NATIONAL RADIO ASTRONOMY OBSERVATORY

Next-generation VLA

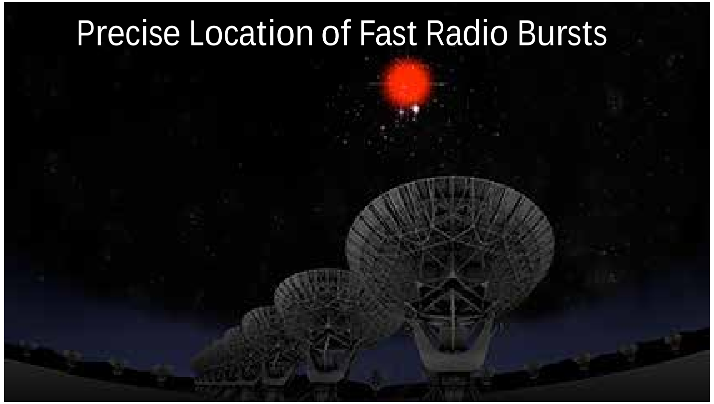
Tony Beasley, NRAO

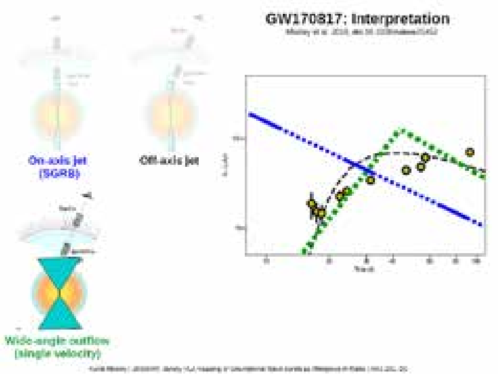
Next Generation Very Large Array

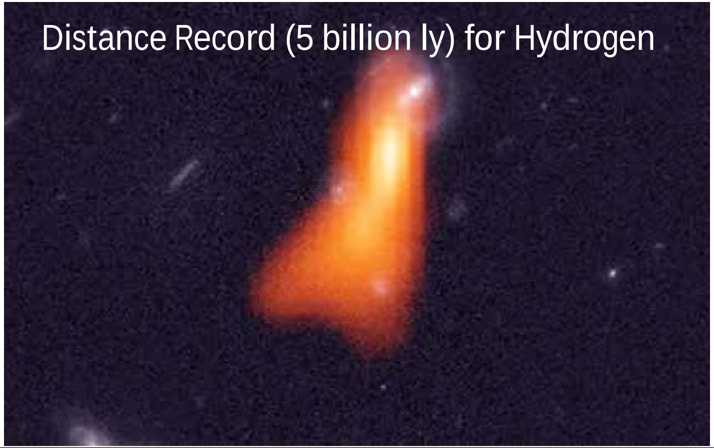
The Jansky Very Large Array

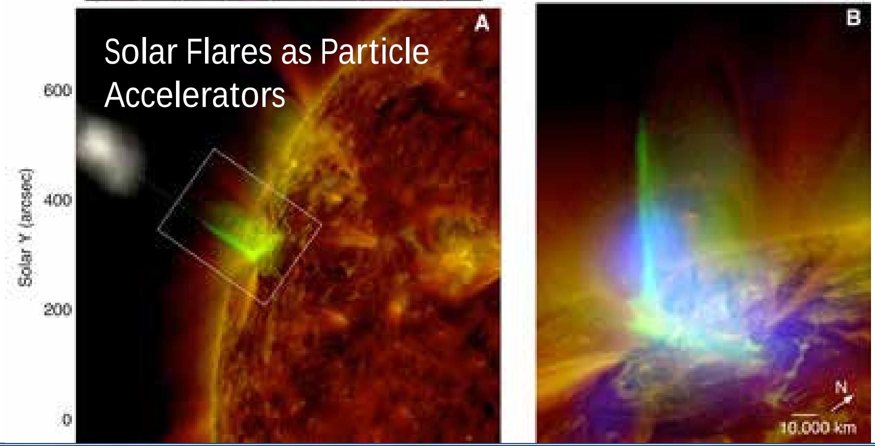
- 1972 – Approved by Congress
- 1975 – First Antenna in place
- 1980 – Full science operations
- 2001 – Upgrade approved by NSF
- 2011 – Jansky VLA full science ops

Still a Radio Astronomy Powerhouse: VLA Recent Discoveries









A next generation VLA

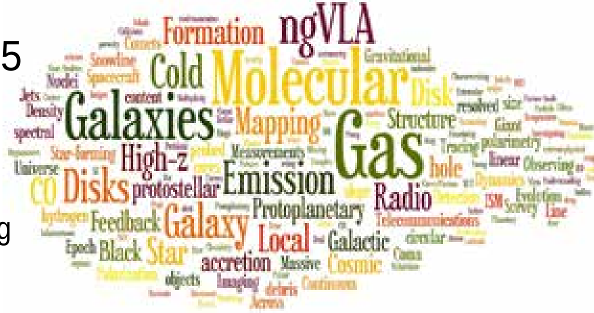
- Scientific Frontier: **Thermal imaging at milli-arcsecond scale resolution**
- Core Design Requirements
  - *10x sensitivity of JVLA and ALMA*
  - *10x resolution of JVLA and ALMA*
  - *Frequency range: 1.2 –116 GHz*
- Located in Southwest U.S. (NM+TX) & Mexico, building on JVLA site
- Baseline design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

https://ngvla.nrao.edu

Developing the ngVLA Science Case

EVLA Phase 2 (2000) ® NMA ® NAA (2010) ® ngVLA (2018)

- 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



- **Community Studies Program**: 38 studies approved over 2 Rounds, *financially supported by NRAO (https://science.nrao.edu/futures/ngvla/ngvla-community-studies)*
- **International Workshop in Socorro: June 2017.**
- **Community-Led Science Use Case**s: 80 submitted for ‘Reqs to Specs’ process (ngVLA memo # 18)
- **ngVLA Science book in preparation** (ready late 2018)

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**)

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**)

Japanese Participation in both SAC/TAC…

Community Participation

Jet Propulsion Laboratory
Johns Hopkins University
University of Virginia
Ohio State
The University of New Mexico
California State University Northridge
ASIAA
Cornell University
NOAO
The George Washington University, Washington, DC
BYU Brigham Young University
Michigan State
University of Maryland
University of Wyoming
LSST Large Synoptic Survey Telescope
Rice
Green Bank Observatory
Texas Tech University
Harvard-Smithsonian Center for Astrophysics
Berkeley University of California
Texas The University of Texas at Austin
The University of Arizona
The University of Iowa
UC San Diego
West Virginia University
STScI Space Telescope Science Institute
Caltech

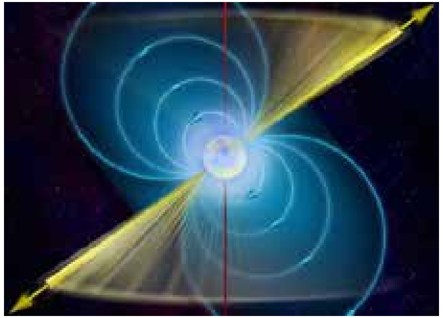
General Dynamics Mission Systems
Quantum Design
REhnu Next Generation Solar
LaserLaB Amsterdam
VU
MINEX Engineering Corp.

NRC-CNRC Canada
The University of Western Australia
University of Sussex
国立天文台 NAOJ National Astronomical Observatory of Japan
Universidad Nacional Autónoma de México
東京大学 The University of Tokyo
ICRAR International Centre for Radio Astronomy Research
RIKEN

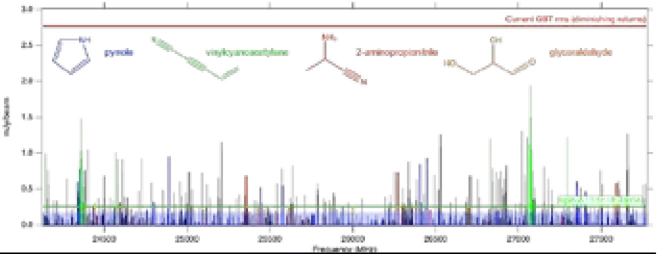
ngvla
NRAO
NSF
AUI

ngVLA Key Science Missions

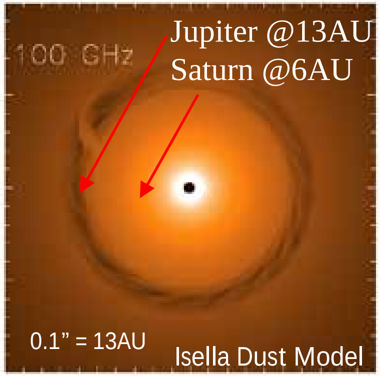
(ngVLA memo #19)

