Developments toward Photon Counting Terahertz Interferometry

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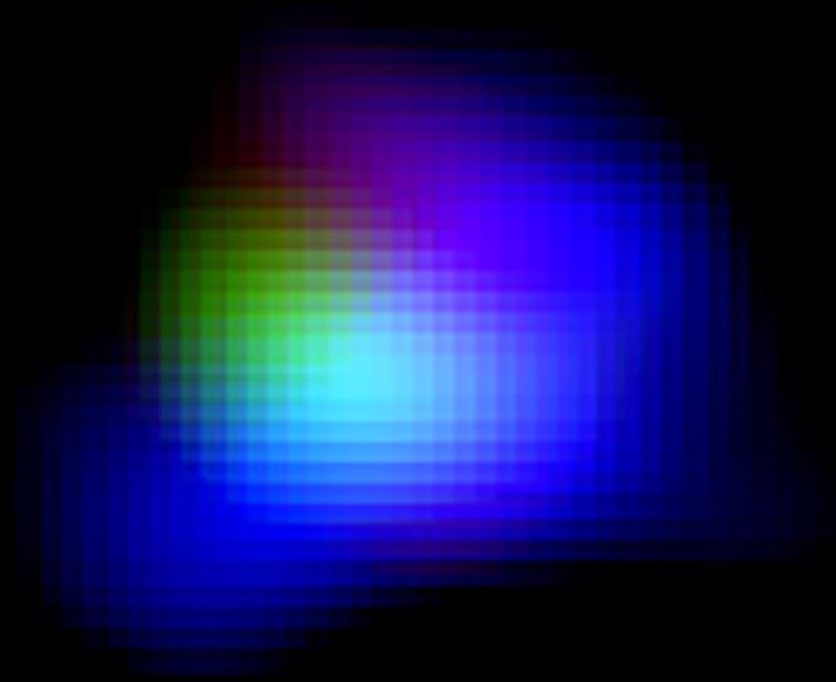
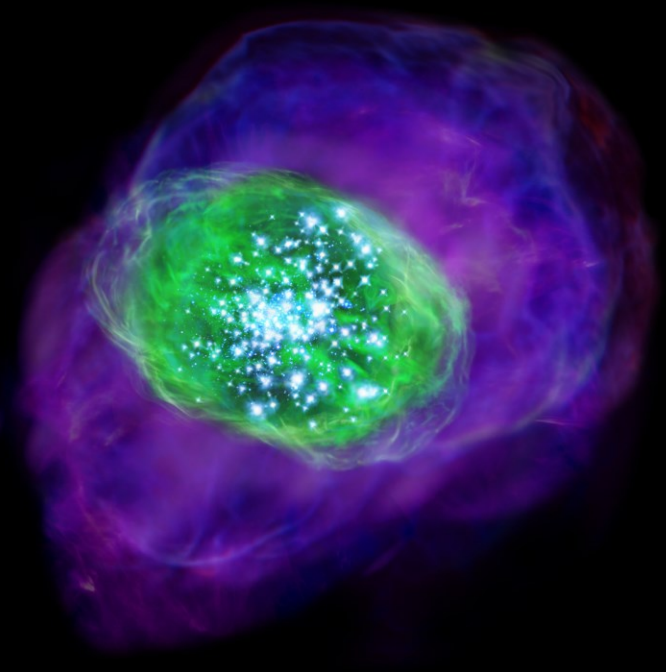
Atacama Large Millimeter/submillimeter Array
DV-11
Credit: ALMA (ESO/NAOJ/NRAO)

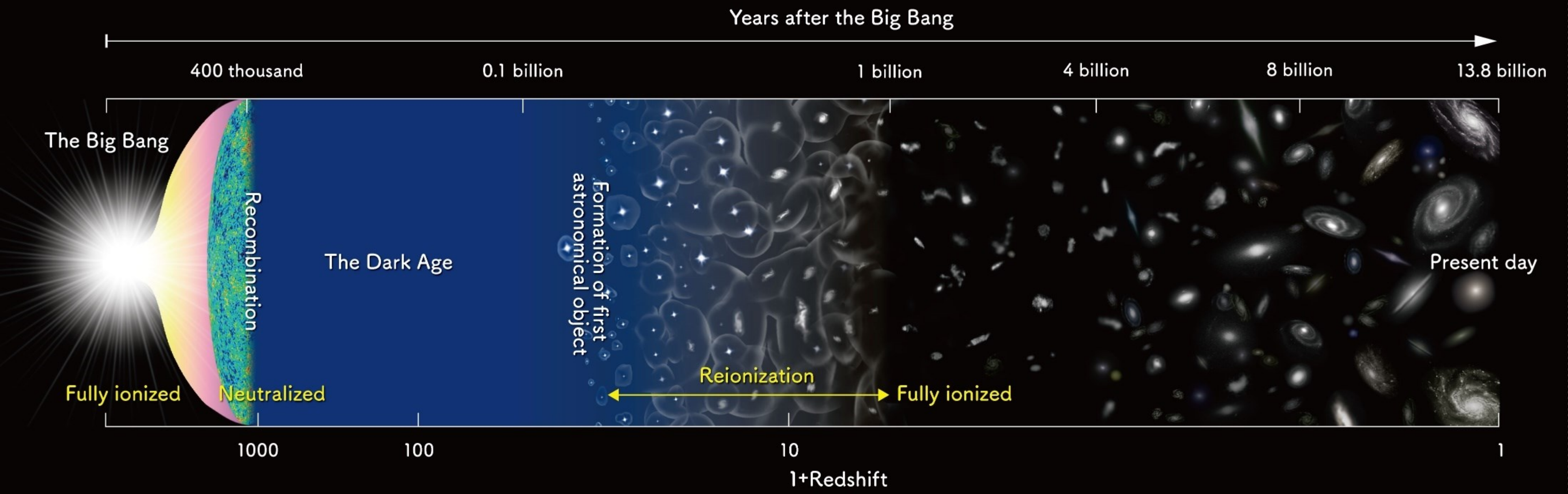
ALMA observed [OIII] 88μm (3.4THz) from z=7.2 SXDF-NB1006-2





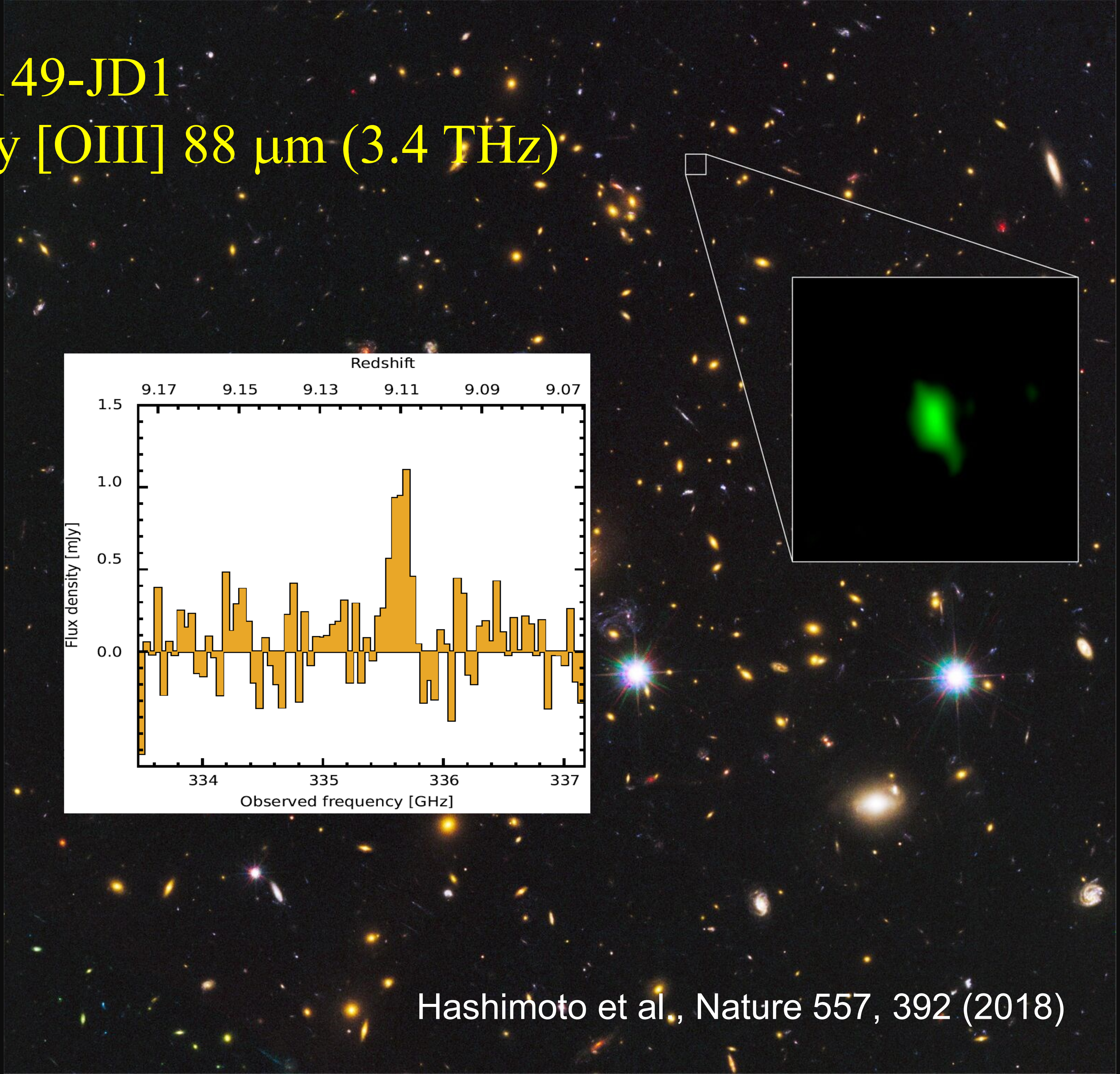
From NAOJ press release
Inoue, Tamura, Matsuo et al., Science 352, 1559 (2016)

