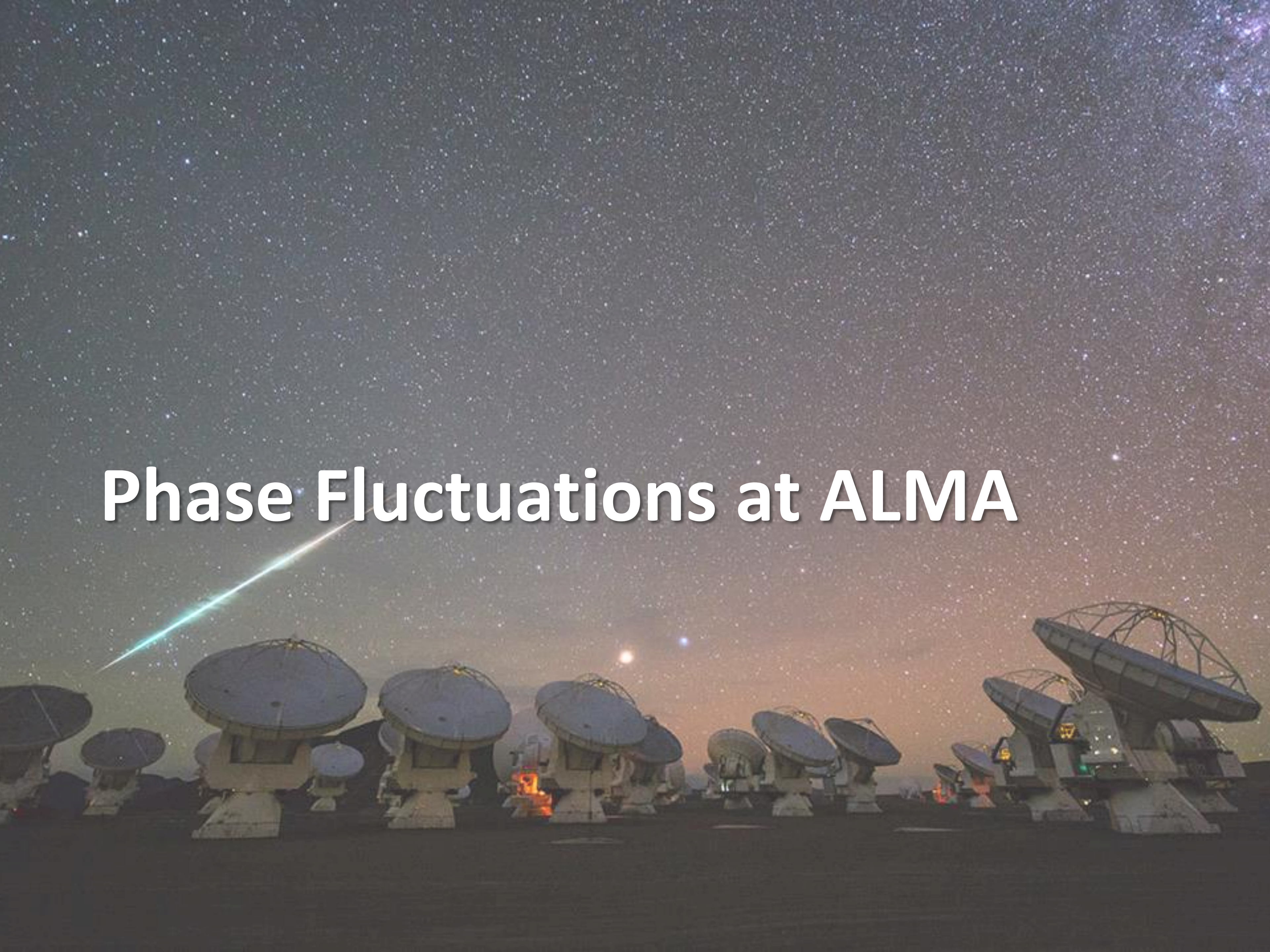
What we have learned from the ALMA Long Baseline Campaigns

Satoki Matsushita (ASIAA)

