Millimeter-Wave Astronomy – The Green Bank Connection

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NATIONAL RADIO ASTRONOMY OBSERVATORY

Topics

- Part 1
  - Millimeter-wave Astronomy -- 50 years that changed our view of the universe
- Part 2
  - Much of it started here in Green Bank!
- Part 3
  - How it came full circle
- Part 4
  - What's Next?

Part 1: 50 Years that Changed Astronomy

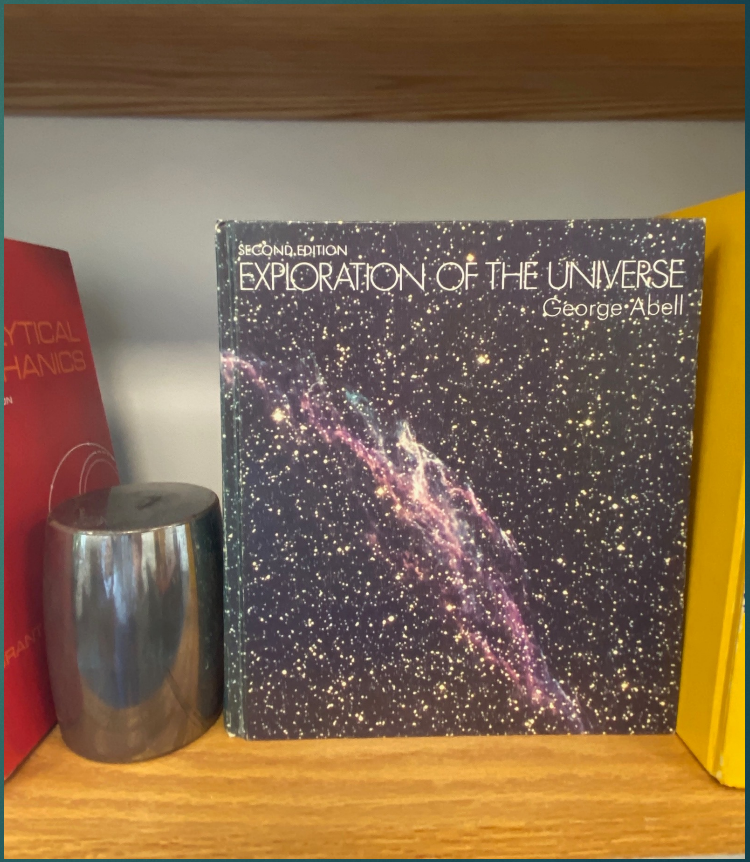
A COOK'S TOUR OF MILLIMETER / SUBMILLIMETER-WAVE ASTRONOMY

The Headliners…..

- Over the past 52 years…. Millimeter / Submillimeter astronomy has
  - Defined the gas content and structure of our Galaxy and other galaxies
  - Revealed the chemical content, and chemical complexity of the Galaxy….
  - Shown how galaxies evolve from the very early universe onward
  - Greatly advanced understanding of many fundamental astrophysical processes, including
    - Star formation
    - Planet formation
    - Life-cycle of stars – return of material to the ISM from dying stars
  - Revealed amazing physical phenomena, including
    - Einstein Rings
    - Images of the event horizons of black holes

What was known pre-1970

- Abell 2nd Edition 1969 edition
  - My Intro to Astronomy textbook
  - One chapter on ISM
    - Focus on Dark Nebulae, Reflection Nebulae, HII Regions
    - What was known from optical astronomy
  - 3 paragraphs on how dust and gas condense into stars
    - Not much detail, other than it must happen
  - Nothing much known about molecular gas or how galaxies evolve



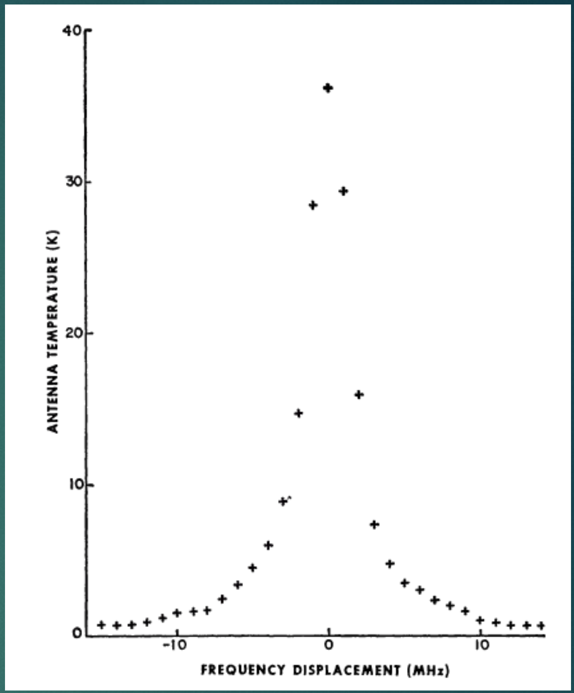
Interstellar Molecular Gas

- The first interstellar molecules detected
  - CH, CH+, CN – known optically (1937-1941)
  - OH – Weinreb 1963
  - NH_3 - Cheung +4 1968 – Hat Creek
  - H_2O – Cheung +4 1969 – Hat Creek
  - H_2CO (Formaldehyde) 1969 Snyder, Buhl, Zuckerman, Palmer - 140 Foot
    - 1969 Phys. Rev. Lett., Vol. 22, 679
    - First polyatomic organic molecule found in space

And Then…..

- In 1970: CO, HCO^+ , and HCN were detected…
  - Wilson, Jefferts & Penzias 1970 ApJ **161** L43
  - Buhl & Snyder 1970 Nature **228**, 267
  - Snyder & Buhl 1971 ApJL **163**, L47

- Millimeter-wave astronomy was off to the races….



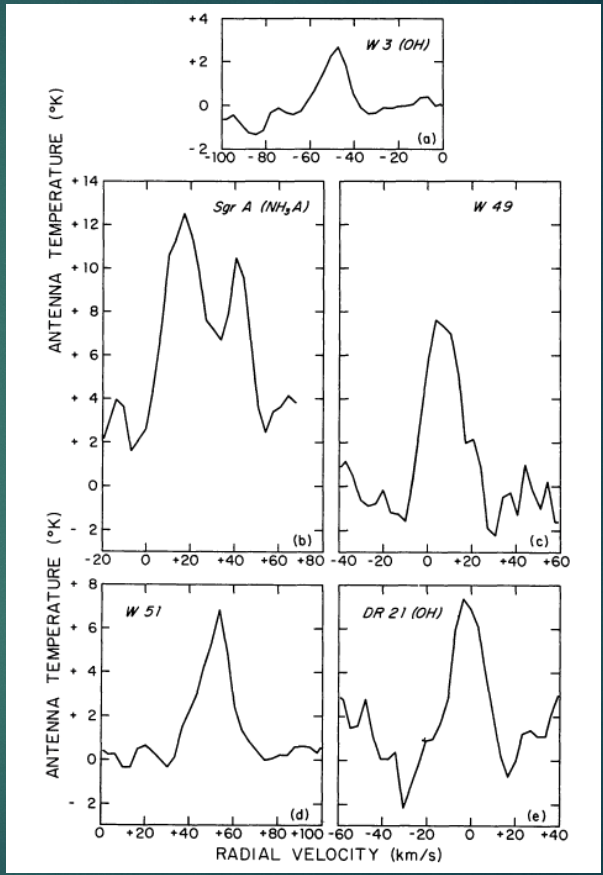
First detection of CO in Orion
Wilson, Jefferts, Penzias

The detection of the first few mm-wavelength molecular lines changed astronomy

- Early observations yielded:
  - CO is ubiquitous in the Galaxy (and the universe)
  - It is a proxy for molecular hydrogen (H_2), for which most molecular mass resides, but is difficult to observe owing to its rotational symmetry
  - HCN, HCO+ less optically thick, could probe denser regions….
- => mm-wave spectroscopy could explore chemical make-up, and be used as an astrophysical diagnostic

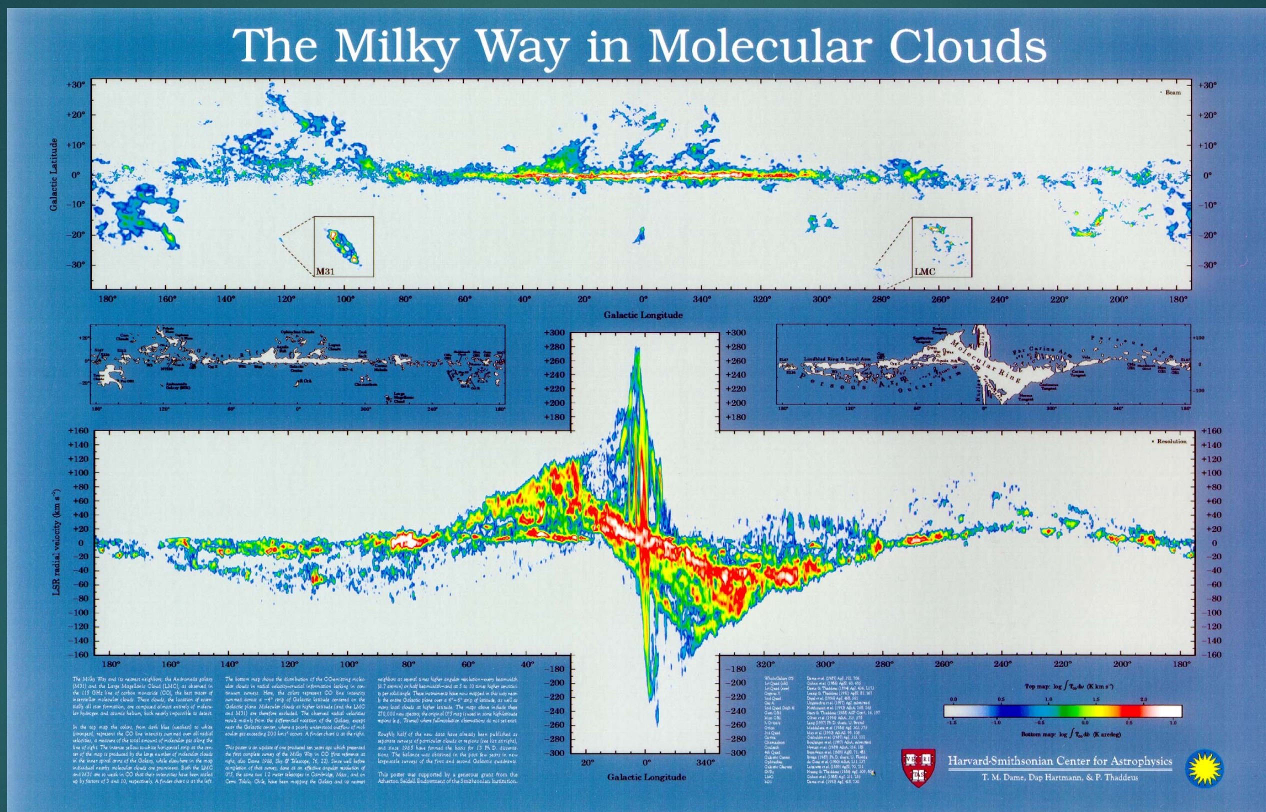
Early mm-wave astronomy was difficult – and highly competitive!

- First lines were a struggle even to detect →
- But by 1975, ^{12}CO surveys were already characterizing the Galactic distribution of molecular hydrogen
  - Scoville & Solomon 1975 ApJL **199**, L105
  - Burton, Gordon, Bania & Lockman 1975 ApJ **202** 30
- And ~10 years later, surveys were yielding this……



First detection of 1-0 HCN – Snyder & Buhl

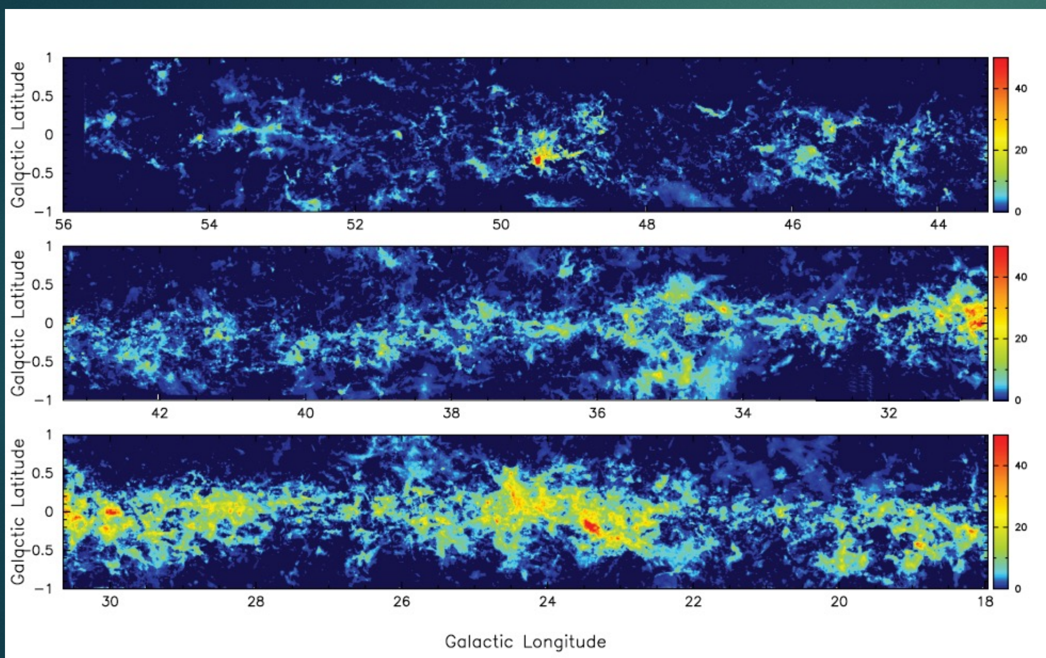
Molecular Cloud Structure of the Galaxy was Defined