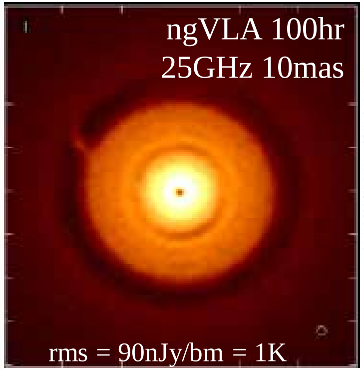


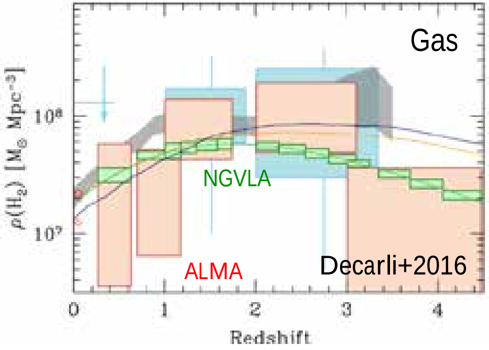
- *Unveiling the Formation of Solar System Analogues*
- *Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry*
- *Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time*
- *Using Pulsars in the Galactic Center as Fundamental Tests of Gravity*
- *Understanding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

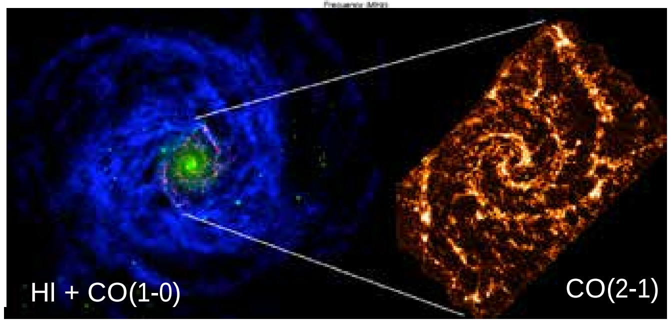


Highly synergistic with next-generation ground-based OIR and NASA missions.



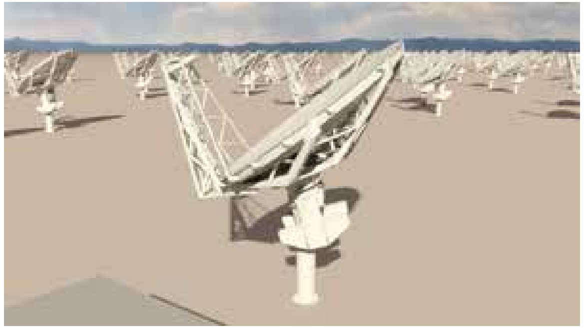






Current Reference Design Specifications

(ngVLA Memo #17)



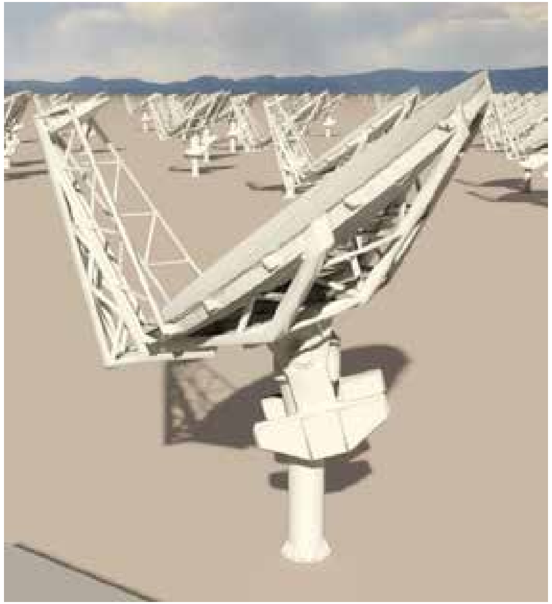
- 214 18m offset Gregorian (feed-low) Antennas
  - Supported by internal cost-performance analysis
- Fixed antenna locations across NM, TX, AZ, MX
  - ~1000 km baselines
- 1.2 – 50.5 GHz; 70 – 116 GHz
  - Single-pixel feeds
  - 6 feeds / 2 dewar package
- 19x 6m short spacing array + 4x 18m in TP mode to fill in (*u, v*) hole.

- Continuum Sensitivity: ~0.1uJy/bm @ 1cm, 10mas, 10hr => T_B ~ 1.75K
- Line sensitivity: ~21.5uJy/bm @ 1cm, 10 km/s, 1”, 10hr => T_B ~ 35mK

Receiver Configuration

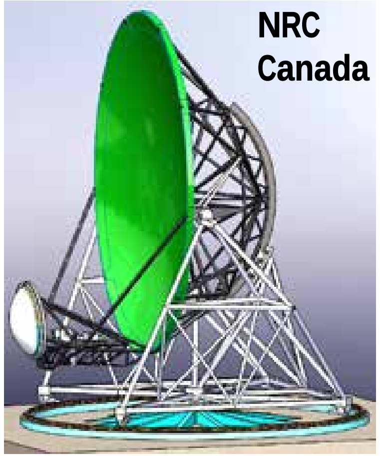
Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.35	3.5	2.91	2.3
2	B	3.5	7.90	12.3	3.51	8.8
3	B	12.3	16.4	20.5	1.67	8.2
4	B	20.5	27.3	34.0	1.66	13.5
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0

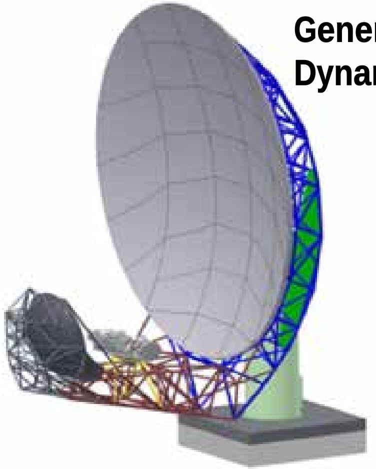
Antenna Concept



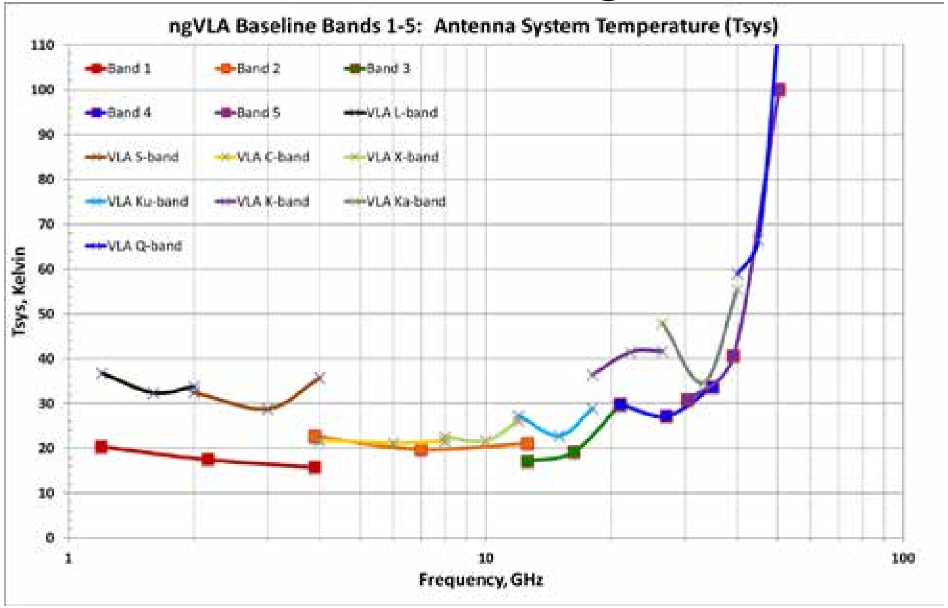
- **18m Aperture**: Based on cost and performance modeling.
- **Offset Gregorian**: Off-axis geometry minimizes scattering, spillover, and sidelobe pickup
- **Feed Low**: Performance and maintenance requirements favor a receiver feed arm on the low side of the reflector
- **Mount concept**: TBD.
  - Evaluating pedestal mount vs wheel and track.
  - Pointing specification is a design driver.