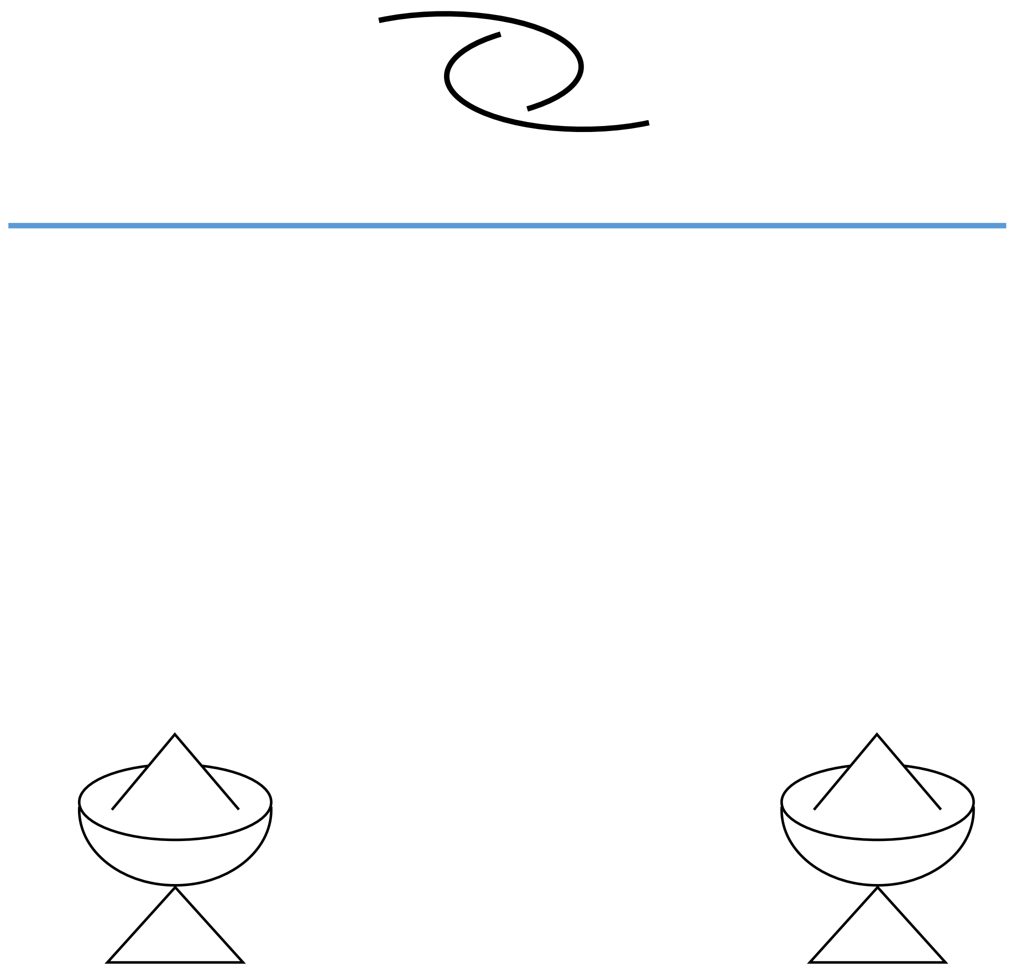
Based on

Matsushita et al. 2017, PASP, 129, 035004

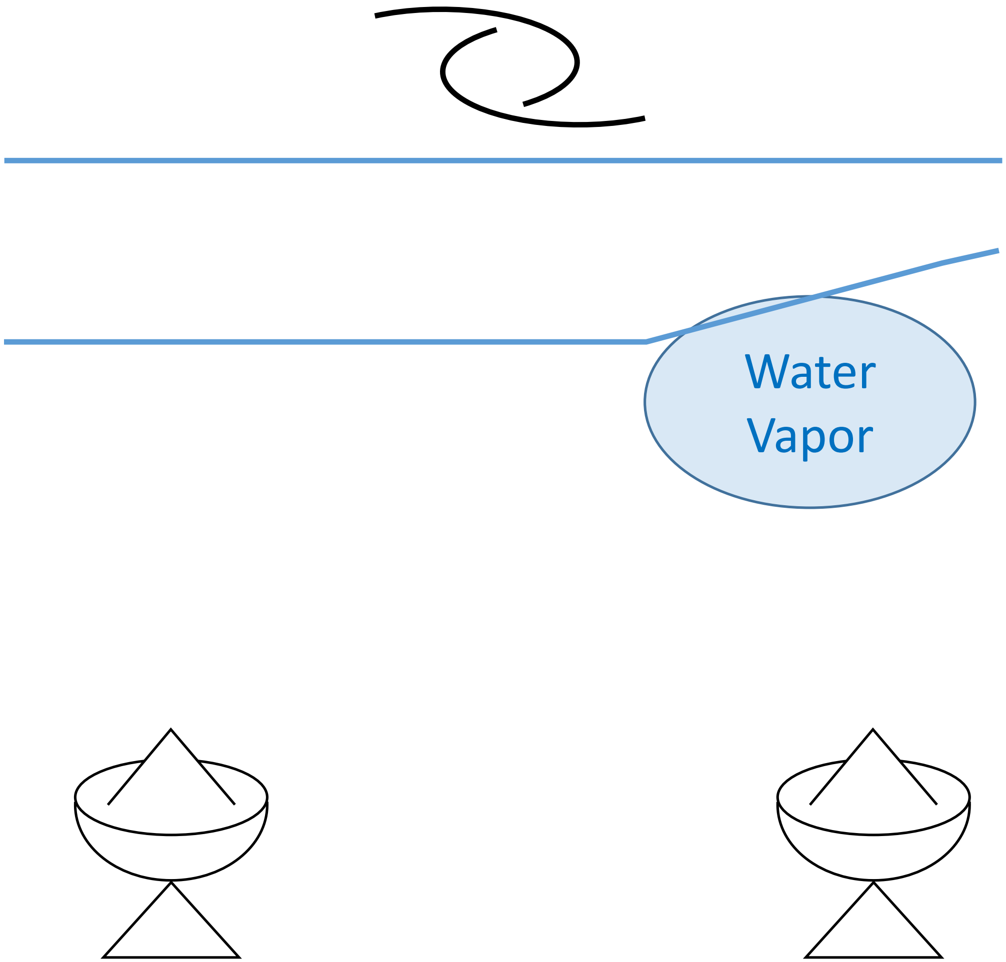
Phase Fluctuations at ALMA



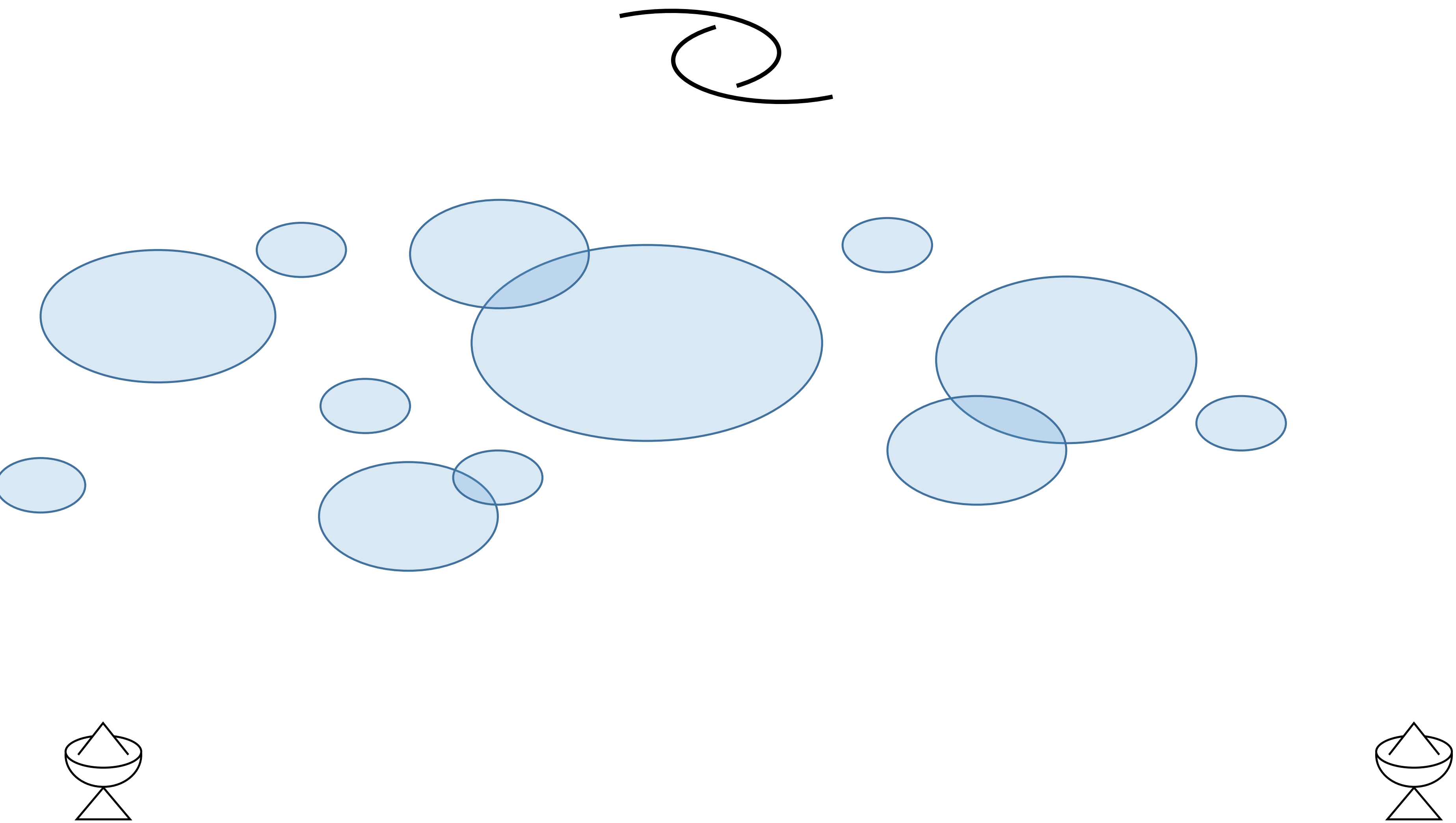
Without Atmosphere



With Atmosphere



With Atmosphere




Cerro Chajnantor
ASTE
APEX
Purico Complex
Cerro Chascon
15 km
Array Configuration of the
ALMA Long Baseline Campaign 2014
地図
航空写真
27
Google
地図データ ©2014 Google, Mapcity 画像 ©2014 TerraMetrics
利用規約

Spatial Structure Function (SSF)

- Spatial Structure Function (SSF):
  RMS phase fluctuation as a function of baseline length.

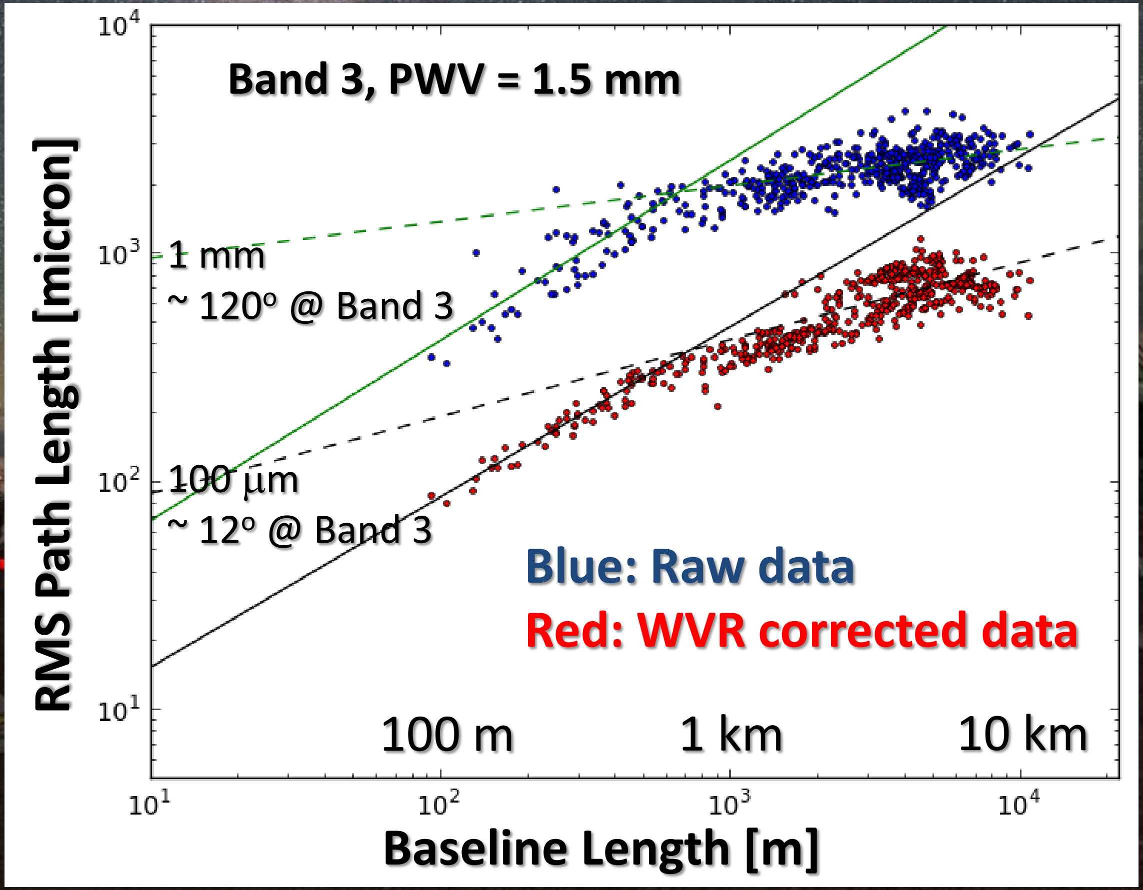
$$[\text{RMS phase}] = \sqrt{\langle\{Phase(x) - Phase(x-d)\}^2\rangle}$$

(namely, the phase difference at the baseline length of d).

