SMA upgrades for wide bandwidth observations

Nimesh A Patel
Center for Astrophysics | Harvard & Smithsonian

EAO: Futures meeting, Nanjing, 19-24 May 2019

Image: Nimesh Patel 2018

SMA is a collaboration between Smithsonian Astrophysical Observatory and Academia Sinica Institute for Astronomy and Astrophysics

Scientific Cooperation Agreement signed between SAO – NUSASS (Nanjing University School of Astronomy and Space Science) for a limited partnership that allows access of SMA observing time

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Talk outline:

- Science goals
- Upgrades:
  - Receivers
  - Correlator
  - (Software)

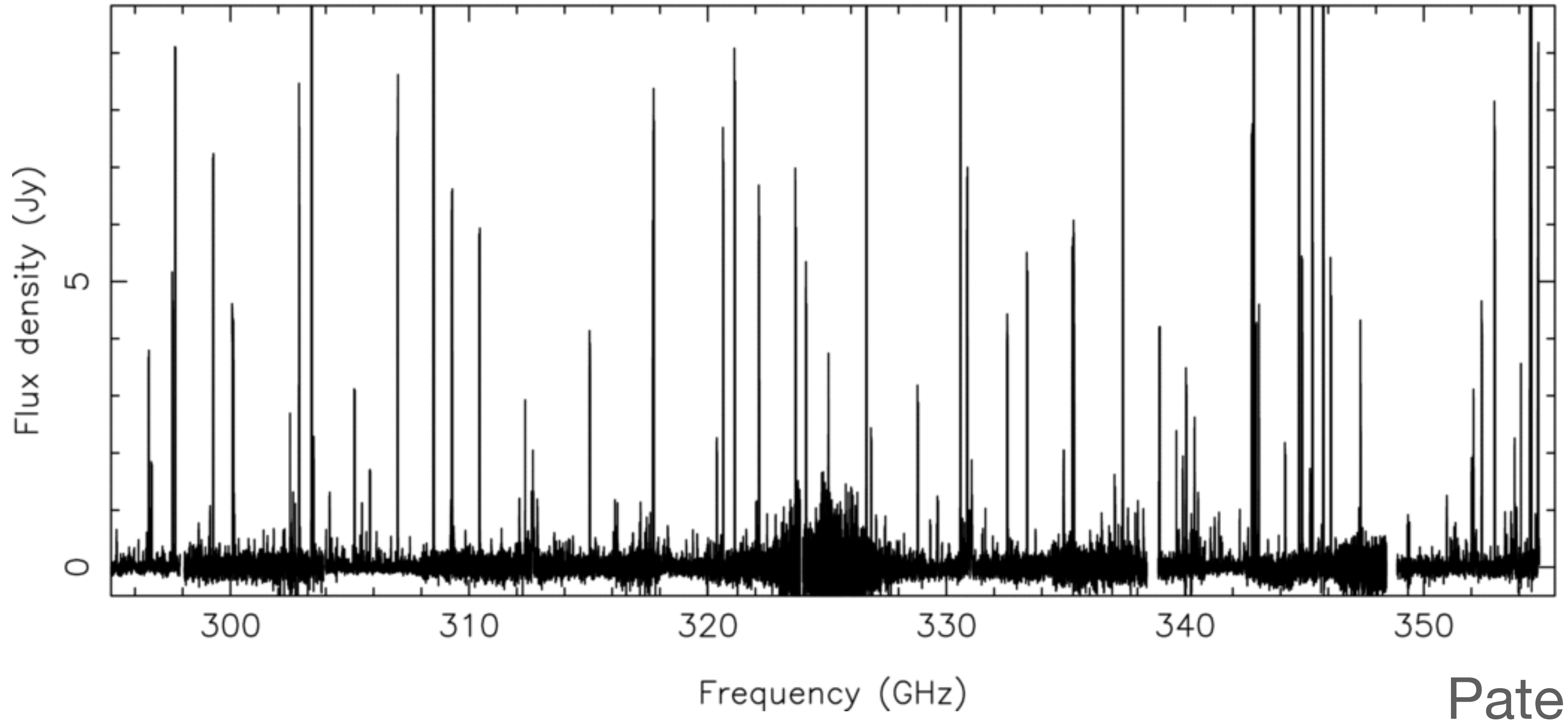
	year	receiver bandwidth	bands × pols	total bandwidth	number of channels	continuum rms (μJy) 230 GHz	345 GHz
stage 0	2004	2 GHz × 2 sb	2	8 GHz	1.2288×10^4	600	1250
stage 1	2016	8 GHz × 2 sb	2	32 GHz	5.24288×10^5	230	520
stage 2	2020	16 GHz × 2 sb	4	128 GHz	2.097152×10^6	140	330

SMA Memo #165

Science with the wideband Submillimeter Array:
A Strategy for the Decade 2017–2027

ed. D. Wilner *contributing authors:* E. Keto, G. Bower, T.C. Ching, M. Gurwell, N. Hirano, G. Keating, S.P. Lai, N. Patel, G. Petitpas, C. Qi, TK Sridharan, Y. Urata, K. Young, Q. Zhang, J.-H. Zhao

Spectral line survey of the extreme carbon star IRC+10216



Patel et al. 2011

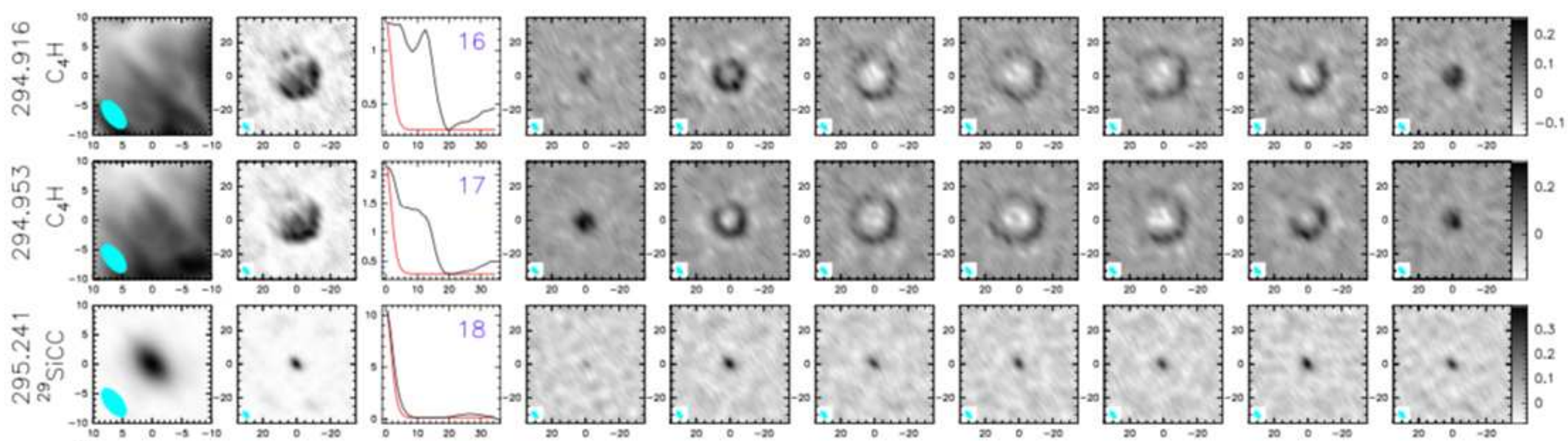
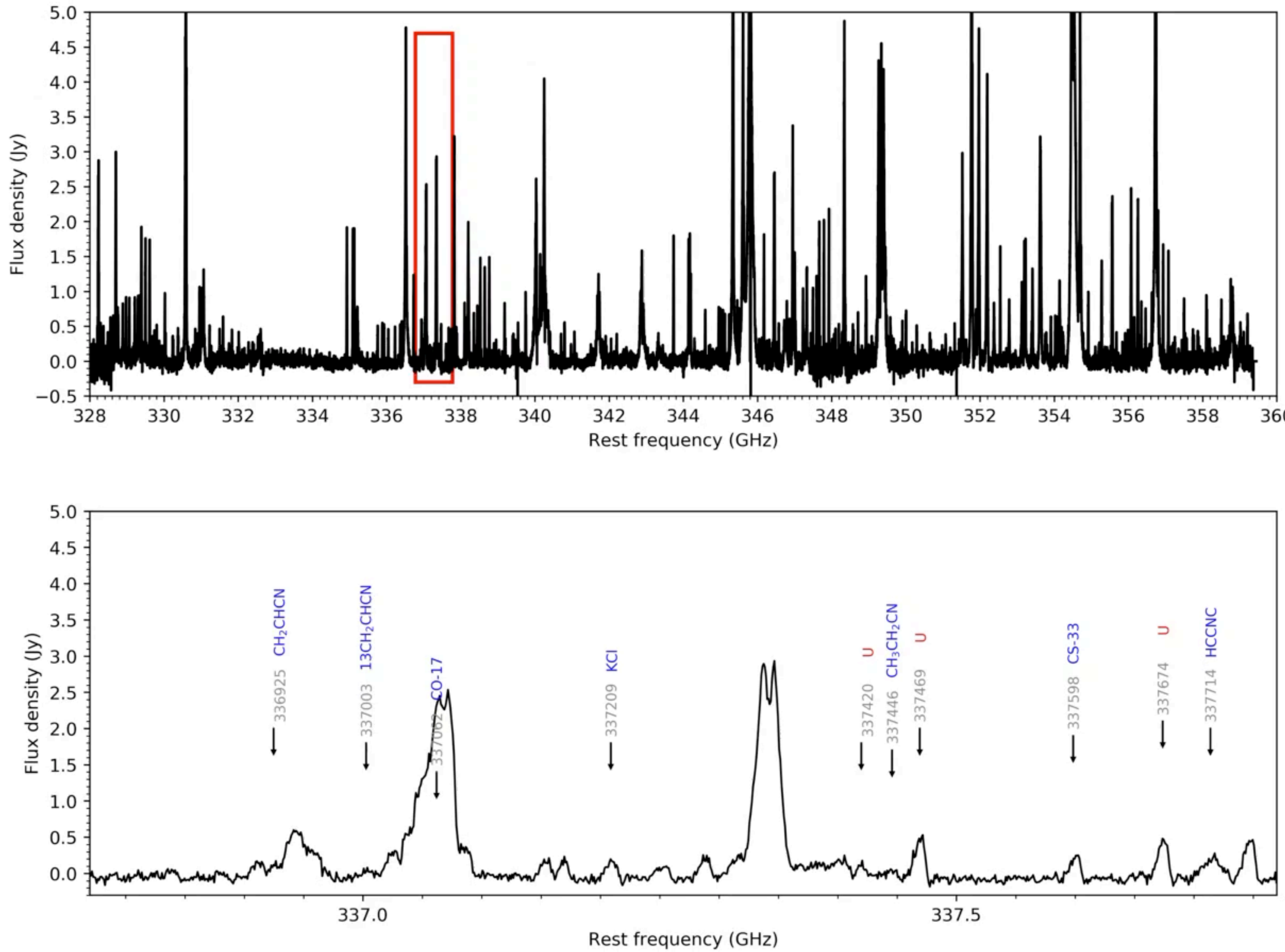


Figure 8: (upper) *The integrated 64 GHz spectrum of the evolved star IRC+10216 from the SMA line survey of Patel et al. (2011), with 442 lines detected.* (lower) *Sample images showing the emission line structure for a few lines at the low frequency end of the survey, including integrated intensity, radial profile, and velocity resolved channel maps. Note the ring -like distribution of C_4H compared to the compact and strongly centrally peaked distribution of SiCC; this butadinyl molecule is created in the outer part of the envelope where chemistry is influenced by the interstellar radiation field.*

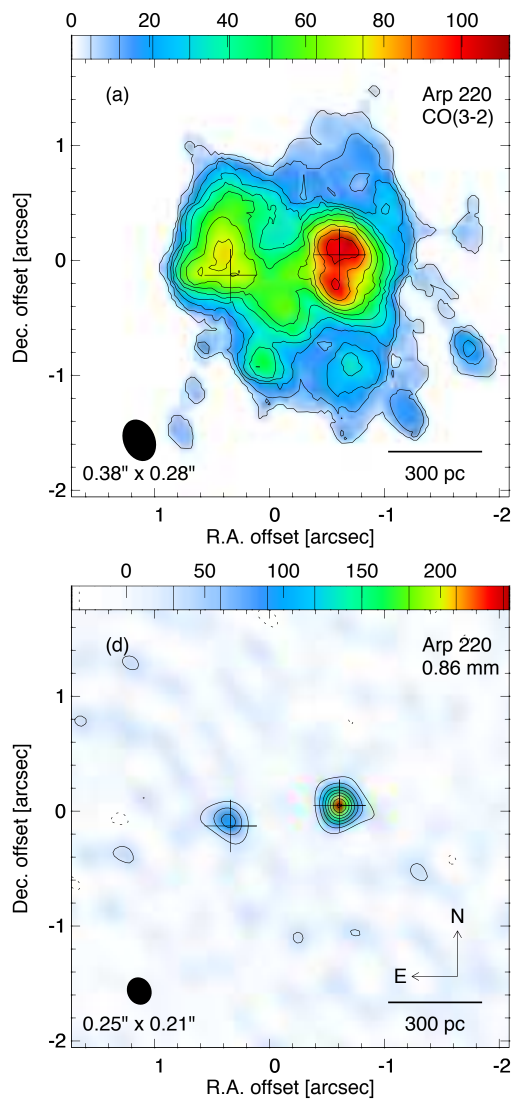
Spectral line survey of proto-planetary nebula CRL 618

