Measurement of attenuation length for radio wave in natural rock salt samples concerning ultra high energy neutrino detection

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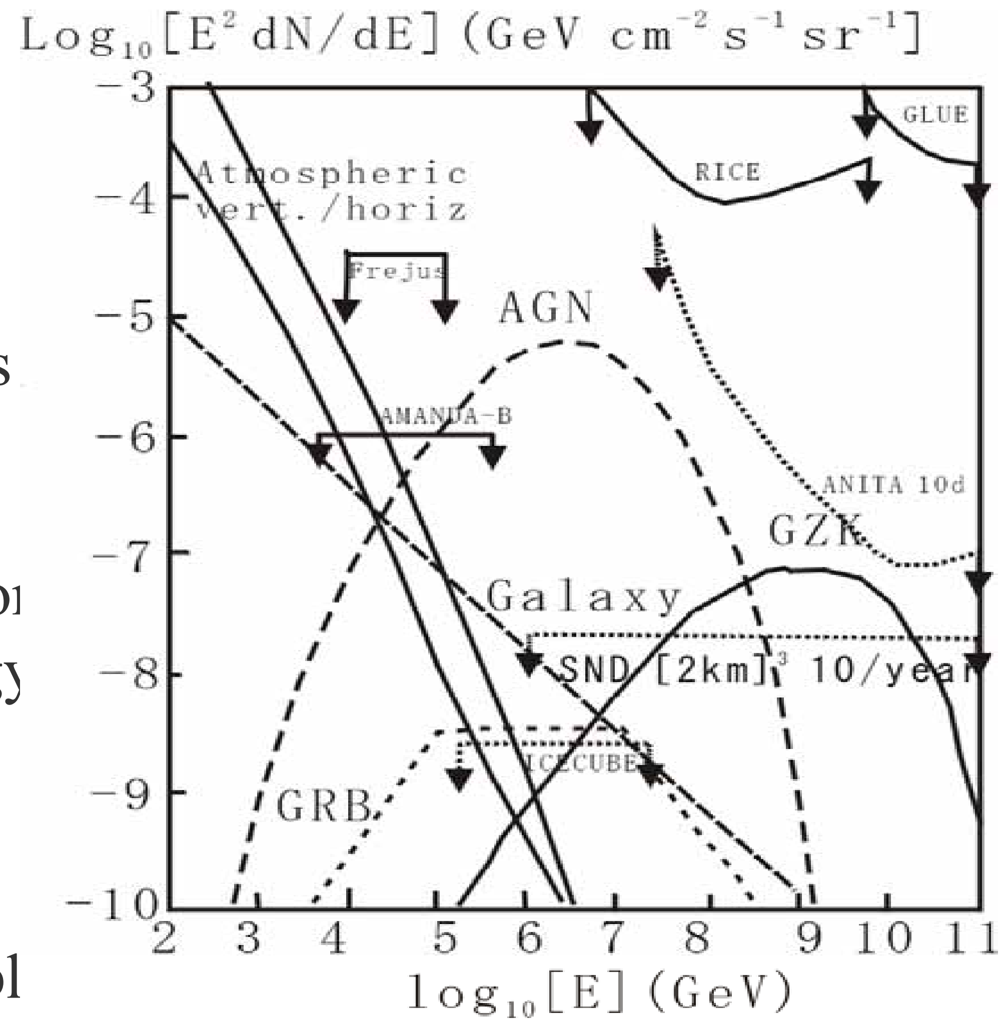
Neutrino flux and optimal detector

1. It is natural to aim at GZK neutrino at first.
2. Additions are direct UHE neutrinos from AGN, GRB, Topological Defects, etc.
3. GZK neutrino flux is as low as 1(km^{-2} day^{-1}).
4. Large detector is needed with information of energy, directio[n], time and flavor. For the energy measurement, calorimetric detection is better than muon track detection.
5. Radio wave detection is suitabl[e] way to realize a large detector.



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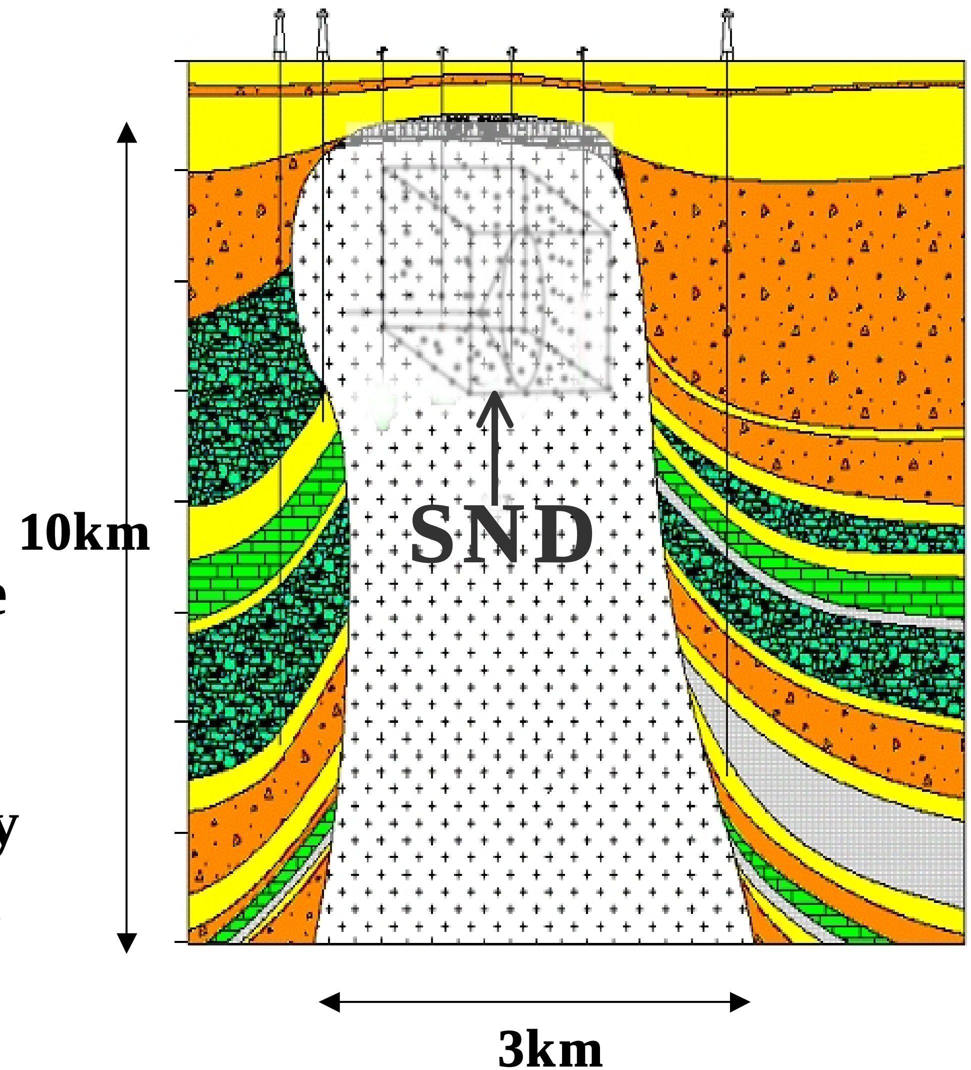
Salt neutrino detector installed in a salt dome

