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LMT Heterodyne Receivers: Current & Next Gen

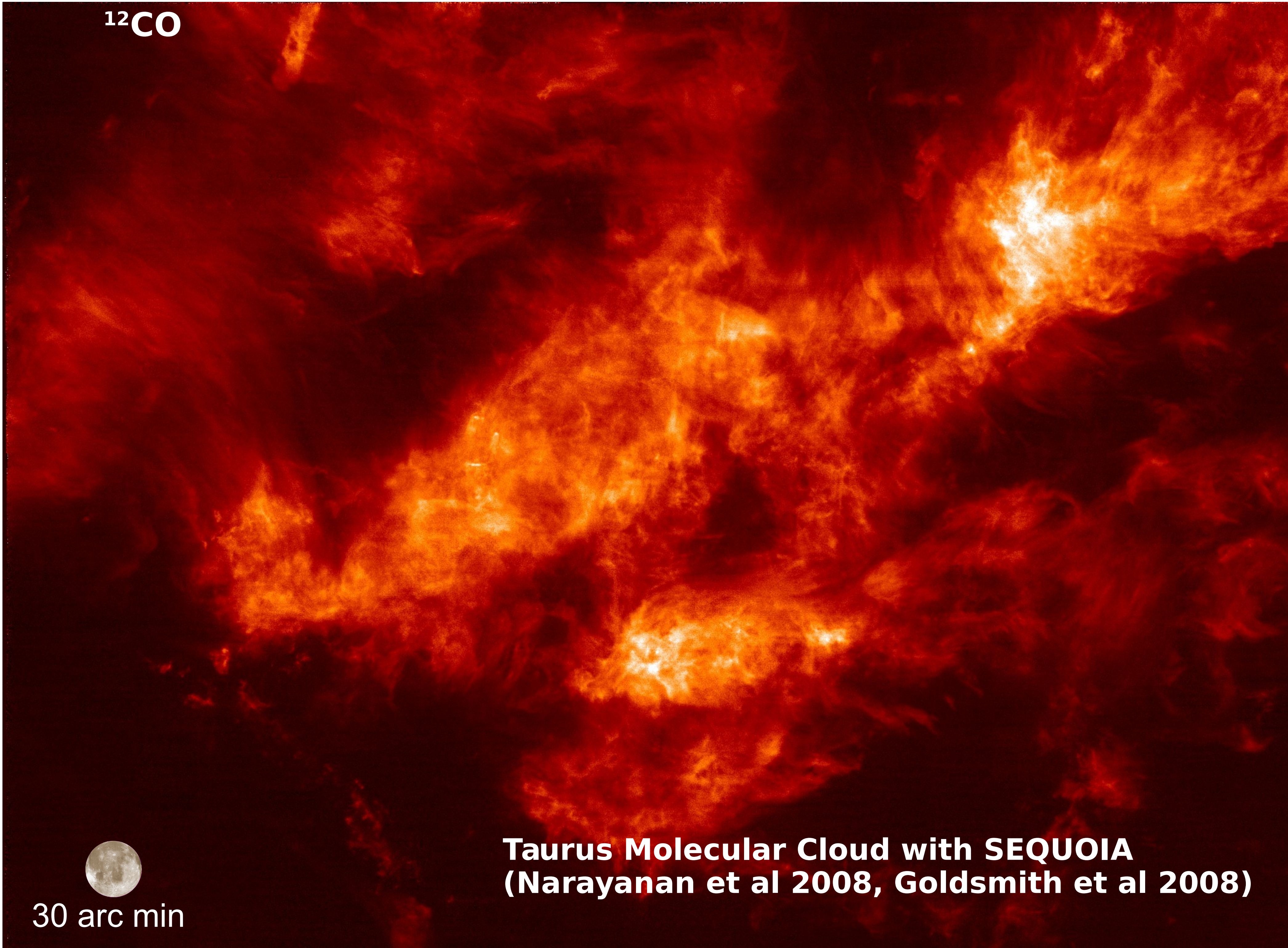
Overview of Talk:

- **SEQUOIA**
- Redshift Search Receiver (RSR)
- Event Horizon Telescope VLBI Instruments
- One Millimeter Array Receiver for Astronomy (OMAyA)
- Digital Spectrometers
- PHAMAS (Phased Array Receiver for Millimeter Astronomy)

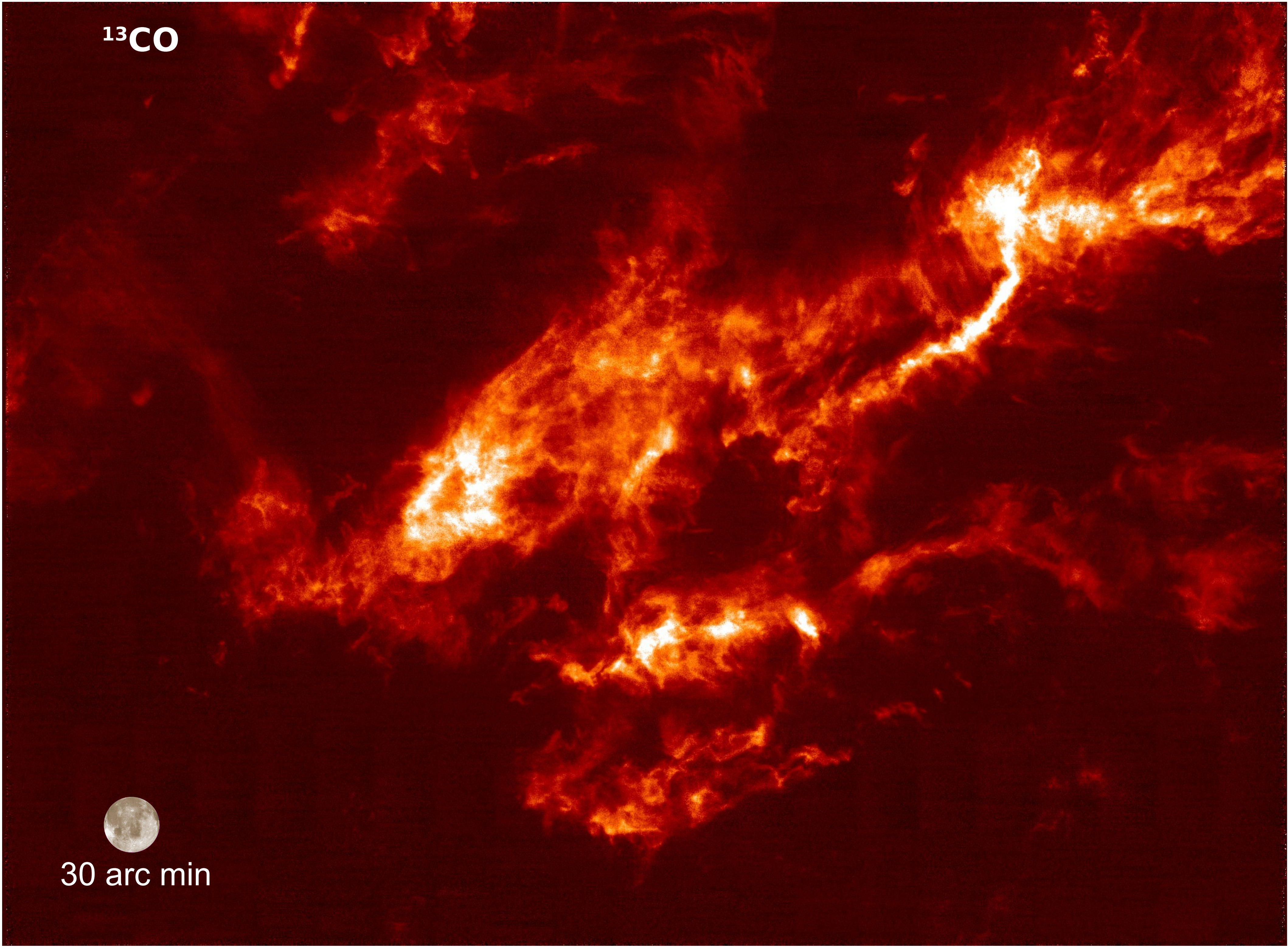
SEQUOIA

World's fastest imaging heterodyne array at 3mm wavelength

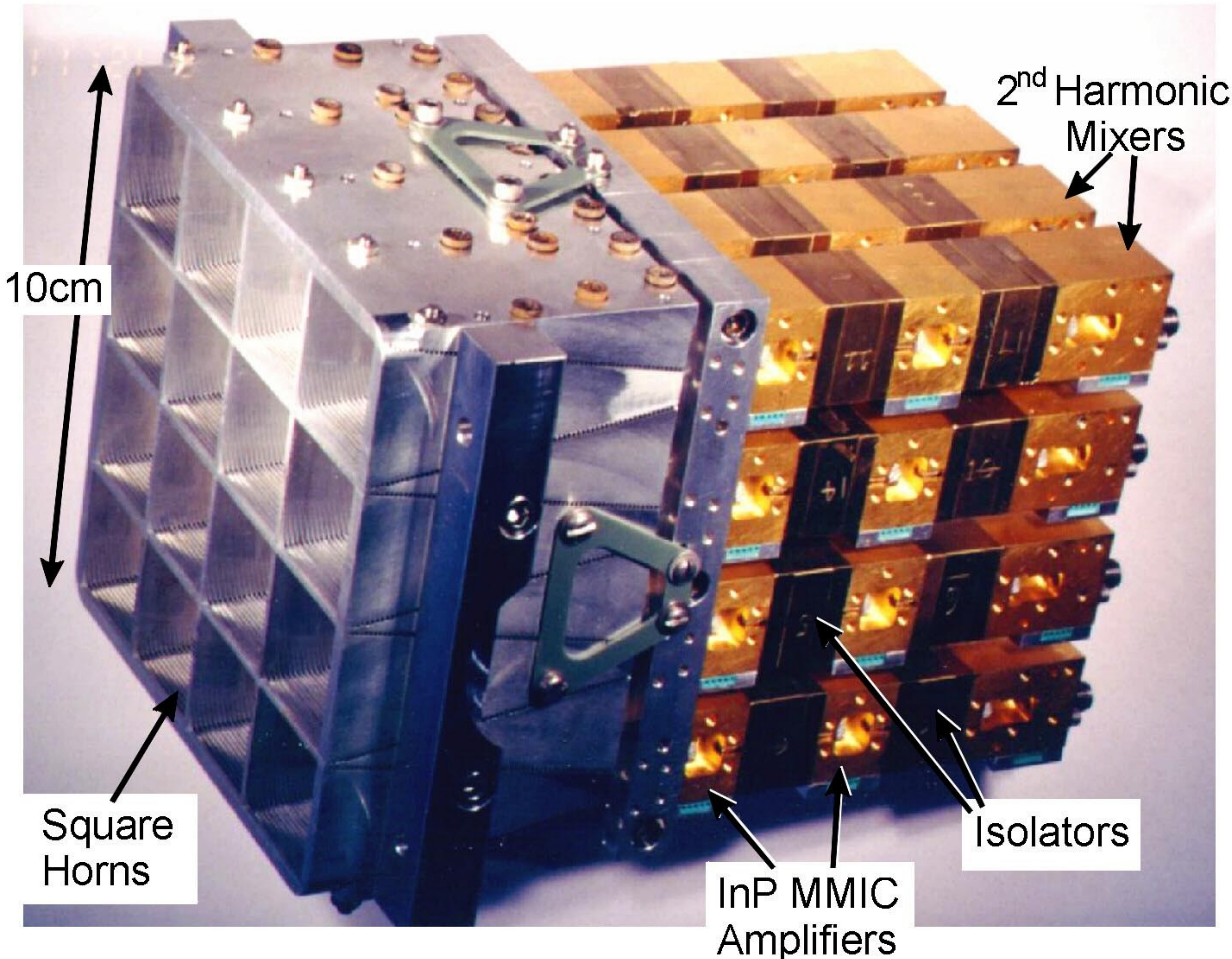
- Cryogenic Focal Plane array operating at frequencies of 85 – 115.6 GHz
- 16 pixels in 4 x 4 array
- Uses InP pre-amplifiers with 35-40 dB gain
- Possibility of multiple backend spectrometers per pixel, can be independently tuned within 15 GHz
- Used at the Quabbin 14m telescope as a workhorse instrument for 6 years. Installed and partially commissioned at the LMT in Spring 2018
- Of order 50 million spectra taken on the 14m telescope!



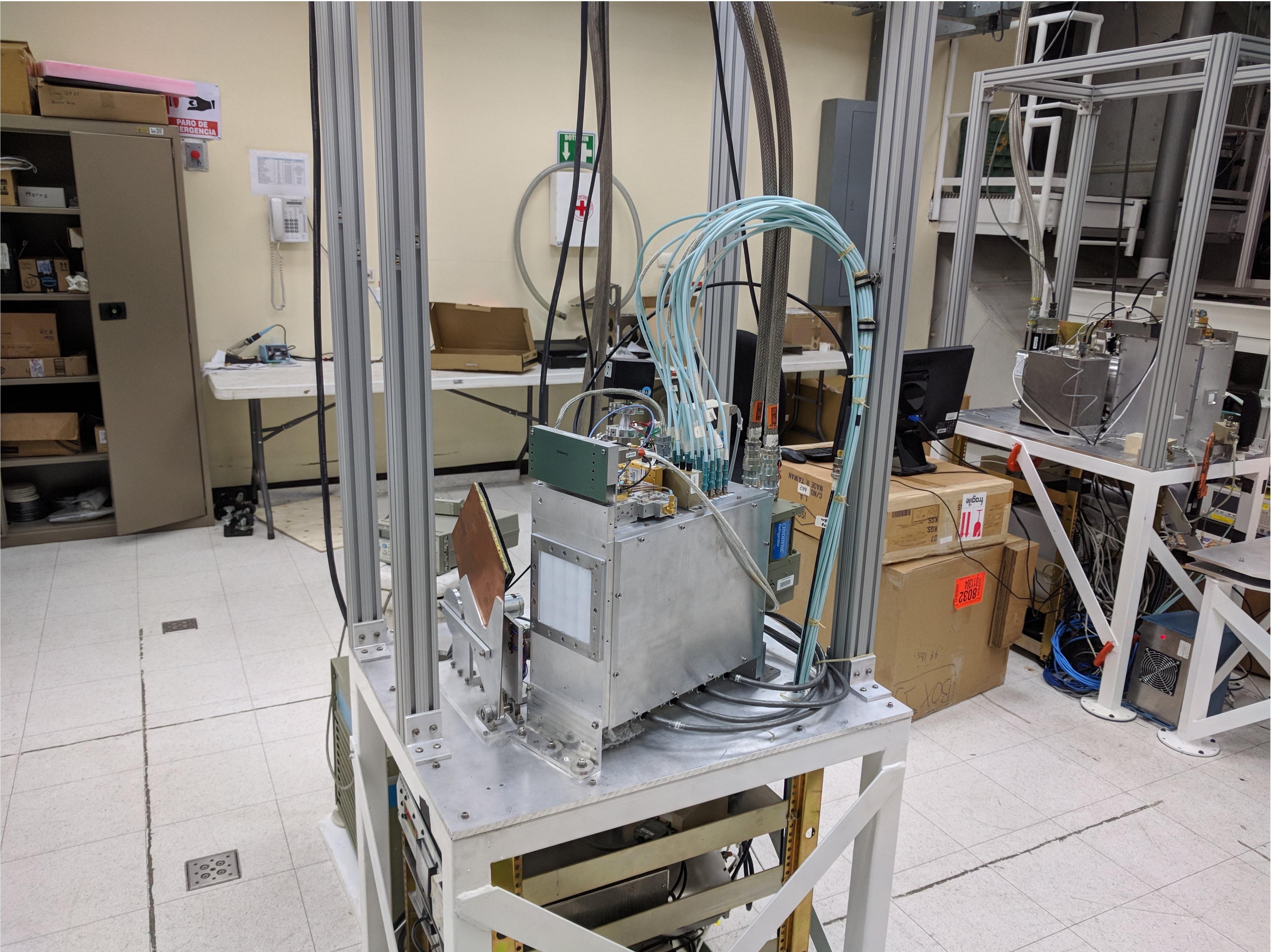
^{12}CO
30 arc min
Taurus Molecular Cloud with SEQUOIA
(Narayanan et al 2008, Goldsmith et al 2008)



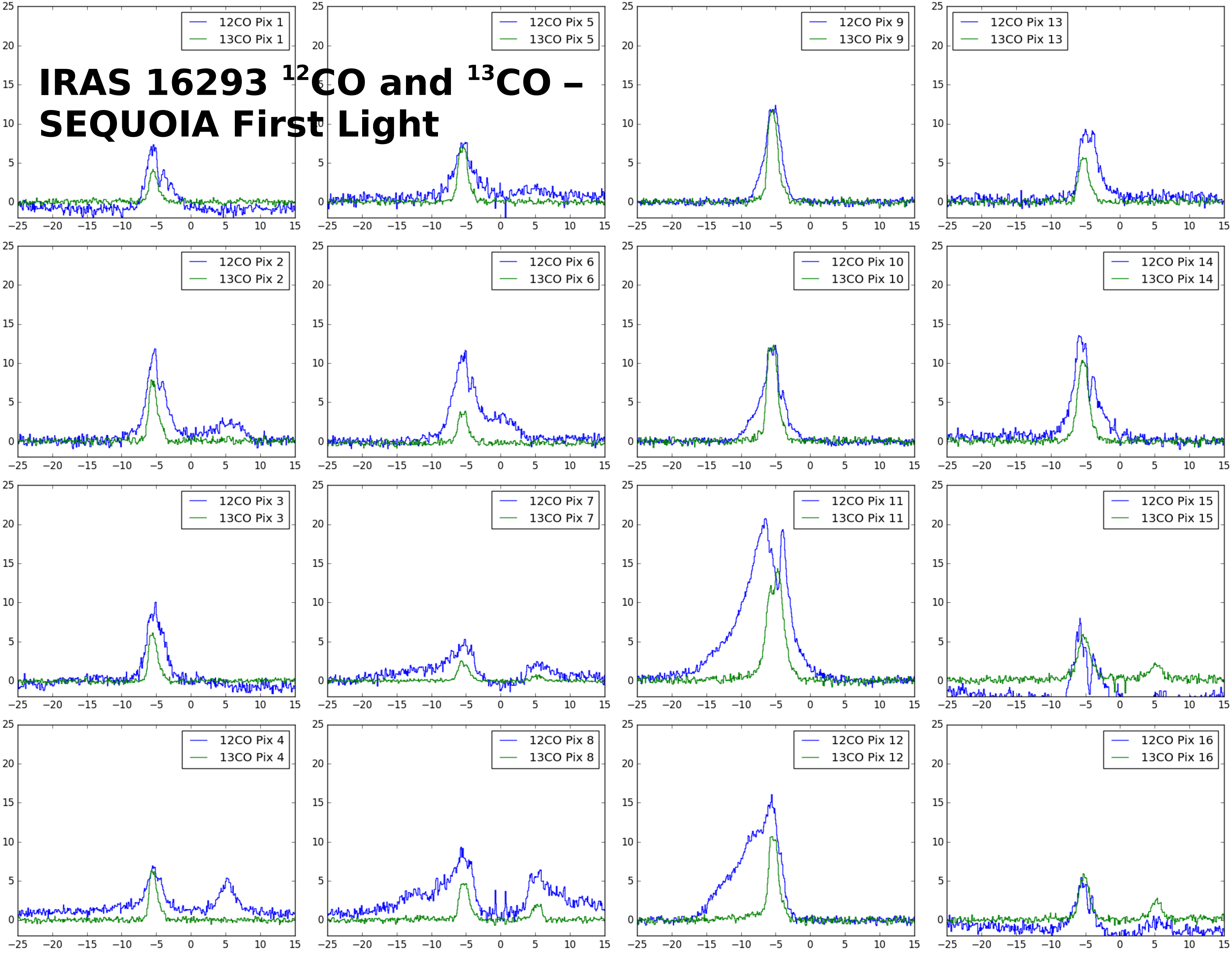
^{13}CO
30 arc min



10cm
2nd Harmonic Mixers
Square Horns
InP MMIC Amplifiers
Isolators


PARO DE
CRYODYNE
fragile
8032

IRAS 16293 ^{12}CO and ^{13}CO – SEQUOIA First Light



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Redshift Search Receiver (RSR) – Erickson & Narayanan, UMass

- Detection of redshifted millimeter CO lines (~ dozens of objects) shows large amounts of molecular gas that could participate in SF at high z

