Next Generation Large-Format Spectroscopic Arrays for SOFIA

How a new generation of heterodyne arrays will justify continuing SOFIA's operation

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SOFIA Instrument Roadmap workshop II

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With special thanks to Jose Siles, Jon Kawamura, and Imran Mehdi

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California Institute of Technology

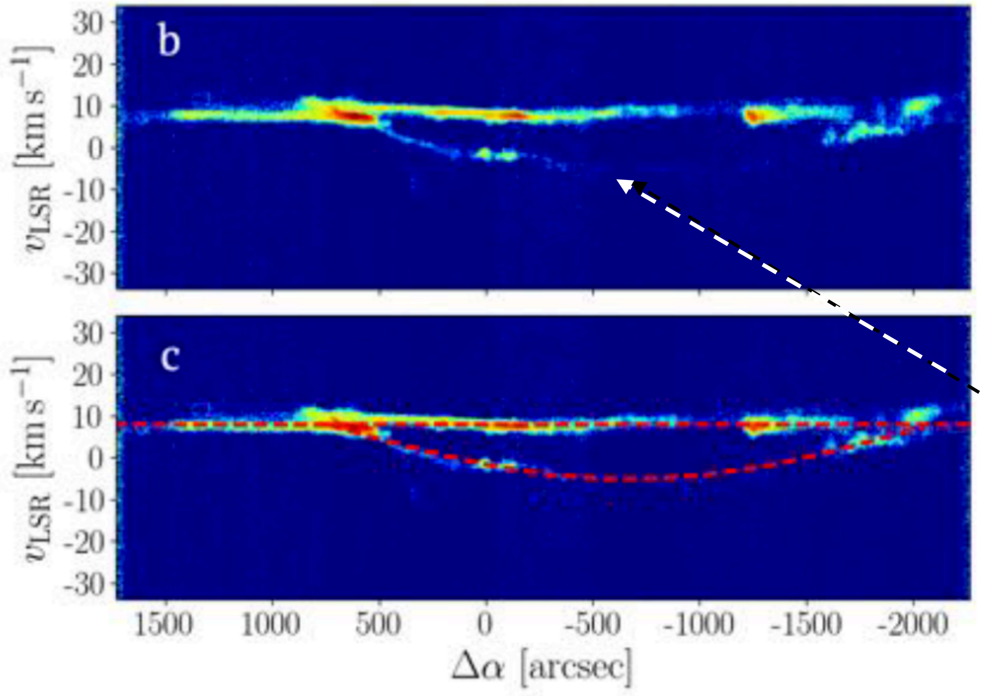
The Importance of Velocity-Resolved Spectroscopic Imaging

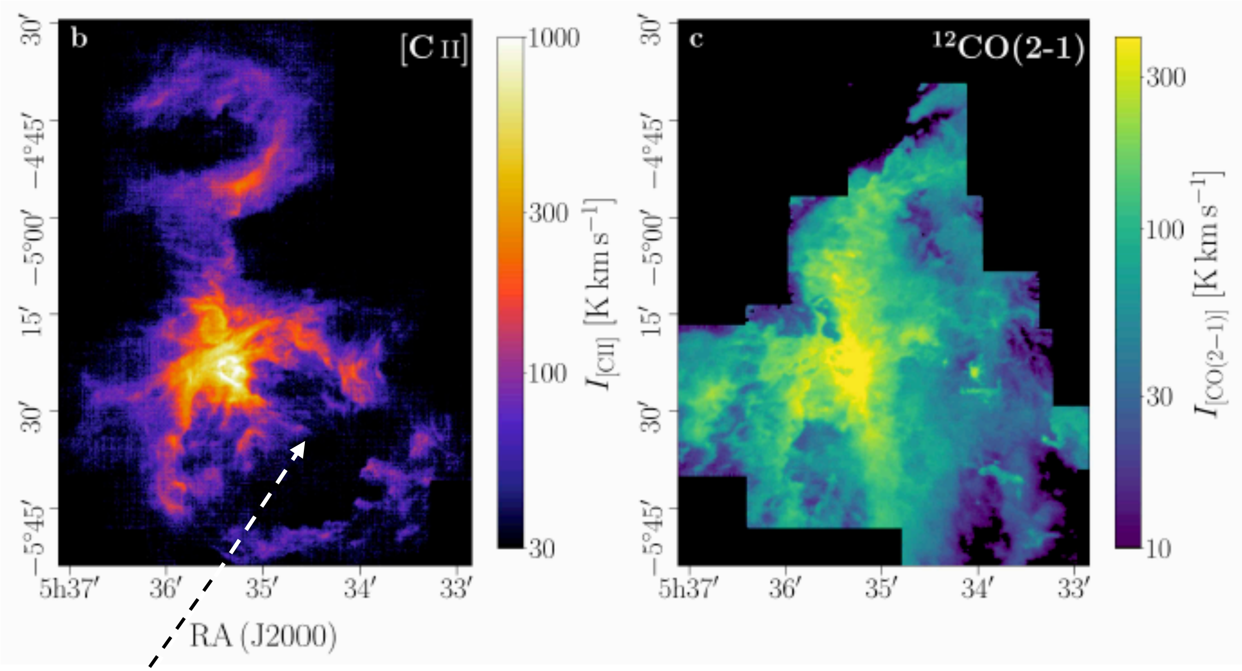
- Spectroscopy has for years been recognized as SOFIA's strongest area of contribution to astrophysics
  - ❖Access to critical lines blocked by the atmosphere (fine structure lines including [CII], [NII], [OI]), unique molecular lines (HF), and high-J CO lines
- High resolution spectroscopy is even more favorable for SOFIA
  - ❖Residual warm atmosphere and warm telescope DO NOT significantly degrade sensitivity of observations (this is not the case for photometry and low-resolution spectroscopy)
- The value of such data for unraveling key processes related to star formation, the life cycle of the ISM, and feedback is enormously enhance by **high resolution spectroscopic imaging**

GREAT (with upGREAT & 4GREAT) has Enabled High Resolution Spectroscopic for SOFIA + Significant Imaging

Pabst+ 2020

- upGREAT LFA has 14 pixels at 1.9 THz and 7 pixels at 4.7 THz with limited tunability

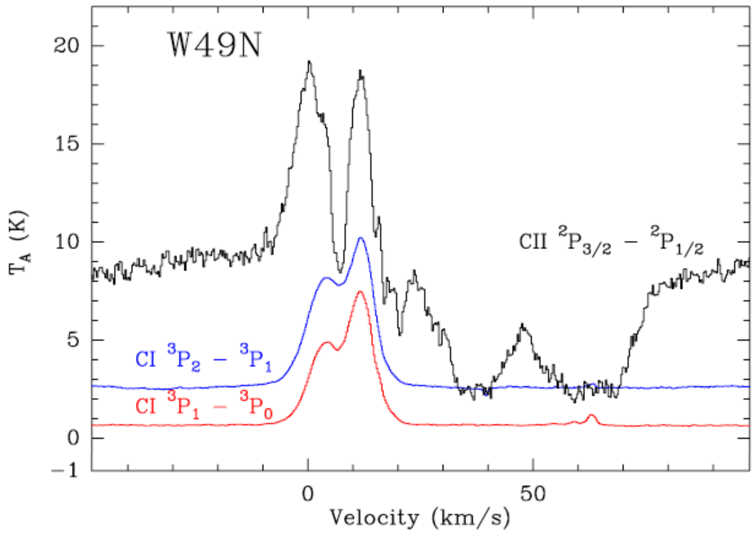




[CII] traces component of ISM not seen in CO

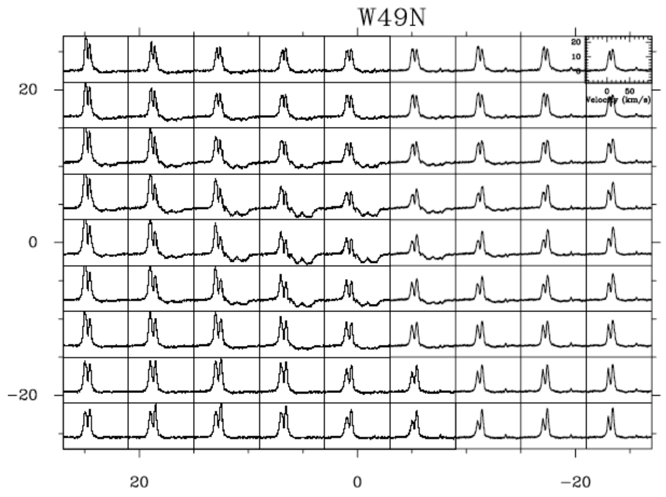
The large structure to South of θ^1 Ori C is an expanding bubble. Requires high resolution imaging to understand the structure: **2600 M_{sun} shell expanding at 13 kms^{-1}. E = $4x10^{48}$ erg**

[CII] Line Profiles are Complex due to Source Structure and Line of Sight Absorption

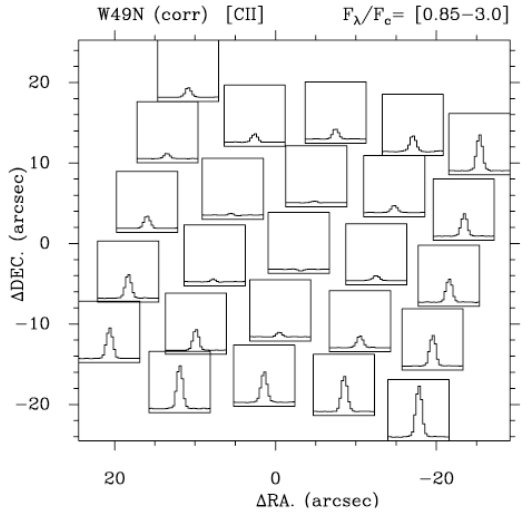


Gerin+ 2015 Herschel HIFI & PACS

Herschel HIFI



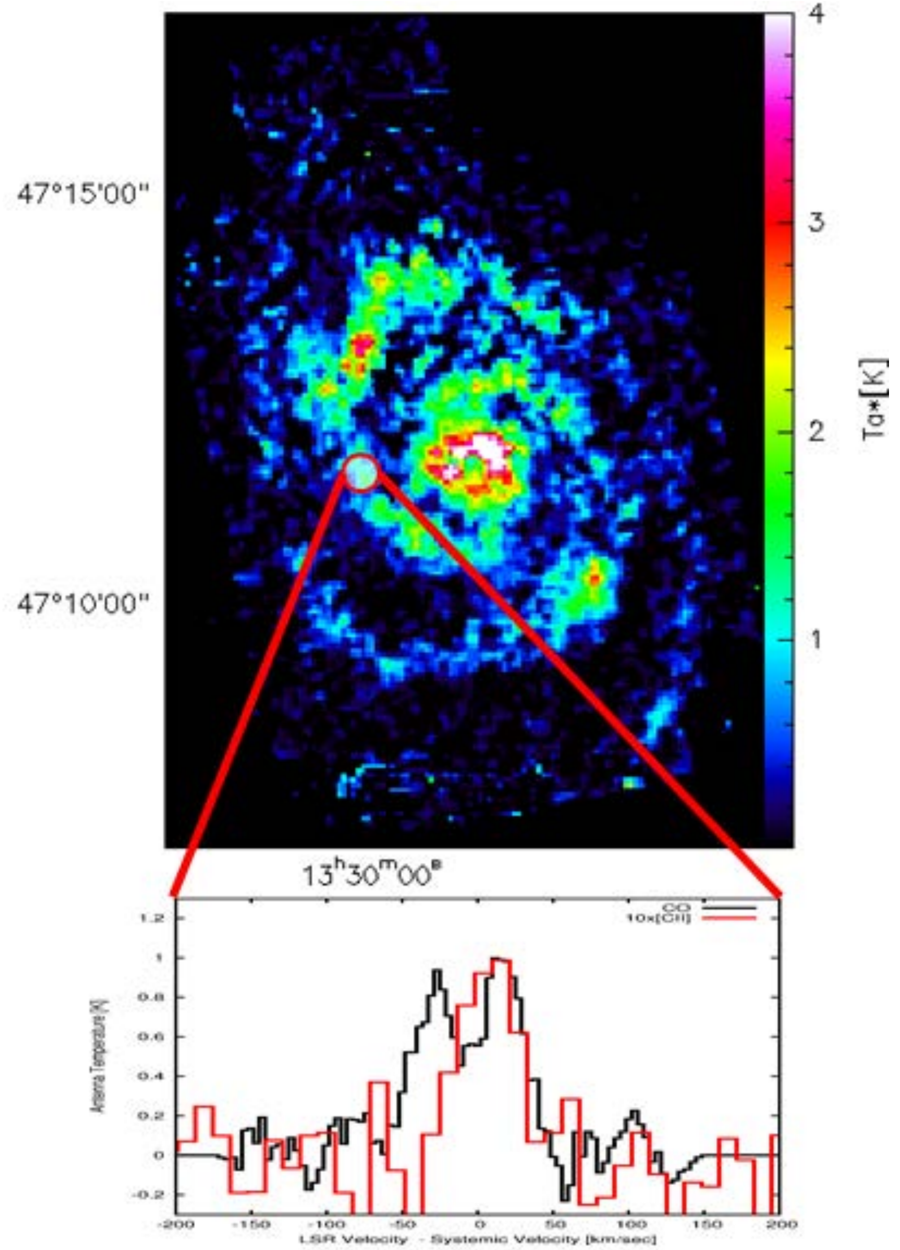
Herschel PACS
R~ 1200
(250 kms^{-1})



