NATIONAL RADIO ASTRONOMY OBSERVATORY

From the VLA to the ngVLA

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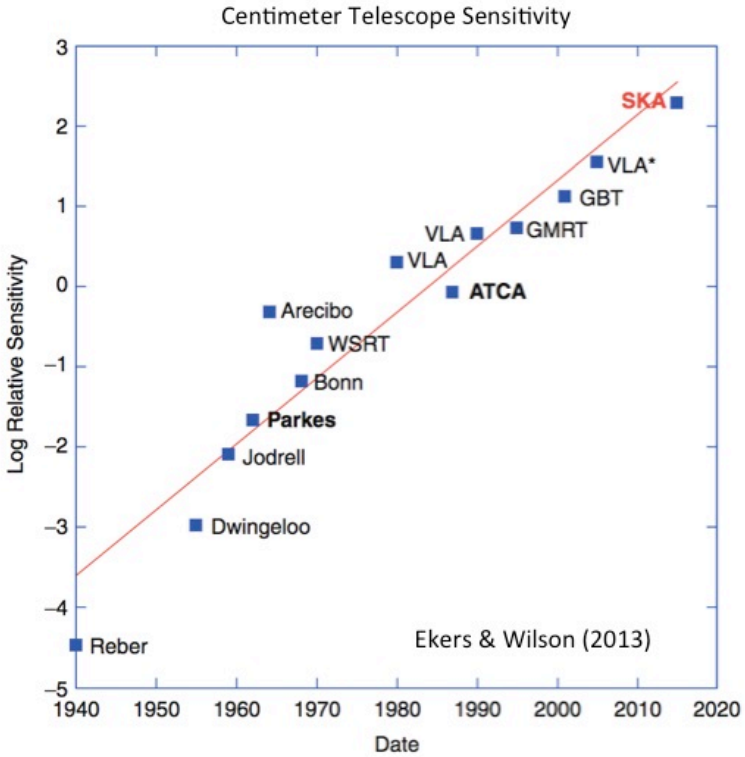
ngVLA
The Next Generation Very Large Array

Thinking in the next generation of instruments…

- A source of ideas and challenges are the things that you cannot do with the present instruments.
- However, serendipity will probably produce the most exciting and unexpected results of the new instrument.


Centimeter Telescope Sensitivity
Log Relative Sensitivity
Date
SKA
VLA*
GBT
GMRT
VLA
VLA
ATCA
Arecibo
WSRT
Bonn
Parkes
Jodrell
Dwingeloo
Reber
Ekers & Wilson (2013)
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1940
1950
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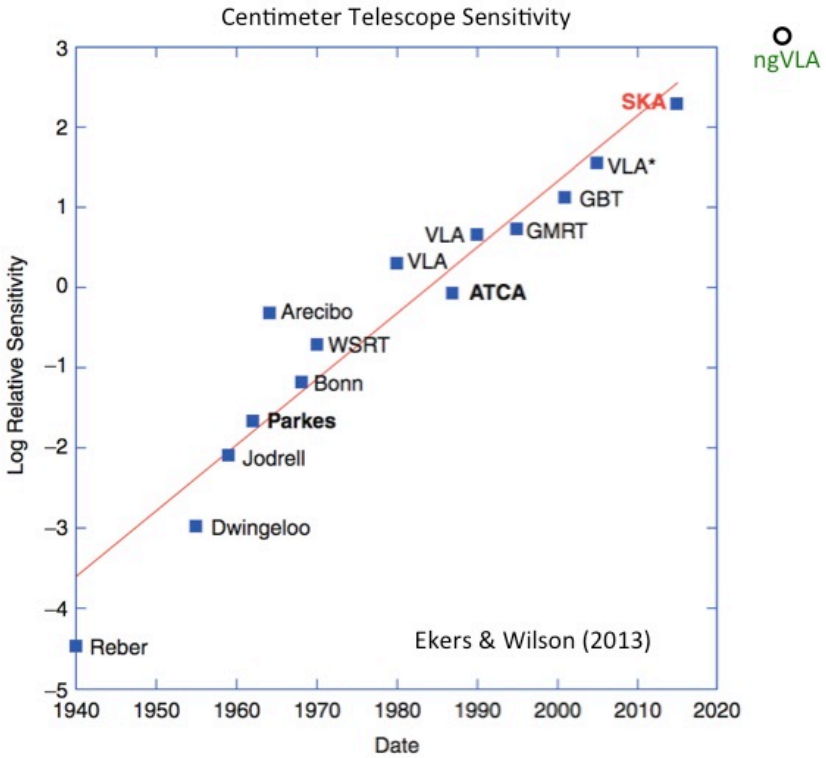
2020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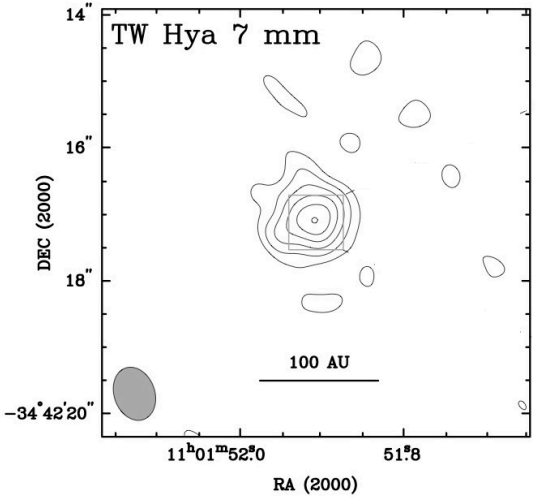
Fast improvement in the field of disks

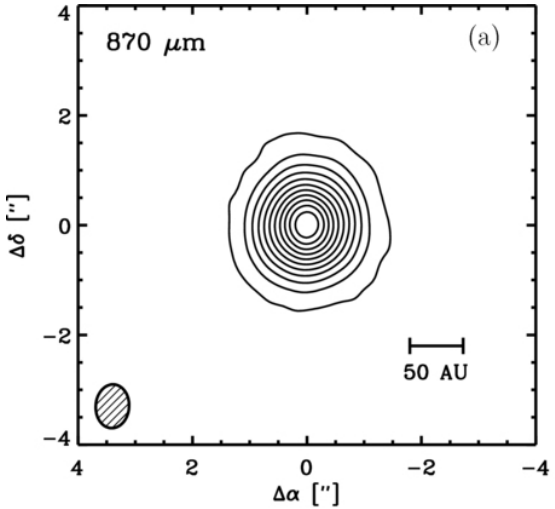
The case of TW Hya D=54 pc Age=9 million years

