Far-infrared intensity interferometry for future space mission

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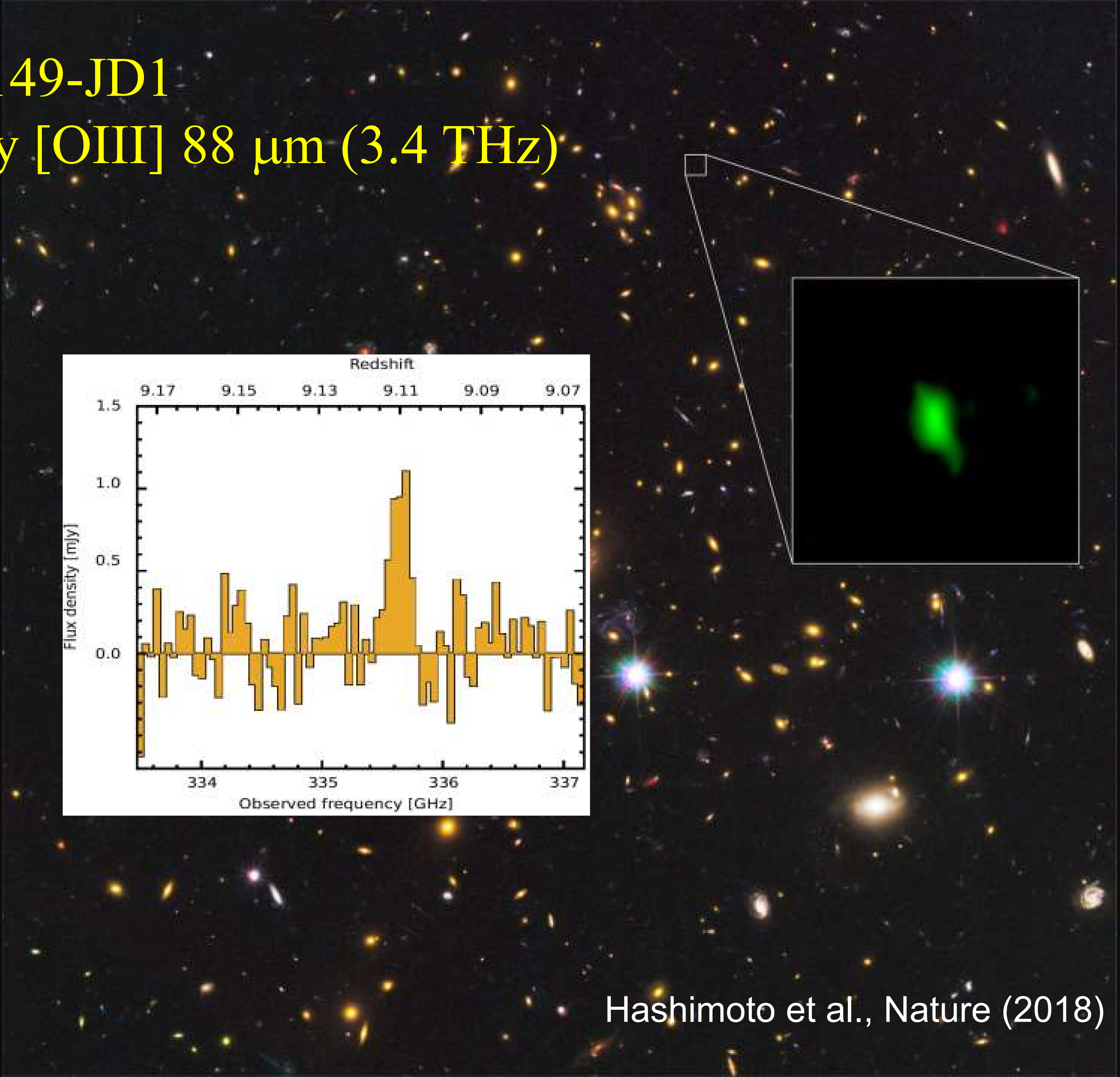
Contents

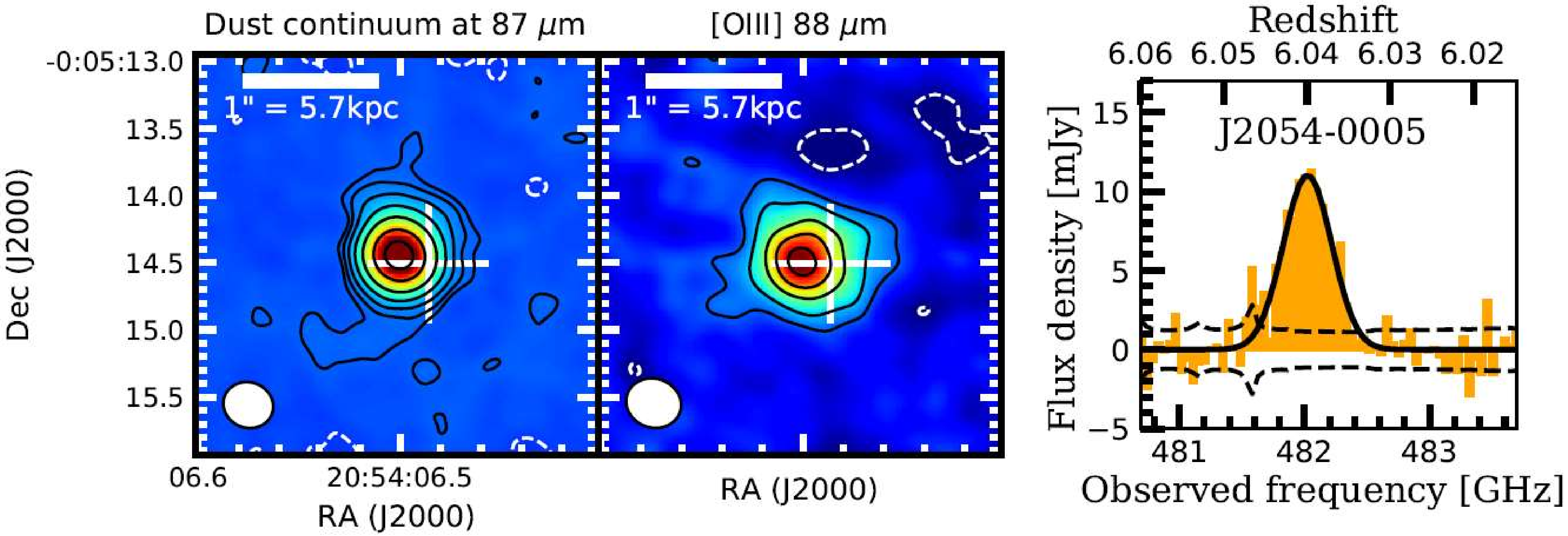
- High angular resolution Far-IR observations
- HBT intensity interferometry
- Imaging technique
- Merit of direct detectors
- Possible future programs

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



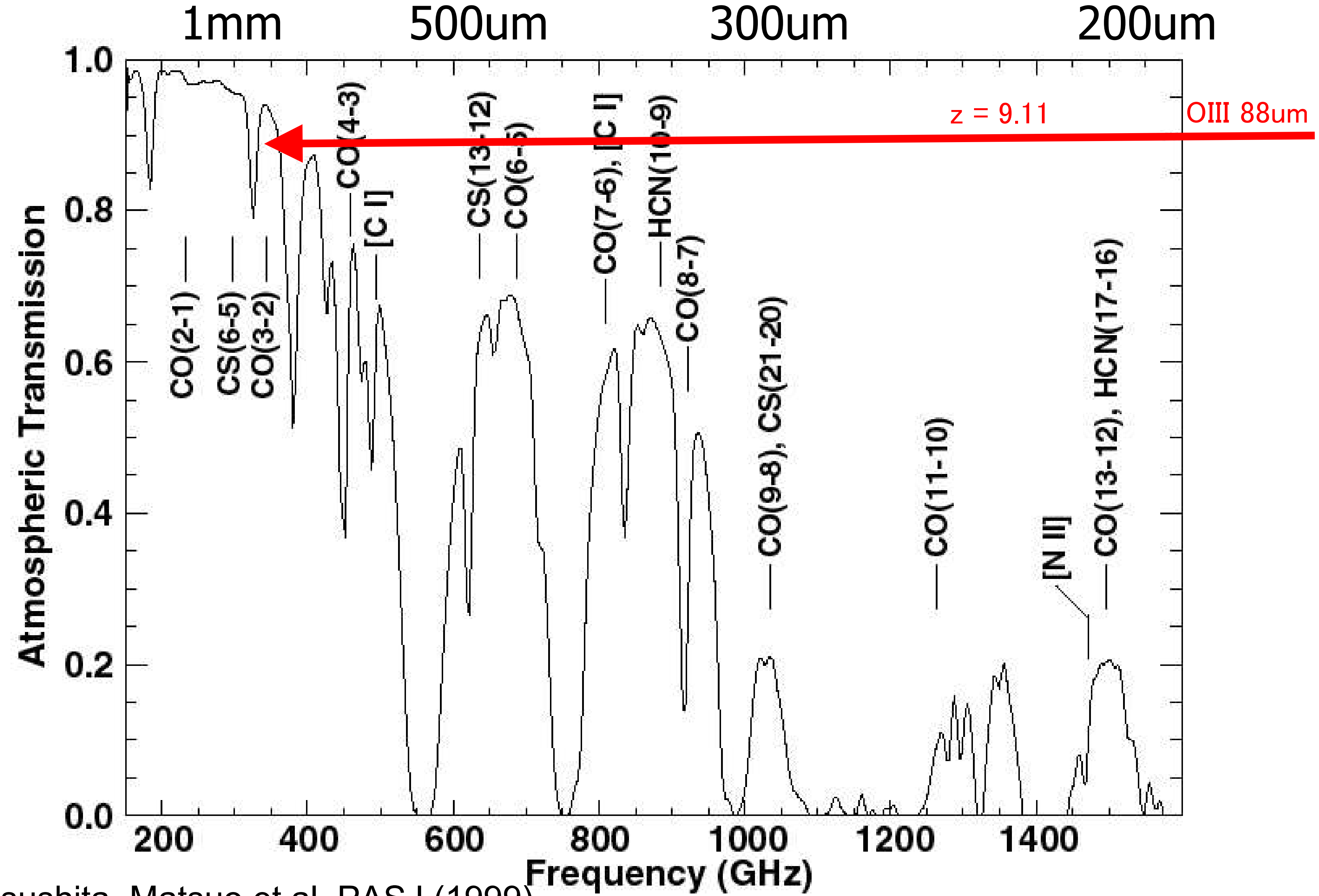
Hashimoto et al., Nature (2018)

Strong [OIII]88um from a Quasar (z=6.04)



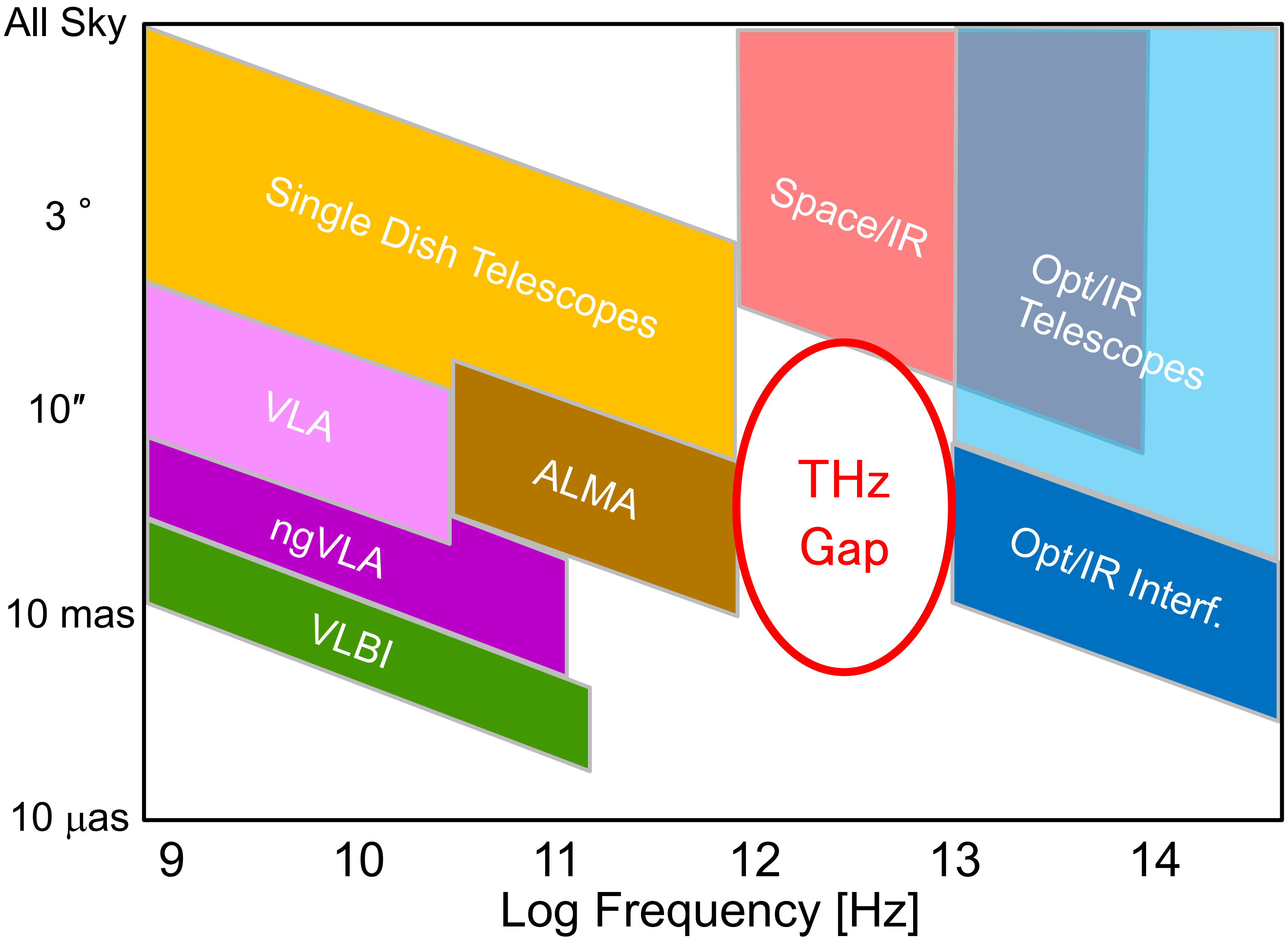
Hashimoto et al. PASJ (2019)

Atmospheric Windows from Atacama（alt. 4800m）

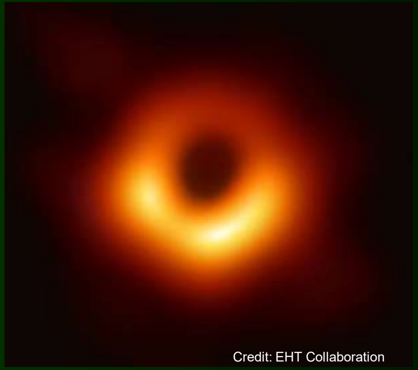


Matsushita, Matsuo et al. PASJ (1999)

Angular Scale of Observation

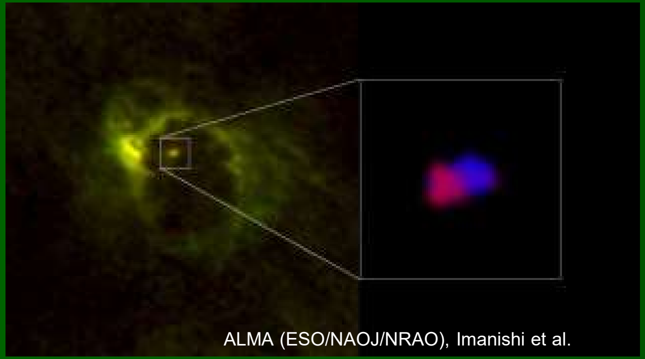


Far-Infrared
Intensity Interferometry



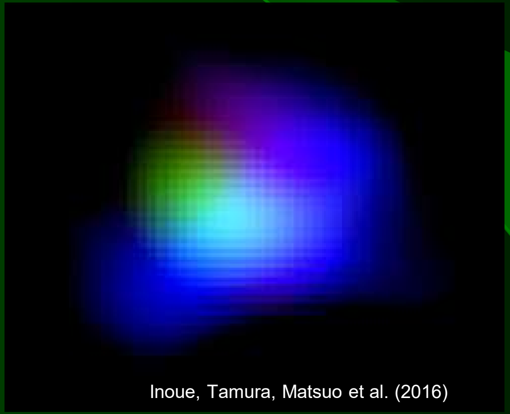
Credit: EHT Collaboration

- Closer to the central activities !