Dame, Hartmann, & Thaddeus / Dame +8 1987 ApJ **322** 706; updated in Dame, Hartmann & Thaddeus 2001 ApJ **547** 792

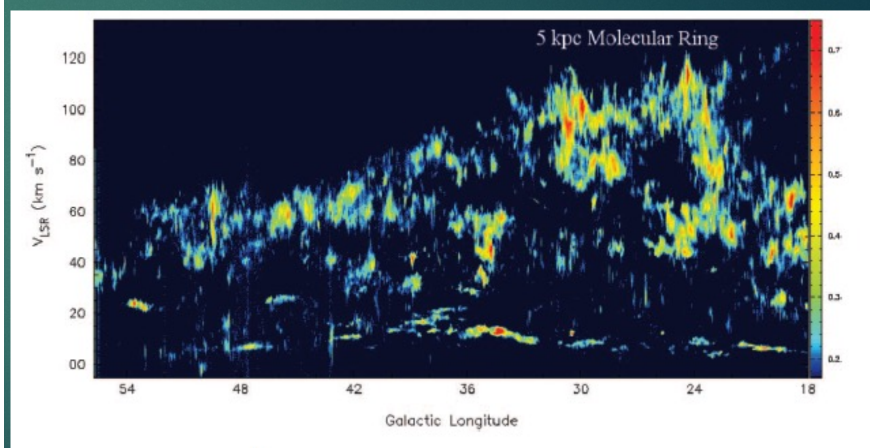
Galactic Molecular Structure Refined….

- ^{13}CO 1-0 Survey of the 5 kpc Galactic Ring
  - ^{13}CO less optically thick, less line blending



Integrated Intensity

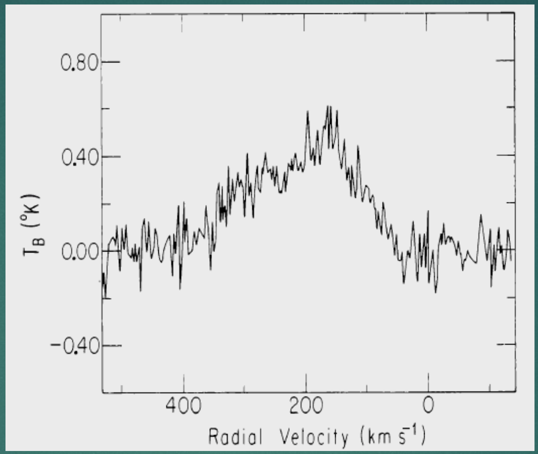
J. Jackson +9 2006 ApJS **163** 145



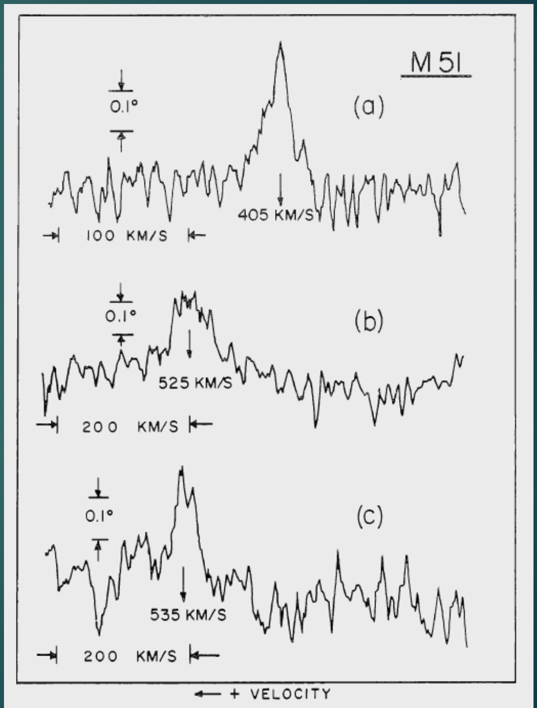
Position-Velocity

Extragalactic CO…

- In 1975, CO was detected in other galaxies
  - Rickard, Palmer, Morris, Zuckerman & Turner 1975 ApJL **199** L75 [M82, NGC 253]
  - Solomon & de Zafra 1975 ApJL **199**, L79 [M82, NGC 253, M31]
    - NB – back-to-back ApJ Letters!
- Detections were similarly difficult….
- But from these challenging early days, we can now do this…..



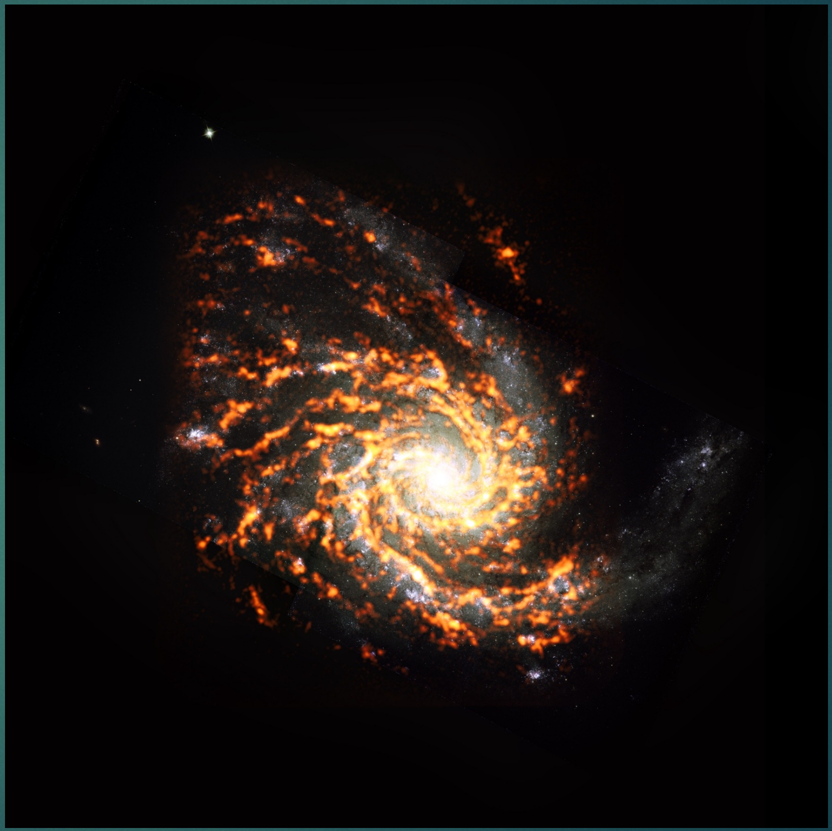
Detection of J=1-0 CO in M82
Rickard, Palmer, Morris, Zuckerman & Turner 1975



Detection of J=1-0 CO in M51
Solomon & de Zafra 1975

Determine the detailed structure of other galaxies….

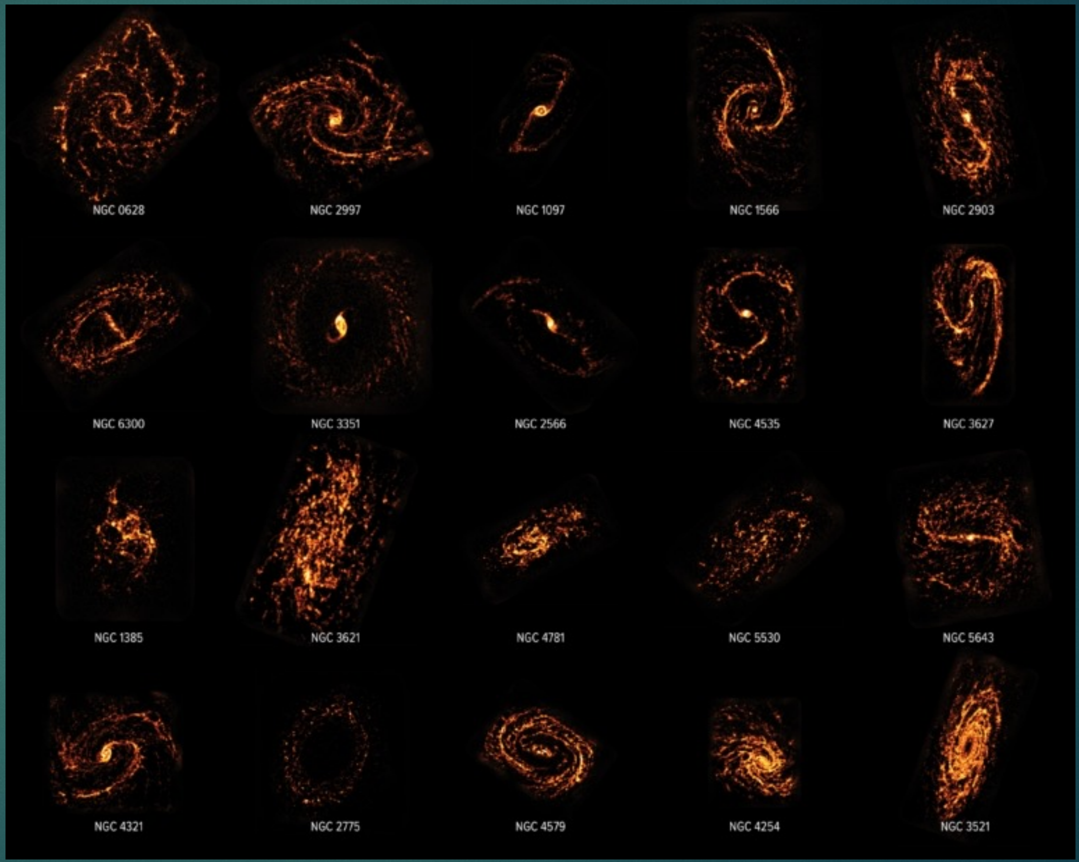
- PHANGS-ALMA Arcsecond CO(2-1) Imaging of Nearby Star-Forming Galaxies.
  - Leroy, Schinnerer +many 2021 ApJS **257** 43
  - NGC 4254
    - Composite Image with HST
    - ALMA 2-1 CO in Orange



ALMA (ESO/NAOJ/NRAO)/ESA/NASA/PHANGS, S. Dagnello (NRAO)

Determine diversity of structures….

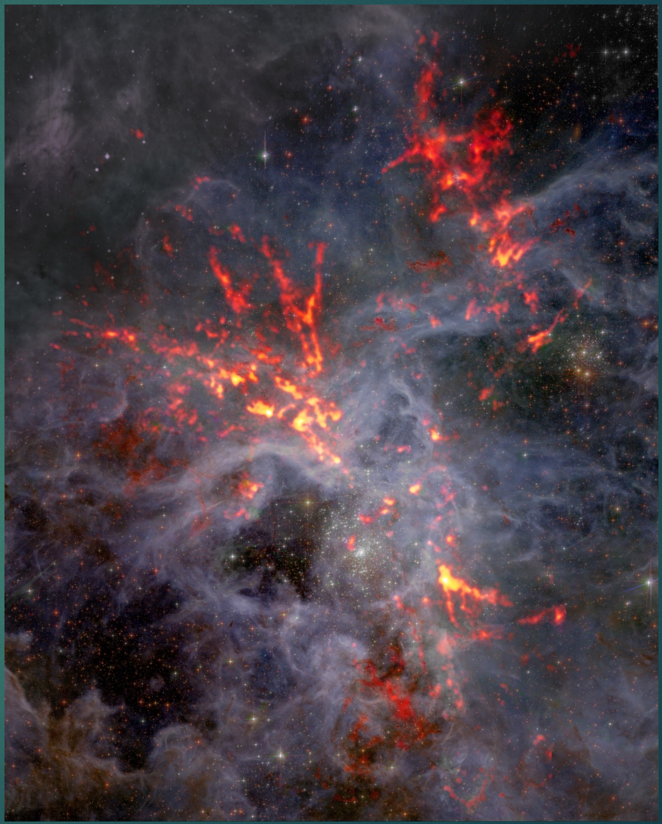
- PHANGS-ALMA
  - Leroy, Schinnerer +many 2021 *ApJS* **257** 43
- PHANGS found great diversity among galaxies –
  - ~same angular resolution as optical surveys
  - stellar nurseries vary widely in appearance and behavior – not all the same!
  - characteristics depend heavily on where the stellar nurseries are located.



ALMA (ESO/NAOJ/NRAO)/ESA/NASA/PHANGS, S. Dagnello (NRAO)

And see this….

