Greenland Telescope (GLT): Imaging the Black Hole Shadow

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& the GLT Project Team (ASIAA & SAO)

Primary Science Target: Direct Imaging of the Shadow of Black Holes

Sizes of Black Holes

	Shadow Size (μasec)	Mass (10^6 Mo)	Distance (Mpc)
Sgr A*	50	4.1 +- 0.6	0.008
M87	39	6600 +- 400	17.0
M31	18	180 +- 80	0.80
M60	12	2100 +- 600	16.5
NGC 5128 (Cen A)	7	310 +- 30	4.5

Note: Here we assume $R_{shadow} \sim 5 \times R_{sch}$

Gebhardt et al. (2011)

Spatial Resolution

- Spatial resolution goes high with shorter wavelength (or higher frequency) and bigger telescope (or longer baseline):
  - Resolution ~ λ/D

    λ: Wavelength

    D: Diameter of telescope (or baseline length)

- Spatial resolutions of the optical/infrared telescopes:
  - Hubble Space Telescope (HST): 0.04” (40 milliarcsec)
  - James Webb Space Telescope (JWST): 0.03” (30 milliarcsec)
  - VLT Interferometer (VLTI): 0.002” (2 milliarcsec)

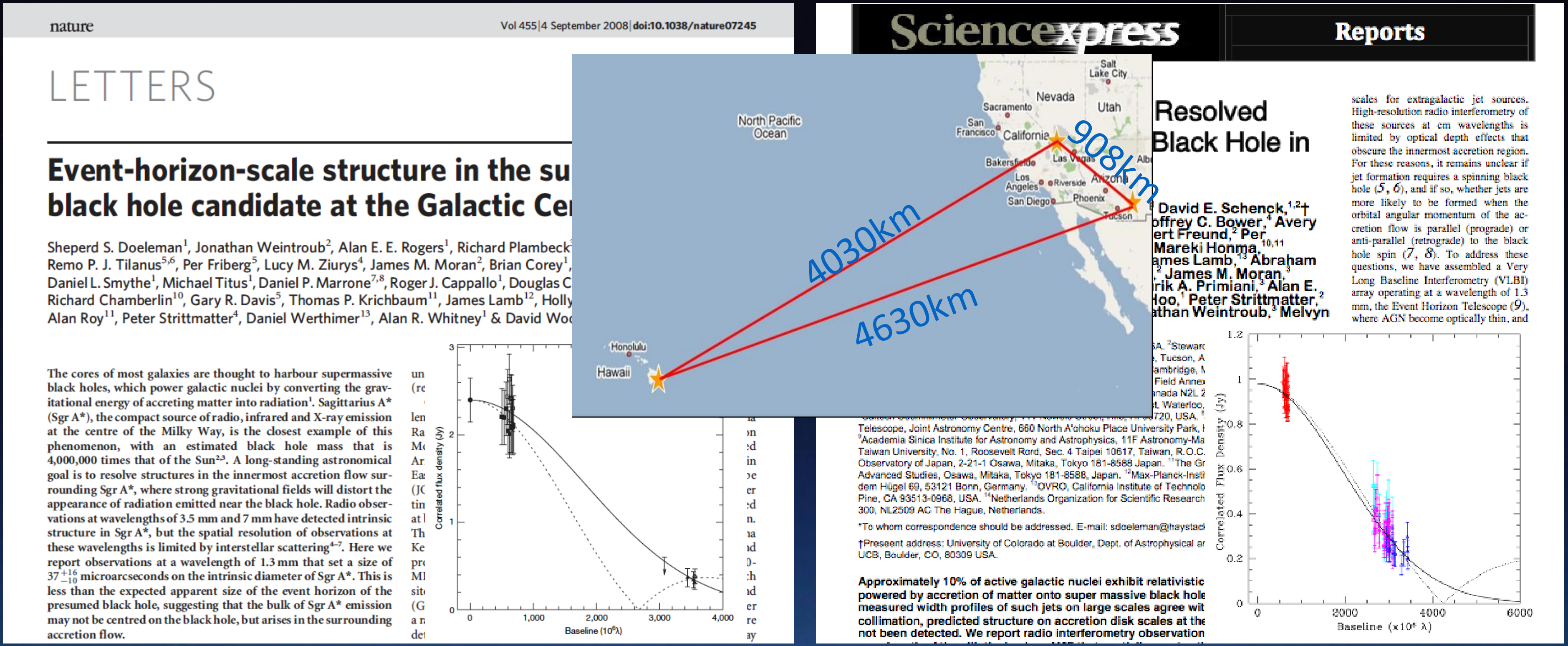
⇨ Too large to image black holes, whose sizes are μarcsec scale.

⇒ Submillimeter Interferometry !!!

Feasibility of Submillimeter VLBI

Doeleman et al. (2008)

Doeleman et al. (2012)



nature Vol 455|4 September 2008|**doi:10.1038/nature07245**

LETTERS

Event-horizon-scale structure in the su
black hole candidate at the Galactic Ce

Sheperd S. Doeleman[1], Jonathan Weintroub[2], Alan E. E. Rogers[1], Richard Plambeck
Remo P. J. Tilanus[5,6], Per Friberg[5], Lucy M. Ziurys[4], James M. Moran[2], Brian Corey[1],
Daniel L. Smythe[1], Michael Titus[1], Daniel P. Marrone[7,8], Roger J. Cappallo[1], Douglas C
Richard Chamberlin[10], Gary R. Davis[5], Thomas P. Krichbaum[11], James Lamb[12], Holly
Alan Roy[11], Peter Strittmatter[4], Daniel Werthimer[13], Alan R. Whitney[1] & David Wo

The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation[1]. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun[2,3]. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering[4–7]. Here we report observations at a wavelength of 1.3 mm that set a size of 37^{+16}_{-10} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A* emission may not be centred on the black hole, but arises in the surrounding accretion flow.

Sciencexpress **Reports**

Resolved
Black Hole in

David E. Schenck,[1,2]†
offrey C. Bower,[4] Avery
ert Freund,[2] Per
Mareki Honma,[10,11]
ames Lamb,[13] Abraham
,[2] James M. Moran,[3]
rik A. Primiani,[3] Alan E.
Hoo,[1] Peter Strittmatter,[2]
athan Weintroub,[3] Melvyn

scales for extragalactic jet sources. High-resolution radio interferometry of these sources at cm wavelengths is limited by optical depth effects that obscure the innermost accretion region. For these reasons, it remains unclear if jet formation requires a spinning black hole (5, 6), and if so, whether jets are more likely to be formed when the orbital angular momentum of the accretion flow is parallel (prograde) or anti-parallel (retrograde) to the black hole spin (7, 8). To address these questions, we have assembled a Very Long Baseline Interferometry (VLBI) array operating at a wavelength of 1.3 mm, the Event Horizon Telescope (9), where AGN become optically thin, and

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dem Hügel 69, 53121 Bonn, Germany. [13]OVRO, California Institute of Technolo
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Approximately 10% of active galactic nuclei exhibit relativistic
powered by accretion of matter onto super massive black hole
measured width profiles of such jets on large scales agree wit
collimation, predicted structure on accretion disk scales at the
not been detected. We report radio interferometry observation

Sgr A*

Size ≈ 40 µas (≈ 4 r_{sch})

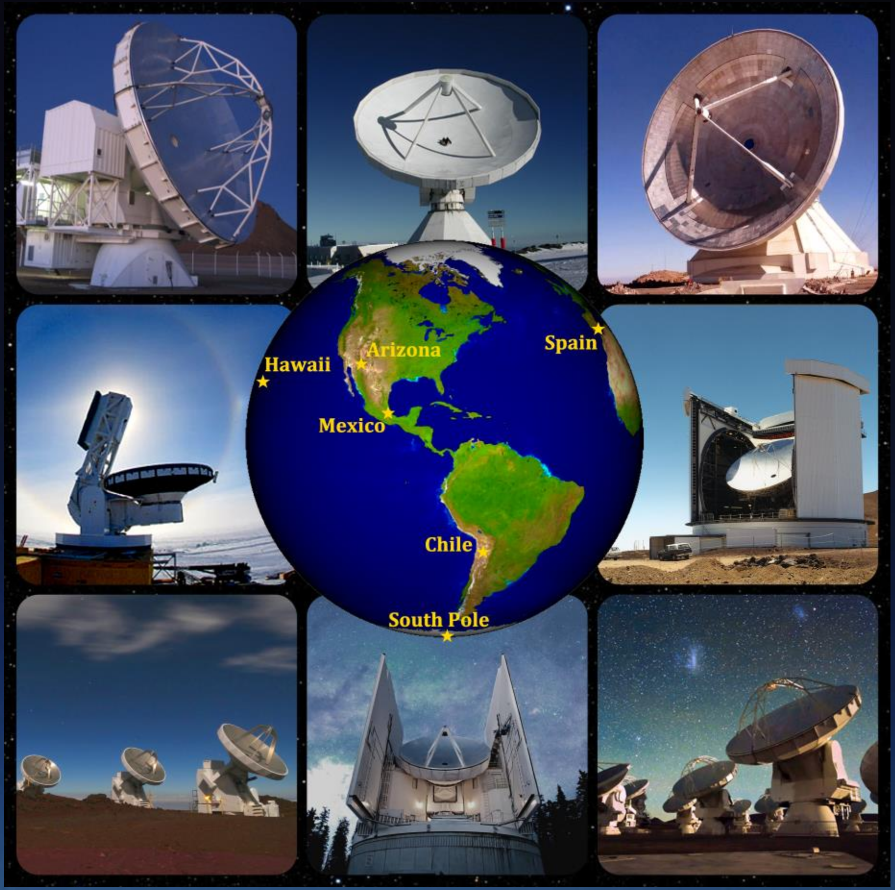
Vir A* (M 87)

Size ≈ 40 µas (≈ 5 r_{sch})

Why Greenland?