Cosmic Reionization



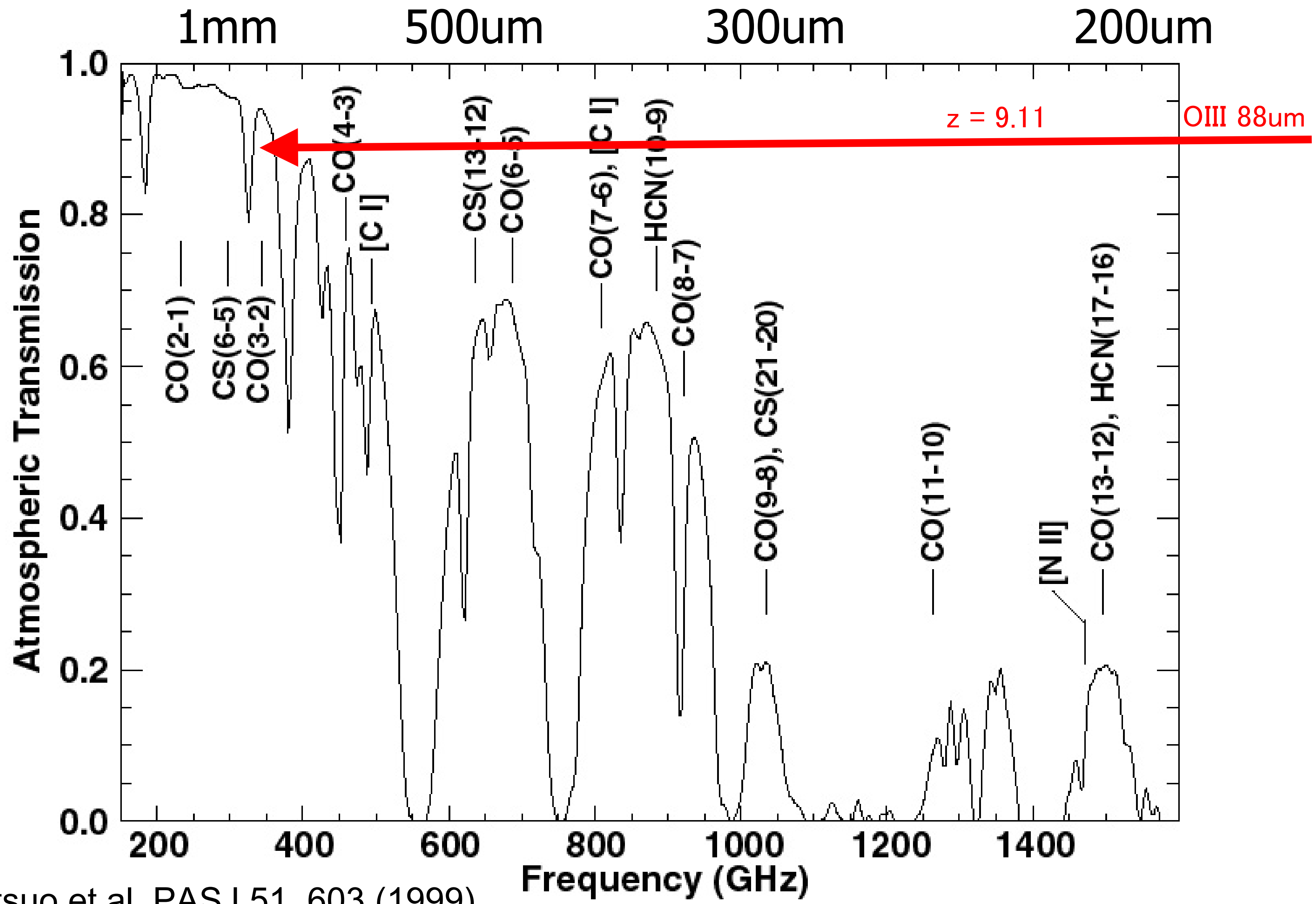
From NAOJ press release
Inoue, Tamura, Matsuo et al., Science 352, 1559 (2016)

MACS1149-JD1
z=9.11 by [OIII] 88 μm (3.4 THz)



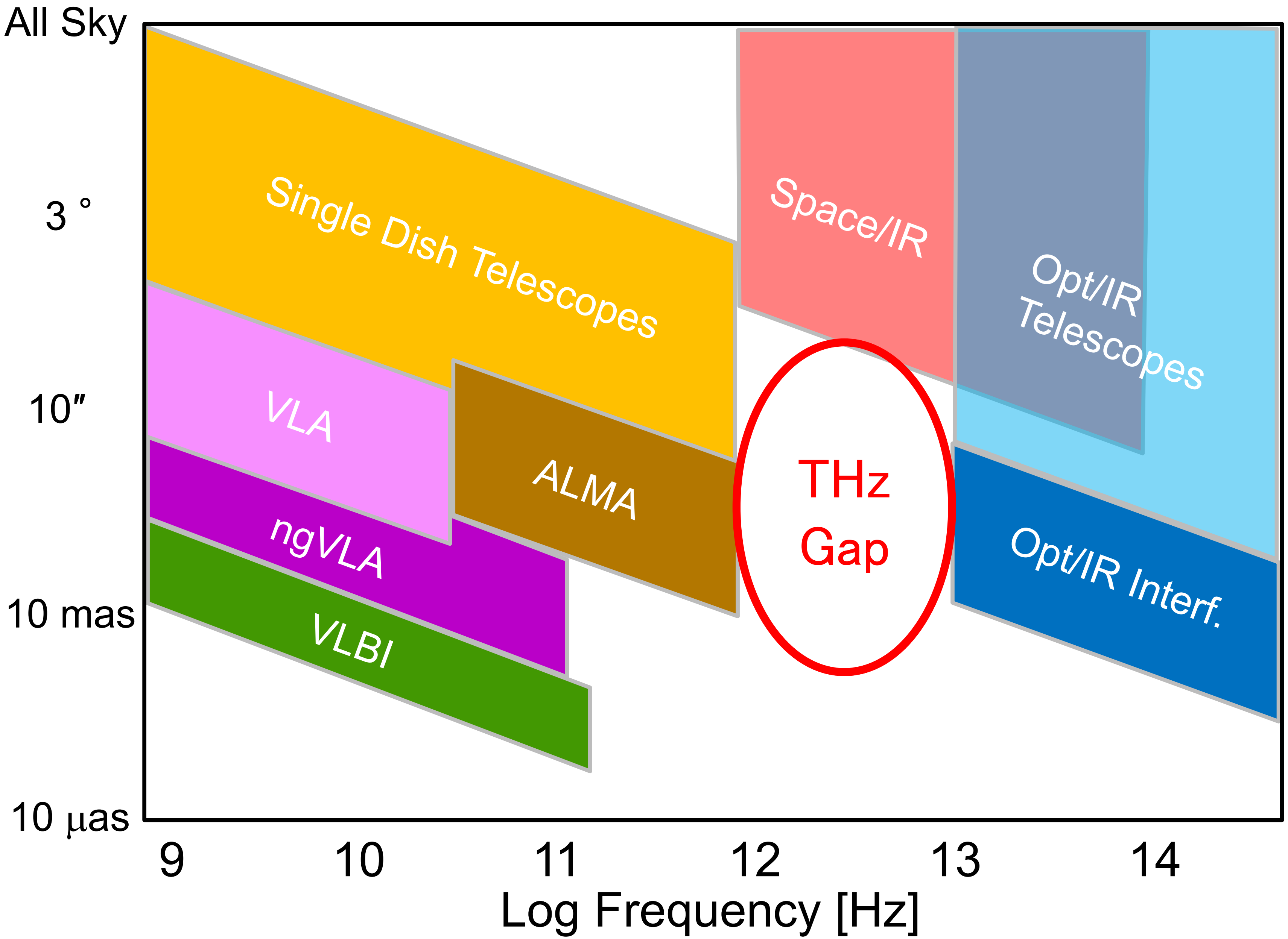
Hashimoto et al., Nature 557, 392 (2018)

Atmospheric Windows from Atacama（alt. 4800m）



Matsushita, Matsuo et al. PASJ 51, 603 (1999)

Angular Scale of Observation



Narrabri Stellar Intensity Interferometer

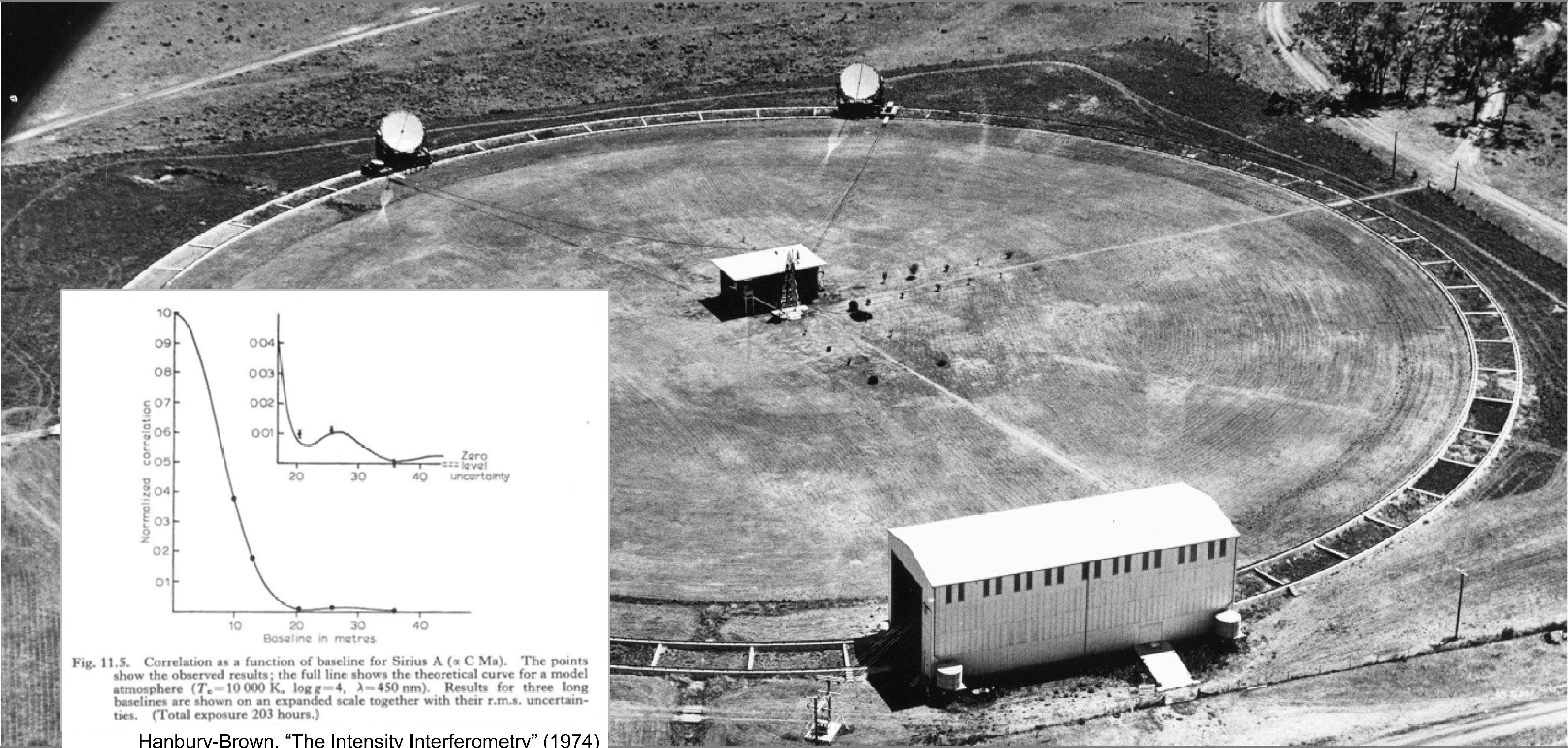
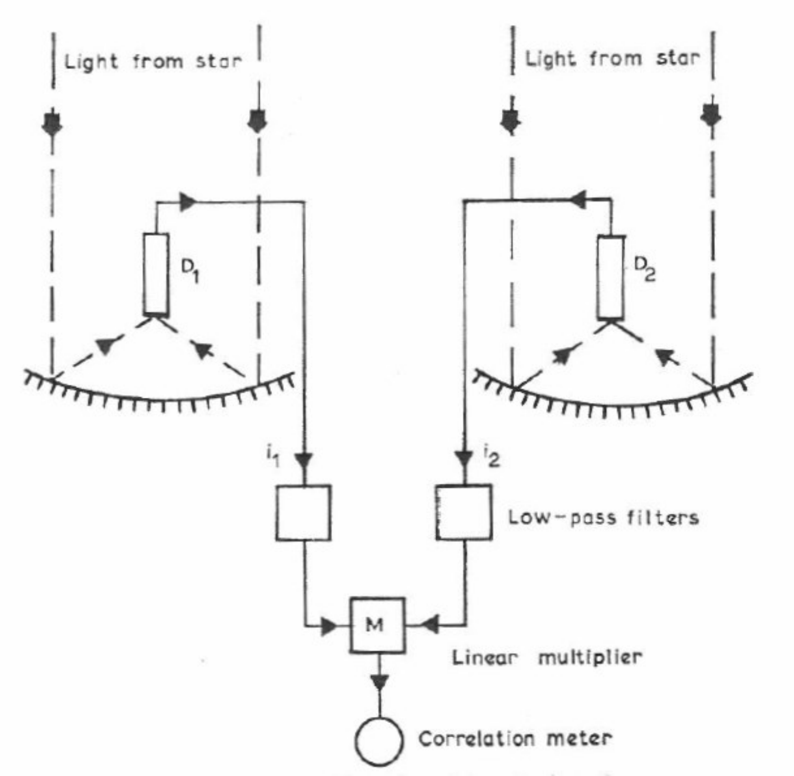


Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model atmosphere ($T_e = 10\,000$ K, $\log g = 4$, $\lambda = 450$ nm). Results for three long baselines are shown on an expanded scale together with their r.m.s. uncertainties. (Total exposure 203 hours.)

