Heterodyne Technology for future SOFIA Instruments

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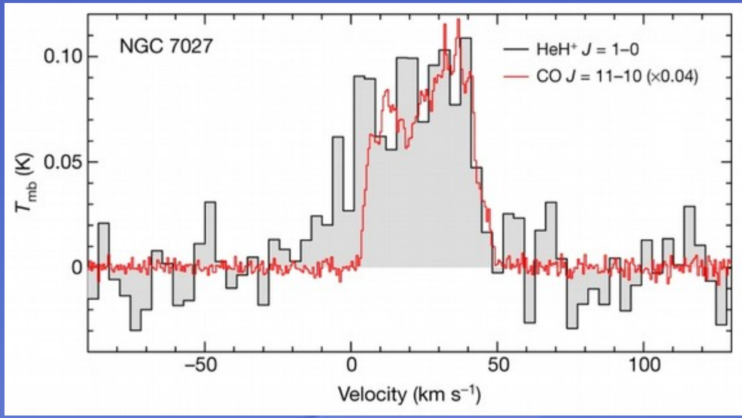
Heterodyne Spectroscopy with SOFIA

Important tool to study physical properties over a wide range of sources:

- **Detailed studies of localized sources**
  - multi-line studies
  - line detection experiments
  - absorption lines

  → spectral mapping: few pixels, many frequencies

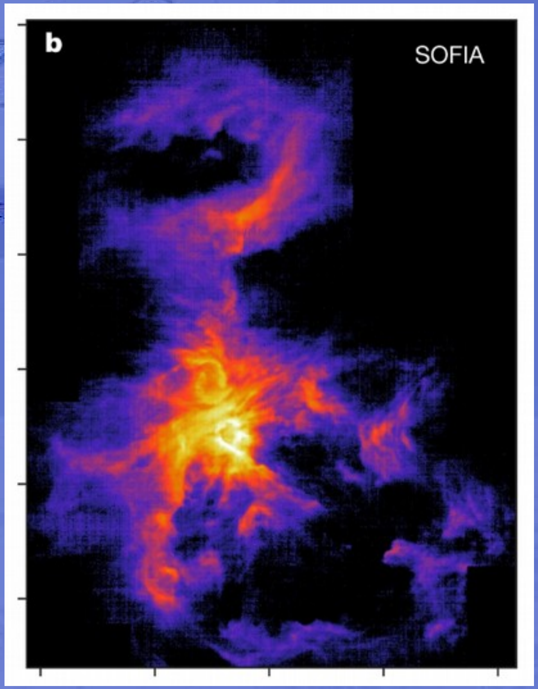


Güsten+ 2019

- **Mapping of strong lines in extended sources**
  - gas kinematics
  - 3D structure

  → spatial mapping: many pixels, few frequencies

  Canonical lines of interest:
  - [NII]: 1461 GHz (205 µm)
  - [CII]: 1900 GHz (158 µm)
  - [OI]: 2060 GHz (145 µm)
  - [OI]: 4745 GHz (63 µm)

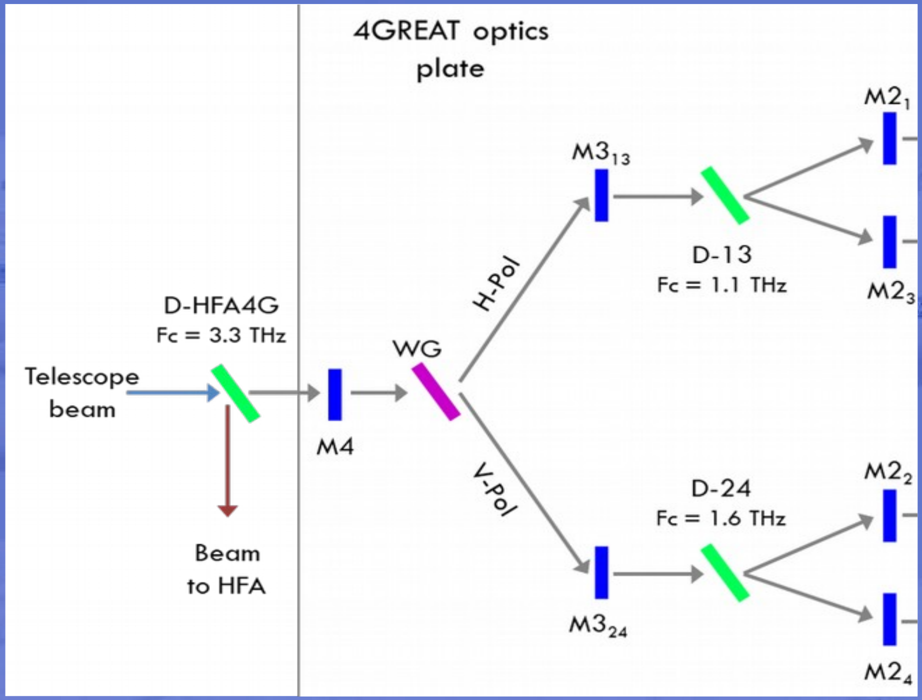


Papst+ 2019

Spectral Mapping: current Status

- **Mixer bandwidth is limited**
  - many mixers needed for full spectral coverage
  - optical pre-separation of bands may be complex

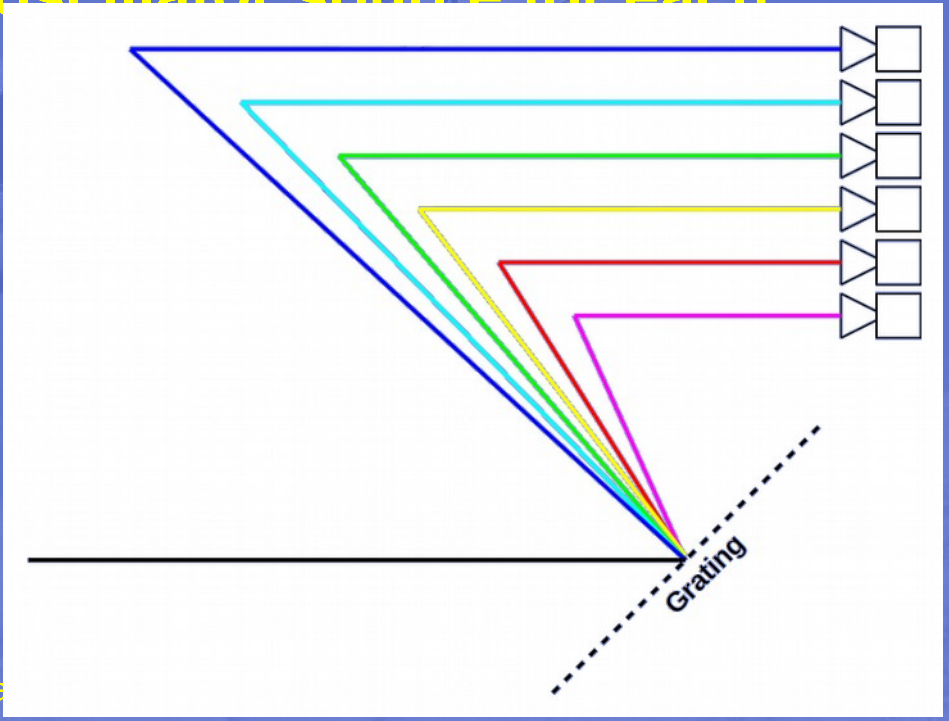
  Example 4GREAT: two dichroic mirrors (D_{13}, D_{24}) and one wiregrid polarizer (WG) to separate 4 bands