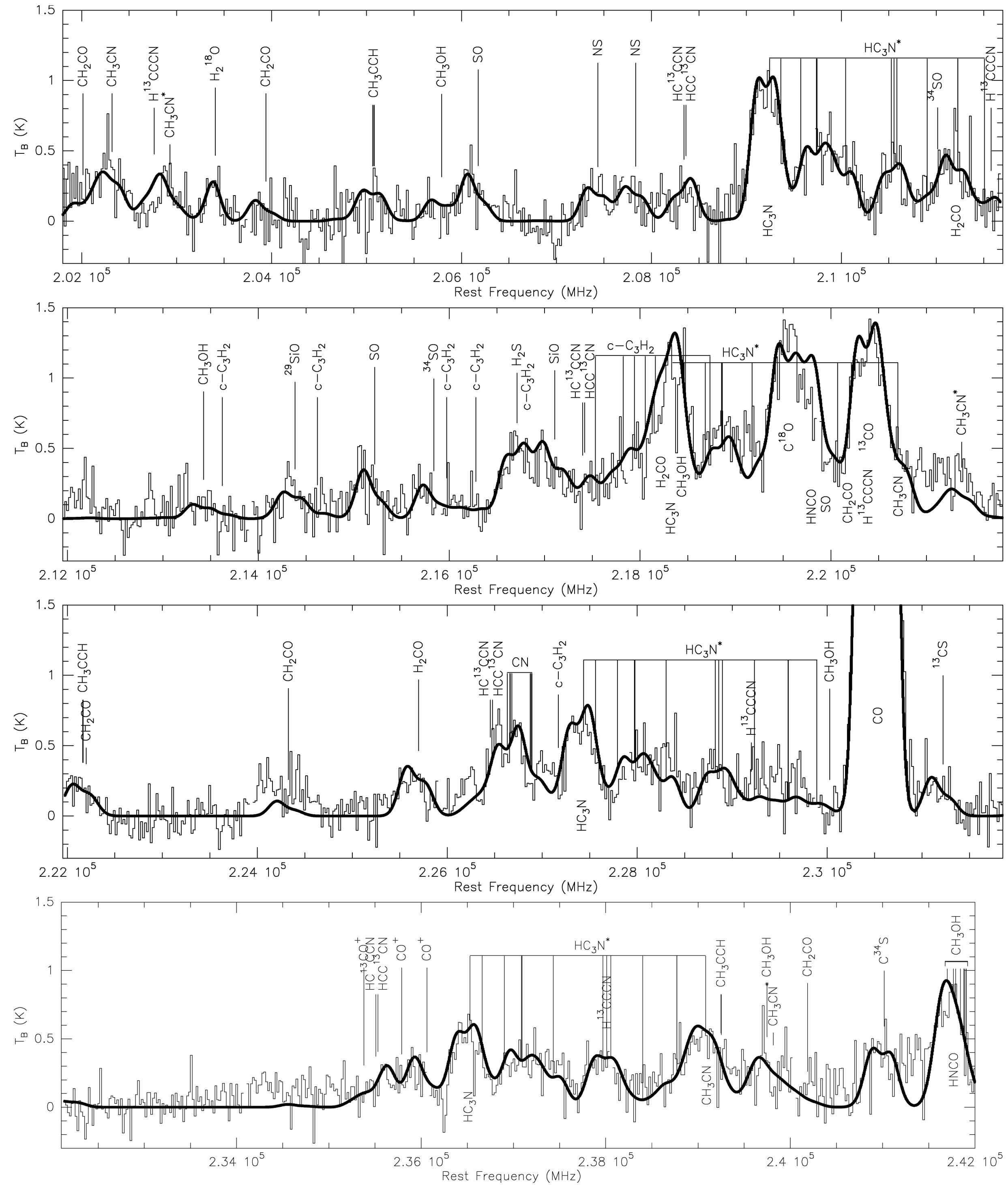
Patel et al. 2019



Arp 220

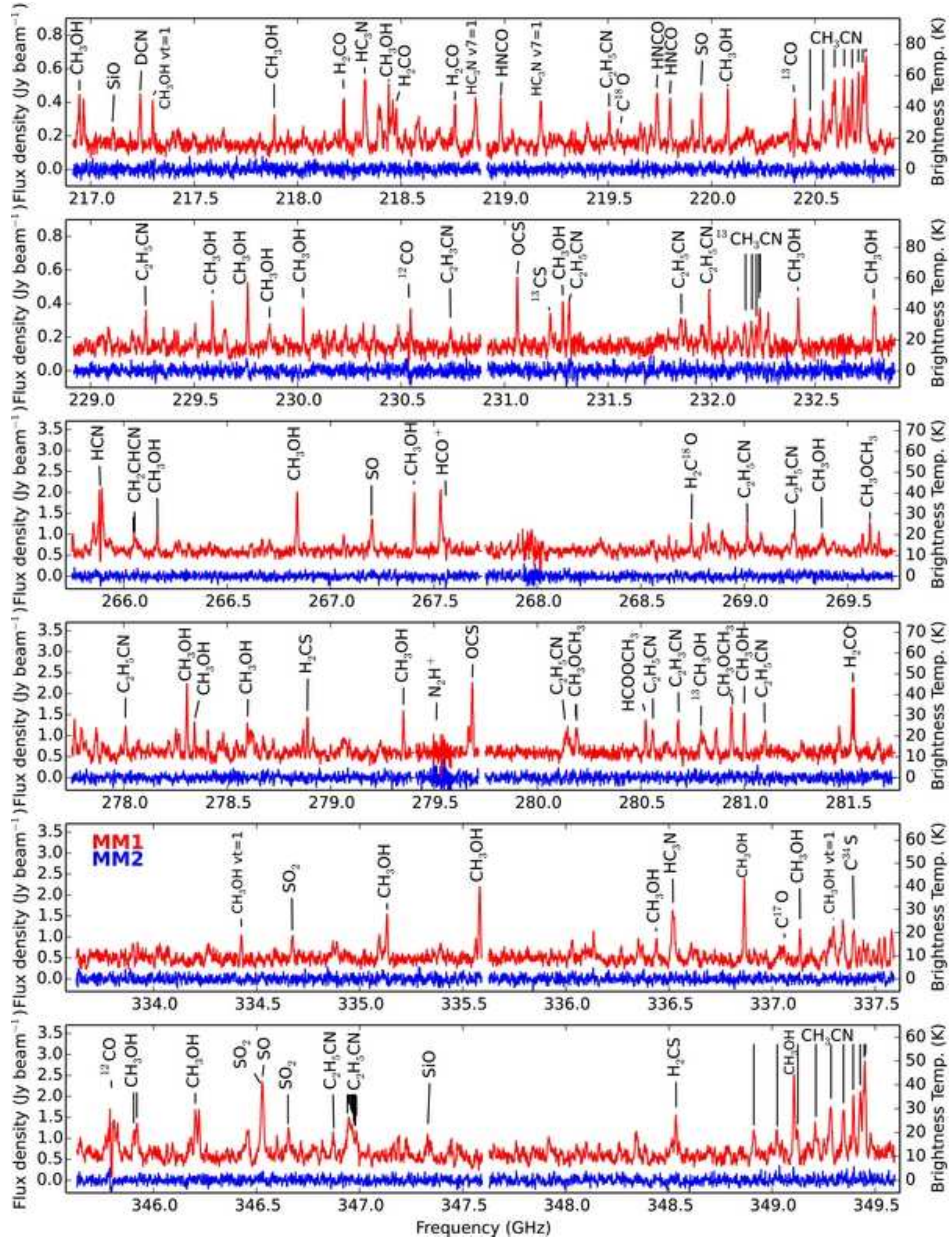
Martin et al. 2011





Sakamoto et al. 2008

Figure 6: (left) *SMA subarcsecond images of CO 3-2 line and dust continuum emission of the nearby ultraluminious galaxy Arp 220, from Sakamoto et al. (2008).* (right) *The composite SMA 1.3 mm spectral scan of the nuclear region of Arp 220, from 202 to 242 GHz (Martín et al., 2011). The thick solid curve shows an LTE model of the identified molecular species, consisting of two kinematic components (one for each of the nuclei visible in the images).*



G11.92-0.61
high mass
star-forming region

Cyganowski et al. 2014

Figure 5: *SMA spectra covering 24 GHz towards two dust continuum peaks in the G11.92-0.61 star forming region, MM1 (red) and MM2 (blue), which are separated by only* ~ 0.12 *pc. The rich spectrum of MM1 indicates a protostellar hot core, while paucity of spectral lines in MM2 suggests it is starless. (Cyganowski et al., 2014)*

Qi et al. 2010

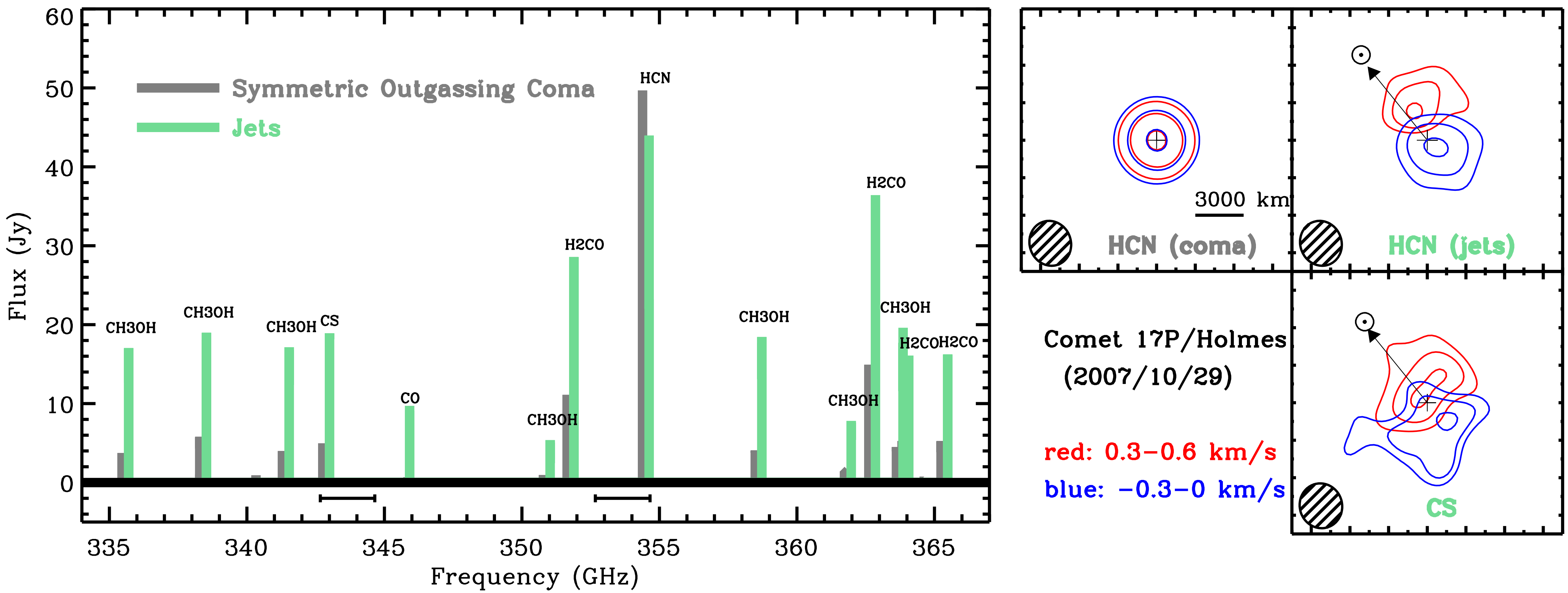


Figure 11: *(left) Simulation of molecular emission from a comet, showing a suite of spectral lines in the 345 GHz band that the wSMA could observe simultaneously at high spectral resolution to probe the abundances of jet and coma material. (right) SMA images of HCN and CS emission from comet P17/Holmes obtained simultaneously, showing blue- and red-shifted emission from a jet, and the extended coma.*

Bradford et al. 2011

Rawle et al. 2014

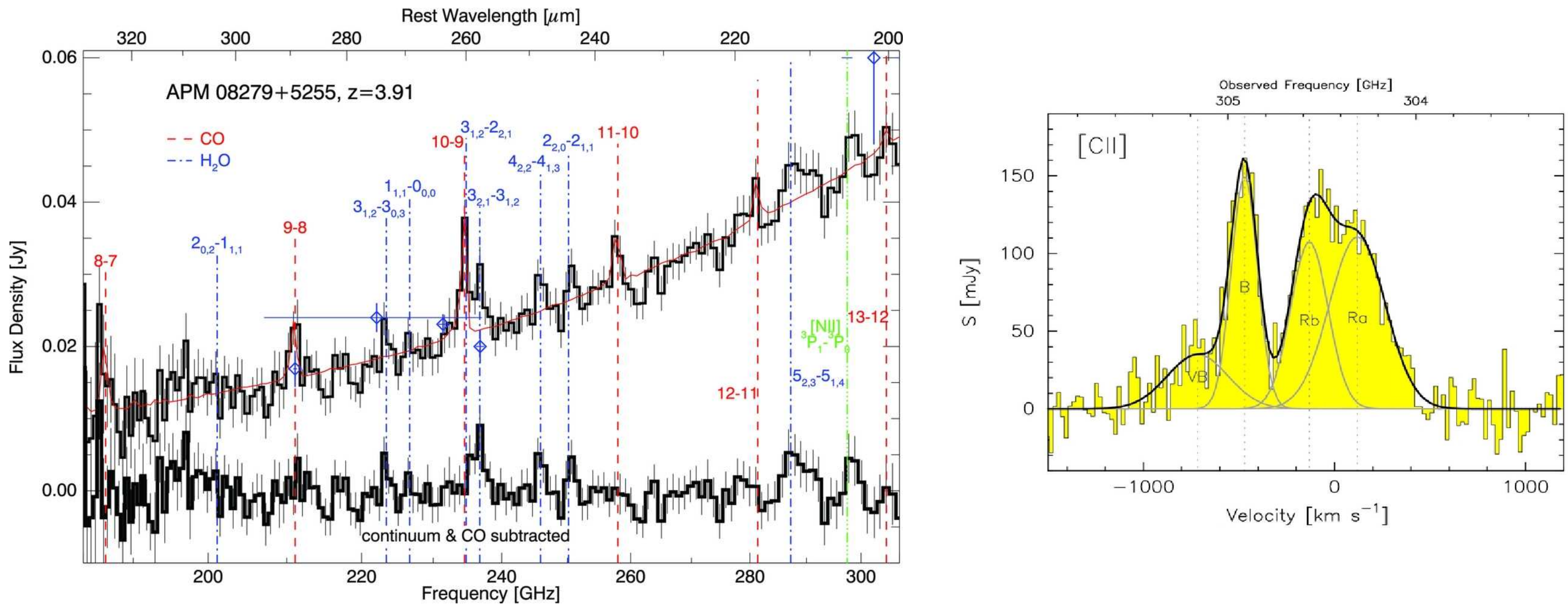
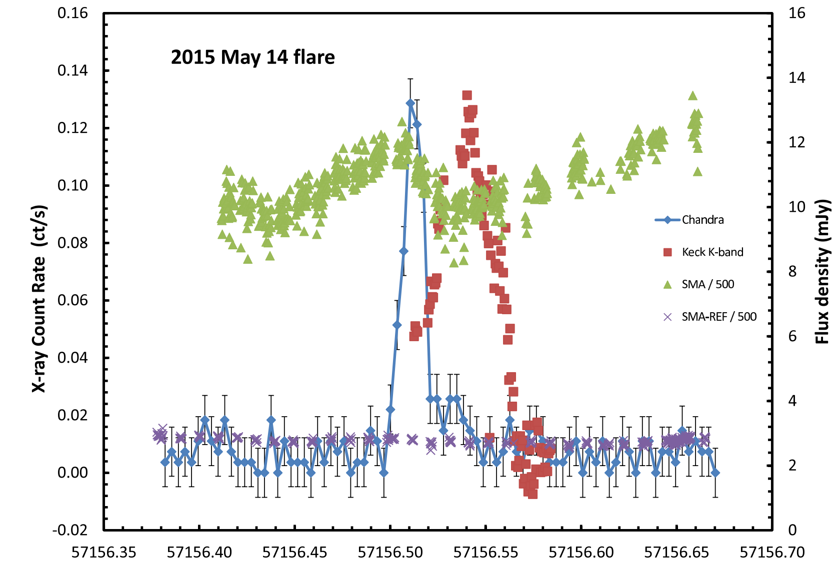


