The Submillimeter Array

Raymond Blundell Taipei 27 October 2016

The Submillimeter Array – current status

The Submillimeter Array is an 8-element radio interferometer located close to the summit of Mauna Kea, Hawaii.

Operating at frequencies from 180 GHz to 418 GHz, the 6m dishes may be arranged into configurations with baselines as long as 509m, producing a synthesized beam of sub-arcsecond dimensions.

Each element can observe with two receivers simultaneously, with 8 GHz or more instantaneous bandwidth for each receiver.
The new digital correlator backend (SWARM) provides a uniform resolution of 140 kHz.

The Submillimeter Array, Mauna Kea, Hawaii (SMA)

Eight 6m antennas

Antennas transported between different stations using purpose-built transporter

Four configurations offer different resolutions
sub-compact, compact, extended
and very extended (> 500 meters)

Compact configuration

Extended configuration

How did we get here?

mm-wavelength astronomy in mid 1980's

Submm-wavelength astronomy in mid 1980's

Two single-dish telescopes under construction, both on Mauna Kea, Hawaii

JCMT – 15m diameter

CSO – 10.4m diameter

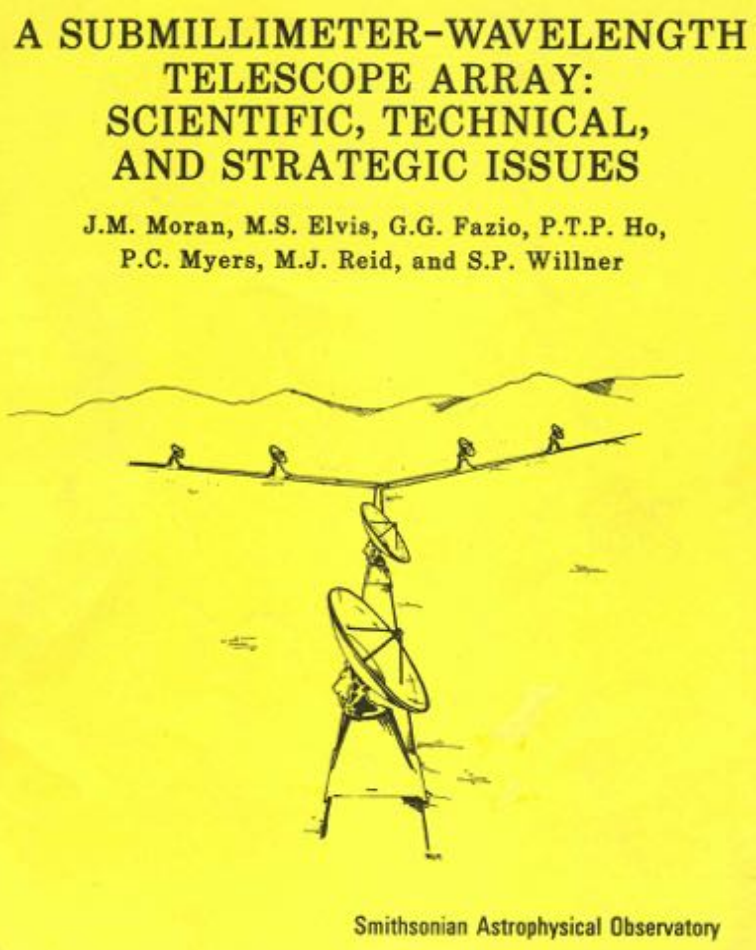
Nothing available for high angular-resolution submm observations

1984 SAO Director Irwin Shapiro formed a committee to propose a new instrument

Submillimeter Telescope Committee
Chaired by J. M. Moran (1984)

Committee proposed:

- Six 6 m diameter antennas
- 1.3 – 0.3 mm wavelength
- High altitude developed site
- Sub-arcsecond resolution
- Set up receiver lab ASAP
- Projected performance (SSB)
  - 300 K receiver noise at 230 GHz
  - 900 K receiver noise at 345 GHz
- 1988 – SAO receiver lab funded
- 1992 – SMA construction began
- 1996 – ASIAA joined SAO
  - 2 more antennas + receivers
  - And 2x correlator capacity

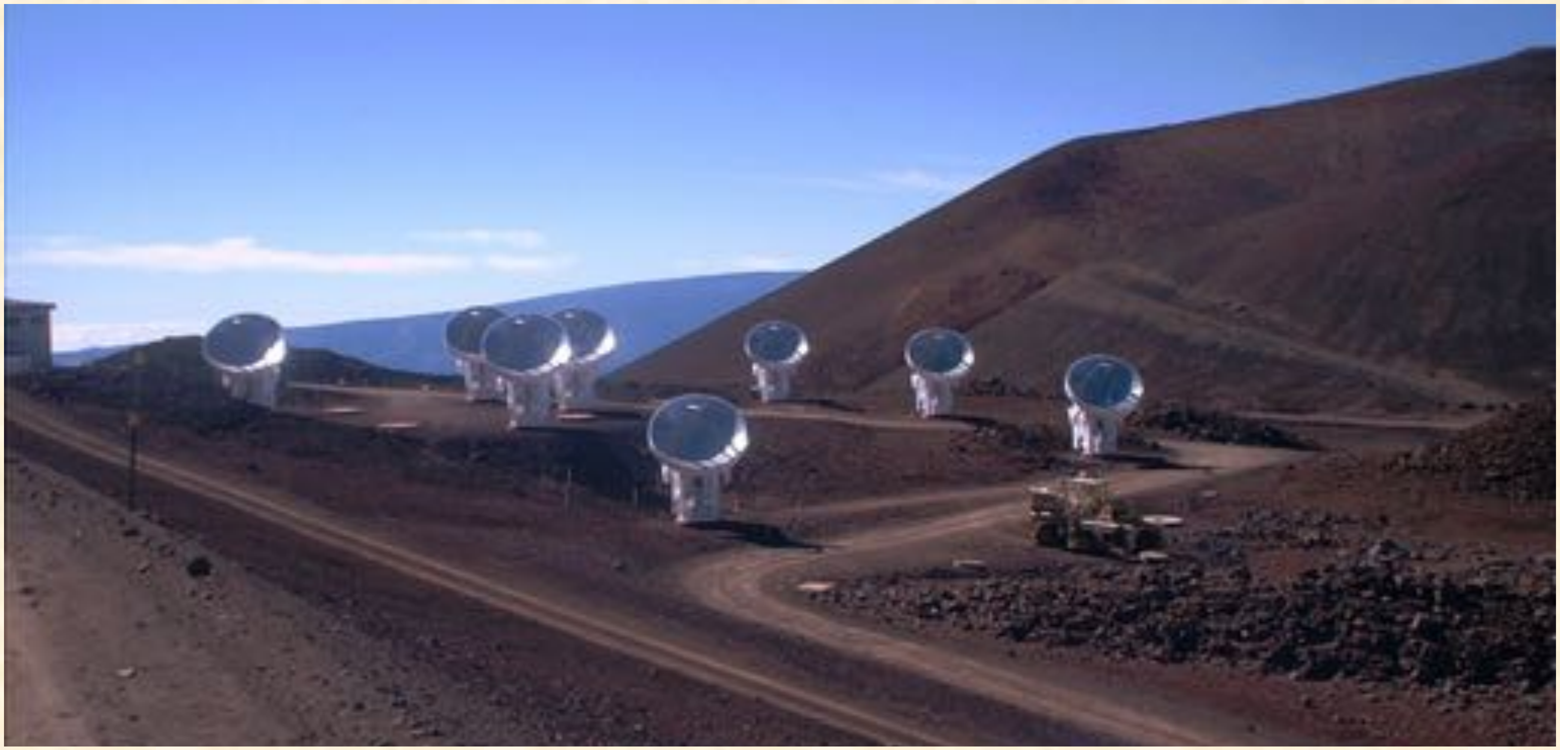

A SUBMILLIMETER-WAVELENGTH TELESCOPE ARRAY: SCIENTIFIC, TECHNICAL, AND STRATEGIC ISSUES

J.M. Moran, M.S. Elvis, G.G. Fazio, P.T.P. Ho, P.C. Myers, M.J. Reid, and S.P. Willner

Smithsonian Astrophysical Observatory

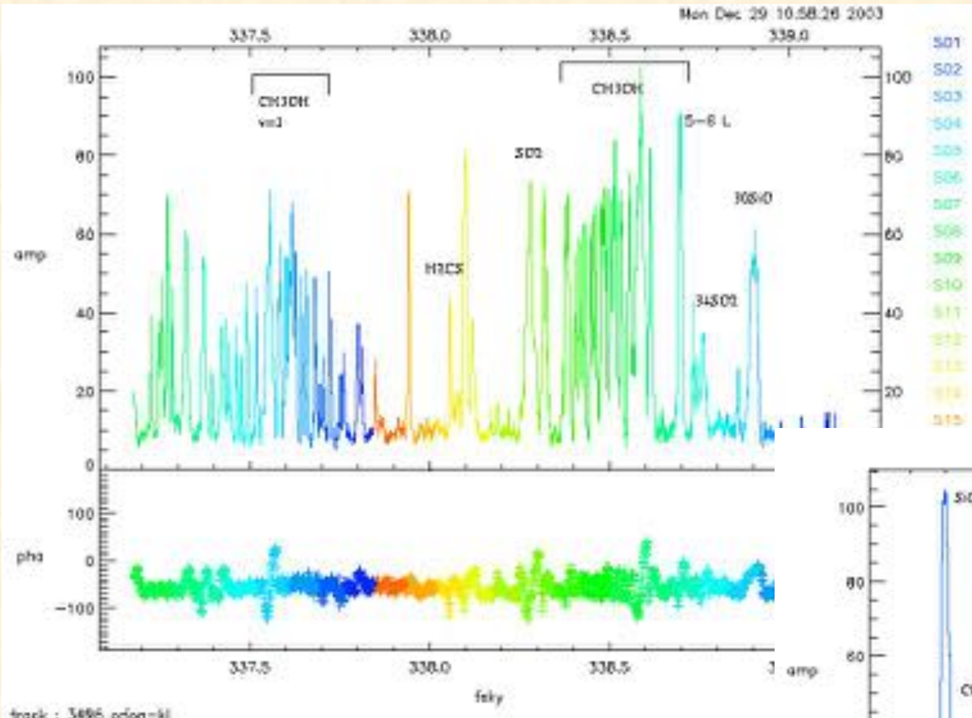
8 SMA antennas on Mauna Kea

(Dedication, November 2003)



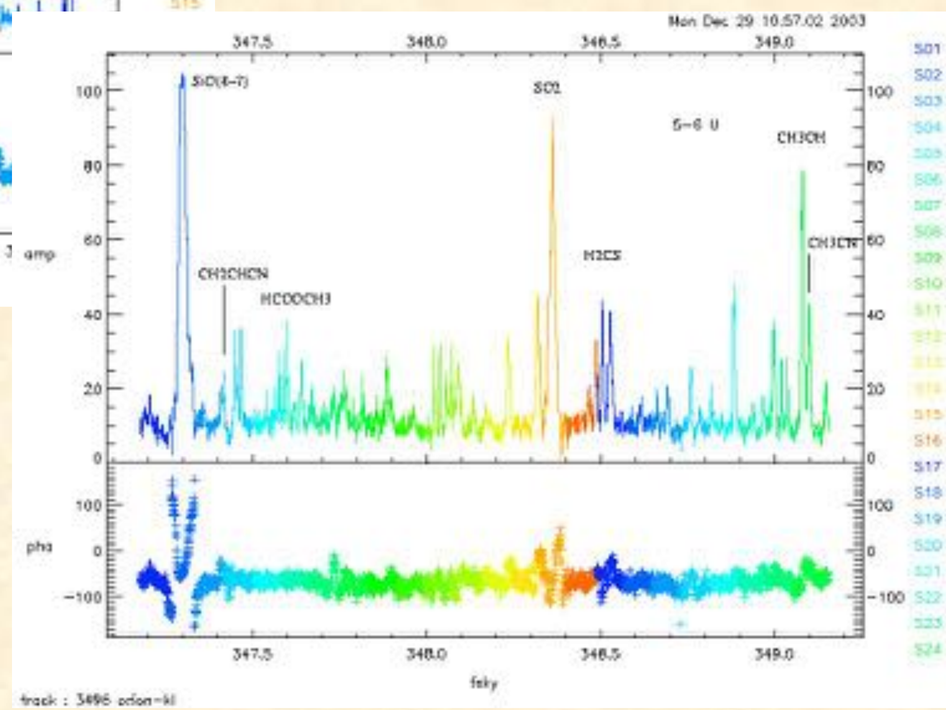
8 DSB receiver sets available at 230 and 345 GHz, 6 available at 650 GHz
IF bandwidth 2 GHz, centered at 5 GHz
Correlator available to process output from either 230 or 345 GHz receivers, and 650 GHz receivers in dual receiver mode

Early observations with the SMA: spectra towards Orion-KL
(Beuther, December 2003)



LSB: 337.2 – 339.2 GHz

USB: 347.2 – 349.4 GHz



Instruments available in 2007

- Low frequency receiver sets at 230 GHz and 345 GHz
- High frequency receiver sets at 400 GHz and 650 GHz
- 2 receiver operation possible
  - 1 low frequency rx (< 350 GHz) with 1 high frequency rx (> 350 GHz)
  - And dual polarization available in the 330 – 350 GHz range
- IF bandwidth 2 GHz-wide, centered at 5 GHz
- DSB receiver operation
- Total bandwidth per receiver = 2 GHz x 2 sidebands = 4 GHz
- Total processed bandwidth (two receivers) of 8 GHz