Durán+ 2020, submitted

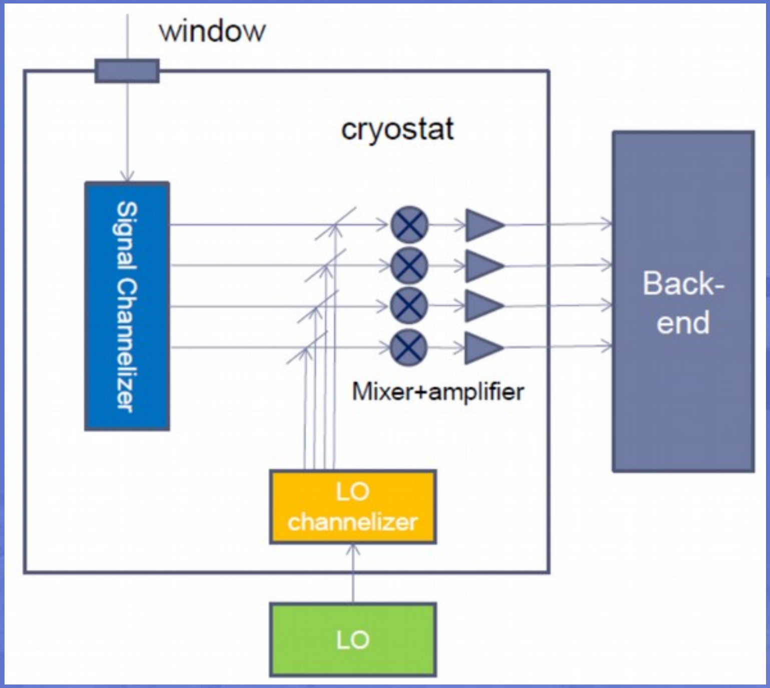
Spectral Mapping: possible new approaches

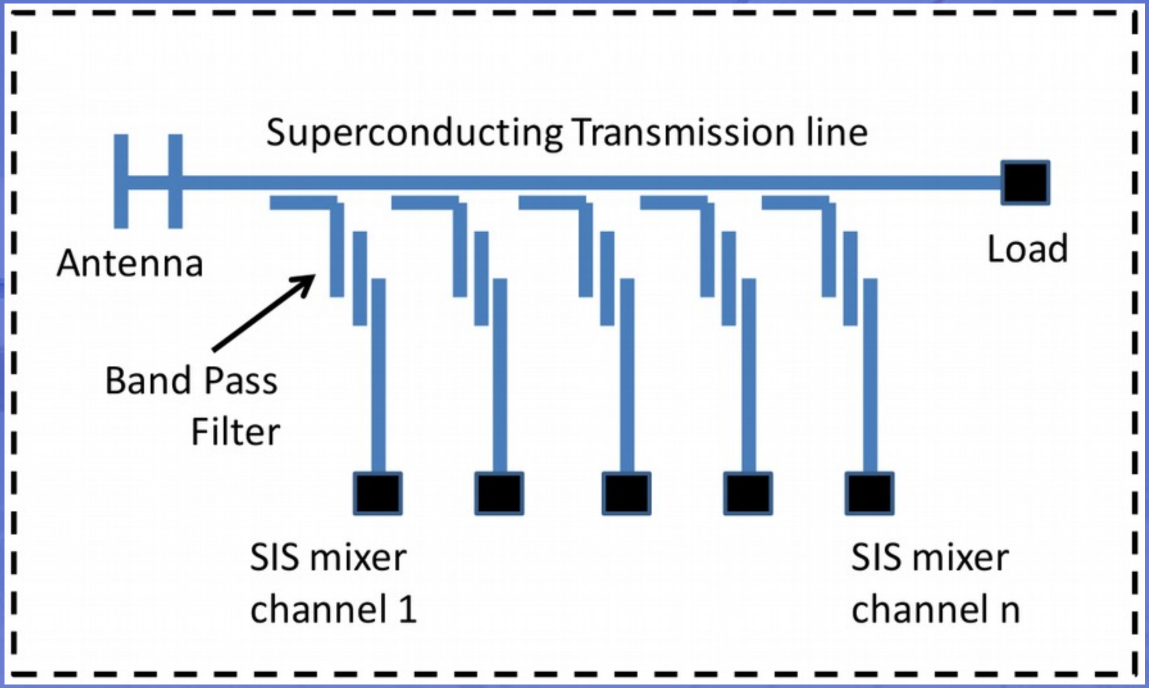
- **Grating or grism as "predisperser"**
  - disperse signal to *N* individual mixer bands
  - allows observing *N* lines simultaneously
  - may achieve continuous spectral coverage (however not instantaneous!) with a manageable number of conventional mixer channels
  - requires dedicated local oscillator source for each band
  - opto-mechanically challenging
  - S/N will vary strongly between bands



Spectral Mapping: possible new approaches

- **Dedicated spectral mapper (RF filter bank)**
  - frequency comb LO feeds array of mixers spectrally spaced by their IF bandwidth
  - instantaneous continuous frequency coverage
  - requires mixers with large IF bandwidth (not HEB)