Hanbury-Brown, “The Intensity Interferometry” (1974)

HBT Intensity Interferometry

- Correlate “Intensities”
  from two individual telescopes
- Radio intensity interferometer at 125 MHz
  - Hanbury-Brown et al. (1952)
- Optical interferometer
  - Hanbury-Brown and Twiss (1956)



from Hanbury-Brown (1974)
“The Intensity Interferometer”

Limitation of intensity interferometers

- High Dynamic Range is required
  - Intensity correlation $\propto$ (Amplitude correlation)^2
- Low efficiency for optical observations
  - Observation of bright early type stars only
- Phase information is missing
  - Measurement of stellar diameters only

Fluctuation of thermal radiation

$$\Delta n = \sqrt{n + n^2}\ , \quad \text{where}\ \ n = \frac{1}{e^{h\nu/kT} - 1}$$

n : photon occupation number

$$A\Omega = \lambda^2$$

$$\text{NEP} = \sqrt{2P \cdot \left(h\nu + kT_B\right)}\ [\text{W}/\sqrt{\text{Hz}}]$$

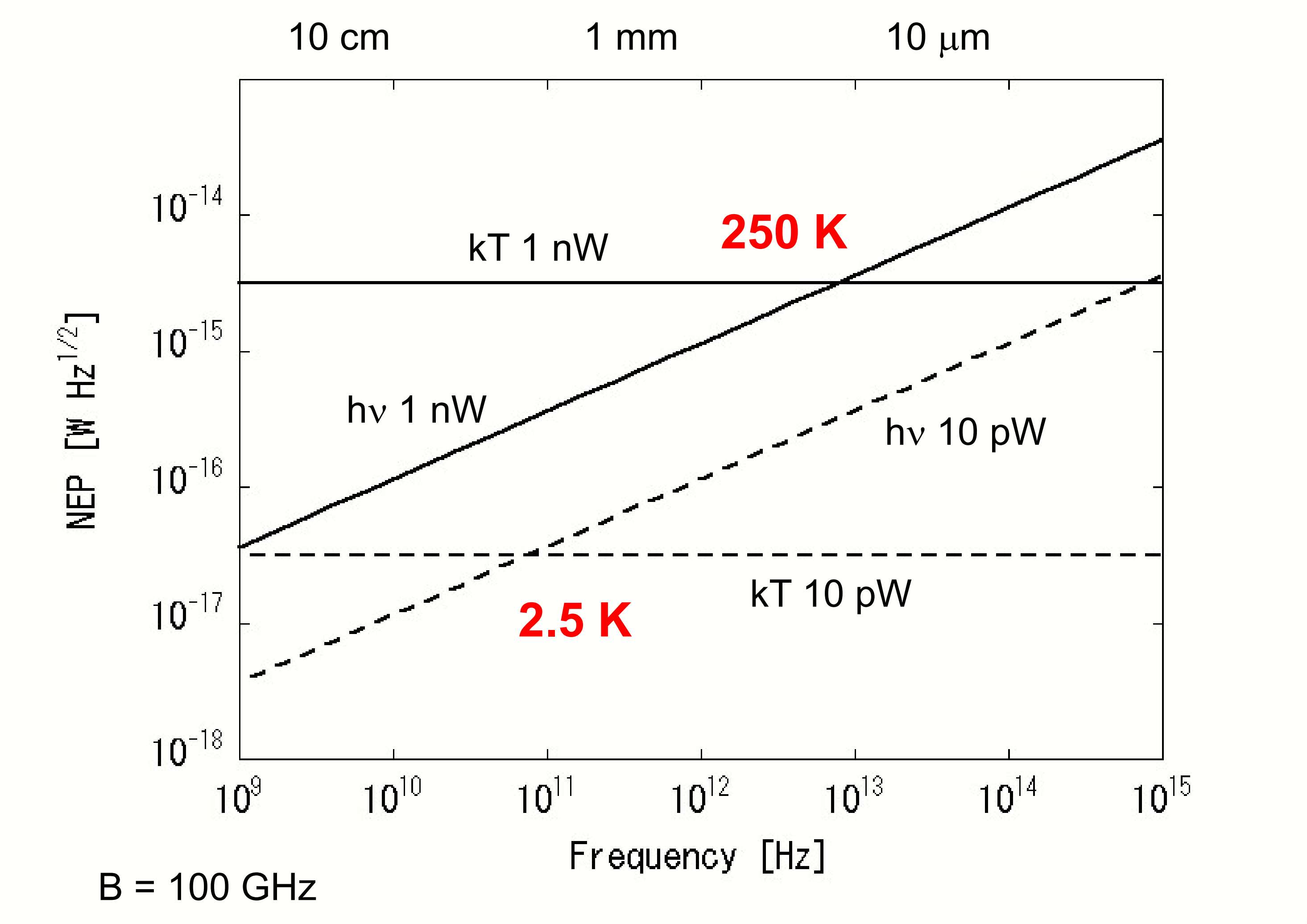
$\Delta T = T_B / \sqrt{B\tau}$

Photon bunching

References

A. Einstein (1909)
J. Mather (1984)
J.M. Lamarre (1986)
J. Zmuidzinas (2003)

THz photon statistics



Matsuo, JLTP 167, 840 (2012)

$$\mathrm{NEP} = \sqrt{2P \cdot (h\nu + kT_B)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

$$T_B = \left(\frac{\mathrm{NEP}^2}{2P} - h\nu \right) \times \frac{1}{k} \quad [\mathrm{K}]$$

de Bernardis and Masi (1982)

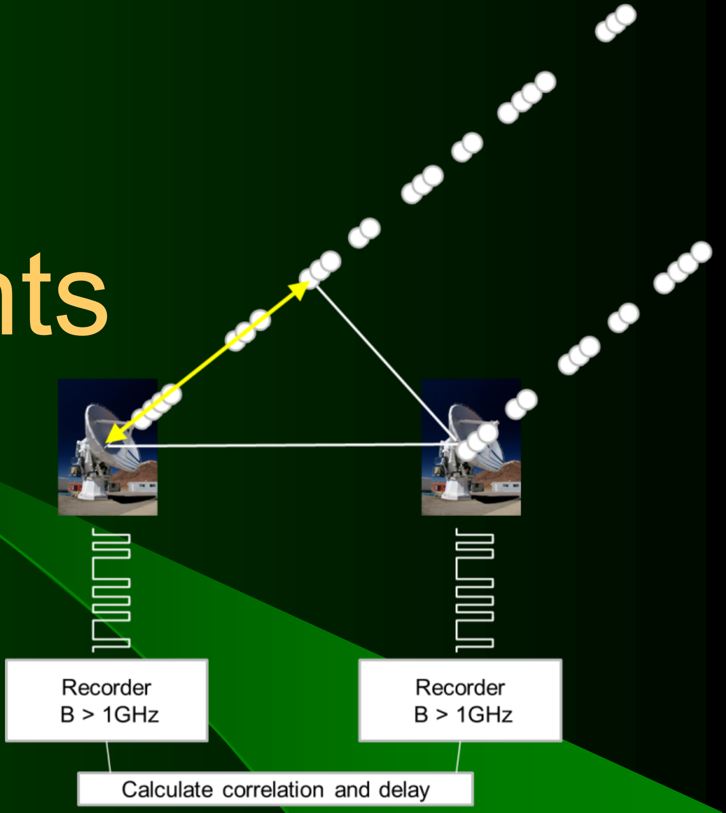
Photon Bunches for delay time measurements

- Photon bunch can be a measure of delay time.
  - Complex visibility can be obtained.
- Large number of THz photon is expected.

  100 M photons/sec from Stars and AGNs

  1 Jy at 1 THz (B=100 GHz), using ϕ10 m telescope

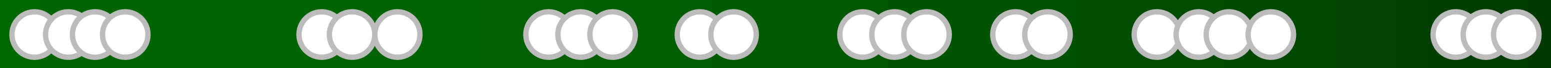
  $\Delta t = 10^{-13}$ sec in 100 sec is expected.



$$\Delta t = \frac{1}{N\sqrt{N \cdot \tau}}$$

N: photon rate

τ : integration time



THz Photons are bunched !

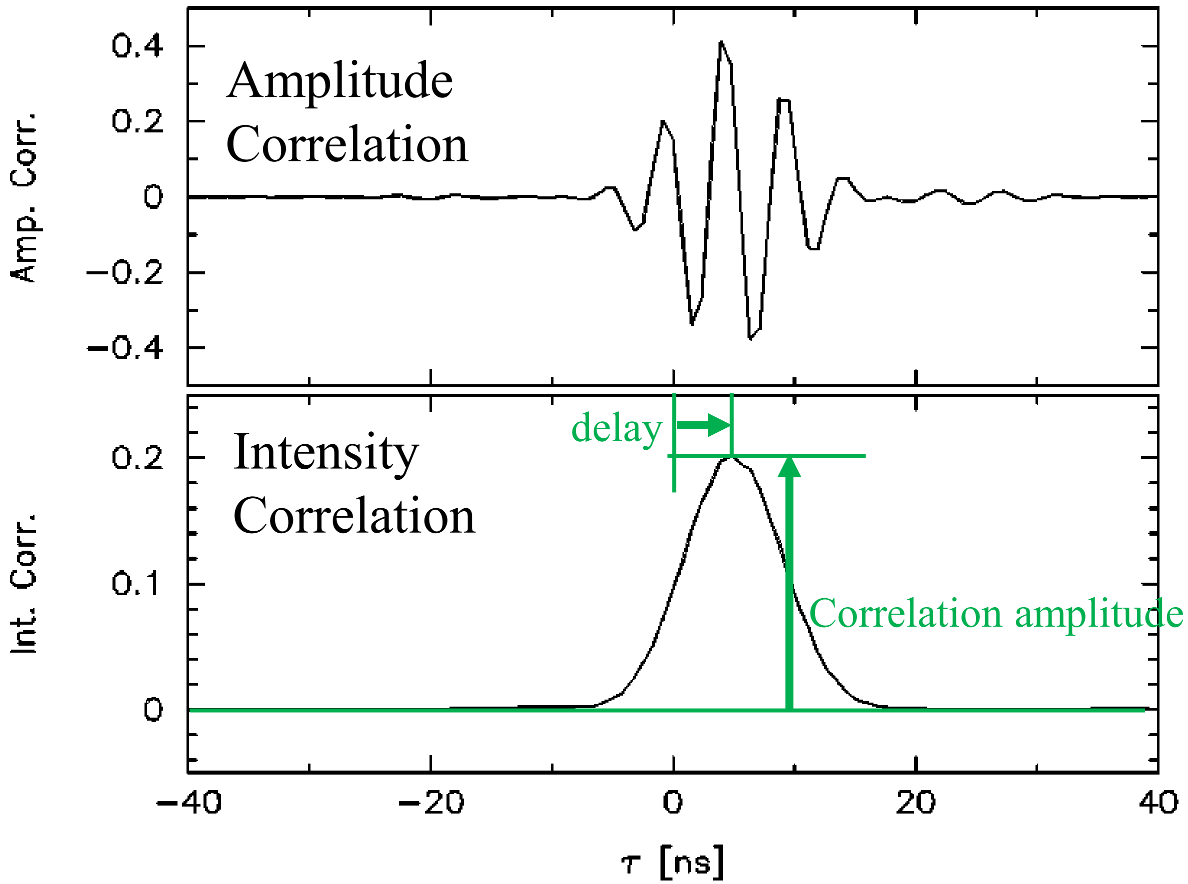
Nobeyama Radioheliograph (NoRH)