A few science highlights

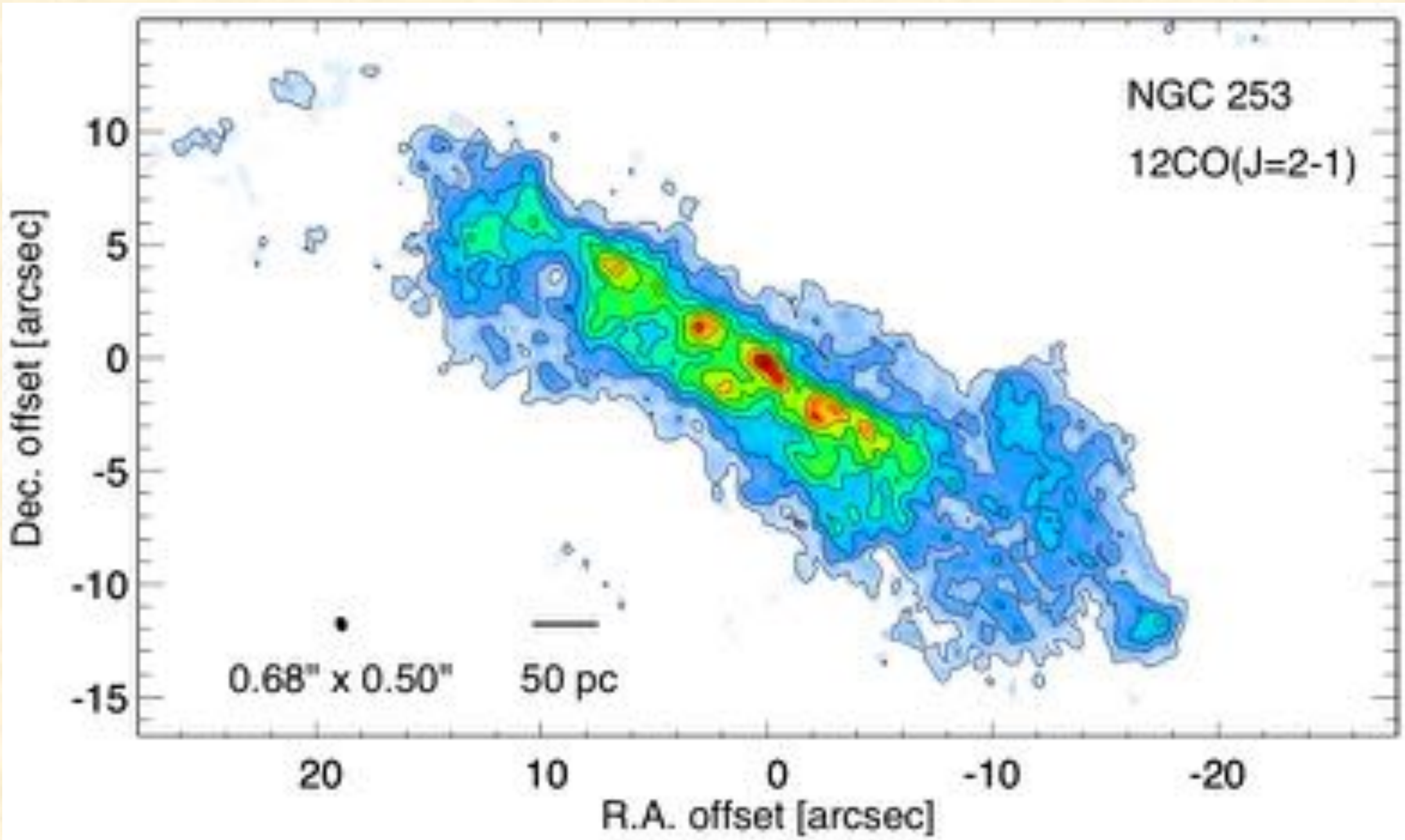
The SMA has been used to conduct a wide range of science, including:

Planetary science
The Galactic center
Star formation
- Protostars
- Jets
- Evolved stars
- Protoplanetary disks
- Studies of polarized dust emission

Neary galaxies
The distant universe – submillimeter galaxies – high-z galaxies
High energy astrophysics – GRB's
The SMA has also made valuable contributions to a number of monitoring programs
And is a key partner in VLBI – EHT science

I will select a few examples by way of illustration – not a popularity contest

Molecular gas in prototypical starburst galaxy NGC253



Subarcsecond image
Includes some of the earliest very extended data (Sakamoto et al. 2006)

Protoplanetary transition disk survey (Andrews)

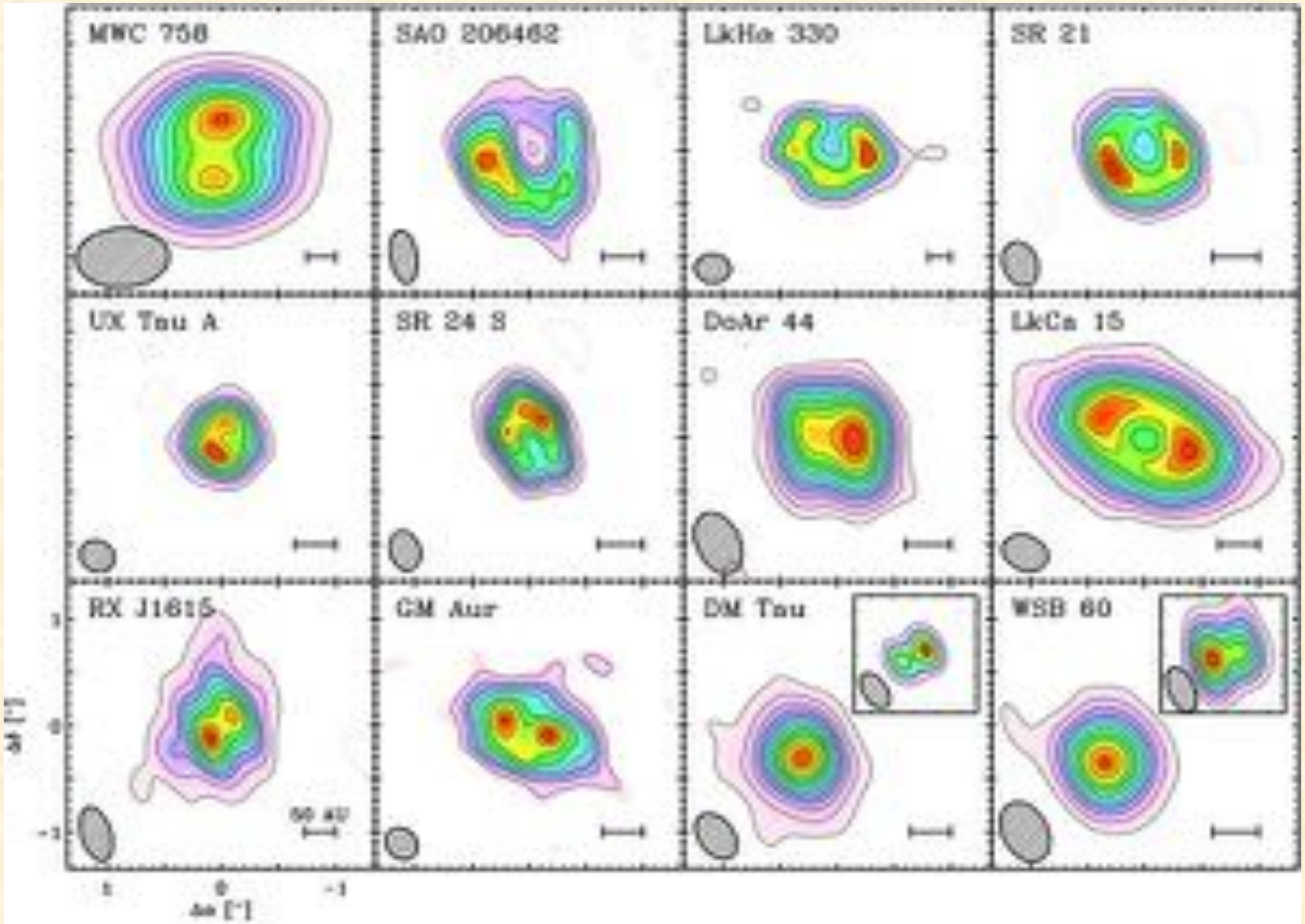
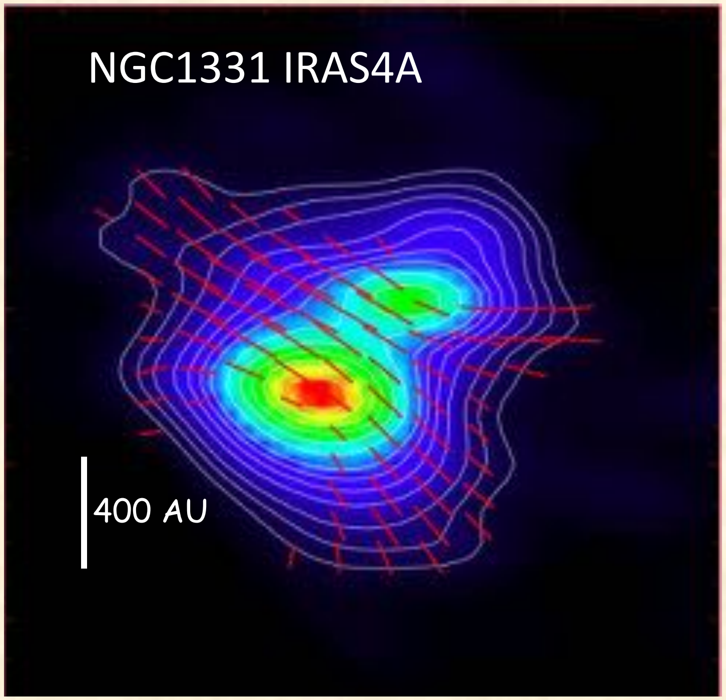


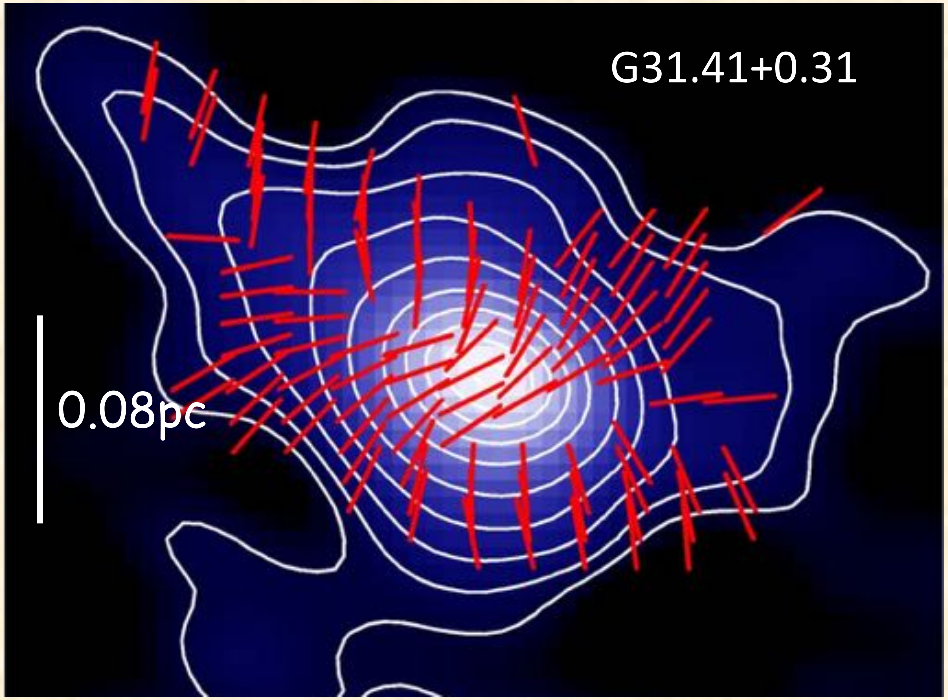
Figure 1. SMA aperture synthesis maps of the 880 μm continuum emission from this sample of transition disks. Each panel is 2.7 arcsec on a side and contains a 50 AU projected scale bar in the lower right for reference. Contours are drawn at 3σ intervals, and the synthesized beam dimensions are marked in the lower left. The inset images for the DM Tau and WSB 60 disks were synthesized with higher angular resolution and are shown to scale.

Polarized Dust Emission

Red bars -- magnetic field direction. Contours: 0.8mm dust continuum

Both objects show ordered magnetic field and a pinched hour glass morphology, indicating an important role of magnetic field in star formation

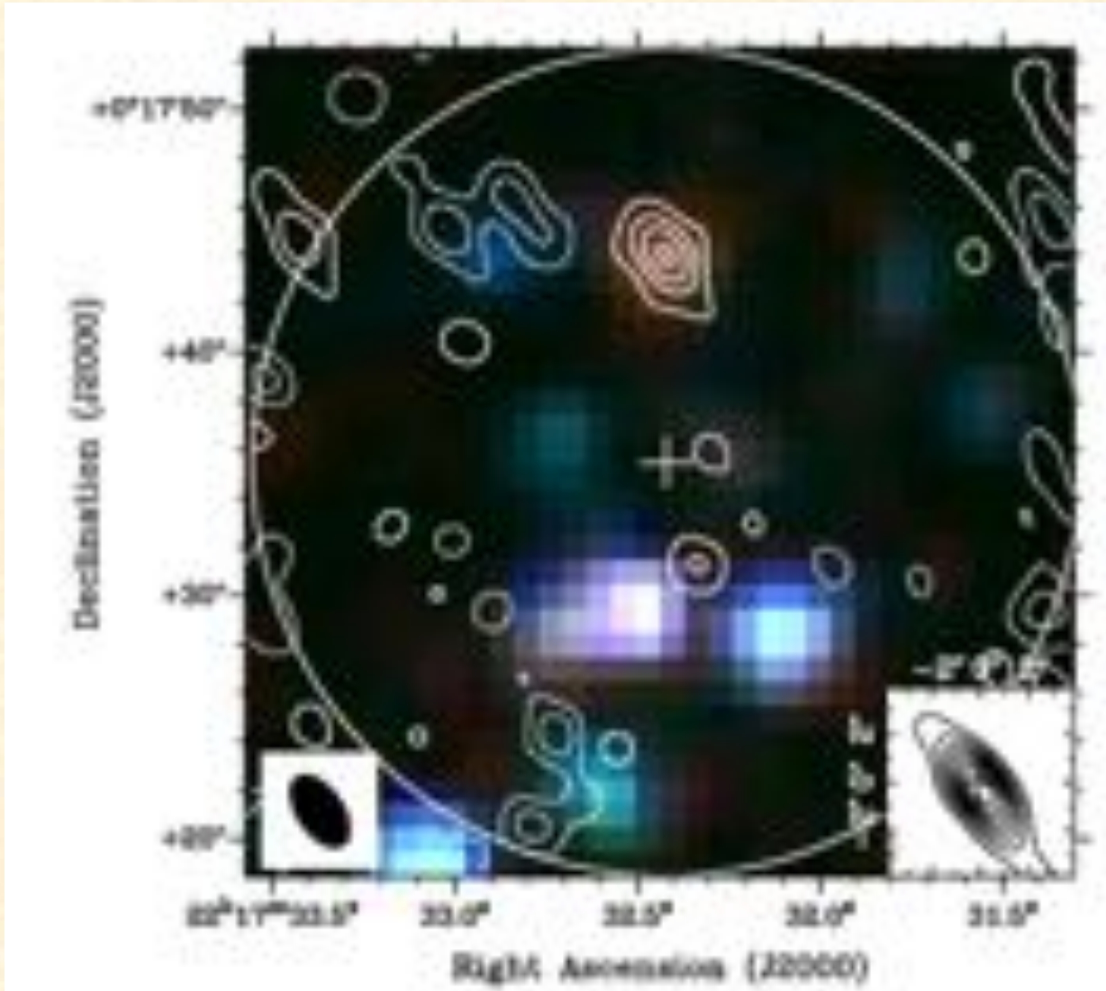




Girart, Rao & Marrone (2006)

Girart, Beltran, Zhang, Rao, Estalella (2009)

The first detection of submm galaxies with the SMA (Tamura et al. 2010)



8.4 mJ source detected at 350 GHz in a single track in excellent weather (τ ~ 0.05)
If the SMA were built to original specs, this would have taken two weeks for same S/N

