Front-end instrumentation for sub-mm single dish and VLBI in space

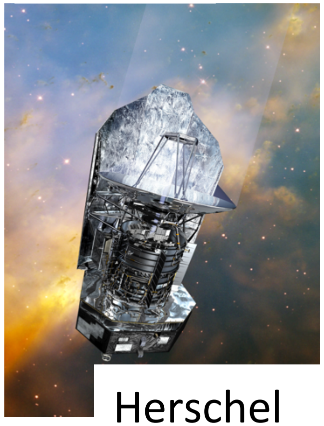
Martina C. Wiedner

LERMA, Paris Observatory, PSL, CNRS

Some Submm Telescopes

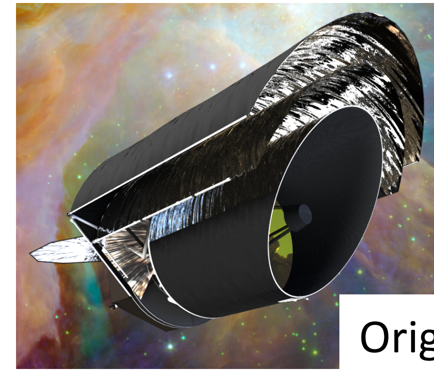
Past

Future



Herschel

Spitzer



Origins

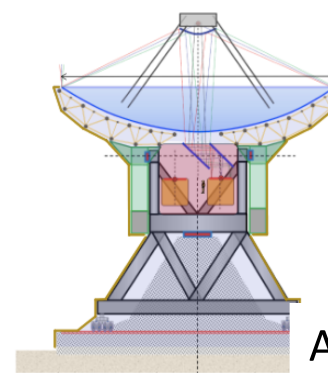
Blast, STO, Gusto

SOFIA

ASTHROS

CSO, JCMT, SMA

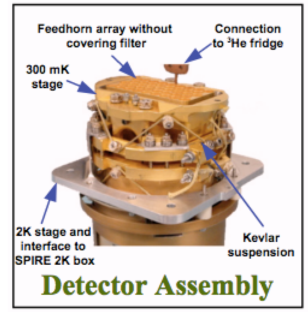
ALMA



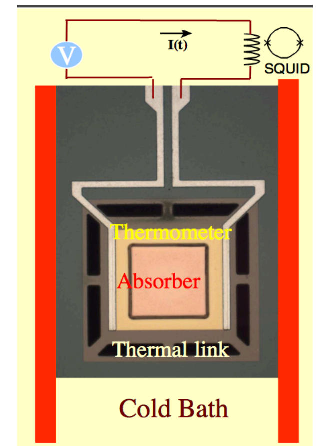
AtLAST

Receivers for Sub-mm telescopes

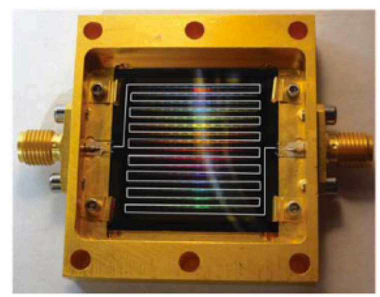
1. Incoherent Receivers
   - Bolometer detector arrays
   - Transition Edge Sensors (TES)
   - MKIDs (Microwave Kinetic Inductance Detectors)
2. Coherent Receivers
   - Heterodyne