Figure 7: (left) *A Zspec grating spectrum of the z=3.91 lensed galaxy APM 08279+5255, showing multiple lines of CO, H_2O, and N^+ (Bradford et al., 2011). The wSMA will be capable of surveying systems like this at* 100× *higher spectral resolution, allowing precise spectroscopic redshift determinations (even when only crude SED-based model fits are available), and at the same time obtaining high resolution studies of morphology.* (right) *Integrated line profile of C^+ in the z=5.24 lensed galaxy HLSJ091828.6+514223, spectrally resolving at least four distinct kinematic components in this system (Rawle et al., 2014).*

- Planetary atmospheres (Titan, Io line surveys, M. Gurwell)
- Magnetic fields imaging: star-formation, proto-planetary nebulae
- Gamma Ray Bursts
- Time monitoring of polarized emission from SgrA*
- CII Intensity Mapping (large scale project led by Karto Keating)



Marrone et al. 2016

Figure 10: *Light-curves of SgrA* in the submillimeter (SMA), infrared (Keck) and X-ray (Chandra), showing a flare with a timescale of order an hour (Marrone et al., 2016). The wSMA will provide sufficient continuum sensitivity to detect such flares easily and to measure changes in polarization during the flare events.*

Gurwell et al. 2012

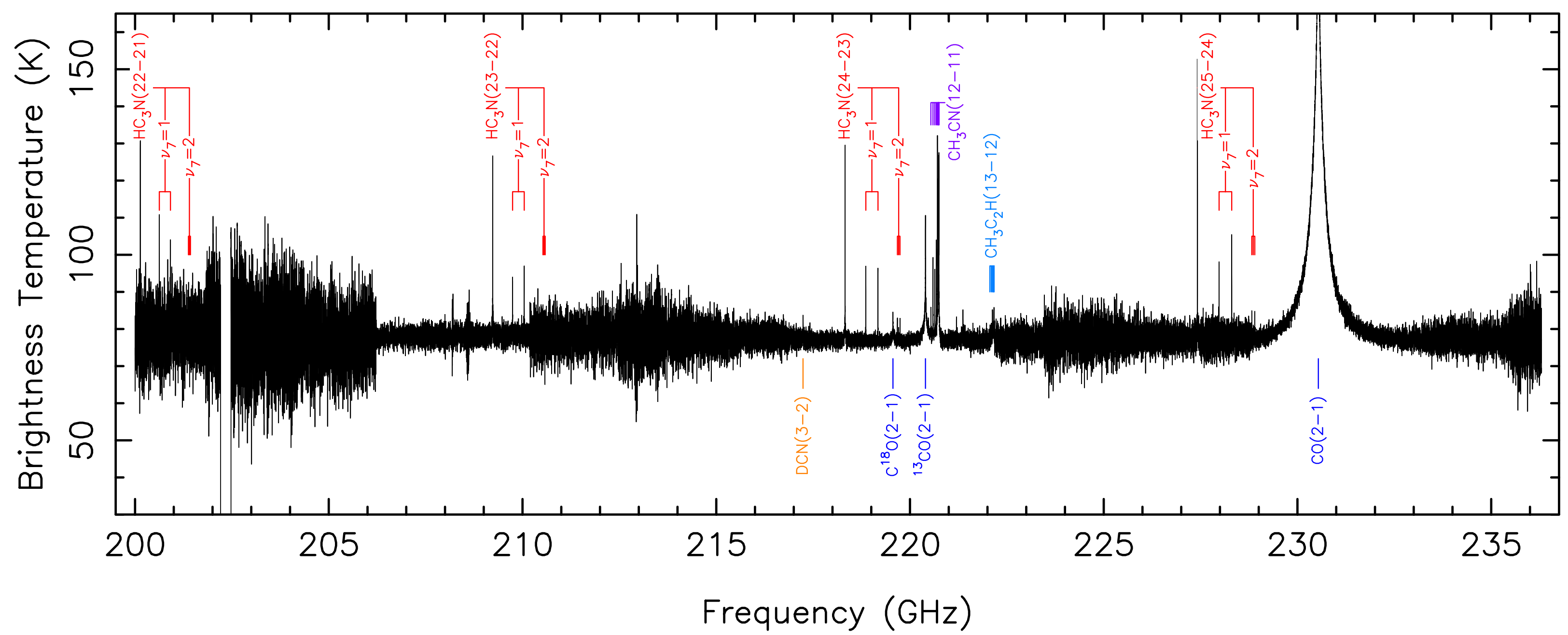
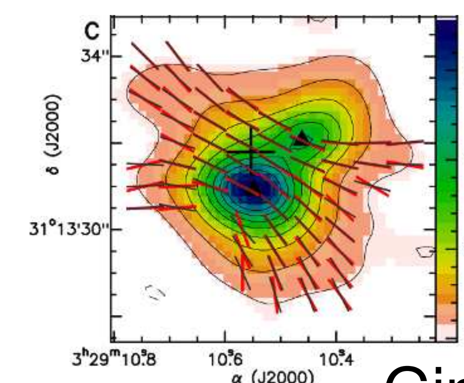


Figure 9: *A serendipitous 36 GHz line survey of Titan, obtained by piecing together more than 100 short, narrow band, archival observations (Gurwell et al., 2012). Each observation was calibrated, aligned, and smoothed to a common spectral resolution, and scaled to a common source reference diameter.*



Girart et al. 2006

Figure 13: *SMA observations of polarized 870 μm dust continuum emission from NGC 1333 IRAS 4A provided the first textbook example of an hourglass-shaped magnetic field (red bars) in a low mass protostellar system (Girart et al., 2006). The color image shows the dust emission from the dense molecular core that surrounds two still-forming Sun-like stars. Gravity pulls the gas and dust of this cloud clump inward and warps the magnetic field in the process.*

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Upgrade Path of SMA

2018

Current Status of SMA
Dual DSB Rx
4 - 12 GHz IF
4Q SWARM
32 GHz On sky BW

2019

Interim Upgrade
Keep Cryostat
4 - 16 GHz IF
6Q SWARM
48 GHz On sky BW

2021-
2022

wSMA Goal
New Cryostat
4 - 20 GHz IF (min)
Next gen Correlator (?)
> 64 GHz On sky BW

Edward Tong

- New receiver has two dual pol receiver cartridges
- Receivers selected by four position rotating selector wheel
- Straight through, mirror, grid, dichroic options

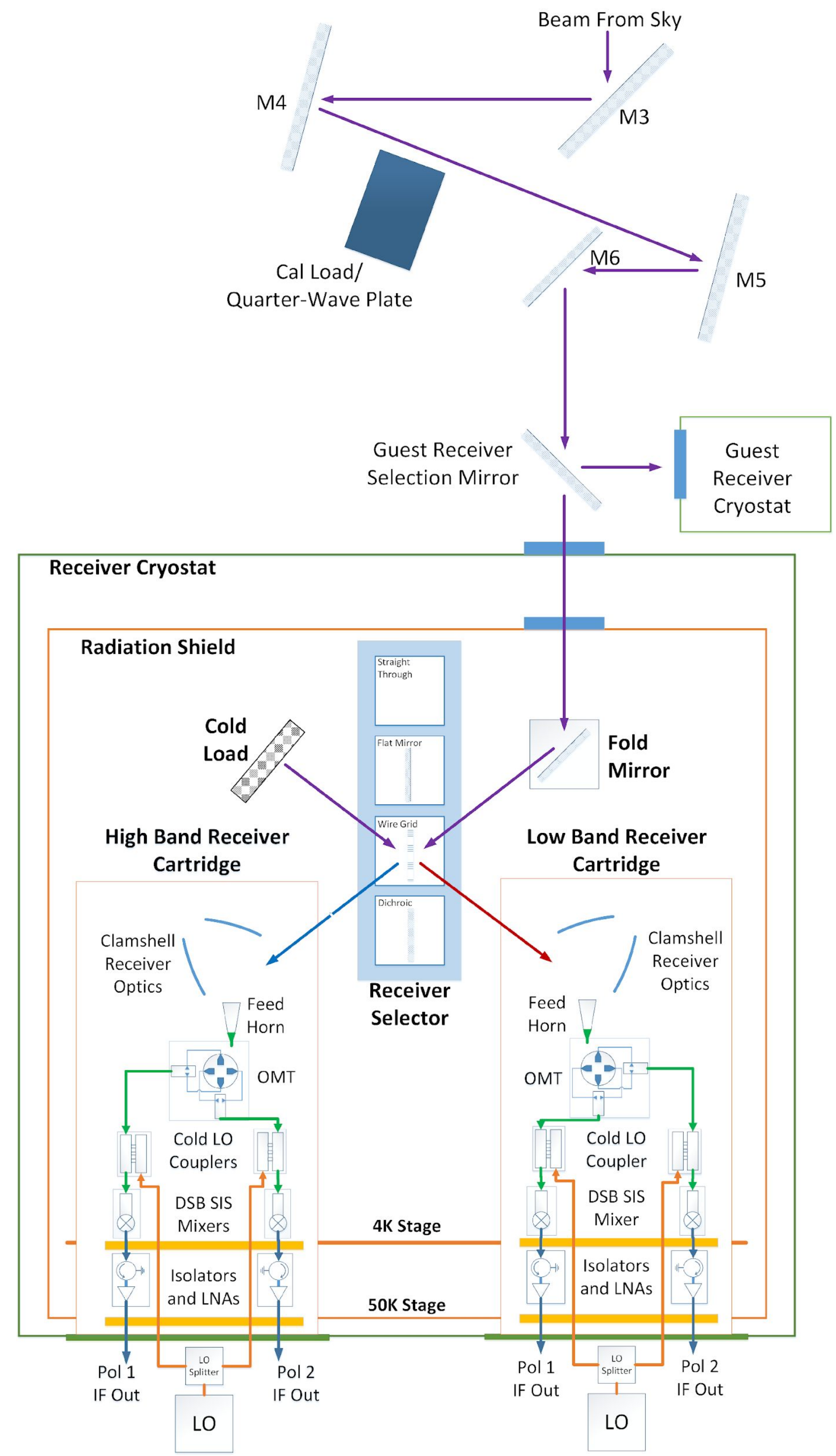
wSMA Receiver Selector

Selection	Lo Band Rx	Hi Band Rx
Thru	Cold Load	Dual Pol
Grid	Pol. #1	Pol. #2
Dichroic	Dual Pol	Dual Pol
Mirror	Dual Pol	Cold Load

- Smaller cryostat allows space for possible "Guest Receiver"
- Selector mirrors between M6 and cryostat.

Guest (PI) Receiver Selector

Selection	SMA Main Rx	Guest (PI) Rx
Thru	Inactive	Dual Pol
Grid	Single Pol	Single Pol
Mirror	Dual Pol	Inactive