⇨ Possible to reveal statistically the size distribution of water vapor clumps in the atmosphere.

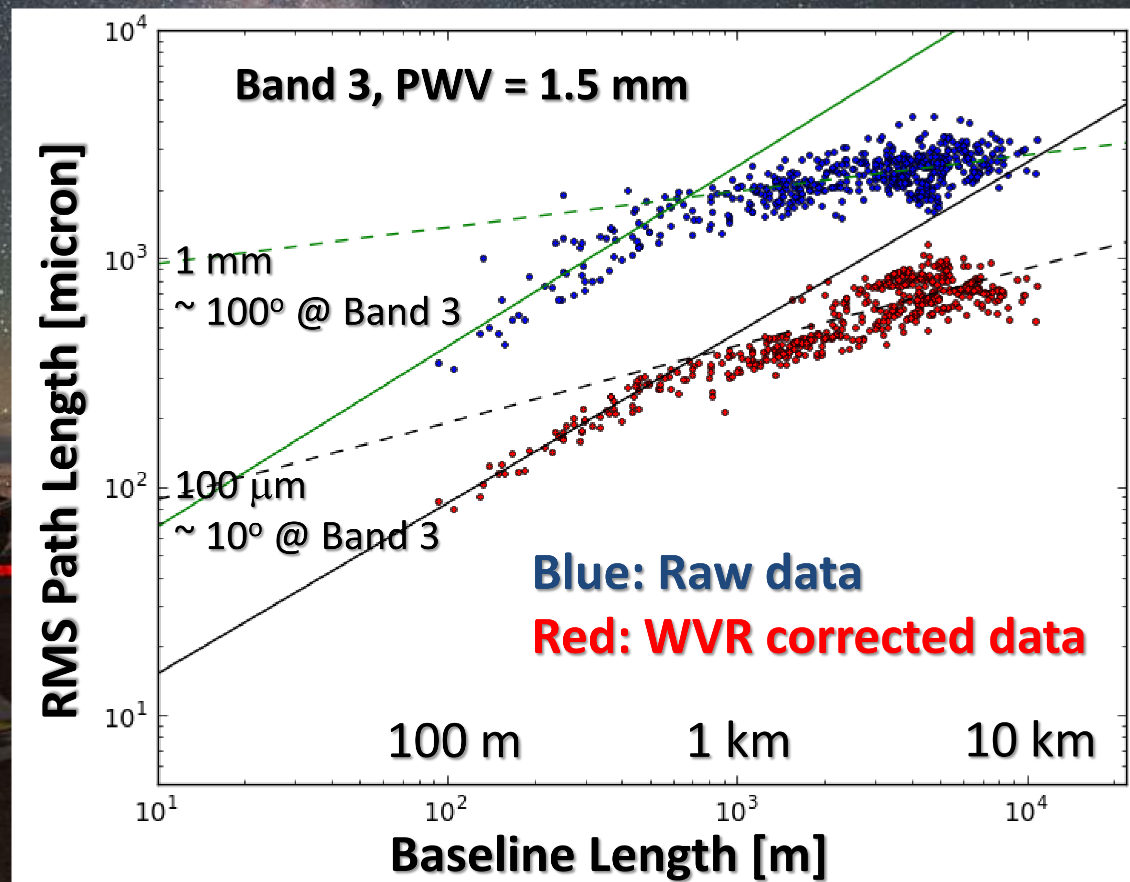
– 3-D Kolmogorov turbulence: slope = 0.83

– 2-D Kolmogorov turbulence: slope = 0.33



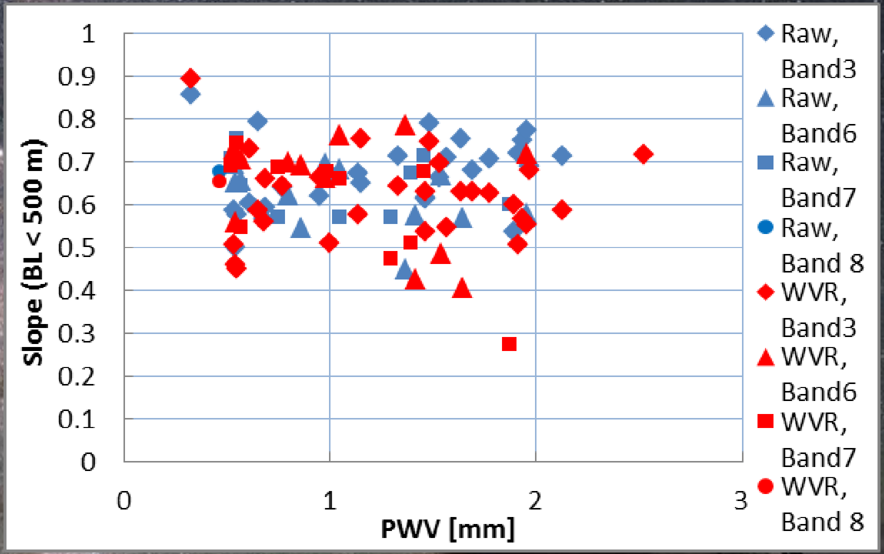
Spatial Structure Function (SSF)

- Typically, there is a turn-over around 1 km.
- Increase of phase fluctuation at longer baselines is small.
  ⇨ Good news for longer baseline interferometry.



SSF Slopes at Short Baseline Lengths

- At short baselines (< 500 m), SSF slopes are almost constant under whatever conditions:
  - Before WVR: 0.65 +- 0.06
  - After WVR: 0.62 +- 0.09
- 50% quartile slope for the 3-year 11.2 GHz Radio Seeing Monitor data: 0.63 (Butler et al. 2001).
  - Raw data we took seem typical phase fluctuation condition at the ALMA site.

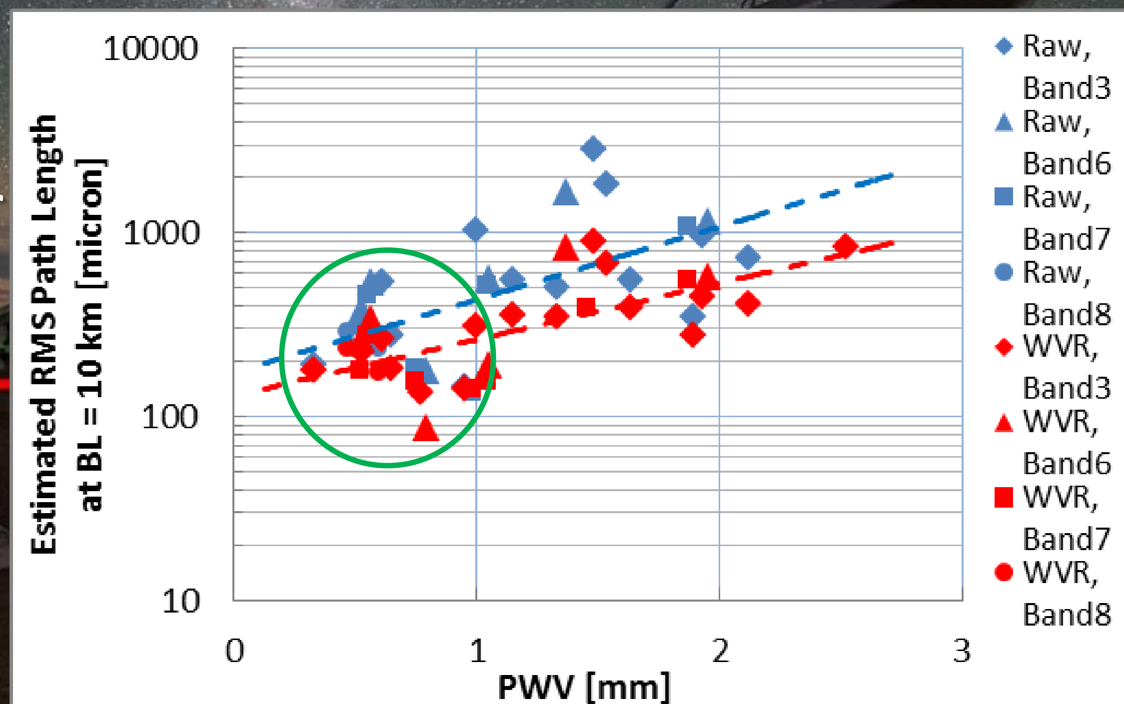


RMS Path Length at 10 km Baseline

- Estimate the rms path length at the baseline length of 10 km.
  - $\log_{10}$(rms path length) = [long baseline slope] x [baseline length] + [long baseline constant]
- Higher PWV data have larger rms path length at 10 km.
- Even when PWV < 1 mm and after WVR phase correction, mean rms path length is ~200 μm.