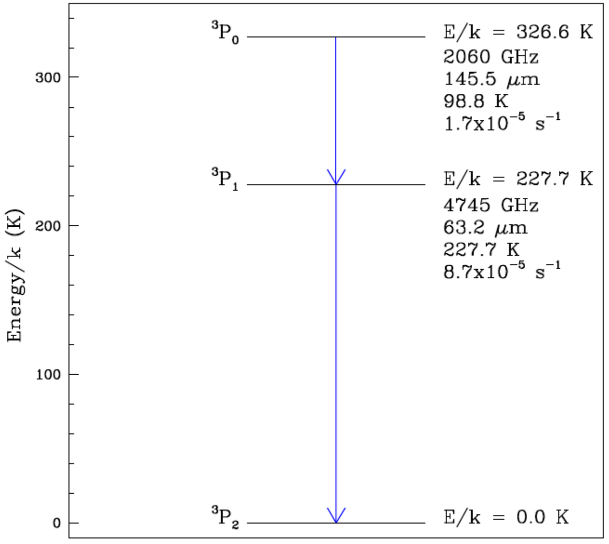
The low velocity resolution PACS spectra give completely erroneous picture of the [CII] emission from the source due to blending with foreground absorption by diffuse LOS clouds

What we Learn from Fine Structure Line Emission from Nearby Galaxies is Greatly Enhanced by Resolving Spectral Lines ($R > 10^5$)

[CII] Emission from M51 (Pineda+ 2020)



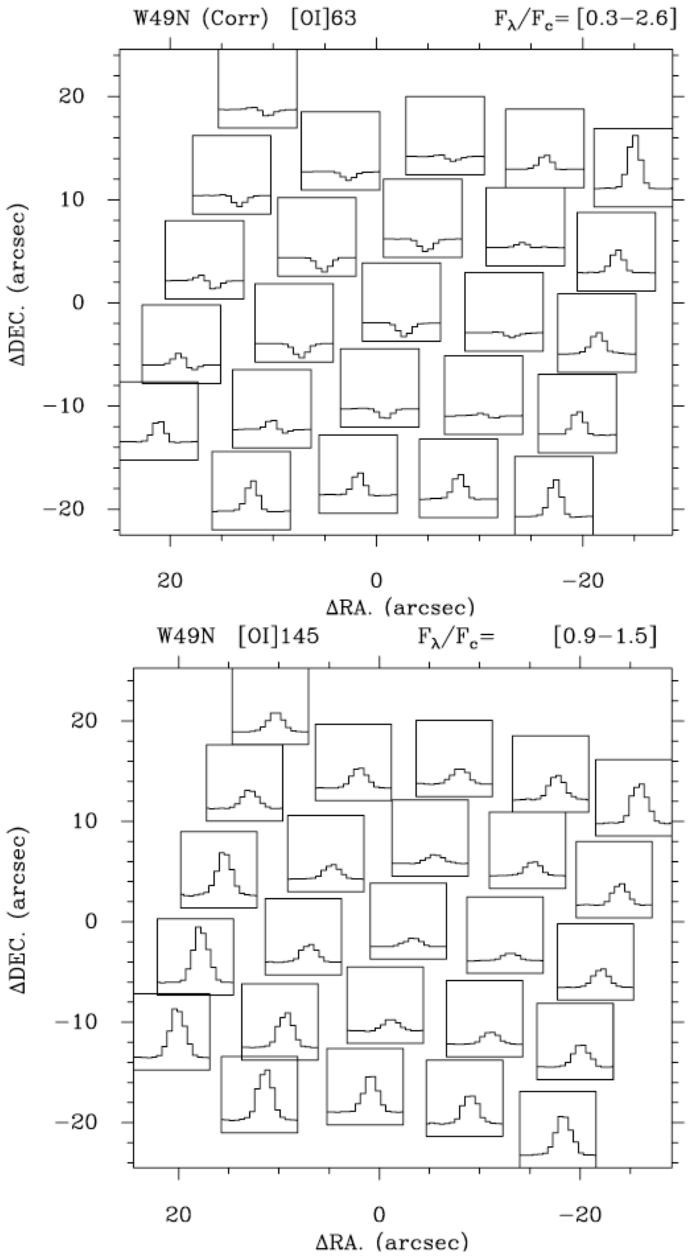
[OI] Fine Structure Line Emission has been Difficult to Interpret



Oxygen is the 3rd most abundant element
IP of O^0 = 13.614 eV, just greater than H^0

In Photon Dominated Regions (PDRs) associated with massive young stars, oxygen fine structure line emission is extremely strong, and the 63 µm line is widely used as a tracer of star formation

QUESTIONS:
How much neutral atomic oxygen is there in GMCs?
How does [OI] 63 µm trace star formation?



Herschel/PACS data (Gerin+ 2015)

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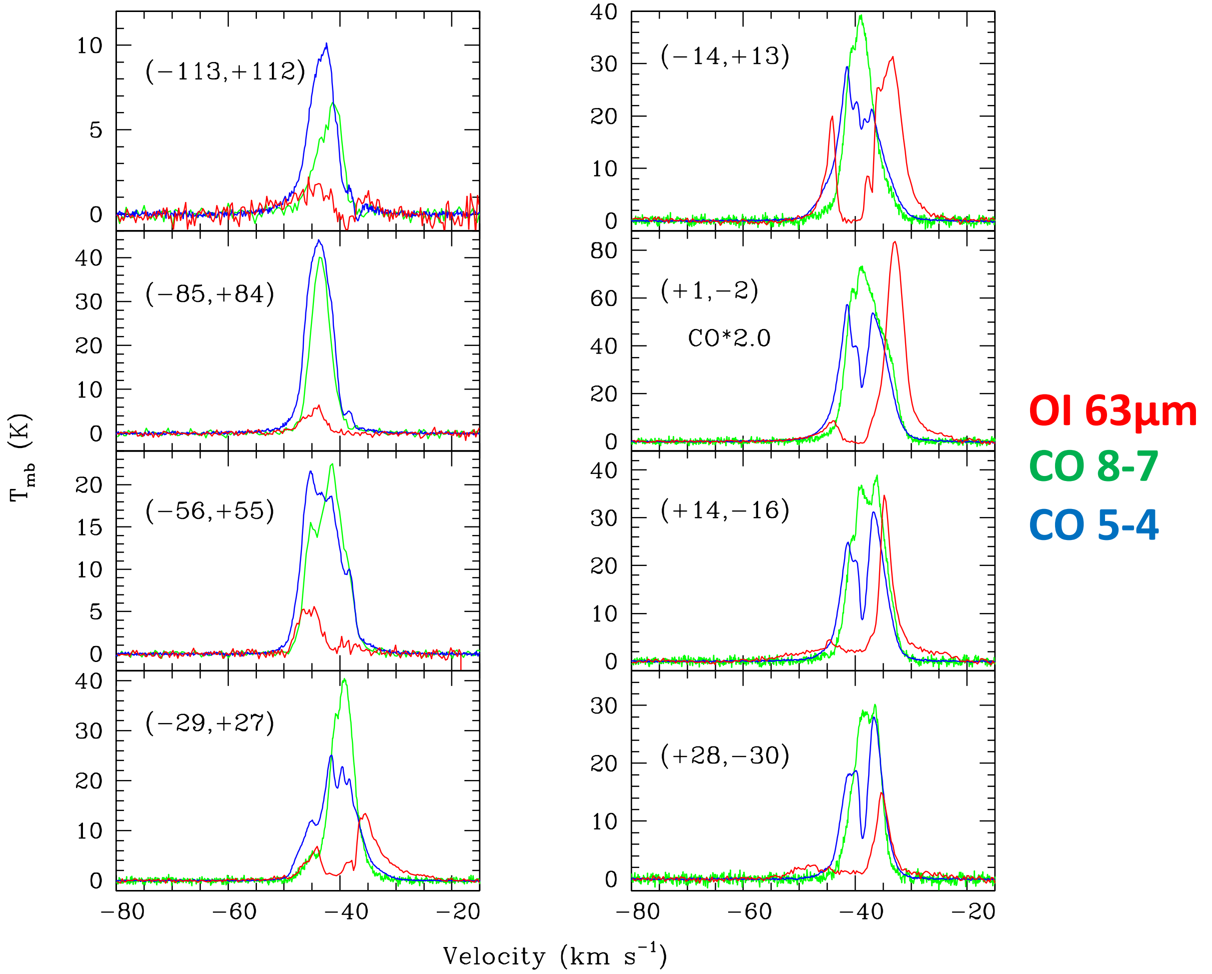
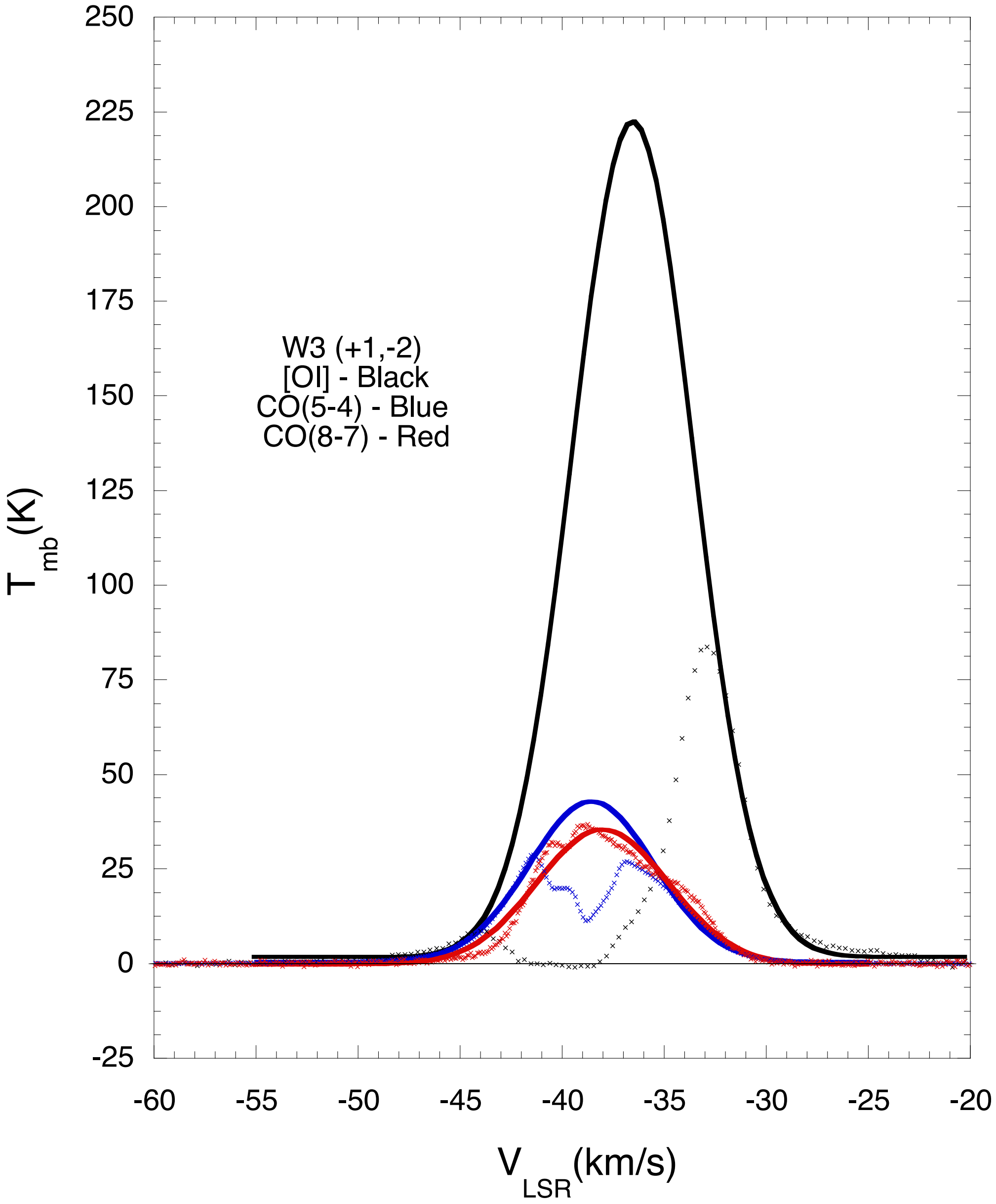
[OI] Mapping of W3 Galactic GMC/PDR

