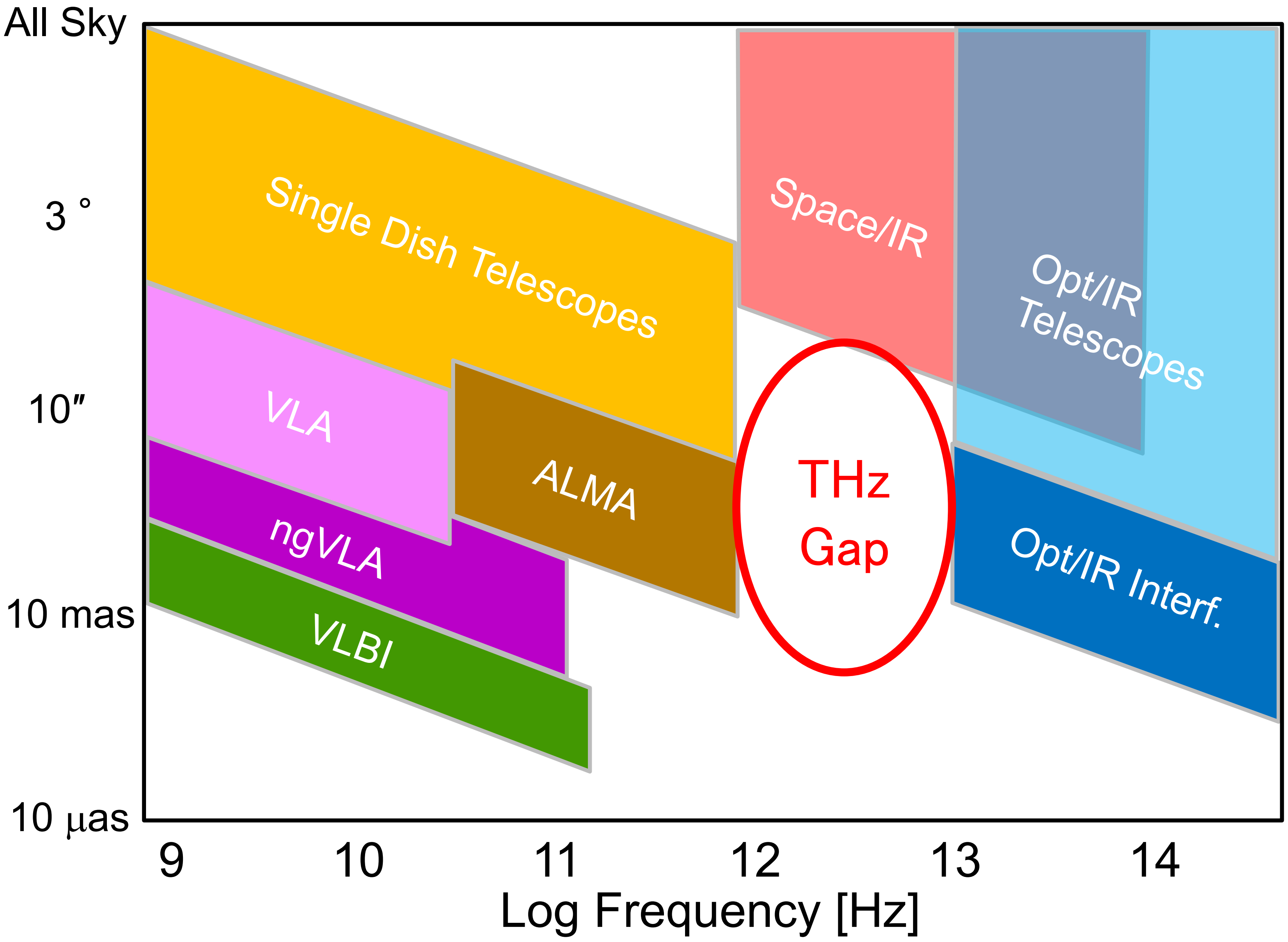
南極活動の新しい方向性
将来のスペースとのリンク

松尾　宏

国立天文台・先端技術センター

Angular Scale of Observation

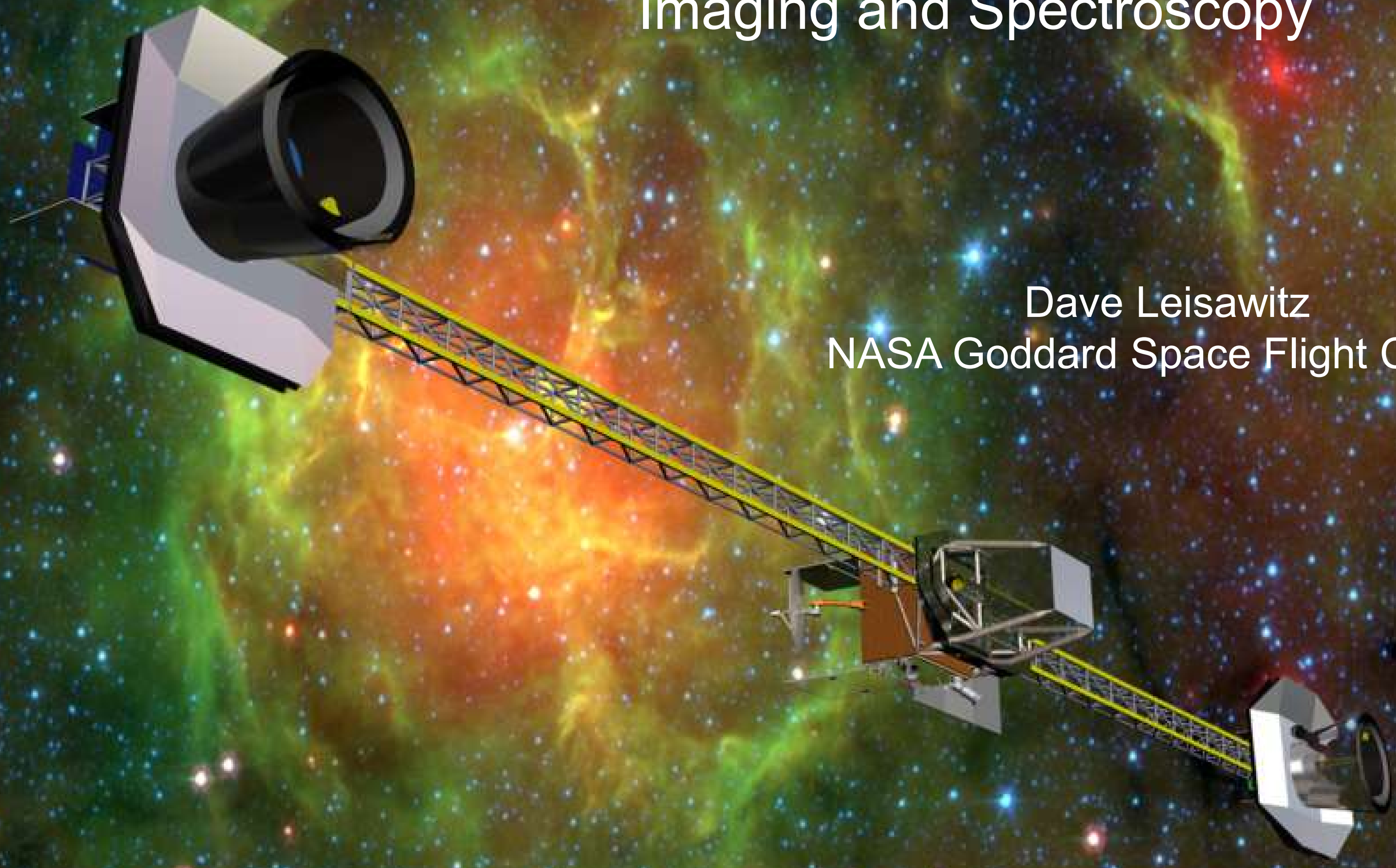


Studies in US and EU

- In US
  - Far-IR Community Workshops in 2014 and 2015
  - Single Dish or Interferometry ?
  - Origins Space Telescope
- In EU
  - ESPRIT, FIRI
  - FP7-FISICA (Far-IR Space Interferometer Critical Assessment)
  - HEterodyne Receiver for Origins (HERO)

