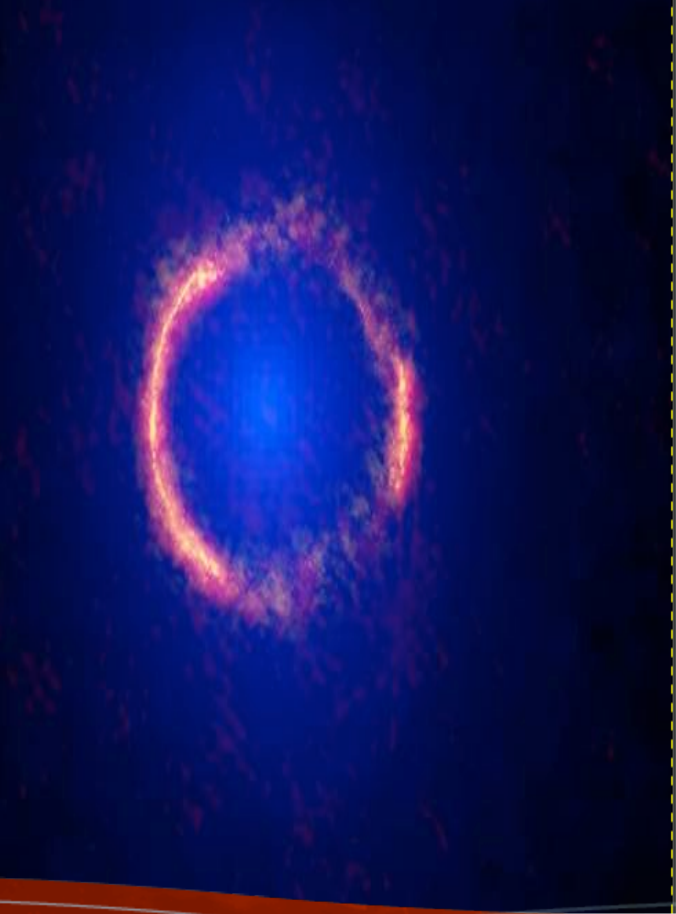
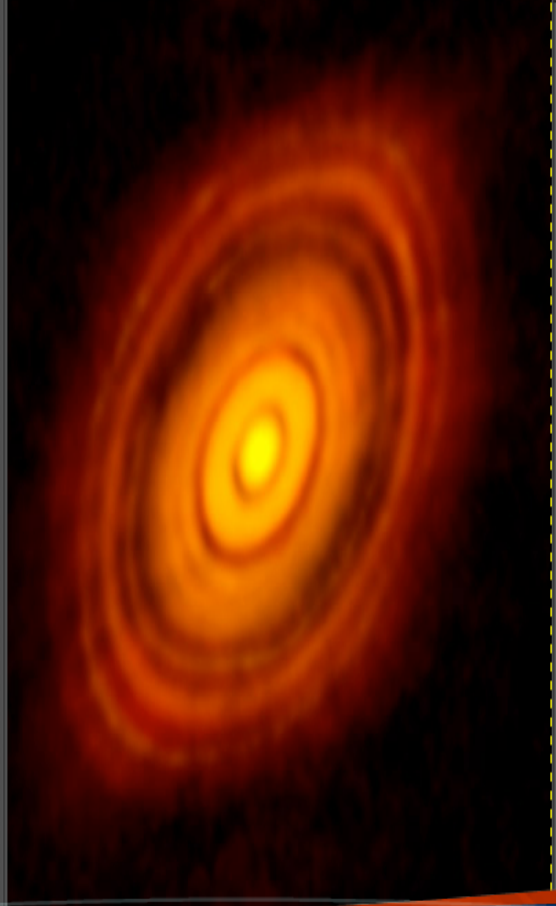
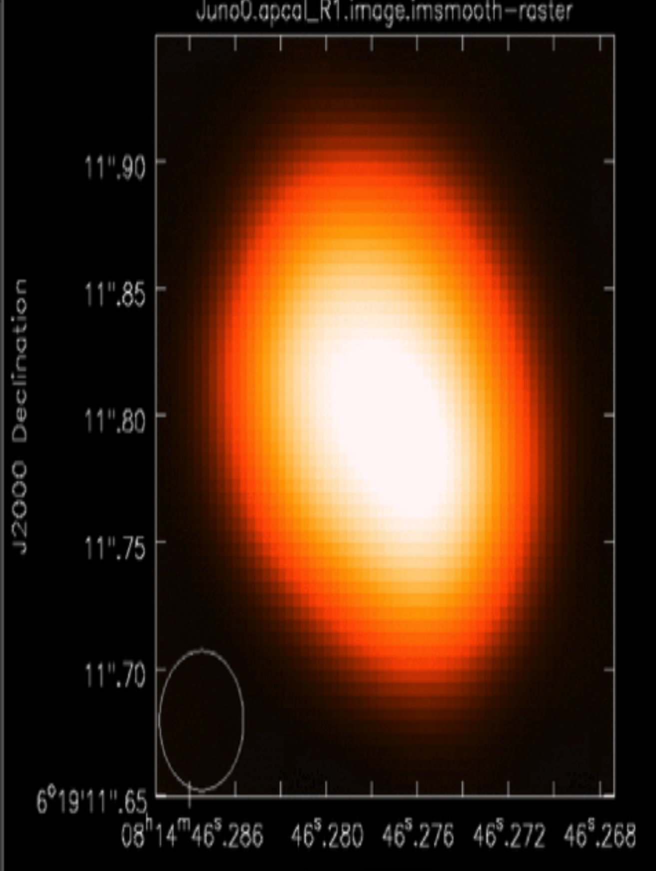






Future Prospects for Submillimeter Spectroscopic Observations

Al Wootten

What are the Big Questions:

Summarized in ESA Cosmic Vision & NASA Astrophysics Roadmap

- What are the conditions for planet formation and the emergence of life; how does the Solar System work—how did we get here and are we alone?
- What are the fundamental physical laws of the Universe—how did we get here?
- How did the Universe originate, what comprises it and how does it work?