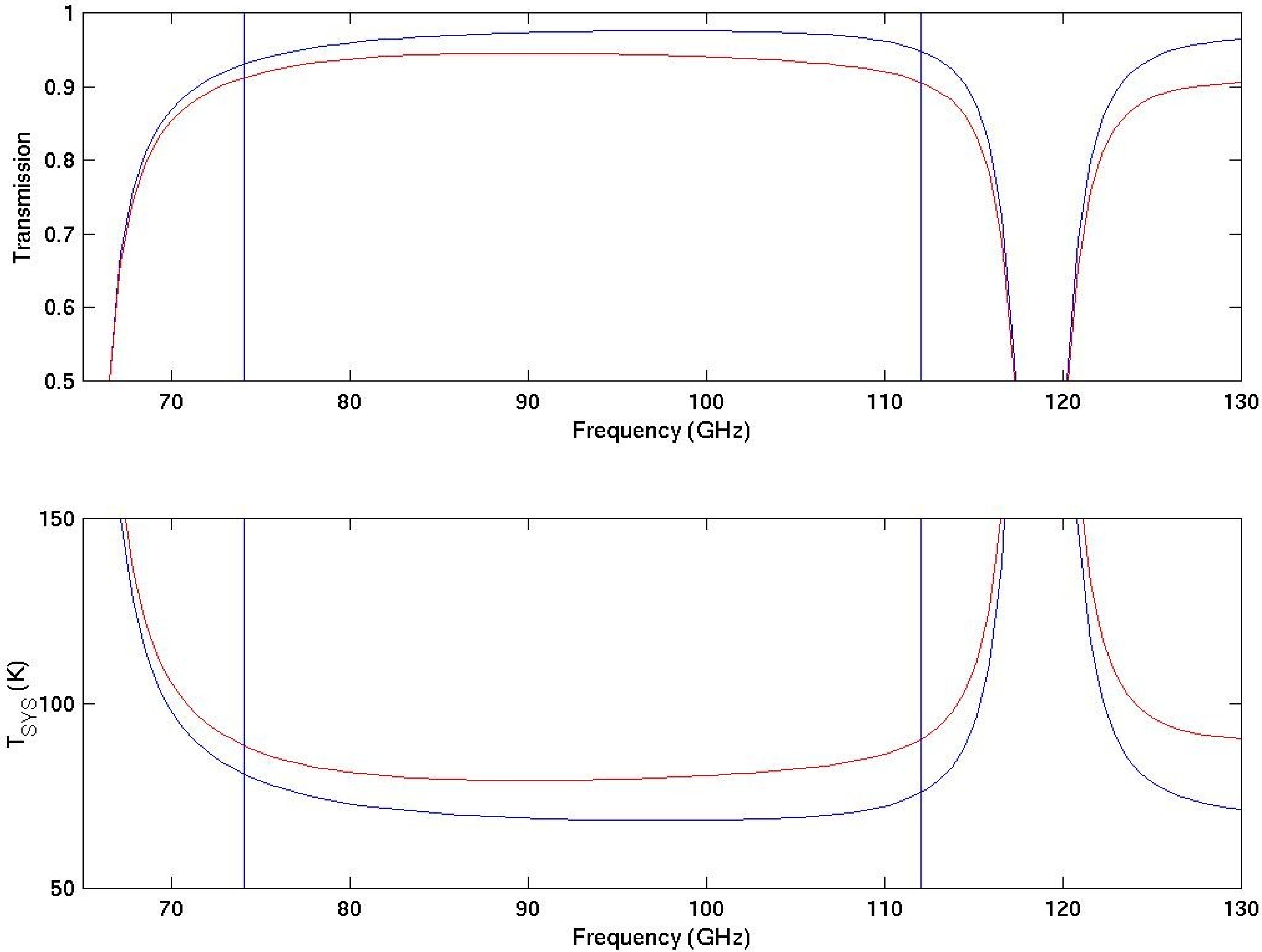
- Molecular gas and dust at high z provides an excellent probe of both stellar and ISM processes in cosmological objects

- Identification ambiguity between submm sources and optical/IR counterparts

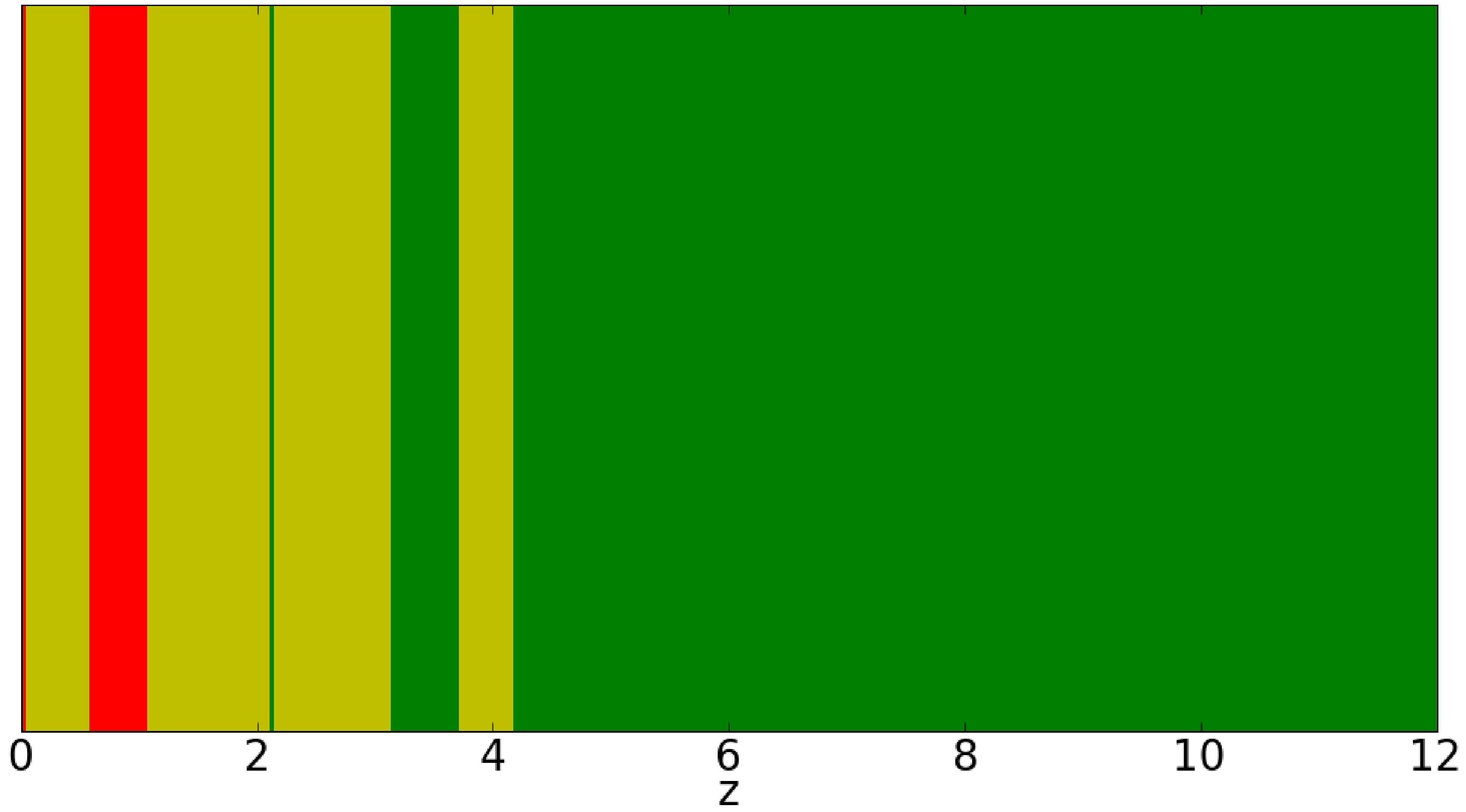
- Submm-mm (300/1100 μm) colors could be used as photometric redshift estimators - but technique need to be calibrated

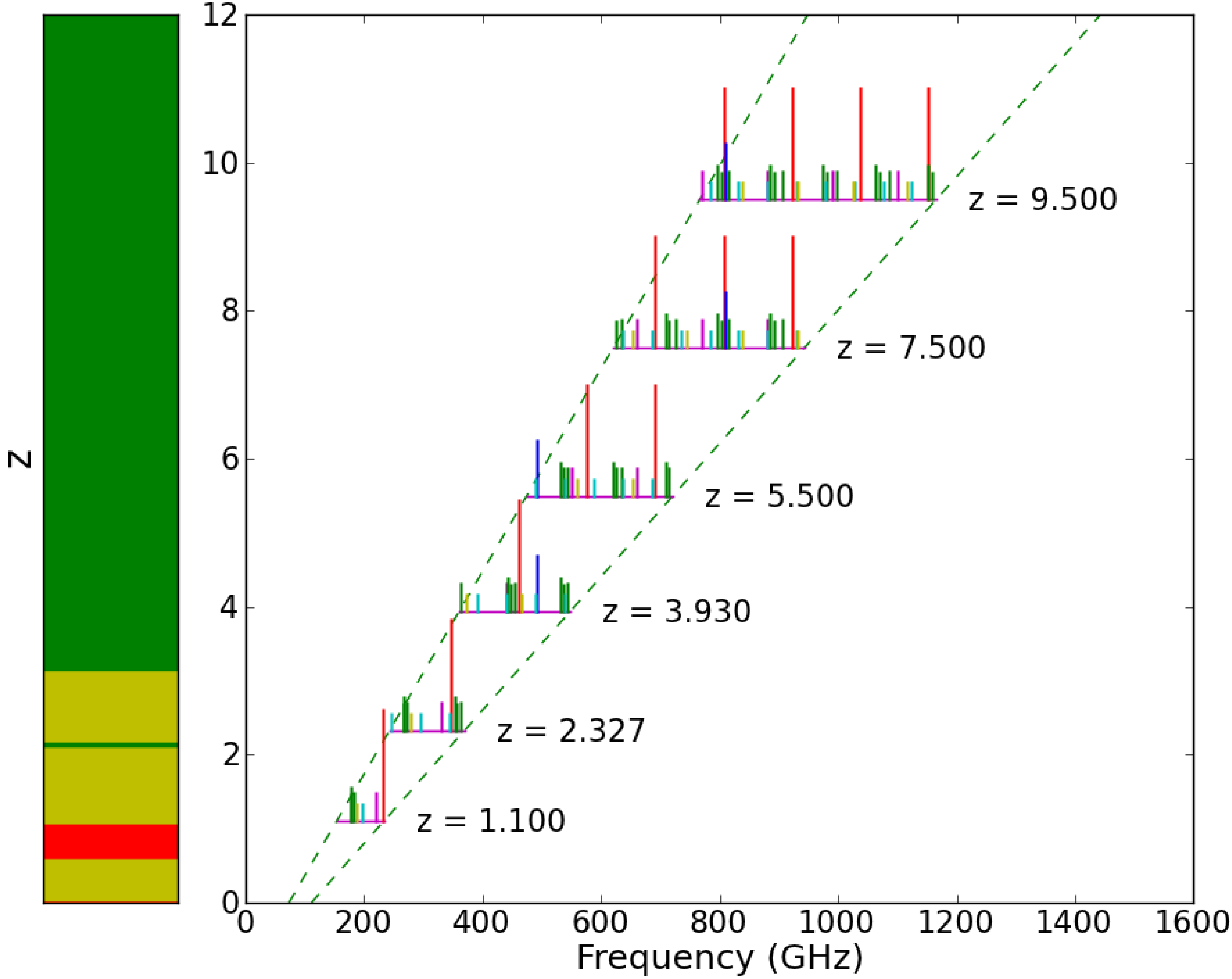
- Frequency separation of adjacent CO J-transitions $\Delta f \sim 115/(1+z)$. For $z>2$, two adjacent CO lines will fall within $\Delta f < 35$ GHz

Atmospheric Window For Redshift Search

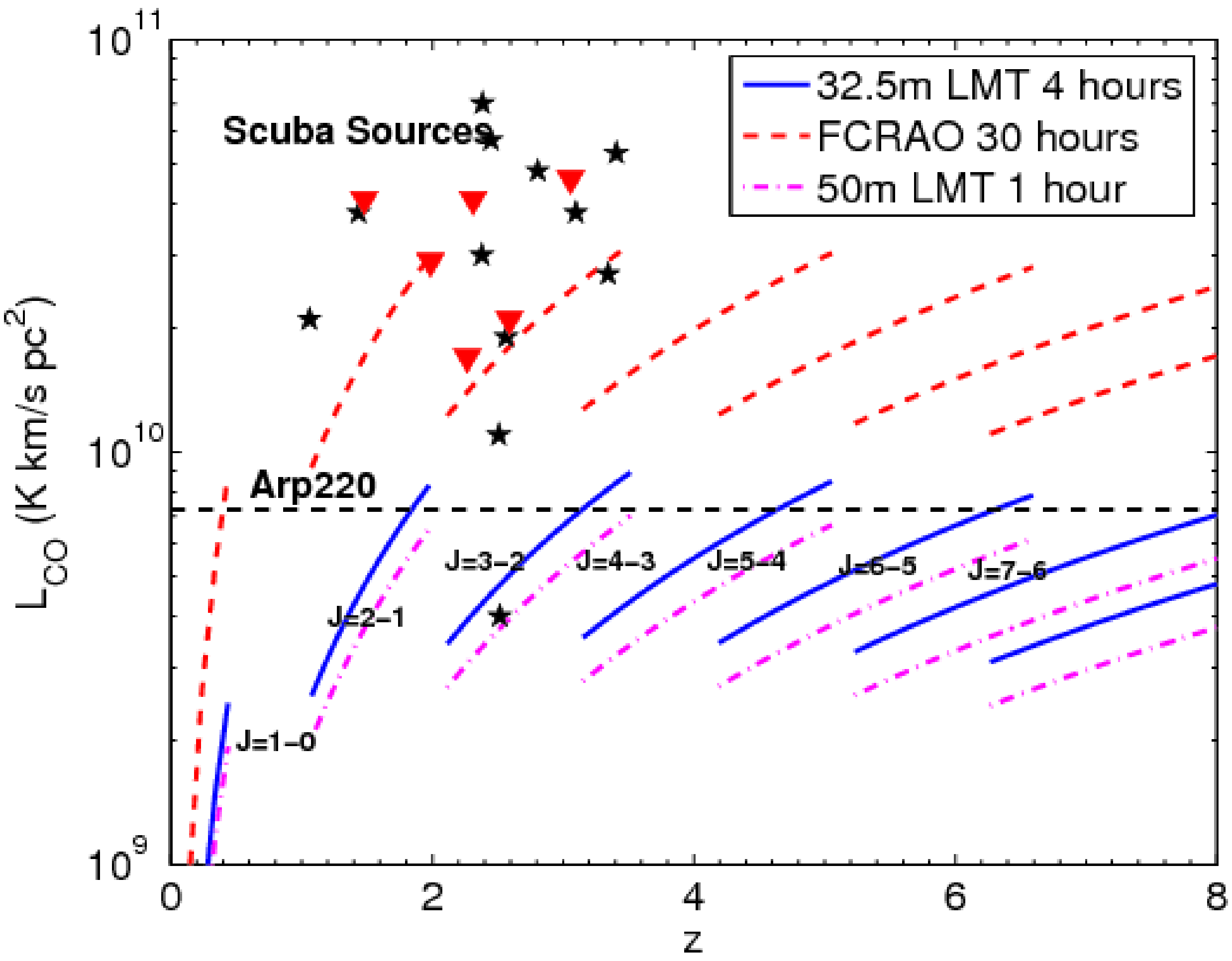


Redshift Coverage with 38 GHz in the 3mm band




z
12
10
8
6
4
2
0
0
200
400
600
800
1000
1200
1400
1600
Frequency (GHz)
z = 9.500
z = 7.500
z = 5.500
z = 3.930
z = 2.327
z = 1.100

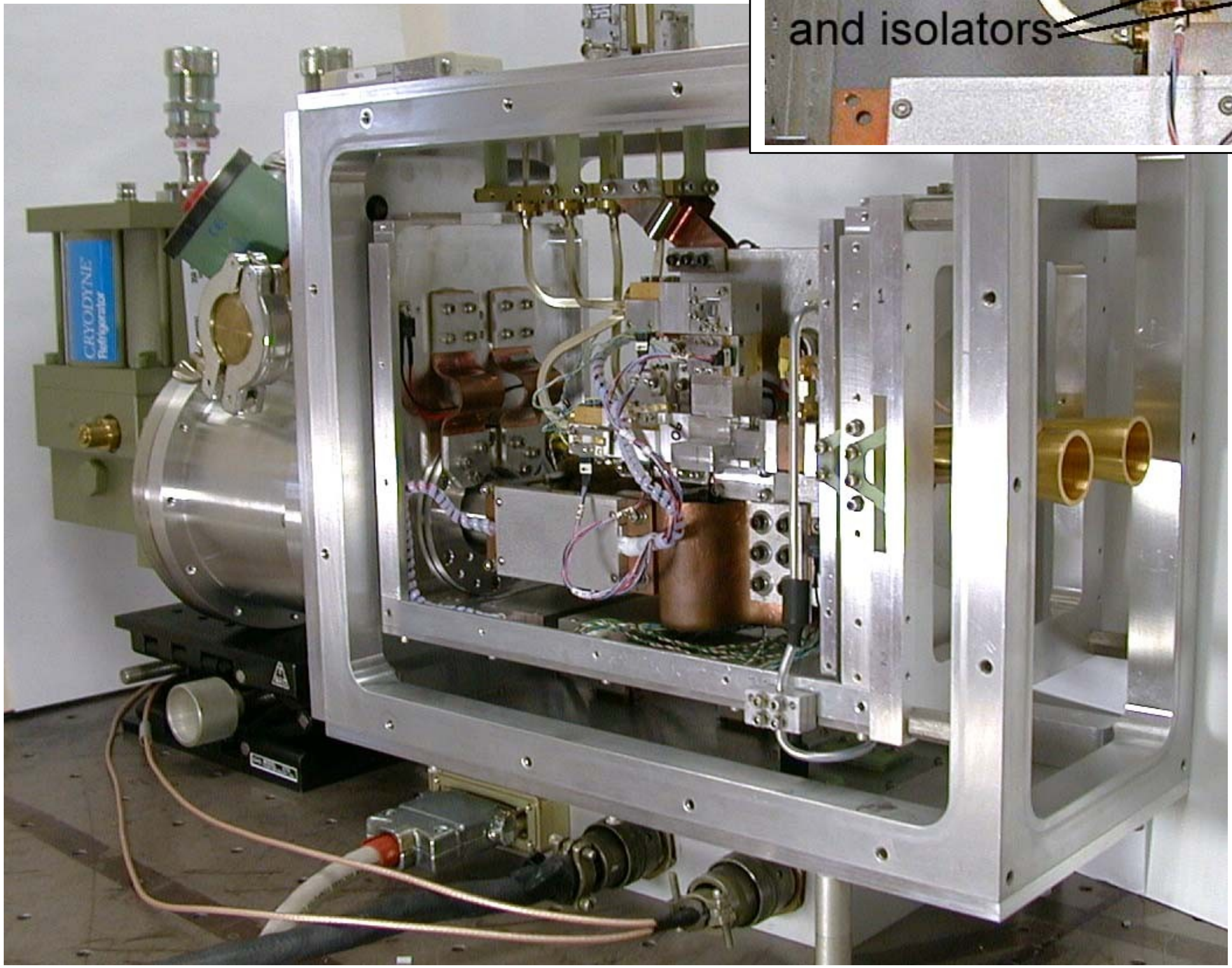
Expected Sensitivity of Redshift Receiver

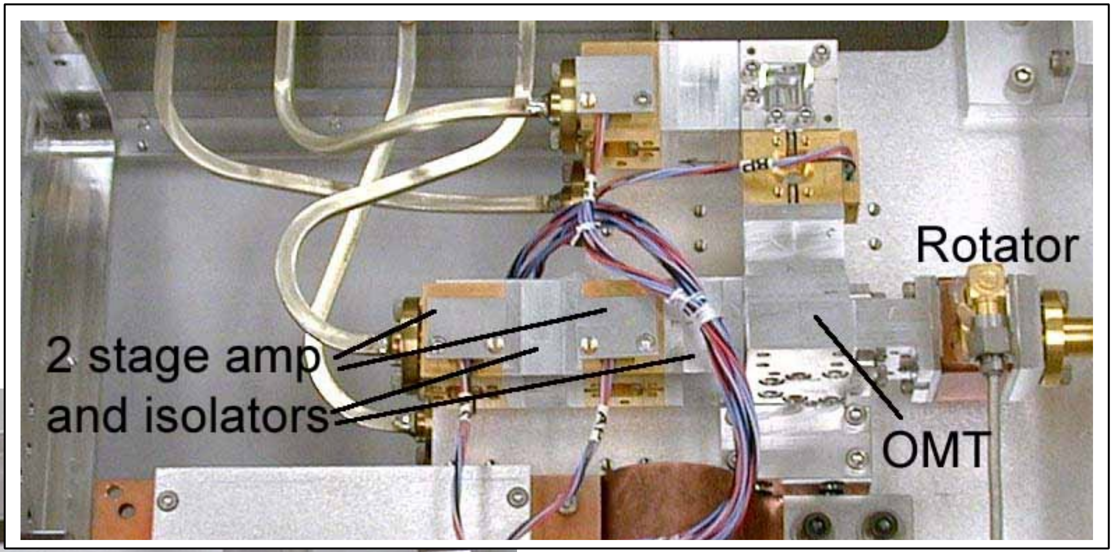


Ultra Wideband Redshift Search Receiver

- Science goal is to measure galaxy redshifts where z is unknown.
- 73 – 110.5 GHz covered simultaneously with a receiver/spectrometer having 30 MHz resolution.
- Wide bandwidth with very low noise is practical with InP MMIC amps operated at 20 K.
- Full receiver has 4 pixels – two dual polarization feeds with ortho-mode transitions.
- 1 KHz ferrite beam switch on input for very flat baselines.
- Each receiver has 2 IF outputs 1.5-20 GHz x 4 receivers
- ~ 146 GHz total IF bandwidth!
- A new generation of spectrometer is needed for this problem.

Room temp frontend components mount to the outside of the dewar at the waveguide feedthroughs.