VLA: 7 mm



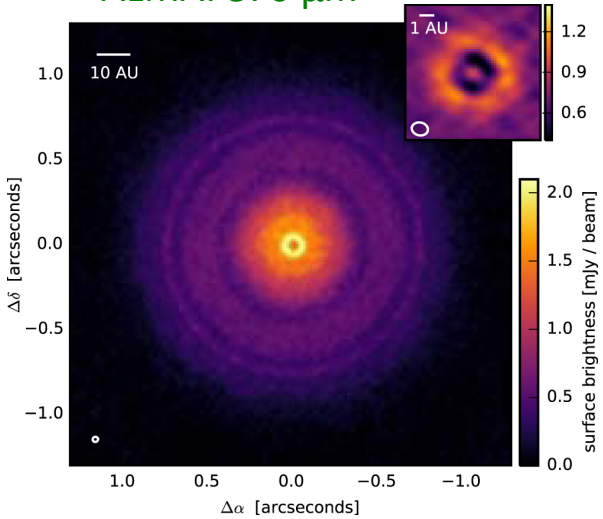
Wilner et al. (2000)

SMA: 870 µm



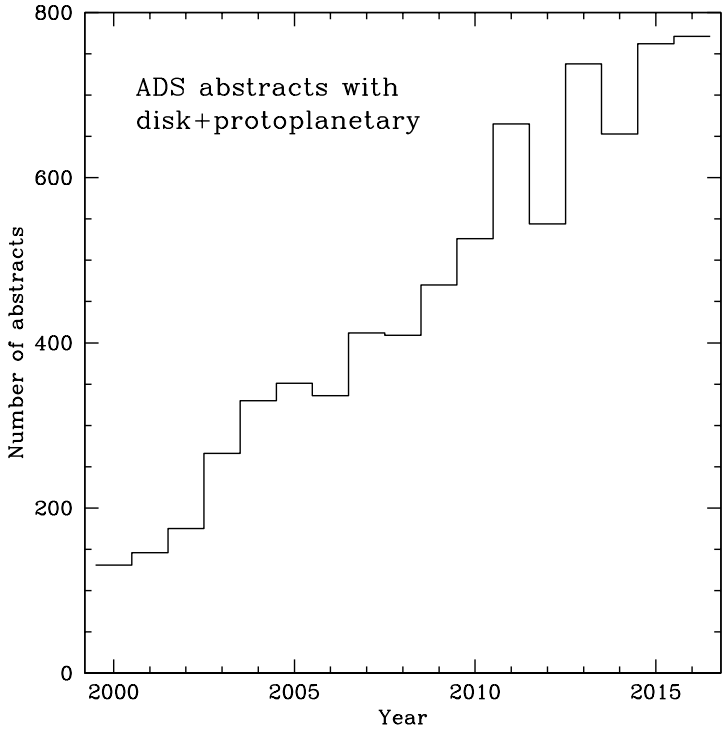
Andrews et al. (2012)

ALMA: 870 µm

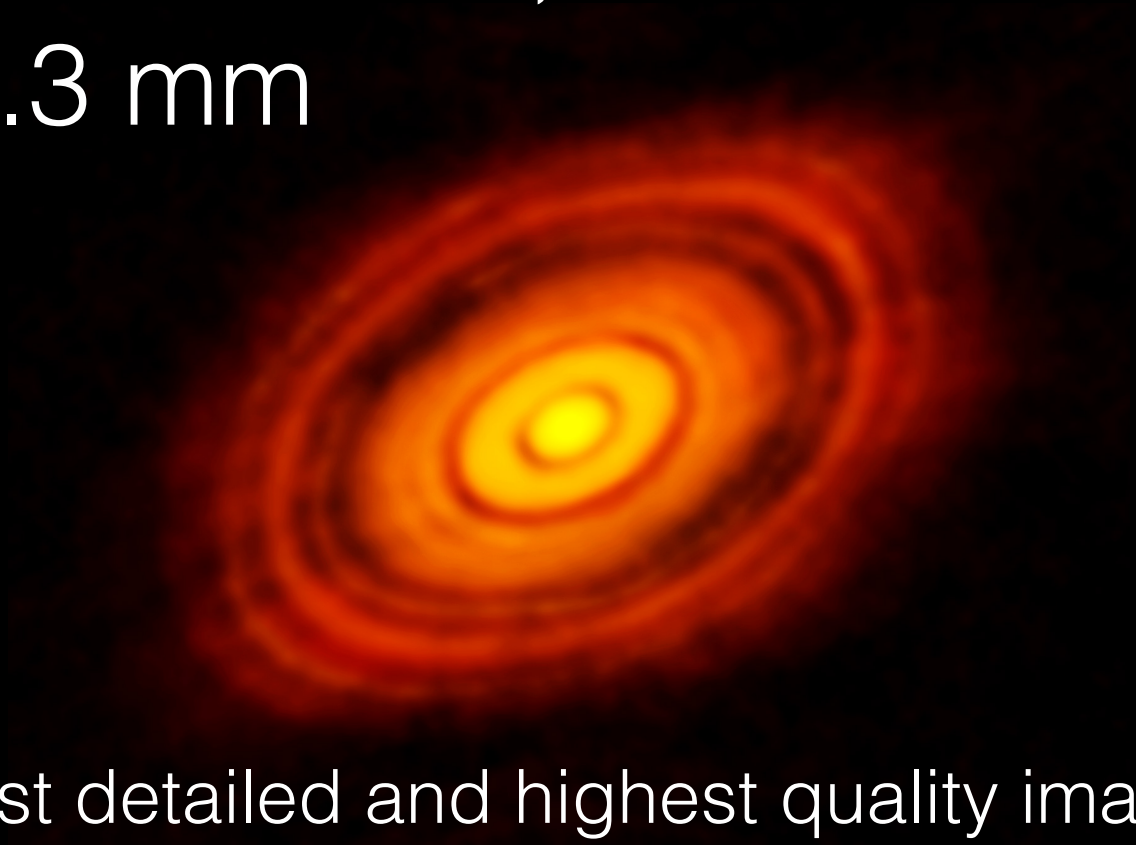


Andrews et al. (2016)