- Interferometer exclusively observing the Sun
- 84 antennas of 80 cm diameter
- 17 GHz R+L / 34 GHz
- Fundamental Spacing 1.528 m

Date: April 14, 2014
Utilized:
17 GHz (17 mTHz) R+L
Central 16 elements aligned East-West

Nobeyema Radioheliograph at 17 GHz

Shortest baselines averaged over 16 antennas



Antenna Temperature T_A^* [K]

System Temperature T_{sys} [K]

Frequency ν [Hz]

Bandwidth $\Delta\nu$ [Hz]

$$\Delta t = \frac{T_{sys}}{T_A^*} \cdot \frac{1}{\sqrt{\Delta\nu \cdot \tau}} \cdot \frac{1}{\Delta\nu} \text{ [s]}$$

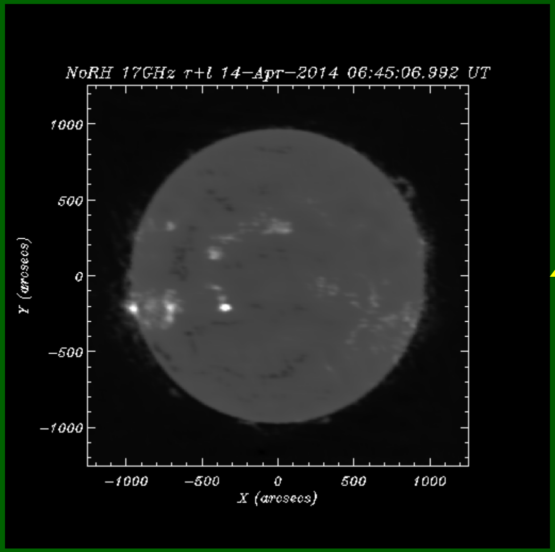
$$\Delta\varphi = 2\pi\nu\Delta t \text{ [rad]}$$

Δt ~ 5ps in 50 ms integration

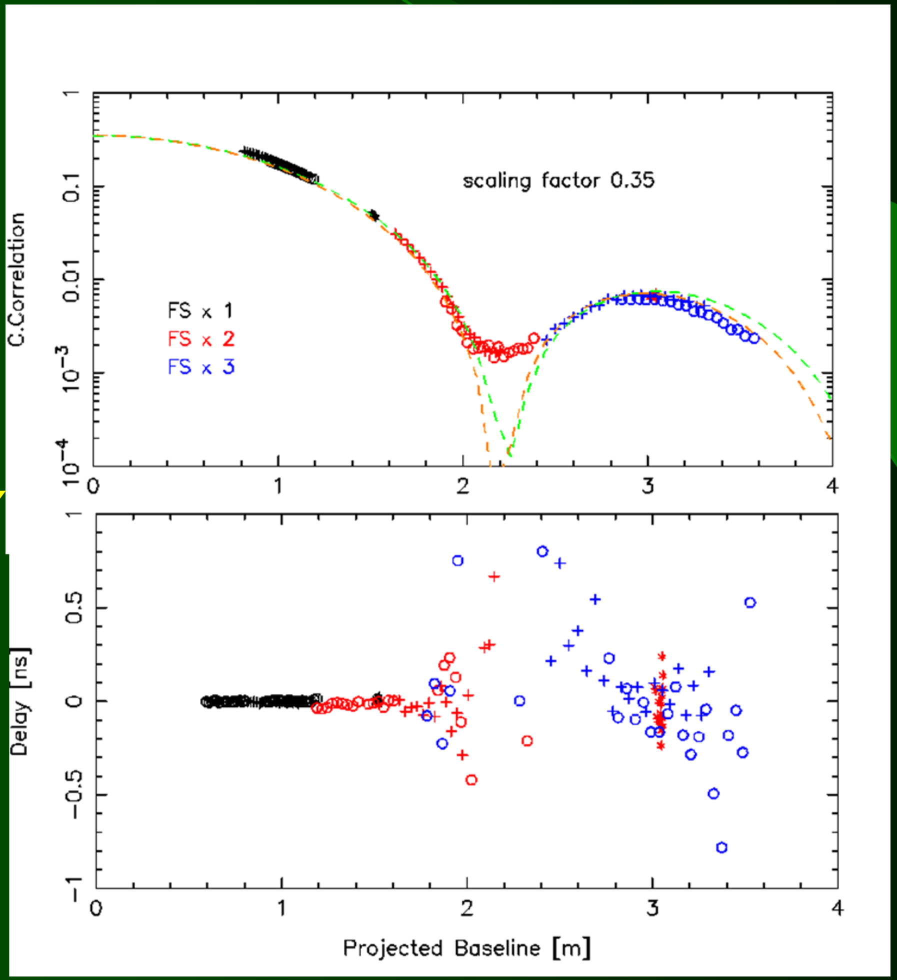
Ezawa, Matsuo et al., JLTP 184, 244 (2016)

Experiment at 17 GHz
with Nobeyama Radioheliograph

- Real Part of Visibility
  - (Intensity Correlation)$^{0.5}$
- Imaginary Part
  - $\Delta\varphi = 2\,\pi\,\nu\,\Delta t$



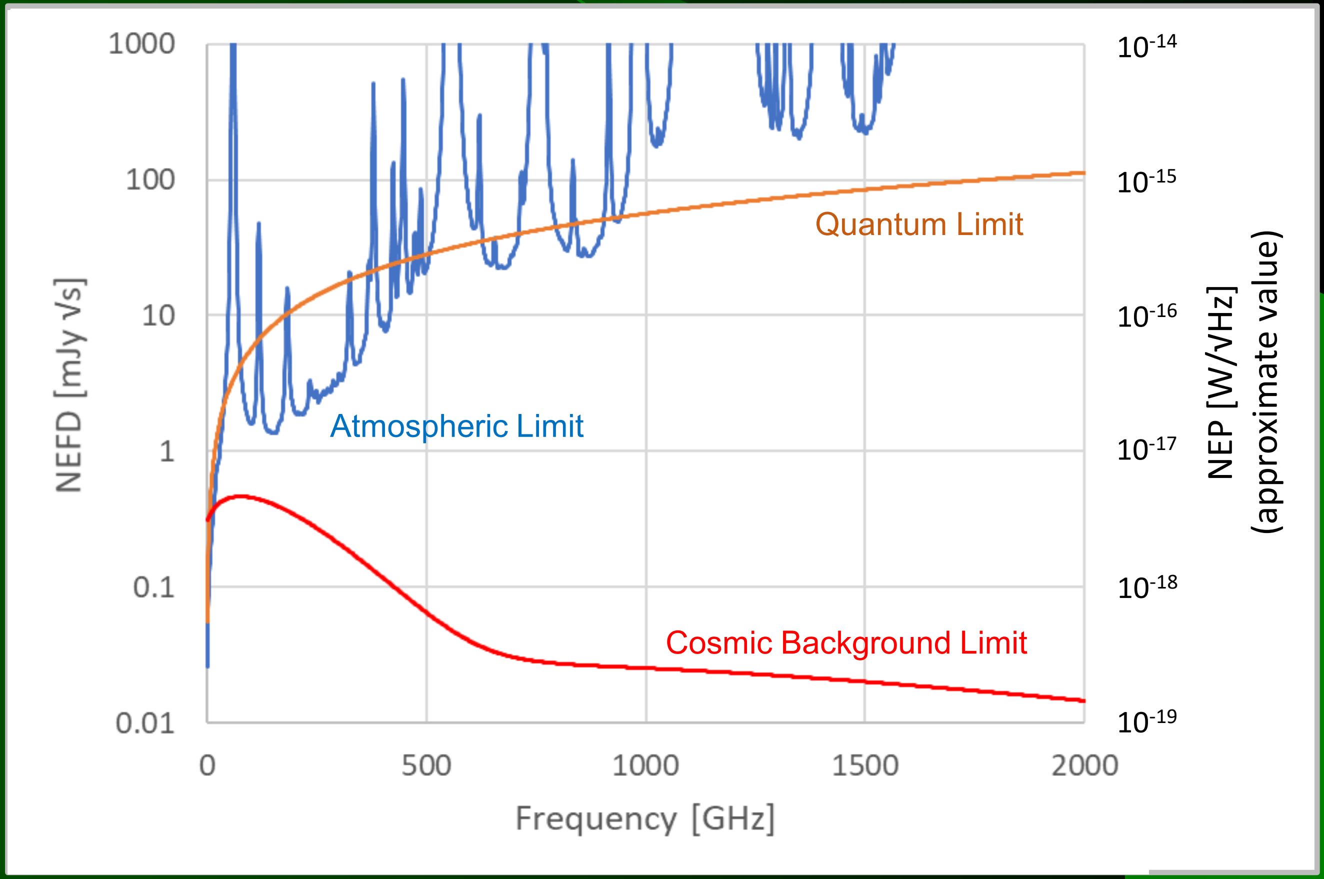
Van Cittert
Zernike



Background limited observation with Space THz Intensity Interferometry

- Quantum noise of heterodyne receivers
  - $T_{QL} = h\nu/k$ [K] = 150 K @ 3THz
  - $n = kT_{QL}B/h\nu = B$ [photons/s]
- Background limit of direct detectors
  - NEP = 10^{-19} W/Hz$^{0.5}$, B =100 GHz
  - T_{RX} = NEP / (2k $B^{0.5}$) = 10 mK
  - Background vs. Quantum limit

