

Estimated sensitivity for auxiliary degrees of freedom of KAGRA interferometer

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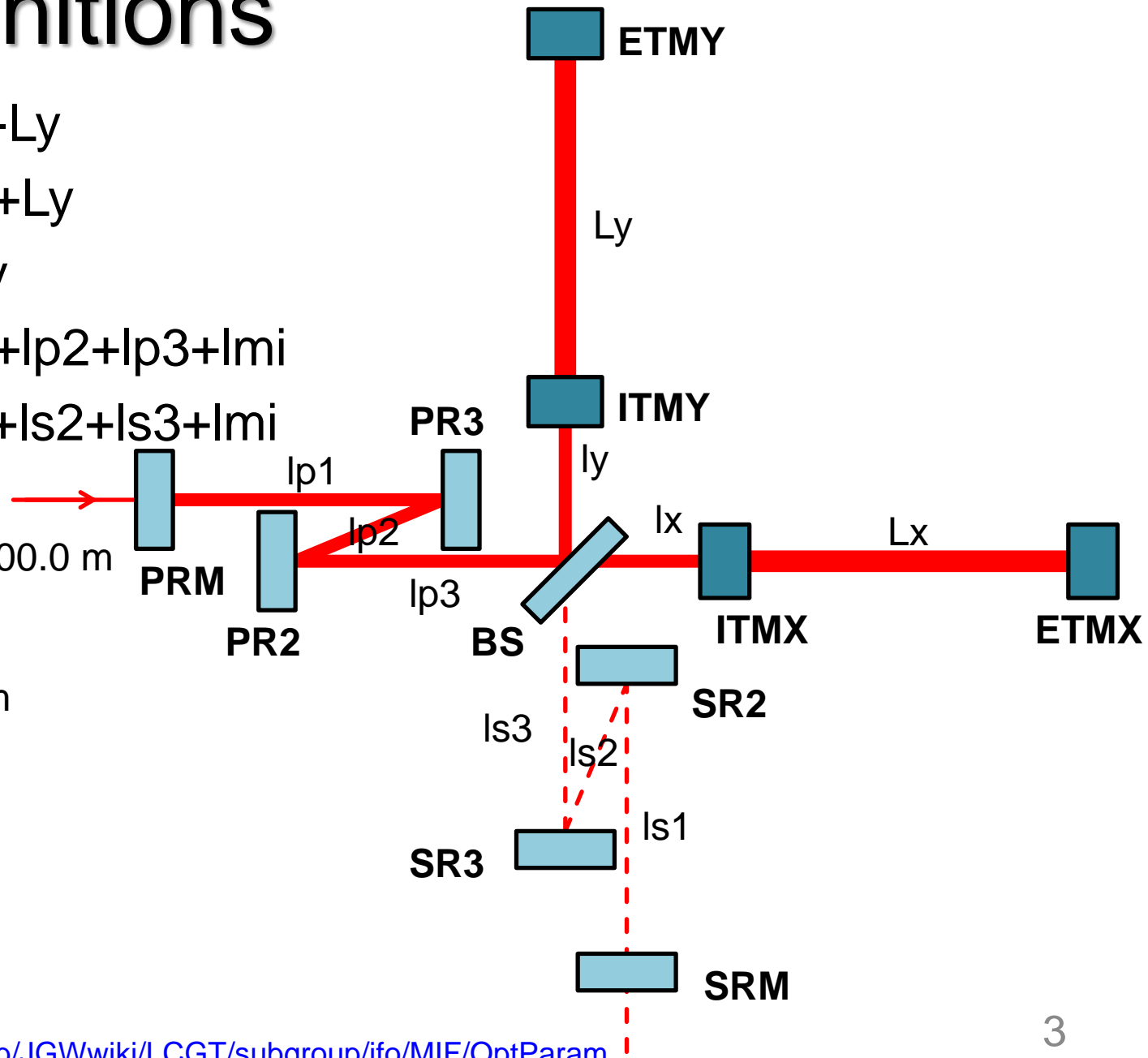
Scope

- Estimate the displacement sensitivity for CARM, MICH, PRCL, SRCL
 - useful for the noise budget of auxiliary DoFs
- Based on the latest estimated sensitivity code ([JGW-T1707038](#))
- Seismic noise
 - fitted function from suspension model
- Suspension thermal noise
 - analytical calculation
- Mirror thermal noise
 - analytical calculation (we have to guess coating thickness)
- Quantum noise
 - analytical calculation for DARM, fitting of Optickle result for auxiliary DoFs

