GO BIG!

Tracing the large scale gas and dust associated with star formation using large feed arrays and large single dishes

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North American ALMA Science Center

National Radio Astronomy Observatory

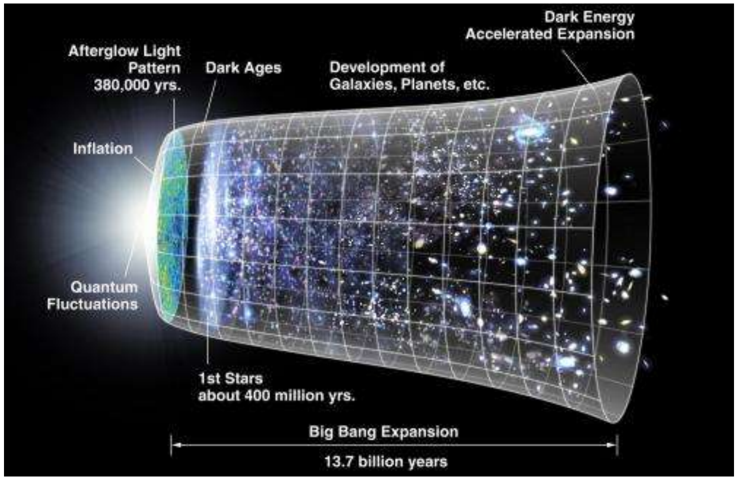
TAKE-HOME MESSAGE:

Single dishes need to invest in large (~100s of pixel) feed arrays at frequencies of crucial molecular transitions (ammonia, HCN, HCO+, ^{13}CO, $C^{18}O$, etc) to map the large scale gas structures associated with star formation in order to be competitive with large interferometers like ALMA and the ngVLA.

DISCLAIMERS:

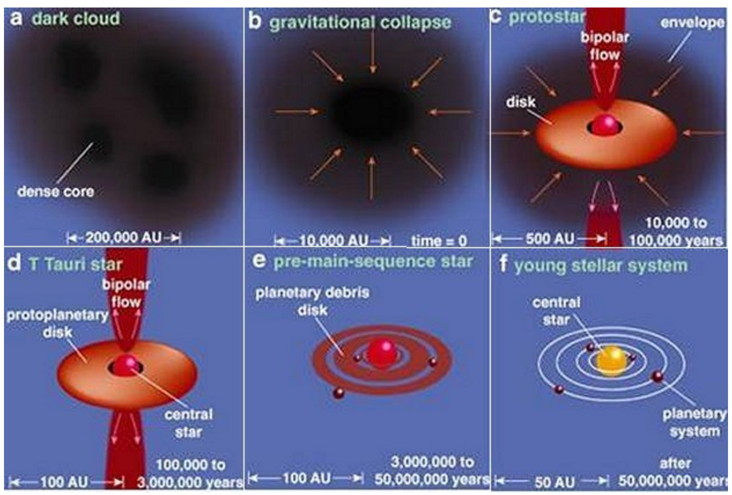
- These are my own opinions and not the opinions of NRAO.
- I'm a long-time GBT user, so I'm going to draw mainly on my experiences with that telescope.
- My research is largely extragalactic, so there may be some topics in Milky Way star formation that I've overlooked.

UNDERSTANDING STAR FORMATION IS KEY TO MODERN ASTRONOMY'S EMPHASIS ON ORIGINS.



NWNH Decadal Review

- How did the first galaxies and first stars form?
- Are there nearby habitable planets?

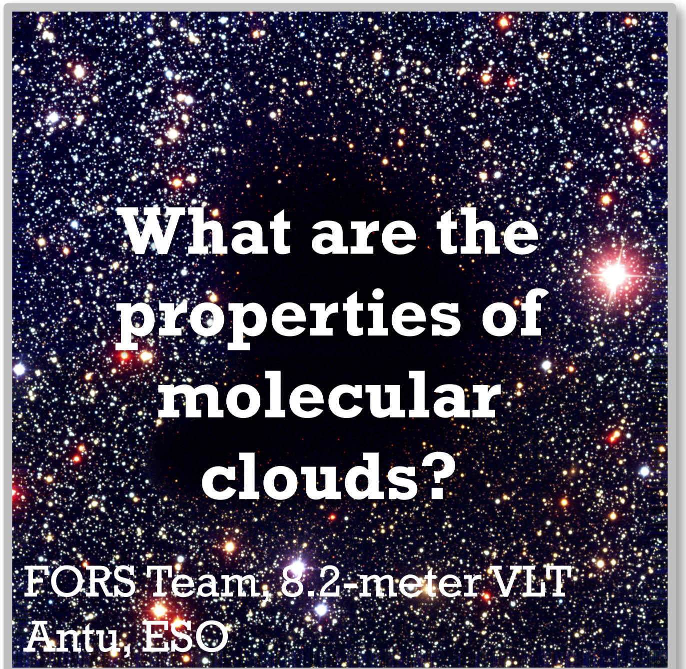


NASA SMD

- How does the universe work?
- How did we get here?
- Are we alone?

How are molecular clouds (re)formed?

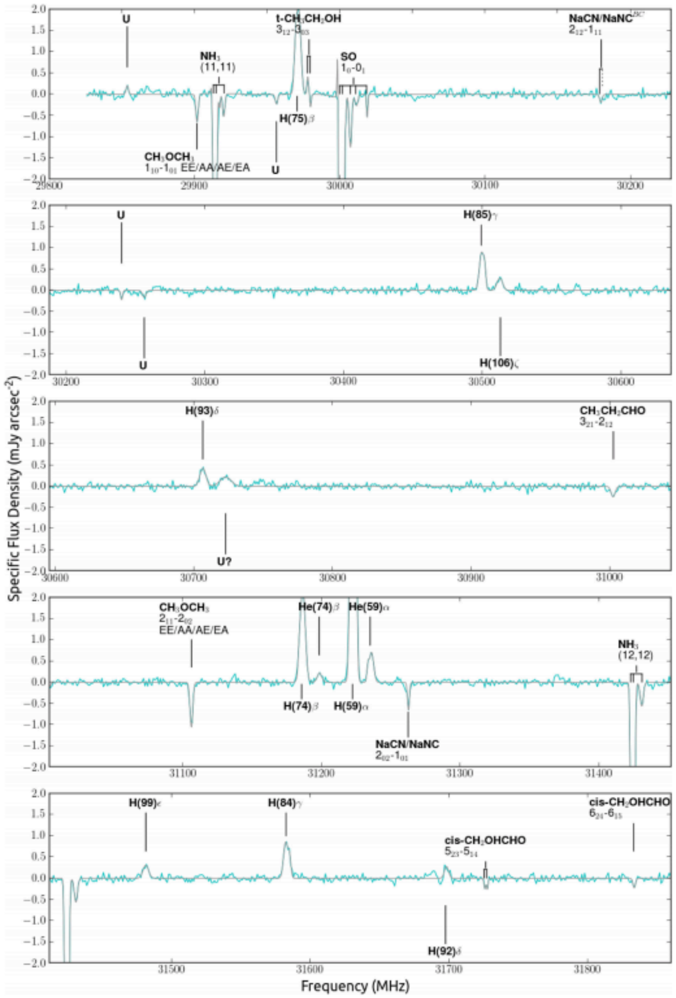
What effect do the young massive stars have on molecular clouds?



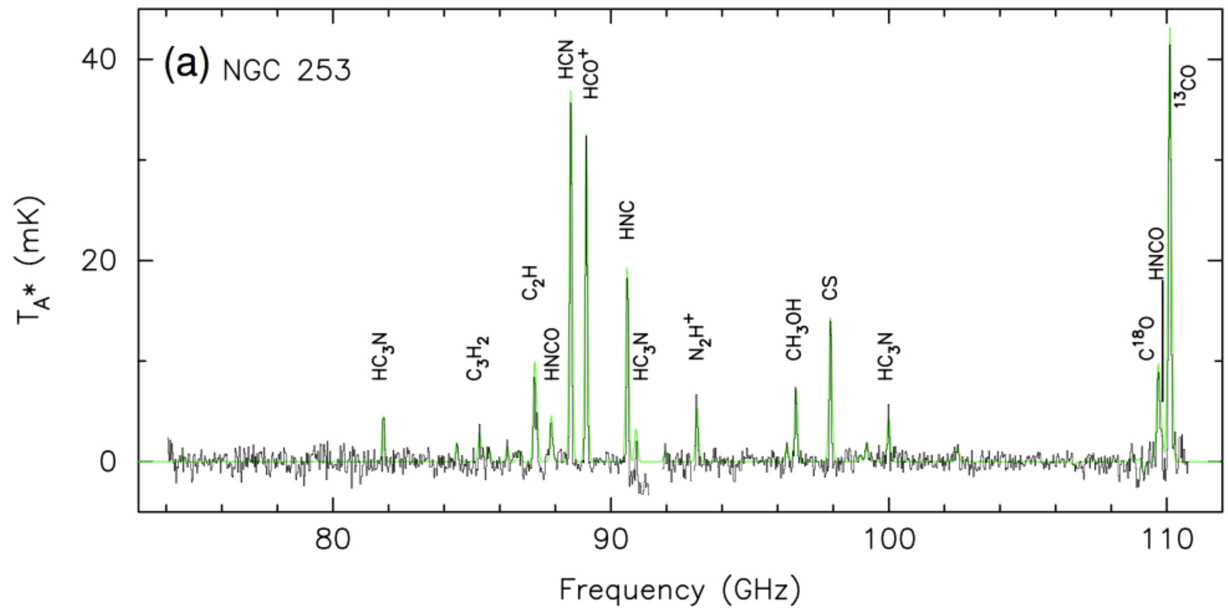
How do you convert molecular gas into stars?