Disk fever: major topic in astronomical literature

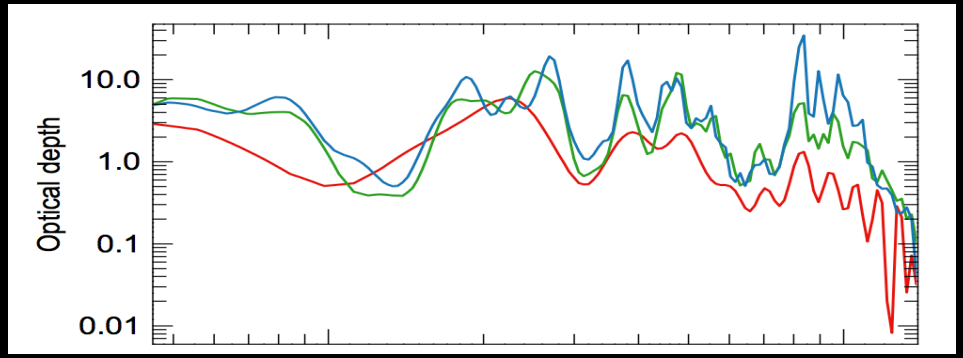


HL Tau @ ALMA;
1.3 mm

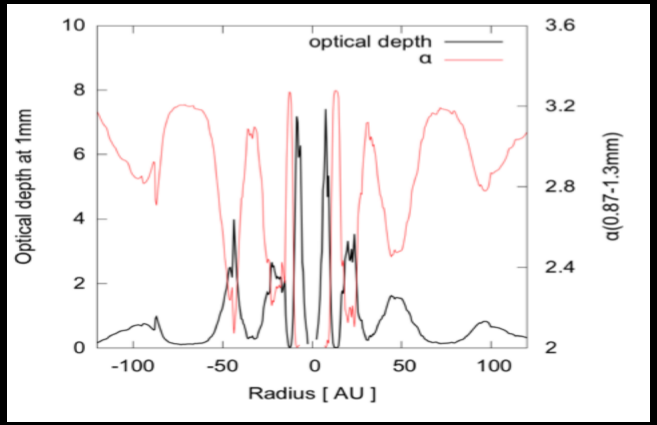


The most detailed and highest quality image of a circumstellar disk (Brogan et al. 2015)

Emission at all ALMA wavelengths is **optically thick**



Pinte et al. (2016)



Jin et al. (2016)

ALMA emission is **optically thick** at the densest parts,
In particular the **internal disk** (<50 AU),
where **terrestrial planets** are expected to form.

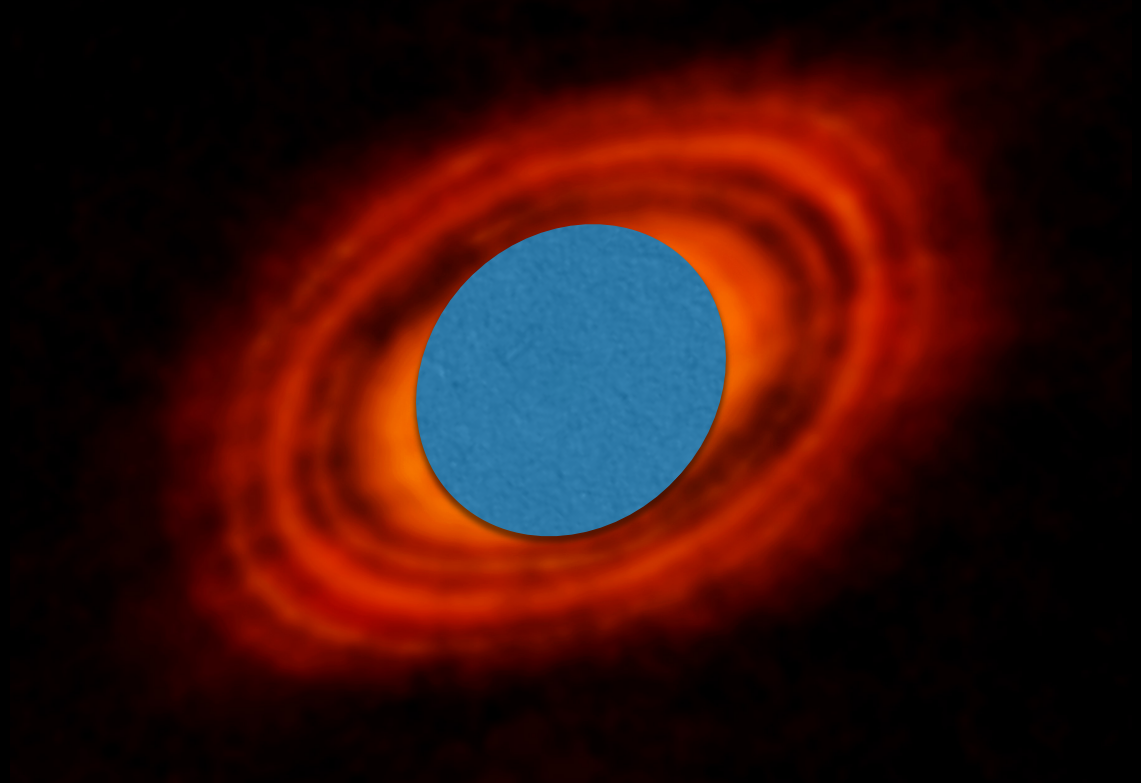
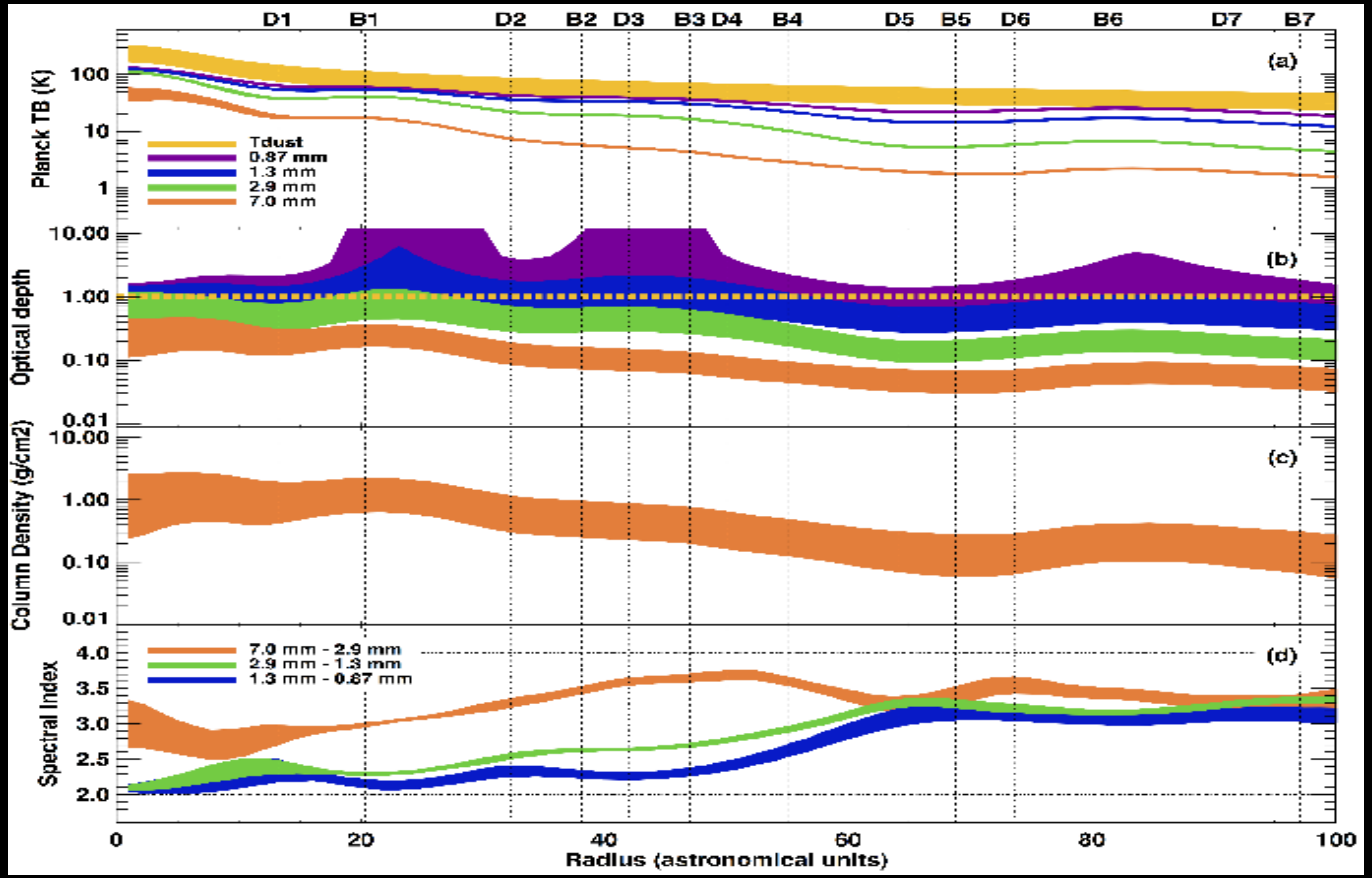