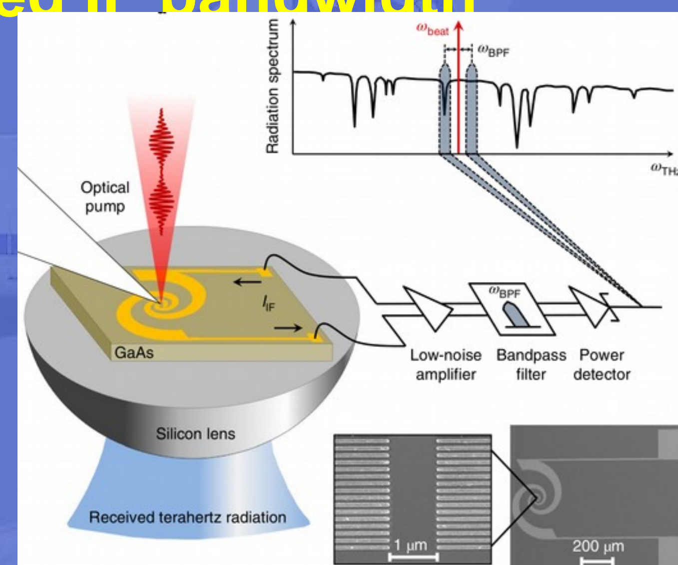




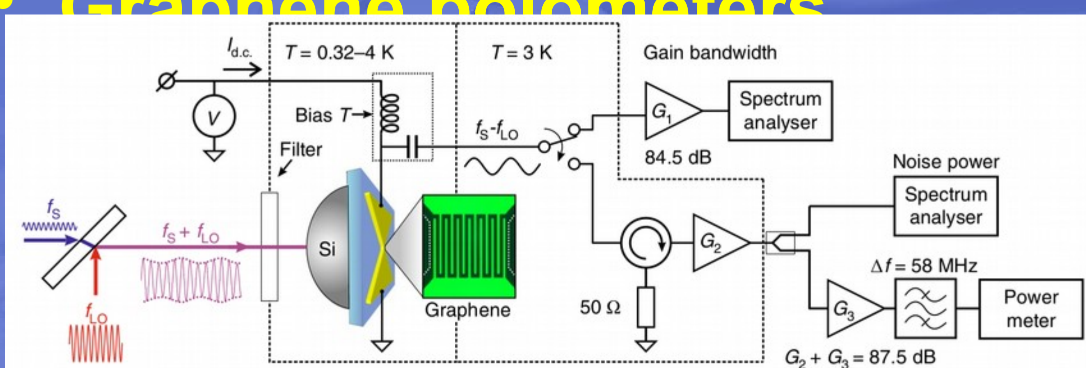
Groppi+ 2019

Mixer Technology

- **SIS (superconductor-isolator-superconductor) tunnel junctions: work horse at *f* < 1 THz**
  - **limited RF frequency, but large IF bandwidth**
- **HEB (hot electron bolometer): work horse at *f* > 1 THz**
  - **unlimited RF frequency, but limited IF bandwidth**
- **Photomixing detectors (room temperature!)**
- **Graphene bolometers**



Wang+ 2019



Lara-Avila+ 2019

Spatial Mapping: pixels, pixels, pixels!

Limitations to array size:

- **Telescope:**
  - Field of view
  - Instrument mass (600 kg; upGREAT weighs 595 kg)
- **Aircraft:**
  - Electrical power
- **Operating efficiency**
  - Tuning overhead
- **Technology, complexity, money, …**
  - optimistic price tag: 25,000 US-$ / pixel

Field of View

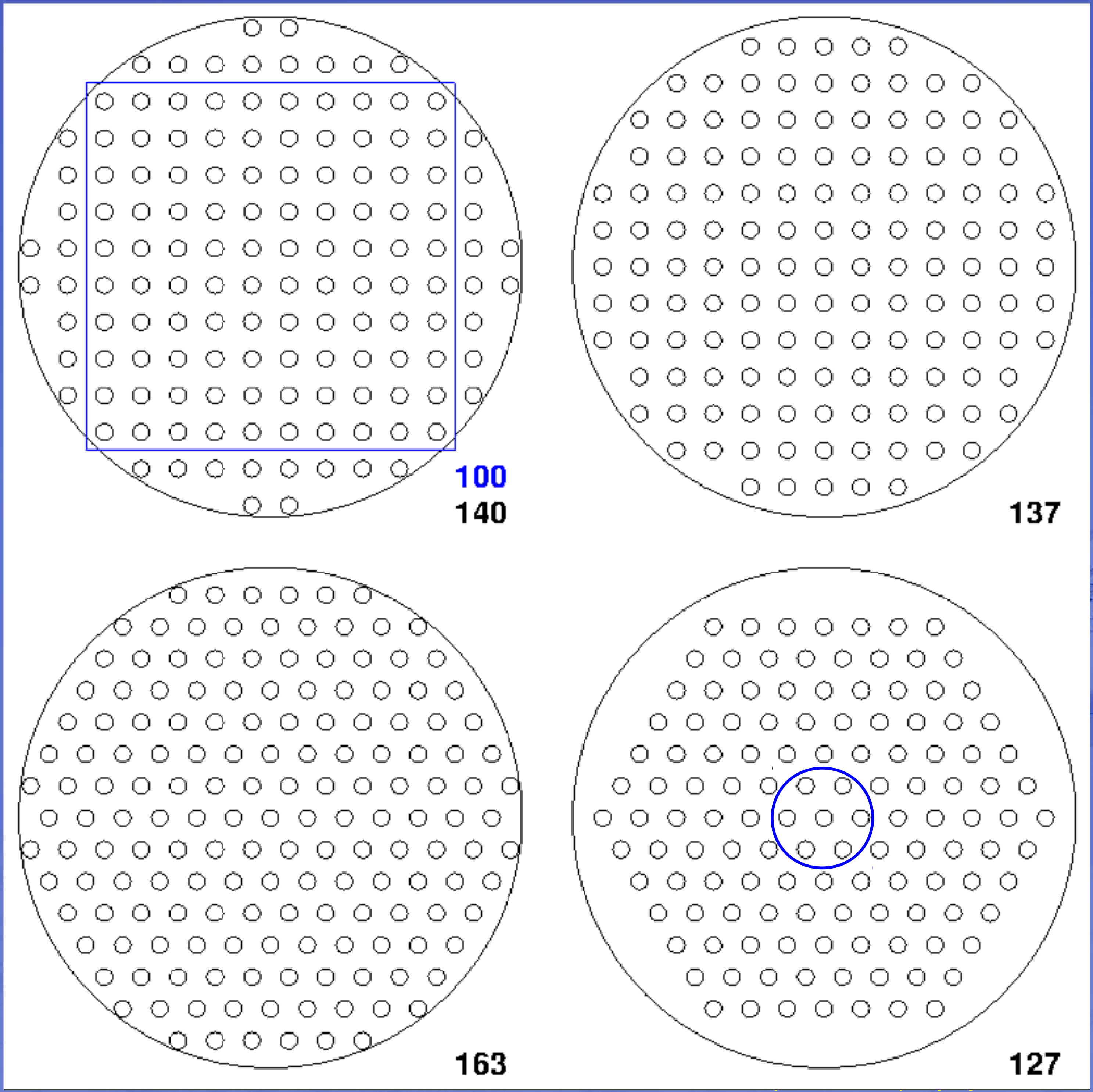
- SOFIA's FOV is 8 arcmin ∅, 50 arcmin^2
- Beam FWHM is ~0.1 arcsec x λ / μm
- Minimum beam spacing in heterodyne system is ~2 x FWHM

→ each beam occupies ≥0.04 arcsec^2 x (λ / μm)^2

→ SOFIA's focal plane accommodates

≤ 4.5 x 10^6 / (λ / μm)^2 heterodyne pixels

- Canonical lines of interest:
  - [NII]: 107 pixels
  - [CII]: 180 pixels
  - [OI_{145}]: 214 pixels
  - [OI_{63}]: 1133 pixels
  - dual polarization: take any TWO of the above