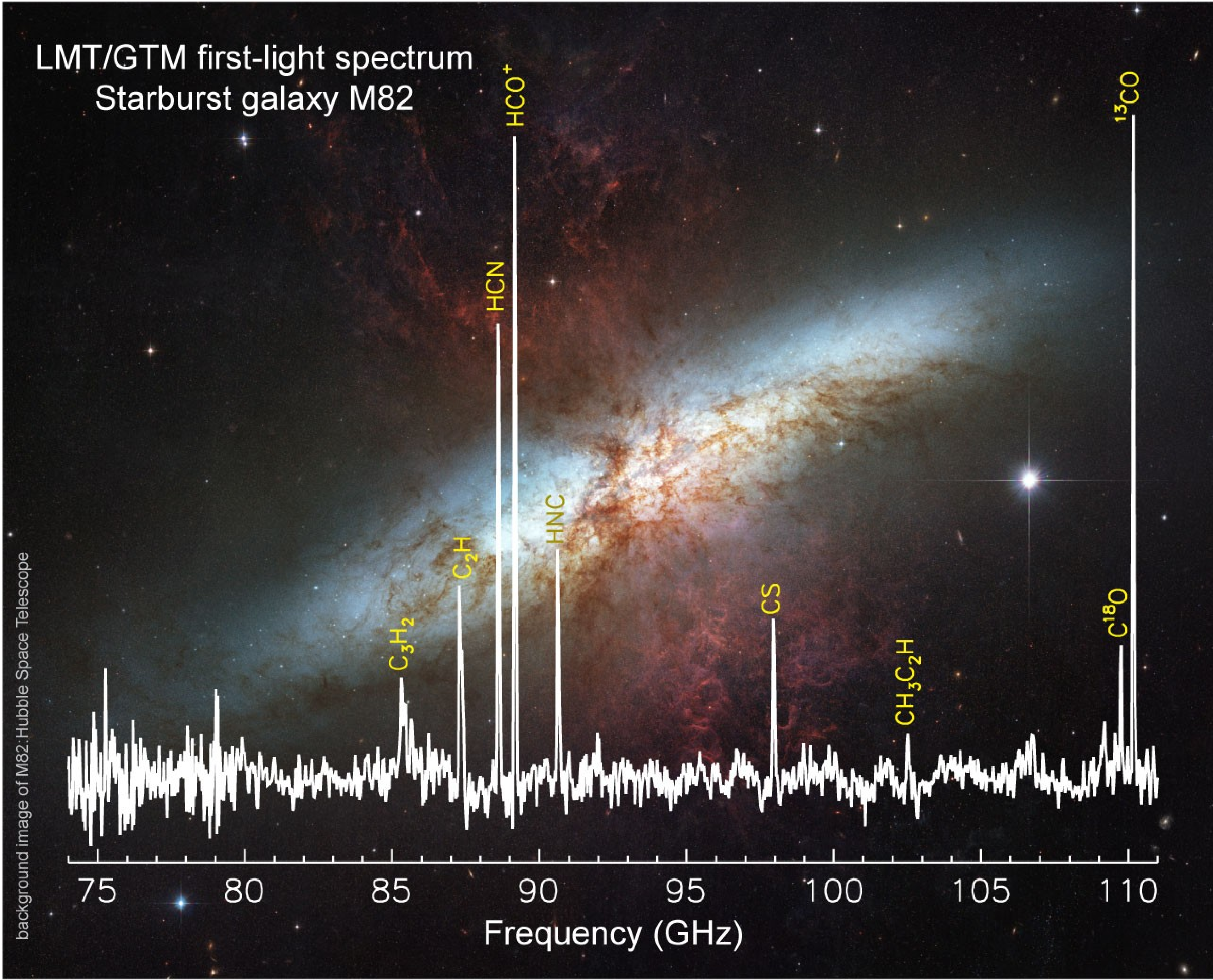




Detail of one dual polarized receiver.

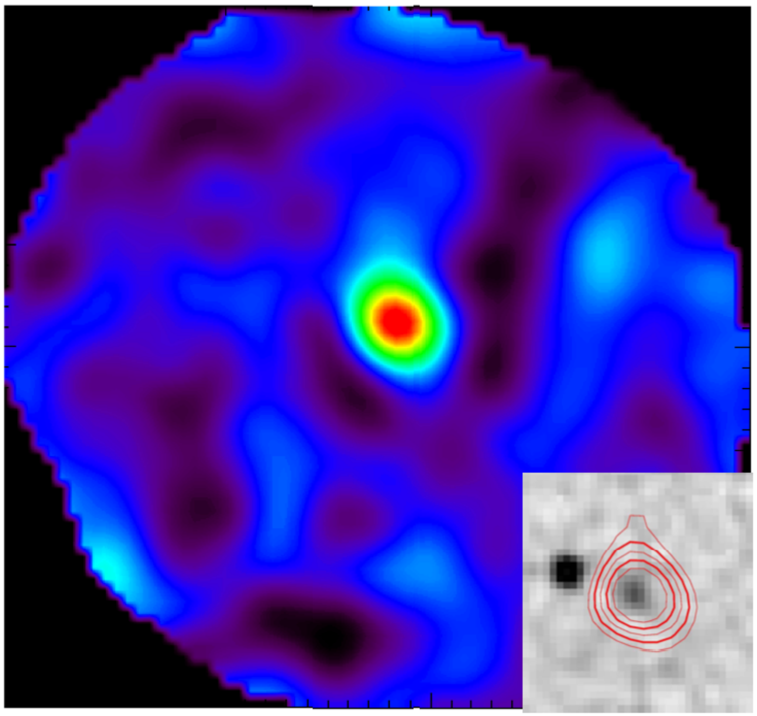
First Light on the LMT with the Redshift Search Receiver in June 2011

- Three chassis each with full 38 GHz coverage coupled to 3 redshift frontend pixels
- Receiver installed on the LMT and all hardware and software commissioned successfully
- Many nearby galaxies (M82, NGC253, M51, IC342, etc.) studied.
- Many previously high-redshift SMGs detected
- Receiver was able to be used in improving telescope pointing model and in verifying surface accuracy

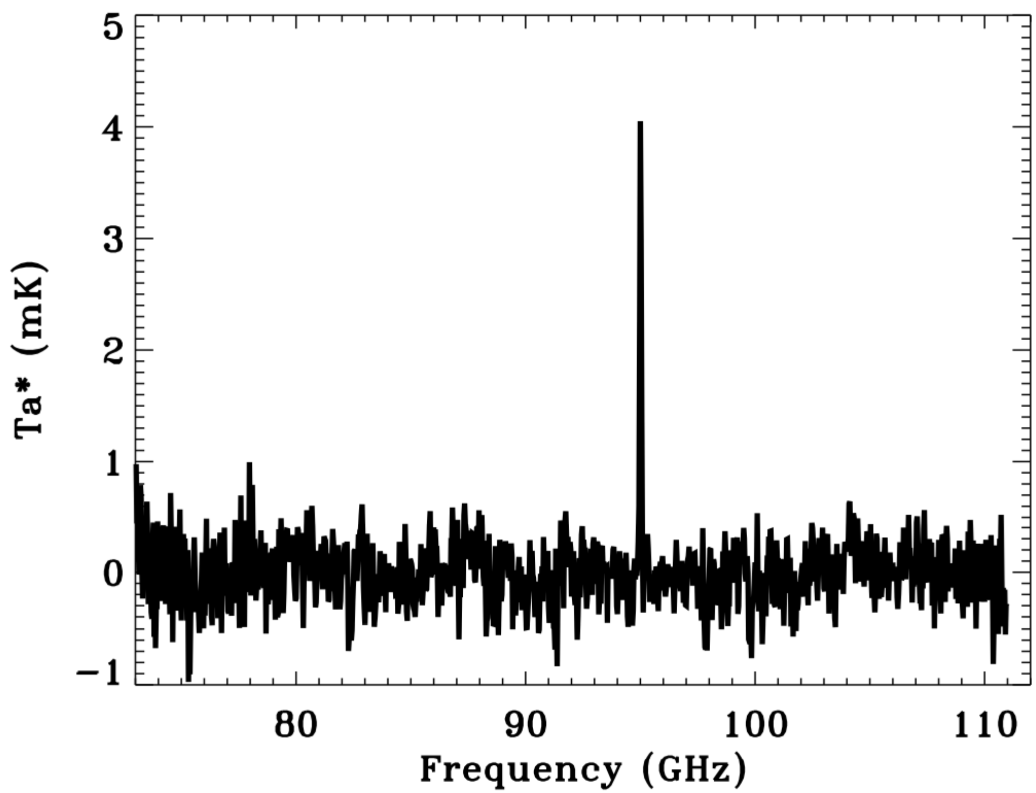


LMT/GTM first-light spectrum
Starburst galaxy M82
HCO+
13CO
HCN
HNC
C2H
CS
C3H2
CH3C2H
C18O
75
80
85
90
95
100
105
110
Frequency (GHz)
background image of M82:Hubble Space Telescope

Atacama Cosmology Telescope Survey Bright Source Followup



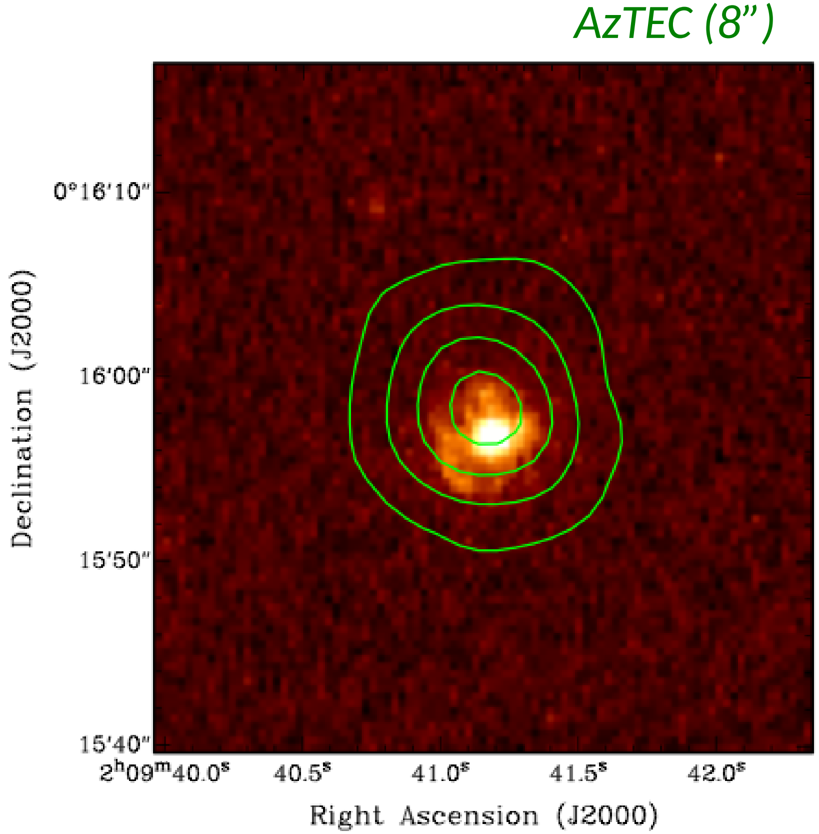
AzTEC Image
Locates the source at high resolution

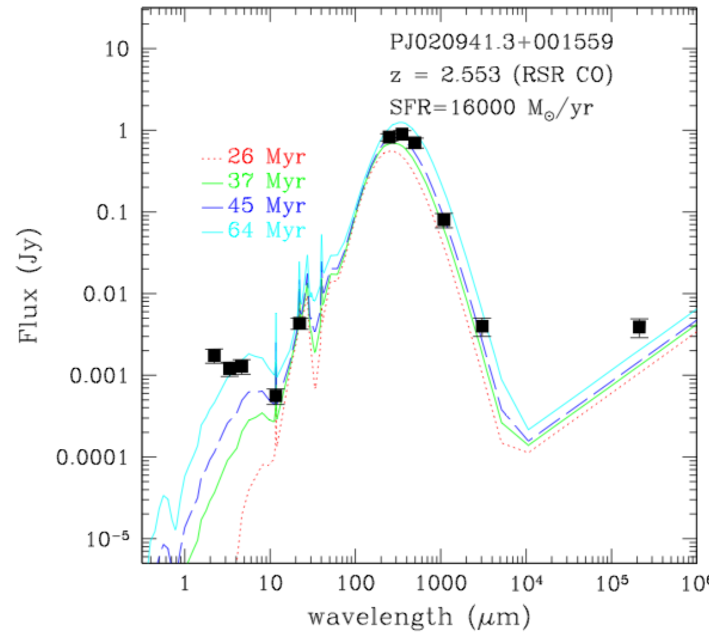


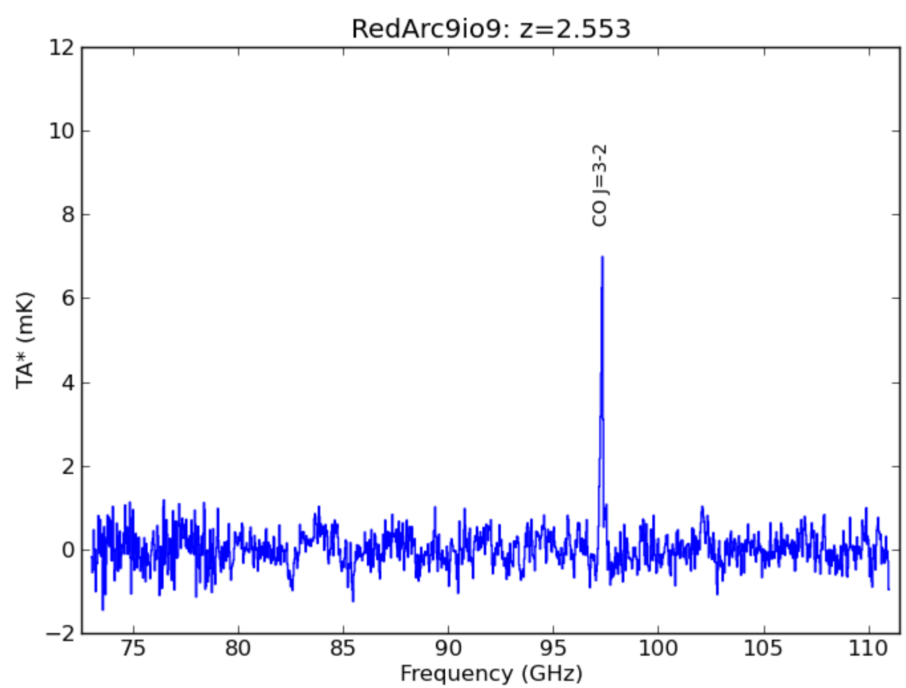
Redshift Receiver Spectrum
Determines the Redshift

arXiv: 1503.05824 (Geach et al 2015)

9io9 (z=2.54)

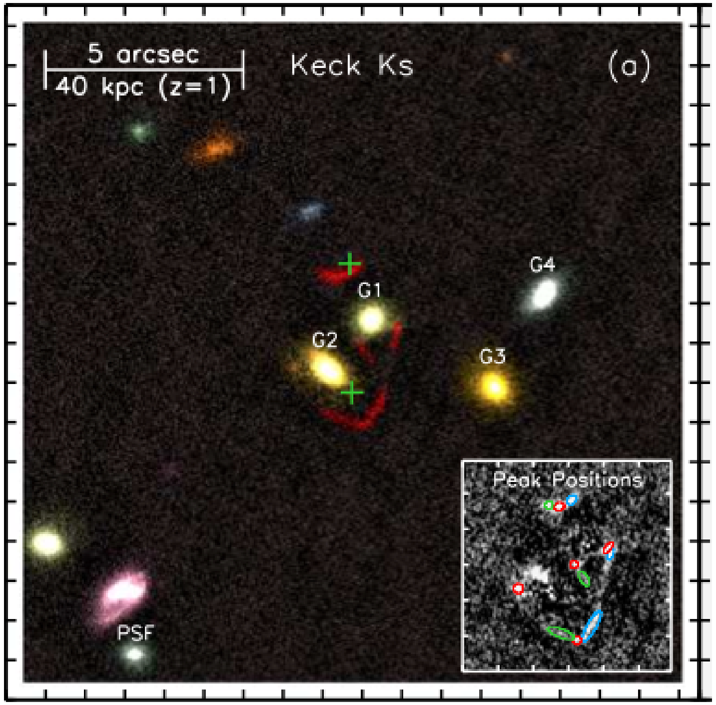






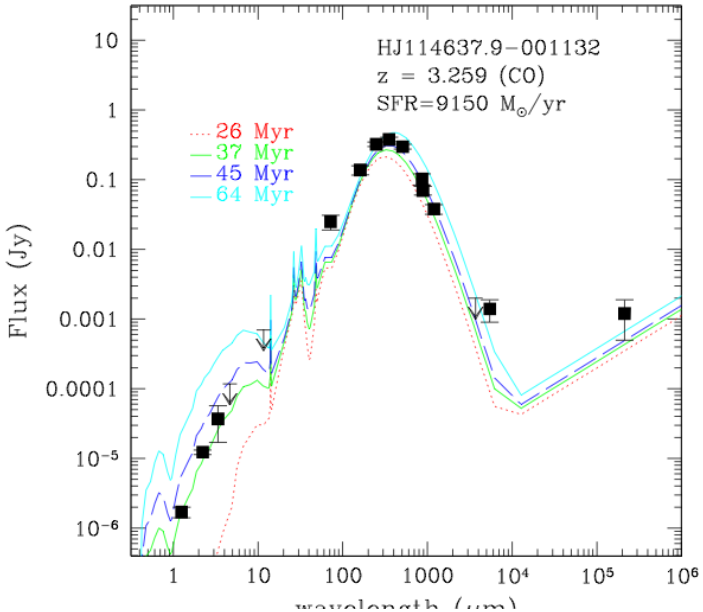
9io9 identified as lensed object by volunteers in Zooniverse Project!

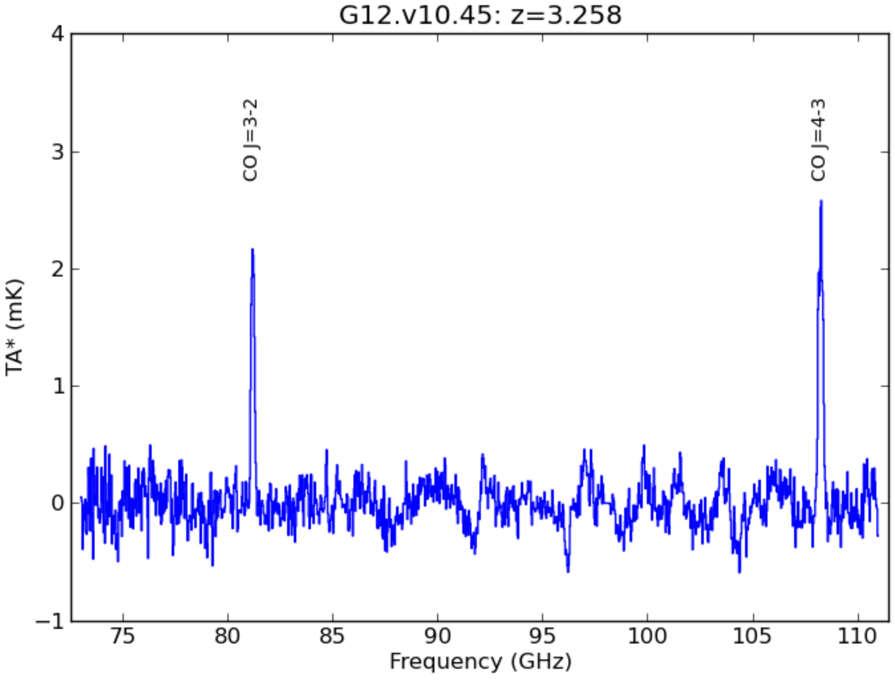
HJ114637 (z=3.26)



Fu et al. (2012)

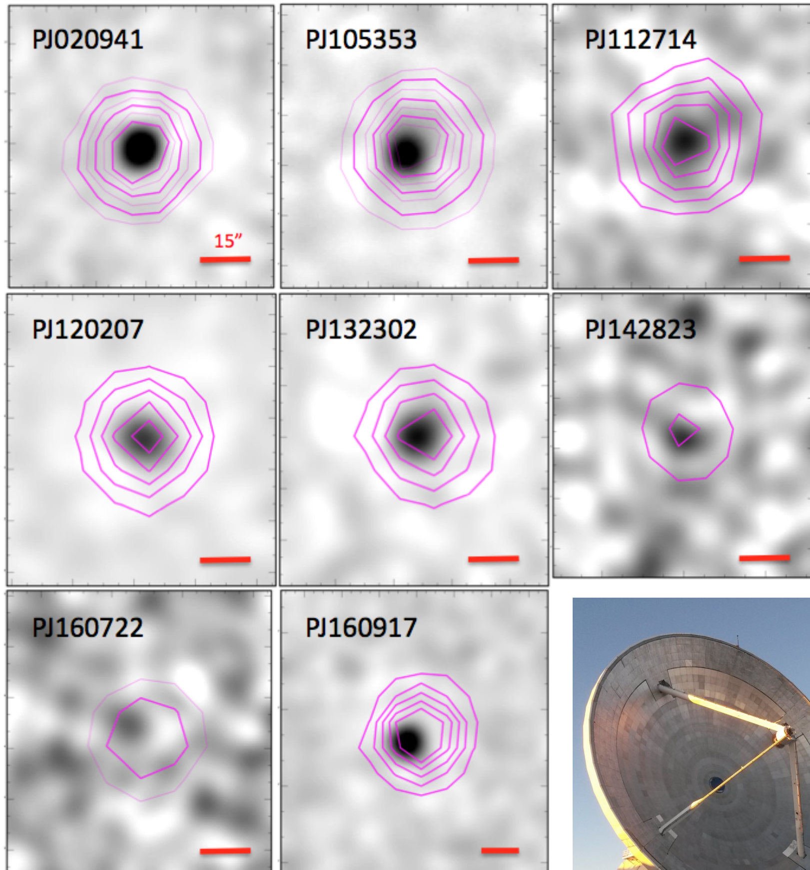
Red “arcs” are lensed images of the z=3.26 galaxy





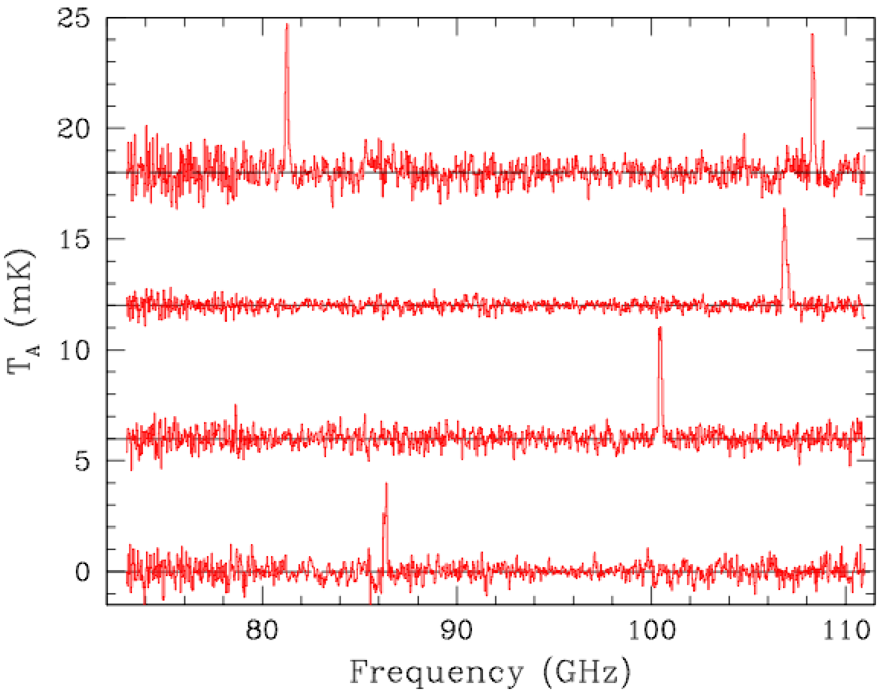
LMT: AzTEC & RSR Observations
Brightest candidates from Planck