    ~ 4 orders



Intensity Interferometry

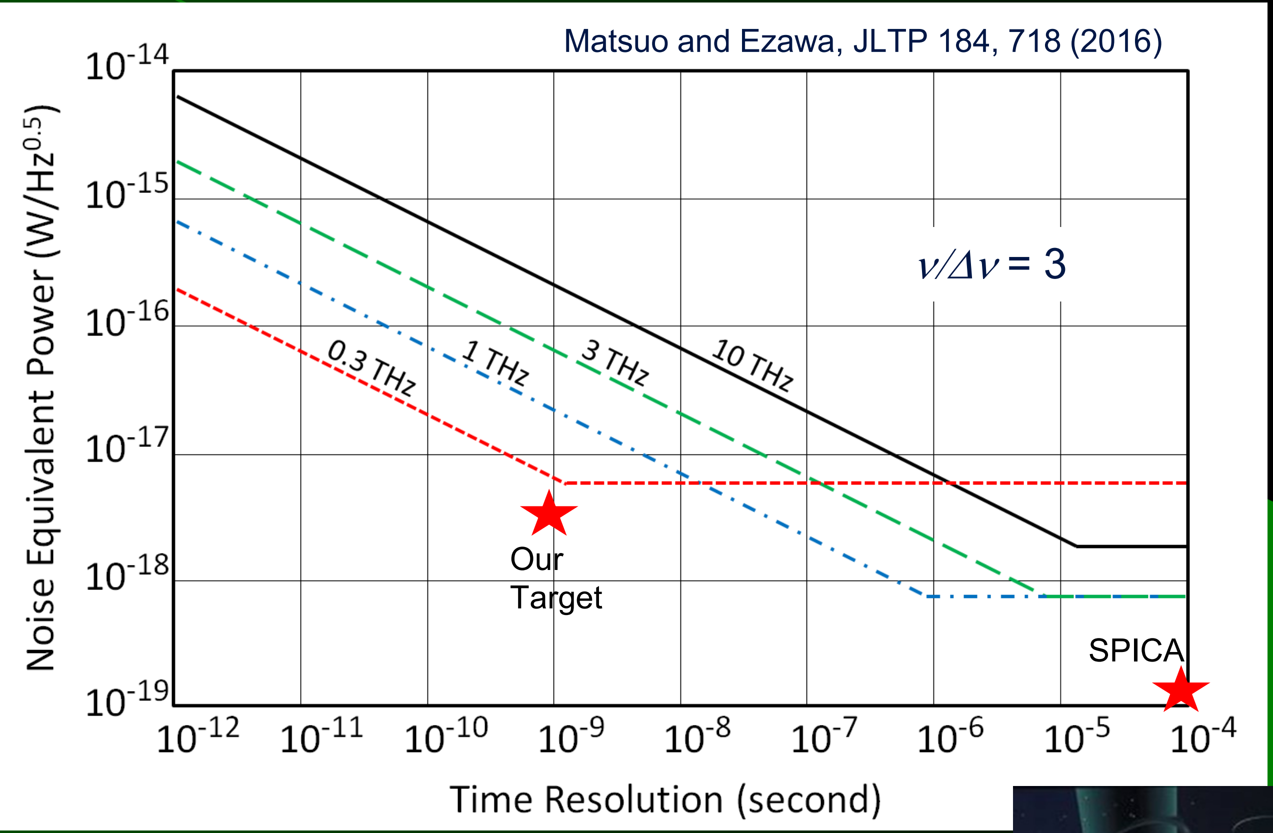
- Cross correlation of Intensity (E^2)
  - High correlation efficiency in far-infrared
  - Missing phase information
- Stable against phase fluctuation
  - Coherence lengths >> Wavelengths
- Photon counting detector can be used
  - No receiver quantum limit
- Photon bunches enable delay measurements
  - Aperture synthesis imaging

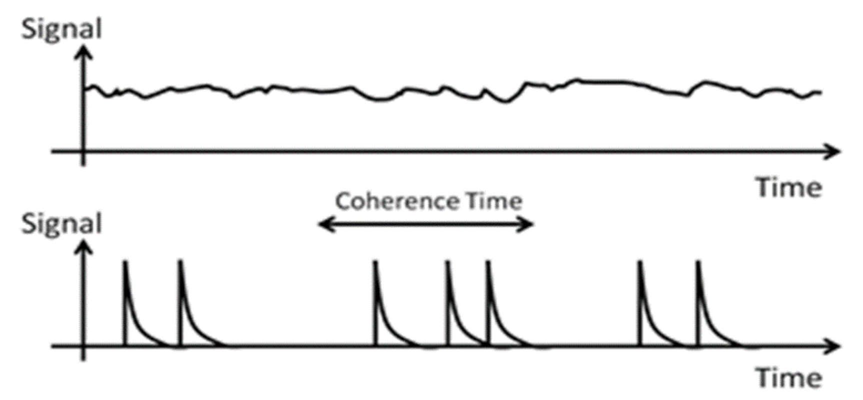
Requirements to Detectors

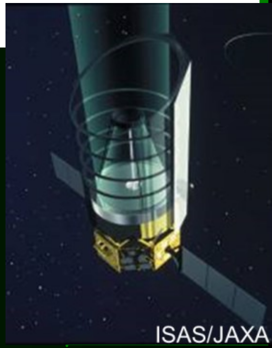
- Sensitive to THz photons
  - Photon energy ~10^{-21} Joule
- Fast response
  - B = 1 GHz for 100 M photons/s
- NEP(Noise Equivalent Power)

  $= 10^{-21} \times (1\ \text{GHz})^{0.5}$

  $\sim 10^{-17}\ \text{W/Hz}^{0.5}$







SIS Photon Detectors

$$S = \eta \cdot \frac{e}{h\nu} \quad [\mathrm{A/W}]$$

$$N = \sqrt{2eI_0} \quad [\mathrm{A}/\sqrt{\mathrm{Hz}}]$$

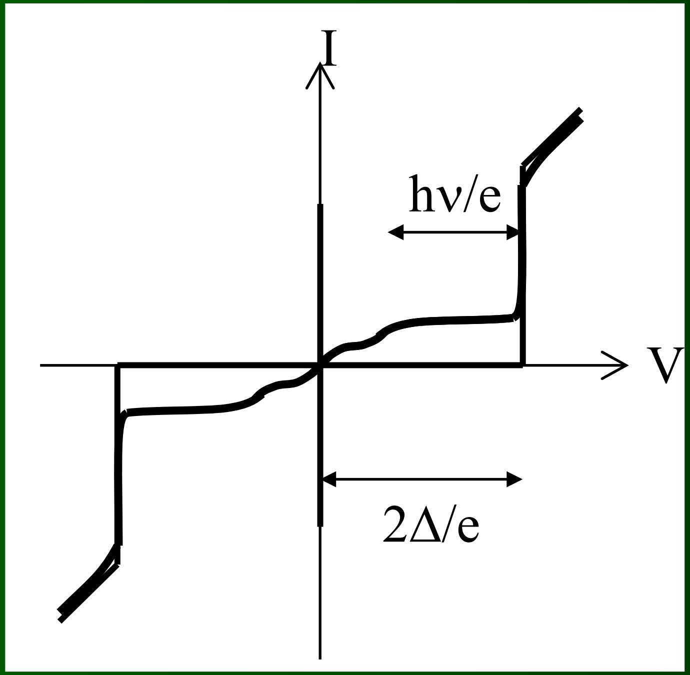
$$NEP = \frac{h\nu}{\eta} \cdot \sqrt{\frac{2I_0}{e}} \quad [\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

$$NEP \approx 3\times10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$$

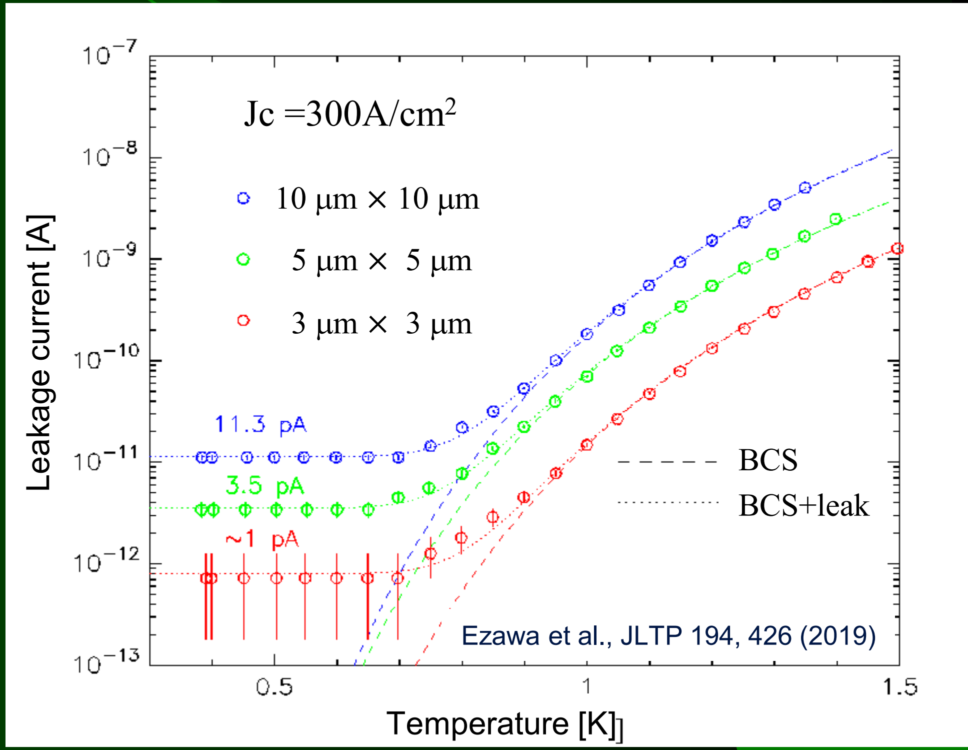
for $I_0 = 1\,\mathrm{pA}$ $\eta = 0.5$

at 650 GHz

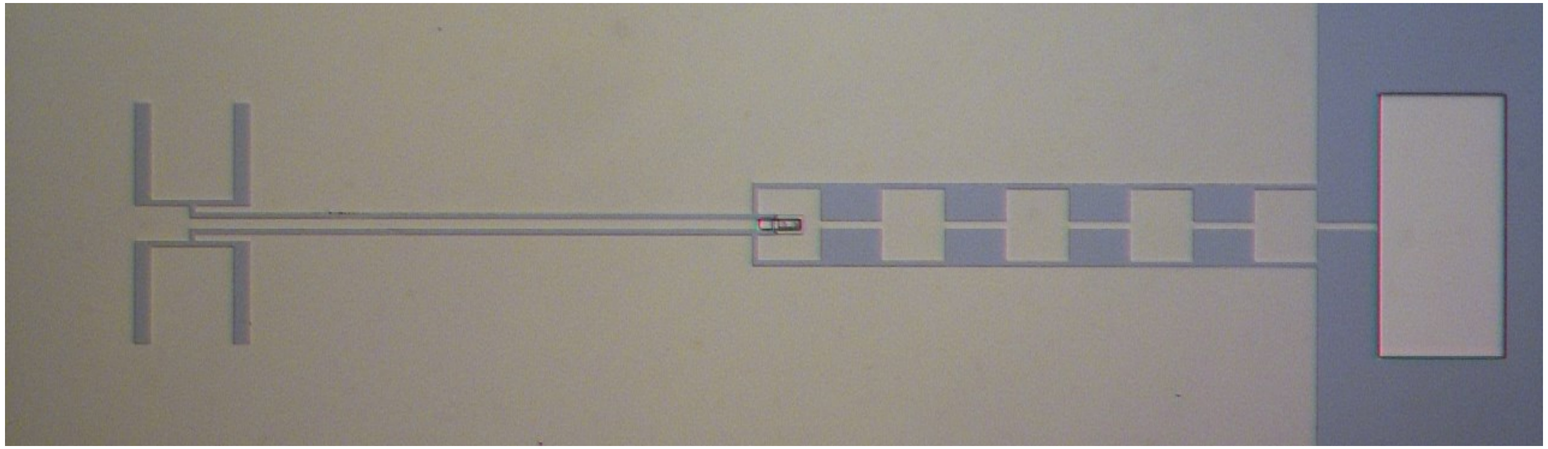
Photon Assisted Tunneling



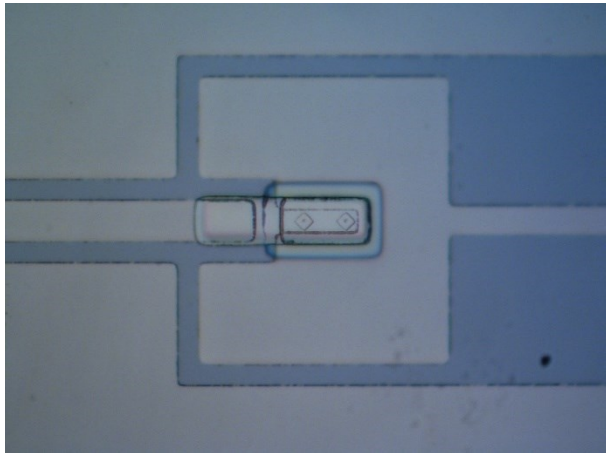
Low leakage SIS junctions



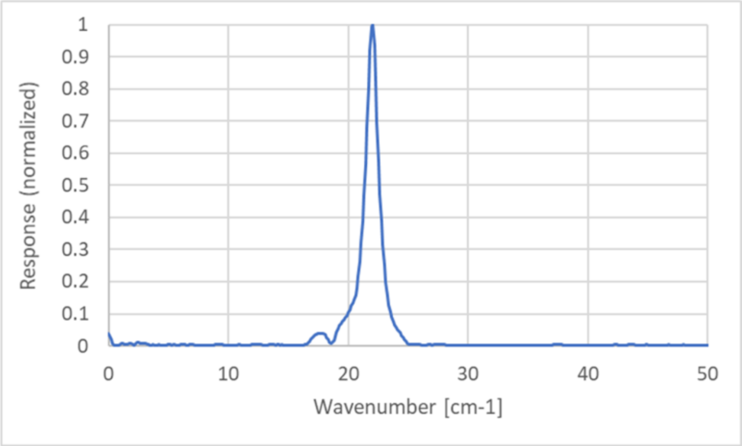
Superconducting detectors in THz frequencies