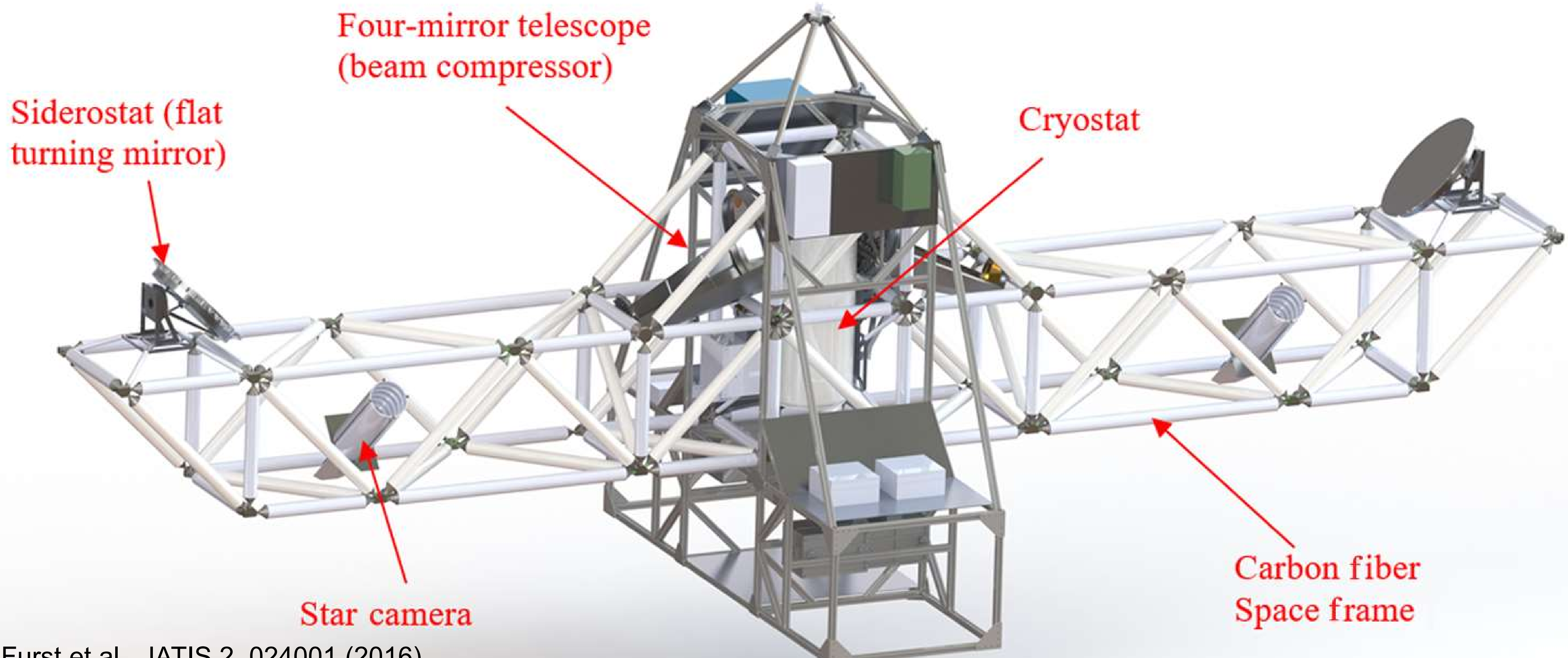
The Space Infrared Interferometric Telescope (SPIRIT)

A Far-IR Observatory for High-resolution Imaging and Spectroscopy



Dave Leisawitz
NASA Goddard Space Flight Center

BETTII (Balloon Experimental Twin Telescope for Infrared Interferometry)



Furst et al., JATIS 2, 024001 (2016)

ESA Voyage 2050 White Papers

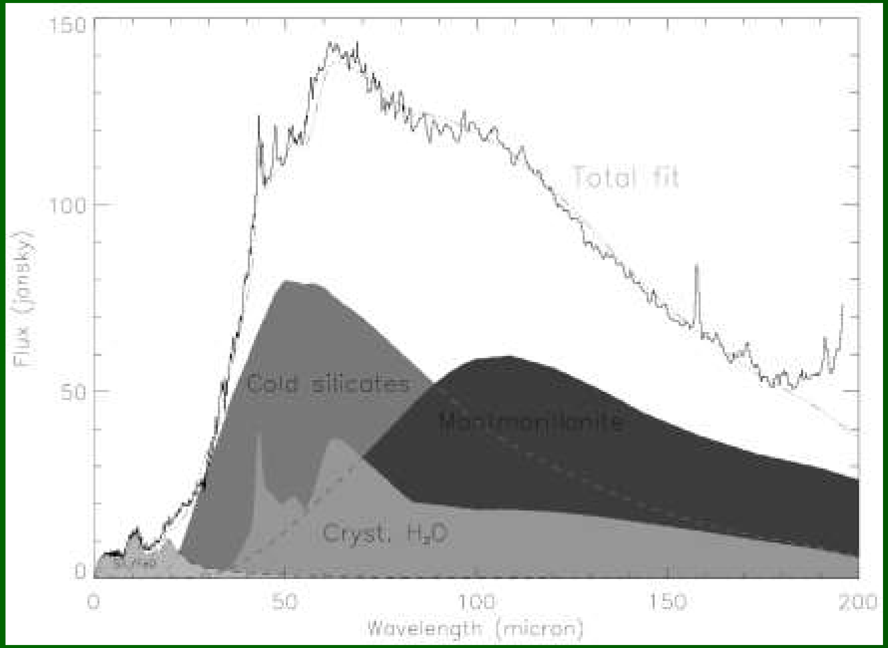
- Atmospheric characterization of terrestrial exoplanets in the Mid-infrared: biosignatures, habitability & diversity
  - Nulling interferometer, four 2.5 m telescopes, 170 m baseline
  - CH_4, O_3, N_2O, CO_2, H_2O
- Bringing high spatial resolution to the Far-infrared – A giant leap for astrophysics
  - Heterodyne interferometer, five 4 m telescopes, 1 km baseline
  - or Deployable single dish telescope 20 m diameter
  - H_2O, atomic lines, HD112μm

ESA Voyage 2050 White Papers

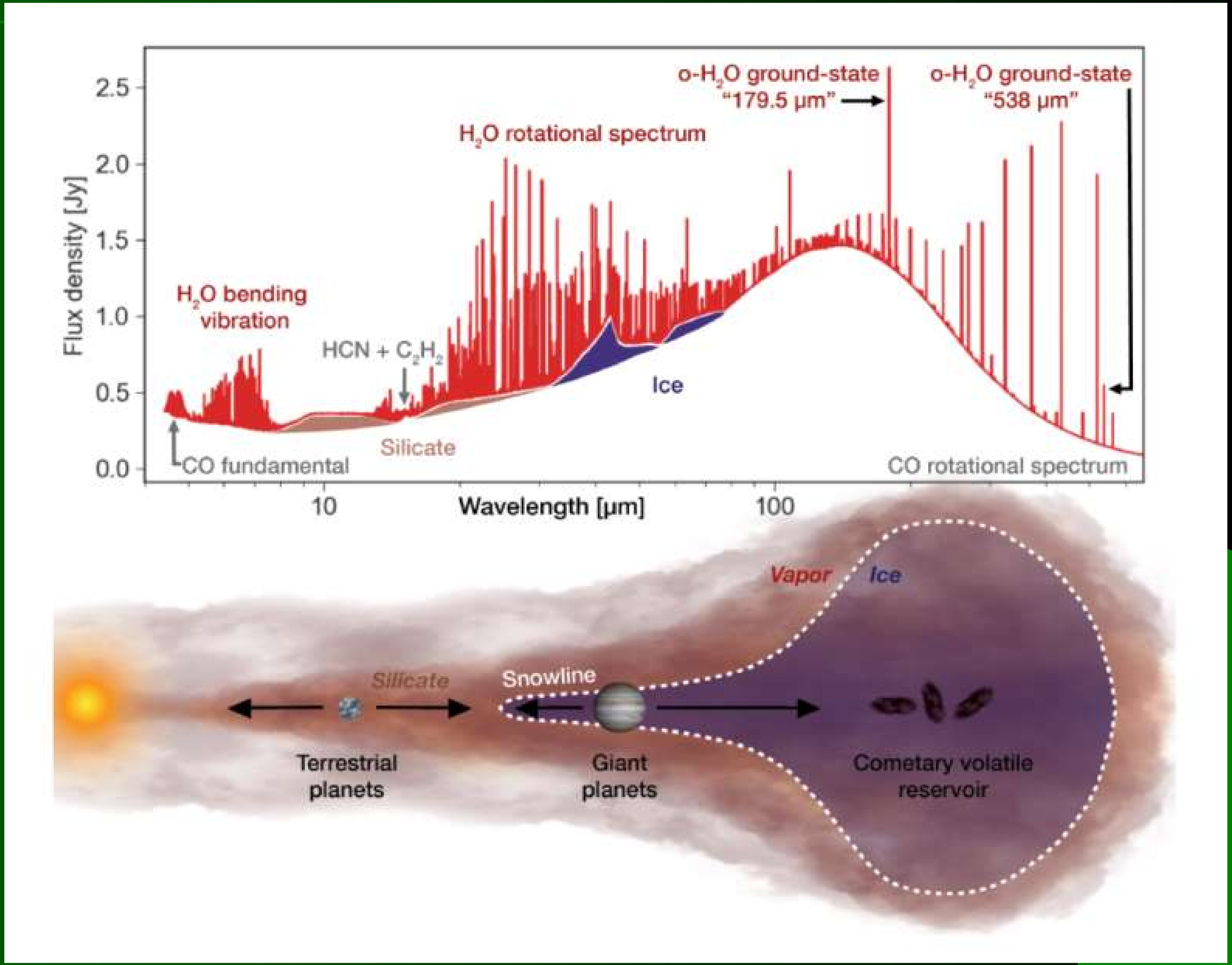
- TeraHertz Exploration and Zooming in for Astrophysics (THEZA)
  - Event Horizon Imager with two 4.4 m telescope VLBI
  - Less than 10 μarcsec resolution
- The Far-Infrared Spectroscopic Surveyor (FIRSS)
  - Heterodyne Receivers on 1-2 m Single Dish; atomic lines
- Origins Space Telescope: From First Light to Life (OST)
  - Far-Infrared Cryogenic Telescope; H_2O, atomic lines, HD112μm
  - Background limited observation (+ Heterodyne receivers ?)