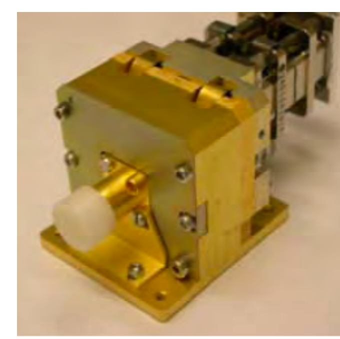
SPIRE, Herschel
250 – 500 microns



TES, SRON

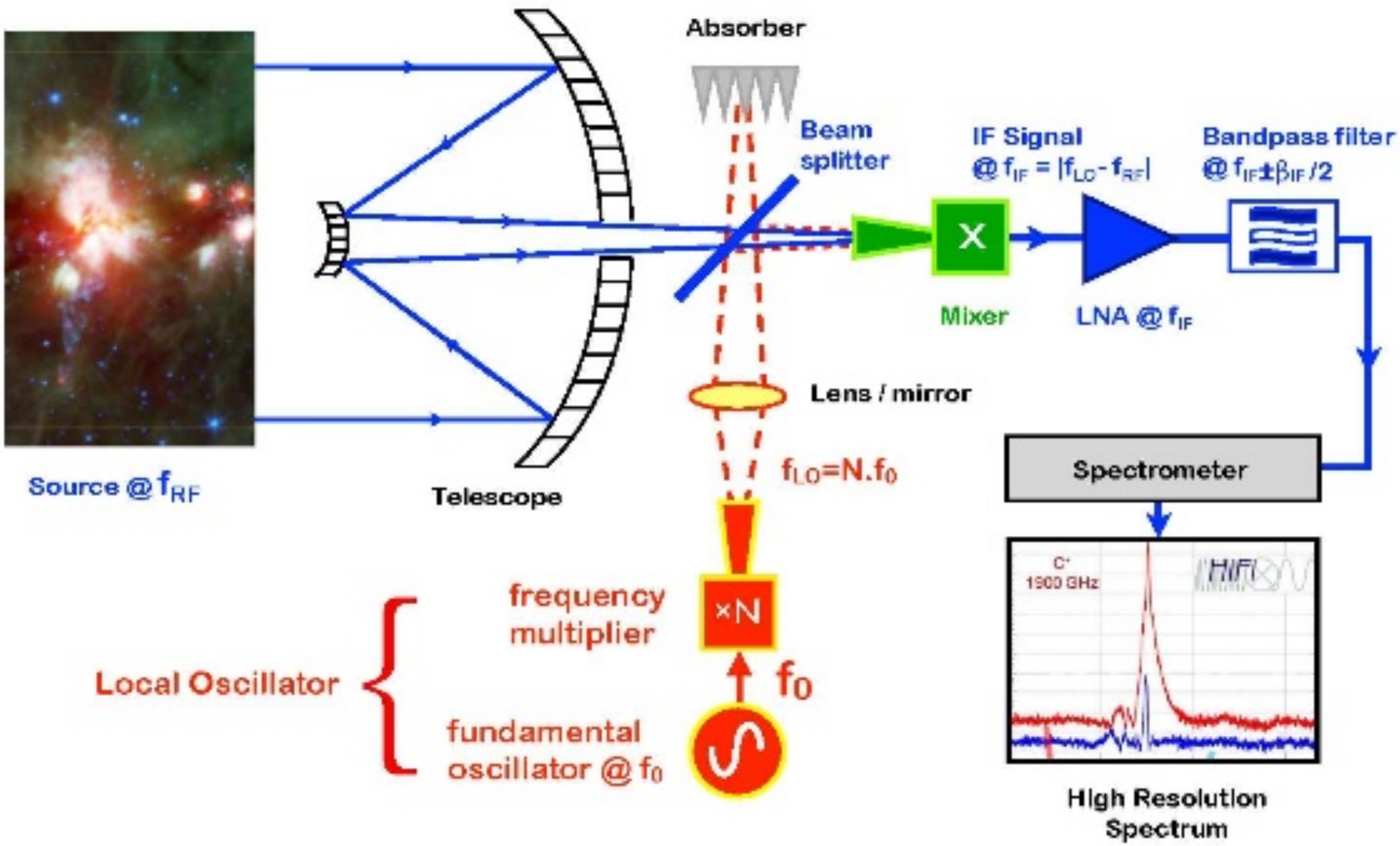


Hailey-Dunsheath, et al. 2021,

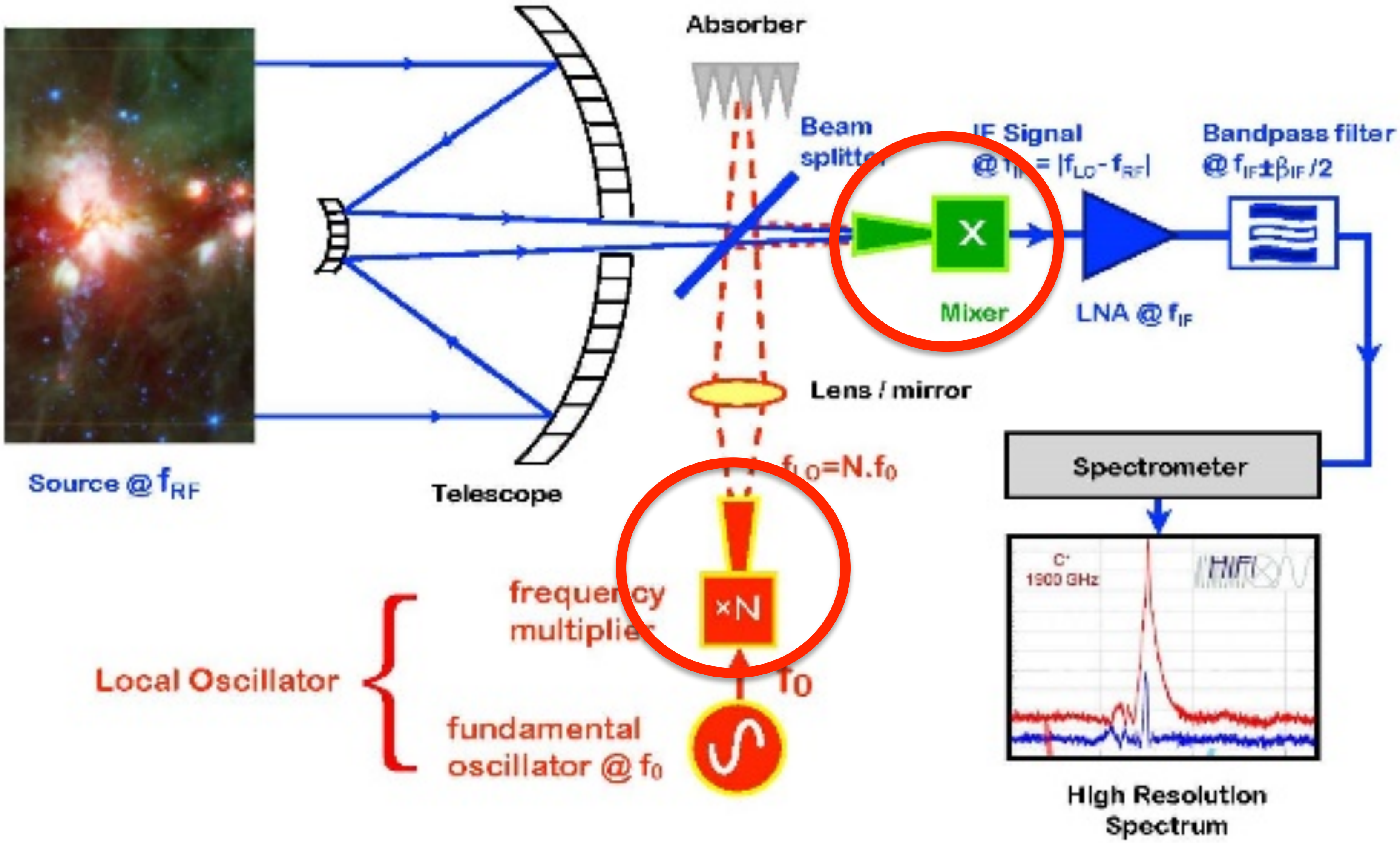


HIFI, Herschel
480 – 640 GHz,
Paris Observatory

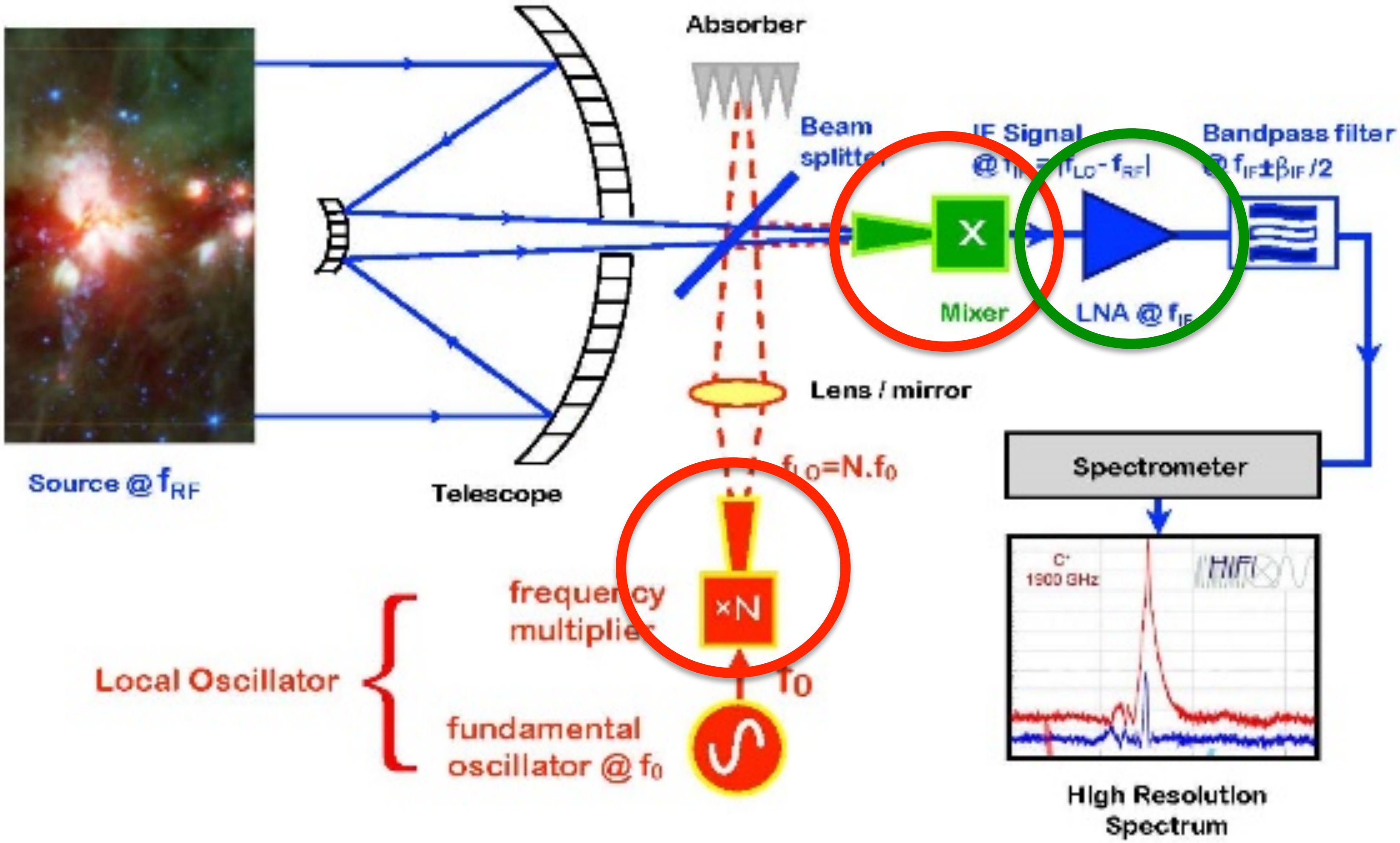
Submm/THz Receivers



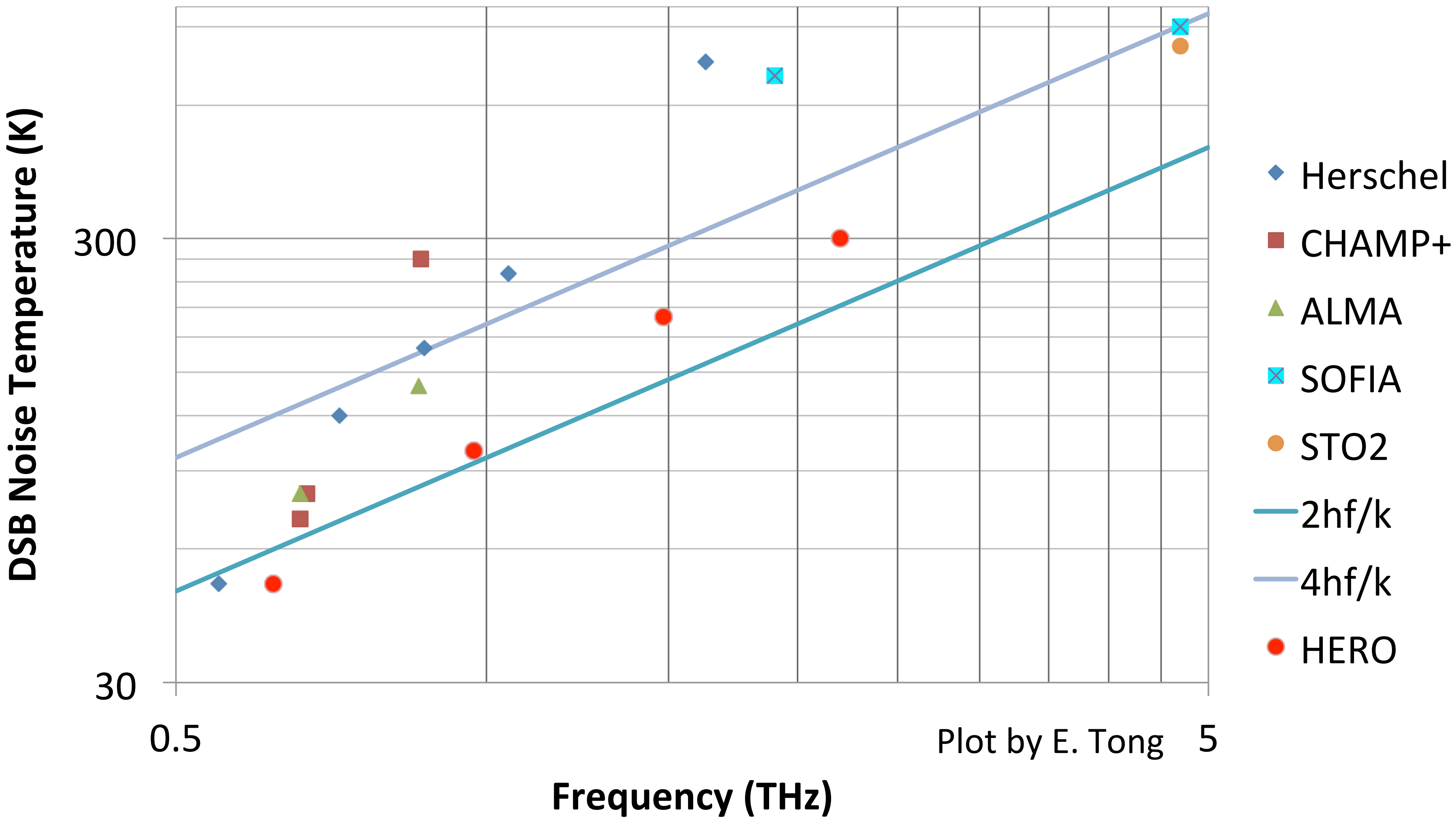
Submm/THz Receivers



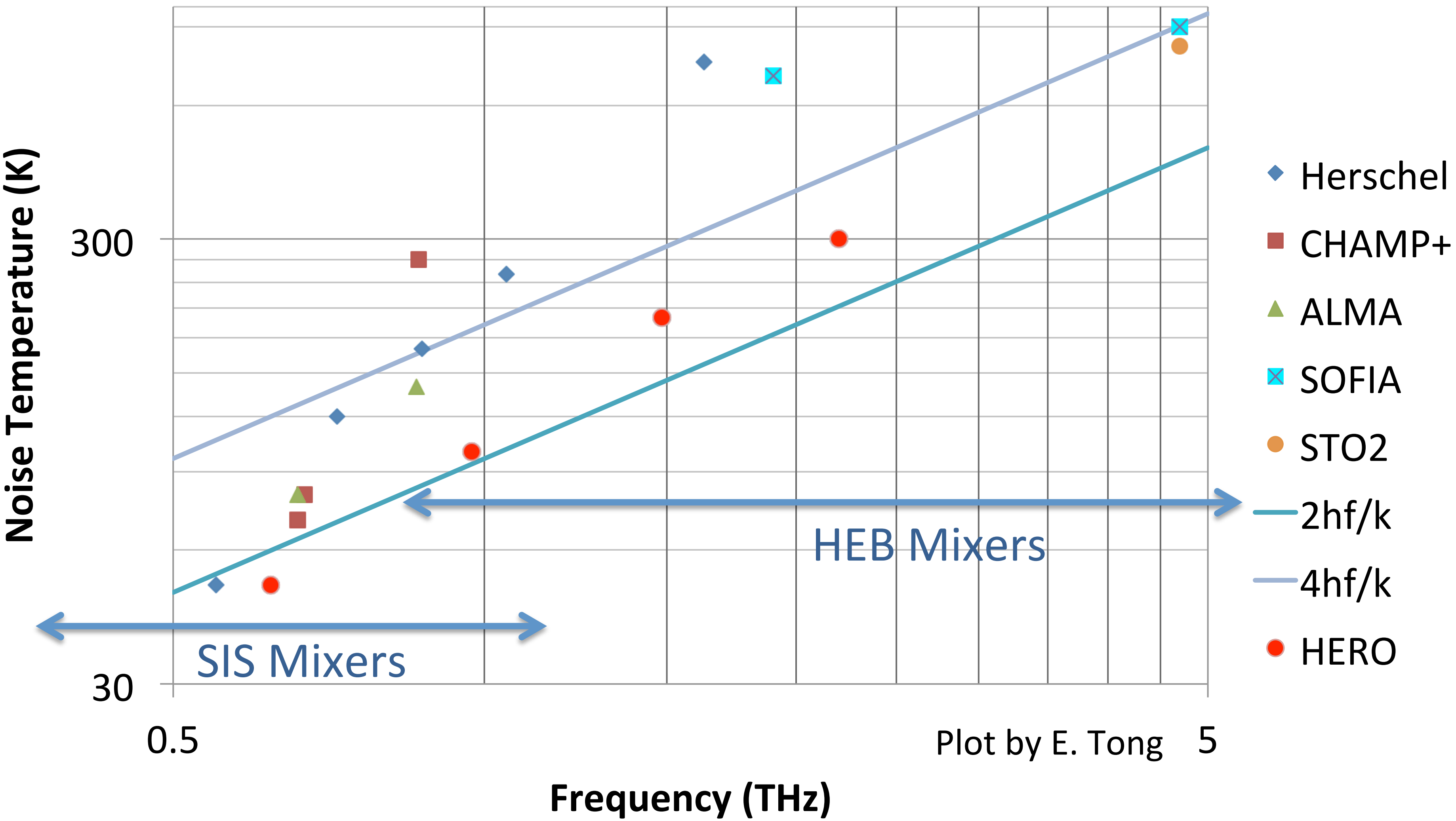
Submm/THz Receivers



Superconducting Mixer

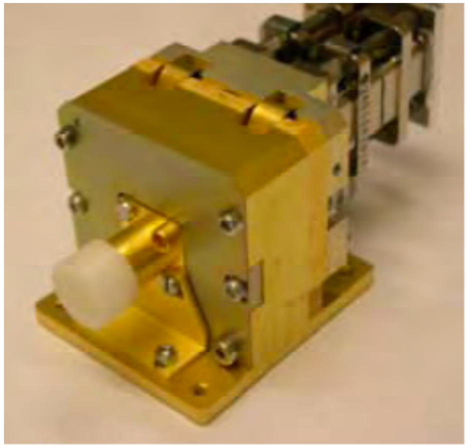


Superconducting Mixer



SIS Mixers

- Superconducting Isolating Superconducting Mixers
  - T_{mixer} 30 to 250K (2 – 5 $h\nu/k$)
  - 100 to 1280 GHz, max. 50% BW
  - IF BW typical 4 to 8 GHz
  - 5K, better at lower T
  - Required LO power 1μW
  - Total Power Allan time ~ 10 sec
  - Spectral Allan time over 1 GHz 200 sec
  - DSB, SSB, or 2SB



