遠赤外線光子計数型干渉計による超高解像度観測

強度干渉計

1ミリ秒角－10マイクロ秒角

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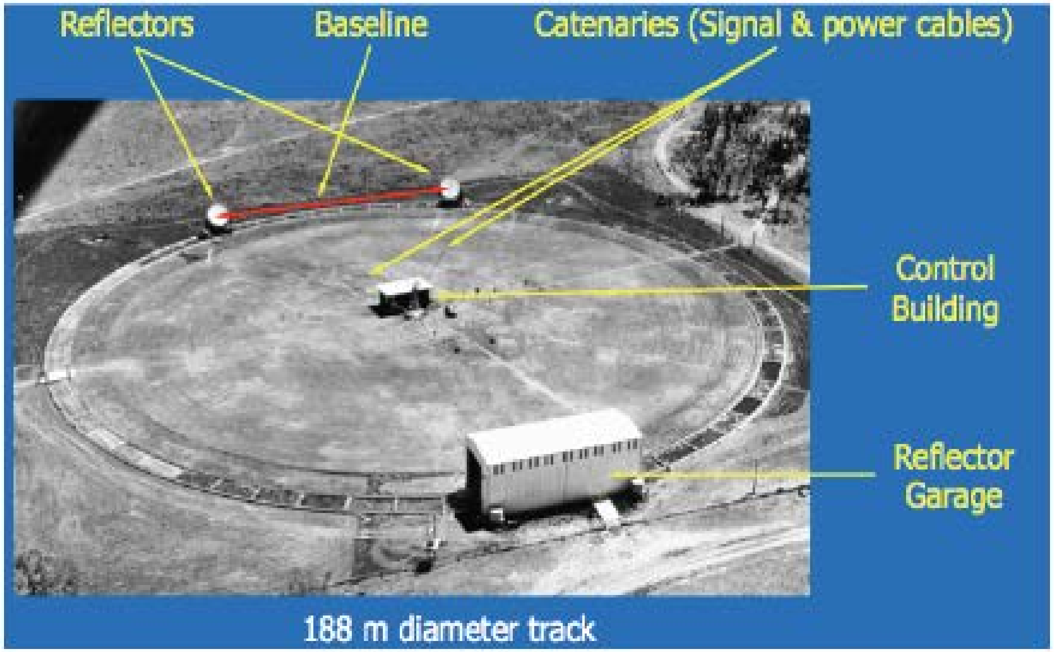
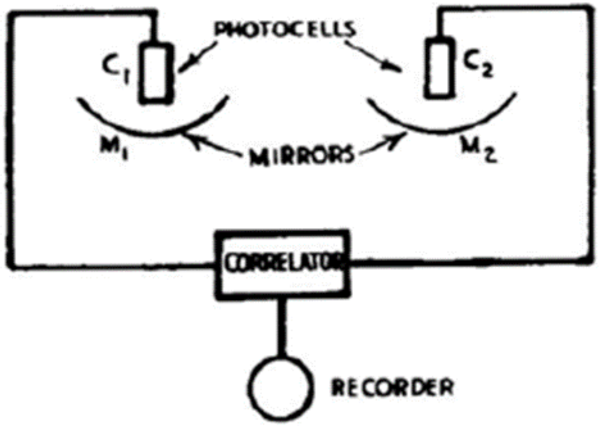
国立天文台・先端技術センター

Narrabri Stellar Intensity Interferometer



Hanbury-Brown et al. (1974)

Narrabri Stellar Interferometer



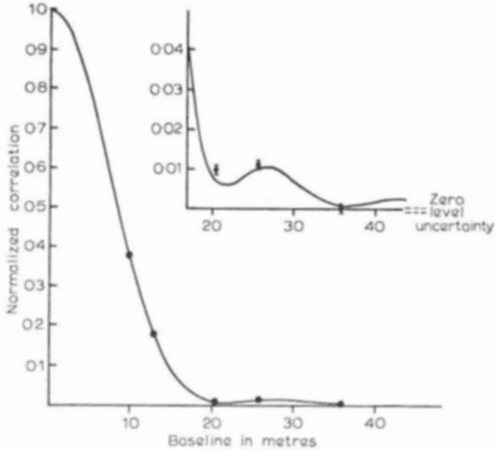
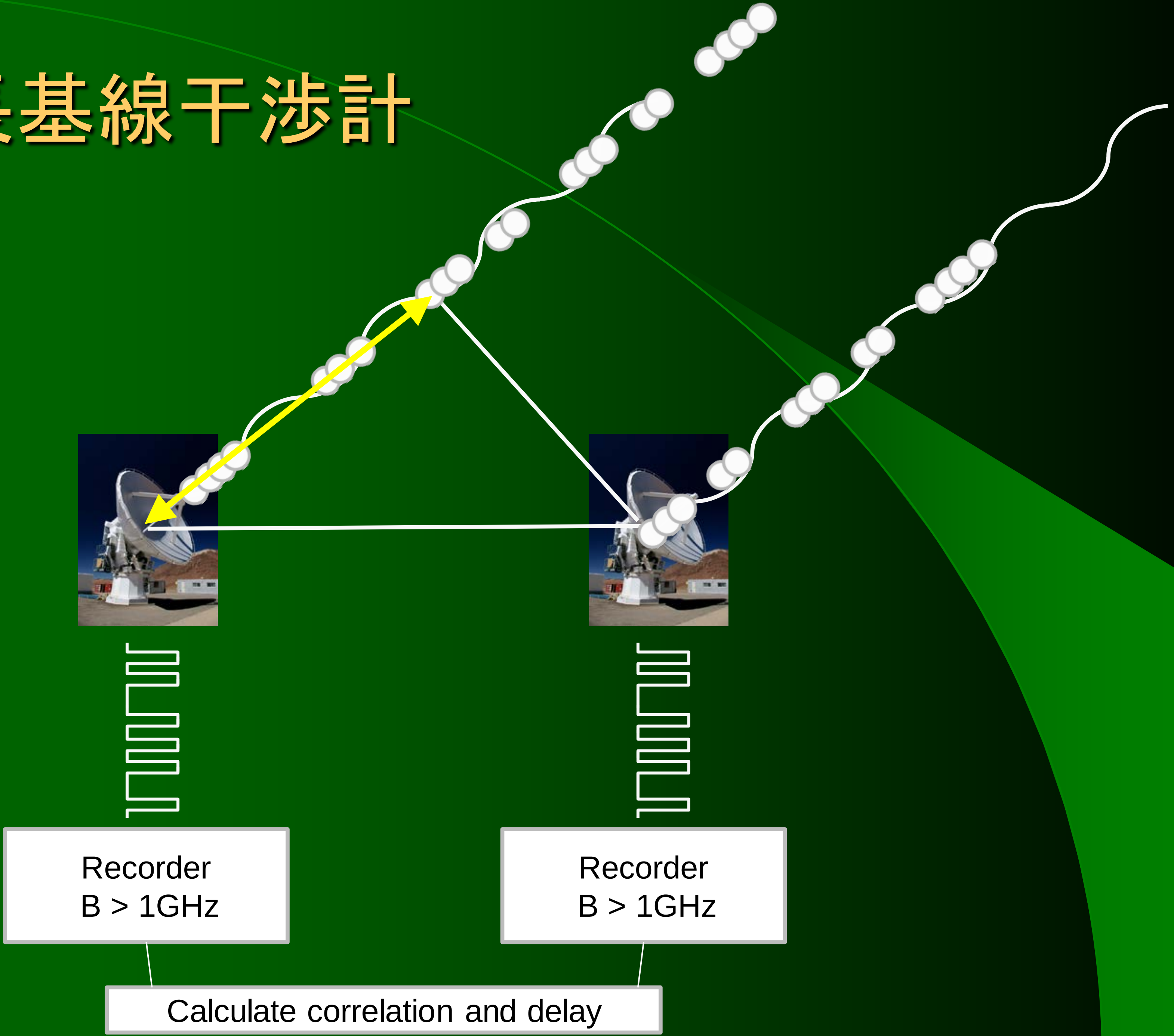