Paul Grimes

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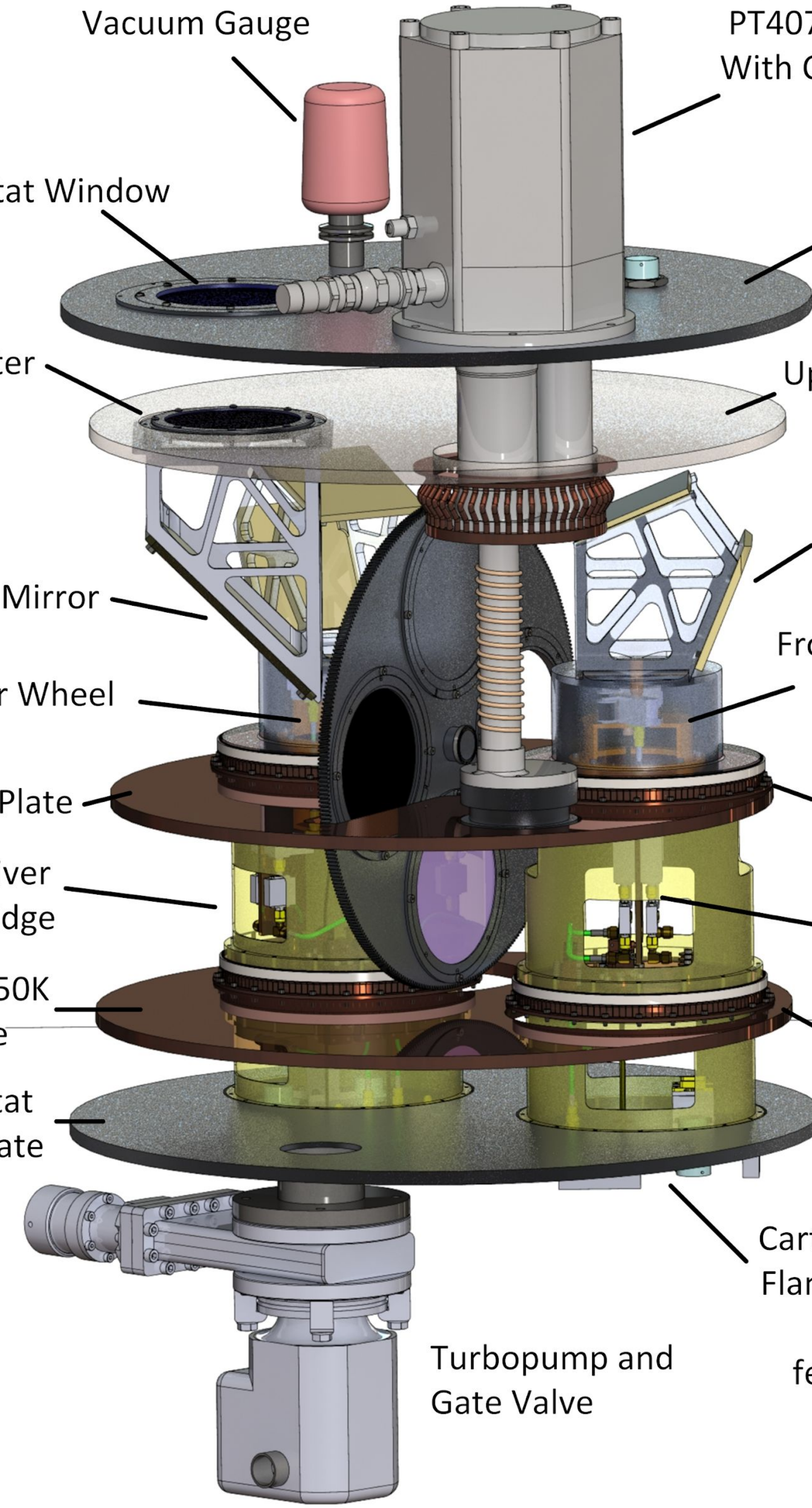
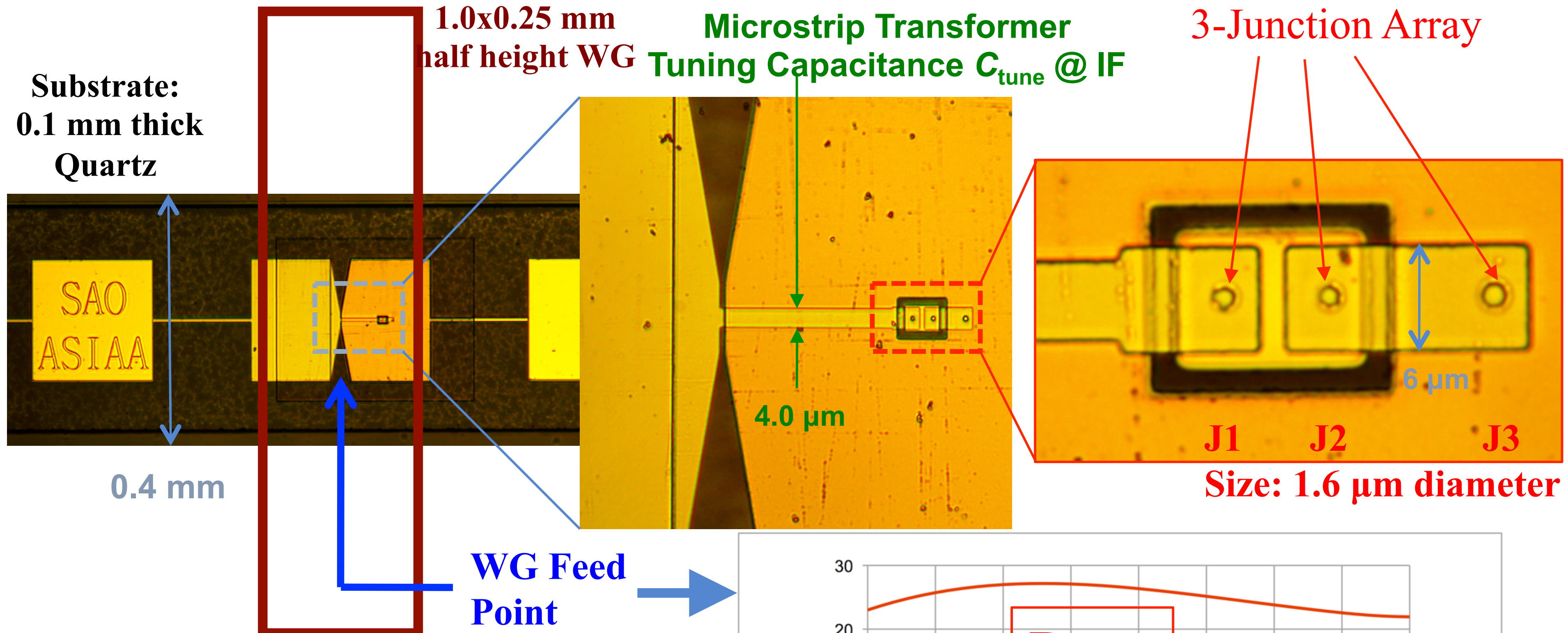
wSMA Receiver

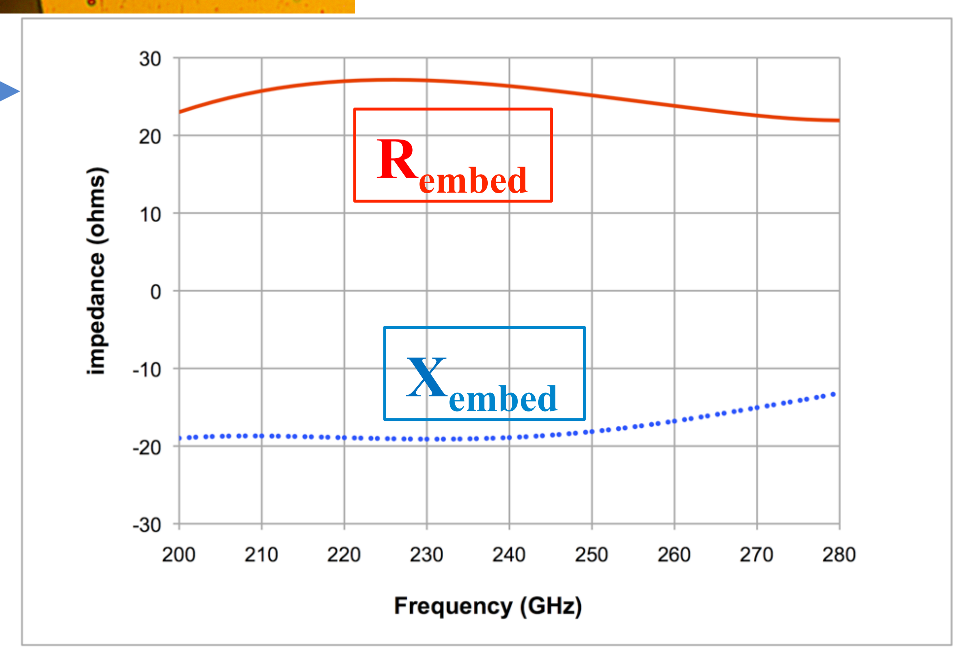
- Diameter of cryostat: about half of current one. Height is similar
- Two temperature stages – 50K for radiation shield and selection optics and 4K for receivers
- Cooled receiver selection optics replaces Optics Cage – Cryostat top plate is higher
- Selector wheel mounted on radiation shield top plate
- Single cryostat window and IR filter
- Two receiver inserts, each housing a dual pol receiver
- Use automatic thermal links similar to ALMA
- No manual connections to cartridges inside cryostat



Paul Grimes

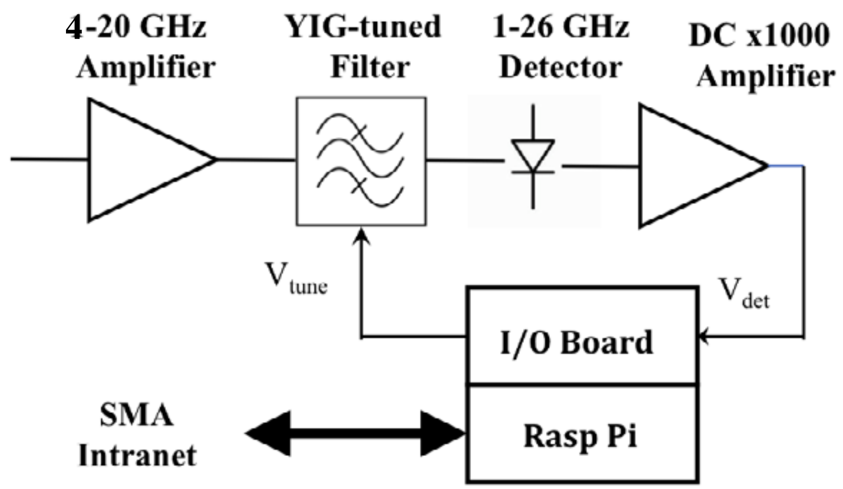
SIS Mixer for wSMA-240

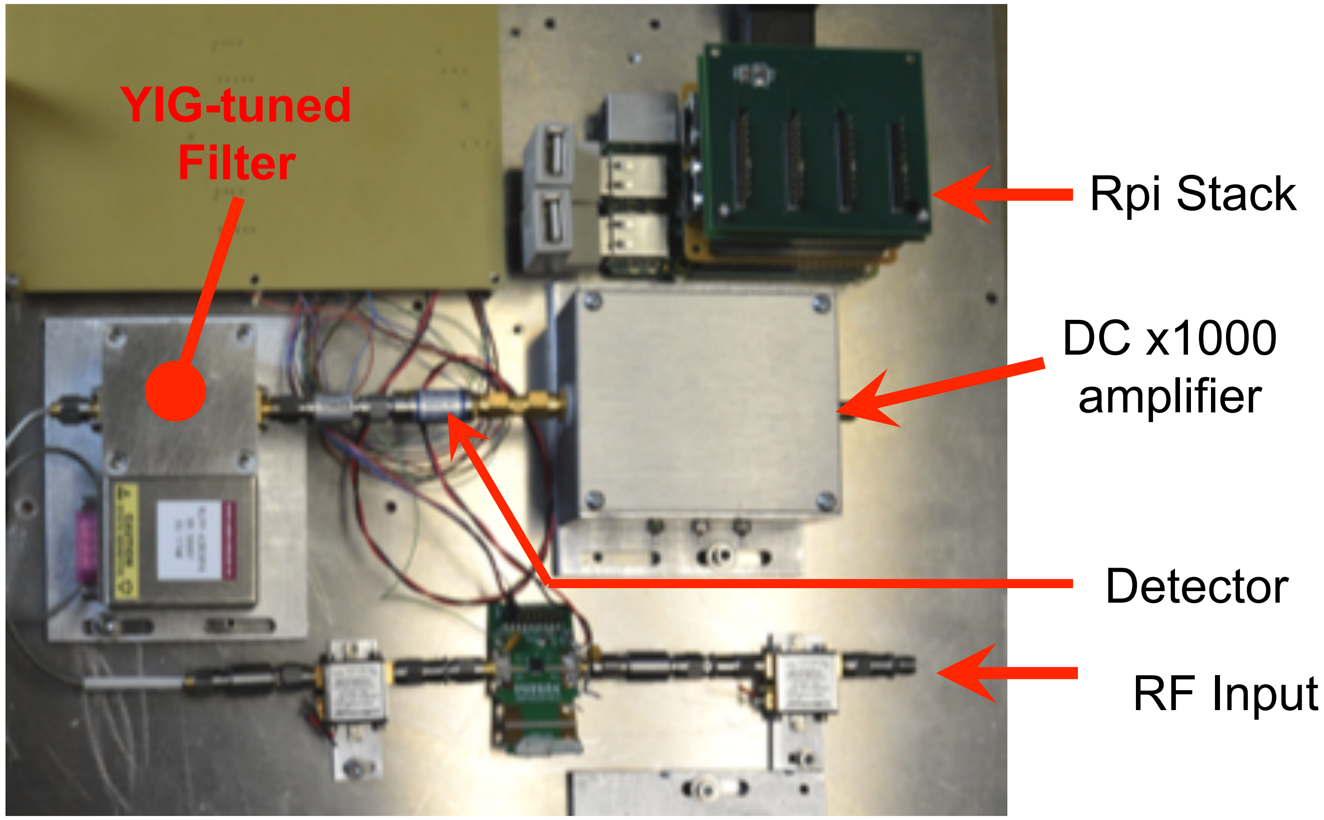




- $C_{array} = C_j / 3$
- $C_{mixer} = C_{array} + C_{tune} \sim 115$ fF.
- RC time constant of mixer gives $F_{3dB} > 25$ GHz.