SPIRE 350um on AzTEC



FWHM ~ 8"
(3-20 minutes integration)

Harrington et al. (2016)



One or more CO line detected in 8/8 sources observed (15 to 30 minutes per source)

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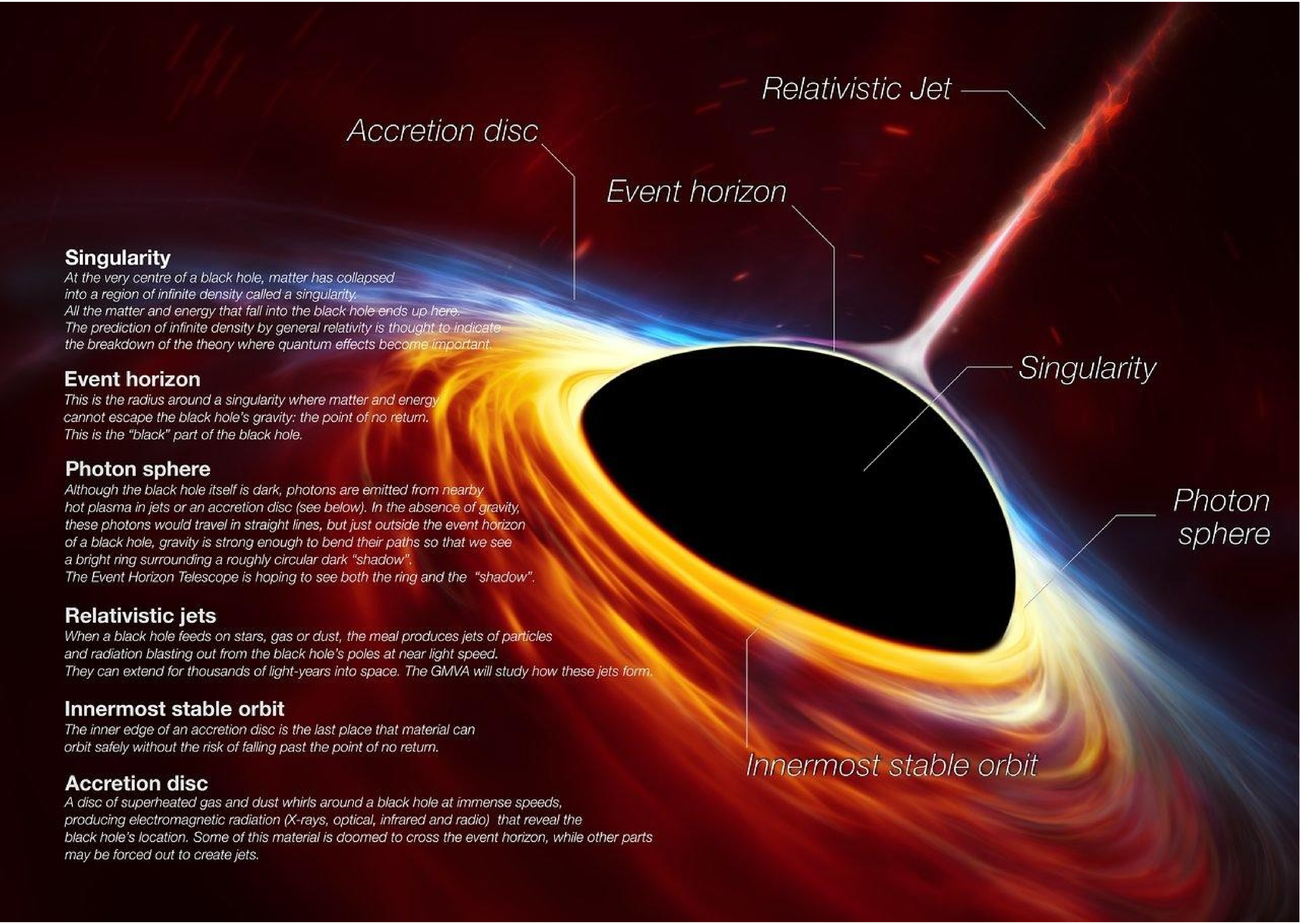
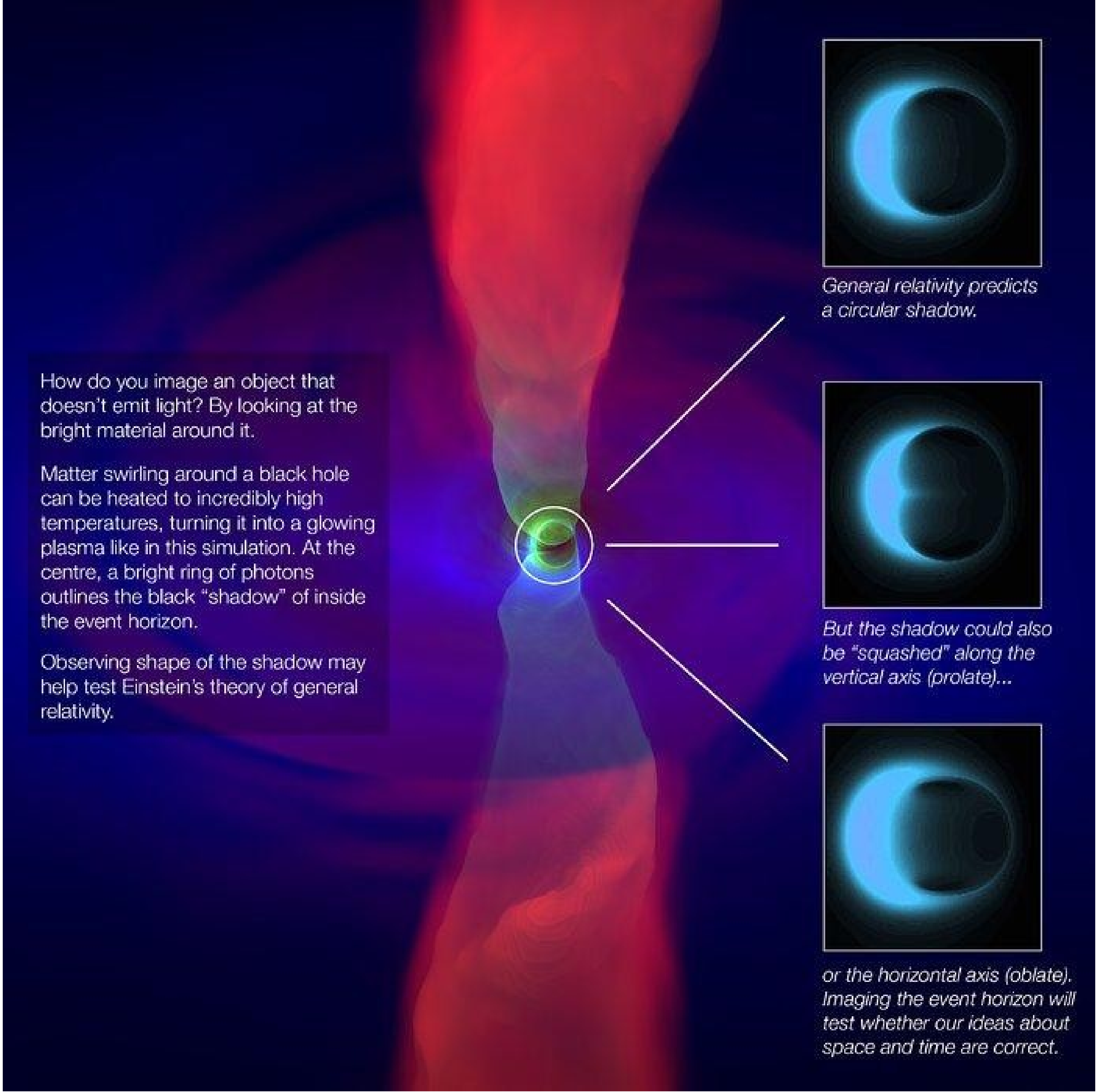
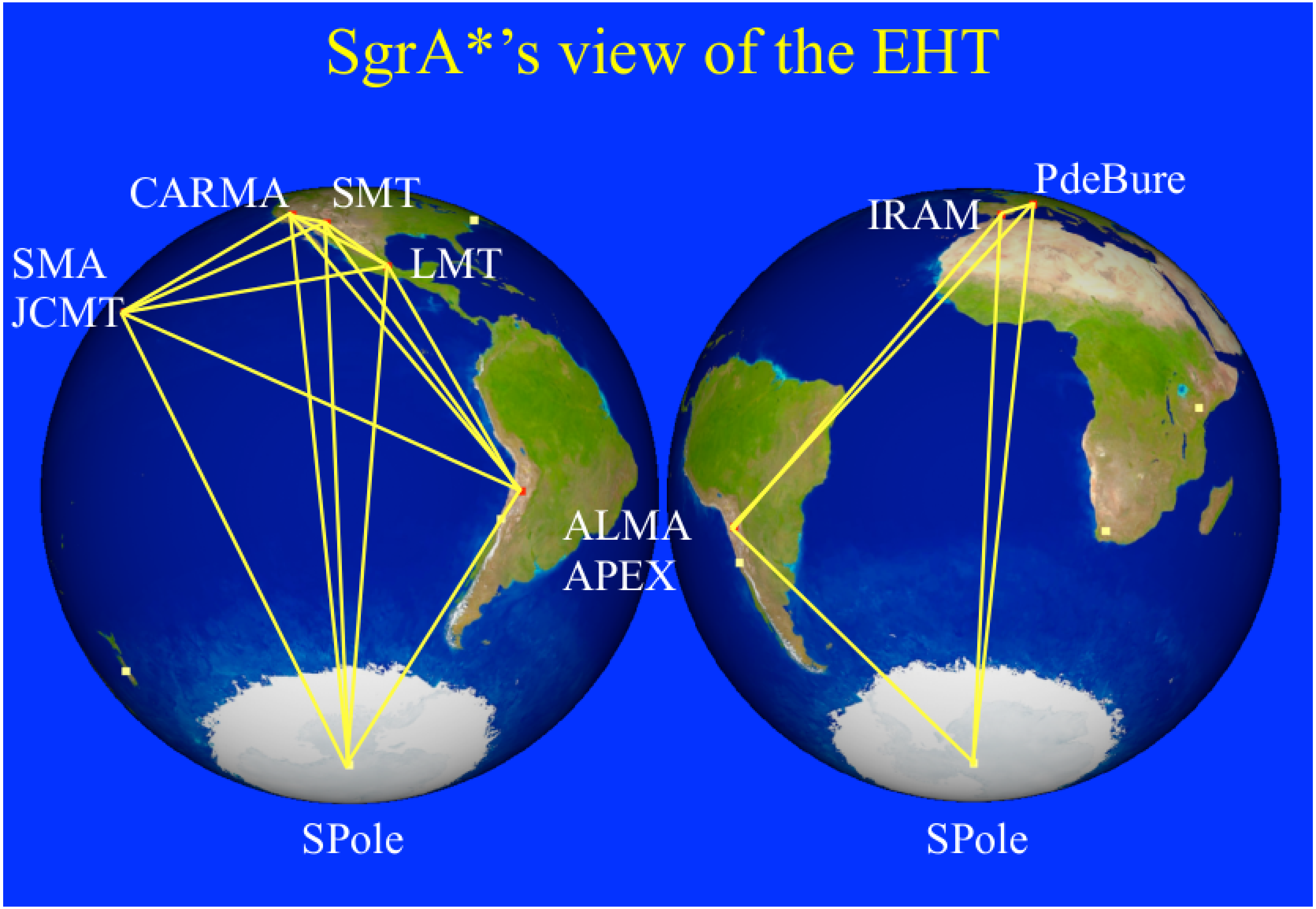
VLBI at the LMT

- LMT is fully equipped now for 3mm and 1mm wavelength VLBI
- Has a Symmetricom (now Microsemi) Maser Model MHM-2010, a 10 MHz distribution system, Mark V and VI recorders, 1pps distribution and versatile backends
- LMT officially part of the VLBA, HSA (High Sensitivity Array), Global mm VLBI Array
- Under MSIP funding, LMT is a key element for the Event Horizon Telescope (EHT) experiment

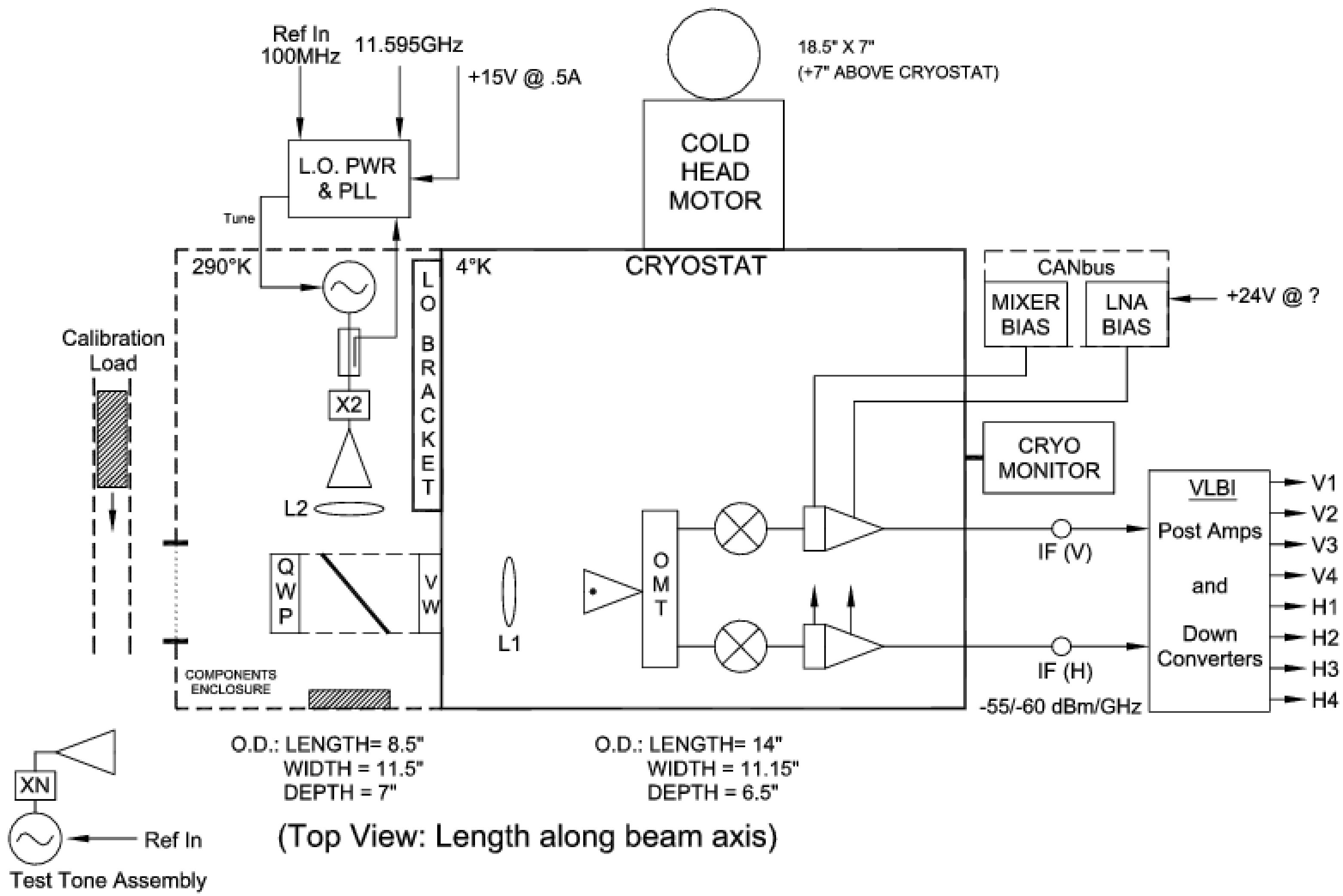

Relativistic Jet
Accretion disc
Event horizon
Singularity
Photon sphere
Innermost stable orbit
Singularity
At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.
Event horizon
This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.
Photon sphere
Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow". The Event Horizon Telescope is hoping to see both the ring and the "shadow".
Relativistic jets
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.
Innermost stable orbit
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.
Accretion disc
A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.


How do you image an object that doesn't emit light? By looking at the bright material around it.
Matter swirling around a black hole can be heated to incredibly high temperatures, turning it into a glowing plasma like in this simulation. At the centre, a bright ring of photons outlines the black "shadow" of inside the event horizon.
Observing shape of the shadow may help test Einstein's theory of general relativity.
General relativity predicts a circular shadow.
But the shadow could also be "squashed" along the vertical axis (prolate)...
or the horizontal axis (oblate). Imaging the event horizon will test whether our ideas about space and time are correct.

The LMT is a critical hub of the EHT

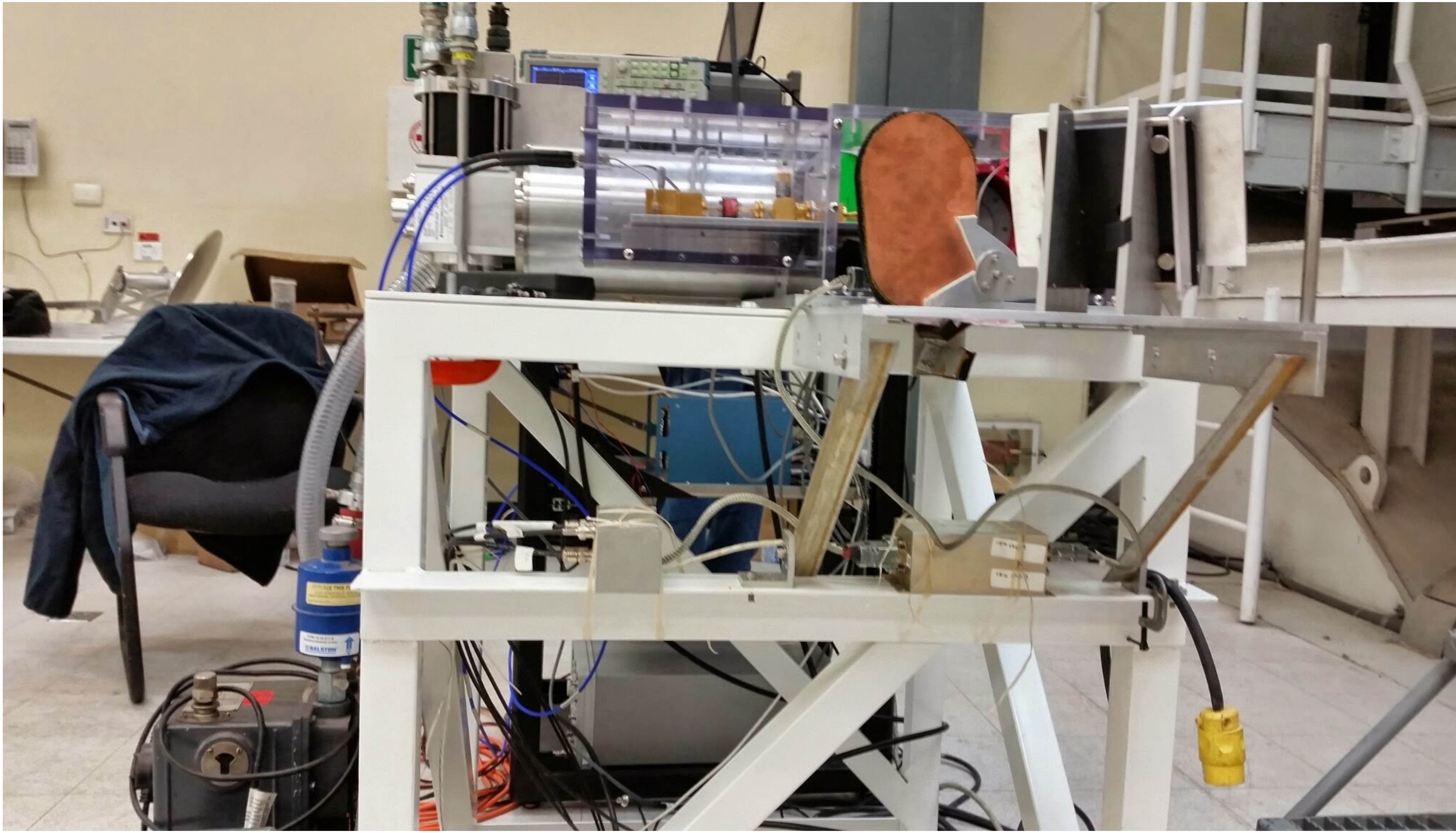


Interim 1mm VLBI Receiver



LMT 1.3 mm
CARMA mixers


NO TOCAR
AUTORIZADO

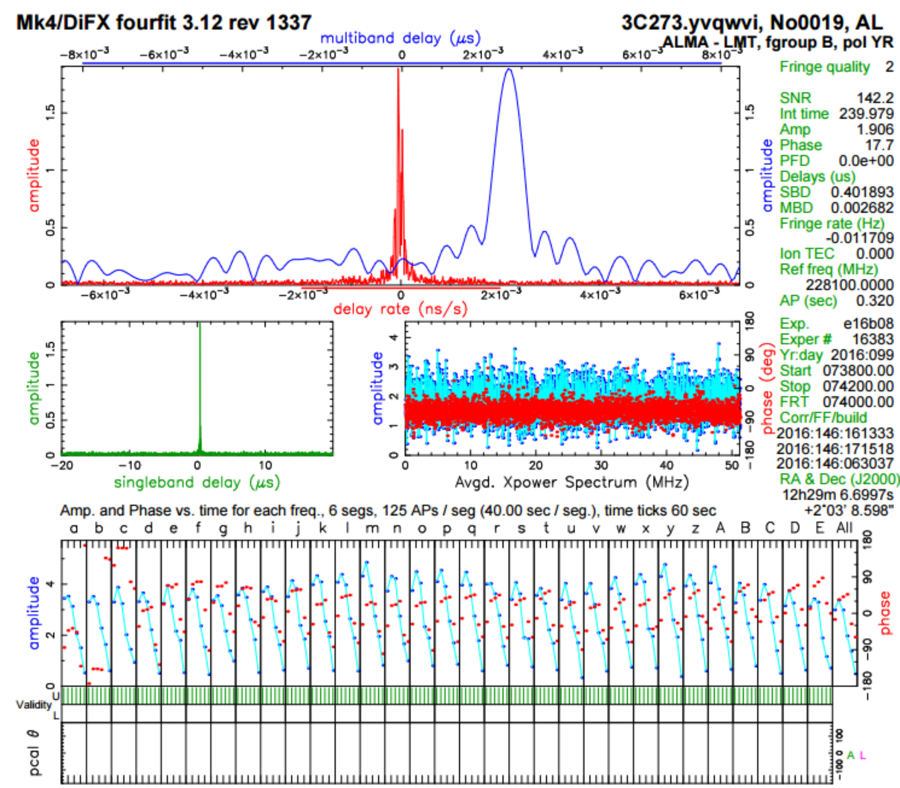


EHT Experiment March 2015

- 1mm EHT Run between Mar 20 – Mar 30
- Telescopes that participated in run: LMT, APEX, CARMA, IRAM, SMA, SMT, JCMT
- Mode: 16 Gbps = Dual-pol 2 GHz bandwidths (2x2 GHz)
- Center Sky Frequency: 227.1 GHz (i.e. IF 226.1-228.1 GHz)
- Target: 5 nights of 12 hrs at 50% duty cycle = 216 TB/station
- Big Cast of Characters for Participants at LMT
  - Shep Doeleman + 2 postdocs from Smithsonian;
  - Gopal + student from UMass
  - Jonathan Leon Tavarez (INAOE), Gisella Ortiz (Morelia)
  - LMT Observers (David Sanchez, David Hughes, etc.)
  - Seth Fletcher (Journalist from Scientific American)
  - Dennis Overbye – New York Times