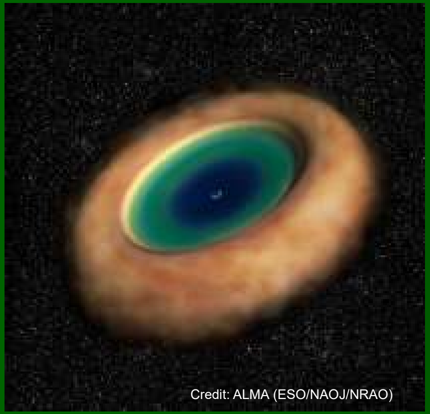


ALMA (ESO/NAOJ/NRAO), Imanishi et al.

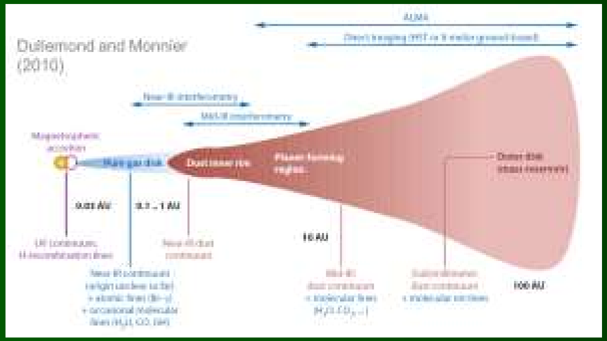
ALMA (ESO/NAOJ/NRAO)



Inoue, Tamura, Matsuo et al. (2016)



Credit: ALMA (ESO/NAOJ/NRAO)



Dullemond and Monnier (2010)

Credit: ALMA/NAOJ

Narrabri Stellar Intensity Interferometer

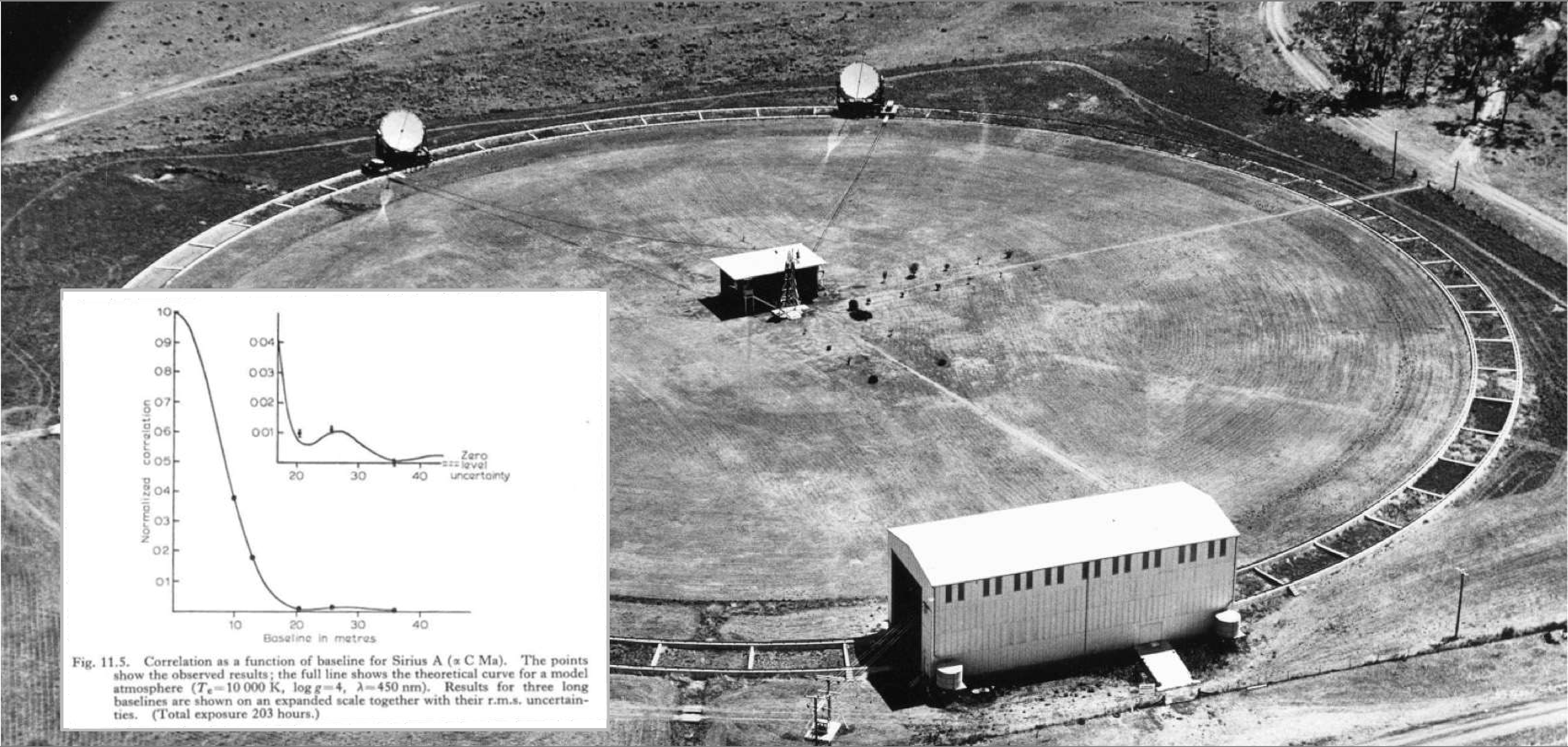


Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model atmosphere ($T_e = 10\,000$ K, $\log g = 4$, $\lambda = 450$ nm). Results for three long baselines are shown on an expanded scale together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

Hanbury-Brown and Twiss Experiment (1956)

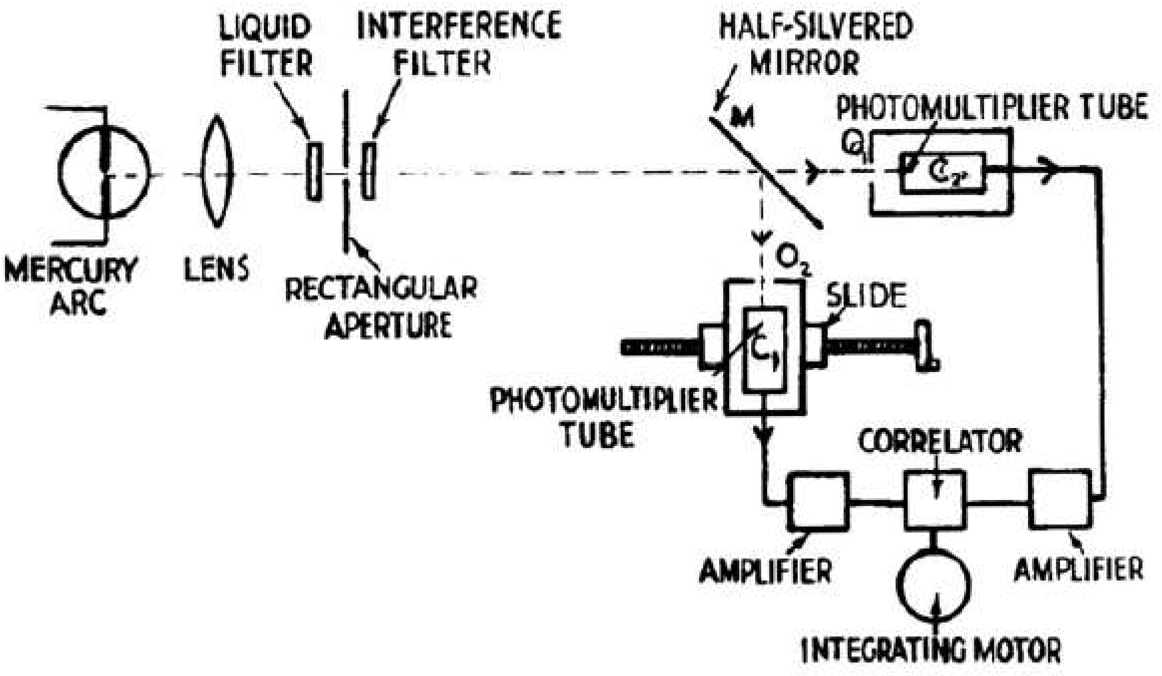


Fig. 2. Simplified diagram of the apparatus

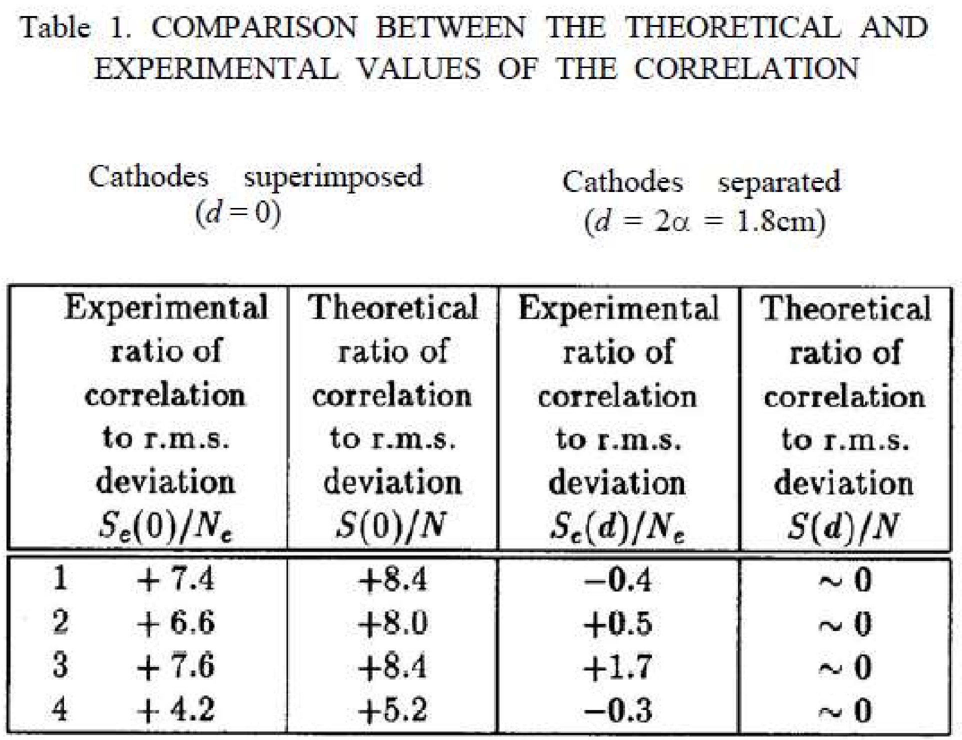
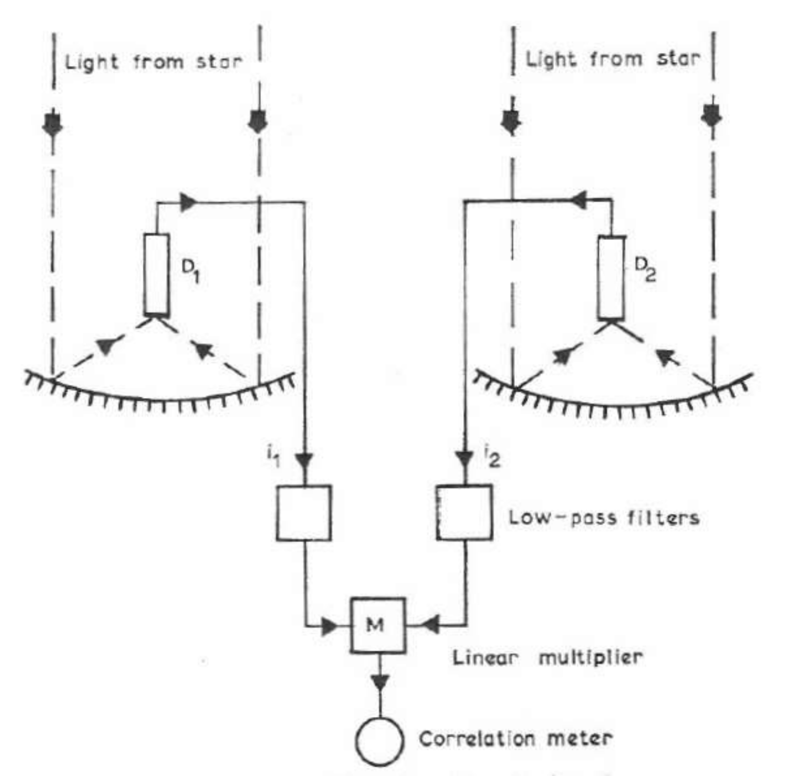


Table 1. COMPARISON BETWEEN THE THEORETICAL AND EXPERIMENTAL VALUES OF THE CORRELATION

	Cathodes superimposed $(d = 0)$		Cathodes separated $(d = 2\alpha = 1.8\text{cm})$	
	Experimental ratio of correlation to r.m.s. deviation $S_e(0)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(0)/N$	Experimental ratio of correlation to r.m.s. deviation $S_e(d)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(d)/N$
1	+ 7.4	+8.4	−0.4	~ 0
2	+ 6.6	+8.0	+0.5	~ 0
3	+ 7.6	+8.4	+1.7	~ 0
4	+ 4.2	+5.2	−0.3	~ 0

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)

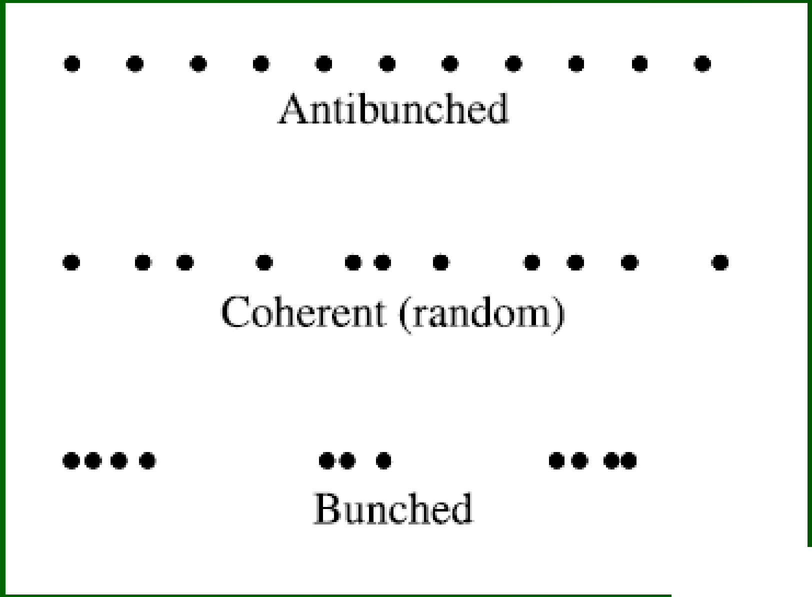


from Hanbury-Brown (1974)
“The Intensity Interferometer”

Limitation of intensity interferometers

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

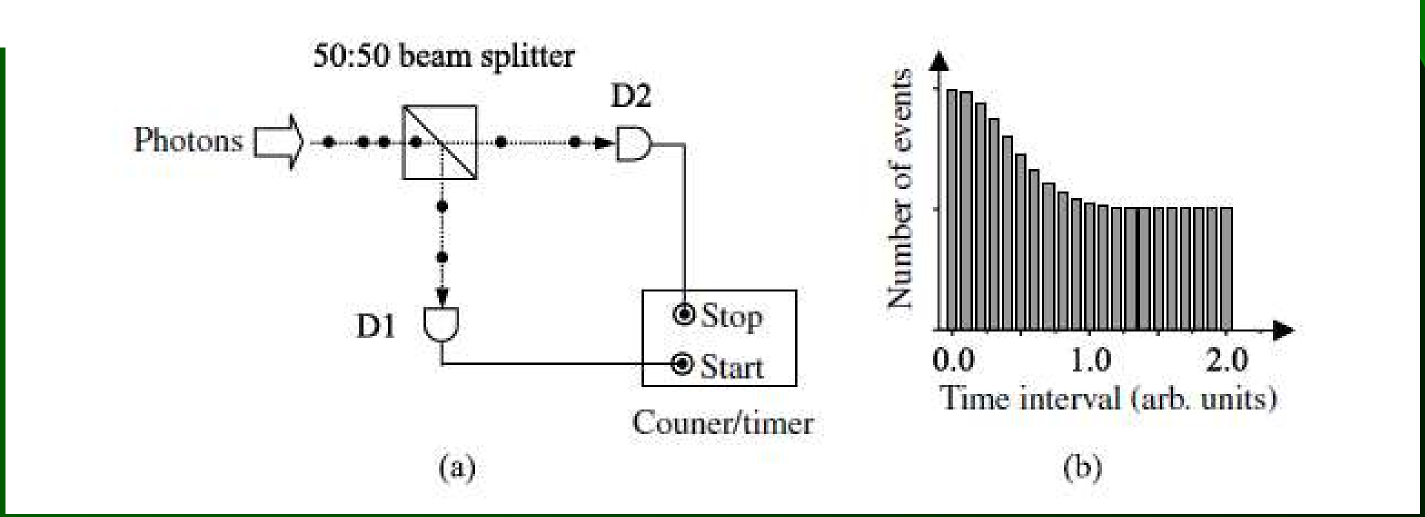
Photon Bunching, Anti-bunching



2nd order correlation function

$$g^{(2)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\mathcal{E}(t)\rangle}{\langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle\langle \mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\rangle} = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle},$$

- bunched light: $g^{(2)}(0) > 1$,
- coherent light: $g^{(2)}(0) = 1$,
- antibunched light: $g^{(2)}(0) < 1$.