Big Questions

Addressed by submillimeter spectroscopy

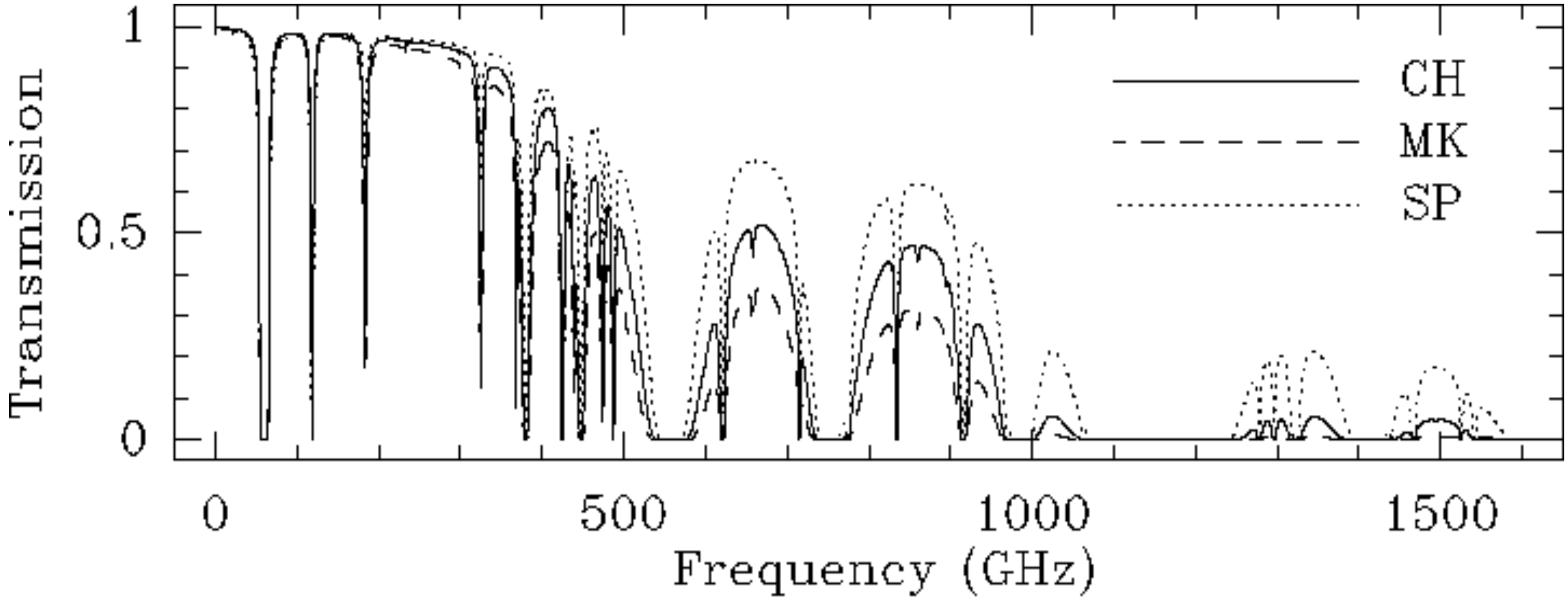
Many of the answers to these questions may be addressed through submillimeter spectroscopy, which provides us with the tools to measure both the chemical components of the Universe and through their redshifts, their evolution with time.

In fact, Seven of Nine emphases of the NASA Roadmap are addressed by submillimeter spectroscopy!

Of those seven, three were discussed in depth in this meeting.

The Submm Transmission of Earth’s Atmosphere

ALMA, VLA cover all windows where transmission>50%



Decode the histories of neighboring galaxies

Images in detail their molecular and stellar content to understand how they became what they are

Goicoechea: Velocity-resolved [C II[emission linking the closest massive star-forming region as a template to understand observations of [C II] in distant galaxies.
Indriolo: OH+ and H2O+ : the H2 fraction and cosmic ray ionization rate in the Galaxy
Di Li: Probing Dark Molecular Gas
Martin: Spectroscopy of nearby luminous galaxies.
Neufeld: Halogen-bearing molecules in our own and nearby Galaxies.
Ossenkopf: SuperTHz observations of major coolants in galaxies.

Characterize the evolution of nearby planetary systems

Detail the nature of star birth, the evolution of disks and the transport of water to inner regions and planets

Belloche: Complex organics in hot cores. ALMA and NOEMA
Fagas: AFGL4176
Kulczak-Jastrzebska: HDO in high mass retions W49, W51 and G34.26
Tychoniec: PDR and shock in W3IRS5
Matuszak: FIR CO and H2O from intermediate mass protostars
Benedettini: Spectroscopy of Outflow shocks: BHR71
Cernicharo: IRC+10216 from external layers to dust formation regions
Szczerba: Ammonia in IRC+10216
Teyssier: High resolution study of evolved stars\
Tylenda: CK Vul submm emission
Chapillon: Disk Chemistry in the ALMA Age
Karska: feedback from deeply embedded low mass protostars
Keto: H2O in L1544
Kristetnsen: Shocks in low mass protostars
Lefloch: Molecular complexity in protostellar shocks
Maret: Dense core chemistry
Mottram: Star formation theory linking high and low mass star formation
Schmidt: Vibronic bands of C3 in translucent clouds
Semenov: protoplanetary disk chemistry from Herschel
Sobolev: Studies of water masers in star-forming regions

Search the atmospheres of nearby planets for habitability signs and signatures of life (TBD).

- Hartogh: Sprectroscopy of Solar System Objects
- Lis ortho/para in water from the ISM to comets
- Szutowicz: Water as probes of cometary comae

Needs for submm spectroscopy

- **The Obscured Universe:** The Formation of Stars and Planets, AGN Tori
  - imaging the region inside the $T \sim 150$ K (~ 5 AU for M_{sun}) "frost" or "snow" line in circumstellar disks at distances ~ 100 pc
  - $R = \lambda / \Delta\lambda \sim 3 \times 10^5$ (velocity resolution $\Delta v \sim 1$ km s^{-1}) is needed for Galactic sources
- **Evolution of Galaxies** from Early Times to the Present:
  - studying the evolution of star formation in obscured galaxies back to $z \sim 3$.
  - The required angular resolution $\theta \leq 0.02$ arcsec at $\lambda \sim 100$ μm implies km-length baselines
- **Origins of Biogenic Molecules** and chemical evolution of the universe

See e.g. Far-Infrared (FIR) Community Plan "Far-Infrared/Submillimeter Astronomy from Space: Tracking an Evolving Universe and the Emergence of Life" (Harwit et al. 2009)

Terrestrial Heterodyne Interferometers

ALMA, NOEMA, SMA, VLA

☑ Angular resolution $\theta \leq 0.1$ arcsec FWHM at all $\lambda < 1$ cm

☑ Spectral resolution $R \sim 3 \times 10^5$

☑ Instantaneous bandwidth $\Delta\nu / \nu > 1/300$ ($\Delta v > 1000$ km s^{-1})

☑ Sensitivity $S \sim 10$ μJy / beam (5σ) in 24 hours from $A \sim 10^4$ m^2

☑ Superior imaging dynamic range from $N >> 1$ telescopes

☒ Maximum continuum frequency $\nu \sim 850$ GHz ($\lambda \sim 350$ μm)

☒ 50% atmospheric opacity at 850 GHz costs ~ 4X in sensitivity

☒ Few $z = 0$ lines of atmospheric molecules (e.g., 557 GHz H_2O line)

☒ Good observing weather only ~ 10% of the time at 850 GHz

Strengths, weaknesses of existing instruments

- Strengths of ALMA, NOEMA, SMA:
  - Large collecting area for ALMA, NOEMA, VLA high sensitivity
  - Subarcsec angular resolution on baaselines ~2-10km
  - Good imaging speed and fidelity (12-50 antennas on long baselines)
  - High spectral resolution up to ~1THz
- Drawbacks
  - Atmosphere blocks $z = 0$ spectral lines of many terrestrial molecules above $\nu \sim 300$ GHz and most continuum above $\nu \sim 1$ THz
  - Only probes the long λ tail of thermal SED
  - Only reaches lower energy lines of CO, abundant molecules
  - Water difficult if possible
  - Can reach [C II] only at redshift.