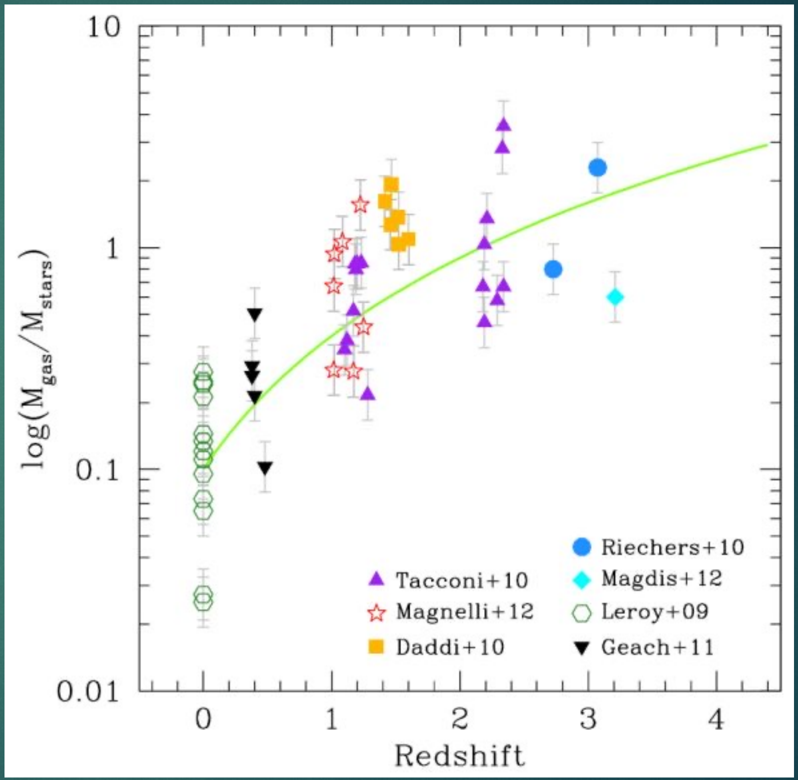
- ALMA observations of the 30 Doradus Star formation region in the Large Magellanic Cloud
  - T. Wong +23 2022 ApJ **932** 47
- 2-1 ^{12}CO & ^{13}CO
- Complex filamentary structures
- Turbulence and stellar feedback evident, but gravity dominant



ALMA (ESO/NAOJ/NRAO), T. Wong et al (U. Illinois, Urbana-Champaign), S. Dagnello (NRAO/AUI/NSF)

Evolution of the Universe

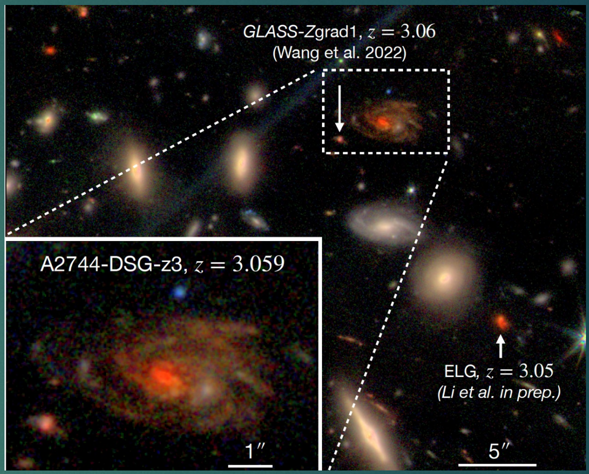
- Multiple observers using different telescopes have characterized the mass content of galaxies vs redshift -- largely via CO observations
- Peak of star formation occurs at redshifts of ~z=2.5-3
  - Gas mass exceeds stellar mass at these redshifts

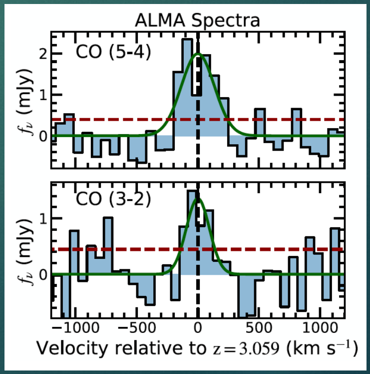


Carilli & Walter 2013 Ann Rev A&A **51**, 105

Dusty Grand Design Spiral Galaxy at z=3.06 Revealed by ALMA+JWST

- Wu+ arXiv:2208.08473 ; (SOS) award SOSPA7-022, ALCS LP data
- A gravitationally lensed (by a factor of a few) submm galaxy found by ALMA is imaged by JWST.
  - Redshift 3.07 from ALMA CO observation took ~10 mins each line;
  - Most distant grand-design stellar spiral structure seen thus far
  - Consistent with cosmological simulations which suggests z≈3 as the epoch when grand-design spirals emerge.
- Galaxy is similar to grand design spirals such as Milky Way
  - Meets the ALMA science goal to 'detect CO or [CII] in a galaxy 'like the Milky Way' at a redshift of z=3, in less than 24 hours of observation.'





Chemical Content & Complexity of the Universe….

- Since initial detections, >260 other interstellar and circumstellar molecules have been detected
  - Provide physical diagnostics – temperature, density, morphology & *kinematics*
  - Indicate path of chemical evolution in interstellar and protostellar nebulae – including biological precursors
- ***cf. Brett McGuire colloquium in this anniversary series – Sep 22nd!!***

McGuire – 2022 ApJS, **259**, 30

Table 2

List of Detected Interstellar Molecules with Two to Seven Atoms, Categorized by Number of Atoms, and Vertically Ordered by Detection Year

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	H_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

Table 3

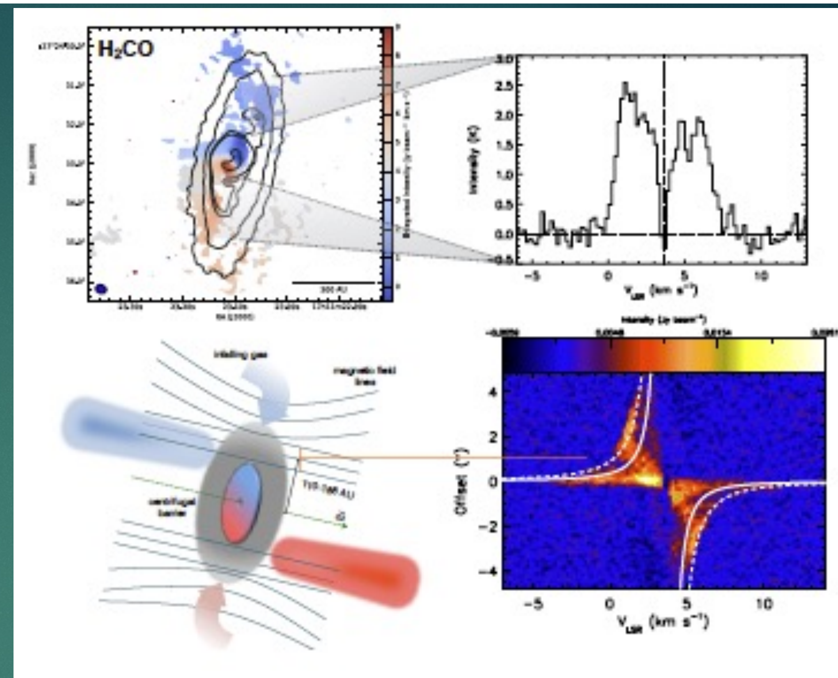
List of Detected Interstellar Molecules with Eight or More Atoms, Categorized by Number of Atoms, and Vertically Ordered by Detection Year

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3CH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	HCCCHCHCN						
CH_2CHCCH	H_2CCHC_3N						

Note. Column headers and molecule formulas are in-document hyperlinks in most PDF viewers.

Star Formation

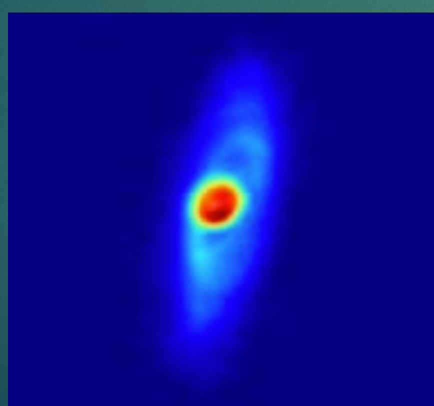
- Jeans instability for gravitational collapse derived in 1902 (when gravitational mass exceeds internal gas pressure)
- Not much advancement between 1902 and late 1960s -- no new observational information!
- Following the detection of CO, this changed!
- Theorists dominated the 70s and 80s (e.g, Shu, Larson, ++) as observations were sensitivity and resolution-limited
- Now, the features of those models can be observed in action



Alves +7 2017 A&A **603** L3

Object exhibits bipolar outflow that appears efficient in removing angular momentum from the system

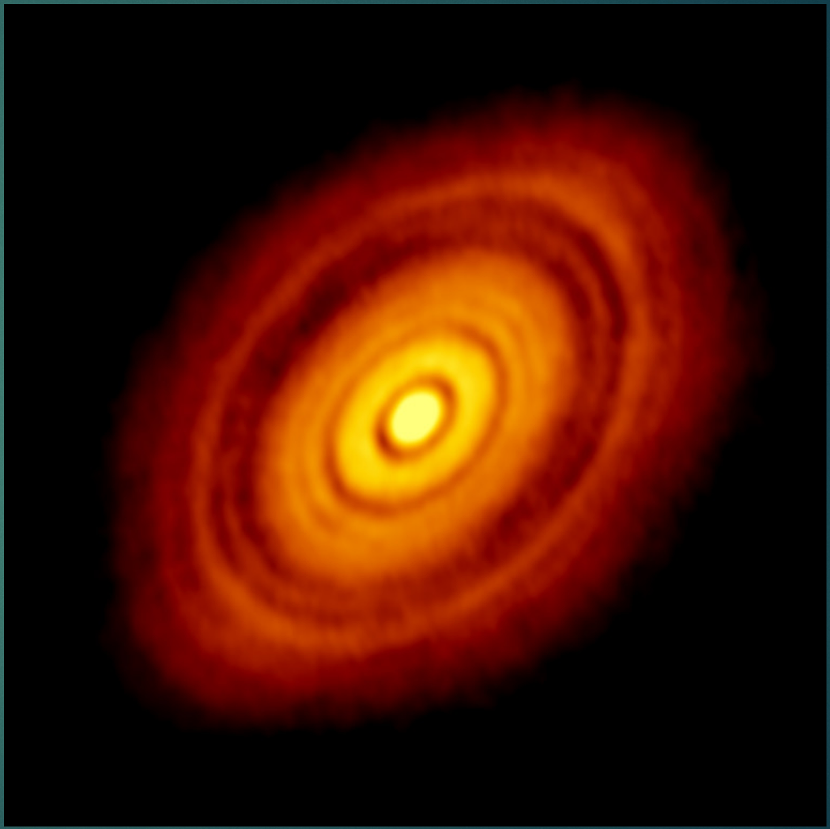
Spectrum in upper right is characteristic of infall motion



BHB07-11 (B59)
Continuum contours

Formation of Planets

- HL Tau circumstellar disk
  - Continuum emission at 2.9, 1.3, and 0.87mm -> cold dust!!
- ALMA Partnership, C. L. Brogan +many 2015 *ApJL* **808** L3
  - Paper recently passed 1000 citations!



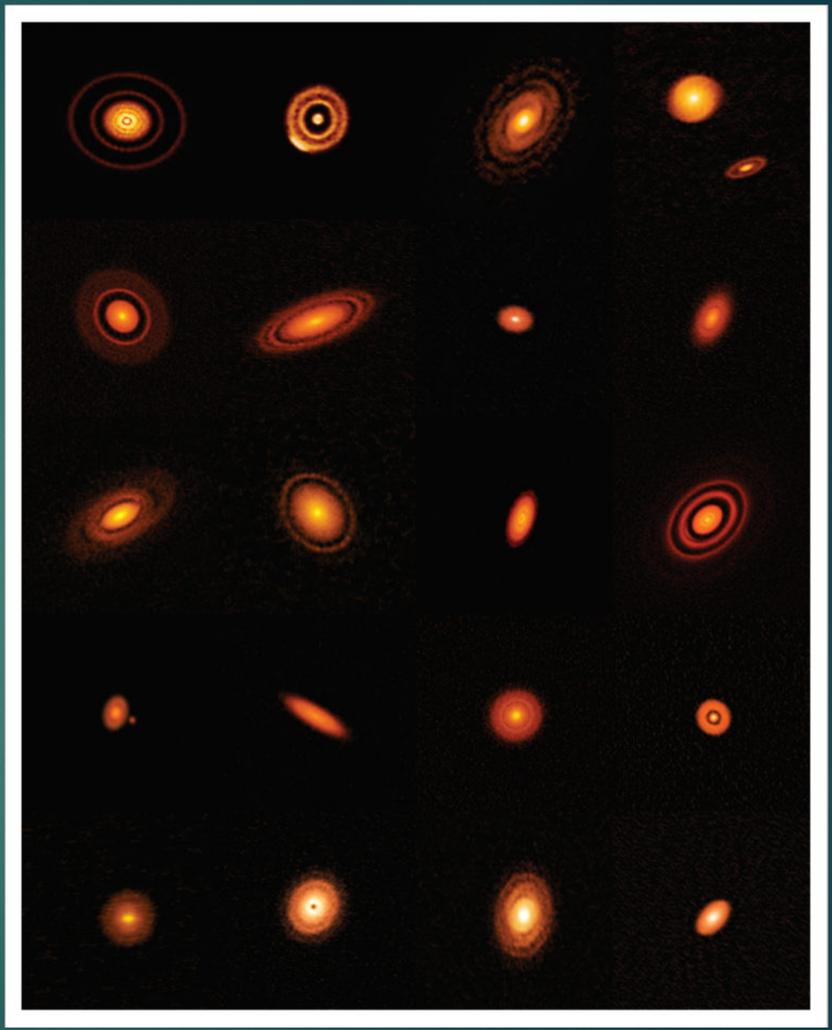
Credit: ALMA(ESO/NAOJ/NRAO); C. Brogan, B. Saxton (NRAO/AUI/NSF)

