電波光子の統計的振る舞いと強度干渉計による画像合成について

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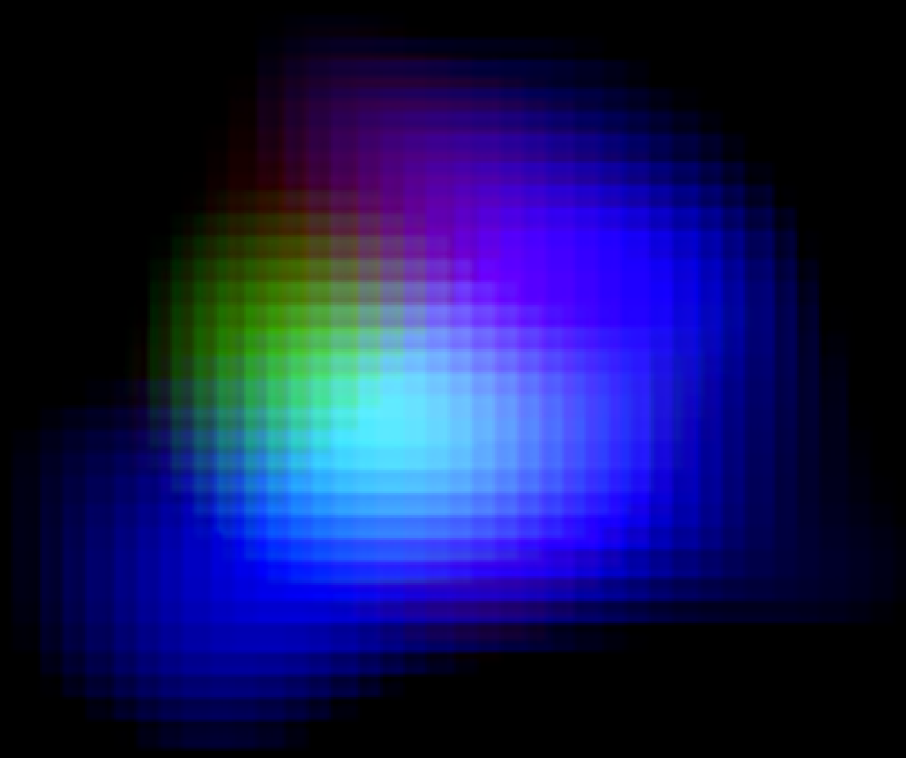
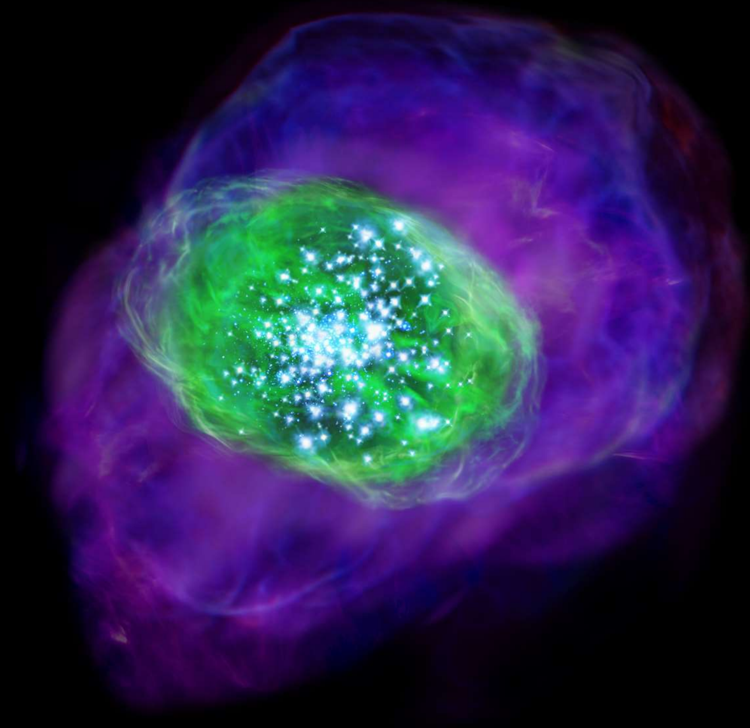
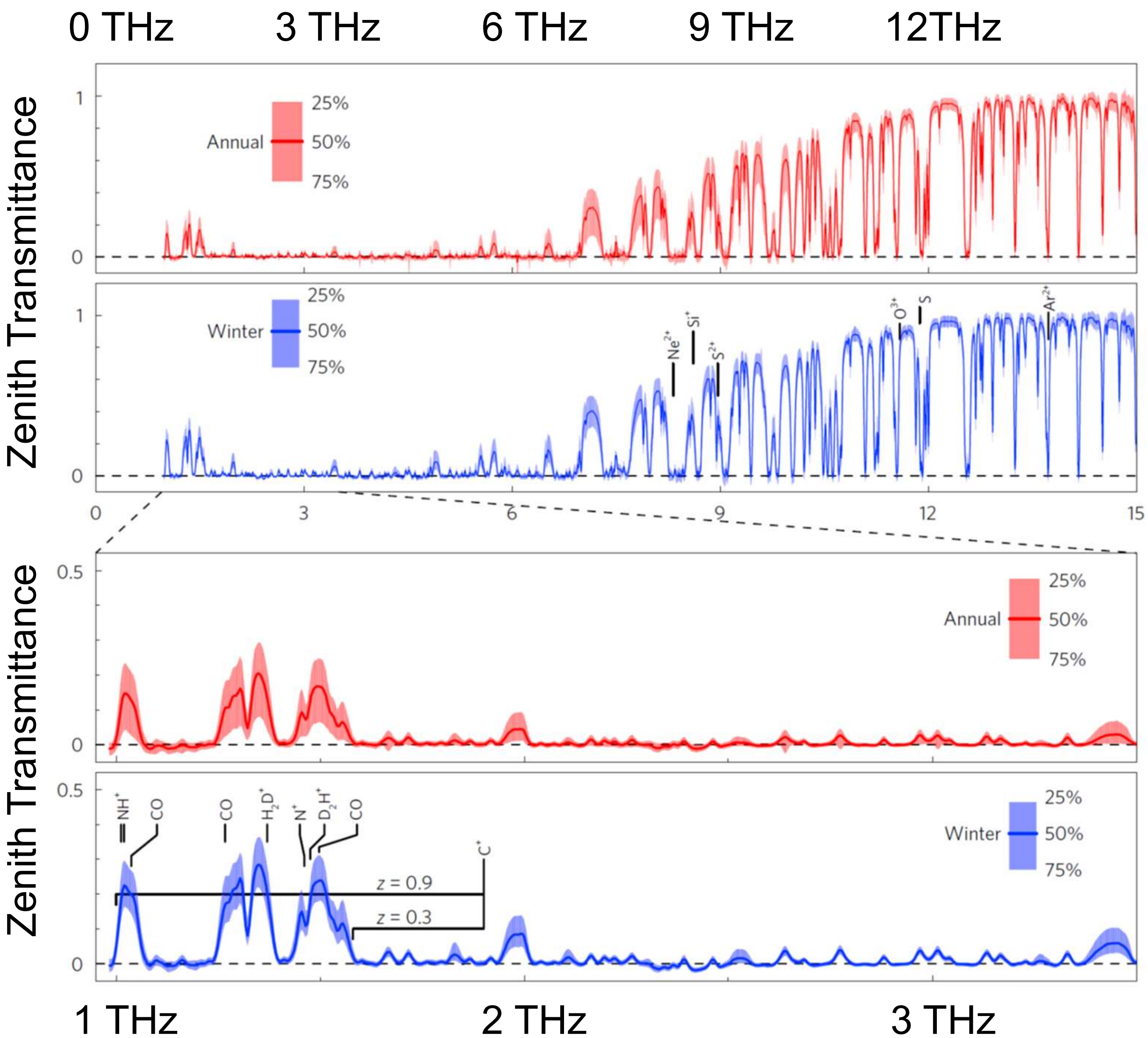
ALMA observed [OIII] 88μm from z=7.2 SXDF-NB1006-2





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

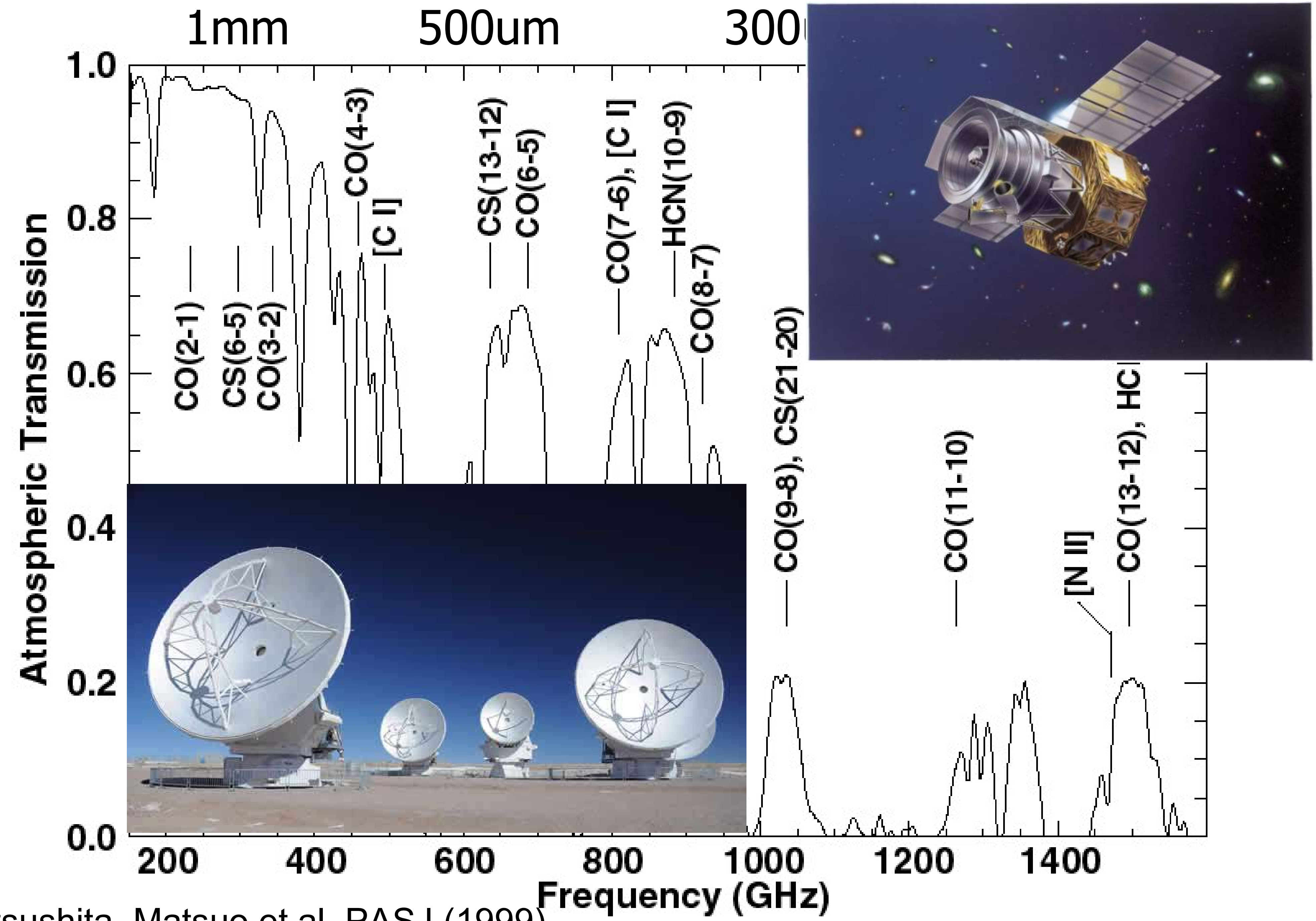
Terahertz and far-infrared windows opened at Dome A in Antarctica