Submillimeter Telescopes in the World

- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter Telescope (SMT), Arizona

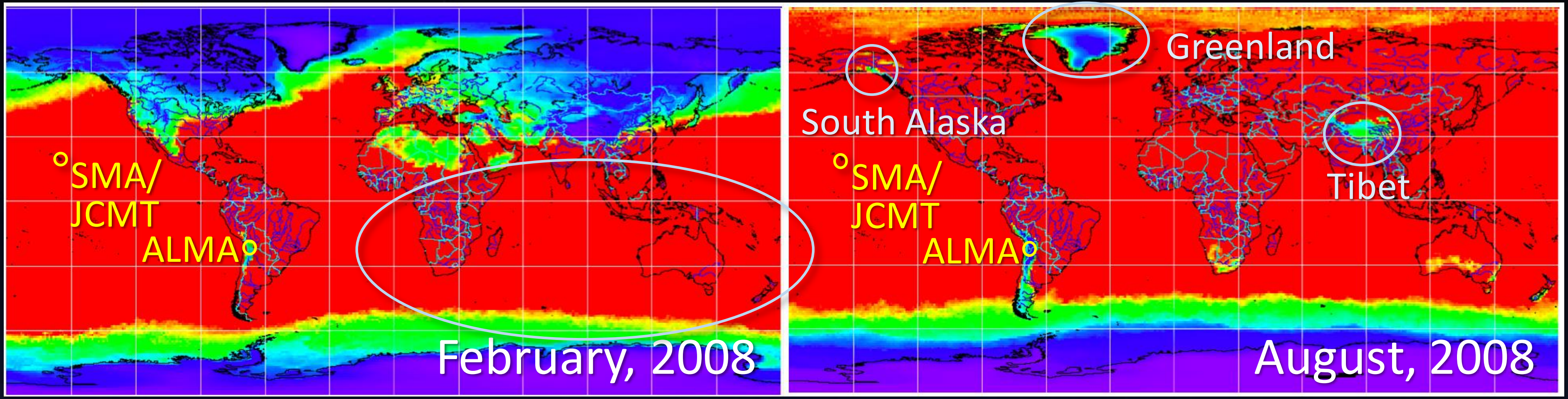


M. Johnson/SAO

Telescope Site Selection

- Site selection criteria:
  - Precipitable water vapor (PWV) is low.
  - Longest possible baselines with existing submm telescopes.
    (i.e., site with no existing submm telescopes)
  - Overlapping sky coverage with ALMA.
    - ALMA has the largest aperture size.
      (corresponds to 85 m single-dish telescope)
    - Interferometric baseline sensitivity $\propto \sqrt{A_1 A_2}$
  - Accessible.

Telescope Site Selection



Winter in the North, Summer in the South

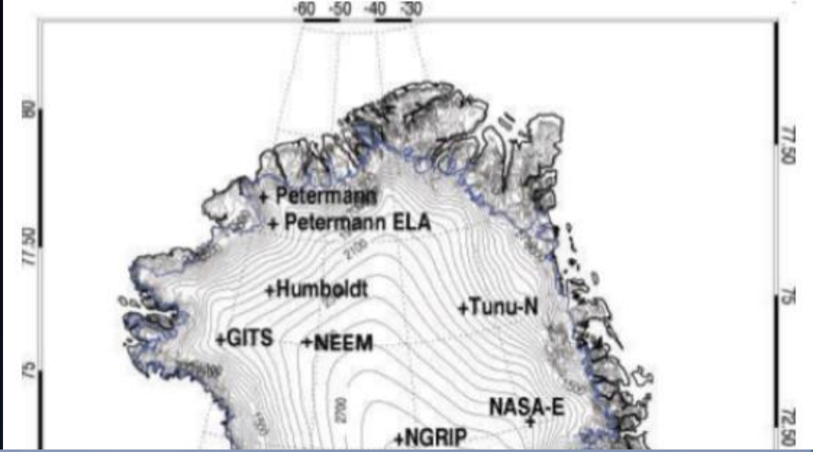
Winter in the South, Summer in the North

NASA Aqua & Terra/MODIS Satellite Data. PWV > 3 mm is displayed as red color.

- No obvious site in the Southern Hemisphere, except Northern Chile and Antarctica.
- South Alaska (Mt. McKinley or Mt. Denali): Difficult to access.
- Tibet: opposite side of ALMA, so impossible to have baseline with it.
- Greenland: Similar condition as South Pole. It is also possible to have baselines with ALMA/SMA/JCMT.

Greenland - Summit Station

- Established/operated by US NSF & Greenland Government.
  - Established on 1989.
  - Atmospheric and weather researches are mainly ongoing.
  - N72.60°, W38.42°. Altitude: 3210m.
  - Summer: 45 people, Winter: 5 people (3 months shift)
  - Possible to carry things by flights with C-130, etc., or through land.

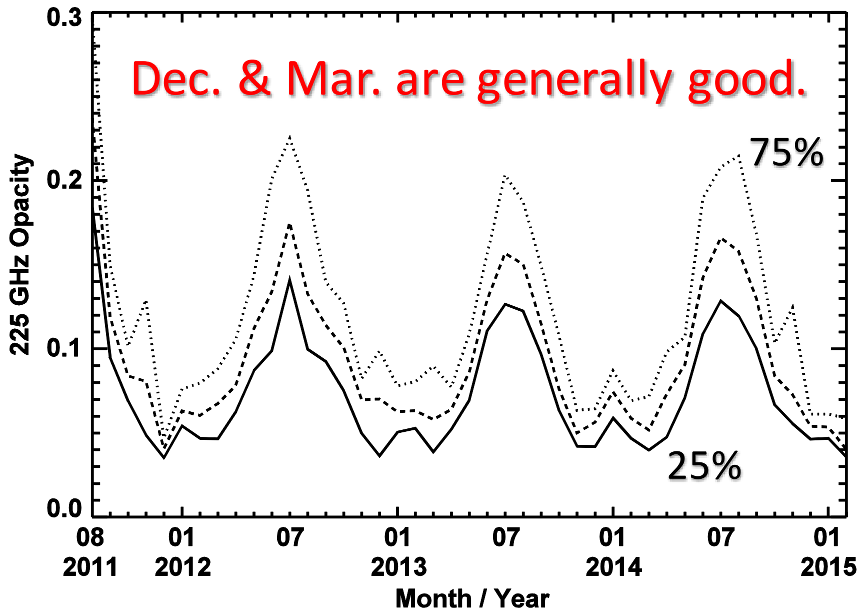


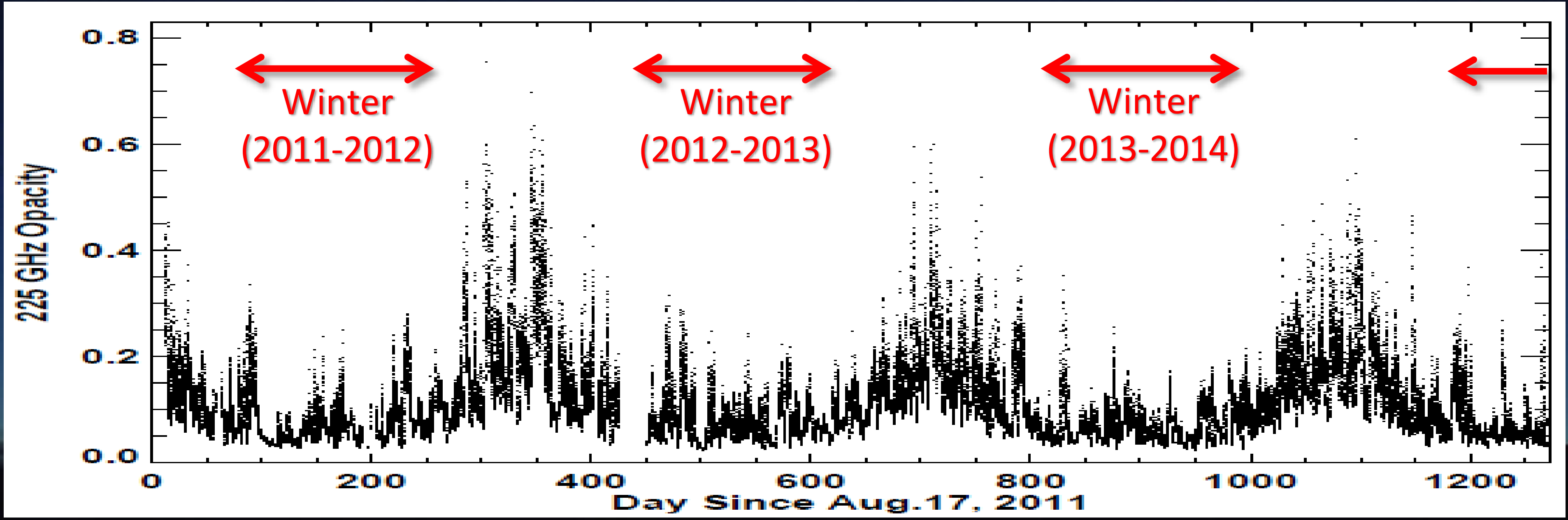
225 GHz Opacity at the Summit of Greenland