EHT Experiment Apr 2016

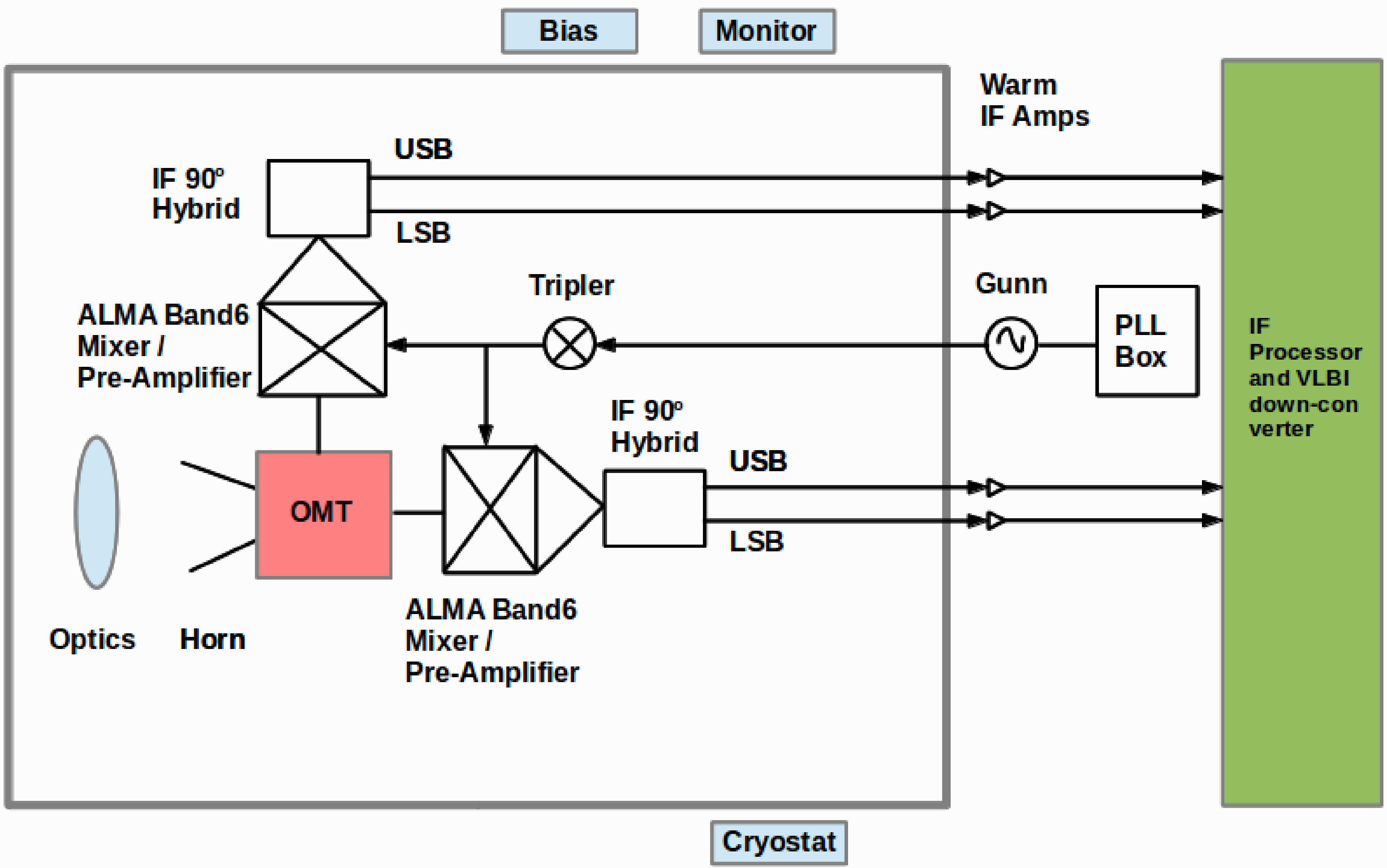
- 1mm EHT Run between Apr 4 – 8, 2016
- Telescopes that participated in run: LMT, ALMA, JCMT, SMA, SMT
- Successful fringes from LMT to ALMA and LMT to all other telescopes



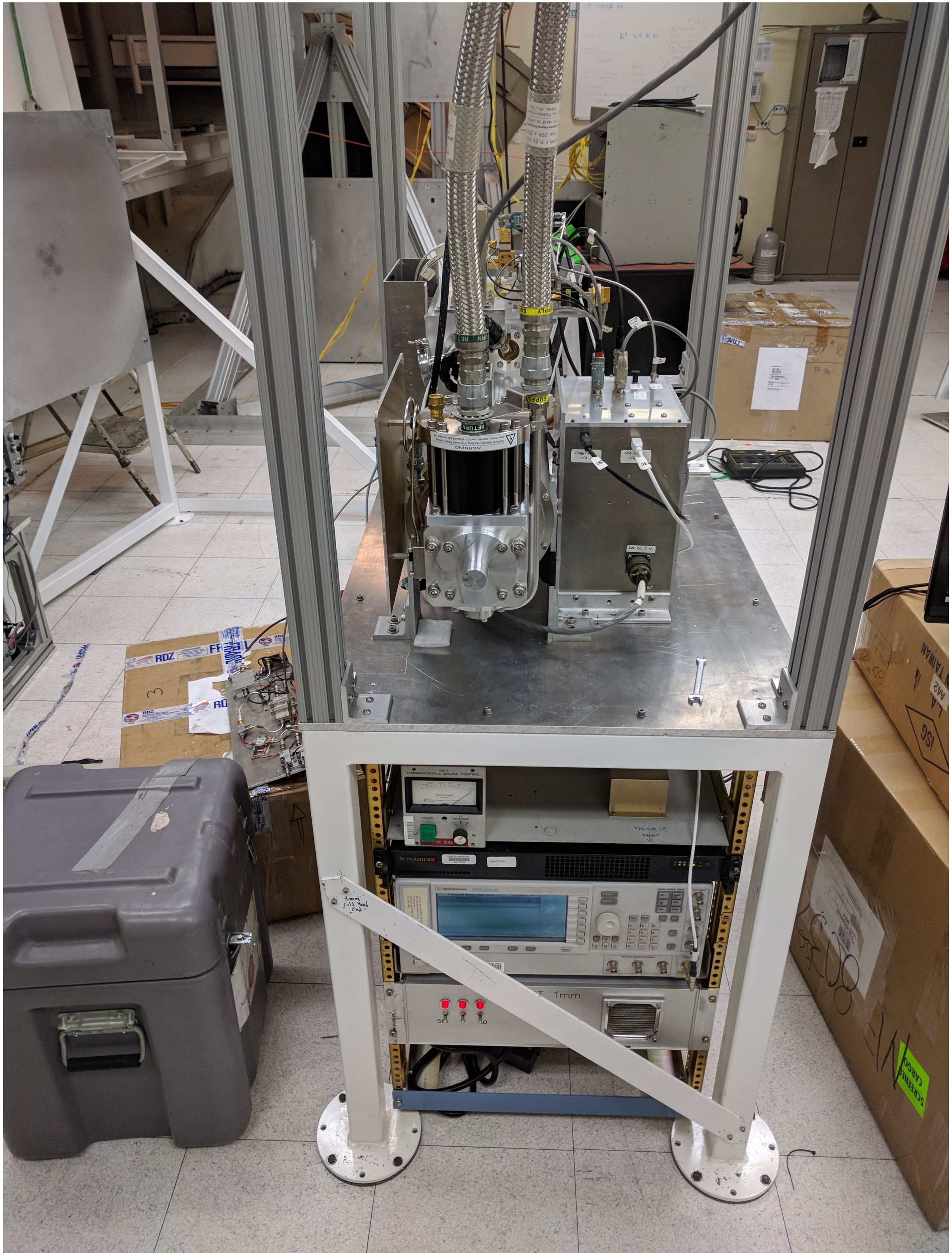
EHT Commissioning 2017

MSIP 1mm Receiver for EHT at the LMT

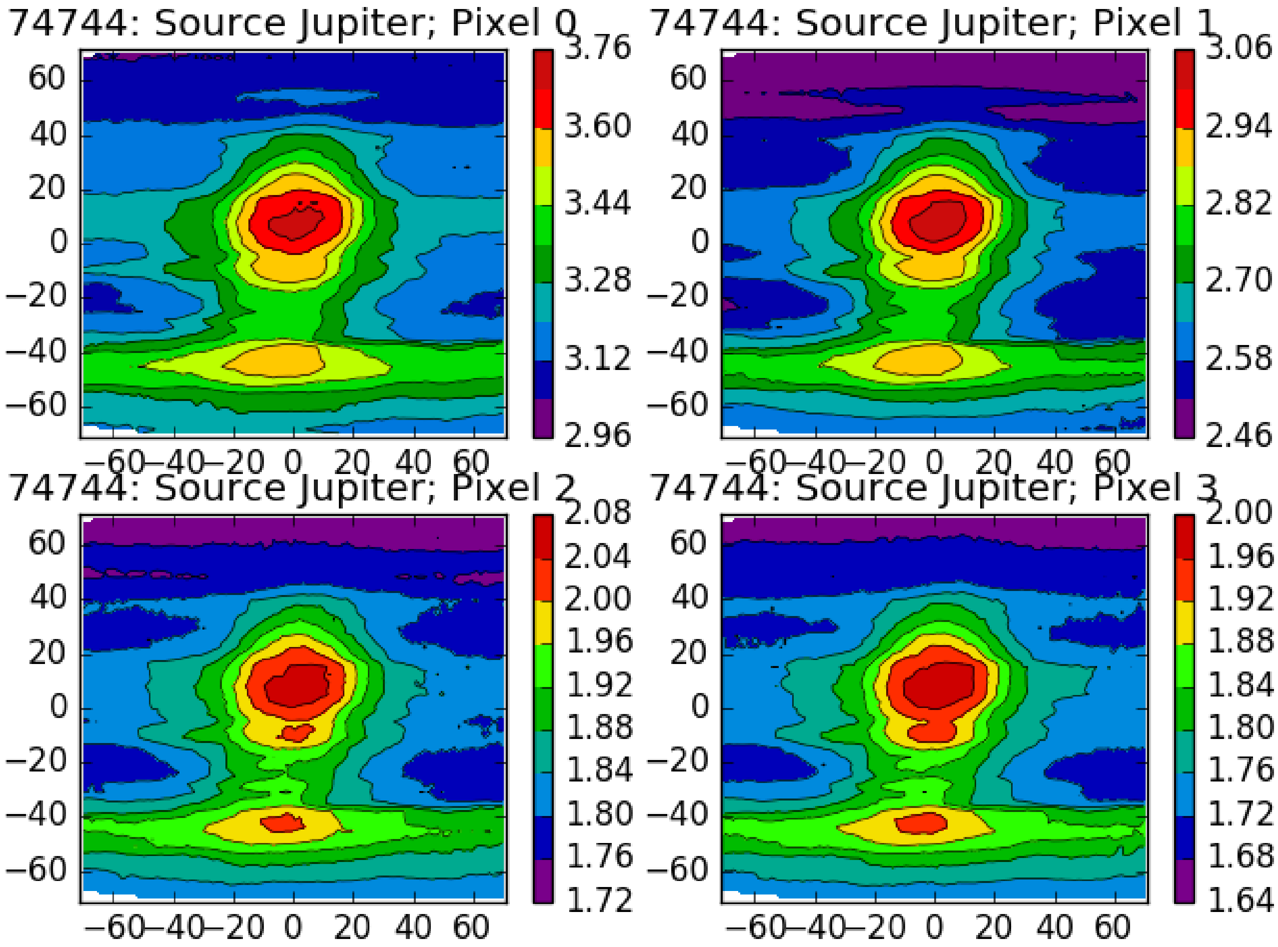
Installed and commissioned on LMT Apr 2018



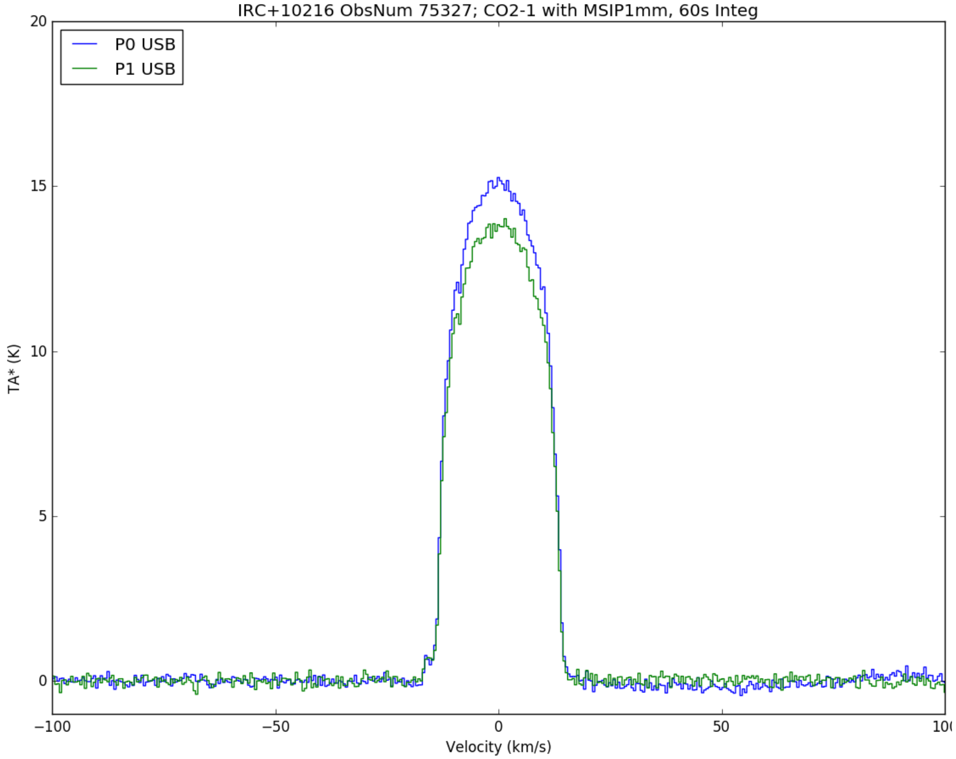
LMT 1mm Receiver

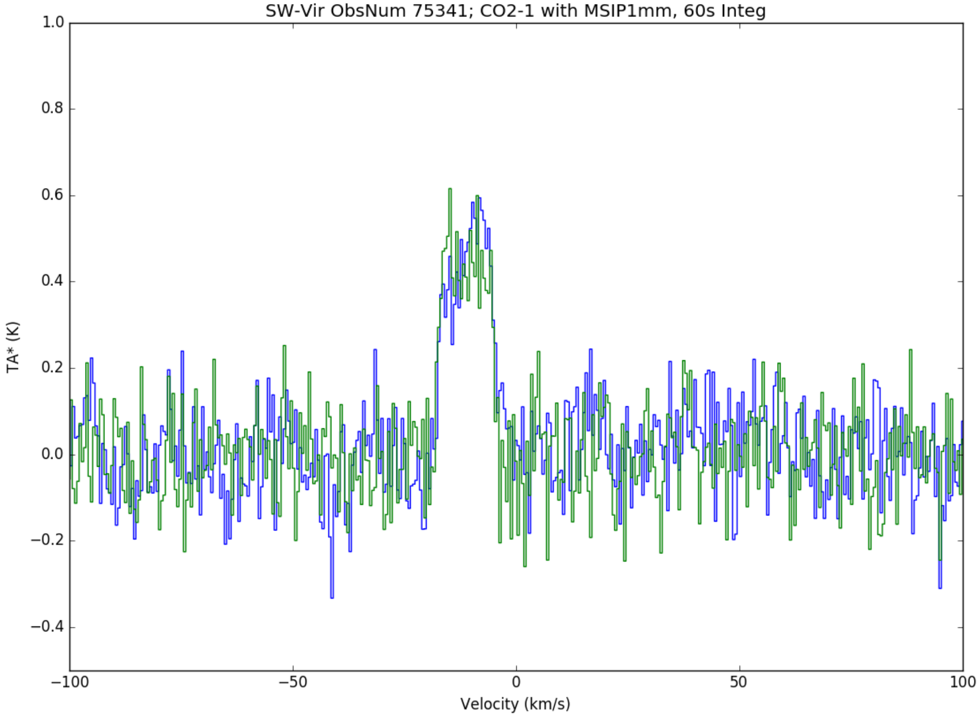


First Light Jupiter Map with 1mm Receiver

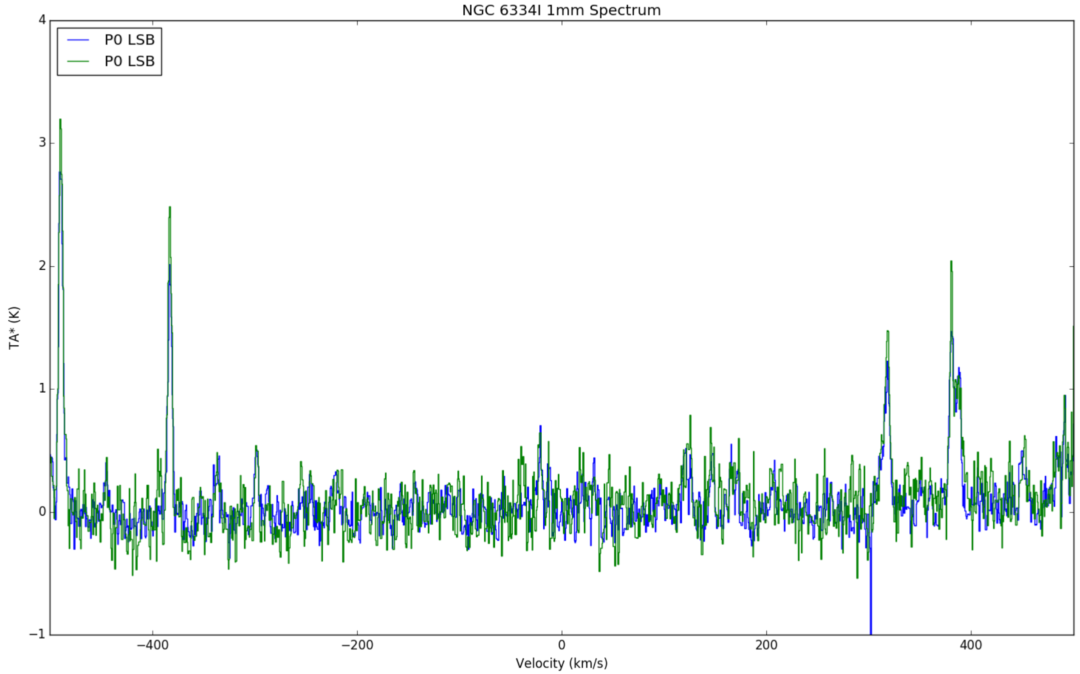


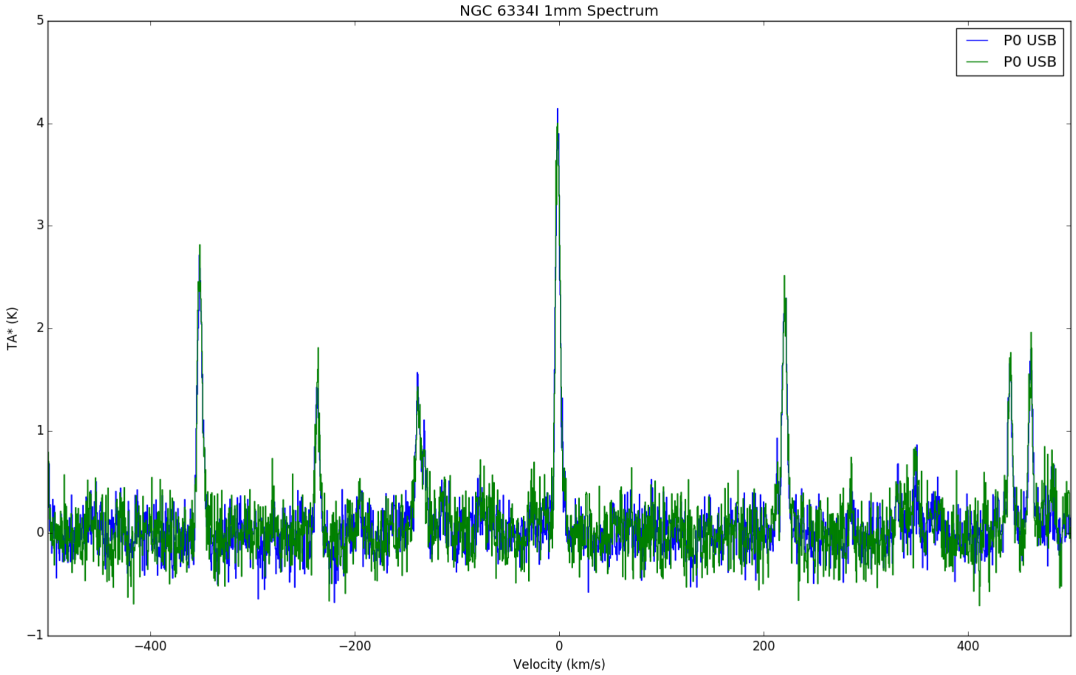
Line Pointing Capabilities with 1mm Receiver