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

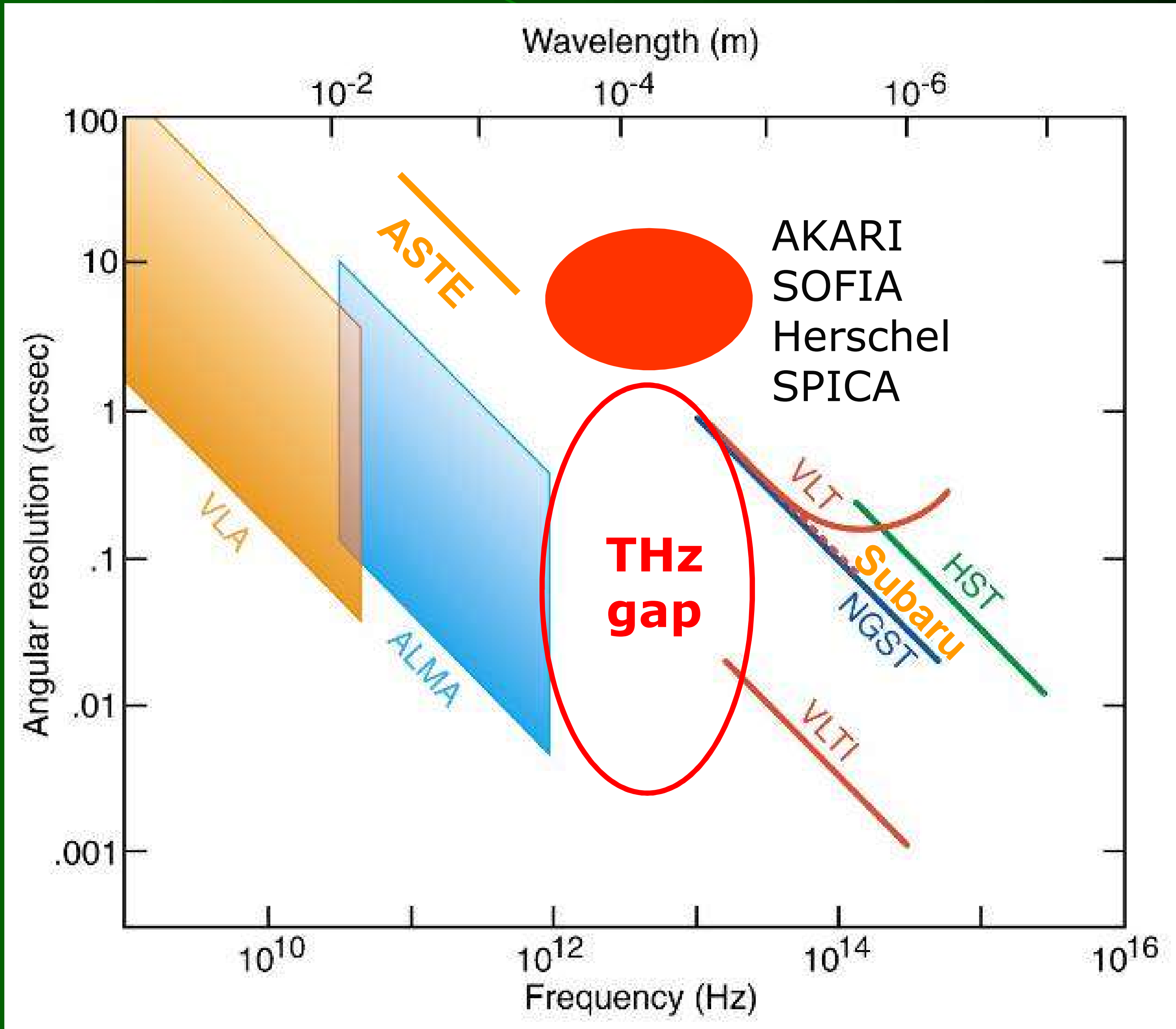
Shi et al.
Nature Astronomy (2017)

Atmospheric Windows from Atacama（alt. 4800m）



Matsushita, Matsuo et al. PASJ (1999)

THz Gap of Spatial Resolution



Original from W.Wild

Hanbury-Brown and Twiss Experiment (1956)

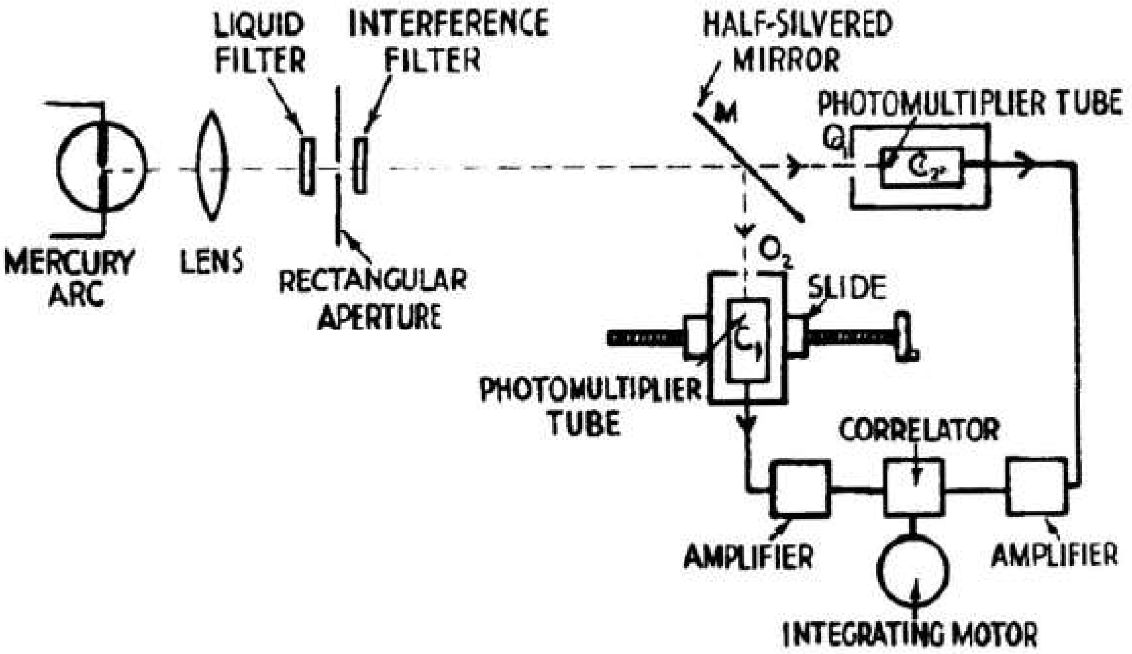


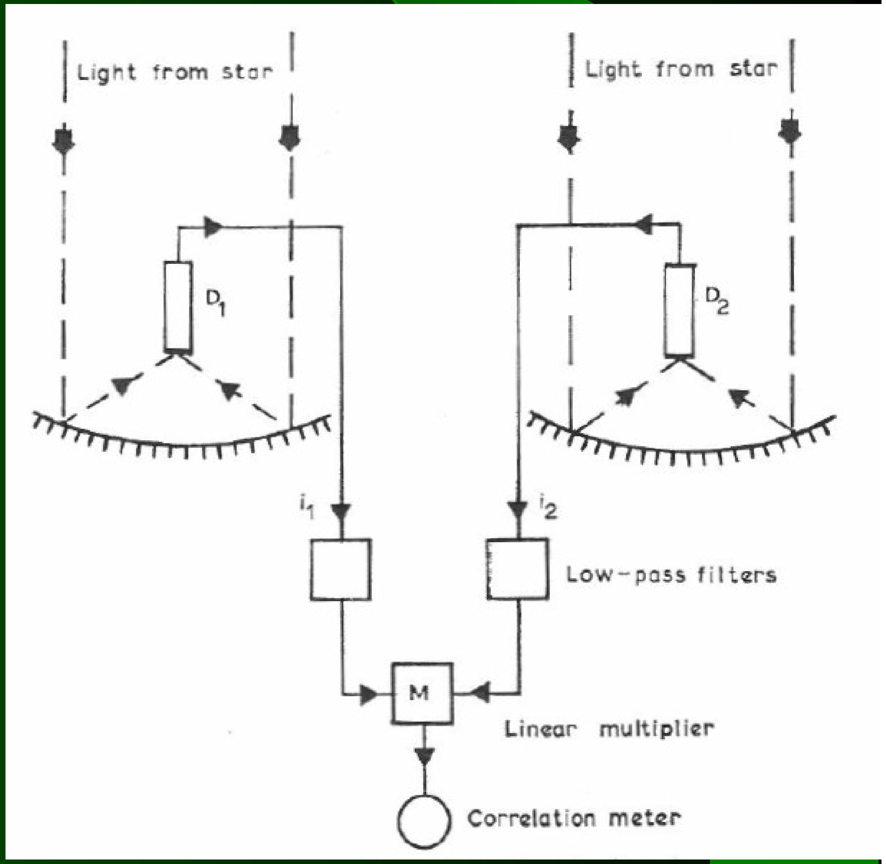
Fig. 2. Simplified diagram of the apparatus

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

	Cathodes superimposed ($d = 0$)		Cathodes separated ($d = 2\alpha = 1.8$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"

Radio Intensity Interferometer

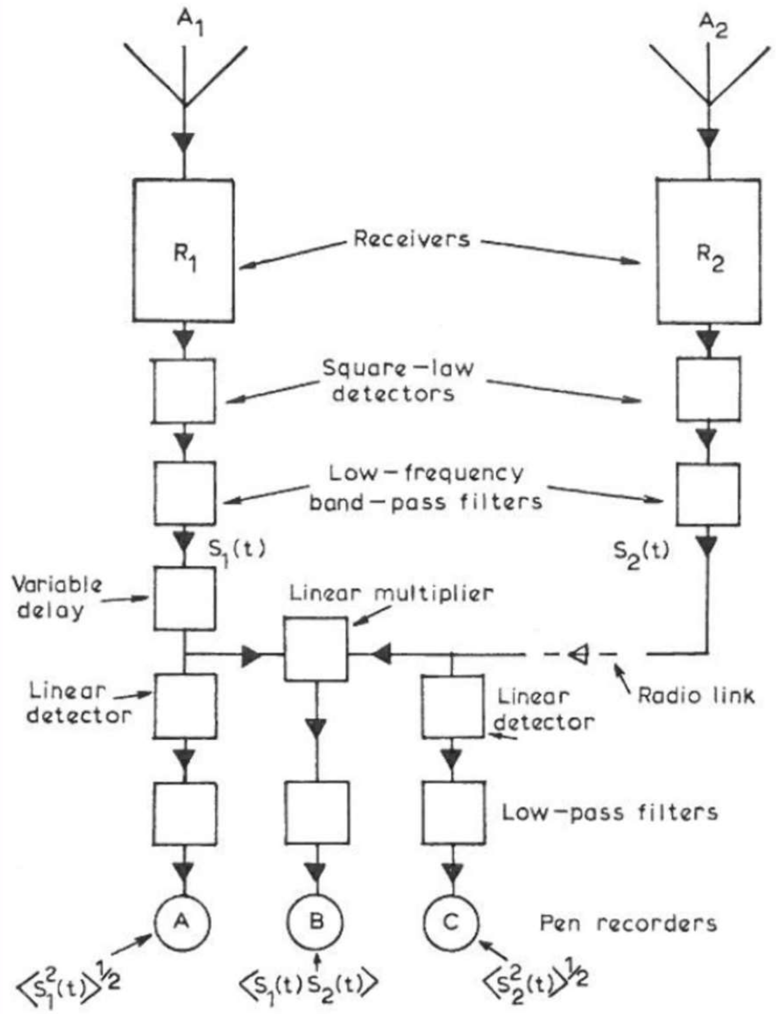


Fig. 7.1. Outline of a radio intensity interferometer.

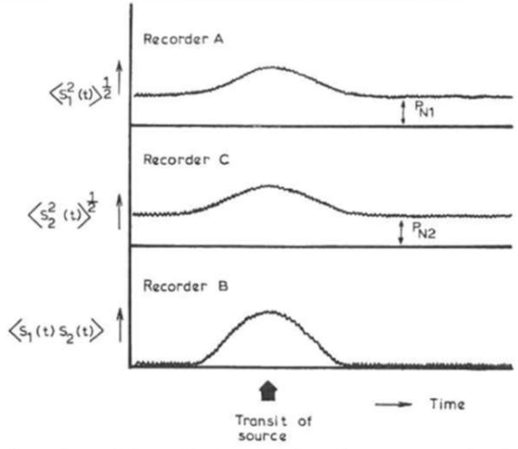


Fig. 7.2. The output of the radio intensity interferometer showing the transit of a source through the aerial beam.

