南極高地からの
高解像度テラヘルツ天体観測
High Angular Resolution Terahertz Astronomy from Dome A

Hiroshi Matsuo (ATC/NAOJ)

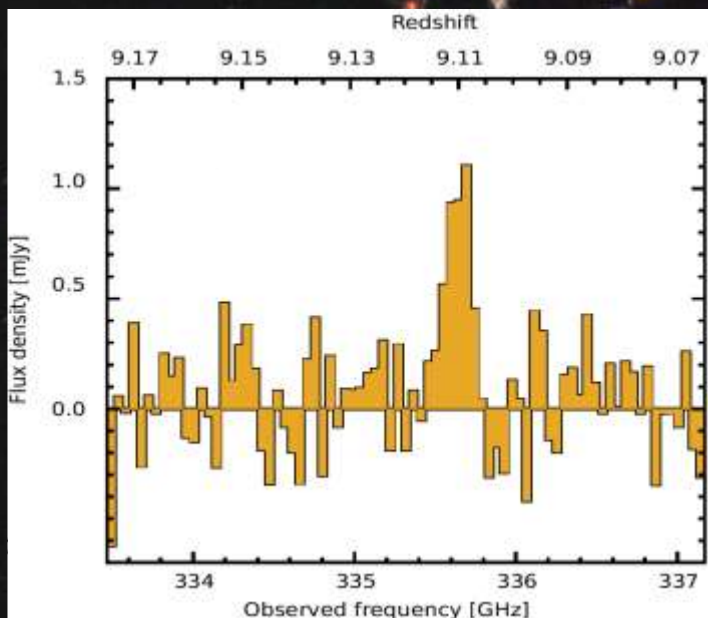
THz Observation

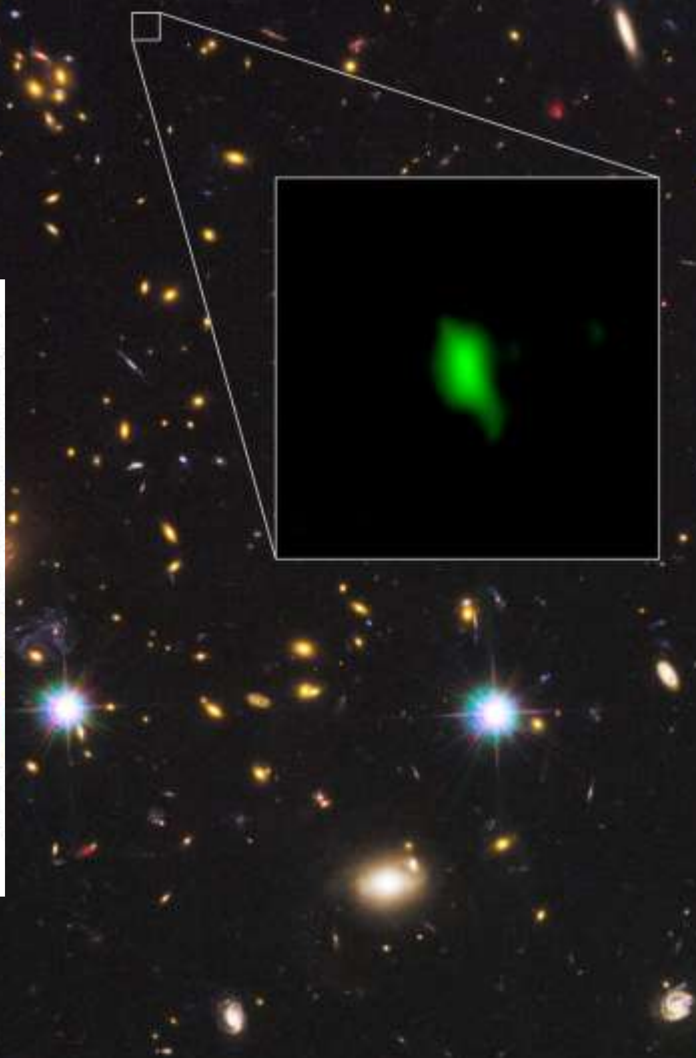
High Angular Resolution

THz Atmosphere

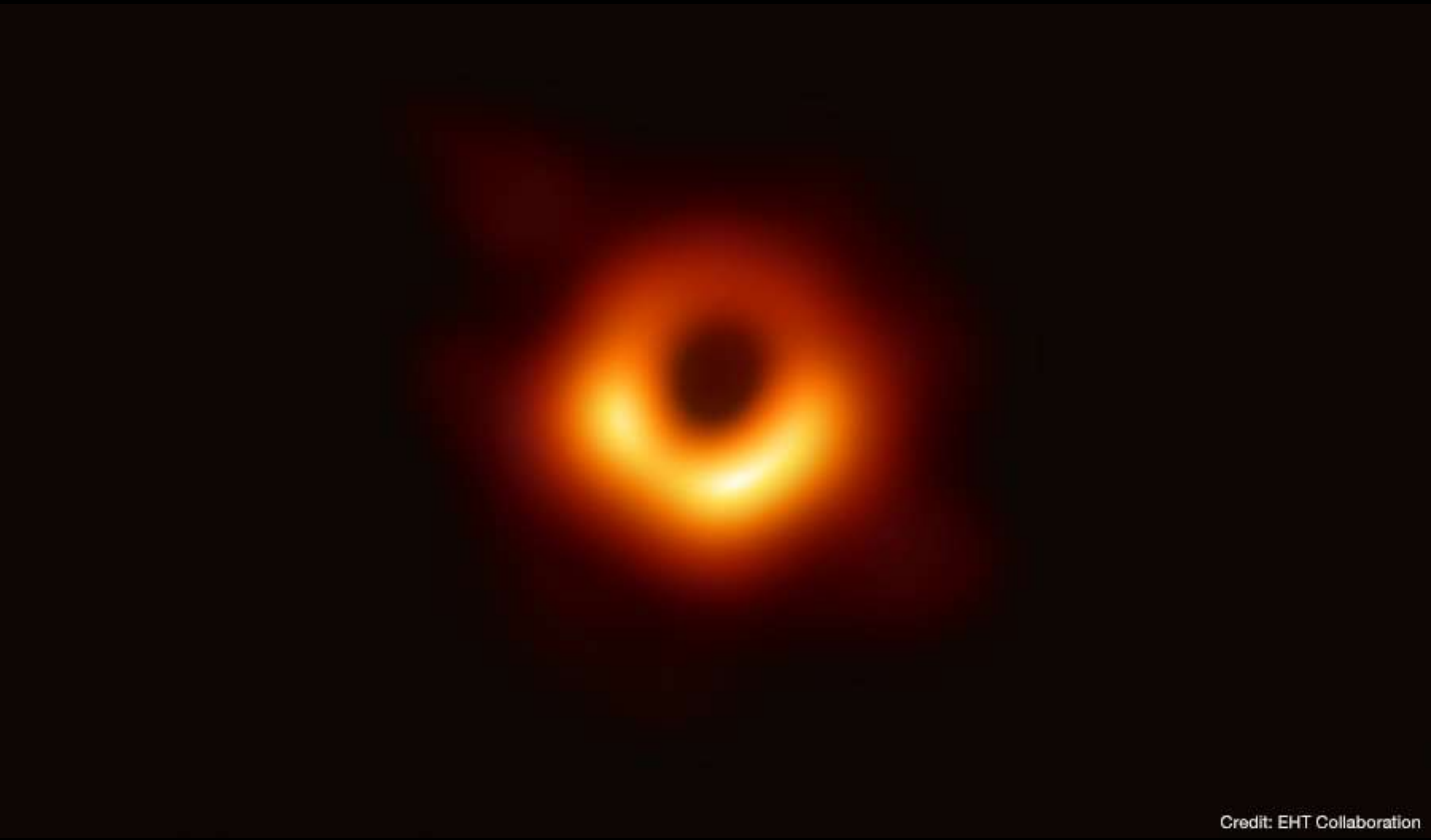
Intensity Interferometry

The Most Distant z=9.11 Spectroscopic Identification with [OIII] 88 μm





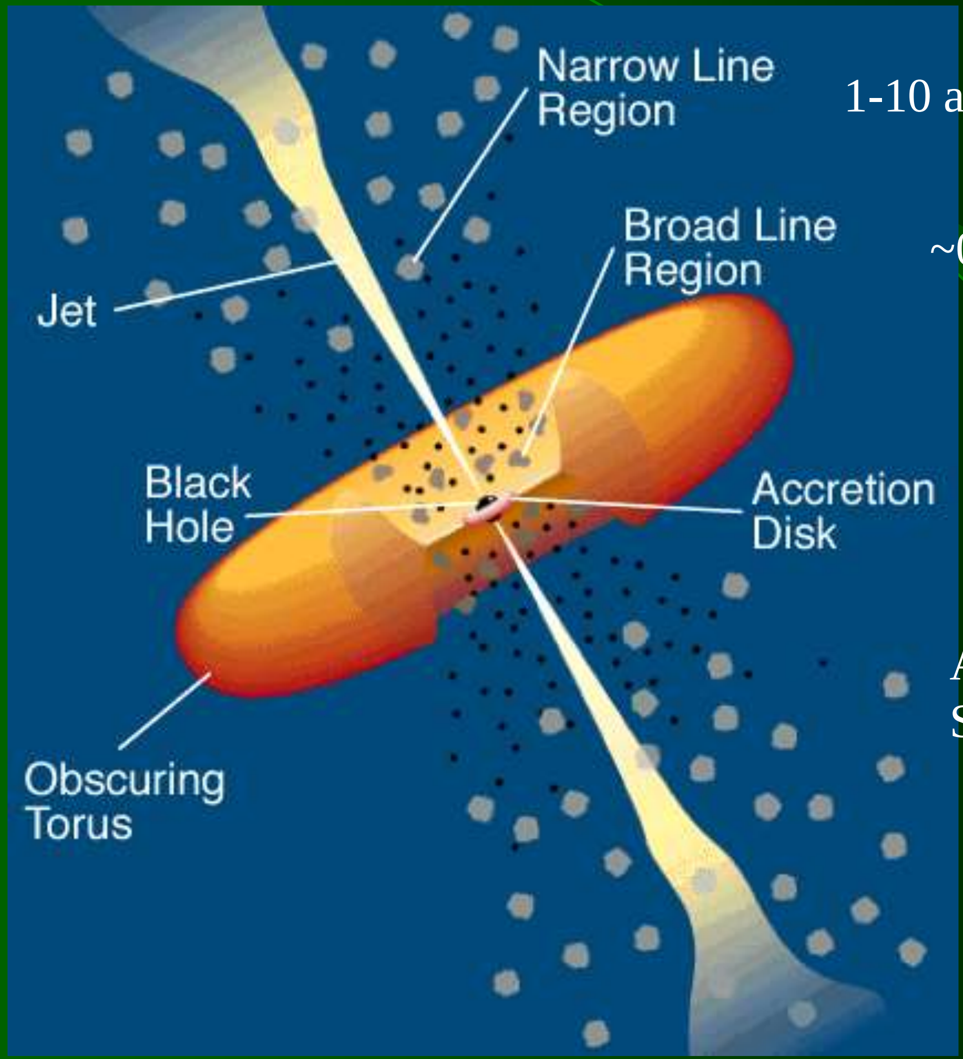
Hashimoto et al., Nature (2018)


Credit: EHT Collaboration

Structure of an AGN

1-10 arcsec

~0.01 arcsec



~0.001 arcsec

Angular Scales for 16 Mpc
Such as NGC1068

~0.1 arcsec

Urry and Padovani (1995)

FIR atomic fine structure lines

		Critical Densities
OI		
– 63.185μm	4.745THz	5.0×10^5 cm^{-3}
– 145.54μm	2.060THz	1.5×10^5 cm^{-3}
OIII 35.1eV		
– 51.815μm	5.786THz	3.4×10^3 cm^{-3}
– 88.356μm	3.393THz	5.0×10^2 cm^{-3}
NII 14.5eV		
– 121.80μm	2.461THz	2.8×10^2 cm^{-3}
– 205.30μm	1.460THz	4.5×10^1 cm^{-3}
NIII 29.6eV		
– 57.330μm	5.229THz	3×10^3 cm^{-3}
CII 11.3eV		
– 157.68μm	1.901THz	2.7×10^3 cm^{-3}