NGC 6334I
Hot Core
LSB and USB





LMT Team Apr 2018

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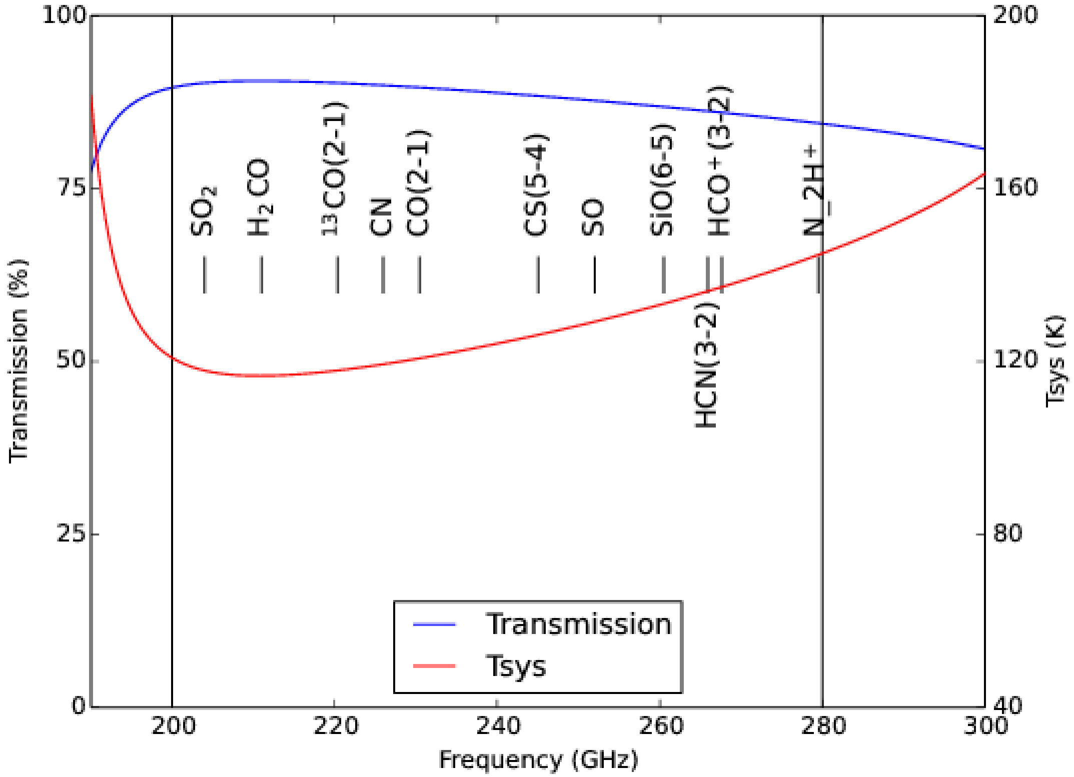
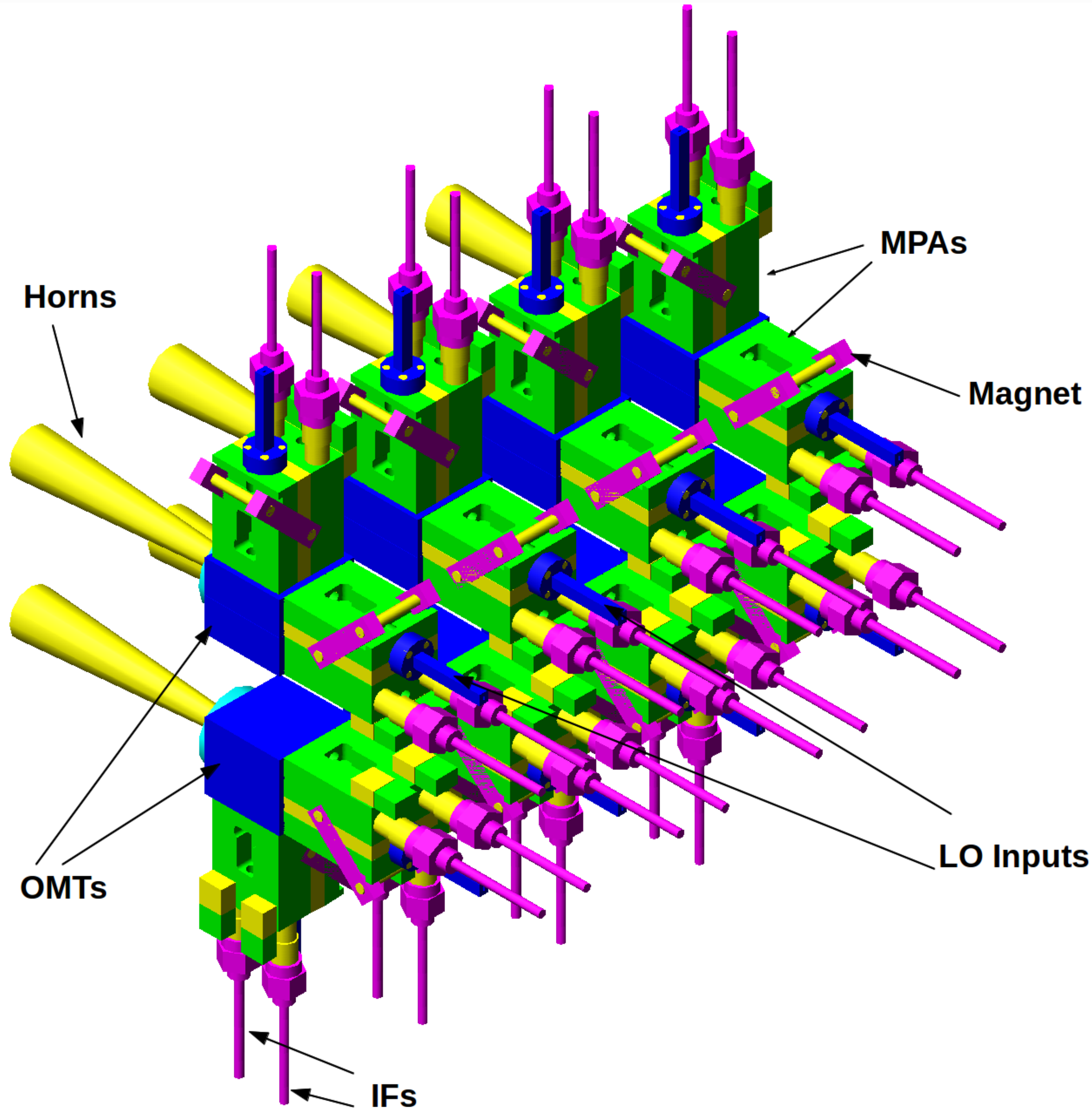
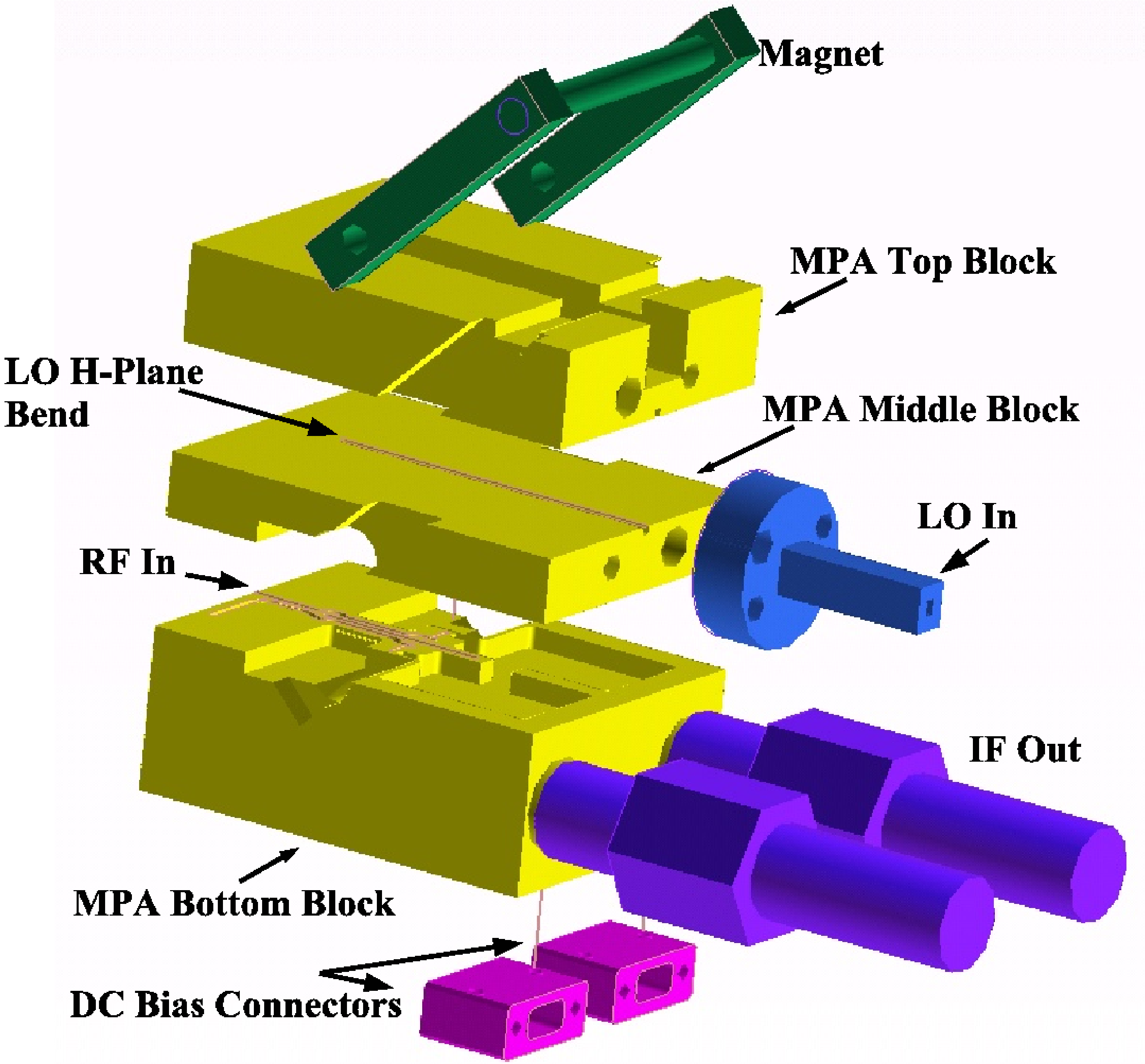
OMAyA – One Millimeter Array – A Funded NSF ATI Instrument

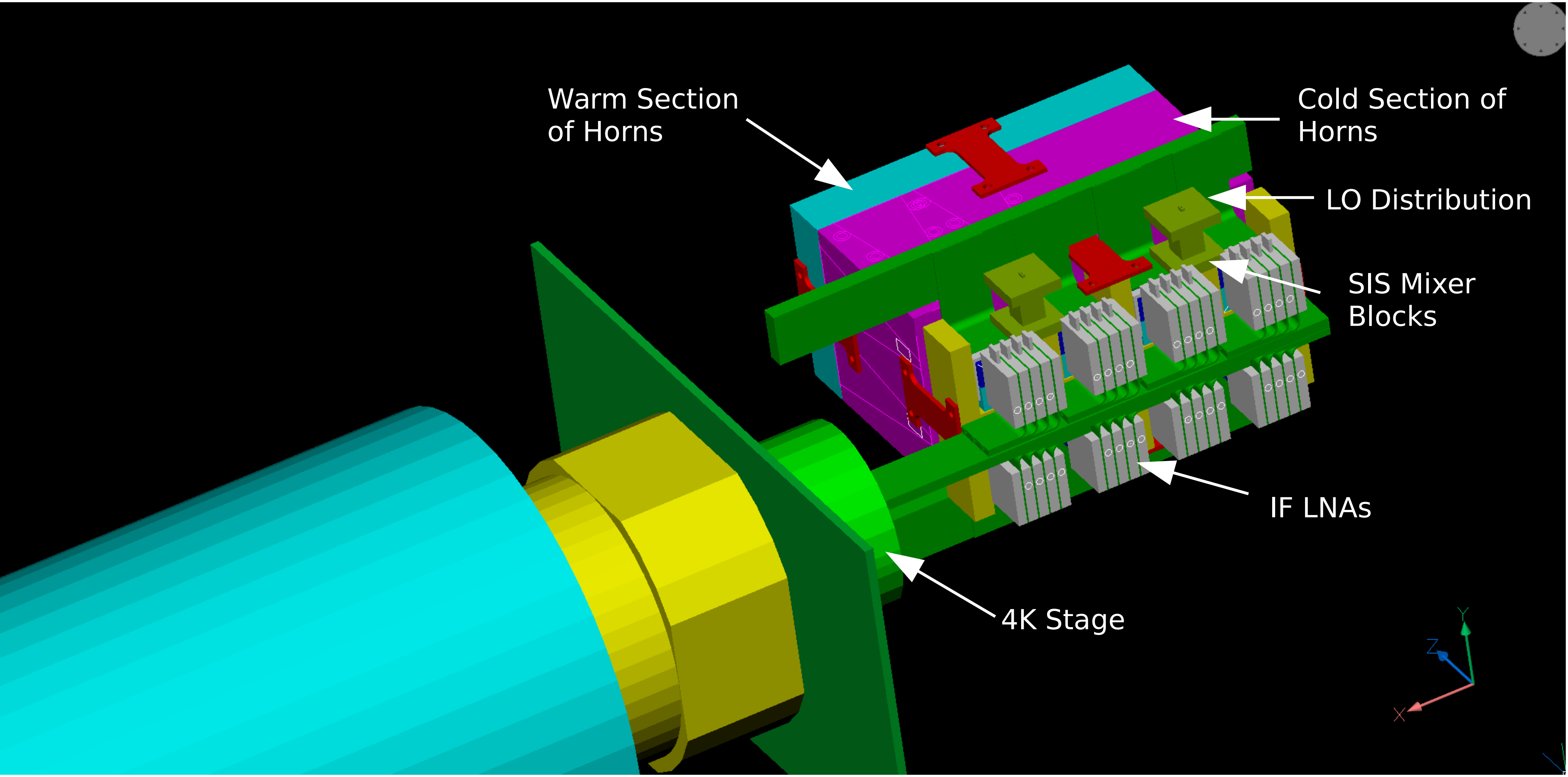
- 8 dual polarized pixels on the sky
- Each pixel uses sideband separation SIS mixer
- RF frequency coverage 200 – 280 GHz
- IF Frequency 4 – 12 GHz in each sideband
- Will be installed on the LMT in 2019-20 season




Horns
MPAs
Magnet
LO Inputs
OMTs
IFs


Magnet
MPA Top Block
LO H-Plane
Bend
MPA Middle Block
LO In
RF In
IF Out
MPA Bottom Block
DC Bias Connectors

Design of OMAyA Cryostat



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Array Digital Spectrometers

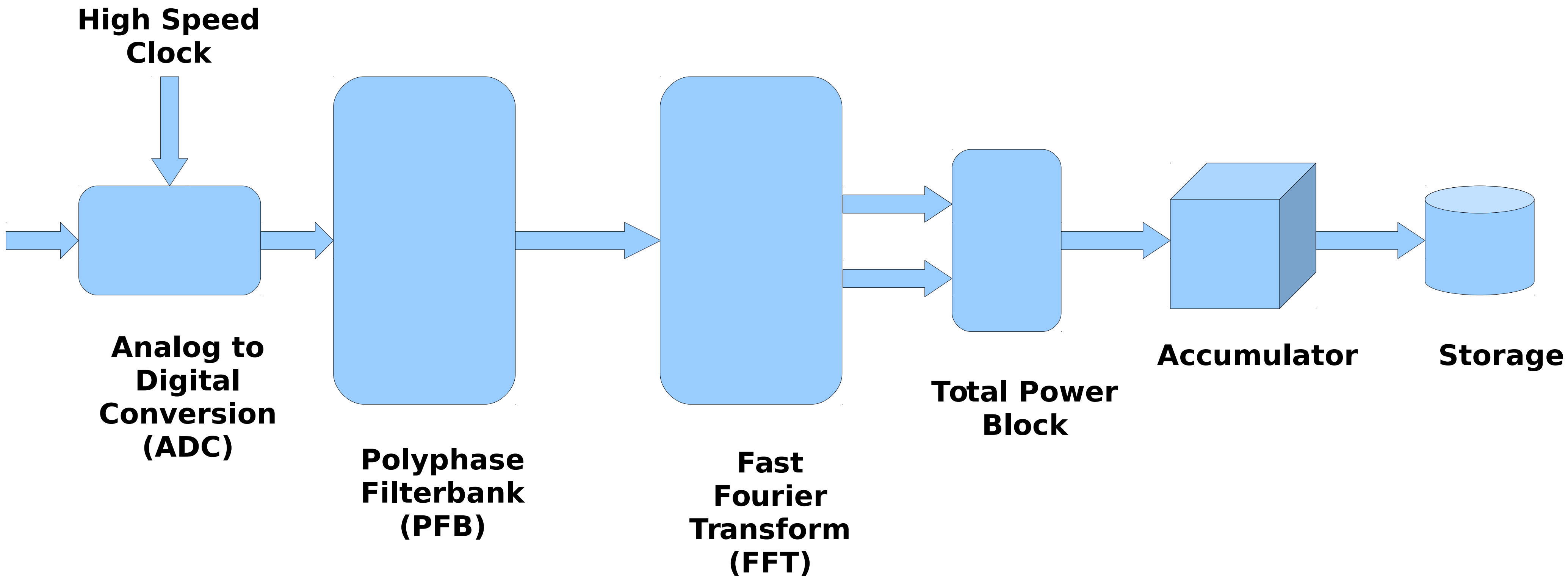
- With SEQUOIA and OMAyA and several single pixel broadband heterodyne receivers (eg. EHT 1mm Rx.) need flexible digital spectrometer system

- Use CASPER (Center for Astronomy Signal Processing and Electronics Research) FPGA (Field Programmable Gate Array) boards to develop versatile broad-band digital spectrometers

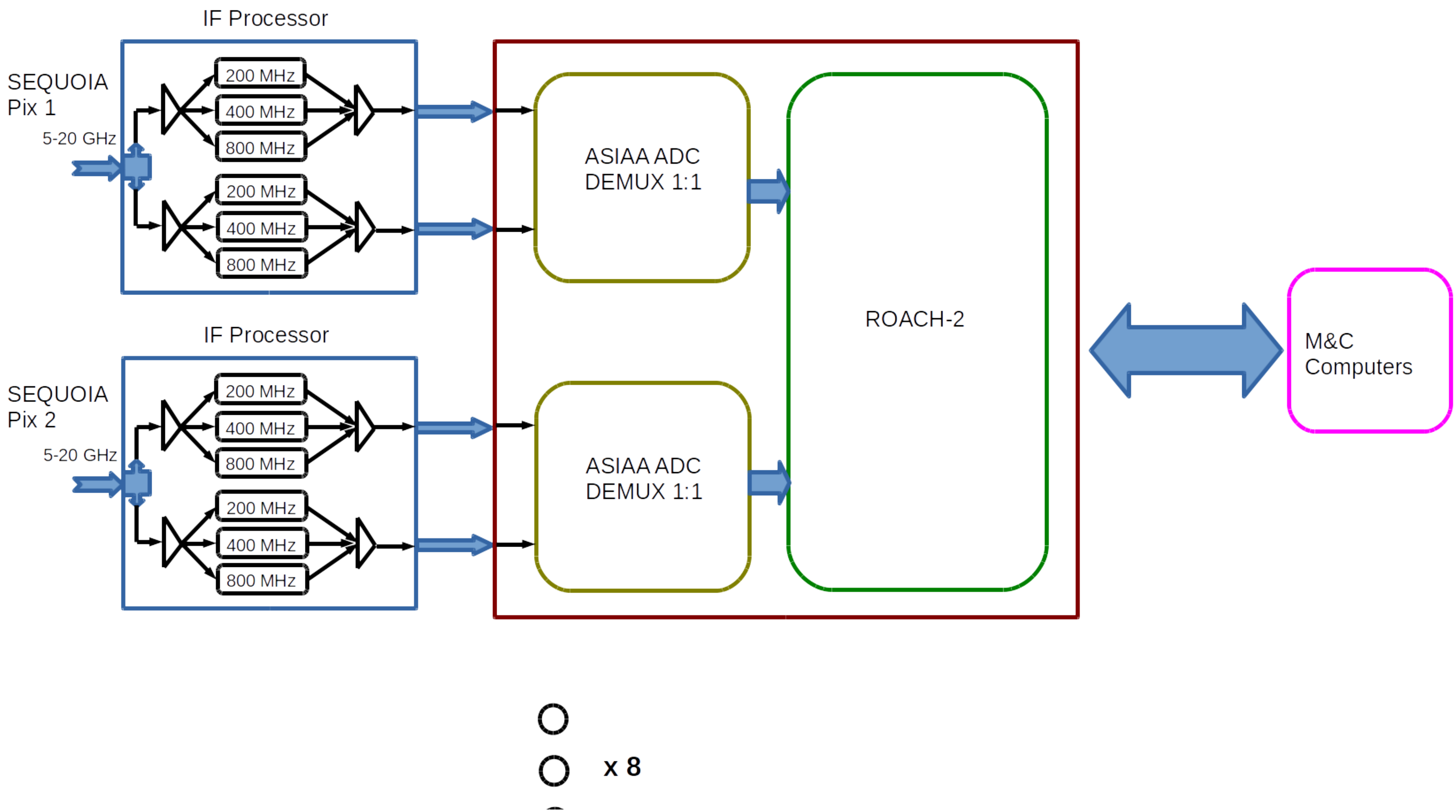
- Collaboration between UMass (Narayanan + students: Aleks Popstefanija, Tim Costa, Teddy Kareta), INAOE (Edgar Castillo, Sandra Bustamante), and UNAM Morelia (Stan Kurtz and Dani Diaz)