225 GHz Tipping Radiometer
at Greenland Summit Station

Start operation from Aug.17, 2011

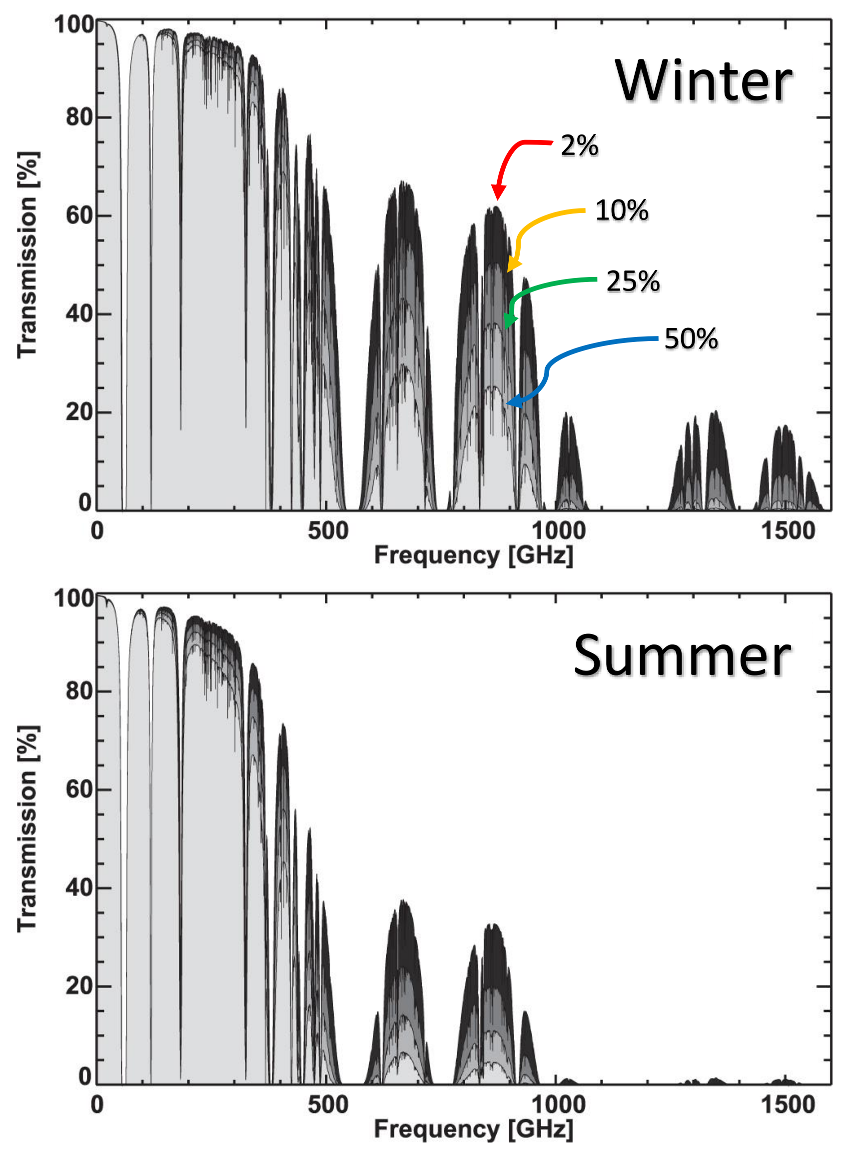
Matsushita et al. 2017, PASP, 129, 025001


Dec. & Mar. are generally good.



Atmospheric Transmission

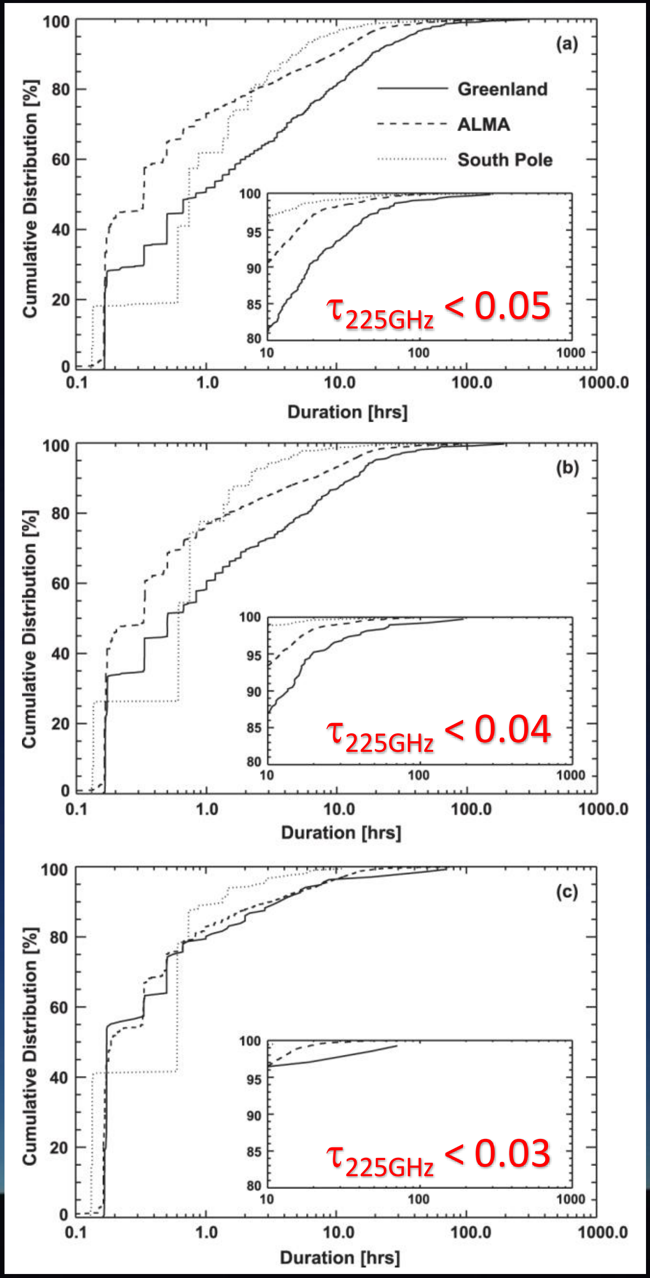
- Using the radiative transfer program “am” (Paine 2016), we estimated the atmospheric transmission spectra.
- Observable time:
  - Winter
    - < 450 GHz: Little atmospheric attenuation (τ < 0.5) most of the winter time.
    - 450 ~ 1000 GHz: Half of the time with τ < 1.2.
    - THz windows: 10% of the winter time will have an atmospheric transmission > 10%.
  - Summer
    - < 380 GHz: Little atmospheric attenuation (τ < 0.5) most of the summer time.
    - 450 GHz window: More than half of the time with τ < 1.
    - 450 - 1000 GHz: 25% of the summer time will have an atmospheric transmission > 10%.
    - THz windows: Hopeless in summer.



Matsushita et al. 2017, PASP, 129, 025001

Duration of Low Opacity Conditions

- Calculated time durations of opacity conditions continuously lower than certain values.
- Duration with $\tau < 0.05$ & $\tau < 0.04$:
  - Greenland Summit (solid line) has a long tail toward the long duration of > 100 hrs.
  - ALMA (dashed line) always exhibits higher cumulative distributions, and reaches 100% around several x 10 hrs.
  - South Pole (dotted line) shows the steepest distribution, and reaches 100% around a few x 10 hrs, much shorter than the other 2 sites.
- Duration with $\tau < 0.03$:
  - Very similar distribution between Greenland and ALMA.
  - But Greenland Summit shows a long tail up to several x 10 hrs.
  - South Pole is much shorter, only up to 10 hr.
- Greenland is suitable for the observations that need very stable opacity conditions.



Imaging Supermassive Black Holes

Sizes of Black Holes

	Shadow Size (μasec)	Mass (10^6 Mo)	Distance (Mpc)
Sgr A*	50	4.1 +- 0.6	0.008
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Note: Here we assume $R_{shadow} \sim 5 \times R_{sch}$

Gebhardt et al. (2011)

M87

- Heavy BH mass compared to Sgr A*
  ➪ Comparable angular size with Sgr A*.
- Heavy BH mass.
  ➪ Rotation period of the accretion disk is >> 1 day.
  ➪ Beneficial for imaging.
- Prominent Jets. Beneficial for understanding jet emitting mechanism.