Table 1. Summary of VLA observations at Q band

Obs. Date	Project Code	Conf.	On-source total time
2014-Dec-07	14B-485	C	1.7 h
2015-Feb-15	14B-485	B	1.6 h
2015-Aug-13	14B-487	A	1.1 h
2015-Aug-25	14B-487	A	1.1 h
2015-Sep-16[a]	14B-487	A	1.1 h
2015-Sep-19	14B-487	A	1.7 h
2015-Sep-20	14B-487	A	2.2 h
2015-Sep-20	14B-487	A	1.5 h
2015-Sep-21	14B-487	A	1.7 h
2015-Sep-21	14B-487	A	1.7 h

Carrasco-González et al. (2017)

Dust emission at 7 mm is optically thin



1. Mass distribution in the disk

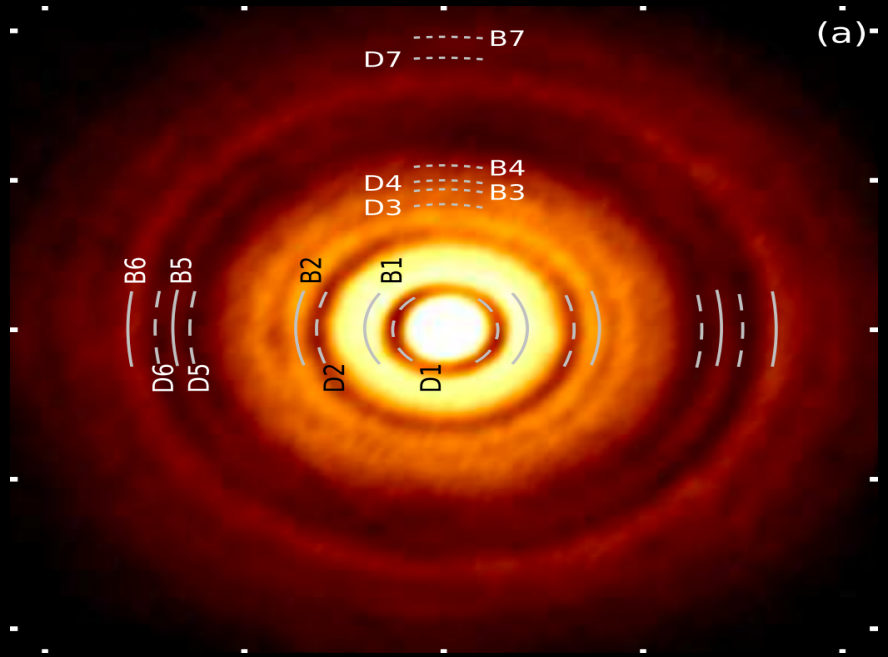
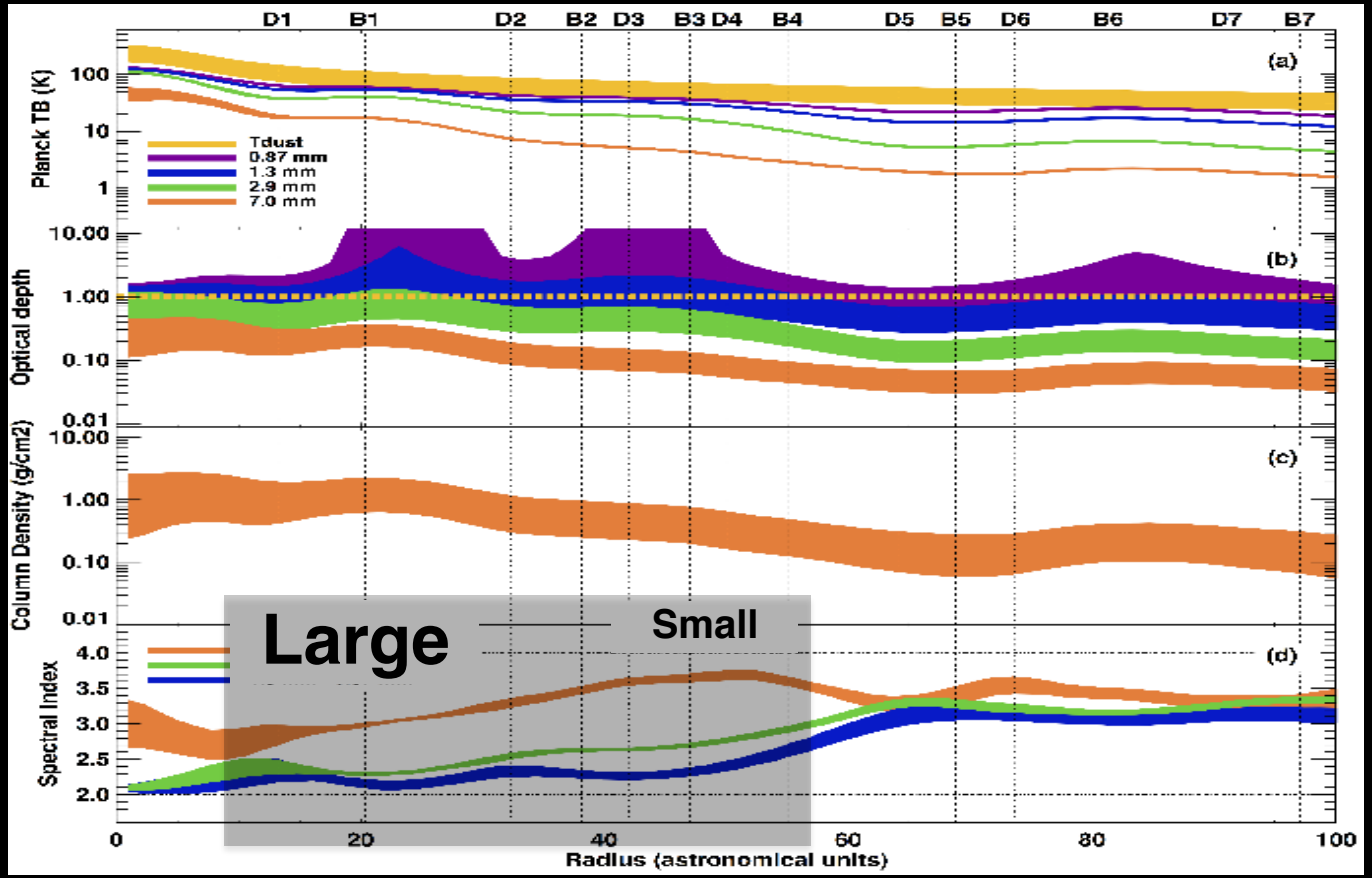