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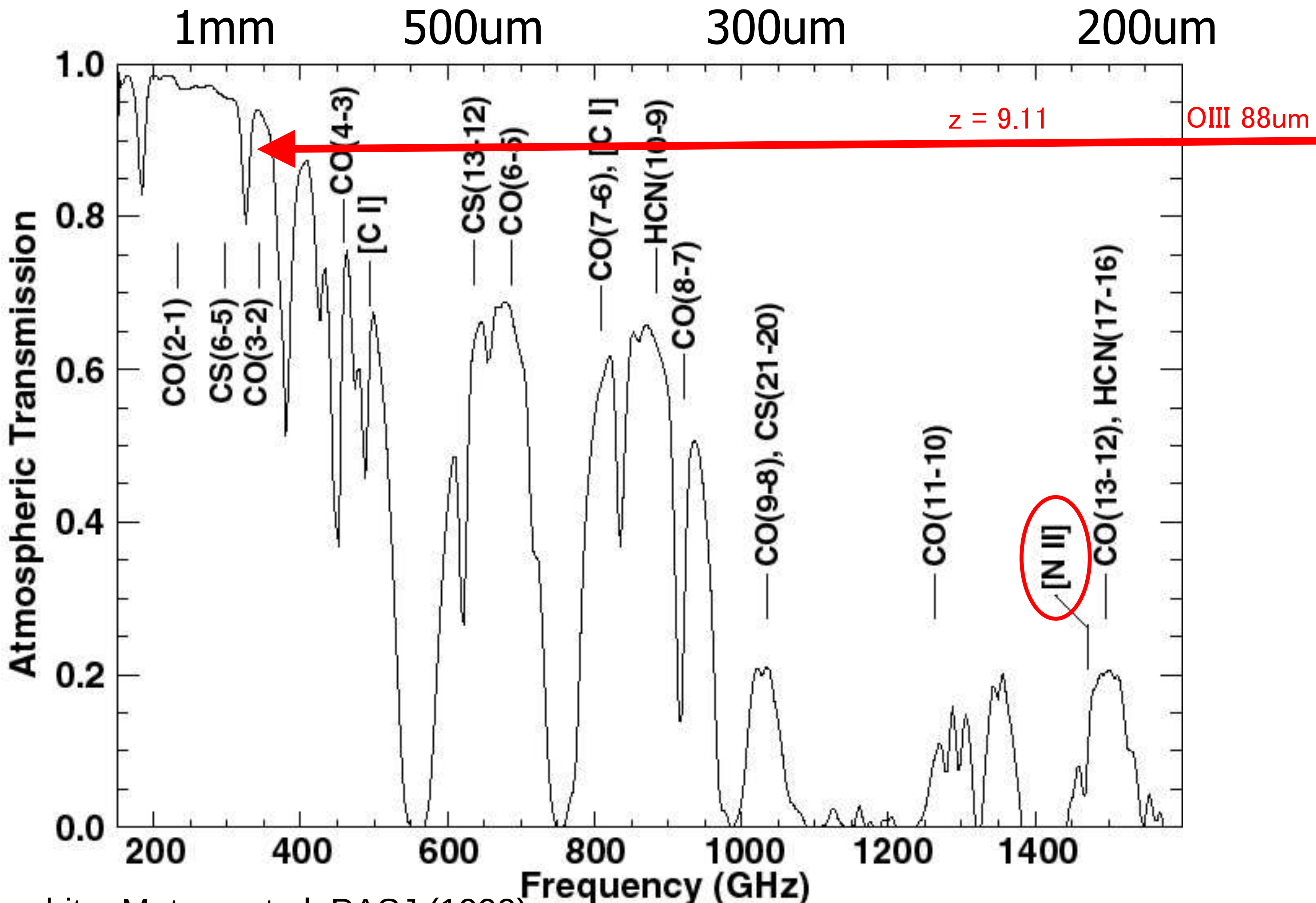
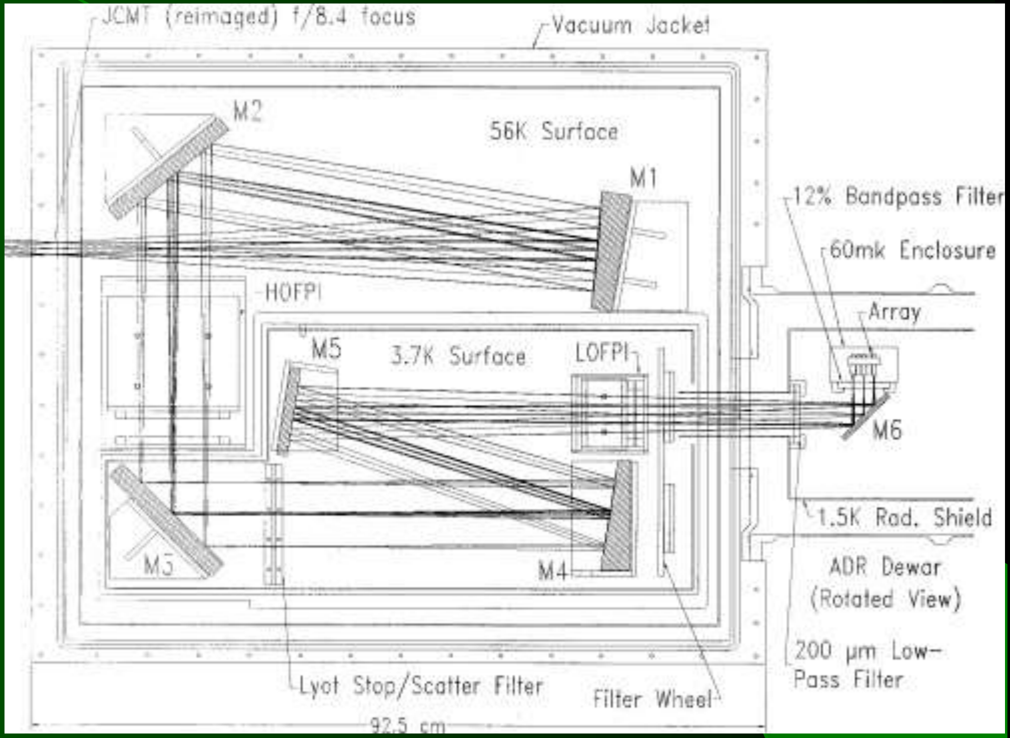
Atmospheric Windows from Atacama（alt. 4800m）



Matsushita, Matsuo et al. PASJ (1999)

AST/RO

SPIFI

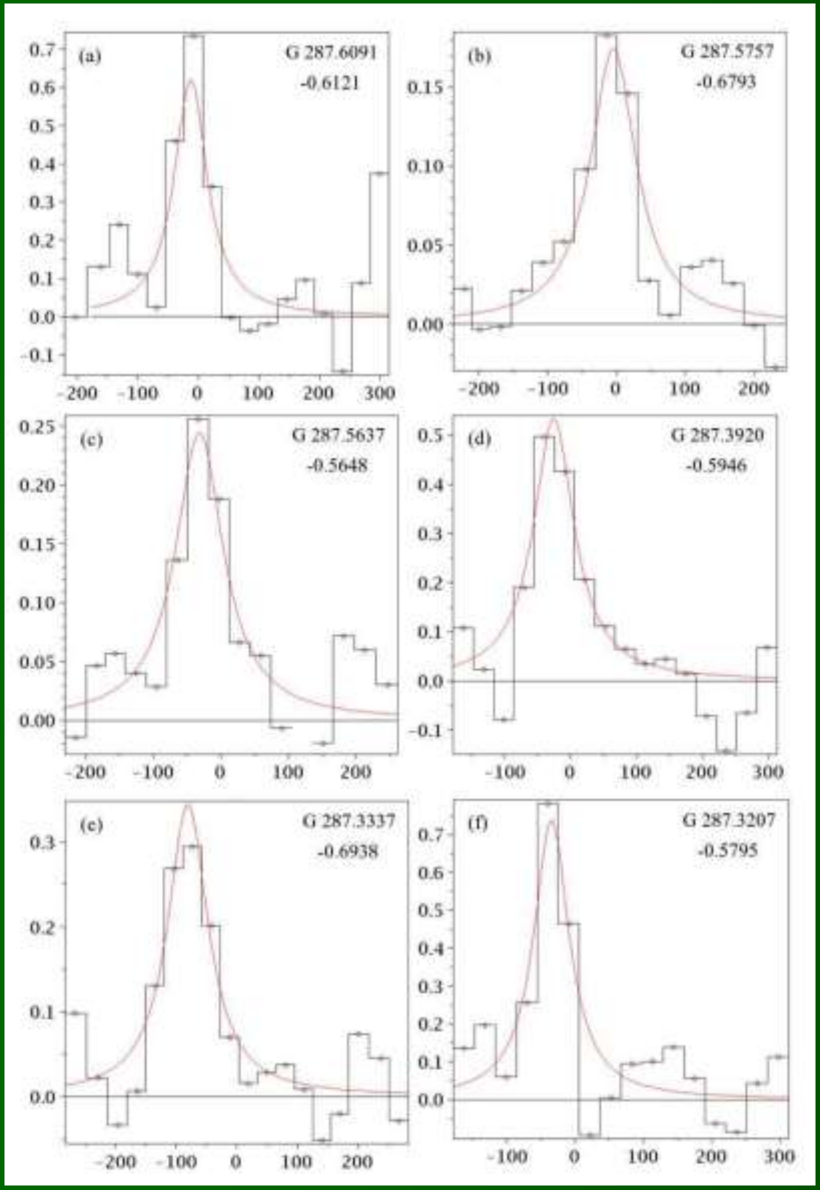


Fabry-Perot Spectrometer

5x5 bolometer array

From the submillimeter astronomy group, Cornell University

[NII] 205 μm from South Pole



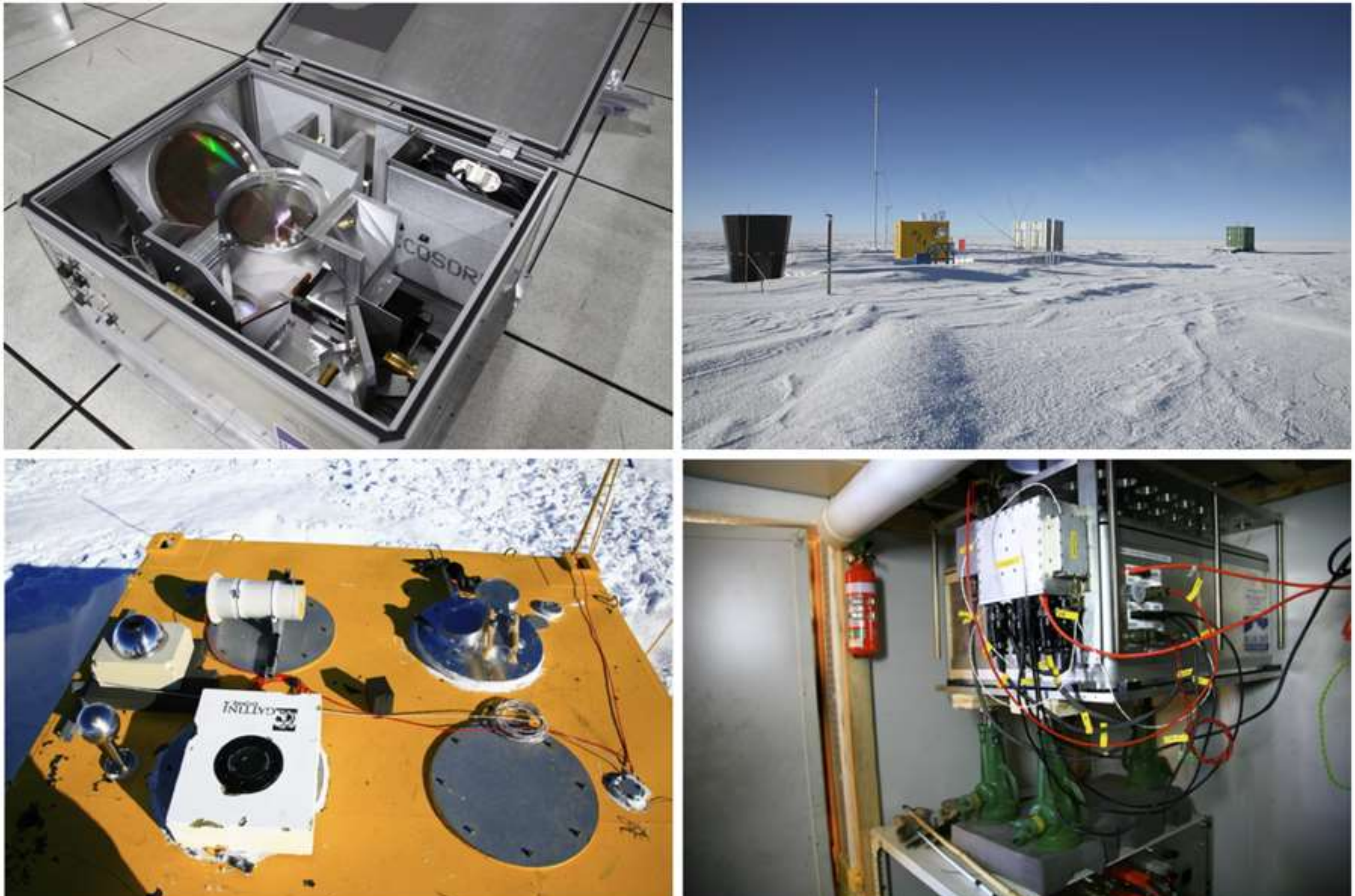
Atmospheric Transmission only 3-6 %

Obserst et al. (2011)

Figure 2.6: Select Detections of the 205 μm [NII] Spectral Line

Spectra in the vicinity of Car II are shown in panels (a), (b), and (c) (SPIFI Car II raster positions 32, 37, and 61, respectively), and spectra in the vicinity of Car I are shown in panels (d), (e), and (f) (SPIFI Car I raster positions 29, 45, and 73, respectively). The x-axes give the source velocity relative to the Local Standard of Rest (LRS) in units of [km s^{-1}], and the y-axes give the main beam brightness temperature in units of [K]. (The conversion between these units and those of Tables 2.4 and 2.5 is given by Equation 2.8). The (black) data points and bars mark the processed data, and the (red) smooth lines are the least χ^2 Lorentzian fits. The data have been smoothed with a Hann window.