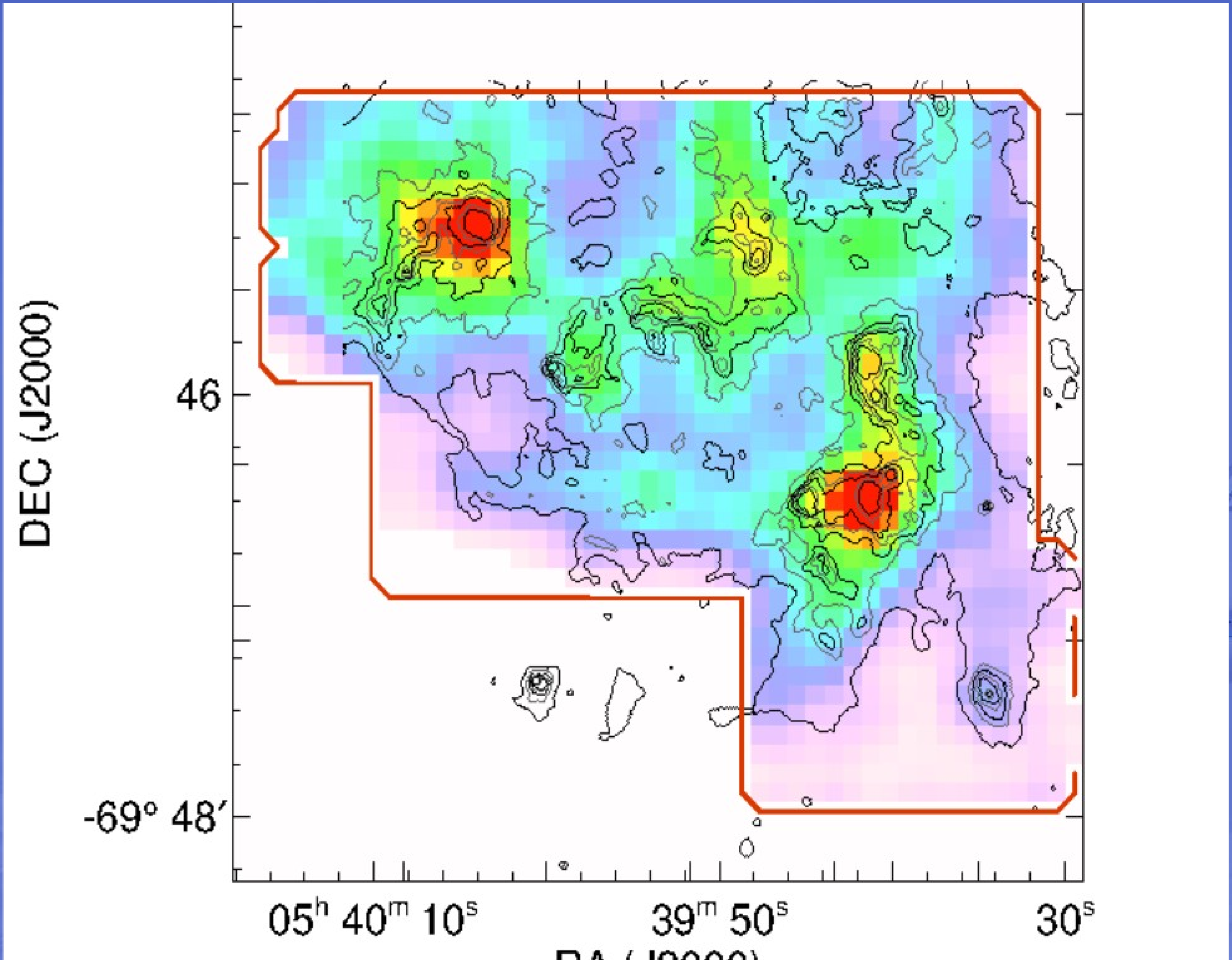


Pixel-#
@1.9 THz

up to 163 pixels possible

technical reasons (LO-distribution, manufacturing) may limit to 100 or even 64 pixels