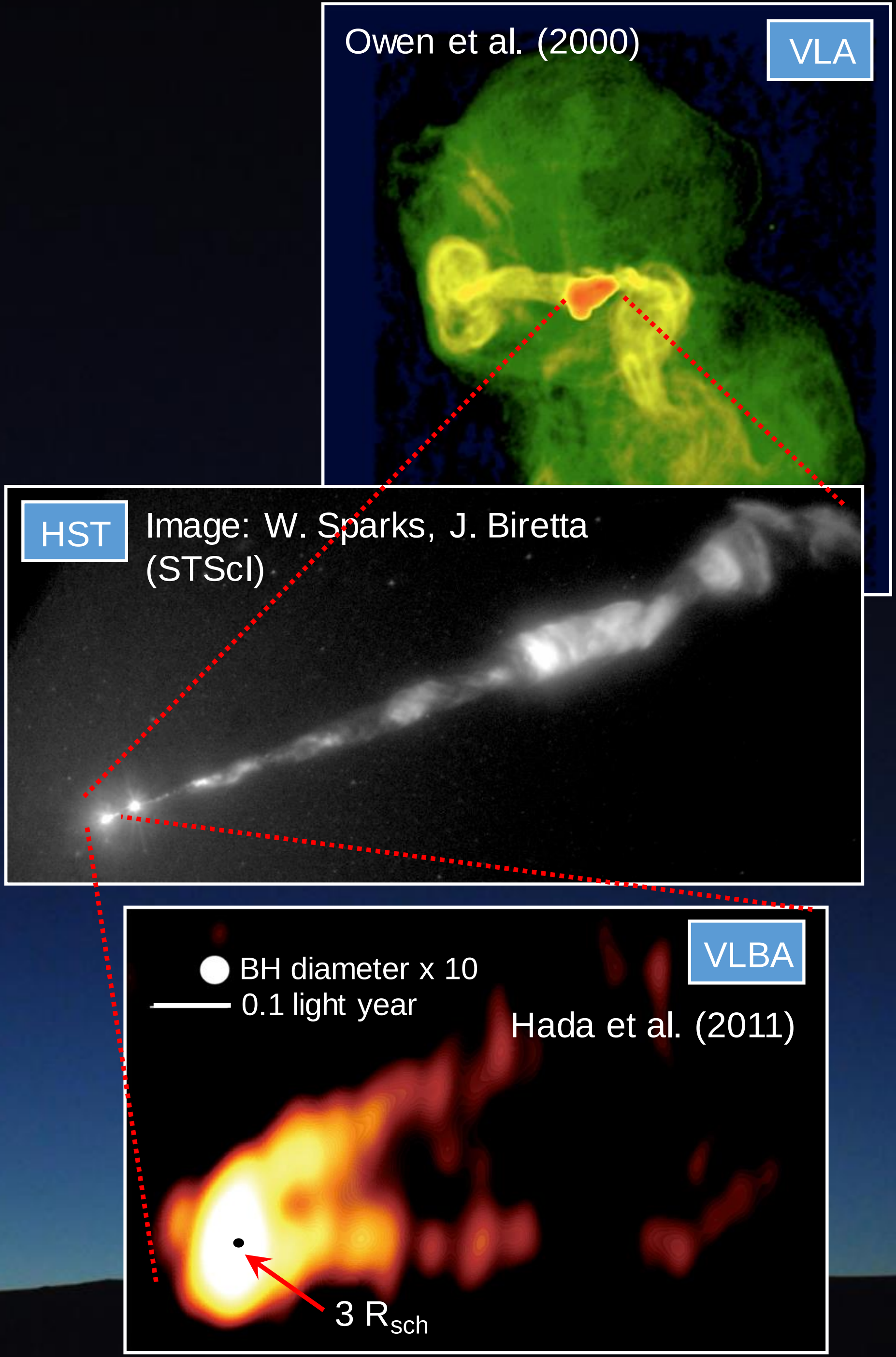

Owen et al. (2000)

Image: W. Sparks, J. Biretta (STScI)

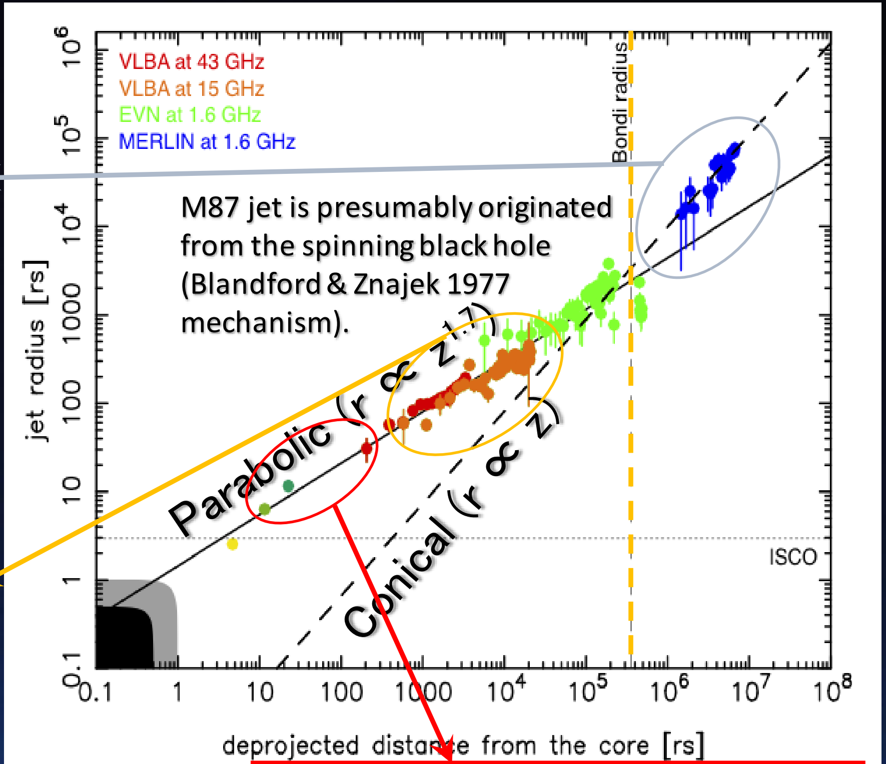
Hada et al. (2011)

Collimation of M87 Jet

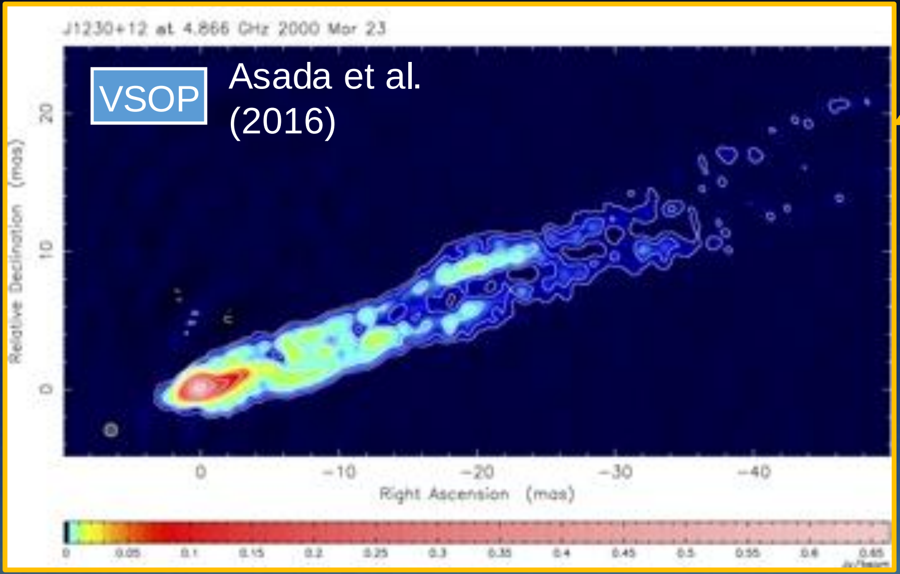
Asada & Nakamura 2012, ApJ, 745, 28
Nakamura & Asada 2013, ApJ, 775, 118

HST Image: W. Sparks, J. Biretta (STScI)

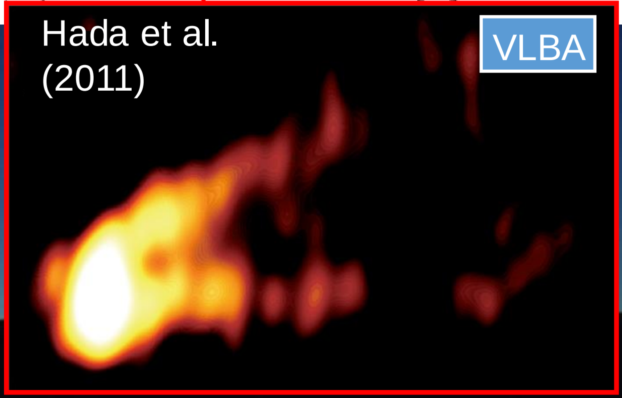
HST1
~ Bondi Radius



M87 jet is presumably originated from the spinning black hole (Blandford & Znajek 1977 mechanism).