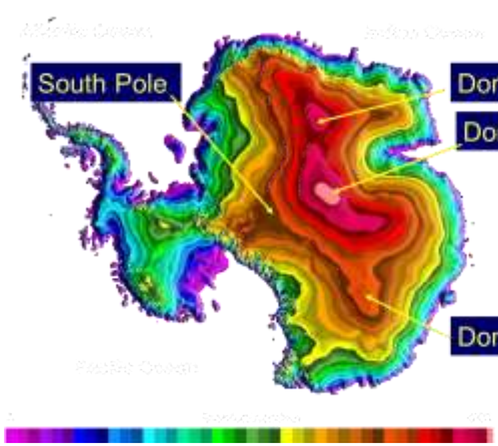
FTS in Dome A, Antarctica

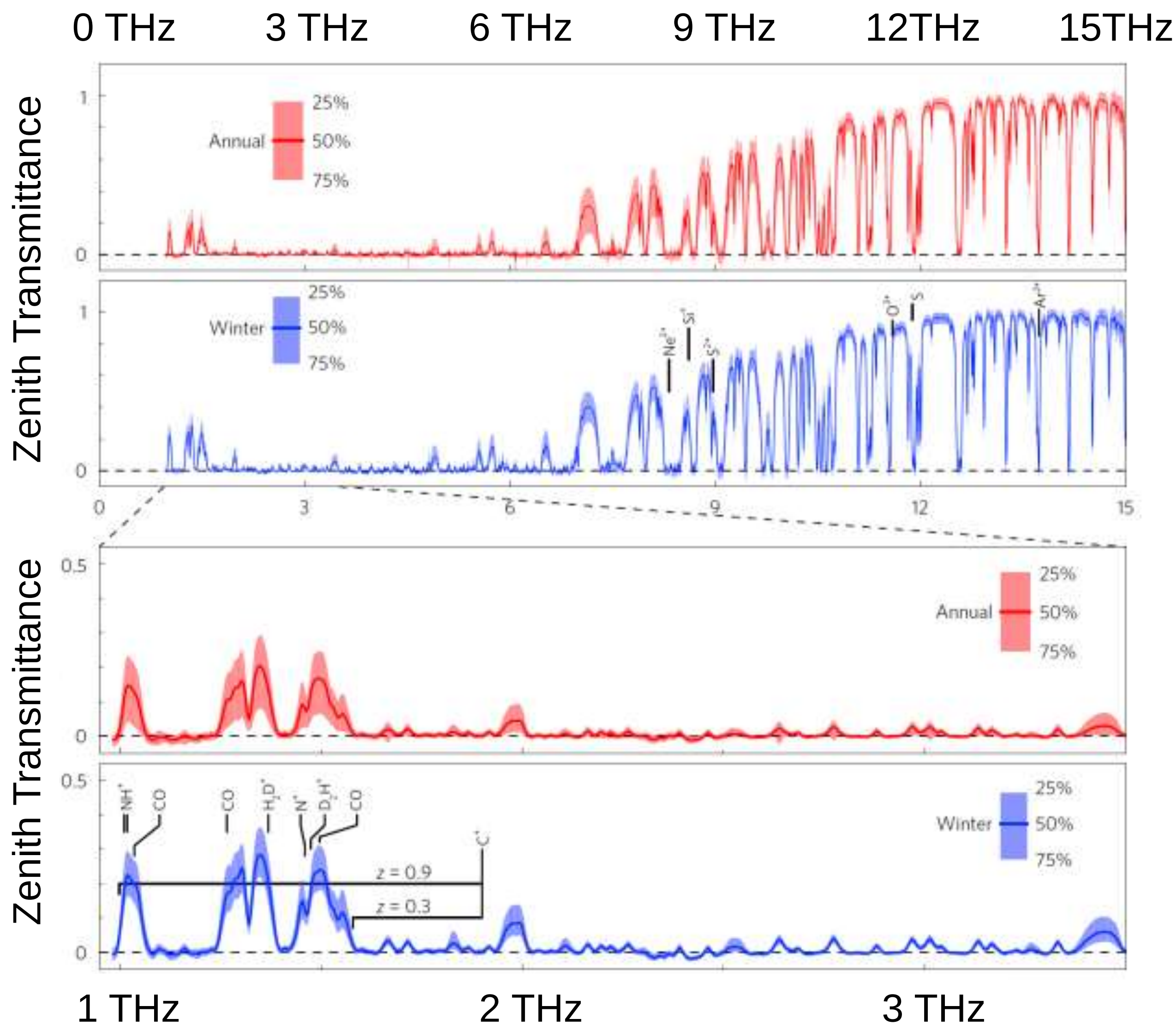


Terahertz and far-infrared windows opened at Dome A in Antarctica

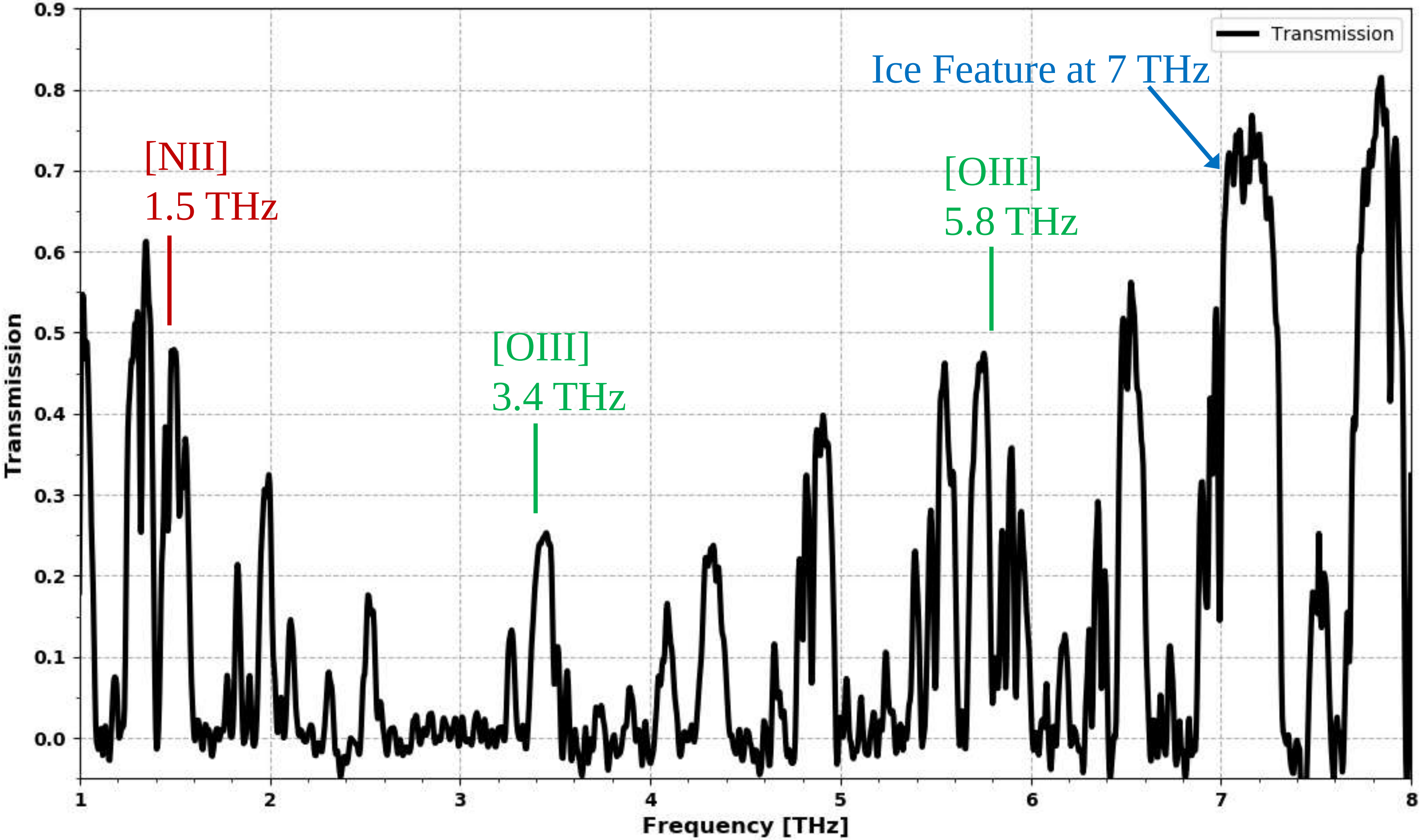
Annual and winter (April-September) transmittance spectra measured at Dome A during 2010-11.

Shi et al.
Nature Astronomy (2016)





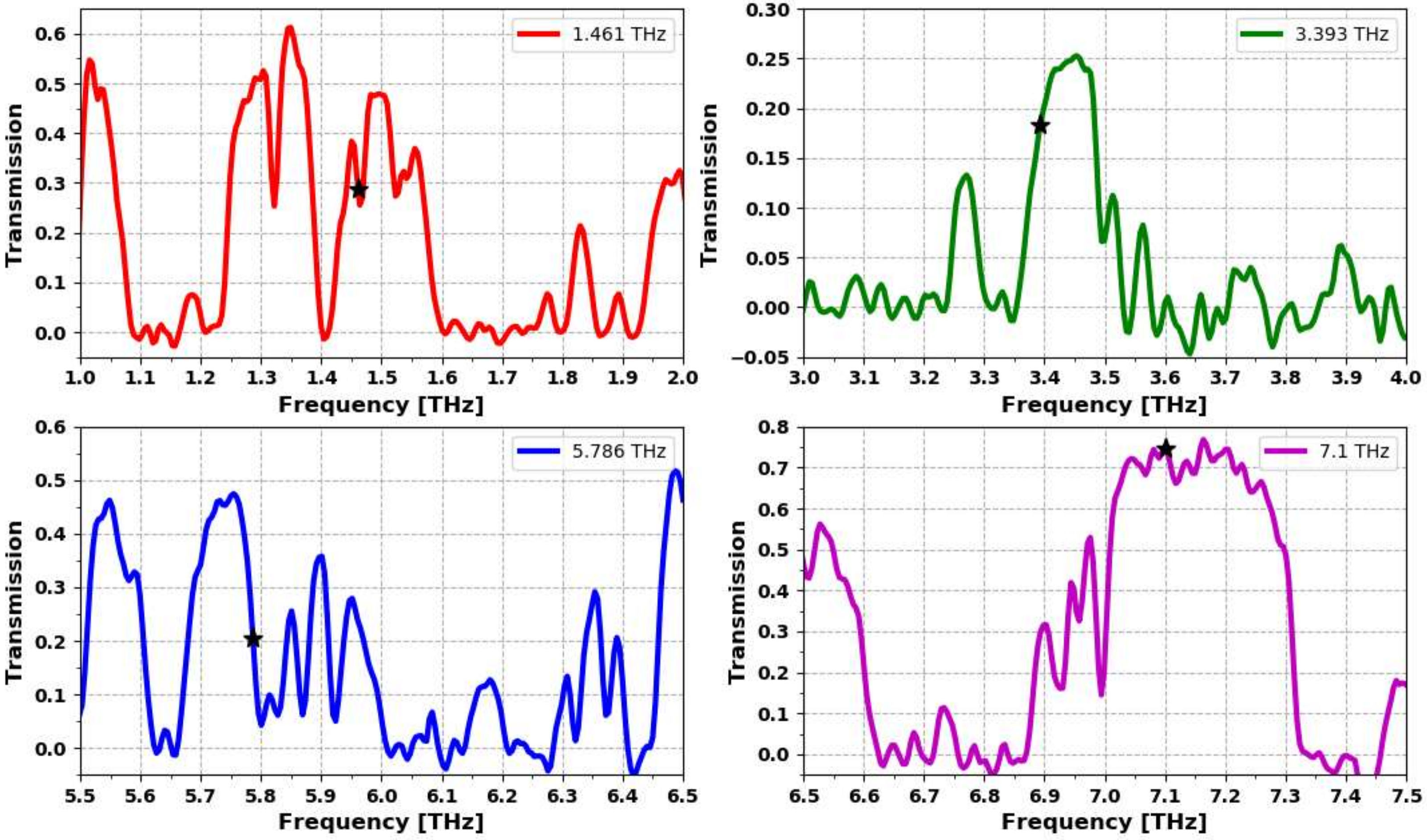
The Most Transparent Atmosphere



August 9th 12–18h UTC, 2010

Matsuo et al. APS (2019)