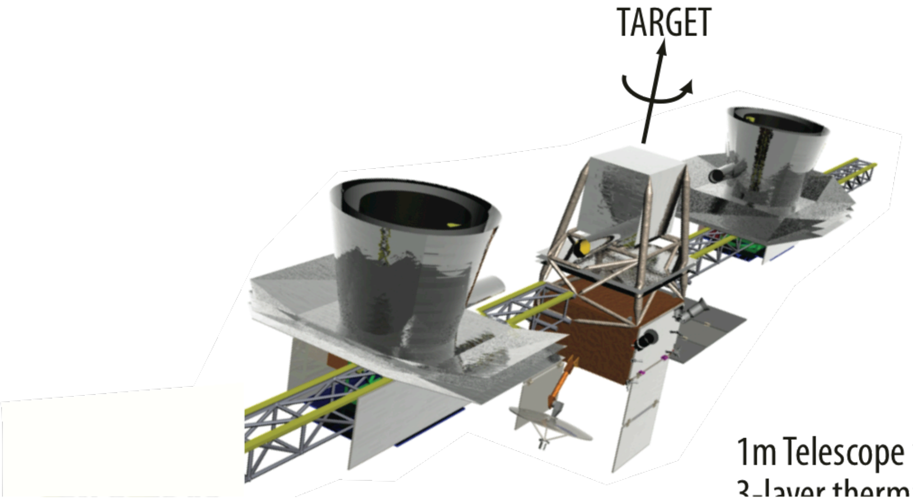
Need spectral, spatial resolution above $\nu \sim 1$ THz

- $D = 3.5$ m Herschel telescope, has a beamwidth $\theta \sim \lambda / D \sim 3 \times 10^{-5}$ rad ~ 6 arcsec FWHM at $\lambda \sim 100$ μm
  - bigger than distant galaxies, disks
  - source confusion quickly limits FIR continuum sensitivity.
- SOFIA
  - Smaller aperture but flexible instrumentation
  - Some limitations inherent in the airplane platform
- SPICA - 3.2m telescope (5-210um) to be launched in 2025 in L2.
- Millimetron – 10m class telescope beam ~ 6"
- None of these provide the needed resolution—therefore one must consider interferometers
  - See Condon et al. White Paper '**Far-Infrared Interferometry in Space**' at 12-13 May 2014 Goddard Workshop

FIR from Space: Interferometry

Direct Detection (Michelson) vs Heterodyne

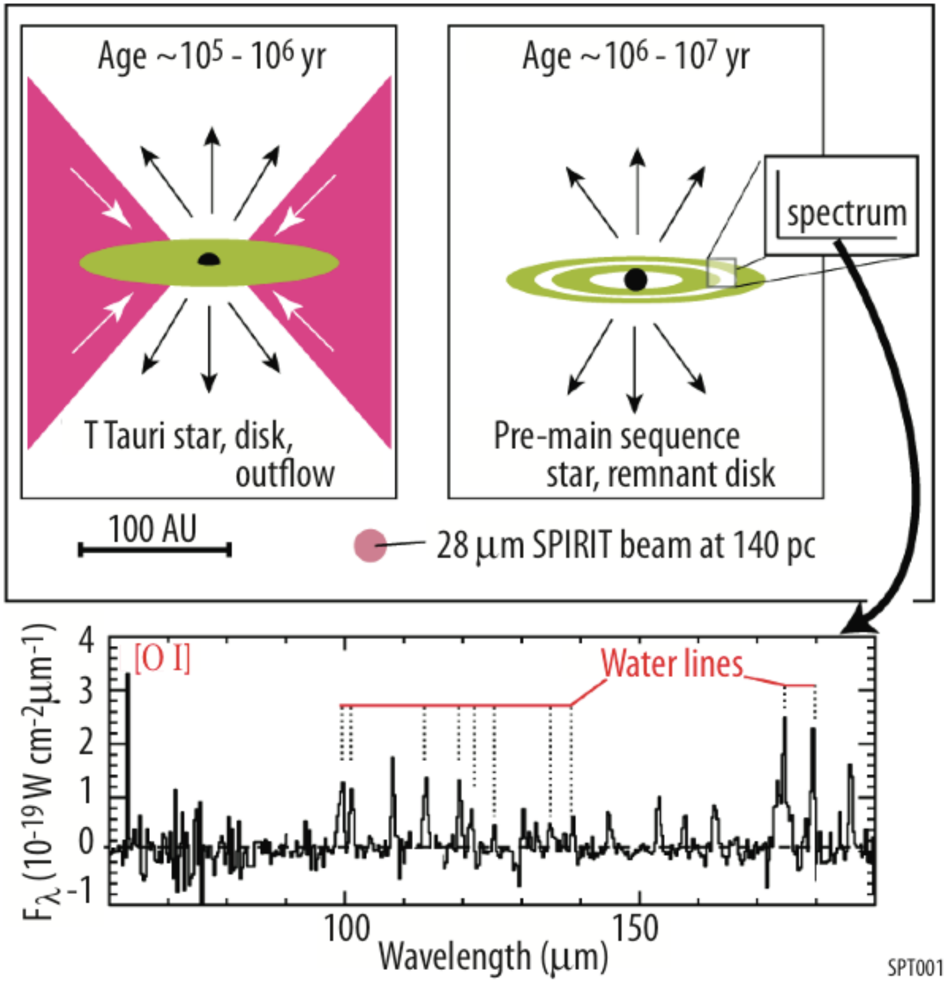
- Direct-detection interferometers in orbits near L2 are very sensitive but have limited spatial and spectral resolution.
  - Really need a total power complement such as SPICA
  - Spectral resolution inadequate for galactic sources (Δv ~ 100 km s^{-1})
  - Faint extended sources have never been imaged with incoherent adding interferometers—precursor missions (e.g. SPIRIT) are needed



SPIRIT

Proposed Space Interferometric Forerunner

- Goal: Hi-res imaging, spectroscopy of water in protoplanetary systems
  - Needs $\theta < 0.02$ arcsec
  - $\Delta v < 1$ km s^{-1}
- Cost est \$1.26 B FY2009
- Unfortunately it is expensive, unproven and cannot reach either of the above goals.