- Also develop necessary OTF (On-the-Fly) mapping software and utilities to rapidly process large volumes of data produced by digital spectrometers and array receivers

Schematic of A Spectrometer implemented in FPGA



Wideband Spectrometer System for SEQUOIA
WARES (Wideband Arrayed ROACH Enabled Spectrometer)



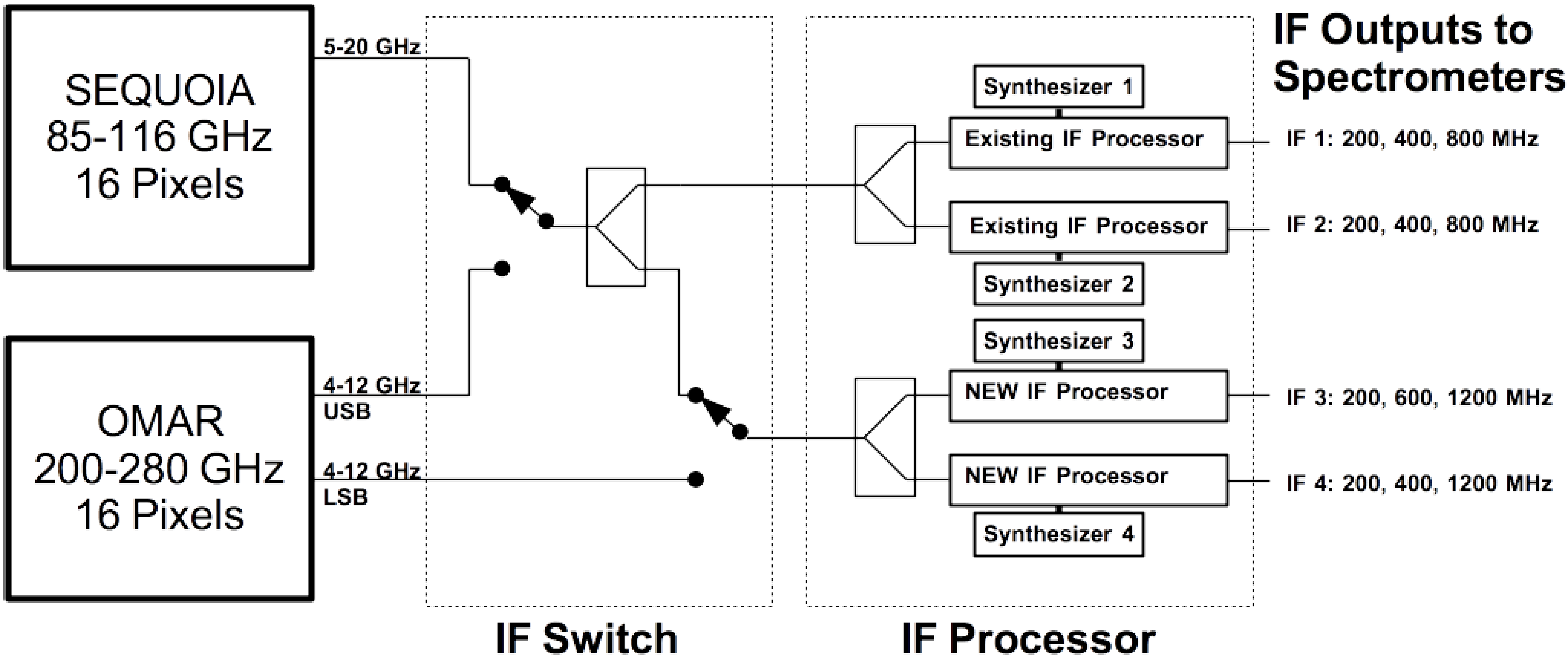
Wideband Spectrometer Modes

Mode	BW (MHz)	NumChannels	Resolution (kHz)	Velocity Resolution (km/s)
1	800	2048	390	1.2
2	400	4096	97.7	0.3
3	200	8192	24.4	0.07

Future NB Spectrometer Based on LEDA 16-channel ADC using 2 (or 4) ROACH-2 boards

Mode	BW (MHz)	NumChannels	Resolution (kHz)	Velocity Resolution (km/s)
1	50	4096	12.2	0.037
2	25	4096	6.1	0.018
3	12.5	4096	3	0.009

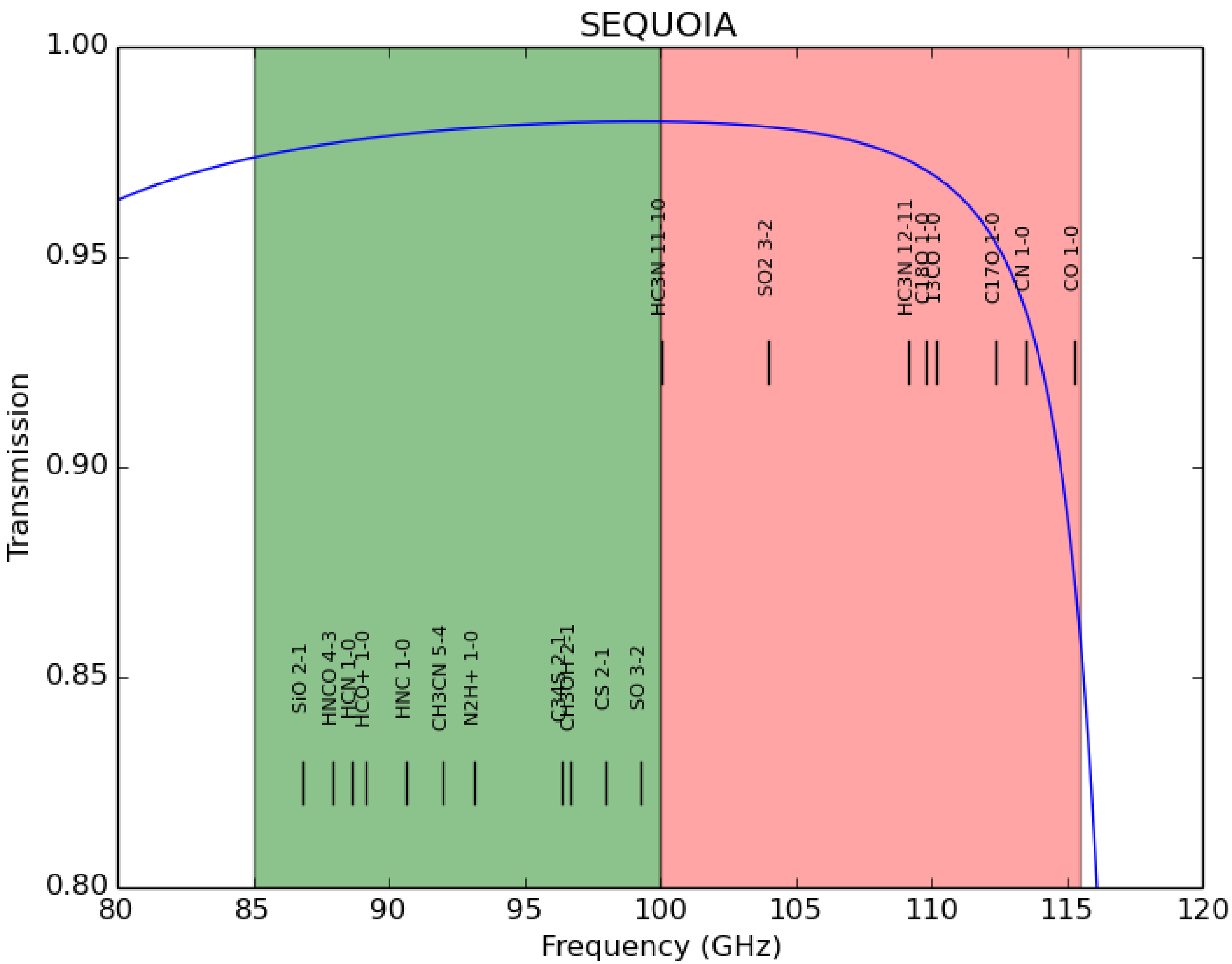
FPA IF Switch & Processors



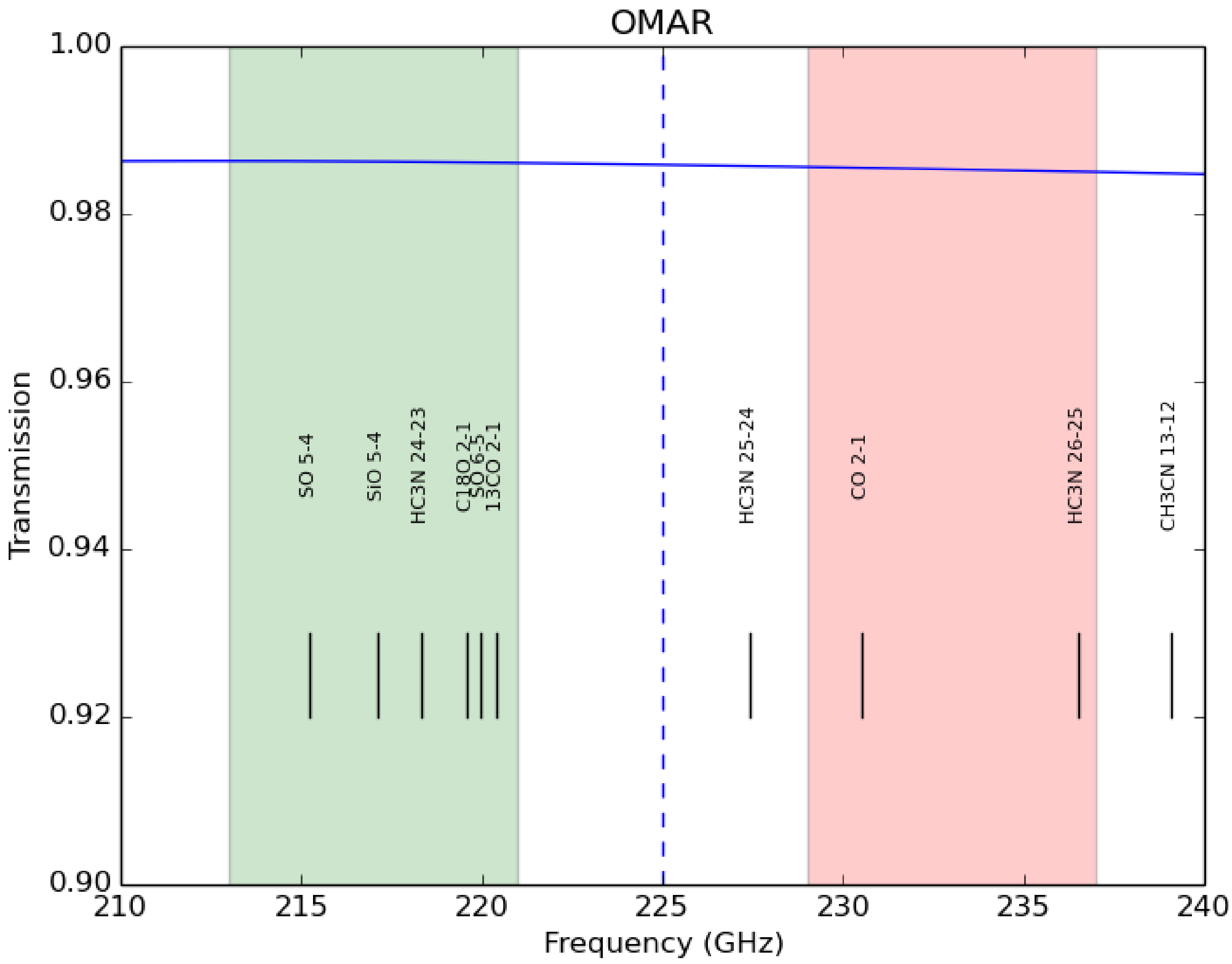
Spectral Line Modes

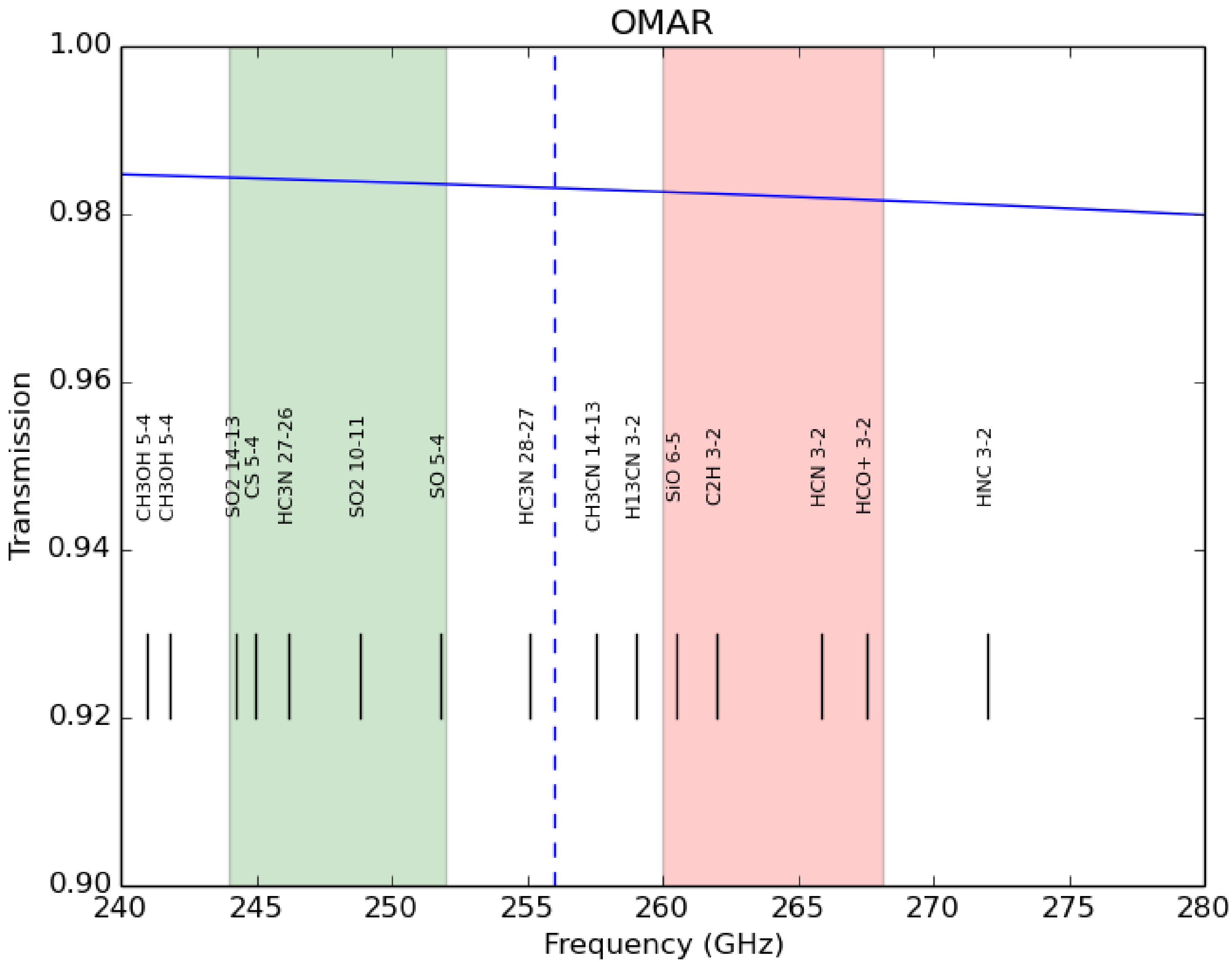
Parameter	Existing IF Processors			New IF Processors		
Mode	W	I	N	W	I	N
Bandwidth (MHz)	800	400	200	1200	600	200
N Channels	2048	2048	8192	2048	2048	8192
Resolution (kHz)	391	195	24	586	293	24
SEQUOIA - HCN 1-0						
Bandwidth (km s^{-1})	2697	1348	674	4045	2022	674
Resolution (m s^{-1})	1317	658	82	1975	988	82
SEQUOIA - CO 1-0						
Bandwidth (km s^{-1})	2087	1043	522	3130	1565	522
Resolution (m s^{-1})	1019	510	64	1529	764	64
OMAR - CO 2-1						
Bandwidth (km s^{-1})	1043	522	261	1565	783	261
Resolution (m s^{-1})	510	255	32	764	382	32
OMAR - HCN 3-2						
Bandwidth (km s^{-1})	903	451	226	1354	677	226
Resolution (m s^{-1})	441	220	28	661	331	28

SEQUOIA Spectral Lines



Cover any 4 lines in one 15 GHz IF band


OMAR
Transmission
Frequency (GHz)
1.00
0.98
0.96
0.94
0.92
0.90
210
215
220
225
230
235
240
SO 5-4
SiO 5-4
HC3N 24-23
C18O 2-1
SO 6-5
13CO 2-1
HC3N 25-24
CO 2-1
HC3N 26-25
CH3CN 13-12


OMAR
Transmission
Frequency (GHz)
1.00
0.98
0.96
0.94
0.92
0.90
240
245
250
255
260
265
270
275
280
CH3OH 5-4
CH3OH 5-4
SO2 14-13
CS 5-4
HC3N 27-26
SO2 10-11
SO 5-4
HC3N 28-27
CH3CN 14-13
H13CN 3-2
SiO 6-5
C2H 3-2
HCN 3-2
HCO+ 3-2
HNC 3-2

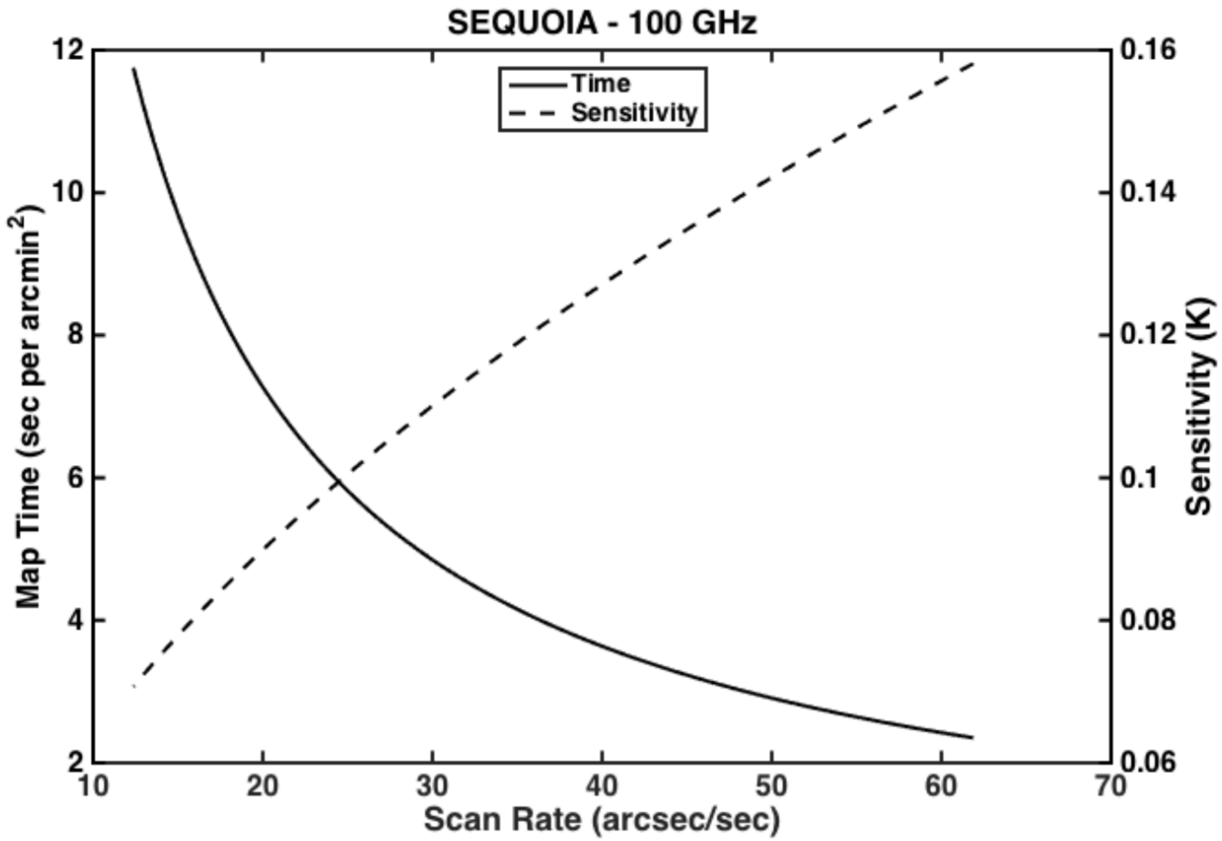


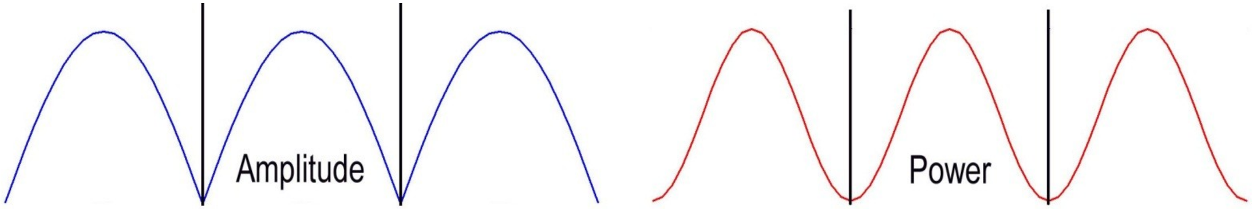
Figure 2: Calculation of map time and map rms sensitivity with LMT as a function of the scanning rate. The left figure shows the time required per square arcminute of map for SEQUOIA at 3mm wavelength (solid) and the RMS achieved in a 1 km s^{-1}bandwidth (dashed). At 60"/s scan rate, SEQUOIA will complete a 1 square degree field in about 2.4 hours with a sensitivity of 0.16 K.

Overview of Talk:

- Brief Introduction to Heterodyne (Spectroscopic) Receivers
- SEQUOIA
- Redshift Search Receiver (RSR)
- Event Horizon Telescope VLBI Instruments
- One Millimeter Array Receiver (OMAR)
- Digital Spectrometers
- **PHAMAS (Phased Array Receiver for Millimeter Astronomy)**

Conventional Focal Plane Array

- Large gaps between elements, 2x HPBW spacing.