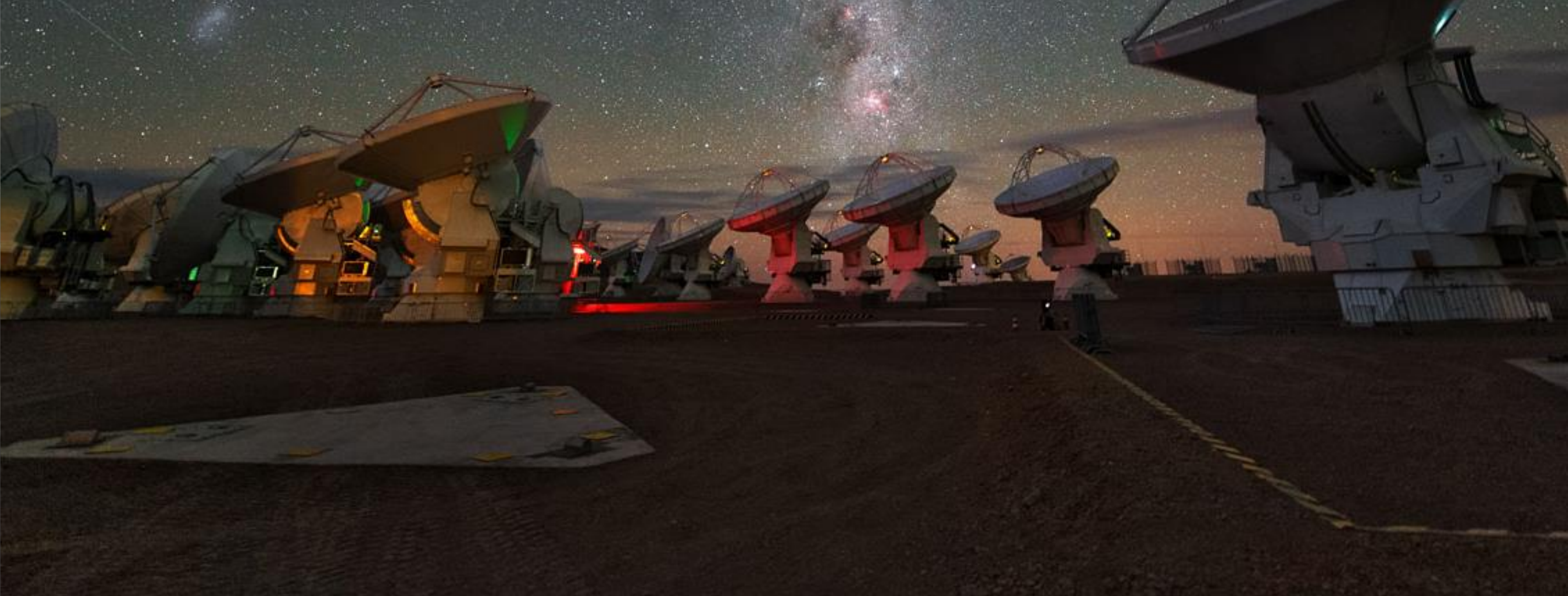
⇨ Peak-to-peak phase fluctuation is ~2π or more for 600 – 1000 GHz (300 – 500 μm).

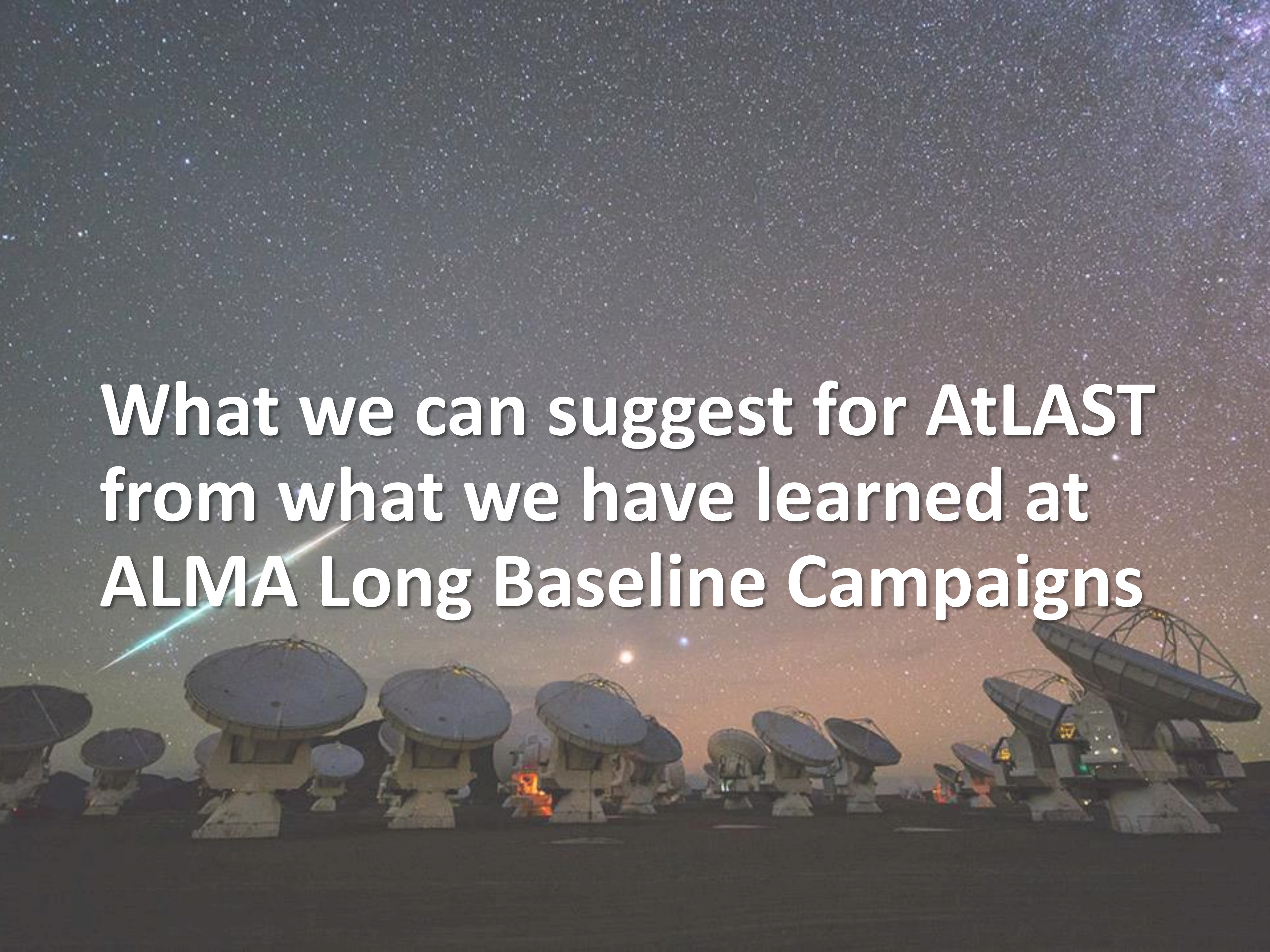
⇨ Need additional phase calibration methods.