Goldsmith, Langer, Seo 2020





[OI] 63 µm Self-Absorption Evident in ~1/2 of Clouds Surveyed

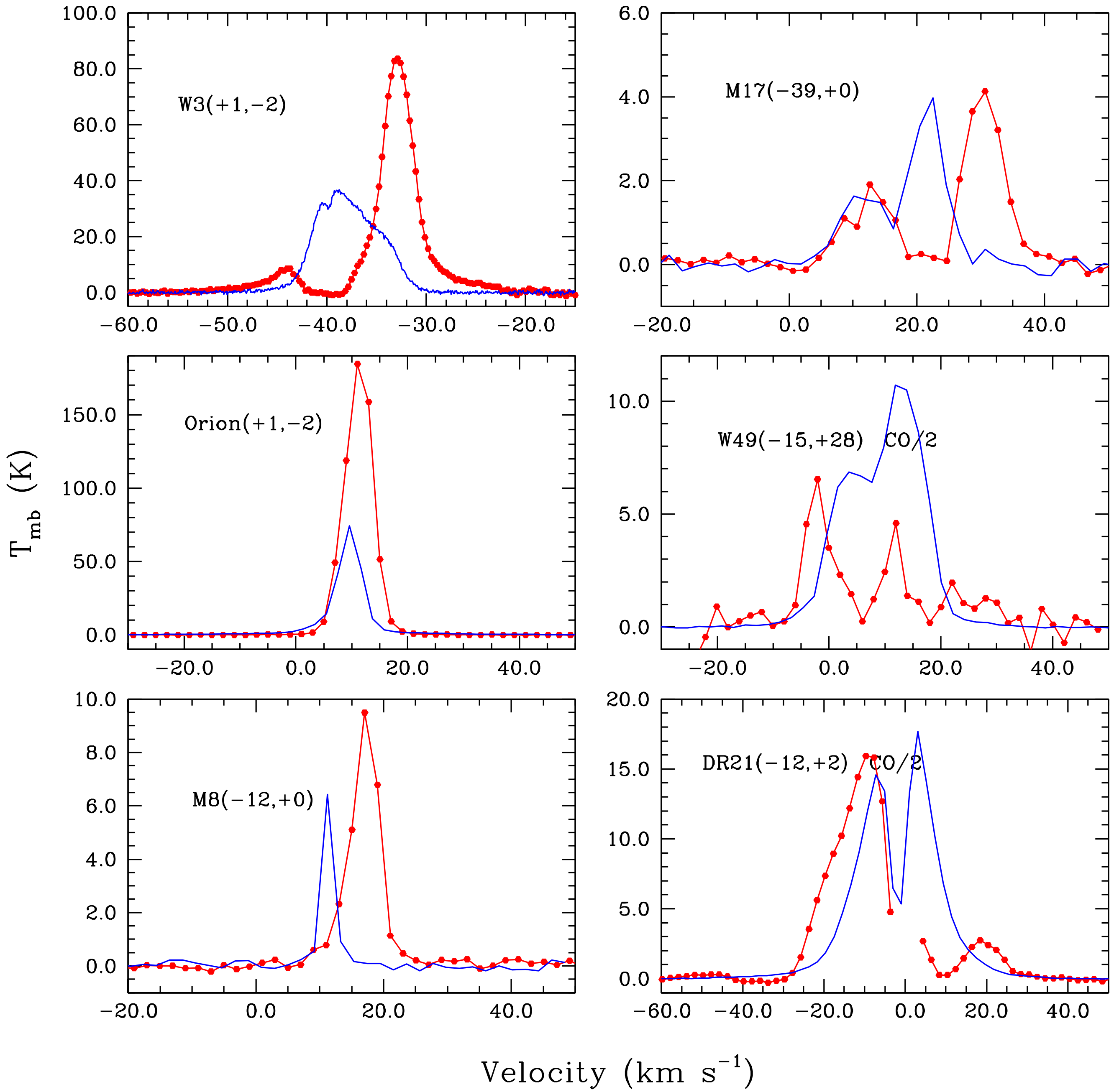
W3 is likely the most extreme case with absorbing O^0 having $\tau = 7$

Orion shows no clear evidence of self-absorption

The radiation from O^0 in "hot" portion of PDR largely absorbed by intervening low-excitation material

Result is **vastly weakened** [OI] 63 µm line
Unresolved spectroscopy of 145 µm line suggests it is relatively unaffected

What we see is highly dependent on **geometry**

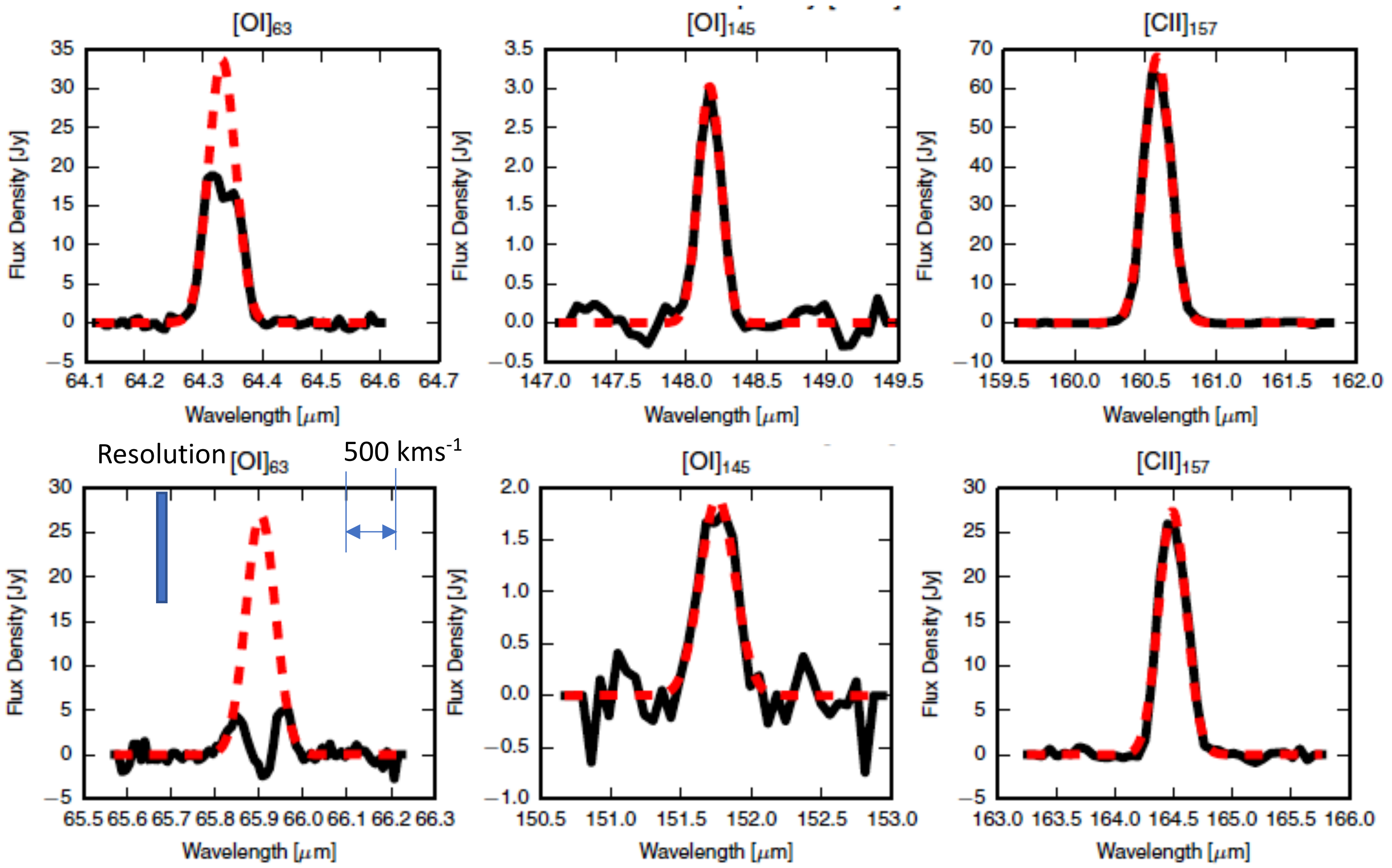


Herschel/PACS Gave Tantalizing Glimpse of Fine Structure Line Emission from (U)LIRGS