H_2Oの観測

Infrared Space Observatory
Water ice feature at 43/63 μm



HD142527
Malfait et al. (1999)



Pontoppidan et al. (2019)

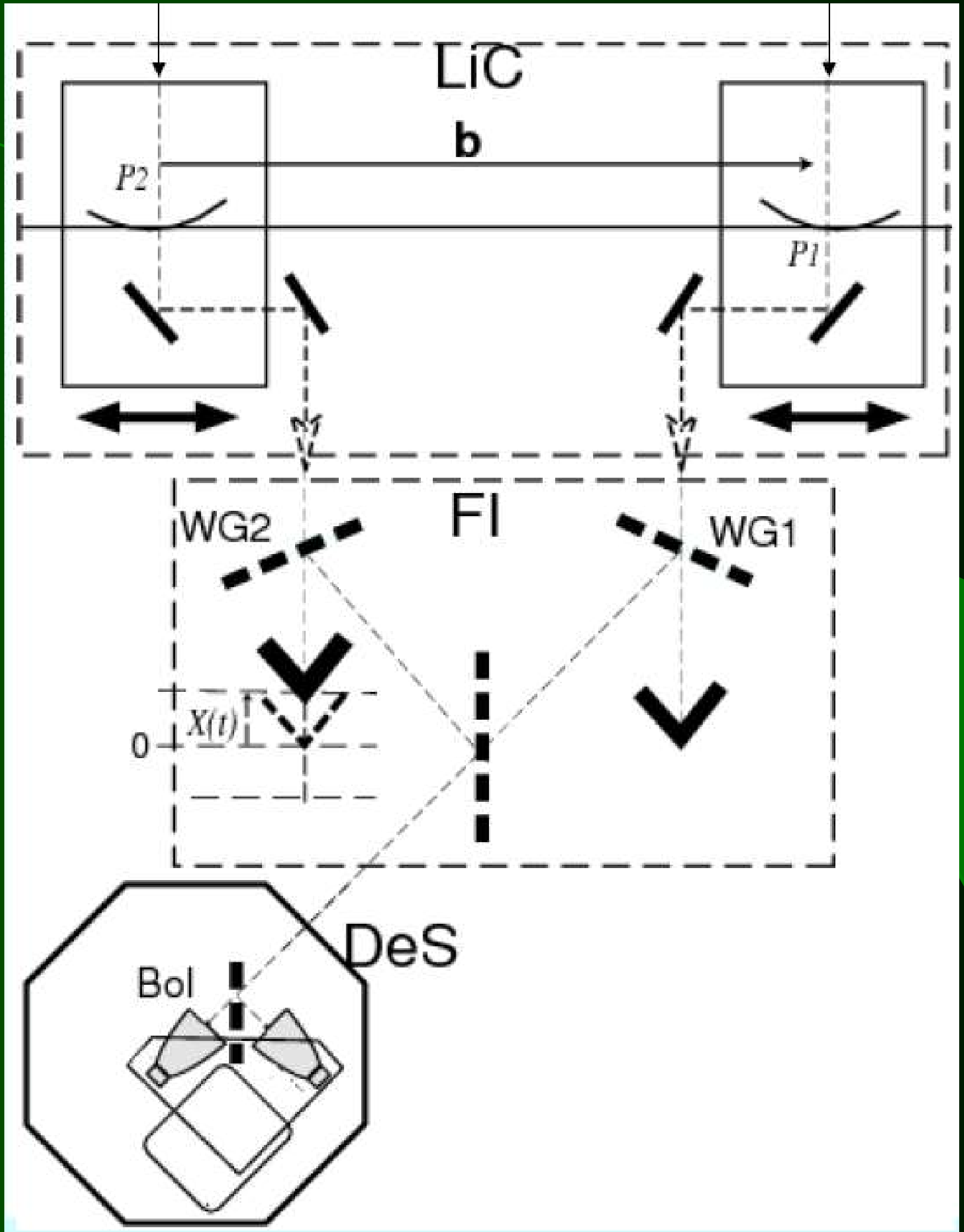
MuFT

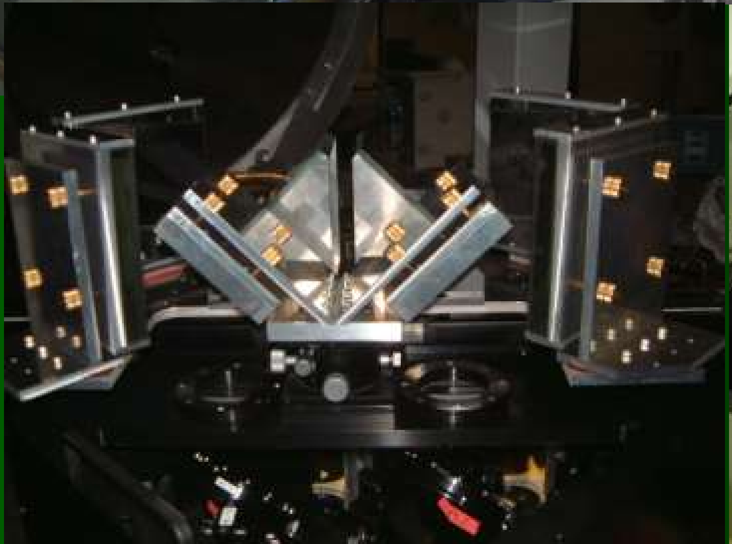
Multi-Fourier Transform interferometer

- High Dynamic Range
- Imaging Spectrometer
- Polarizing beam combiner

Ohta et al. Appl. Opt. 45, 2576 (2006)

Ohta et al. Appl. Opt. 46, 2881 (2007)