Dow Earth Sciences, Geol: J.Hertzing



1. **Rock salt is free from liquid and gas permeation：petroleum or natural gas are likely to deposit around the salt dome.**
2. **Free from water permeation results good radio wave transparency.**
3. **Covered soil prevents surface radio wave to penetrate.**
4. **Penetrating cosmic rays underground are too spatially disperse to generate coherent Cherenkov radiation effectively.**

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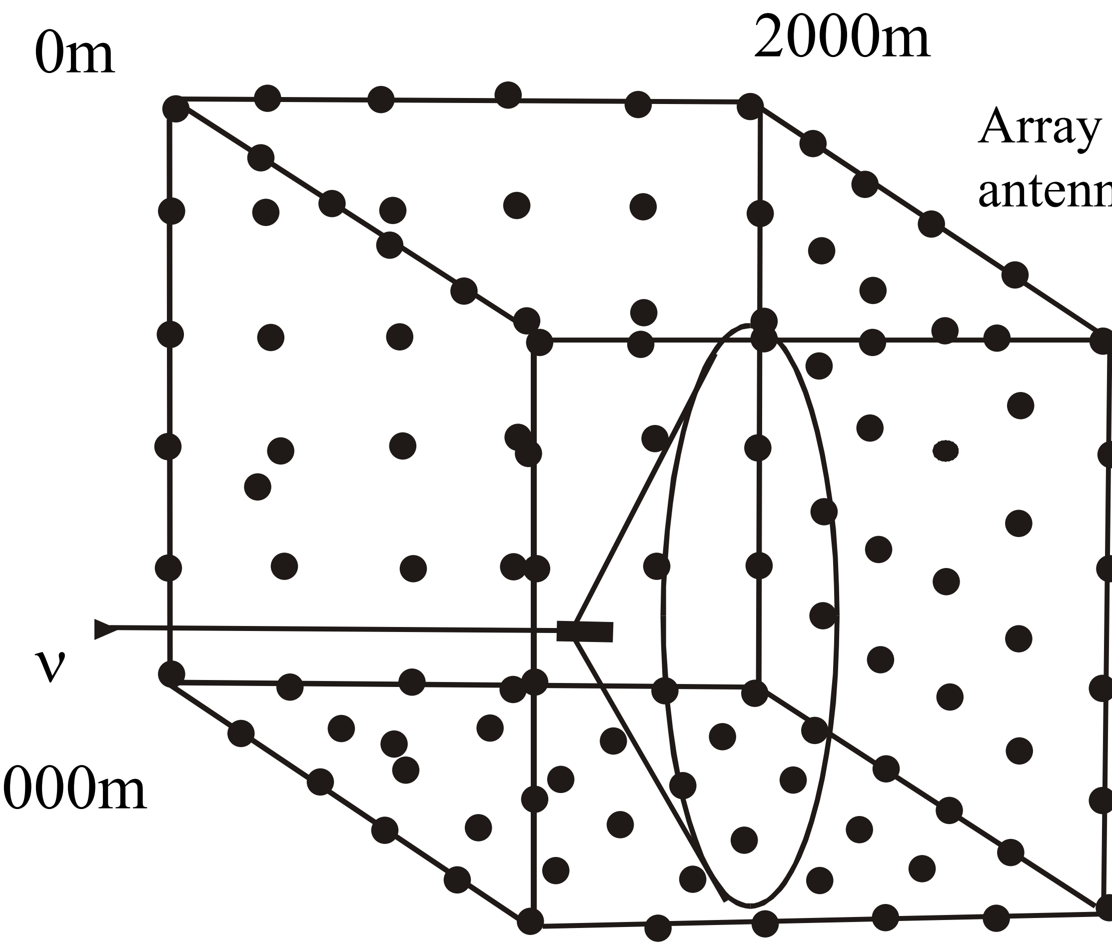
Underground Salt Neutrino Detector

Hockley salt mine, Texas



Moderate number of radio wave sensors could detect the neutrino interaction in the massive rock salt. It works as an imaging calorimetric detector.

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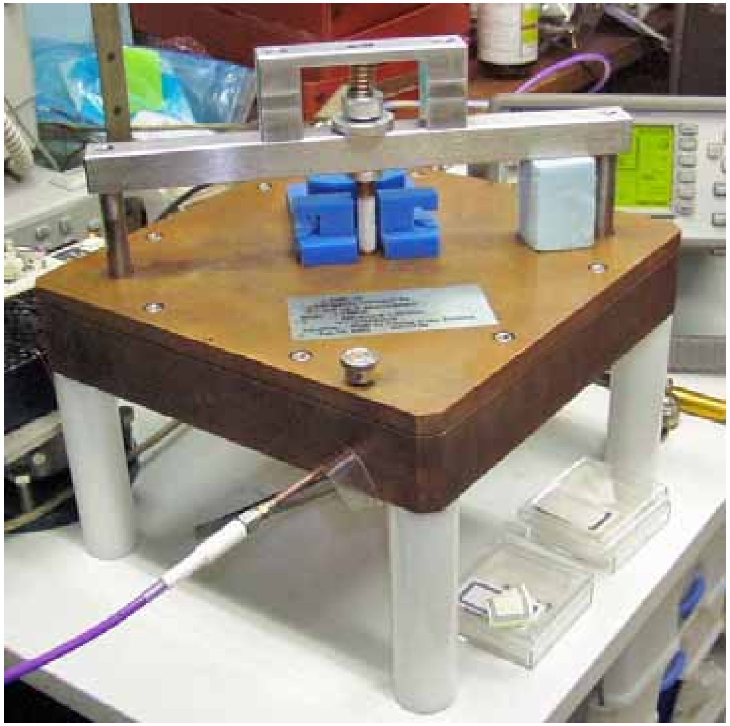
1GHz Cavity Resonator