Rosenberg+ 2015

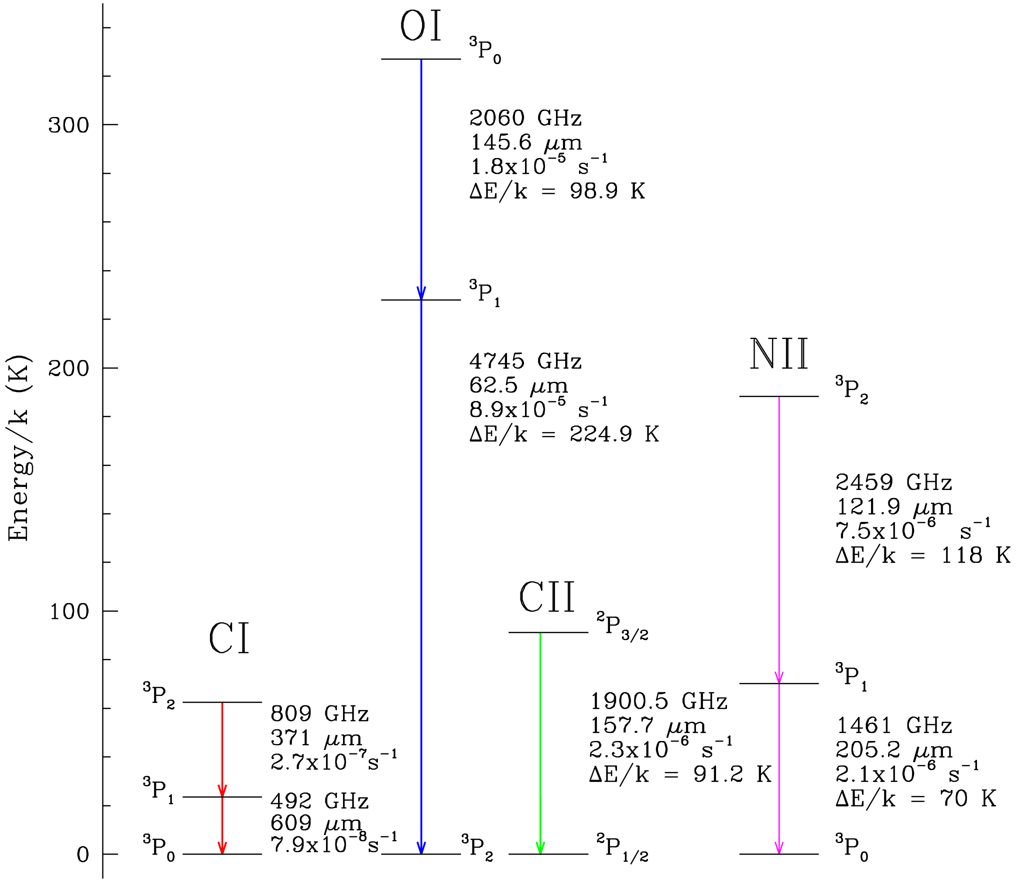
Mrk 331
z = 0.018

IRAS
F17207-0014
z = 0.043

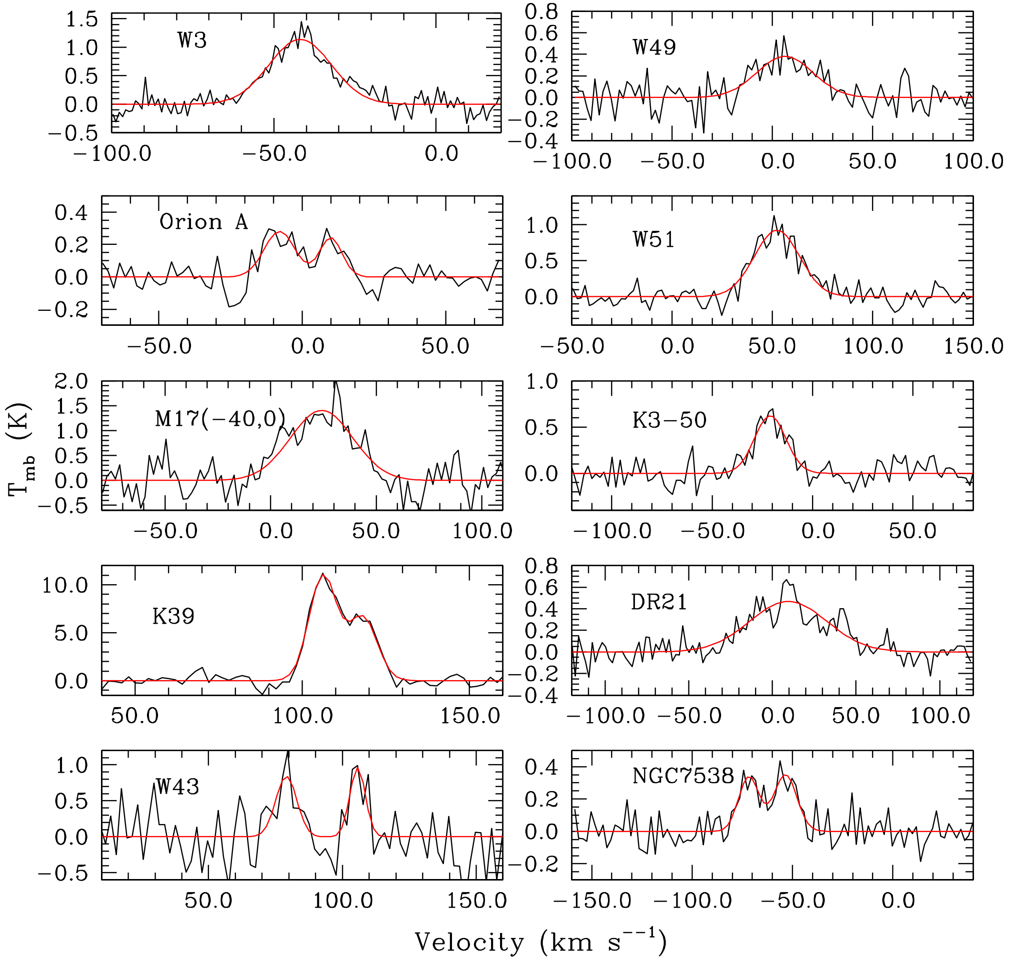


PACS
R ~3000 @ 63 μm
(100 kms^{-1})

Tracing the Ionized ISM – Direct Probe of Massive Star Formation



NII 205 μm SOFIA/GREAT



Most are well-behaved but some have hints of complex structure that deserves follow up

Why is K39 10x stronger than all the others?

Need: High Spectral Resolution Imaging Receiver for SOFIA Studies of FIR Fine Structure & Molecular Lines

FREQUENCY COVERAGE

- [NII] 205 µm 1461 GHz
- [CII] 158 µm 1900 GHz
- [OI] 145 µm 2060 GHz
- [NII] 122 µm 2459 GHz(atmos. poor)
- [OIII] 88 µm 3395 GHz
- [OI] 63 µm 4745 GHz
- [OIII] 52 µm 5790 GHz
- Multiple high-J CO lines; other FS lines

RESOLUTION R = 10^6 (0.3 km s^{-1})

PIXEL COUNT AND MAPPING SPEED

- Time on SOFIA is limited and expensive!
- Combine
  - State of the art noise temperature
  - High coupling efficiency
  - Extended bandwidth
  - Maximum pixel count

WHAT IS FEASIBLE?

1400 – 2100 GHz now!

{3300 – 5800 GHz with development}

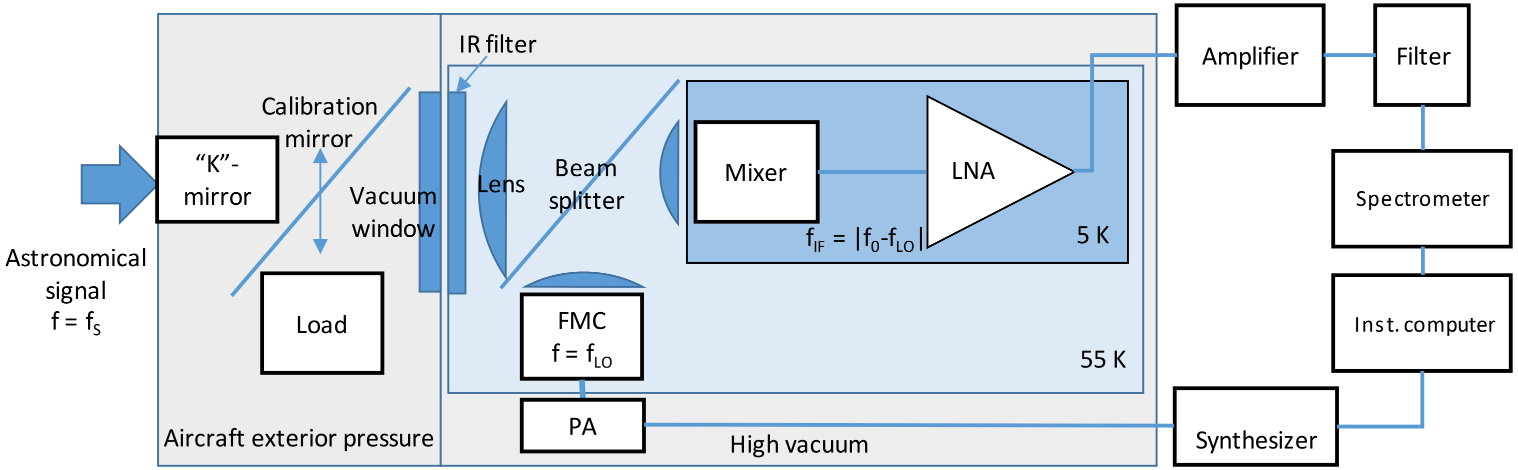
4 GHz IF bandwidth (650 kms^{-1} for [CII])

128 pixel square array

8X8 array times 2 polarizations

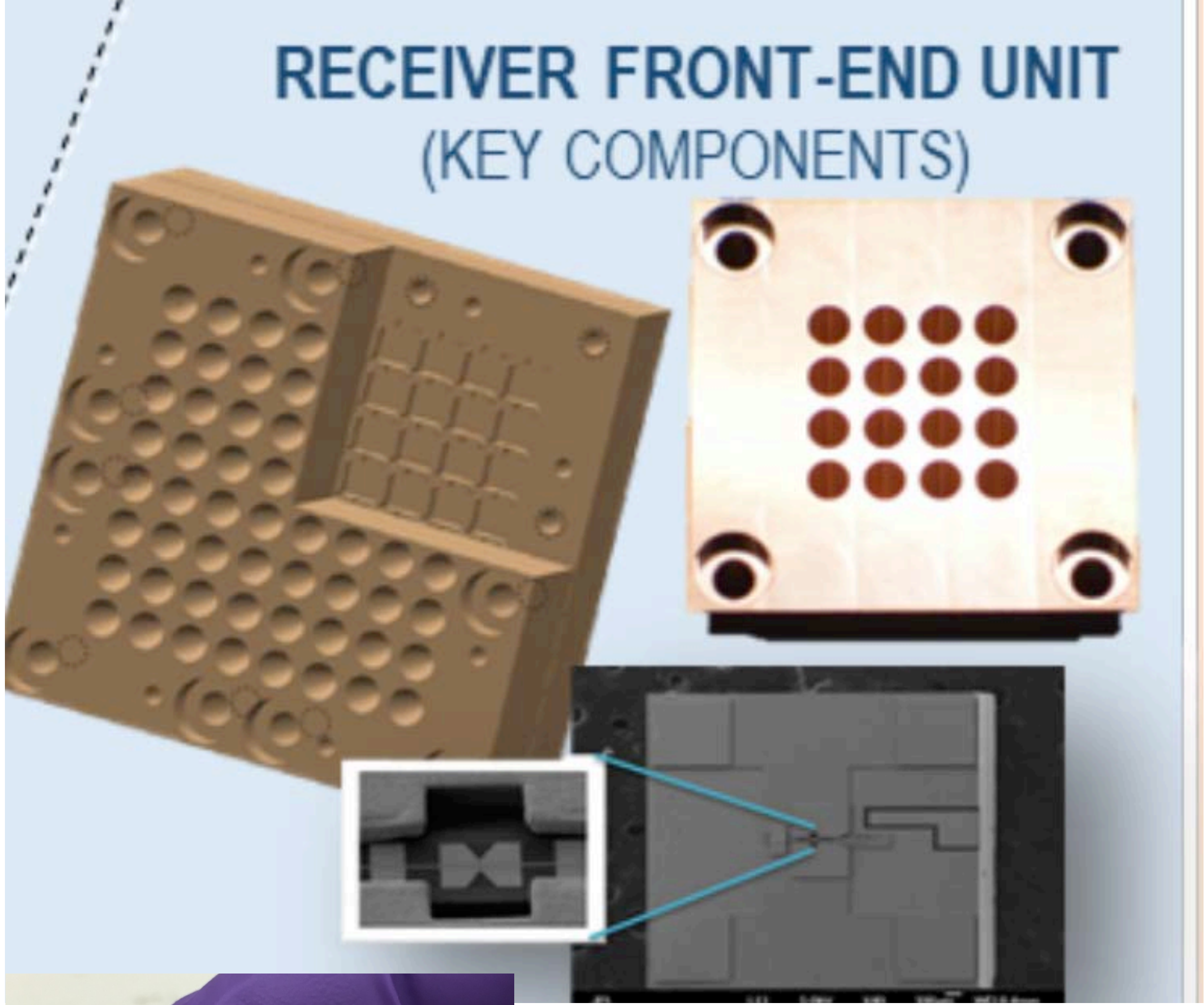
Enabling Technology for Next-Generation Submm Heterodyne Arrays I. – REPRODUCIBLE, HIGH SENSITIVITY HEB MIXERS