Planetary disks abound… and can be studied in detail

- DSHARP
  - Andrews *et al* 2018 *ApJL* **869** L41ff (ApJ Letters special issue)

- Observations of 20 Planetary Disks

- Possible interpretation: Large planets similar in size and composition to Saturn and Neptune form early and rapidly, and serve to protect terrestrial-type planets from collision & destruction

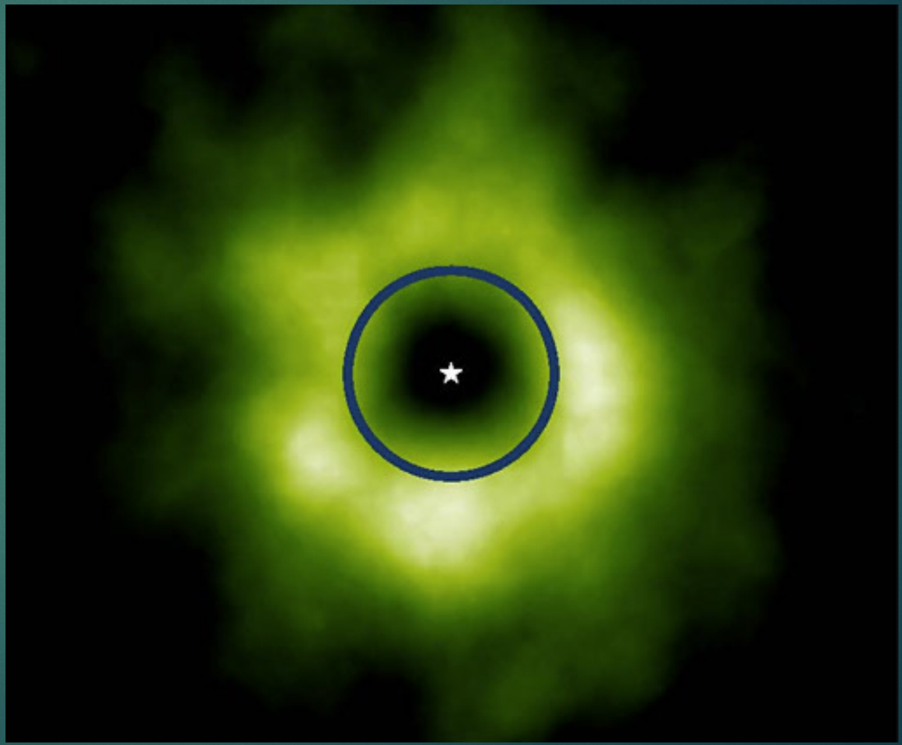


Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello

Understanding of planet formation grows…

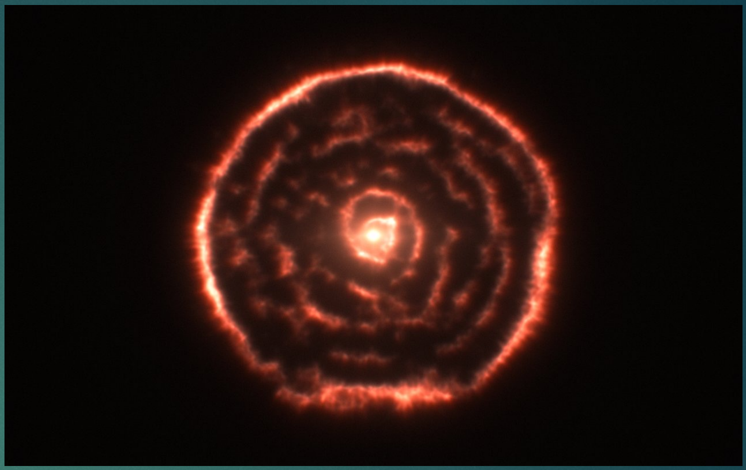
- TW Hydrae snow line detection
  - Qi +8, Science, **341**, 630
- As gas freezes out on grains – the snow line – the grains become stickier and can promote grain growth

- Right: ALMA image (green) shows the region where CO snow line has formed around the star TW Hydrae (indicated at center). The blue circle represents where the orbit of Neptune would be when comparing it to the size of our solar system.



Stellar Death

R Sculptoris



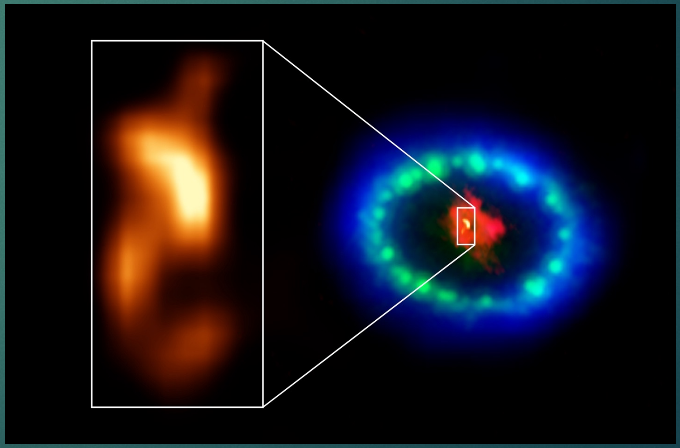
Credit: ALMA (ESO/NAOJ/NRAO)/M. Maercker et al.

TOP

- Maercker +12 2012 Nature **490** 232
- ALMA observations of ^{12}CO @ 1.3"
- Was previously thought to be only a thin, spherical shell with a clumpy structure, now revealed to contain a spiral structure
- Likely a binary system that underwent a thermal pulse 1800 yrs ago

BOTTOM

- SN 1987A composite image
  - Page ea 2020. *ApJ* 898, 125
  - Cigan ea 2020.. *ApJ 886*, 51
- Hot blob in the dusty core of SN 1987A (inset), may be the location of the long-sought neutron star in SN1987A

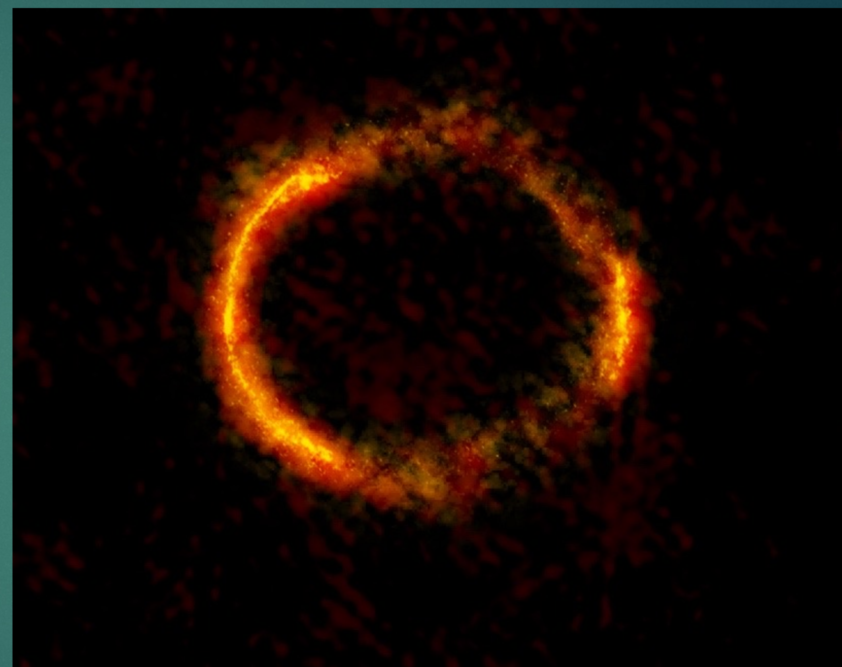


Credit: NASA, ESA, and NRAO

SN1987A Composite
Red: ALMA (dust)
Green: HST
Blue: Chandra

Physics & Phenomena

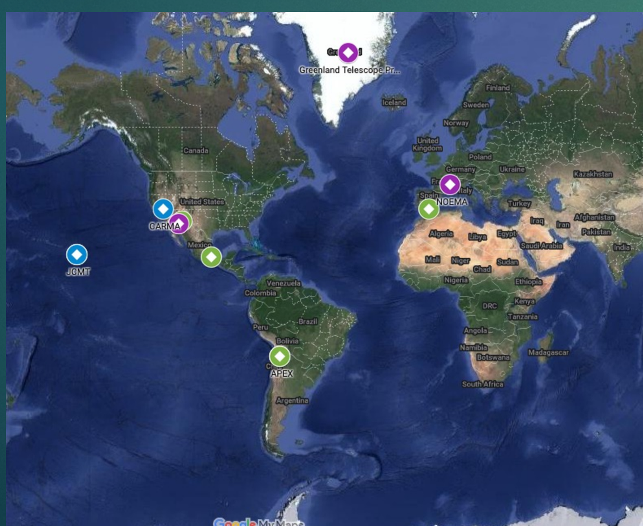
- SDP.81 – aka "The Ring of Fire"
  - ALMA Partnership, Vlahakis +many 2015 ApJL **808** L4
- Z=3 gravitationally lensed submm galaxy (foreground lensing galaxy at z=0.3)
  - Continuum imaging at 151, 236, 291 GHz / resolutions down to 23 mas
- Following the initial detection from the ALMA initial Long Baseline Campaign subsequent work has been done to model / reconstruct the submm galaxy

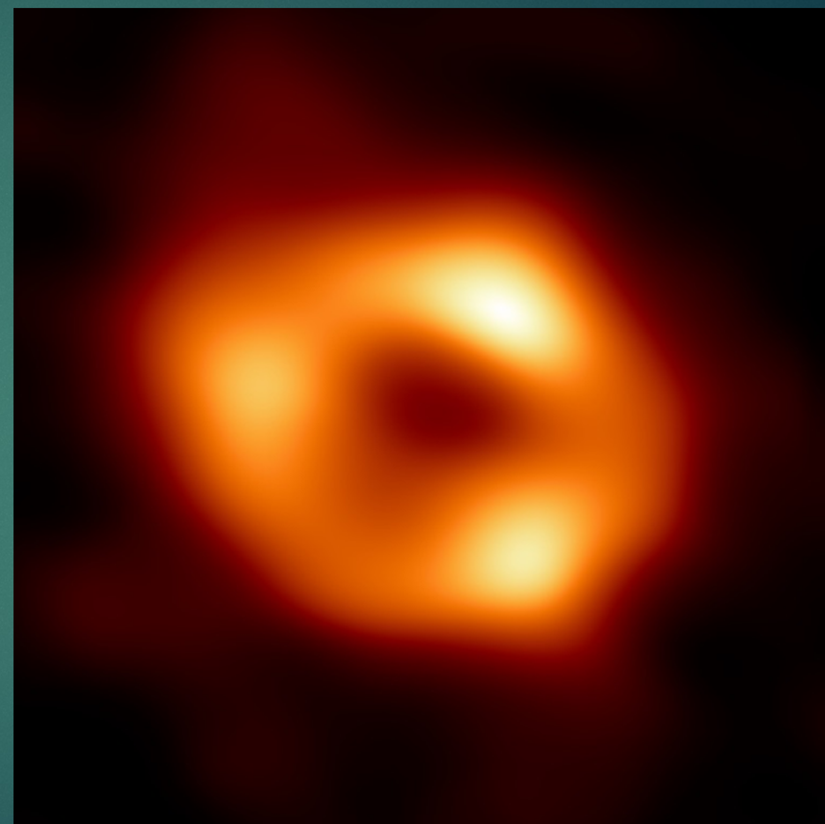


Credit: ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF

Physics & Phenomena

- EHT image of the event horizon around the black hole in the Galactic Center, Sgr A*
- mm/submm wavelengths reduce the scatter-broadening of the image
- Combined with a global vlbi array, can achieve the angular resolution needed to image the event horizon





Credit: EHT Collaboration

Part 2
Millimeter-wave Astronomy
The Origin Story

MUCH OF IT HAPPENED HERE IN GREEN BANK!!