A. Kepley

RADIO/MM OBSERVATIONS ARE CRUCIAL BECAUSE KEY GAS TRACERS LIE IN AT 22GHZ (AMMONIA) TO 115GHZ (CO).



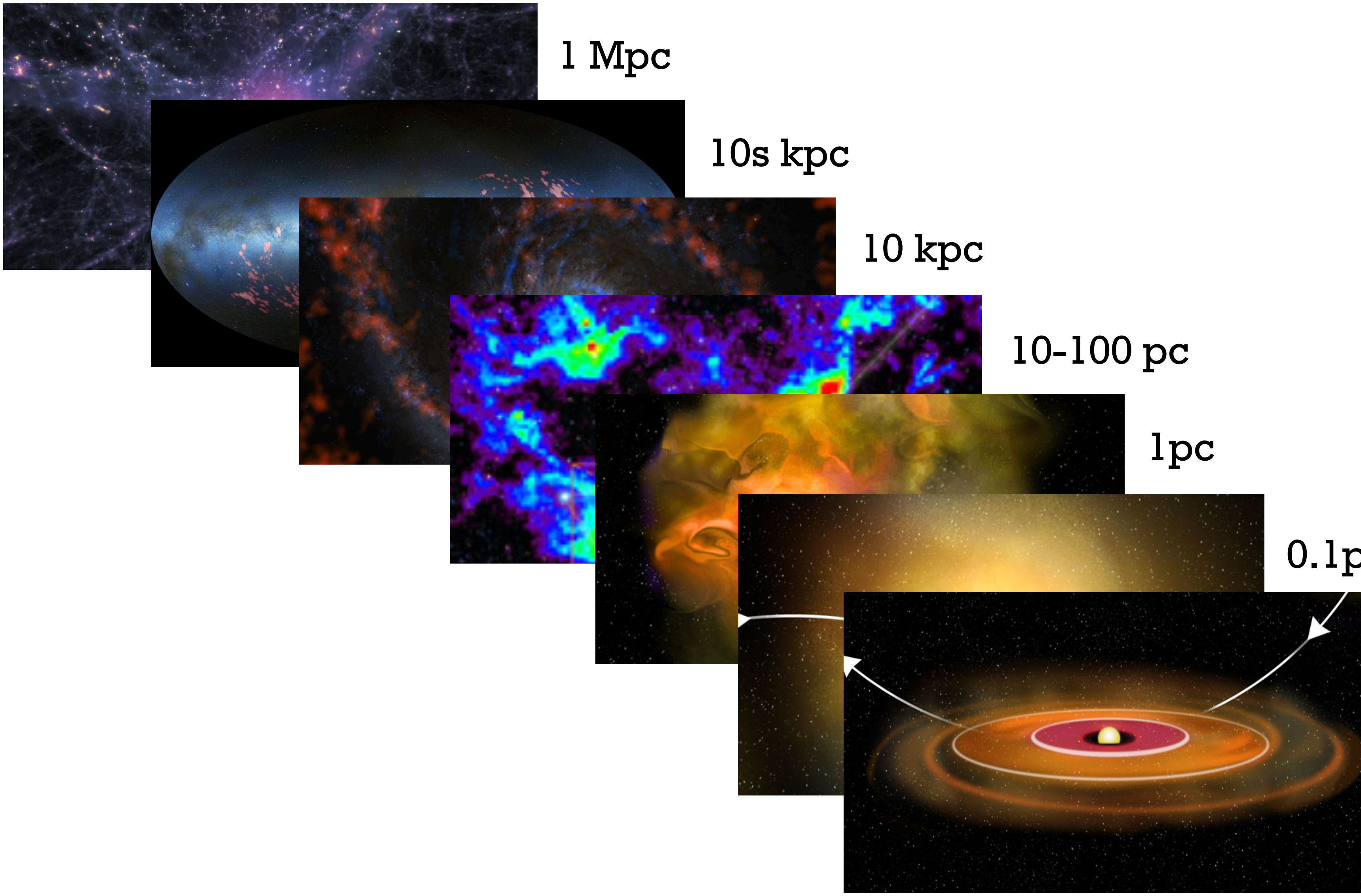
Corby+ 2015



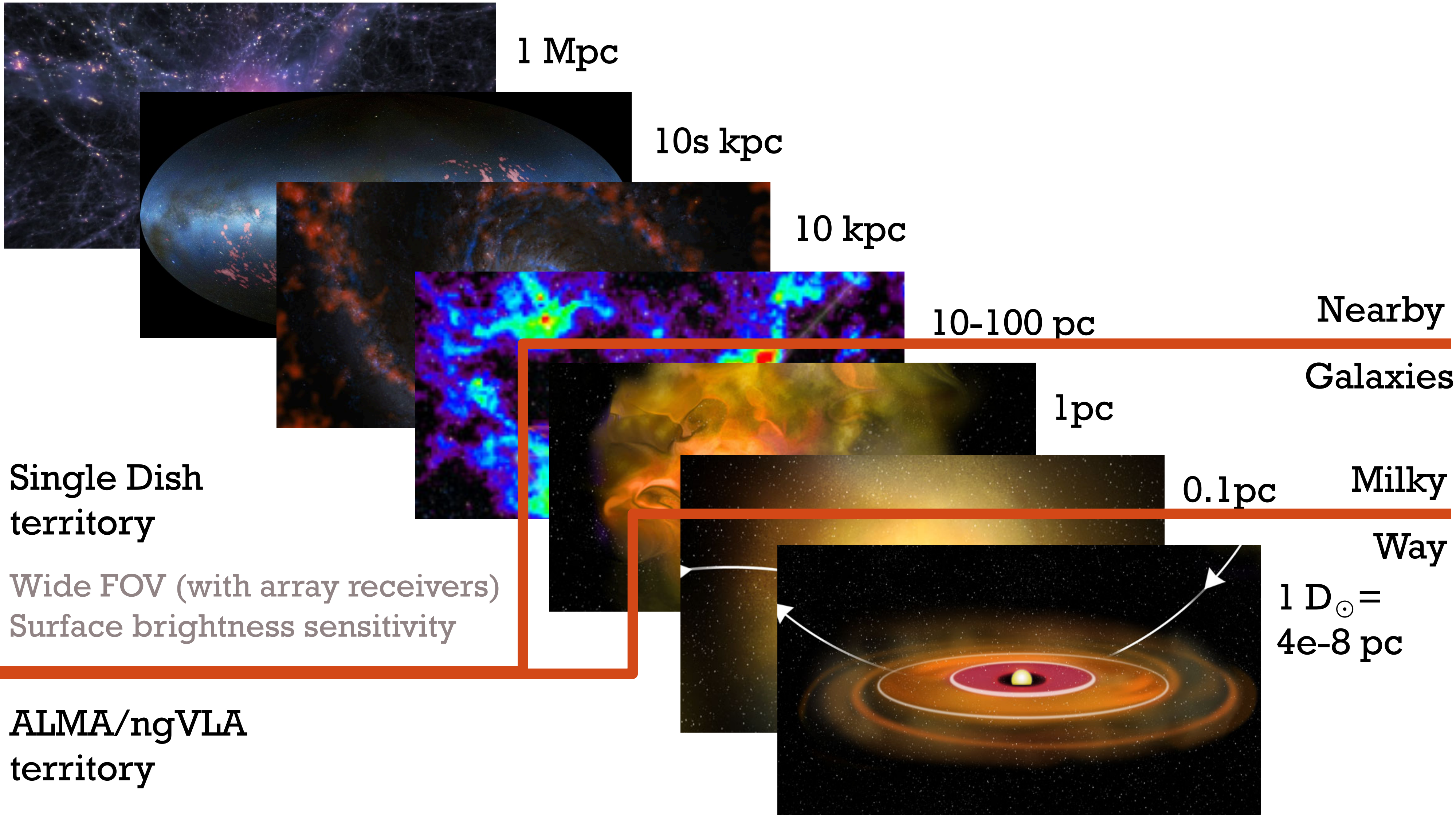
Snell+ 2011 (LMT RSR!)