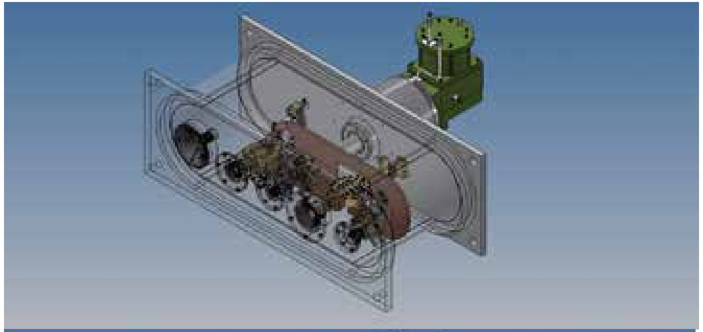
- ***Multiple Design Studies in Progress***





Receiver/Feed Configuration Concept

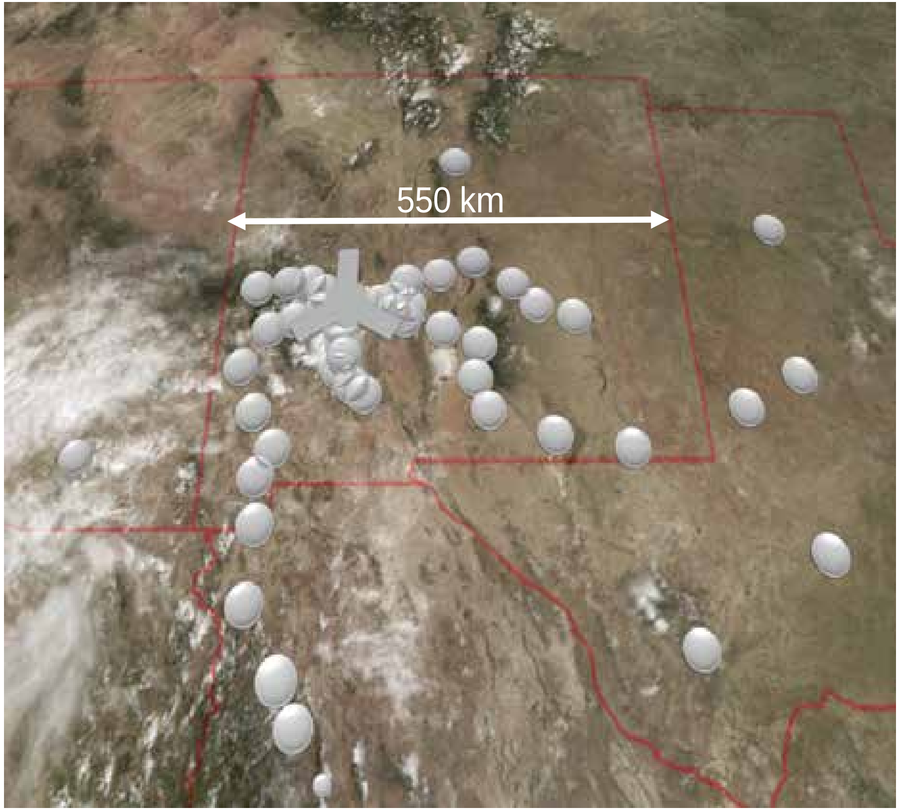




- 6 Bands in 2 Cryogenic Dewars
- 1.2-3.5 GHz and 3.5-12.3 GHz Quad-Ridge Horns, 3.25:1 bandwidth, coaxial LNAs.
- 12.3-50.5 GHz using three 1.67:1 BW corrugated horns and waveguide LNAs.
- 70-116 GHz 1.67:1 BW corrugated horn and waveguide LNAs with block down conversion.
- Single stage down-conversion to baseband for 5 bands. Direct SSB or IQ sampling using modular devices @ FE.

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”

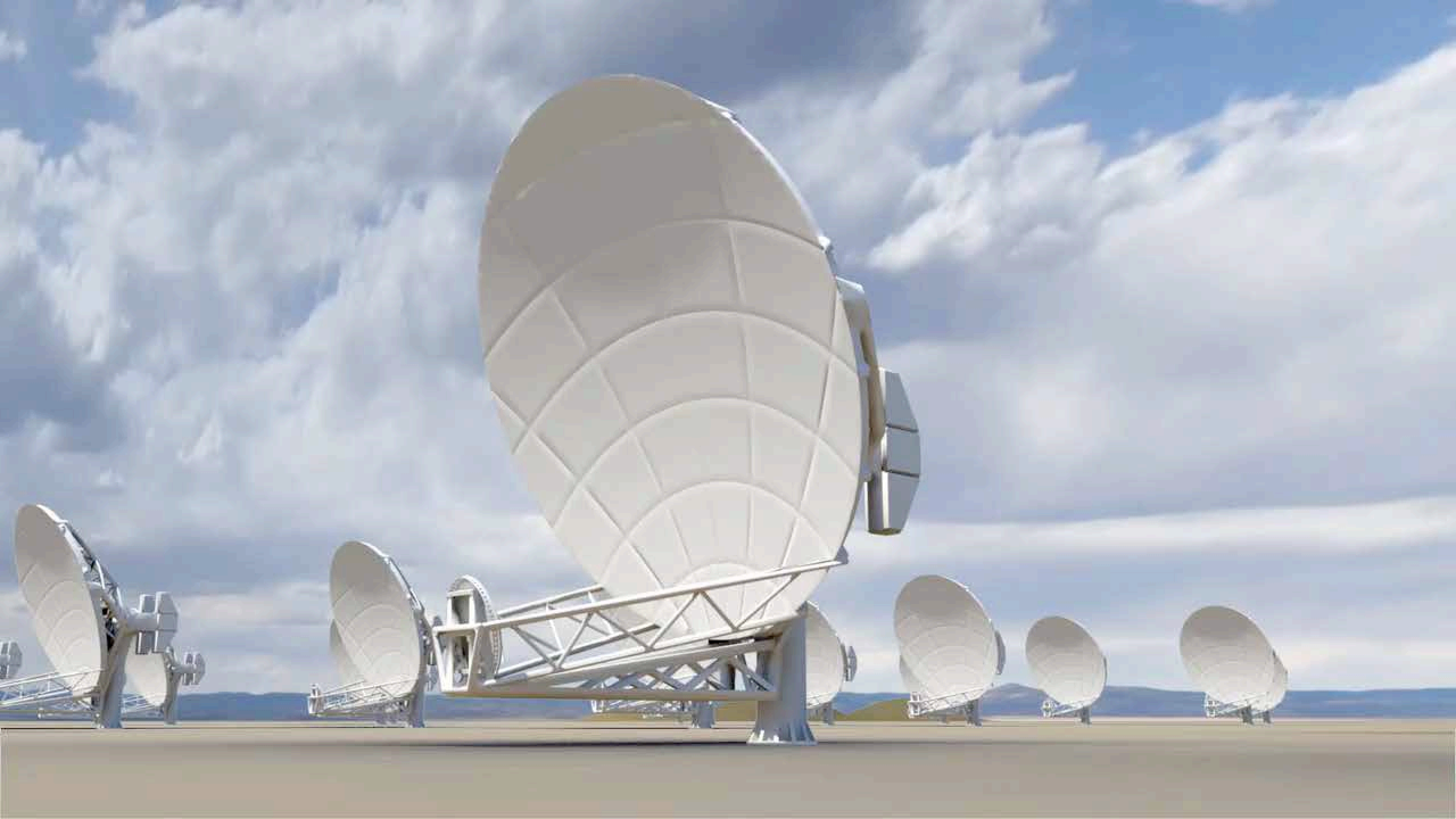


Nominal 18m homogeneous array

- Consensus design
- Challenge of tri-scale-array: Sensitivity vs. resolution
- **Short Baseline Array**: 19 x ~6m array + 4 x 18m total power

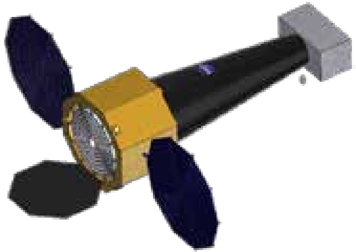
Options

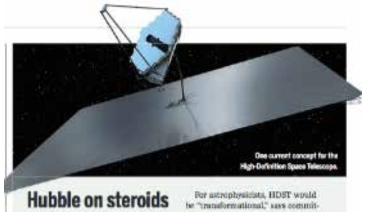
- 5 antenna cluster in Green Bank
- Long baselines: continental VLBI

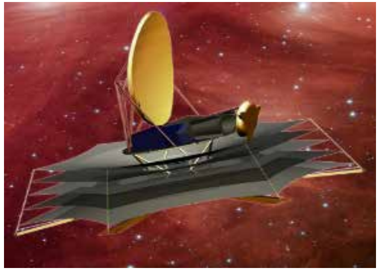


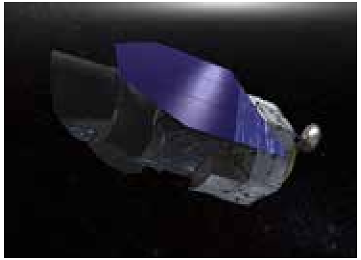
Highly Synergistic with Other Facilities on Similar Timescales

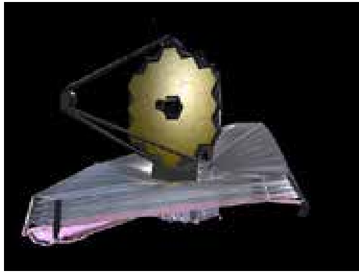
- SKA/Lynx
    - Atomic/non-thermal
    - *Molecular/thermal*
- ALMA
    - Warm/star-forming
    - *Cold/dense fuel for SF*
- LUVOIR/HabEx
    - Image earth-like planets
    - *Image terrestrial-zone planets forming*
- OST (FIR surveyor)
    - C/WNM & WIM
    - *Cold Molecular Medium*
- TMT/GMT
    -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