Millimeter-wave Astronomy & Green Bank

- *Millimeter-wave astronomy was not "invented" at Green Bank*
- *But arguably….the through-line of development that started here in Green Bank in the 1960s directly traces to much of modern millimeter-wave astronomy*
- References

  - M. A. Gordon 2005 "Recollections of Tucson Operations – The Millimeter Wave Observatory of the National Radio Astronomy Observatory," (Springer)
  - K. Kellermann, E. Bouton, S. Brandt – 2020 "Open Skies – The National Radio Astronomy Observatory and Its Impact on US Radio Astronomy," (Springer)

Centimeters to Millimeters

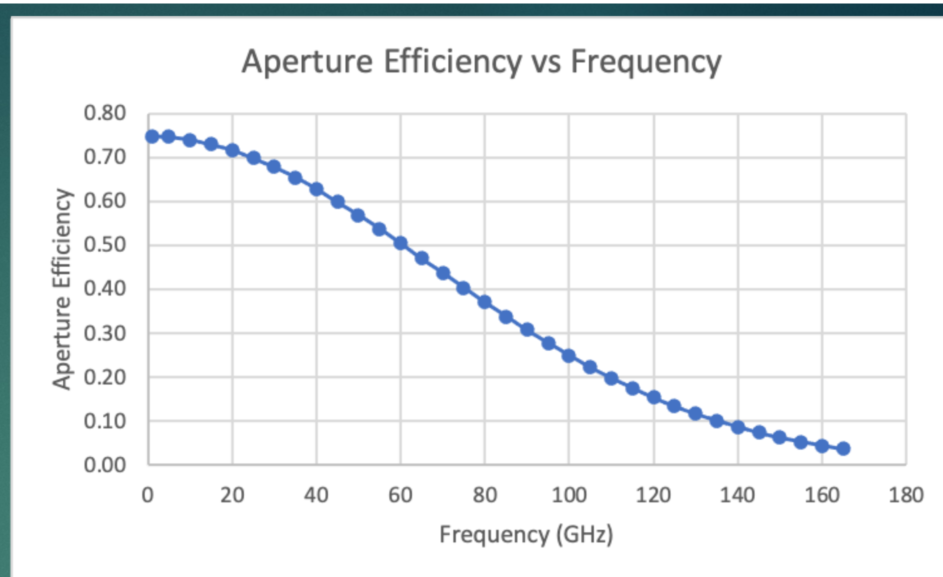
- Millimeter waves were a natural progression from meter-wave, centimeter-wave astronomy
- The electromagnetic spectrum is a continuum – nothing particularly special happens between 1 cm and 9 mm
- But a few big challenges happen on the way to shorter wavelengths:

Mechanical

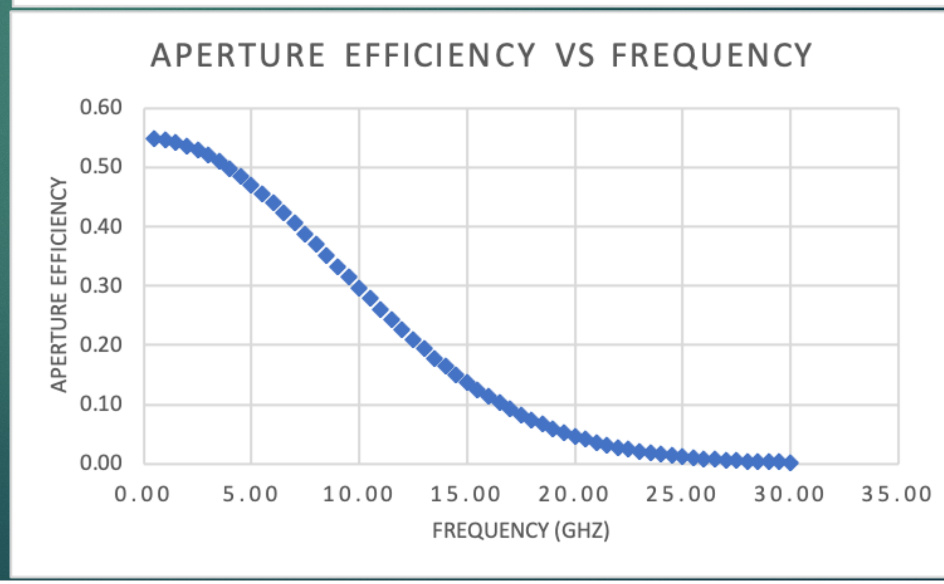
$$\eta = \eta_{Ao} \exp[-(4\pi\sigma/\lambda)^2]$$

- Ruze Equation for aperture efficiency, where
  - η_{A0} = long wavelength eff
  - σ = RMS surface accuracy
  - λ = wavelength
- Rule of thumb:
  - Surface accuracy at high frequency operating limit must be $\lambda/16$ (~1/e)

"3 mm dish"
$\sigma = 250\ \mu m$
$\eta_{A0} = 0.75$

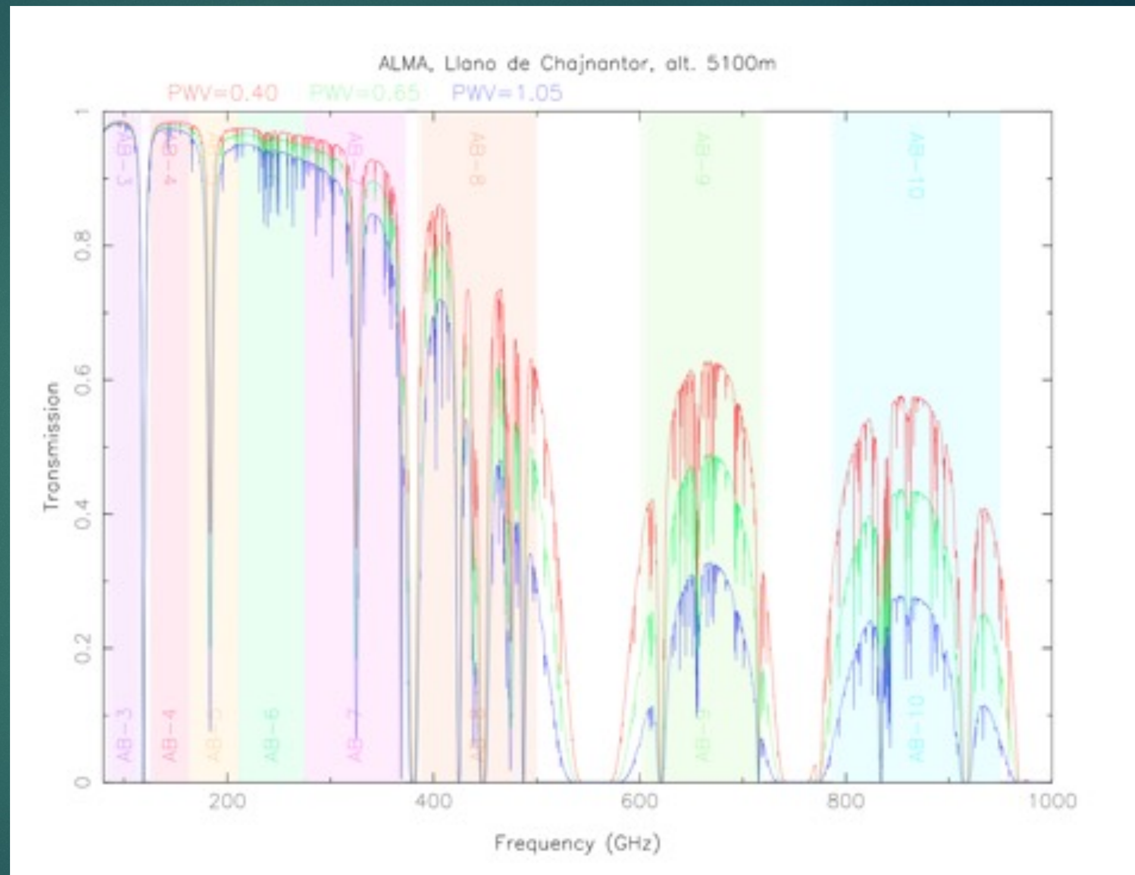


"X-Band dish"
$\sigma = 1.875mm$
$\eta_{A0} = 0.55$



Atmospheric

- Atmospheric Water Vapor absorption requires a dry site
  - Normally achieved by going to a high, dry desert site
    - As was later appreciated – GB also has many good days for 3 mm
  - O_2 also a limitation, but has a high scale height



ALMA Science Portal Transmission Chart

Receiver Technology

- Few options for mm-wave receivers / detectors in early 1960s
- Direct amplification at mm RF is (still) difficult
  - State of the art even today, using HEMT LNAs and MMICs
- First generation uncooled heterodyne mixers had noise temperatures of thousands of degrees
  - First cryogenic Schottky diode mixer – 1974 (Weinreb & Kerr)
- Continuum direct detectors (bolometers) were in their infancy (see following)

Green Bank mm-wave origins

- Notion of observing over the entire radio spectrum, including mm-waves, began early in the course of radio astronomy:
  - Lebedev Institute 22 m operated to 8 mm as early as 1953 (surface manual adjusted by turning 40,000 bolts)
  - In 1959, an improved version (RT-22) was built in Crimea and observed the Sun, Moon, planets (Salomonvich 1984)
- In the US, the 1961 Pierce Panel report on radio telescopes encouraged exploitation of the millimeter range
- Staff members at NRAO in Green Bank took up the cause….

cf. Kellermann et al. (2020)

Green Bank mm-wave origins

The staff member leading this effort was…

Establishing a millimeter-wave astronomy effort would require both an antenna, instrumentation, and a suitable site

NRAO did not have instrumentation to observe at millimeter waves, but….

Drake knew about an innovative scientist working at Texas Instruments who had developed germanium bolometers….

In 1961, Drake flew to Dallas and recruited Low to join NRAO to build mm-wave detectors

cf. Gordon (2005), Kellermann et al. (2020)

Frank Drake

Frank Low

Mm-wave Development at GB ….

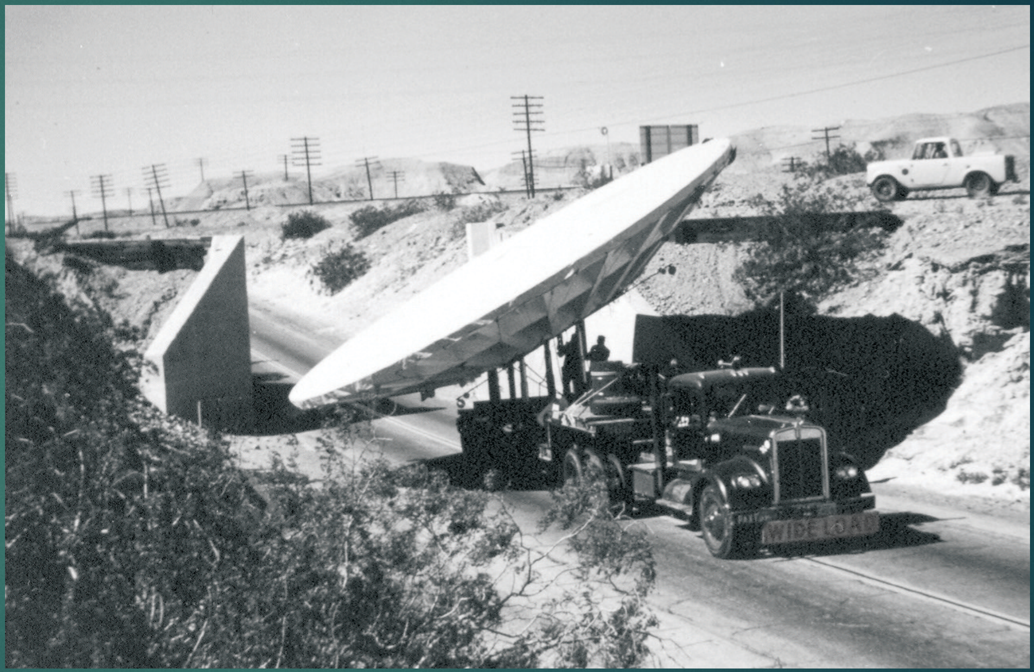
- Low began his mm-wave development on bolometers in GB
  - Focus was on continuum science only – no molecular lines detected at that time
  - Included first use of a cryogenic He_3 system
- Bolometer work was ultimately not successful, but did lay the groundwork for IR detectors and a later generation of mm-wave bolometers
- In 1963, both Drake and Low departed NRAO (for JPL and UAz, resp), but the seed had been planted….

mm-wave Test Antenna outside Jansky Lab

cf. Gordon (2005), Kellermann et al. (2020)

The Kitt Peak 36-Foot takes root from GB mm Program

- Initial mm tests at GB had yielded detections only of the moon
- Was clear to Low and Drake that a better site was needed to observe as short as 1.3 mm
- 1964 Budget submission to the NSF included $600k for construction of a 36 foot reflector
  - Justified by Drake with a few paragraphs
  - Championed by Dave Heeschen
- Development efforts led by John Findlay and Hein Hvatum following the departure of Drake and Low

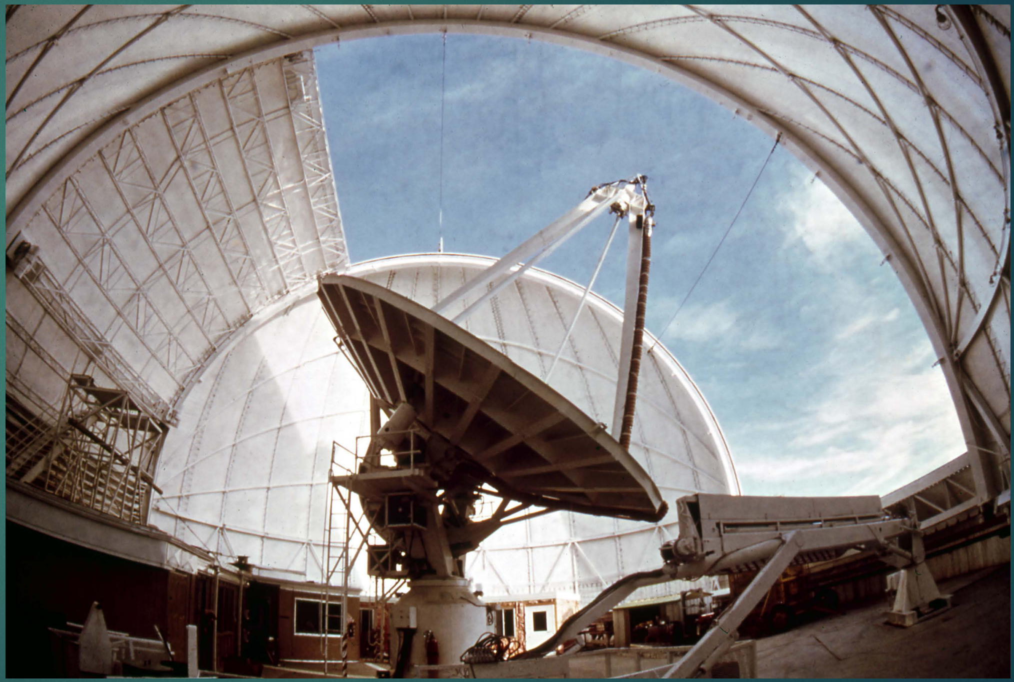


February 1966, 36-Ft reflector en route from Rohr Corp in Chula Vista, CA to Kitt Peak, Arizona

cf. Gordon (2005), Kellermann et al. (2020)

The 36-Foot

- Telescope was delivered and erected in 1966
- Turned over to NRAO in 1967
- The 36-Foot was *the* pioneering mm-wave telescope for molecular spectroscopy
- Ultimately, its performance was not good – surface accuracy, thermal properties, and pointing were all deficient
- Was upgraded to the 12-Meter in 1984 using the same mount



NRAO 36-Foot Telescope – 1967-1983
upgraded to 12-m in 1984

cf. Gordon (2005), Kellermann et al. (2020)

Other mm telescopes in the first generation….