Fig. 11.5. Correlation as a function of baseline for Sirius A (α C Ma). The points show the observed results; the full line shows the theoretical curve for a model

強度干渉計の特徴

- 位相の揺らぎに強い
  - 大気揺らぎの影響を受けにくい。
- 直接検出器が使える
  - 受信機量子雑音（T > hν/k）の制限がない。
- 感度が悪い？
  - 赤外線では強度相関が強い。
- 画像合成ができない
  - 光子バンチから遅延時間が得られる。

超長基線干渉計



Recorder
B > 1GHz

Recorder
B > 1GHz

Calculate correlation and delay

強度干渉計による
複素ビジビリティの取得は可能？

- 手法① コーシー・リーマンの方程式

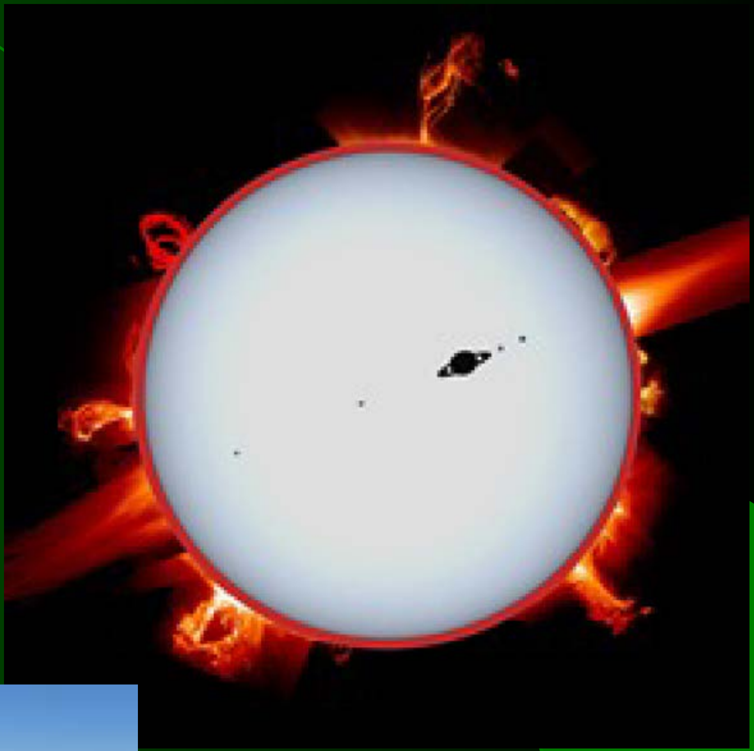
$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}, \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x},$$

$$\text{where } f(x+iy) = u(x,y) + iv(x,y)$$

- 手法② 光子バンチによる遅延時間測定
  - Bose-Einstein統計による光子バンチ
  - 強度相関と遅延時間の取得

CTA as Intensity Interferometer

- Phase recovery
  - Cauchy-Riemann equation (amplitude and phase relation)
- Angular resolution
  - 30 μas



Dravins, SPIE 99070M (2016)