Taking Out the Phase Fluctuations

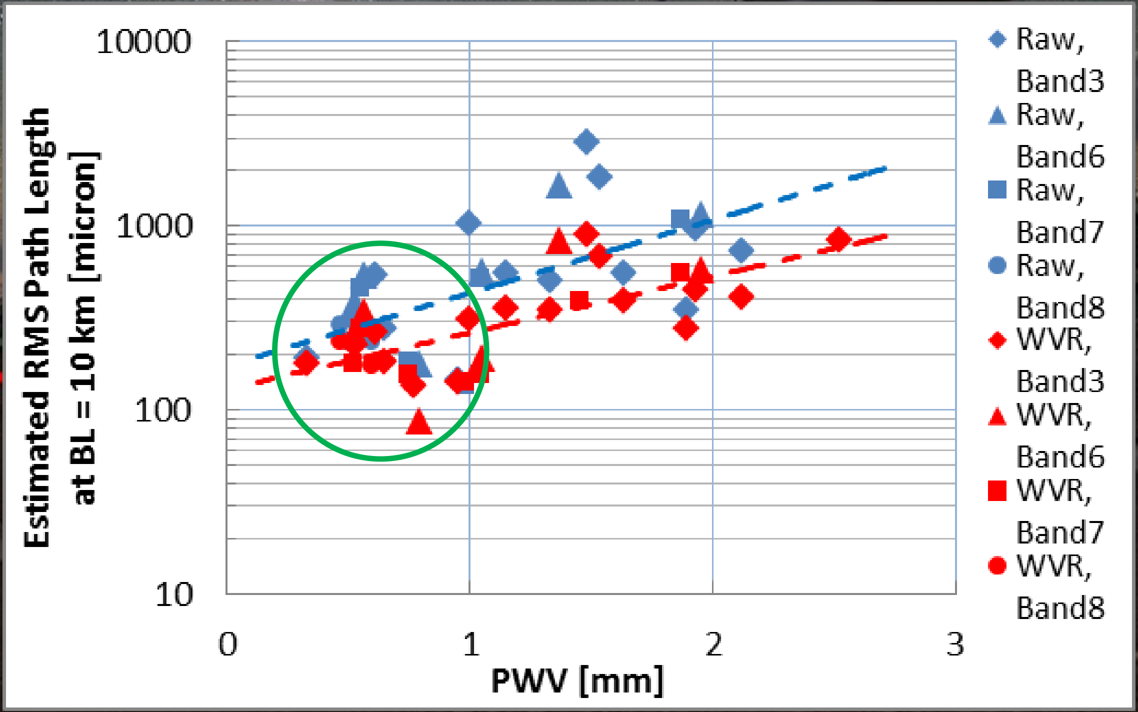
- 183 GHz Water Vapor Radiometer (WVR) Phase Correction Method.
- Fast Switching Phase Correction Method.
- Band-to-Band Phase Correction Method.
- Paired Antenna Phase Correction Method.



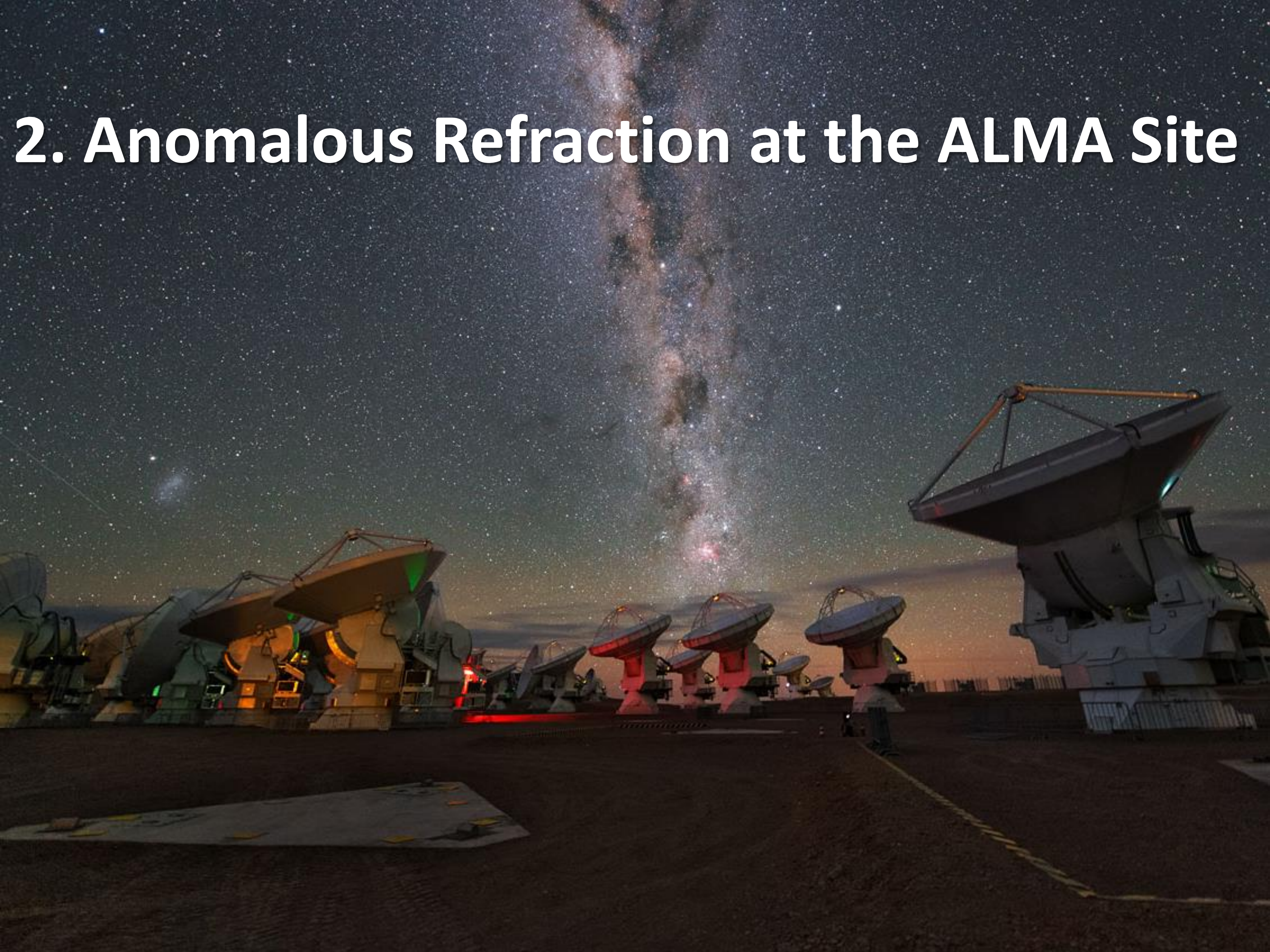

What we can suggest for AtLAST
from what we have learned at
ALMA Long Baseline Campaigns

1. Link to ALMA? Where to put?

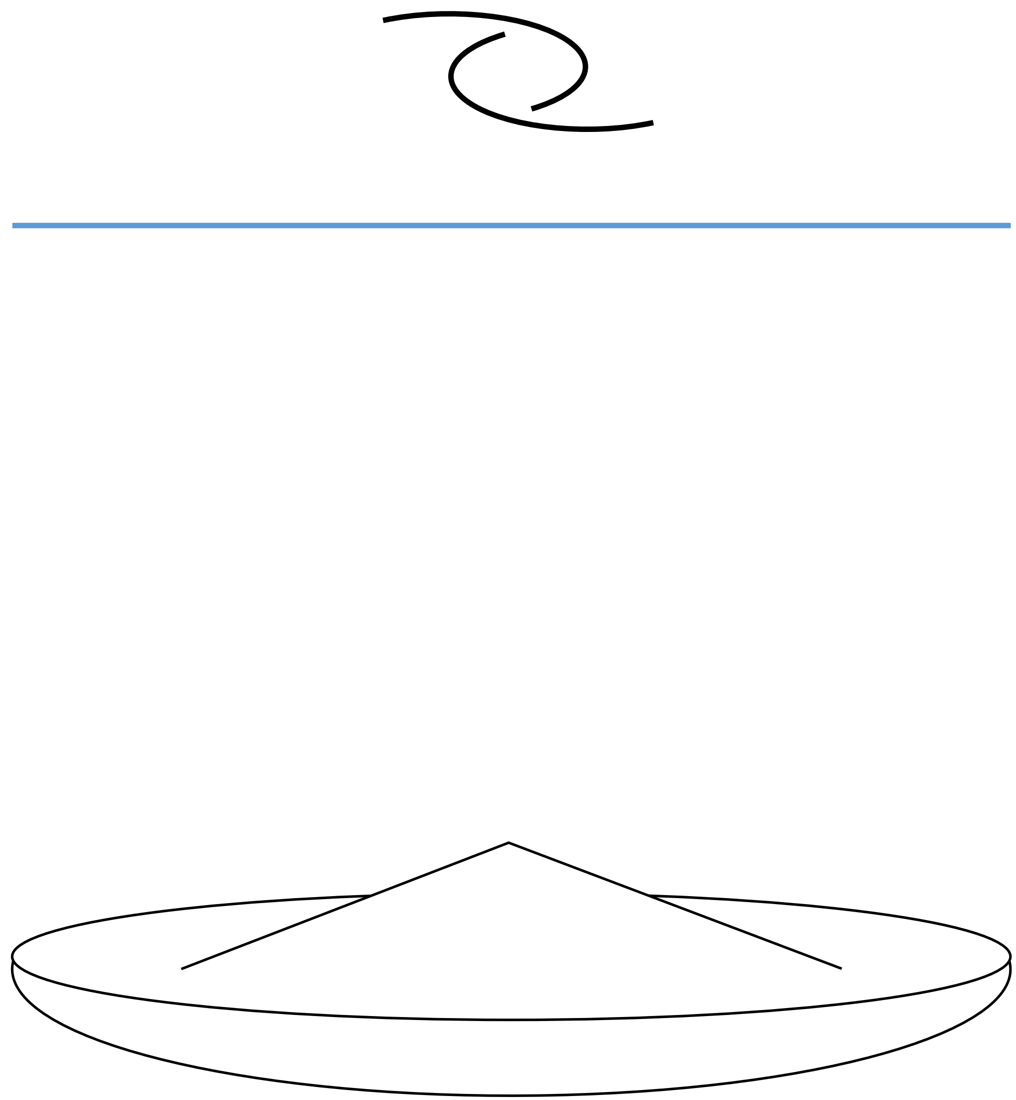
- RMS Path Length at 10 km Baseline
  - Even when PWV < 1 mm and after WVR phase correction, mean rms path length is ~200 μm.
    ⇨ Peak-to-peak phase fluctuation is ~2π or more for 600 – 1000 GHz (300 – 500 μm).
    ⇨ Need additional phase calibration methods.
- Need to consider telescope capabilities:
  - Must install 183 GHz WVR
  - Fast Switching
  - Band-to-Band
  - Paired Antenna