From M. Fox
Quantum Optics (2006)

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

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

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

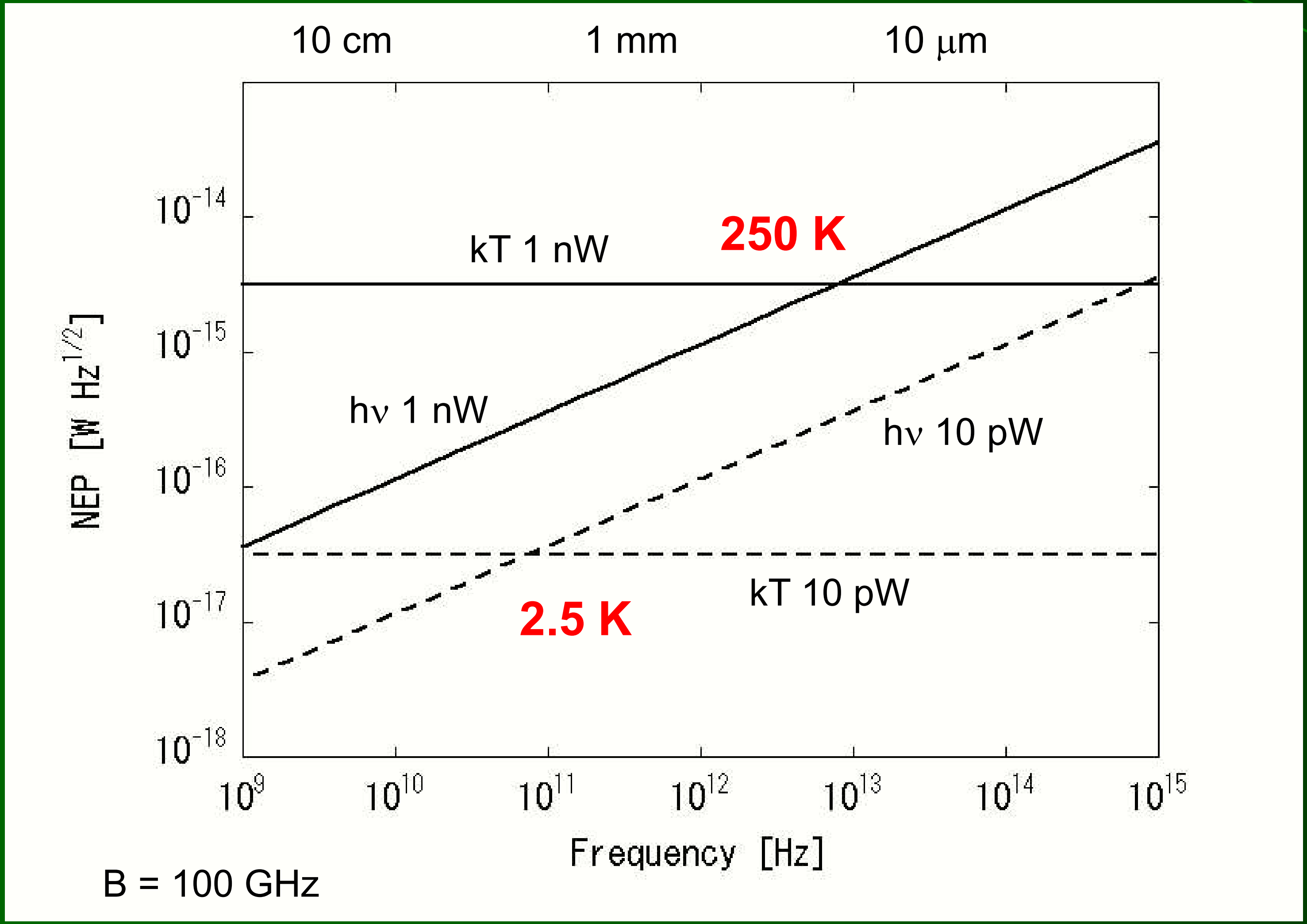
$\Delta T = T_B / \sqrt{B\tau}$

Photon bunching

References

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

THz photon fluctuation

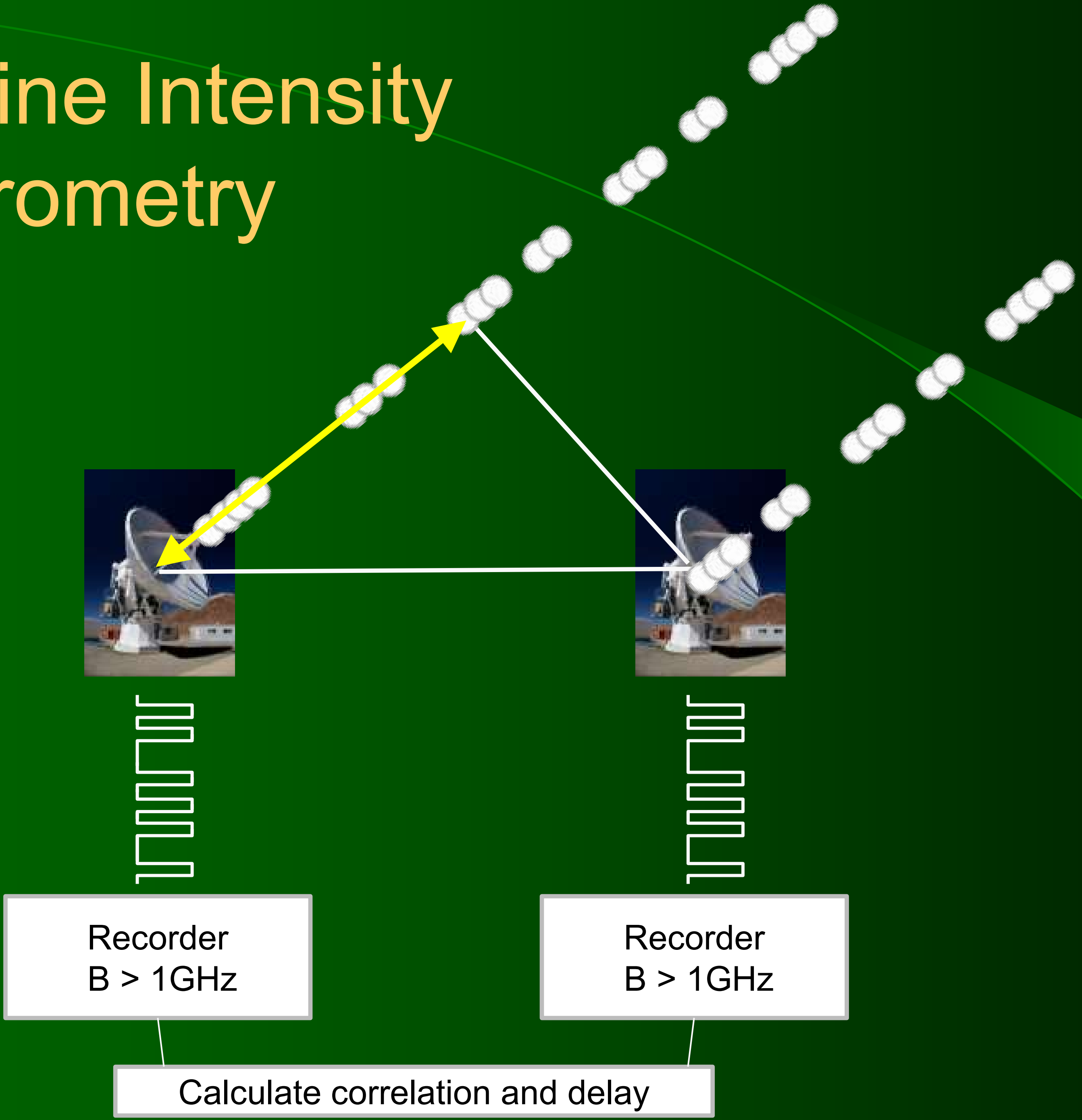


$$\mathrm{NEP} = \sqrt{2P\cdot\left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

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

de Bernardis and Masi (1982)

Long Baseline Intensity Interferometry



Recorder
B > 1GHz

Recorder
B > 1GHz

Calculate correlation and delay

Photon Bunches for delay time measurements

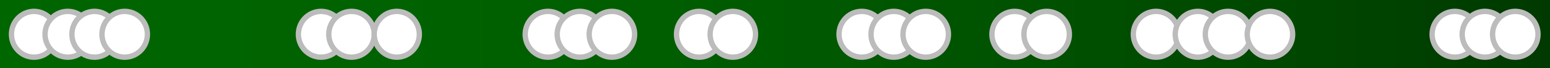
- Photon bunch can be a measure of delay time.
  - Complex visibility can be obtained.
- Large number of THz photon is expected.

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.

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

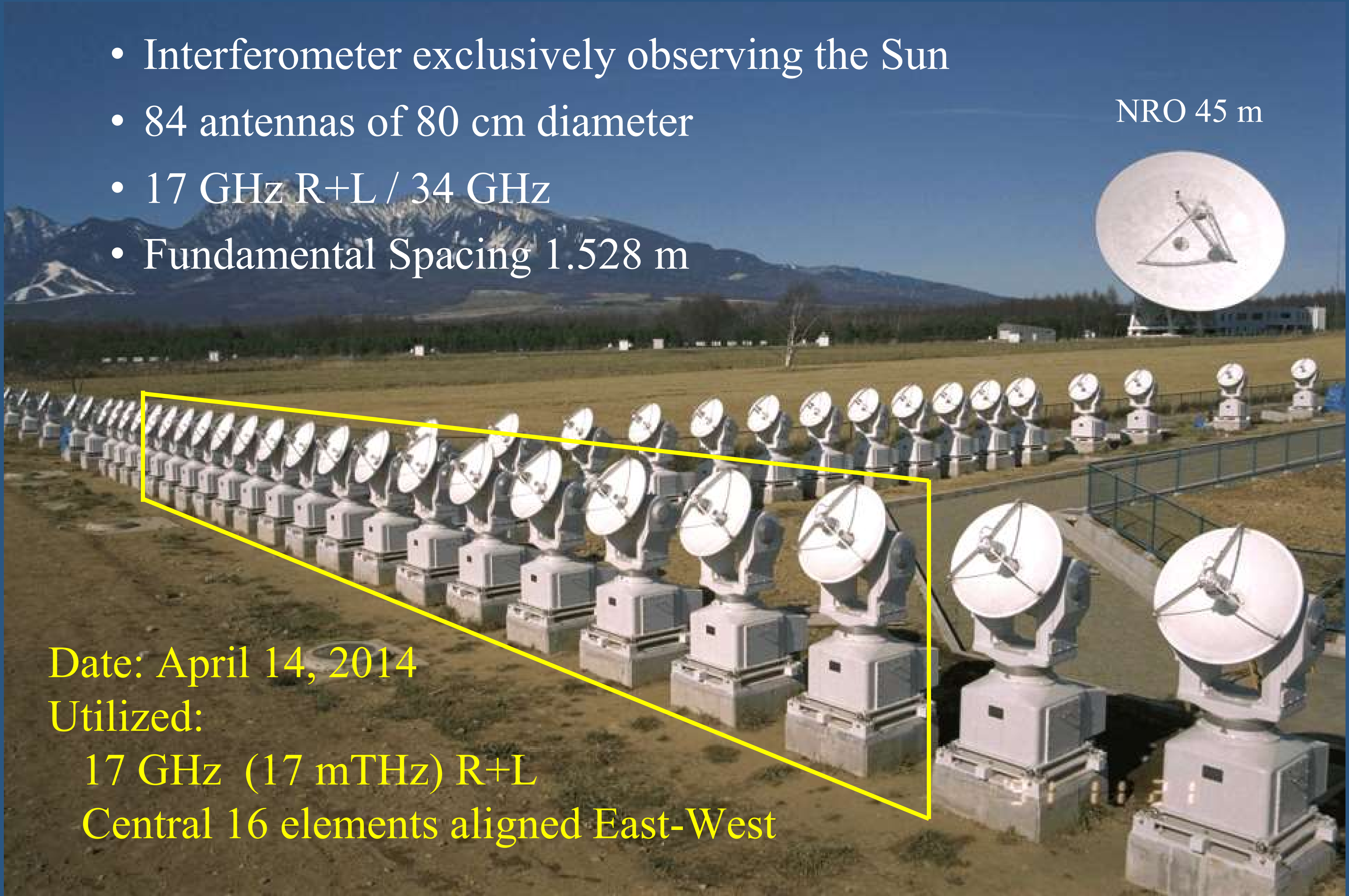


THz Photons are bunched !