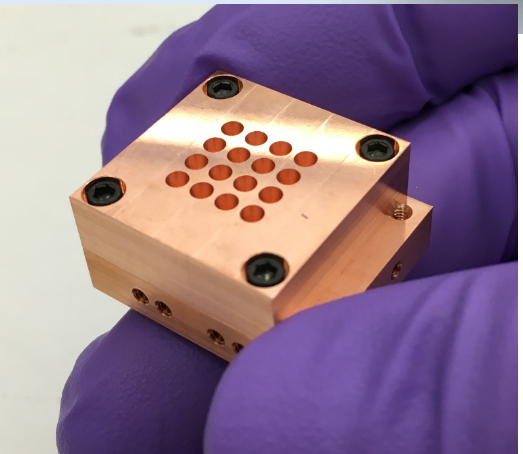
Heterodyne: Combine (weak) astronomical signal with (strong) Local Oscillator (LO) signal in nonlinear device. Then amplify the *difference* frequency (called IF for intermediate frequency) signal generated in low noise amplifier, and finally analyze spectrally



Hot Electron Bolometer (HEB) mixers are widely used throughout submillimeter. Used in Herschel/HIFI, SOFIA/GREAT, STO2, GUSTO, ASTHROS

Well-developed
Undemanding (T > 6 K) thermally Low LO power (few μW)
4GHz IF bandwidth ⇔ 650 kms^{-1} @ [CII]





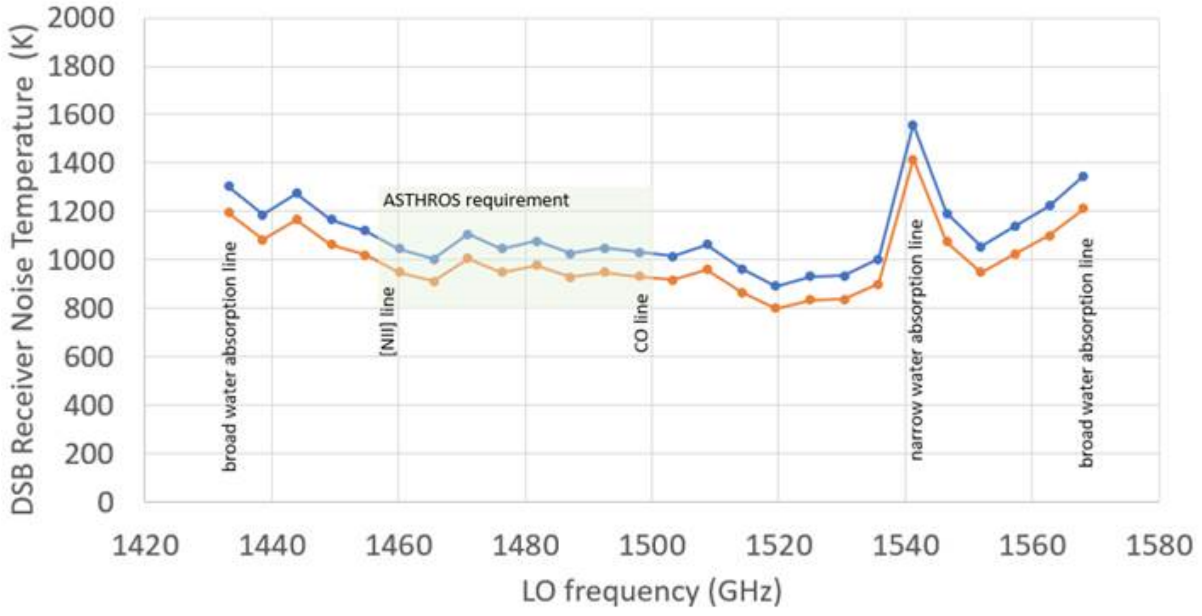
HEB Array Technology

- NbN devices routinely processed in MDL at JPL
- Individual devices diced from wafer
- Dropped into backshort/holder coupling to waveguide input
- Held in place by frontpiece consisting of 16 drilled multi-flare-angle feedhorns*
- 4 frontpieces + backshort make 64-pixel mixer array

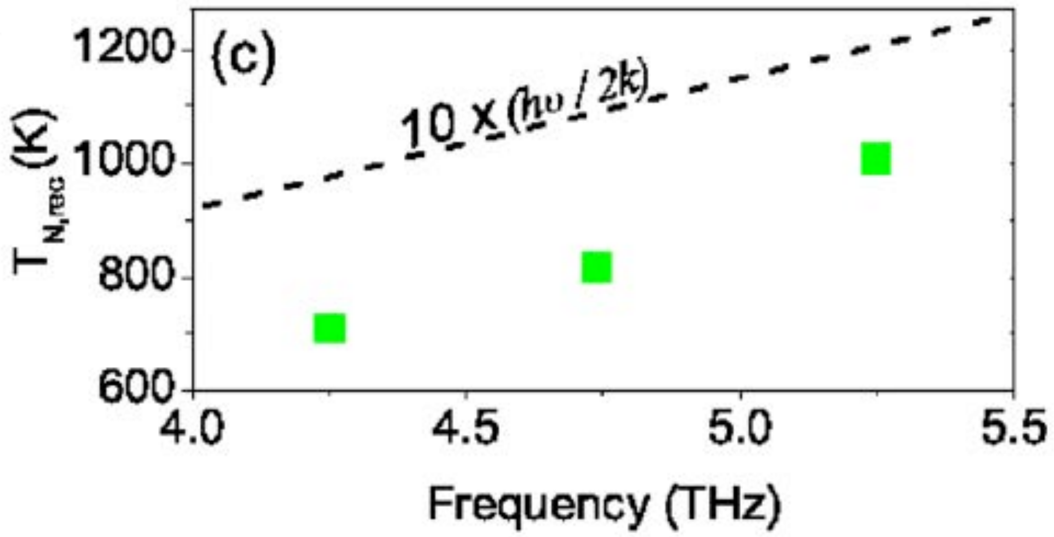
* These feedhorns offer broadband, high efficiency coupling to symmetric Gaussian beam

HEB Mixer Performance is Well-Established: T(DSB) < 1000 K between 1.4 THz and 5 THz