- Gas properties (densities, temperatures, etc)
- Kinematics
- Chemistry

STAR FORMATION-RELATED PROCESSES OPERATE OVER 14 ORDERS OF MAGNITUDE.



FOR MILKY WAY AND NEARBY GALAXIES, DIFFERENT SIZE SCALES ACCESSIBLE TO DIFFERENT TELESCOPES.



Single Dish
territory

Wide FOV (with array receivers)
Surface brightness sensitivity

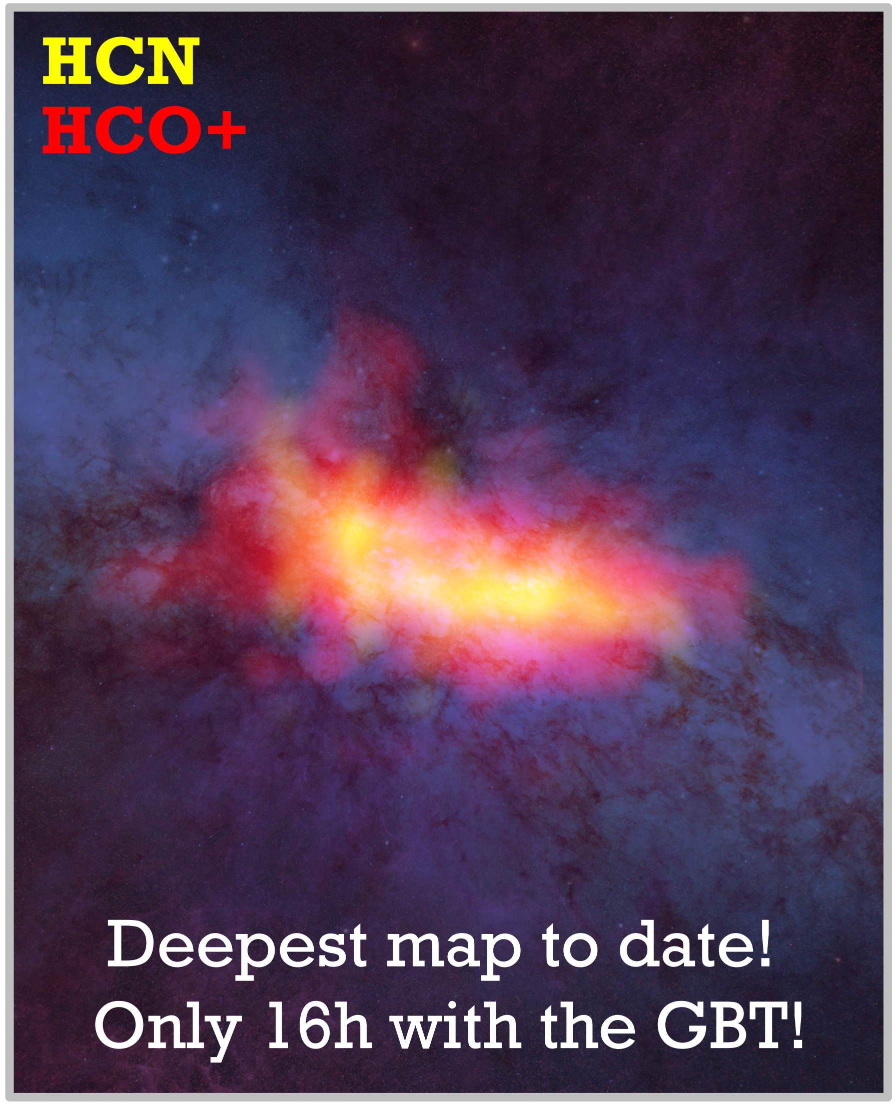
ALMA/ngVLA
territory

Narrow FOV
High resolution

ALMA PROPOSALS FROM U.S. COMMUNITY ARE HAMPERED BY LACK OF MM/SUBMM SINGLE DISHES.

- Want to make sure you can detect sources before you spend ALMA time
    - Cf. Robert's talk!
- Delta call for 7m only proposals received ~300 proposals with only 1 month's notice (prior to ALMA call)
- Many would be suited to large single dish like the GBT.

THE HIGH SURFACE BRIGHTNESS SENSITIVITY OF THE GBT REVEALED NEW FEATURES IN M82.



Kepley + 2014

GBT MAPPING SPEED LIMITED BY SINGLE PIXEL RECEIVERS.

Table 1. Time to map spectra at 86 GHz over a $3' \times 3'$ field to 20 mK rms[a]

GBT 2015 1 Pixel $8''$	Argus 2015 16 Pixels $8''$	GBT 2020 50 Pixels $8''$	ALMA 50x12m $3''$	ALMA 50x12m $1''$	ALMA 10x7m $23''$	ngVLA 300x18m $1''$
21h	3.3h	< 1h	19h	1,500h	0.5h	17,500h

[a]For $\delta = 0°$, 1 km s^{-1} channels, GBT Ta* 2000 h/yr opacity, ngVLA tapered to $1''$ resolution at 80 GHz for the Clark/Conway configuration [11]. GBT2020 has dual polarization. ALMA numbers from the ALMA sensitivity calculator on 10 July 2016. No allowances for overhead.

Lockman et et al. 2016, astroph/1610.02329

THE MAPPING SPEED OF THE GBT COULD EASILY EXCEED THAT OF ALMA AND NGVLA WITH LARGE ARRAYS.

Table 1. Time to map spectra at 86 GHz over a $3' \times 3'$ field to 20 mK rms[a]

GBT 2015 1 Pixel $8''$	Argus 2015 16 Pixels $8''$	GBT 2020 50 Pixels $8''$	ALMA 50x12m $3''$	ALMA 50x12m $1''$	ALMA 10x7m $23''$	ngVLA 300x18m $1''$
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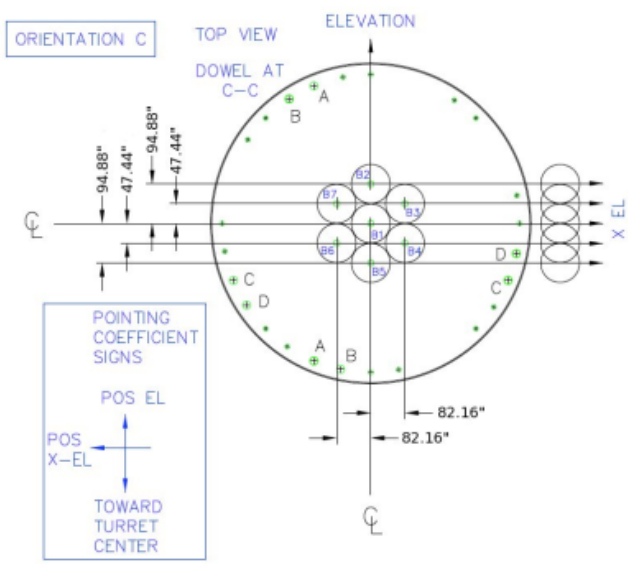
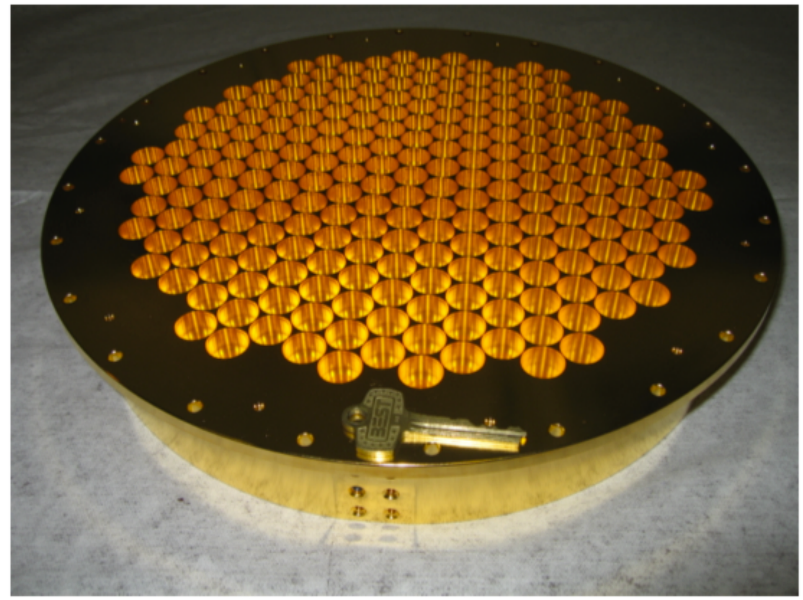
Lockman et et al. 2016, astroph/1610.02329

THE 3 CURRENT FOCAL PLANE ARRAYS ON THE GBT ARE ALREADY PRODUCING KEY SCIENCE.