Operational considerations (2007)

The SMA was originally conceived for dual frequency receiver operation

- One low frequency receiver paired with one high frequency receiver

230, 345 GHz	400, 650 GHz

Mauna Kea is a really good mm site, not so good at submillimeter wavelengths

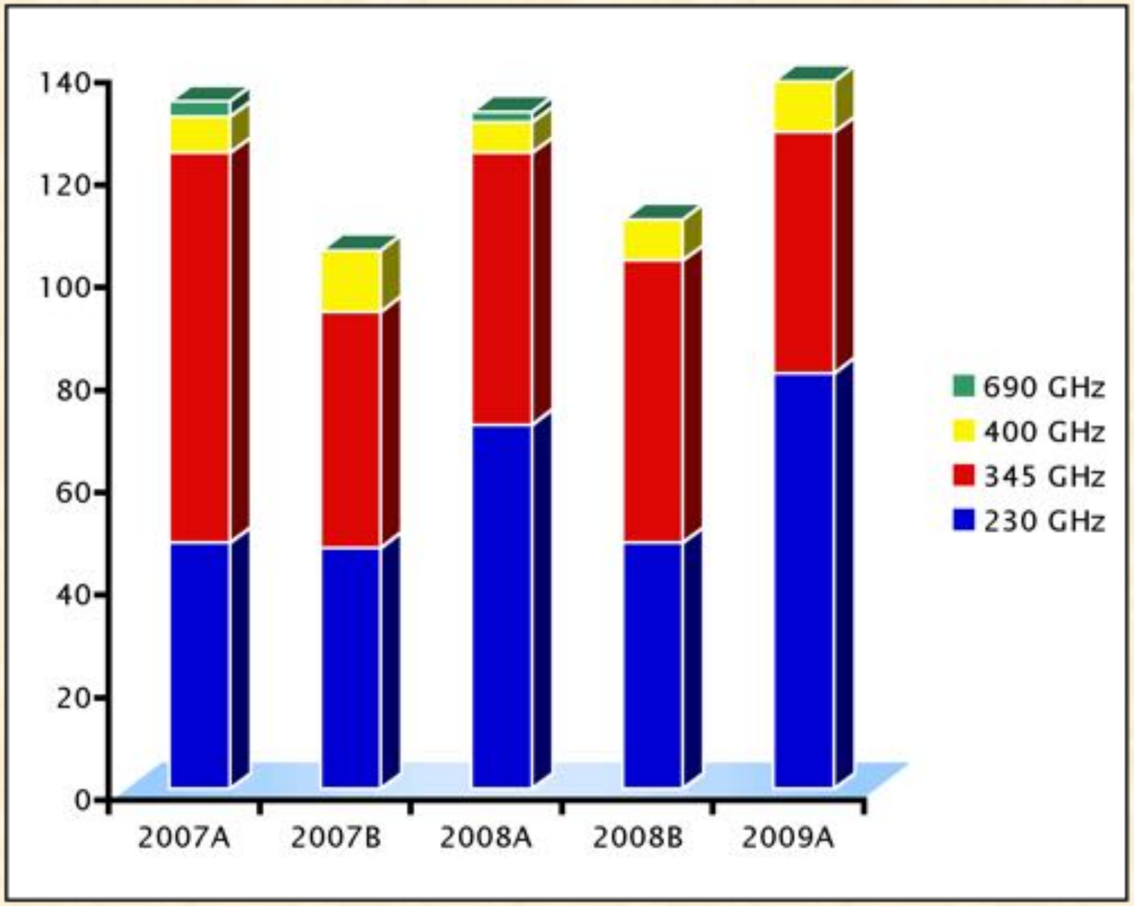
- The SMA typically spends 50% of the time at 230 GHz and 50% of the time at 345 GHz
- Very few observations have been made at higher frequencies
- We have not used the 650 GHz receivers since 2011 (have now been removed)

The SMA IF system was designed to feed two receivers into the ASIC correlator

- Half the correlator capacity remained used most of the time
- Idea – use this capacity to support wider IF-bandwidth receivers

Operational considerations
Observing statistics (2007 – 2009)

Number of successful observing tracks



Observing semester

Double the bandwidth for single receiver use

Modest changes to the SMA IF system, coupled with wide-band receivers

- Enable twice the IF bandwidth for single receiver use
- 4 – 8 GHz, compared to 4 – 6 GHz previously

Originally proposed to SMA advisory committee, December 2007

- All 8 antennas equipped with bandwidth doubler assemblies, November 2009

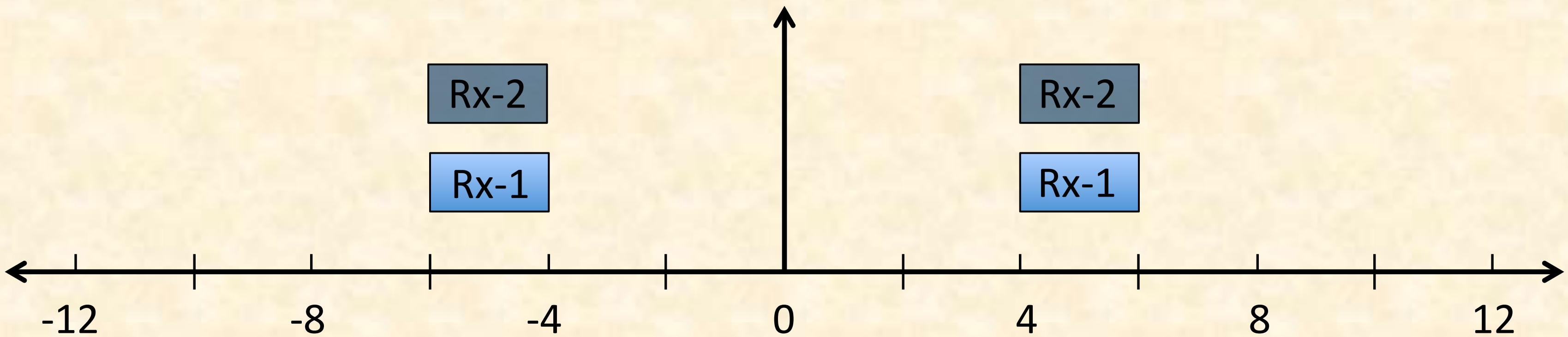
Since then most single receiver observations have been made using this mode

Even wider bandwidth IF's allowed for more flexibility in 2012

- 4 – 6 GHz IF, plus any other 2 GHz-wide IF band between 6 and 12 GHz

Benefits most SMA observations (continuum and multi-line)

The SMA IF and correlator system

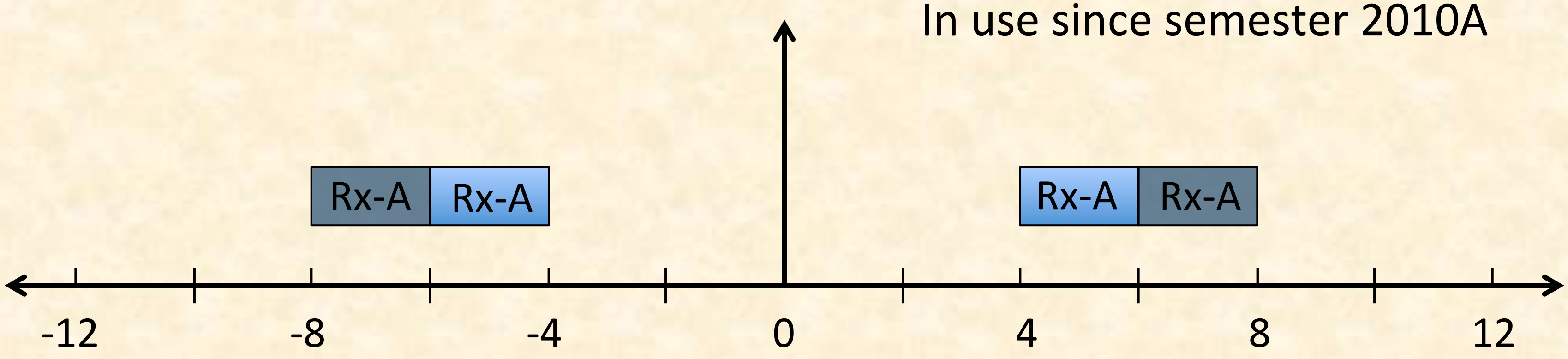


Original SMA design called for the simultaneous operation of two receivers

- One low frequency < 350 GHz and one high frequency > 350 GHz
- 2 receivers with 2 GHz-wide IF and 2 sidebands = 2x2x2 = 8 GHz total BW

Double the IF bandwidth for single receiver use

In use since semester 2010A



Original SMA design called for the simultaneous operation of two receivers

One low frequency < 350 GHz and one high frequency > 350 GHz

2 receivers with 2 GHz-wide IF and 2 sidebands = 2x2x2 = 8 GHz total BW

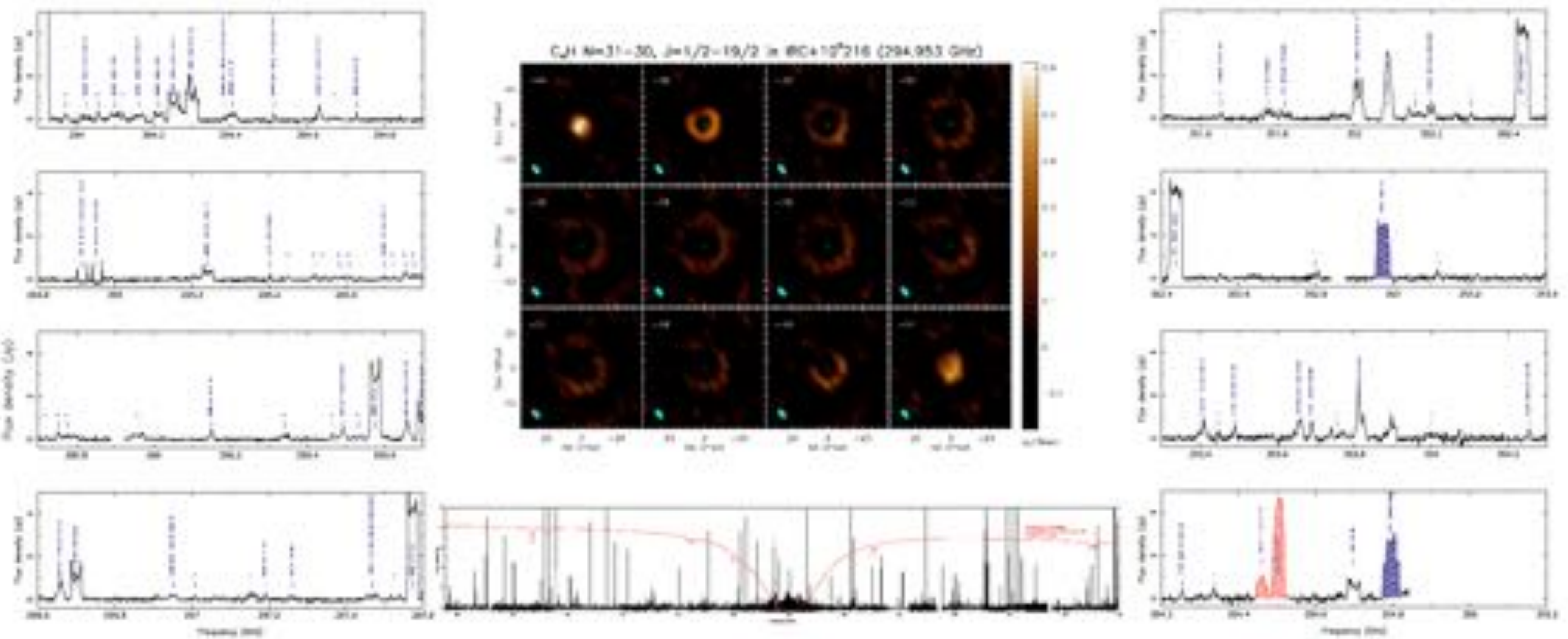
Double bandwidth mode of operation for single receiver use

Develop IF hardware to enable double bandwidth receiver operation

1 receiver with 4 GHz-wide IF and 2 sidebands = 8 GHz total BW

- Improves continuum sensitivity for all observations
- Improves spectral coverage for line observations

SMA line survey towards Irc+10216 (Patel et al. 2011)



60 GHz total bandwidth - first use of double bandwidth mode
First use of SMA subcompact configuration (2007)
Combined a total of 13 tracks from 2007 and 2009
Some in normal 4 GHz mode and some in 8 GHz double bandwidth mode

Improved sensitivity enables extragalactic science – high z galaxies

Gravitational lens models based on submillimeter array imaging of Herschel-selected strongly lensed submillimeter galaxies at z > 1.5 (Bussman et al. 2013)

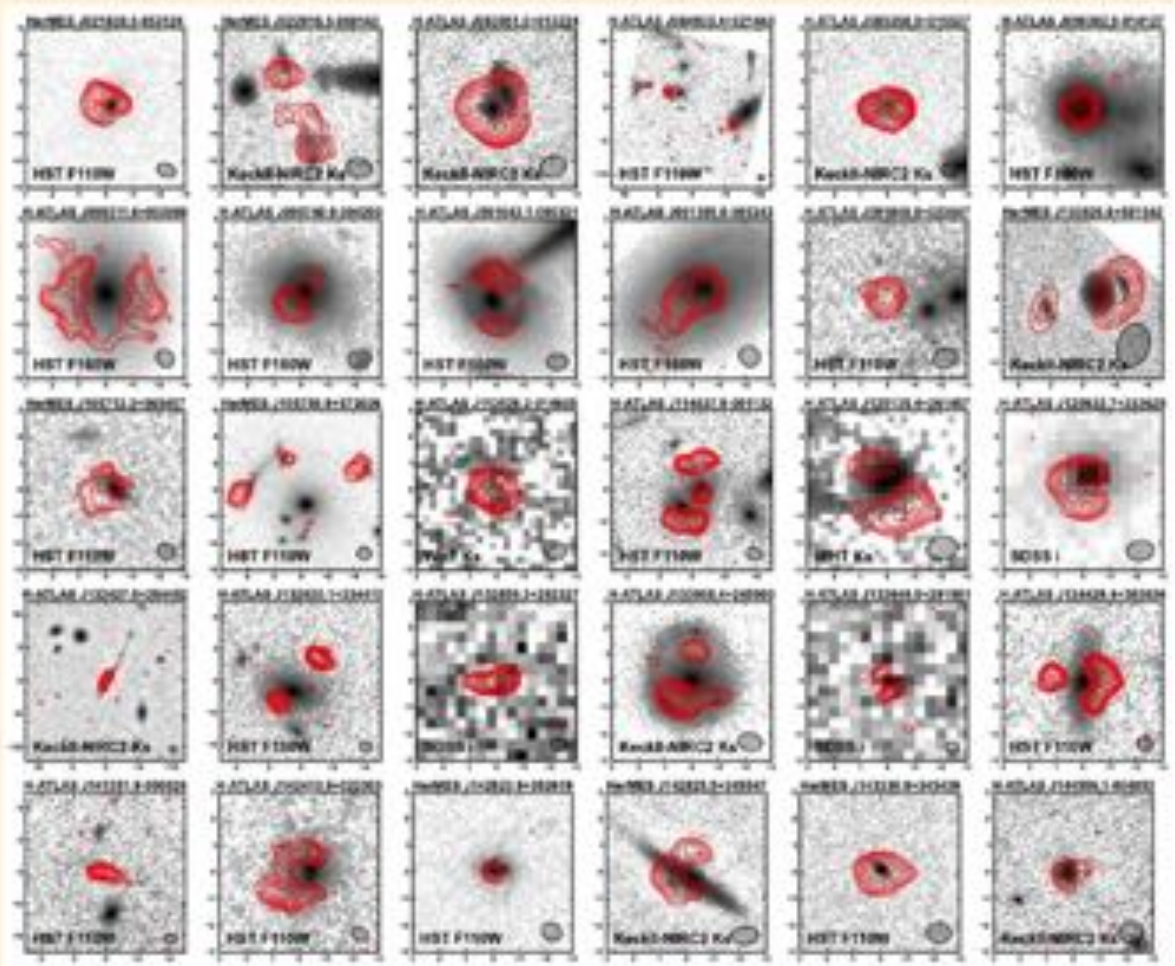


Figure 1: Postage stamp images of 30 Herschel-selected strongly lensed SMGs. Red contours show SMA observations of the 880μm thermal dust emission. Greyscale images show the best available optical or near-IR imaging. The lenses are not detected in the submm images and the sources are generally not detected in the optical or near-IR images.