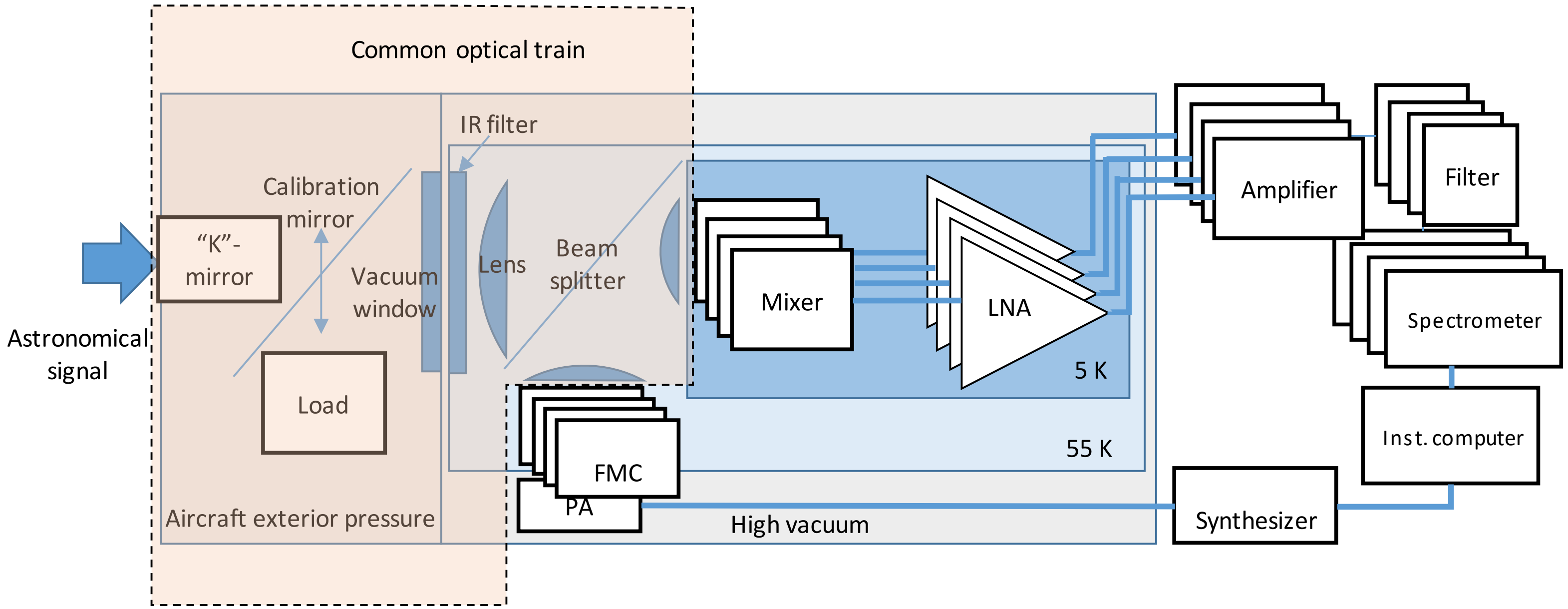
JPL 2020



Kloosterman+ 2012



Array Concept: Replicate Single-Pixel Chain

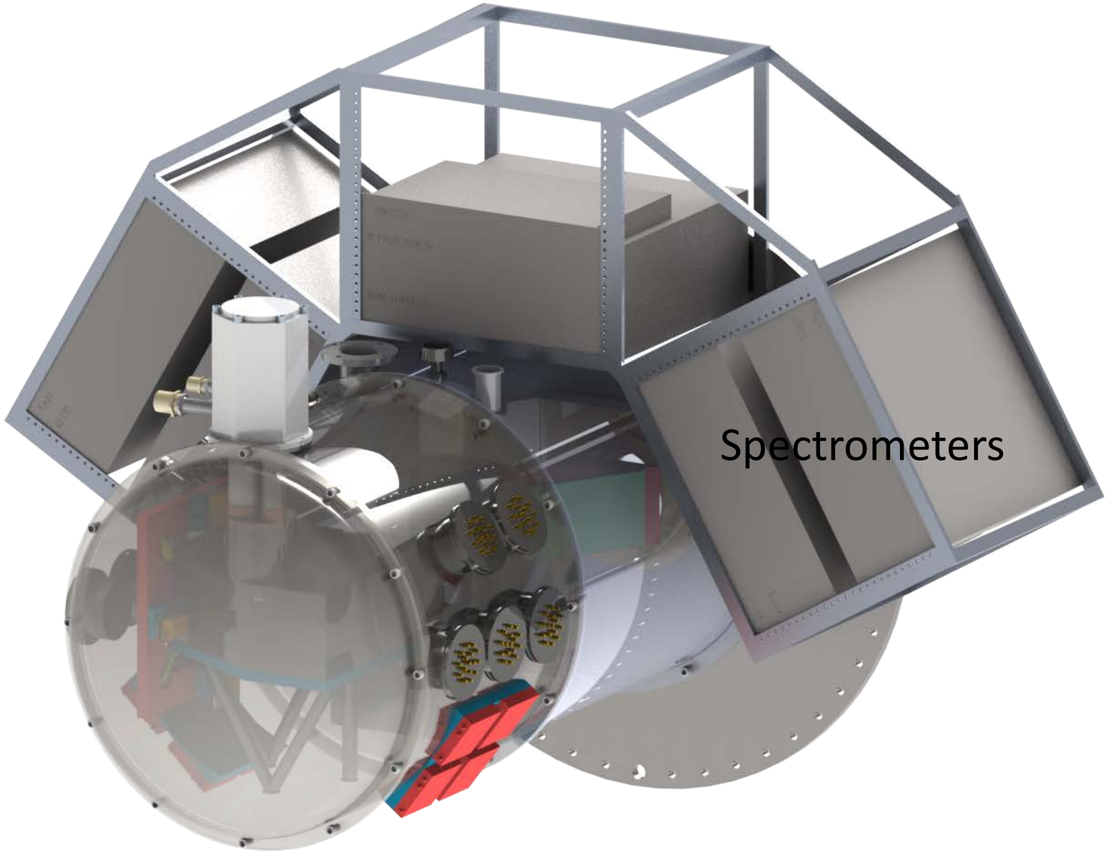


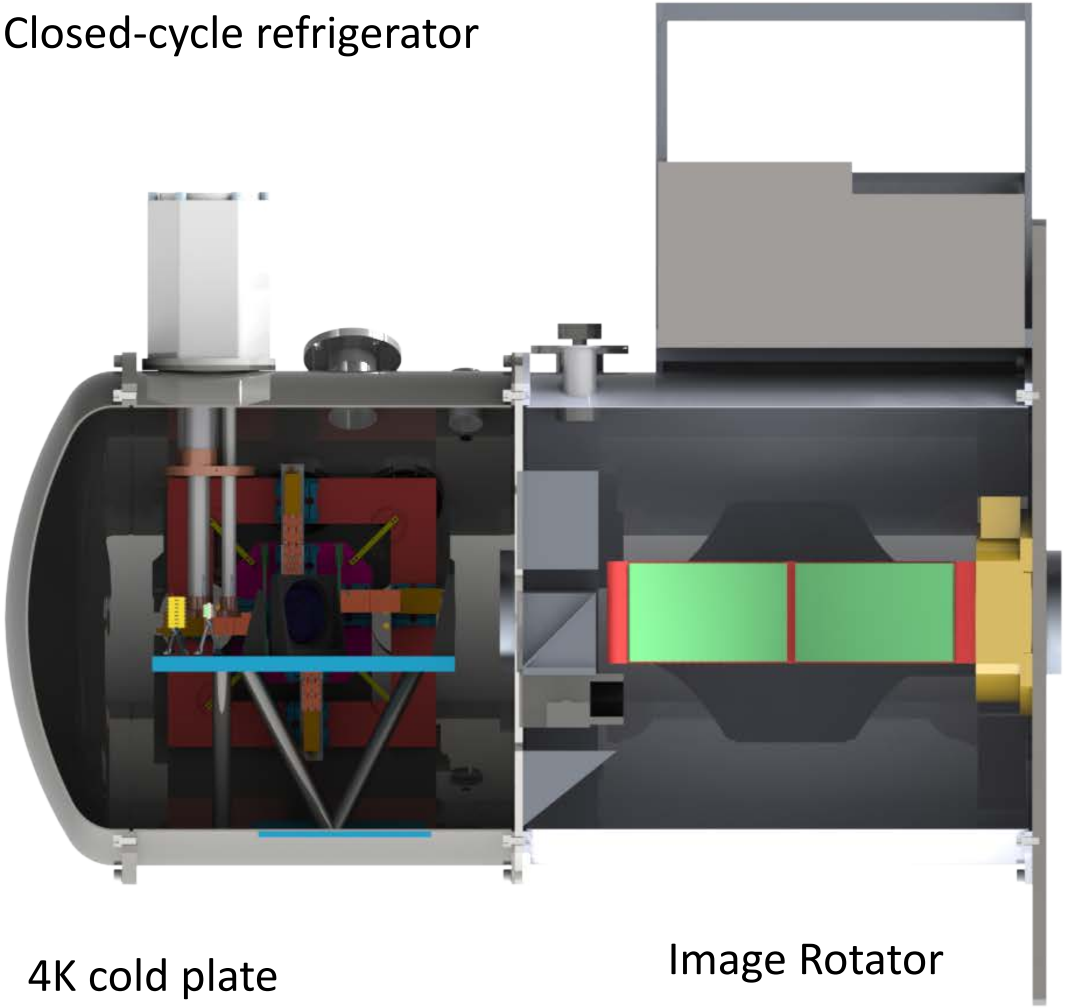
Individual final LO frequency multiplication stages for EACH mixer allows OPTIMIZATION of power and achieving lowest noise temperature

Not shown: input polarizing grid separates linear polarizations. 64 pixels in 8x8 array *per polarization*

Very low risk; simple assembly, alignment, and cooling

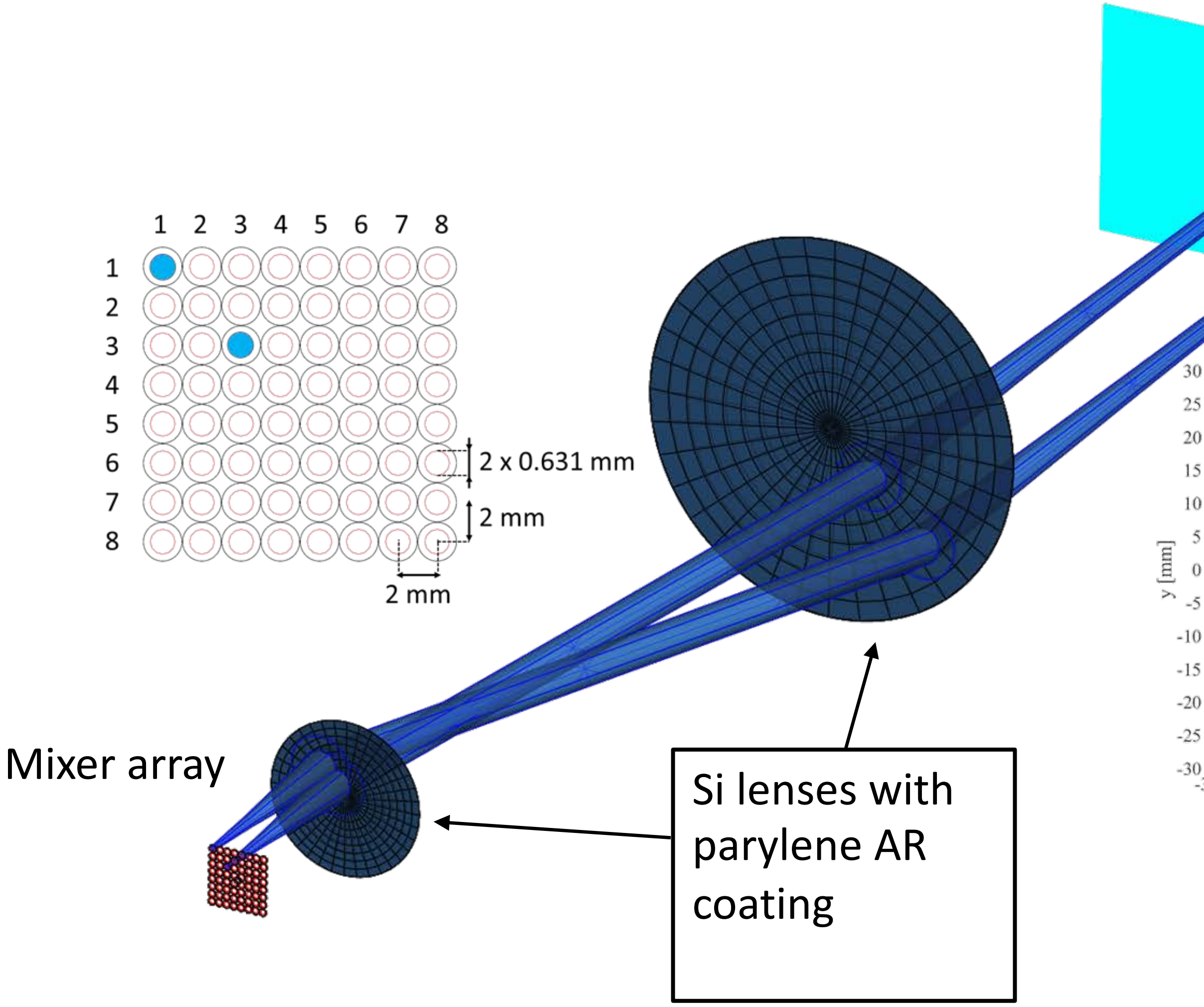
Heterodyne Focal Plane Array Imager on SOFIA - simple and low risk

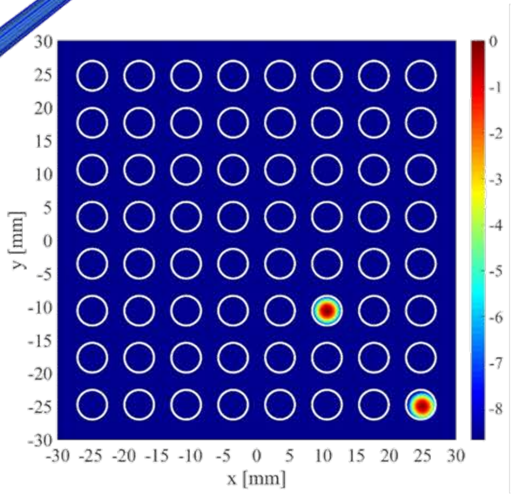




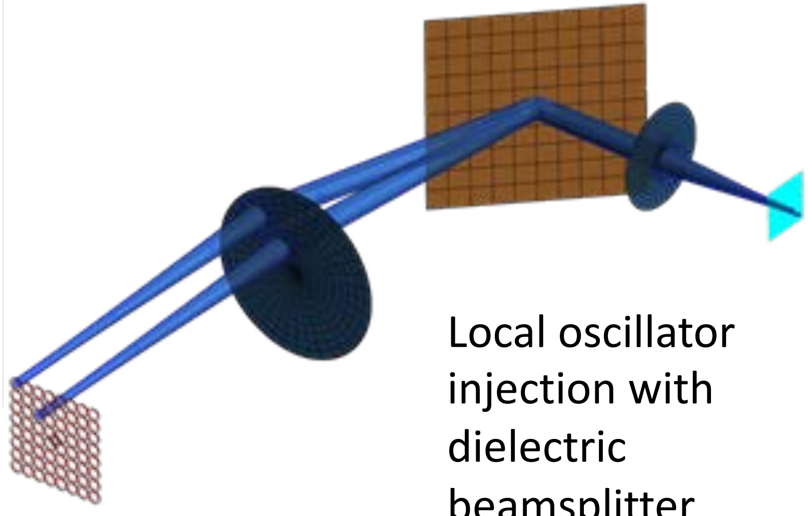
Heterodyne Focal Plane Array Optics – Low Loss and Very Straightforward

- Gaussian beam telescope and multi-taper feed horns provide high efficiency over octave bandwidth
- Two 8x8 mixer arrays diplexed by polarizing grid





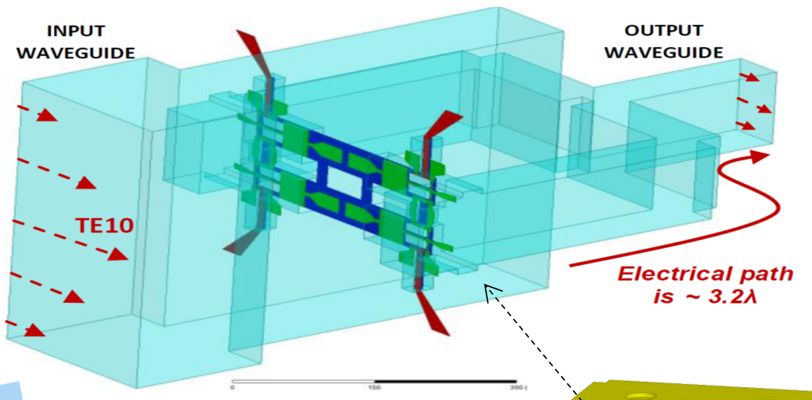
Field pattern in dB

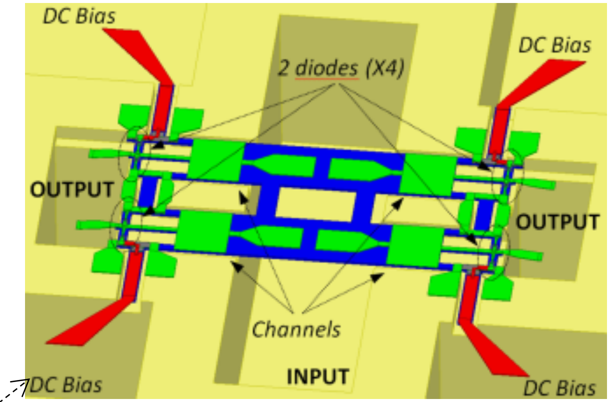


Enabling Technology for Next-Generation Submm Heterodyne Arrays II. – WIDELY TUNABLE LOCAL OSCILLATOR SOURCE