N: photon rate

τ : integration time

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

NRO 45 m

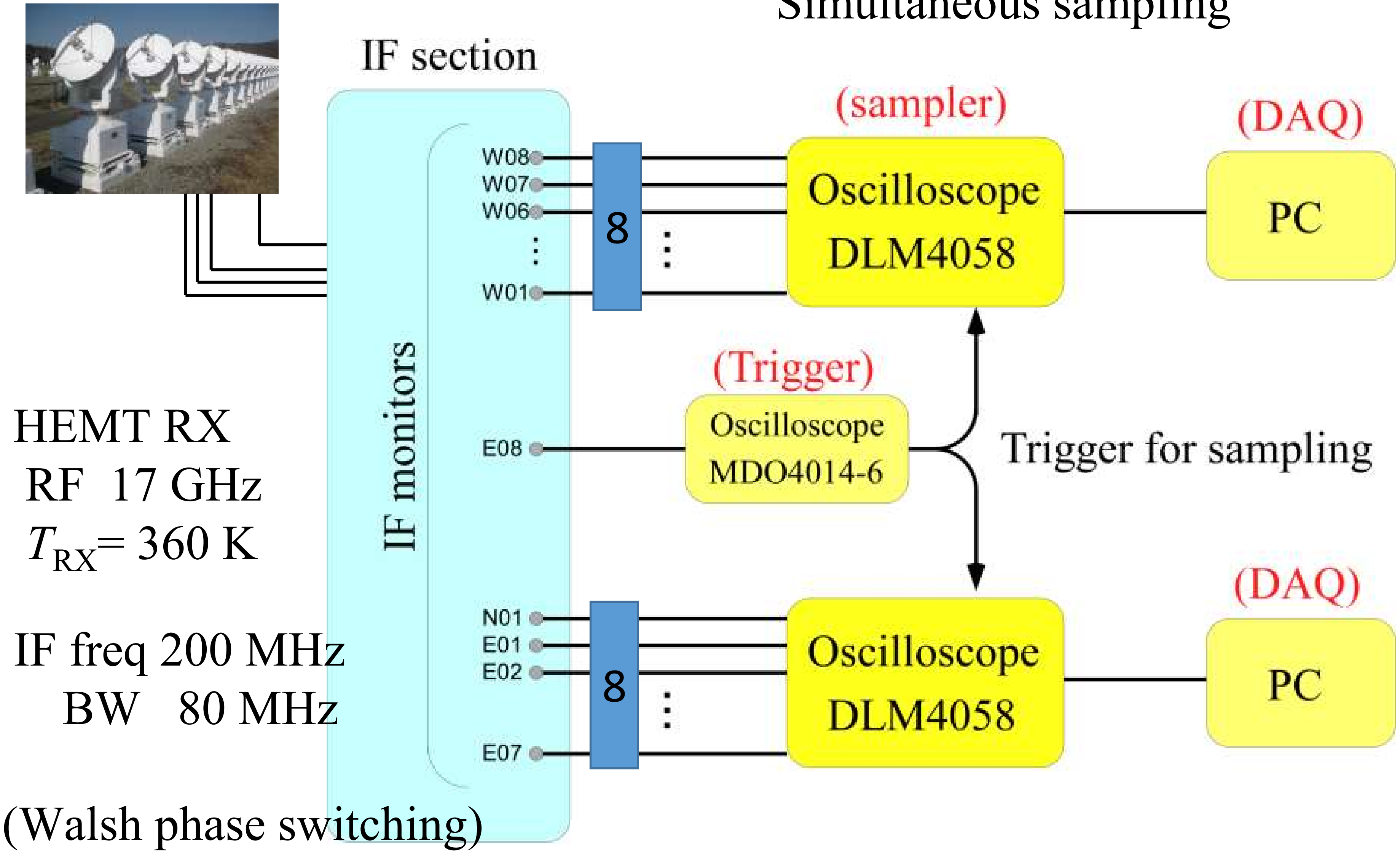
Date: April 14, 2014
Utilized:
17 GHz (17 mTHz) R+L
Central 16 elements aligned East-West

Experiment Setup

Yokogawa DLM4058

8 CH 1.25 GS/s, BW 500 MHz

Simultaneous sampling



IF section

IF monitors

W08
W07
W06
⋮
W01

8

⋮

(sampler)

Oscilloscope DLM4058

(DAQ)

PC

(Trigger)

E08

Oscilloscope MDO4014-6

Trigger for sampling

N01
E01
E02
⋮
E07

8

⋮

Oscilloscope DLM4058

(DAQ)

PC

HEMT RX

RF 17 GHz

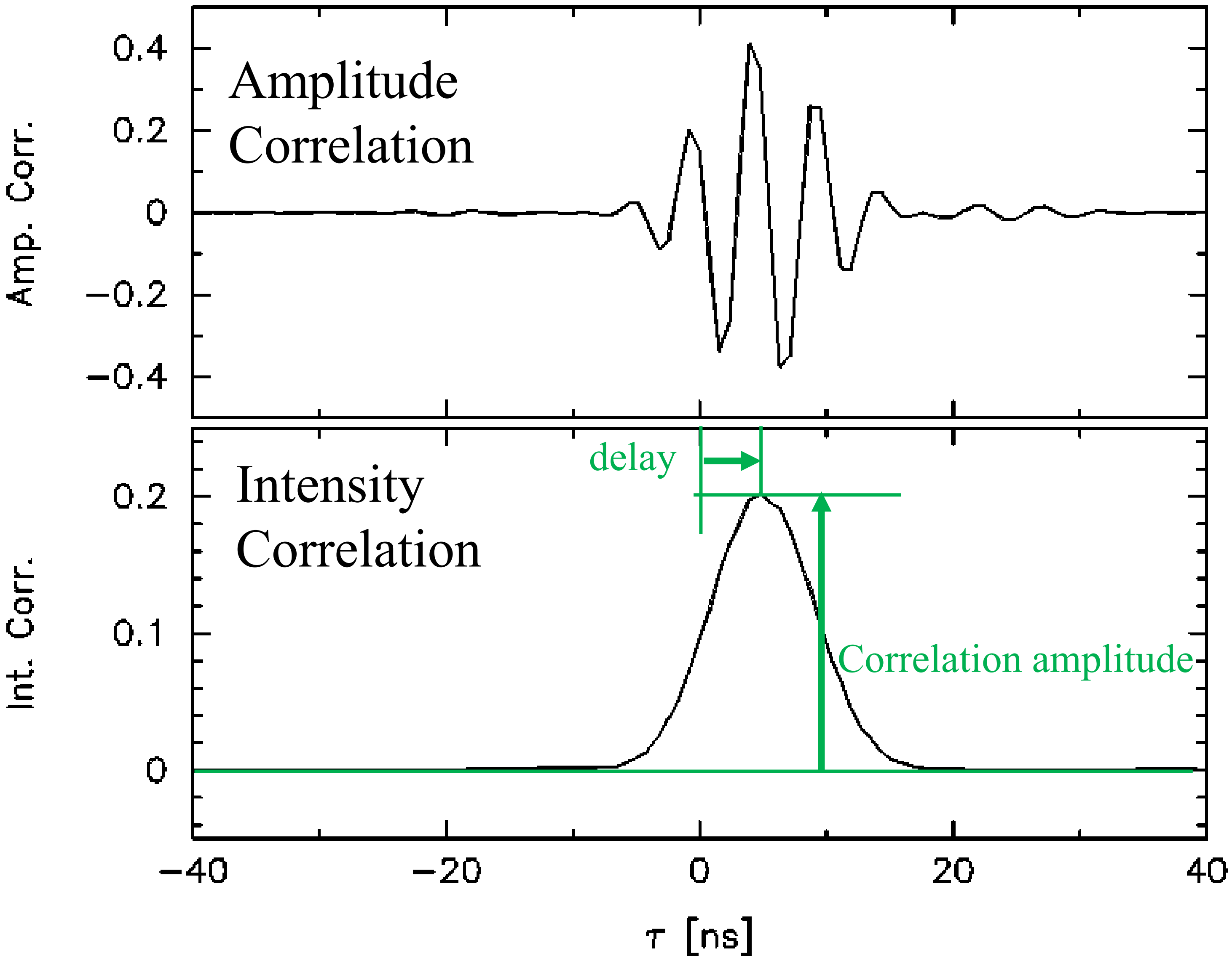
T_{RX}= 360 K

IF freq 200 MHz

BW 80 MHz

(Walsh phase switching)

Nobeyema Radioheliograph at 17 GHz



Ezawa, Matsuo et al. (2015)

Delay vs Time

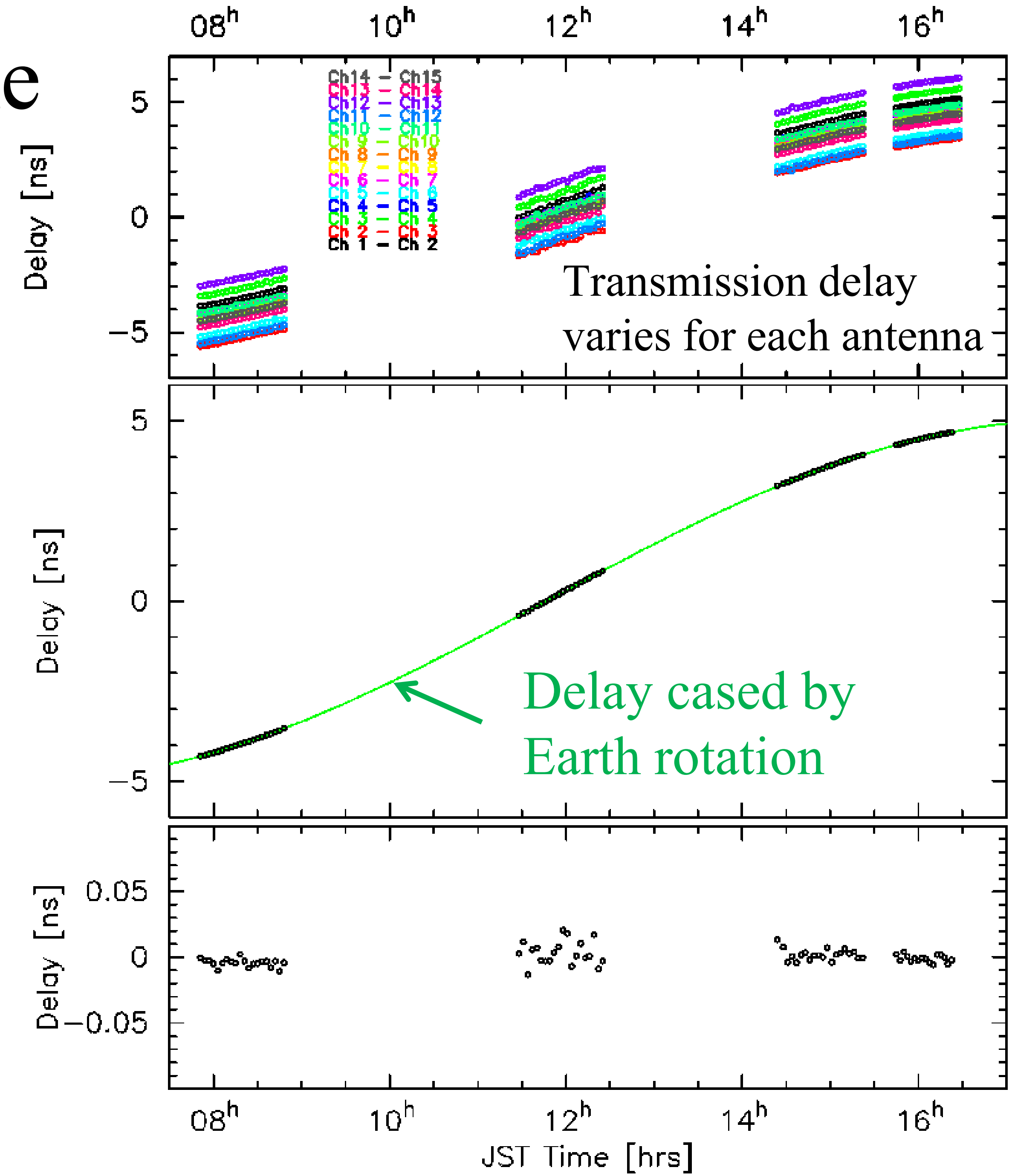
Derive the **delay** for each Neighboring antenna pairs

Correct for transmission delay and average over antennas

Data fits to the delay calculated from Earth rotation

Delay time accuracy

$\sigma < 5\text{-}10$ ps



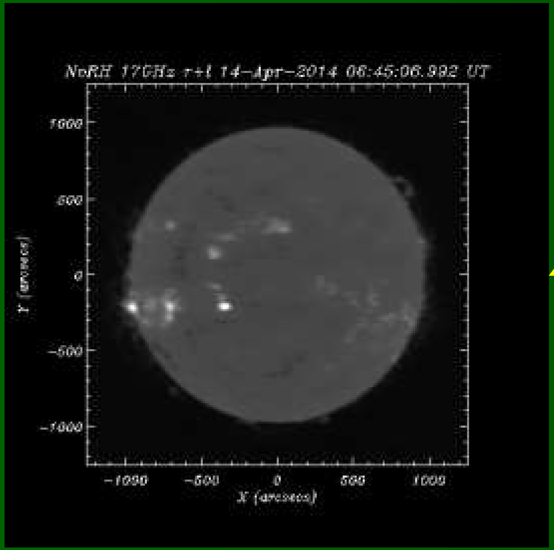
Transmission delay varies for each antenna