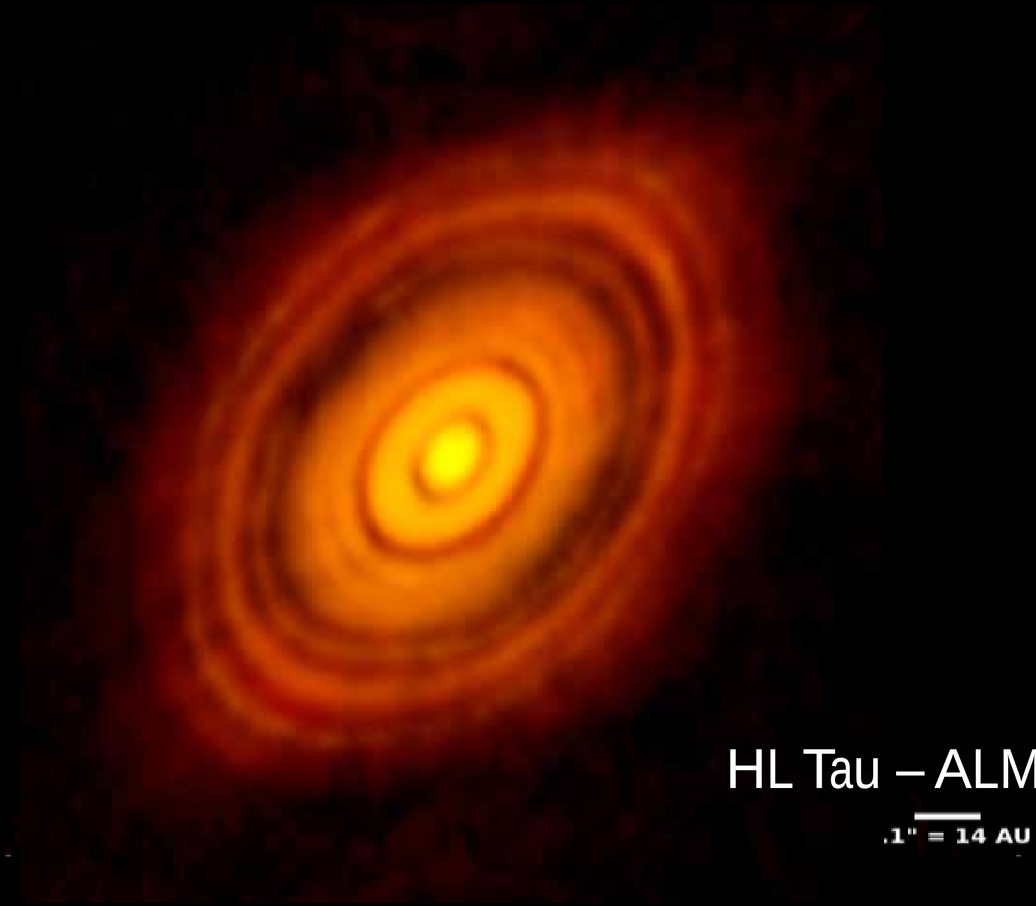








Thermal Imaging on Milliarcsecond Scales

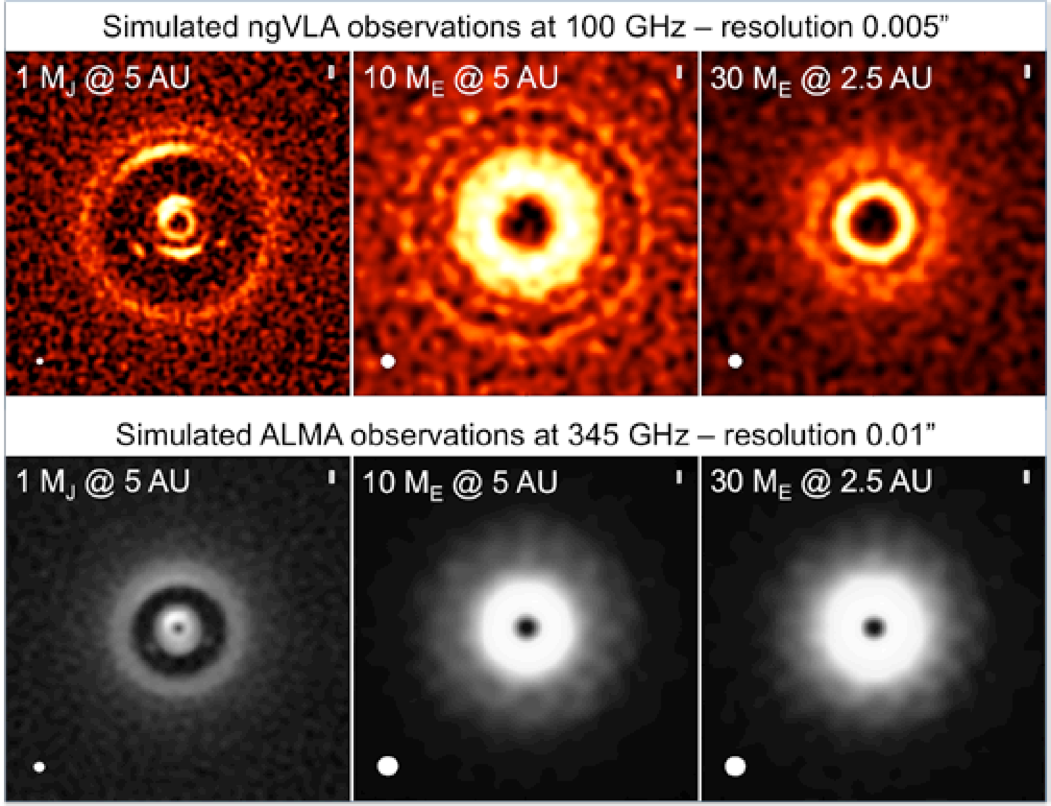


HL Tau – ALMA B6

Unveiling the Formation of Solar System Analogues

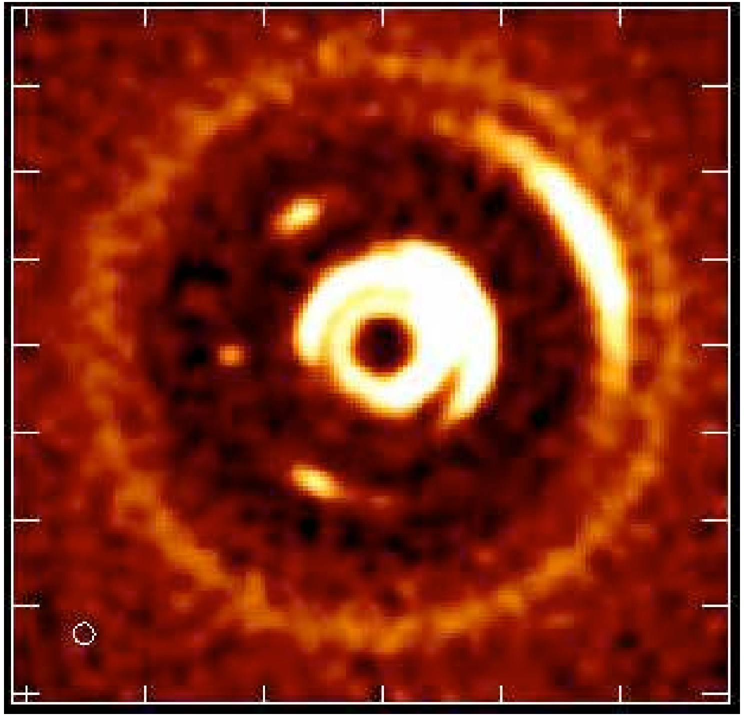
- The ngVLA will measure the planet initial mass function down to a mass of 5-10 Earth masses and unveil the formation of planetary systems similar to our own Solar System.
- The ngVLA will reveal circumplanetary disks and sub-structures in the distribution of mm-size particles created by close-in planets. and will measure the orbital motion of these features on monthly timescales.