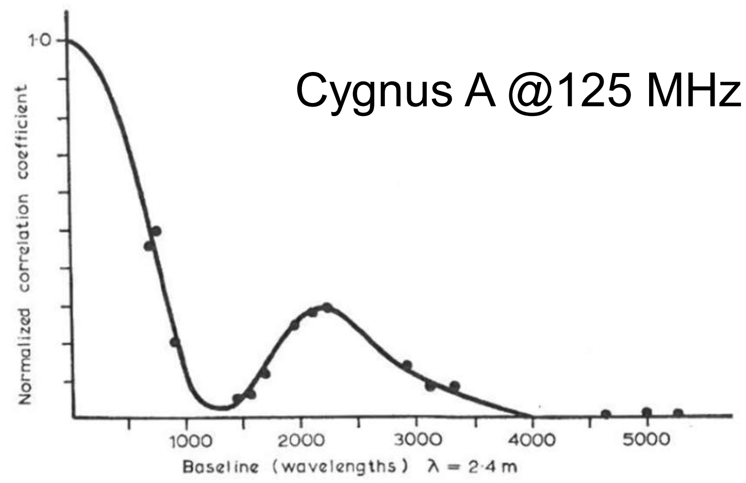
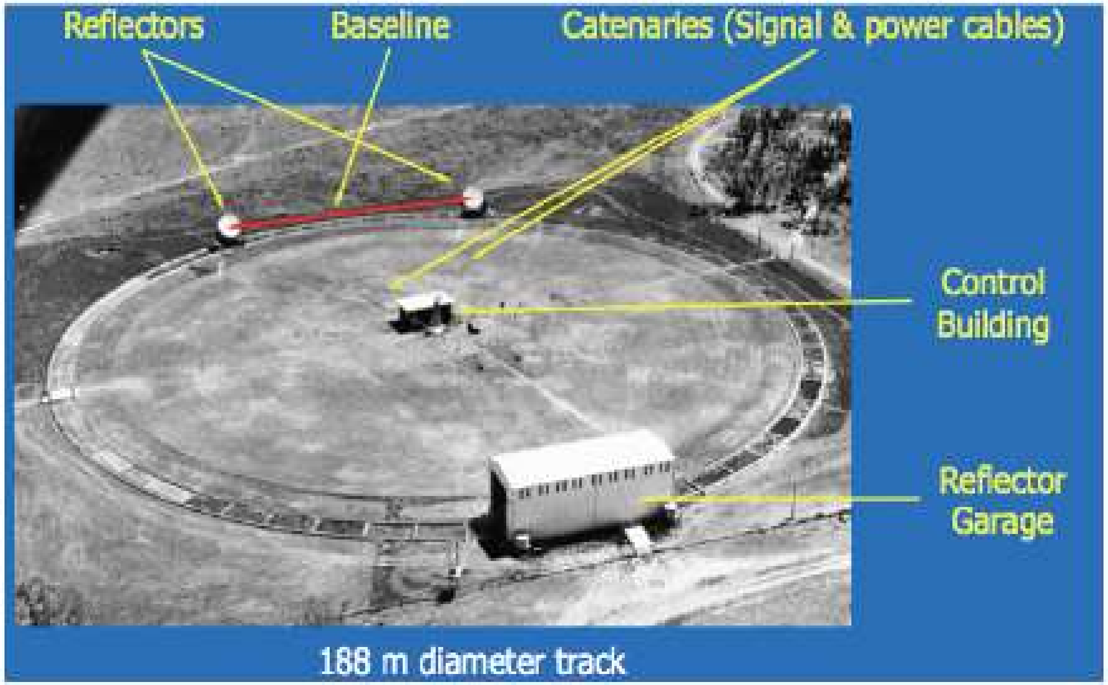


Fig. 7.3. The variation of the normalized correlation coefficient for the source Cygnus A observed at 2·4 m (125 MHz) along the major axis. From Jennison and Das Gupta (1966).

from Hanbury-Brwon (1974)
"The Intensity Interferometer"

Narrabri Stellar Intensity Interferometer



Narrabri Stellar Interferometer

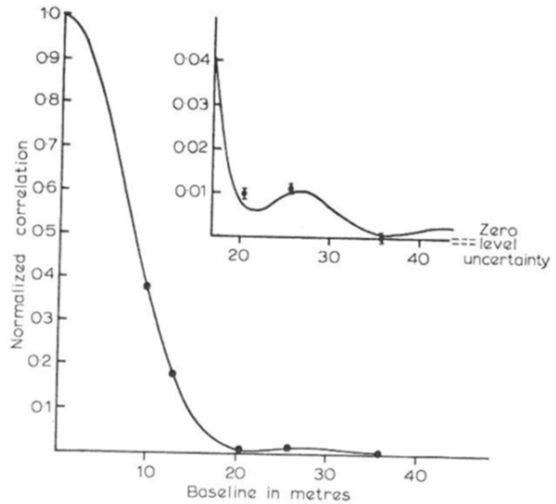


Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model atmosphere ($T_e = 10\,000$ K, $\log g = 4$, $\lambda = 450$ nm). Results for three long baselines are shown on an expanded scale together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

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

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

Introduction of Quantum Optics

from “Quantum Optics” by Mark Fox (2006)

Photon Statistics

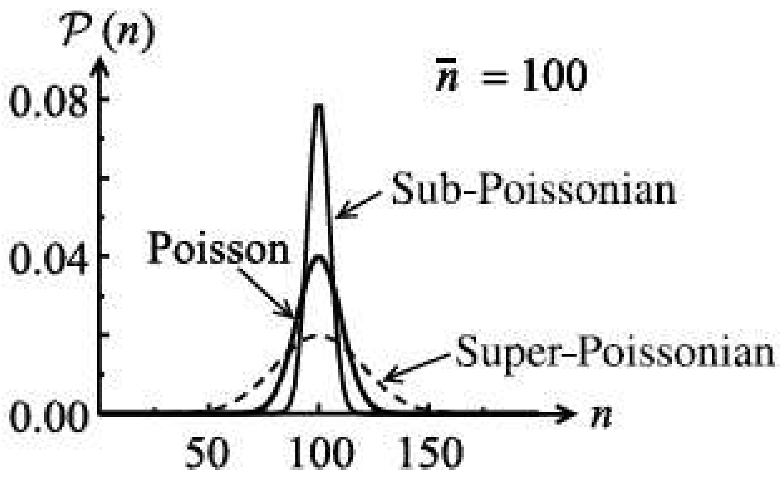


Fig. 5.4 Comparison of the photon statistics for light with a Poisson distribution, and those for sub-Poissonian and super-Poissonian light. The distributions have been drawn with the same mean photon number $\overline{n} = 100$. The discrete nature of the distributions is not apparent in this figure due to the large value of $\overline{n}$.

- sub-Poissonian statistics: $\Delta n < \sqrt{\overline{n}}$,
- Poissonian statistics: $\Delta n = \sqrt{\overline{n}}$,
- super-Poissonian statistics: $\Delta n > \sqrt{\overline{n}}$.

Fluctuation of Thermal Radiation

$$\Delta n = \sqrt{n + n^2}$$

$$n = \frac{1}{e^{h\nu/kT} - 1}$$

First order correlation function

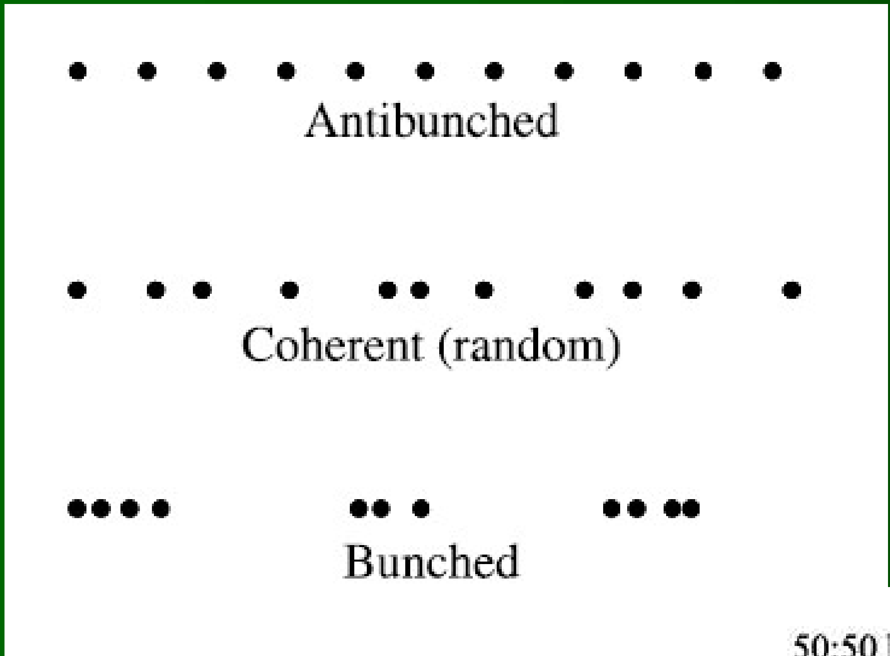
$$g^{(1)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}(t+\tau)\rangle}{\langle |\mathcal{E}(t)|^2\rangle}.$$

Second order correlation function

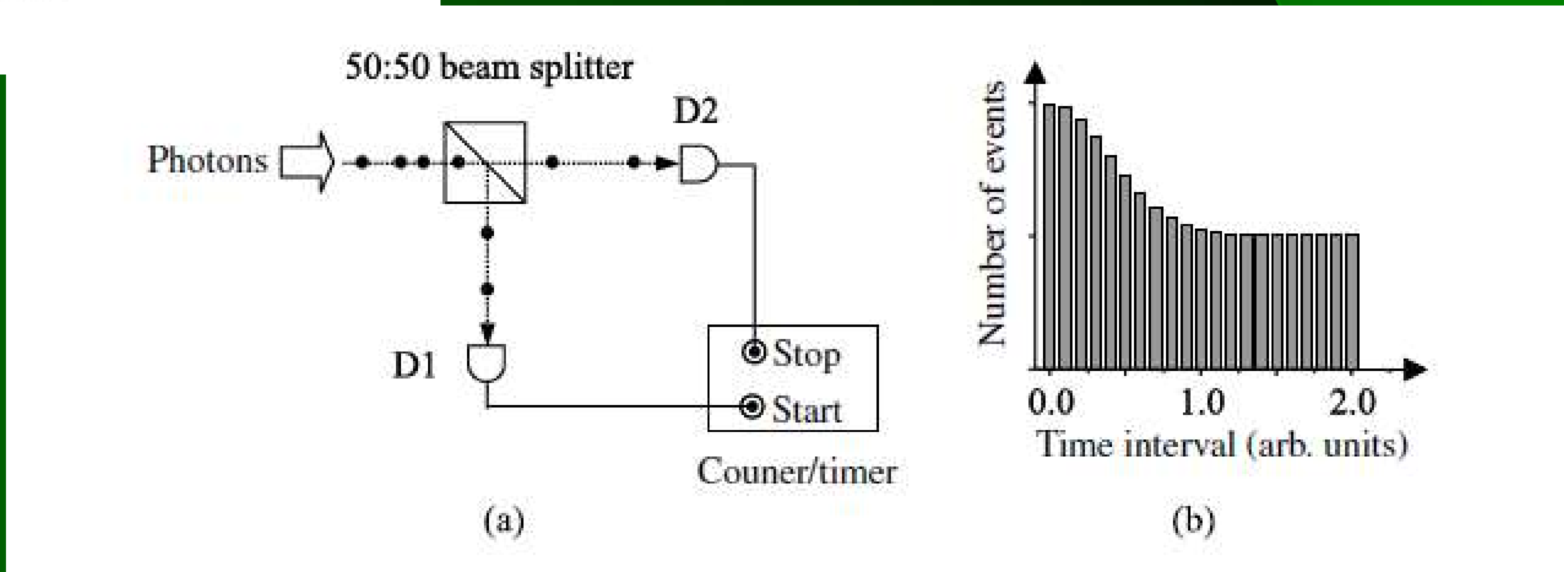
$$g^{(2)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\mathcal{E}(t)\rangle}{\langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle\langle \mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\rangle} = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle},$$

From M. Fox
Quantum Optics

Photon Bunching, Anti-bunching



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



From M. Fox
Quantum Optics

THz photon bunches measured from a Synchrotron Source

$YBa_2Cu_3O_{7-\delta}$ thin film detectors for picosecond THz pulses

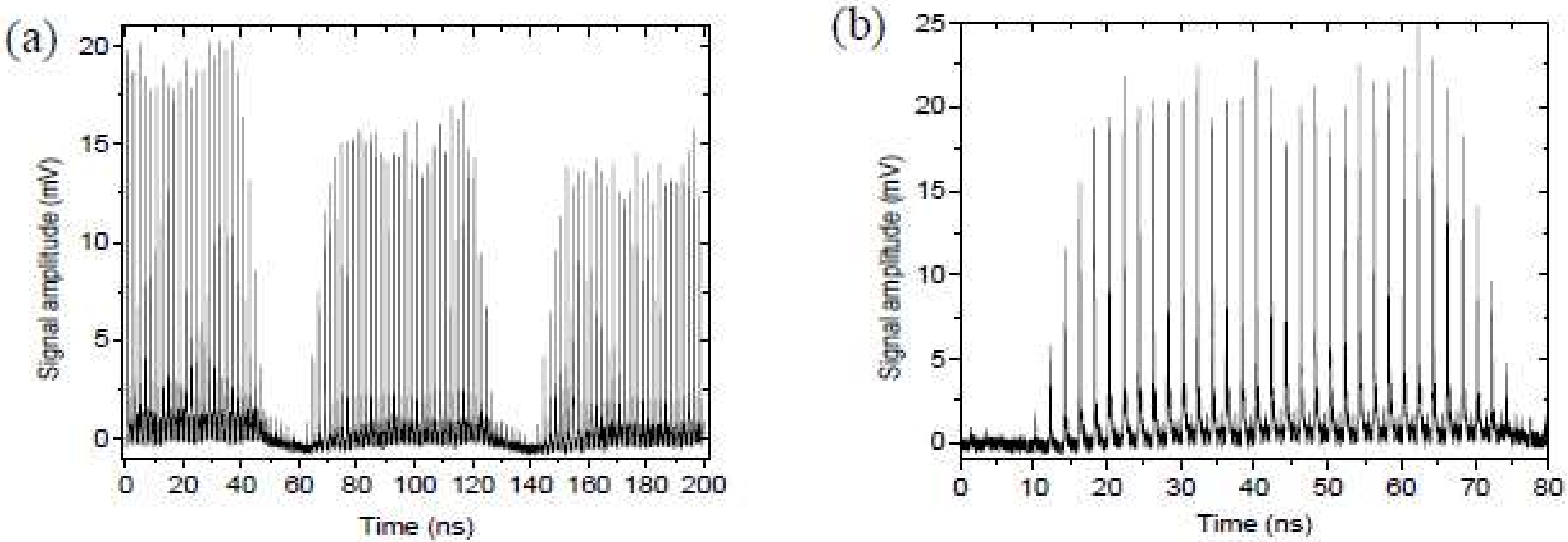


Fig. 3 (a) Measured detector signal of a 15 nm YBCO THz HEB over time. The distance between two trains is 20 ns (50 MHz). In (b) one train with 33 bunches is depicted in detail.