Cherenkov Telescope Array

熱放射の揺らぎ

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

$$n : \text{光子占有数 (photon occupation number)}$$

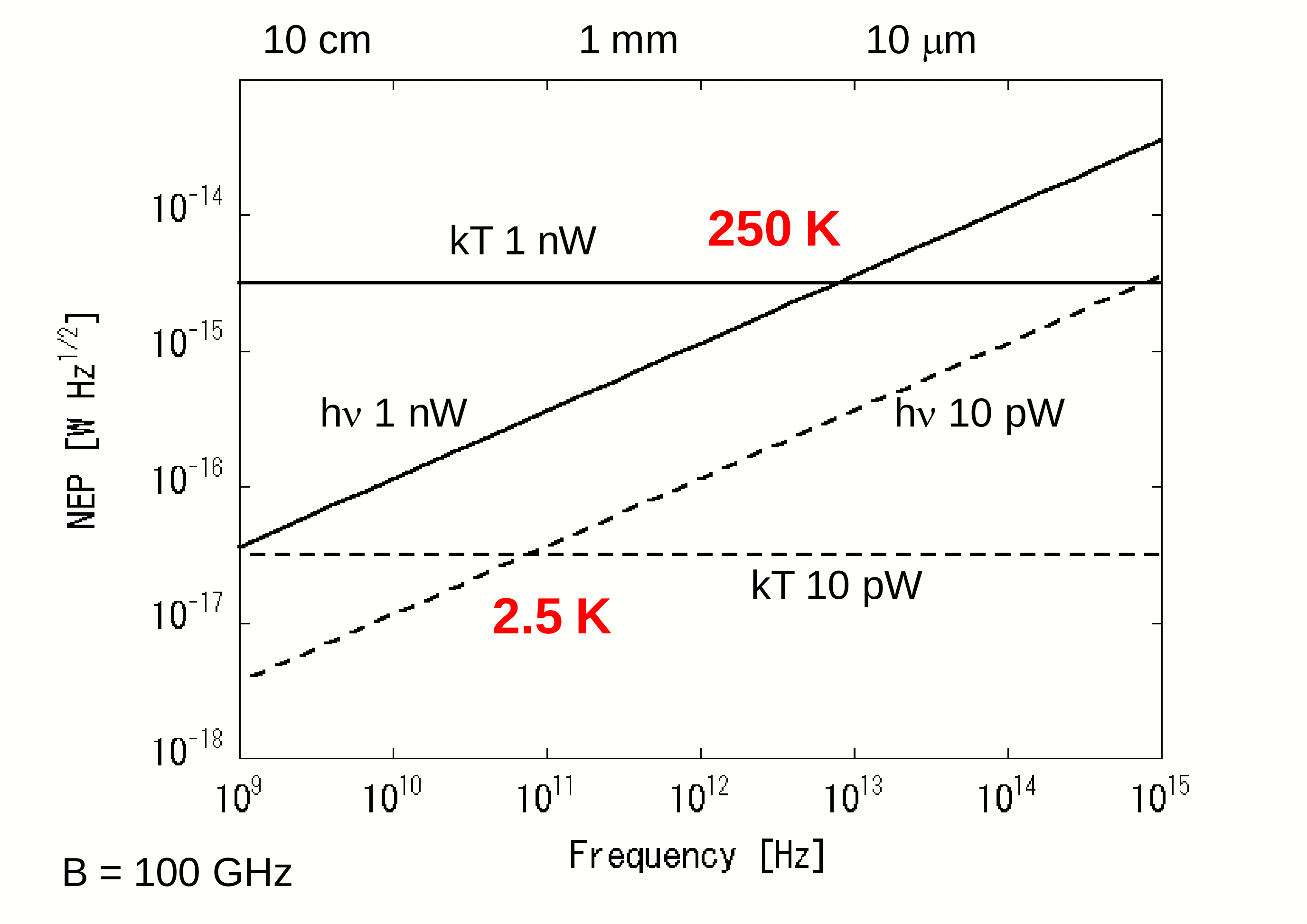
$$\mathrm{A} \cdot \Omega = \lambda^2$$

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

References A. Einstein (1909)
J. Mather (1984)
J. Zmuidzinas (2003)

テラヘルツ波の粒子性、波動性

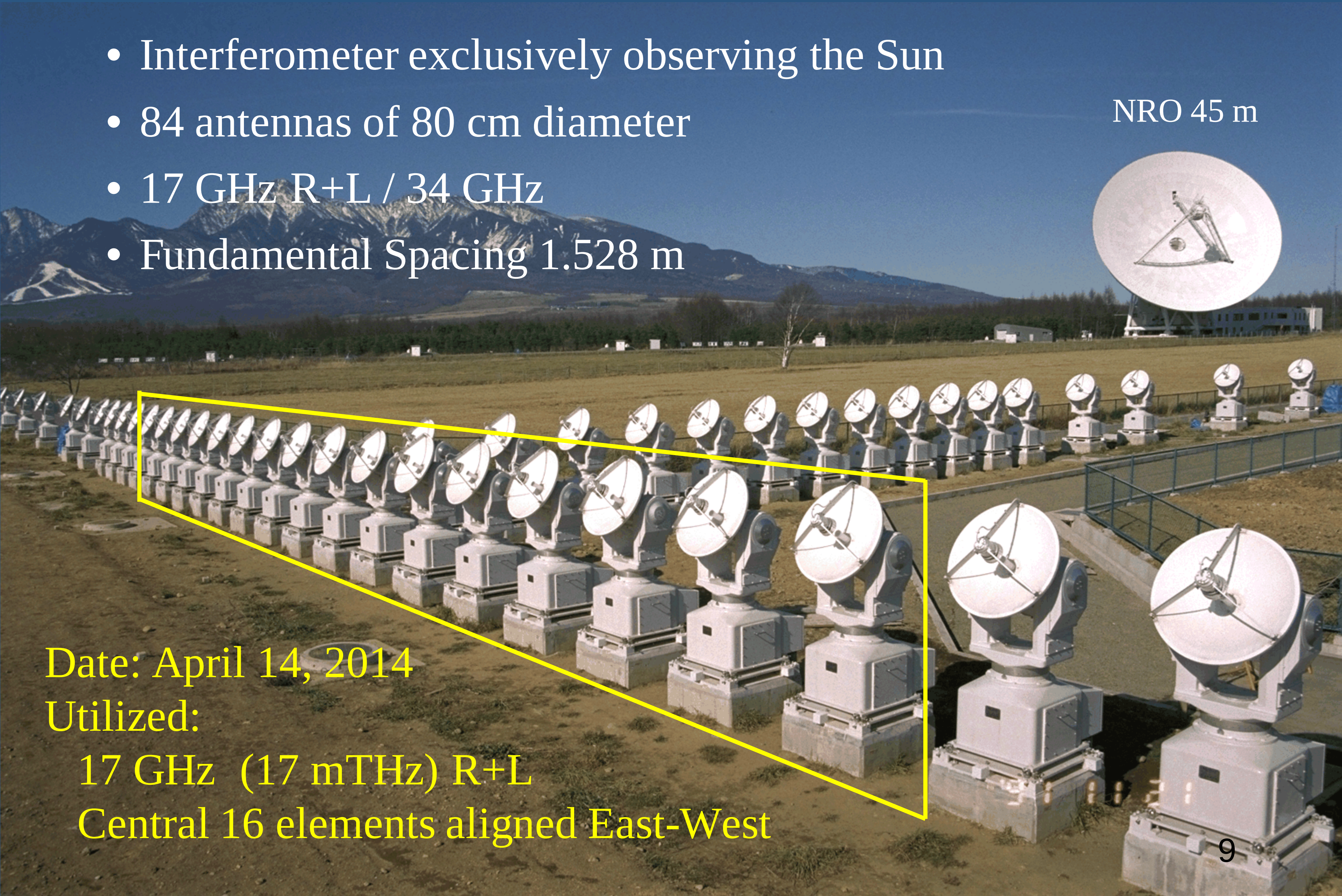
$$\mathrm{NEP}_{\mathrm{direct}} = \sqrt{2P\cdot\left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$



Matsuo（2009） シリーズ現代の天文学 16巻 「電波天文学」5.5章

Nobeyama Radioheliograph (NoRH)

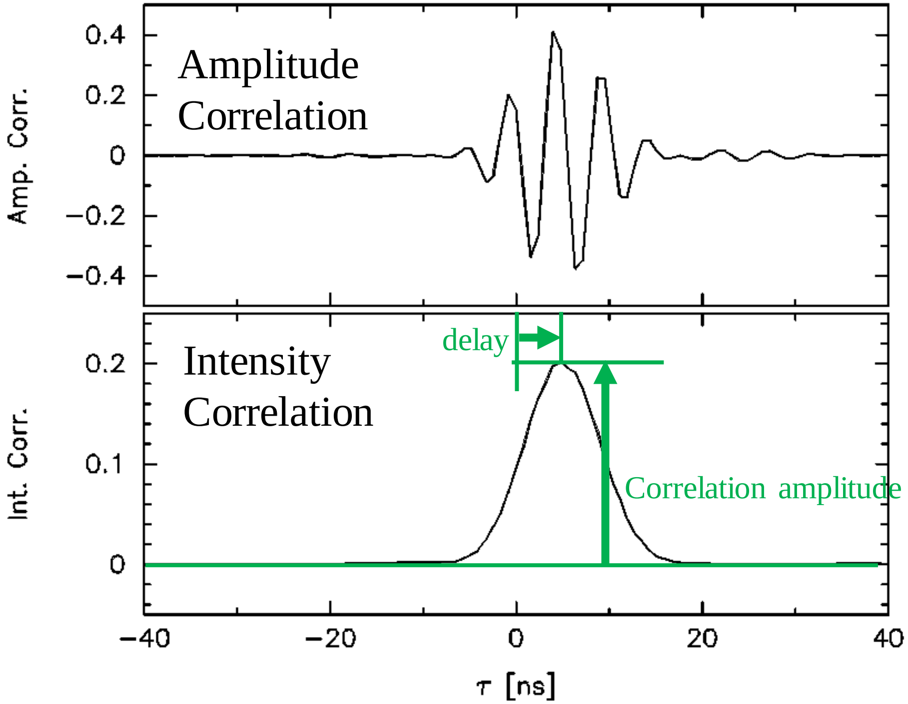
- Interferometer exclusively observing the Sun
- 84 antennas of 80 cm diameter
- 17 GHz R+L / 34 GHz
- Fundamental Spacing 1.528 m