Luca Ricci et al. (in preparation)



Unveiling the Formation of Solar System Analogues

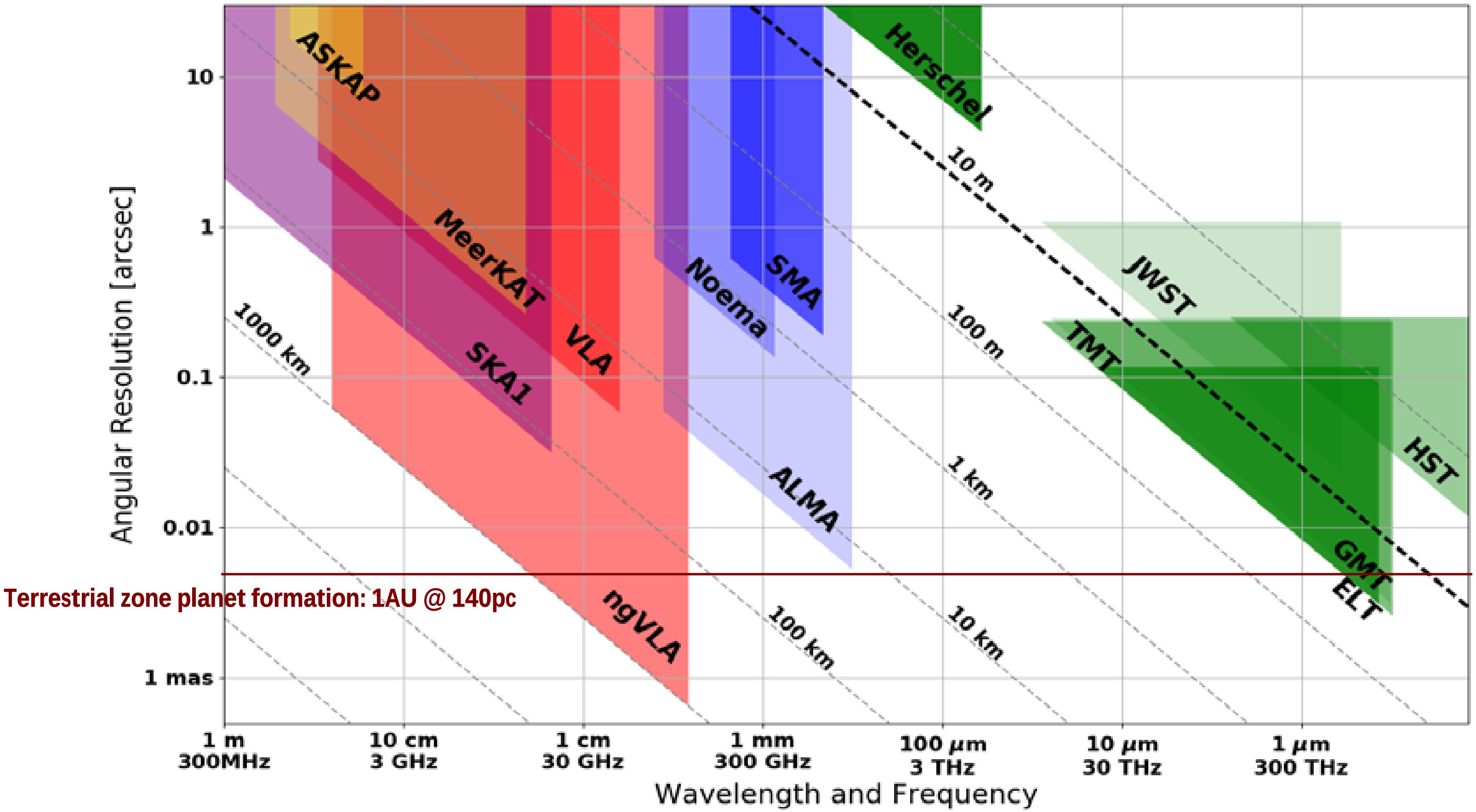
The ngVLA will measure the orbital motion of planets and related features on monthly timescales.



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.

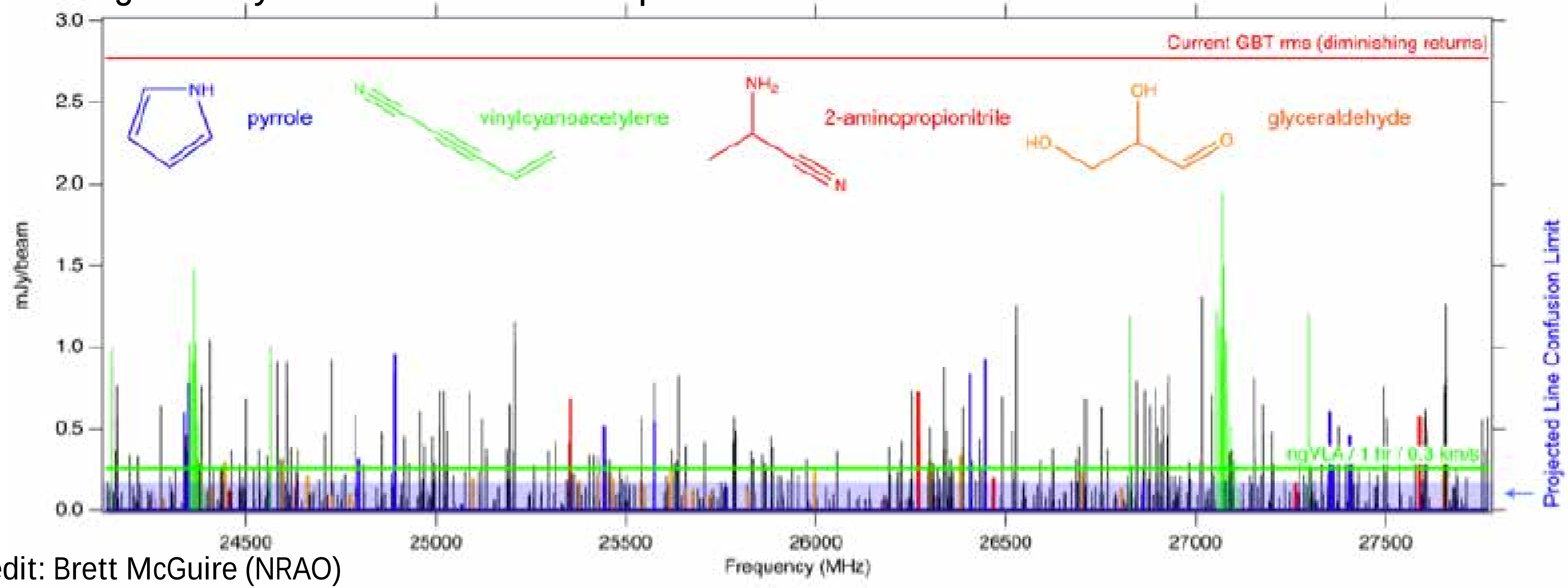
Simulated 100 GHz ngVLA observations of a newborn planetary system comprising a Jupiter analogue orbiting at 5 AU from a Solar type star.

Ricci et al. (2018)


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

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

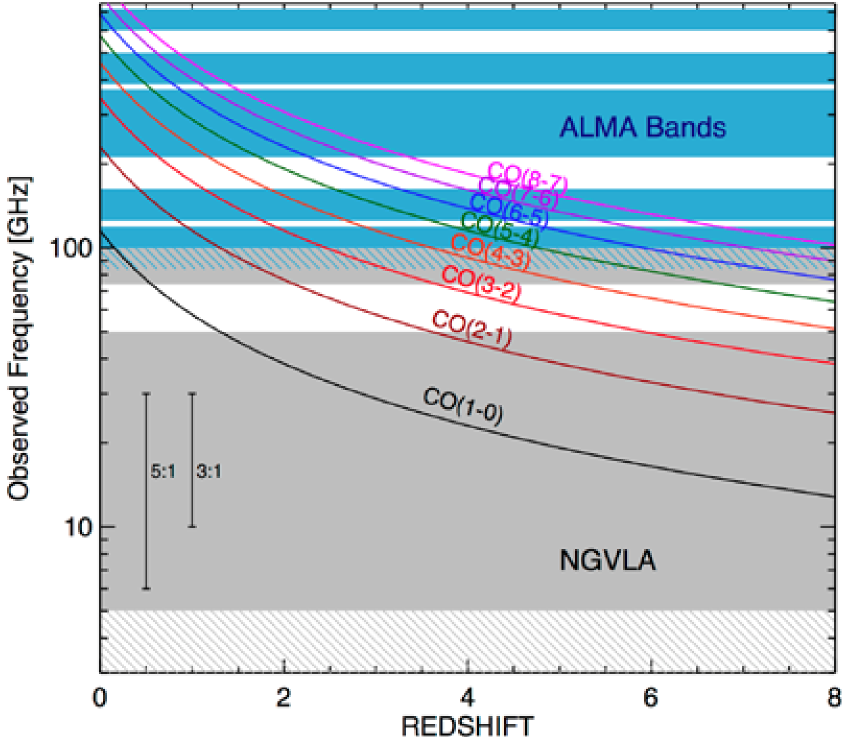


Credit: Brett McGuire (NRAO)