An antenna-coupled Nb-SIS photon detector at 650 GHz fabricated in CRAVITY(AIST)

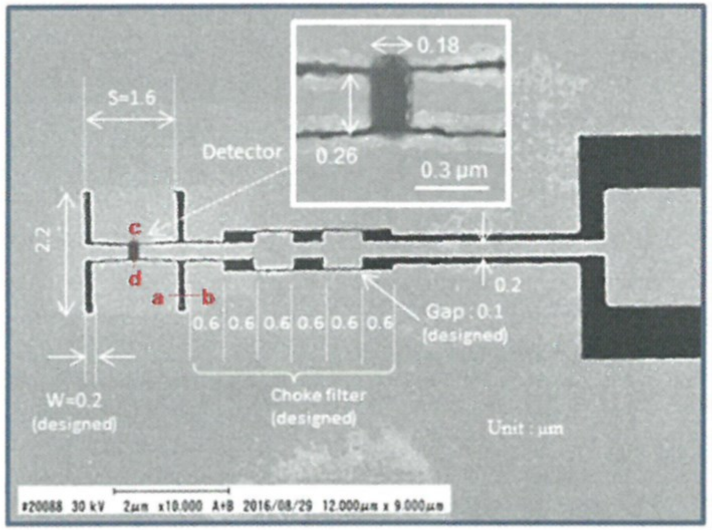


Spectral Response
ν=660 GHz Δν=35GHz

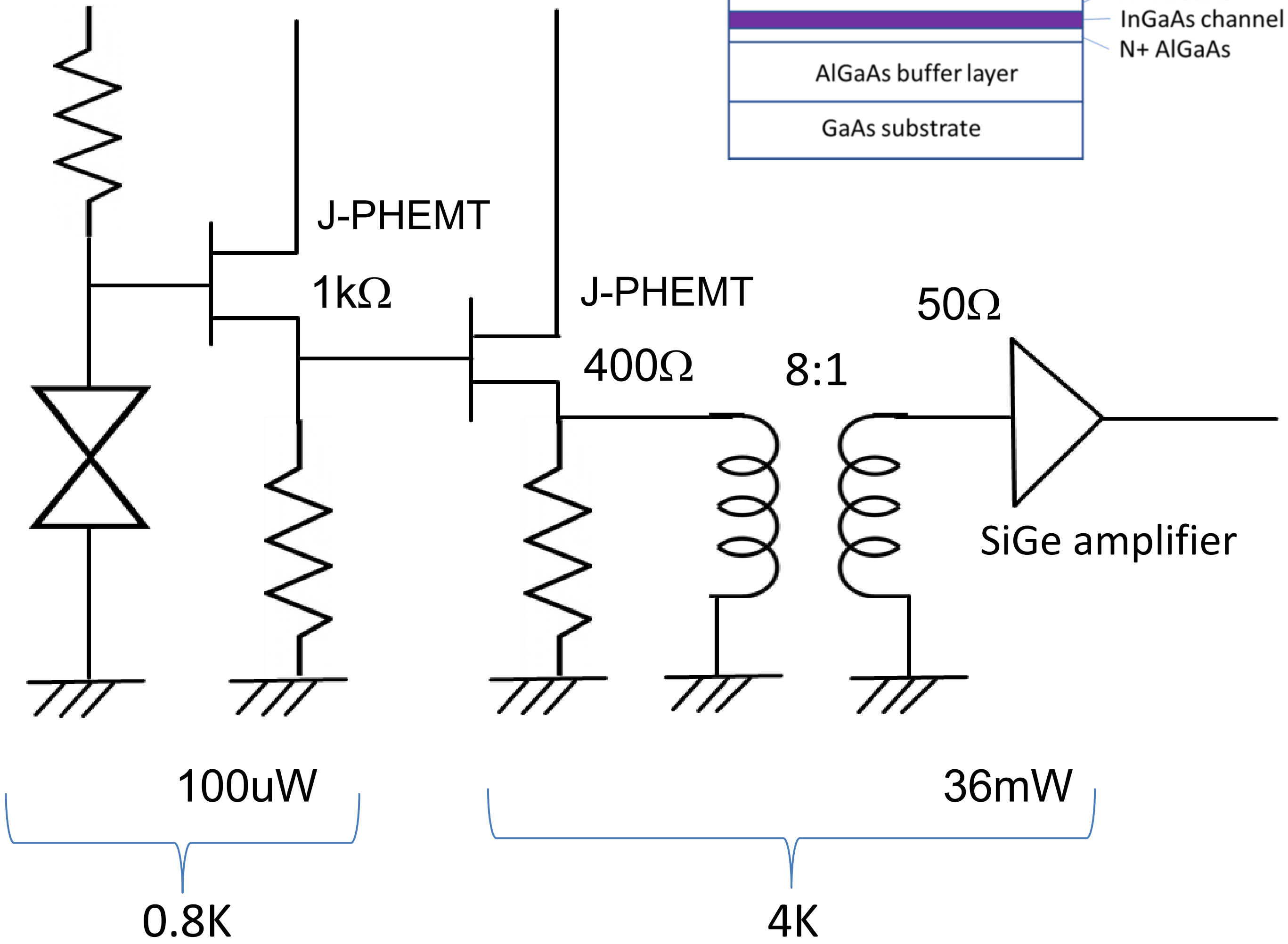


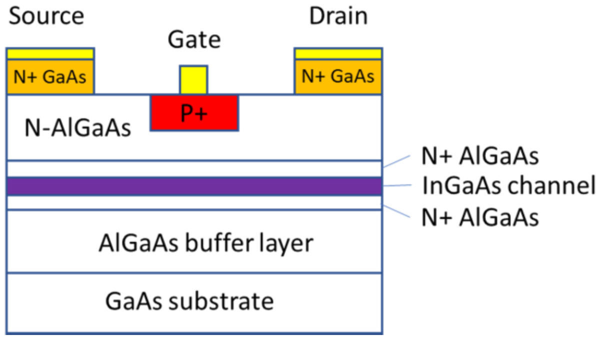
Ezawa et al. JLTP 200, 226 (2020)

An example of superconducting detector at 10um (30THz)
Kawakami et al. (2019)



Readout Electronics





SIS photon detector signal

One electron/photon with a bandwidth of 1 GHz.