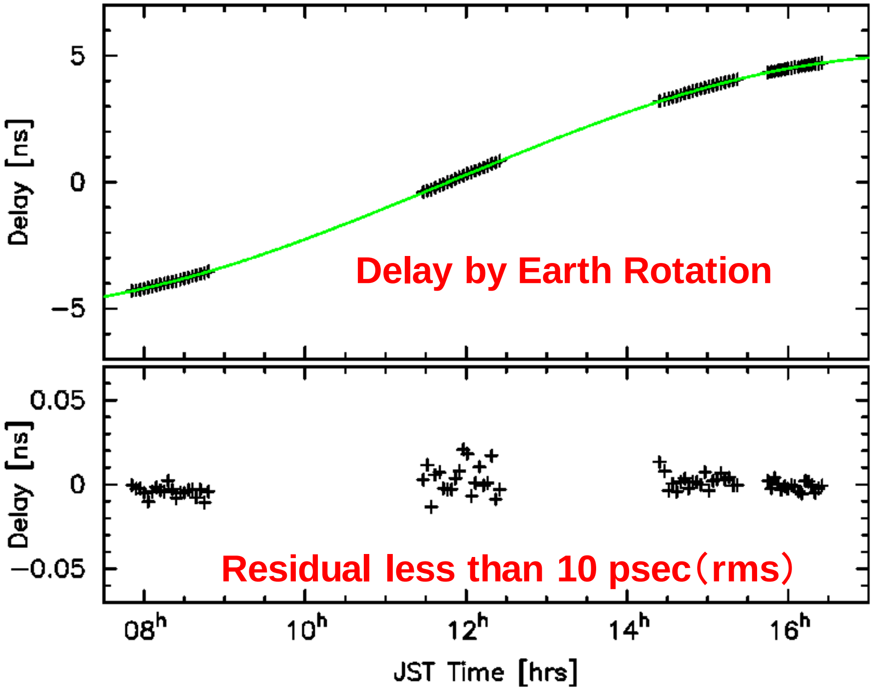
Date: April 14, 2014
Utilized:
17 GHz (17 mTHz) R+L
Central 16 elements aligned East-West

Nobeyema Radioheliograph at 17 GHz

Cross correlation between 2 nearby antennas (t_{int} = 50 msec)



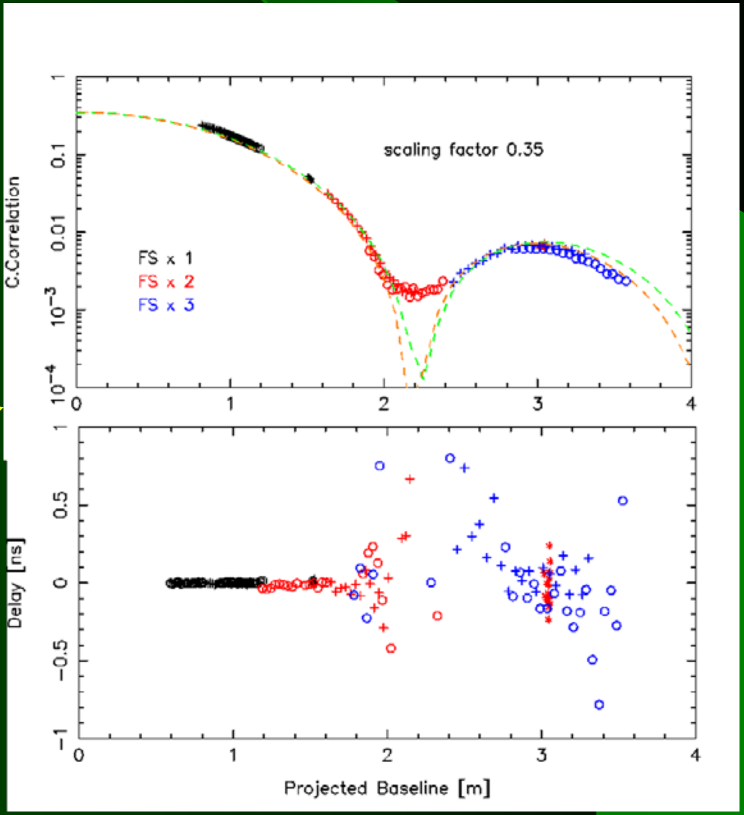
Delay measurement during daytime

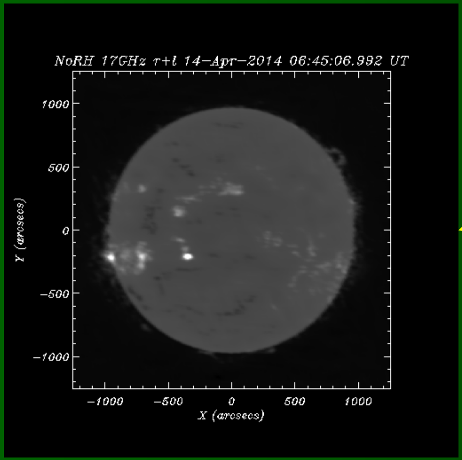


Ezawa, Matsuo et al. (2015)

Complex Visibility for Aperture Synthesis Imaging

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





遅延時間の測定精度

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

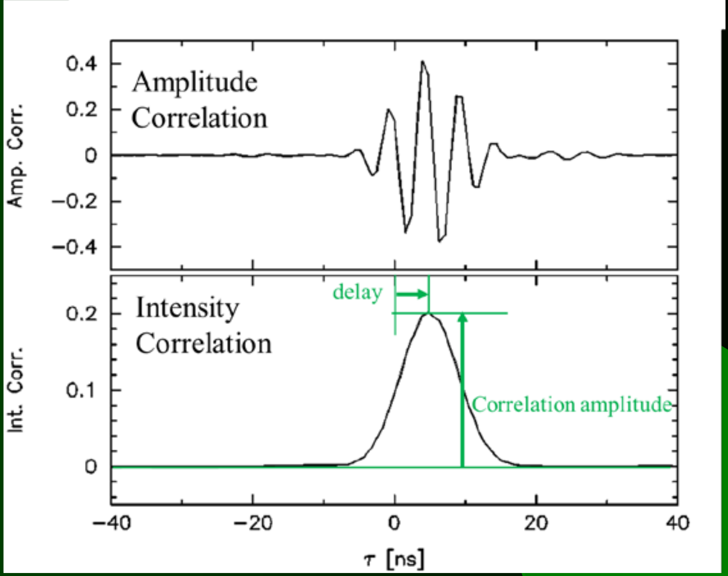
System Temperature T_{sys} [K]