MuFT and Heliostat in Nobeyama 2005

MuFT image of the sun

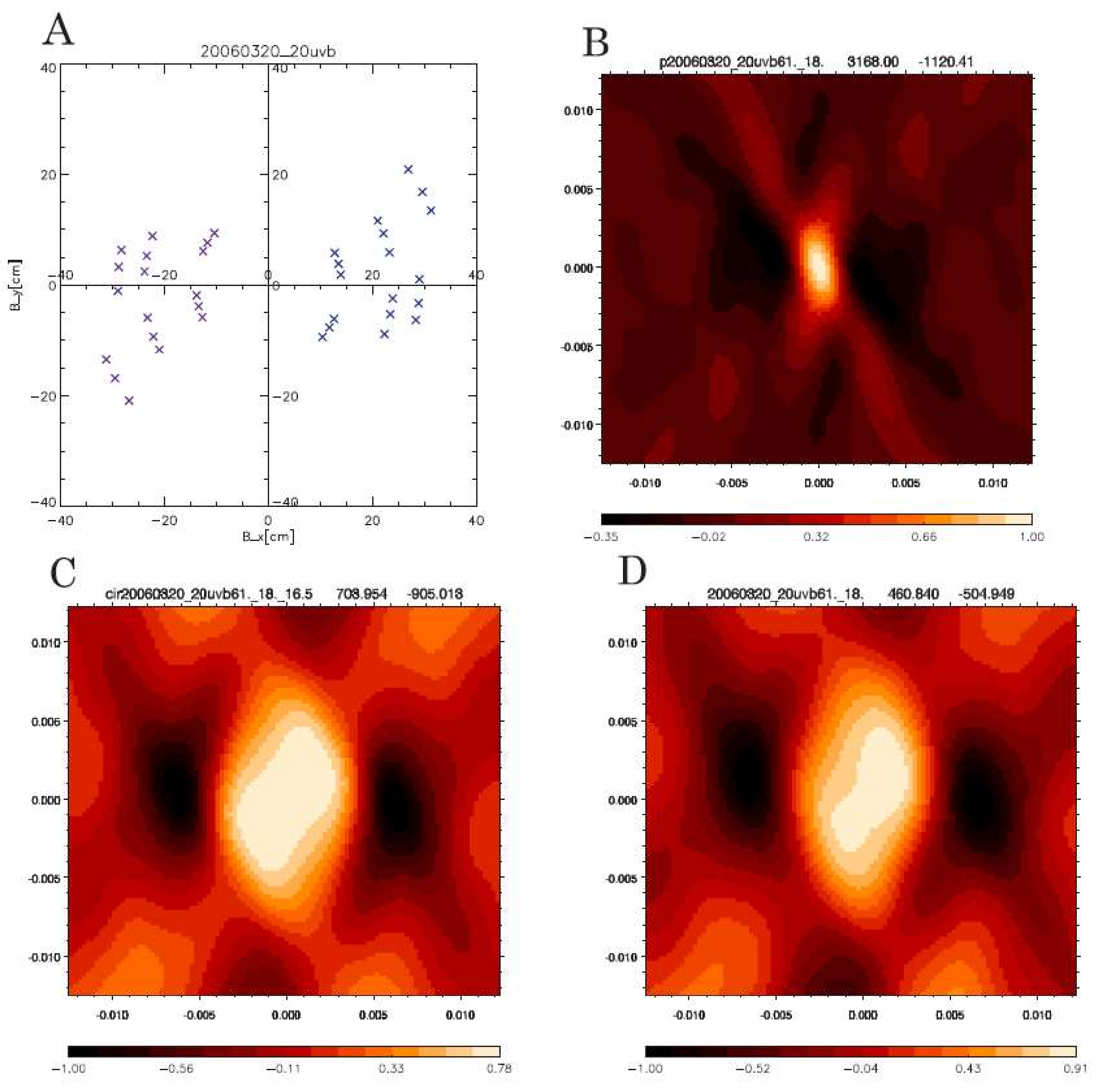
A. baselines sampled

B. synthesized beam

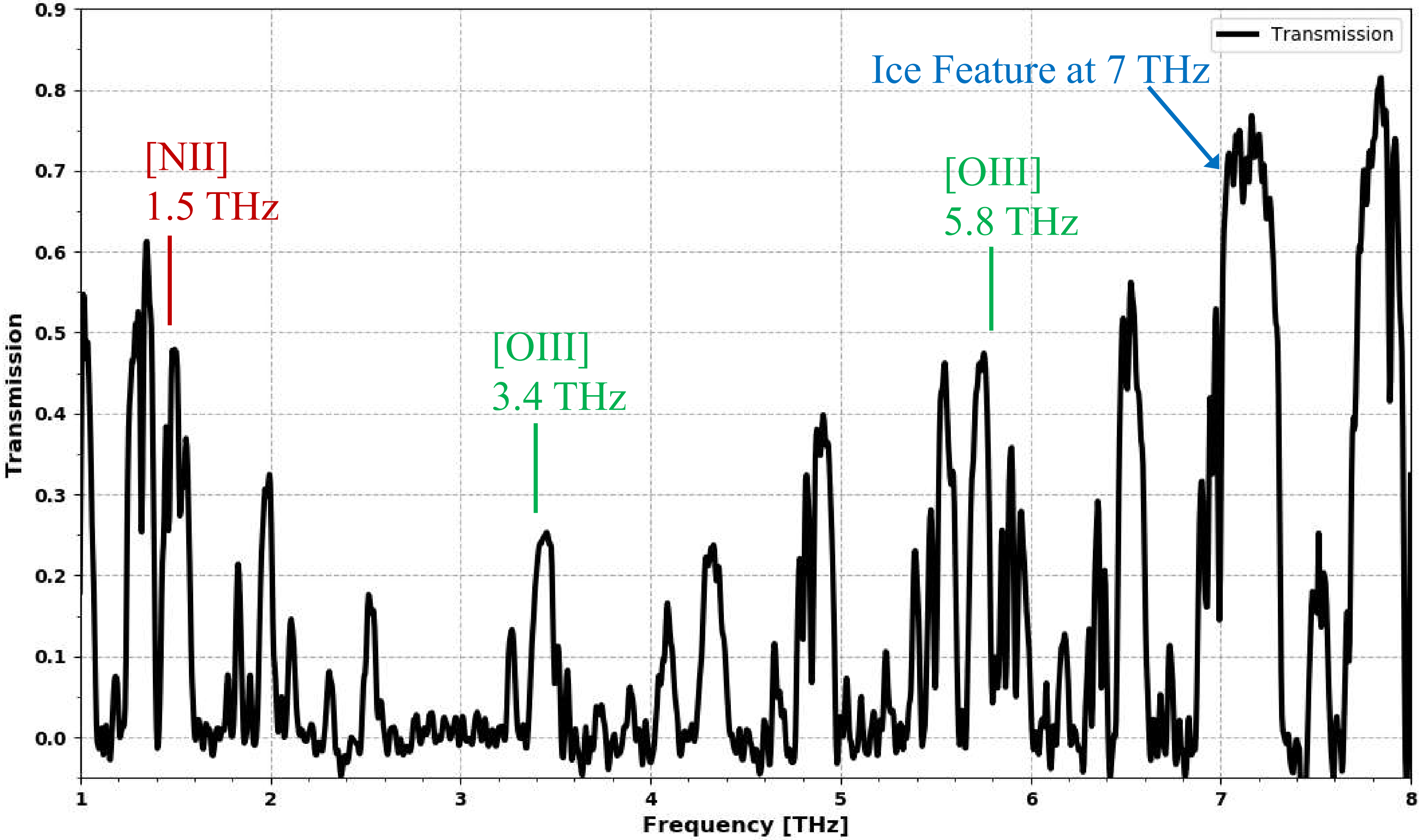
C. simulated image

D. observed image

Ohta et al.
IRMMW-THz2007



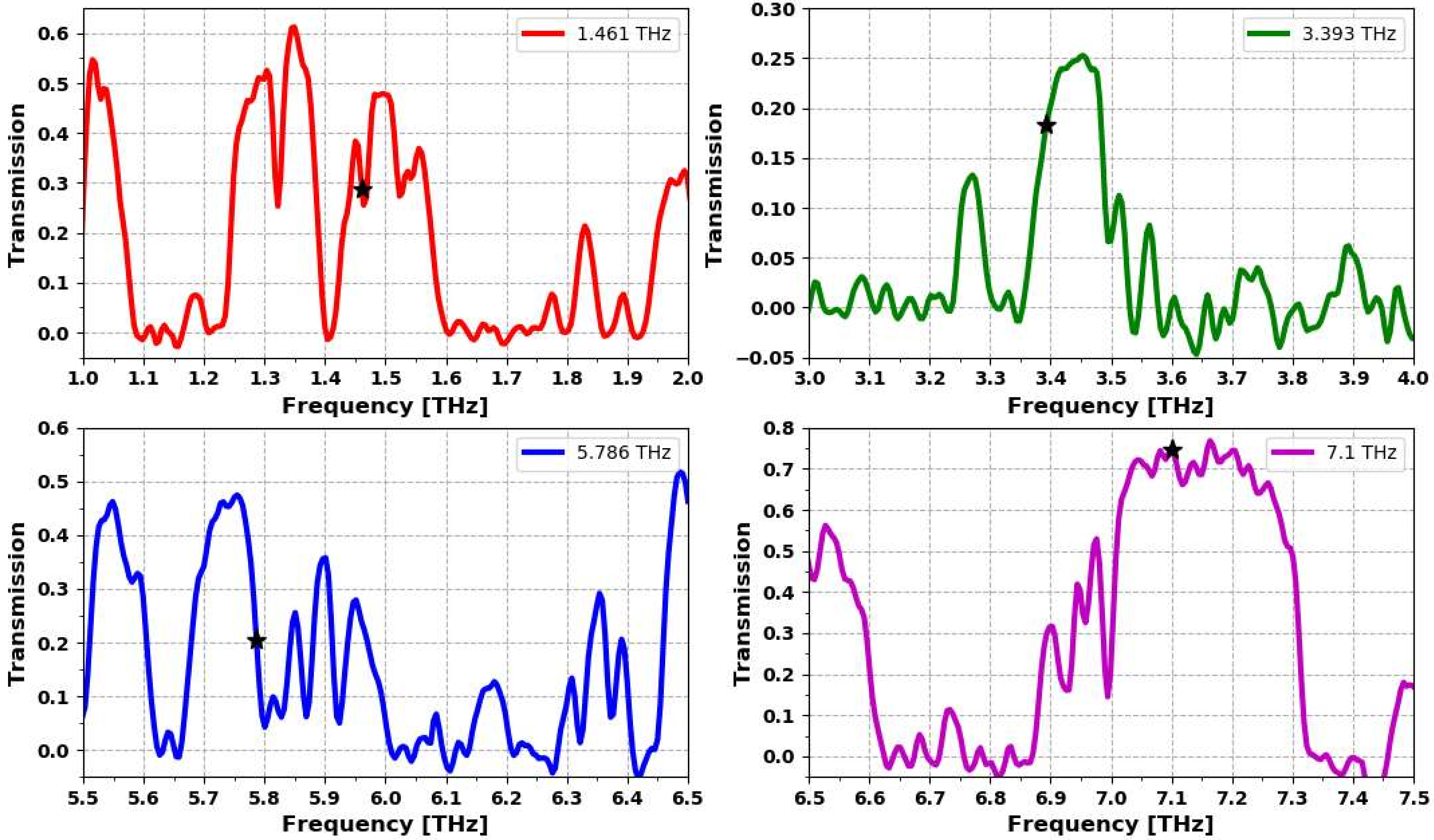
The Most Transparent Atmosphere from Dome A



August 9th 12–18h UTC, 2010

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

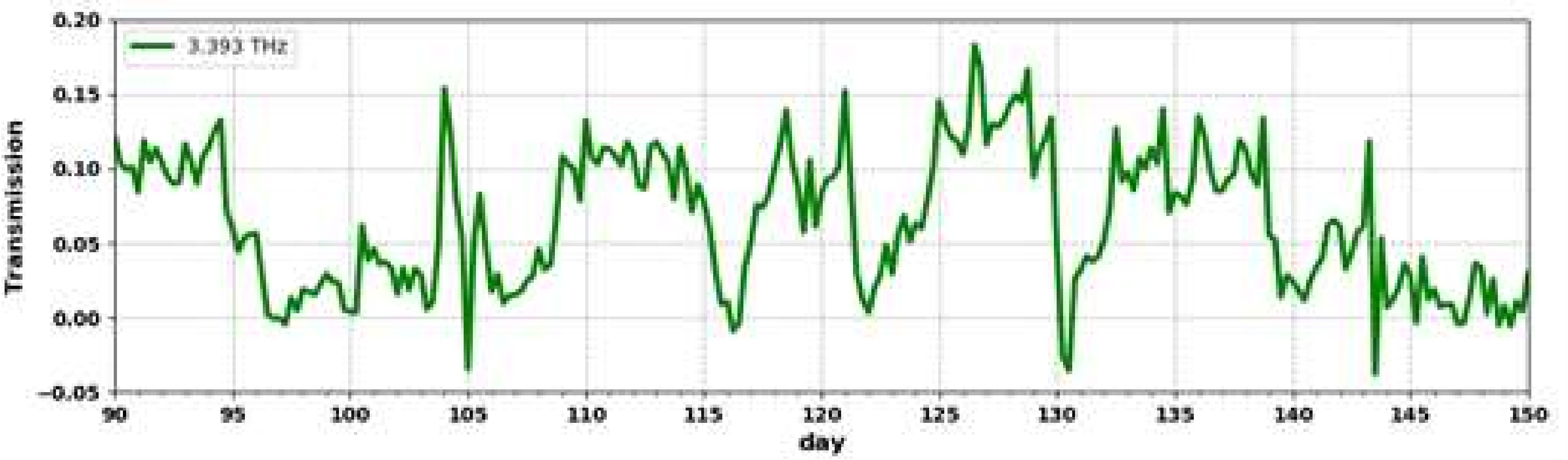
Windows for [NII], [OIII] and Ice Feature



August 9th 12–18h UTC, 2010

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