Scanning Spectrometer



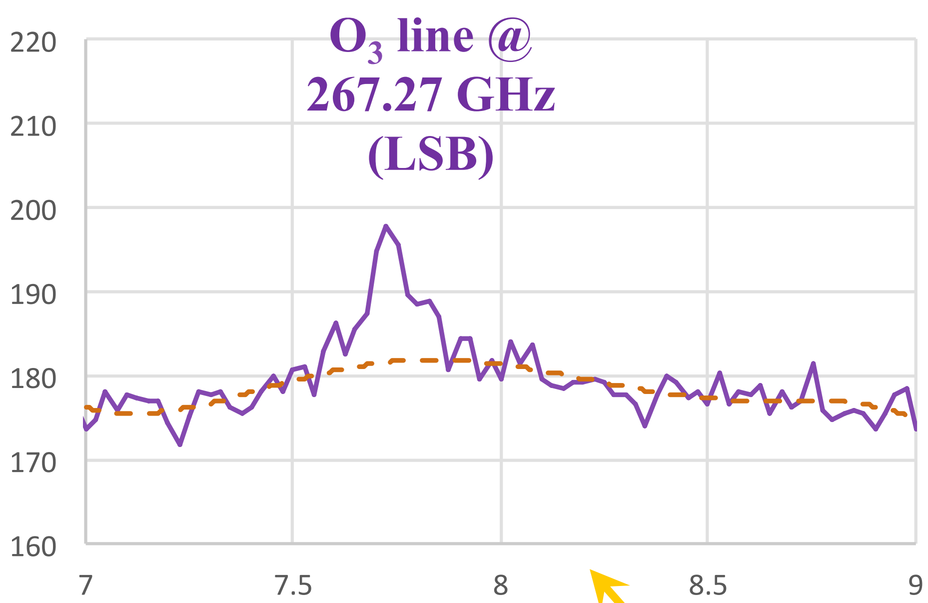


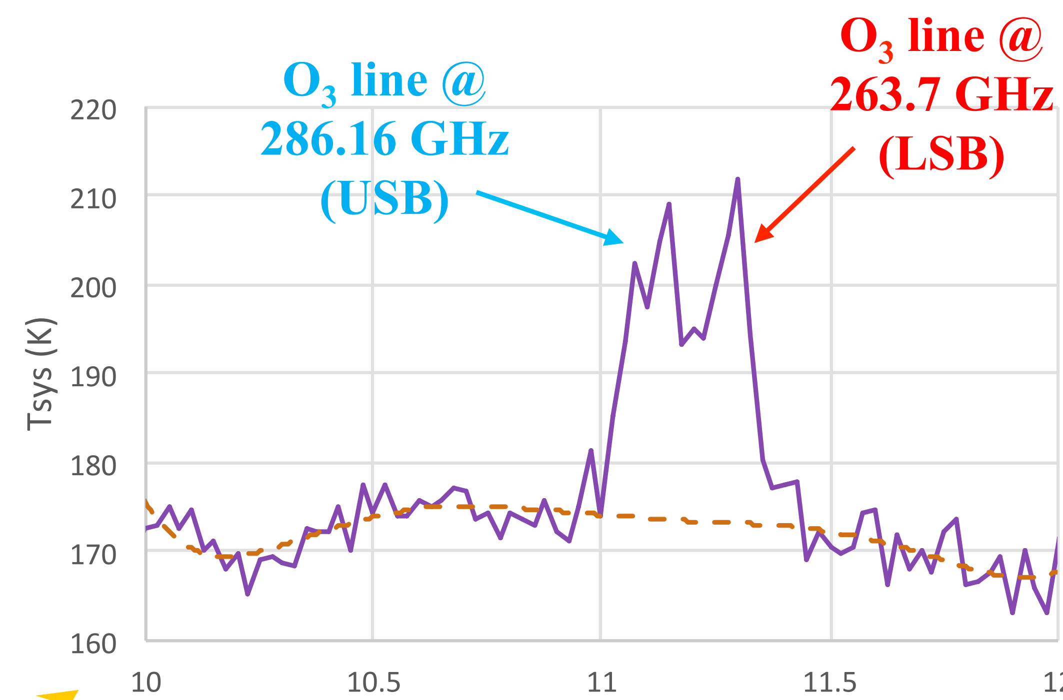
RF amplifier chain
+ Digital Attenuator

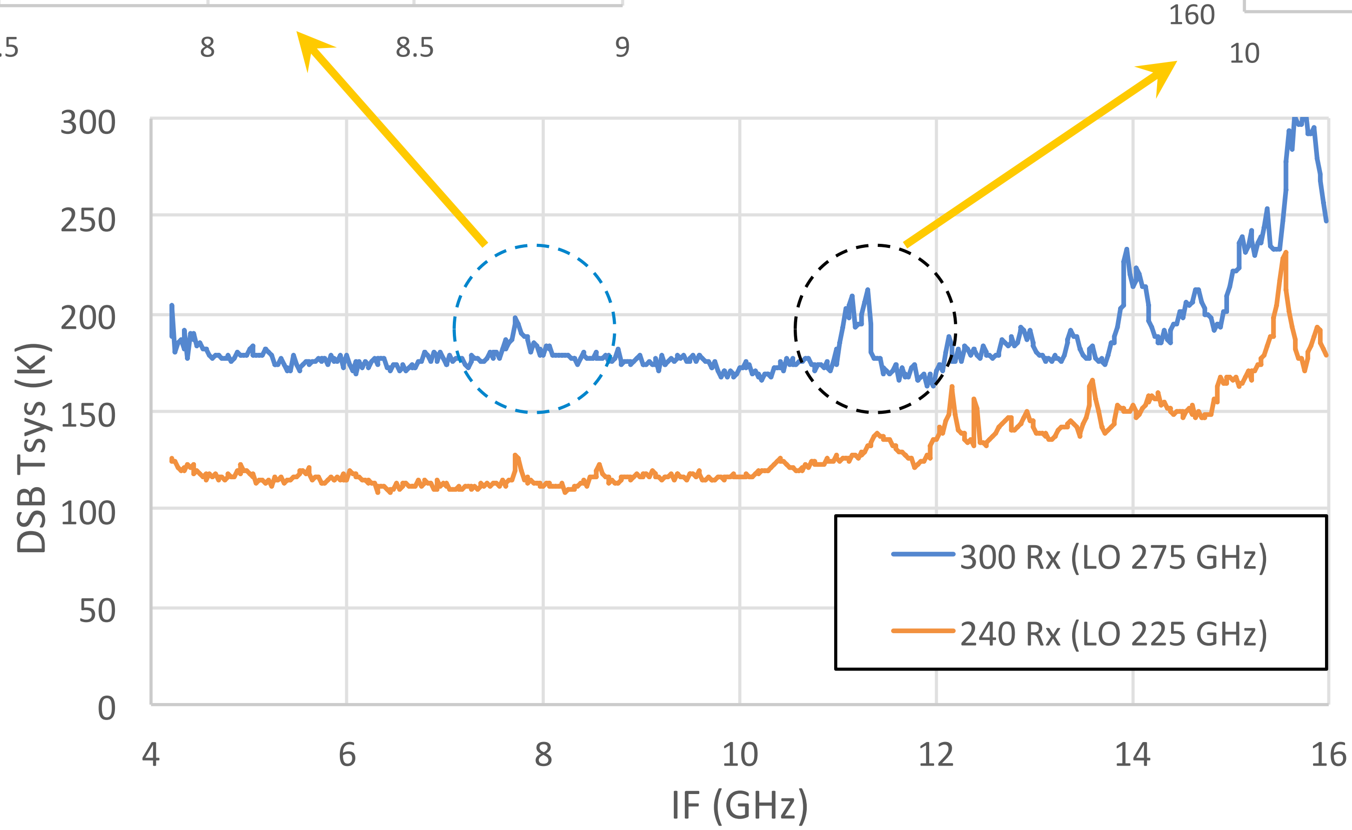
- **To provide Tsys measurement as a function of IF (currently a single value of Tsys is logged)**
- **Useful for system diagnosis**
- **Able to observe atmospheric ozone lines.**
- **Resolution of YIG filter: ~30 MHz**
- **Scan Time: ~0.5 s**

- Prototype installed in antenna 7.
- Awaiting reorganization of network to synchronize with other real time components.
- Two more units to be installed in fall

2018-07-06
Antenna 7
Elevation 67º







Tau225 ~ 0.150

Average of 8 scans

Integration time per channel
= 1.2 ms x 8 ~ 10 ms

Channel spacing 25 MHz

Expected baseline ΔT ~ 0.3 K

Observed ΔT ~ 1 - 2 K

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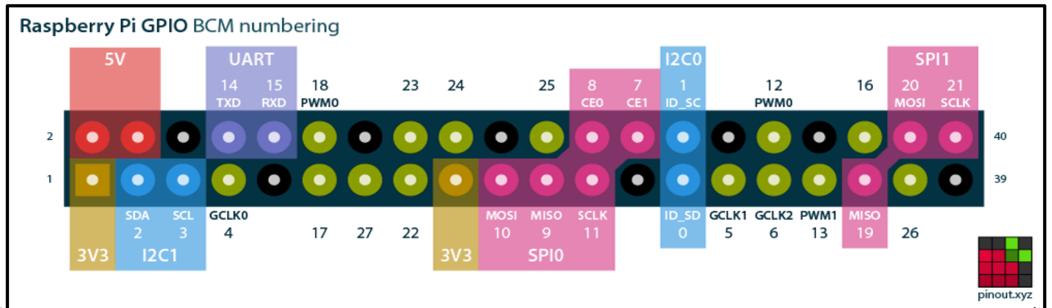
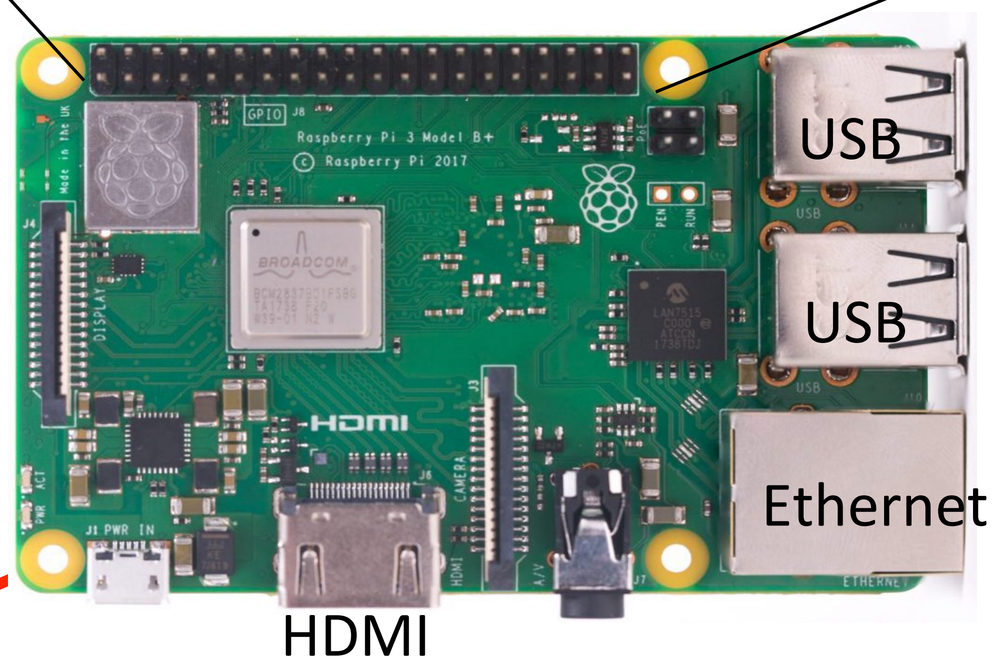
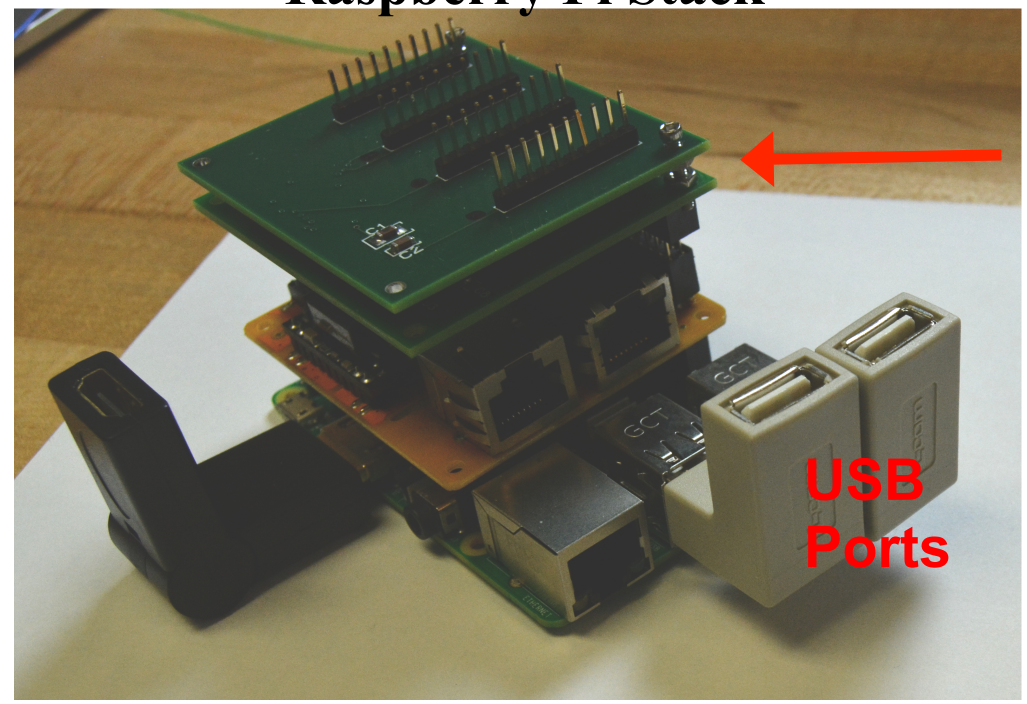
Raspberry Pi-based Controllers





Raspberry Pi model 3b+ showing various connectors plus the top 40- pin GPIO connectors