Assuming,
Capacitance = 10 fF
$$V_s = \frac{e}{C} = 16\ \mu\text{V}$$

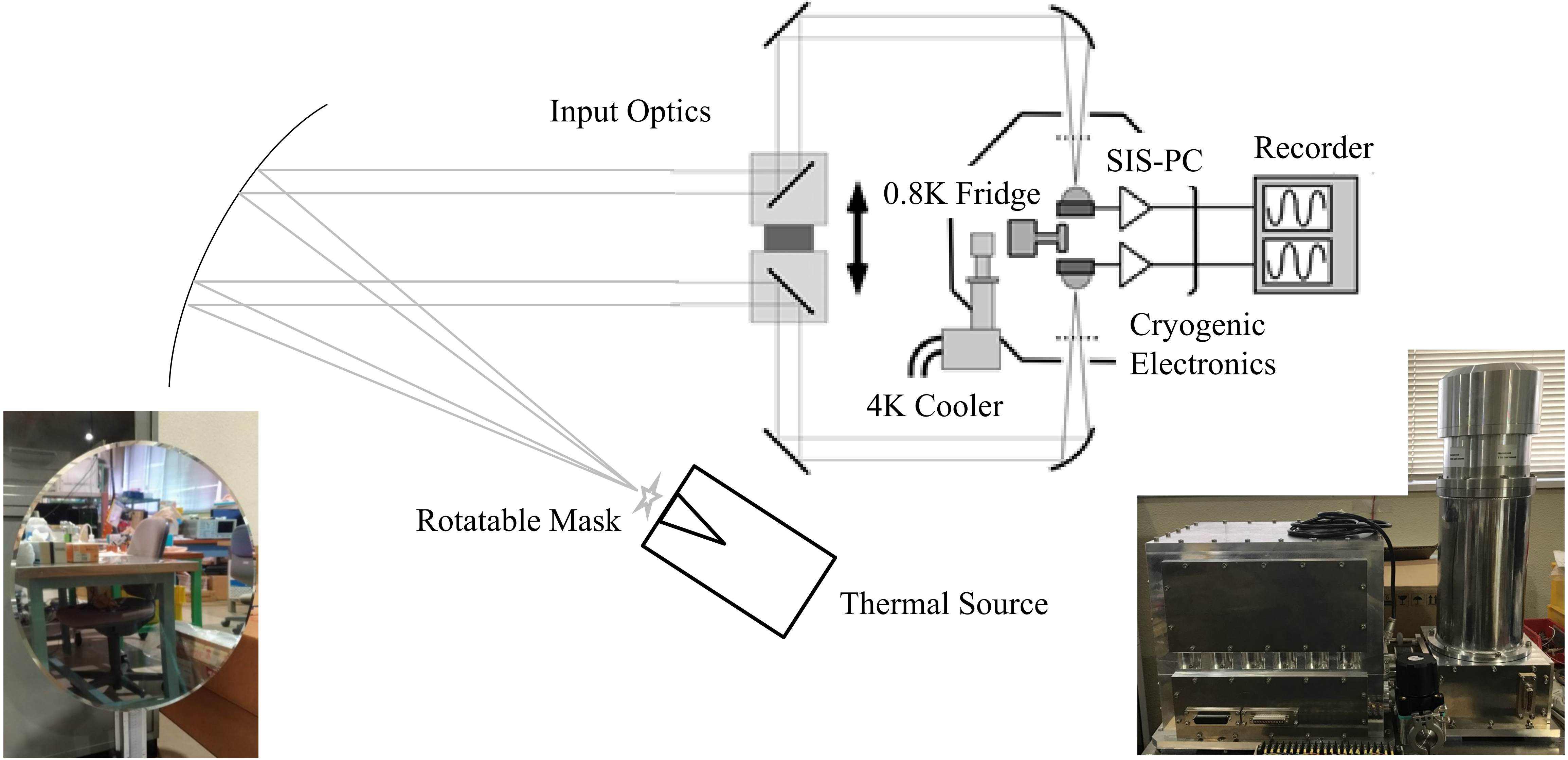
FET thermal noise at 0.8K

$$v_n = \sqrt{4k_B T R_D} = 0.2\ n\text{V}/\sqrt{H_Z}$$

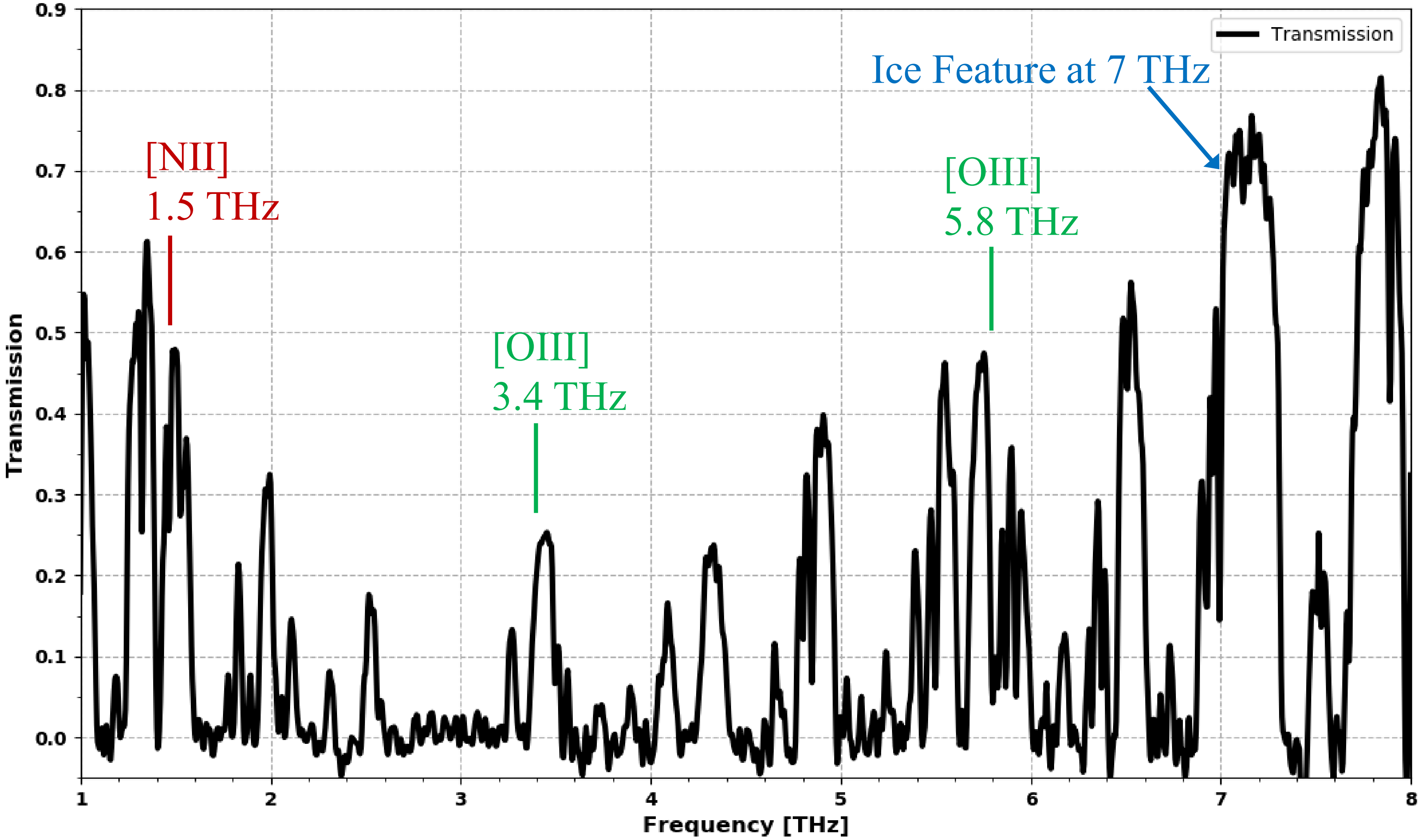
$$R_D = \frac{1}{g_m} = \frac{dV_g}{dI_d} = 1\ \text{k}\Omega$$

With a bandwidth of 1 GHz,
$$V_n = v_n \times \sqrt{B} = 6\ \mu\text{V}_{\text{rms}}$$

Experimental Setup for Intensity Interferometry



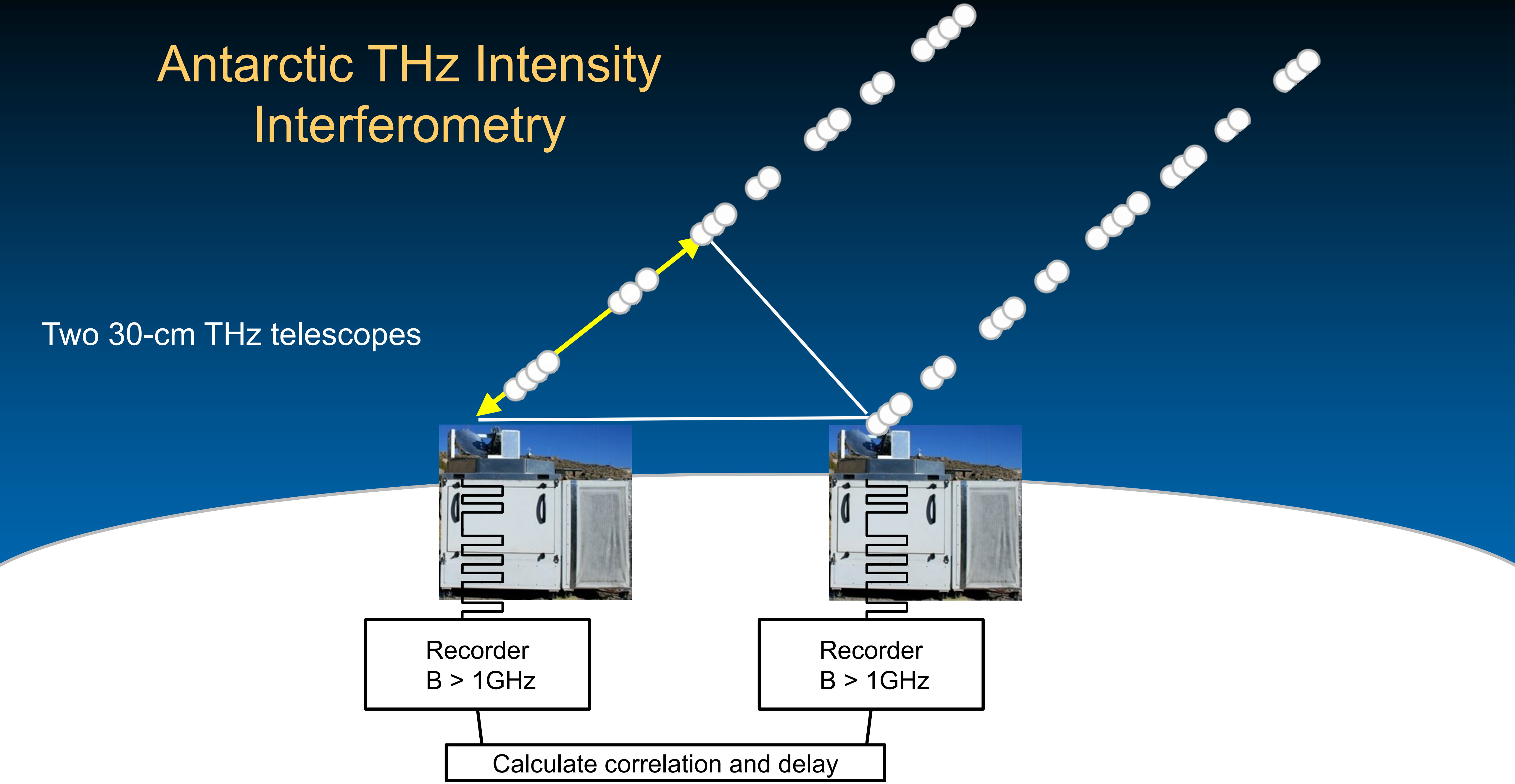
The Most Transparent Atmosphere from Dome A



August 9th 12–18h UTC, 2010

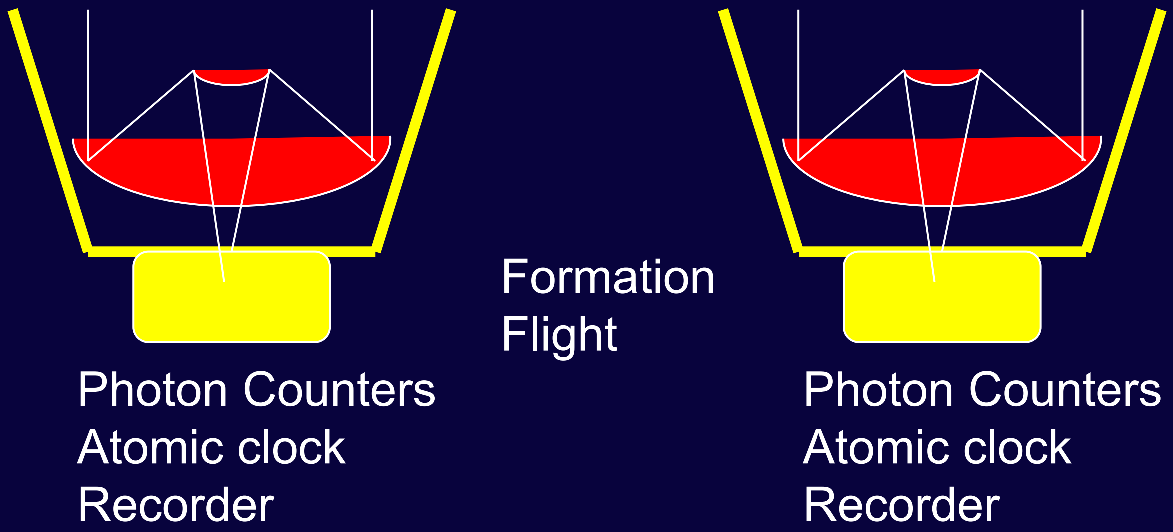
Matsuo et al. Advances in Polar Science 30, 76 (2019)

Antarctic THz Intensity Interferometry



Technologies for Space Terahertz Interferometry

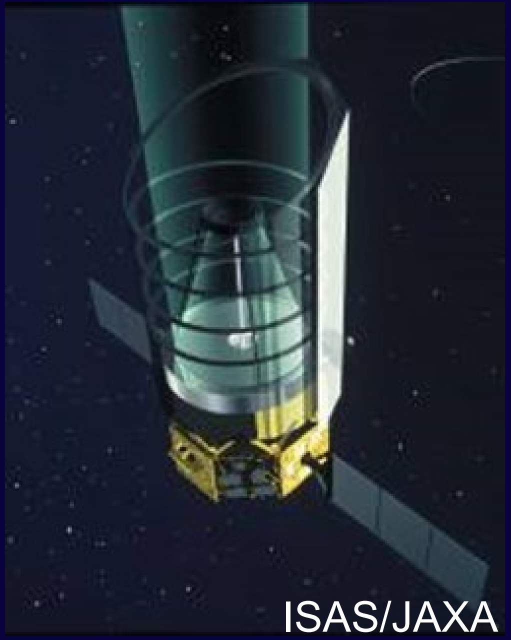
- Cryogenics - AKARI, SPICA, Astro-H
- VLBI technology - HALCA, Astro-G
- Superconducting detectors - SMILES

