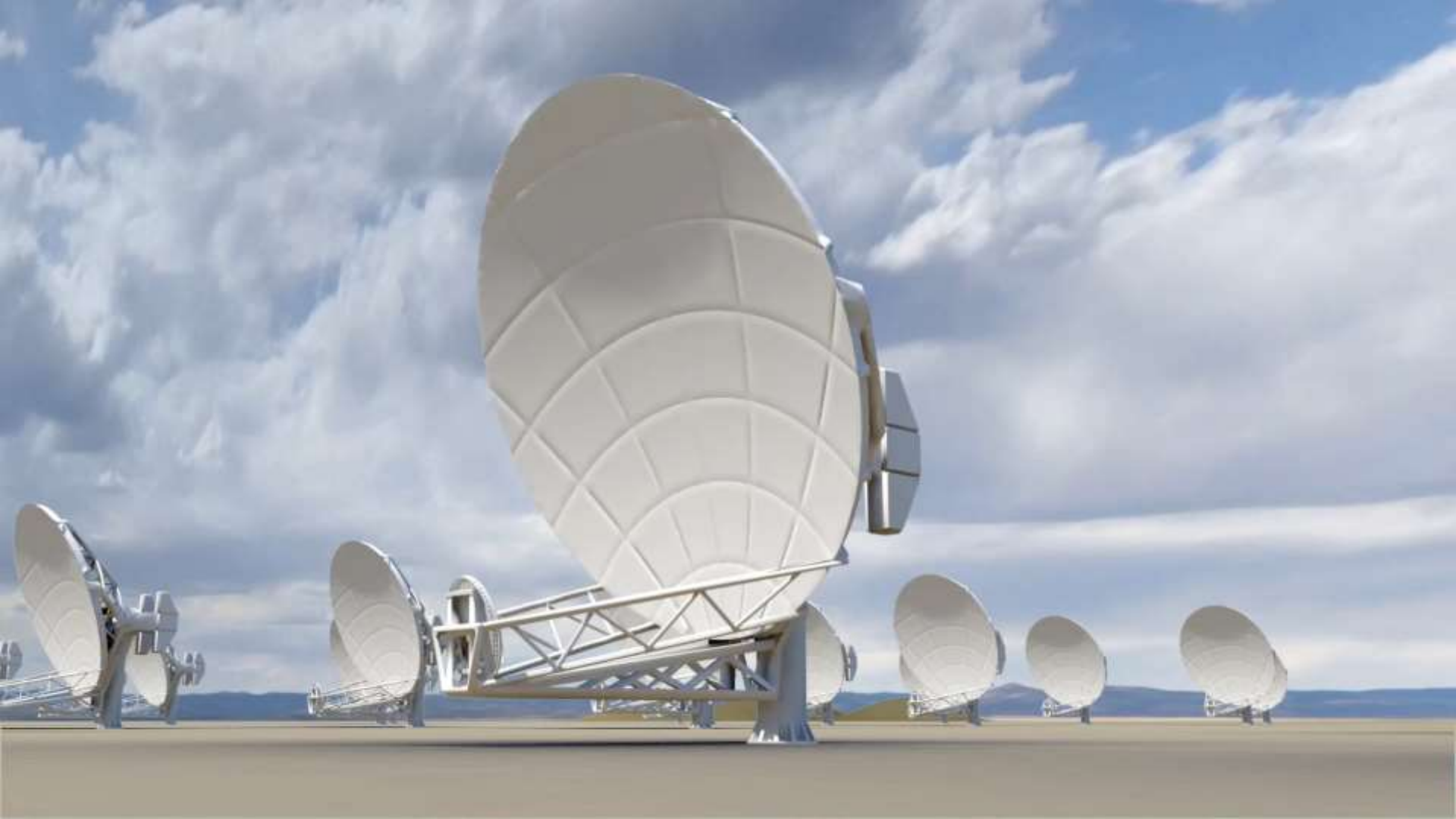
SOC co-Chairs

Brenda Matthews (NRC – Cradle of Life)
Caitlin Casey (UT – Galaxy Evolution)
Laura Chomiuk (MSU – BHs and Transients)

ngVLA
The Next Generation Very Large Array







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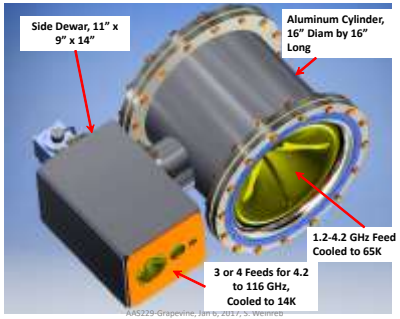
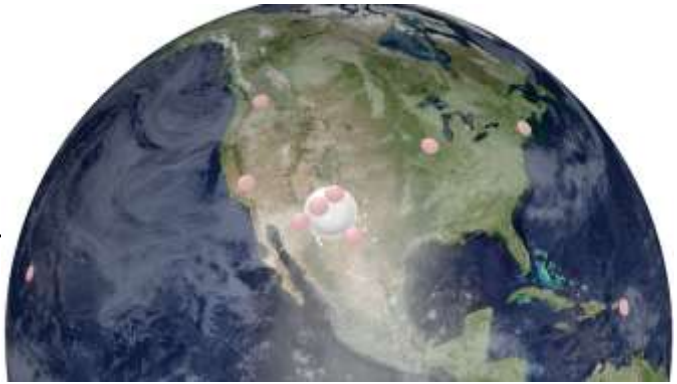
The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Key Open Questions

- Phase calibration
  - Paired antennas, dedicated reference array, water vapor radiomet calibration
- Short Spacings
  - *Is 30 – 40m minimum spacing good enough?*
    - *Require a large single dish w/ FPA (e.g., 45m x 20 beams)*
    - *Short-spacing array of small dishes (e.g., <~6m x 16)?*
- Single dewar receiver configuration?
- Array configuration
  - Surface brightness sensitivity: % in core, intermediate, lor
  - VLBI option
  - Low Frequency (<1 GHz) options

4-band/1-Dewar Concept





The Road to Astro 2020

Goal: NRAO CoDR-level 'proposal' to 2020 Decade Survey

Compelling science program & defensibly costed design of all major elements