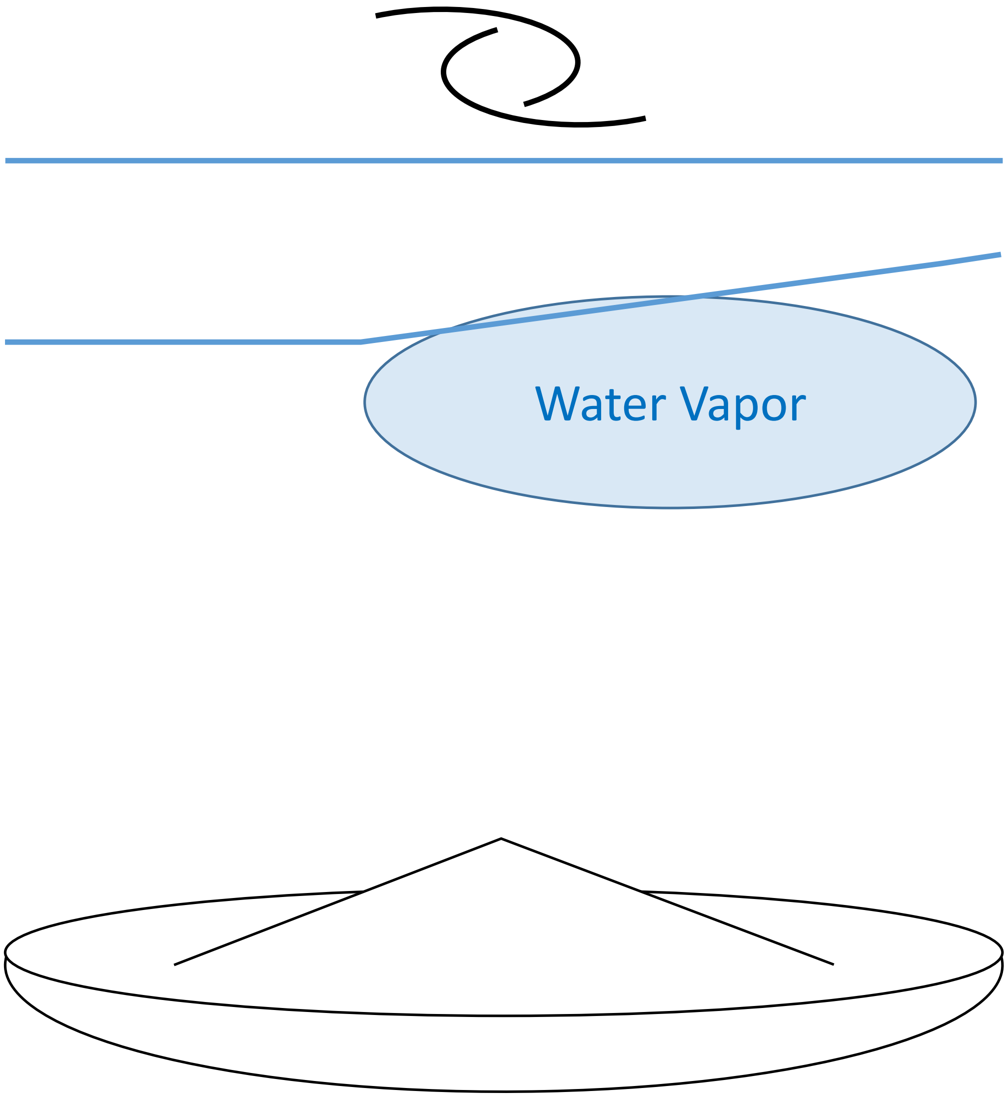
2. Anomalous Refraction at the ALMA Site