Definitions

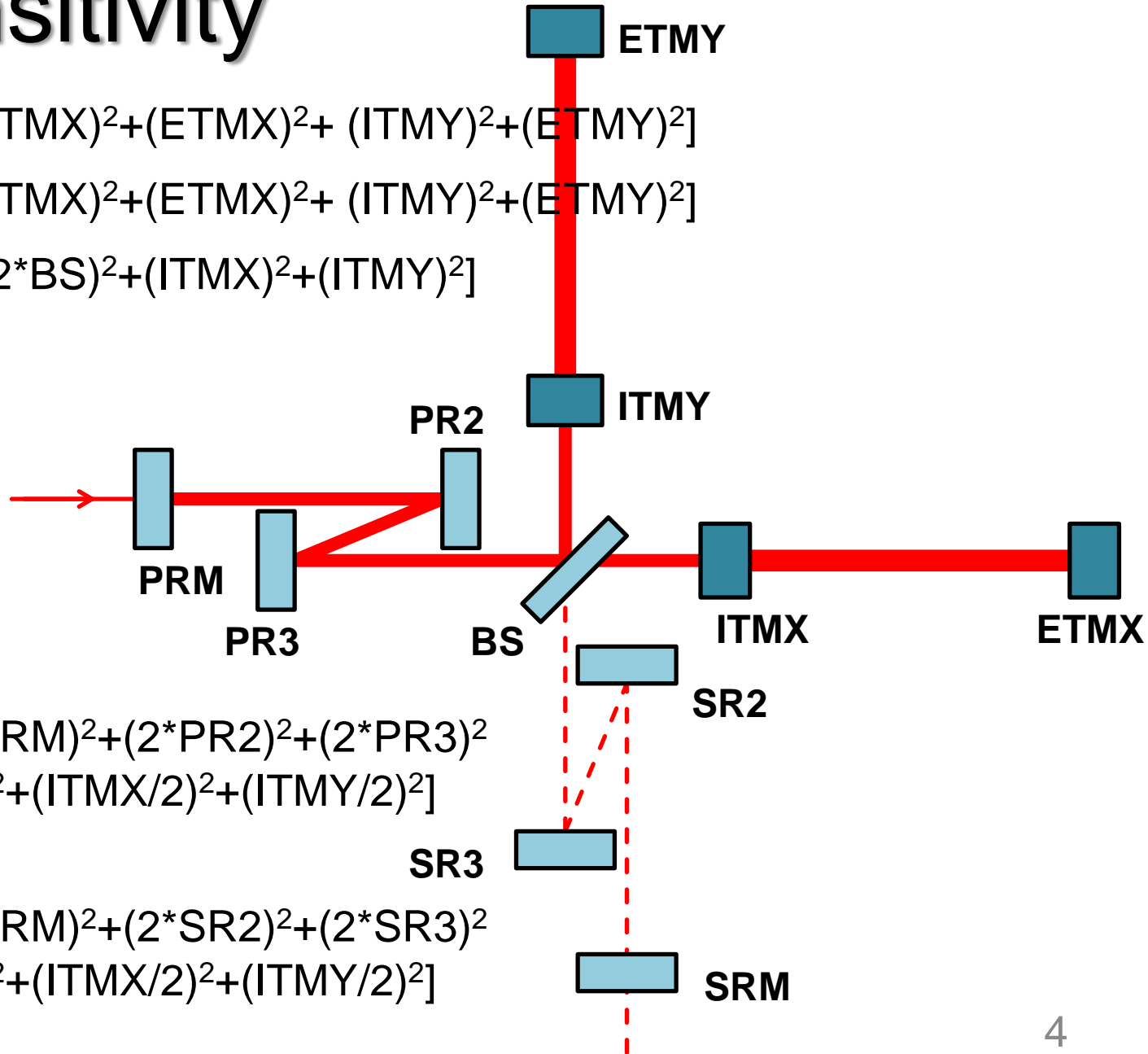
- DARM: $L_x - L_y$
- CARM: $L_x + L_y$
- MICH: $l_x - l_y$
- PRCL: $l_{p1} + l_{p2} + l_{p3} + l_{mi}$
- SRCL: $l_{s1} + l_{s2} + l_{s3} + l_{mi}$

$L_x = L_y = L_{arm} = 3000.0 \text{ m}$
 $L_x = 26.6649 \text{ m}$
 $l_y = 23.3351 \text{ m}$
 $l_{mi} = (l_x + l_y) / 2 = 25 \text{ m}$
 $l_{p1} = 14.7615 \text{ m}$
 $l_{p2} = 11.0661 \text{ m}$
 $l_{p3} = 15.7638 \text{ m}$
 $l_{s1} = 14.7412 \text{ m}$
 $l_{s2} = 11.1115 \text{ m}$
 $l_{s3} = 15.7386 \text{ m}$



Sensitivity

- DARM: $\sqrt{[(ITMX)^2+(ETMX)^2+ (ITMY)^2+(ETMY)^2]}$
- CARM: $\sqrt{[(ITMX)^2+(ETMX)^2+ (ITMY)^2+(ETMY)^2]}$
- MICH: $\sqrt{[(\sqrt{2}*BS)^2+(ITMX)^2+(ITMY)^2]}$