Raspberry Pi Stack

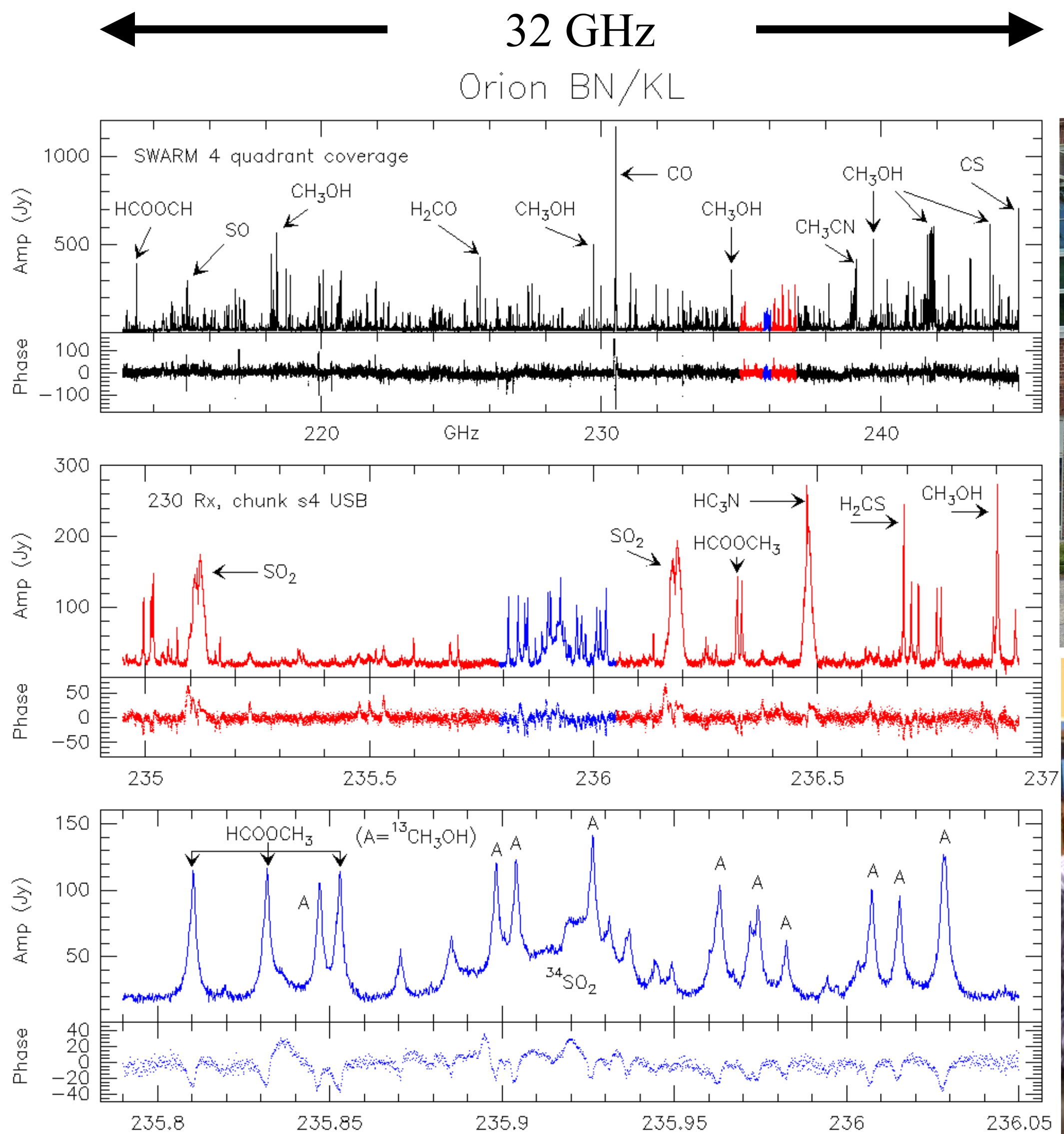


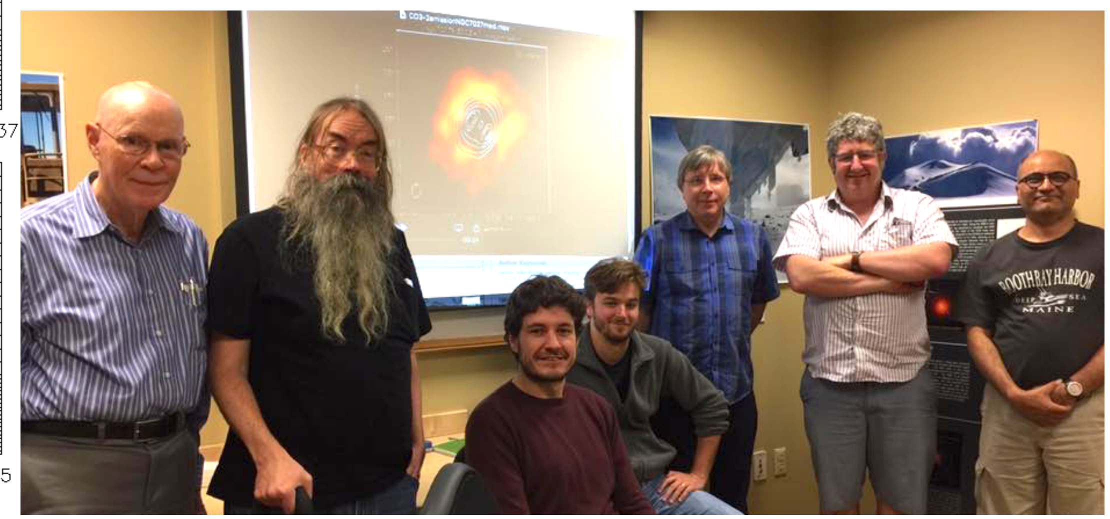
Daughter & Grand-daughter Boards for IO

POE Board (Power on Ethernet)

- **Low cost compact Linux computer allowing efficient analog & digital I/O interface thru add-on boards**
- **Very useful as distributed controllers, remotely accessible through its ethernet port.**

SWARM 2.0: Future Wideband Digital Technology for wSMA





Jonathan Weintroub
SAO/CfA

SMA Visiting Committee

18 July 2018

CASPER

XILINX®

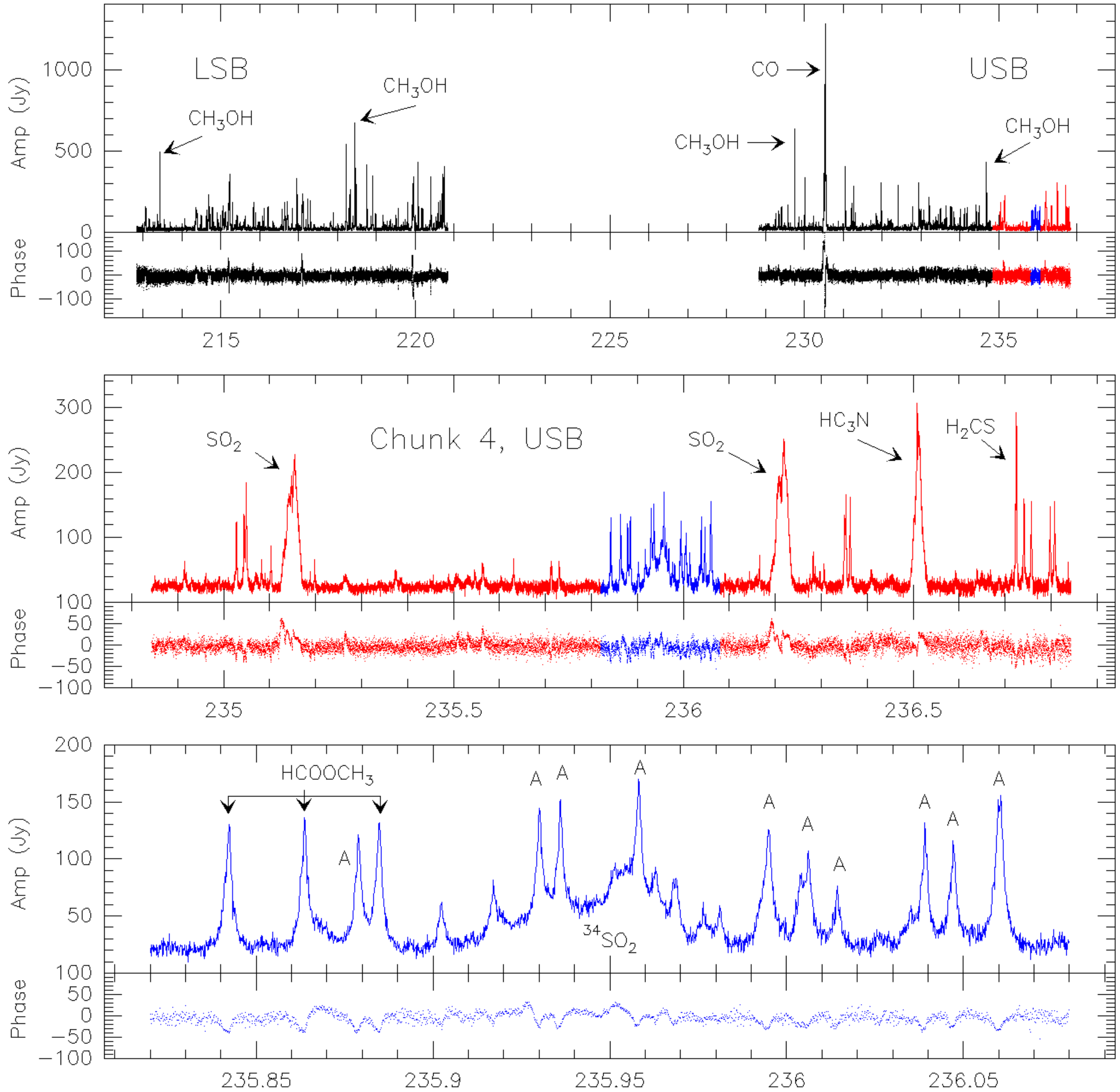


Figure 4: *Example of an SMA single baseline spectrum of the Orion-KL region using SWARM with instaneous spectral coverage of 8 GHz per sideband, at 140 kHz resolution, from Primani et al. (2016). The middle and lower panels present increasingly zoomed views of small sections of the spectrum above them (indicated in red and blue). A multitude of highly structured and resolved spectral line features in amplitude and phase are identified from a variety of molecular species ("A" indicates $^{13}CH_3OH$).*

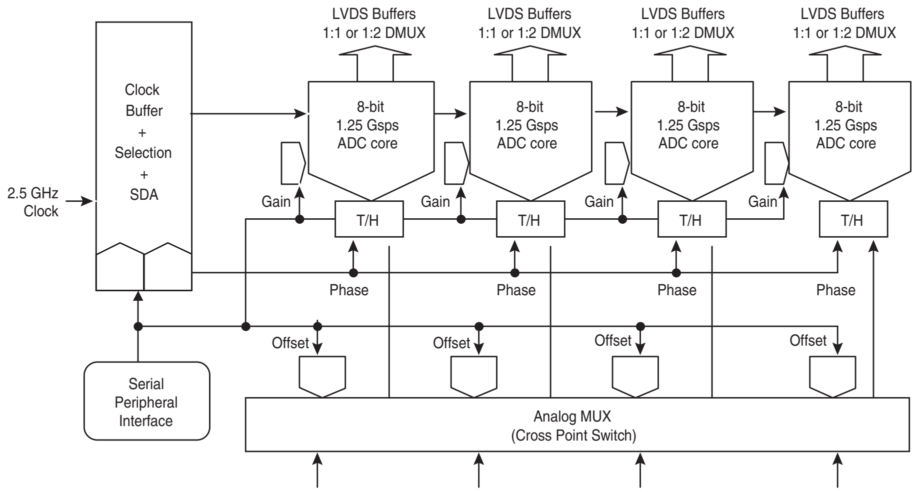
Technology evolution: SWARM (actual) to wSMA (planned)

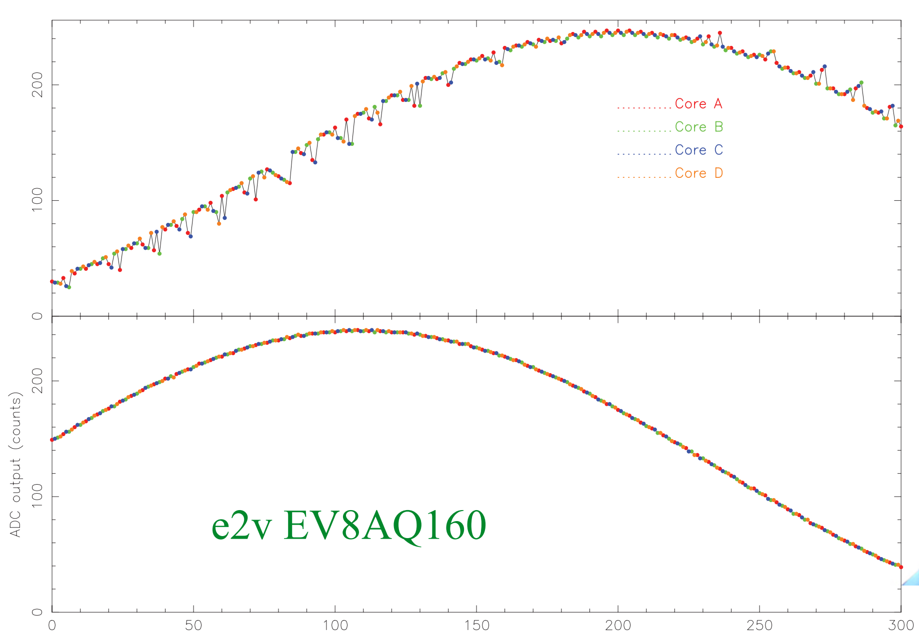
	SWARM (32 GHz)	*wSMA (128 GHz)*
sampled bandwidth	2 GHz *(64 IF blocks, 8/antenna)*	8 GHz *(64 IF blocks, 8/antenna)*
FPGA family	Virtex 6 SX475T *(2016 multipliers, 0.5M logic cells)*	Ultrascale+ VU9P *(6,840 multipliers, 2.8M logic cells)*
Ethernet data rate	10 Gbps	100 Gbps
Sampler/ADC location	Control building	Antennas

SWARM: 5 GSa/s sampler, ROACH2 and 10 Gb/s Ethernet

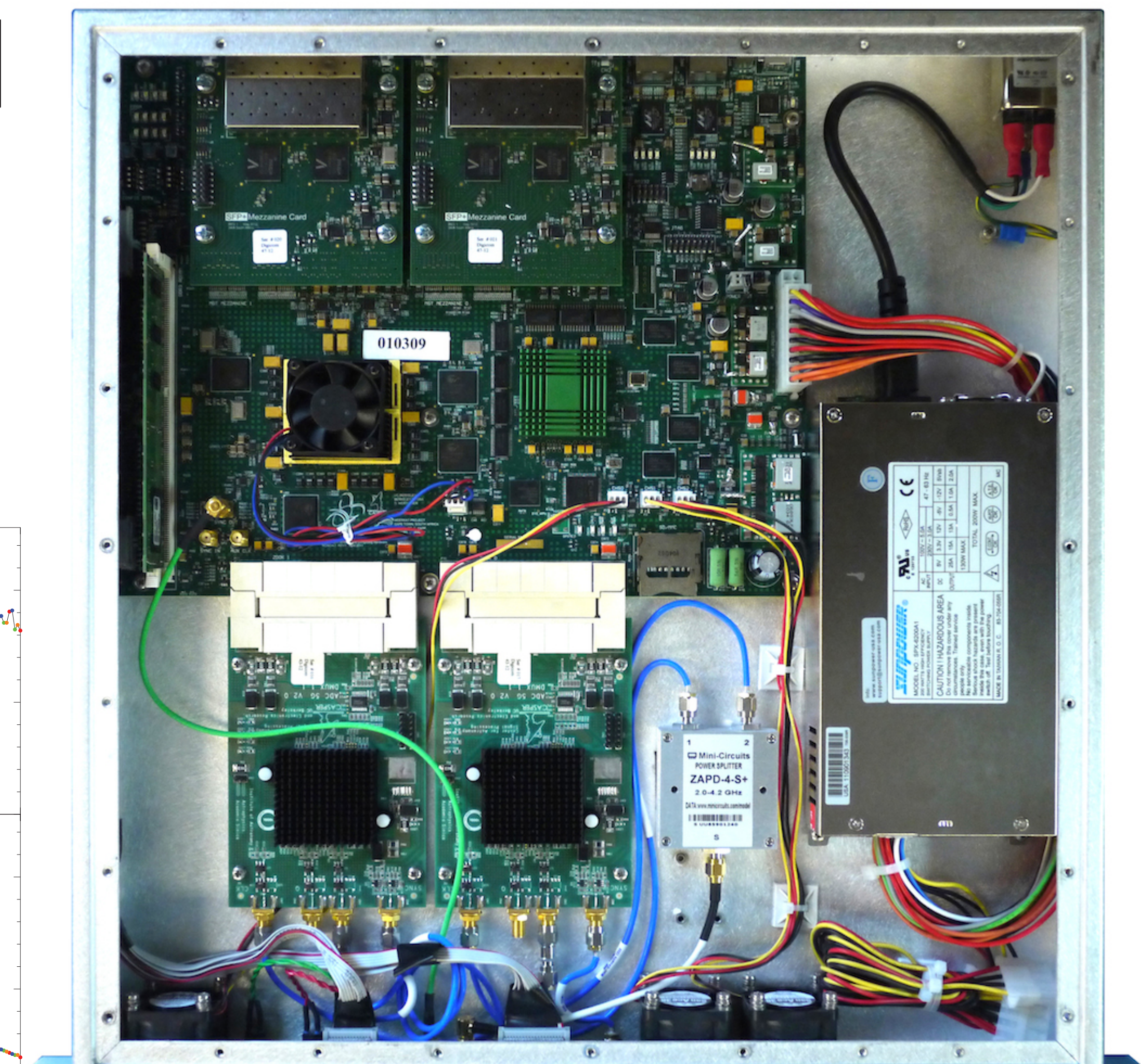
(Jiang et al., PASP 126, 761; 2014; Patel et al., JAI 3, 1 2014, Primiani et al)