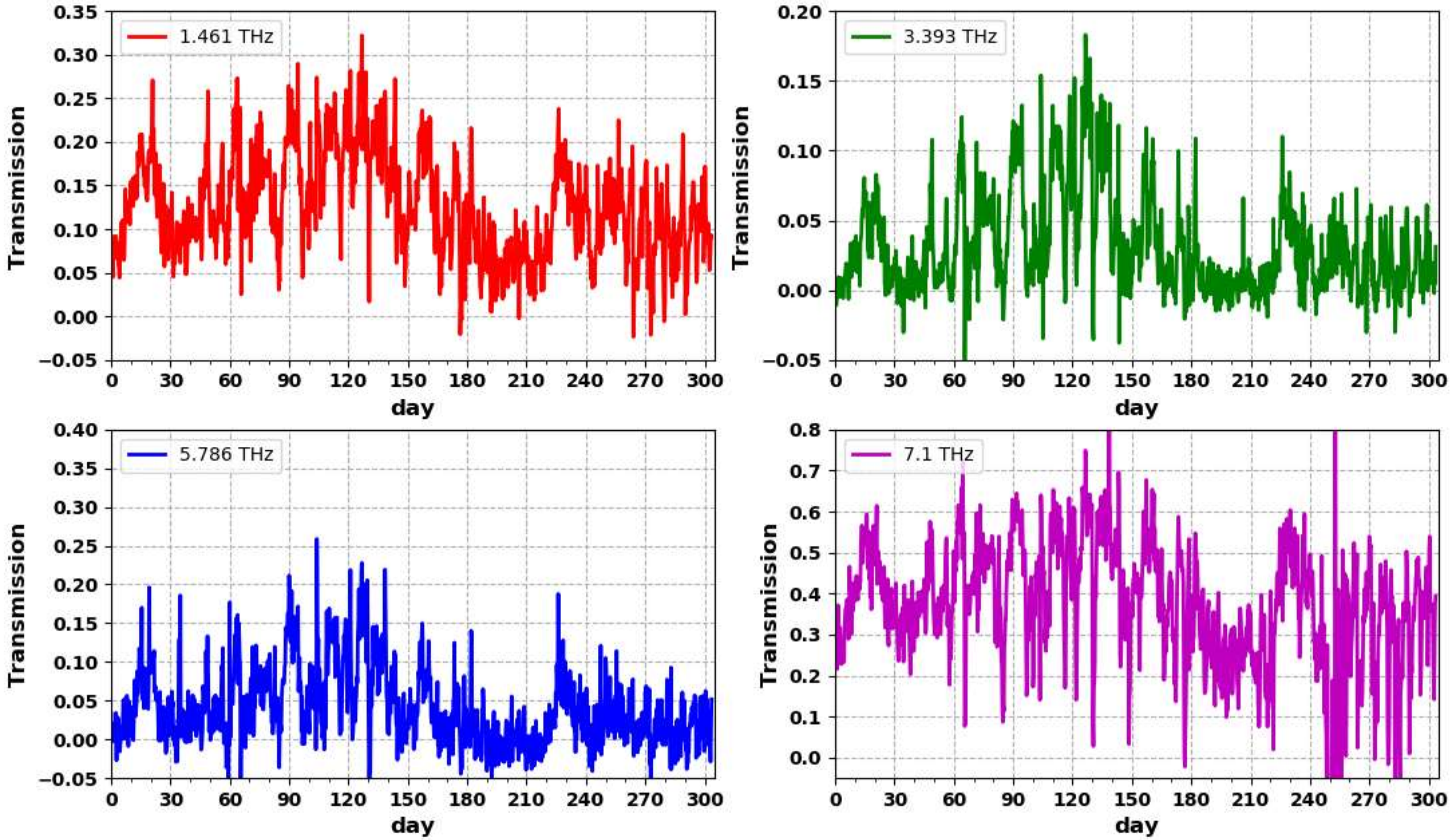
Windows for [NII], [OIII] and Ice Feature



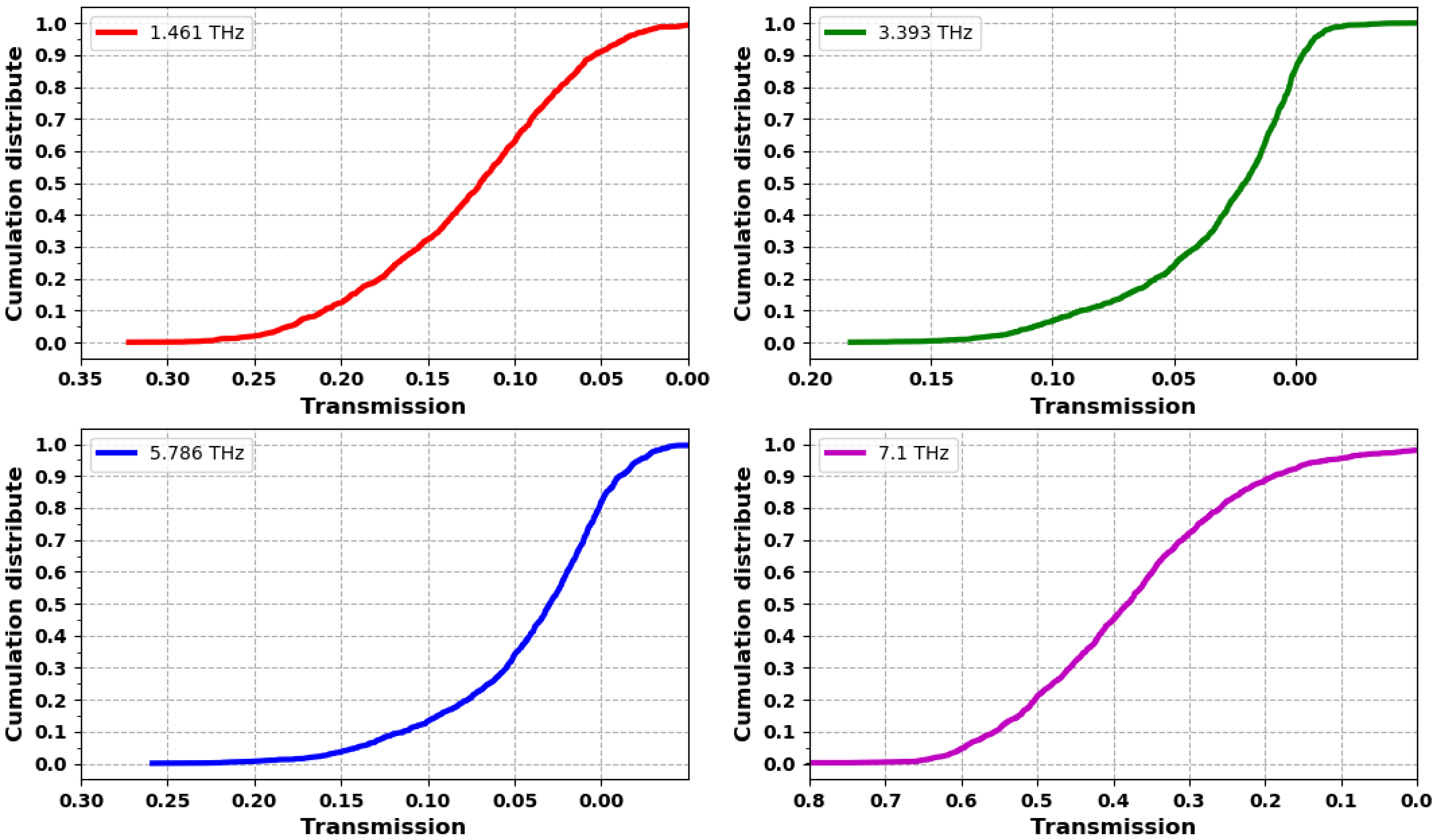
August 9th 12–18h UTC, 2010

Matsuo et al. APS in press

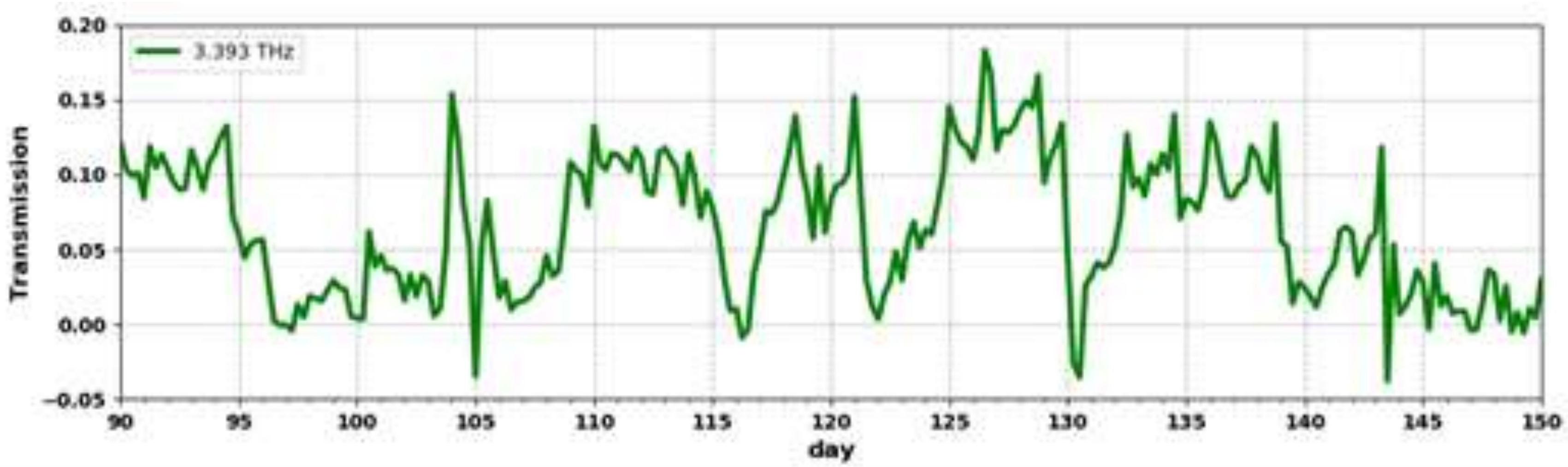
Transmission at 4 windows



Cumulative Analysis (Apr.-Sep.)



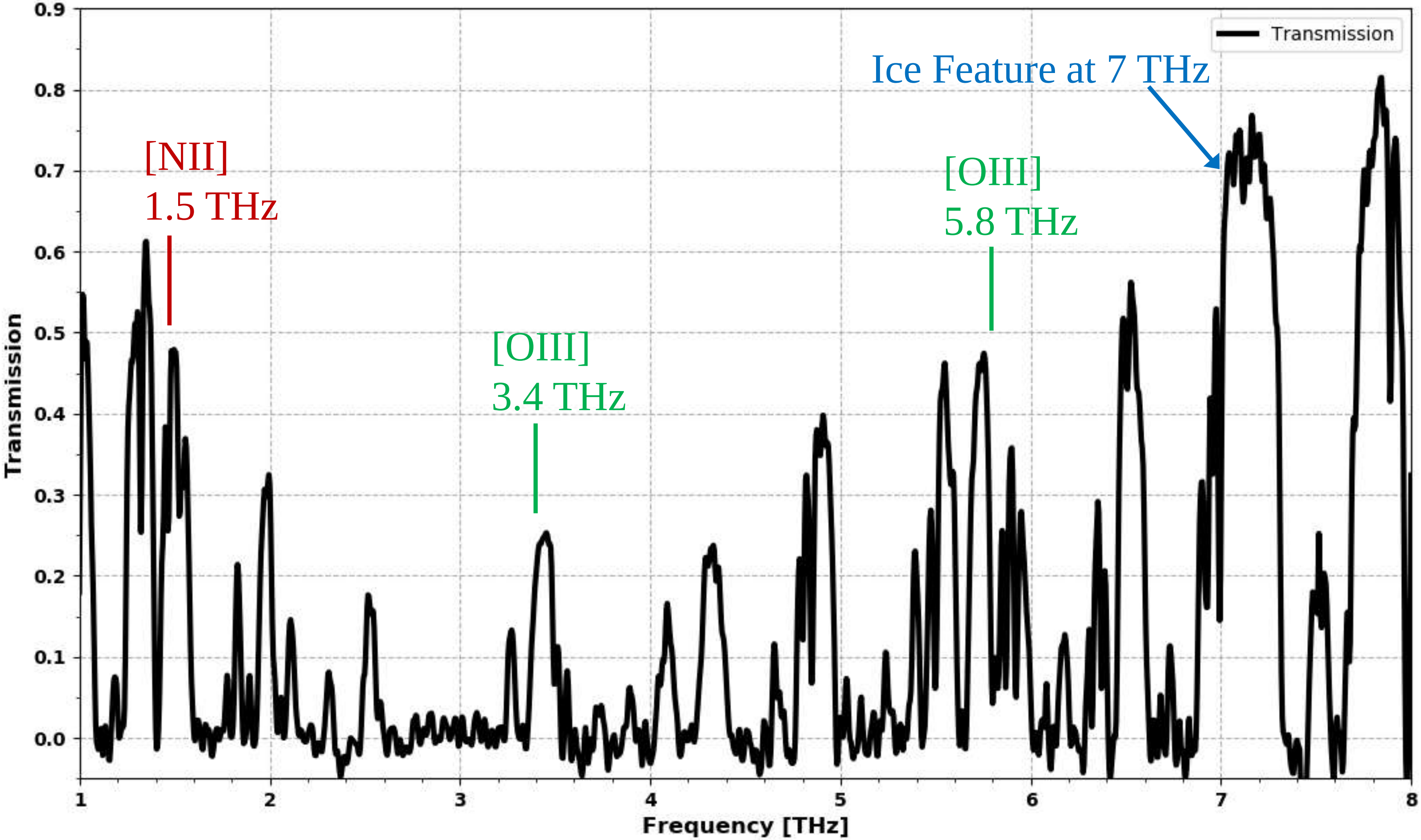
Can we observe [OIII] 88 μm at 3.393 THz ?