Advantages and Disadvantages of 'SPIRIT' Approach

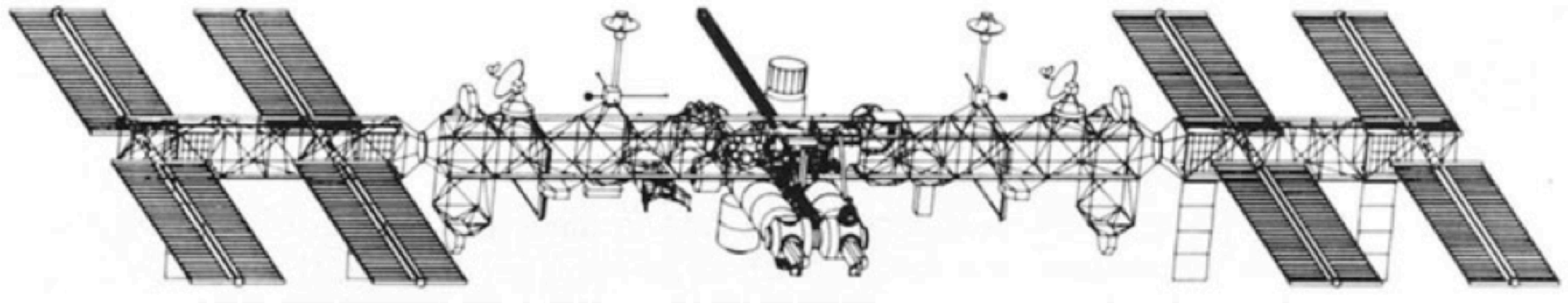
Condon 2014

- ☑ Superior background-limited sensitivity $S \sim 10\ \mu\mathrm{Jy}$ / beam in 24 hours in L2 orbits despite very small collecting area $A \sim 1\ \mathrm{m}^2$
- ☑ Instantaneous bandwidth $\Delta\nu / \nu >> 1/300$ ($\Delta v >> 1000\ \mathrm{km\ s^{-1}}$)
- ☒ Angular resolution $\theta > 0.9$ arcsec ($\lambda > 150\ \mu\mathrm{m}$, $D_{\mathrm{max}} = 36$ m)
- ☒ Spectral resolution $R \sim 3000$ with double-Fourier spectrometer
- ☒ Limited imaging dynamic range from $N = 2$ telescopes
- ☒ Adding interferometer affected by unwanted backgrounds
- ☒ Needs large single telescope to fill $D_{\mathrm{min}} = 7$ m hole in (u,v) plane (SPICA)

Heterodyne Interferometer in Near-Earth Orbit

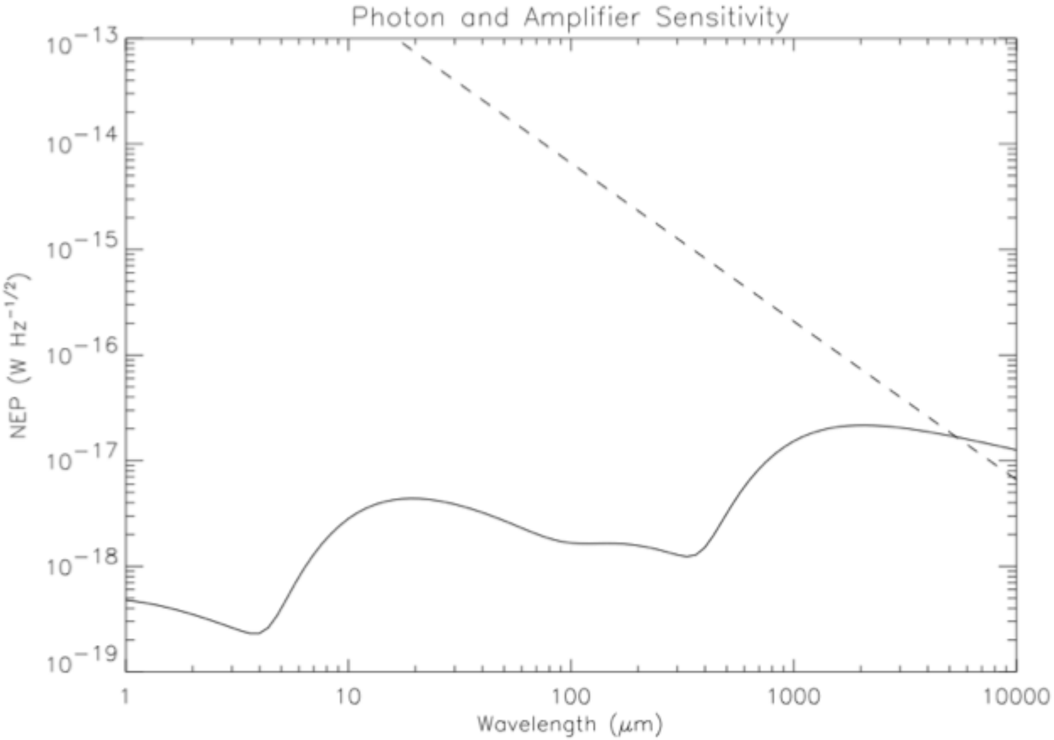
(ESPRIT, HISAT)

- Heterodyne interferometers
  - May be in near-Earth orbits
  - Higher spatial and spectral resolution
  - Suffer from quantum noise and small bandwidth.
    - Instantaneous bandwidth poor for extragalactic spectroscopy above $\nu \sim 3$ THz, and their sensitivity is badly degraded by quantum noise at frequencies above $\nu \sim 1$ THz



Heterodyne Limits

Not the Sky!



- Noise equivalent power (NEP) from quantum noise (dashed line) and astronomical backgrounds at L2 (solid curve) for 100% bandwidth $\Delta\nu = \nu$, two polarizations, and diffraction-limited telescopes with $A\Omega = \lambda^2$ (Mather et al. 1998). Ideal heterodyne detectors are almost 10^4 times noisier than background-limited direct-detection interferometers at $\lambda = 100$ μm.

Space Heterodyne Advantages, Disadvantages

Condon 2014

- ☑ Angular resolution $\theta \sim 0.1$ arcsec at $\lambda \sim 150$ μm ($D_{max} = 300$ m)
- ☑ Spectral resolution $R \sim 3 \times 10^5$
- ☑ Can operate with uncooled telescopes in near-Earth orbits
- ☑ Good imaging dynamic range from $N > 2$ telescopes
- ☑ Multiplying interferometer suppresses unwanted backgrounds
- ☒ Sensitivity limited by quantum noise $T_{sys} > h\nu/k \sim 50 \text{ K} \times (\nu/\text{THz})$ and by small collecting area
- ☒ Instantaneous bandwidth $\Delta\nu/\nu < 1/300$ when $\nu > 1$ THz
- ☒ Needs large single telescope to fill $D_{min} = 7$ m hole in (u,v) plane

Summary: Space FIR Interferometric Needs

- No single instrument concept meets all science goals
  - Galaxy evolution needs best met by direct-detection interferometer near L2
  - Narrow-line galactic spectroscopy best met by near Earth heterodyne spectroscopy
  - Terrestrial heterodyne interferometers work well for $\lambda > 350$ μm
- Best path would appear to include careful planning toward the goals
  - Any interferometric solution in space would need a large aperture for short spacing (SPICA-like)
  - Define upgrade paths for terrestrial instruments for complementarity