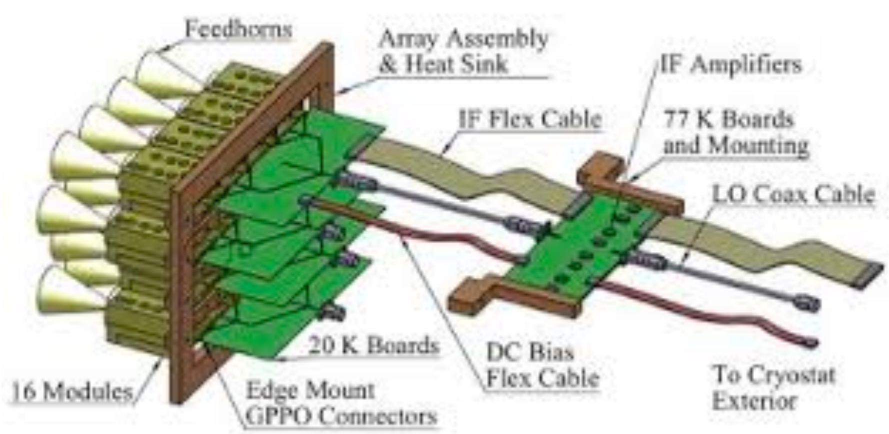
K-band Focal Plane Array



Mustang/Mustang 2

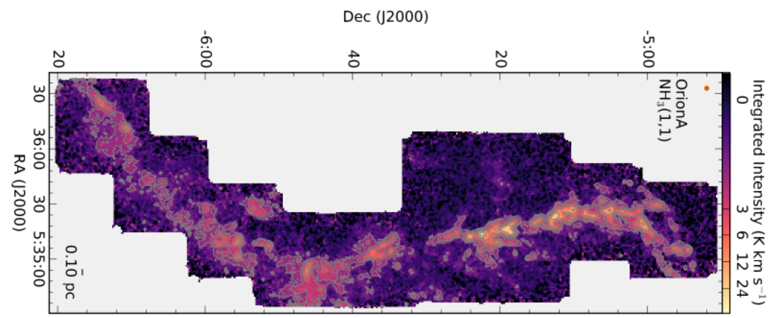


ARGUS

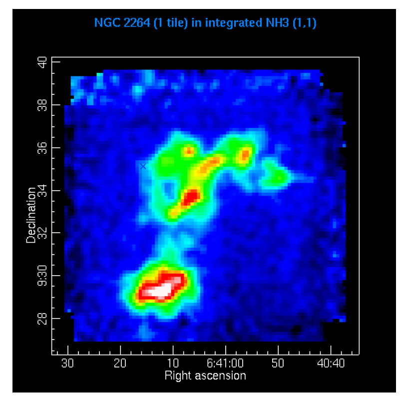


THE KFPA EXCELS AT MAPPING THE TEMPERATURE, DENSITY, AND KINEMATICS OF STAR-FORMING GAS IN THE MILKY WAY.

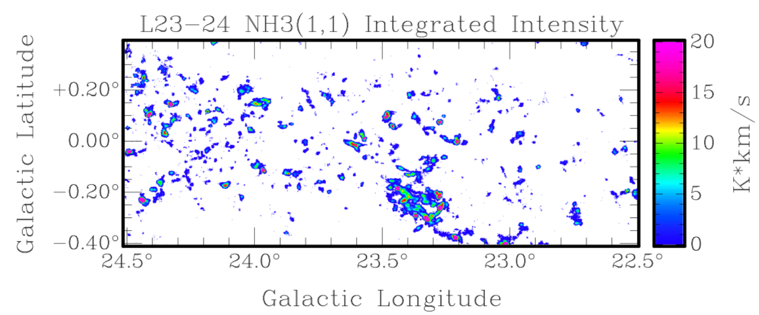
Green Bank Ammonia Survey (GAS)
Co-PIs: R. Friesen and J. Pineda
DR1: arXiv:1704.06318, ApJS accepted
Gould Belt regions with Av~>7
Physical resolution: 0.02-0.08pc
Transitions: NH3(1,1) → NH3(3,3), HC_5N, HC_7N, C_2S



KFPA Examinations of Young Stellar (O-star) Natal Environments (KEYSTONE)
PI: J. Di Francesco
Observing year 1 of 2 finished
12 GMCs at d < 3 kpc targeted
Transitions: NH3(1,1) → NH3(5,5), H_20 maser, CCS, HC_5N, HC_7N

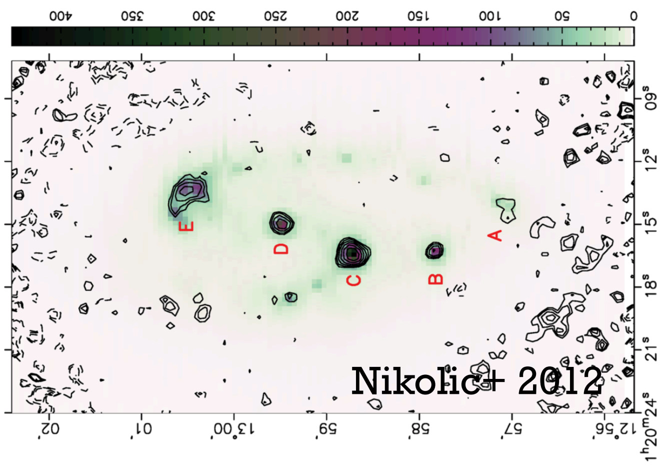


Radio Ammonia Mid-Plane Survey (RAMPS)
PI: J. Jackson
Pilot survey data release forthcoming (Hogge+)
Galactic plane (10 < l <40, -0.5 < b < 0.5)
Transitions: NH3(1,1) → NH3(5,5) + H_2O & CH_3OH masers

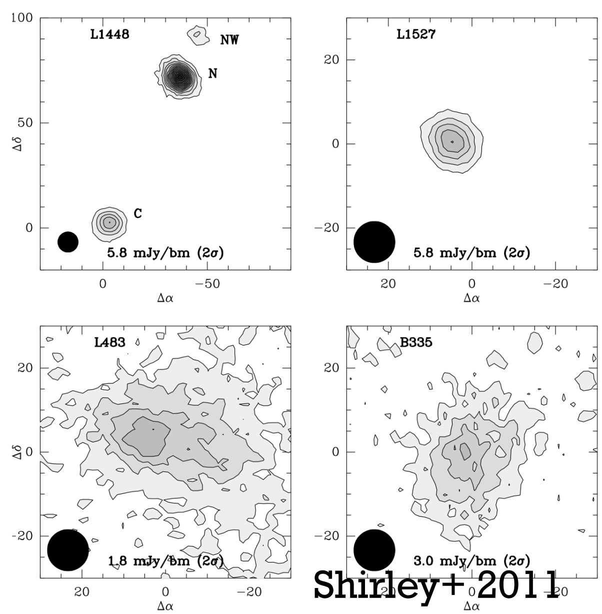


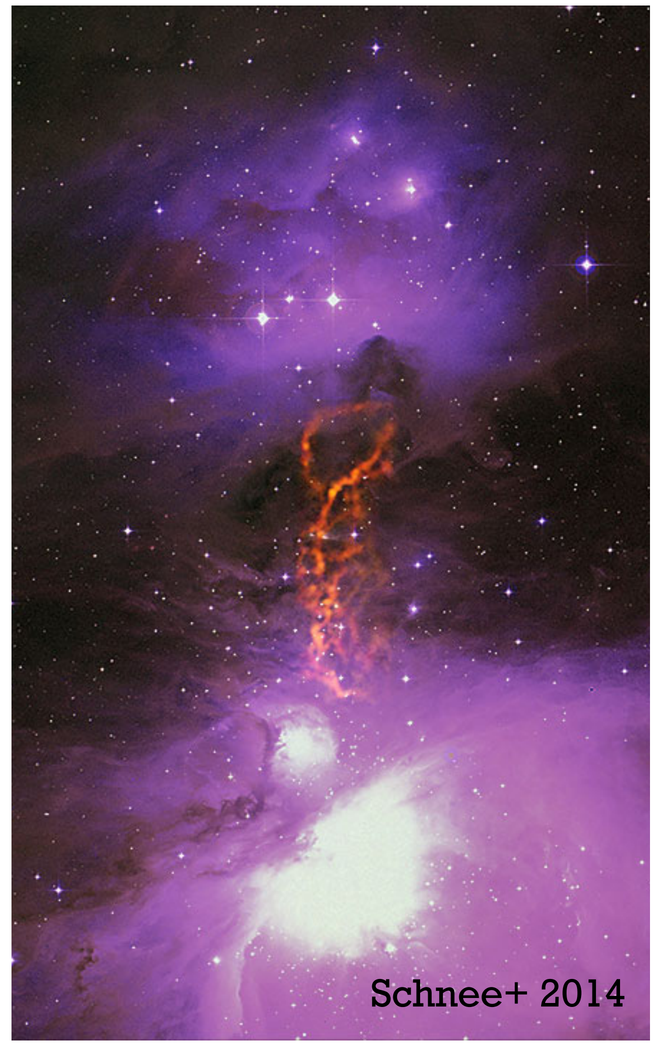
MUSTANG MAPPED DUST IN THE MILKY WAY AND FREE-FREE EMISSION IN NEARBY GALAXIES.