Delay cased by Earth rotation

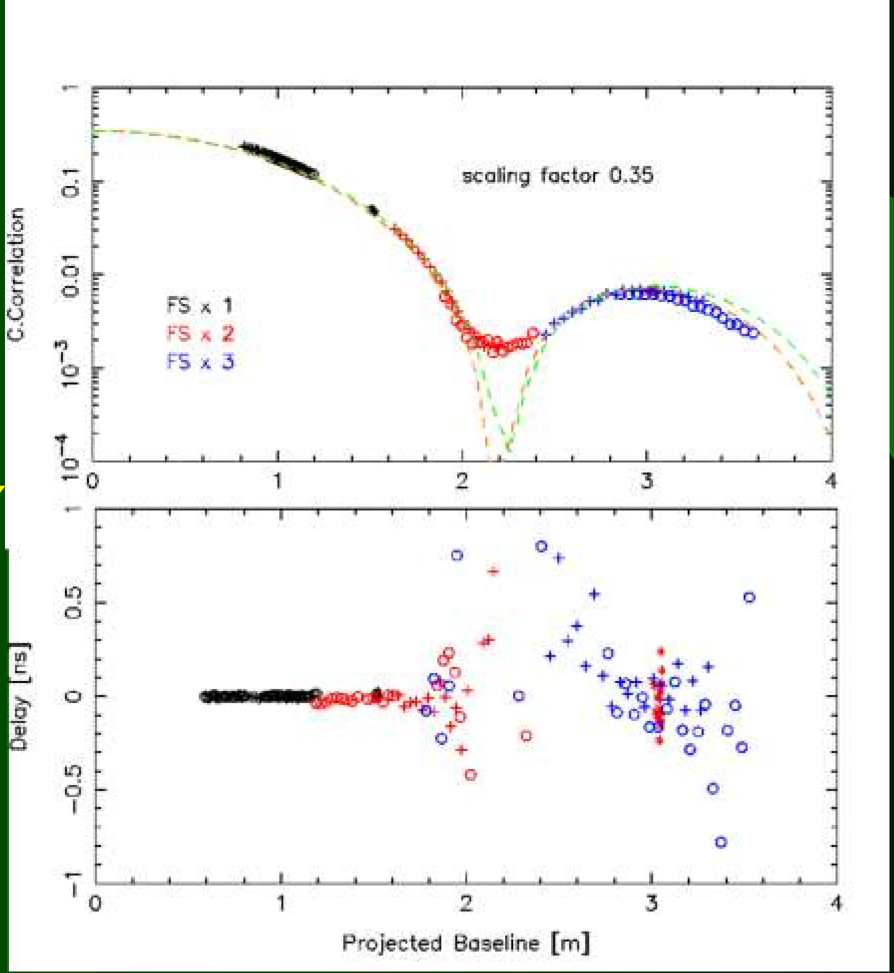
Experiment at 17 GHz

with Nobeyama Radioheliograph

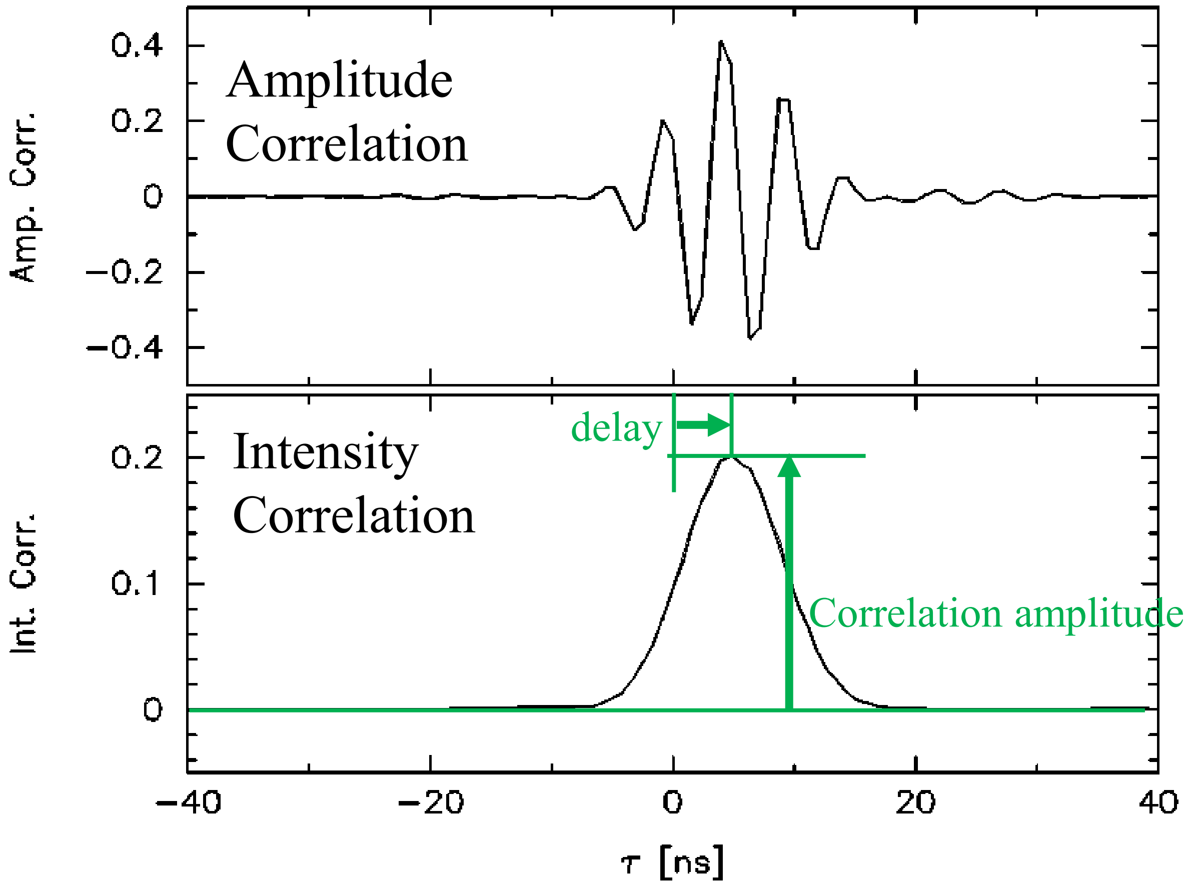
- Real Part of Visibility
  - (Intensity Correlation)$^{0.5}$
- Imaginary Part
  - $\Delta\varphi = 2\pi\nu\Delta t$



Van Cittert
Zernike



Nobeyema Radioheliograph at 17 GHz



Antenna Temperature T_A^* [K]

System Temperature T_{sys} [K]

Frequency ν [Hz]

Bandwidth $\Delta\nu$ [Hz]

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

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

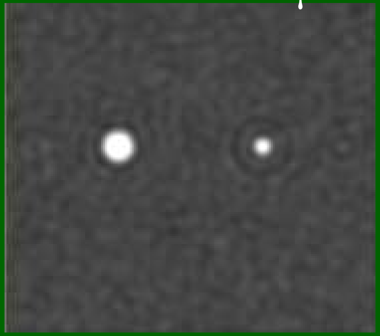
Δt ~ 5ps in 50 ms integration

Ezawa, Matsuo et al. (2015)

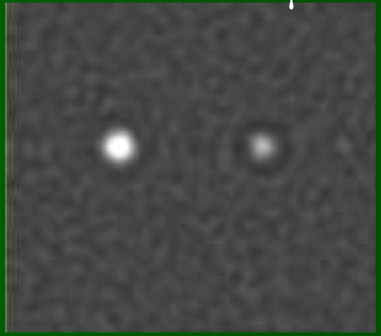
Amplitude vs. Intensity Interferometry

contribution of receiver noise and phase error

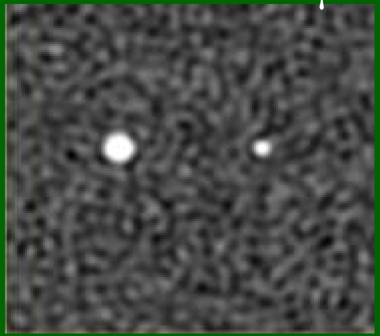
Amplitude
$\Delta\nu = 10$ GHz, t=60 sec
Phase error 50 μm



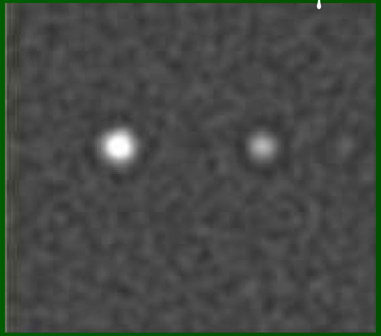
Intensity
$\Delta\nu = 100$ GHz, t=600 sec
Phase error 50 μm



Amplitude
$\Delta\nu = 10$ GHz, t=60 sec
Phase error 100 μm



Intensity
$\Delta\nu = 100$ GHz, t=600 sec
Phase error 100 μm



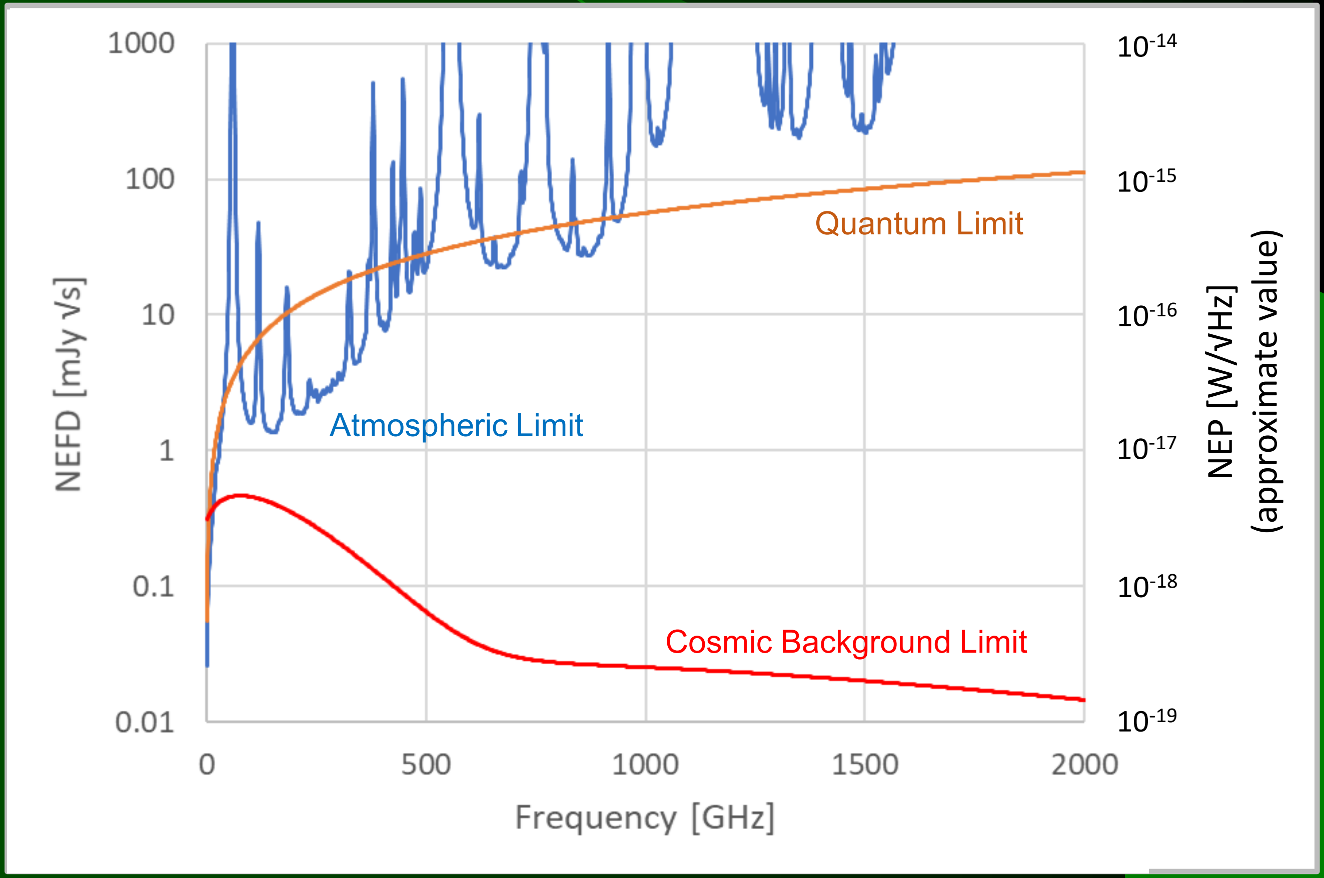
- Betelgeuse like star with a companion.
  $T_A^* = 0.13$ K, $T_{sys} = 500$ K,
  $\nu = 1$ THz
  using 10-m dish with 6-km baseline
- Longer integration time for intensity interferometry
- Intensity correlation is stable against large phase error.

~2000 visibility points (uniform weight) for image reconstruction

Background limited observation with Space Far-IR 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)
  - Missing phase information
- Stable against phase fluctuation
  - Coherence lengths >> Wavelengths
- Photon counting detector can be used
  - High sensitivity, no receiver quantum limit
- High correlation efficiency in infrared
- Photon bunches enable delay measurements

Terahertz Photon Rates

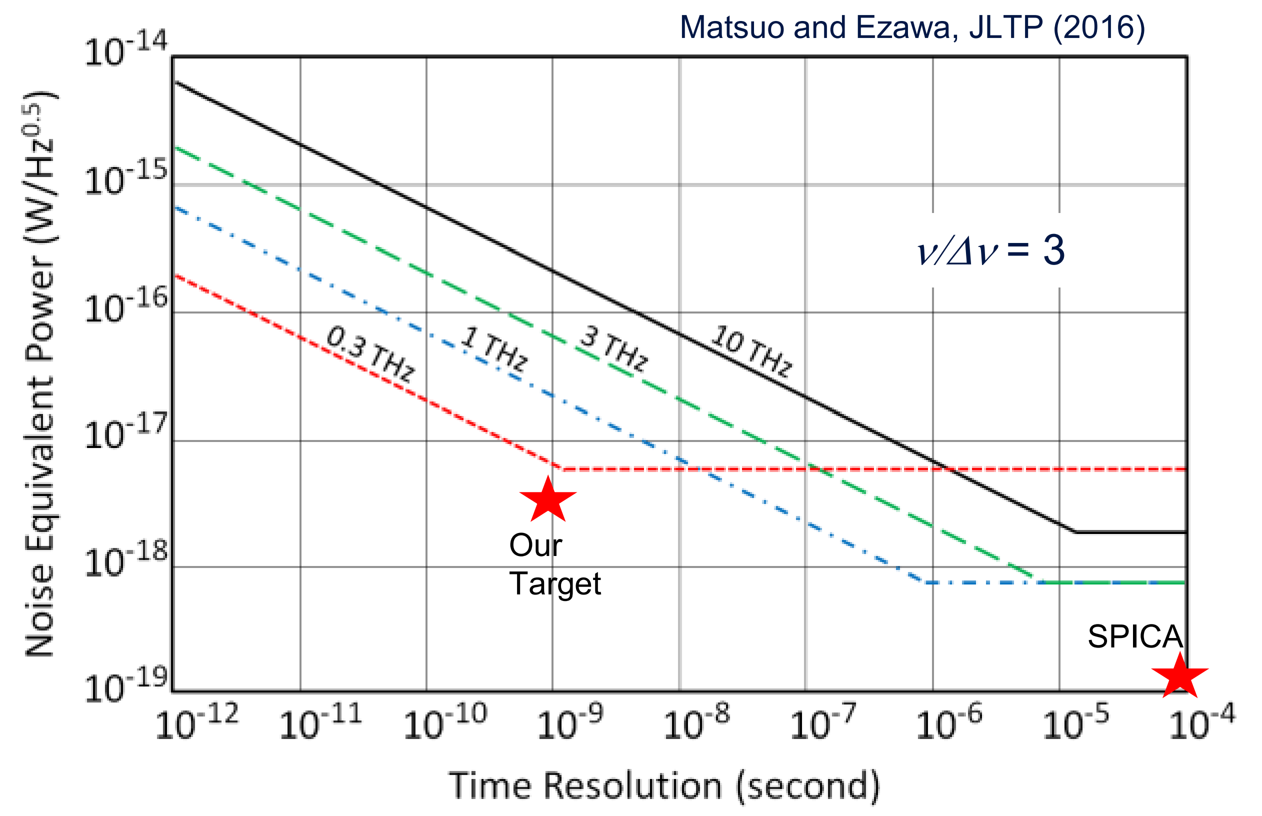
- Atmospheric emission (100 pW)
  - 100 G photon/s
- Cosmic Microwave Background
  - 100 M photon/s (ν=300 GHz, B=100 GHz)
- Cosmic Terahertz Background (10^{-16} W)
  - 100 k photon/s
- 1 Jy sources (=10^{-26} W/m^2/Hz)
  - 100 M photon/s (B=100 GHz, ϕ=10 m)
- Receiver Quantum Limit
  - $P = h\nu B \rightarrow$ 100 G photon/s

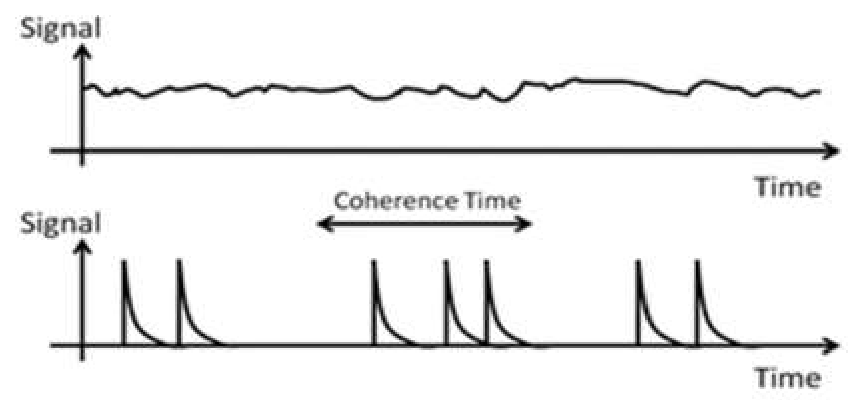
Requirements to Detectors

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

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

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





SIS Photon Detectors

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

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

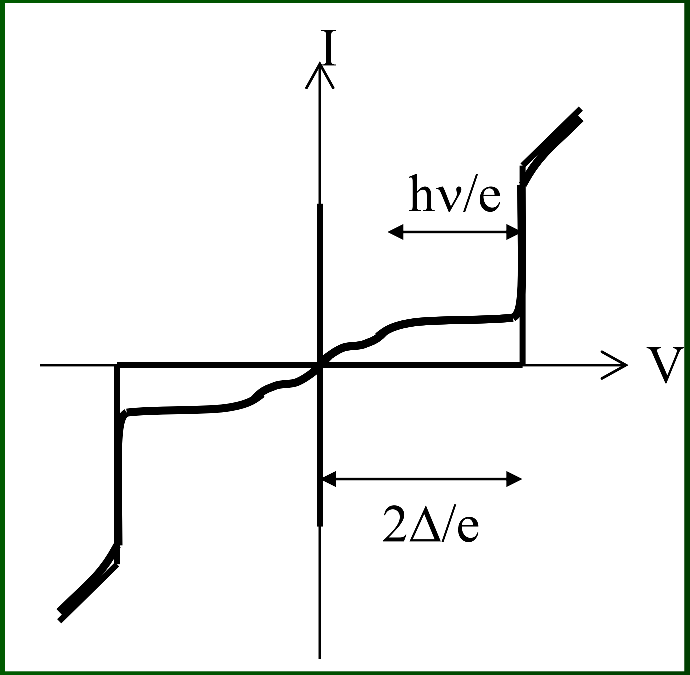
$$NEP = \frac{h\nu}{\eta} \cdot \sqrt{\frac{2I_0}{e}} \quad [\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