Improved sensitivity enables extragalactic science – high z galaxies

Figure 1: Imaging of HLS0918 covering a 10"x10" field centered on the lensed source. (left) Map of redshifted [CII] integrated line emission observed with the SMA (color scale and dark contours). (center) 1mm observed frame continuum emission morphology (also reproduced as white contours in left and right panels) showing resolved structure indicative of lensed. (right) complementary map of redshifted CO(1-0) integrated line emission observed with the VLA. (from Fig. 1 of Rawle et al 2014)

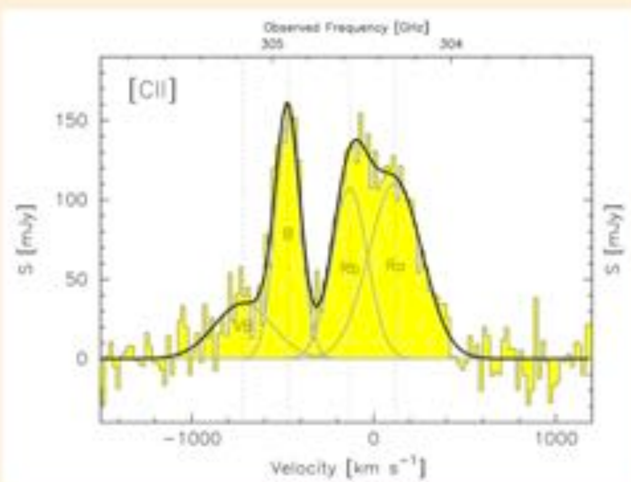
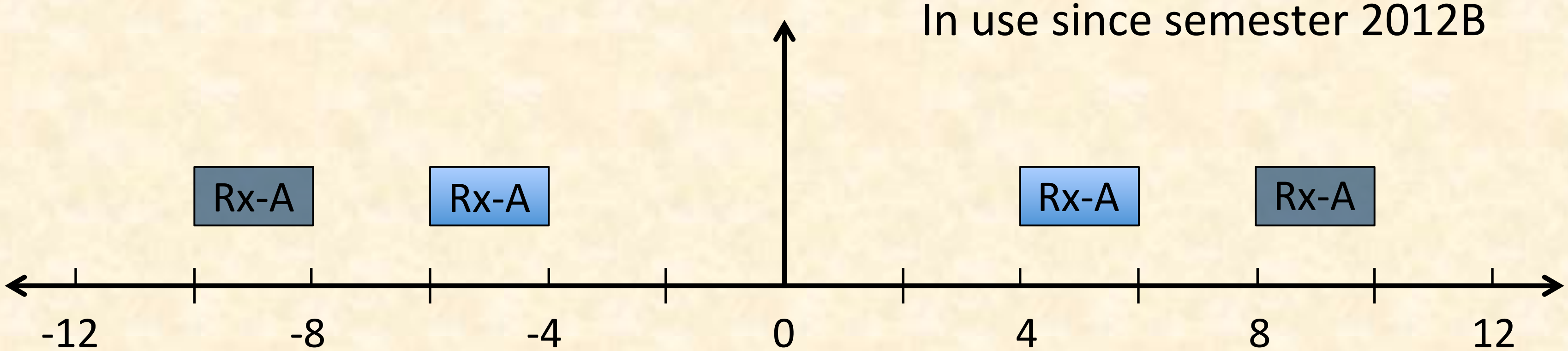


Figure 2: Continuum-subtracted and spatially integrated CII line profile

SMA observations of spatially-resolved continuum and CII emission from a strongly-lensed interacting system at z = 5.24 (Rawle et al. 2014)

Additional spectral flexibility in double bandwidth mode

In use since semester 2012B



Double bandwidth mode of operation for single receiver use

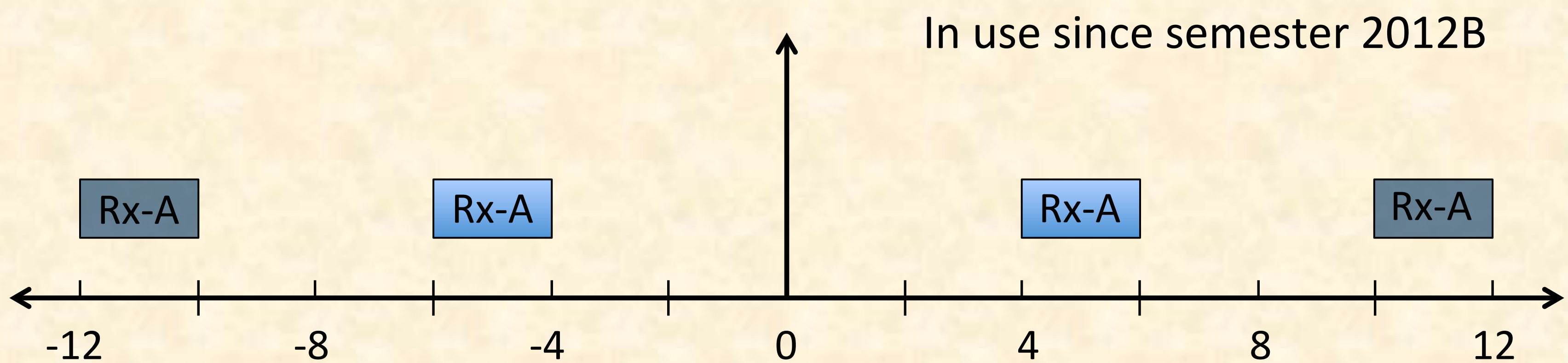
Develop IF hardware to enable double bandwidth receiver operation

1 receiver with 4 GHz-wide IF and 2 sidebands = 8 GHz total BW

- Improves continuum sensitivity for all observations
- Improves spectral coverage for line observations

Additional IF hardware enables added spectral flexibility for single receiver use

Additional spectral flexibility in double bandwidth mode



Double bandwidth mode of operation for single receiver use

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1 receiver with 4 GHz-wide IF and 2 sidebands = 8 GHz total BW

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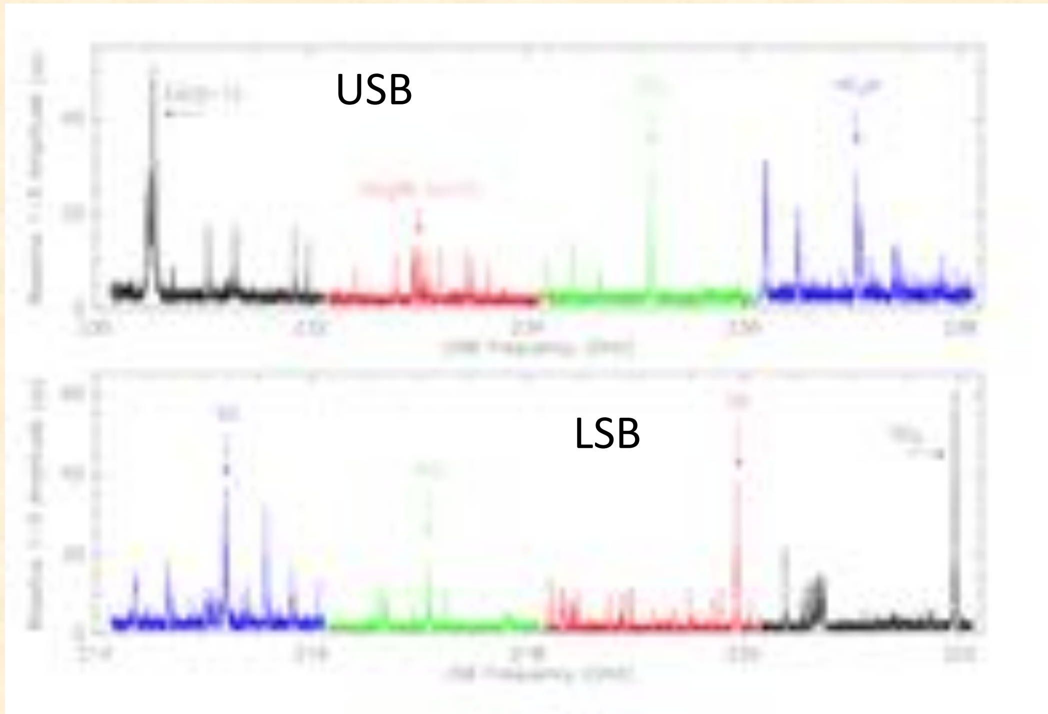
- Improves spectral coverage for line observations

Additional IF hardware enables added spectral flexibility for single receiver use

SMA Throughput – Double Bandwidth Mode

Test observations towards Orion BN/KL: LO at 226 GHz



4 – 6 GHz IF processed as usual (Black curve)
6 – 8 GHz IF added using standard bandwidth doubled mode (Red curves)
Additional IF hardware enables 8 – 10 and 10 – 12 GHz IF to be processed

SMA Future Committee (May 2010)
The future of the SMA in the ALMA era

The SMA Future committee considered two options in detail:

1. Move the SMA to a high altitude site to enable high frequency observations
2. Remain on Mauna Kea and perform significant upgrades

Option 2. was recommended:

1. Develop the most sensitive dual polarization receivers in all frequency bands
   - Concentrate initially on 345 GHz band
2. Increase receiver bandwidth as technology develops
3. Initiate a program to develop multi-beam receivers
4. Add 2 more antennas
5. Establish collaborations with CARMA/ALMA/IRAM

SMA Advisory Committee – November 2010

Endorsed many of the recommendations made by the Future Committee:

Medium scale improvements:

1. Develop the most sensitive dual polarization receivers in all frequency bands
   - Concentrate initially on 345 GHz band
2. Increase receiver bandwidth as technology develops

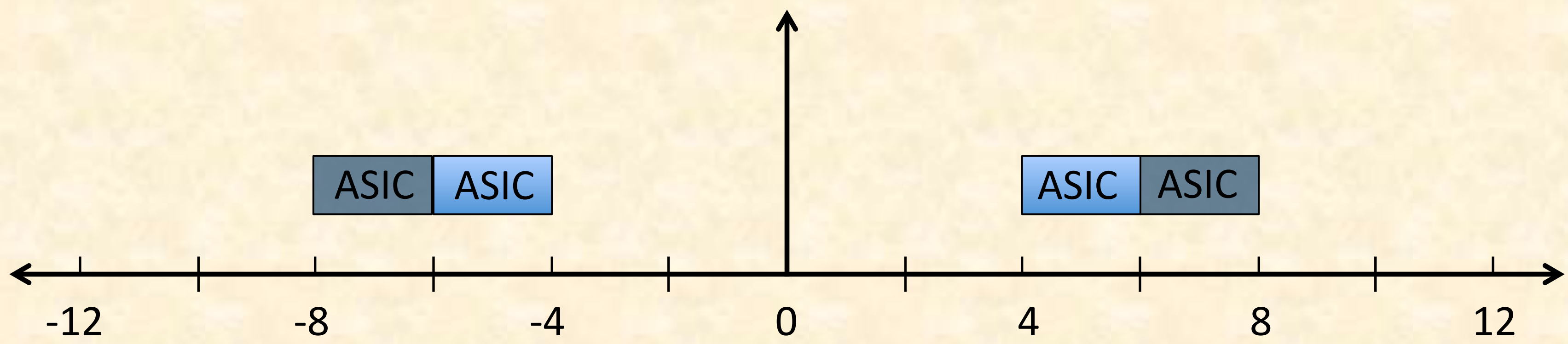
And added

3. Develop processing capacity for up to 18 GHz IF bandwidth per receiver

Evaluate directions / major improvements on 3 – 5 year timescale

1. Focal plane arrays

Develop additional correlator capacity



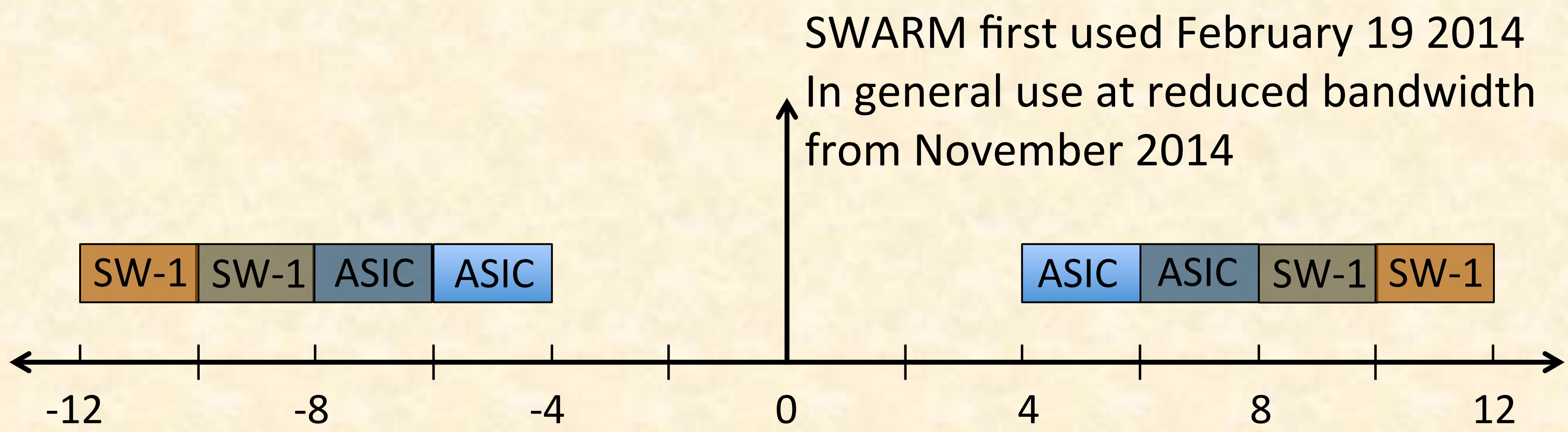
Initially the SMA ASIC correlator was used to cover the 4-6, and later, 4-8 GHz IF