90GHz continuum in nearby galaxy consistent with being all free-free. Extinction-free(ish) SFRs?



Emissivity spectral index used to distinguish between envelope and disk emission. Probe of early obscured massive star formation?

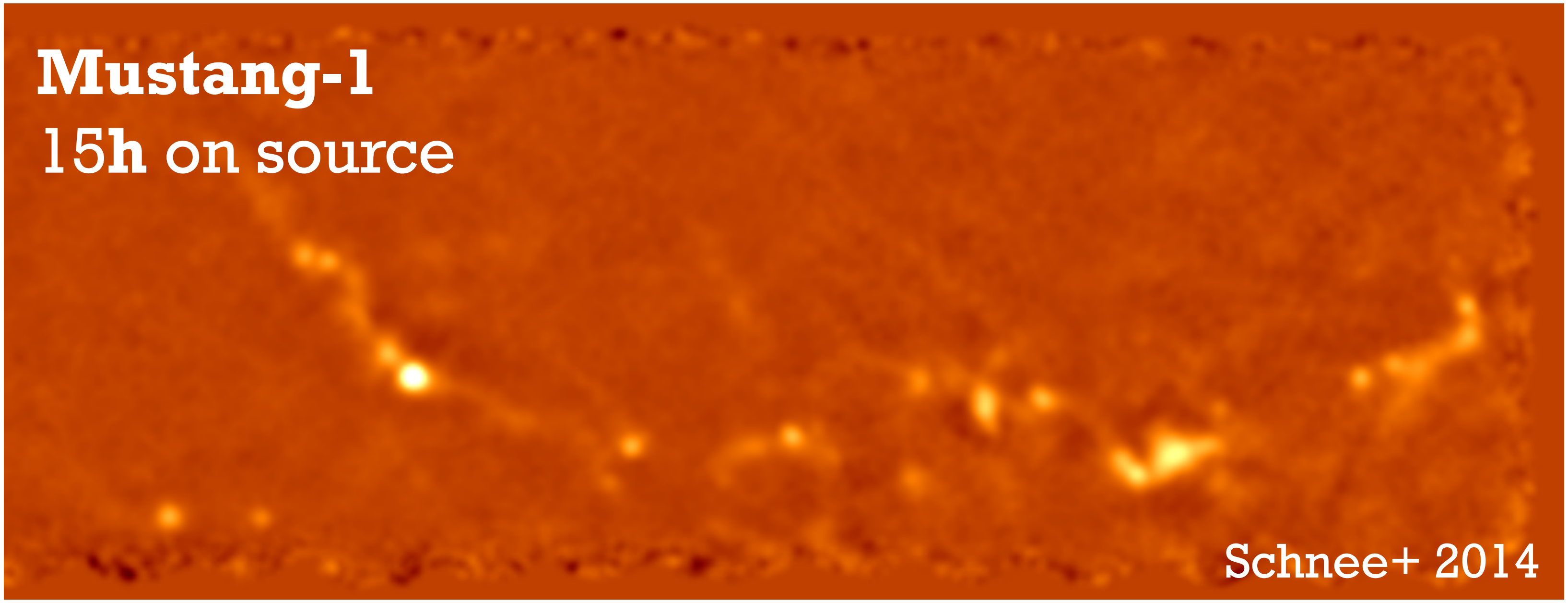




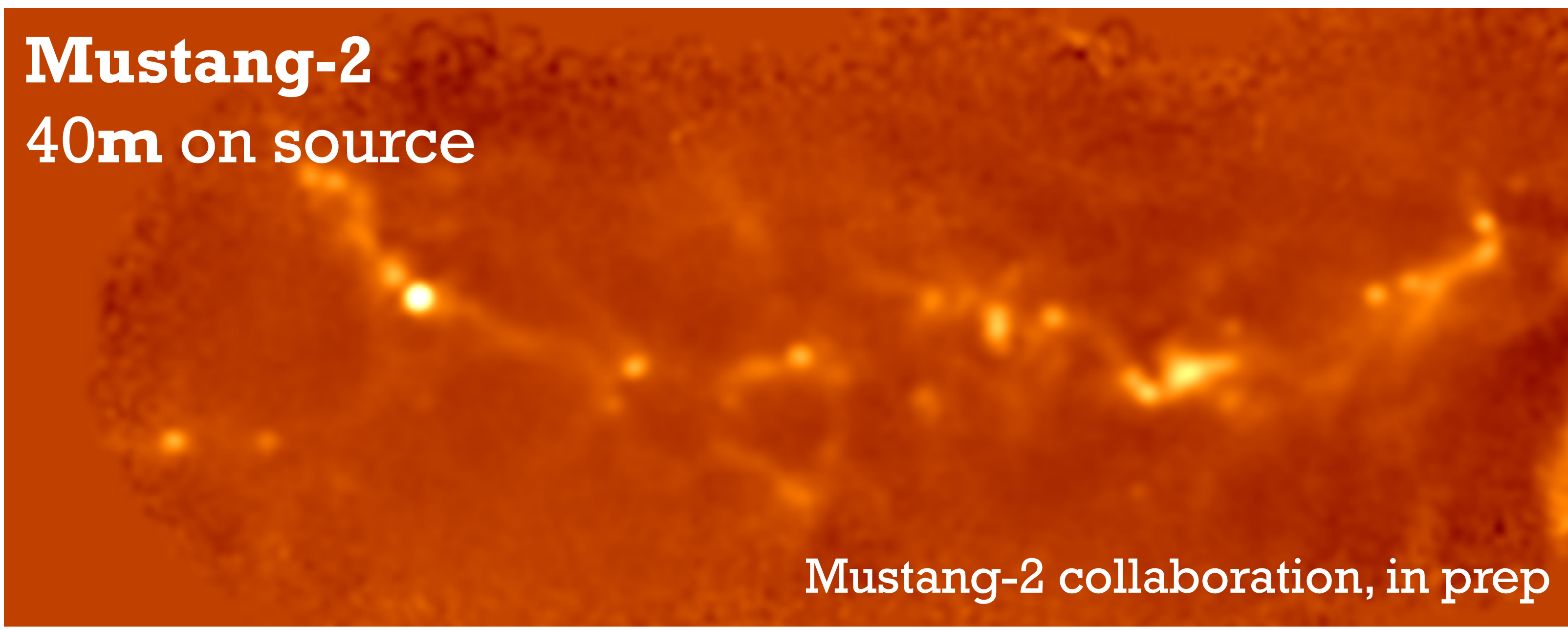
Emissivity spectral index and ammonia data used to probe dust in nearby massive star-forming region. Found large (>1mm) dust grains in filaments in Orion.

MUSTANG 2 IS EVEN MORE POWERFUL

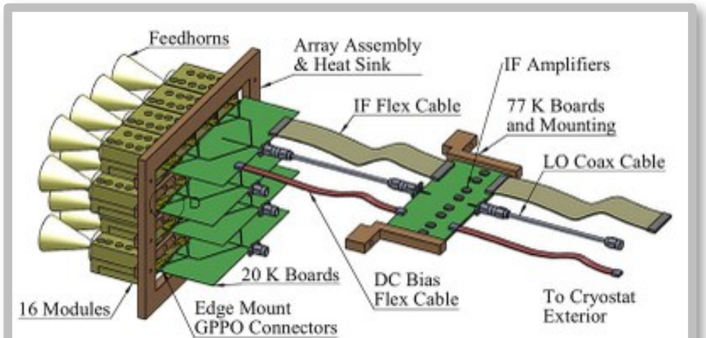
64 pixels
42" FOV



3x more pixels
5x the FOV
More sensitive/beam



GBT+ARGUS IS AN IDEAL COMBINATION FOR SPECTRAL LINE SURVEYS.