Table 2. Dust masses for the inner disk and bright rings

Disk Feature	Radius (au)	Dust Mass ($M_\oplus$) This paper[a]	Pinte et al.[b]
ID	<13	10 - 50	>2.3
B1	13 - 32	70 - 210	>47
B2	32 - 42	30 - 90	30 - 69
B3	42 - 50	20 - 80	14 - 37
B4	50 - 64	30 - 90	40 - 82
B5	64 - 74	10 - 50	5.5 - 8.7
B6	74 - 90	40 - 140	84 - 129

The most **internal features** of the disk are much **more massive** than previously inferred

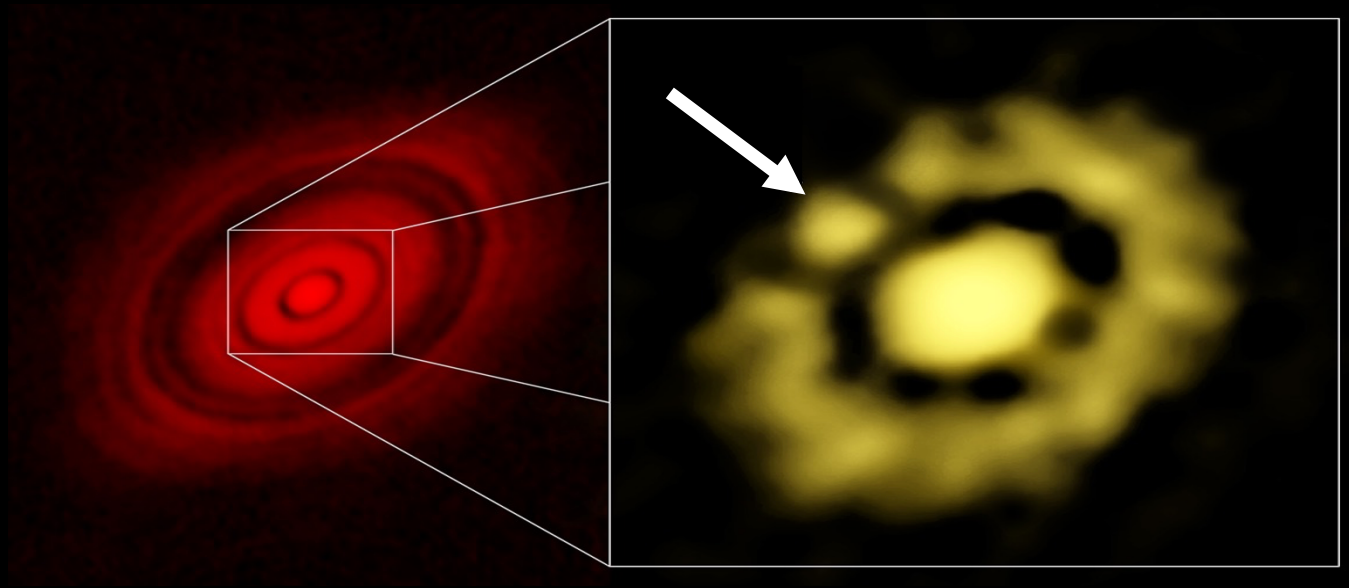
2. Grain Size Distribution



3. Substructure Within the Rings

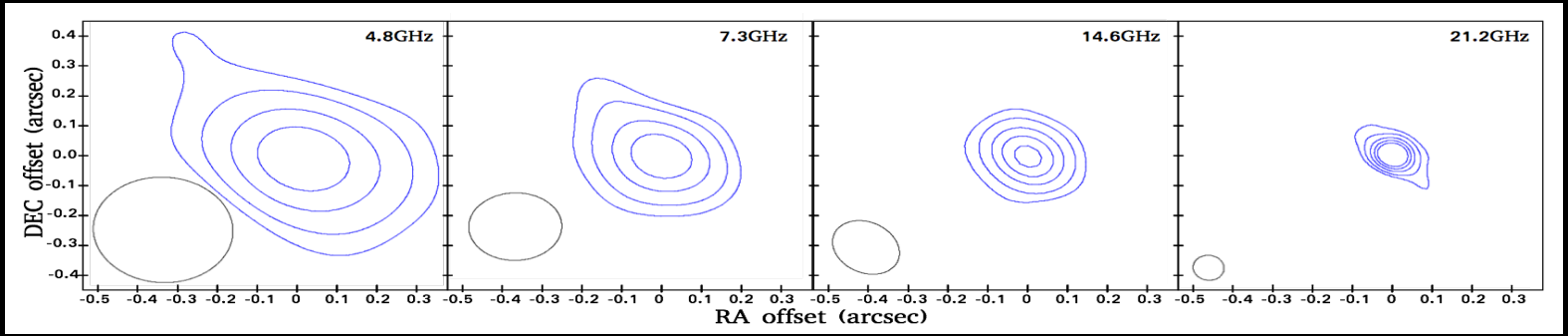
ALMA@
1.3 mm

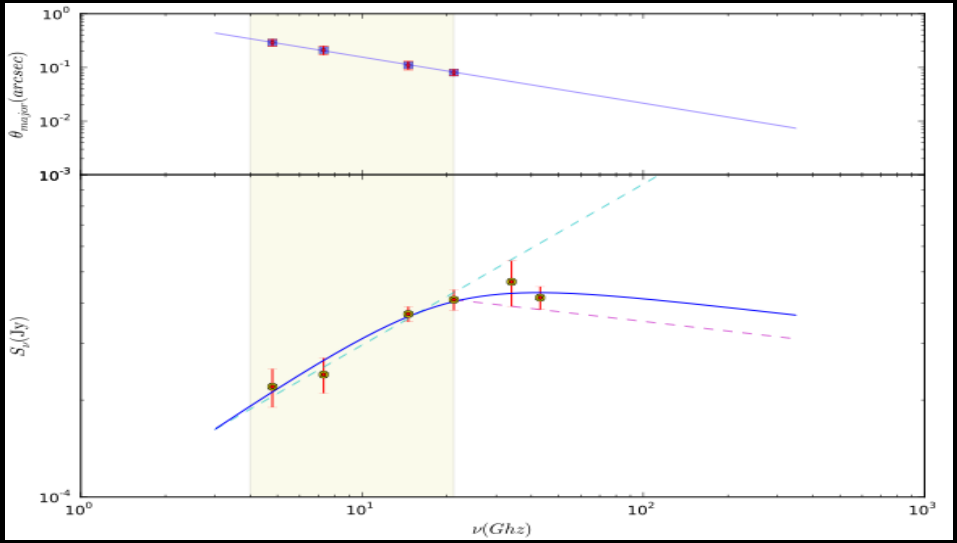