Further augment the frequency coverage using new, modular correlator

Take advantage of CASPER collaboration using ROACH 2 technology

- Develop SWARM correlator (SMA Wideband Astronomical Roach 2 Machine)

Develop additional correlator capacity



Initially the SMA ASIC correlator was used to cover the 4-6, and later, 4-8 GHz IF

Further augment the frequency coverage using new, modular correlator

Take advantage of CASPER collaboration using ROACH 2 technology

- Develop SWARM correlator (SMA Wideband Astronomical Roach 2 Machine)
    - First add two 2 GHz-wide chunks to further double the processed bandwidth
    - Modular approach allows more sections to be added later
    - The addition of SWARM should enable the ageing ASIC correlator to be retired

SMA Advisory Committee – June 2014

The committee discussed the choice of the SMA receiver bands:

- Wise, if disappointing to drop the 650 GHz band
- Endorsed development of dual polarization 210 – 270 GHz receiver

Recommended building on in-house DSP developments:

- Complete new SWARM correlator as a top priority
- Bandwidth expansion beyond current SWARM would be natural

Consider adding a ninth antenna (in order to have 8 permanently in use)

- October 2014 – October 2015 average 6.5 antennas / track
- October 2015 – October 2016 average 7.1 antennas / track

Strategic planning:

- Develop a strategic plan with 5 – 10 year horizon in the next 5 years

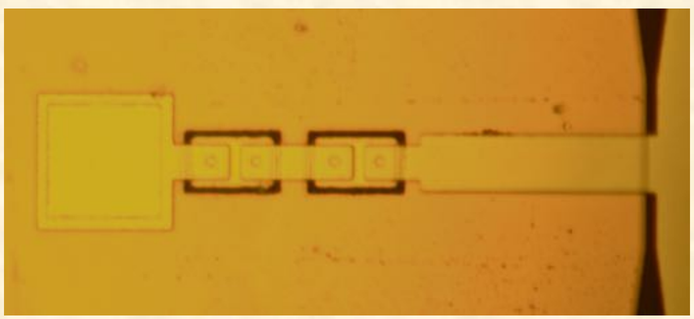
Upgrades to receivers / additional capabilities

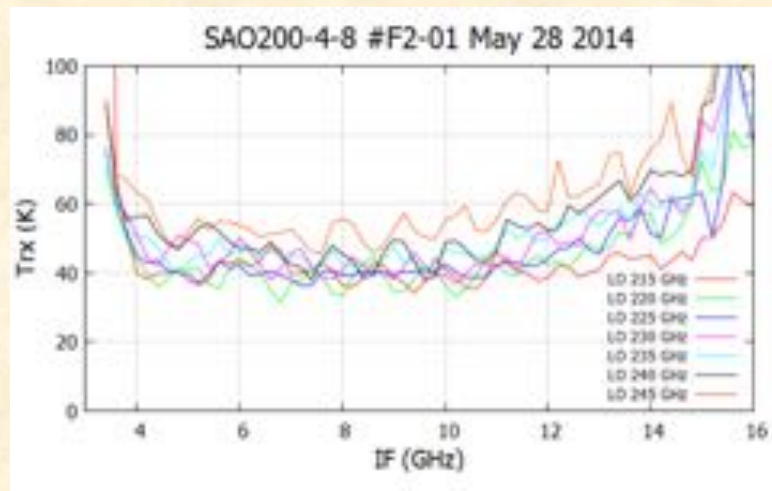
Edward Tong has led the effort to upgrade and add new receiver capabilities

The SMA is now equipped with four sets of wideband, low noise receivers:

230 GHz; 240 GHz; 345 GHz; and 400 GHz bands

With dual polarization capability in both bands, at 230 and 345 GHz

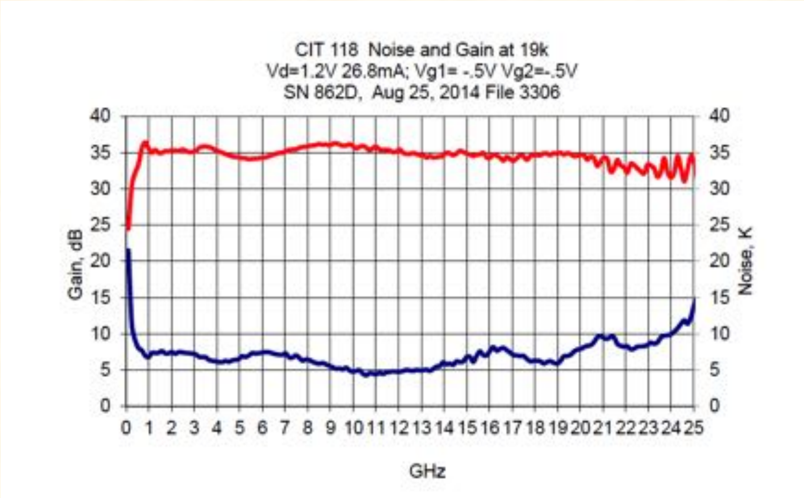


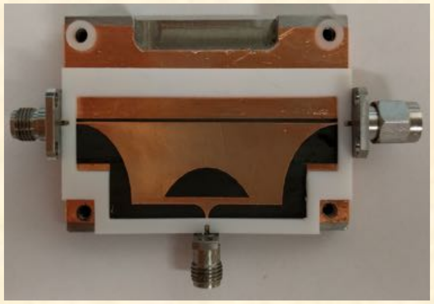


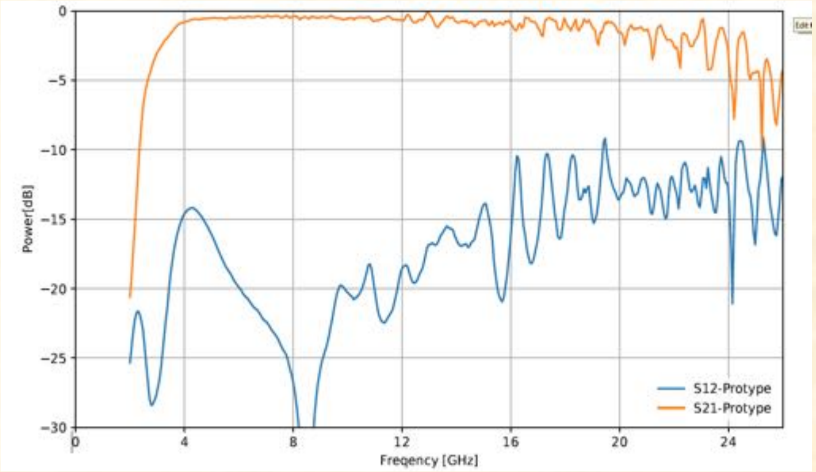
The 4-junction SIS mixer (fabricated by Min Je Wang) coupled with new IF amplifier shows good performance at frequencies up to 15 GHz

Advances in technology will enable even wider-band receivers

Low-noise amplifier (Weinreb)



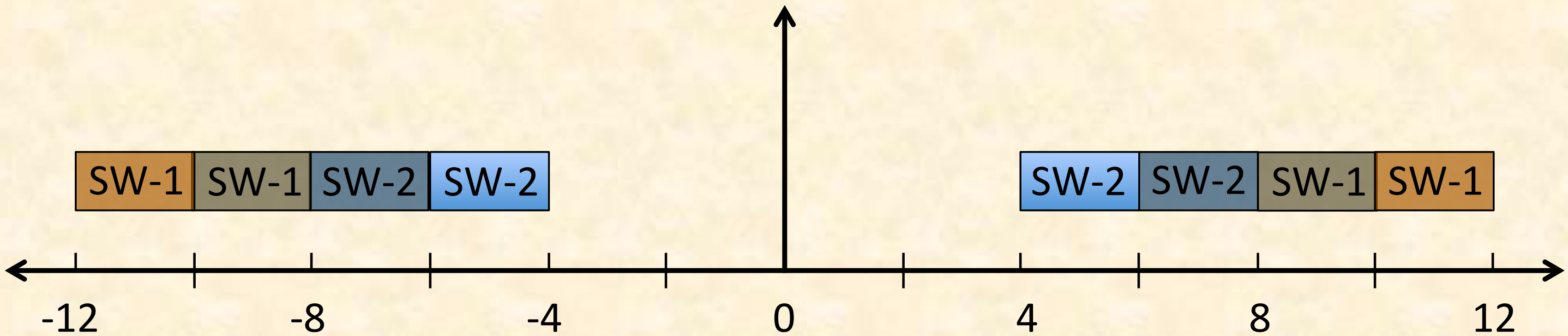




Broad-band isolator SAO (Zheng)

Develop additional correlator capacity

July 21th 2016

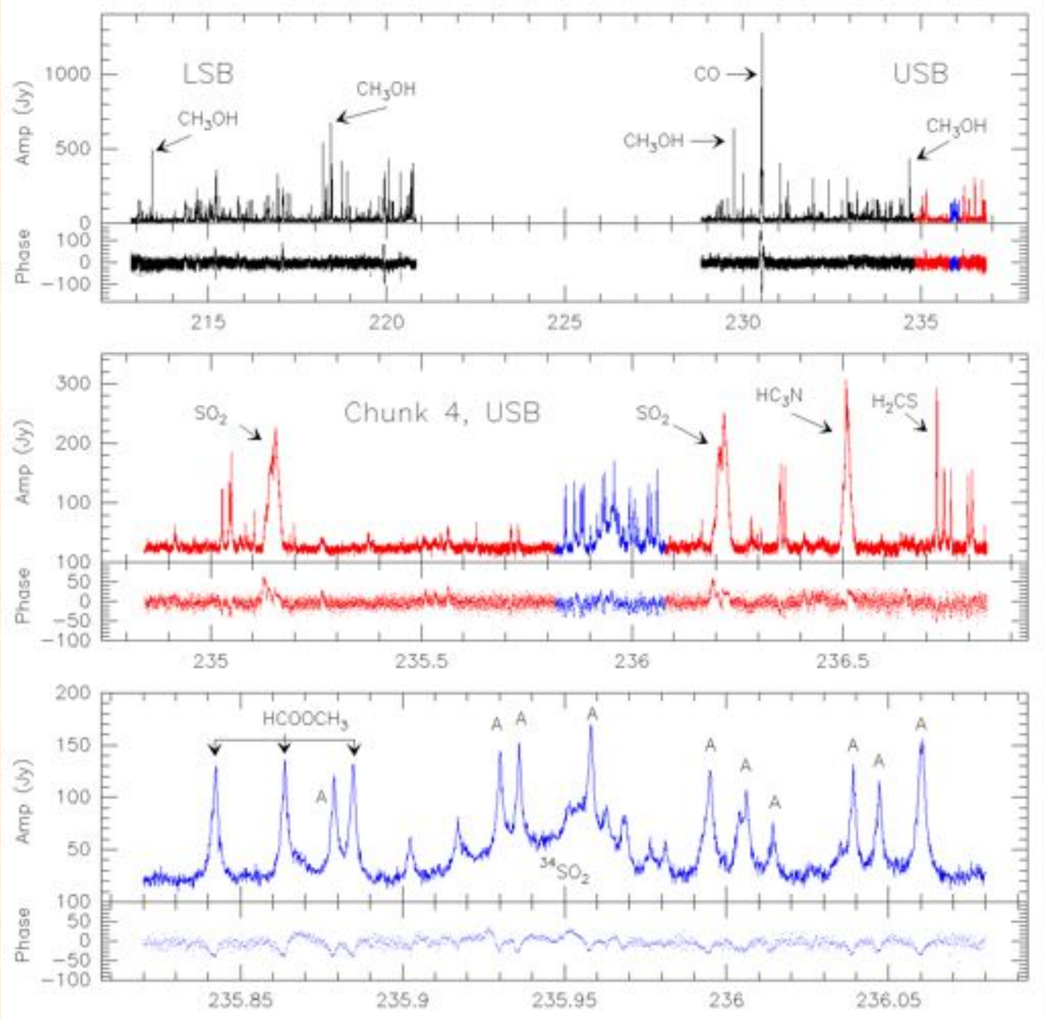


Two quadrants of SWARM first used at full speed (full BW) on 21 July 2016

- This gives 16 GHz instantaneous on-sky bandwidth
  - Can be used in single receiver mode (16 GHz BW)
  - Or dual frequency (8 GHz BW x 2 receivers)
  - Or dual polarization (8 GHz BW x 2 receivers)

Sample Output from SWARM Correlator – 2 quadrants

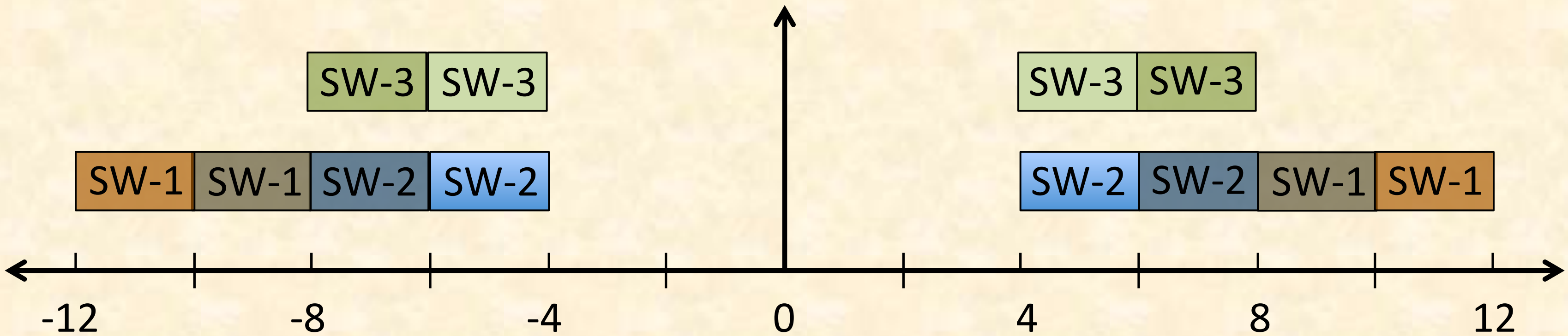
First used at full speed, full BW July 2016



140 kHz uniform resolution (A = $^{13}CH_3OH$)

Further develop additional correlator capacity

October 6th 2016



The third quadrant of SWARM was installed at the SMA in September

It has been operation since October 6th 2016, with 24 GHz BW available:

- 16 GHz across any single receiver with 8 GHz across a second receiver
  - in the same band for dual polarization or increased frequency coverage
  - or in a different band for dual band observations