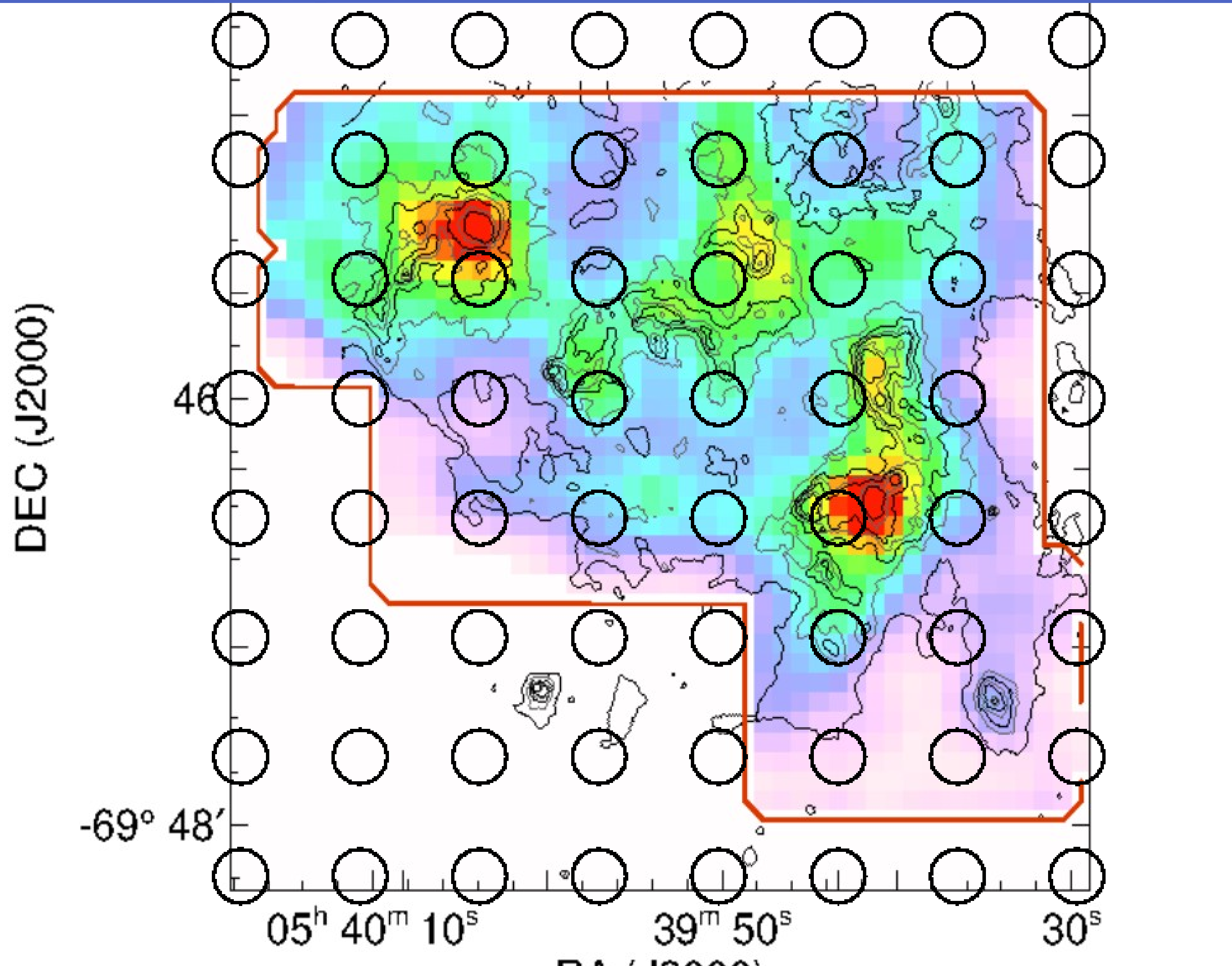
Size comparison: N159



Okada et al. 2014

3.25 h GREAT observing time
~15 sec / point

Size comparison: N159



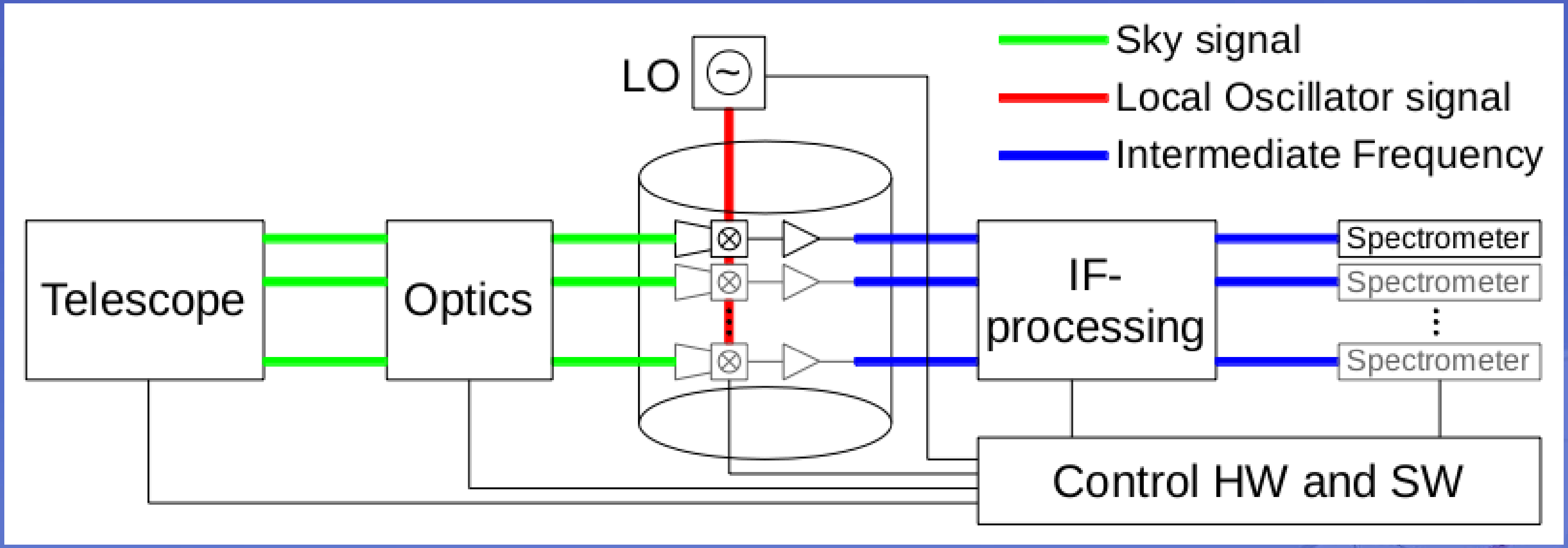
Okada et al. 2014

3.25 h GREAT observing time ~15 sec / point

64 pixel array requires ~25 pointings for Nyquist sampling

⇒ 6 min plus overhead (typically ~15 min)

Heterodyne Array Components

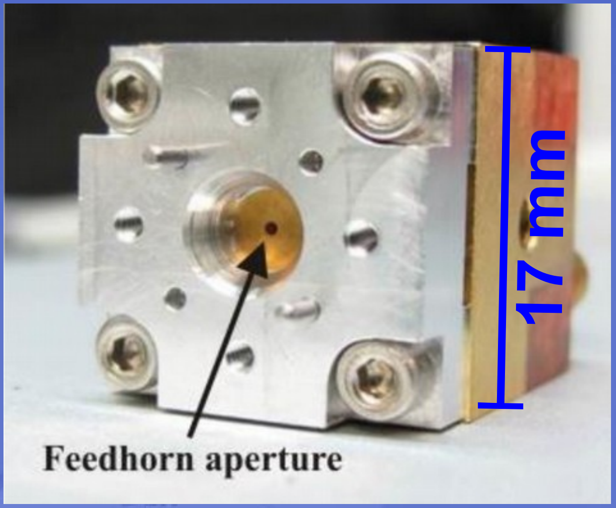


- high per pixel cost, weight and complexity → need to be efficient!
- optics (mostly) and cryogenics same as for single pixel
- IF-processing/backends: every component needs to be multiplied!
- mixers and LO coupling: highest concentration of critical components and no space available...

Mixer Focal Plane: sizes and reimaging

- Pixel size in telescope focal plane ~50λ
  - 8.3 mm @ 1.9 THz
  - 3.3 mm @ 4.7 THz
- "natural" optical pixel size ≲6λ
  - 1.0 mm @ 1.9 THz
  - 0.4 mm @ 4.7 THz
- "natural" mechanical pixel size: ~10 mm (IF-connector)
- Reimaging required (pixels individually, whole array)
- Possible approaches:
  - open structure mixers: very tight tolerances!
  - waveguide mixers: difficult machining

upGREAT
4.7 THz mixer

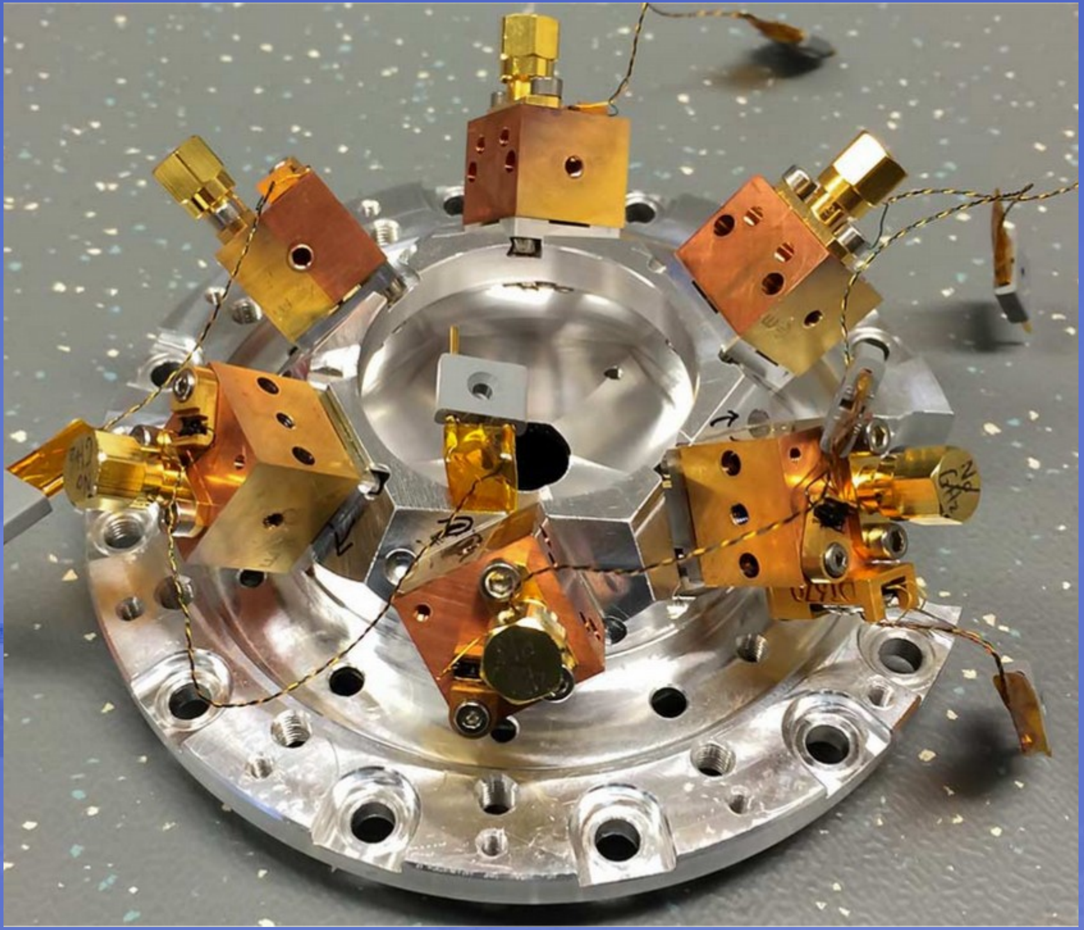


Büchel+ 2014

Focal Plane Unit

- **individual mixer approach (upGREAT) not attractive for large array**
- **multi-mixer blocks (e.g. SuperCam, CHAI)**
- **fully integrated focal plane?**