VLA@
7 mm

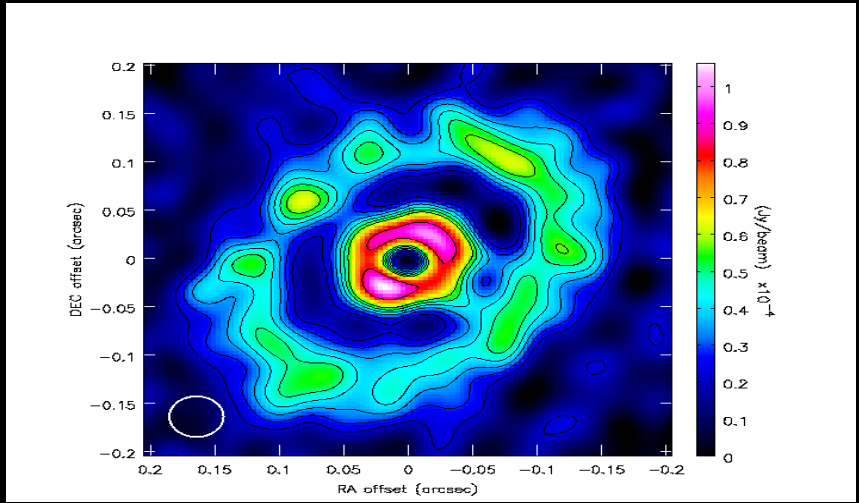


Carrasco-González et al. (2017)

Problem at long wavelengths: The JET







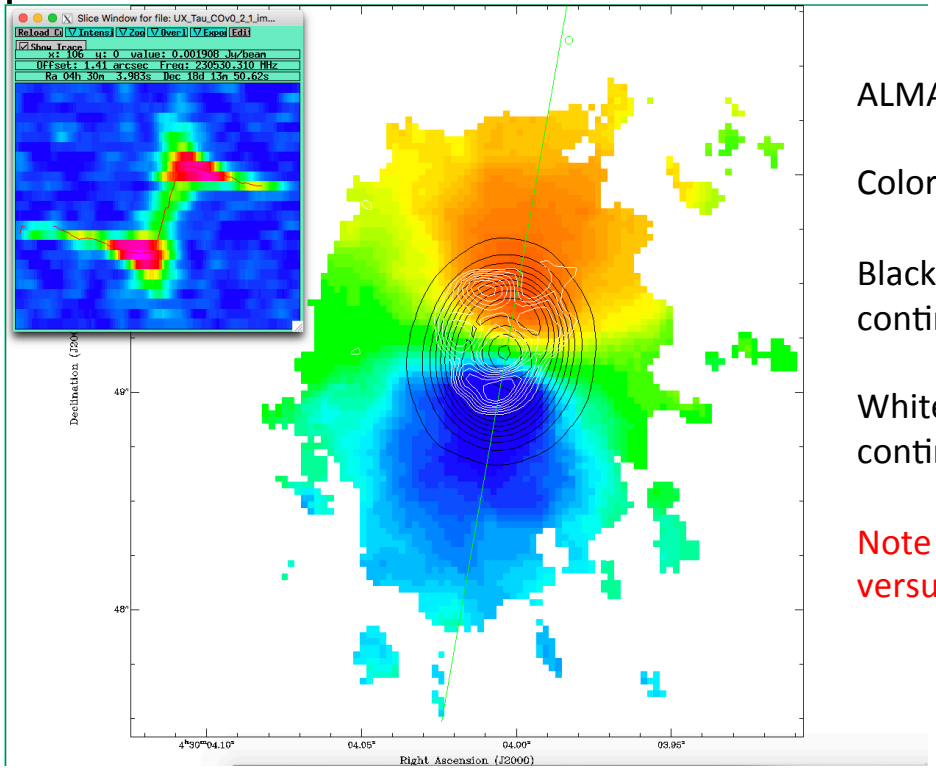
Lumbreras et al., in prep.

You need to understand both the disk and the jet

- Characterization of free-free emission will require very sensitive, high angular resolution observations at centimeter wavelengths, not only a 7 mm.

- Disentangle dust emission from free-free emission. Also other free-free mechanisms such as photoevaporated disks could be present and excellent data will be needed to distinguish it from jets.