Frequency ν [Hz]

Bandwidth $\Delta\nu$ [Hz]

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

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



強度干渉計から光子計数型干渉計へ

- テラヘルツ光子レートの見積もり
  - 100 M photons/sec

    100 Jy source, ν=10 THz, B=1 THz with 1 m telescope

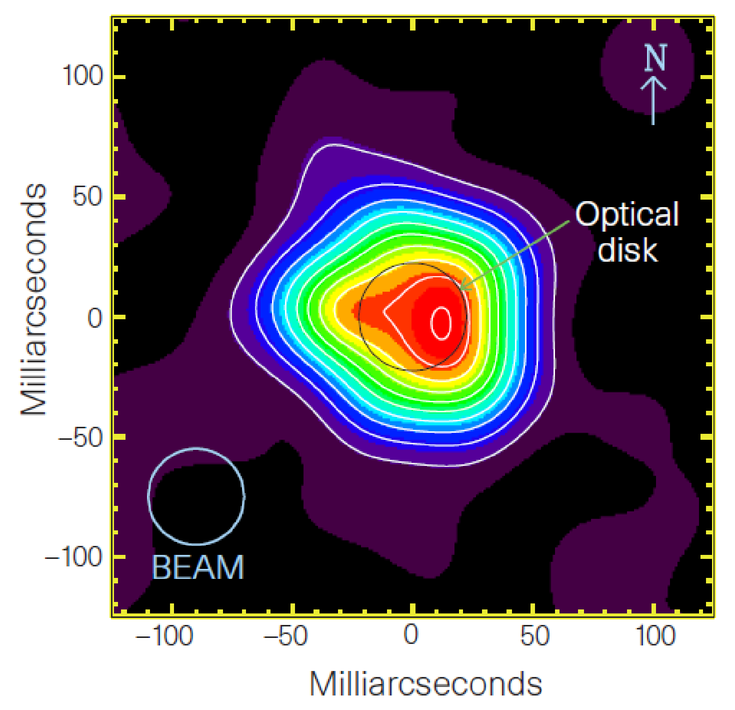
    1 Jy source, ν=1 THz, B=100 GHz with 10 m telescope
- 遅延時間測定精度
  - $\Delta t = 1/100\mathrm{M} / (100\mathrm{M} \cdot T)^{0.5} = 10^{-13}$ sec (T=100 sec)
- 高速動作の光子計数型検出器
  - 時間分解能 1 nsec で 10 THz 光子1個は、

    $\mathrm{NEP} = 2 \times 10^{-16}\ \mathrm{W/Hz}^{0.5}$

THz Photons are bunched !

Betelgeuse

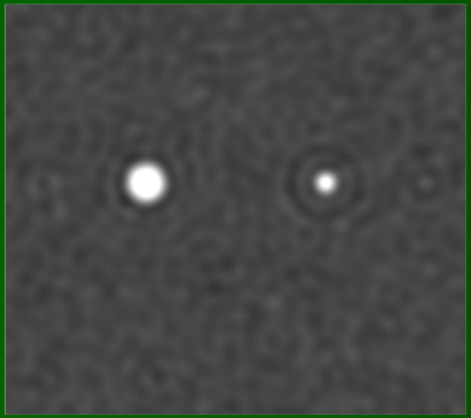
- Photospheric radius
  - 22.5 mas
- Temperature
  - 3600 K
- Flux Density
  - 3 Jy at 1 THz
  - T_A = 0.13 K (10 m dish)
  - $\Delta T = 500$ K / (10 GHz)$^{0.5}$
  - $\Delta t = 4$ psec / $(t_{int})^{0.5}$ = 0.2 psec (t_{int} =10 min)



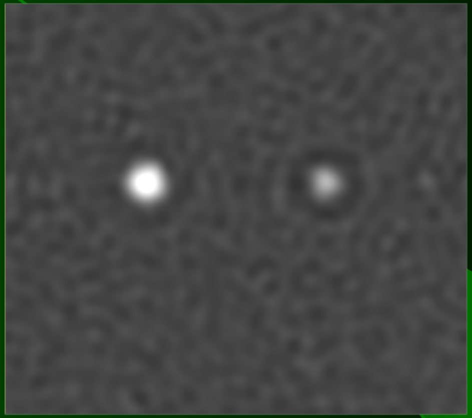
VLA 7 mm
Lim et al. Nature (1998)

波長300μm 1 THz でのシミュレーション（BL=6km）

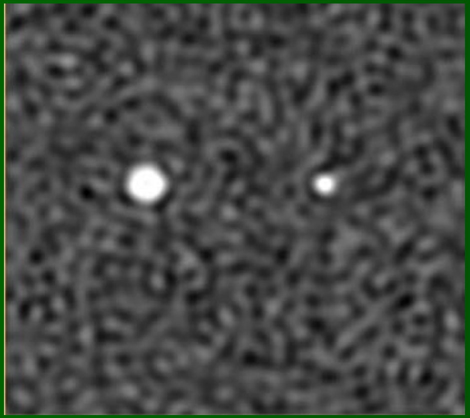
Amplitude
Δν = 10 GHz, t=60 sec
Phase error 50 μm



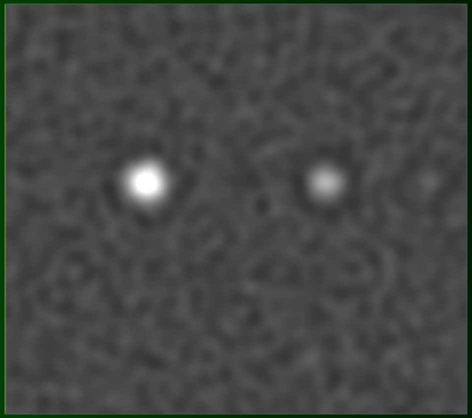
Intensity
Δν = 100 GHz, t=600 sec
Phase error 50 μm