Ultra Fast Analog-to-Digital Converters are typically interleaved multi-core devices
This introduces interleaving artifacts which must be calibrated





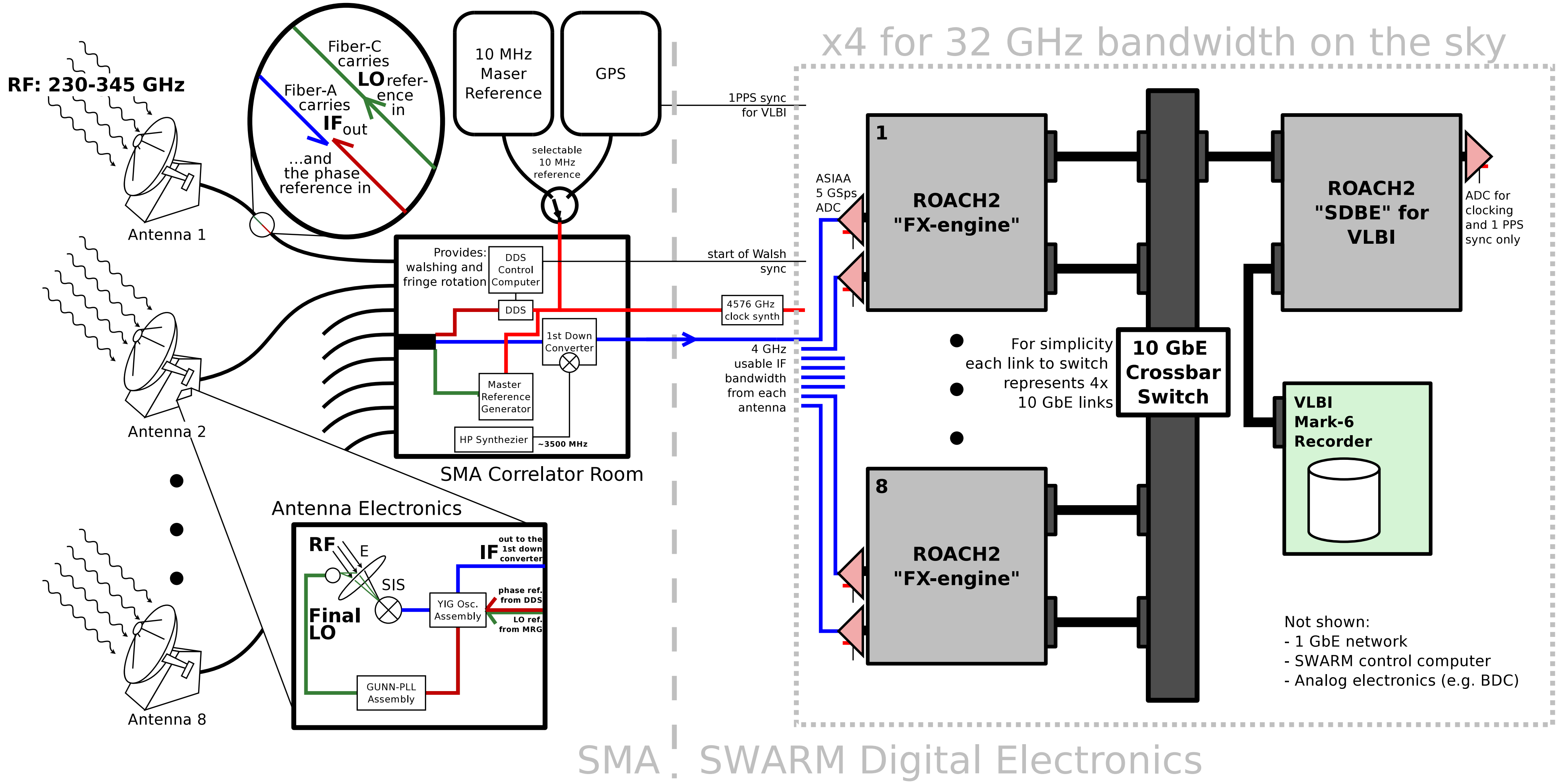
CASPER ROACH2 with Dual ASIAA ADCs
as configured for SWARM
Photo by Derek Kubo



(For more on CASPER see Hickish et al., JAI, 2016)

SWARM: SMA Wideband Astronomical ROACH2 Machine

(Primiani et al., JAI, V5 (4) 2016)



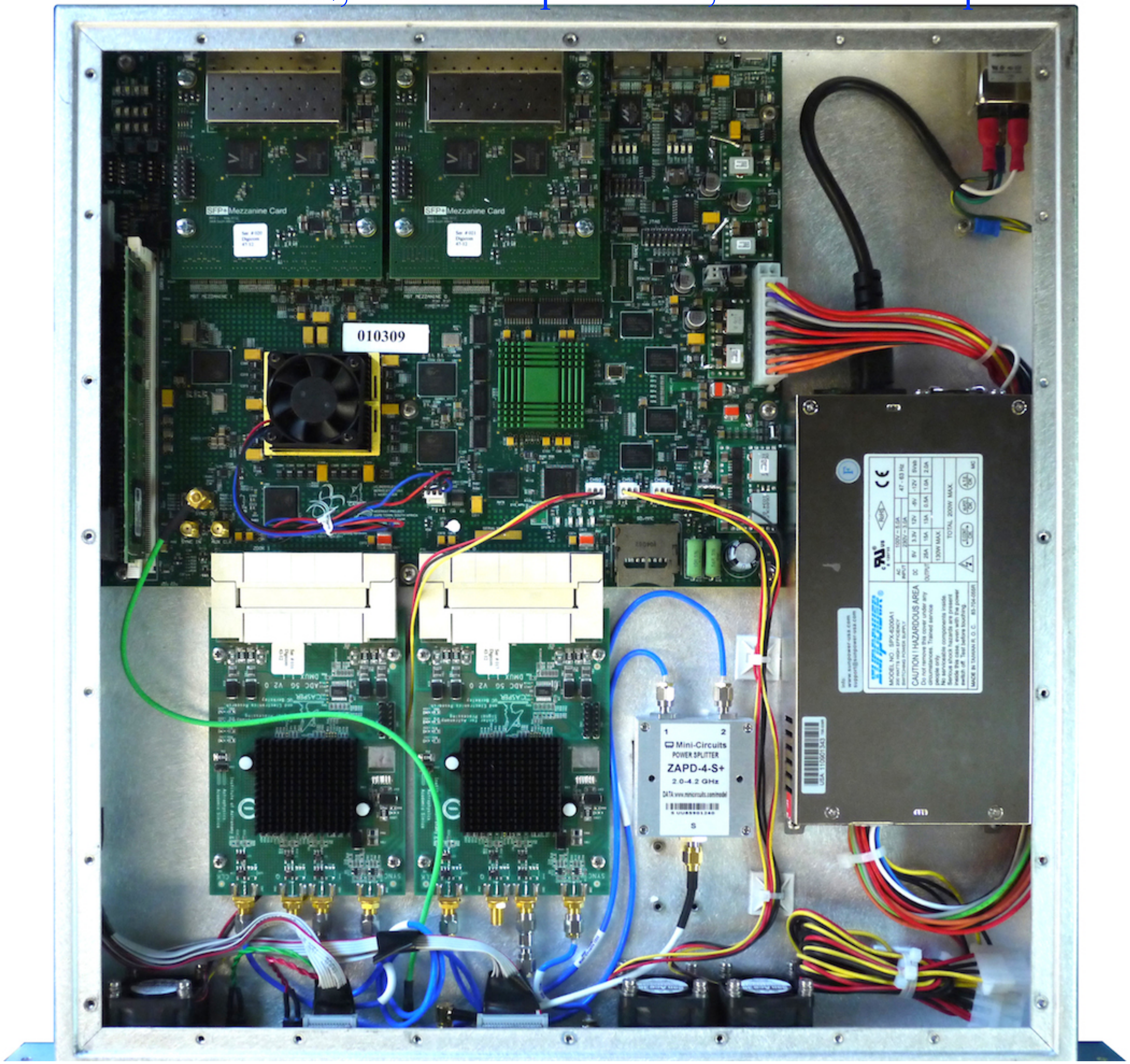
1 "quadrant": 2 GHz per receiver per sideband = 8 GHz; 32 GHz total

Benefits relative to ASIC correlator:

1. high uniform spectral resolution with no sacrifice of bandwidth,
2. smaller footprint and power consumption.
3. better digital efficiency with 4-bit cross-correlation
4. 2 GHz wide bands easier to reduce, result in higher quality spectra
5. Natively supports VLBI phasing and recording, 16 Gbps/quadrant
6. Built with CASPER and COTS components

Correlator upgrades

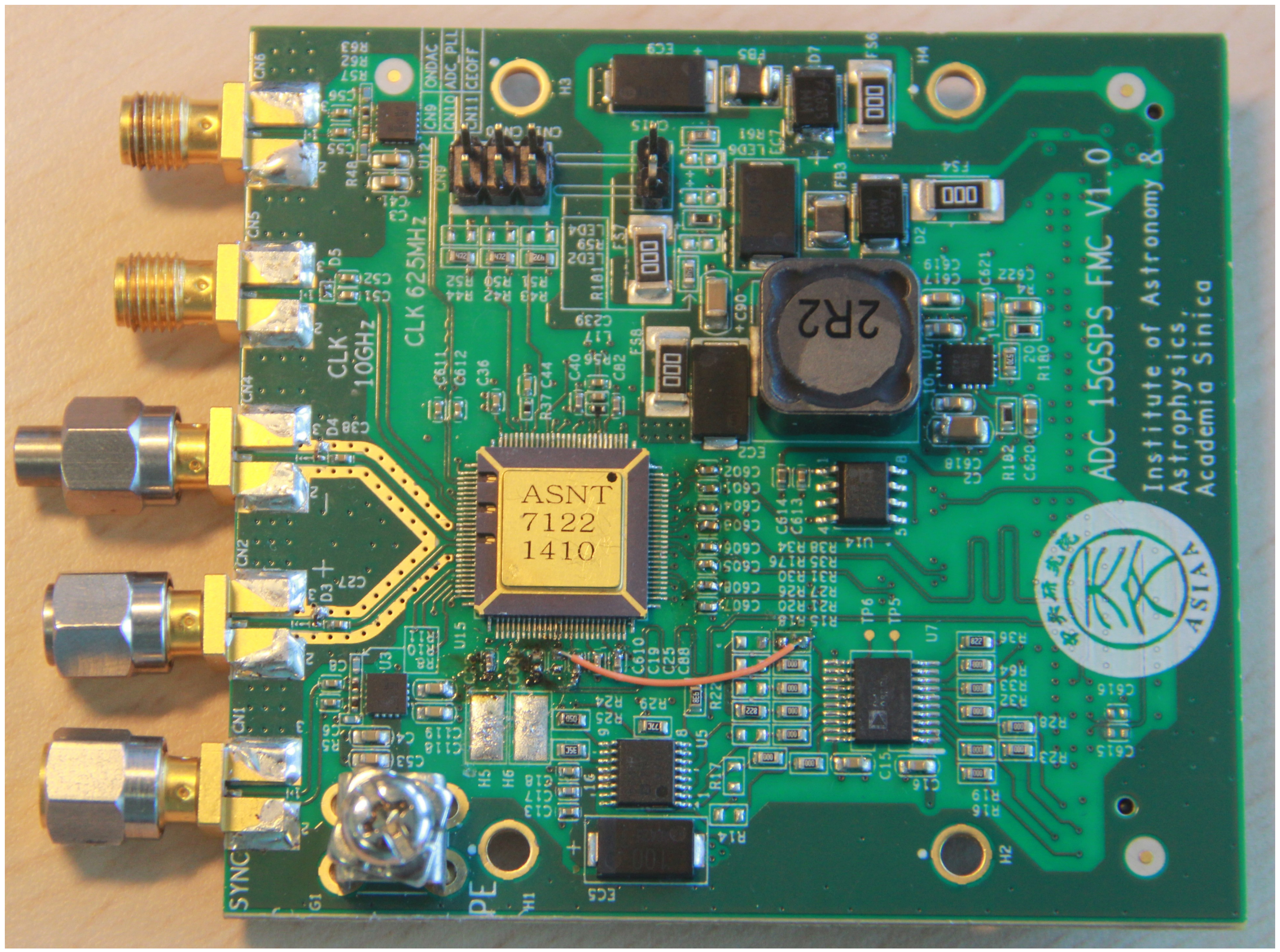
CASPER ROACH2, dual 5 Gsps ADCs, Octal 10 Gbps Ethernet