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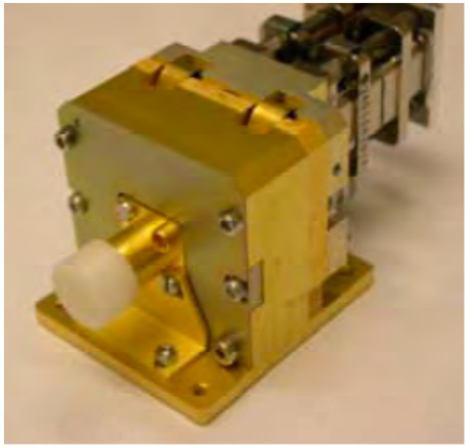


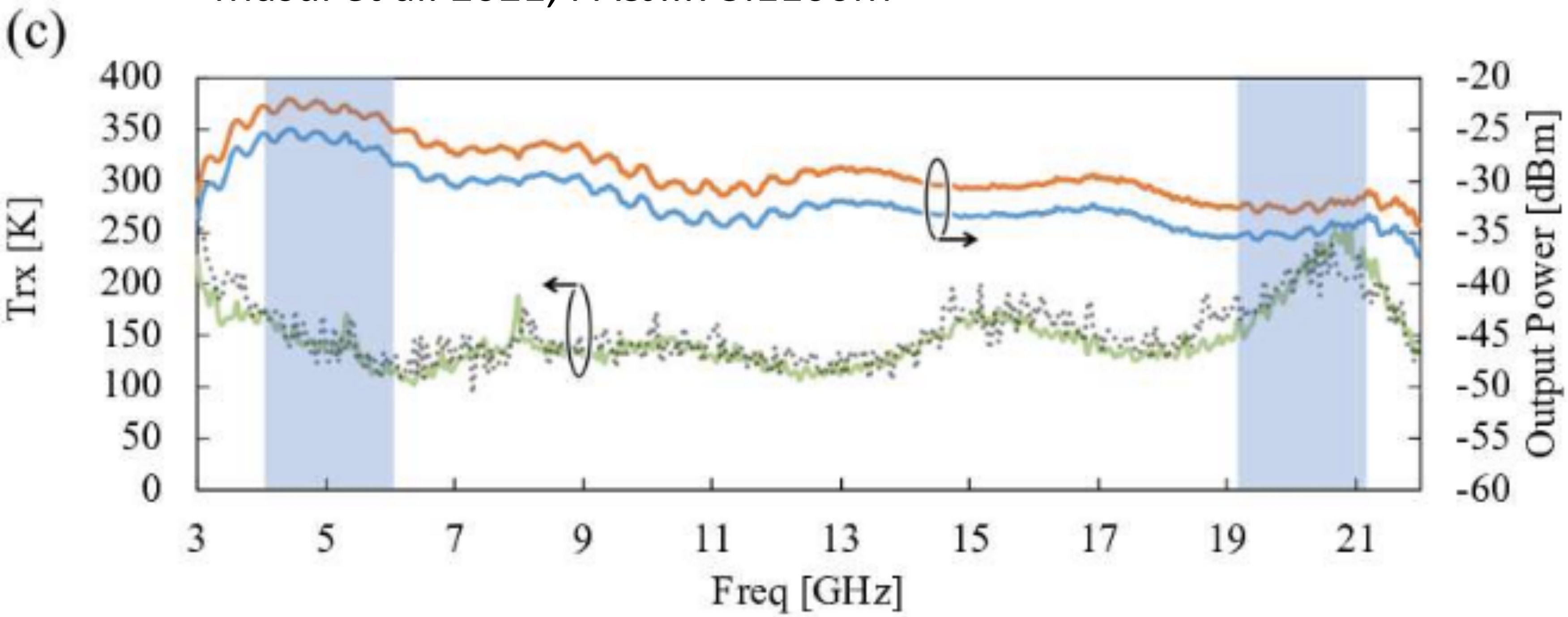
Wideband SIS Mixers

3- 11 GHz DSB @ 220 GHz, CfA, Blundell et al 2013

4-21 GHz @210 to 350 GHz (Kojima et al. 2020, A&A)

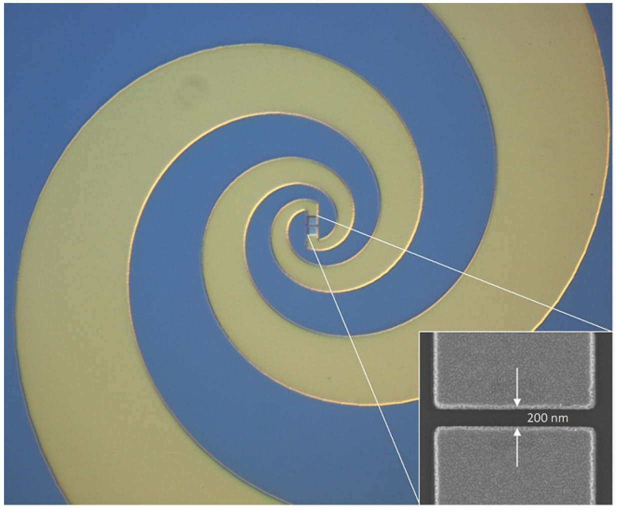
2 – 20 GHz, Groningen, Baryshev, priv. com.

Masui et al. 2021, PASJ...73.1100M



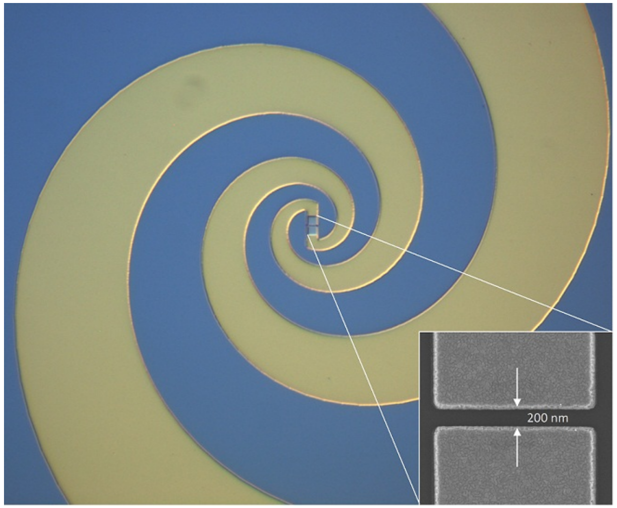
HEB Mixers

- Hot Electron Bolometer Mixers
  - T_{mixer} 300 to 3000K (5 – 10 $h\nu/k$)
  - any GHz
  - IF BW typical 2 to 4 GHz
  - < 6K
  - Required LO power 1μW
  - Total Power Allan time ~ 1 sec
  - Spectral Allan time over 1 GHz 20 sec
  - DSB



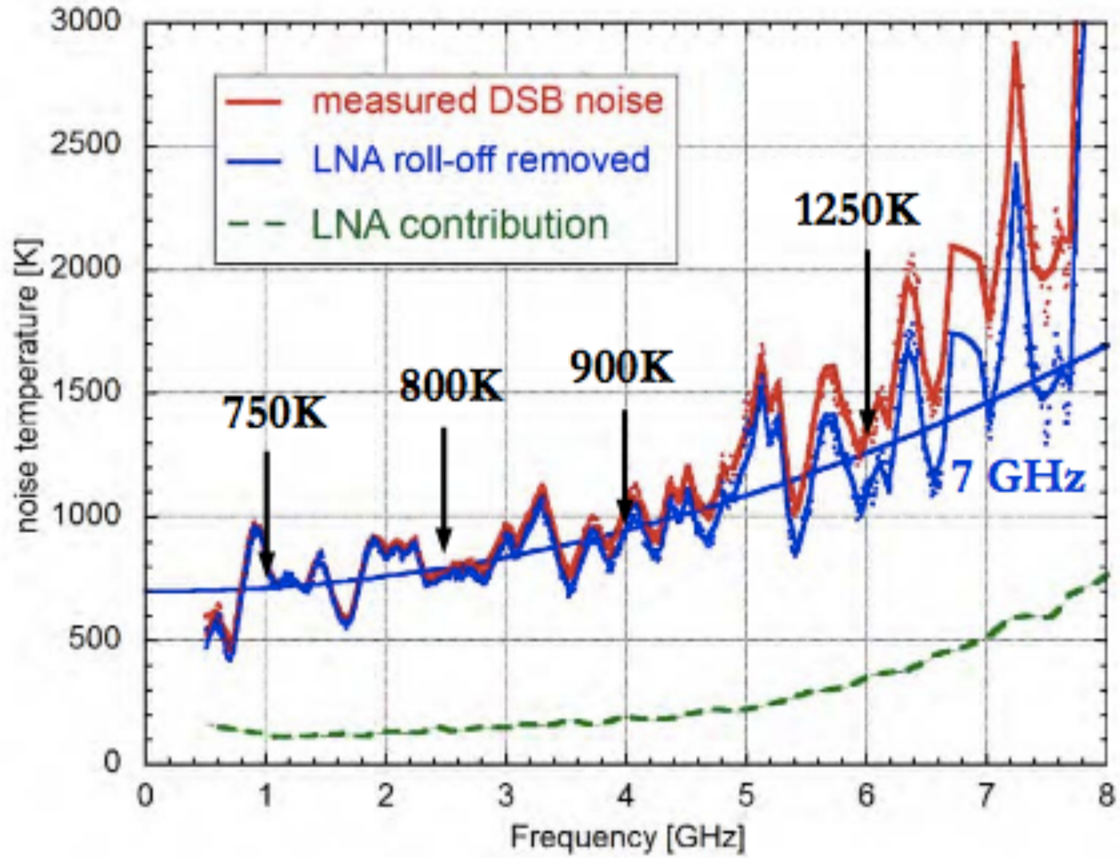
HEB Mixers

- Hot Electron Bolometer Mixers
  - T_{mixer} 300 to 3000K (5 – 10 hν/k)
  - any GHz
  - IF BW typical 2 to 4 GHz
  - < 6K
  - Required LO power 1μW
  - Total Power Allan time ~ 1 sec
  - Spectral Allan time over 1 GHz 20 sec
  - DSB