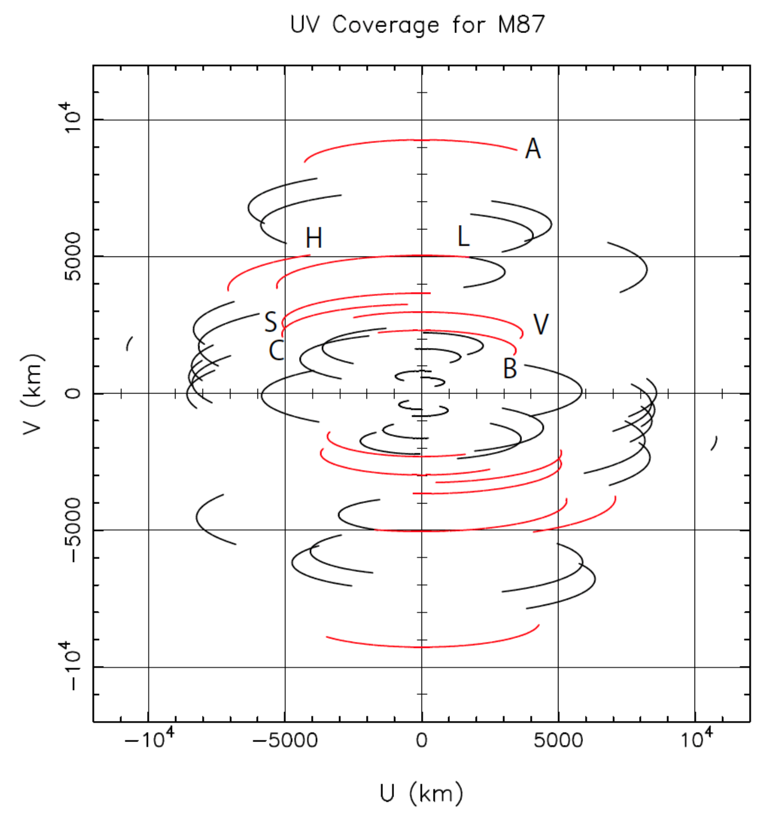
VSOP Asada et al. (2016)



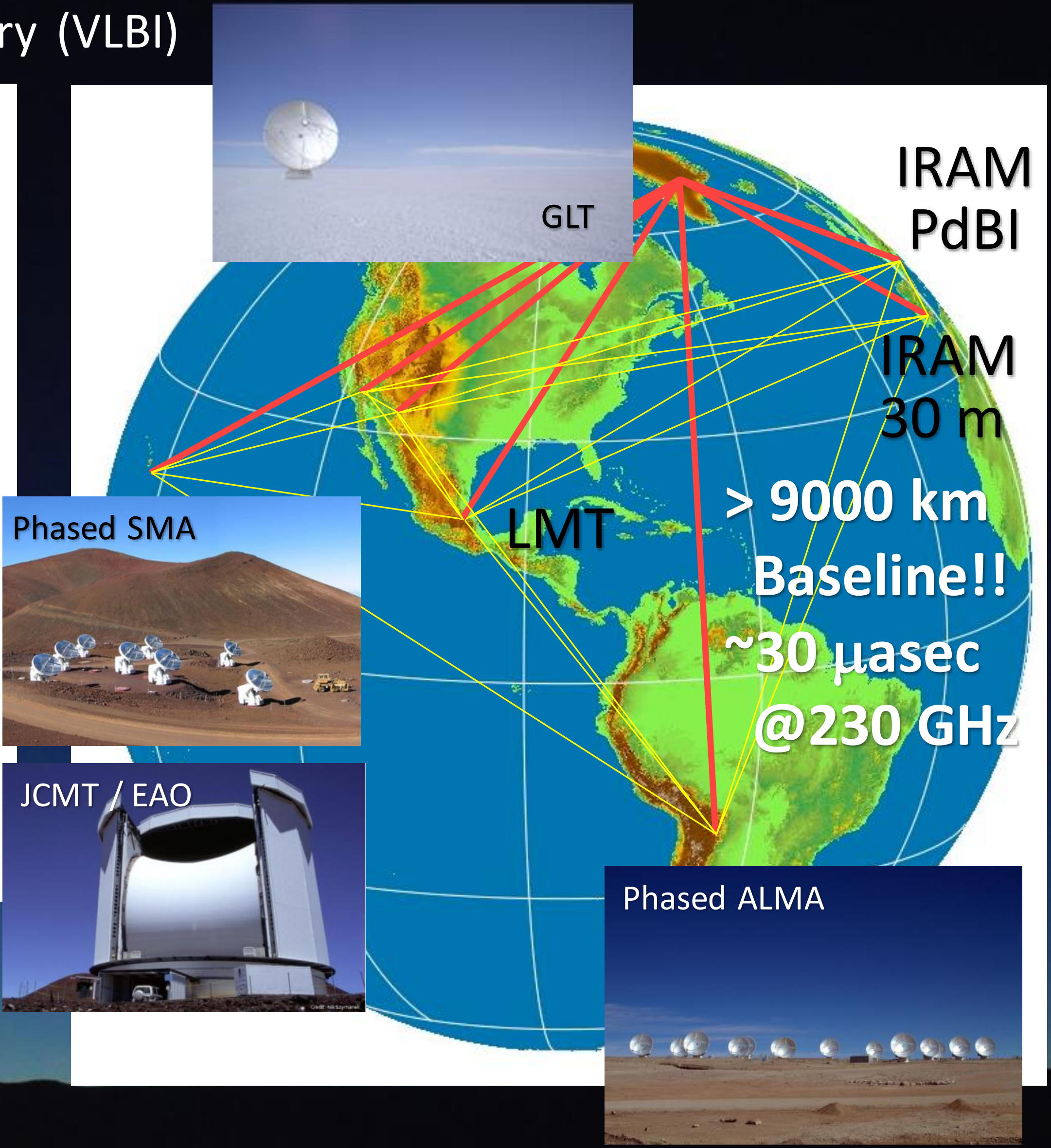
Hada et al. (2011) **VLBA**

Expected uv Coverage with GLT

Very Long Baseline Interferometry (VLBI)



uv coverage for M 87 with GLT, ALMA, SMA/JCMT, LMT, SMT, CARMA, IRAM 30m, and PdBI. Baselines with GLT are shown in red.

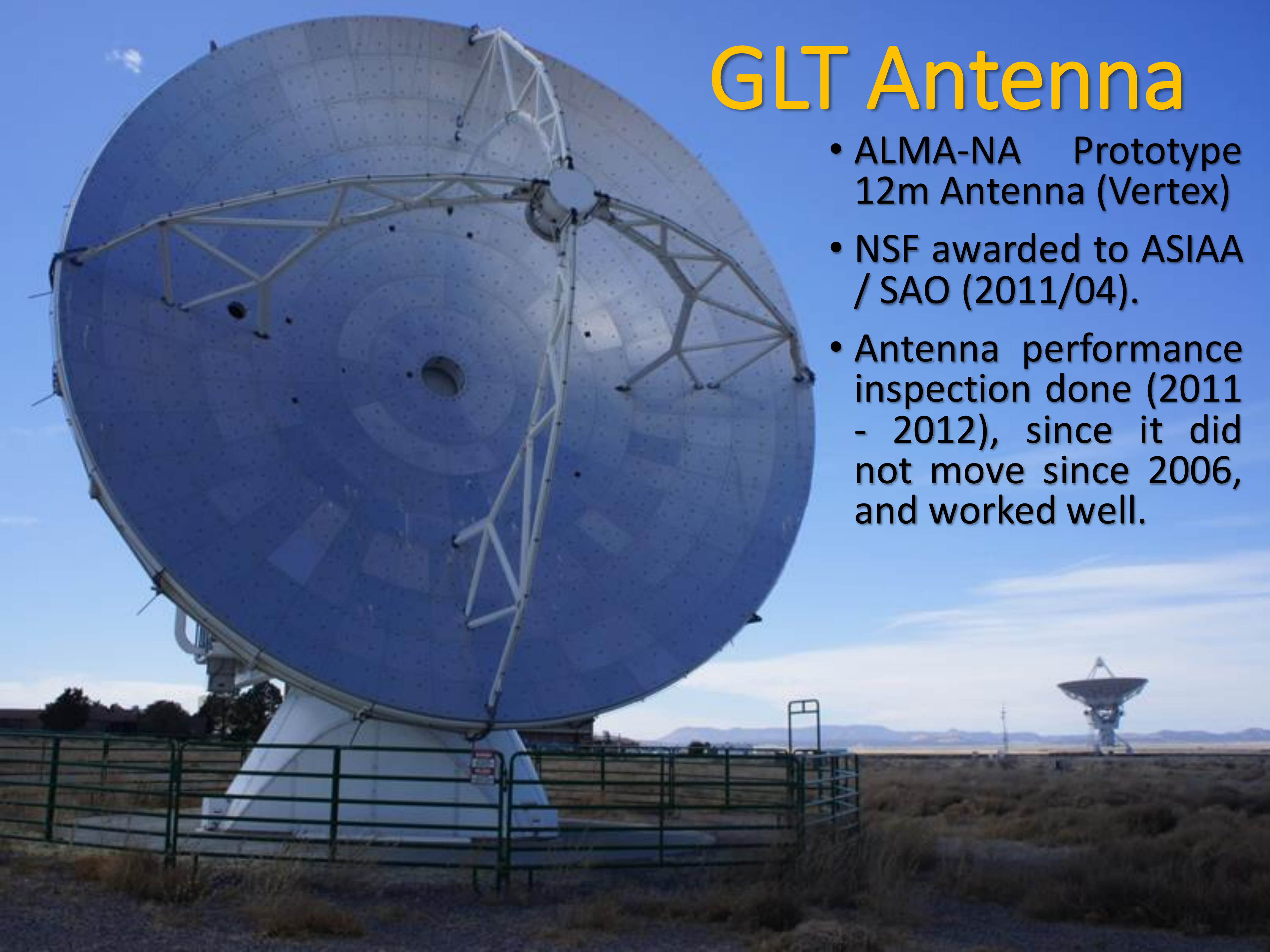


> 9000 km Baseline!!

~30 μasec @230 GHz

Telescope Re-Assembly at Thule

GLT Antenna



- ALMA-NA Prototype 12m Antenna (Vertex)
- NSF awarded to ASIAA / SAO (2011/04).
- Antenna performance inspection done (2011 - 2012), since it did not move since 2006, and worked well.