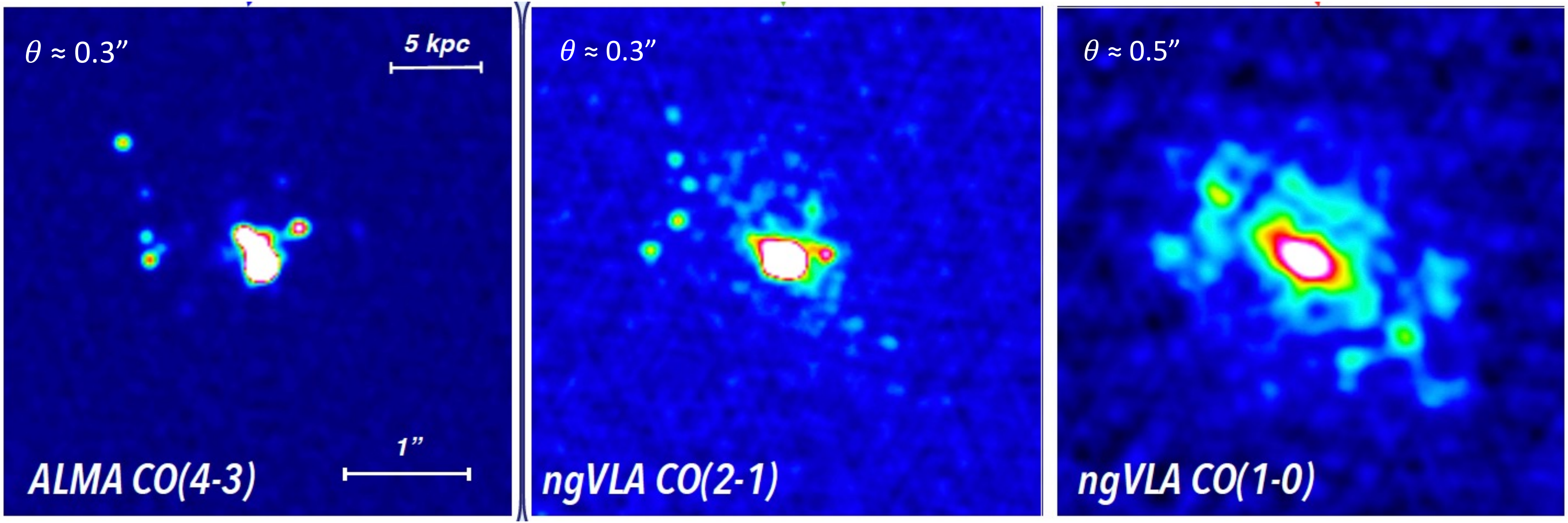
Charting the Assembly, Structure, and Evolution of Galaxies from the First Billions Years to the Present

- Order-of-magnitude improvement in depth and area for surveys of cold gas in high-z galaxies

- Routine sub-kpc imaging of the structure of protogalactic disks at any redshift where CO exists



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

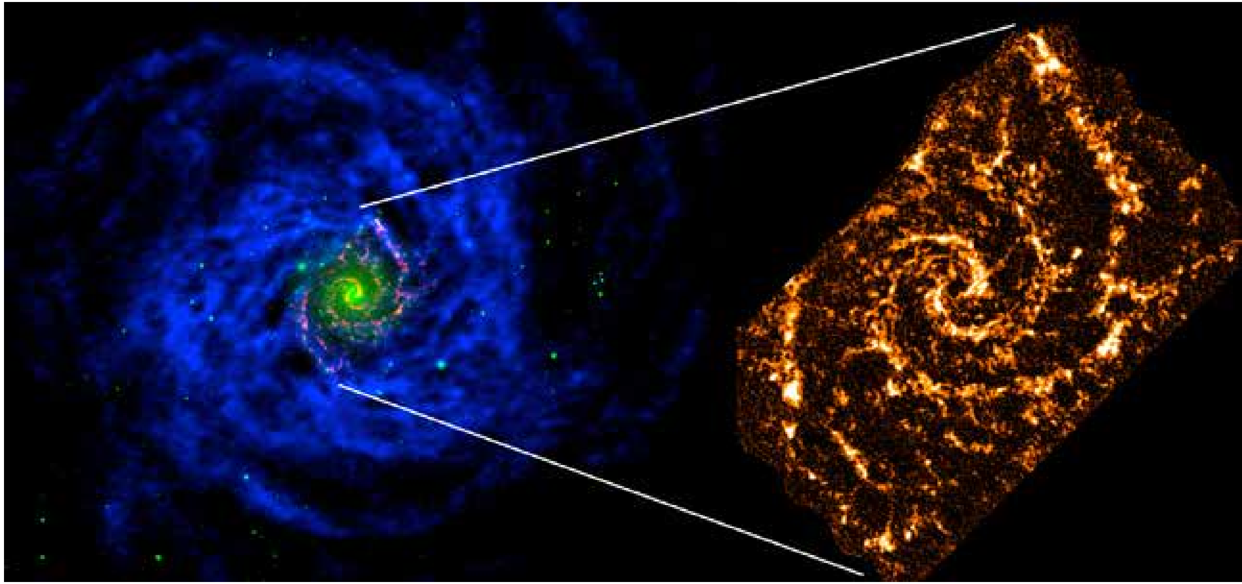


SMG at z = 4.4; SFR ≈ 400 $M_{\odot}$ /yr
Total molecular gas content largely missed by high-J lines

Credit: Caitlin Casey (UT Austin)

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

- Understanding How Galaxies Produce New Generations of Stars
  - The ngVLA can study extended atomic reservoirs and large samples of GMC populations
  - Unique windows into the physical and chemical properties of accretion, transport, phase change, and expulsion processes

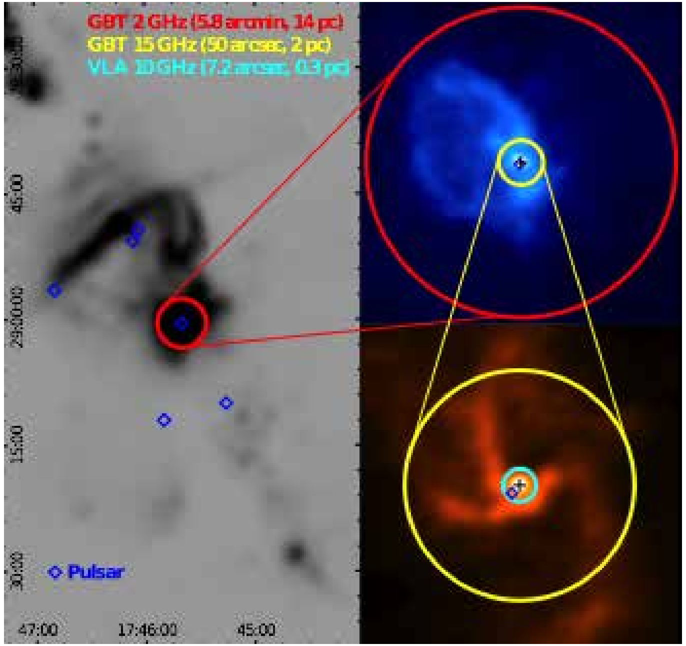


NGC 628: THINGS HI (12”, blue), PHANGS ALMA CO (1”, red), IRAC 4.5 um (green)

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*

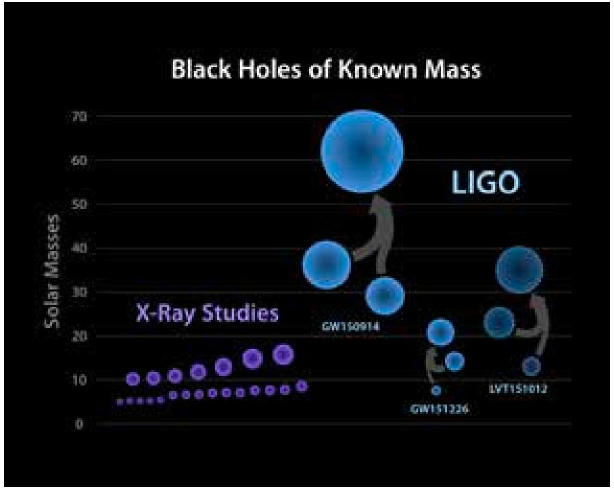
- Estimates are as high as 1,000 PSRs. Only known example is PSR J1745-2900 magnetar, which are extremely rare (<1%)



Credit: R.Wharton

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.