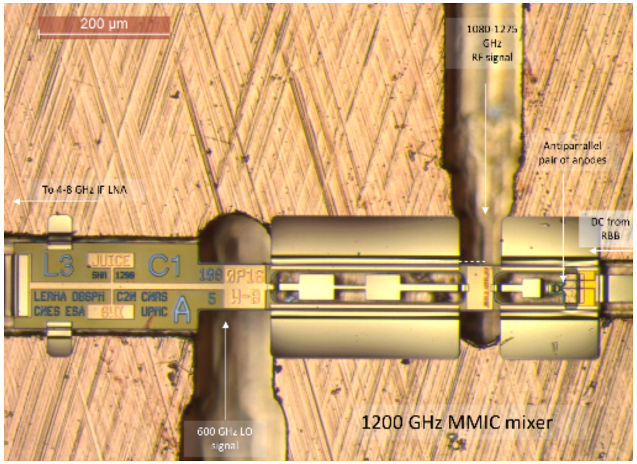
HEB Mixers, IF Bandwidth

- NbN/GaN HEB with 5.5 GHz 3dB BW (Krause et al. 2018)

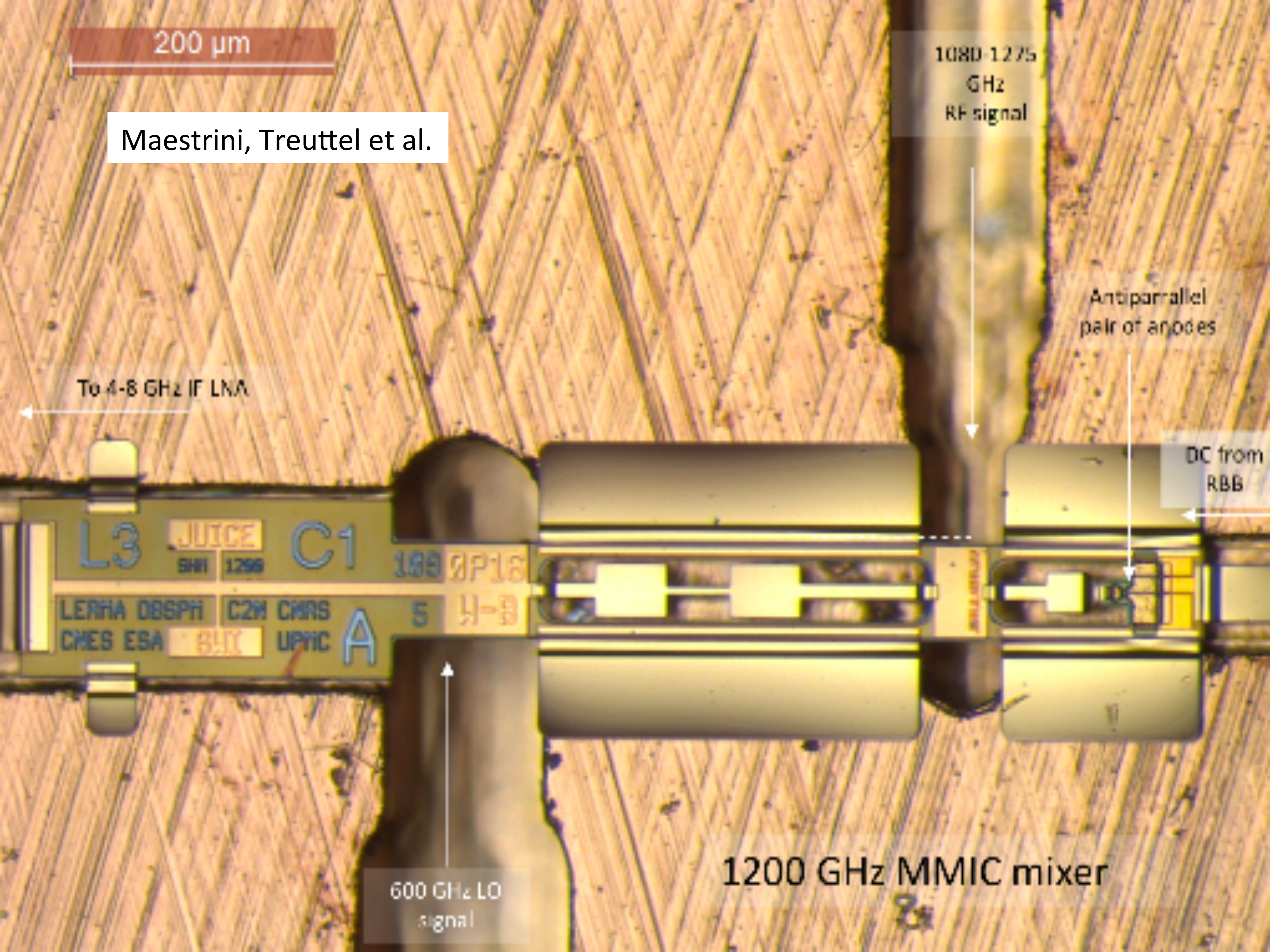


Schottky Mixers

- Schottky Mixers
  - T_{mixer} 1000K to 100000K
  - any GHz
  - IF BW
  - 0 – 400 K
  - Required LO power 1mW
  - Fundamental, SH, 4th Harm.

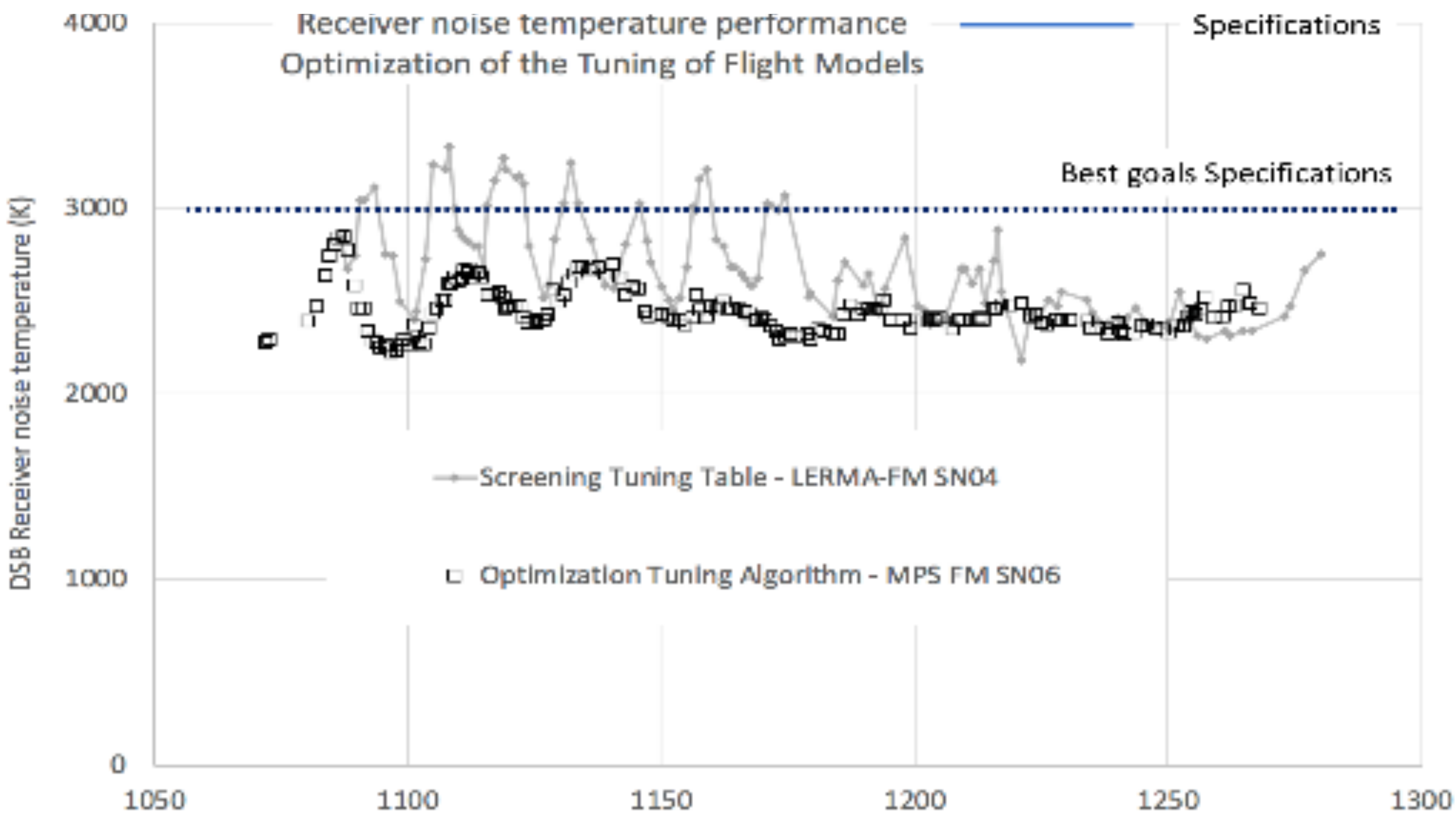


Maestrini, Treuttel, Gatilova et al., JUICE Mixer, LERMA, Paris Observatory and C2N