Probst et al., Journal of Low Temp. Phys. (2012)

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

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

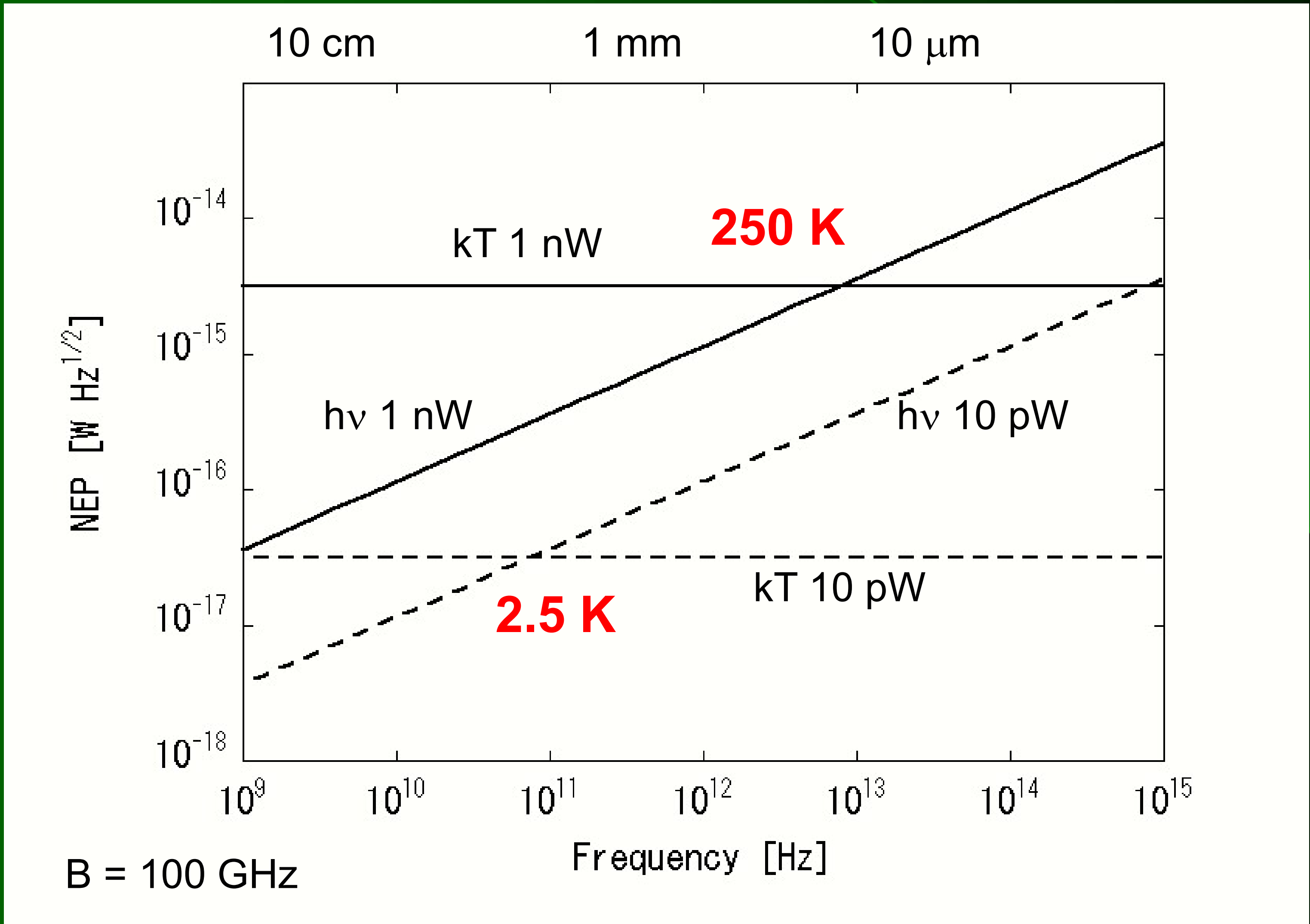
$$\mathrm{NEP} = \sqrt{2P \cdot \left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

References

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

THz photon fluctuation

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



The use of photon bunching ?

- Brightness temperature measurements
  - $T_B \sim 10^8$ K in X-ray
  - $T_B \sim 10^5$ K in optical
  - $T_B \sim 100$ K in terahertz
  - Application to CMB
- Application to Terahertz Interferometry
  - FIR atomic lines, black holes, exo-planet imaging

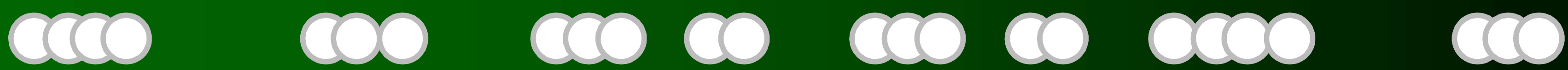
Photon Bunches for delay time measurements

- 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.



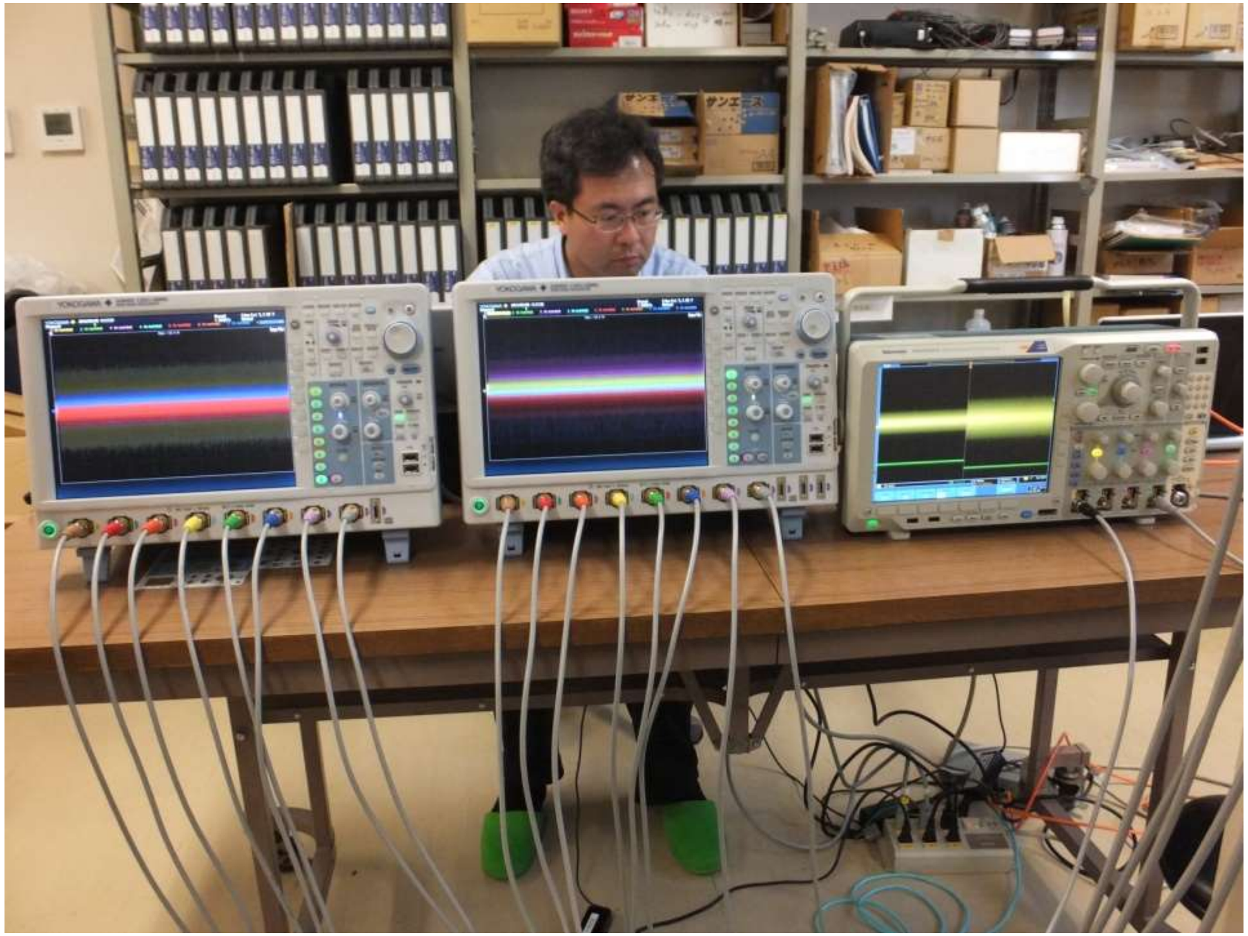
THz Photons are bunched !

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

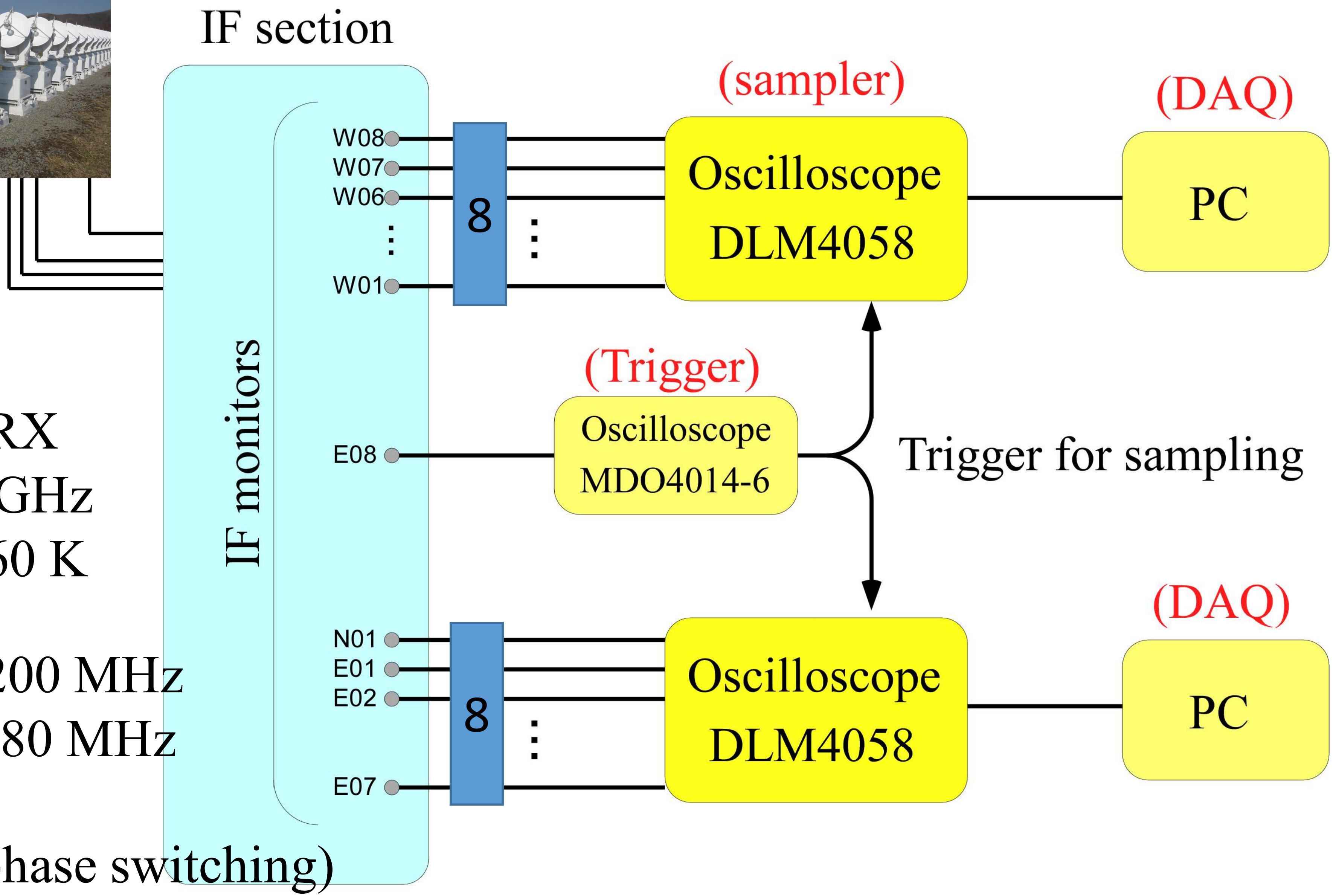
The actual experiment was….