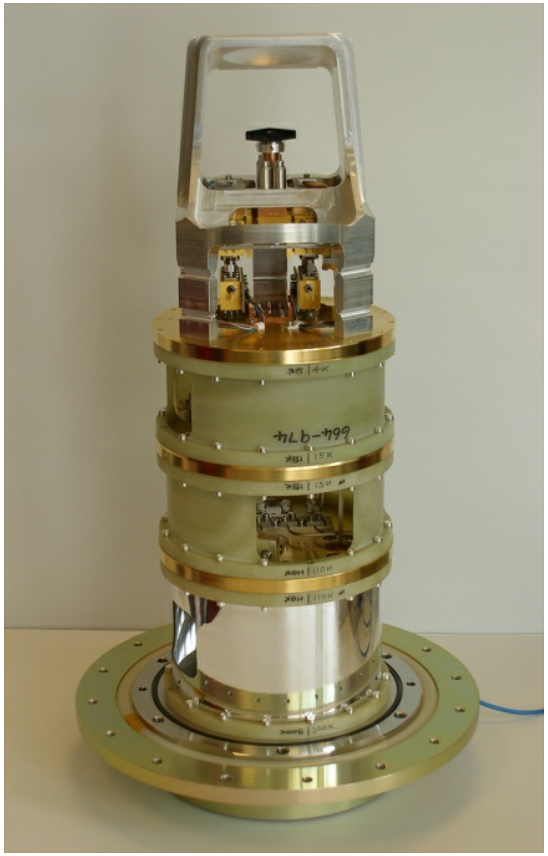
An ALMA Upgrade Path: Development Projects

NA Development Projects Status

- ALMA Projects continue from First Call (wrapping up) and most recent (2013) Call.
- 2011 Call (Cycle 1)
  - Band 5 (163-211 GHz): Band 5 units are manufactured, and are being installed now on ALMA. *New band, water, [C II] focus*
  - ALMA Phasing Project: All APP hardware is in place and thoroughly tested at the component level. Passed the hardware acceptance review on 12 Dec 2014, & ALMA has been phased up. *Imaging Black Holes*
  - Fiber Optic Connectivity Project: The construction work of the fiber is completed. System end-to-end testing was completed successfully. Final use permit from SILICA received end of April. *>Order of magnitude increase in data volume transmission, better reliability*

EU Led Projects/Studies Underway: Band 5

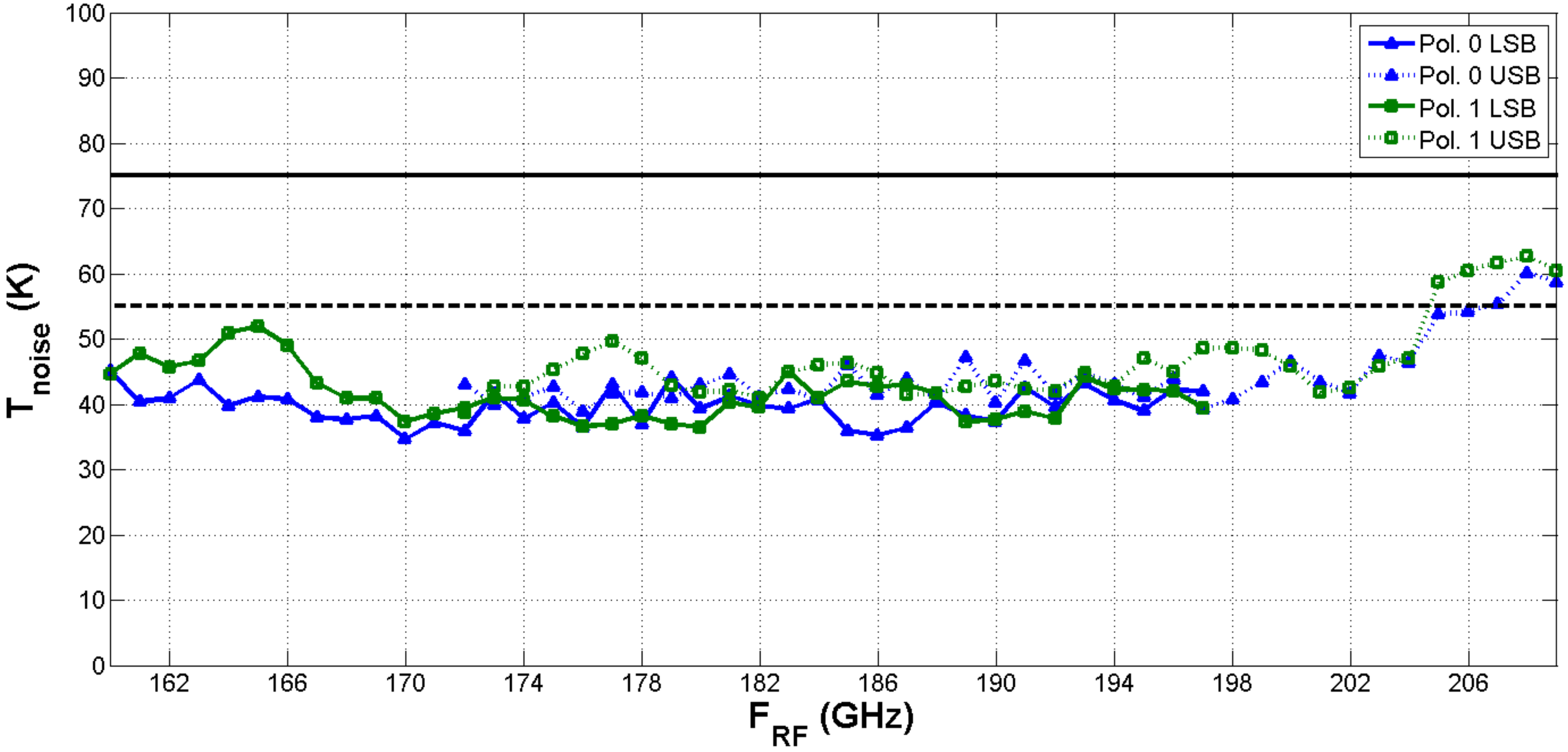
- 1 Feb 2013 – Kick-off meeting
- 2013/14 – Design optimized for series production
- Manufacturing Readiness Review (May 2014)
- Two production type CCAs built, being tested
- Decision to produce 73 units (up from 67)
  - Exactly same hardware, no mix with pre-production units
  - Cost difference small compared to refurbishment
- Band 5 integration at OSF to start in April 2015
  - Using experience from B4/8/10 integration
  - Last cartridge integrated Q2-2017
  - Funded by ESO & NRAO, plan agreed with JAO
  - ESO/NRAO/JAO team testing equipment at OSF now



Band 5 – Technical Status

- Tightened specs as compared to ALMA baseline
  - Receiver noise temperature
    - 80 % of RF band (163 – 211 GHz): 65 K → 55 K (15% better)
    - Whole RF band (163 – 211 GHz): 108 K → 75 K (30% better)
  - Extended LO tuning range (WCA by NRAO)
    - 166 – 203 GHz instead of 171 – 203 GHz (16% wider)
- First Band 5 production cartridge shows good noise temperature performance
- Science case summary: Laing et al 2010 Msngr 141, 14L