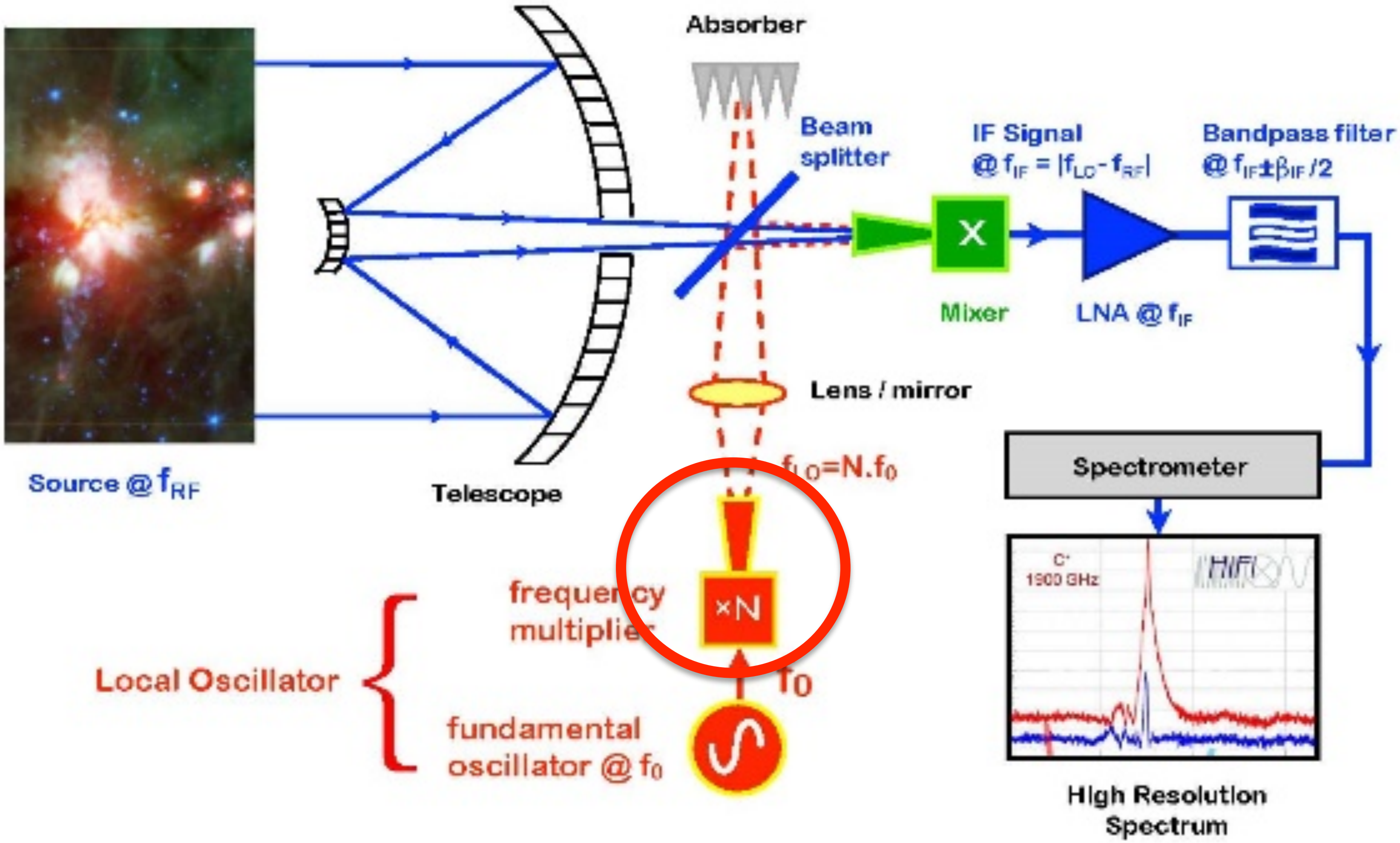

200 µm
Maestrini, Treuttel et al.
1080-1275
GHz
RF signal
Antiparrallel
pair of anodes
To 4-8 GHz IF LNA
DC from
RBB
600 GHz LO
signal
1200 GHz MMIC mixer

LERMA's Mixer at 1.2 THz

LERMA 1200 GHz Schottky Receiver



Submm/THz Receivers



Local Oscillator

- Amplifier Multiplier Chain
- Quantum Cascade Laser
- Photomixer

QCL with its cooler by H-W Huebers et al.

Local Oscillator

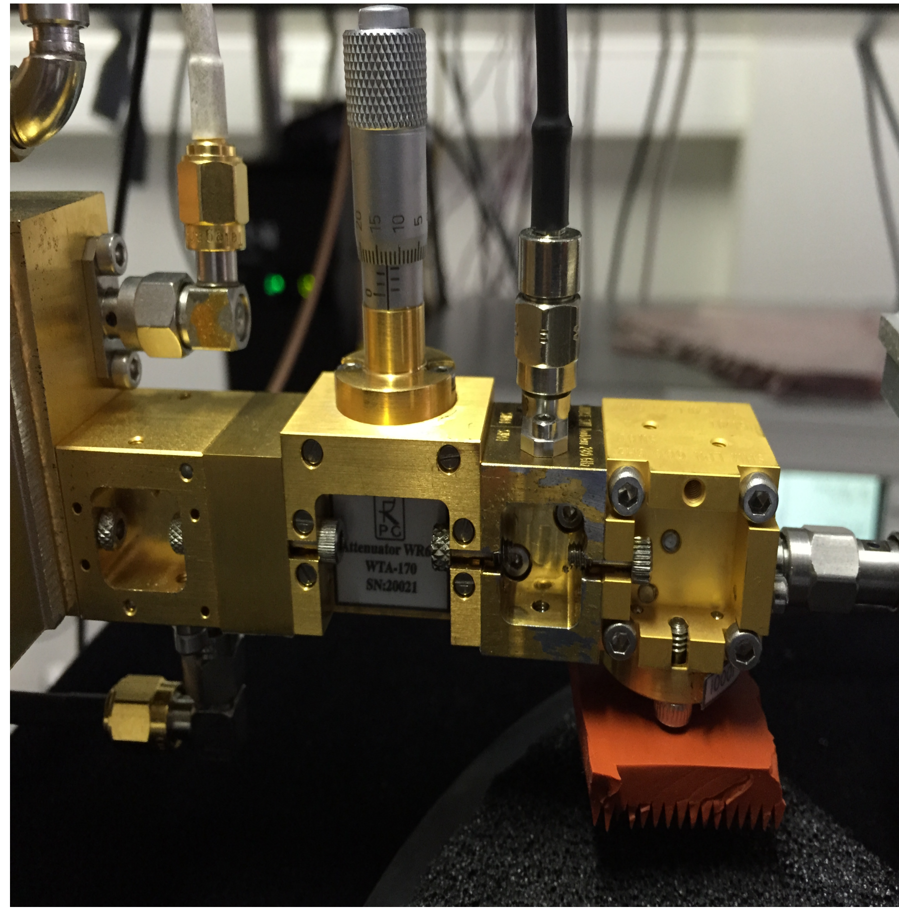
- Amplifier Multiplier Chain
- Quantum Cascade Laser
- Photomixer

All LO in phase

QCL with its cooler by HW Huebers et al.

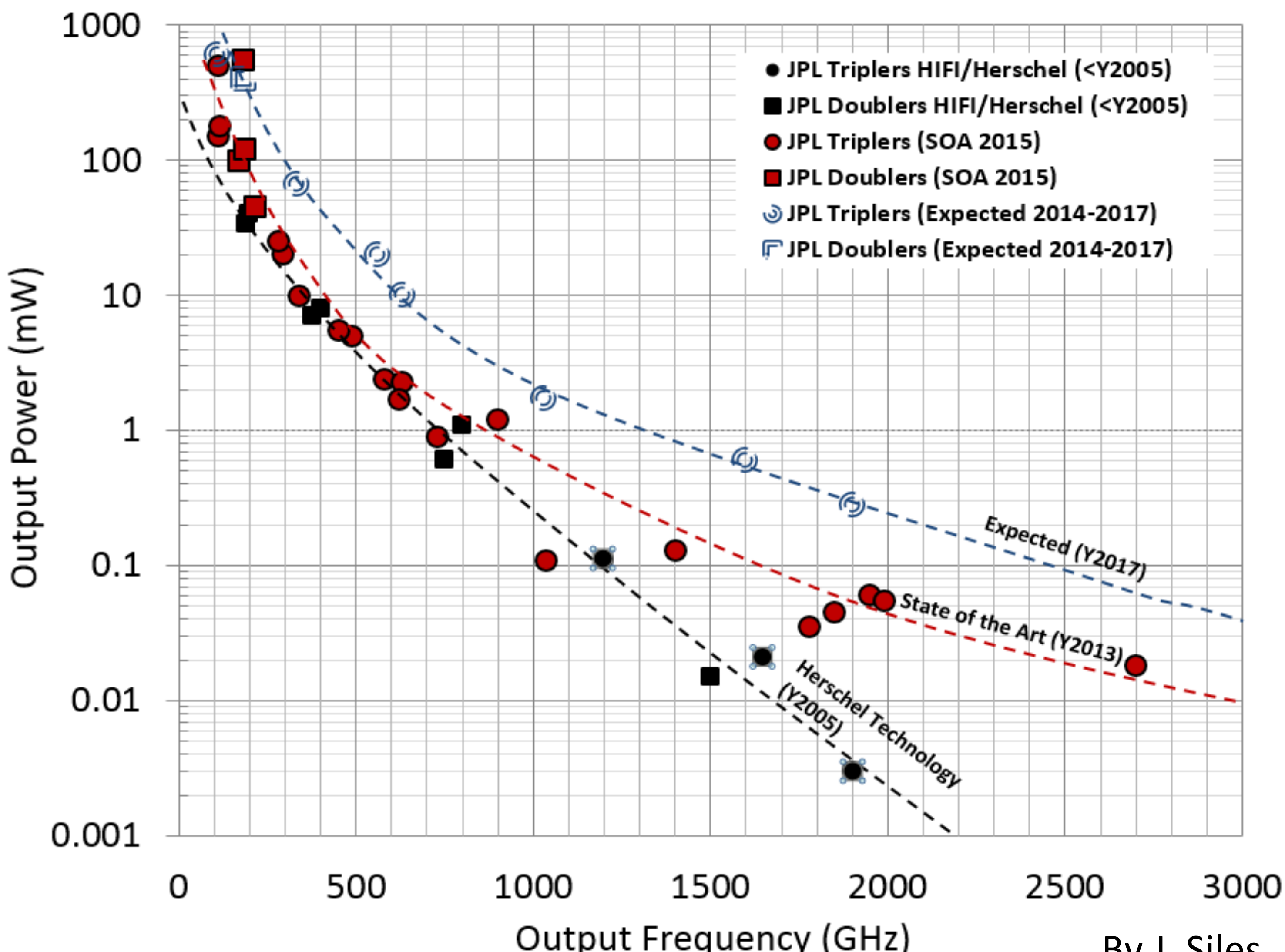
Local Oscillator – Amplifier Multiplier Chain

Characteristic	AMC
Tunability	30%
TRL	7 – 9
Operating Temp	50 - 350
Power output	10 mW @ 300 GHz
	Few µW @ 2 THz
Power cons.	2W/pixel
Reliability	excellent



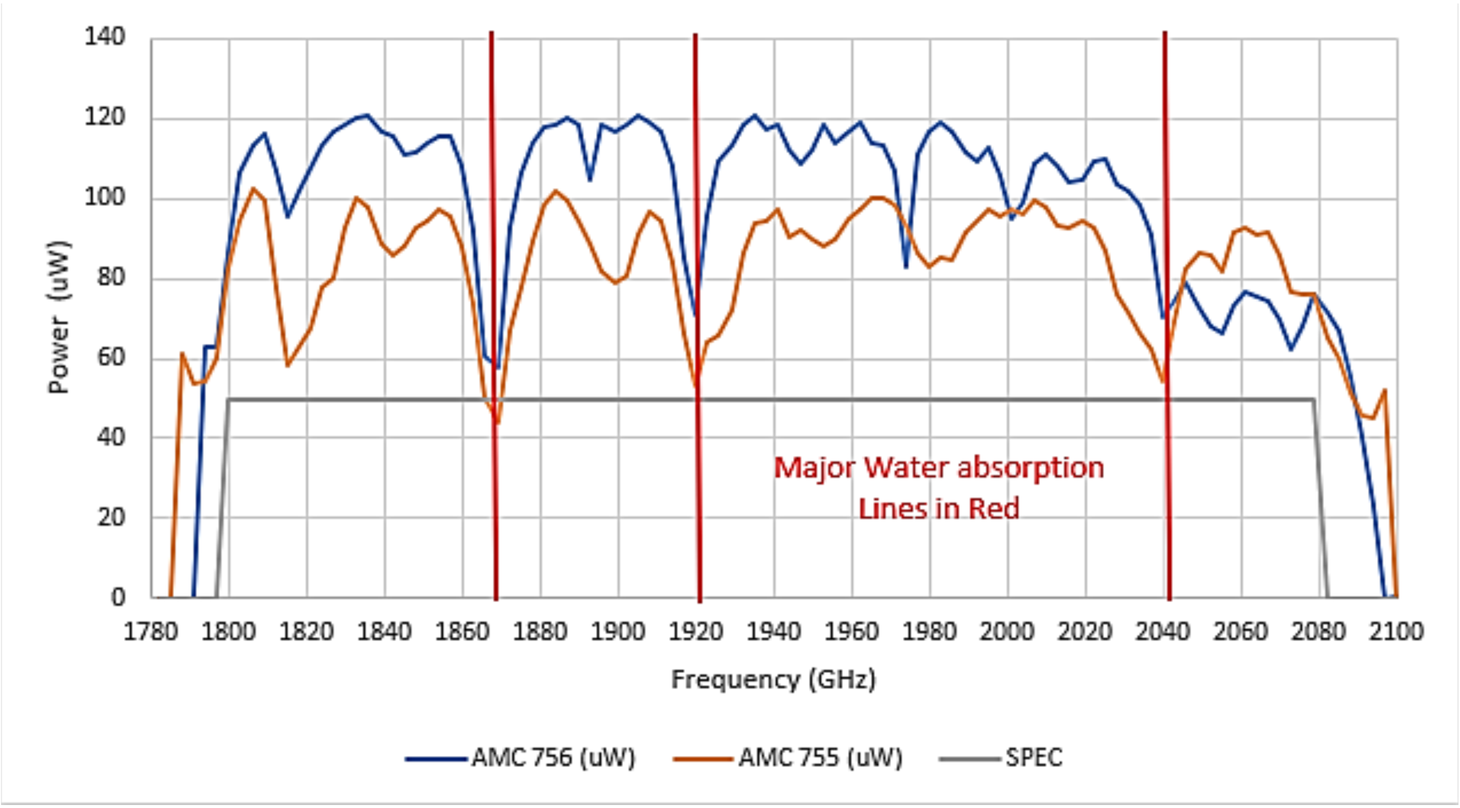
Schottky Multiplier Development
at LERMA, Paris Observatory