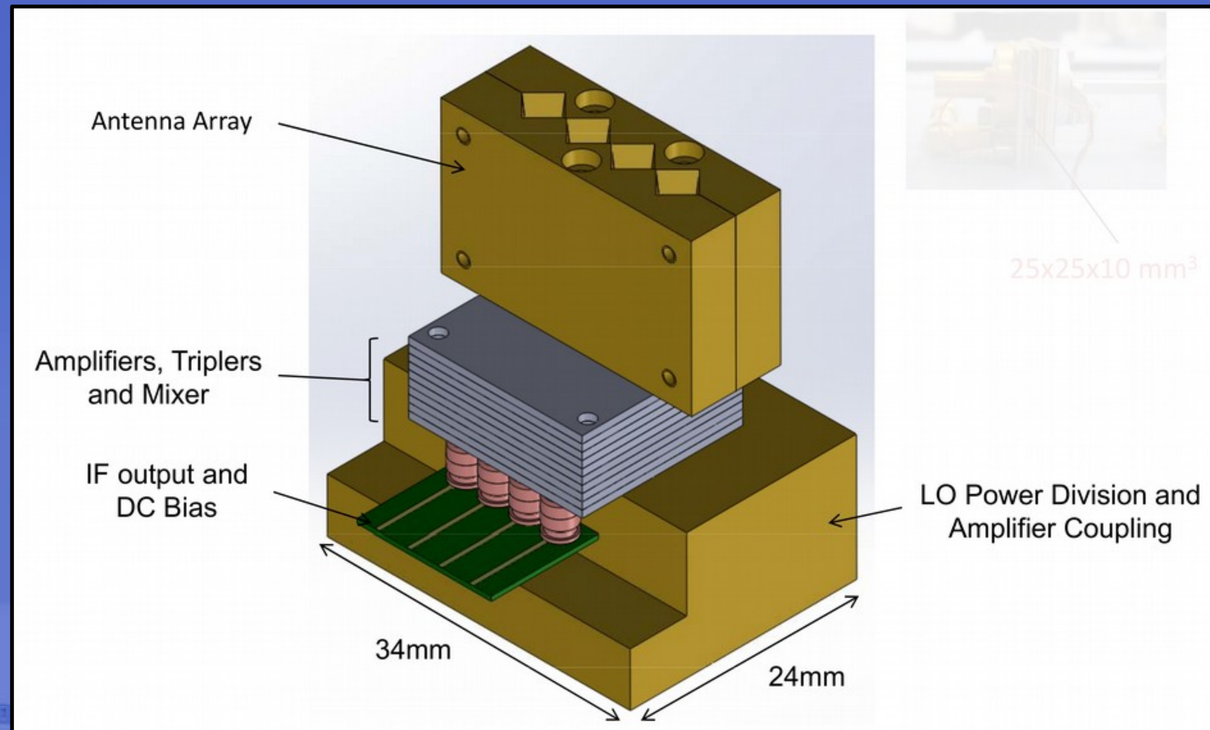
upGREAT FPU



Risacher+ 2016

Focal Plane Unit

Chattopadhyay 2013



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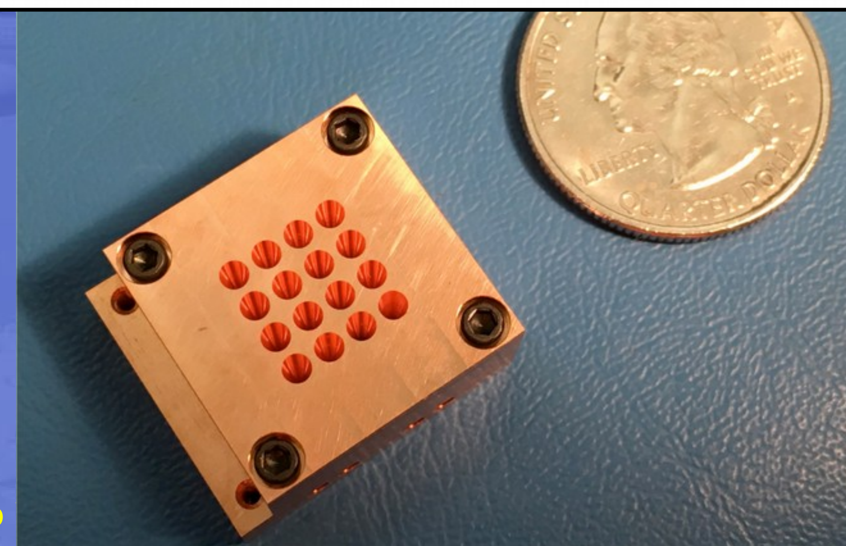
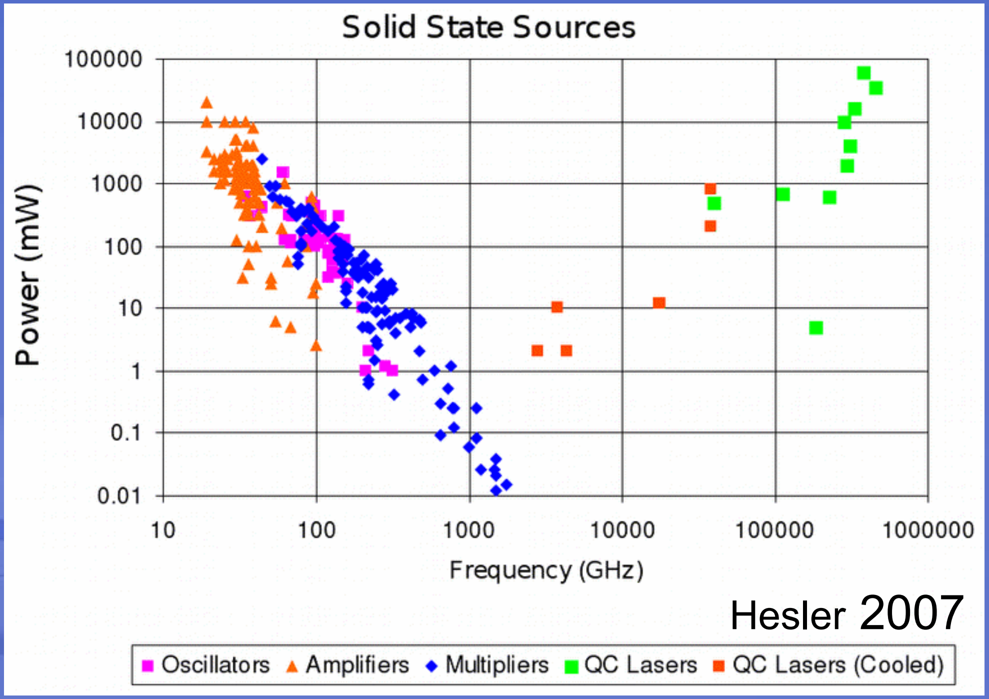