in July - August, 2010

Matsuo et al. APS in press

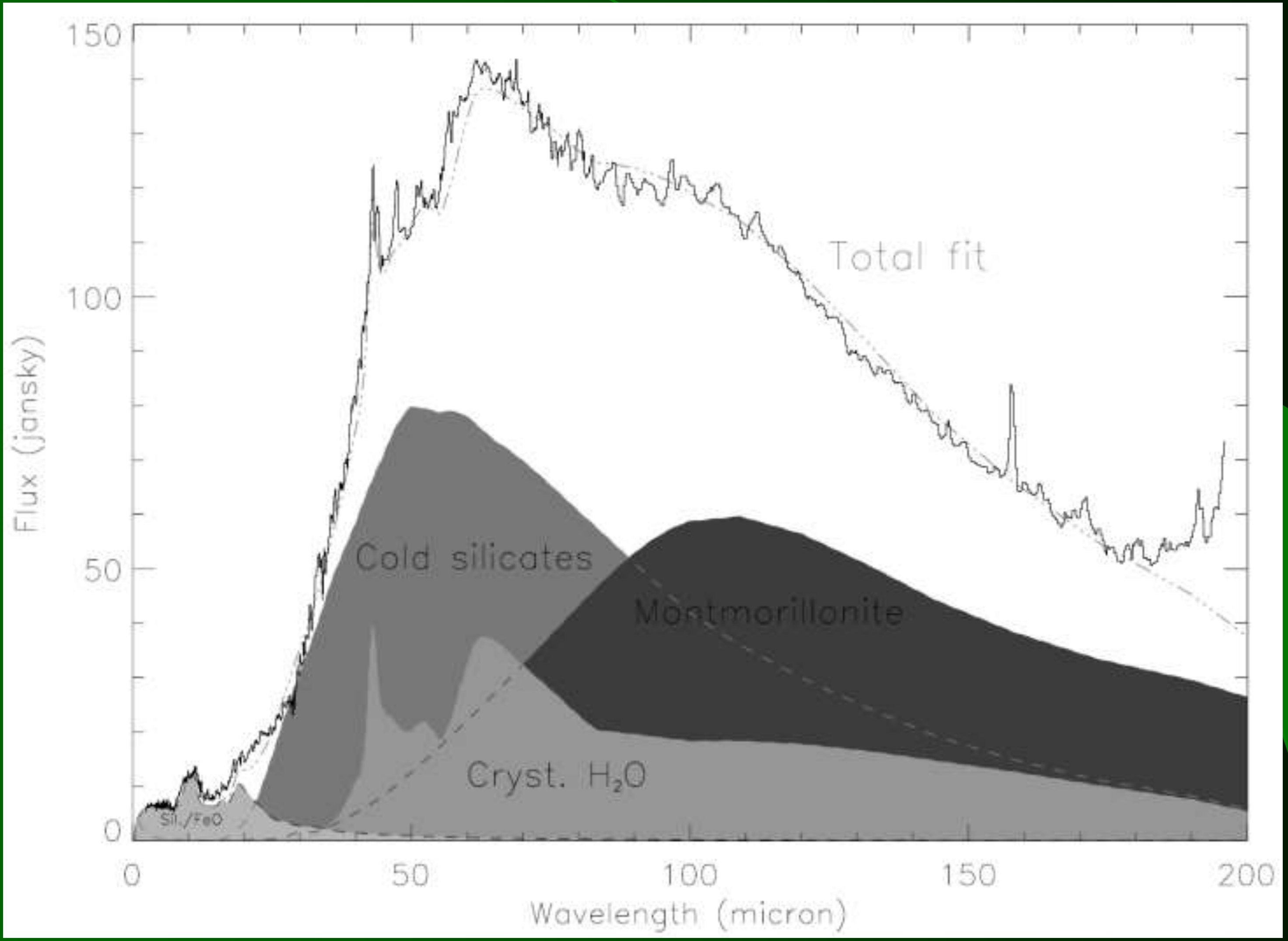
The Most Transparent Atmosphere



August 9th 12–18h UTC, 2010

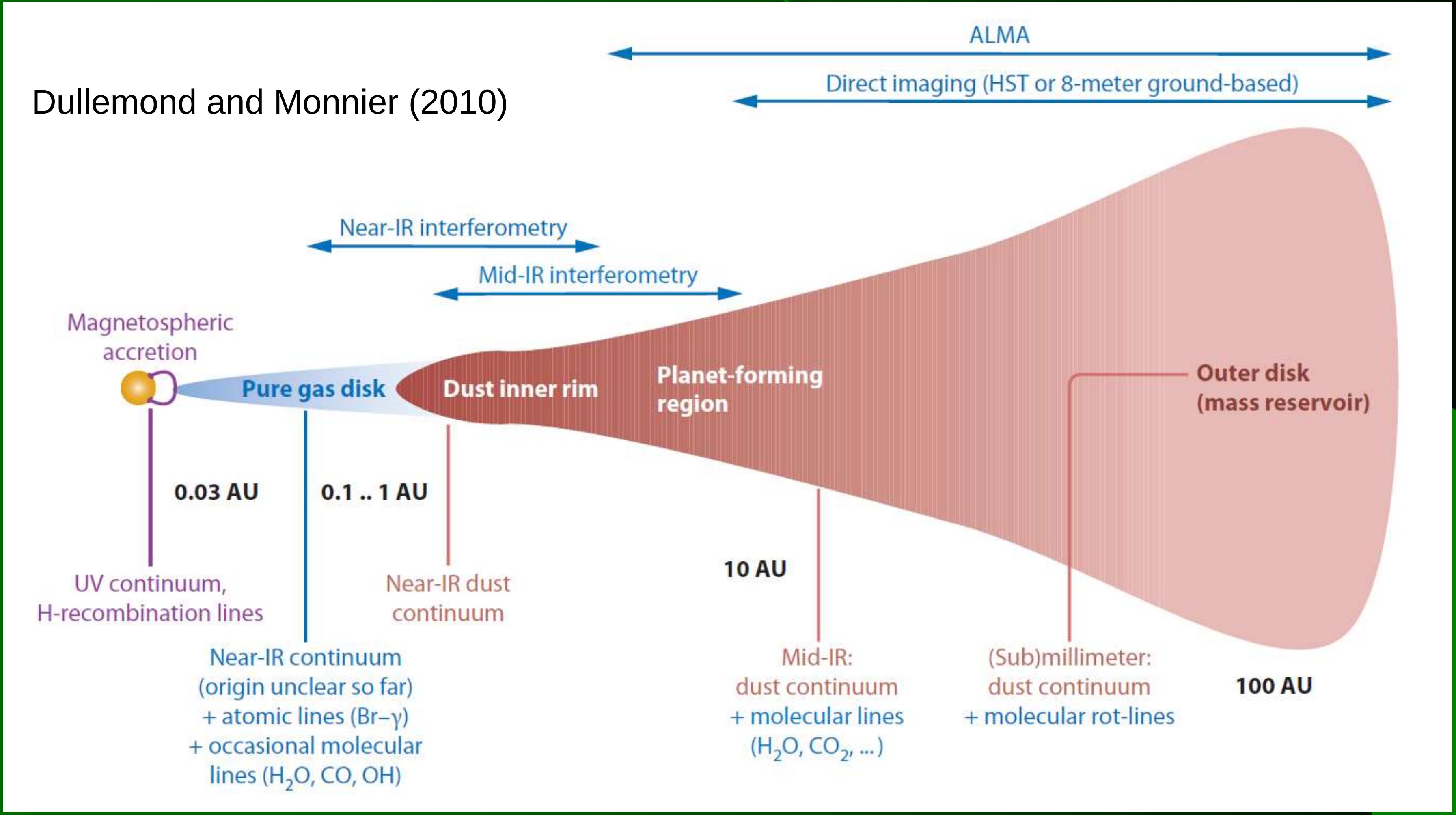
Matsuo et al. APS (2019)

Water ice feature of HD142527 by ISO



Malfait et al. (1999)

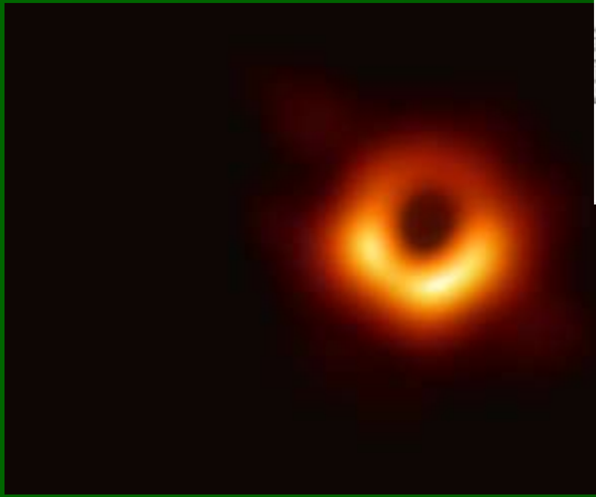
Structure of a protoplanetary disk



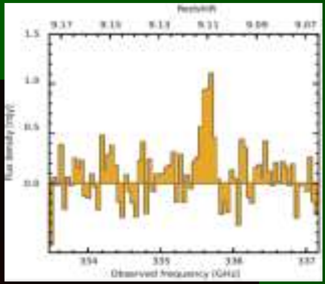
Scales are for Taurus and Auriga region

Heterodyne or Intensity ?

- Start with heterodyne interferometry
  - Shorter baselines, [NII]
- Challenge with intensity interferometry
  - Longer baselines, [OIII] and water ice feature



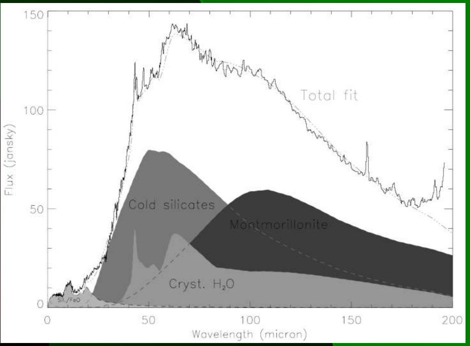
[OIII] 88μm



Hashimoto et al. (2018)

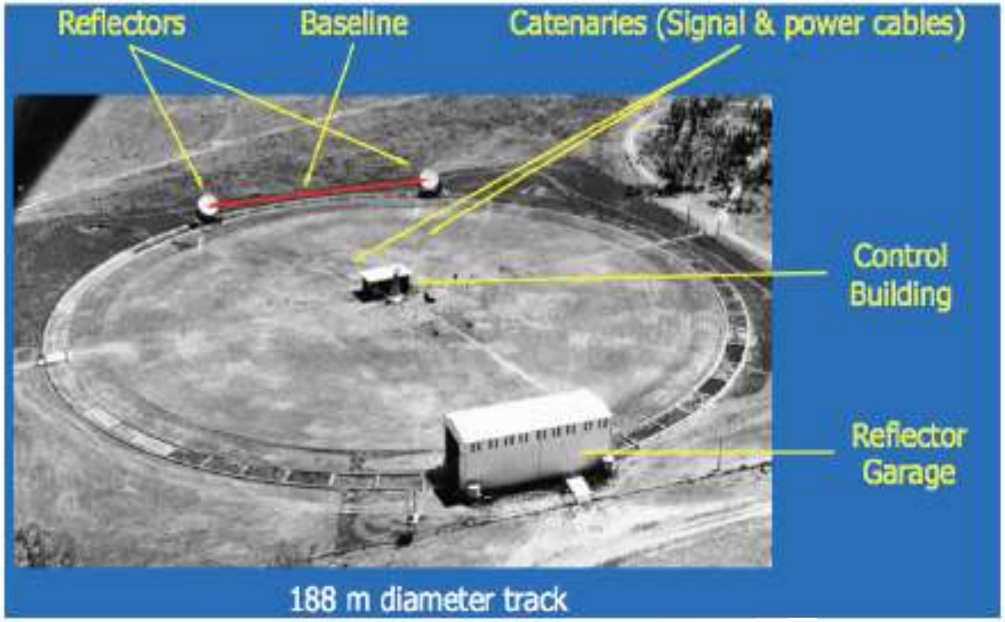
ALMA (ESO/NAOJ/NRAO)

Water ice feature



HD142527
Malfait et al. (1999)