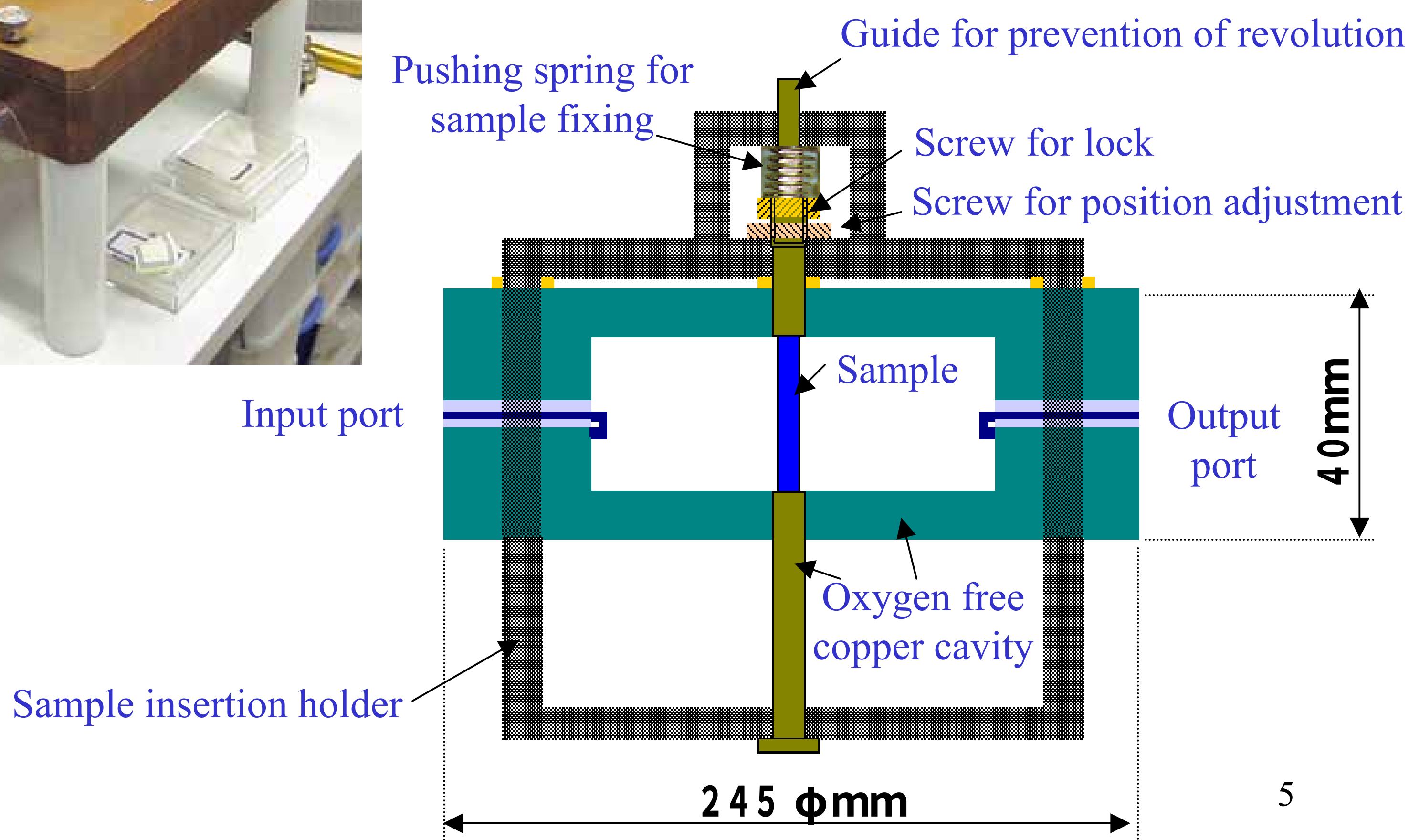


Mode: TM_{010}

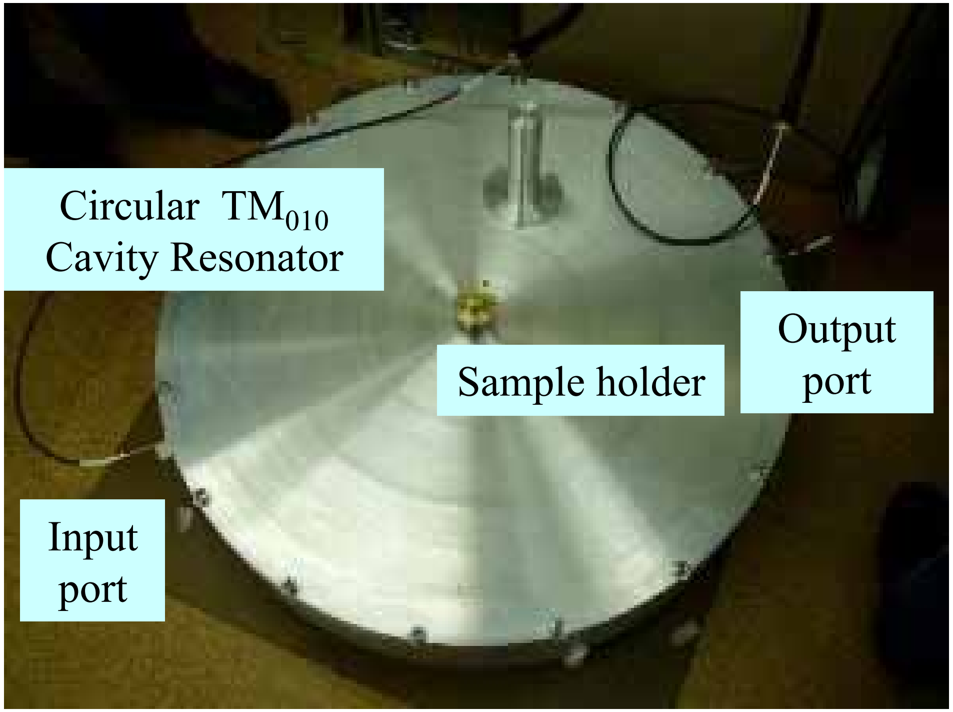
f=1.02GHz Q=10000

Inner Size: 225mmφ x 30mm

Sample Size: <10mmφ



300MHz Cavity



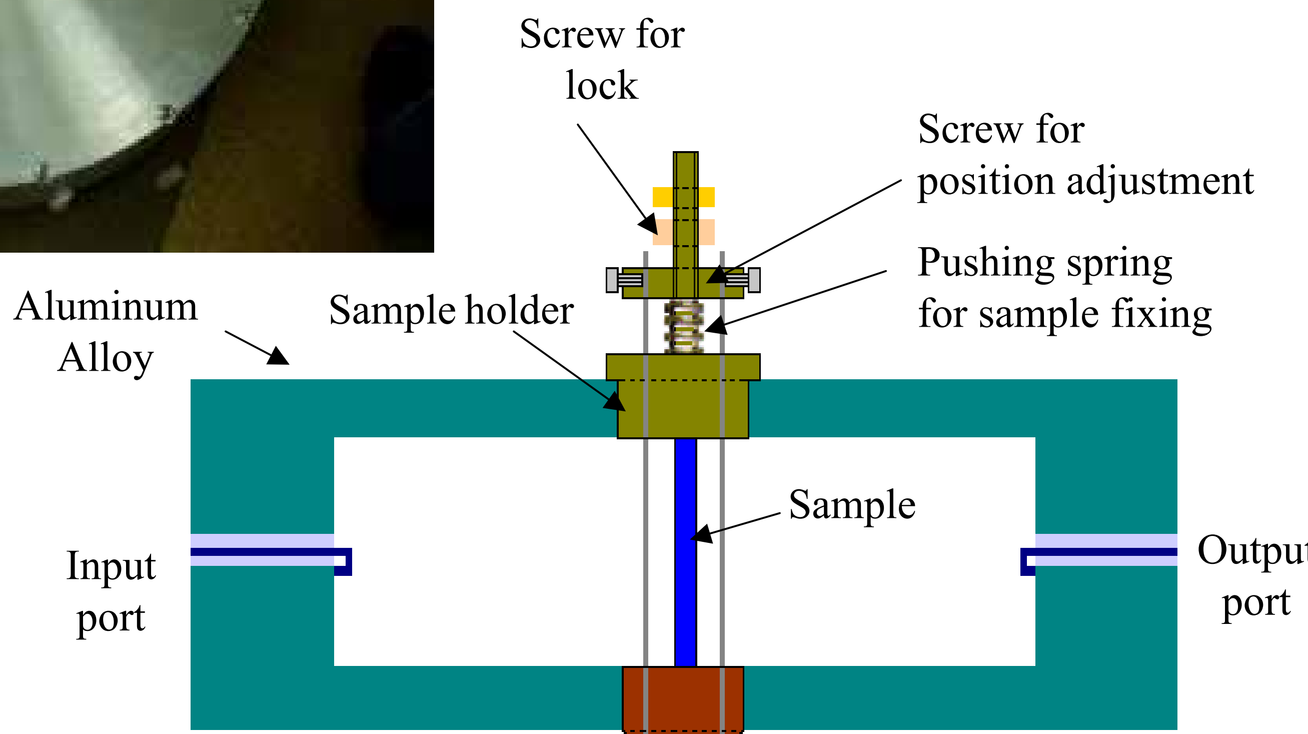
Mode:TM_{010}

f = 300.2GHz Q=12000

Inner Size:749mmϕ x 100mm

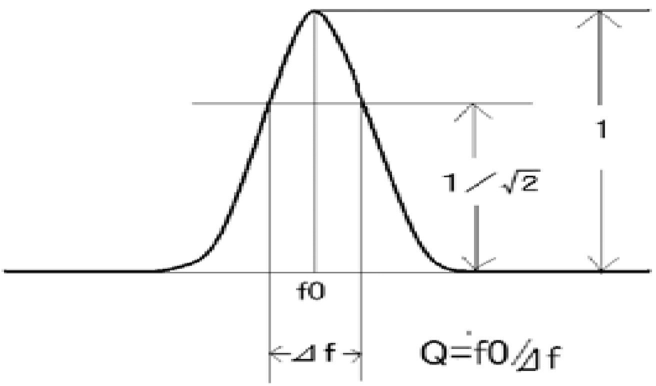
Sample Size: <30mmϕ

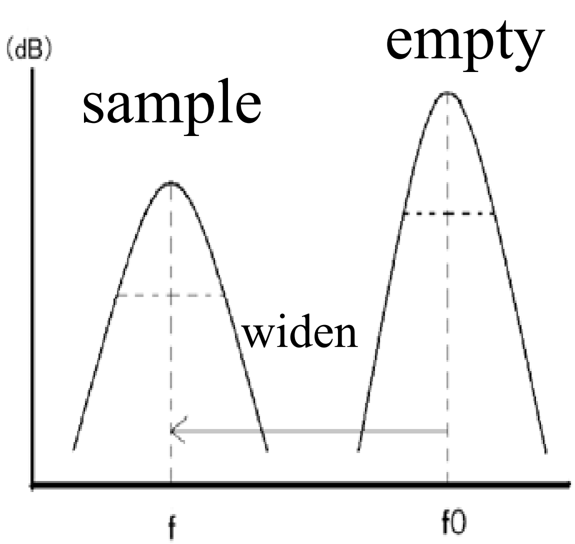
Sample holder with stand



Cavity perturbation method

Resonance curve





Complex permittivity

$$\varepsilon' = 1 - \frac{1}{\alpha_\varepsilon}\frac{f - f_0}{f}\frac{V}{\Delta V} = n^2$$

$$\varepsilon'' = \frac{1}{2\alpha_\varepsilon}\left(\frac{1}{Q} - \frac{1}{Q_0}\right)\frac{V}{\Delta V}$$

f_0: center frequency in empty
f : center frequency with sample
Q_0: empty
Q_0: with sample
ΔV: volume of sample
V : volume of cavity
α_ε=1.855 (TM010)