Semi-automated "slave-style" DAQ

Experiment Setup

<u>Yokogawa DLM4058</u>
8 CH 1.25 GS/s, BW 500 MHz
Simultaneous sampling

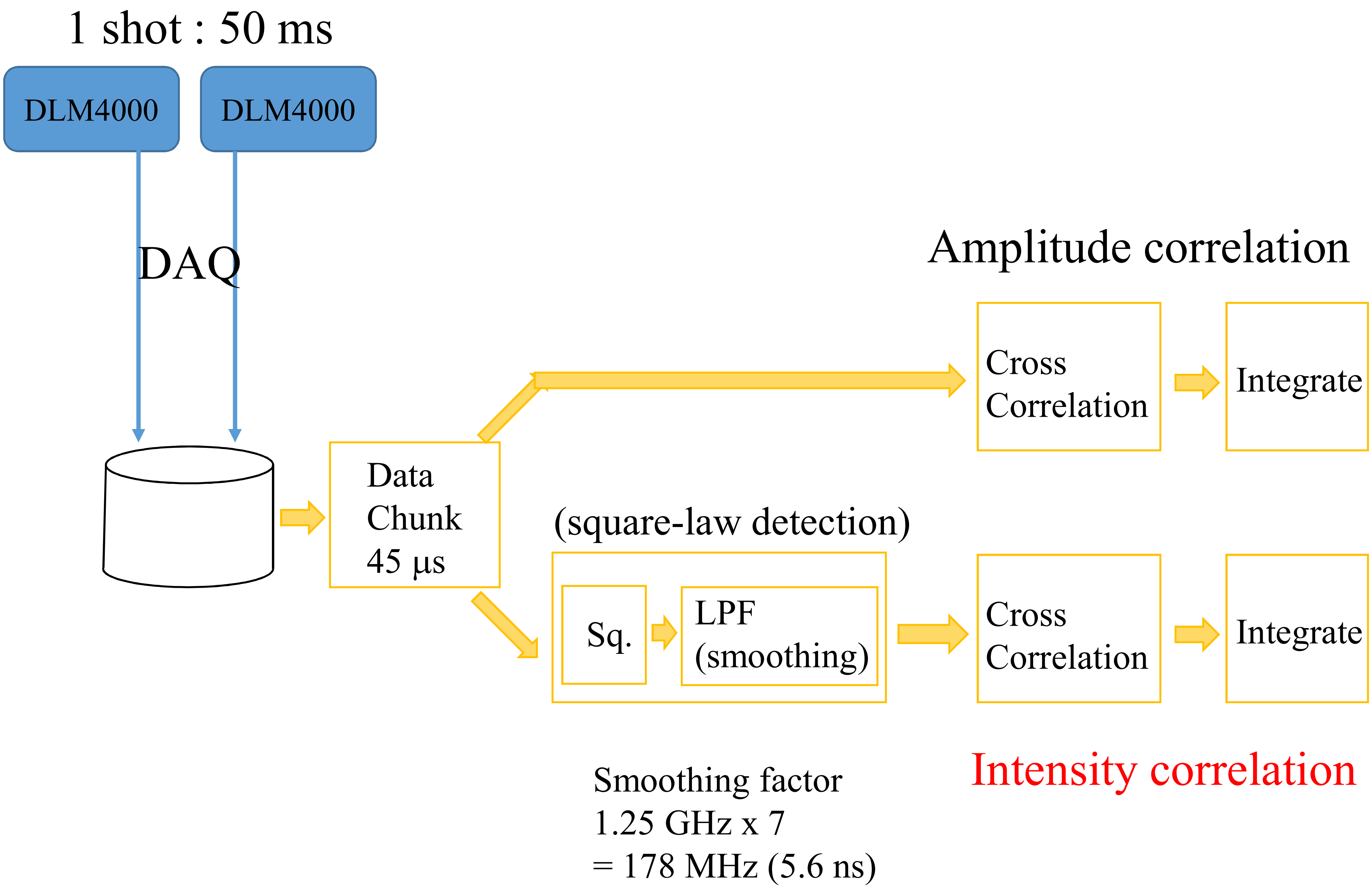


HEMT RX
RF 17 GHz
T_{RX}= 360 K

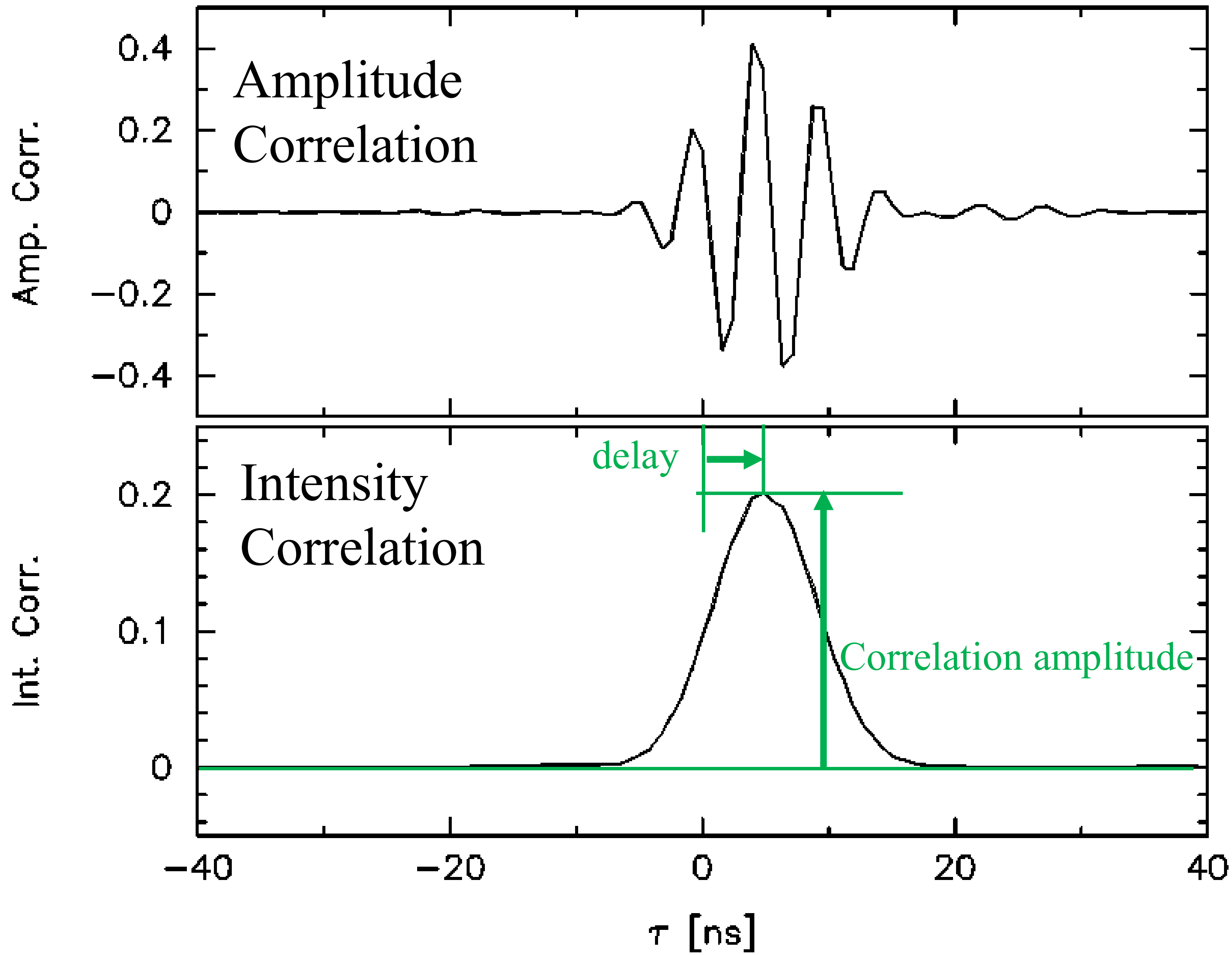
IF freq 200 MHz
BW 80 MHz

(Walsh phase switching)

Data analysis stream



Nobeyema Radioheliograph at 17 GHz



Ezawa, Matsuo et al. (2015)

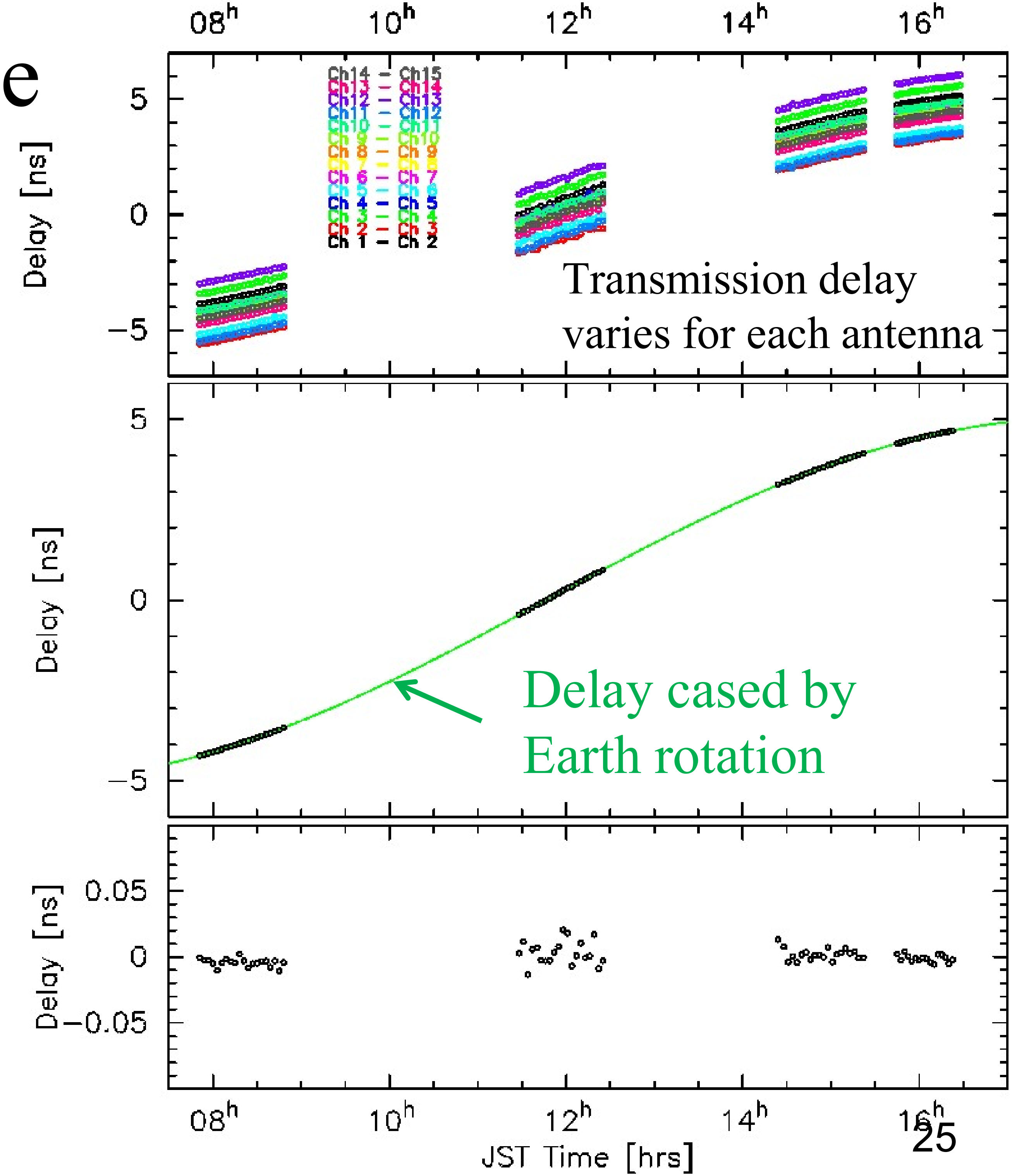
Delay vs Time

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

Correct for transmission delay and average over antennas

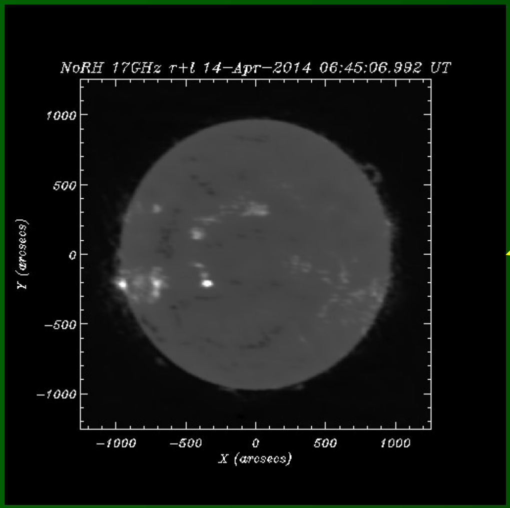
Data fits to the delay calculated from Earth rotation