GLT Antenna Disassembly

- Totally disassembled at VLA site.
(2012/12)

GLT Antenna Shipping & Reassembly

ade for Extreme Weather

Oct. 2, 2016

2016/07

Oct. 6, 2016

Greenland

Thule Reassembly

Feb. 18, 2017

Finishing Antenna Re-Assembly

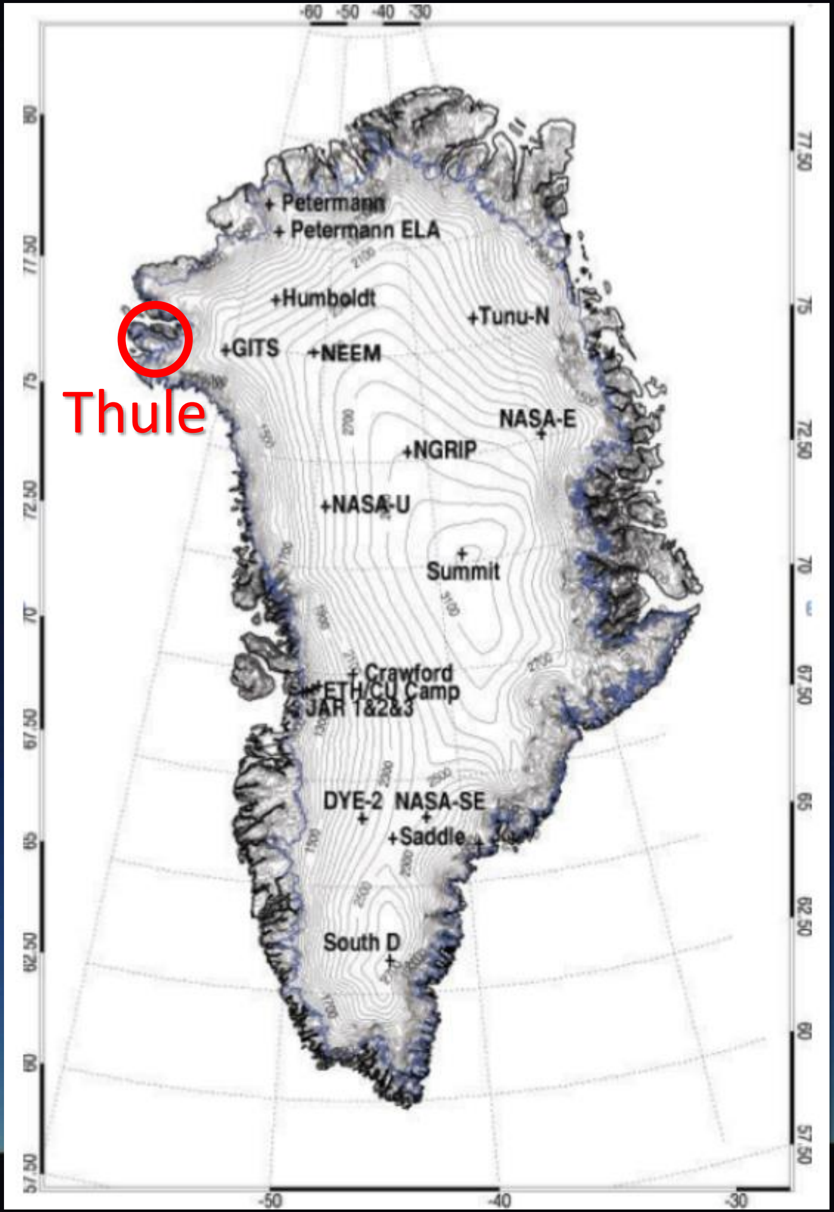
Jul. 24, 2017

Jul. 24, 2017

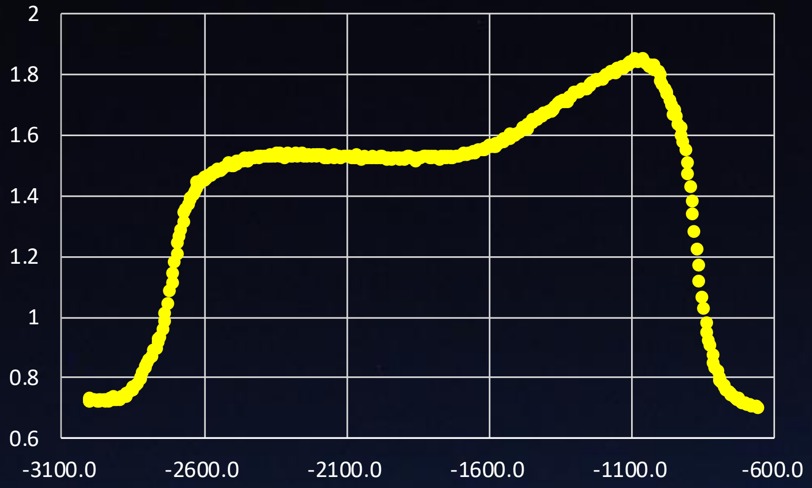
Commissioning and Science Operation

Greenland Telescope (GLT)

Commissioning has started from Dec.1, 2017.



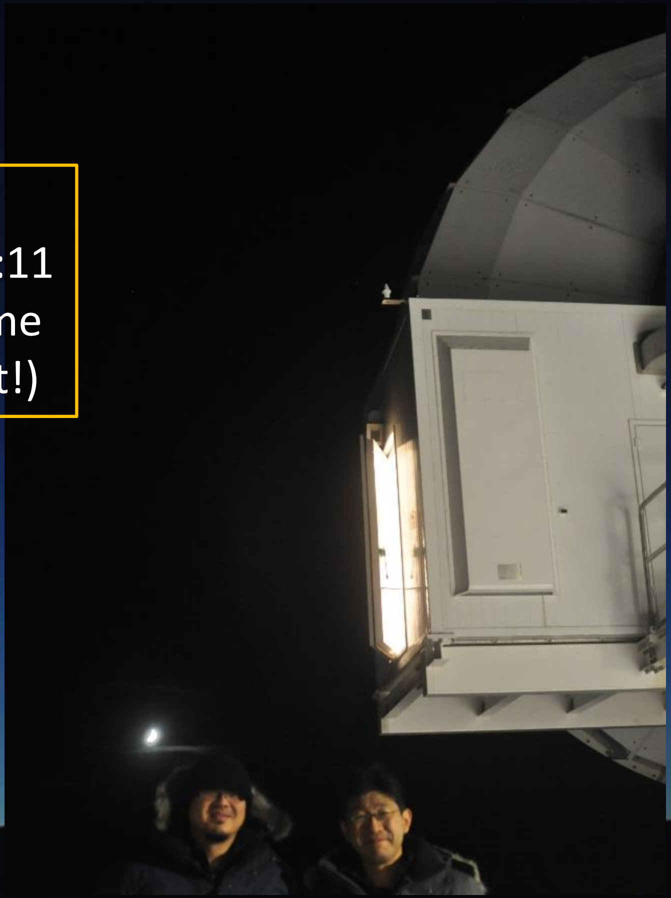
Greenland Telescope (GLT) Astronomical First Light!!!



Azimuth scan of Moon with the GLT 86 GHz Receiver (observed frequency = 94.5 GHz) and with the Continuum Detector.

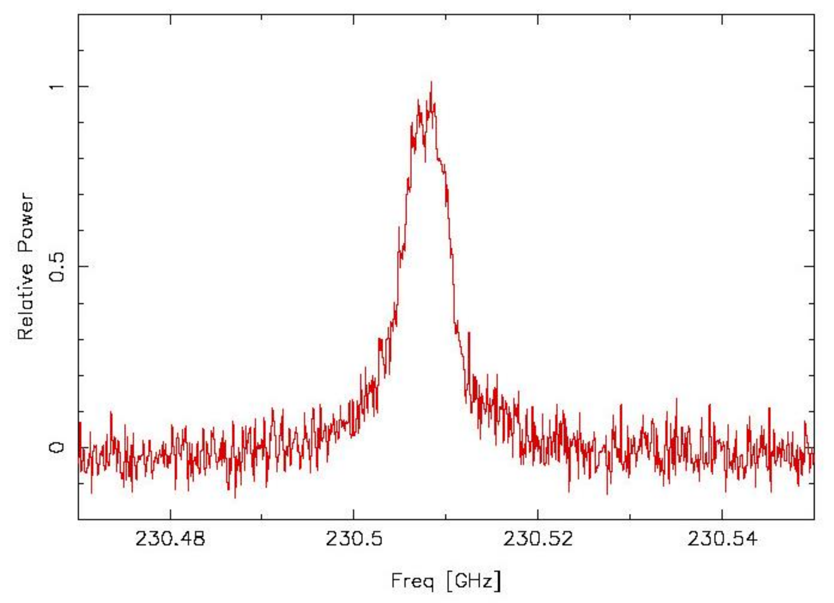
Moon at Christmas
(Size matched with
the above scan)

Detected on
2017/12/25 19:11
Local Thule Time
(Christmas Gift!)