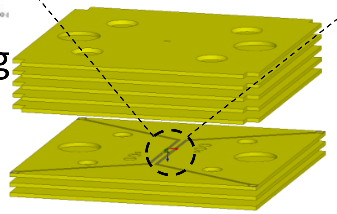
On-Chip Power Combining

- Power x4
- Size /10
- Losses /5
- Lithographic accuracy x10

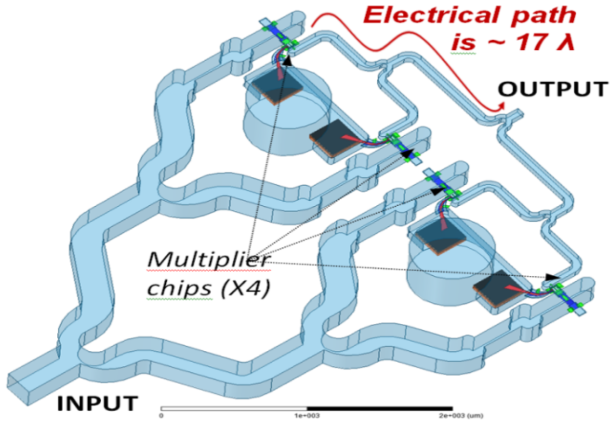




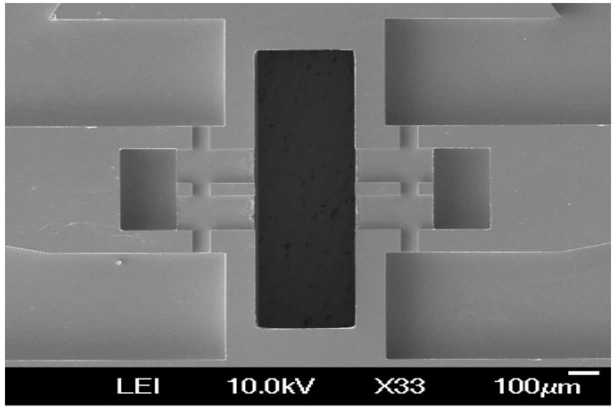
- Lithographic precision for allignment and machining
- No need for waveguide power-dividing

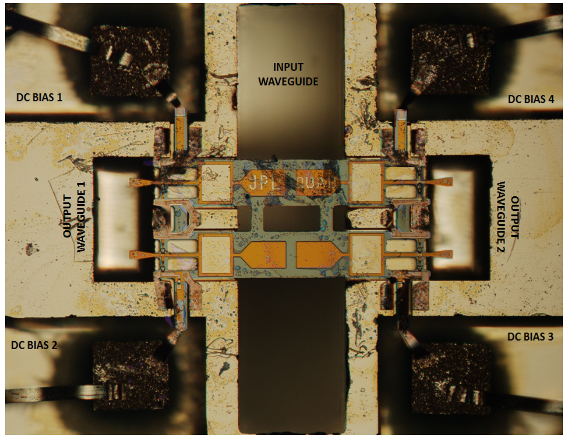


U.S patent (CIT 5953-P), Jet Propulsion Laboratory, California Institute of Technology.



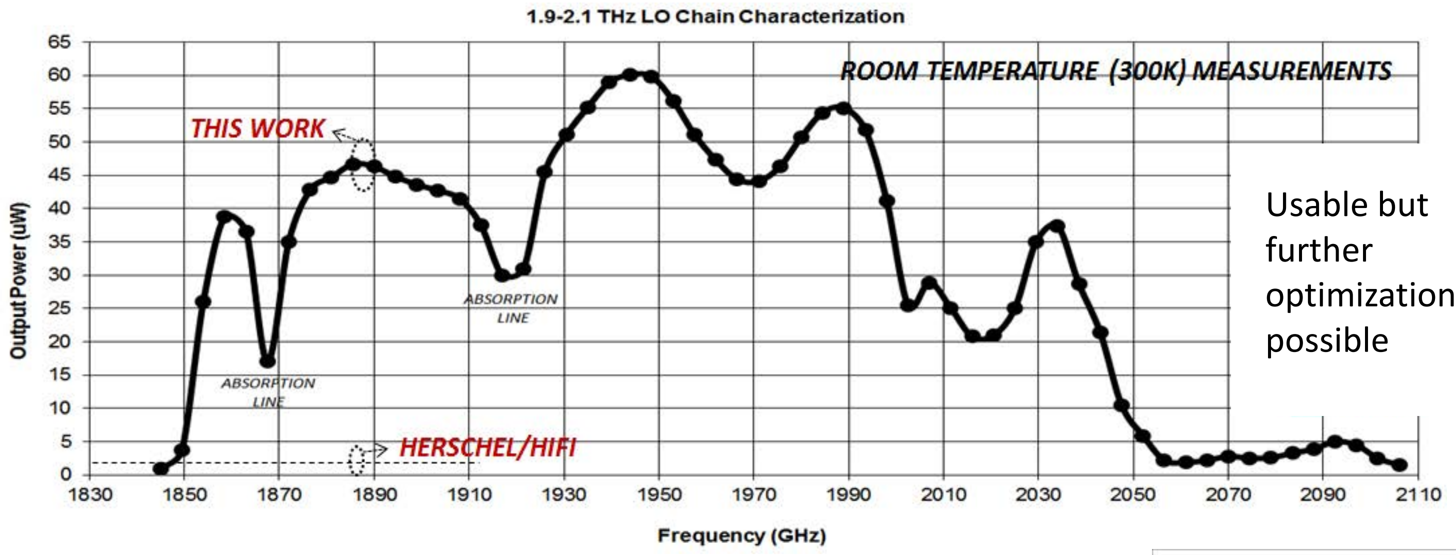
Metal split-block (20mmx20mmx8mm)



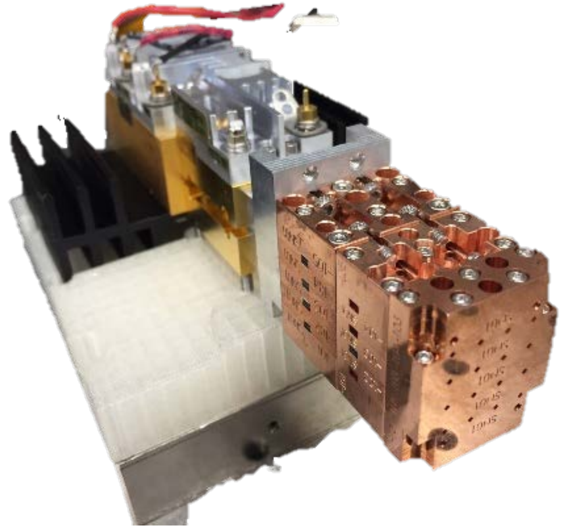


J. Siles, JPL

Huge LO Improvements since Herschel/HIFI



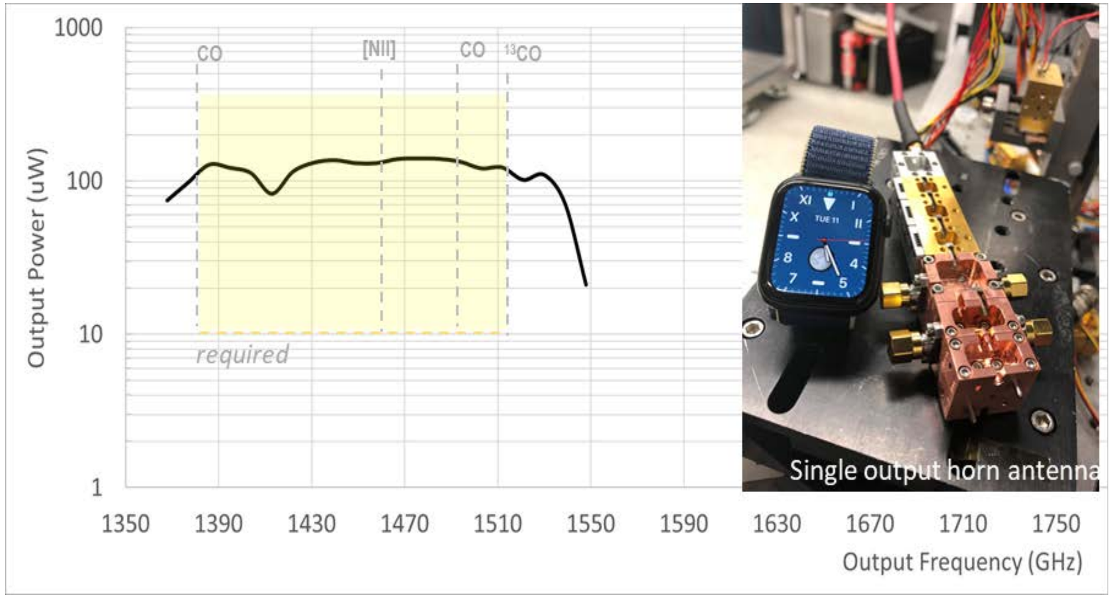
Usable but further optimization possible



16-pixel LO module (~2016)

Insight: If the LO system produces much more power than required, it is straightforward to

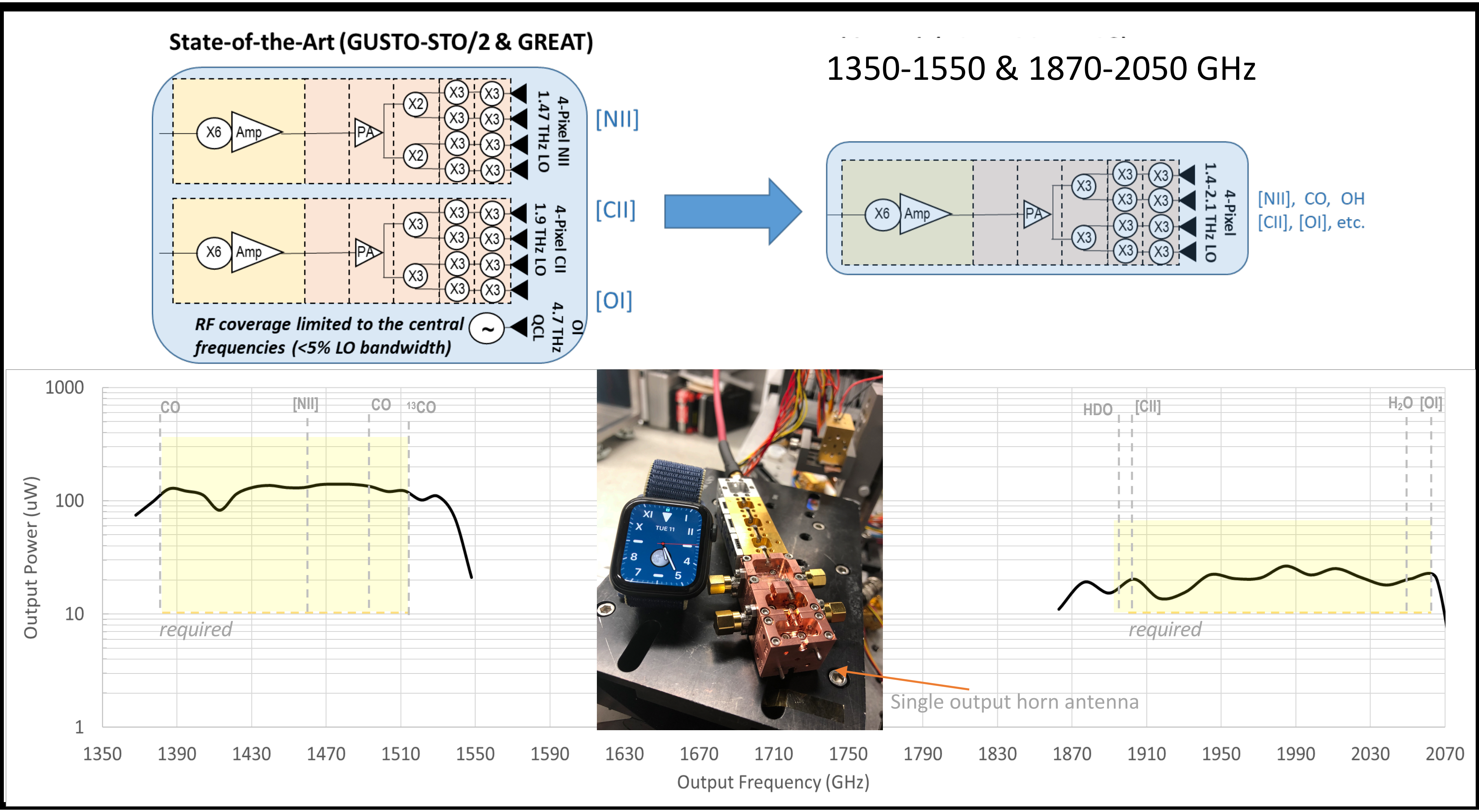
- Optimize LO power for each pixel, pumping even ”demanding” pixels
- Pump N > 100 pixels in array with high yield and minimal rework/replacement