- First Generation mm-wave Telescopes

MWO (Texas) – Vanden Bout ea
1972-88

FCRAO 1969+

1.2 m Columbia / CfA
Thaddeus, Dame ea 1974+

Onsala 20m 1975+

2^{nd} generation mm telescopes

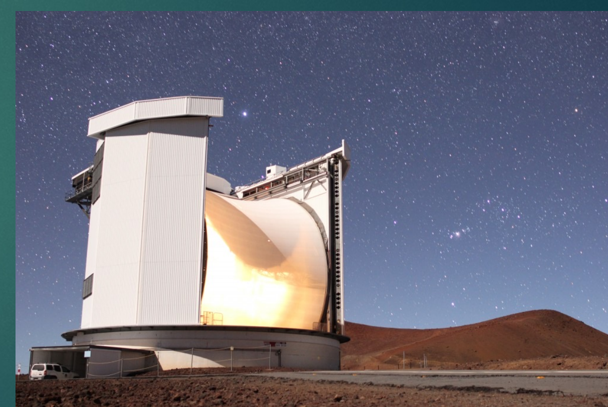
- Millimeter (cm) facilities included:
  - IRAM 30 m
  - Nobeyama 45m
  - LMT

IRAM 30m telescope
Credit: IRAM

Nobeyama 45m
Credit: NAOJ

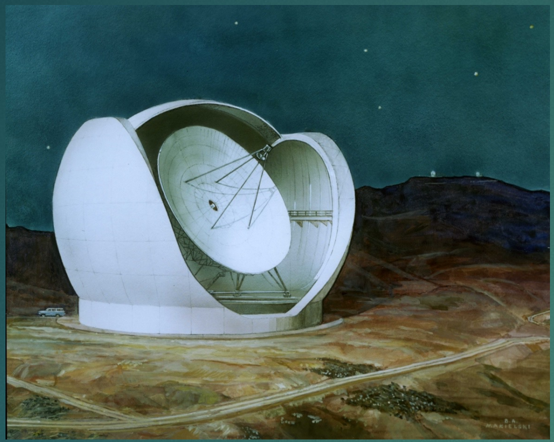
- By the late 1980s, mm pushed into the submm:
  - CSO, JCMT, SEST, ARO, APEX, SPT

Caltech Submm Obs
Credit: CSO

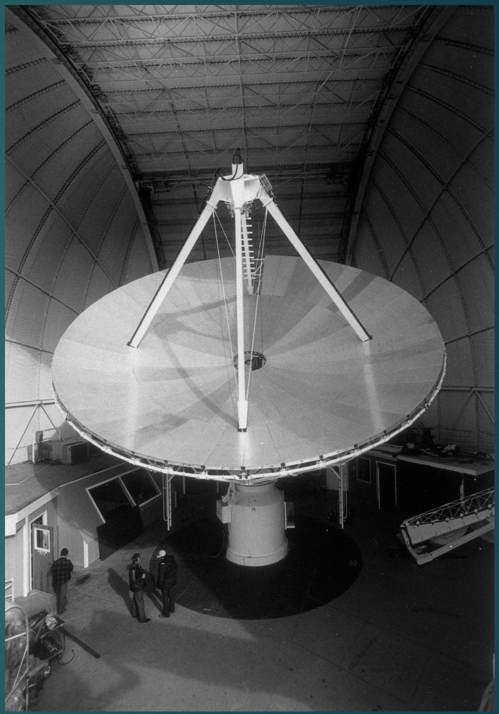


JCMT
Credit: William Montgomerie

Back at NRAO .....



- NRAO's concept for a follow-on to the 36 foot was a high-precision, 25 meter telescope on Maunakea, which ultimately was not funded.
- This failure had two immediate outcomes.
  - NRAO upgraded the 36 Foot to the 12 meter telescope in 1984 – much improved facility that served well until retired in 2000…
  - The NSF convened the Barrett Committee in 1983 (Barrett, Lada, Palmer, Snyder, Welch) to decide next steps for mm science in the US
  - Based on the success of mm single dish astronomy and cm wave interferometry with the VLA, they recommended construction of a large Millimeter Array.
  - This became the MMA project



Millimeter Arrays…..

Credit: CARMA

- In the 1980s, much of emphasis in the university community was in mm arrays
  - Hat Creek->BIMA
  - Owens Valley Millimeter Array

  (Hat Creek->BIMA and Owens Valley Millimeter Array } CARMA)
  - IRAM Plateau de Bure -> NOEMA
  - Nobeyama Array
  - SMA
- Ultimately, all these threads came together:
  - 1st + 2nd + 3rd Gen mm single dishes, University-led arrays, MMA initiative, + work in Europe & Japan led to this…..

And finally led to this….

- ALMA
  - 66 precision antennas
  - 5000m altitude on the Chajnantor Plateau in the Chilean Atacama Desert
  - Operating from 35-900 GHz
- At $1.4B construction cost, the largest ground-based astronomy project ever undertaken

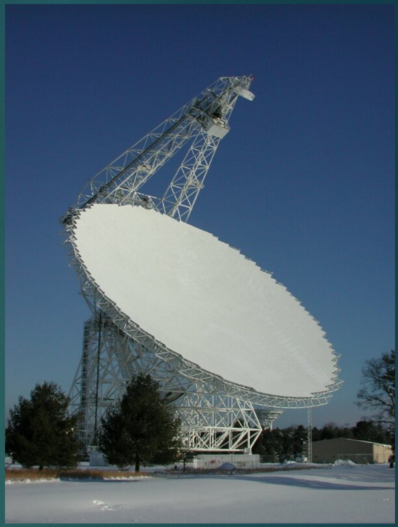
Credit: W. Garnier, ALMA (ESO/NAOJ/NRAO)

The through-line….

- Many, many scientific and technical contributors to the success of mm/submm astronomy
- Many parallel developments
  - Mark Twain: "There's no such thing as a new idea."

We can make a good argument that what started with this:

Led to this…



And this…

Part 3
Millimeter Astronomy Comes Full Circle

WHAT GOES AROUND COMES AROUND IN GREEN BANK!

Millimeter Astronomy Returns to Green Bank

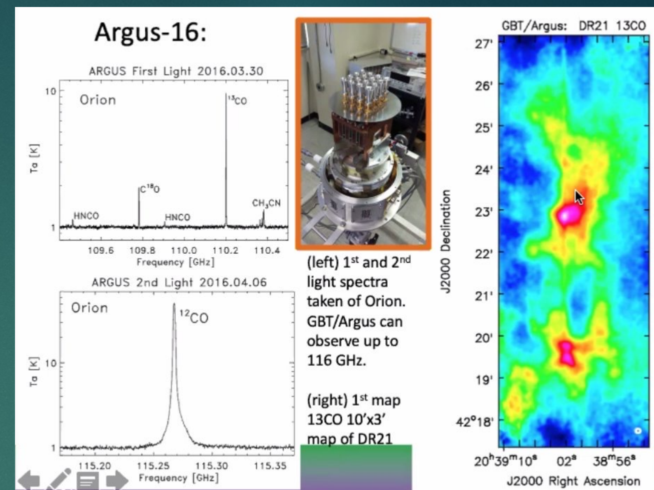
3a. Telescopes & Technology

- Centimeter-wave astronomy remained the focus in GB during the 70s and 80s via the 140 Foot and 300 Foot
- Need for a new facility recognized (but not evident how it would come to pass)
- "New Large Steerable Radio Telescope Study (NLSRT)" formed in 1987
  - Committee was working toward a report by end of 1988, calling for a
    - 70-100m-class telescope ….
    - with useable efficiency to 3mm when….
- The 300 Foot collapsed, which changed everything, and led to the GBT.

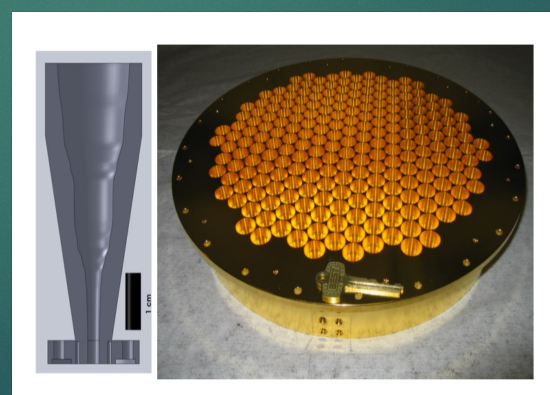
- Will not repeat further details of the familiar story for this audience, but performance to 3mm remained a stretch goal for the GBT
  - [full details provided in Kellermann et al. 2020]

GBT Achieves mm-wave Performance

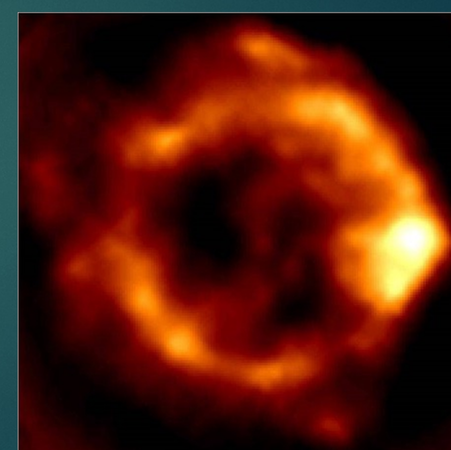
- NRAO staff were intrigued and challenged with making the GBT work at mm waves.
- Staff at the 12 Meter with GB ties returned to work on this problem
  - Notable among these was John Payne
    - Worked tirelessly on the laser measurement system
- From these early days, GB staff have worked in a sustained way to achieve mm performance including
  - Ka Band Rx and 3mm Rx
  - AutoOOF technique
  - Surface Optimization program
  - MUSTANG 1 / MUSTANG 2
  - ARGUS-16 / 144
  - LASSI



ARGUS-16 First Light Images



MUSTANG 2 Feed Horn Array



MUSTANG Cas A Image

The GBT answers a knotty question of mm astronomy

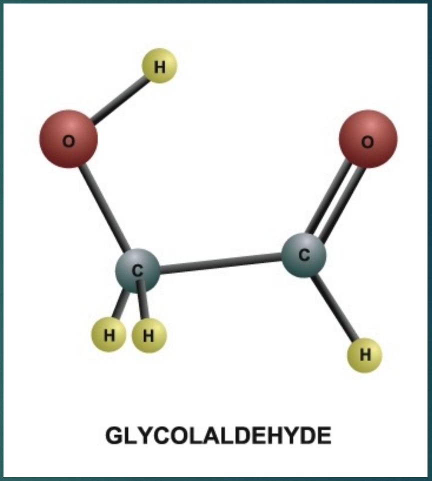
The Story of Glycolaldehyde

- Glycolaldehyde is a molecule with the formula most commonly written as

  CH_2OHCHO, and in simple form as

  $C_2H_4O_2$
- Glycolaldehyde is a *diose* monosaccharide

  $(C + H_2O)_n = C_nH_{2n}O_n$,
  - Where diose means that it contains 2 carbon atoms
  - NB: Chemists debate whether true monosaccharide sugars have $n \geq 2$ or $n \geq 3$
- Glycolaldehyde is a member of this family:
  - n=2 → diose: Glycolaldehyde
  - n=3 → triose: Glyceraldehyde
  - n=5 → pentose: Ribose
- Ribose ($C_5H_{10}O_5$), a pentose class sugar, along with phosphates and nucleic bases are the building blocks of nucleic acids, the carrier of the genetic code