Attenuation length: $L_\alpha = \frac{1}{\alpha} = \frac{\lambda}{\pi\sqrt{\varepsilon'}\tan\delta}$

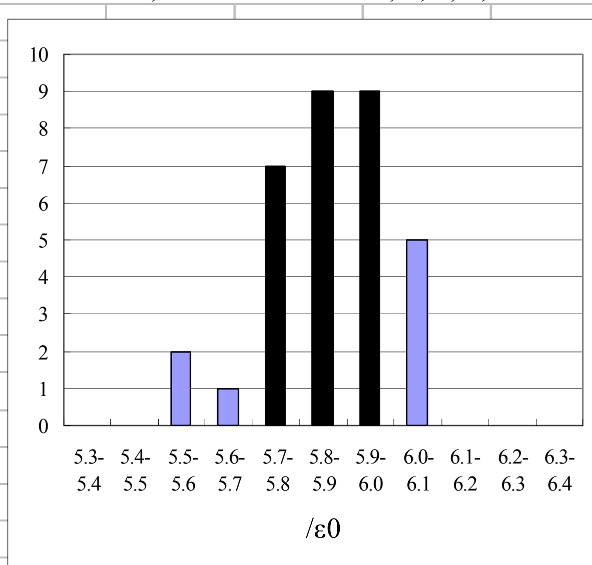
$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta)$$

1GHz synthetic rock salt

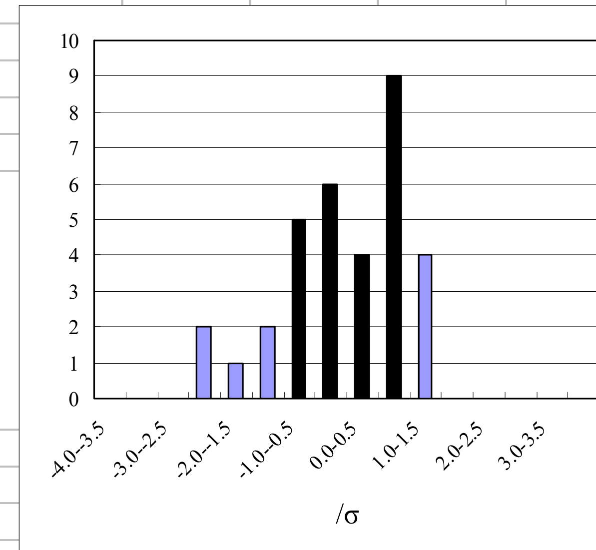
ε'	#
5.3-5.4	0
5.4-5.5	0
5.5-5.6	2
5.6-5.7	1
5.7-5.8	7
5.8-5.9	9
5.9-6.0	9
6.0-6.1	5
6.1-6.2	0
6.2-6.3	0
6.3-6.4	0

ε'=5.87±0.14, OHYO KOKEN 5, 6, 7, 8, 9Φ



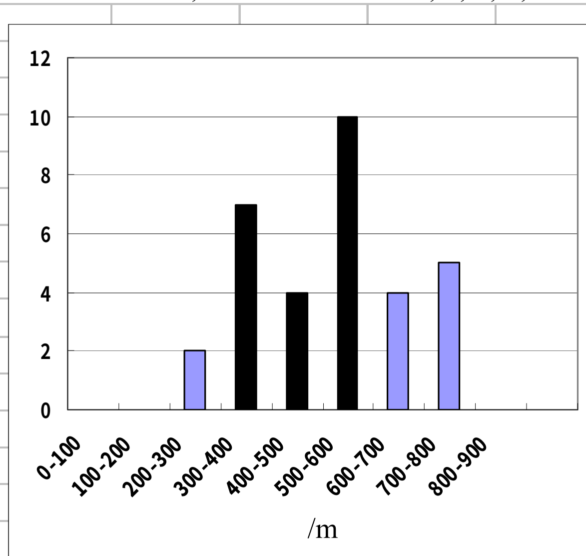
σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	0
-2.5--2.0	2
-2.0--1.5	1
-1.5--1.0	2
-1.0--0.5	5
-0.5--0.0	6
0.0-0.5	4
0.5-1.0	9
1.0-1.5	4
1.5-2.0	0
2.0-2.5	0
2.5-3.0	0
3.0-3.5	0
3.5-4.0	0

(ε'-ε'average)/σ, σ = 0.14



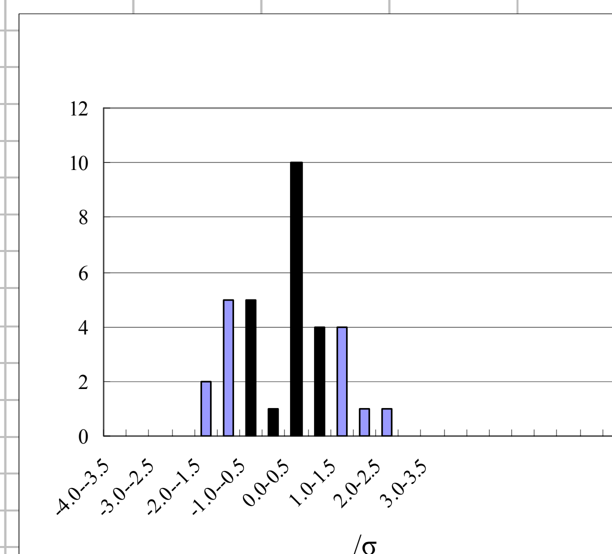
L/m	#
0-100	0
100-200	0
200-300	2
300-400	7
400-500	4
500-600	10
600-700	4
700-800	5
800-900	0