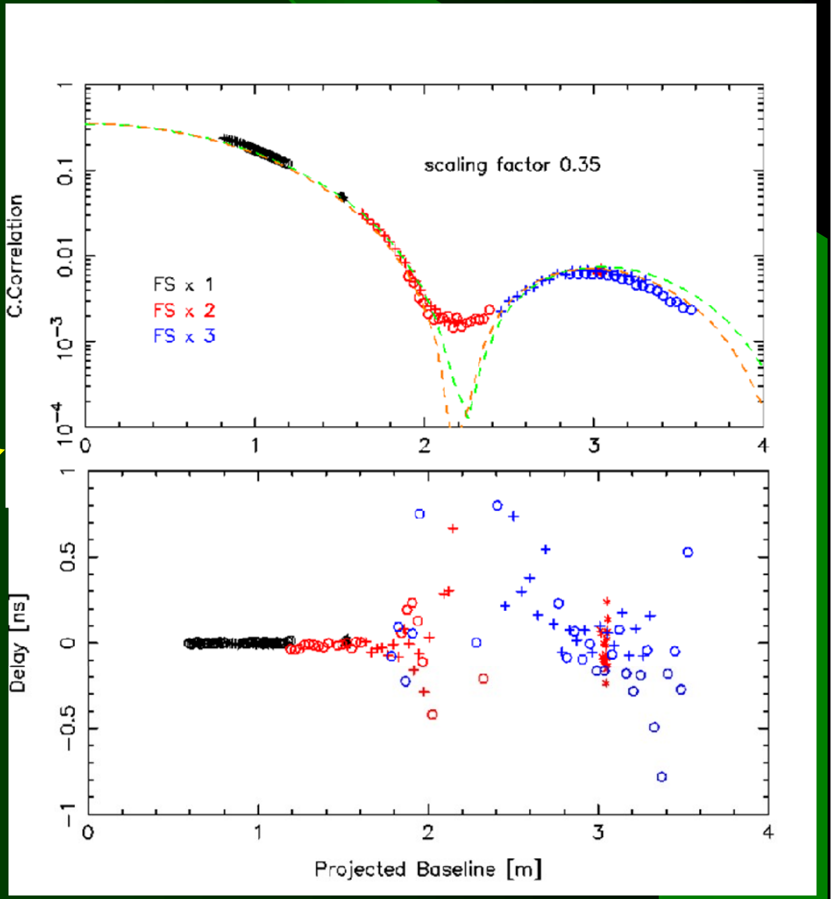
Delay time accuracy
$\sigma <$ 5-10 ps



Complex Visibility for Aperture Synthesis Imaging

- Real Part
  - Sqrt of Intensity Correlation
- Imaginary Part
  - $\Delta\varphi = 2\,\pi\,\nu\,\Delta t$





VERA強度干渉計実験（東北大との共同研究）

- 水メーザの光子統計
  - ポアソン的な揺らぎ？
- シンクロトロン放射の光子統計
  - 電子密度の分布が観測可能？
- 強度相関干渉計による画像合成
  - マルチビーム干渉計が有利

g2(0) の計測は失敗？

From Intensity Interferometry to Photon Counting THz Interferometry (PCTI)

- THz photon detectors
  - No quantum limited receiver noise
  - Photon bunch for delay measurements
- Merit of intensity correlation
  - Stable against phase fluctuation
  - Very Long Baseline Interferometry

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

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

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

References

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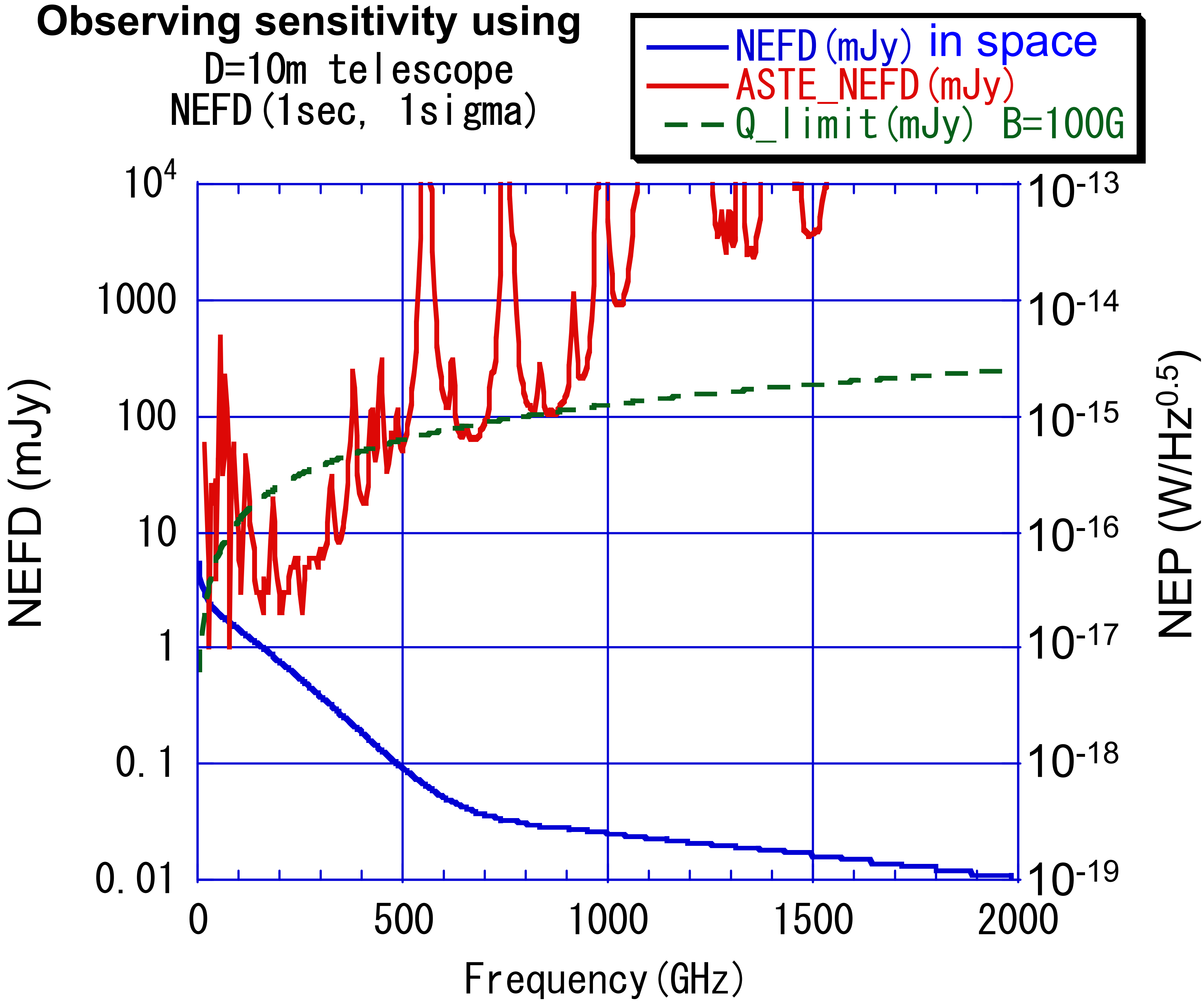


Observing sensitivity using
D=10m telescope
NEFD(1sec, 1sigma)
NEFD(mJy) in space
ASTE_NEFD(mJy)
Q_limit(mJy) B=100G
10^4
1000
100
10
1
0.1
0.01
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
NEFD (mJy)
NEP (W/Hz^0.5)
0
500
1000
1500
2000
Frequency(GHz)

ヘテロダイン干渉計と直接干渉計

- 感度の向上（3THz vs. 100GHz）
  - T_{sys} = NEP / (2k $B^{0.5}$) = 4 mK
  - 量子雑音　vs. 背景放射雑音　4-5桁
  - 帯域幅　Sqrt(1 THz / 1 GHz) = 1.5桁
- 基線長
  - 光学的な干渉では基線が制限される
  - 強度干渉計では光子信号をレコーダに記録

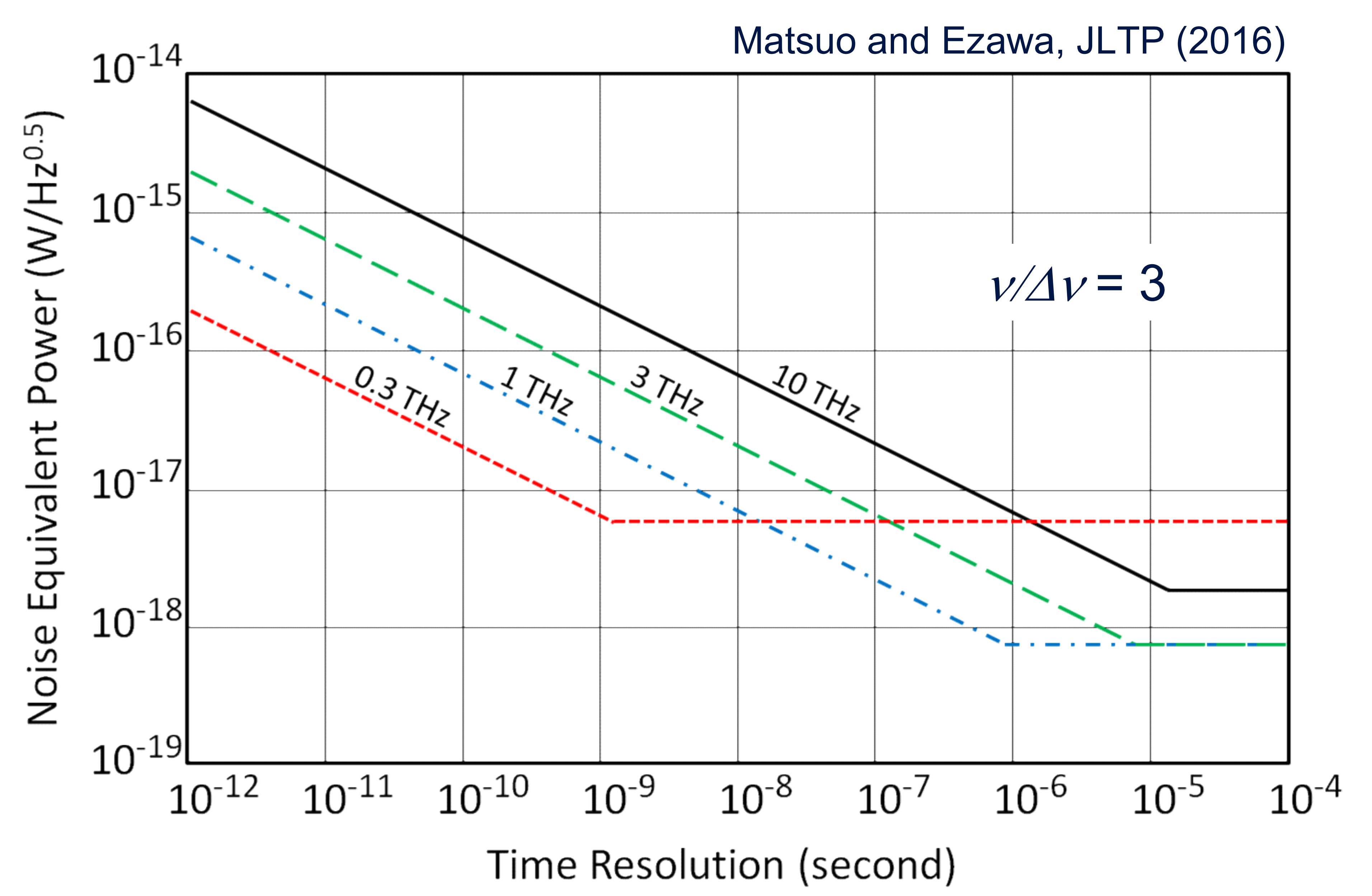
Terahertz Photon Rates

- 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
  - 1 GHz bandwidth for 100 M photons/sec
- 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



SIS Photon Detectors

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

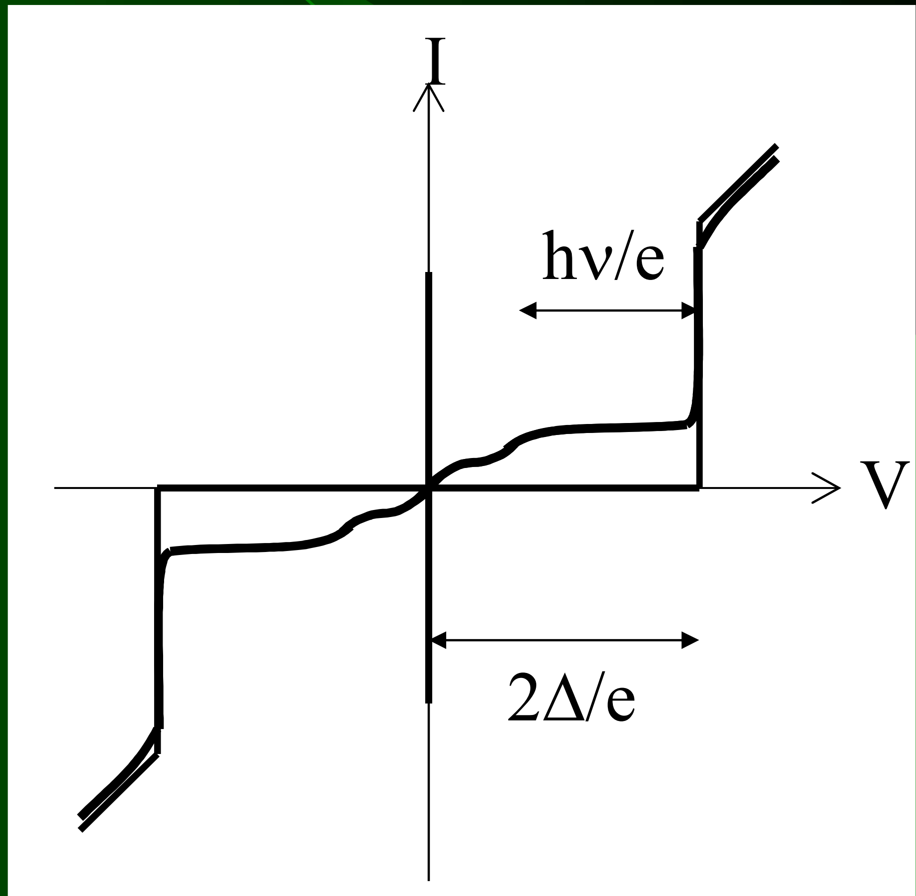
$$N = \sqrt{2eI_0} \quad [\text{A}/\sqrt{\text{Hz}}]$$