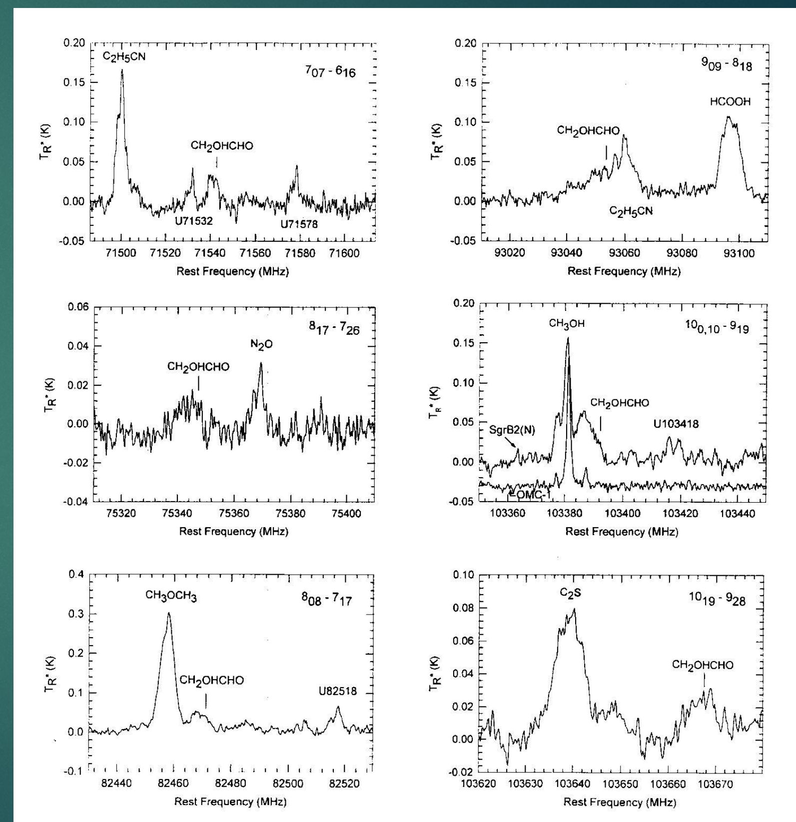


Glycolaldehyde (CH_2OHCHO)

Part of an isomer triplet with methyl formate and acetic acid

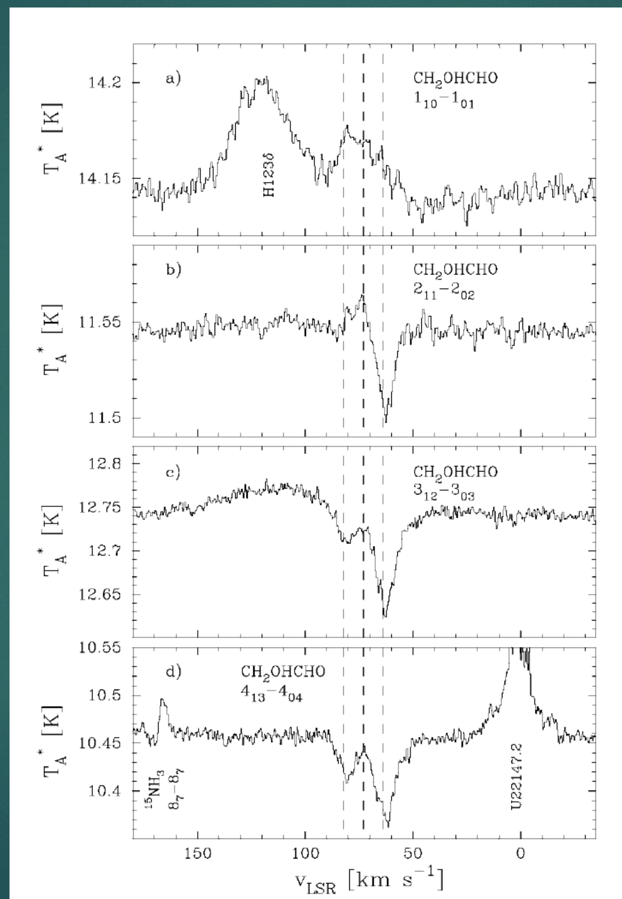
12 Meter Detection of Glycolaldehyde

- Multiple transitions of Glycolaldeyde detected between 71 GHz and 103 GHz toward Sgr B2(N) using the 12 Meter Telescope
  - Hollis, Jewell & Lovas 2000 ApJL **540** L107
- At this point, we expected large molecules of this type to be most easily detectable in the Sgr B2 (N-LMH) = "Large Molecular Heimat" – a ~5" hot core with typical LSR velocity of 64 km/s
- Observed lines were at ~71km/s – within range of known Sgr B2(N) velocities, but somewhat atypical

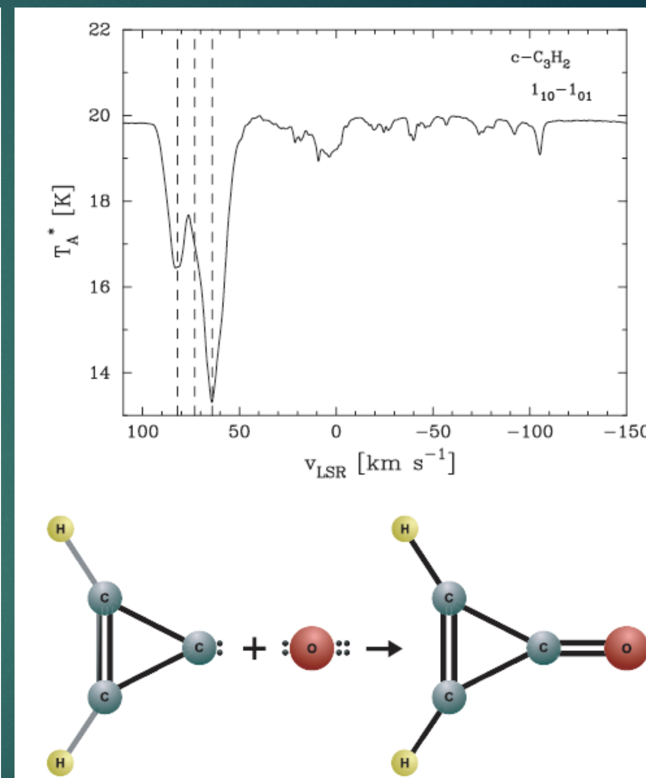


Observations of Glycolaldehyde with the GBT

- Hollis, Jewell, Remijan & Lovas 2004 ApJL **613** L45
- Observed with GBT at Ku and K band
- Morphology & excitation analysis suggests a warm cloud at 50K (71 km/s) surrounded by a cold halo cloud at 64 & 82 km/s. Absorption is against a background continuum source
- This morphology seen with multiple other GBT detections, including cyclopropenone (right) and is commonly seen in the PRIMOS survey



Glycolaldehyde on GBT – velocities of 64, 73, 82 km/s marked with dashed lines

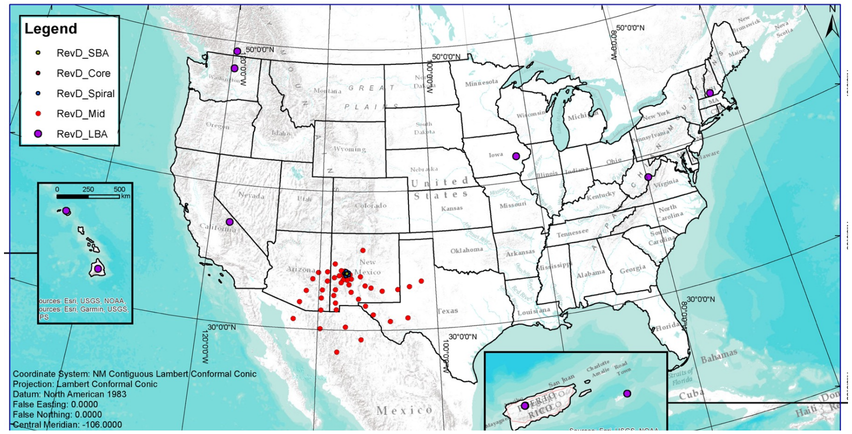


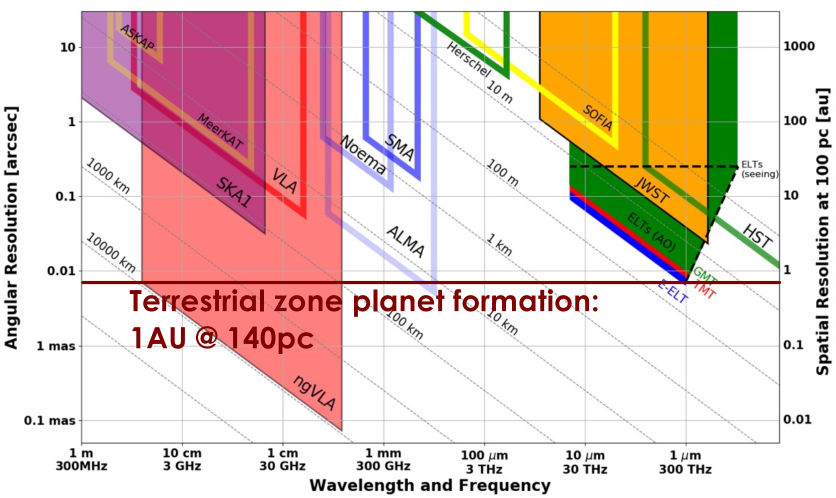
Detection of the ring molecule cyclopropenone
Hollis, Remijan, Jewell & Lovas 2006 ApJ **642** 933

Part 4 – What's Next

WE'RE JUST GETTING STARTED….

ngVLA Scientific and Technical Capabilities





ngVLA Key Science Goals

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

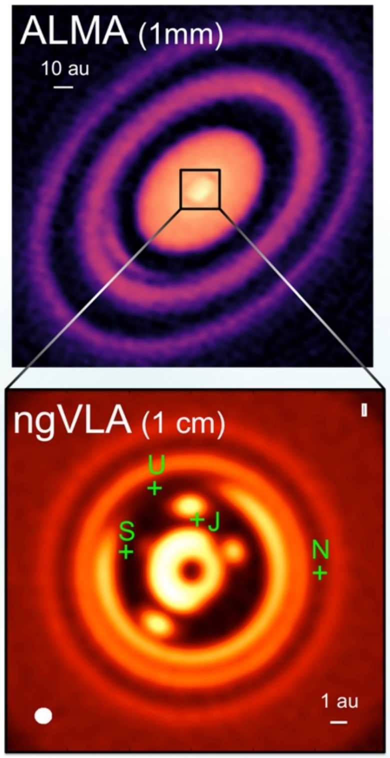
- **1.2 - 116 GHz** Frequency Coverage
- **Array Design**: 244 x 18m offset Gregorian Antennas
  - **Core**: 114 fixed antennas; B_{max} = 4.3 km
  - **Spiral**: 54 fixed antennas; B_{max} = 39 km
  - **Mid**: 46 fixed antennas spread into NM, AZ, TX, MX; B_{max} = 1070 km
  - **Long**: 30 x 18m antennas located across continent; B_{max} = 8860 km
- **Short Baseline Array**: 19 x 6m offset Greg. Antennas
  - Use 4 x 18m in **TP mode** to fill in (*u*, *v*) hole.

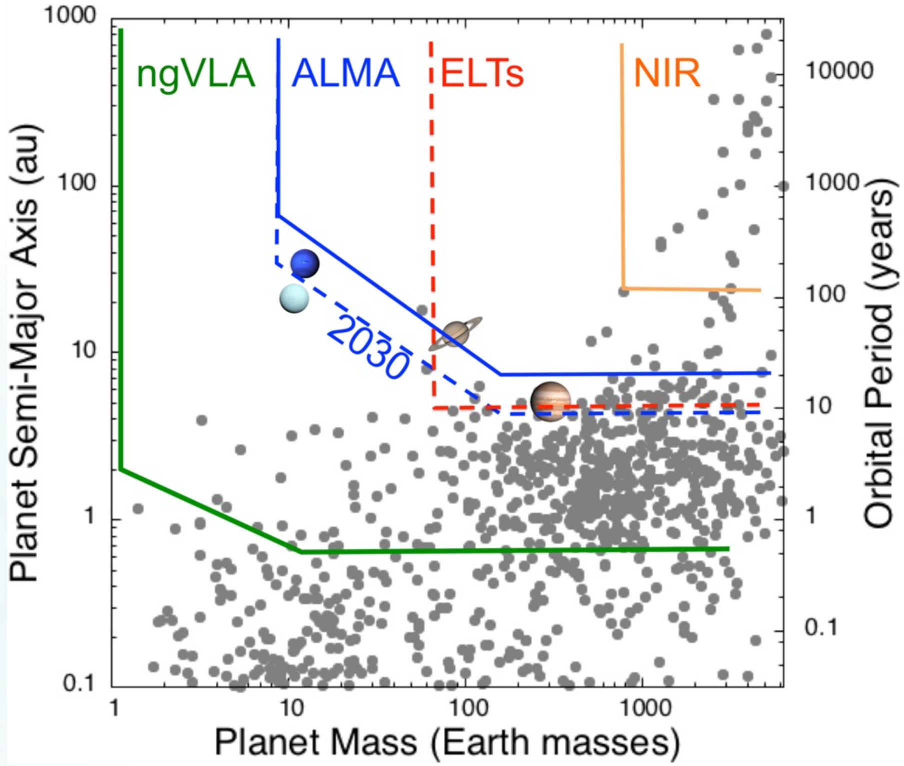
Get Involved! Join an ngVLA SWG to help identify any missing science requirement! https://ngvla.nrao.edu/page/workinggroups

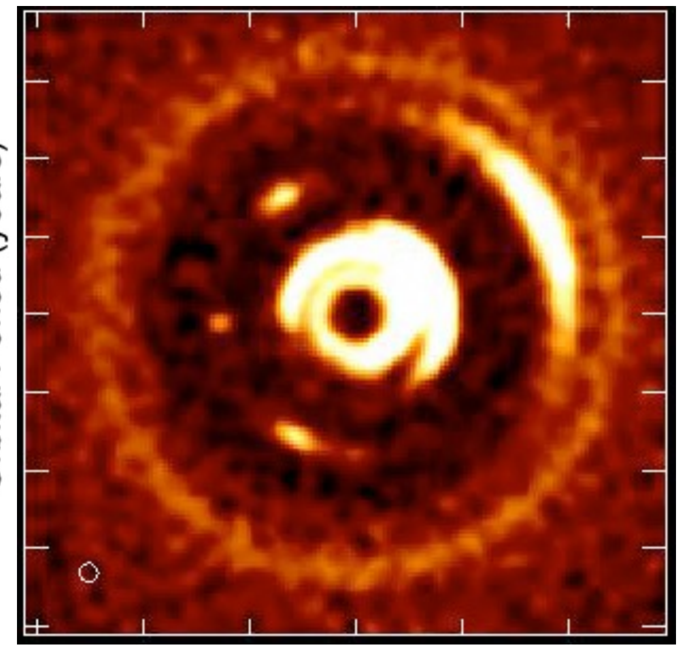
ngvla
Next Generation Very Large Array

KSG1: Unveiling the Formation of Solar System Analogues

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.