Amplitude
Δν = 10 GHz, t=60 sec
Phase error 100 μm



Intensity
Δν = 100 GHz, t=600 sec
Phase error 100 μm



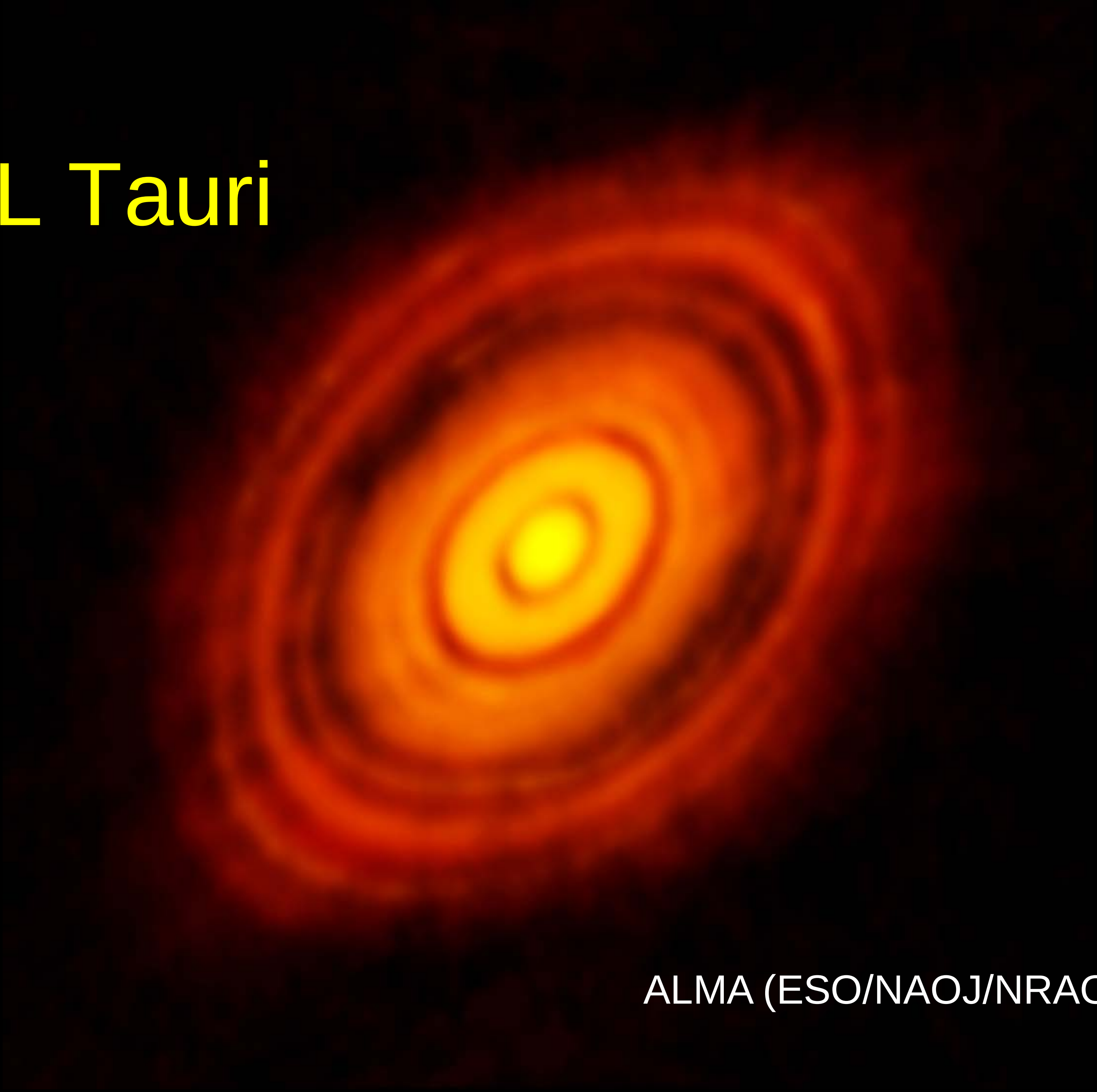
背景放射限界で観測すると

- 感度の向上（3THz vs. 100GHz）
  - T_{sys} = NEP / (2k $B^{0.5}$) = 10 mK
  - 量子雑音　vs. 背景放射雑音　4-5桁
  - 帯域幅　　$(1\ \mathrm{THz} / 1\ \mathrm{GHz})^{0.5}$ = 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

強度干渉計による画像合成

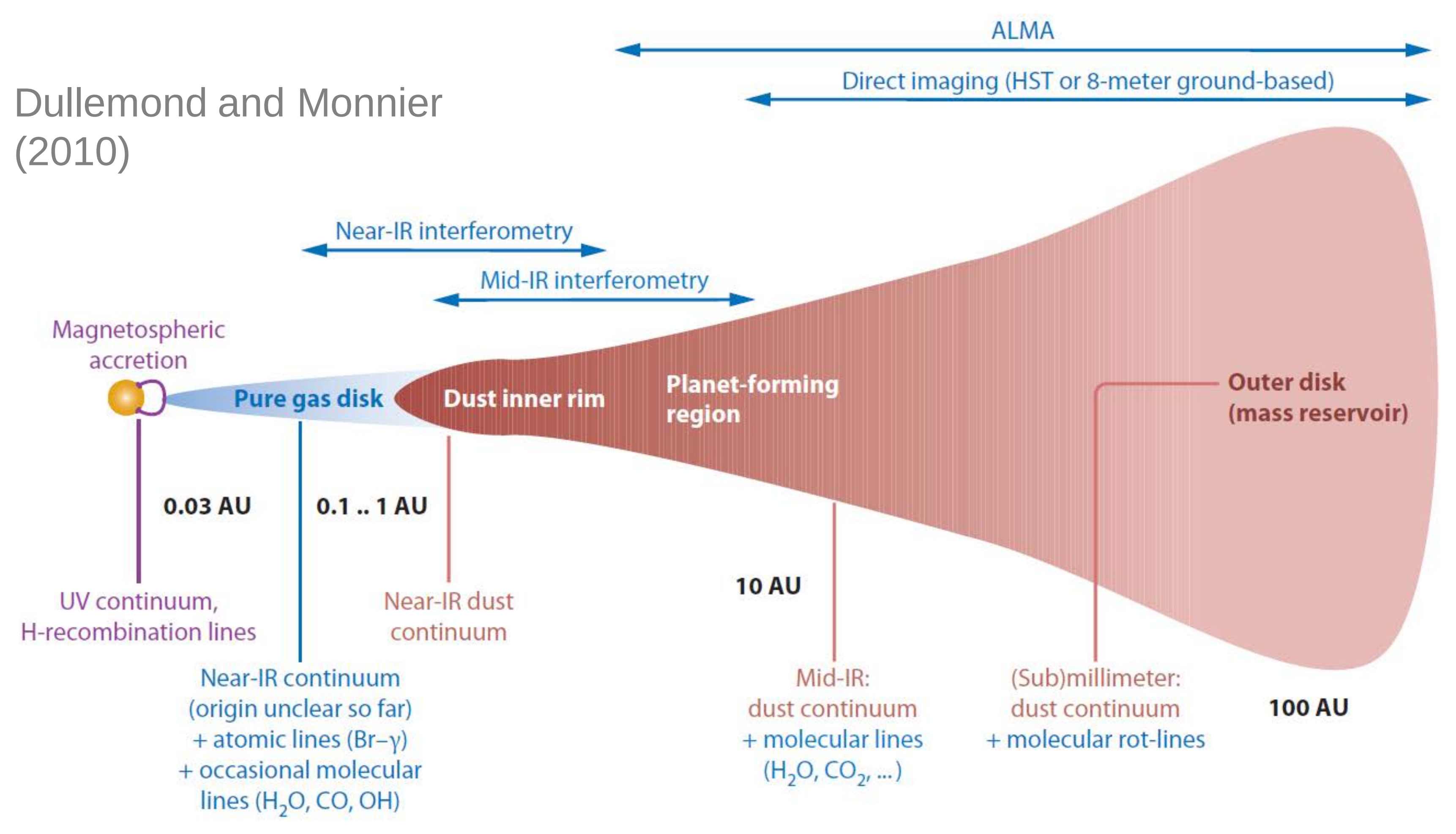
- 強度相関による遅延時間決定には長時間の積分が必要
- 強度干渉計は光度の高いコンパクトな天体の観測に適している
- 大気の位相揺らぎによる影響を受けにくい
- 宇宙空間からの超高感度・高解像度観測が期待される