Ultra-Broadband LOs

Jet Propulsion Laboratory
California Institute of Technology

1350 GHz -2100 GHz range



Ultra-Broadband LOs: First Integrated 1350-2070 GHz LO System

4 pixel frequency multiplied source with two bands integrated into one single channel

One order of magnitude reduction on size, mass and power

Enabling Technology for Next-Generation Submm Heterodyne Arrays III – DIGITAL ASIC SPECTROMETERS

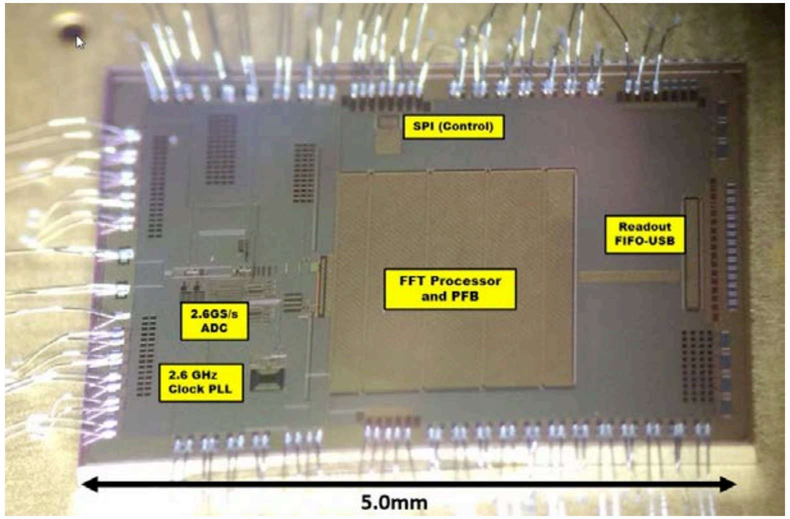
FPGA spectrometers have worked well for GREAT. **However** – while power is modest (~20W), for large-format arrays it becomes excessive (2.5 kW)

The solution is system on chip digital ASIC spectrometer developed by JPL & UCLA

CURRENT: SVII 65 nm **3 GHz** BW, 4096 channels 0.6 W

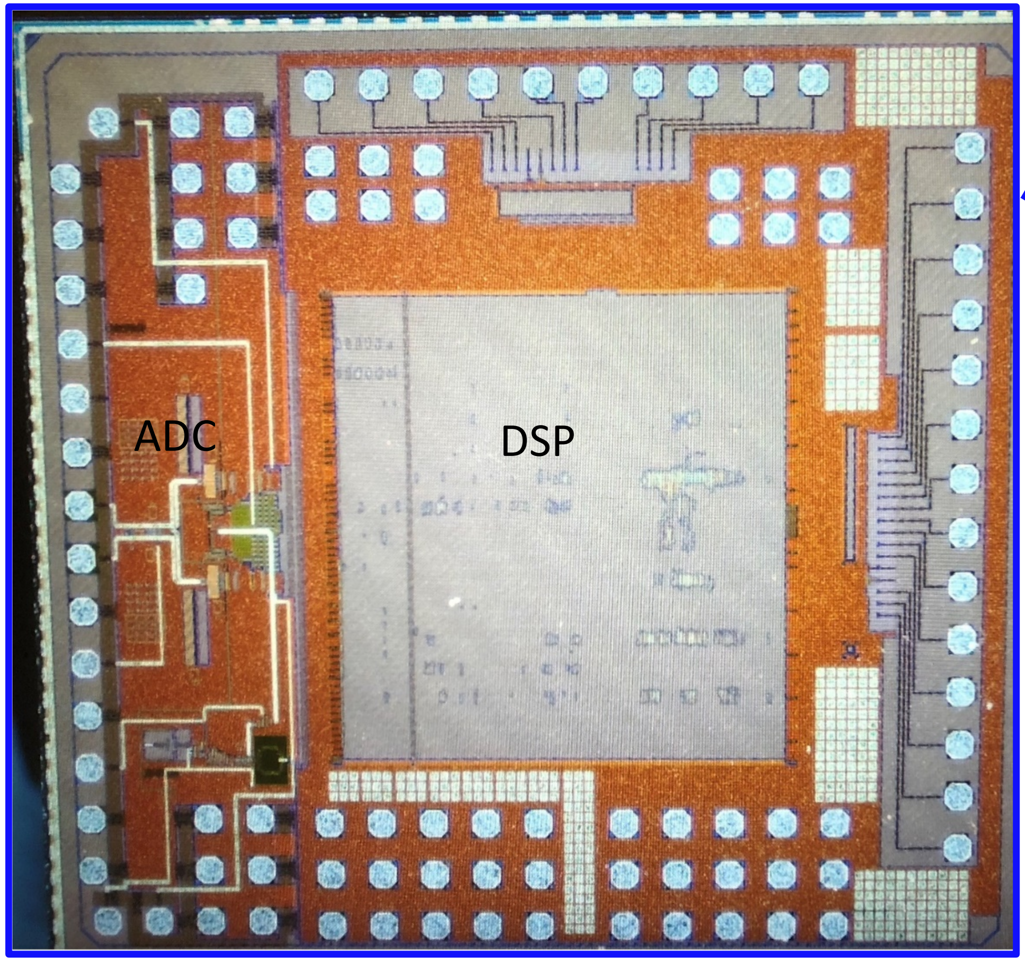
NEARLY DONE: SVIII – **6.5 GHz** BW, 8192 channels, 4 bits, 1.7 W

Have flown on airplanes & balloons (ReckTangLE); being baselined for ASTHROS APRA balloon (launch 2023) and proposed for Astrophysics Pioneer Mission

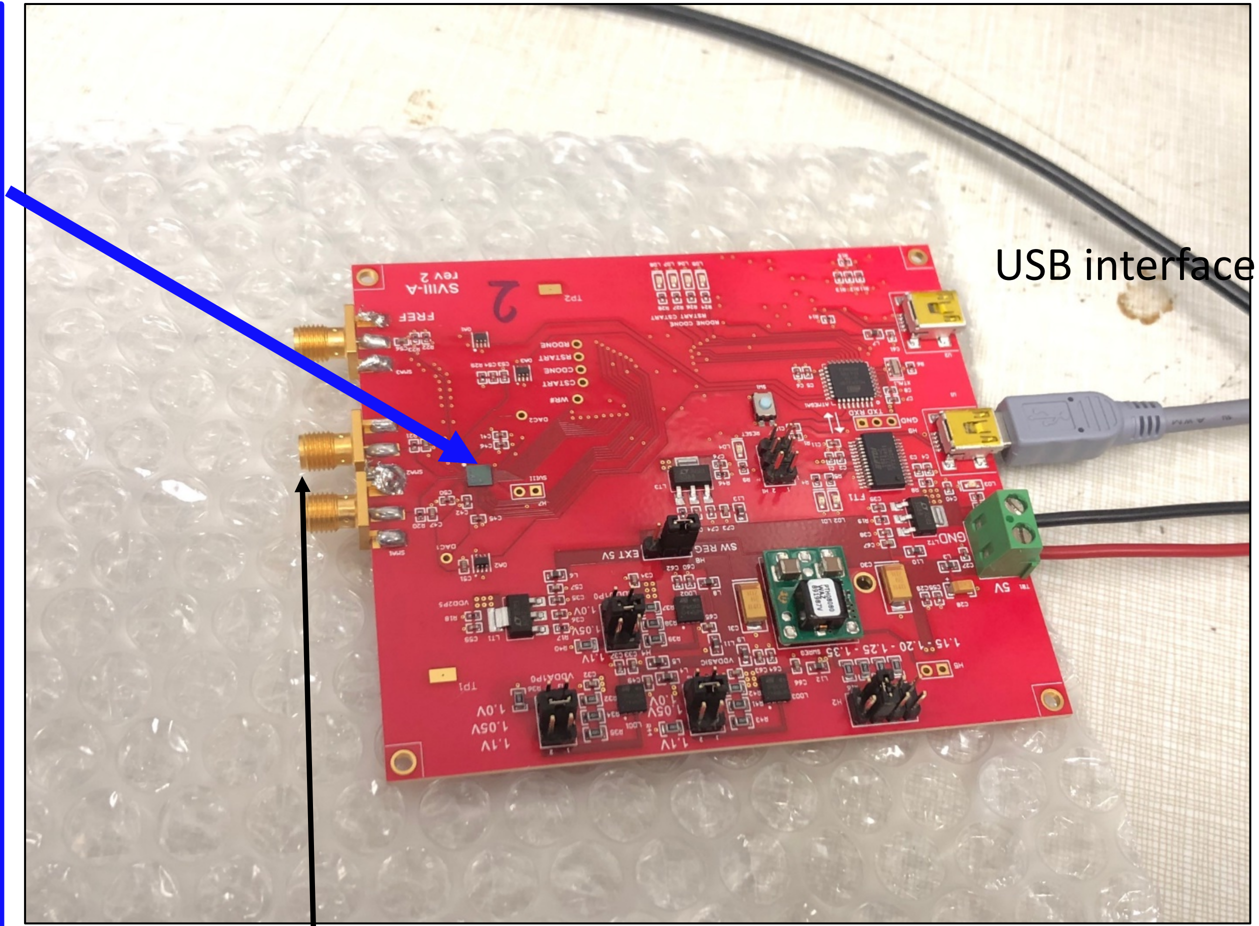


Zhang+ 2018 IEEE Int'l. Symp. Circuits & Systems

SVIII ASIC Digital Spectrometer Chip & Board



0 – 6 GHz (or 6 – 12 GHz aliased)



Analog inputs (ADC included)

Program for space qualification (radiation, temperature…) has been started, but suitable for SOFIA at the present time

Current Status and What Should be Done for the Future of SOFIA

- Velocity resolved spectroscopy has been huge strength for SOFIA thanks to GREAT instrument. It can be even more productive in the future
- To have dramatically greater scientific impact we need to increase mapping speed by an order of magnitude and be able to sample all major components of ISM – (excited) molecular, PDR, and ionized gas
- A 128-pixel spectroscopic array will have an order of magnitude increase in mapping speed compared to upGREAT LFA and hugely more compared to HFA and 4 GREAT, and can cover needed frequency range
- This can be implemented now, but technology development program willß be valuable to
  - Improve **tuning range** of LO sources
  - Support development of frequency-multiplied sources **above 2 THz**
  - Increase IF **bandwidth** of mixers above 2 THz – support development of MgB_2 mixers