The case of the transition disk of UX Tau A D=138 pc



ALMA 1.3 mm

Colors: CO velocity

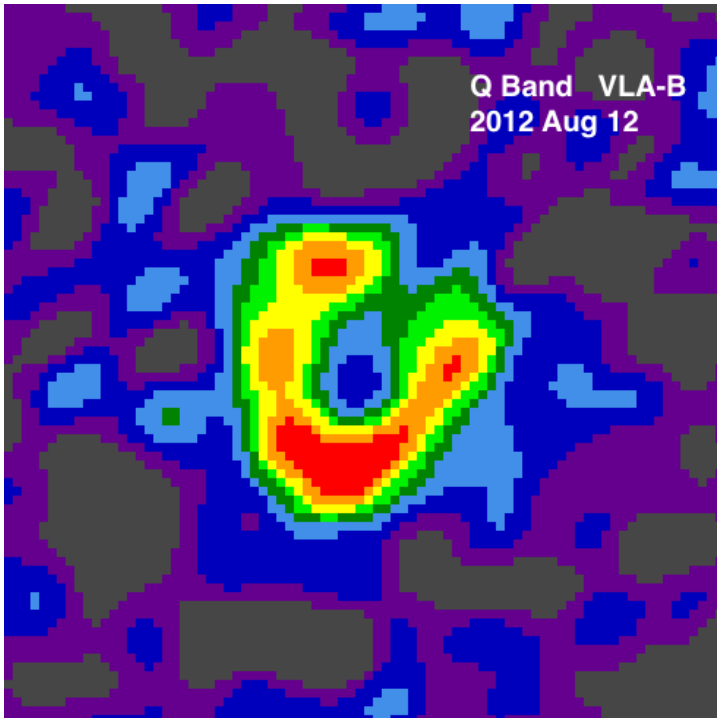
Black contours: 1.3 mm continuum

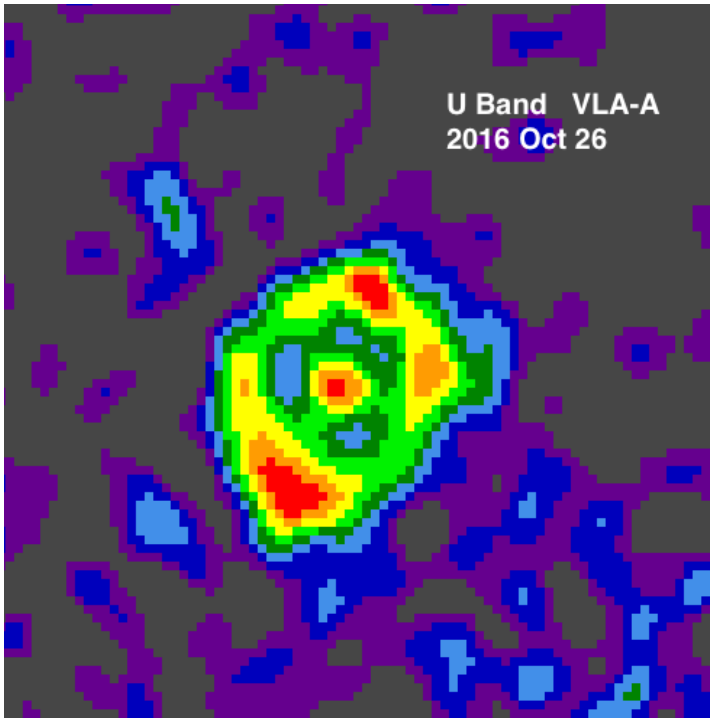
White contours: VLA 7 mm continuum

Note smoothness at 1.3 mm versus clumpiness at 7 mm

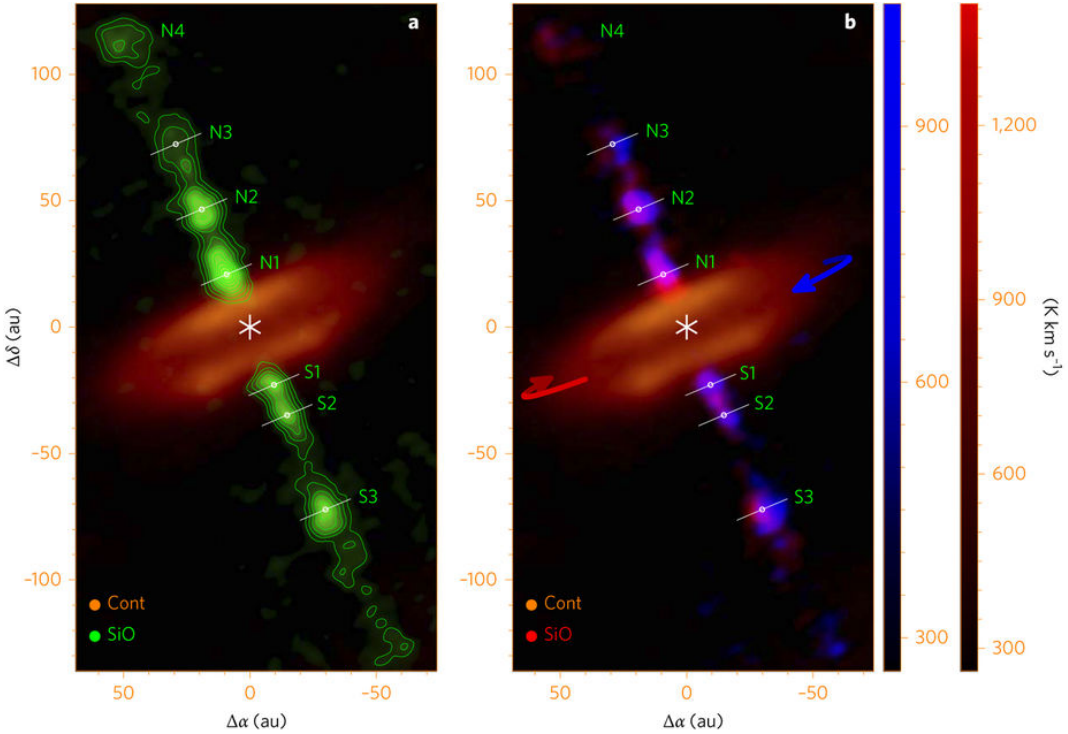
Zapata et al. (2017)

Comparing two optically-thin images: Rotation?