Can we observe [OIII] 88 μm at 3.393 THz ?



in July - August, 2010

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

高感度と高解像度の両立は？

- ヘテロダイン受信機の量子雑音
  - $T_{rx} = h\nu/k$ [K] = 500 K @10 THz
- 結合型干渉計の基線長制限

↳ 強度干渉計の提案

Narrabri Stellar Intensity Interferometer

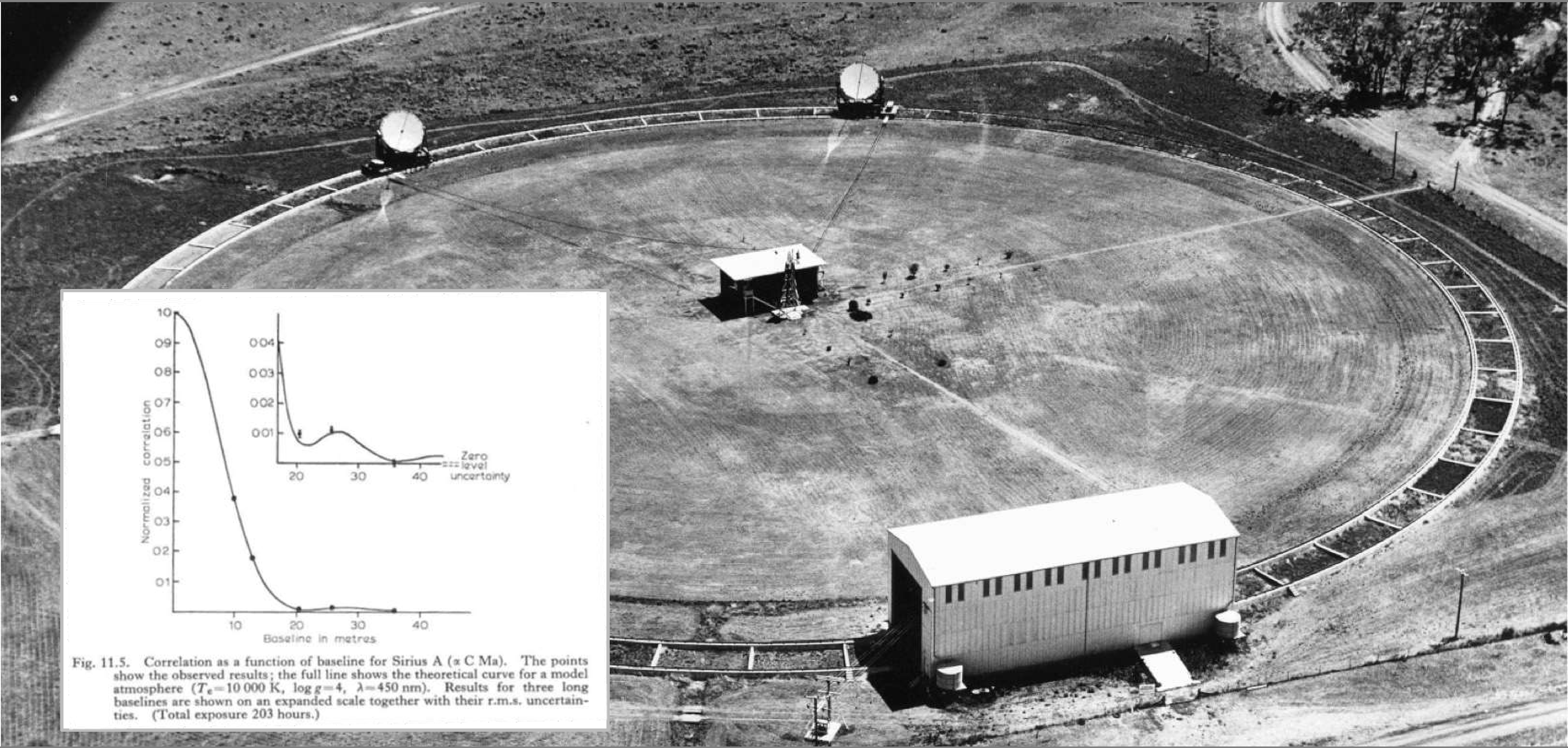


Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model atmosphere ($T_e = 10\,000$ K, $\log g = 4$, $\lambda = 450$ nm). Results for three long baselines are shown on an expanded scale together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