Kevin J.-Y. Koay &
Satoki Matsushita
with GLT tracking
Moon (above left
of Kevin's head)

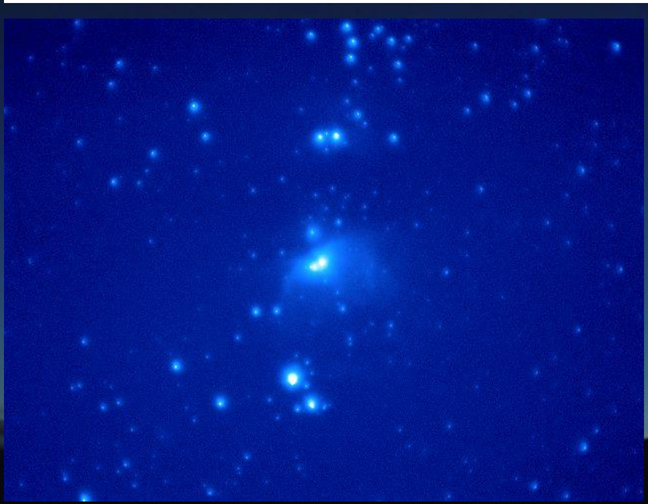
Greenland Telescope (GLT) First Spectrum!!!



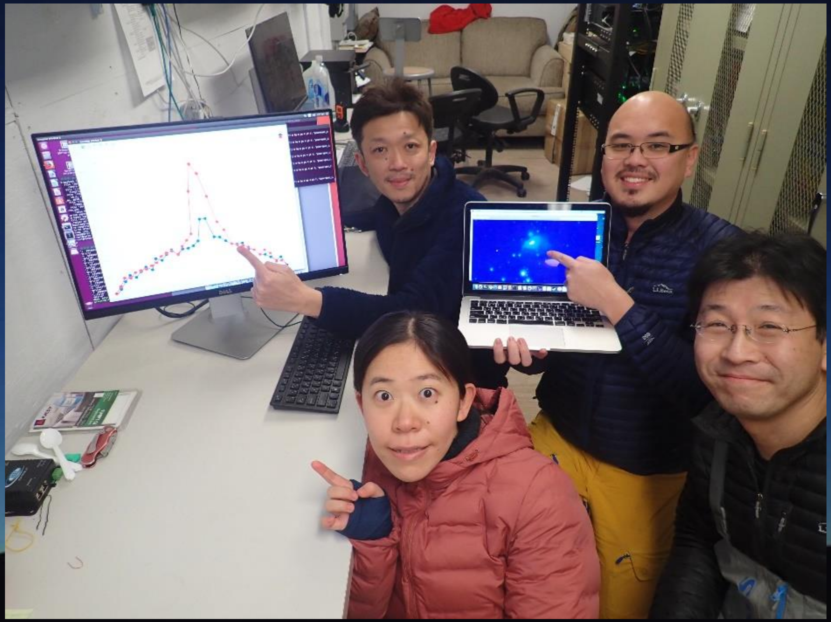
CO(J=2-1) line from Orion-KL with the GLT 230 GHz Receiver (observed frequency = 230.538 GHz) with the ASIAA VLBI R2DBE and the Mark 6 recorder (auto-correlation).

Detected on
2018/1/10 20:12
Local Thule Time

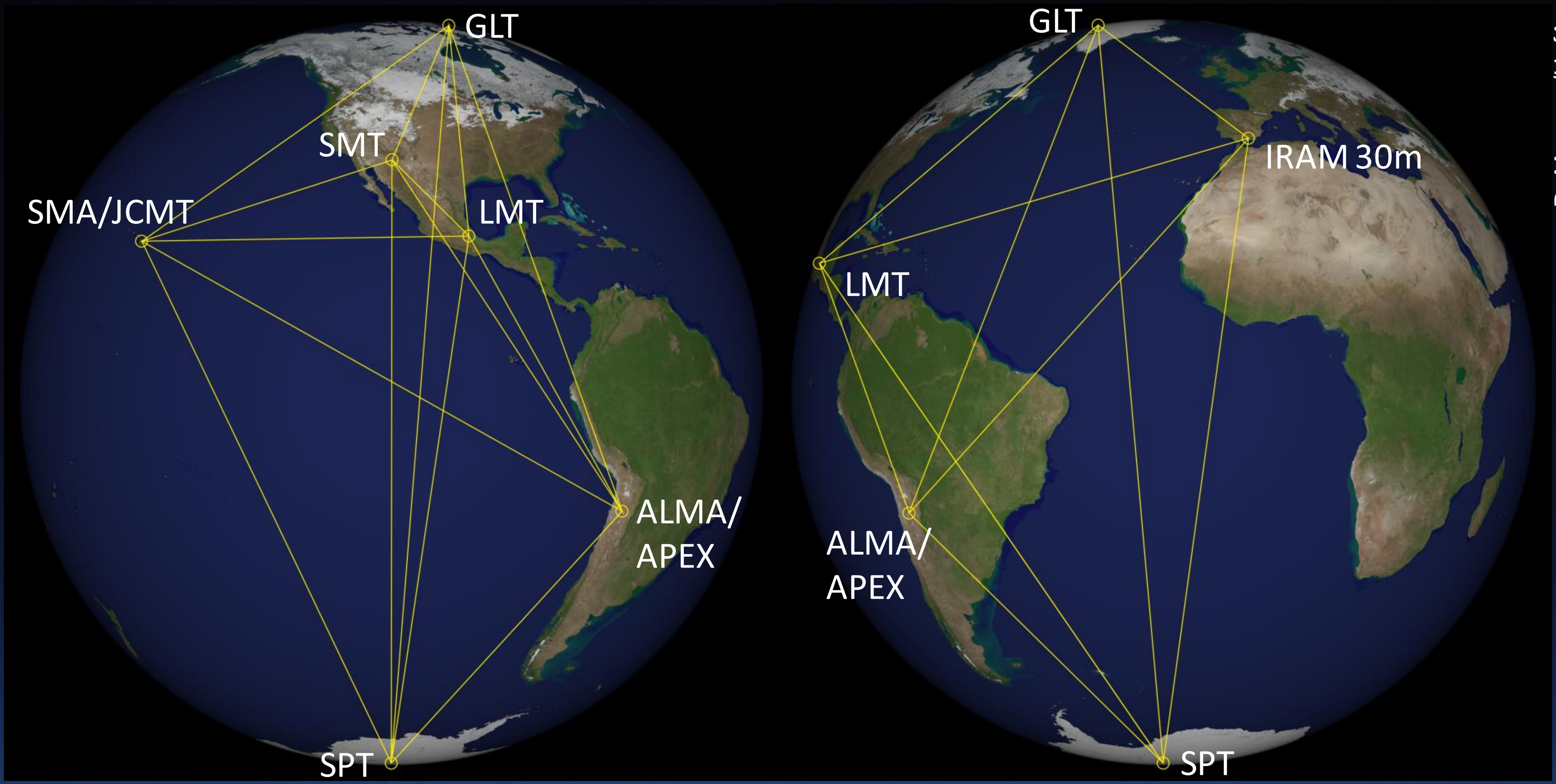
Keiichi Asada, Shoko Koyama, Kevin J.-Y. Koay & Satoki Matsushita at the GLT Control Room



GLT Optical Guidescope image of Orion Nebula.



Event Horizon Telescope (EHT)



D. Marrone/UofA

Joined Event Horizon Telescope (EHT) 230 GHz VLBI Dress Rehearsal!!!

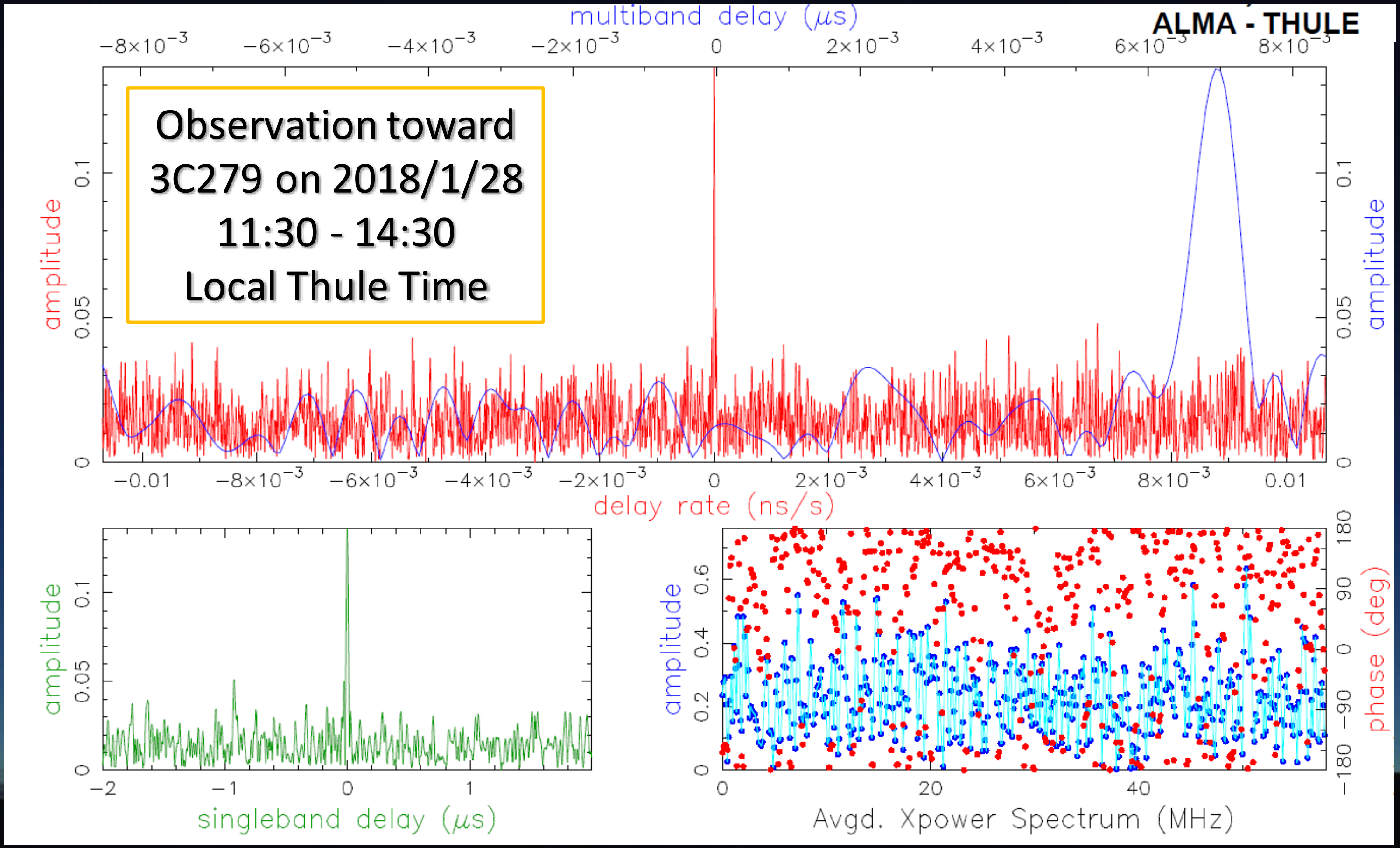
- We joined the Event Horizon Telescope (EHT) 230 GHz VLBI Dress Rehearsal.
- ALMA & South Pole Telescope (SPT) have also joined under good weather.
- JCMT & IRAM 30 m could not join due to bad weather.
- We observed 3C279 with GLT & SPT (EL = 9^o @ GLT & EL = 6^o @ SPT).
- Disk modules have been sent out to the correlation site (MIT Haystack Observatory).