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

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

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

Photon Assisted Tunneling

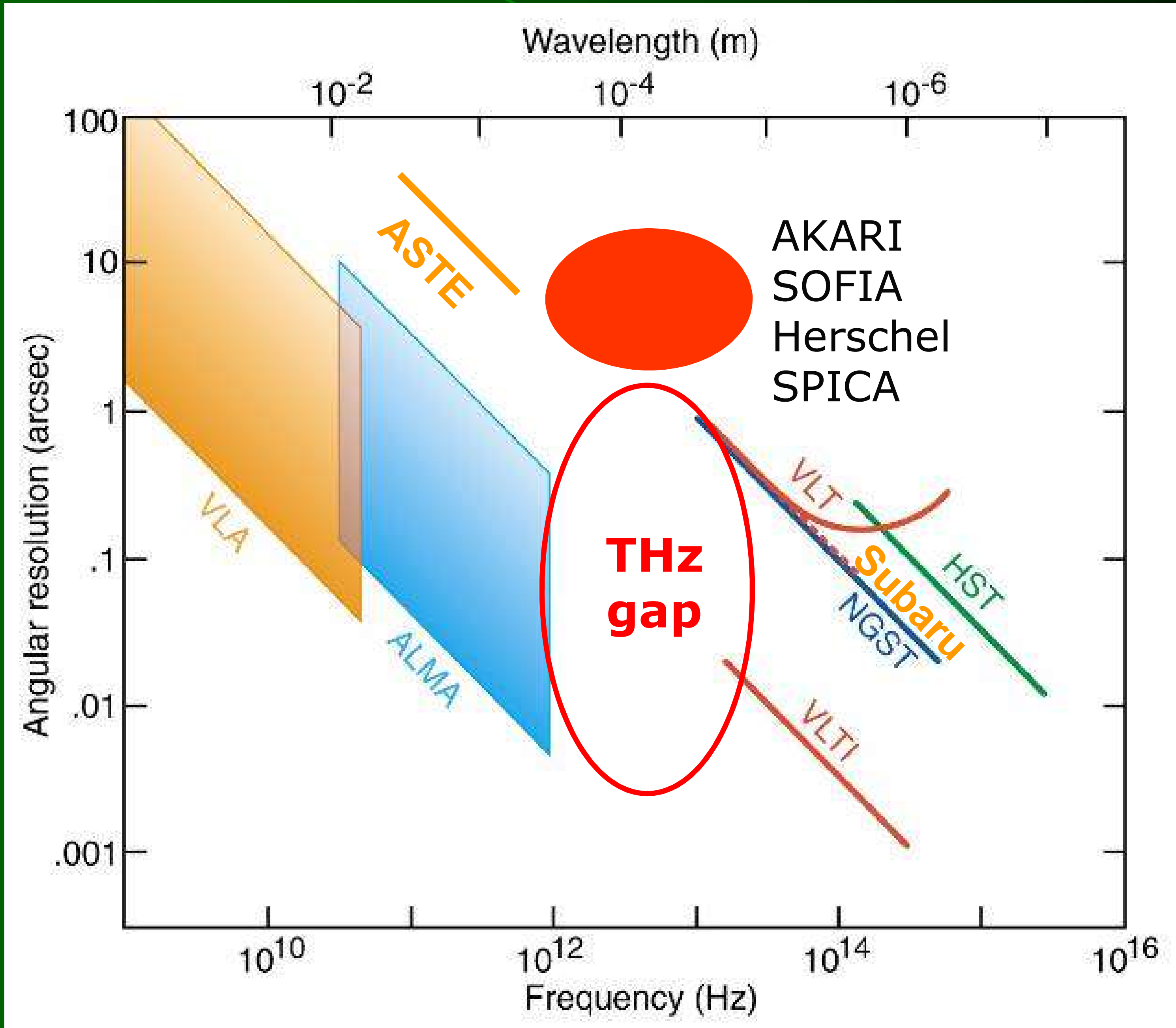


What do we plan next ?

- ALMA is limited by atmosphere
- SPICA is limited by telescope diameter
- Space VLBI is limited by quantum noise

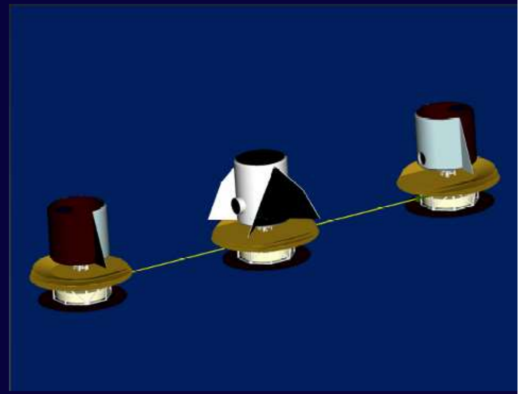
Interferometer using direct detectors, such as SPIRIT and FIRI ?