HL Tauri



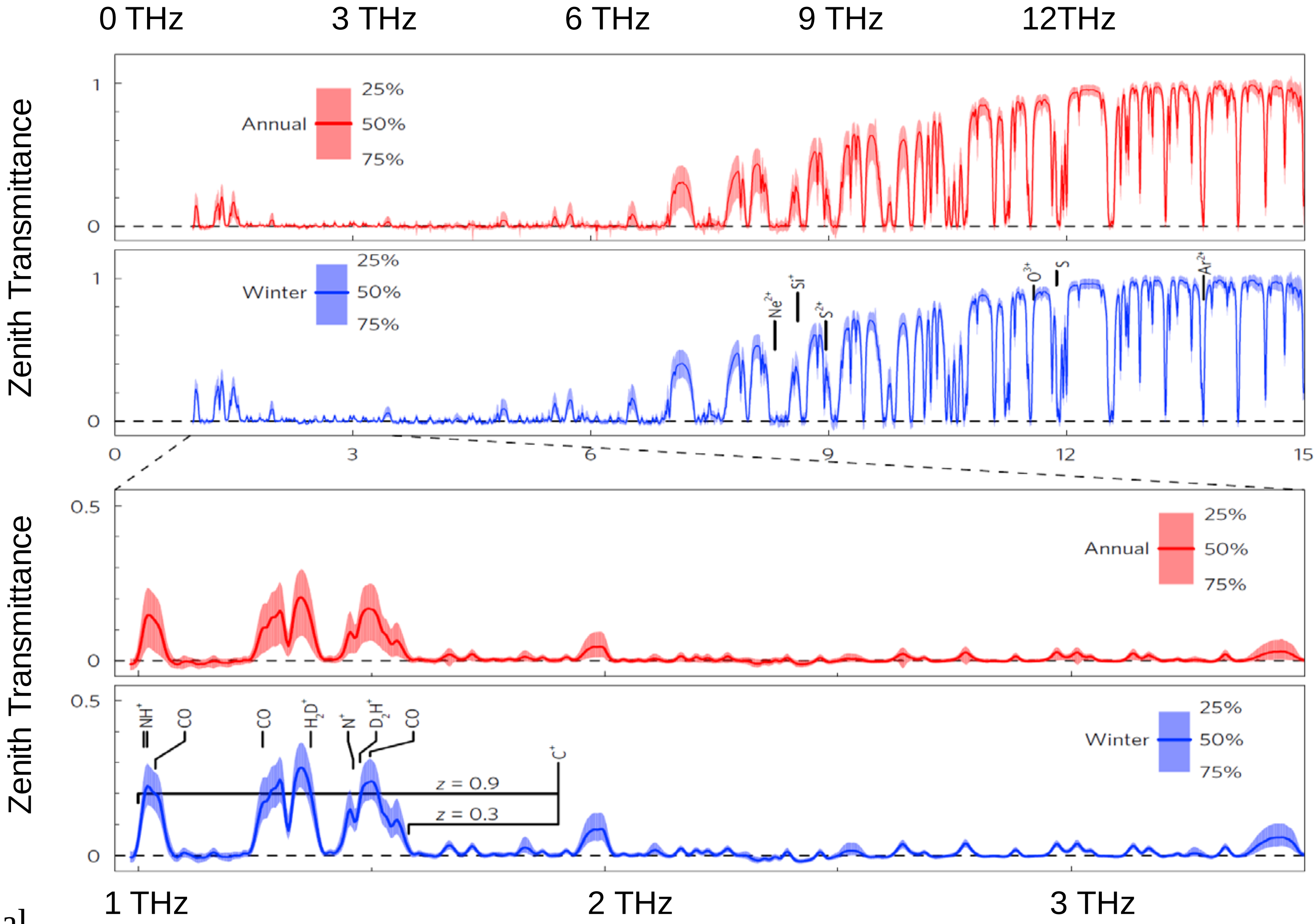
ALMA (ESO/NAOJ/NRAO)