L/m=538±171m, OHYO KOKEN 5, 6, 7, 8, 9Φ



σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	0
-2.5--2.0	0
-2.0--1.5	2
-1.5--1.0	5
-1.0--0.5	5
-0.5--0.0	1
0.0-0.5	10
0.5-1.0	4
1.0-1.5	4
1.5-2.0	1
2.0-2.5	1
2.5-3.0	0
3.0-3.5	0
3.5-4.0	0

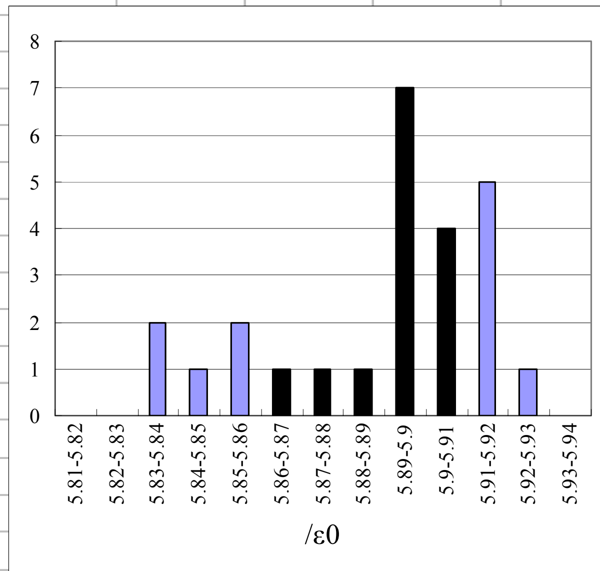
(L-Laverage)/σ, σ=171m



300MHz synthetic rock salt

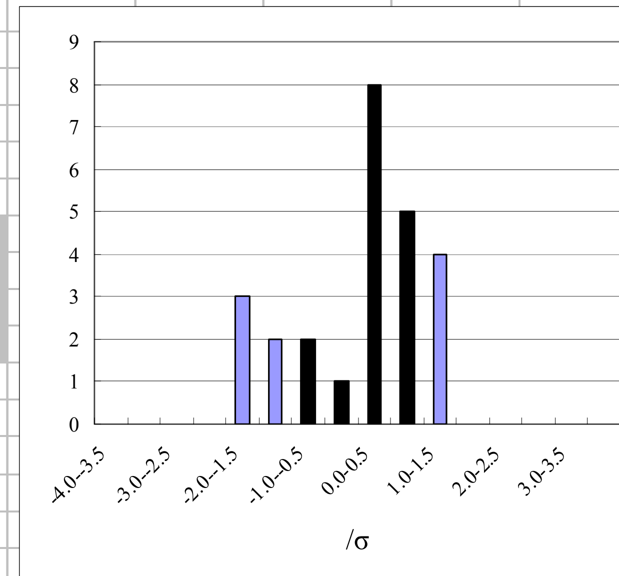
ε'	#
5.81-5.82	0
5.82-5.83	0
5.83-5.84	2
5.84-5.85	1
5.85-5.86	2
5.86-5.87	1
5.87-5.88	1
5.88-5.89	1
5.89-5.9	7
5.9-5.91	4
5.91-5.92	5
5.92-5.93	1
5.93-5.94	0

ε'=5.89±0.03, OHYO KOKEN 25, 30Φ



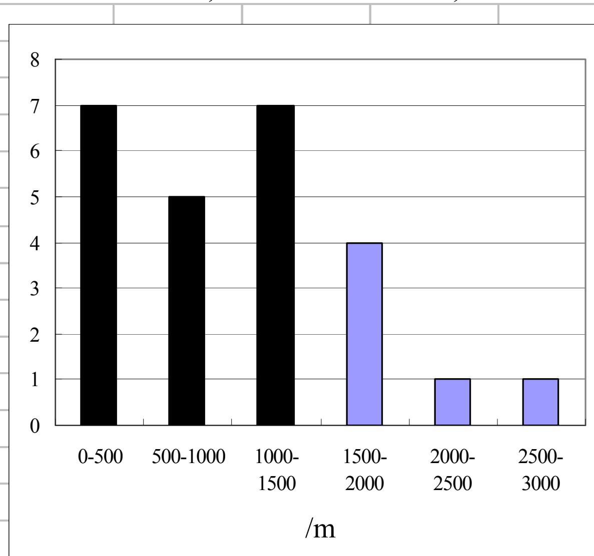
σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	0
-2.5--2.0	0
-2.0--1.5	3
-1.5--1.0	2
-1.0--0.5	2
-0.5--0.0	1
0.0-0.5	8
0.5-1.0	5
1.0-1.5	4
1.5-2.0	0
2.0-2.5	0
2.5-3.0	0
3.0-3.5	0
3.5-4.0	0

(ε'-ε'average)/σ, σ = 0.03



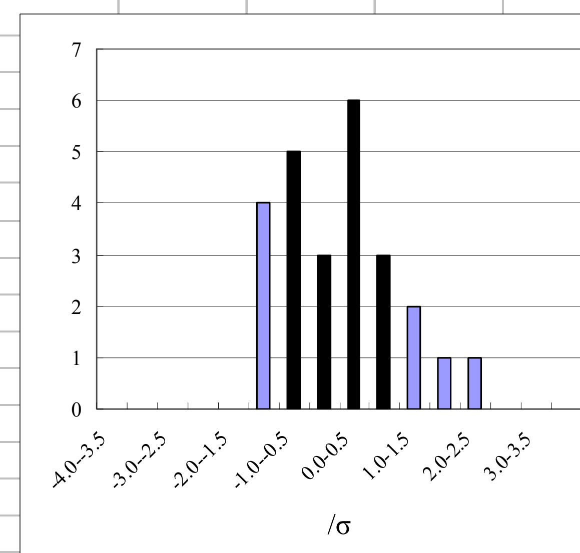
L/m	#
0-500	7
500-1000	5
1000-1500	7
1500-2000	4
2000-2500	1
2500-3000	1