Amplifier Multiplier Chains



By J. Siles, JPL

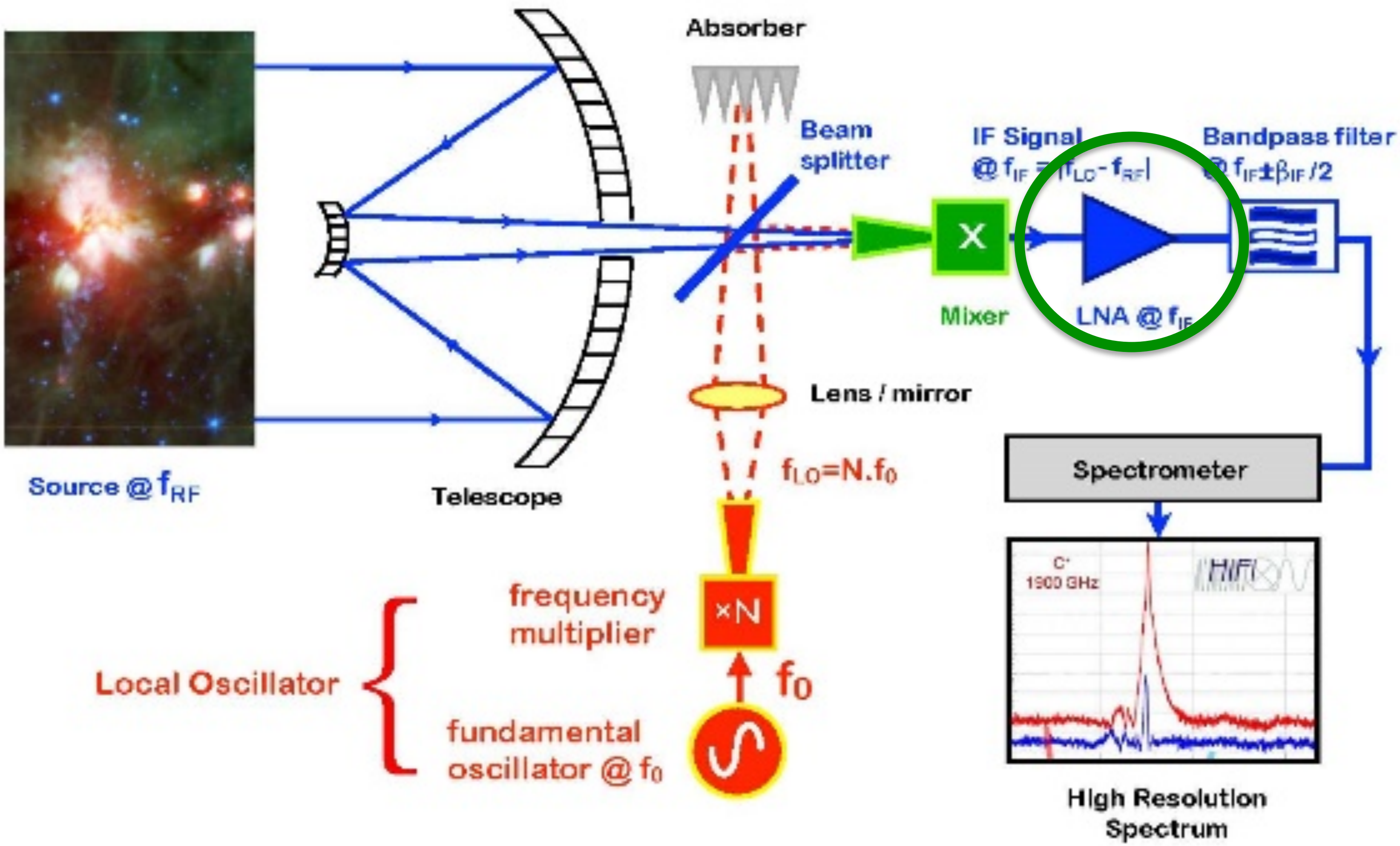
Amplifier Multiplier Chains



Commercial Suppliers:
Virginia Diodes
Radiometer Physics
ACST
RAL etc

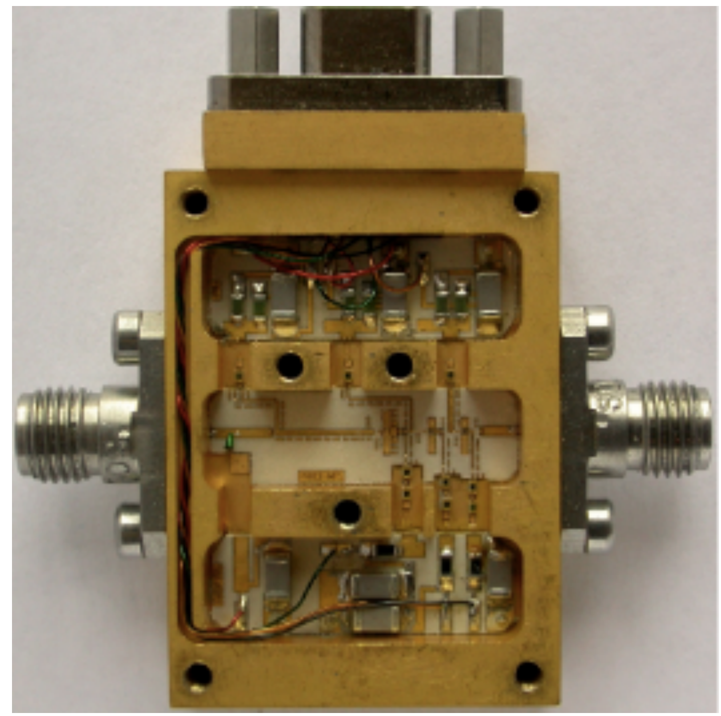
Crowe (VDI), 2022 ISSTT

Submm/THz Receivers



IF Amplifiers

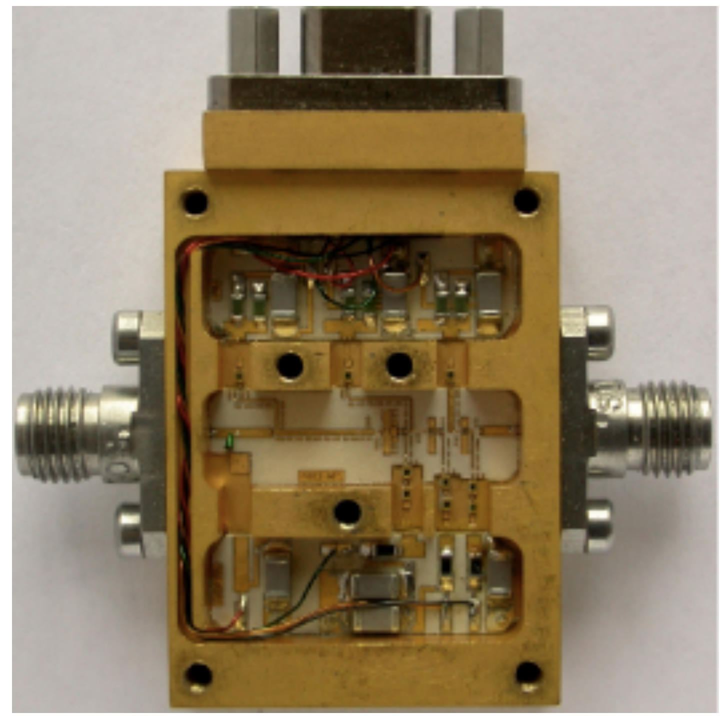
- InP HEMTs
- SiGe amplifiers
- Parametric amplifiers



R.I. Amils *et al* 2016
JINST **11** P10018

IF Amplifiers

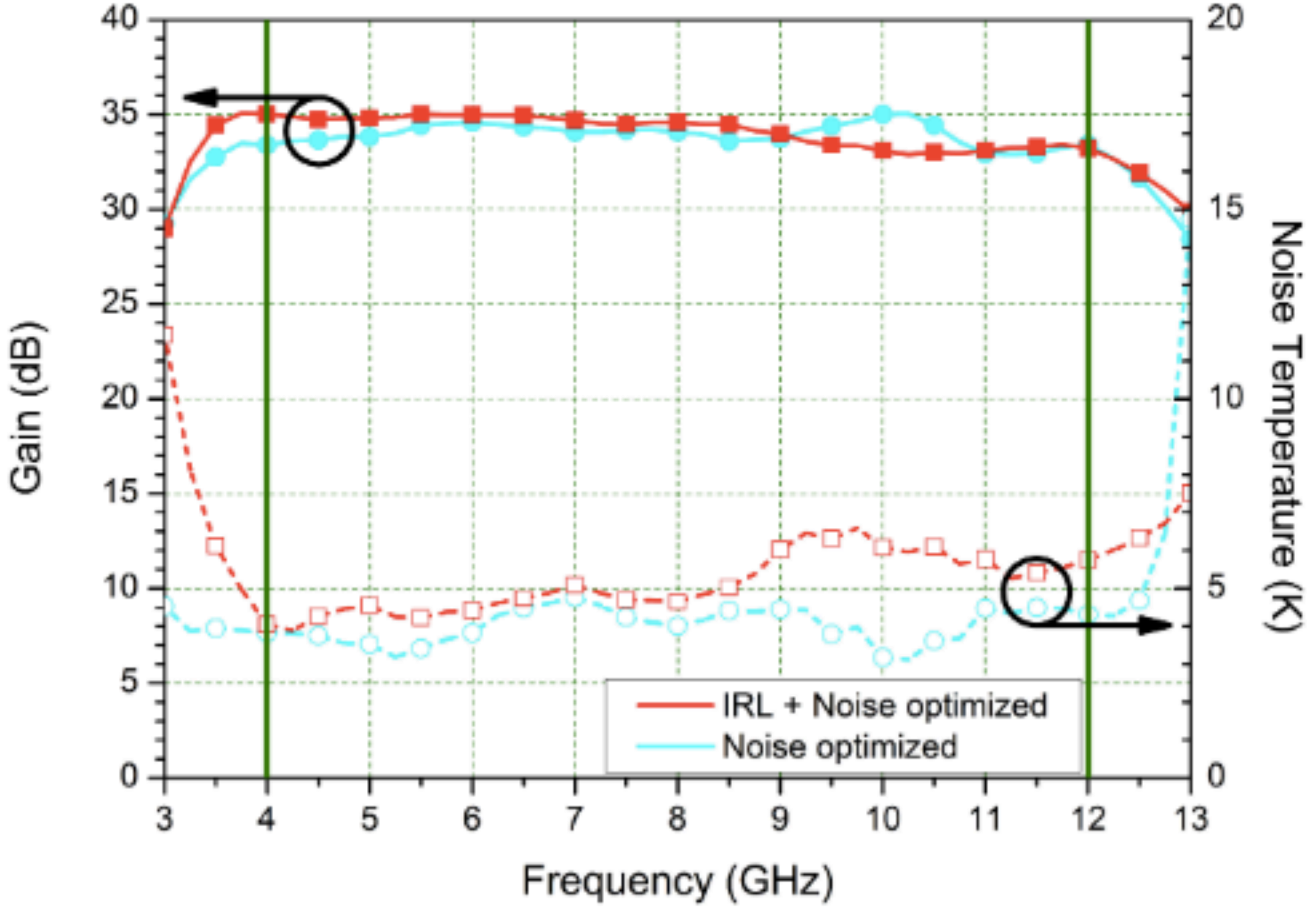
- InP HEMTs
  - Lowest noise, TRL 8/9
- SiGe amplifiers
  - Low dissipation, < 0.5mW
- Parametric amplifiers
  - Lowest dissipation, TRL low