Kawamura+ 2017

Local Oscillators

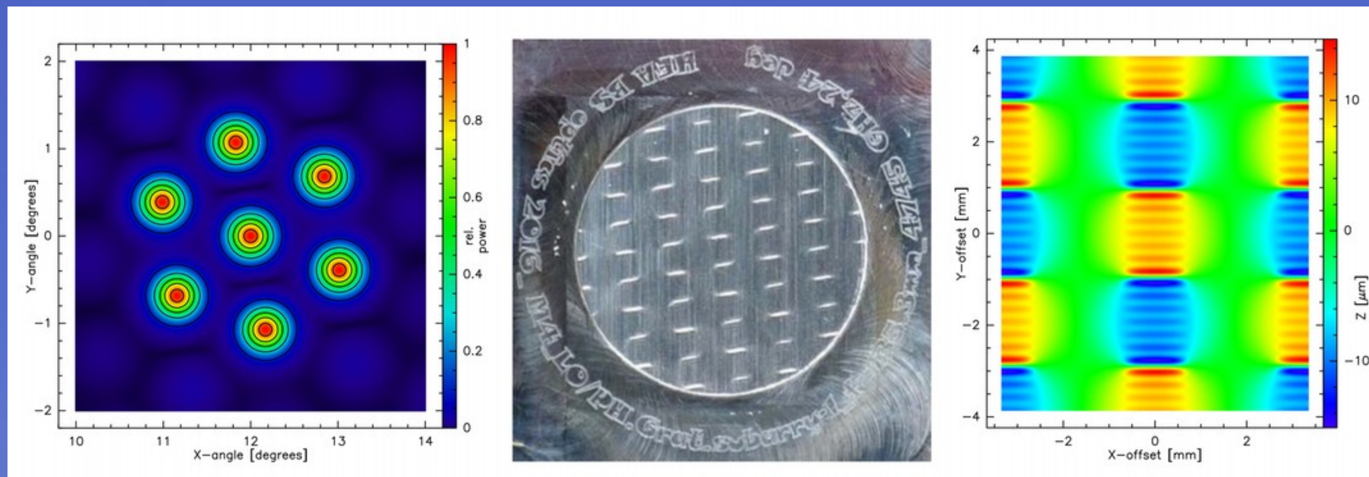
- **Each mixer requires a local oscillator signal to mix with the sky signal**
- **Substantial amount of local oscillator power is needed**
- **Sources of choice:**
  - **≤ 2THz: multiplied microwave sources**
  - **≥ 2THz: quantum cascade lasers**



- **The LO power needs to be distributed to the individual mixers**

LO Distribution I: Fourier Grating

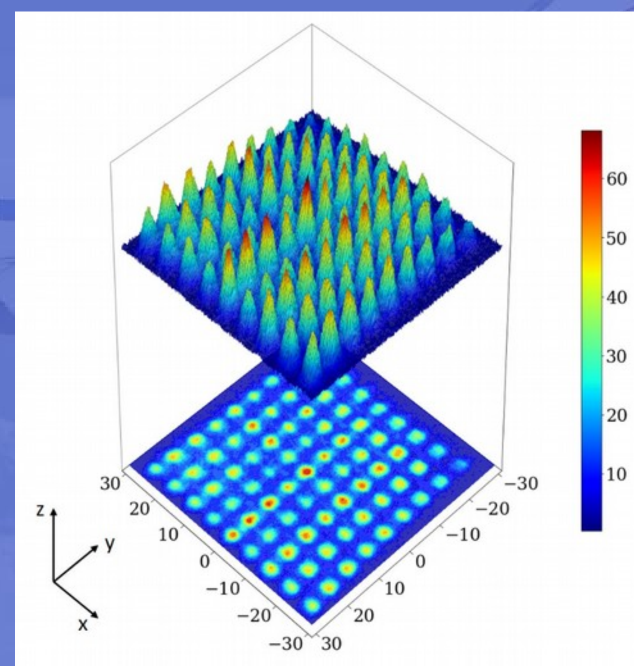
- Reflective phase grating as LO multiplexer



upGREAT's 7-beam Fourier grating

Risacher+ 2018

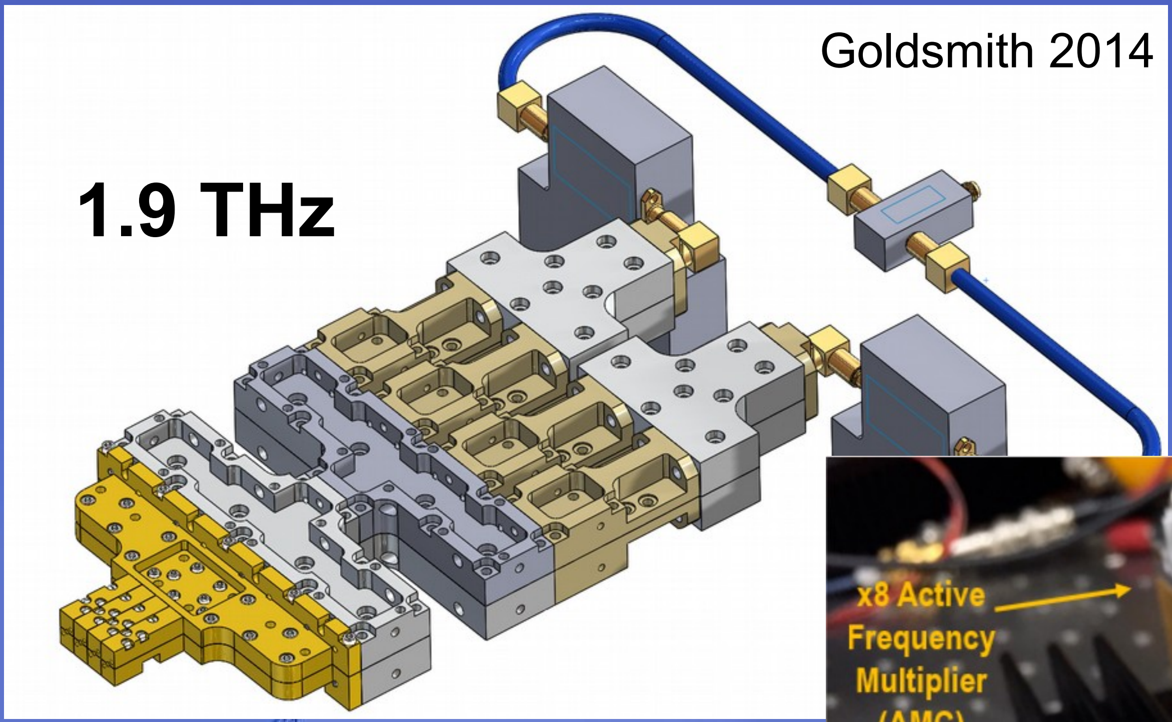
- elegant and simple
- good efficiency (~90%)
- power balancing is challenging