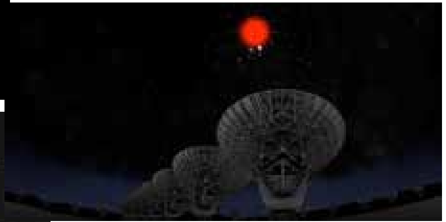
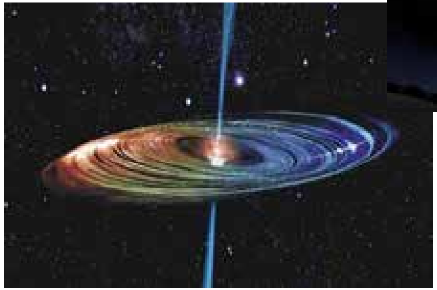


- Key to understanding GW discoveries

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*

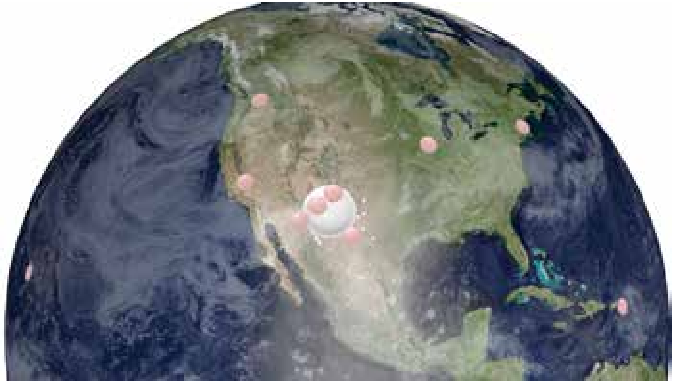


Science Options

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

- **U.S. VLBI Expansion of Capabilities ® NHA?**
  - 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 core



+ GBO Subarray 5-antenna cluster in GB

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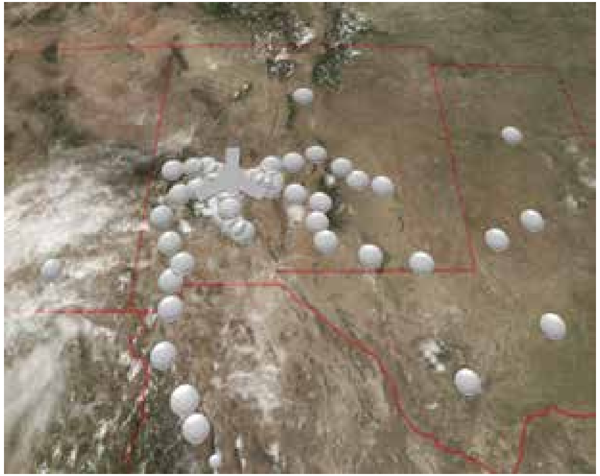
Open Technical Questions

- **Phase calibration**
  - Paired antennas, dedicated reference array, water vapor radiometers, fast switching, self-calibration

- **Array configuration**
  - Surface brightness sensitivity: % in core, intermediate, long
  - VLBI option (Northern Hemisphere)
  - Low Frequency (<1 GHz) options
  - Green Bank cluster

- **Short Spacings**
  - Small Baseline Array – 19 x ~6m + 4 x 18m Total Power Mode antennas – critical for LSB CO science cases



Project Office

- Lean and Mean:
  - **Mark McKinnon** (Project Director)
  - **Eric Murphy** (Project Scientist)
  - **Mike Shannon** (Interim Project Manager)
  - **Bob Treacy** (Interim Systems Engineer)
  - **Rob Selina** (Project Engineer)
  - Ad hoc support from entire NRAO

- $11M in Development Funding for 2 yrs to take us to DS2020
  - Contracted Antenna Trade Study
  - Level 0 Science Requirements Drafted
  - Level 1 System Requirements Drafted
  - Level 2 Antenna Specifications Drafted

Estimated Price Tag

(Internal Preliminary Costing Exercise)

- Target construction baseline budget **~ (2016) $X.Y B**
- Target operations budget of **< (2016) $XY M** (< 3x current VLA)
  - Operations, maintenance, computing, archiving, etc.: optimize as part of design
- Science Partnerships: Current International Involvement in SAC/TAC/Community Studies:
  - Canada, Mexico ® Japan, Germany, Netherlands, Taiwan
- Technical Partnerships:
  - General Dynamics (antennas), NRC (Canada), JPL.

US Open skies – global science…

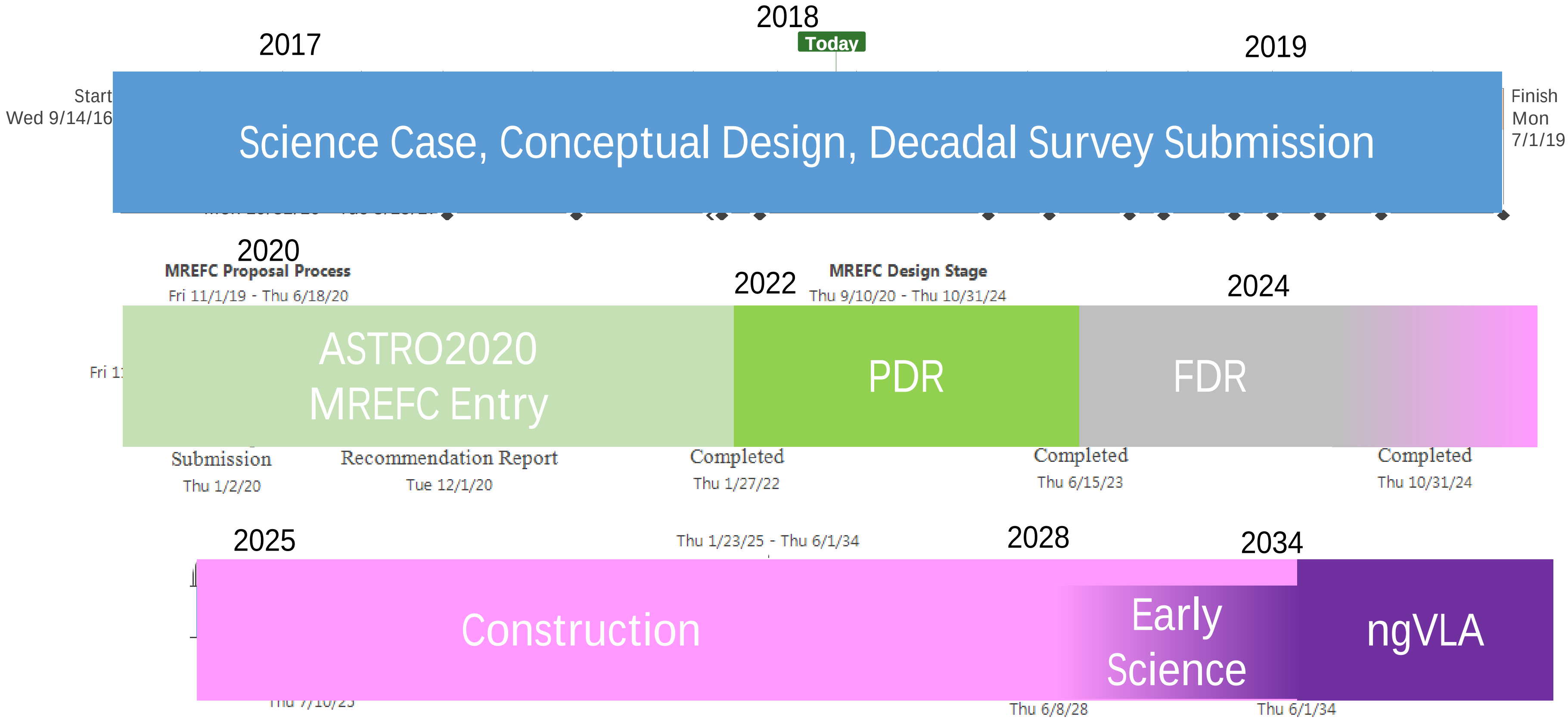
ngVLA Design Development - Underway

- NSF provided $11M for the start of ngVLA design & development, beginning Oct 2017.
- This funding supporting a full-strength Project Office, pursuing concept development and risk reduction activities, for two years.
- In two years time – more funding (& partners) will be required.
- This development funding is the first step on path to reality for ngVLA.