Performed on
2018/1/28
11:30 - 14:30
Local Thule Time

Ming-Tang Chen, Nimesh Patel, Kuan-Yu Liu, Keiichi Asada, & Hiroaki Nishioka at the GLT Control Room

230 GHz VLBI First Fringe with ALMA!!!

- We got the first fringe with ALMA at 230 GHz!!!
- The data have been taken at the EHT Dress Rehearsal, namely within 2 months after the commissioning started.



Observation toward 3C279 on 2018/1/28 11:30 - 14:30 Local Thule Time

Joined the Event Horizon Telescope (EHT) 230 GHz VLBI!!!

Performed on
2018/4/20, 21,
23, 24, 26, & 27

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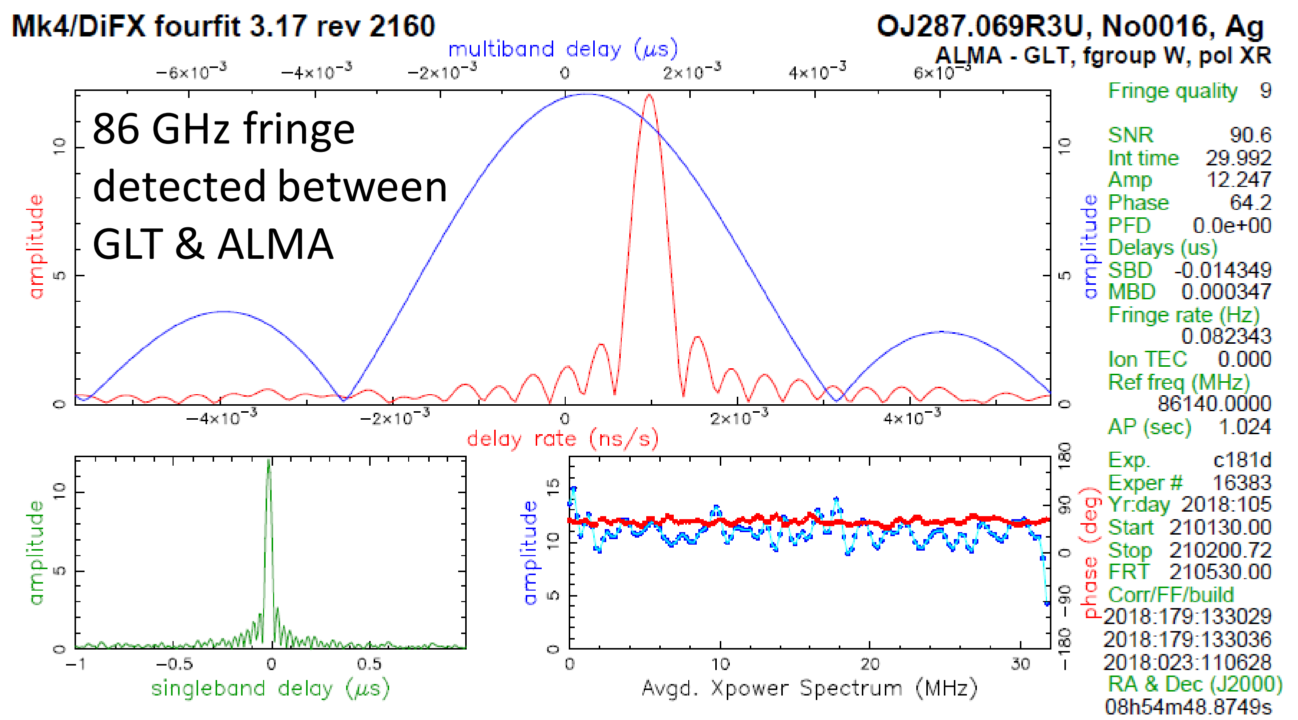
- We also successfully joined the GMVA VLBI observations at 86 GHz.



Mk4/DiFX fourfit 3.17 rev 2160

OJ287.069R3U, No0016, Ag
ALMA - GLT, fgroup W, pol XR

86 GHz fringe detected between GLT & ALMA

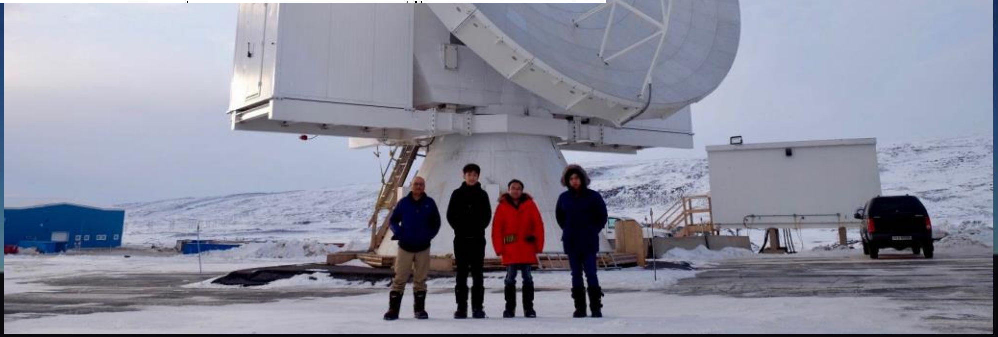
Fringe quality 9

SNR 90.6
Int time 29.992
Amp 12.247
Phase 64.2
PFD 0.0e+00
Delays (us)
SBD -0.014349
MBD 0.000347
Fringe rate (Hz)
0.082343
Ion TEC 0.000
Ref freq (MHz)
86140.0000
AP (sec) 1.024

Exp. c181d
Exper # 16383
Yr:day 2018:105
Start 210130.00
Stop 210200.72
FRT 210530.00
Corr/FF/build
2018:179:133029
2018:179:133036
2018:023:110628
RA & Dec (J2000)
08h54m48.8749s
+20°06'30.641"

Amp. and Phase vs. time for each freq., 30 segs, 1 APs / seg (1.02 sec / seg.), time ticks 1 sec

Nimesh Patel,
Keiichi Asada,
Hiroaki Nishioka,
& Chen-Yu Yu
in front of GLT



Future Plan

Plan

- Test and operation at Thule, including VLBI (2017-2020).
- Transport antenna across ice sheet (2020-2021).
- First light at the Summit Station (2021-2022).

GLT Baselines at 350 GHz

Credit: Nik Szymanek

Image IBCAO
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2011 DigitalGlobe

Baselines are 9,000 km long, and
the resolution reaches 20 μas at 345 GHz.

GLT Baselines at 690 GHz

Baselines are 9,000 km long, and
the resolution reaches 10 μas at 690 GHz.

Sizes of Black Holes

	Shadow Size (μasec)	Mass (10^6 Mo)	Distance (Mpc)
Sgr A*	50	4.1 +- 0.6	0.008
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M31	18	180 +- 80	0.80
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NGC 5128 (Cen A)	7	310 +- 30	4.5

Note: Here we assume $R_{shadow} \sim 5 \times R_{sch}$

Gebhardt et al. (2011)

Greenland Telescope (GLT) Summary

- Primary Science Target:
  Direct Imaging of the Shadow of Black Holes with submm VLBI.
- Telescope re-assemble finished at Thule, Greenland.
- Testing and science observations at Thule are ongoing.
- Plan to move to the Greenland Summit in 2020-21.
- Science observations at the Greenland Summit will start in 2021-22.