$$NEP \approx 3 \times 10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$$

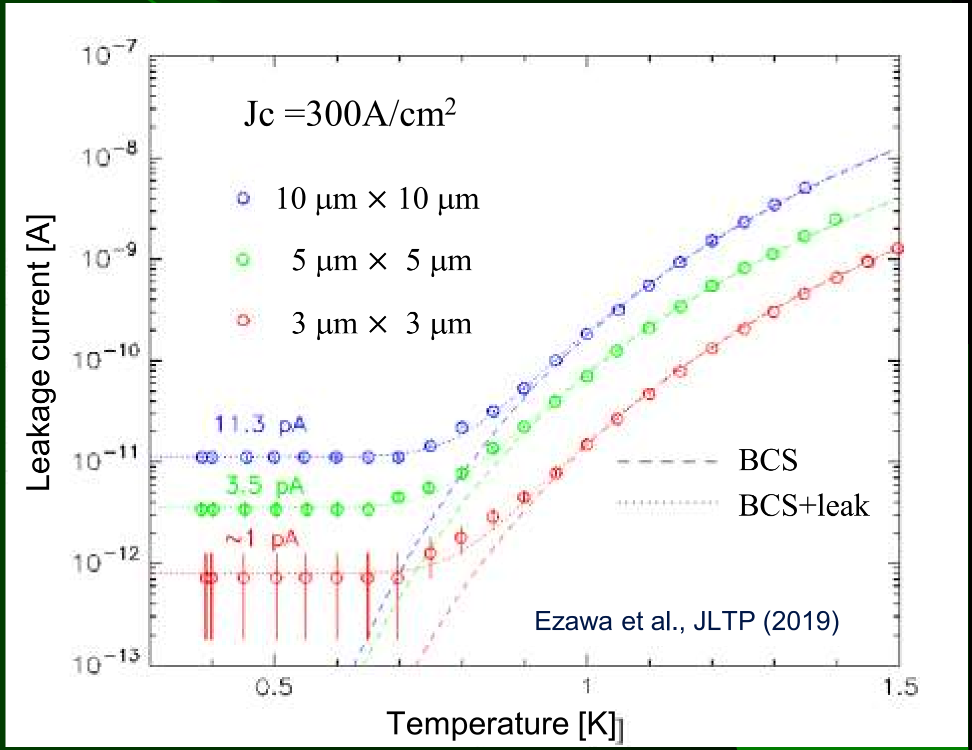
for $I_0 = 1\,\mathrm{pA} \quad \eta = 0.5$

at 650 GHz

Photon Assisted Tunneling

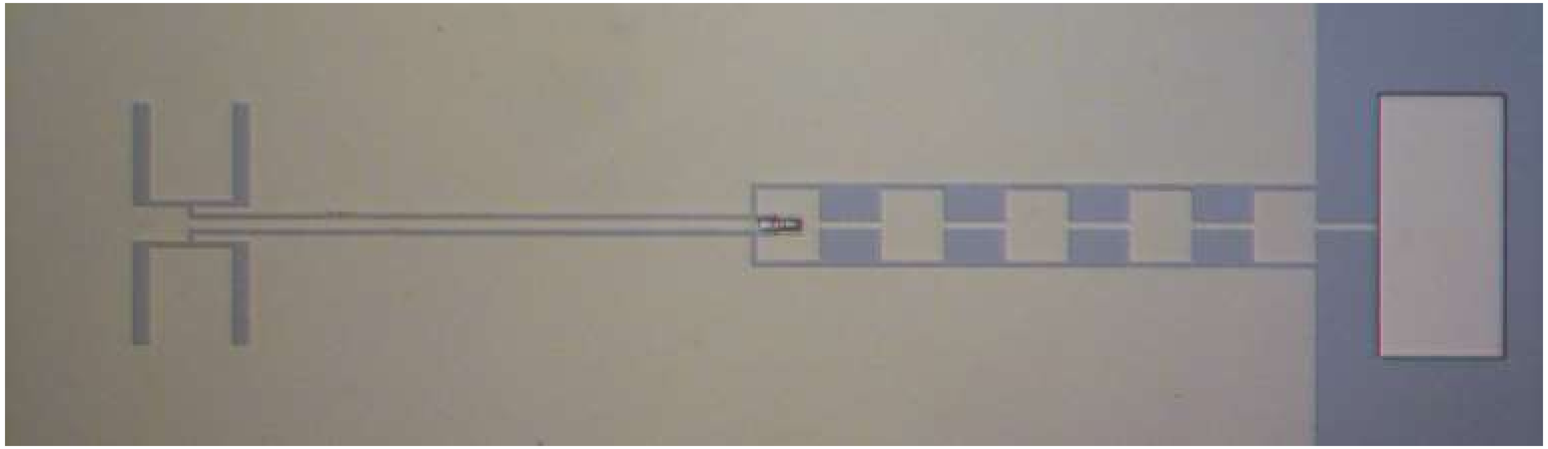


Low leakage SIS junctions

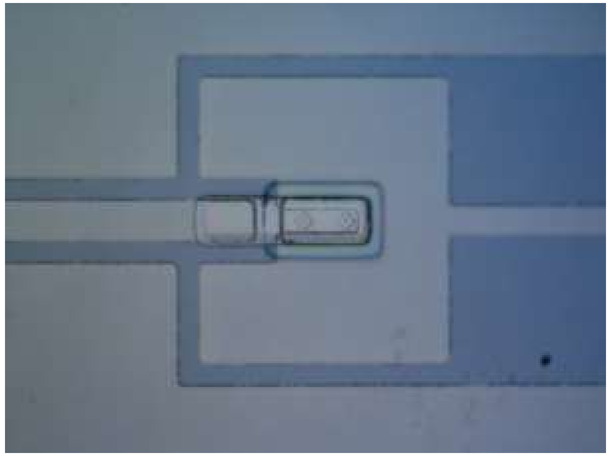


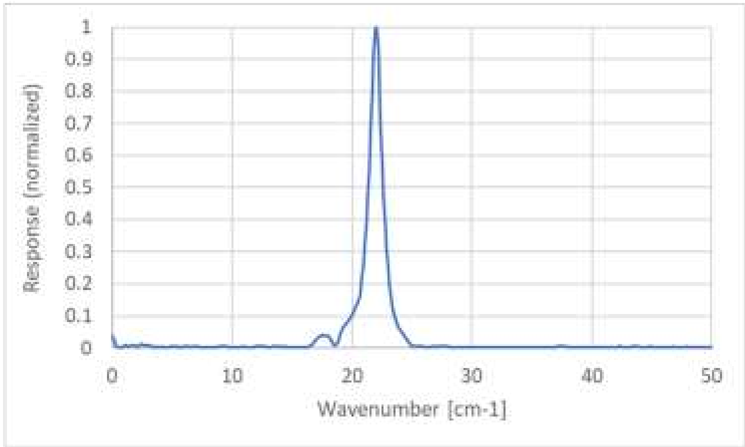
Ezawa et al., JLTP (2019)

Superconducting detectors in THz frequencies



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



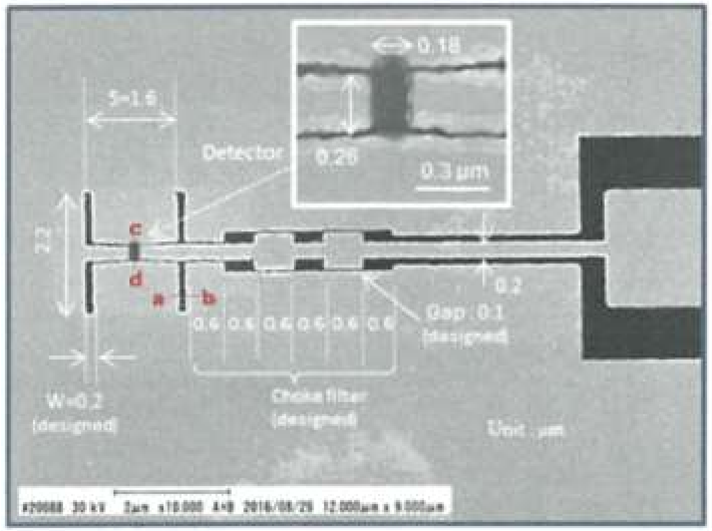


Spectral Response

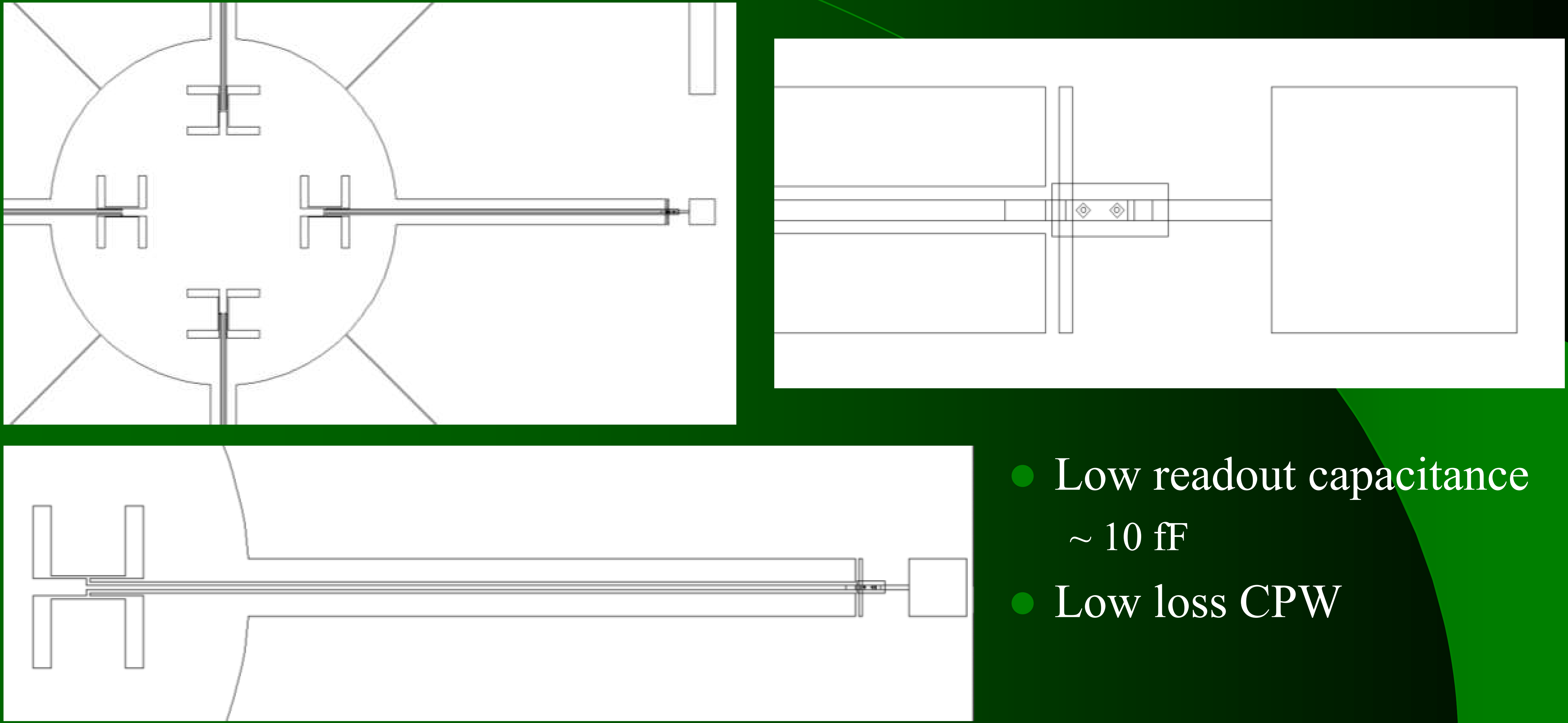
ν=660 GHz $\Delta\nu$=35GHz

Ezawa et al. (2020) JLTP

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



New Detector Design



- Low readout capacitance

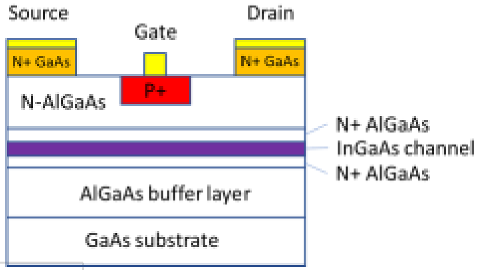
  ~ 10 fF
- Low loss CPW

Readout Electronics

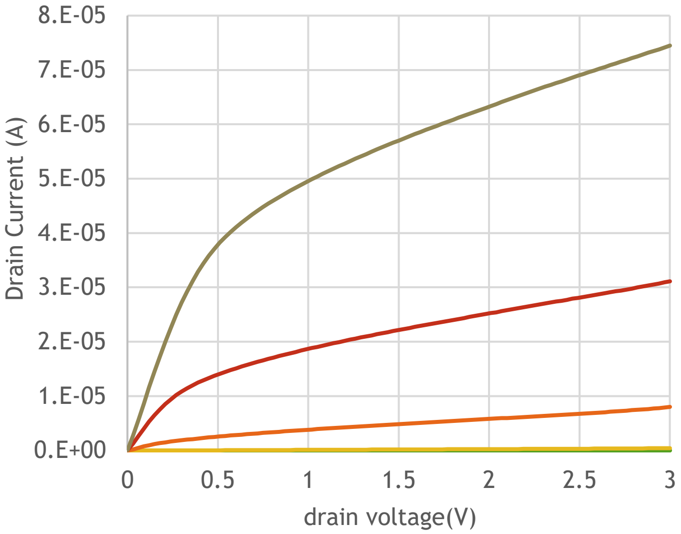
- Low Gate Leakage
  - Less than 1 pA
- Low Gate Capacitance
  - Less than 10 fF
- Low Power Dissipation
  - Less than 100 uW @0.8K
  - Less than 10 mW @4K
  - GaAs-JFET or Junction-pHEMT ?