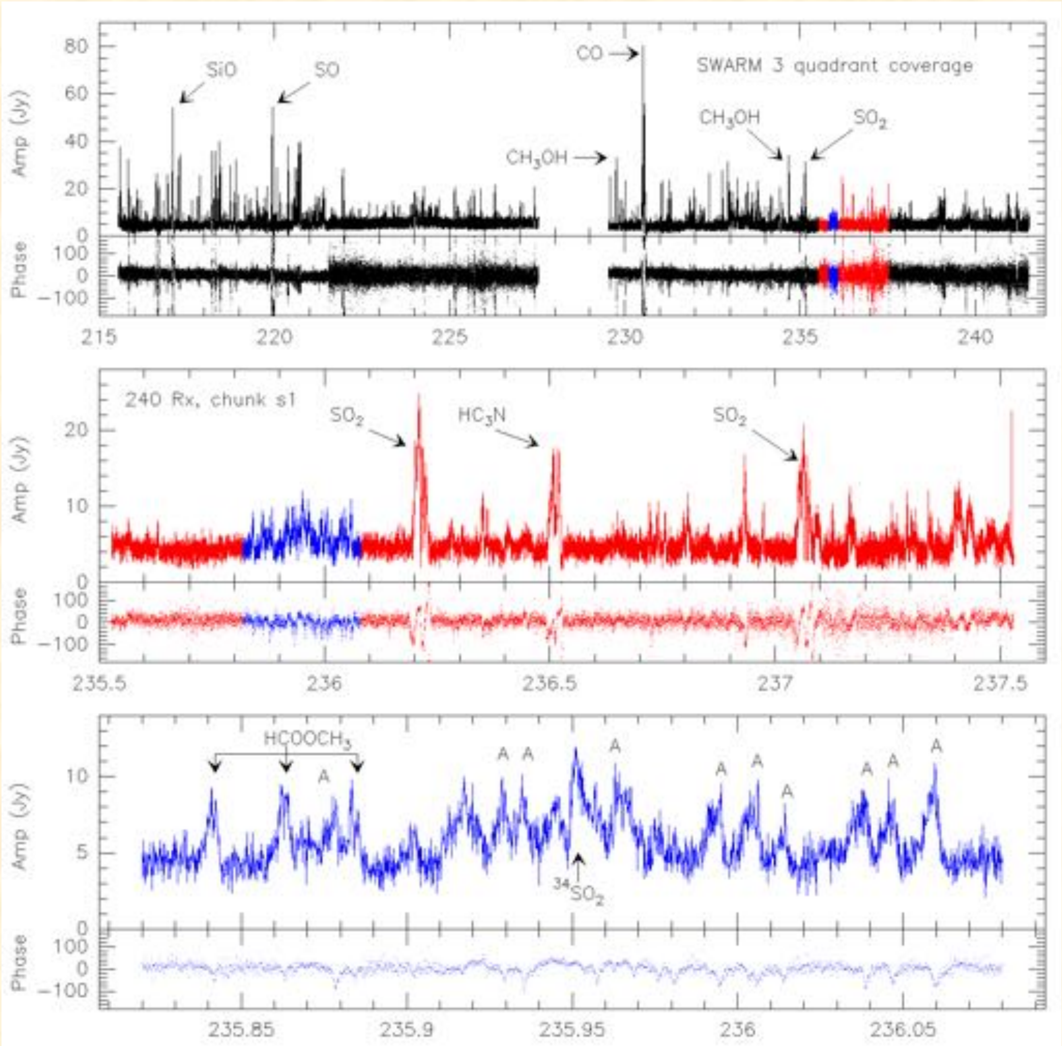
Sample Output from SWARM Correlator – 3 quadrants

First used October 2016

24 GHz BW

2 GHz BW

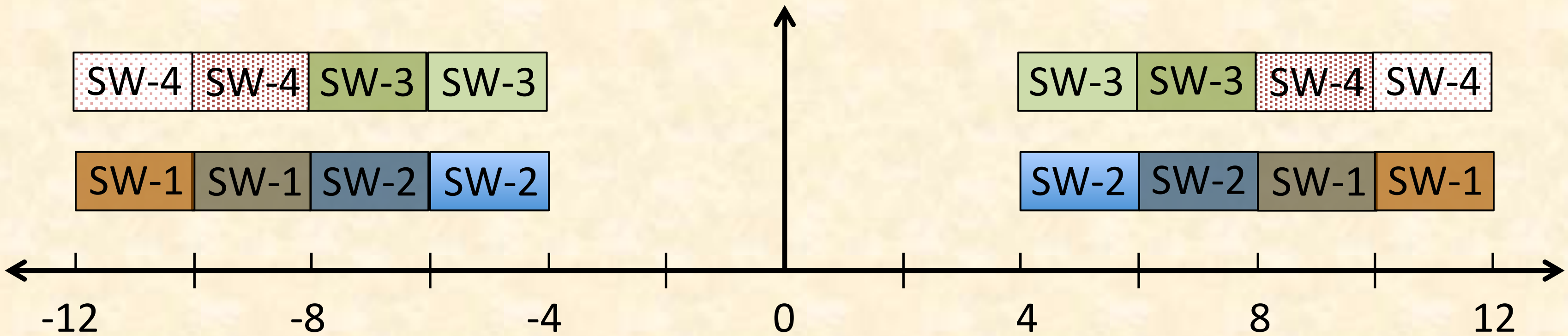
260 MHz BW



One hour integration in extended towards Orion BN/KL

Further develop additional correlator capacity

Installation expected December 2016



The fourth quadrant of SWARM will be installed at the SMA in December

Installation of required downconverter IF hardware planned for December

- 32 GHz total BW - 16 GHz across each of any two receivers
  - in the same band for dual polarization or increased frequency coverage
  - or in a different band for dual band observations
- To date most observations have been made with 8 GHz BW or less
- Expect huge increase in data quality and throughput in the New Year

SMA Governing Board Meeting December 2015

Discussed possible upgrade paths to the SMA in the ALMA era

Specifically - How do we further improve the sensitivity of the SMA ?

- Lower noise receivers
- Increased receiver bandwidth and correlator capacity
- 2SB receivers
- Multi-beam receivers
- More antennas
- Increase antenna diameter

Strategic planning

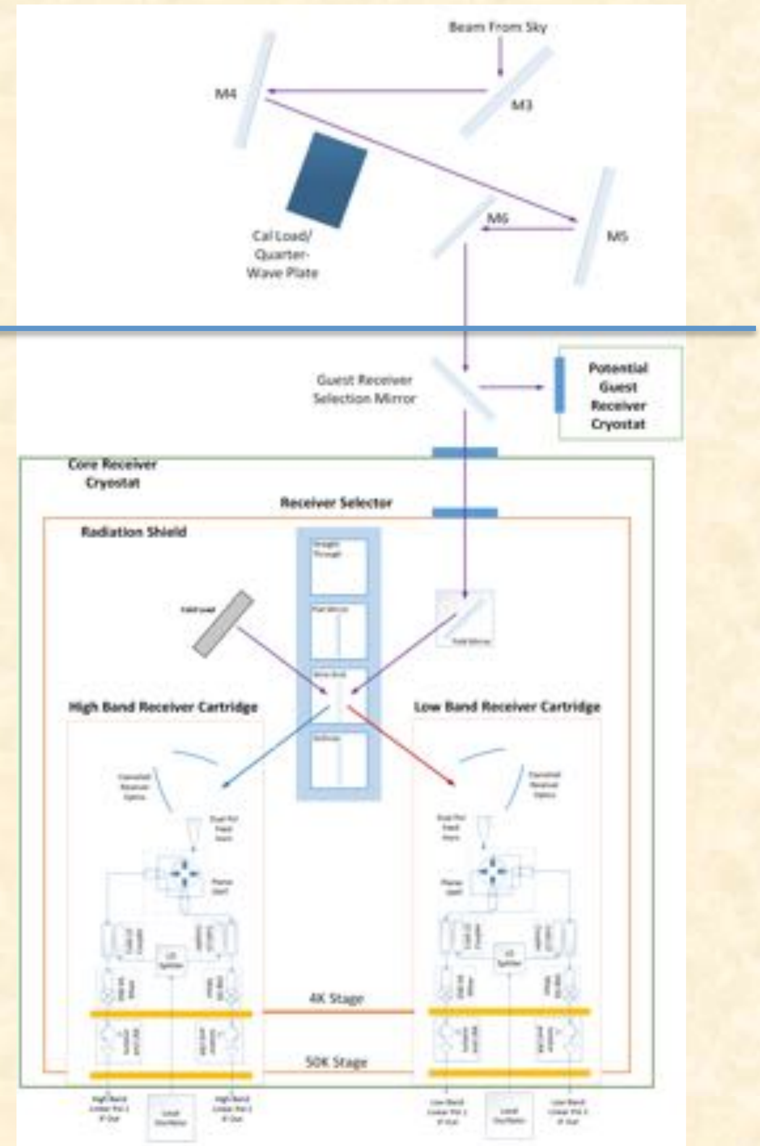
- Further develop a strategic upgrade plan
- Host scientific workshop (October 2016)
- Present strategic upgrade plans to SMA Governing Board (December 2016)

SMA next generation receiver system overview

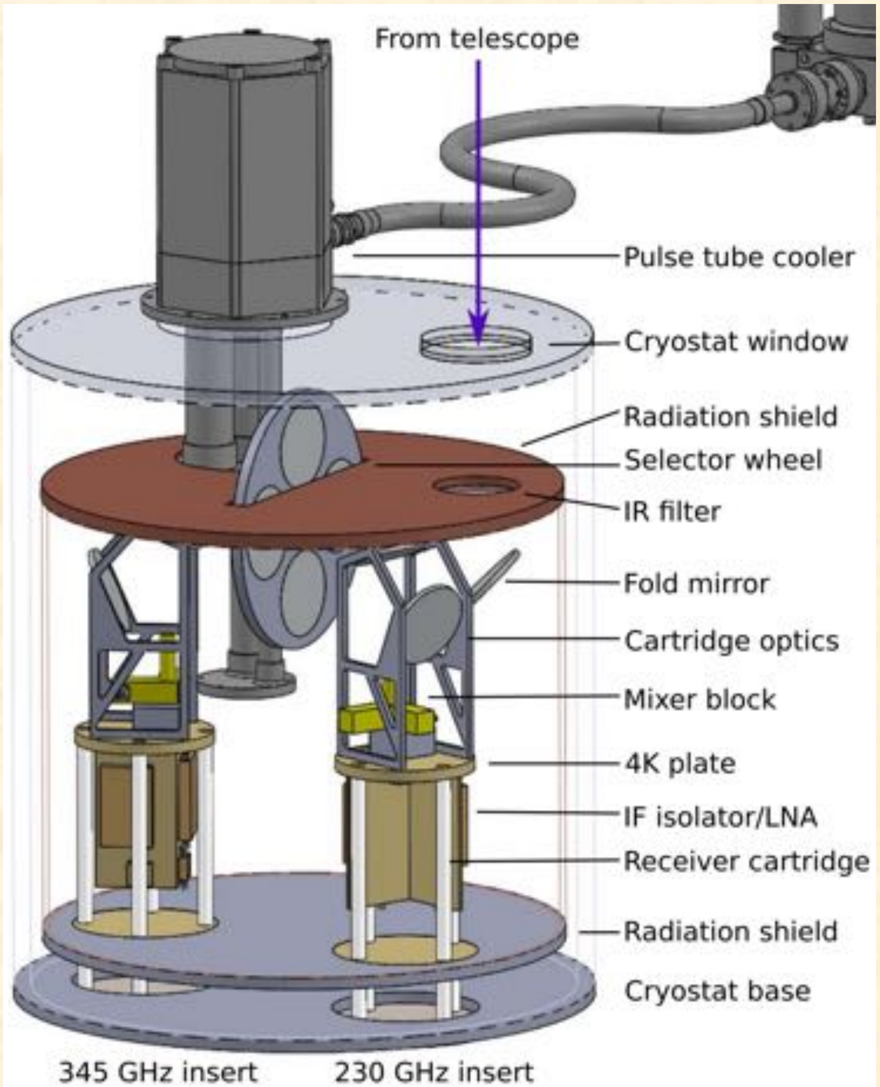
- Low Maintenance Pulse-tube Cryocooler (Lose 10 nights /year due to cryo failures)
- Dual Band Receiver System
  1. Low Band (LO 210 – 270 GHz)
  2. High Band (LO 280 – 360 GHz)
- Even Wider IF Bandwidth: initially 4 – 18 GHz (possibly 4 – 20 GHz or even more)
- Dual Polarization Operation with Waveguide Orthomode Transducer attached directly to SIS Mixer for improved sensitivity and enhanced polarimetry.
- Simultaneous Dual-Band Observation mode through the use of either a cooled wire grid polarizer, dichroic plate or Time Domain Band Switching.
- YIG or VCO-based Local Oscillator to simplify tuning. Module based on commercially available components to lower cost.
- Cold Waveguide LO injection to improve receiver noise performance.
- Double-side-band mixer for lower cost and continuation of technology
- Better logistics for polarimetry using a single Wideband Quarter Wave Plate (210 – 360 GHz)
- Possibility of a Guest/PI Instrumentation.

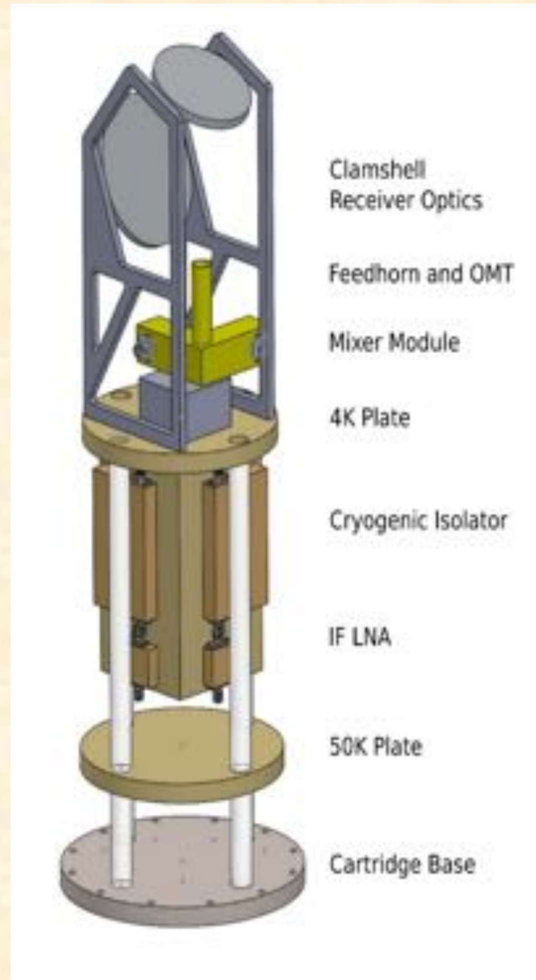
Schematic of the proposed receiver system

- Preserve the M4 -M5 - M6 optics plate located towards the top of the receiver cabin.
- No optics cage between the cryostat and 4-5-6 optics plate.
- Single vacuum window on cryostat.
- Local Oscillator is injected using waveguide couplers in the cold.
- LO modules to attach directly to cryostat.
- 4 IF output ports from cryostat
- Location provided for guest instrument.