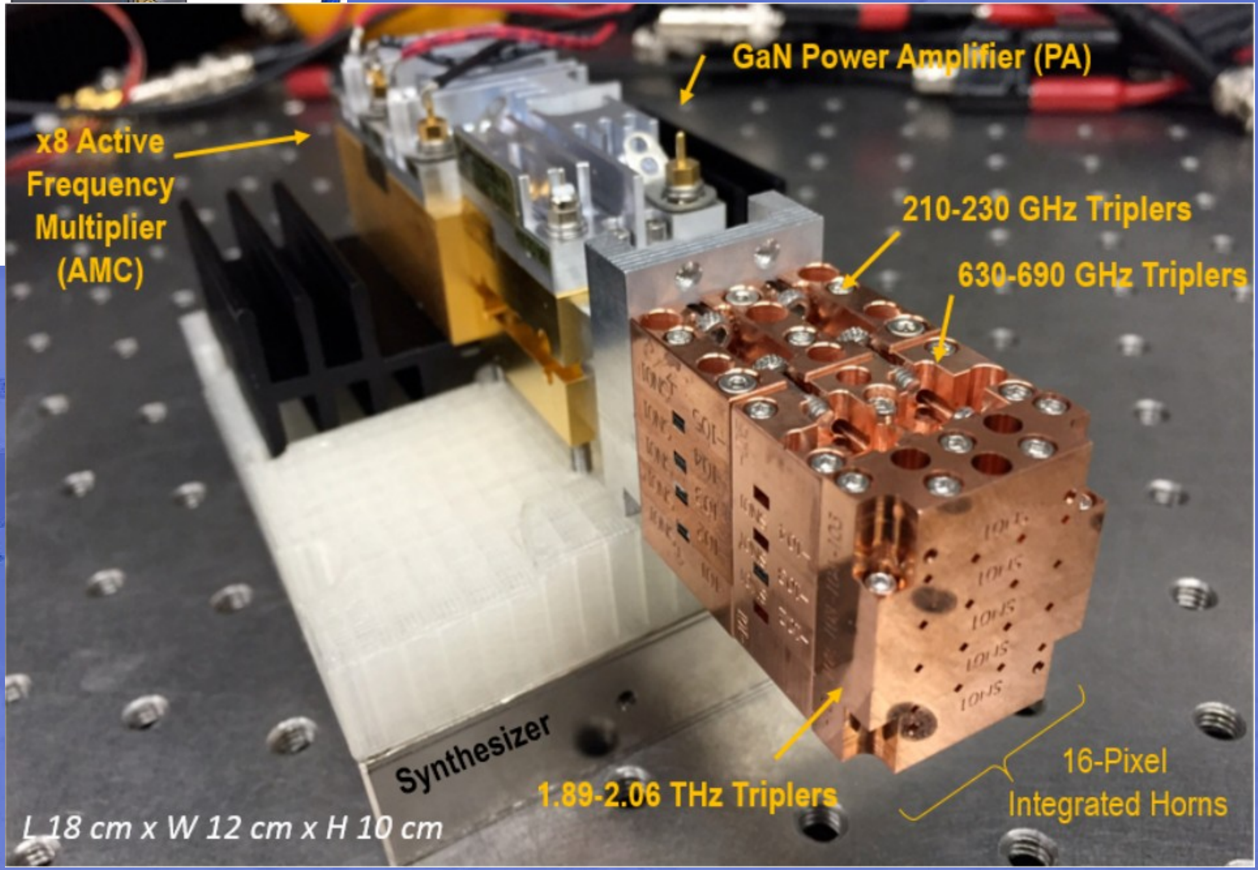


81-beam Fourier grating

Gan+ 2019

LO distribution II: Multi-pixel Multiplier Chain



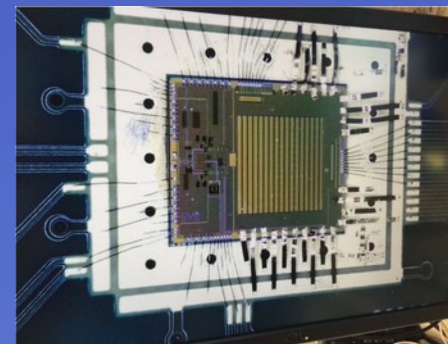


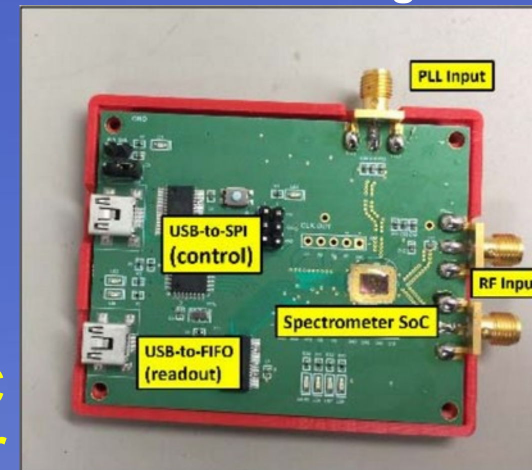
Siles+ 2017

Spectrometer Backend

- Digital Fourier transform spectrometers:
  - FPGA based
  - CMOS SoC
- Bandwidth limitation (250 km/s @ 63 µm)
- Traditionally mounted on telescope structure (CWR) → size & weight limit
  - make more compact and lighter
  - separate sampling (on telescope) and processing (in PI rack)
  - RF over fiber?

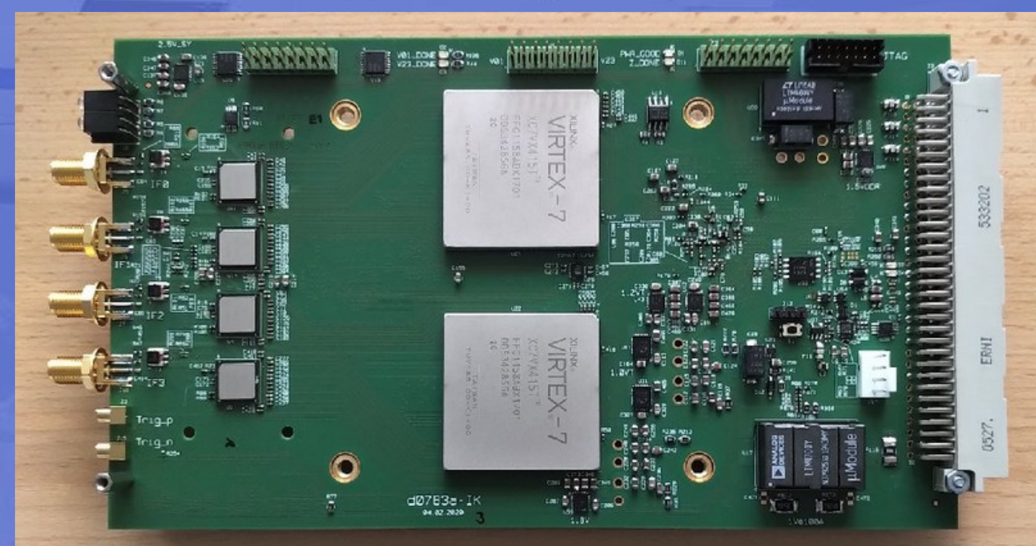
Zhang+ 2019





CMOS SoC spectrometer

4-channel FFTS board



Klein+ 2019

Conclusion

- ~100 pixel array (possibly dual polarization) is challenging but feasible
- main areas of development:
  - mixer, feedhorn, optics
  - local oscillator
  - backends
  - system aspects: electronics, power consumption, tuning

Thank you