Band 5 – Sensitivity

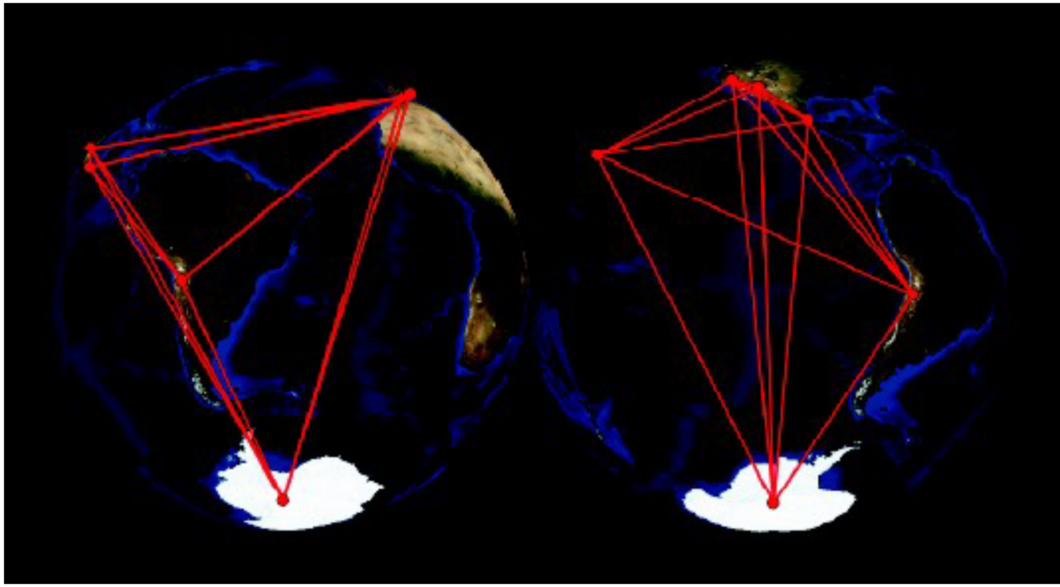


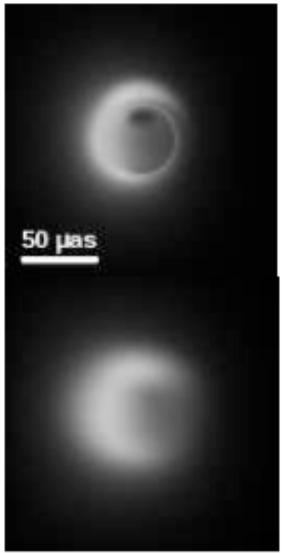
Longer Baselines: Enabling Qualitatively New Science

APEX—AOS fringes demonstrated 13 Jan 2015

24-31 March mission for APP: MIT: Matthews (APP), JAO-EOC: Phillips, Remijan

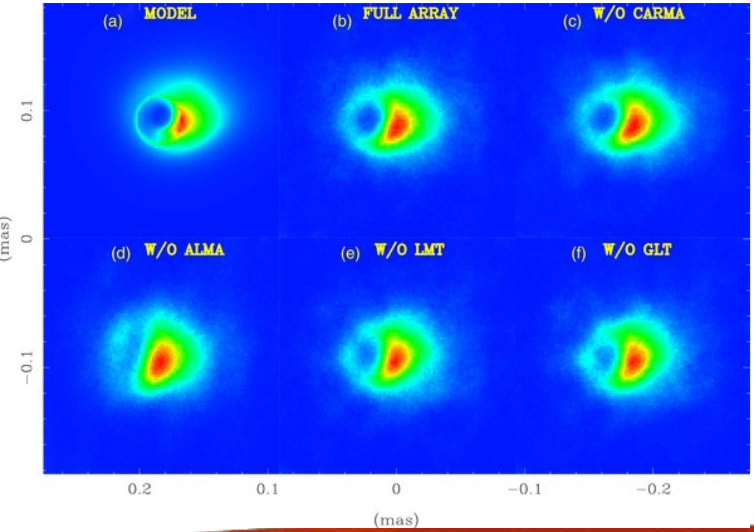
- Discussion/work regarding execution sequences and integration with nominal observing modes





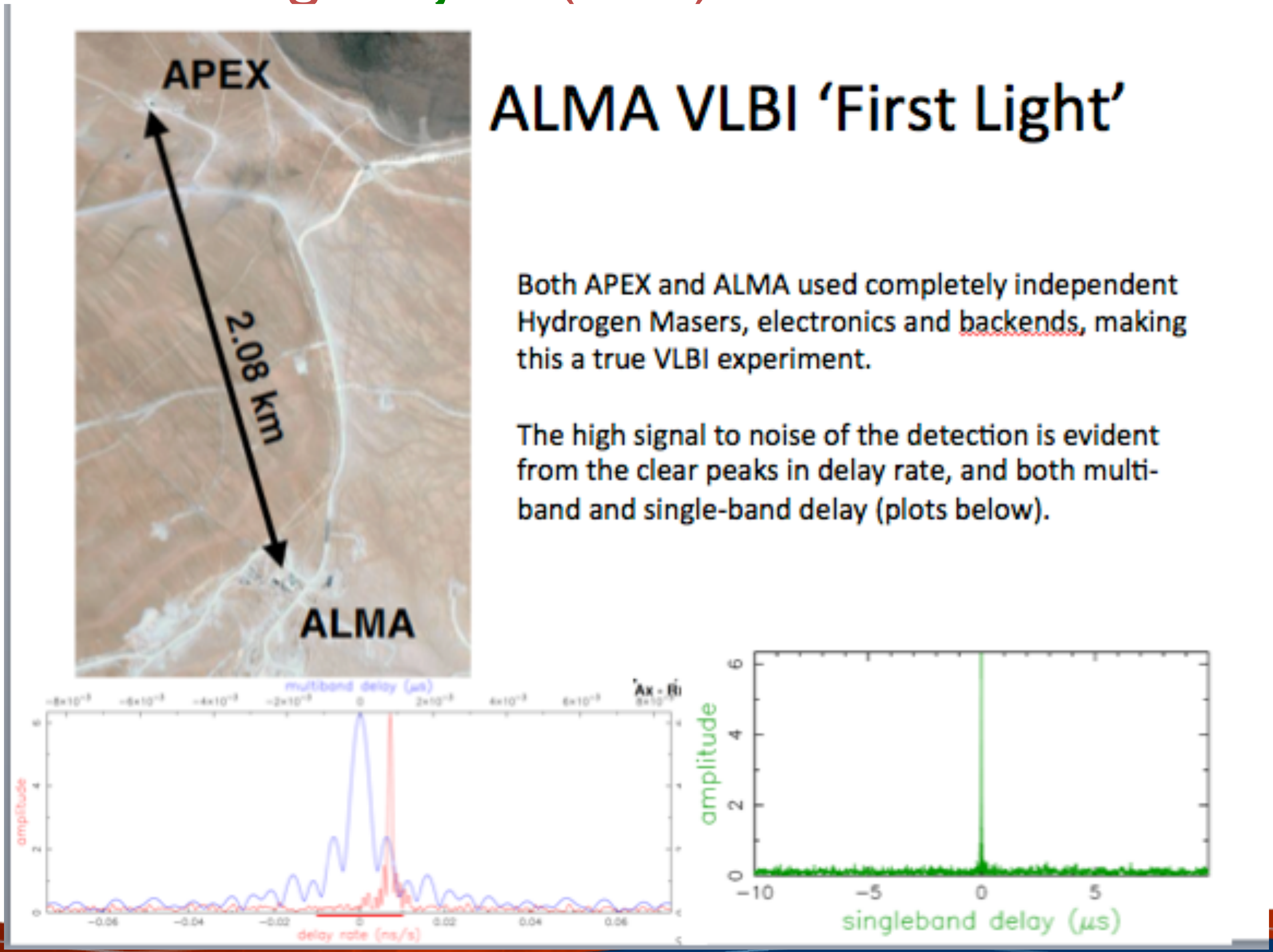
(Left) Image of SgrA* (top) as viewed by the array shown right above at 1.3mm (bottom)

1.3mm stations



M87 simulation
230 GHz
Lu et al. (2014)

ALMA Phasing Project (APP)



ALMA VLBI 'First Light'

Both APEX and ALMA used completely independent Hydrogen Masers, electronics and backends, making this a true VLBI experiment.