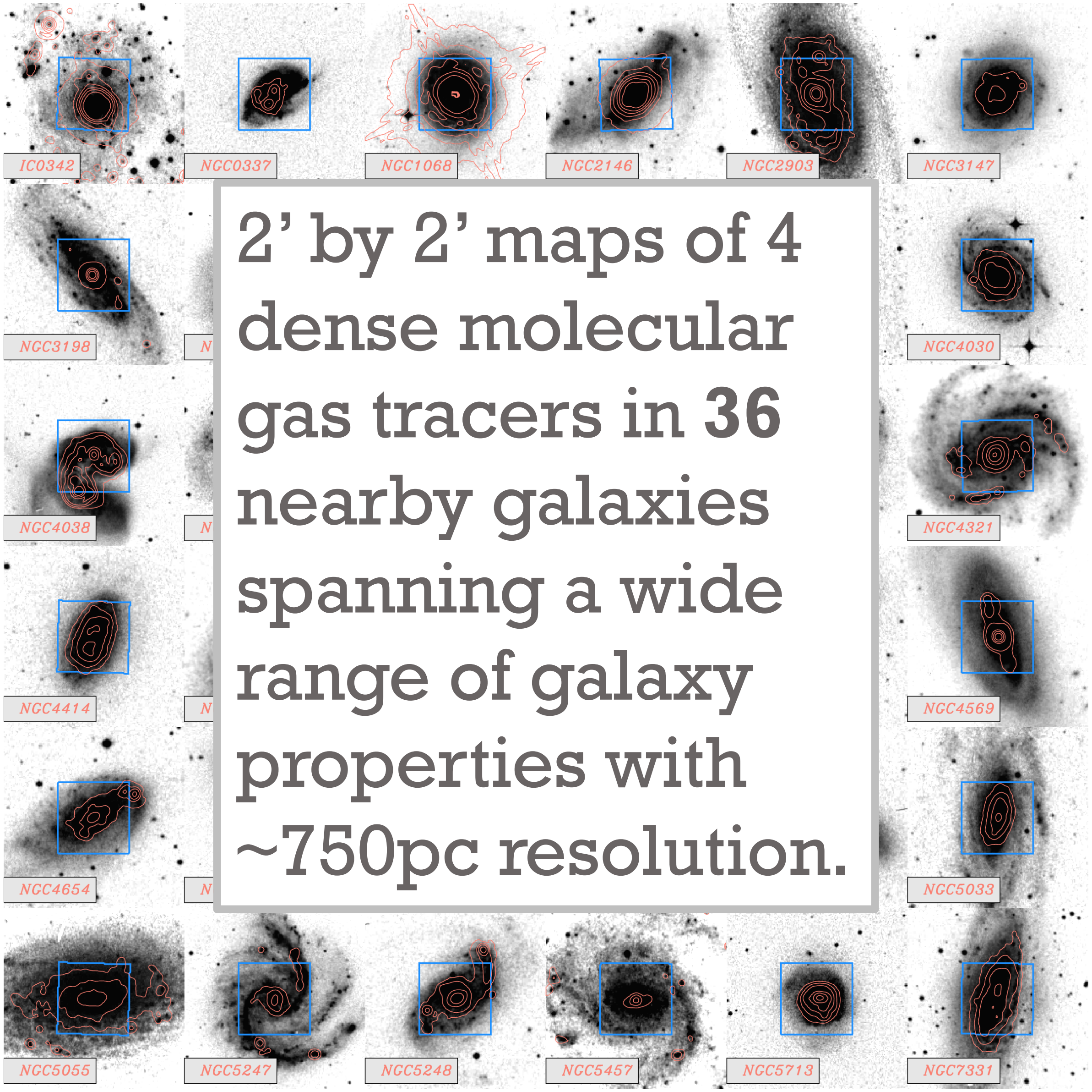


Stanford (PI Sarah Church), Caltech, JPL, U. Maryland, U. Miami, and NRAO.

- GBT has a collecting area slightly larger than ALMA and 4x that of the next largest single dish (LMT).
- ~10arcsec beam means you can distinguish 30 Doradus sized regions at the distance of M82.
- 16 pixels means that you can map galaxies in the order of 5-10 hours instead of >50 hours.

A. Kepley

DEGAS* WILL QUANTIFY THE ROLE OF DENSE GAS IN STAR FORMATION.



2' by 2' maps of 4 dense molecular gas tracers in **36** nearby galaxies spanning a wide range of galaxy properties with ~750pc resolution.

* DENSE EXTRAGALACTIC GBT+ARGUS SURVEY

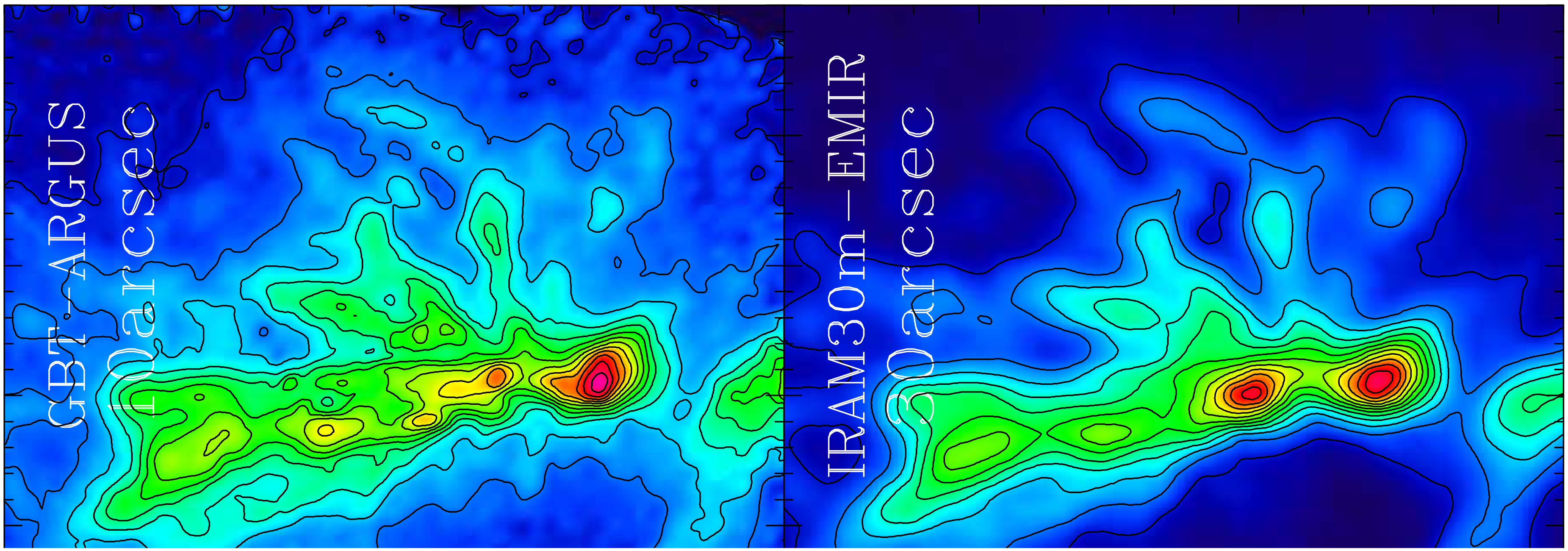
FULL PROPOSAL ACCEPTED!
500H OVER 3 YEARS (GULP)

A. Kepley (PI)
A. Leroy
S. Church
D. Frayer
E. Rosolowsky
A. Harris
A. Bolatto
F. Bigiel
M. Gallagher
J. Gunderson
A. Hughes
M. J. Jimenez
C. Lee
J. Li
J. Meyer
K. Sandstrom
A. Schruba
M. Sieth
E. Schinnener
A. Usero

(grad students)

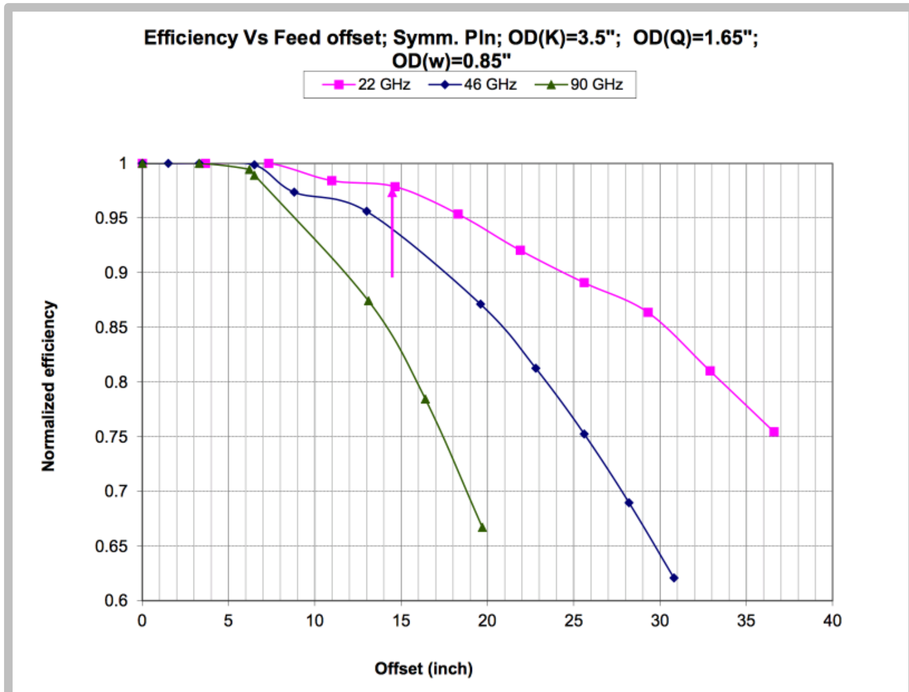
Supported by NSF AST Grant to co-Is.