Narrabri Stellar Intensity Interferometer



Narrabri Stellar Interferometer

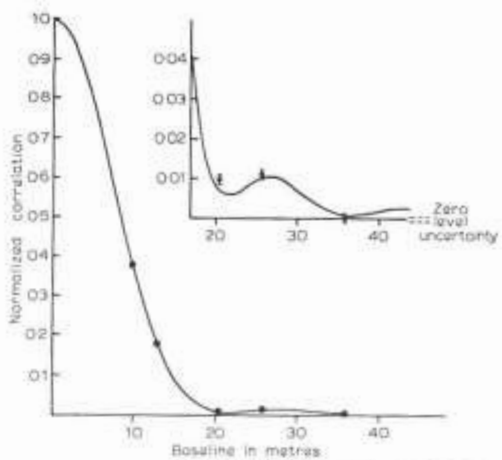
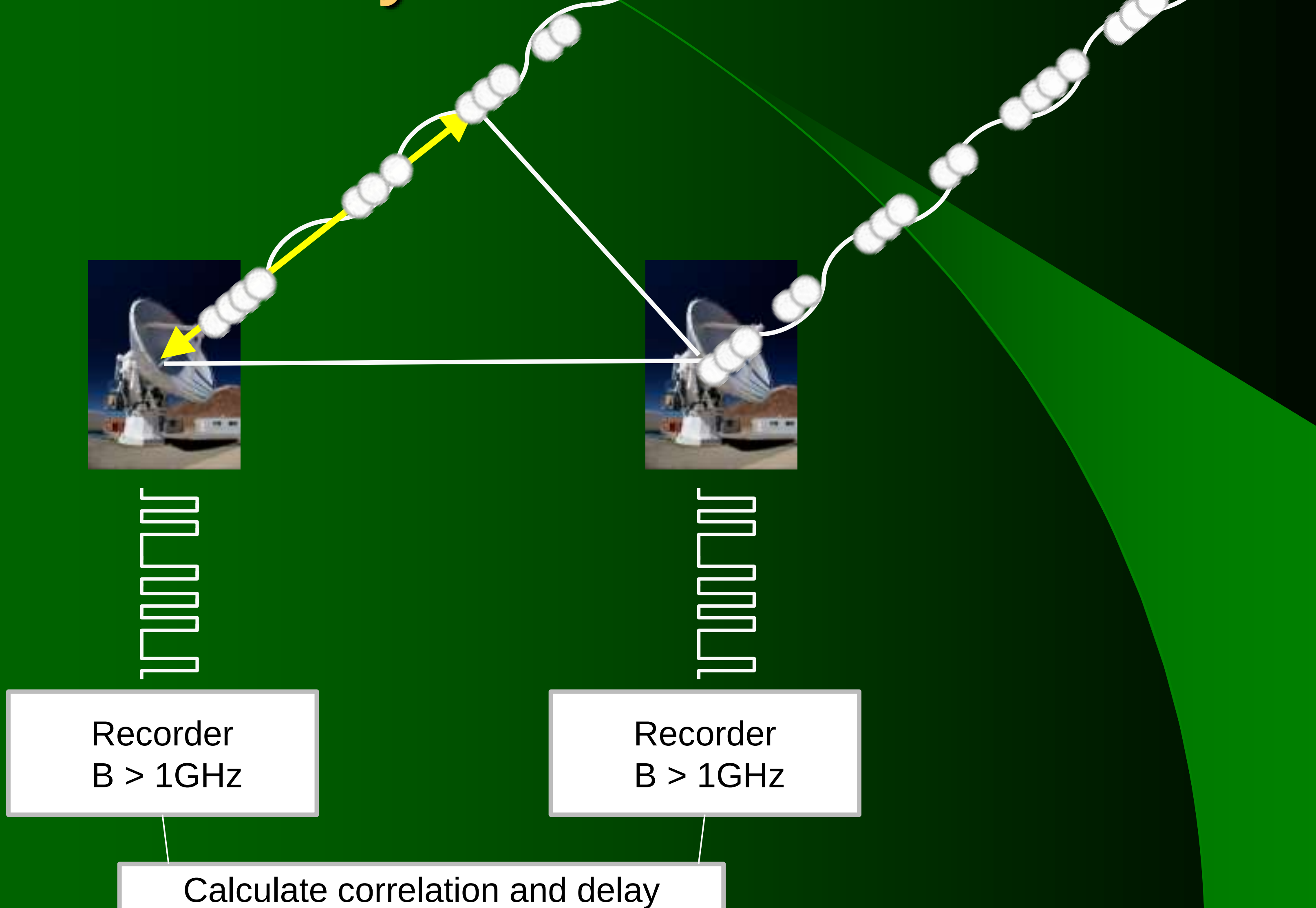


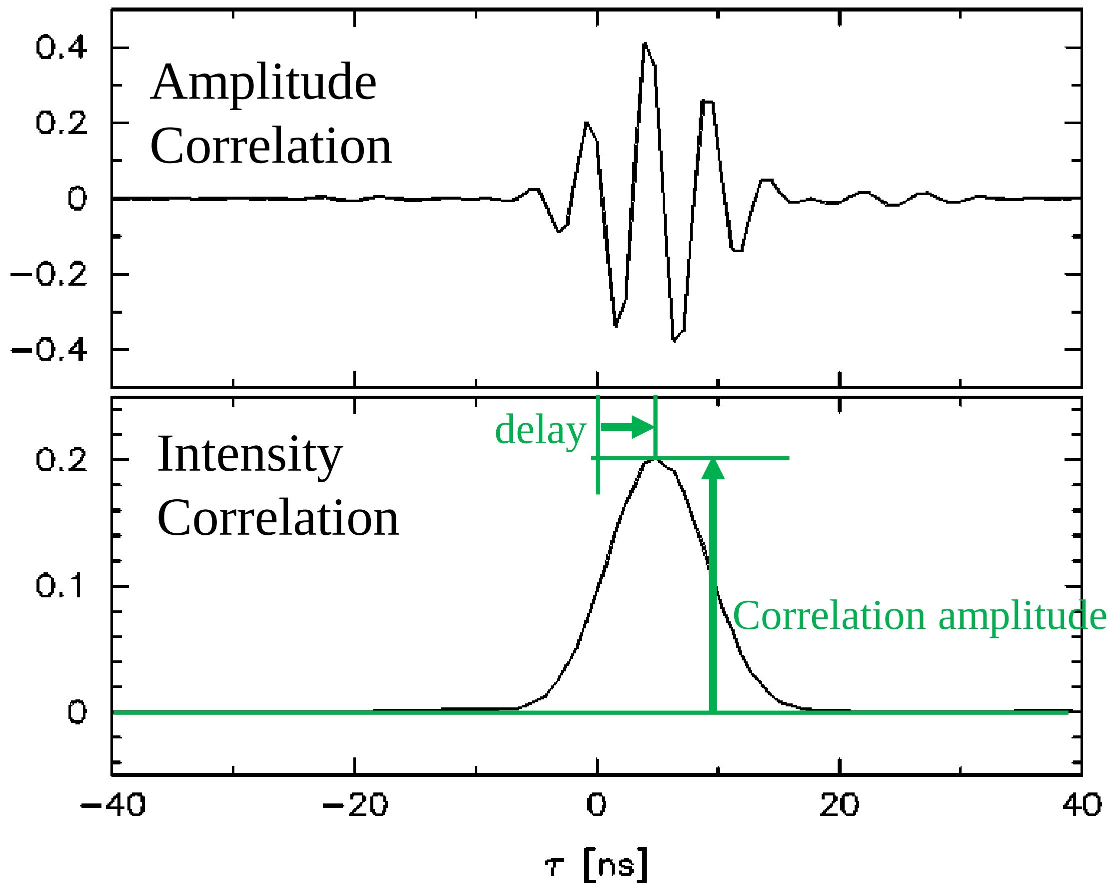
Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model atmosphere ($T_e = 10\,000$ K, $\log g = 4$, $\lambda = 450$ nm). Results for three long baselines are shown on an expanded scale together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

Hanbury-Brown et al. (1974)
Diameter of 32 early-type stars were measured.

Long Baseline Interferometry



Nobeyema Radioheliograph at 17 GHz



Antenna Temperature T_{A}^{*} [K]

System Temperature T_{sys} [K]

Frequency ν [Hz]

Bandwidth $\Delta\nu$ [Hz]

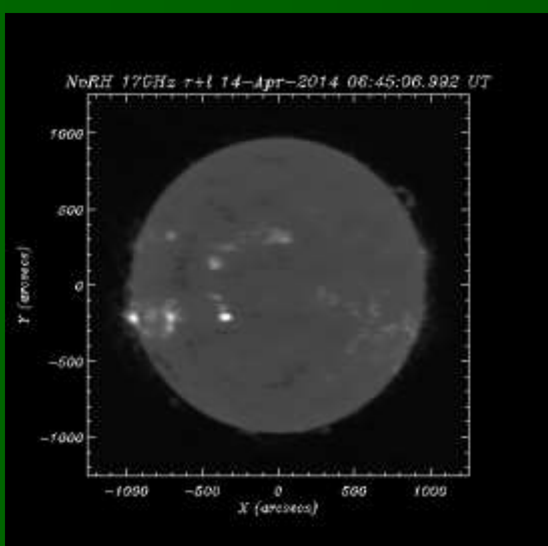
$$\Delta t = \frac{T_{\mathrm{sys}}}{T_{\mathrm{A}}^{*}} \cdot \frac{1}{\sqrt{\Delta\nu \cdot \tau}} \cdot \frac{1}{\Delta\nu} \text{ [s]}$$

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

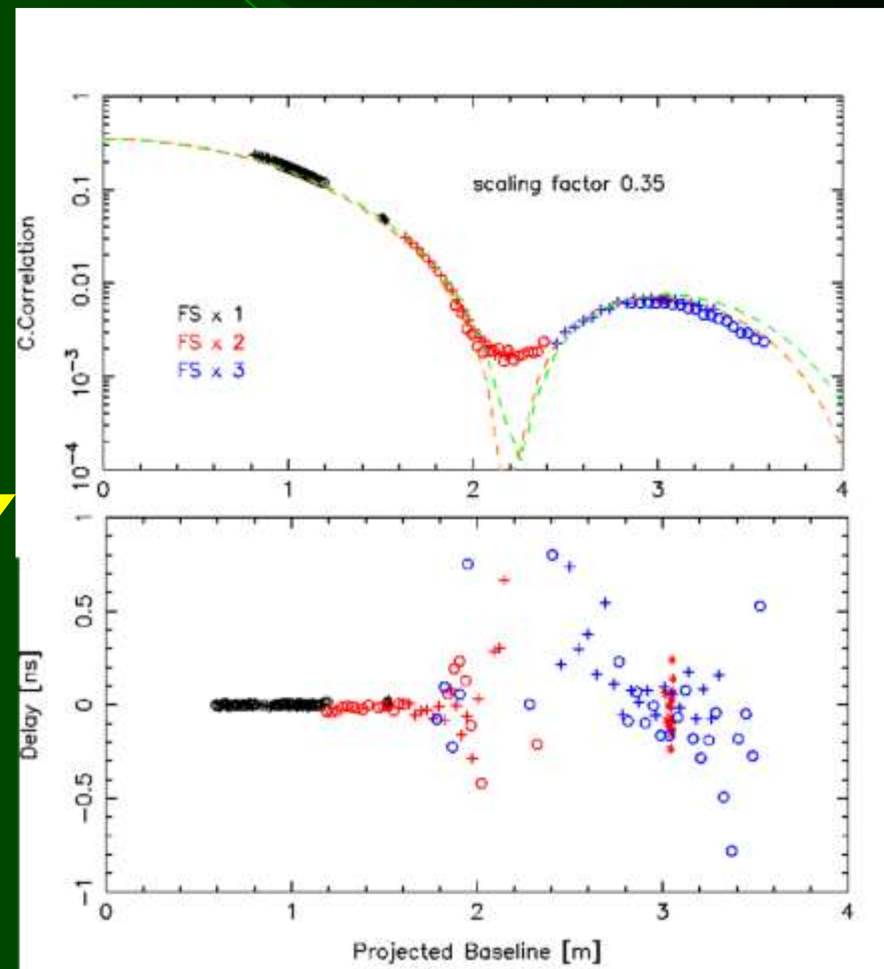
Ezawa, Matsuo et al. (2015)