L/m=1000±640m, OHYO KOKEN 25, 30Φ



σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	0
-2.5--2.0	0
-2.0--1.5	0
-1.5--1.0	4
-1.0--0.5	5
-0.5--0.0	3
0.0-0.5	6
0.5-1.0	3
1.0-1.5	2
1.5-2.0	1
2.0-2.5	1
2.5-3.0	0
3.0-3.5	0
3.5-4.0	0

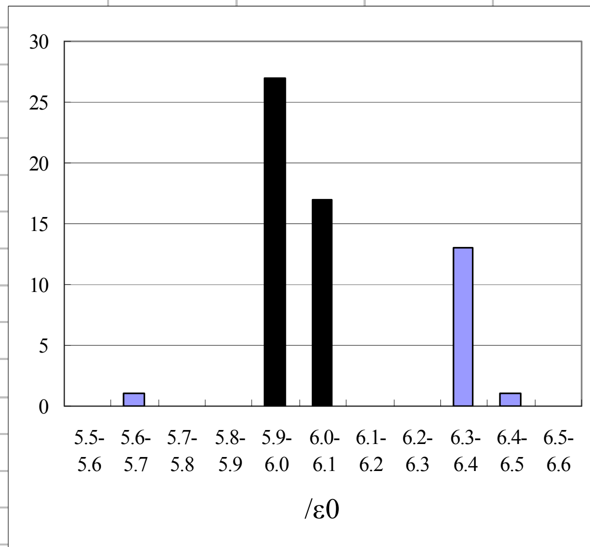
(L-Laverage)/σ, σ=640m



1GHz Hockley

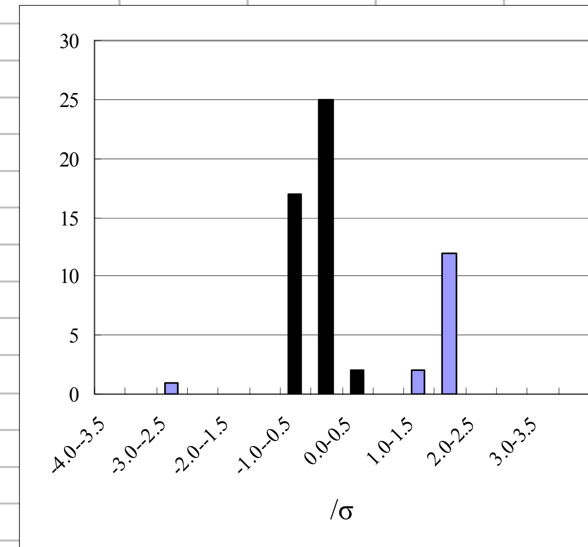
ε'=6.07±0.18, Hockley 6×6, 8, 9, 9Φ

ε'	#
5.5-5.6	0
5.6-5.7	1
5.7-5.8	0
5.8-5.9	0
5.9-6.0	27
6.0-6.1	17
6.1-6.2	0
6.2-6.3	0
6.3-6.4	13
6.4-6.5	1
6.5-6.6	0



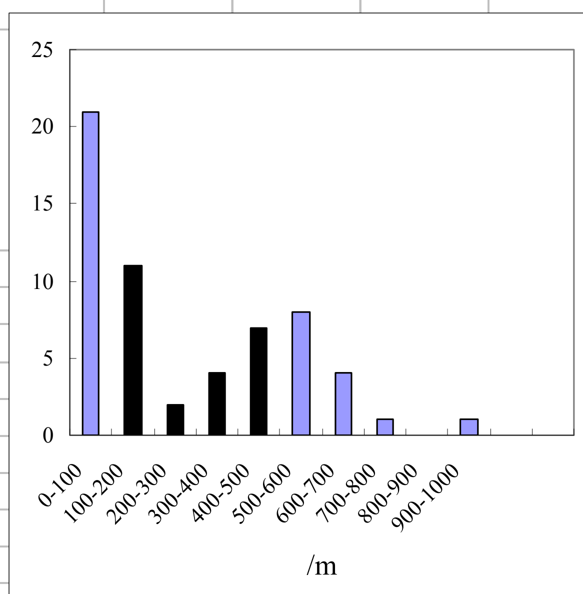
(ε'-ε'average)/σ, σ = 0.18

σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	1
-2.5--2.0	0
-2.0--1.5	0
-1.5--1.0	0
-1.0--0.5	17
-0.5--0.0	25
0.0-0.5	2
0.5-1.0	0
1.0-1.5	2
1.5-2.0	12
2.0-2.5	0
2.5-3.0	0
3.0-3.5	0
3.5-4.0	0



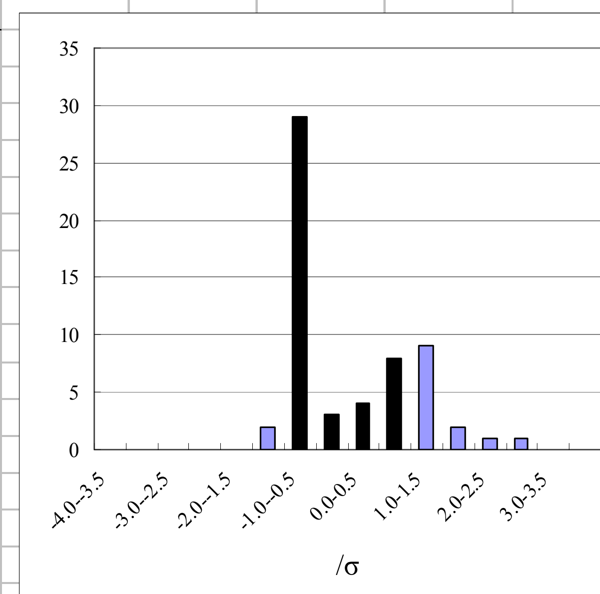
L/m=275±234m, Hockley 6×6, 8, 9, 9Φ

L/m	#
0-100	21
100-200	11
200-300	2
300-400	4
400-500	7
500-600	8
600-700	4
700-800	1
800-900	0
900-1000	1