The high signal to noise of the detection is evident from the clear peaks in delay rate, and both multi-band and single-band delay (plots below).

ALMA’s Connection to the World

150km of fiber connects ALMA/AOS to Chilean Internet backbone (REUNA) thence to the World

Data transmission speeds increased by more than a factor of ten over the current microwave link

Small Development Projects & Upgrade Studies

NA Development Studies: FY2016 Call

- Overview: Describe Call, priorities recently endorsed by ALMA Board ('ALMA2030'), current studies and projects, other opportunities
- New NA Call for Studies published March 2015
  - FY2016 funding, dependent upon budget
  - Funding begins 1 October 2015
  - Notice of Intents due 1 May
    - 16 eligible NoIs received: 12 hardware, 4 techniques, 0 software
  - Deadline mid-June 2015
- Goal: Develop new ideas for study, consistent with the ALMA 2030 vision, outcomes of previous studies

A ROAD MAP FOR DEVELOPING ALMA

ASAC Recommendations for ALMA 2030

- Finish the Scope of ALMA (receivers, VLB capability)
- Recommended development paths
  - 1. Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.
  - 2. Larger bandwidths and better receiver sensitivity: enabling gains in speed.
  - 3. Longer baselines: enabling qualitatively new science.
  - 4. Increasing wide field mapping speed: enabling efficient mapping.

Larger Bandwidths; Better Receiver Sensitivity

Improving sensitivity and spectral grasp

- Construction/Upgrade of receivers to provide increased bandwidth to the digital system—there are Studies and Projects toward this end
  - New receiver Projects for uninstrumented ALMA Bands
    - Band 5 Project (Eu & NA): First of 73 of 8 GHz x 2 polzn 163-211 GHz receivers on ALMA in April; installation continues for ~2 years.
    - Band 2 (NA) Project: a 67-93 GHz prototype will present two 8 GHz sidebands, 2 polarizations to the system (currently of course only 16 GHz of this bonanza can be processed at once) Note Eu Study, below
    - Band 1 (EA & CL & NA) Project a prototype 35-50GHz, 8 GHz x 2 polzn receiver is under construction.

Larger Bandwidths; Better Receiver Sensitivity

- Currently there are several studies moving in this direction:
  - Band 6 Study: (NA) Kerr is studying a 2nd generation B6 (211-270 GHz) receiver incorporating balanced sideband-separating SIS mixers providing flatter gain and noise characteristics over a full 4-12 GHz IF band.
  - Band 10 Study: (NA) B10 (787-950 GHz) currently DSB 8 GHz; Kerr is studying a 2nd generation B10 SSB receiver over a full 4-12 GHz IF band.
  - Band 2+3 Study: (Eu) Band 2+3 development:
    - Prototypes of horn and OMT meet specs over 67-116 GHz
    - LNA development:
      - » UMan: excellent design over full range (being prototyped)
      - » Other LNAs (EU foundries) and packaging (IRAM,INAF & RAL)
    - Bench system test by end of year, full prototype in 2 yrs w/ 16GHz/pol
  - Combination of B2+3 would leave a cryostat slot, Studies for B11?
    - An Eu study investigated B11 science and the ALMA site
    - An EA study: Hot Electron Bolometer mixer with SiGe HBT low noise amplifier has been tested and a new SIS device (Nb/Al-AlOx-Al/Nb) has been fabricated.

Larger Bandwidths; Better Receiver Sensitivity

- Upgrade of existing Receivers:
  - Band 3 (84-116 GHz, NA) Project: Addition of deflux heater, magnets to improve stability, sensitivity
  - Band 3 (84-116 GHz, NA) Study of TKIP (traveling-wave kinetic inductance parameter) amplifier over the 55-175 GHz
  - Band 9 (602-720 GHz, (Eu) Study: upgrading Band 9 to 2SB with wider IF ready for implementation
- Upgrades to backends
  - Digital Study (Eu): Upgrade of the digital system to process increased bandwidth--developing next generation digitizers
  - NAASC Memo 114: suggests upgrade of the correlators to process the increased bandwidth –future Study?

Correlator Performance Enhancements

- frequency and time resolution, and sensitivity

- X8 enhancement in **frequency resolution**.
  - Spectral resolution for every mode increases by a factor of **eight** for integration times of 128 msec and greater. For example, from Table 2 of the correlator specification (next slide). Time resolution enhancement for auto and cross products
- And if you don't need either improved frequency or time resolution, there is still something in it for you: **higher sensitivity** or **shorter observing times** can be obtained using 4-bit x 4-bit modes and/or double Nyquist mode (95% efficiency versus 85% including the effect of the 3-bit sampler). This is equivalent to adding about 8 antennas to the array or cutting integration times down by 12%! True only for BW < 2 GHz. See comparison of modes 2 and 53 on the next slide…