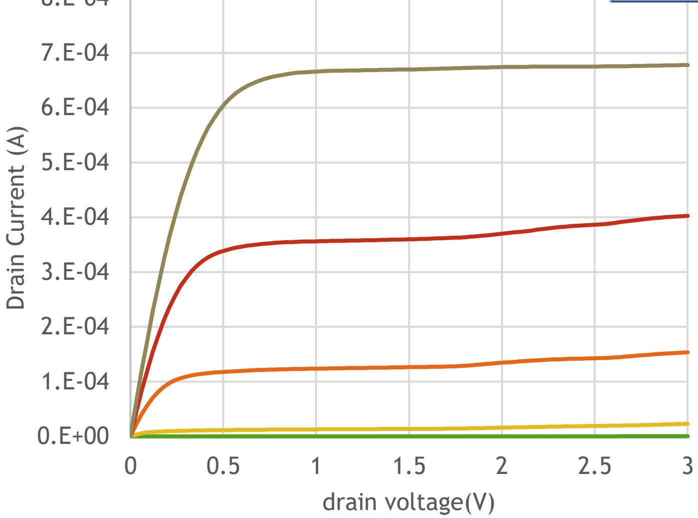
GaAs-JFET

Junction-pHEMT

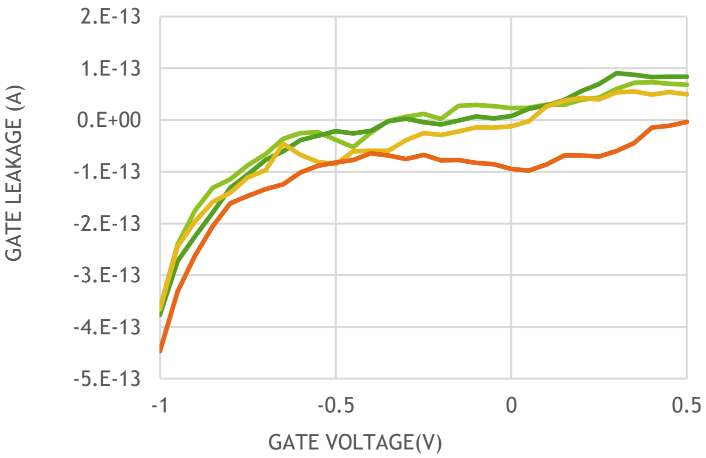


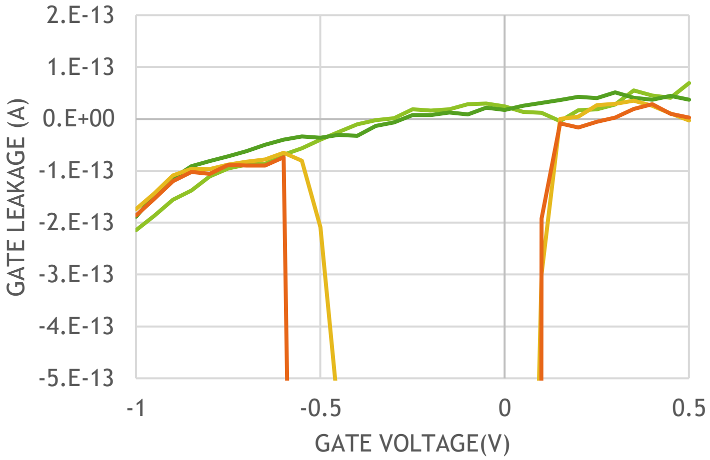
I-V characteristics





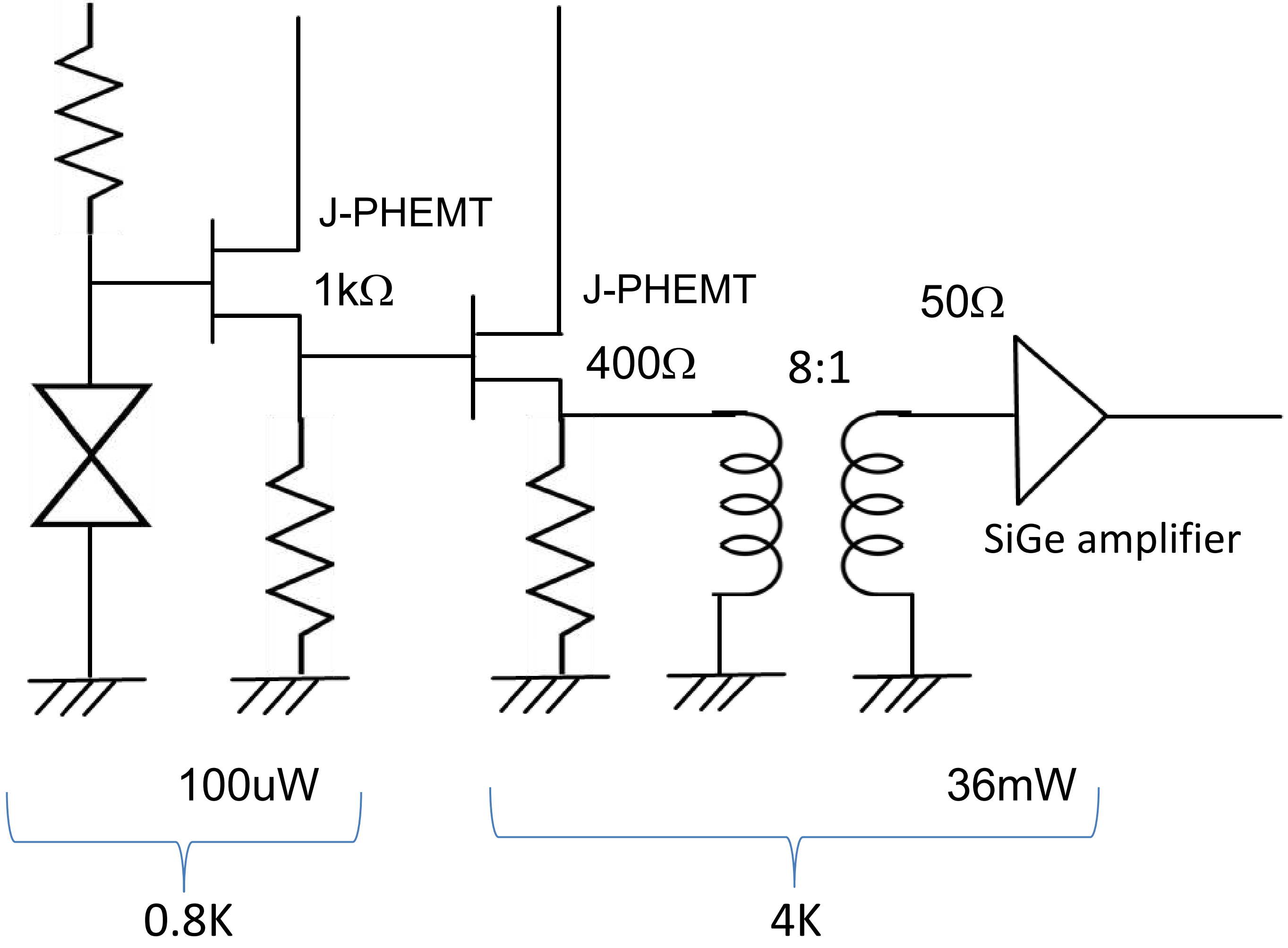
Gate Leakage current





Noji, Koseki and Matsuo (2020)

Readout Electronics



SIS photon detector signal

One electron/photon with a bandwidth of 1 GHz.

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

FET thermal noise at 0.8K

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

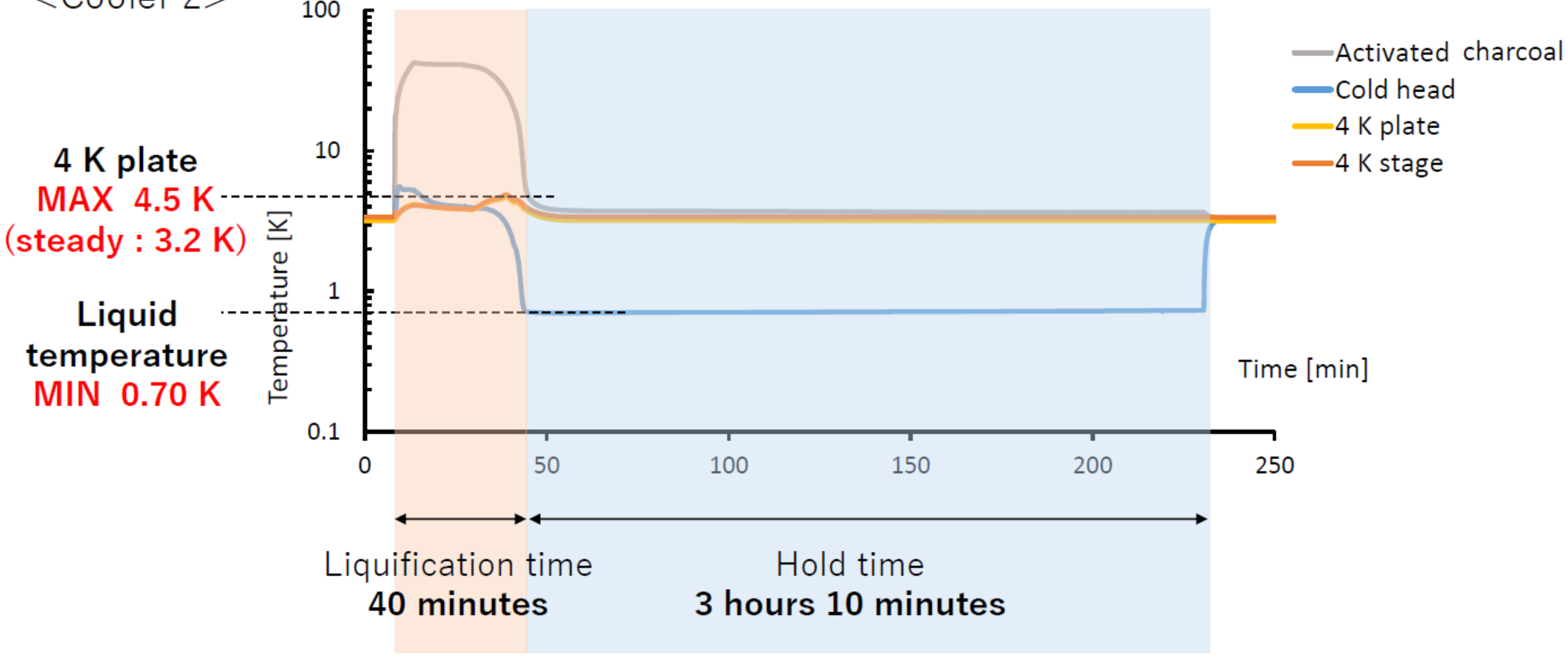
$$R_D = \frac{1}{g_m} = \frac{dV_g}{dI_d} = 1\ \mathrm{k\Omega}$$

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

Development of 0.8K He4 sorption coolers

Operational Temperature: 0.8K
Cooling Capacity: larger than 200 uW
Compact: height less than 900 mm
Heat Load to 4K: less than 100 mW