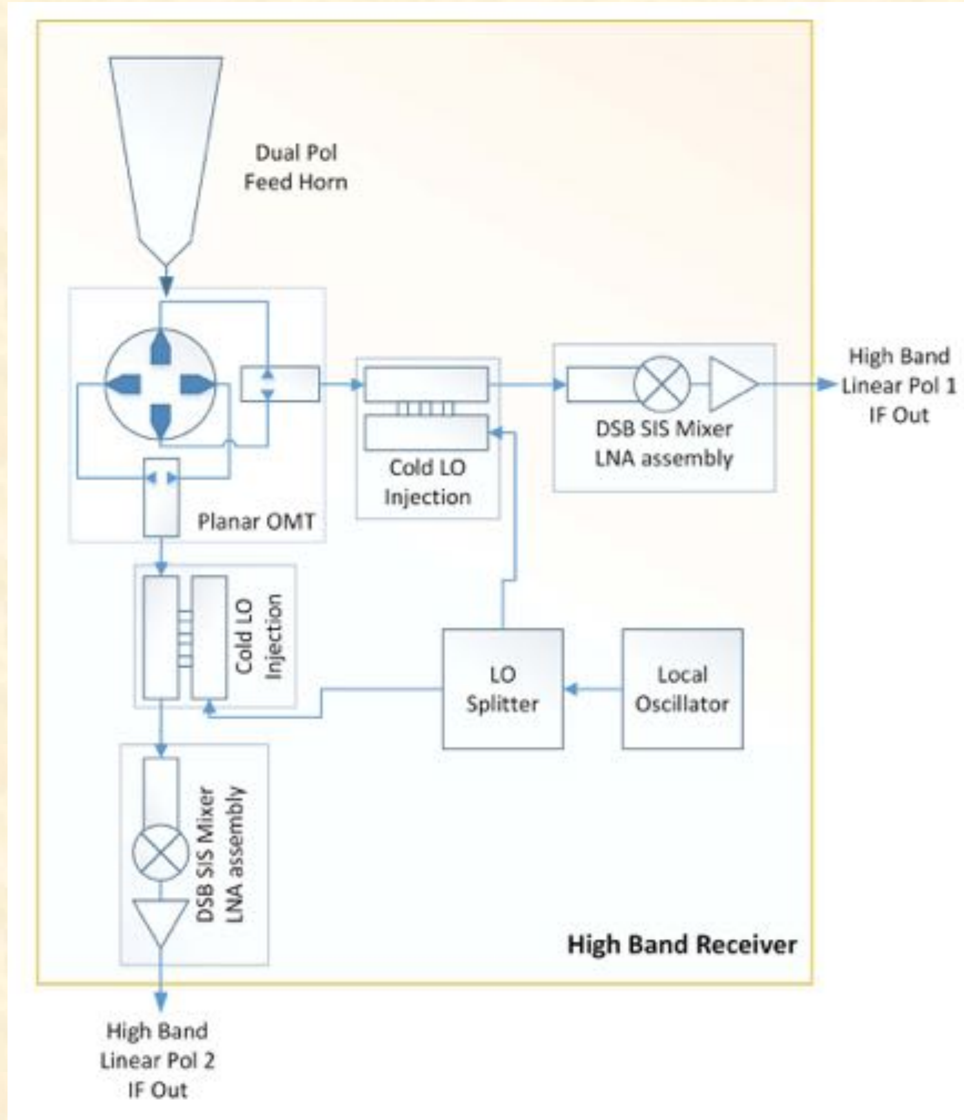
Cryostat / receiver system detail





Many receiver components already in development

- Smooth wall Feed Horn (LZ)
- Planar OMT (PG)
- Coupler (PG/LZ)
- LO Splitter (PG)
- Wideband SIS Mixers (ET/MJW)
- Wideband Isolator (LZ)
- Low Noise Amp (ET)
- YIG-based LO (ET)



Analog subsystem and correlator

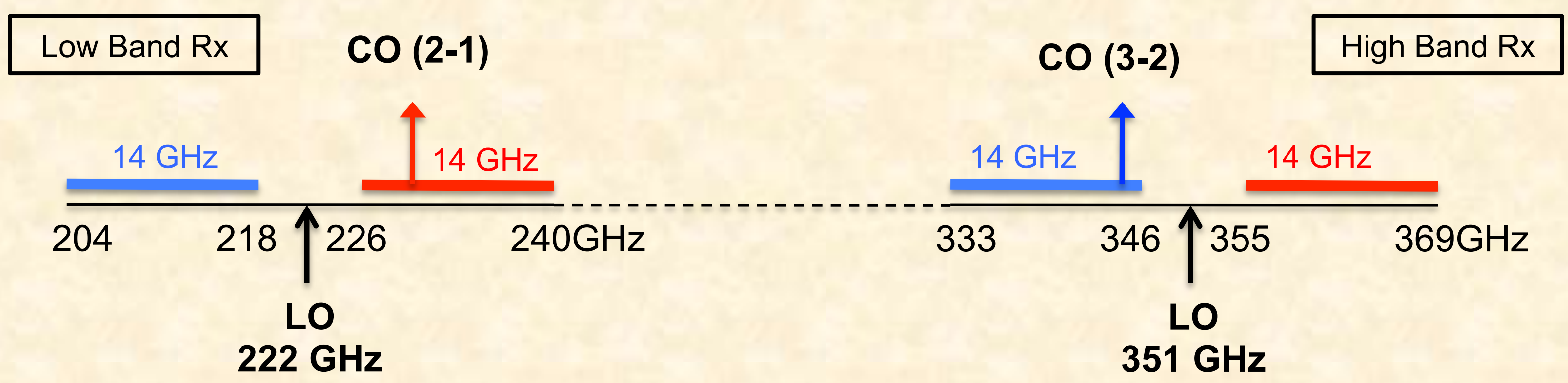
- Require new fiber transceivers with WDM
- New generation, low cost analog down-converter
- If we simply add more SWARM hardware, would need 7 (or 9) x 2 GHz-wide blocks x 2 for DSB for 56 (or 72) GHz total BW
- The current (intermediate) upgrade will use just 4 blocks (for a total of 32 GHz BW
- Digital systems advancing rapidly (both clock rate and data handling capacity) – can wait a couple of years before we need to decide whether to add more SWARM's or use higher speed, wider bandwidth digital hardware

Scientific capabilities of proposed receiver upgrade

- Dual linear polarization observation with IF bandwidth of 14 GHz DSB
  - Target continuum sensitivity (Baseline, 28 GHz processed BW per receiver)
    - 0.3 mJy @ 345 GHz (full track, 1.5 mm pwv)
    - 0.15 mJy @ 230 GHz (full track, 3 mm pwv)

- Enhanced Polarimetry using single feedhorn for each mixer pair in conjunction with wideband Quarter Wave Plate.

- Dual Band mode to yield a total on-sky frequency coverage of at least 56 GHz.



Possible observing modes

- Dual Pol Low Band (LO 210 – 270 GHz), IF BW 2 x 14 GHz DSB = 2 x 2 x 14 GHz
- Dual frequency Low Band (50 GHz or more continuous frequency coverage)

- Dual Pol High Band (LO 280 – 360 GHz), IF BW 2 x 14 GHz DSB – 2 x 2 x 14 GHz
- Dual frequency Low Band (50 GHz or more continuous frequency coverage)

- Dual Band observation is most easily accommodated by the use of a cooled wire grid (polarization combiner) with one 230 GHz and one 345 GHz receiver active

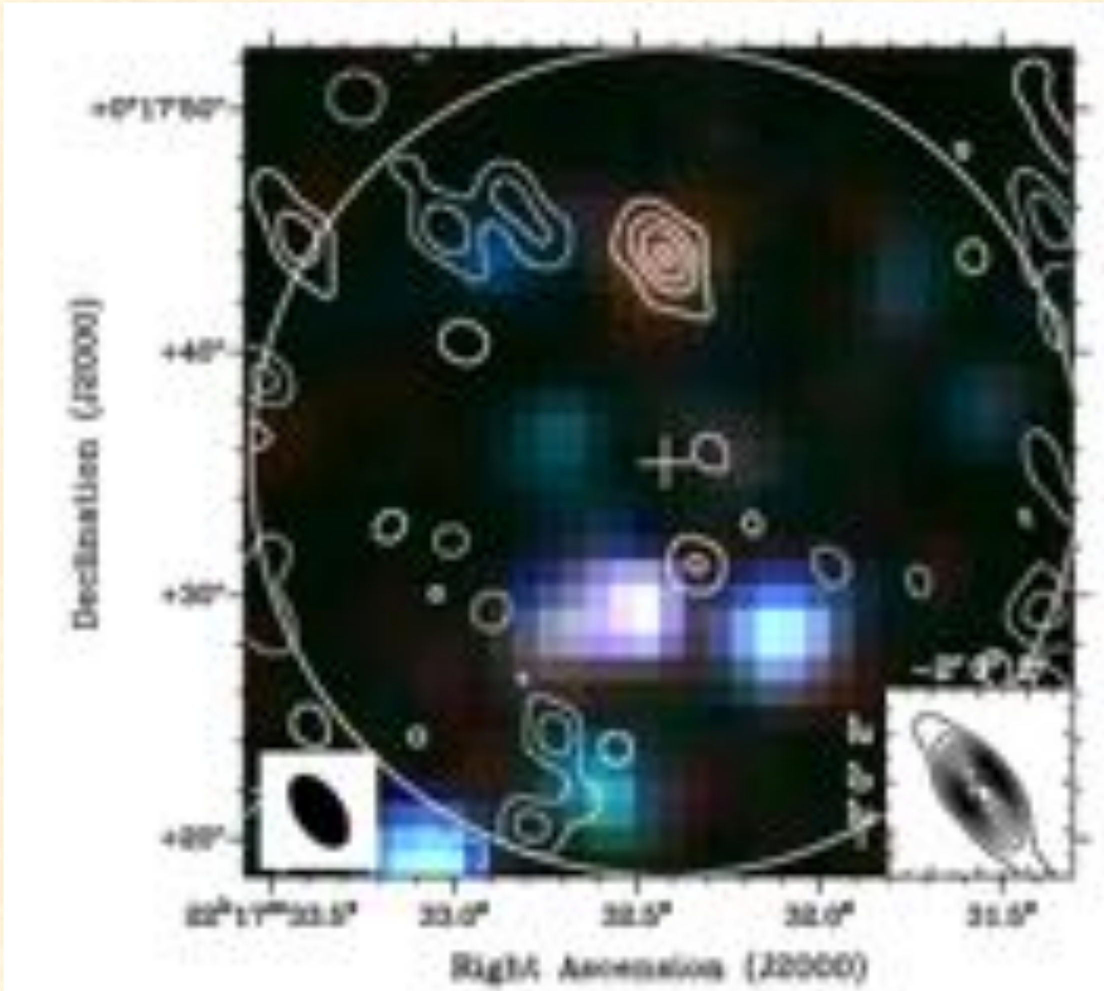
- Dual band observation could also be achieved with all receivers active. This offers the possibility of dual band polarimetry, although some loss of signal is expected due to loss in the Dichroic Plate – will also need 2x correlator capacity.

- Time Domain Switching: Switching between low and high band receivers over minutes time scale. For example 70% 345 GHz + 30% 230 GHz, to achieve similar sensitivity under good weather.

The broader impact of the proposed upgrades

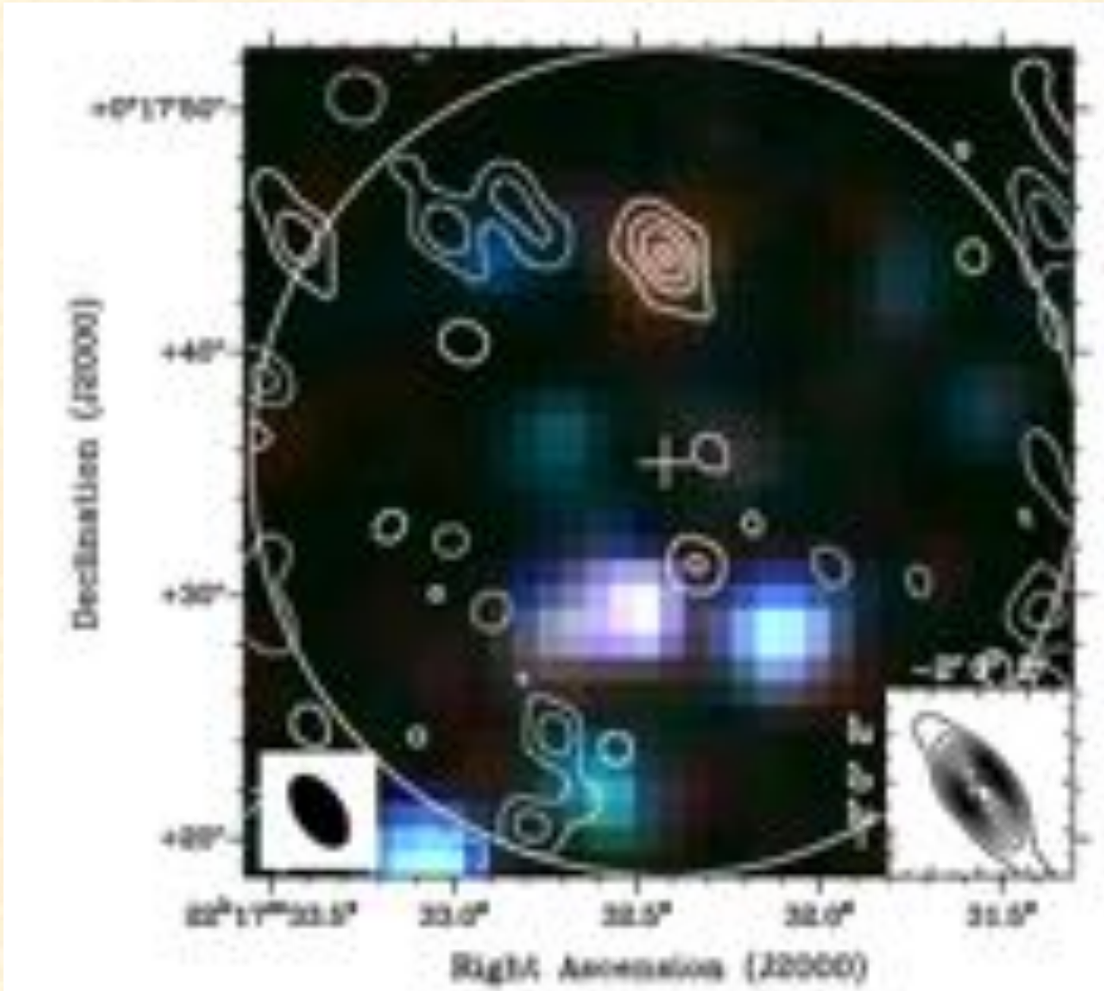
- Modern cryogenics improve receiver stability and reliability
- Continuum sensitivity significantly enhanced – more calibrators
- Wide instantaneous bandwidth relaxes tuning requirements
- Scientifically
  - More spectral coverage in a single tuning
  - Better sensitivity for all observations (especially continuum)
  - Improved polarimetry
  - Better enables large science programs