(L-Laverage)/σ, σ=234m

σ	#
-4.0--3.5	0
-3.5--3.0	0
-3.0--2.5	0
-2.5--2.0	0
-2.0--1.5	0
-1.5--1.0	2
-1.0--0.5	29
-0.5--0.0	3
0.0-0.5	4
0.5-1.0	8
1.0-1.5	9
1.5-2.0	2
2.0-2.5	1
2.5-3.0	1
3.0-3.5	0
3.5-4.0	0



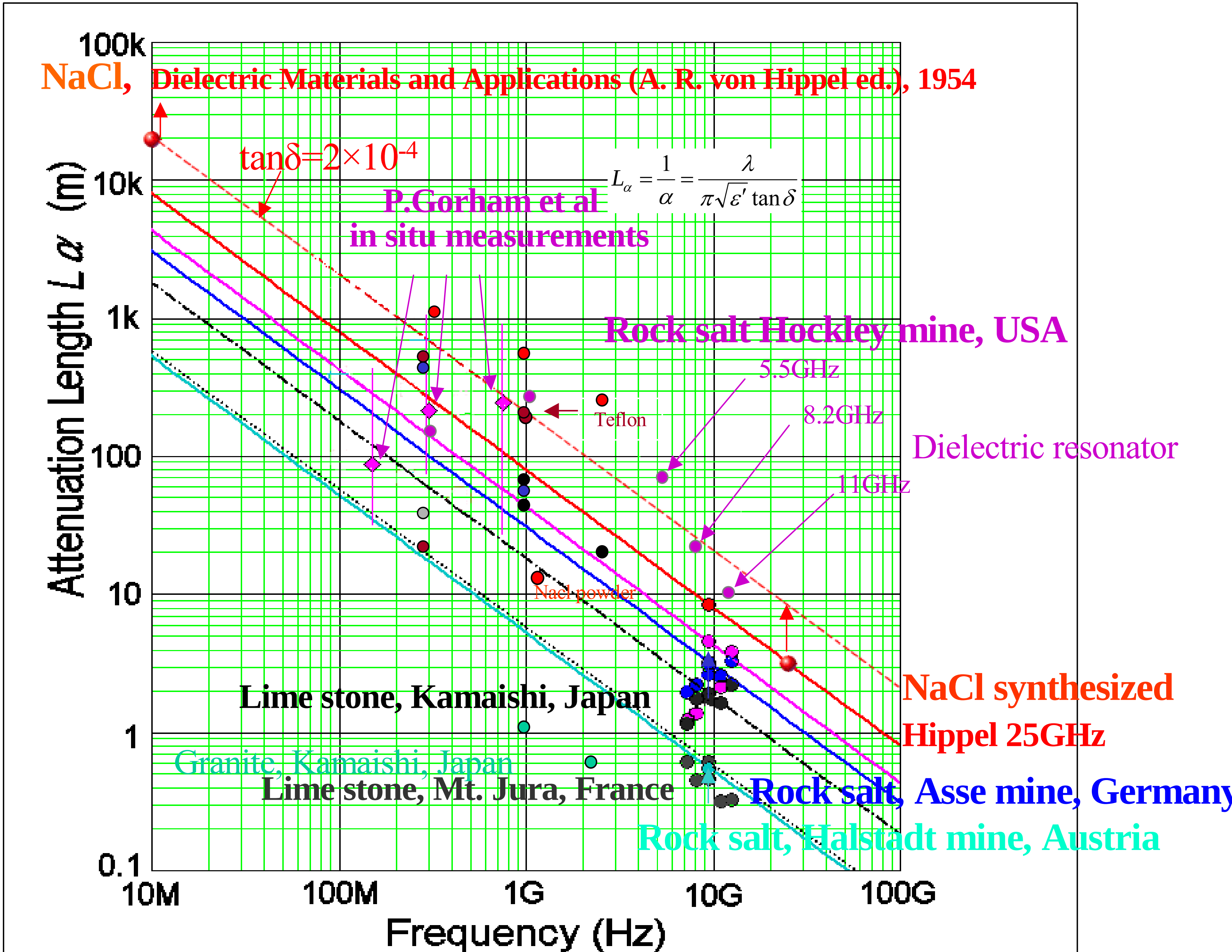
Rock Salts

Length of Samples: 30mm (1GHz), 100mm (300MHz), Errors: 1 standard deviation among the measurements

Freq.	Synthetic Rock Salt Samples (diameter/mm)	ε'	Attenuation Length/m	# of Measurements
300MHz	OHYO KOKEN KOGYO CO.25, 30φ	5.89±0.03	1000±640	25
1GHz	OHYO KOKEN KOGYO CO.5, 6, 7, 8, 9φ	5.87±0.14	538±171	32

Freq.	Natural Rock Salts Samples (diameter/mm)	ε'	Attenuation Length/m	# of Measurements
300MHz	Hockley 10.4×10.9, 28, 29φ (USA)	5.82±0.32	156±112	48
1GHz	Hockley6×6:monocrystalline form, 8φ, 9φ, 9φ (USA)	6.07±0.18	275±234	59
300MHz	Zuidwending 28φ(Netherlands)	6.05±0.03	22±2	24
1GHz	Zuidwending 8φ(Netherlands)	6.23±0.06	77±11	21
300MHz	Asse 25φ, 28φ (Germany)	5.94±0.03	405±166	41
1GHz	Asse 9φ, 10φ(Germany)	6.04±0.06	60±25	39
300MHz	Heilbronn 29φ (Germany)	5.26±0.03	41±3	18
1GHz	Lugansk 9φ, 9φ: monocrystalline form (Ukraine)	6.03±0.03	517±339	36

Attenuation length



Summary

1. Frequency dependences of the attenuation length of synthetic and Asse rock salts are consistent with a hypothesis as $\tan\delta$ being constant with frequency.
2. Asse rock salt would give longer attenuation length (>400m) at the lower frequency (<300MHz).
3. The attenuation length of Hockley increases from 0.3GHz to 1GHz which is consistent with in situ measurement. (P. Gorham et al., Nuclear Instruments & Methods, A490 (2002) 476-491).
4. Hockley rock salt should have a maximum attenuation length between 0.5GHz and 2GHz.
5. Economical antenna spacing ($\sim$300m) could detect GZK neutrinos if we select a suitable site.