Experiment at 17 GHz with Nobeyama Radioheligraph

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



Van Cittert
Zernike

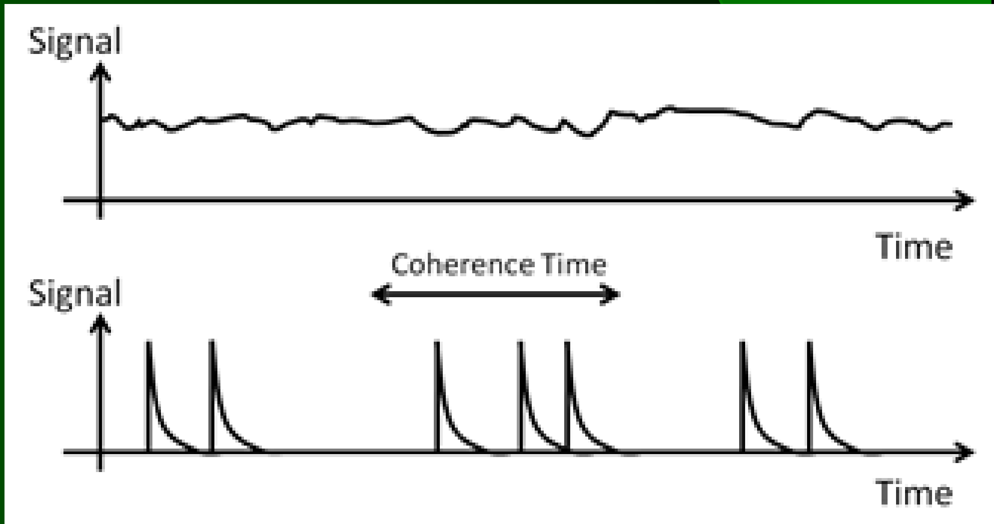


Requirements to Detectors

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

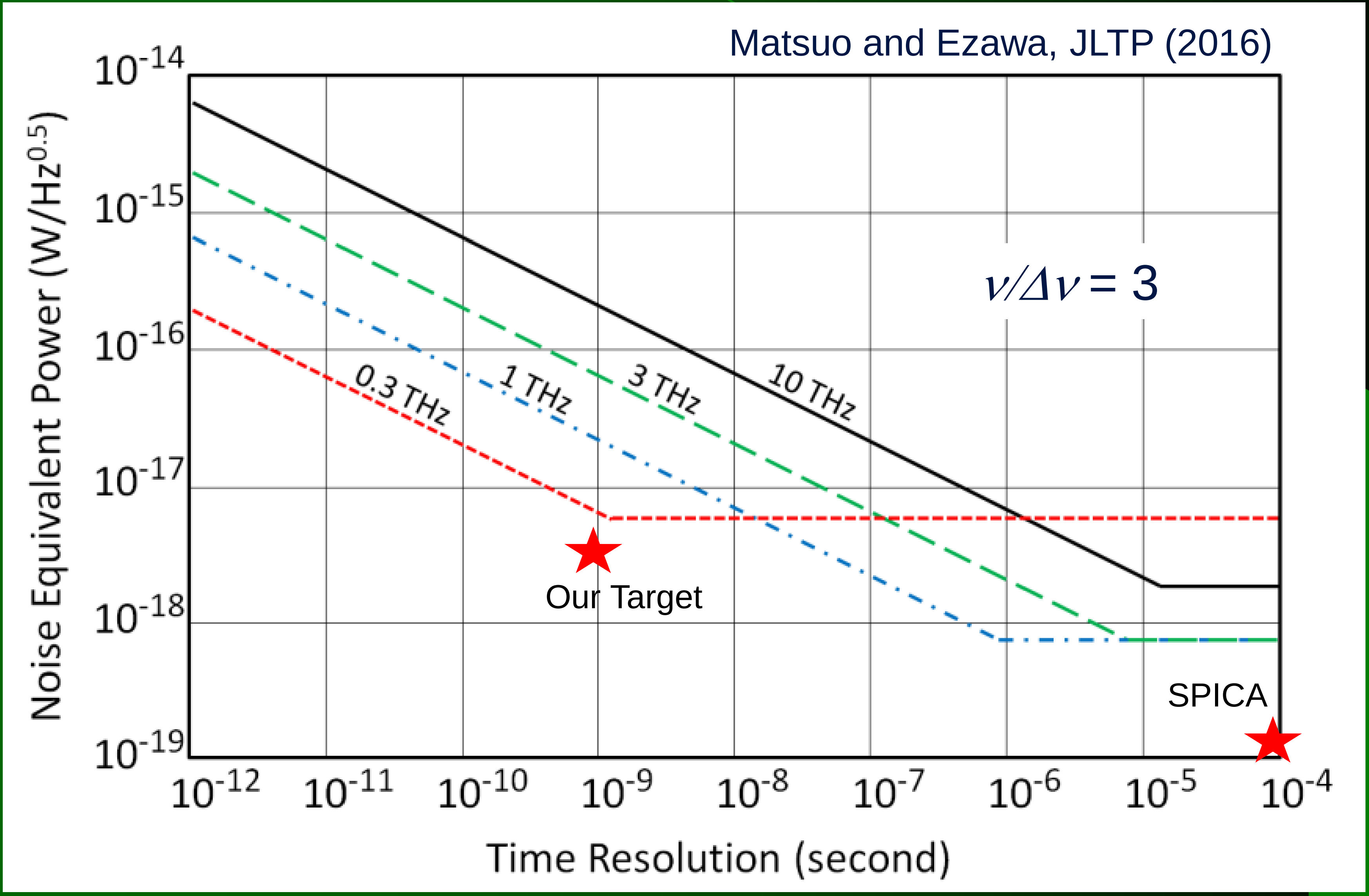
$10^{-21} \times (1\ \text{GHz})^{0.5}$

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



NEP for photon counting vs. time resolution

$\mathrm{NEP} = h\nu/\sqrt{\tau}$



SIS Photon Detectors

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

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

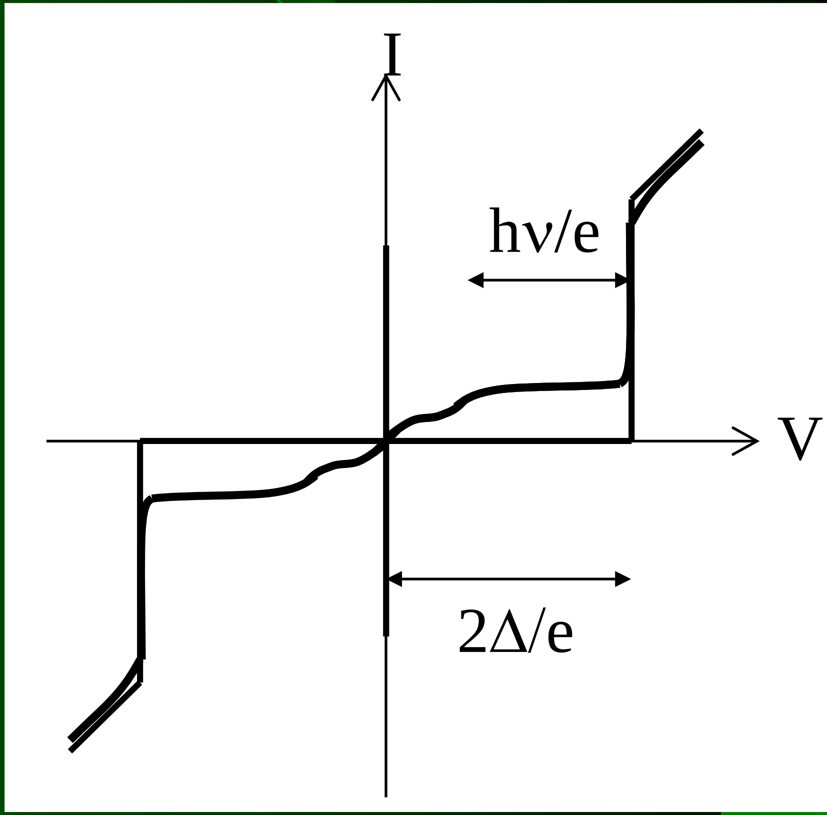
$$NEP = \frac{h\nu}{\eta} \cdot \sqrt{\frac{2I_0}{e}} \quad [\text{W}/\sqrt{\text{Hz}}]$$

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

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

at 650 GHz

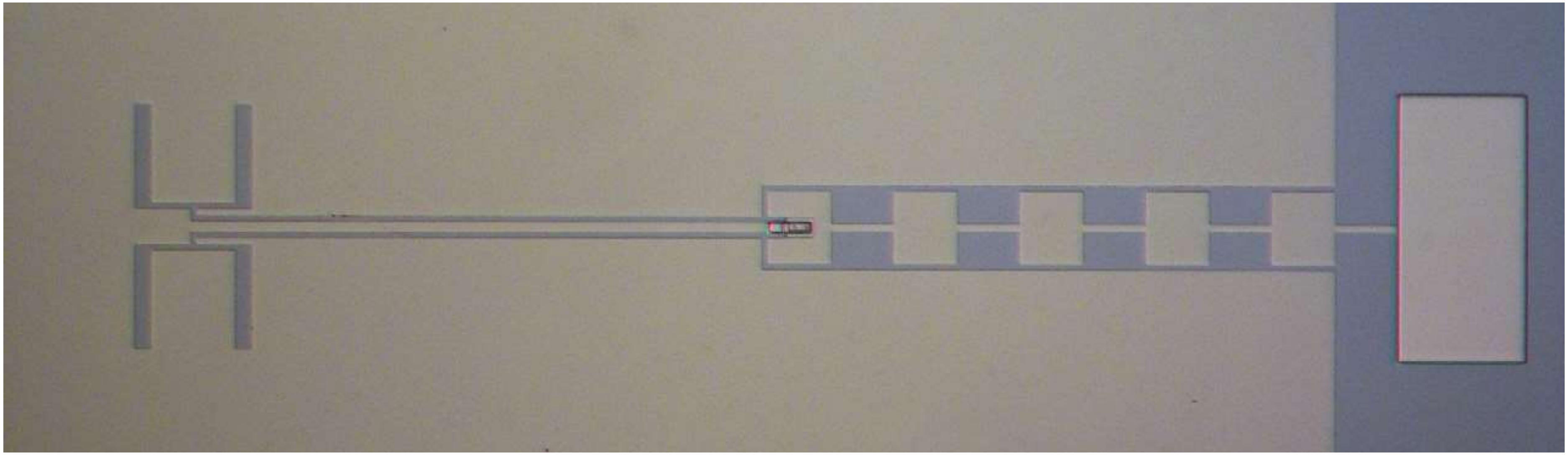
Photon Assisted Tunneling



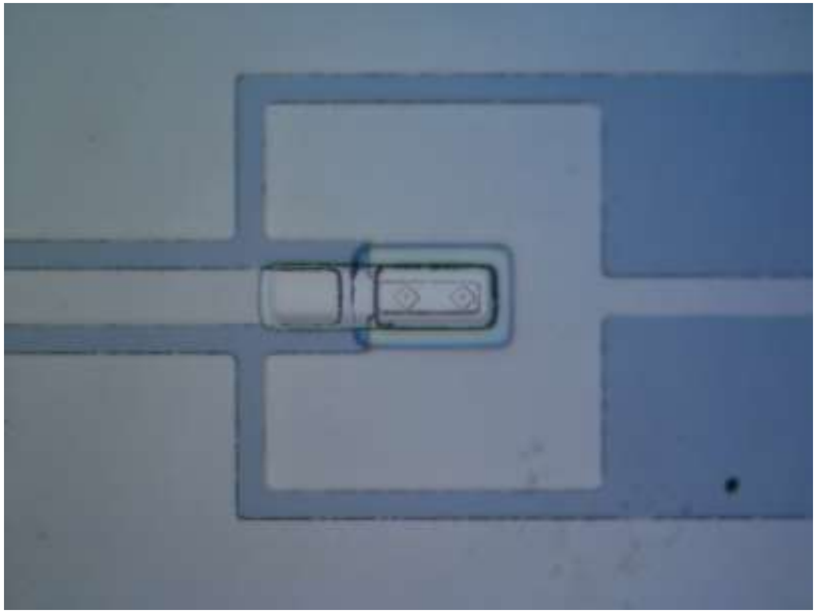
Design Parameters

- Nb-SIS 3×3 μm^2 with J_c= 300 A/cm^2
- $R_n \sim 100\ \Omega$
  - $\omega R_n C_j \sim 150$ at 500 GHz
  - $\Delta\nu \sim 3$ GHz
- Parallel Connected Twin Junction
- Twin-slot antenna and 50 Ω CPW
- Readout using low gate leakage transistors
  - GaAs-JFETs