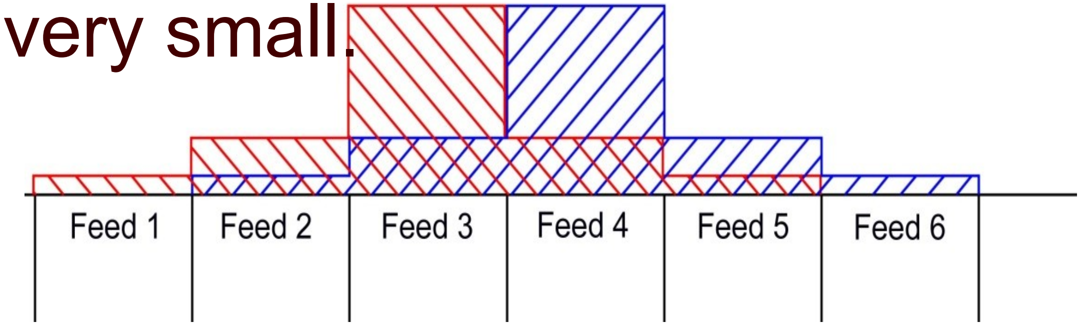


- No ability to optimally illuminate telescope, particularly over a wide bandwidth.
- Relatively few elements fit into focal plane.
- Difficult to adapt to varying f ratios.
- Physically large.

Phased Focal Plane Array

somewhat idealized (from N. Erickson)

- Very small feeds, spaced ~$\lambda/2$, are able to collect all of the signal in the focal plane.
- Combine feeds into groups that synthesize the optimum illumination. Requires amplification before combination.
- Correct for large scale telescope surface errors.
- Easily adapted to any telescope f ratio.
- Physically very small.

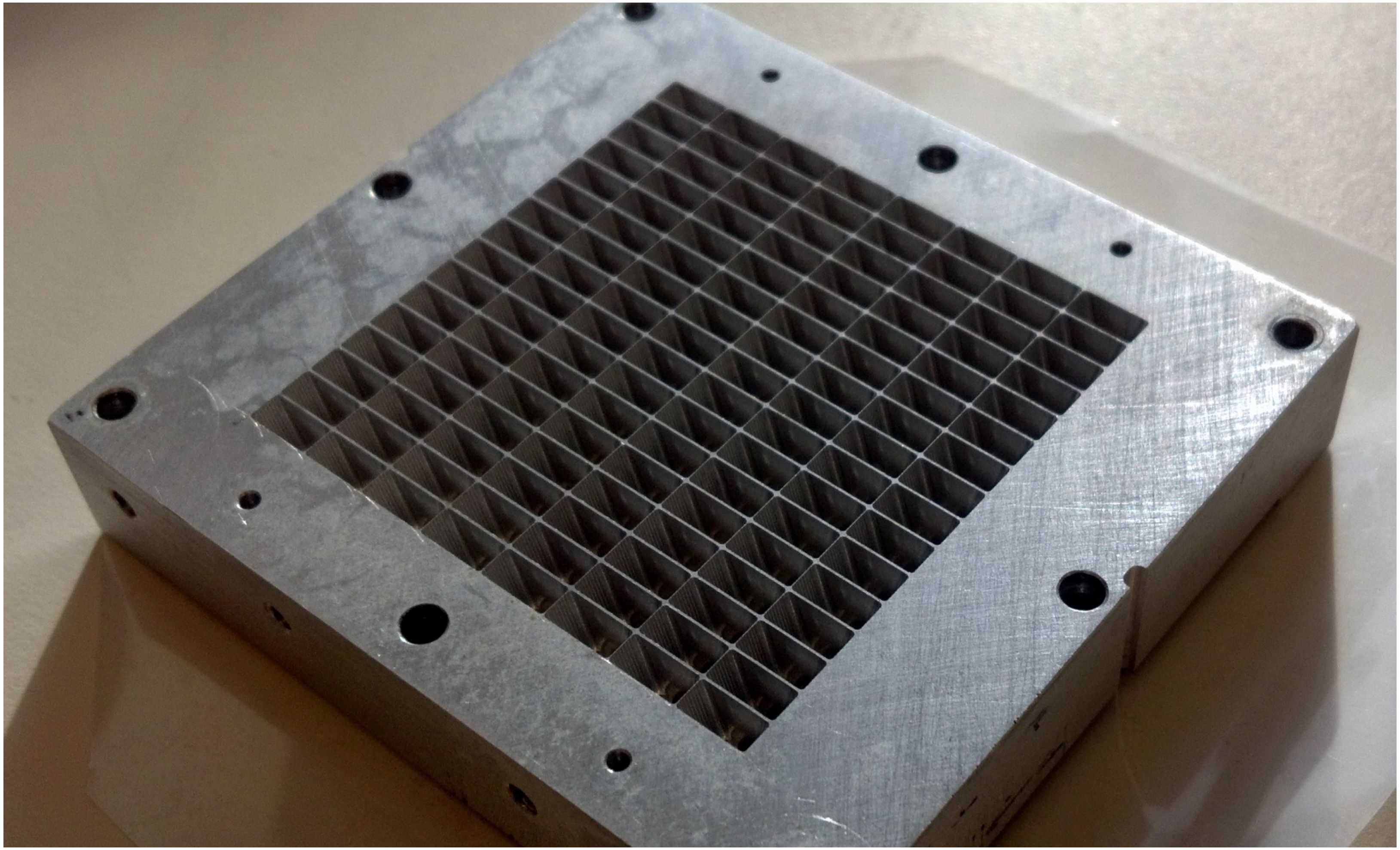


PFPA Prototype

- Built a 64 element receiver.
- Demonstrated at the GBT that this is a viable mm-wave technology.
- RF bandwidth 70-95 GHz. Excellent band for GBT science. SiO, HCN, DCN, HNC, HCO+
- IF bandwidth was ~20 MHz (provided by BYU)
- Beam-forming is **all digital** (no analog summing).
- Budget was limited, $1.3M, 3 years.

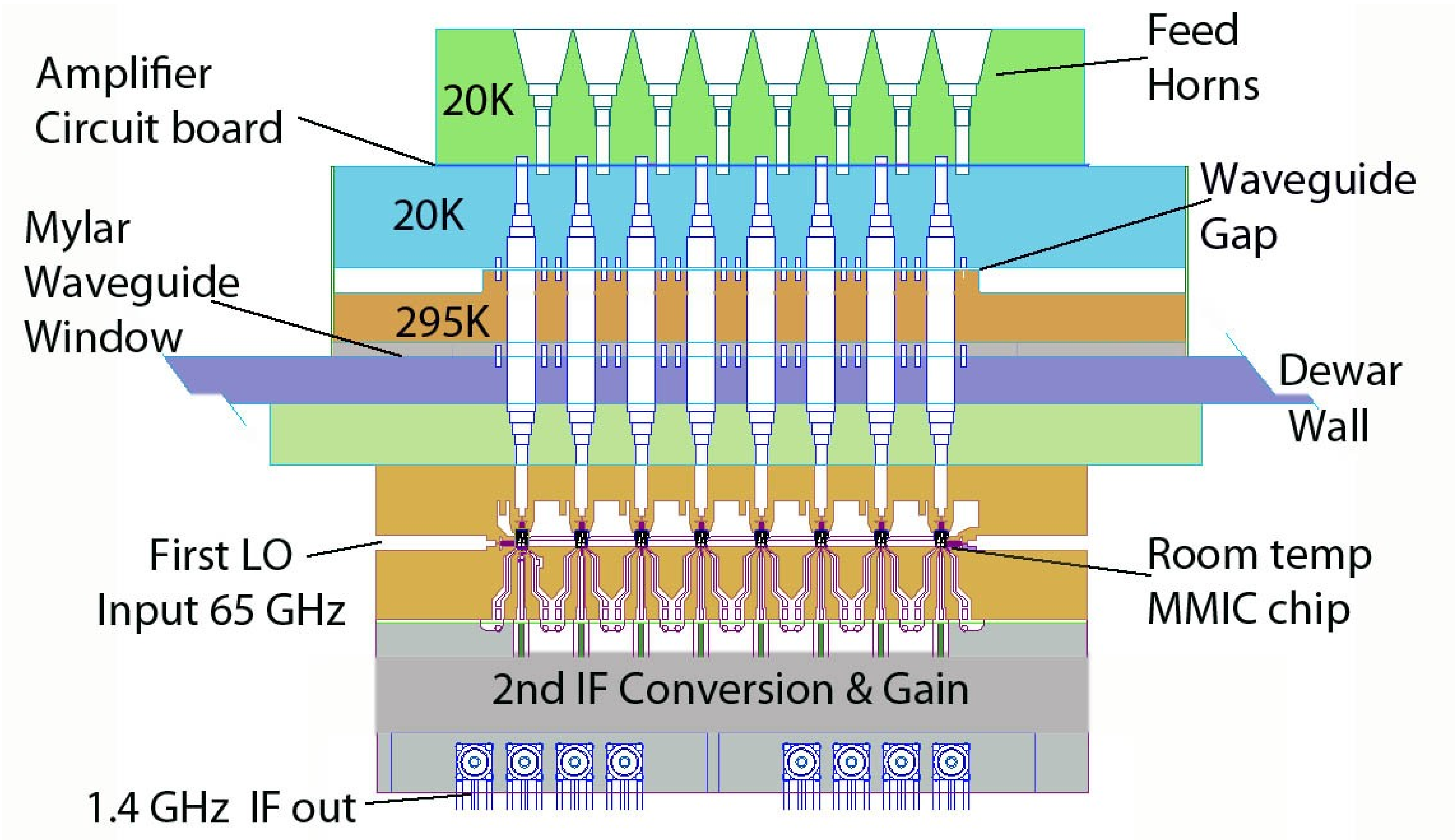
Waveguide Feed Element

Machine the entire feed array including splitter from a single piece of aluminum.

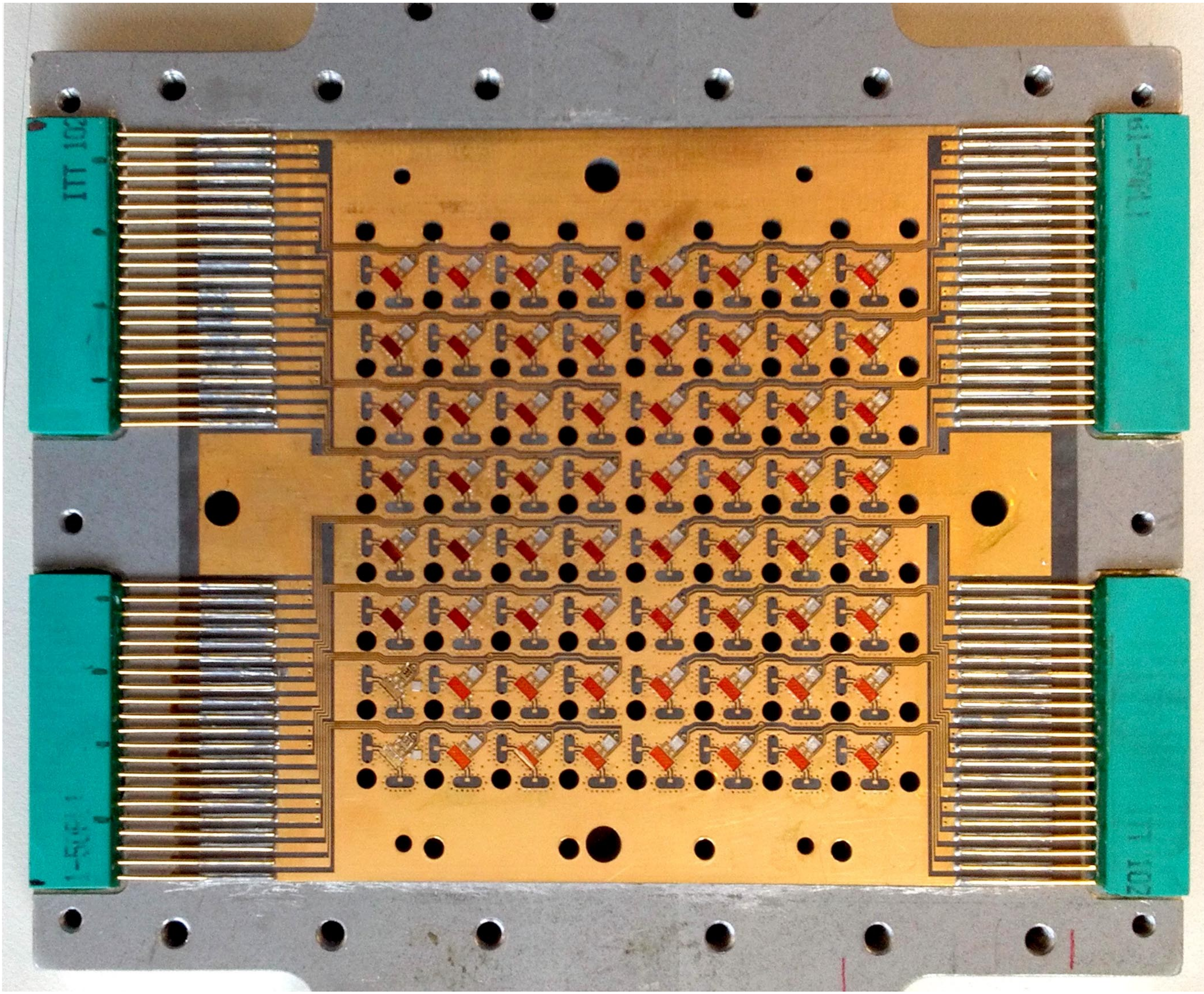


Array Architecture

One MMIC gain stage at 20K, 2nd stage at room temp.



First Stage Amplifier Circuit Board



Separate drain bias for each element.

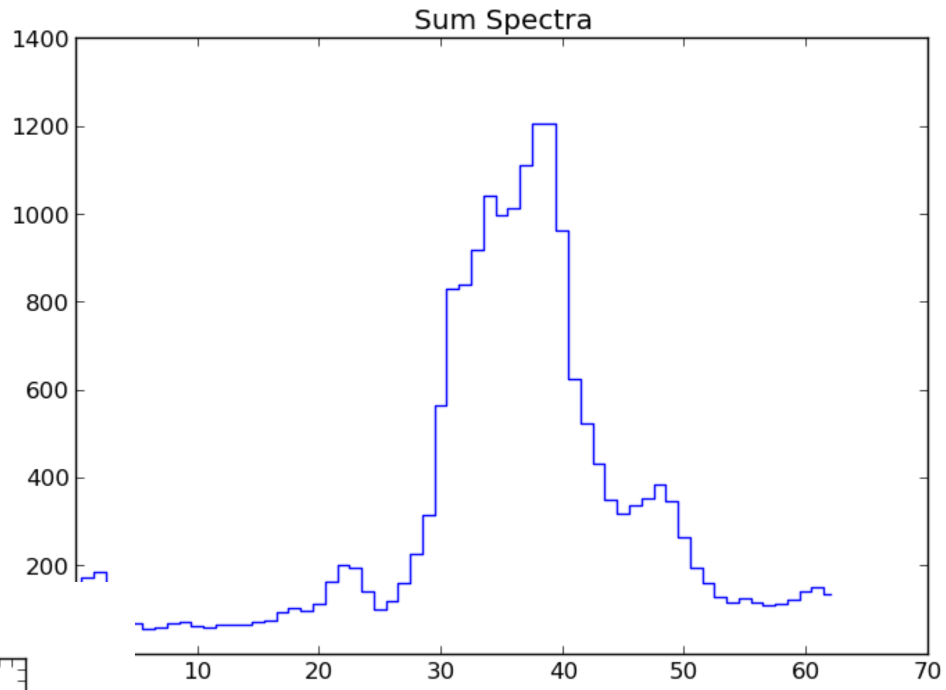
Beam Forming

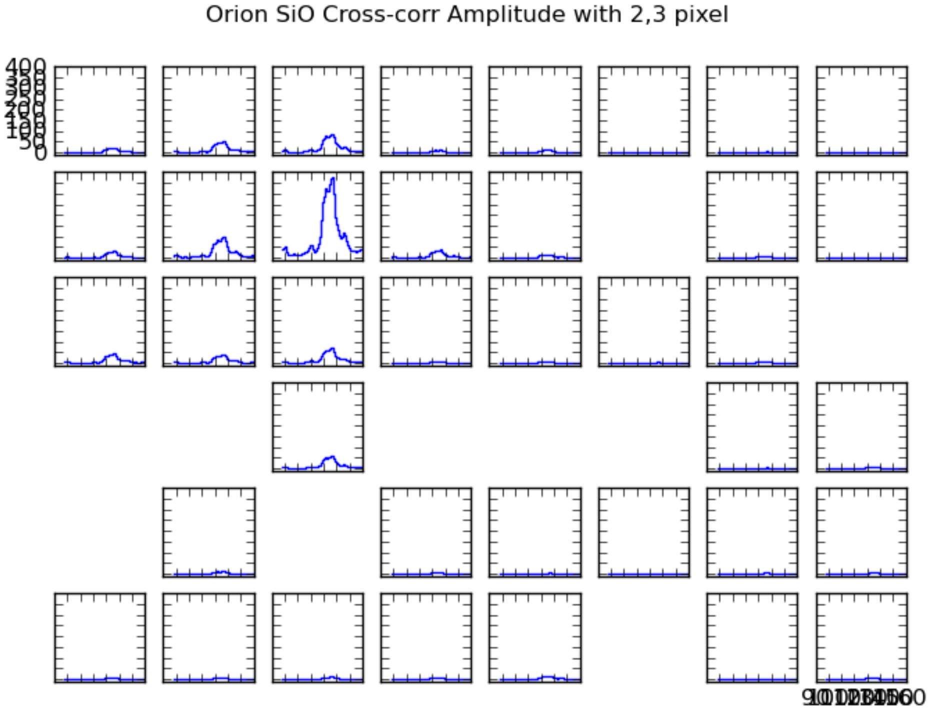
General process is very much like interferometry.

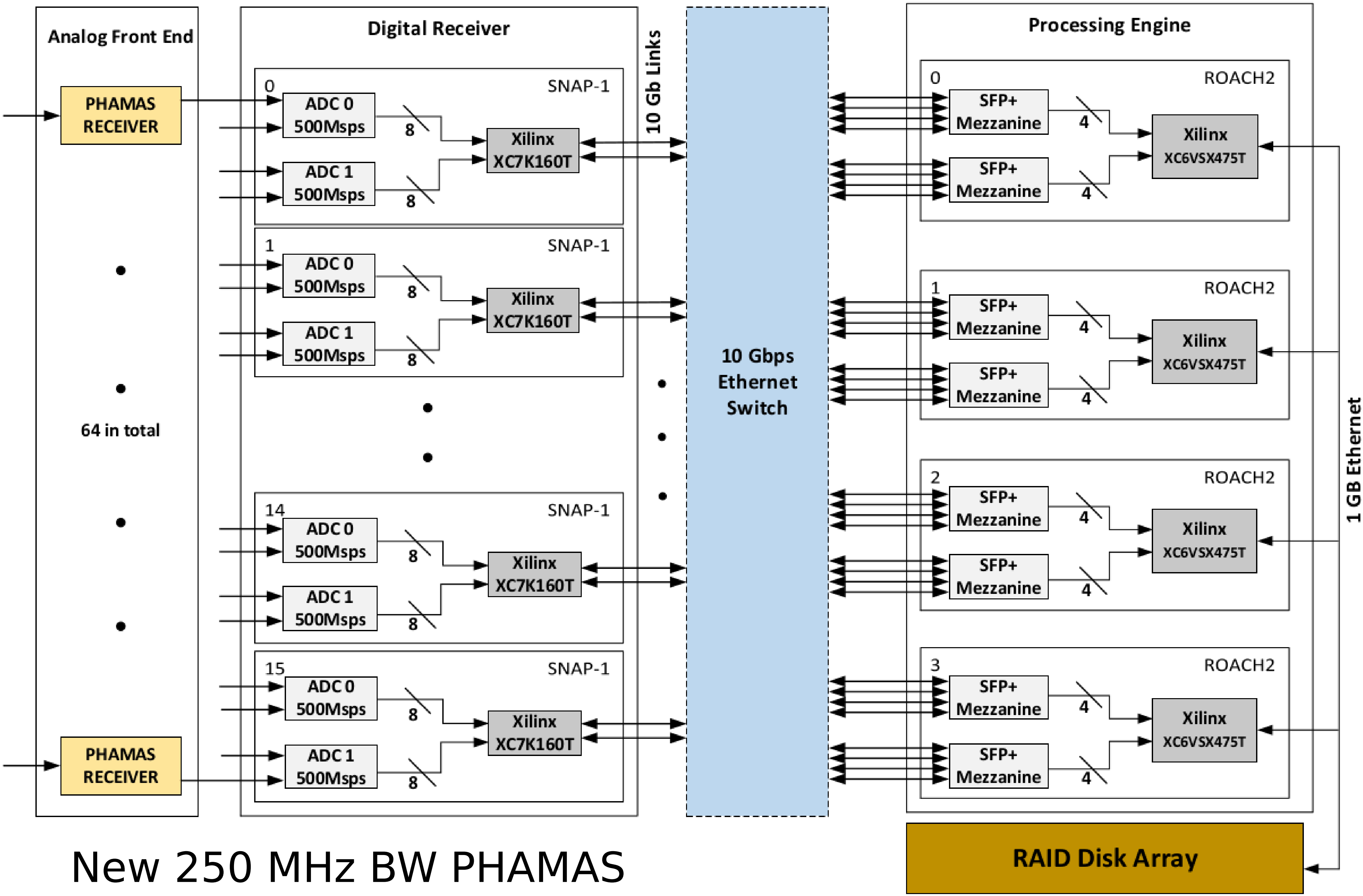
1. Form complex spectrum from each element.
2. Vector **sum** elements with predetermined weights.

- Real-time summing network is very complex, 180 summing engines each with up to 25 inputs
- If we allow for arbitrary focal plane distribution, then each beam requires all 64 inputs
- Record and post-process may be needed

GBT Commissioning Results Oct 2016







New 250 MHz BW PHAMAS