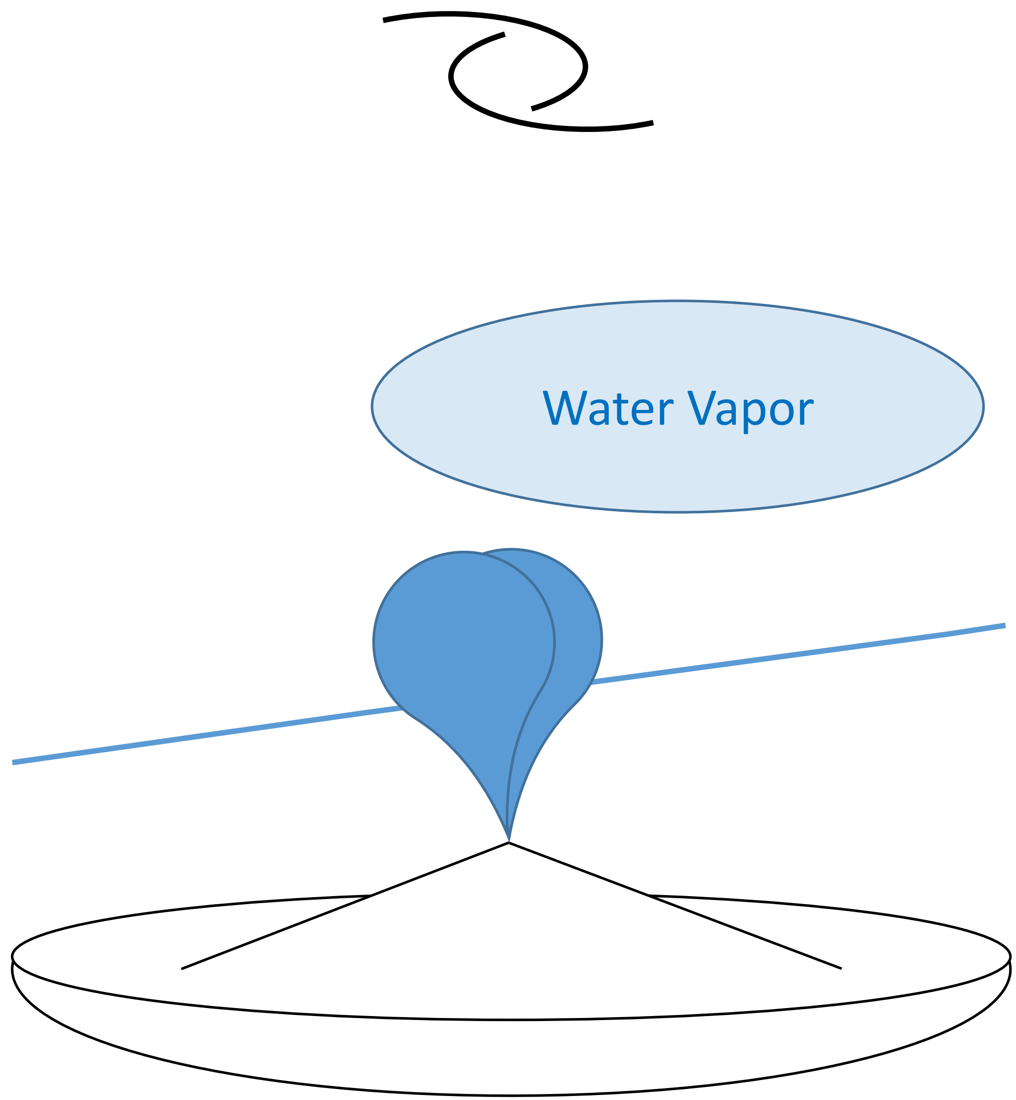
Without Atmosphere



With Atmosphere



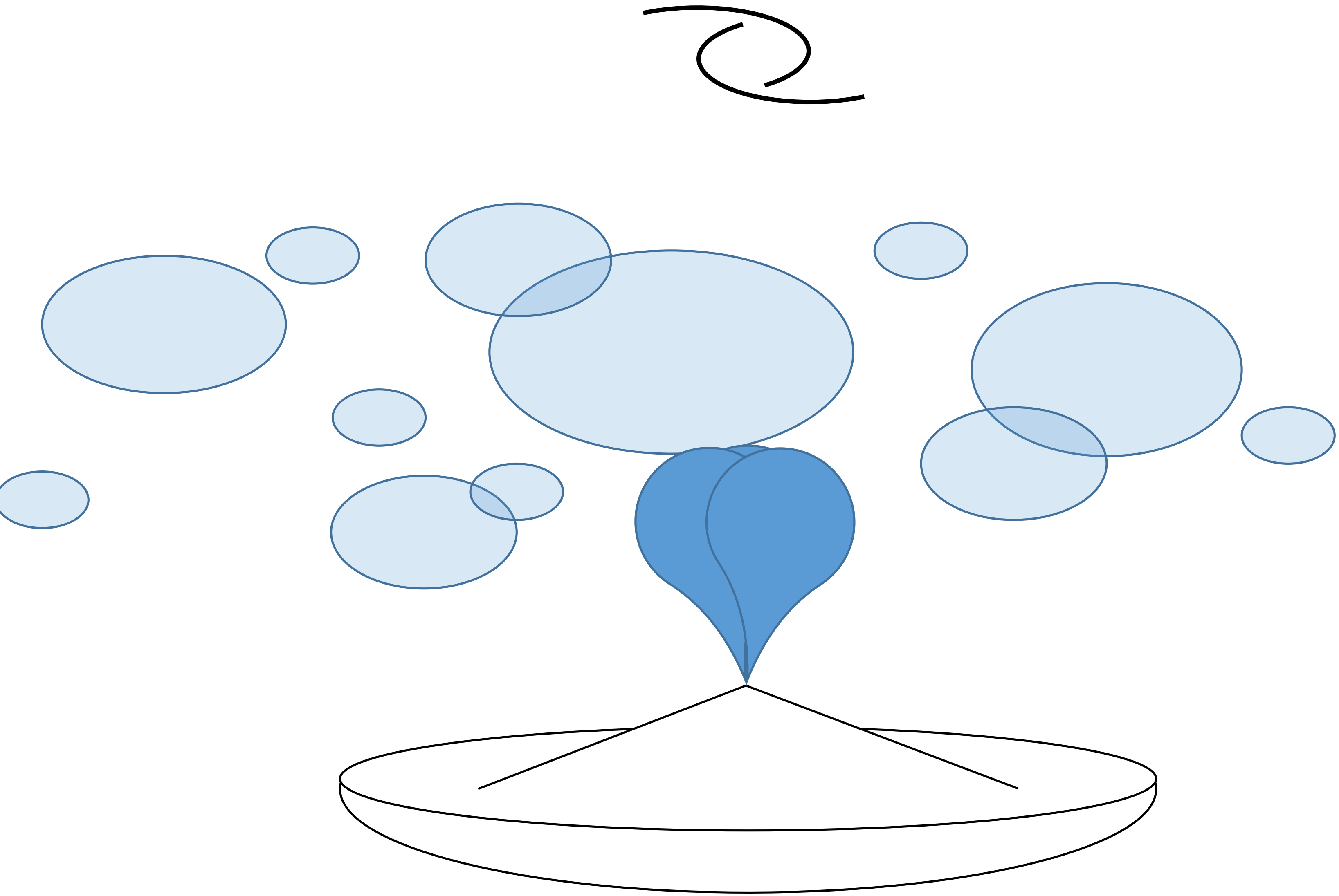
This corresponds to pointing change



From the antenna point of view, wave front has been tilted.
= Change in pointing direction.

Anomalous Refraction / Pointing Jitter

Altenhoff et al. 1987, A&A, 184, 381

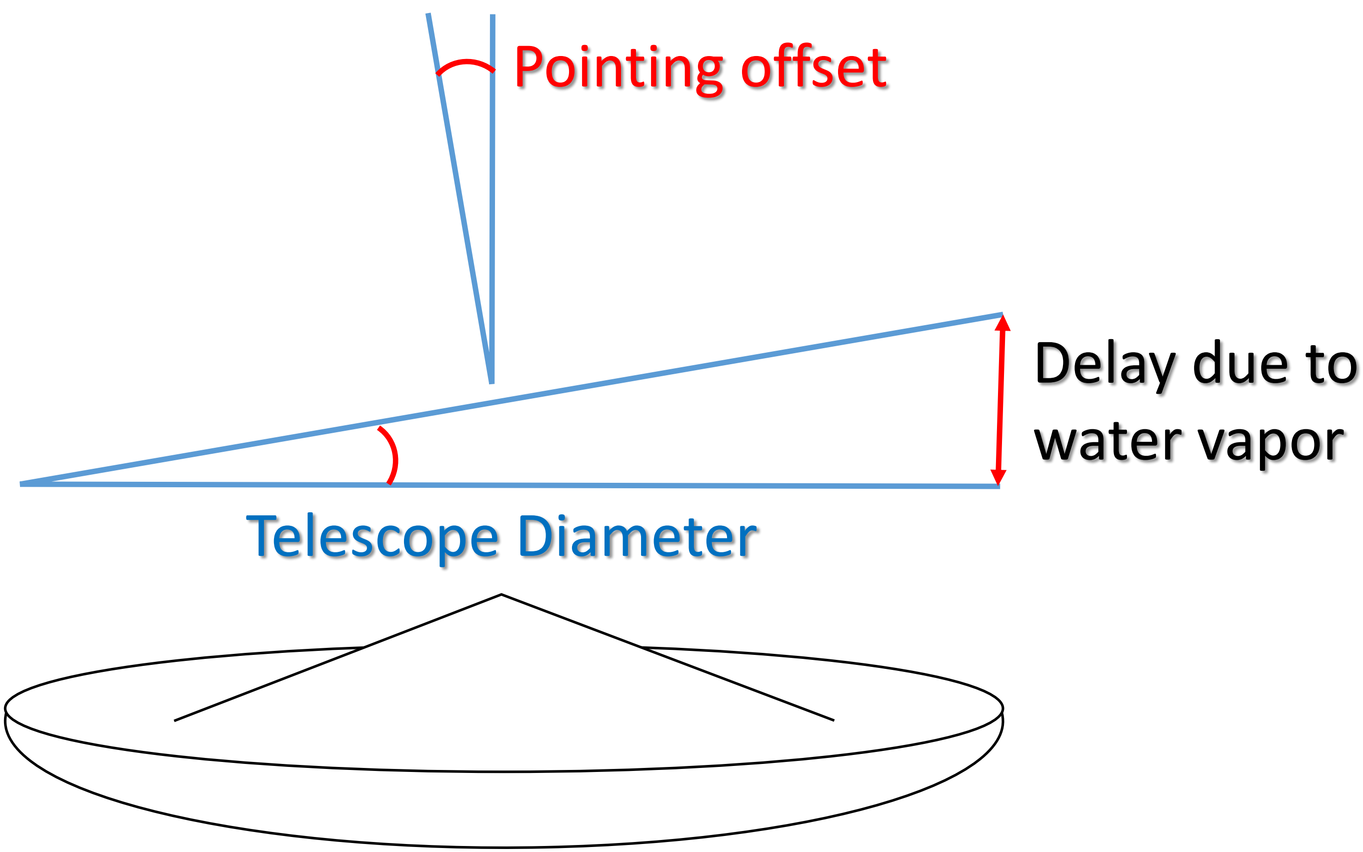


Anomalous Refraction / Pointing Jitter

Altenhoff et al. 1987, A&A, 184, 381

Pointing offset

= [Delay due to water vapor] / [Telescope Diameter]



2. Anomalous Refraction at the ALMA Site

- Based on the ALMA Long Baseline Campaign data, the empirical relationship between the rms excess path length (= phase fluctuation) and the baseline length is:

$$log_{10}(\Delta L[micron]) \\ = 0.65 \times log_{10}(D[m]) + 0.3 \times PWV[mm] + 0.1$$

- So, the anomalous refraction is expressed as:

$$\Delta\theta = \sqrt{2} \times 10^{0.3\times PWV[mm]-5.9} D[m]^{-0.35}[rad]$$

(the factor of $\sqrt{2}$ is for 1-D to 2-D correction, since the SSF above is 1-D, but the dish is 2-D)

2. Anomalous Refraction at the ALMA Site

- At PWV = 1 mm:

Diameter	Anomalous Refraction	Beam Size at 1000 GHz
12 m	0.31”	6.3”
20 m	0.25”	3.8”
30 m	0.22”	2.5”
40 m	0.20”	1.9”
50 m	0.19”	1.5”
100 m	0.15”	0.75”

- Pointing may be affected at larger PWVs.