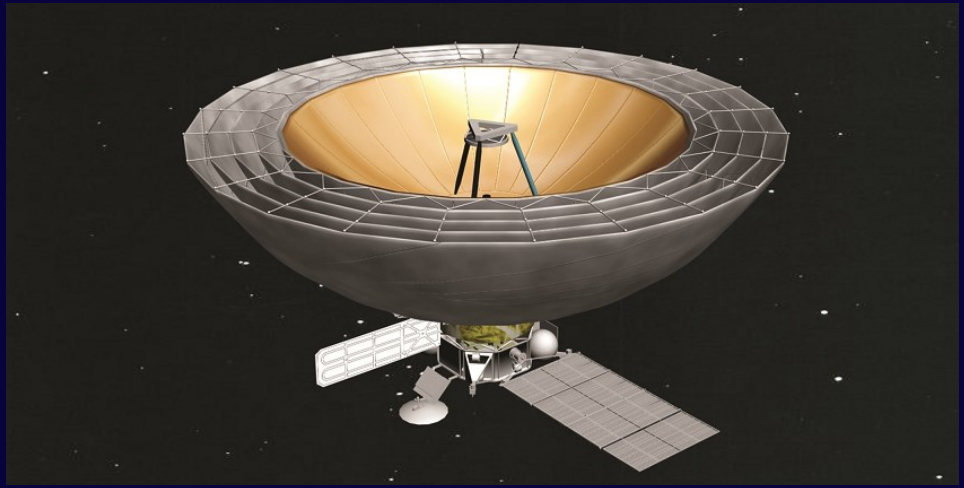


Possible Combination of OST and MSO

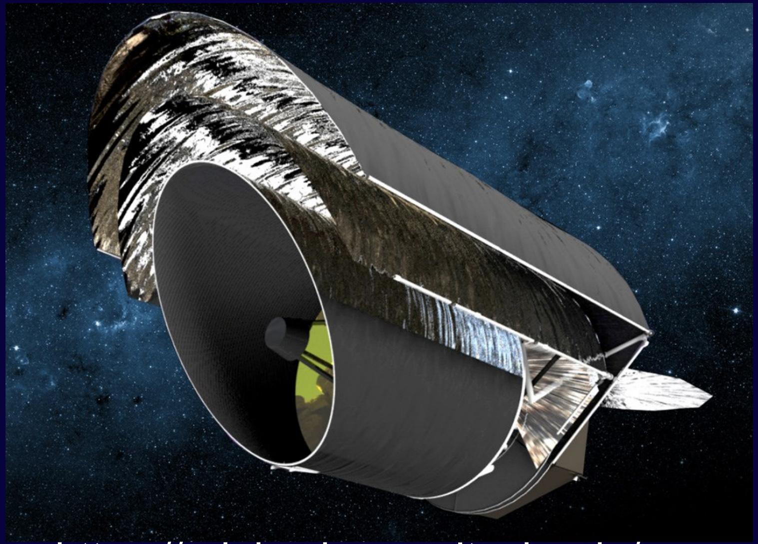
- Large Cryogenic Telescopes in THz
- Direct detectors will be installed.
- Both will situate around S-E L2

SPICA



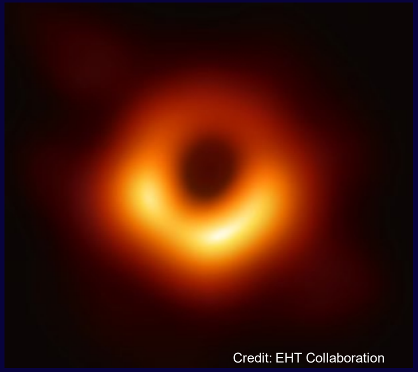


https://www.millimetron.ru/

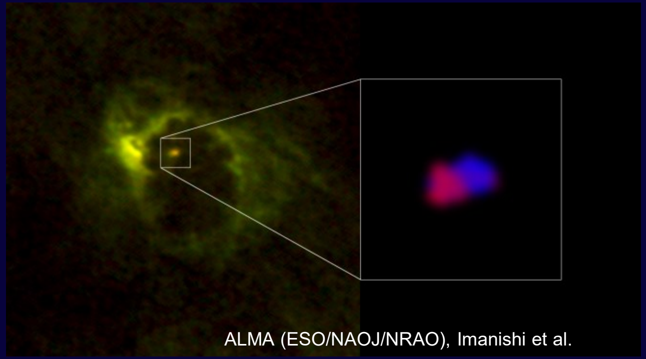


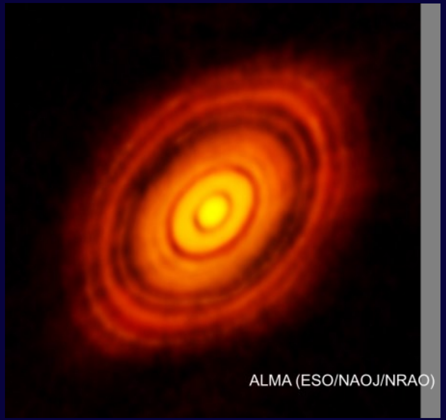
https://origins.ipac.caltech.edu/

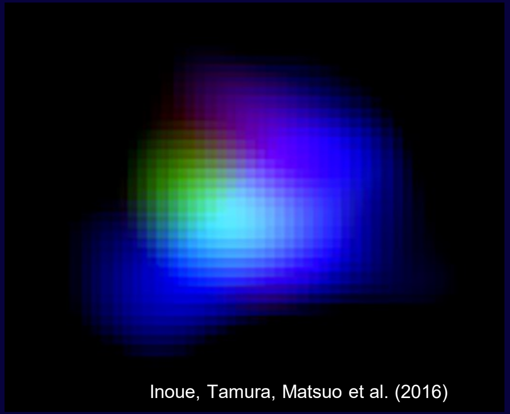
High Angular Resolution with THz Intensity Interferometry

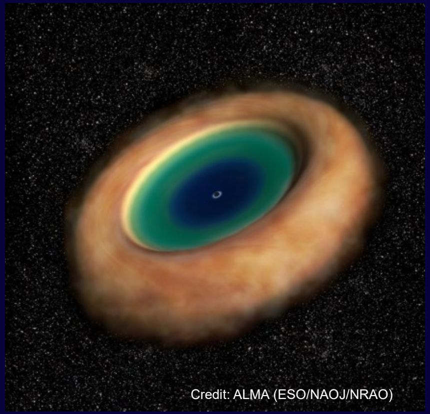

Credit: EHT Collaboration

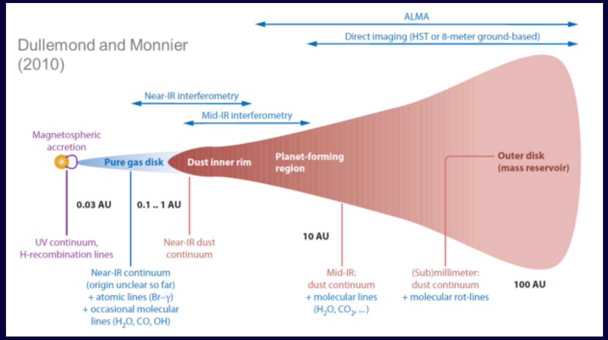
- Closer to the central activities !

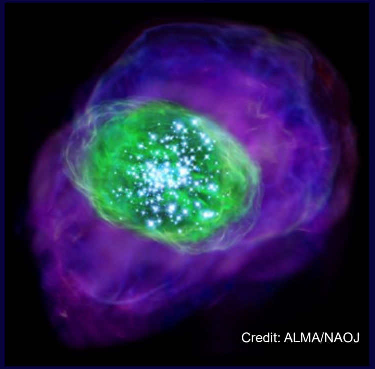

ALMA (ESO/NAOJ/NRAO), Imanishi et al.


ALMA (ESO/NAOJ/NRAO)

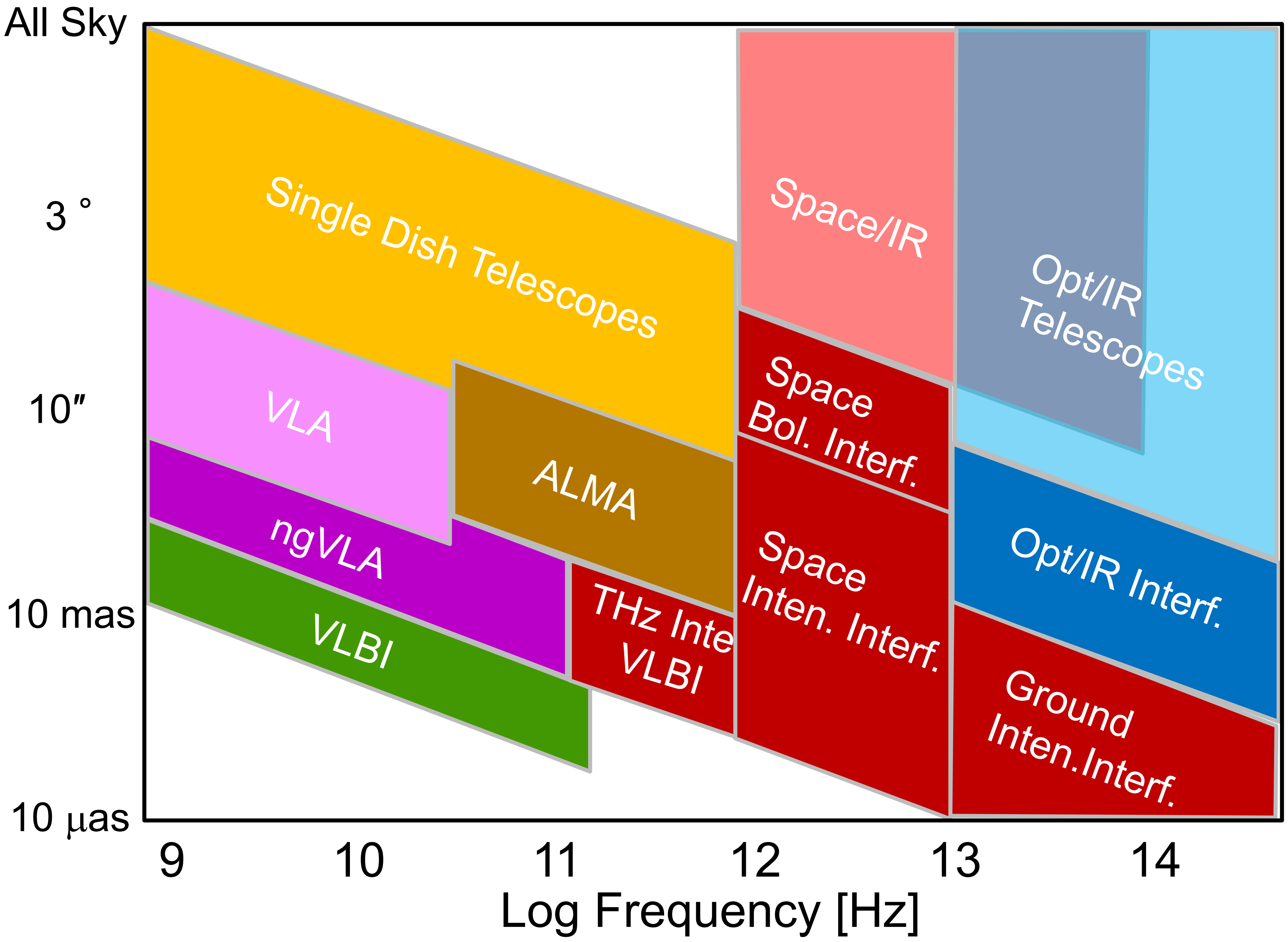

Inoue, Tamura, Matsuo et al. (2016)


Credit: ALMA (ESO/NAOJ/NRAO)




Credit: ALMA/NAOJ

Angular Scale of Observation



Summary

- High angular resolution THz observations
- HBT intensity interferometry
- Imaging technique
- Merit of photon counting detectors
- Possible future programs