R.I. Amils *et al* 2016
JINST **11** P10018

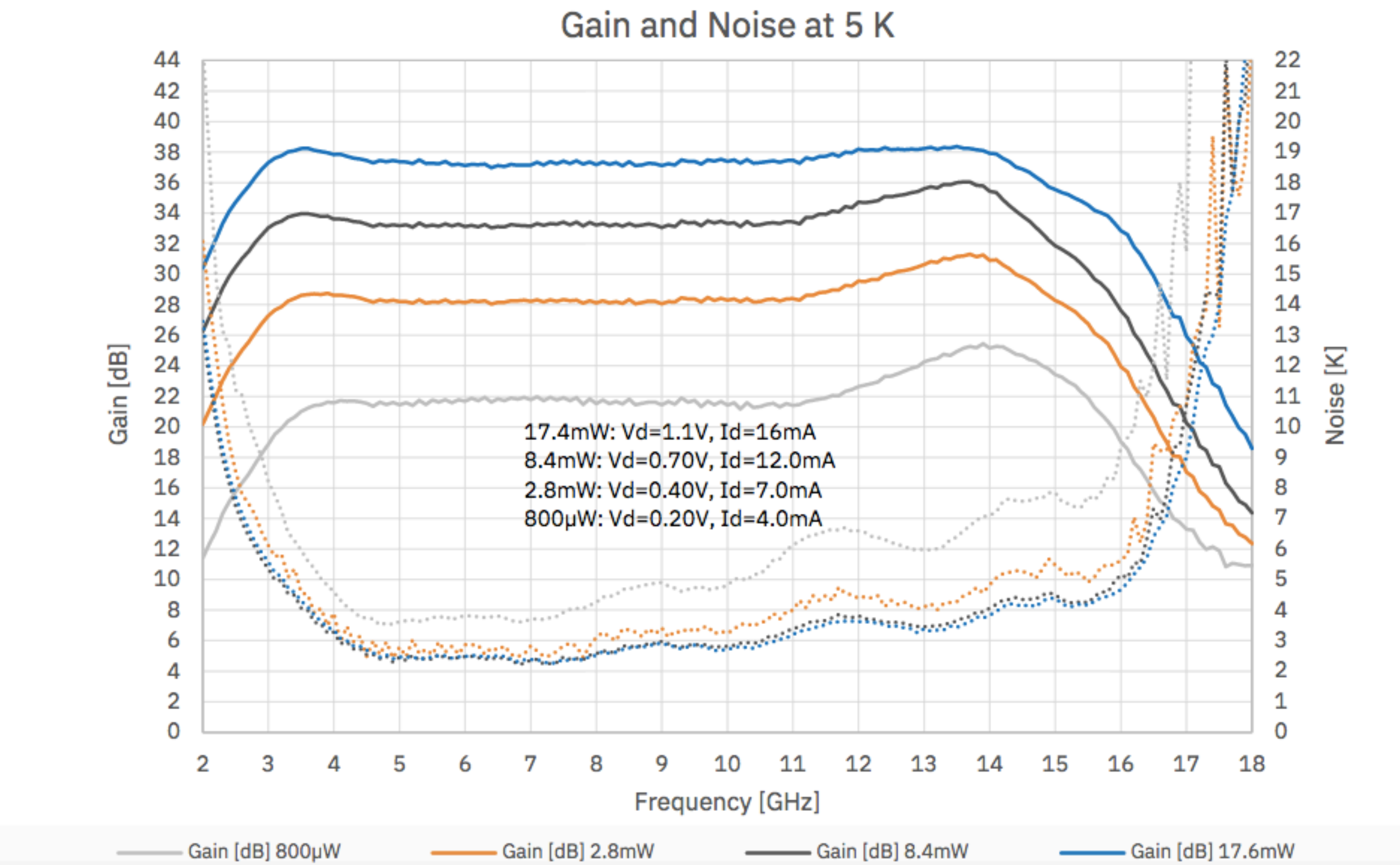
IF Amplifiers

•



R.I. Amils *et al* 2016 *JINST* **11** P10018
Yebes

IF Amplifier



https://lownoisefactory.com/

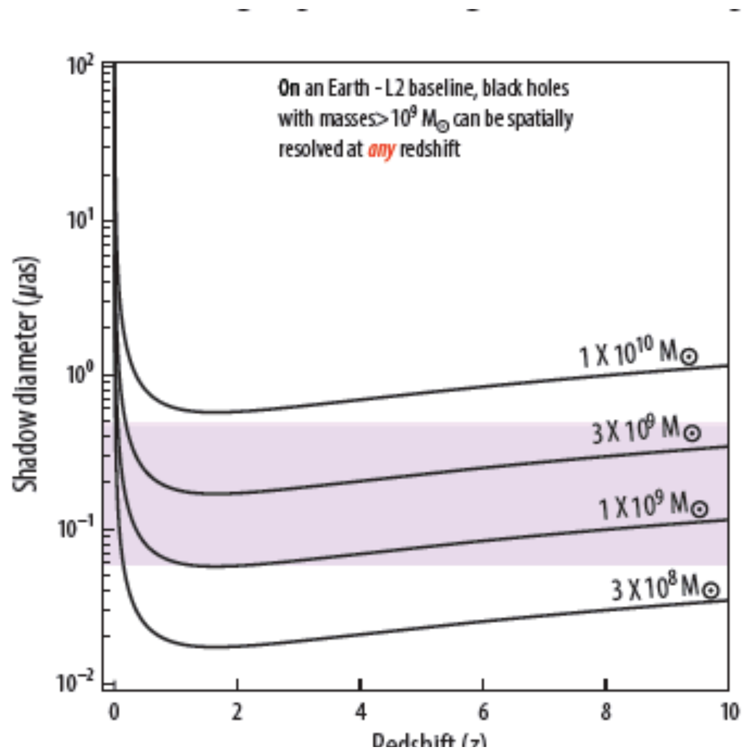
Example: Origins as Event Horizon Telescope Antenna, study by Pesce et al.

- EHT to operate at 85, 345 and 690 GHz
- Baseline: Earth – L2

→ 10^6 BH shadows

→ Resolving photon ring

Black Hole in M87, EHT collaboration

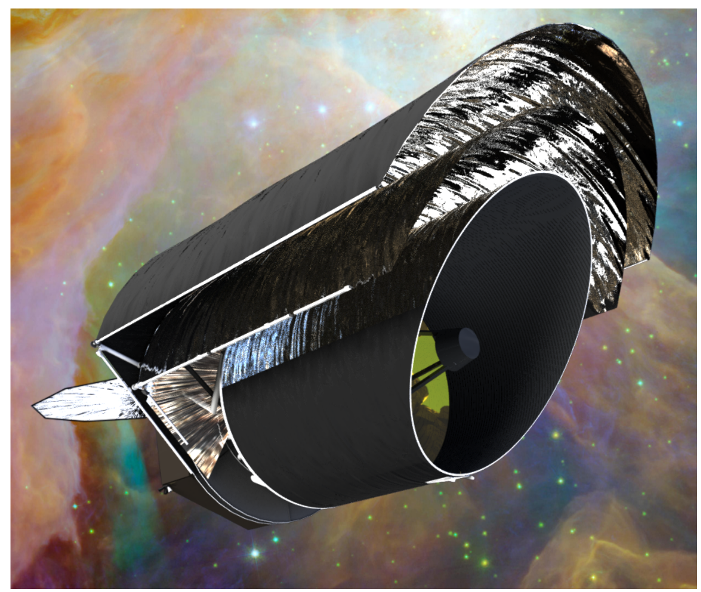


Example: Origins as Event Horizon Telescope Antenna, study by Pesce et al.

Challenges: Sensitivity

1. the geometric mean of the system equivalent flux densities of the individual telescopes
2. averaged bandwidth
3. coherent integration time
   a. Phase perturbations
   b. Clocks or phase referencing

Pesce et al. APC white papers, no. 176; Bulletin of the American Astronomical Society, Vol. 51, Issue 7, id. 176 (2019)



Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/

Example: SPICE by Leisawitz

Study for IR- Probe

- 25 to 400 microns
- 1 baseline, 2 mirros on bar structure
- Beam combiner MKID detectors
- Challenges: stray light

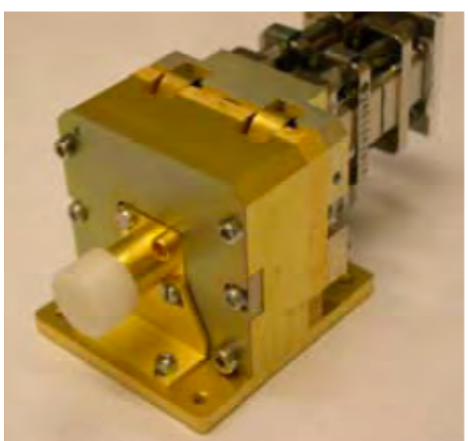
Science:

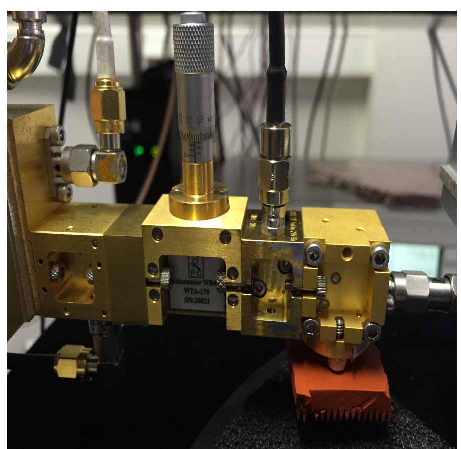
- Galaxy Evolution
- Planet Formation
- Planetary System Architecture