2. Anomalous Refraction at the ALMA Site

- At PWV = 1 mm, but 1σ larger factors in the equation:

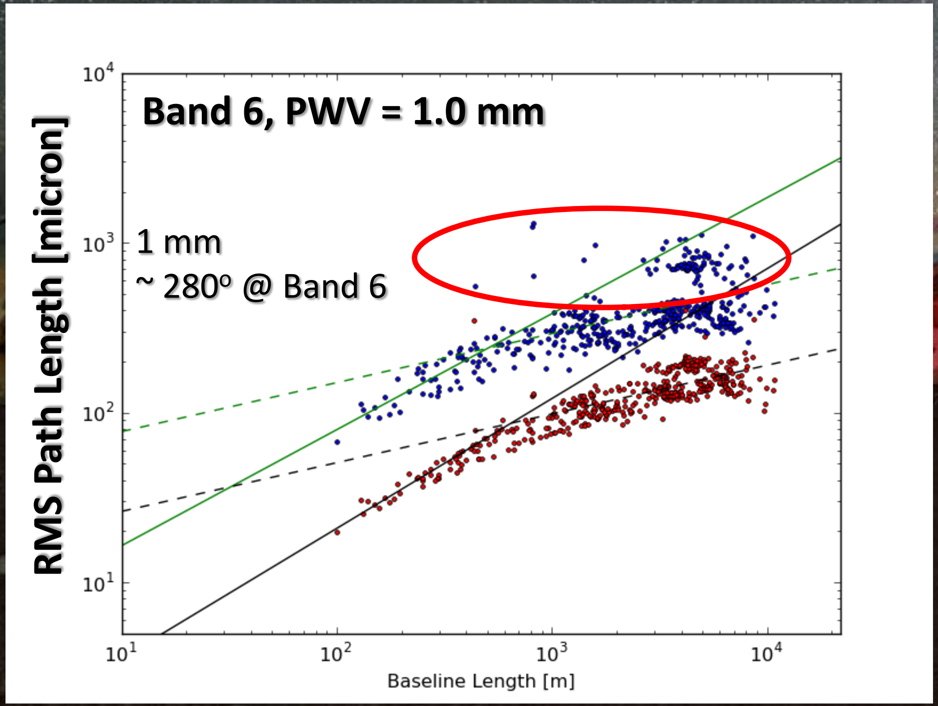
Diameter	Anomalous Refraction	Beam Size at 1000 GHz
12 m	0.56”	6.3”
20 m	0.49”	3.8”
30 m	0.43”	2.5”
40 m	0.40”	1.9”
50 m	0.37”	1.5”
100 m	0.31”	0.75”

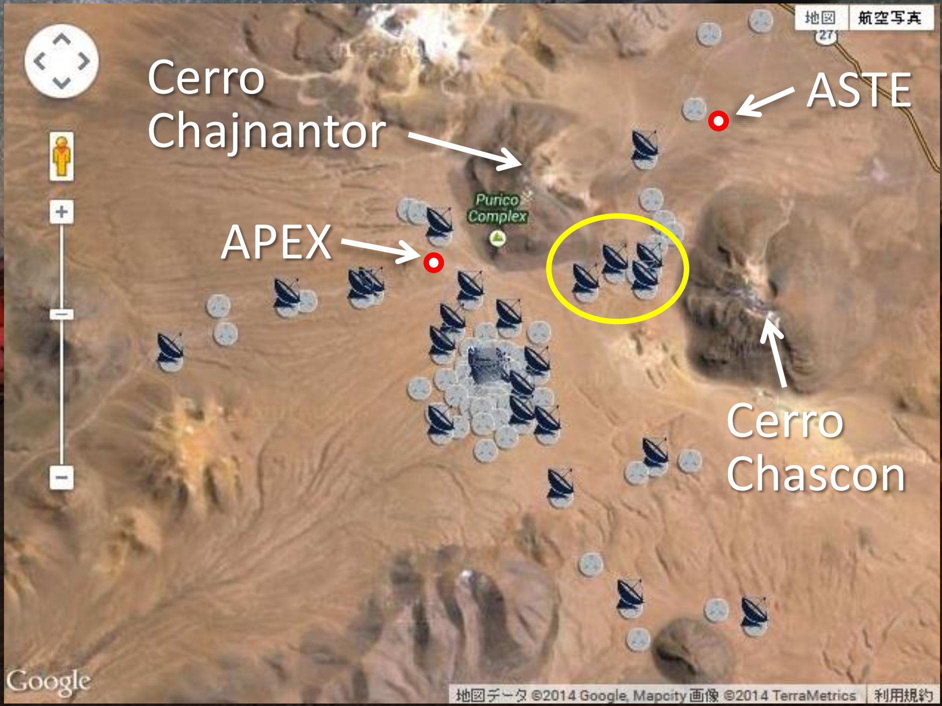
- Pointing will be affected at 3σ fluctuation.

3. Large Phase Fluctuation Between Mountains

- Large phase fluctuation has often (13/22) been observed with the antennas between Cerro Chajnantor and Cerro Chascon.
- WVR phase correction works well.
- WV turbulence due to the mountains.

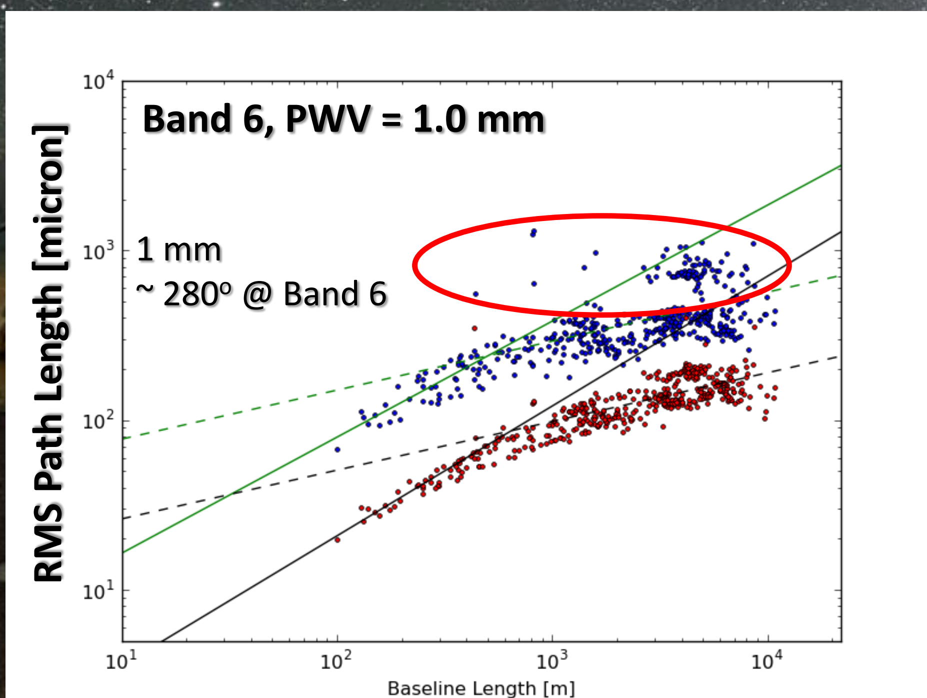
Asaki, Matsushita, et al. 2016, Proc. SPIE, 9906, 99065U





3. Large Phase Fluctuation Between Mountains

- Better not to construct telescopes between mountains
- Probably not the east side of Cerro Chajnantor and the west side of Cerro Chascon, too.
- Radio seeing monitor can measure this effect.



Summary

- Water Vapor Radiometer (WVR) phase correction works well for ALMA, especially when PWV > 1 mm.
- Spatial Structure Function (SSF; rms phase vs baseline length)
  - Often has turnover around 1 km baseline length, and the slope will be shallower at longer baselines.
- Longer baseline (>> 10 km) is promising, if combine with other phase correction methods (fast switching, band-to-band, etc.).
- If AtLAST locates far (> 10 km) from ALMA, and going to link with ALMA, it needs WVR and capabilities of other phase correction methods .
- Anomalous refraction may occasionally affect the telescope pointing at high frequencies.
- Better not to construct AtLAST between mountains.