ATNF Daily Astronomy Picture
17th of August 2015

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

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

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

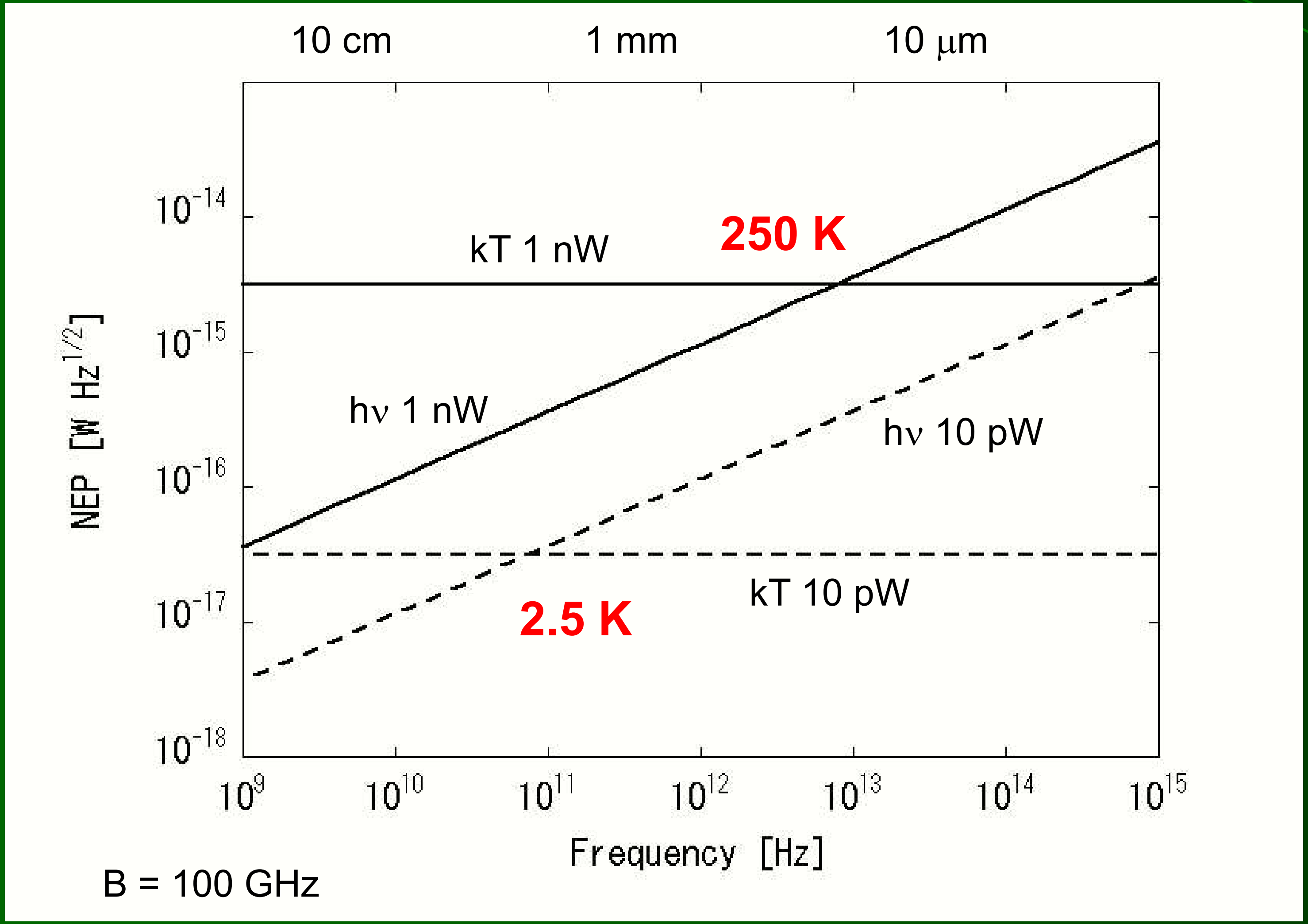
$\Delta T = T_B / \sqrt{B\tau}$

Photon bunching

References

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

THz photon fluctuation



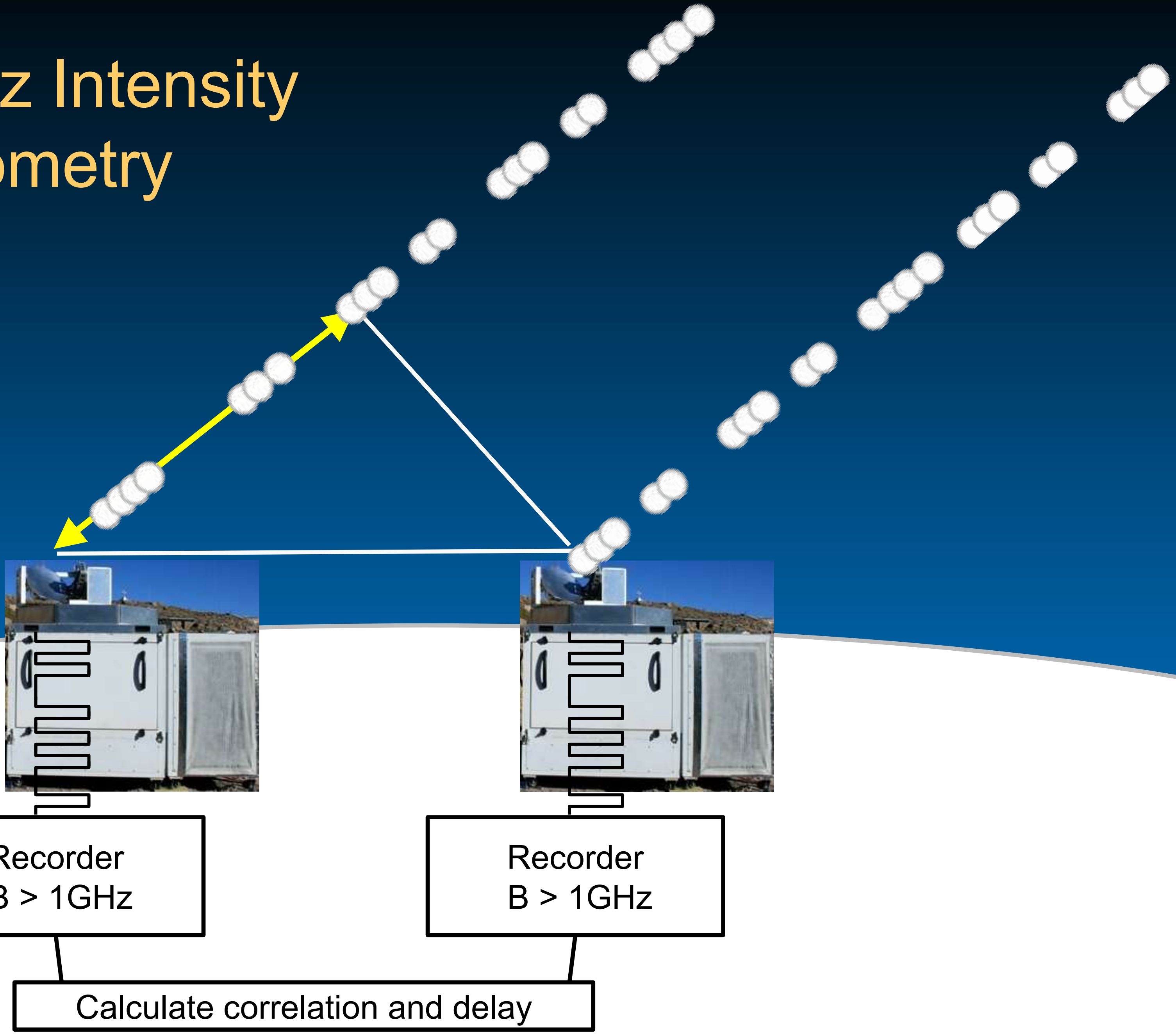
$$\mathrm{NEP} = \sqrt{2P\cdot(h\nu + kT_B)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

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

de Bernardis and Masi (1982)

Antarctic THz Intensity Interferometry

Two 30-cm THz telescopes



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.