THz Gap of Spatial Resolution

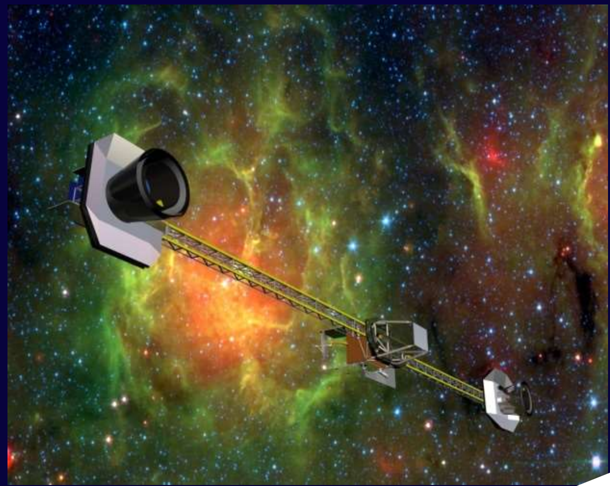


Original from W.Wild

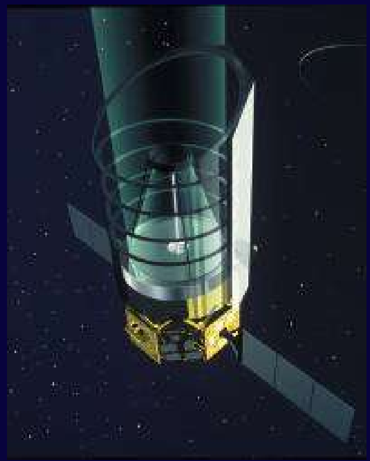
Space THz Interferometer
The Road Map



SPECS



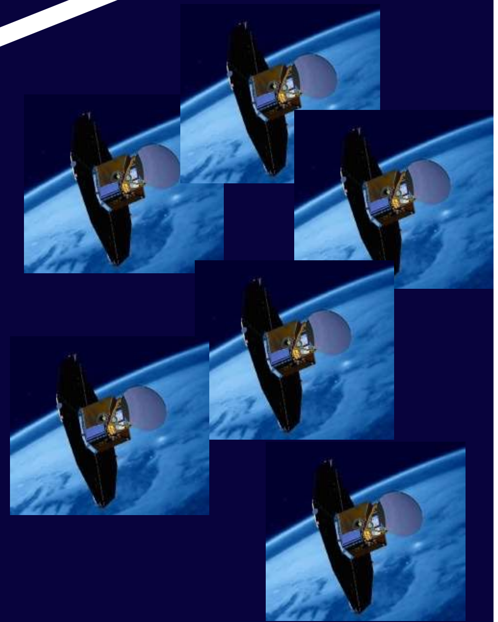
SPIRIT



SPICA

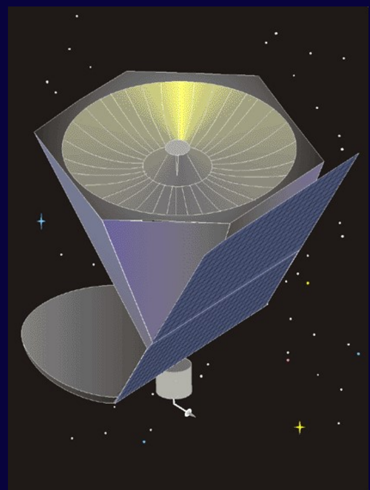
AKARI

FIRI
ESPRIT



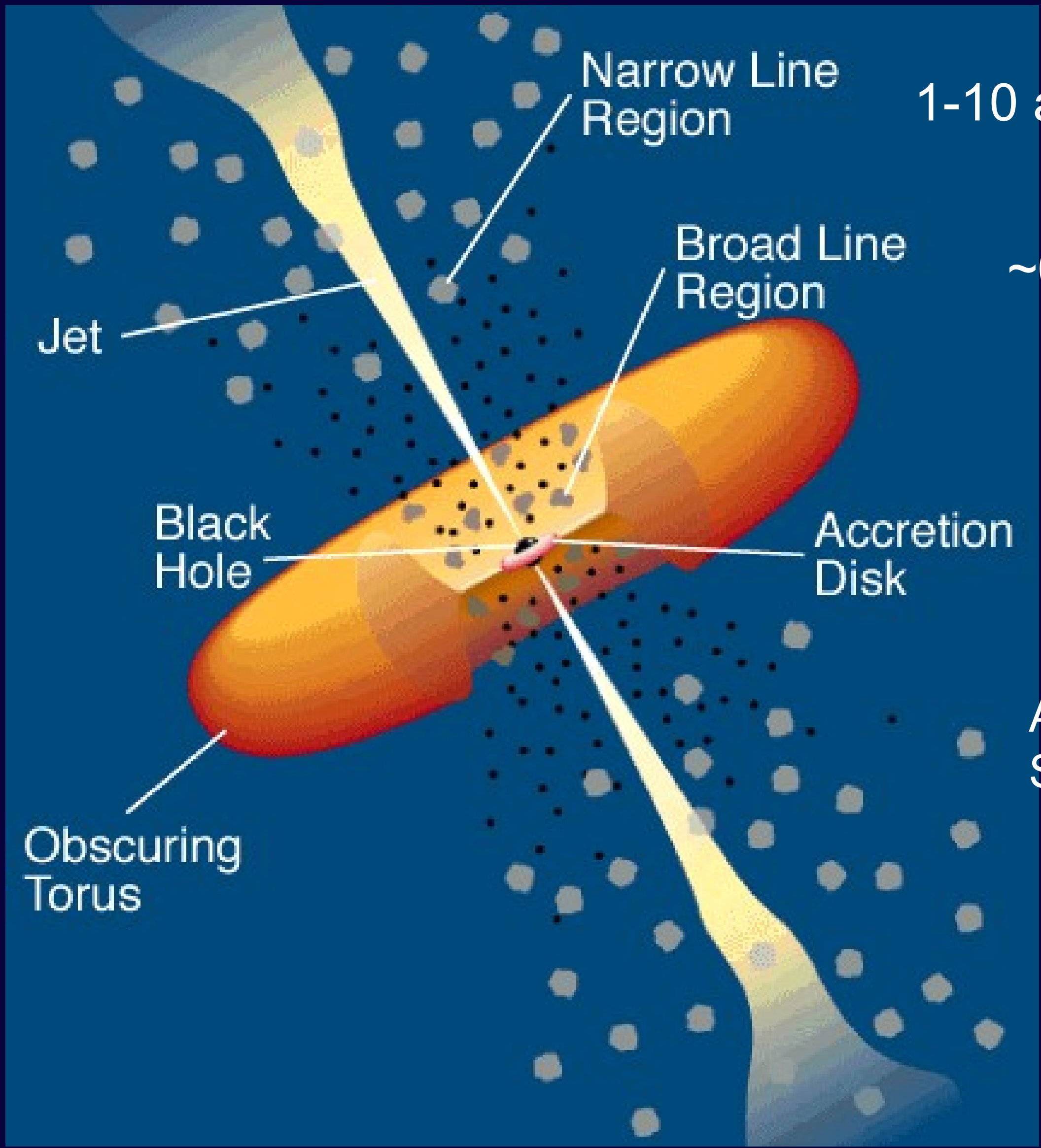
Millimetron

Herschel



Spitzer

Structure of an AGN



1-10 arcsec

~0.01 arcsec

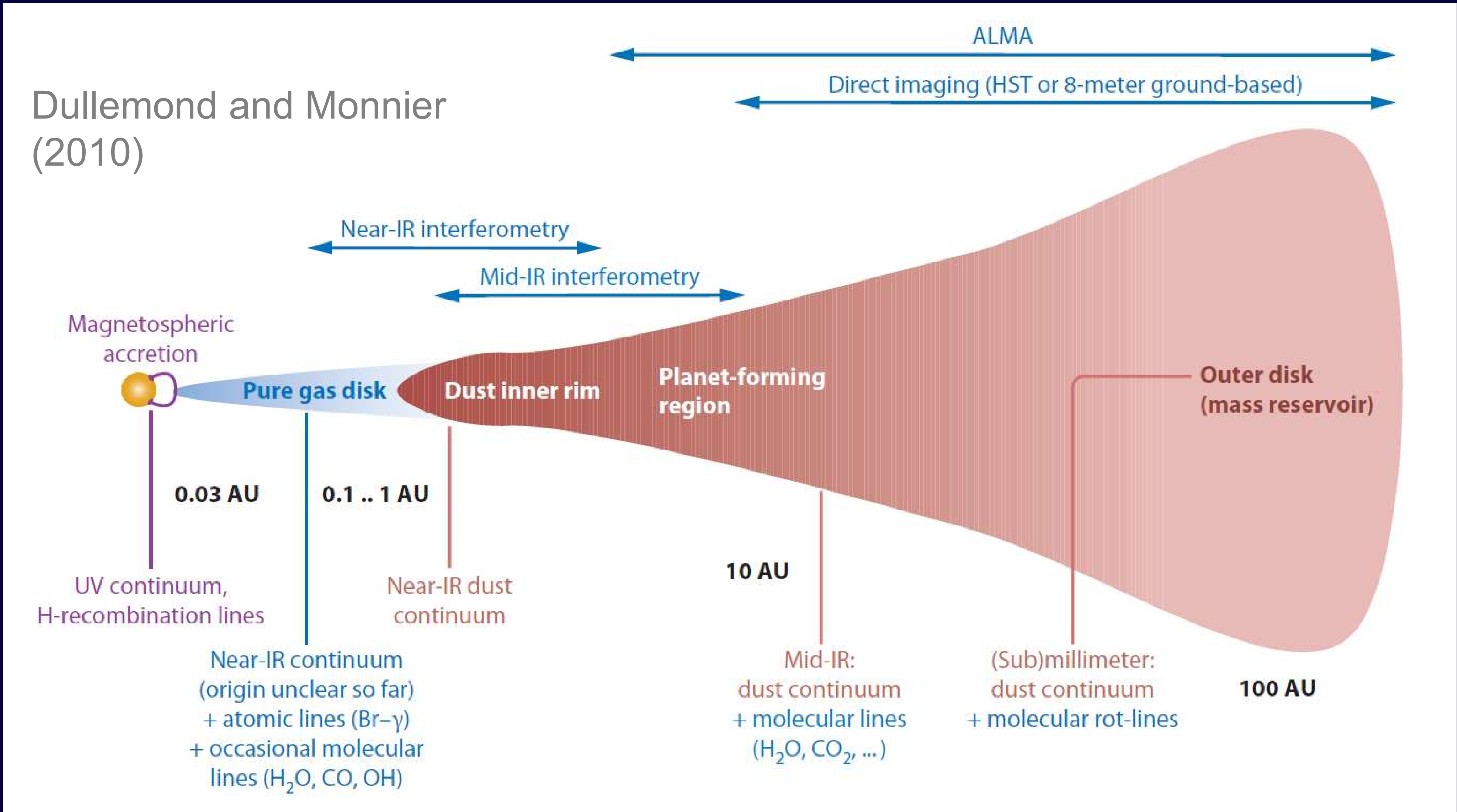
~0.001 arcsec

Angular Scales for 16 Mpc
Such as NGC1068

~0.1 arcsec

Urry and Padovani (1995)

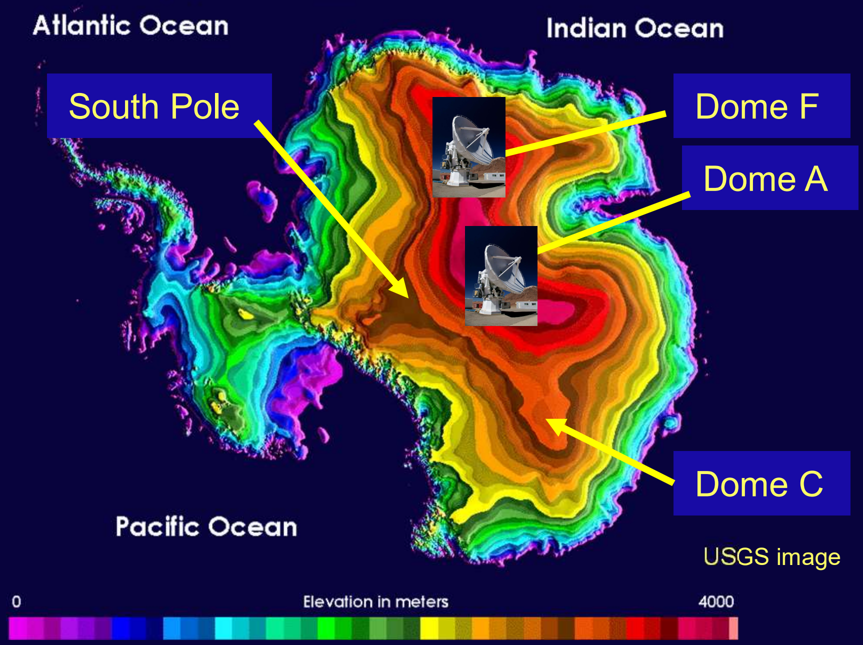
Structure of a protoplanetary disk



Scales are for Taurus and Auriga region

将来計画

- 南極望遠鏡（50 cm 2基）
  - Dome-A, Dome-Fの 1000 km 基線は魅力的
  - [NII] 205 μm,
  - [OIII] 88 μm, [OIII] 52 μm
  - 波長40 μm連続波
  - 原始惑星系円盤

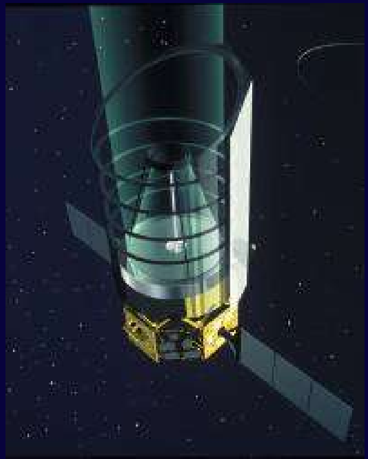


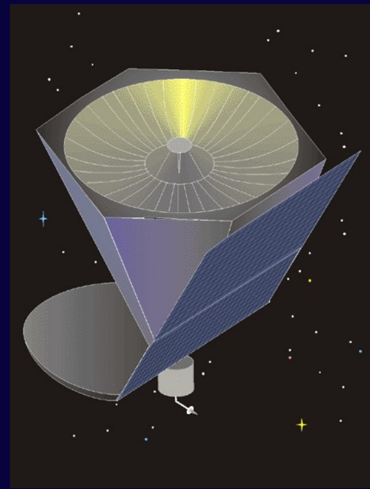
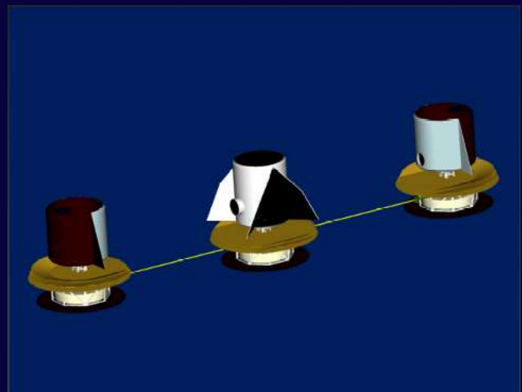
- 小型衛星
  - 口径 50 cm 冷却望遠鏡２素子の干渉計
  - イプシロンロケットで打ち上げ可能か？
  - 「あかり」点源のイメージングが可能

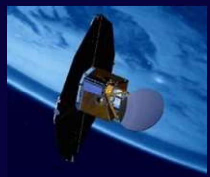
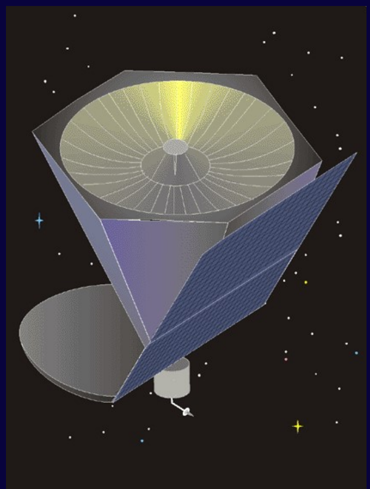
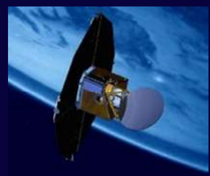
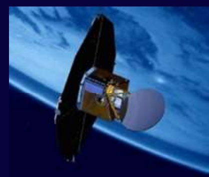
感度見積もり

- 野辺山電波ヘリオグラフ
  - アンテナ温度600 K, B = 80 MHz
  - 数100 photons/bunch, S/N~1 (t =10 nsec)
- 南極からの[OIII] 88 mm 大質量星形成領域
  - アンテナ温度100K, B= 30 MHz, NEP=1×10^{-17} W/Hz$^{0.5}$
  - 約1 photon/bunch, S/N~1 (t = 30 nsec)
- 小型衛星（口径50cm 2基）
  - 1 Jyの連続波源, B= 1 THz, NEP=5×10^{-19} W/Hz$^{0.5}$
  - Signal 3×10^{6} photons/sec, Background 1×10^{5} photons/sec

A Concept of Space Terahertz VLBI

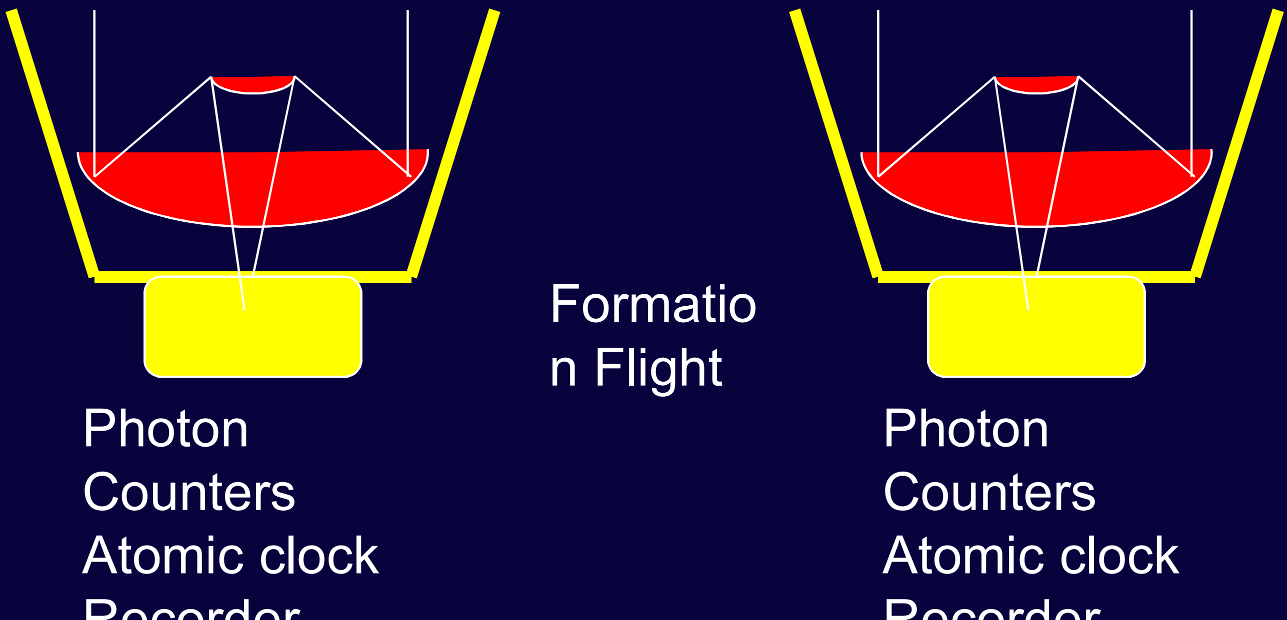



Technologies for Space THz Interferometry

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



まとめ

- 強度干渉計による画像合成は未完成
- 光子統計からわかること？
- 地上実験での検証が必要
- テラヘルツ光子検出器の開発が課題

でも、もし実現したら、

- VLBIで系外惑星が観測可能？
- Photon Counting Terahertz Interferometer in Space