Structure of a protoplanetary disk



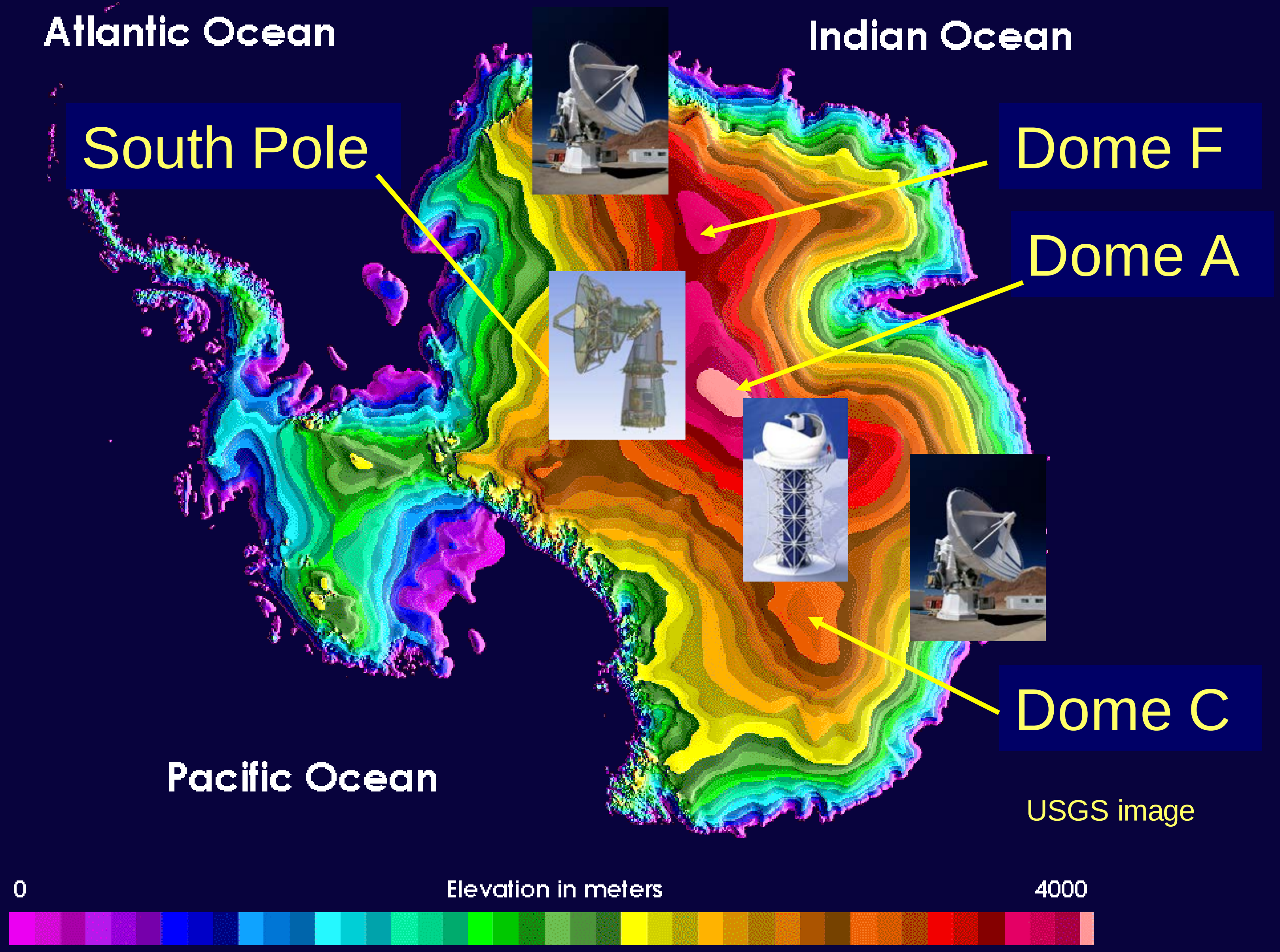
Scales are for Taurus and Auriga region

Terahertz and far-infrared windows from Dome A



Shi et al.
Nature Astronomy 1, 0001 (2016)

Interferometry from Antarctica



South Pole

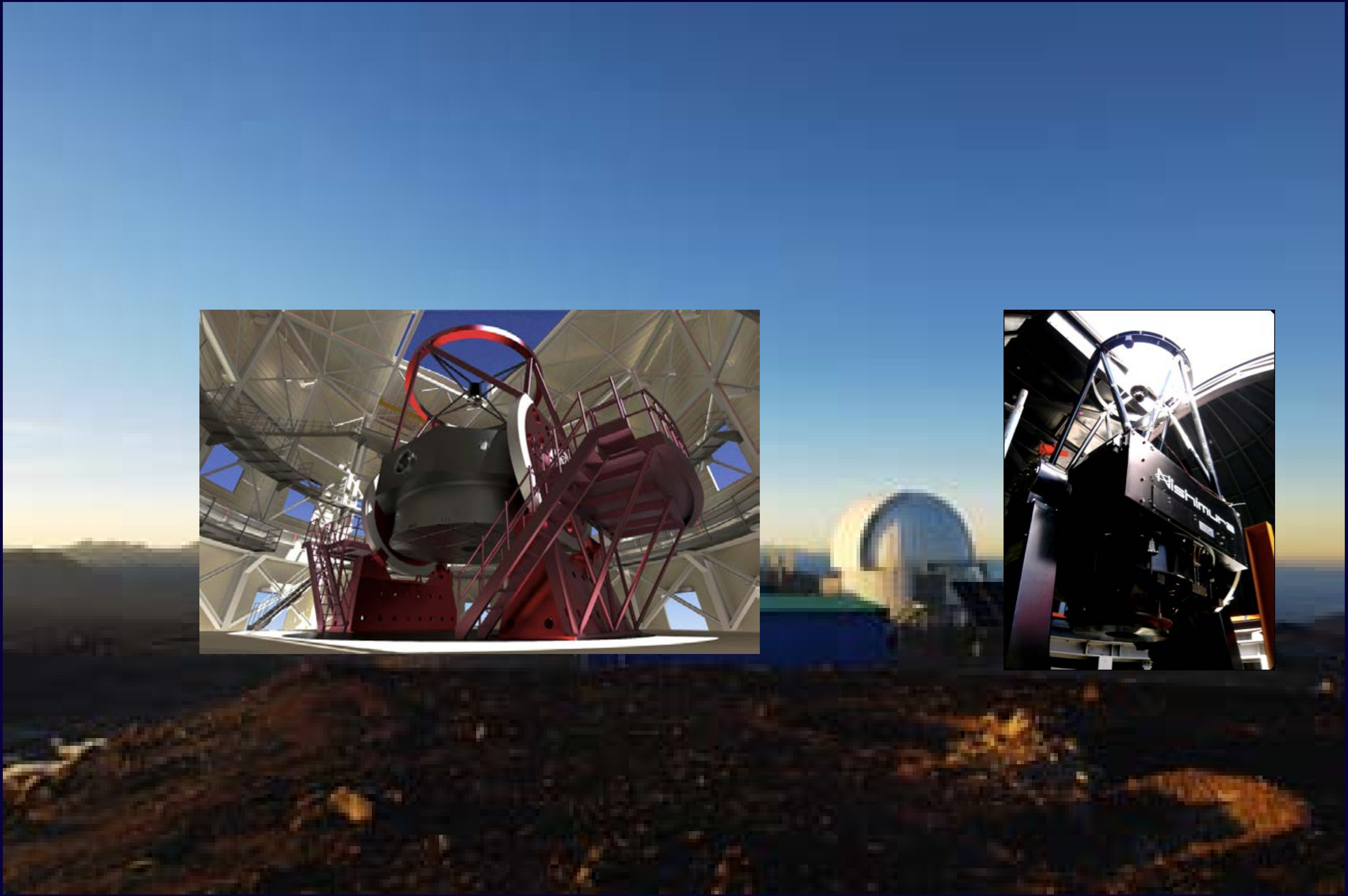
Dome F

Dome A

Dome C

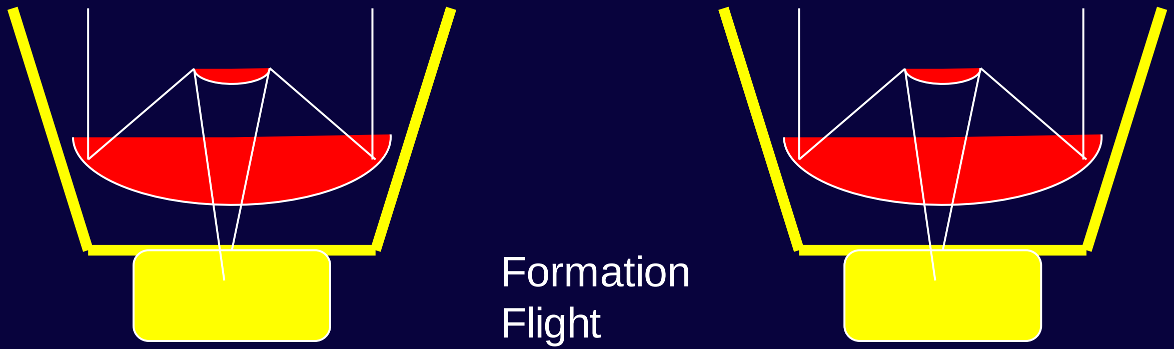
USGS image

TAO Intensity Interferometer



Technologies for Space THz Interferometry

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



Photon Counters
Atomic clock
Recorder

Formation
Flight

Photon Counters
Atomic clock
Recorder

A Concept of
Space Terahertz Interferometer