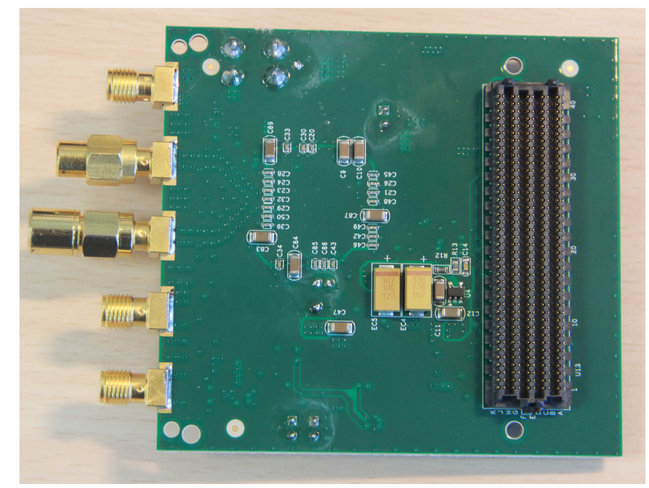


A 16 GSa/s single core CASPER ADC from ASIAA

based on Adsantec ANST7123A-KMA

Jiang, Yu, Chen & Liu (2018)





Digital Interface is SERDES on FMC+

Photos courtesy Homin Jiang, ASIAA

8 GHz bandwidth sampled at 4-bits produces data rate of 64 Gbps (fits comfortably on 100 Gbps Ethernet Link)

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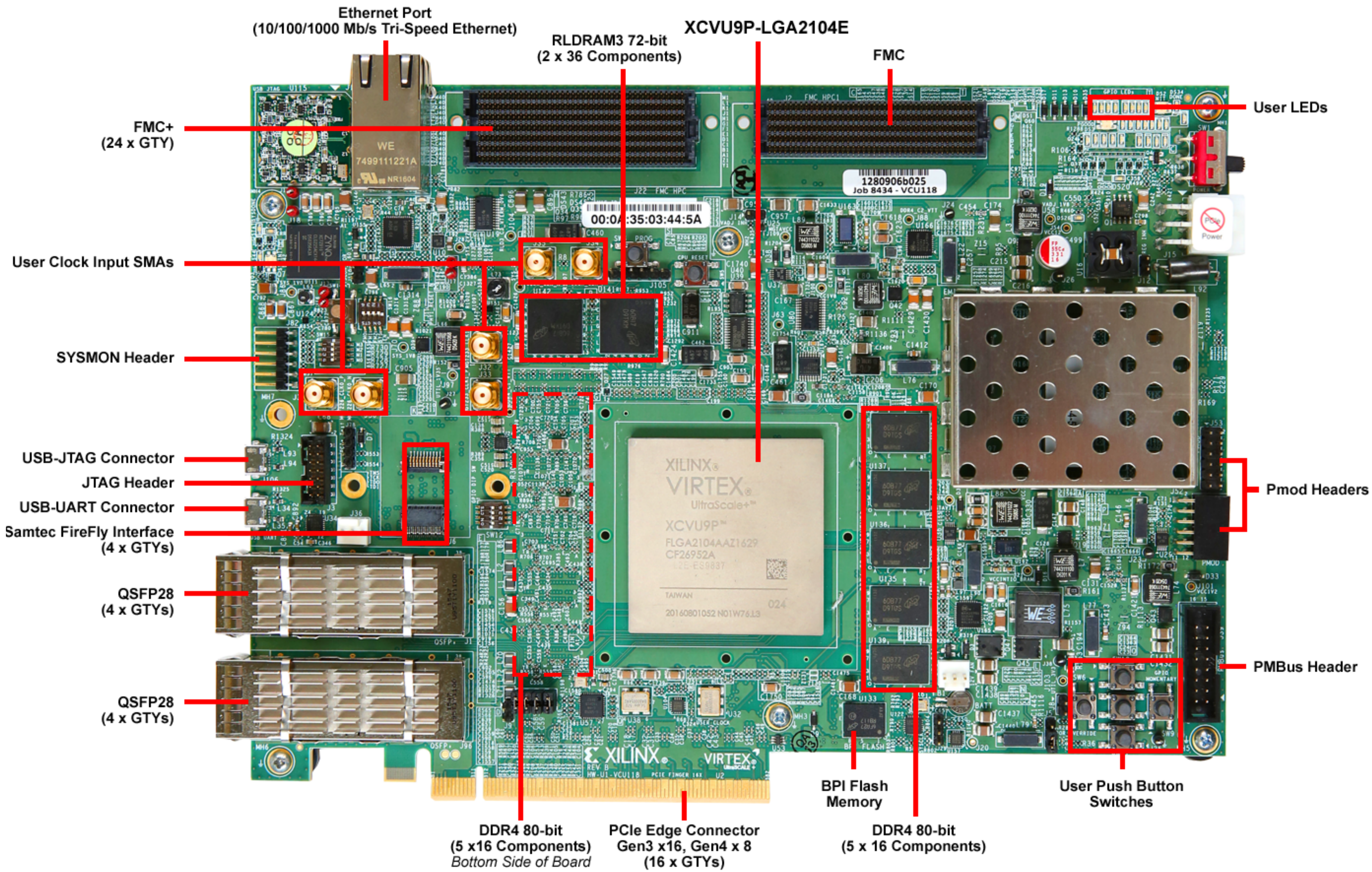
VCU118 COTS hardware, $6,995 each

(Ultrascale+ VU9P FPGA)



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CASPER

The Collaboration for Astronomy Signal Processing and Electronics Research

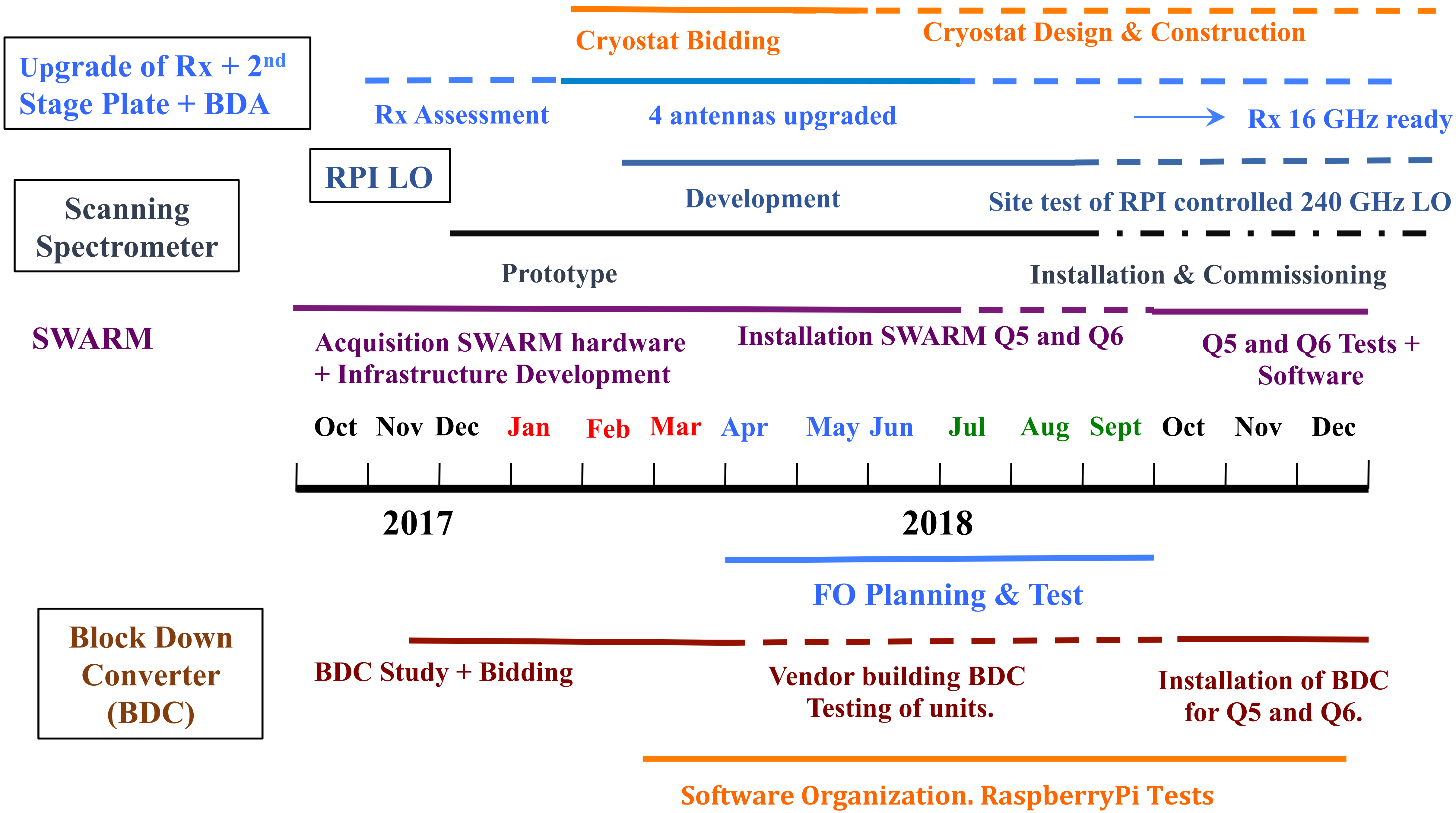
Registration for the 2019 CASPER Workshop is now open!

https://www.cfa.harvard.edu/casper2019

The 2019 CASPER Workshop and PIRE Summer School will be held at the Center for Astrophysics | Harvard & Smithsonian, from August 12th to 16th. The workshop will be teaching and early-career focused, with a technical emphasis on emergent FPGA RF System-on-Chip (RFSoc) technology.

August 12-16, 2019 Cambridge, Massachusetts

Timeline and current status

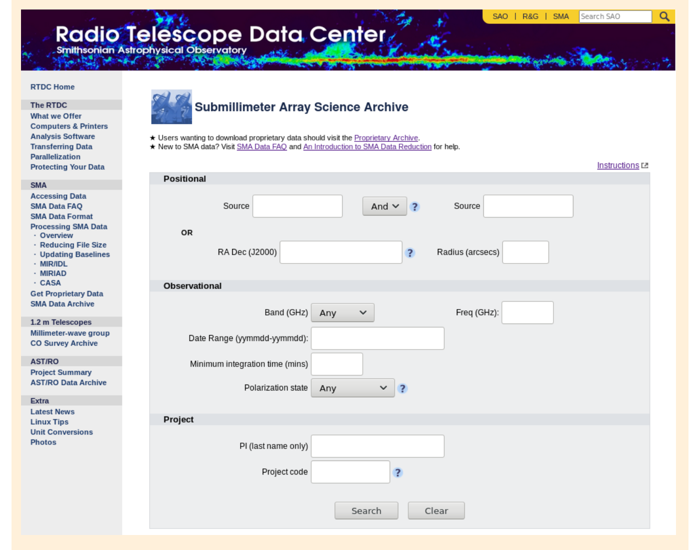


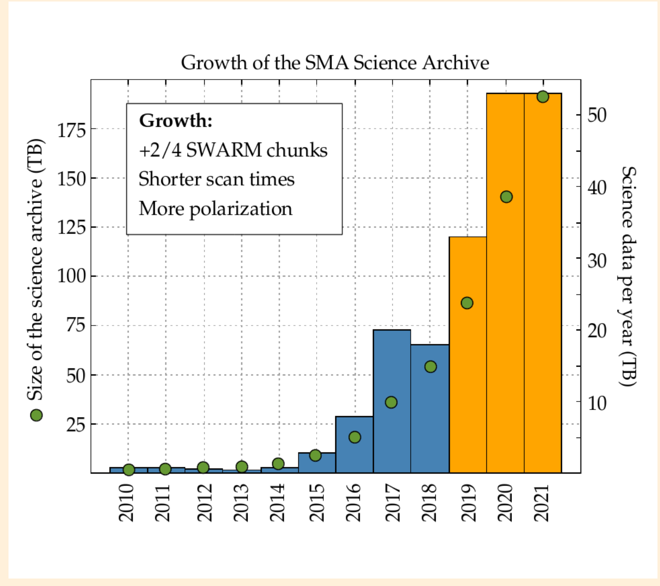
wSMA Planning for 2018 as of 06/29/2018

Edward Tong, Paul Grimes

Software

- Updated Data Archive system (Holly Thomas)
- Re-written old codes to follow better software practices (`Track`, `statusServer`, `dataCatcher`, etc.) (Attila Kovacs)
- Improved interferometric pointing software (Karto Keating)
- Version control: CVS -> Github (Taco, Chris Moriarty)
- Replace legacy, unmaintained, obsolete software: Distributed Shared Memory -> Redis (Attila Kovacs)
- New wSMA receiver control & monitoring software (Bob Wilson, Paul Grimes, Ram Rao, Attila Kovacs, Nimesh Patel)
- Pipeline for data calibration and imaging (Karto Keating)

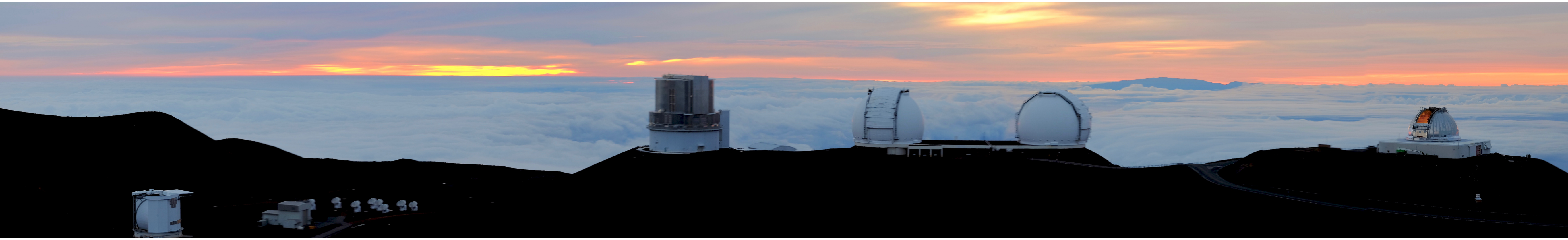




Taco retired on his 60th birthday, February 27, 2018. A foundational mainstay of the SMA, esteemed by all, he will truly be missed. His life was built around the SMA and he was literally always on duty in support of it 24 hours a day. He had intimate knowledge of virtually every aspect of the instrument and as his annual review in 2006 put it succinctly: "he is willing to help anyone at any time." Jim Moran

Summary

- SMA -> wSMA (ultrawide instantaneous bandwidth): upgrades on receivers, digital backend and software; progress is on schedule.
- The wSMA will be complementary to ALMA, particularly for large-scale and ToO projects
- The wSMA design incorporates open space for additional instrumentation to pursue new science goals and technical innovations.
- The wSMA will continue to be a critical station for EHT observations



Acknowledgement

We recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.