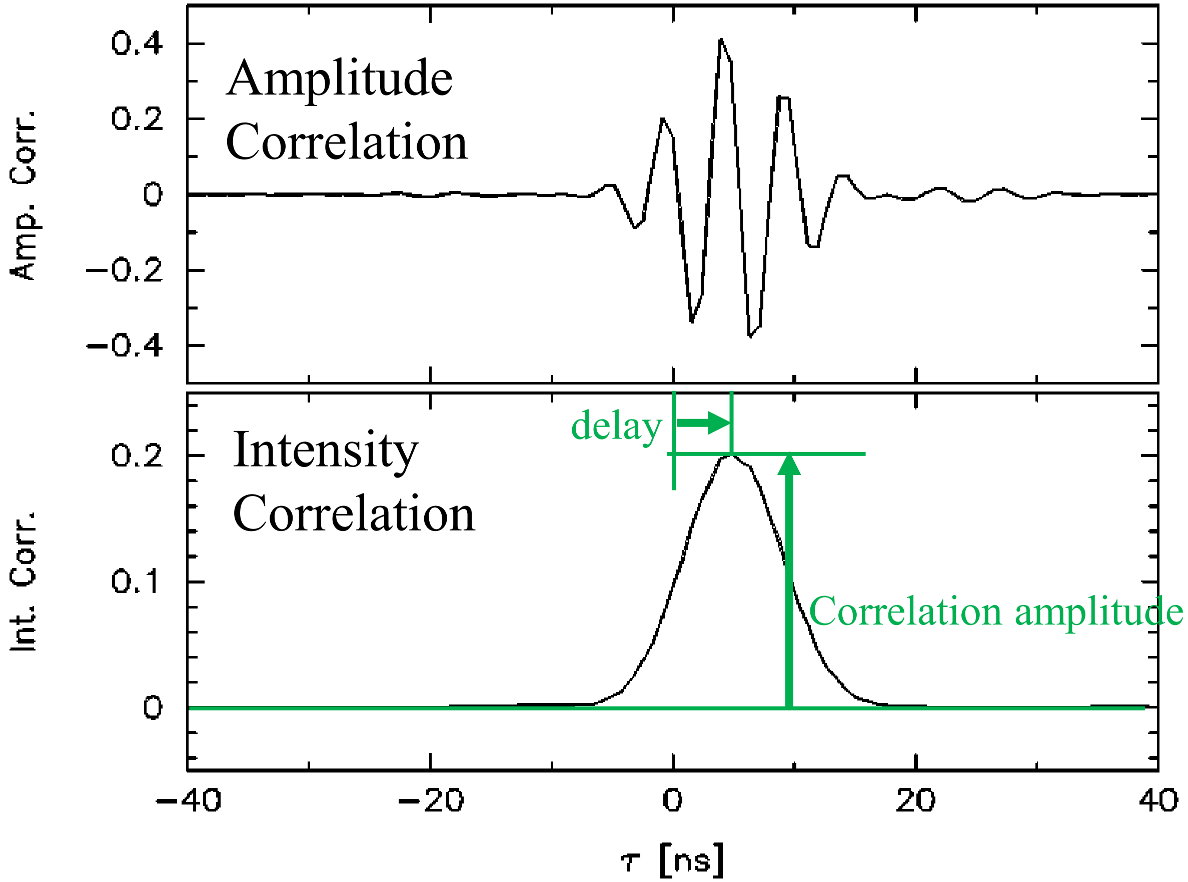
$$\Delta t = \frac{1}{N\sqrt{N \cdot \tau}}$$

THz Photons are bunched !

N: photon rate

τ : integration time

Nobeyema Radioheliograph at 17 GHz



Antenna Temperature T_A^* [K]

System Temperature T_{sys} [K]

Frequency ν [Hz]

Bandwidth $\Delta\nu$ [Hz]

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

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

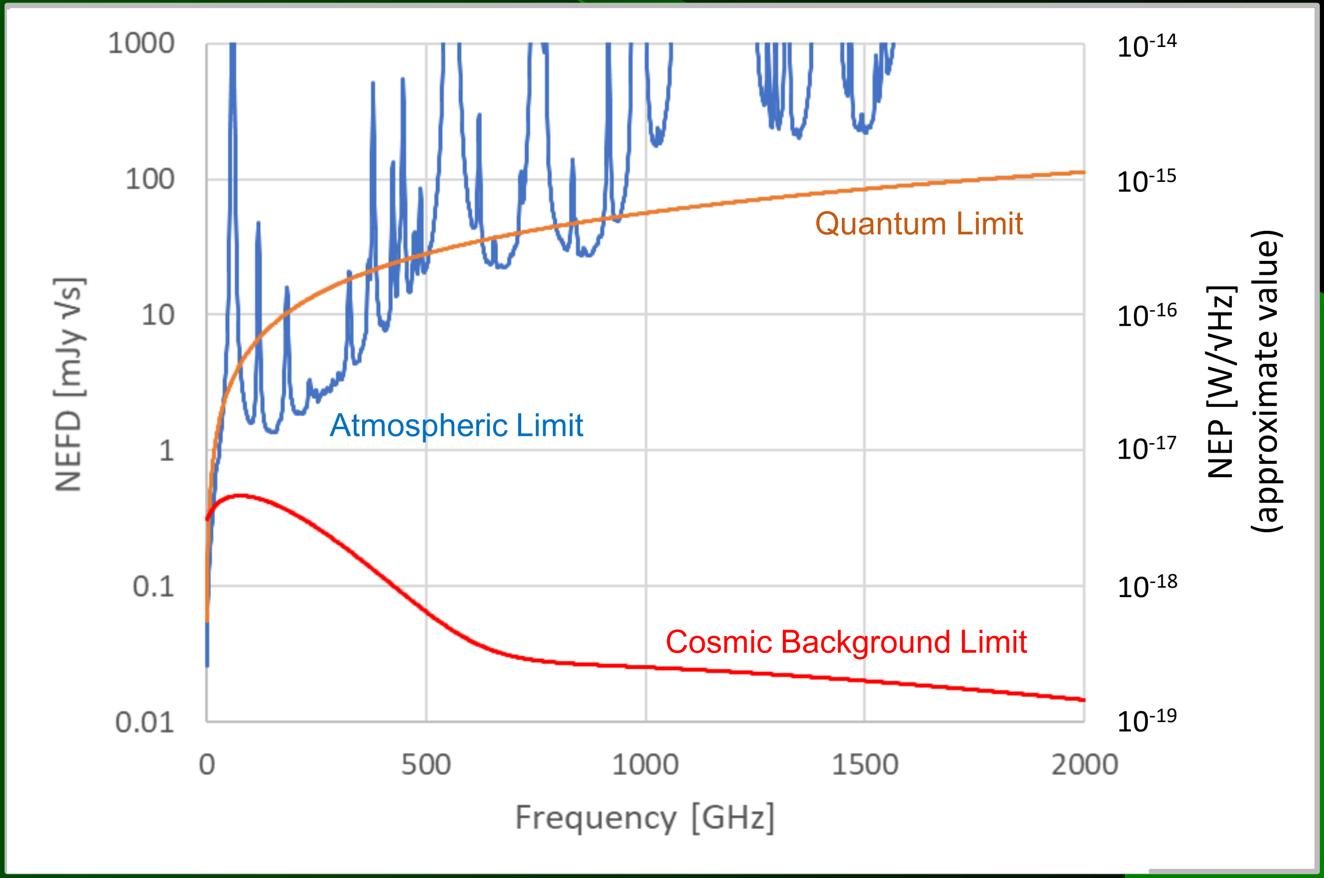
Δt ~ 5ps in 50 ms integration

Ezawa, Matsuo et al. (2015)