The first detection of submm galaxies with the SMA (Tamura et al. 2010)



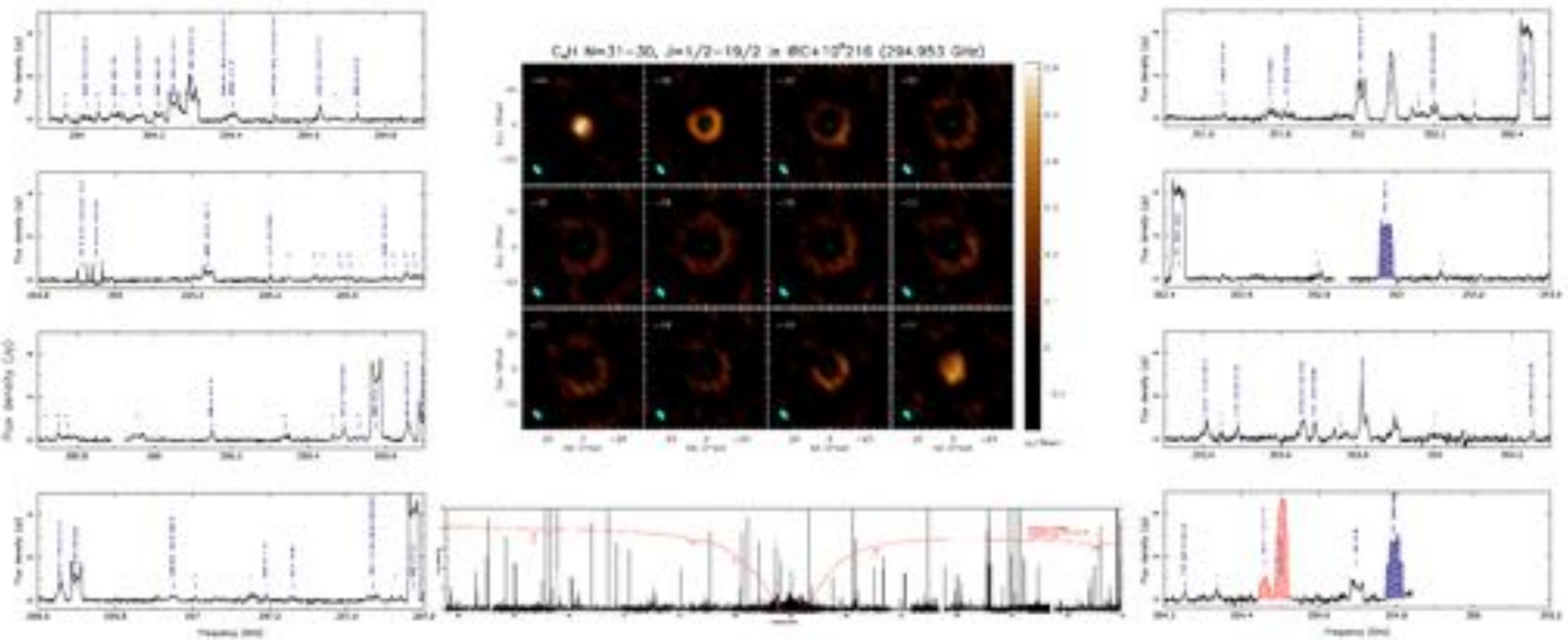
8.4 mJ source detected at 350 GHz in a single track in excellent weather (τ ~ 0.05)

The first detection of submm galaxies with the SMA (Tamura et al. 2010)



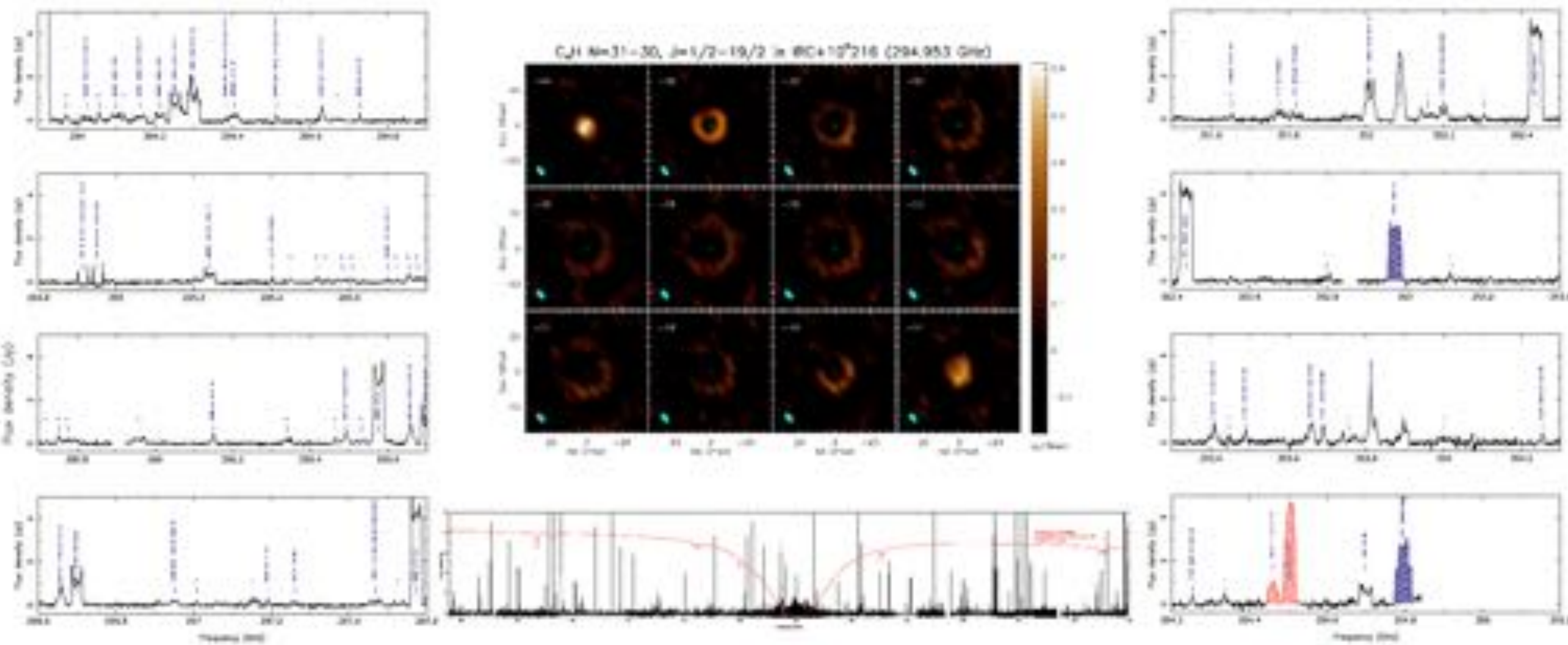
8.4 mJ source detected at 350 GHz in a single track in excellent weather (τ ~ 0.05)
Improved continuum sensitivity will enable detection of > 20 similar sources in a single track

SMA line survey towards lrc+10216 (Patel et al. 2011)



60 GHz total bandwidth - first use of double bandwidth mode
Combined a total of 13 tracks from 2007 and 2009

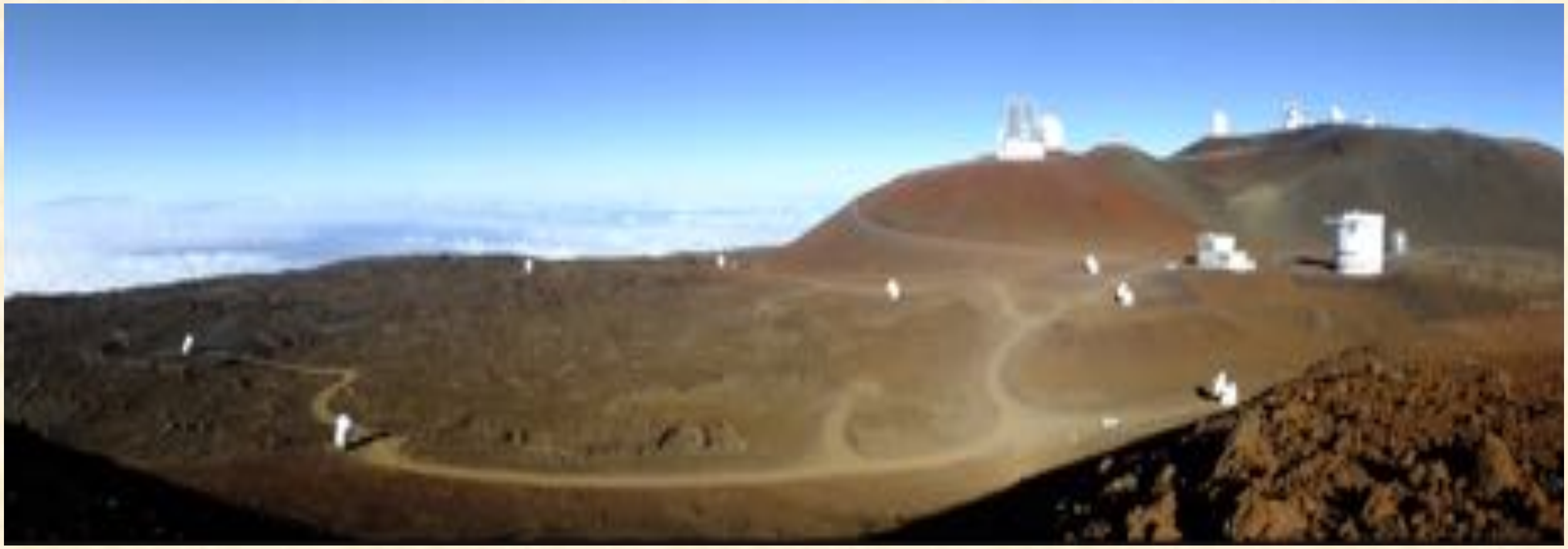
SMA line survey towards Irc+10216 (Patel et al. 2011)



60 GHz total bandwidth - first use of double bandwidth mode
Combined a total of 13 tracks from 2007 and 2009

The proposed increase in instantaneous bandwidth could produce
a similar line survey in a single observation

Upgrade also enables more science in very extended configuration

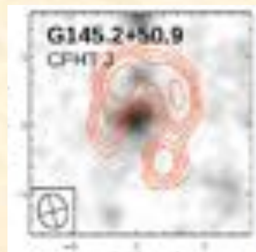


- Gain calibration will significantly improve (better data quality)
- Targets that had been at the cusp of “possible” imaging before will now be feasible
- Brighter, compact targets could now be done in larger surveys (faster/more)

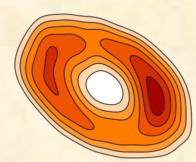
Very extended configuration increases in value

Improve access to crucial spatial scales only accessible at sub-arcsecond resolution

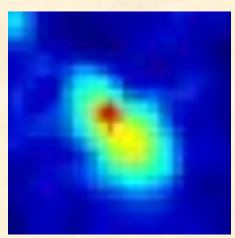
Lensed high-redshift galaxies



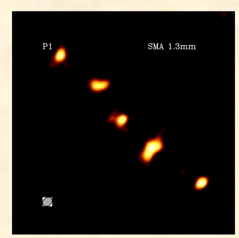
Planetary system sizes in nearby disks



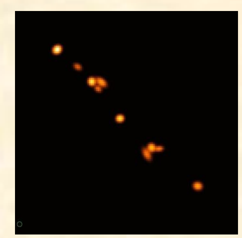
Fragmentation in IRDC's



IRAM 30m



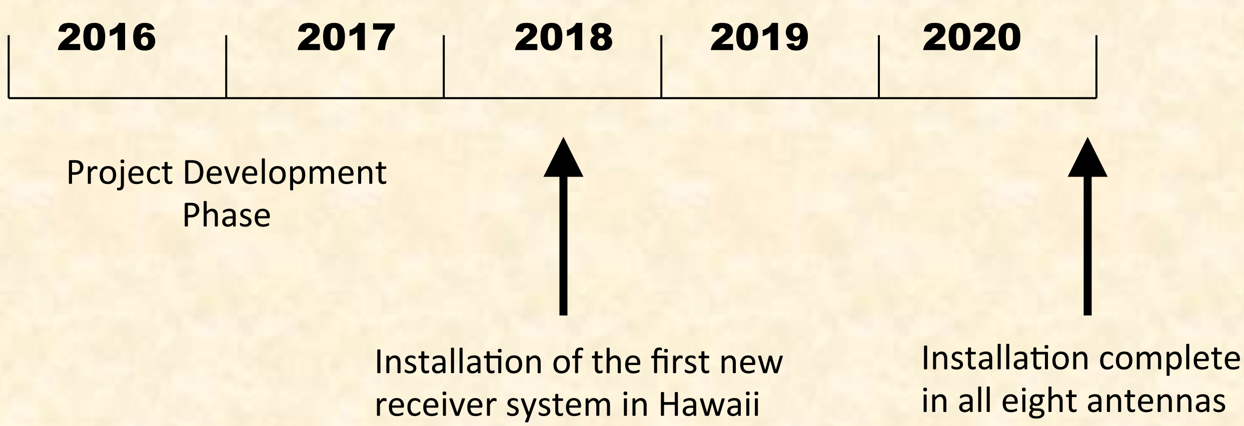
SMA
compact



SMA
extended

Project summary and timeline

- Dual Polarization Receivers, initially with 4 – 18 GHz IF (possibly more BW)
- Two band operation: LO tuning 210-270 GHz & 280-360 GHz
- RMS noise of 0.3 mJy @ 350 GHz (full track, dual pol, 1.5 mm pwv)
- RMS noise of 0.15 mJy @ 230 GHz (full track, dual pol, 3 mm pwv)
- Further increase of sensitivity expected with streamlined optics & receiver enhancements
- Significantly improved sensitivity for polarimetry
- New receiver systems will be backward compatible with existing receivers



Some final thoughts and numbers

SAO and ASIAA have been partners in the SMA for 20 years

ASIAA – SAO partnership remains strong, especially in technical areas

The SMA is a critical partner in the Event Horizon Telescope

Typically publish > 60 papers / year in refereed journals

Observing request oversubscription rate ~ 3:1 for good weather (<2.5mm pwv)

SAO and ASIAA signed an 15-year extension in 2011 (till June 2026)

The SMA lease on Mauna Kea extends till 2033

We will present this upgrade plan to the SMA Governing Board in December

Will enable the SMA to continue to pursue high quality science for the next 10 years