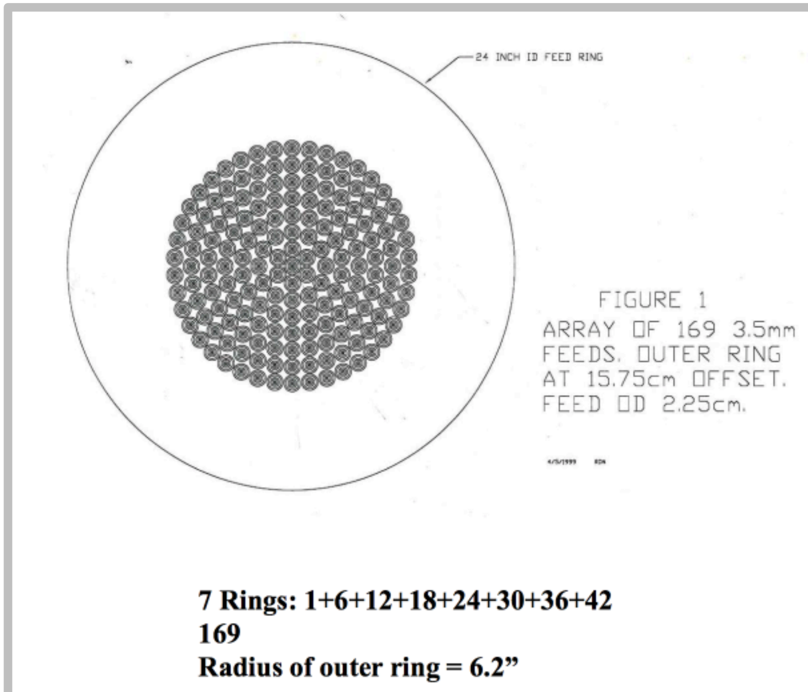
ARGUS WILL ALSO MAP THE KINEMATICS OF LARGE SCALE DENSE GAS STRUCTURES IN THE MILKY WAY.



Preliminary data courtesy Alvaro Hacar

THE FOCAL PLANE OF THE GBT CAN ACCOMMODATE EVEN LARGER ARRAYS.





Freq (GHz)	Pixels	Footprint	HPBW	Worst Coma	Diameter	
22	91	15.8’	34″	-20 dB	~36 in.	13x
46	500	18.1’	16″	-15 dB	~40 in.	500x
90	800	12.0’	8.3″	-15 dB	~30 in.	50x

GBT memos 198 and 199 (Norrod and Srikanth) and GBT Memo 295 (Lockman).

LARGER FOCAL PLANE ARRAYS REQUIRE LARGER BACKENDS AND MORE FIBER.

- Can't just upgrade VEGAS.
  - VEGAS is "mature" technology.
  - VEGAS already limits the 7GHz/sideband bandwidth of ARGUS to 1 GHz.
- Wisdom from Richard Prestage on a possible plan forward:
  - Start with prototype backend for a subset of pixels, then expand to full array
  - Digitize and packetize with a future CASPER board
  - Process the signal with common GBT HPC
  - Not cheap, but cheaper than building another 40 GBTs. ☺
- Will require substantial disk space.
  - 0^{th} order low-ball estimate: 8 bytes x 1024 chan x 2 pol x 800 feeds x 0.5s tint = 45 GB/hr
- Don't forget your fiber!
  - Need fiber (~1 per feed per pol) to transfer signals from array on telescope to backend in equipment room.

DREAM SPECTROMETER SPECS

	Extragalactic			Galactic		
		22GHz	90GHz		22GHz	90GHz
Resolution	1-5 km/s	70-350 kHz	0.5-1.5MHz	0.1km/s	7kHz	50kHz
Bandwidth per line	1000km/s	73MHz	300MHz	600km/s	44MHz	180MHz

- Ability to simultaneously map multiple transitions crucial for efficiency:
  - At 22GHz
    - As many ammonia transitions as possible (NH3(1,1) to NH3(6,6) is 1.5GHz).
    - Also think about water masters, complex carbon chain molecules.
  - At 90 GHz
    - Would like to get transitions like HCN/HCO+ simultaneously.
- Possible starting point would be to make it roughly comparable to ALMA: 4-32 spectral windows spread out over 8 GHz.

KEEPING AND EXPANDING ACCESS TO OBSERVING TIME CRUCIAL FOR MAXIMIZING ROI FOR THESE ARRAYS.

- Essential to retain access to good high frequency weather for science projects.
- Current observing system takes advantage of weather, but is particularly brutal for high frequency observers.
  - Possible solutions:
    - Observing campaigns for large projects (potential to do this now)
    - Service observing for large projects (each project commits to sending a number of observers)
    - Automated observing with a call out number? (would require significantly more stable GBT control system)
- Capital investments to extend to daytime observations with improved OOF would be very exciting
  - Prestage, R.M. 2015, Performance and Properties of the GBT, NRAO Workshop, https://science.nrao.edu/science/meetings/2015/GBT-high-frequency-science/ Richard_GBTHighFreq.pdf

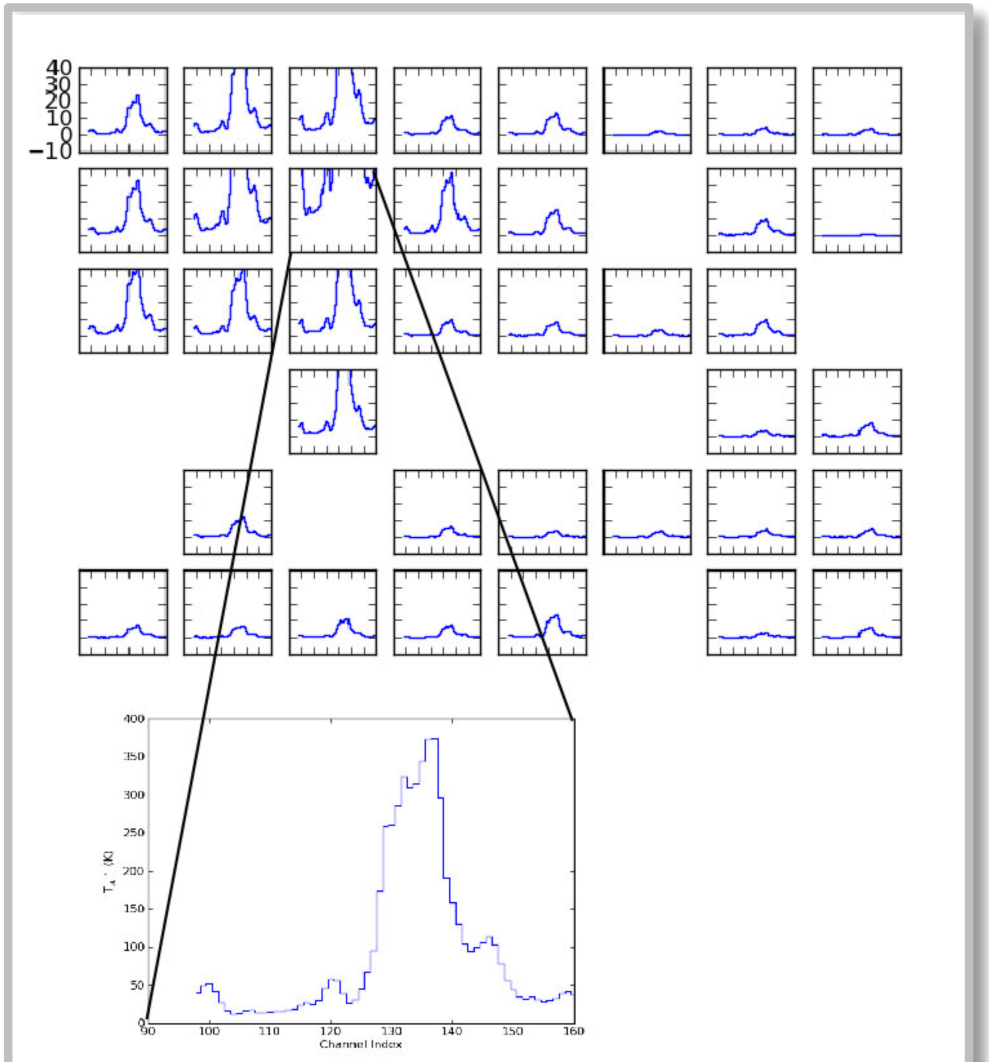
POTENTIAL KEY PROJECTS WITH LARGE ARRAYS.