The Road to Astro 2020

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

Compelling science program & defensibly costed design of all major elements

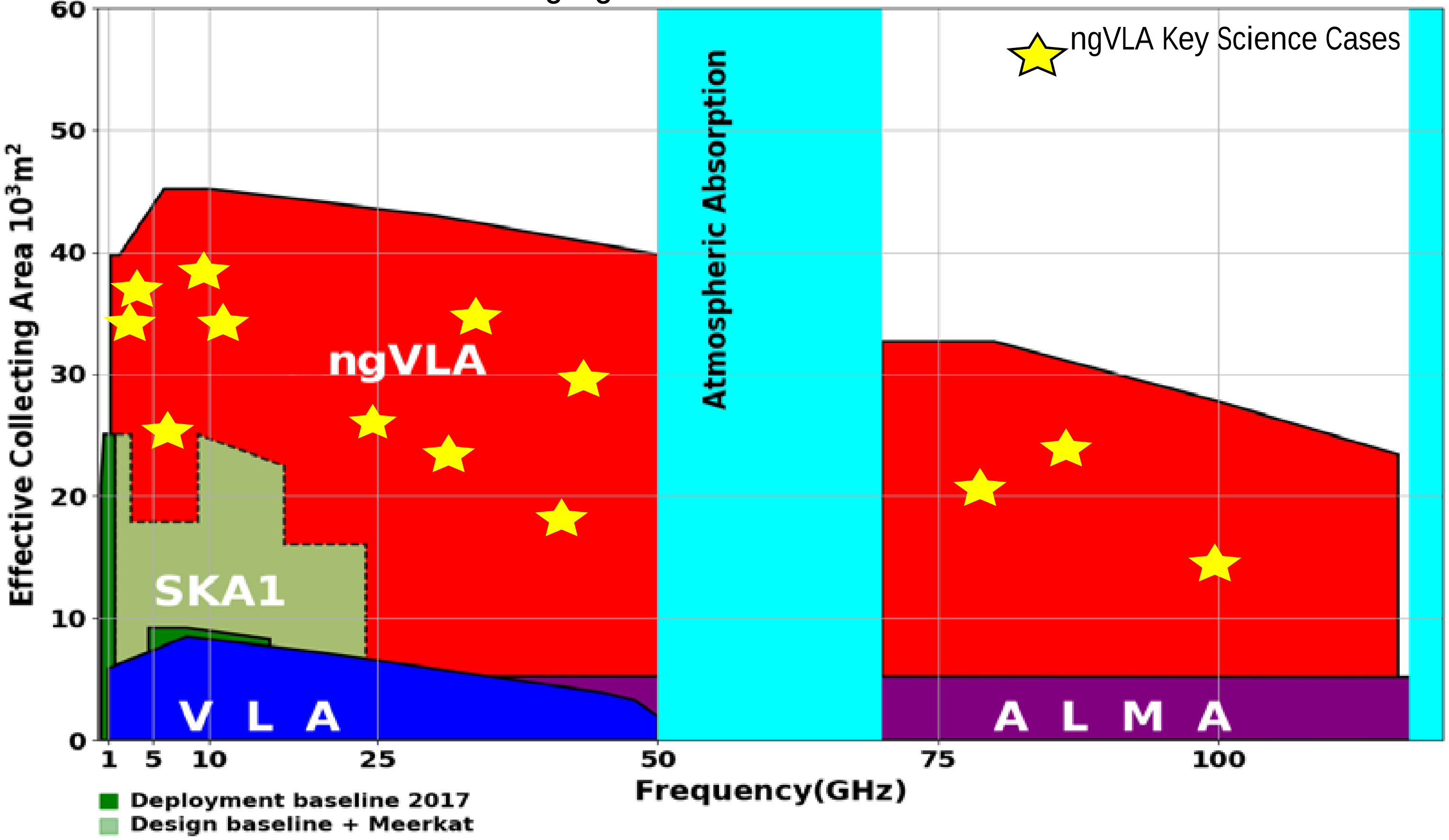


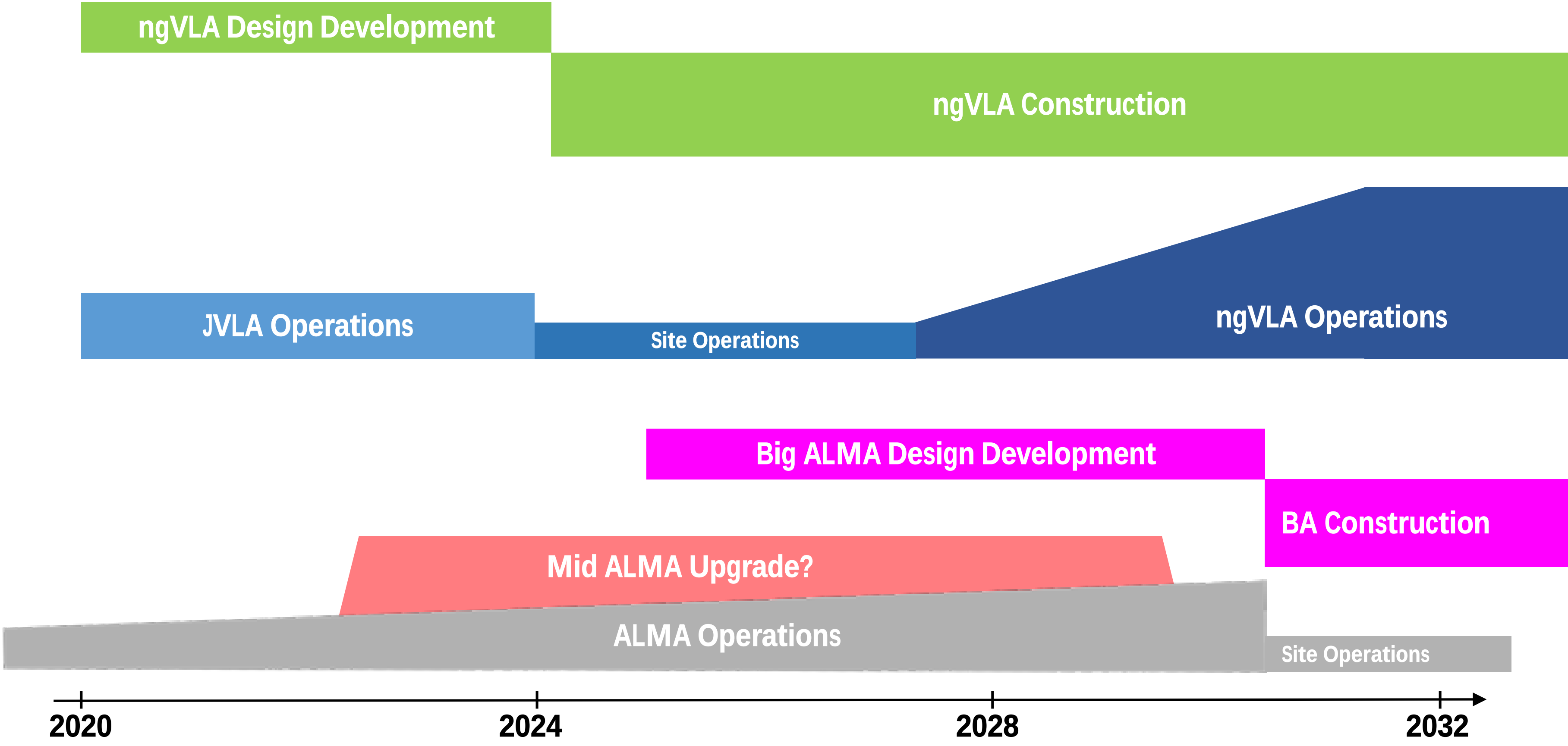
US, SKA & Japan

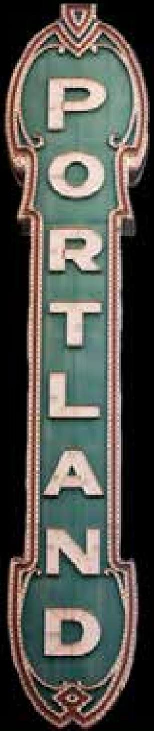
- US & SKA: long history together… parted ways ~2010.
- Currently: external participation in SKAPO, ongoing CASA initiative, no path to SKA1 participation. SKA1 will need CASA.
- US science environment, culture… different drivers, expectations.
- Can ngVLA be thought of as SKA2-HIGH? (Yes; w/ refined science case). ngVLA will bridge SKA1 & ALMA scientifically…
- The combination **SKA1 – ngVLA – ALMA** is powerful. NRAO will seek to establish an open-skies “Global Radio Alliance”, enabling US & international access to all radio instruments.
- Japan/US has major O/IR project underway … ngVLA will be beyond that. Bringing Japanese science interests and technology expertise most important now – seeking design/development partnership.

Bridging SKA & ALMA Scientifically

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




ngVLA Design Development
ngVLA Construction
JVLA Operations
Site Operations
ngVLA Operations
Big ALMA Design Development
BA Construction
Mid ALMA Upgrade?
ALMA Operations
Site Operations
2020
2024
2028
2032



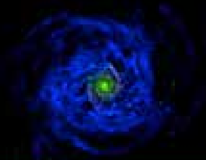
Astrophysical Frontiers in the Next Decade:

Planets, Galaxies, Black Holes, & the Transient Universe

June 26-29, 2018
Hilton Downtown Portland
Portland, Oregon USA

This conference will bring a large cross-section of the community together to discuss how to address the highest-priority astrophysical questions of our time. Parallel sessions will focus on:

- Exoplanet and Protoplanetary Disk Origins
- Galaxy Evolution Mechanisms
- Black Holes & Transient Phenomena



PLENARY SPEAKERS

Ilse Cleeves (CfA/UVa)
Sebastian Heinz (UW Madison)
Andrea Isella (Rice U)
Michael Kramer (Max Planck)
Alex Pope (UMass)
Karin Sandstrom (UCSD)

SOC CHAIRS

Caitlin Casey (UT Austin), Laura Chomiuk (MSU), Brenda Matthews (NRC, Canada)

http://go.nrao.edu/ngVLA18

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.)
- Based on community input to date, the ngVLA is the obvious next step to build on the VLA's legacy and bridge SKA & ALMA capabilities.
- Major Challenges: No major technological risks identified, but continually looking to for major engineering advancements seeking performance/operations optimizations.
- Next Steps: Continue to refine the ngVLA science mission and instrument specifications/performance through detailed science book and reference design study.
- We hope the science case and technical prospects of ngVLA will excite our Japanese colleagues to participate in ngVLA design & development, and continue the long collaboration between Japan and NRAO/US in the 2020s.

Many Thanks to:

- **National Science Foundation – JVLA and ngVLA Design Development**
- The ngVLA Science and Technical Advisory committees
- All ngVLA Science Working Group Participants
- Initial ngVLA Science White Paper Authors
- ngVLA Community Studies Participants

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Science Use Case Summary