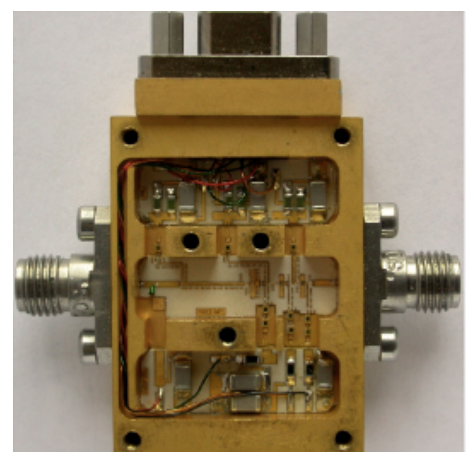
https://asd.gsfc.nasa.gov/spice/

Conclusion for submm space interferometry

- Front end components exist at TRL 8/9
- Front end improvements:
  - bandwidth of mixer, amplifier for increased sensitivity
  - HEB mixer noise and IF bandwidth







Thank you

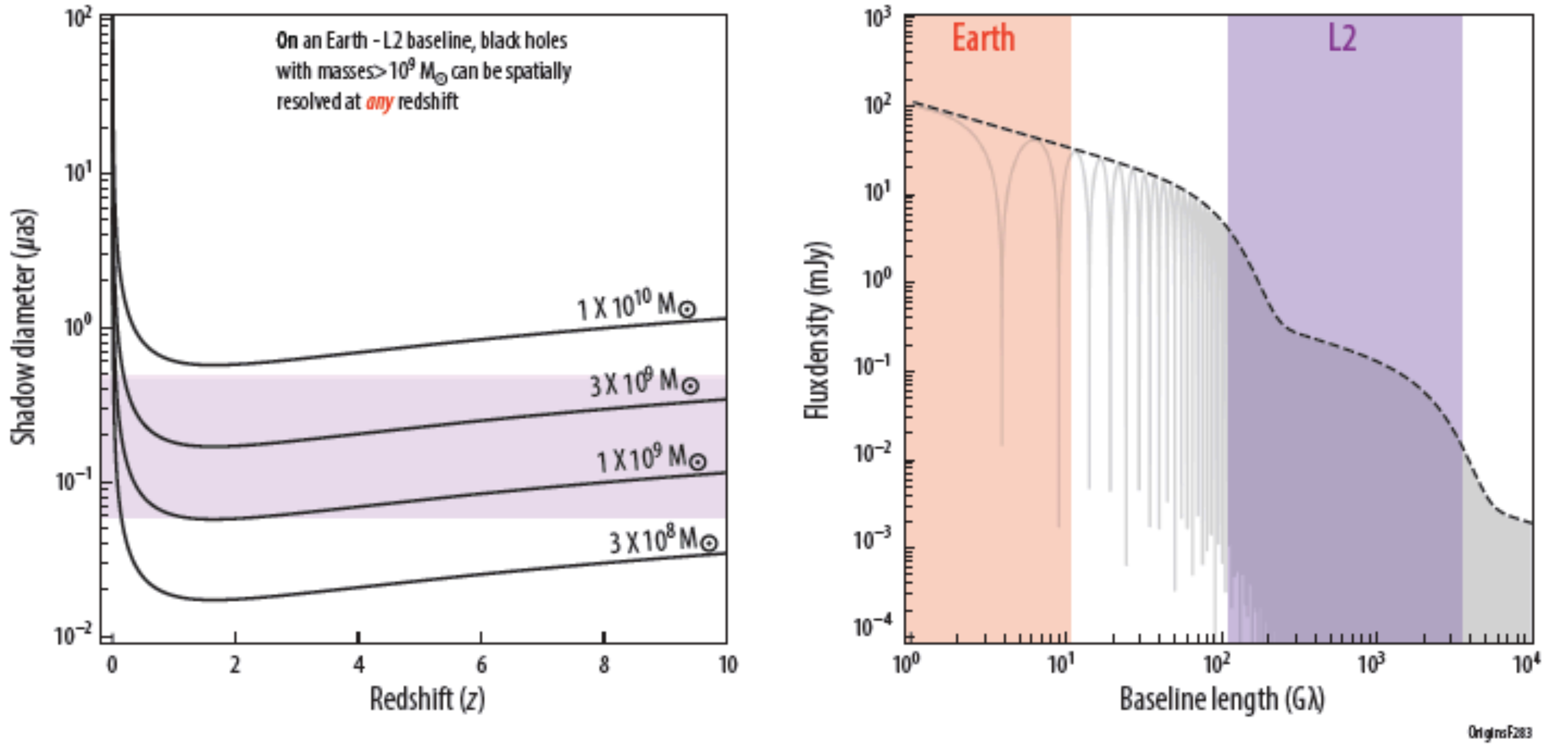


Figure D-13: (Left): Black hole shadow diameter vs. redshift for SMBHs of varying mass; the range of sizes accessible with a maximal Earth-L2 baseline operating at frequencies of 86 – 690 GHz is shaded in purple. We can see that as shadows reach a minimum size at $z \approx 2$, SMBHs with masses greater than $\sim 10^9$ $M_\odot$ are resolvable at all redshifts. (Right): Flux density as a function of baseline length is plotted in gray for a simple model of the M87 photon ring structure (Johnson et al. 2019) with the envelope shown as a dashed black line; note that the periodic structure evident at short baselines continues at longer baselines with the same period. The purple shaded region shows the range of baselines accessible over the course of a year on an Earth–L2 baseline operating at frequencies of 86 – 690 GHz; the long-baseline end of this range corresponds to a maximal baseline at 690 GHz, while the short-baseline end of the range corresponds to a minimal projected baseline (for M87, the minimal projected baseline is a factor of ~ 4 shorter than the maximal baseline) at 86 GHz. For comparison, the range of baselines accessible from the ground at 230 GHz observing frequency is shown in red. The Earth-L2 baseline coverage samples many more periods of the visibility structure than accessible from the ground, enabling correspondingly more precise measurements of the photon ring diameter.

Pesce et al. APC white papers, no. 176; Bulletin of the American Astronomical Society, Vol. 51, Issue 7, id. 176 (2019)

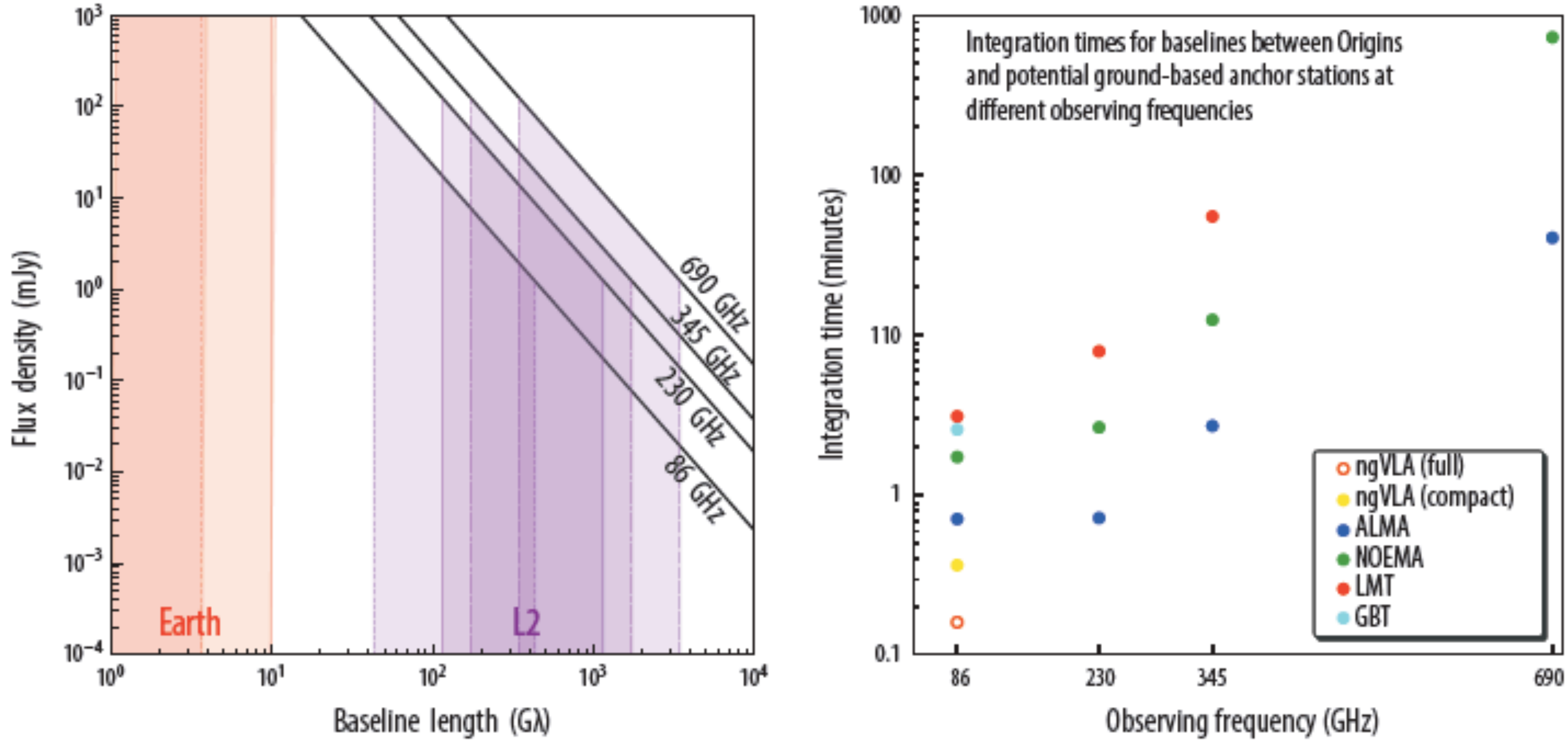


Figure D-14: (Left): For baselines to L2, synchrotron self-absorption and inverse-Compton scattering limit the brightness temperature to $T_b \leq 10^{12}$ K (Kellermann & Pauliny-Toth 1969); the black lines mark this limit for each of the labeled observing frequencies. Below each of these lines, the region shaded purple indicates physically allowed flux densities observable on Earth-L2 baselines ranging between 10 – 100% of the maximum projected baseline length; overlapping regions indicate where sources could be observed with matched resolution at two or more frequencies (albeit at different times). The red shaded regions are analogous to the purple ones, but for Earth-Earth baselines at 86 and 230 GHz only. (Right): Estimated integration times required to achieve a 5σ detection of a source with brightness temperature $T_b = 10^{12}$ K on a maximal baseline between Origins and various potential Earth-based anchor stations as a function of observing frequency. For the sensitivity estimates, we have assumed a total bandwidth (across all sidebands and polarizations) of 32 GHz for the 86 GHz observations, and 64 GHz for all other frequencies. All ground stations are assumed to be observing at 45 degrees elevation, with zenith opacity of 0.05 (ALMA), 0.09 (NOEMA), 0.13 (LMT) at 230 GHz, and 0.05 (GBT, ngVLA) at 86 GHz. An aperture efficiency of 0.7 was assumed for all sites. Receiver temperatures are taken from station specifications or projections.

Pesce et al. APC white papers, no. 176; Bulletin of the American Astronomical Society, Vol. 51, Issue 7, id. 176 (2019)