<Cooler 2>

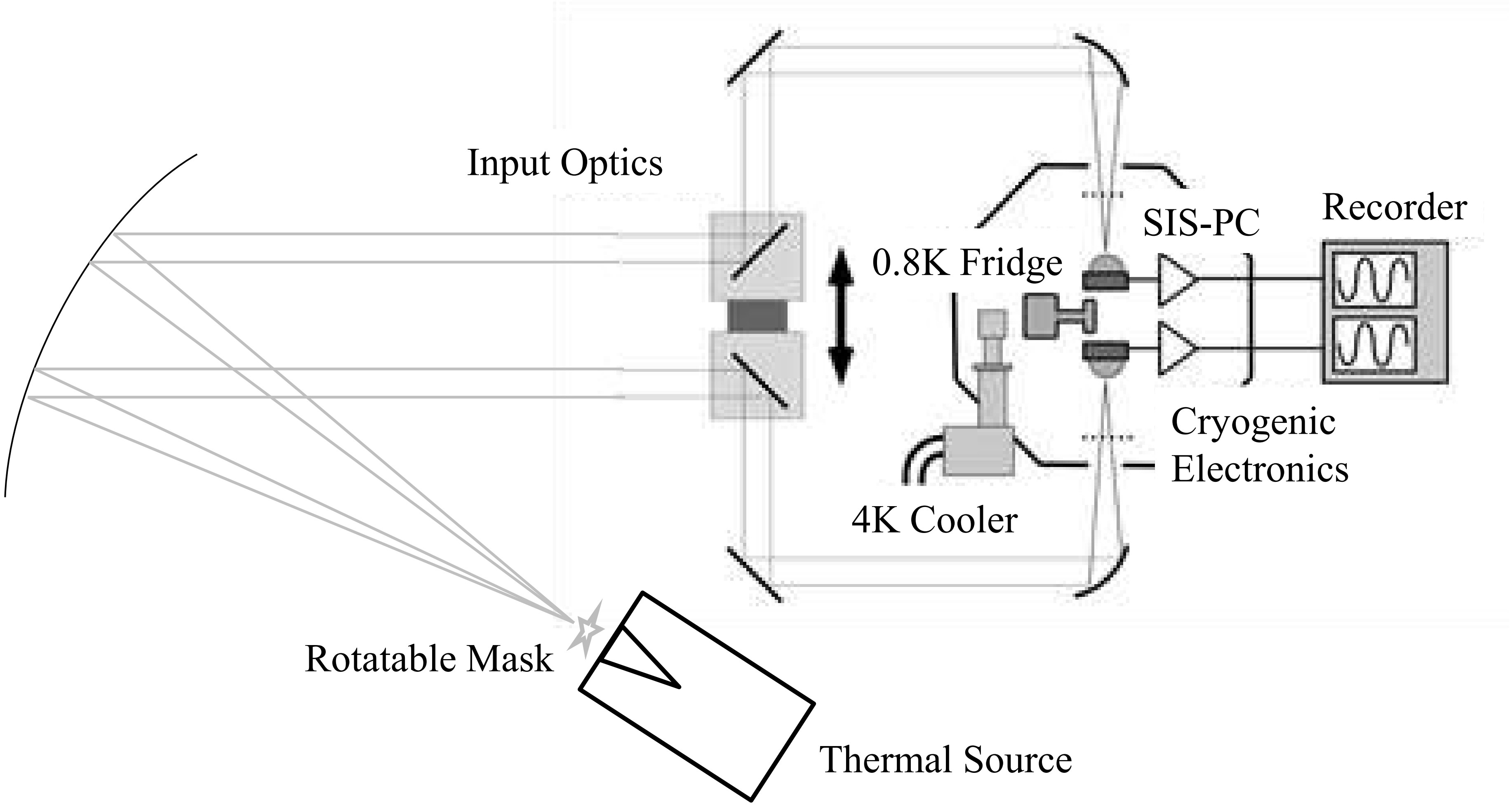


Niwa et al. (2020) EA Receiver Workshop

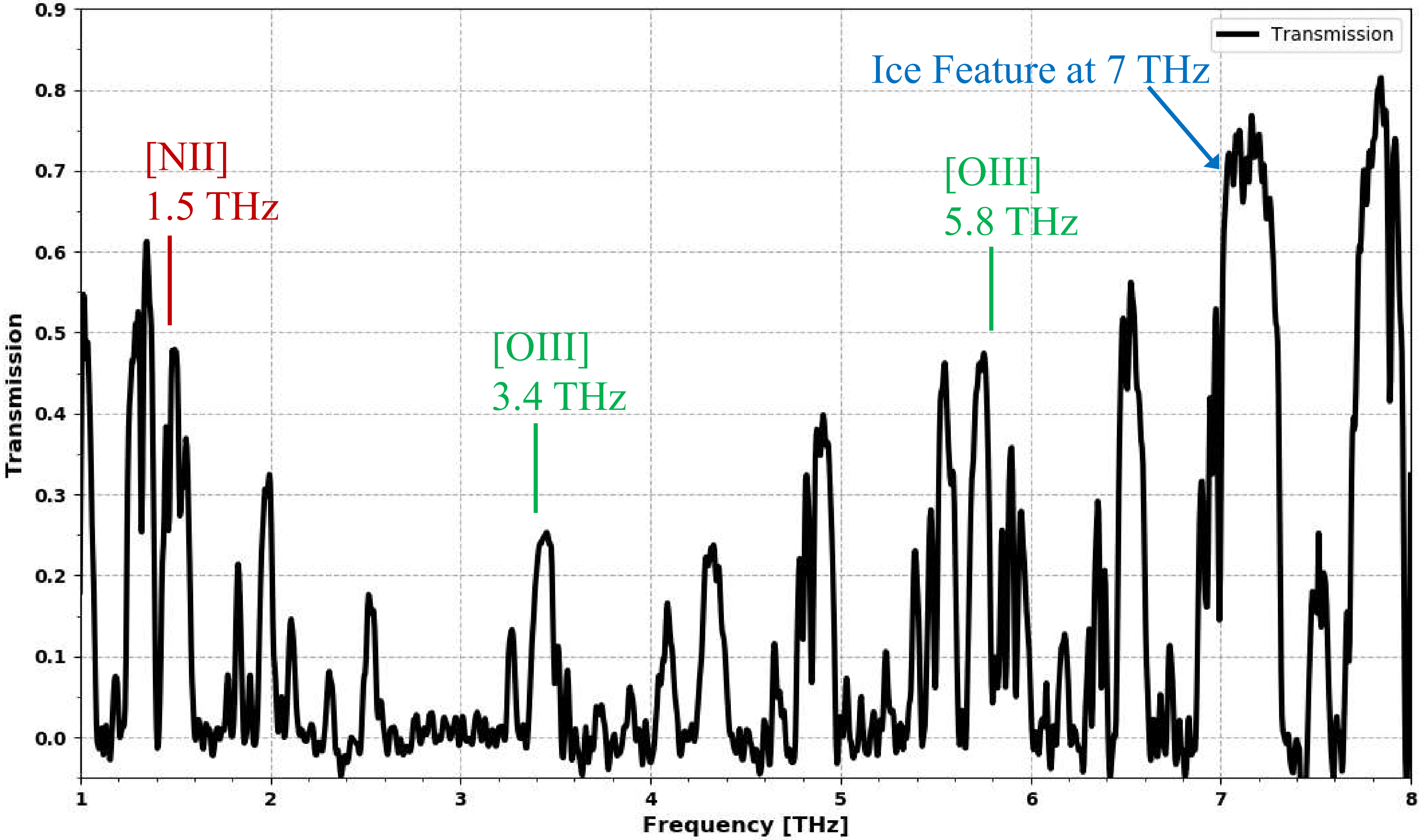
A Cryostat for THz Photon Statistics

Ezawa and Matsuo

Experimental Setup for Intensity Interferometry



The Most Transparent Atmosphere from Dome A

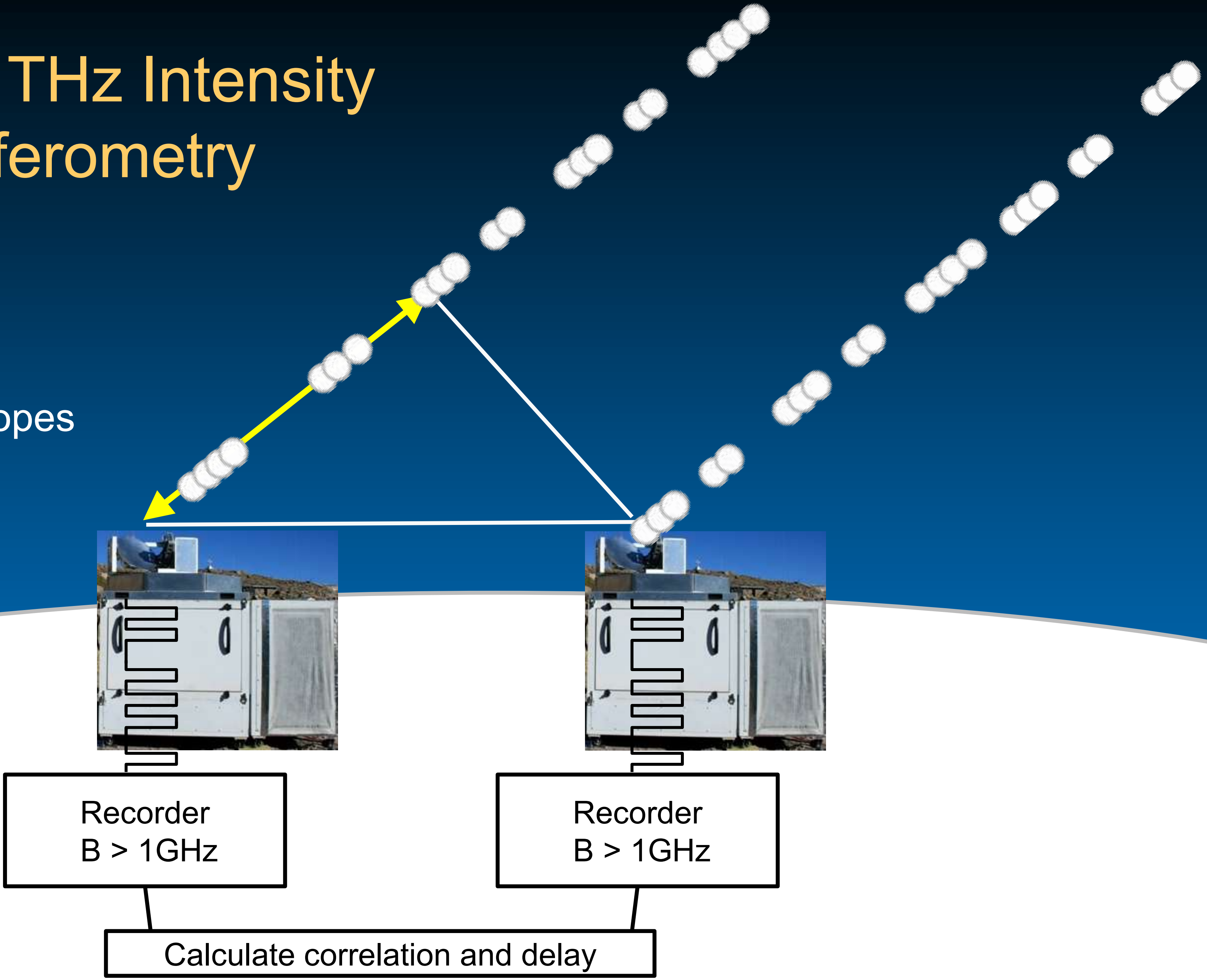


August 9th 12–18h UTC, 2010

Matsuo et al. Advances in Polar Science (2019)

Antarctic THz Intensity Interferometry

Two 30-cm THz telescopes



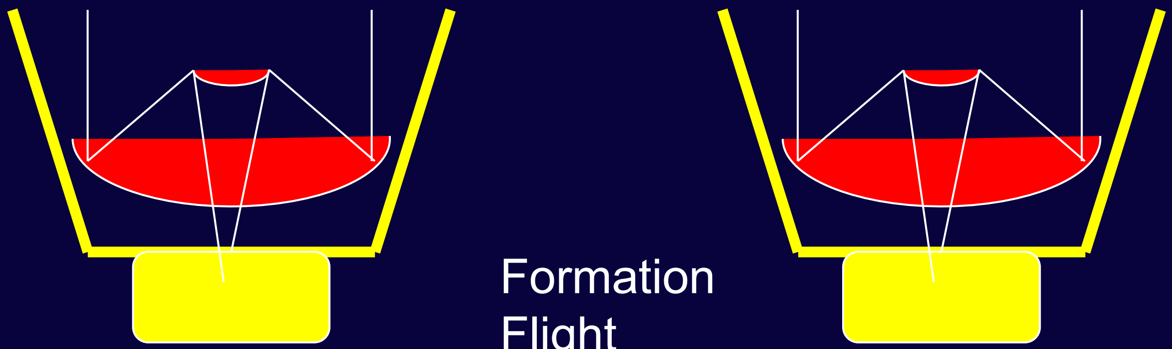
Recorder
B > 1GHz

Recorder
B > 1GHz

Calculate correlation and delay

Technologies for
Space Far-IR Interferometry

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



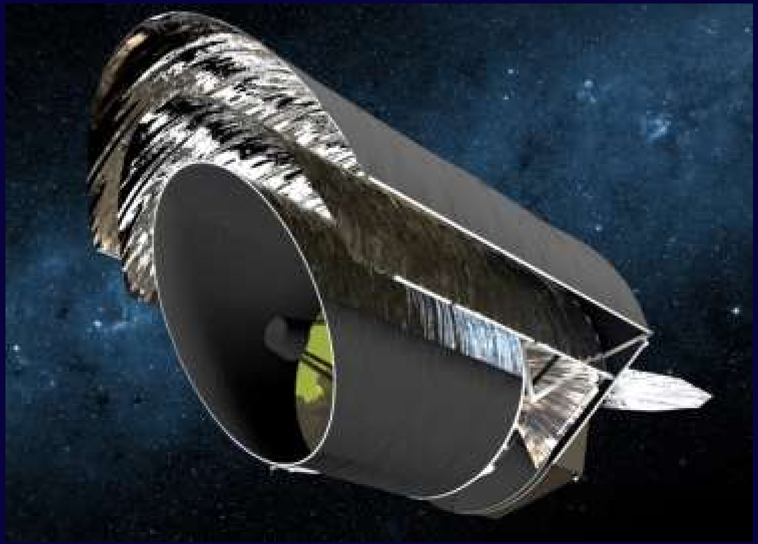
Formation
Flight

Photon Counters
Atomic clock
Recorder

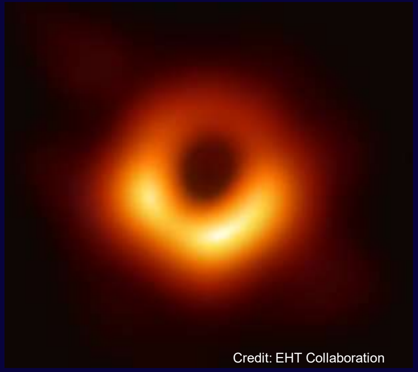
Photon Counters
Atomic clock
Recorder

Combination of OST and MSO

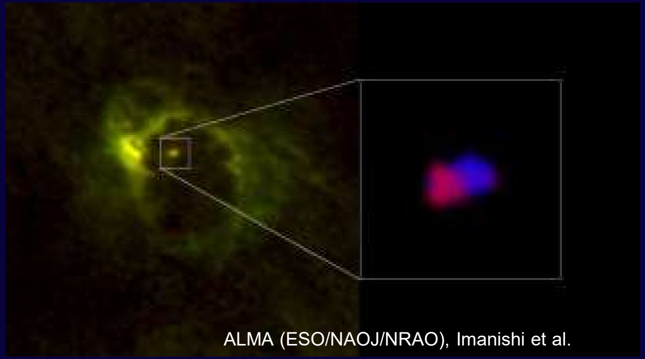
- Large Cryogenic Telescopes in THz
- Direct detectors will be installed.
- Both will situate around S-E L2



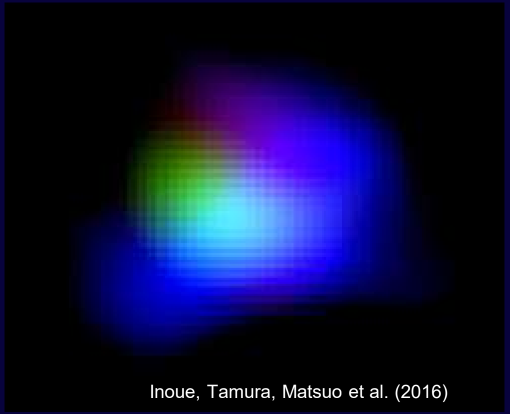
Far-Infrared
Intensity Interferometry

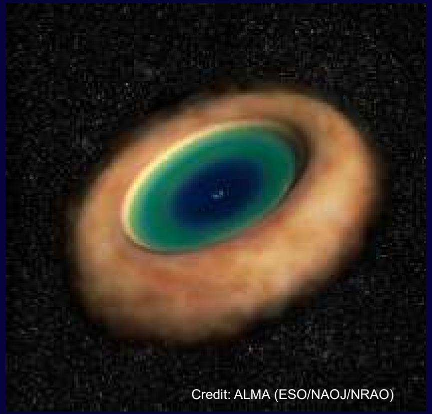

Credit: EHT Collaboration

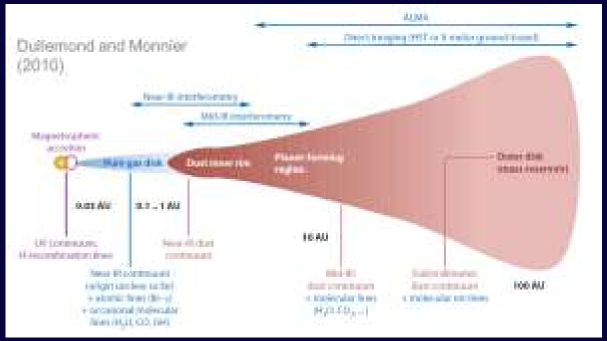
- Closer to the central activities !


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


ALMA (ESO/NAOJ/NRAO)

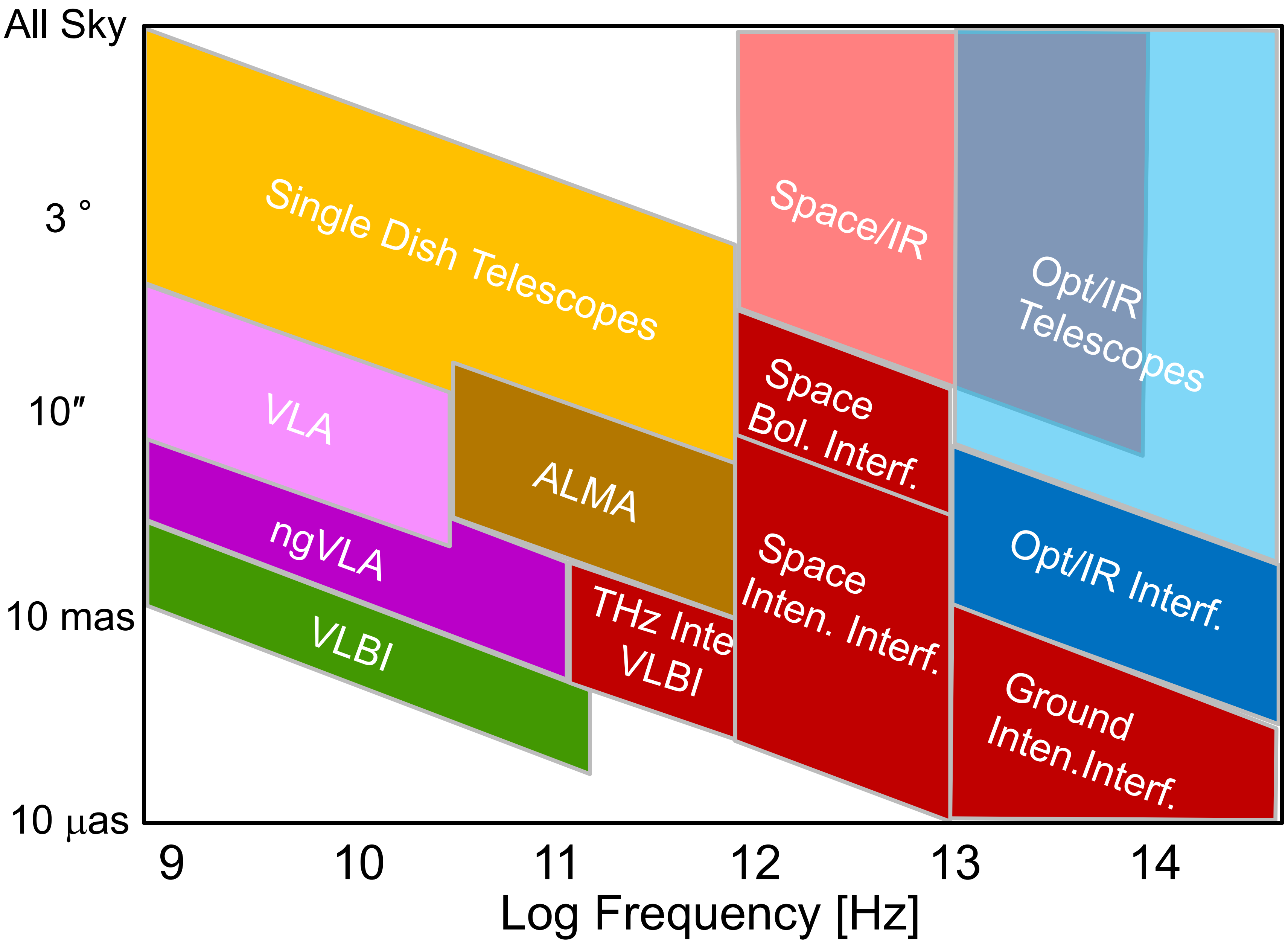

Inoue, Tamura, Matsuo et al. (2016)


Credit: ALMA (ESO/NAOJ/NRAO)


Dullemond and Monnier (2010)


Credit: ALMA/NAOJ

Angular Scale of Observation



Problems to be solved

- Time scale of the project
  - Ground-based demonstration
- Wavelengths of interests
  - Is delay calibration possible in infrared ?
- Fast photon counting technologies
  - Superconducting detectors
- Precision satellite orbit determination
  - Formation flights
- Fast data rates

Summary

- High angular resolution Far-IR observations
- HBT intensity interferometry
- Imaging technique
- Merit of direct detectors
- Combination of OST and Millimetron
- Ground-based demonstrators