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

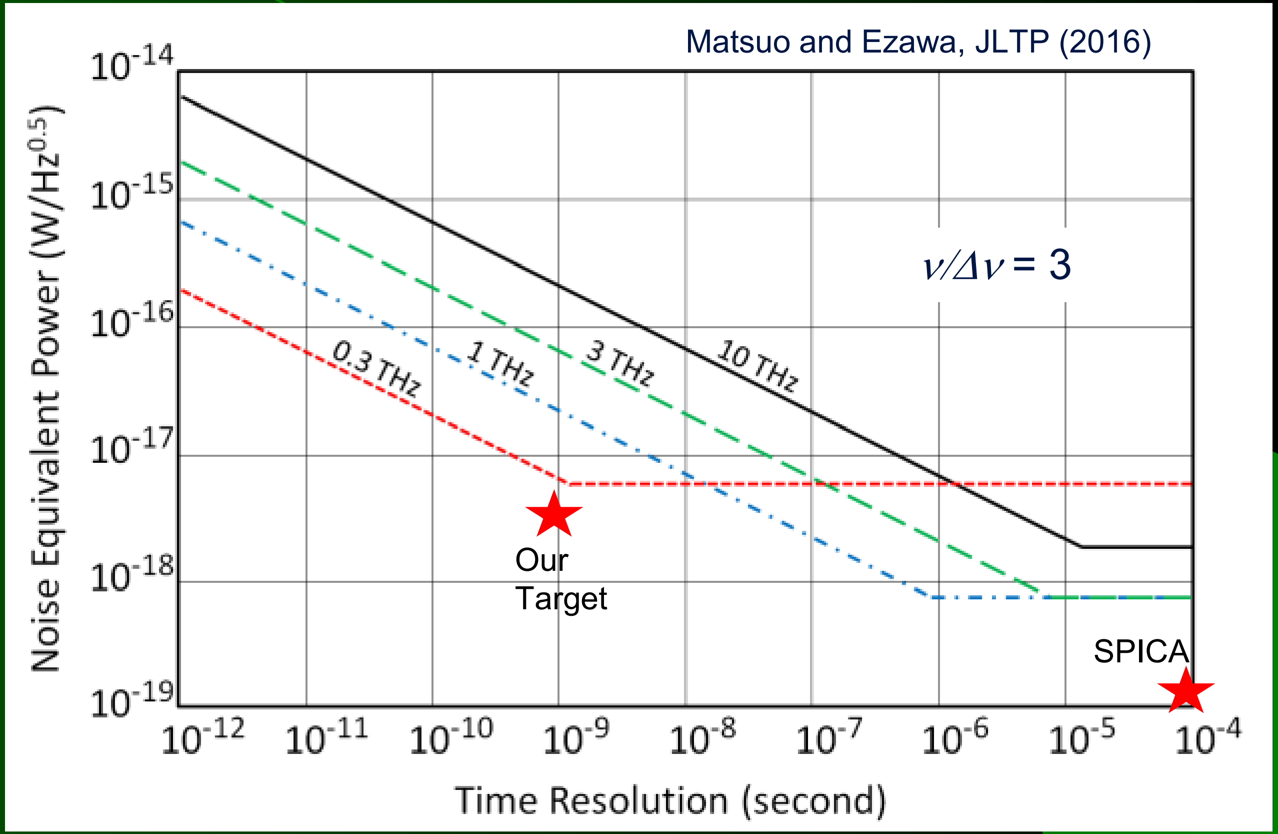


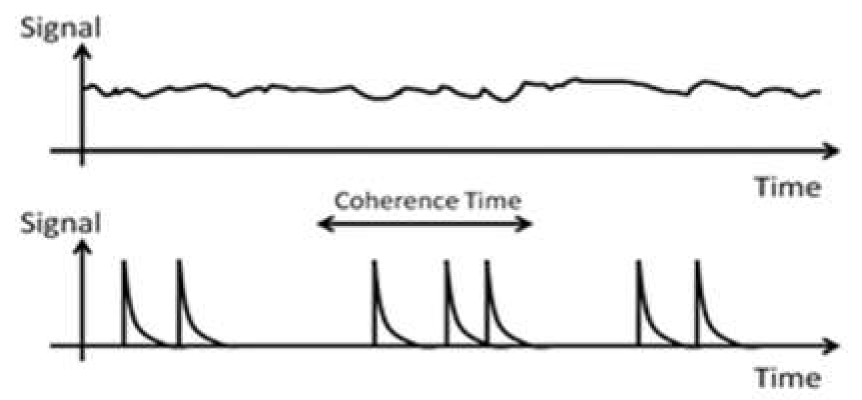
Requirements to Detectors

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

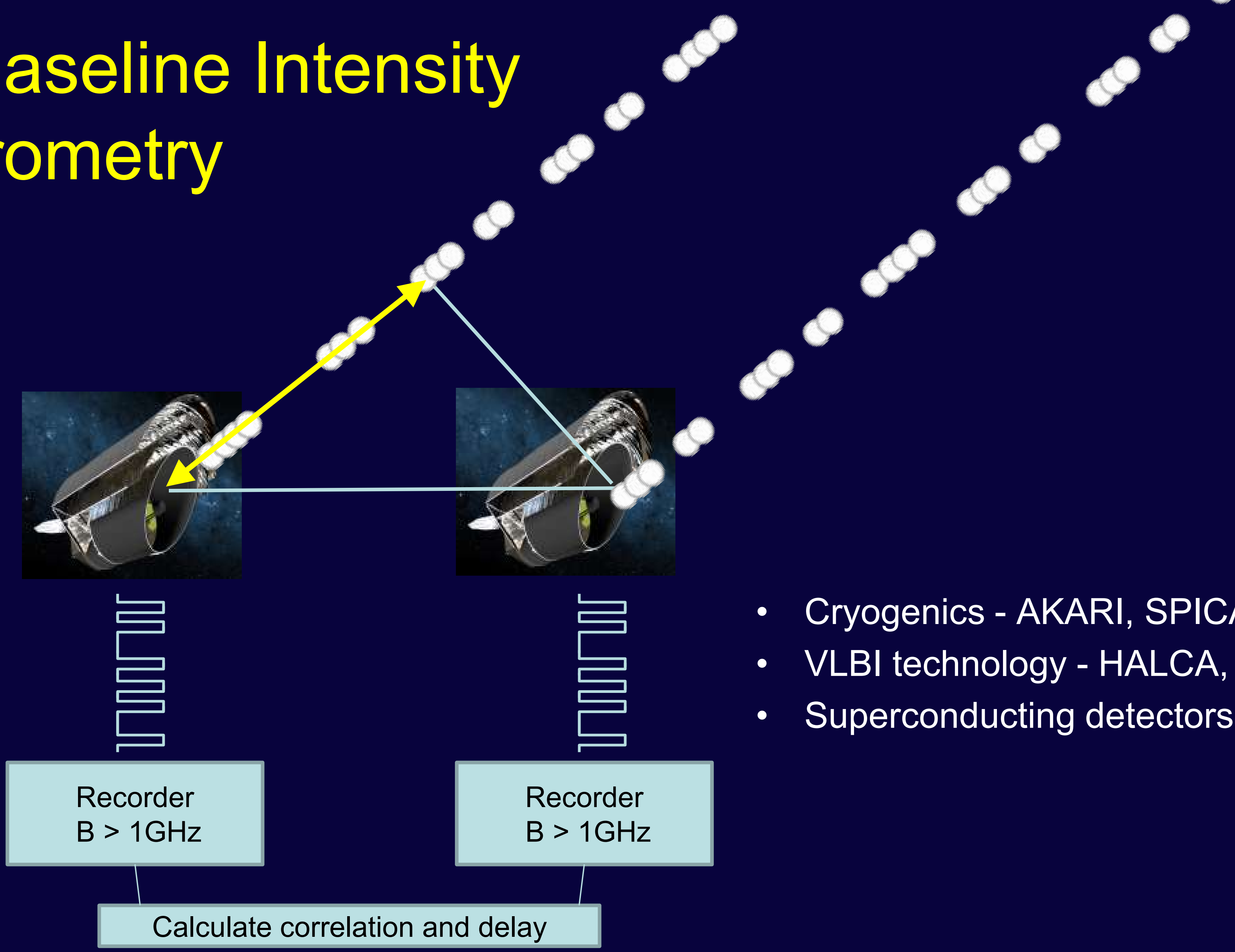
$= 10^{-21} \times (1\ \mathrm{GHz})^{0.5}$

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


Matsuo and Ezawa, JLTP (2016)



Long Baseline Intensity Interferometry



Recorder
B > 1GHz

Recorder
B > 1GHz

Calculate correlation and delay

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

可能なパラメータ

- 望遠鏡口径
  - – 5-10 m, Cryogenic telescopes
  - – Origins, Millimetron
- 波長帯
  - – 10 μm – 300 μm, Far-IR, THz
  - – Photon counting detectors
- 基線長
  - – 100 m – 100 km, VLBI technology
- 角度分解能
  - – 1 marcsec – 10 μarcsec, imaging stars and planets

Angular Scale of Observation