- Scaling from current surveys:
  - For DEGAS, we get to 4mK per 25.0km/s over 0.04sq deg in 167 hr with a 16 pixel 90 GHz focal plane array. For an 800 pixel array, that works out to 2 sq deg in 167hr at the same depth.
  - For RAMPS, 210hr total for 6.5 sq deg. Assume 70% of time on source, 147h per 6.5 sq deg. For a 91 pixel array, would get 84.5 sq deg per 147h.
  - All estimates exclude overhead
- Extragalactic:
  - HCN/HCO+ survey of every galaxy in the CALIFA IFU sample (667)
    - 4.5' by 4.5' maps of all galaxies in ~313 hr.
    - Would like to get at least HCN & HCO+. Would be good to be able to multiplex other nearby tracers with similar brightnesses (HNC, 13CO).
    - CALIFA gives ionized gas, stellar populations, add CO to get bulk gas, HCN/HCO+ would give dense star-forming gas.
- Galactic:
  - HCN/HCO+ survey of Galactic plane
    - ~0.65 km/s resolution. Scaling from DEGAS, get 24mK per 0.65km/s. Close to what you would need for a Galactic HCN/HCO+ survey (assuming CO/HCN~10)
    - Extend in l ~ 40 deg, +/- 1 in b= 80 sq deg in 6700hr. [Large, but not unreasonable]
    - Would like to get at least HCN & HCO+. Would be good to be able to multiplex other nearby tracers with similar brightnesses (HNC, 13CO).
    - Map of the dense star-forming gas. Allows you to directly link Milky Way and extragalactic observations.
  - Ammonia survey of Galactic plane
    - 140deg in l, +/- 1 in b= 280 sq deg in 486.57hr
    - Temperature, density distribution of molecular clouds in Milky Way. Connect to dense gas, star formation, bulk molecular gas
    - Ability to multiplex lines is key here (need multiple ammonia transitions to get information.

GBT, LMT, AND JCMT HAVE HIGHLY COMPLEMENTARY CAPABILITIES.

Beam @ 115GHz ~= Beam @ 230GHz ~= Beam @ 345GHz

IN THE FUTURE, PHASED ARRAY FEEDS COULD HAVE EVEN MORE PIXELS IN THE SAME PHYSICAL AREA.



Unlike focal plane arrays, phased array feeds fully sample the GBT focal plane.

PHAMAS is 48 by 48mm with 225 beams on the sky. (c.f. 800 pixel focal plane array with 30in diameter).

Limitation is the beamformer electronics necessary to provide broader bandwidths.

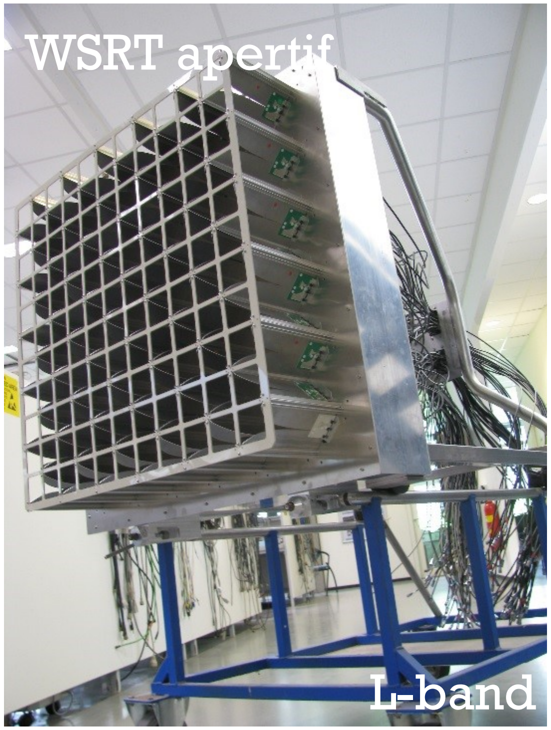
Also need to figure out a viable calibration strategy that deals with telescope pointing issues.

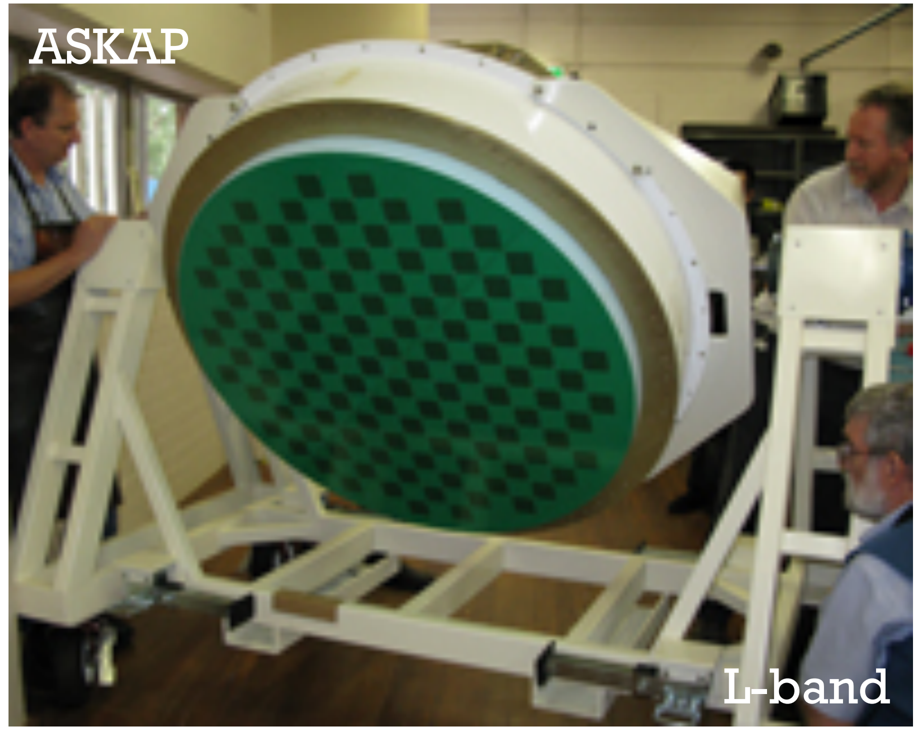
Engineering results from the PHAMAS array
Neal Erickson (UMass) et al. NRAO eNews vol. 8, issue 11

LARGE ARRAYS PROVIDING FAST WIDE-FIELD MAPPING IMPLIES LARGE SURVEY PROJECTS.

- Large arrays with fast mapping speeds make small, PI-based experiments less exciting.
  - Why get 1 galaxy when you can get 100?
- New mode of operation for instruments like the GBT, which have been traditionally PI-driven.
- May require new modes of funding
  - Right now you apply for both an NSF grant to fund the science and the telescope time. Double-jeopardy and can end up in a situation where you have funding, but no time or no time, but funding.
  - However, you don't want the NSF essentially acting as the GBT's TAC.
- Requires a steady flow of instrumentation/science projects
  - Need people conceiving of new instruments while the previous generation are being used for science.
  - The GBT's flexibility is a big asset here. Lots of potential projects surveys from pulsars to star formation.
- Lots of potential overlap with programs that have been previously funded by UROs.

FOCAL PLANE ARRAYS OR PHASED ARRAYS ON INTERFEROMETERS AT THESE FREQUENCIES ARE FAR OFF.

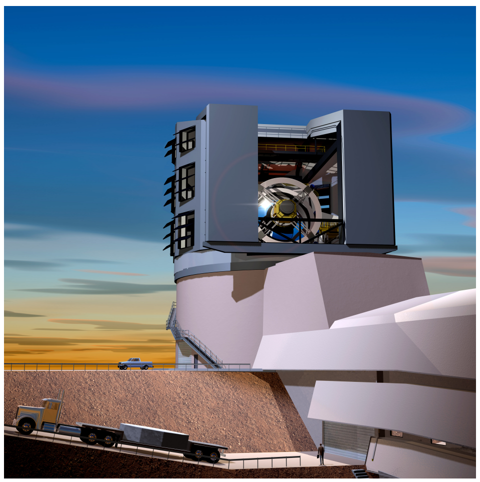




- ngVLA is really only talking about single pixel feeds (emphasis is on wide bandwidth). Ditto ALMA development projects.
- Emphasis with interferometers will likely remain narrow FOV, PI-based projects for the foreseeable future.
- Note that some of ngVLA's science cases (particularly the baryon cycling) would be better done by large single dish with large focal plane array.

AN ANALOGY: GBT:LSST :: NGVLA/ALMA:GMT

LSST



"Only" 8 m
FOV 10sq deg

#1 large priority in last decadal survey

GMT

~30m
FOV 10-20arcmin

#3 large priority in last decadal survey

THANK YOU!!!!

- James Di Francesco
- Rachel Friesen
- James Jackson
- Jay Lockman
- Sarah Church
- Kieran Cleary
- Richard Prestage
- Brian Mason
- Simon Dicker
- Sara Stanchfield
- Paul Goldsmith
- David Frayer
- Neal Erikson
- Yancy Shirley
- Alvaro Hacar
- Adam Leroy
- Brett McGuire
- Tony Remijan

TAKE-HOME MESSAGE:

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