Mode Table Changes

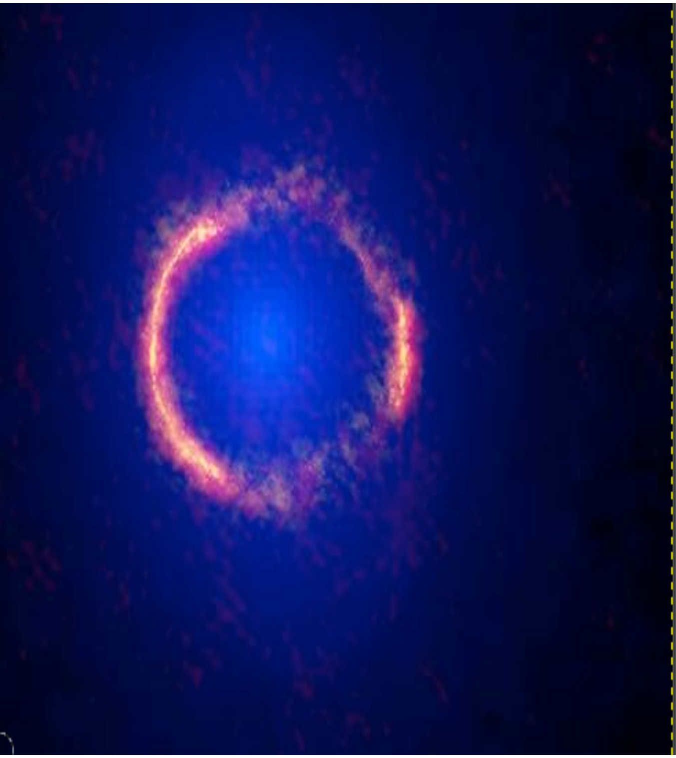
Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points		Spectral Resolution (KHz)		Correlation	Sampling	Sensitivity (x 0.96)
			Current	Proposed	Current	Proposed			
1	32	2 GHz	8192	65536	244	30.5	2-bit x 2-bit	Nyquist	0.88
19	32	2 GHz	4096	32768	488	61	2-bit x 2-bit	Twice Nyquist	0.94
38	32	2 GHz	2048	16384	976	122	4-bit x 4-bit	Nyquist	0.99
2	16	1 GHz	8192	65536	122	15.25	2-bit x 2-bit	Nyquist	0.88
20	16	1 GHz	4096	32768	244	30.5	2-bit x 2-bit	Twice Nyquist	0.94
39	16	1 GHz	2048	16384	488	61	4-bit x 4-bit	Nyquist	0.99
53	16	1 GHz	1024	8192	976	122	4-bit x 4-bit	Twice Nyquist	0.99
3	8	500 MHz	8192	65536	61	7.625	2-bit x 2-bit	Nyquist	0.88
21	8	500 MHz	4096	32768	122	15.25	2-bit x 2-bit	Twice Nyquist	0.94
40	8	500 MHz	2048	16384	244	30.5	4-bit x 4-bit	Nyquist	0.99
54	8	500 MHz	1024	8192	488	61	4-bit x 4-bit	Twice Nyquist	0.99
4	4	250 MHz	8192	65536	30	3.75	2-bit x 2-bit	Nyquist	0.88
22	4	250 MHz	4096	32768	61	7.625	2-bit x 2-bit	Twice Nyquist	0.94
41	4	250 MHz	2048	16384	122	15.25	4-bit x 4-bit	Nyquist	0.99
55	4	250 MHz	1024	8192	244	30.5	4-bit x 4-bit	Twice Nyquist	0.99
5	2	125 MHz	8192	65536	15	1.875	2-bit x 2-bit	Nyquist	0.88
23	2	125 MHz	4096	32768	30	3.75	2-bit x 2-bit	Twice Nyquist	0.94
42	2	125 MHz	2048	16384	61	7.625	4-bit x 4-bit	Nyquist	0.99
56	2	125 MHz	1024	8192	122	15.25	4-bit x 4-bit	Twice Nyquist	0.99
6	1	62.5 MHz	8192	65536	7.6	0.95	2-bit x 2-bit	Nyquist	0.88
24	1	62.5 MHz	4096	32768	15	1.875	2-bit x 2-bit	Twice Nyquist	0.94
43	1	62.5 MHz	2048	16384	30	3.75	4-bit x 4-bit	Nyquist	0.99
57	1	62.5 MHz	1024	8192	61	7.625	4-bit x 4-bit	Twice Nyquist	0.99
25	1	31.25 MHz	8192	65536	3.8	0.475	2-bit x 2-bit	Twice Nyquist	0.94
58	1	31.25 MHz	2048	16384	15	1.875	4-bit x 4-bit	Twice Nyquist	0.99

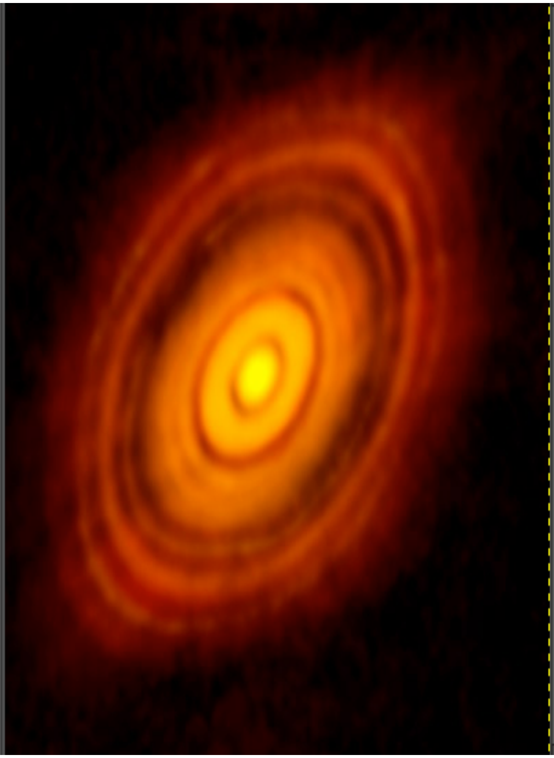
Future Correlator Upgrades

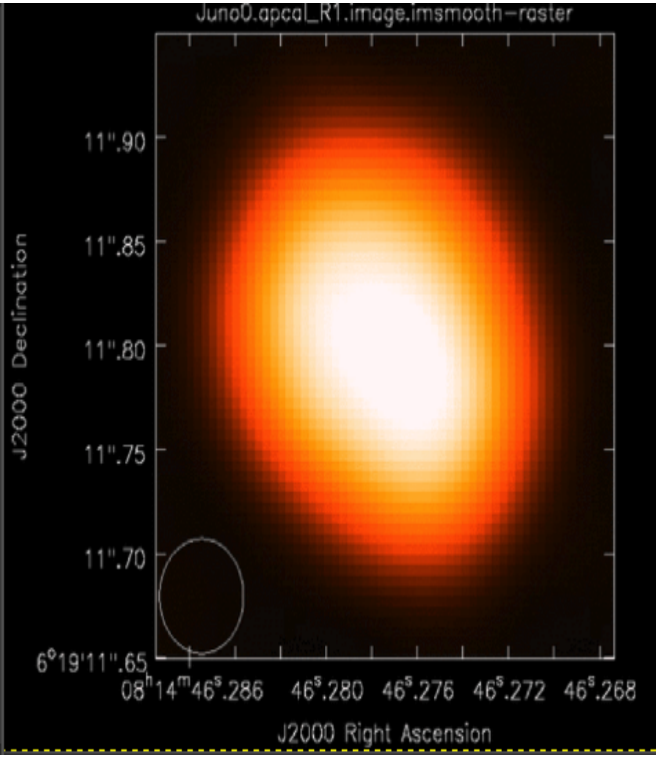
- New chips may also allow 250MHz operation, doubling the bandwidth
  - New digital system needed to implement that
  - Probably a second upgrade
- New chip technology should cut power consumption considerably

Summary

- Any space interferometer will need a total power element for short spacings owing to the extended nature of much submm emission.
    - Need a follow-up to Herschel
- Space interferometry needs considerable development and is far in the future
    - Need balloon-borne predecessors
- Ground-based instrumentation (ALMA, NOEMA, SMA, VLA) should maintain an upgrade path to remain the backbone of submm spectroscopy, with complementarity to space developments.







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