Antenna, CPW, PCTJ, Choke

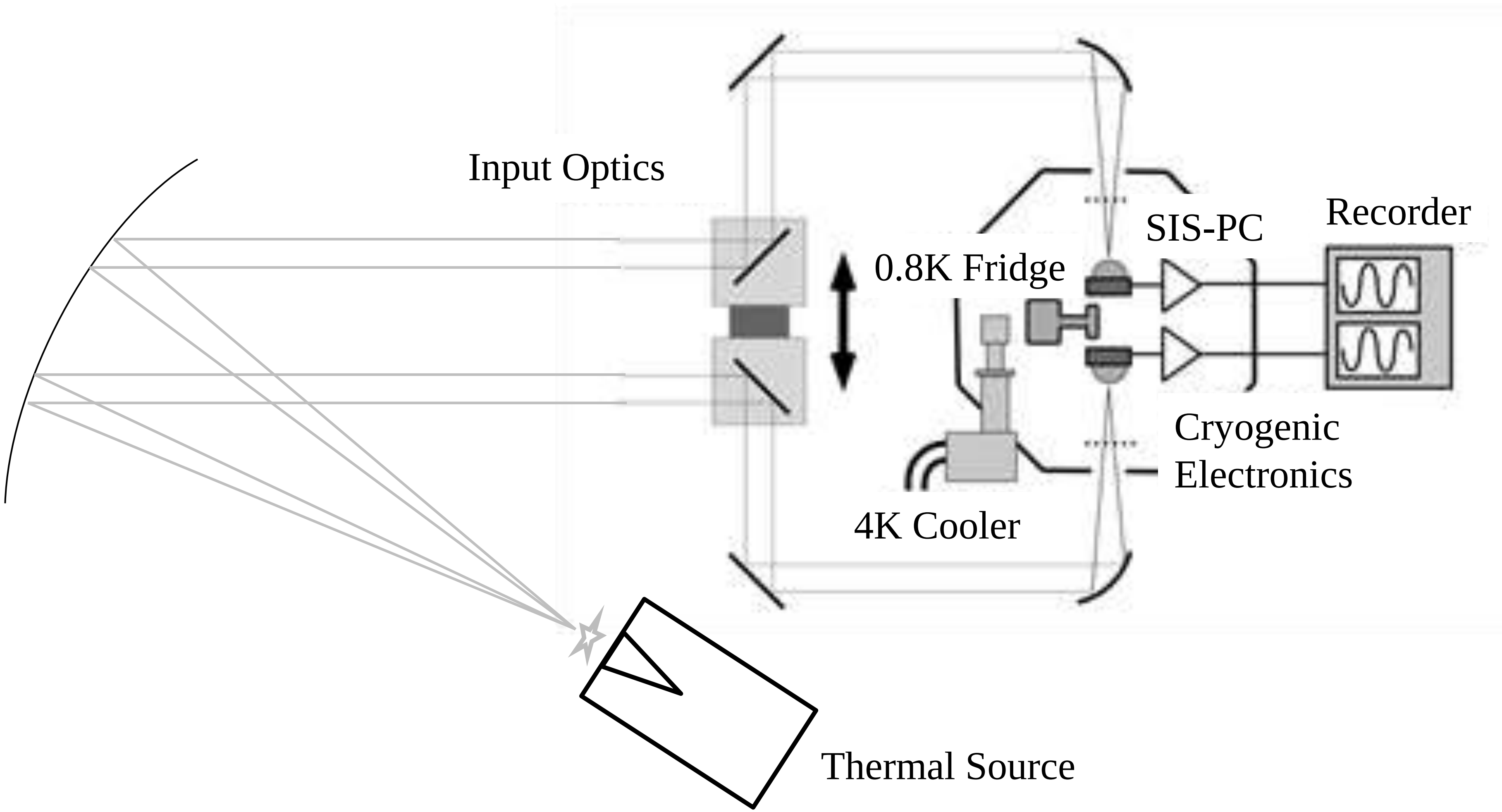


An antenna-coupled Nb-SIS photon detector at 500 GHz fabricated in CRAVITY

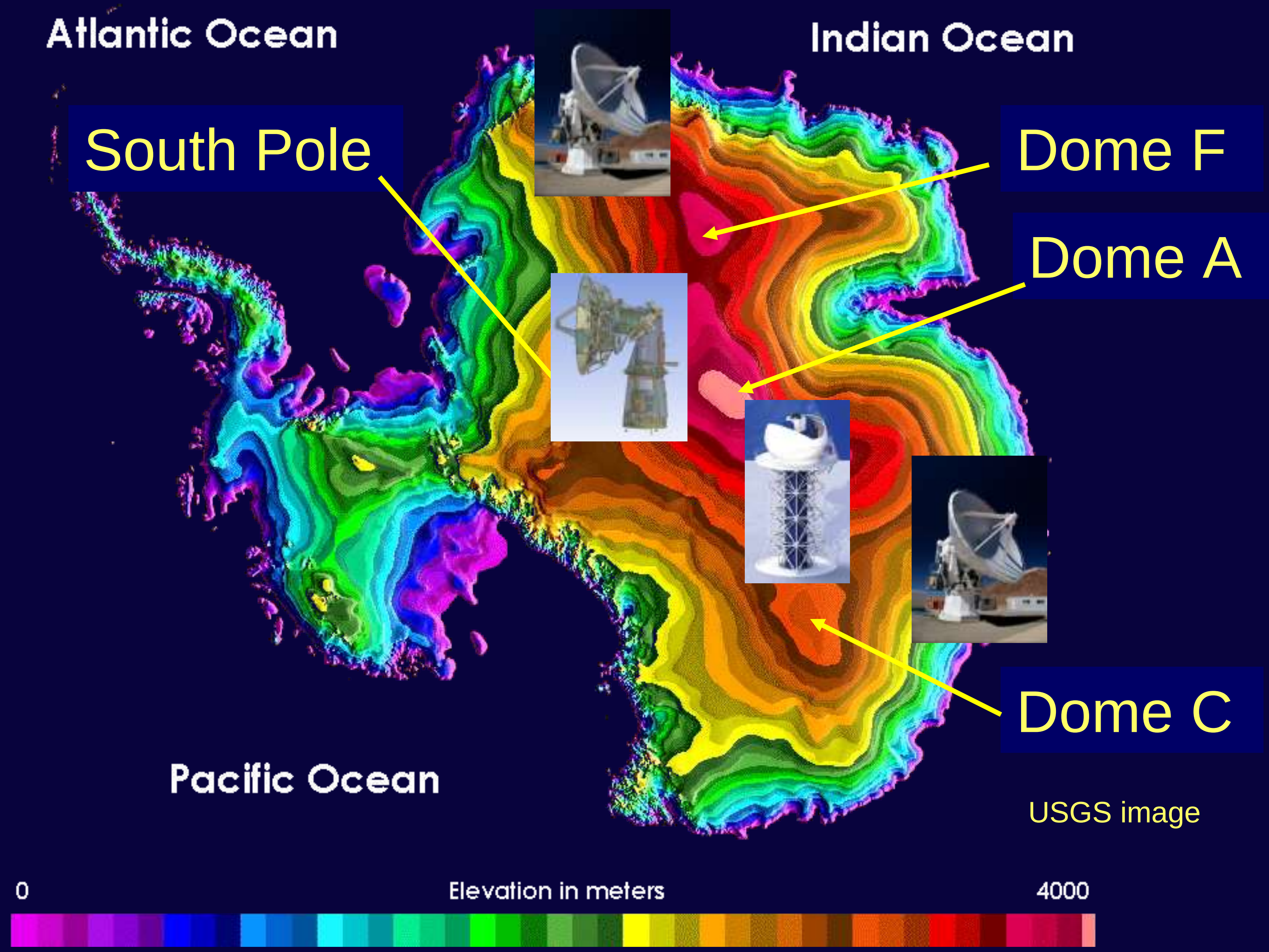


PCTJ designed with SISMA
Shan et al. IRMMW-THz2018

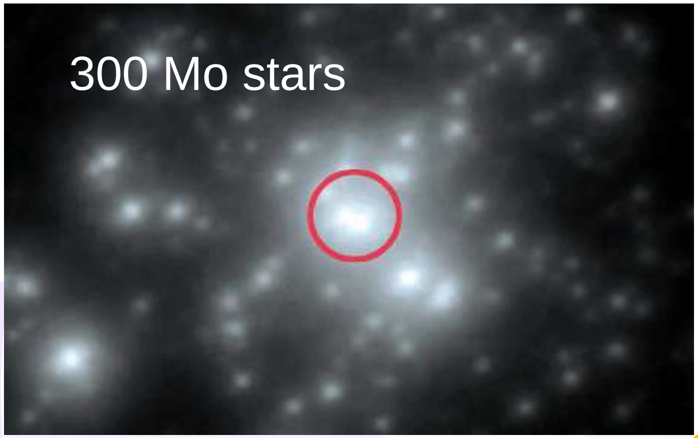
Experimental Setup Plan

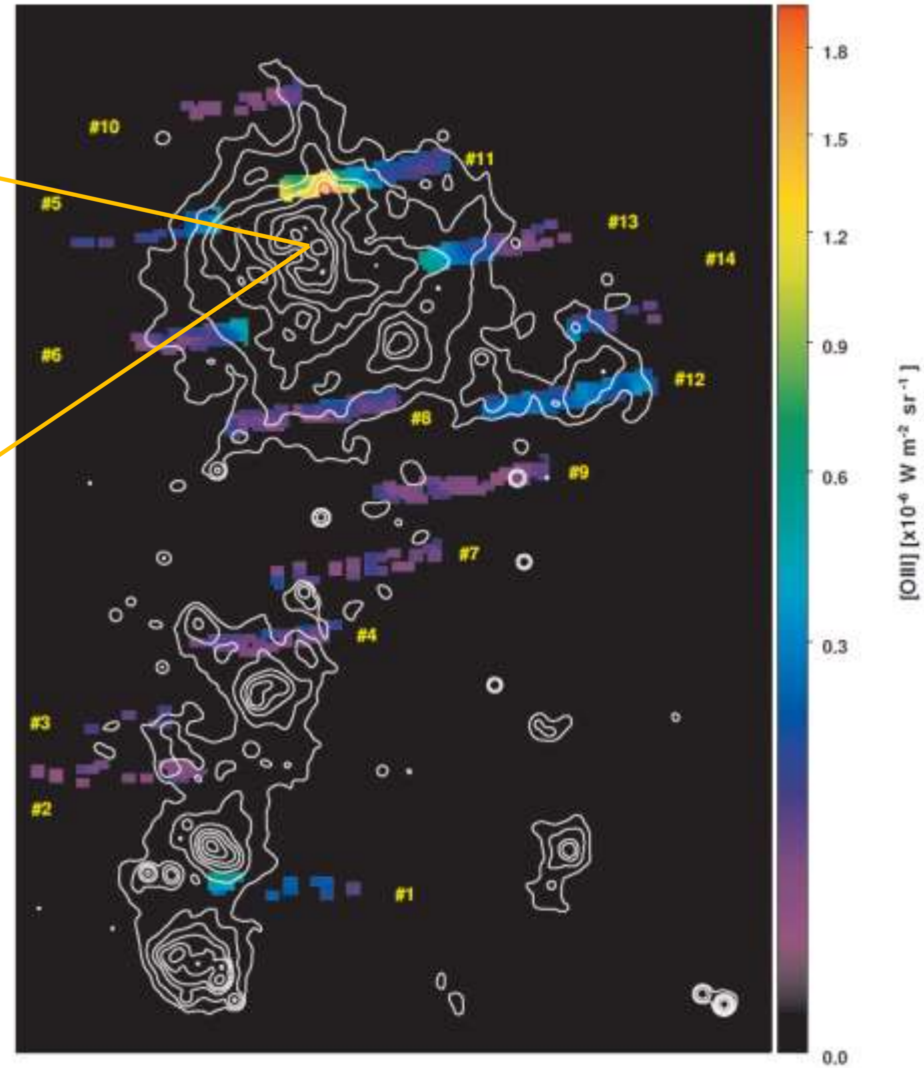


Interferometry from Antarctica



30Dor region and R136





- [OIII] 88μm is observed widely distributed around R136

  Contour: MIPS 24μm

Kawada et al. (2011)

Fig. 3. [OIII] 88μm line intensity map, shown together with the MIPS 24μm contour map

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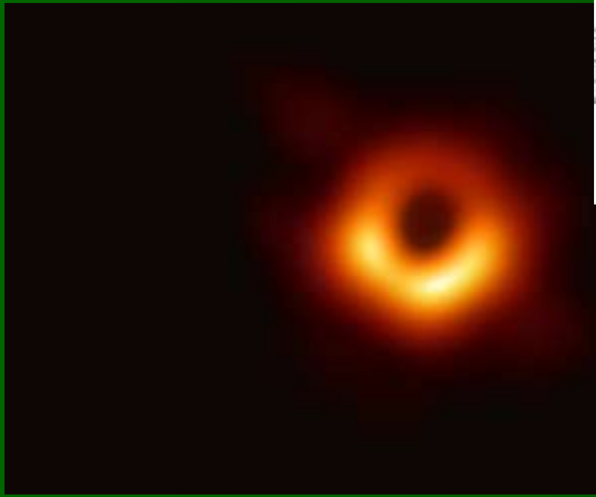

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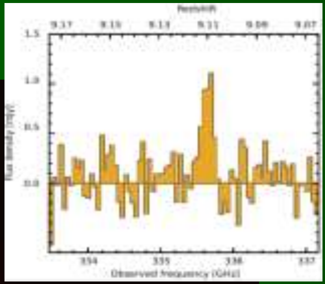
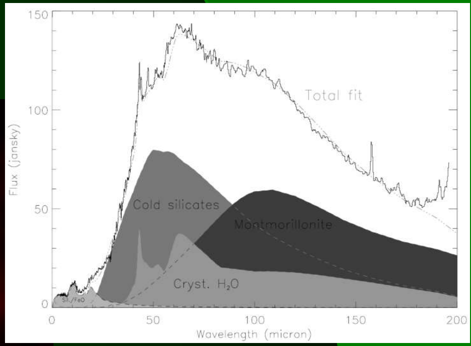


Hashimoto et al. (2018)

Water ice feature



HD142527
Malfait et al. (1999)

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THz Atmosphere

Intensity Interferometry