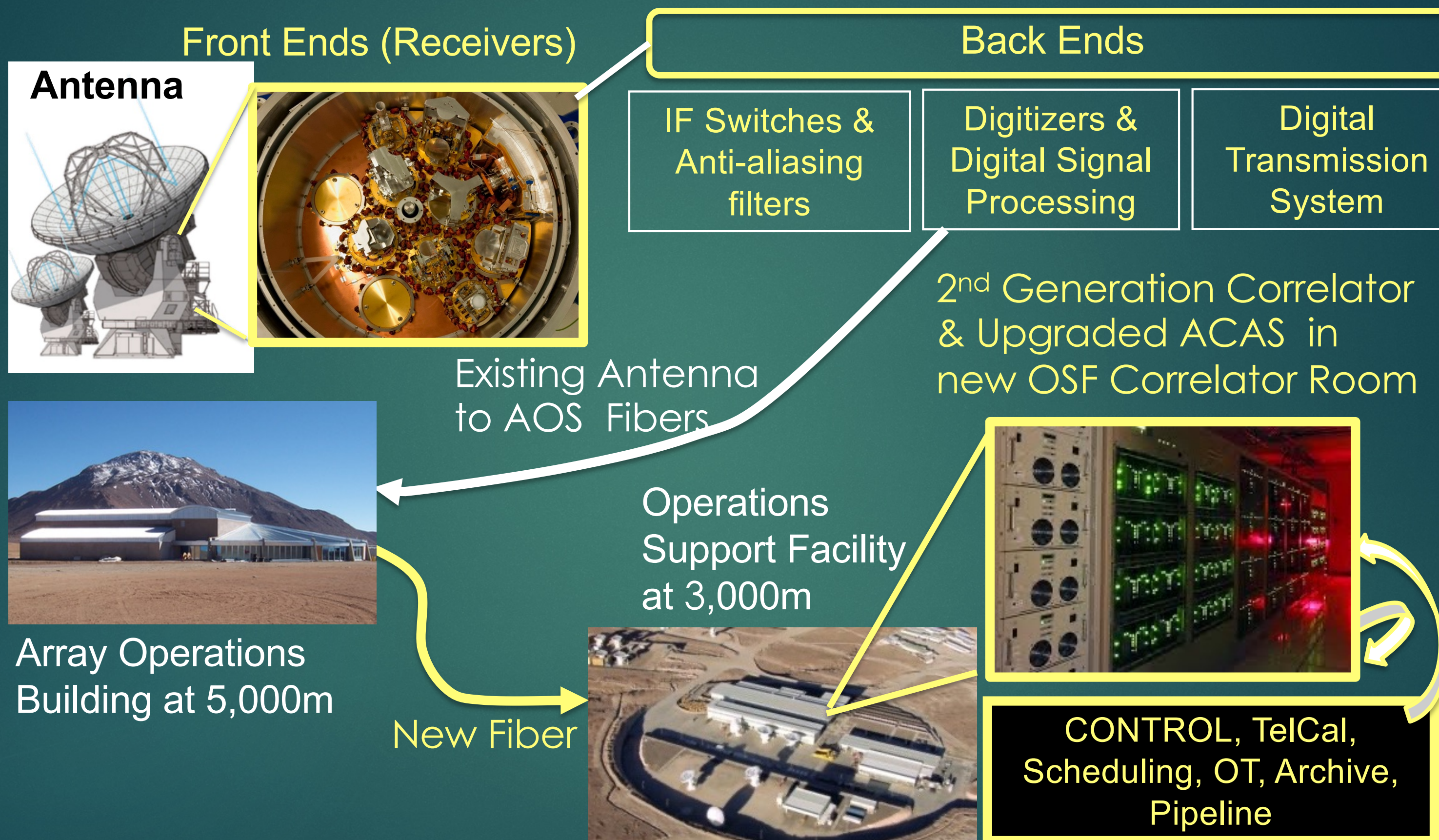




Courtesy E. Murphy

ALMA Wideband Sensitivity Upgrade (WSU) – An Upgrade for the 2020s

Goal: Expand system bandwidth by <u>at least</u> 2x with improved sensitivity

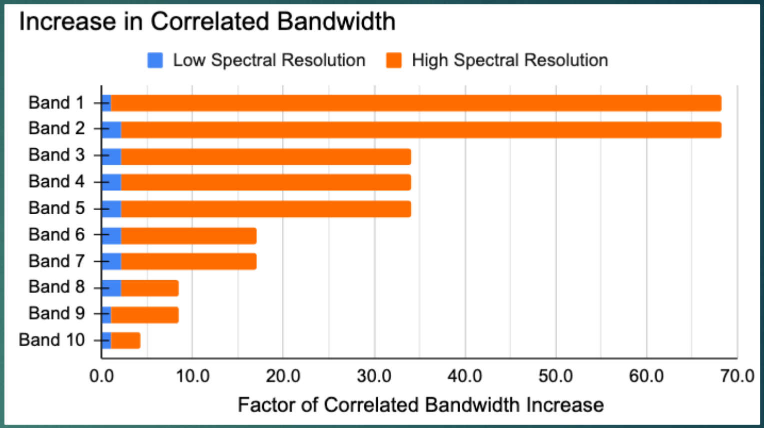


New or Upgraded Components are in yellow

Courtesy C. Brogan

ALMA Wideband Sensitivity Upgrade (WSU)

- WSU will provide major increases in
  - Receiver Bandwidth
  - Correlated Bandwidth at the highest spectral resolution
  - Observing speed



Example: Increase in Band 6v2 observing speed after WSU

Observing mode	Increase in speed over current system*
Continuum	4.8x (with goal of 9.6x)
Spectral line	2.25-4.7x

Simultaneous ^{12}CO & ^{13}CO (2-1)

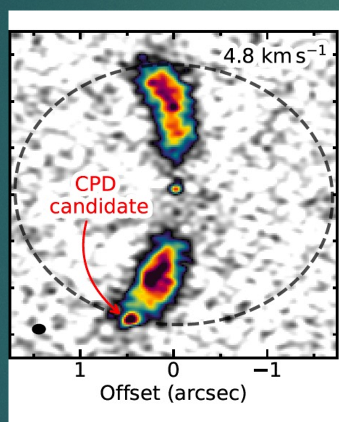
* To reach same sensitivity as current system with single tuning

Courtesy C. Brogan

ALMA x10 – A Project for the 2030s

- Goal: Increase spectral line sensitivity by a factor of 10 from the present
- Technical options just starting to be considered, but will require an expansion of collecting area, perhaps in synergy with ngVLA development
- Science cases also just starting to be developed – but a few are obvious:

AS 209 Circumplanetary Disk Candidate from MAPS project **First such object detected by gaseous emission** (velocity perturbations in ^{12}CO)



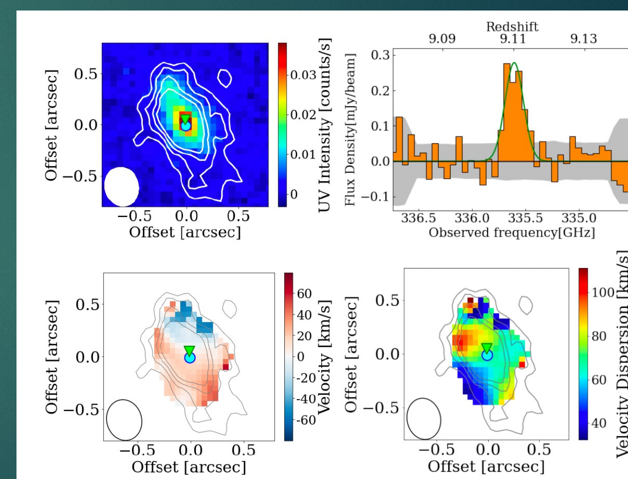
Bae+: ArXiv 2207:2207.05923v1

MACS1149-JD1 is a gravitationally-lensed galaxy at z=9.1, from ALMA [OIII] data

Spatial resolution of 0.3 kpc in the source plane, enables *the most distant* morpho-kinematic study of a galaxy

A clear velocity gradient present, suggesting a rotation-dominated system.

Tokuokoa+ arXiv:2205.14378



Study of planet formation by kinematic signature

Study of star formation, structure, and kinematics of the earliest galaxies

Conclusions

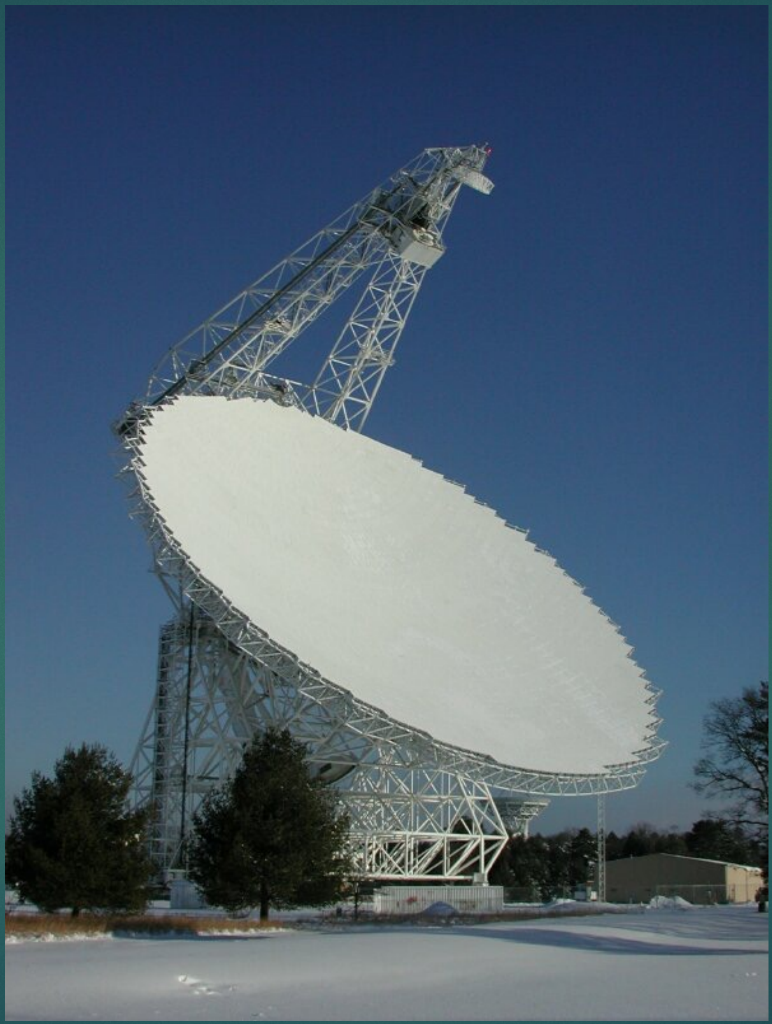
- As a science, millimeter-wave astronomy is just over 50 years old
- In that time, it has revealed:
  - Molecular Universe
  - Star Formation
  - Planet Formation
  - Chemical complexity of the Galaxy and beyond
  - Structure and evolution of the earliest galaxies
  - Imaged black hole event horizons
  - and much, much more….
- We're just getting started with amazing discoveries
- This has been accomplished by thousands of astronomers and dozens of observatories
- But it got its start -- right here

Thanks

- To all my mm (and cm!) observatory colleagues at
  - Tucson, James Clerk Maxwell Telescope, Green Bank, Charlottesville, and Chile
- And to my science collaborators
  - Lew Snyder, Mike Hollis, Frank Lovas, and Tony Remijan

Lew Snyder

Tony, Phil & Frank @ NIST



GBT – as seen in perfect 3 mm observing conditions!