HH 212: Indirect determination of jet launching radius



ALMA data
Orange = 352 GHz dust continuum
Green, blue, violet = SiO J=8-7 transition

Lee et al. (2017)

HH 212 (Lee et al. 2017)

$$\frac{2l_j}{v_j^2}\left(\frac{GM_\star}{r_0}\right)^{1/2} - \frac{3GM_\star}{v_j^2} - r_0 \approx 0 \qquad (1)$$

to find approximate solutions analytically, where r_0 is the launching radius at the footpoint, v_j is the jet velocity, l_j is the specific angular momentum of the jet measured at a large distance, G is the graviational constant and $M_\star$ is the mass of the central protostar. Solving this equation, we find the jet launching radius to be:

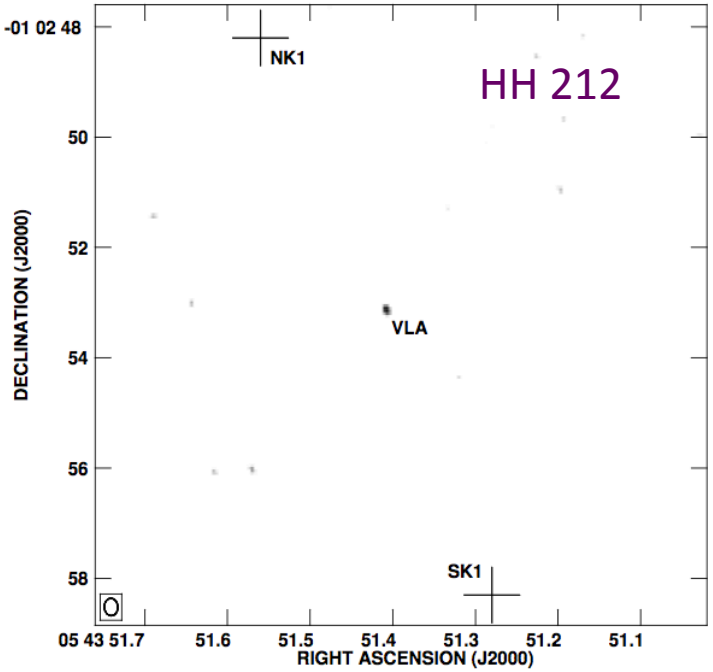
$$r_0 \approx \left(\frac{2l_j}{v_j^2}\right)^{2/3} (GM_\star)^{1/3}\left[1 - \tfrac{2}{3}\eta + \tfrac{1}{9}\eta^2\right] \qquad (2)$$

with

$$\eta = \frac{3}{2^{2/3}}\left(\frac{GM_\star}{v_j l_j}\right)^{2/3} \qquad (3)$$

➔ $r_0 \approx 0.05$ AU

The jet is also detected as faint, compact VLA source



VLA-A, X-band

Jet detected at 40±10 μJy

Galván-Madrid et al. (2004)

ngVLA will reach resolution of 1 AU in nearby regions of star formation, allowing the best direct estimate of jet launching and collimation scales.

Radio recombination lines from jets and other faint free-free sources (stellar winds, UCHII regions)

- Wide (100s of km/s), weak lines in the centimeter regime.
- Assume jet or wind:
- $S_C(\nu)$ goes as $\nu^{0.6}$ Assume line has Δv = 300 km s^{-1}

$$\frac{S_L}{S_C} = 0.19\left(\frac{\nu_L}{\mathrm{GHz}}\right)^{1.1}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1.1}\left(\frac{\Delta v}{\mathrm{km\ s^{-1}}}\right)^{-1}(1+Y^+)^{-1}$$

Anglada et al. (2017)

Further assume S_C(10 GHz) = 1 mJy ➔ S_L(10 GHz) = 8 μJy

Which present-day VLA band gives you the best chance?

Radio recombination lines from protostellar jets

Channels of 100 km s^{-1}, 20 hours total time, stacking all lines in band.

Band	Frequency (GHz)	Number of RRL	Noise in channel (μJy)	RRL flux density (μJy)	Signal-to-noise ratio
L	1.5	37	17	0.3	0.02
S	3.0	31	9	1.0	0.11
C	6.0	23	6	3.4	0.57
X	10.0	11	6	8	1.3
Ku	15.0	5	10	16	1.6
K	22.0	8	13	31	2.4
Ka	33.0	8	11	61	5.5
Q	45.0	4	26	103	4.0

Many other important problems in “Craddle of Life”

Table 2 Technical requirements of the ngVLA “Cradle of Life” science cases

(1) Science case	(2)	(3) Frequency (GHz)	(4) Sensitivity (μJy bm^{-1})	(5) Angular res. (mas)	(6) Max. Ang. Scale ($''$)	(7) Vel. res. (km/sec)
§ 2.1 **HII regions & high-mass jets**	cont	10–50	1-10	5–20	5	—
§ 2.1 **HII regions & high-mass jets**	line	40–100	1	20	5	1
§ 2.2 Infall via spectral line absorption	line	18–40	100 K	20	10	1
§ 2.3 Polarization in star-cluster-forming cores	cont	40–50	—	5–100	5	—
§ 2.4 Star formation in the galactic center	cont	20–70	0.1	10–20	2	—
§ 3.1 **Binary/multiple protostars**	cont	10–30	1–10 K	20	< 1	—
§ 3.2 Dust polarization	cont	20–50	1	100–3000	< 5	—
§ 3.3 Structure of protostellar jets	cont	4–30	0.5	20–150	10	—
§ 4.1 **Mapping planet formation**	cont	10-50	1 K	1–10	<5	—
§ 4.2 **Probing dust/pebble distribution in disks**	cont	10–50	1 K	1–50	<5	—
§ 5.1 Complex molecules in hot cores	line	18–50	0.15 K	20–100	<5	0.1–0.5
§ 5.2 **Chemistry (NH_3) of planet-forming regions**	line	10–40	1K	20–5000	<5	0.1-1
§ 6.1 Debris disks	cont	10–100	0.1	1000–5000	50	—
§ 7.1 **Deep atmospheric mapping**	cont	1–50	—	<0.5	50	—
§ 7.2 (Sub)surface thermal emission	cont	10–50	—	<0.05	8	—
§ 7.3 (Sub)surface structure using bistatic radar	cont	2–8	—	<0.05	1	—
§ 7.4 Comet chemistry	line	22–24	—	<0.5	300	<0.2
§ 7.5 Planetary rings	cont	10–50	—	—	120	—
§ 7.6 Jupiter synchrotron emission	cont	10–50	—	—	200	—
§ 8.1 SETI	line	5–100	>5× JVLA	—	0.5 deg^2 FOV	0.1 Hz

Table 2: Technical requirements for each of the ngVLA science cases presented by the “Cradle of Life” working group. Key Science Projects (KSPs) are in bold.

Murphy et al. (2017)

Requirements on:

Sensitivity
Angular Resolution
Spectroscopy
Polarization
Extended emission
Variability in time

Conclusions

- The study of disks and jets will require of observations over a wide range of frequencies to obtain optically-thin emission images and to correct for contribution of free-free. Also need to understand different sources of free-free.
- The possibility of imaging radio recombination lines from free-free jets and very faint HII regions will be valuable for kinematics.
- The ngVLA will be key instrument for these observations and many other related to star formation.