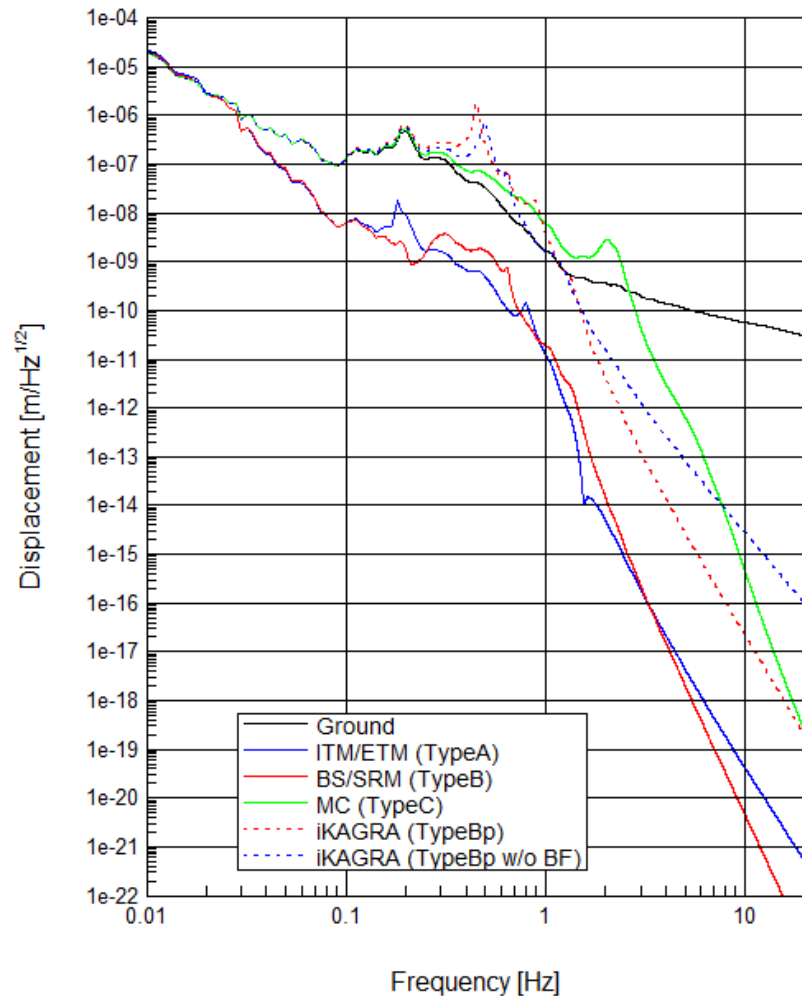


- PRCL: $\sqrt{[(PRM)^2+(2*PR2)^2+(2*PR3)^2 +(\sqrt{2}/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]}$
- SRCL: $\sqrt{[(SRM)^2+(2*SR2)^2+(2*SR3)^2 +(\sqrt{2}/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]}$

Seismic noise

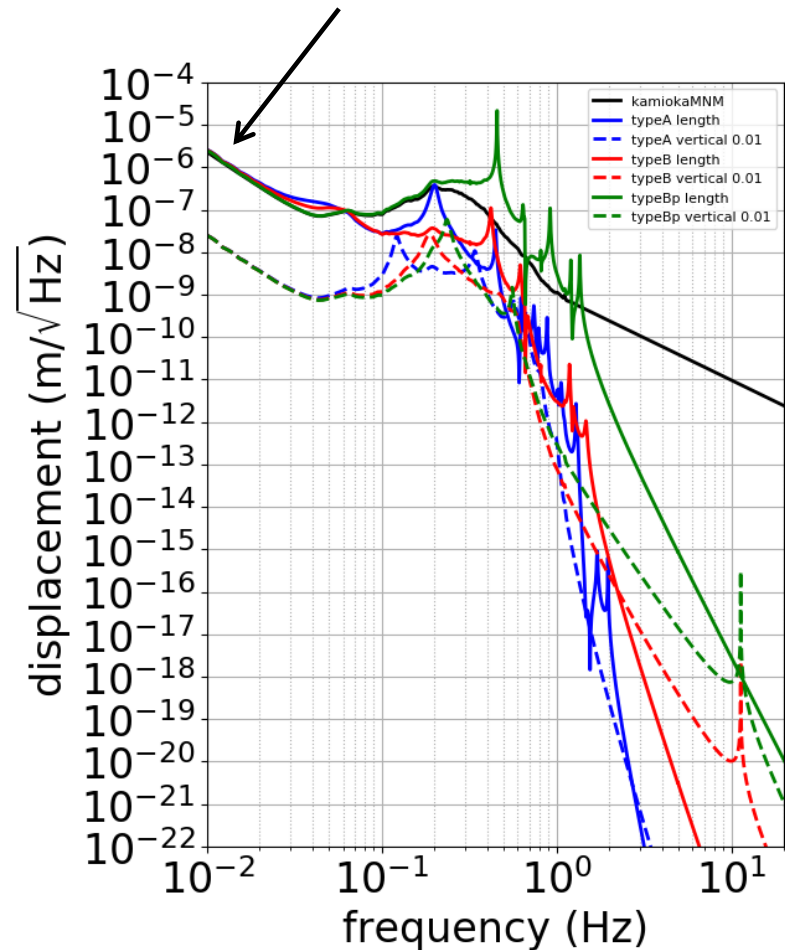
Models

- There exists several models



TypeA-C rev3.png
from R. Takahashi
(used for K. Somiya's fitting)

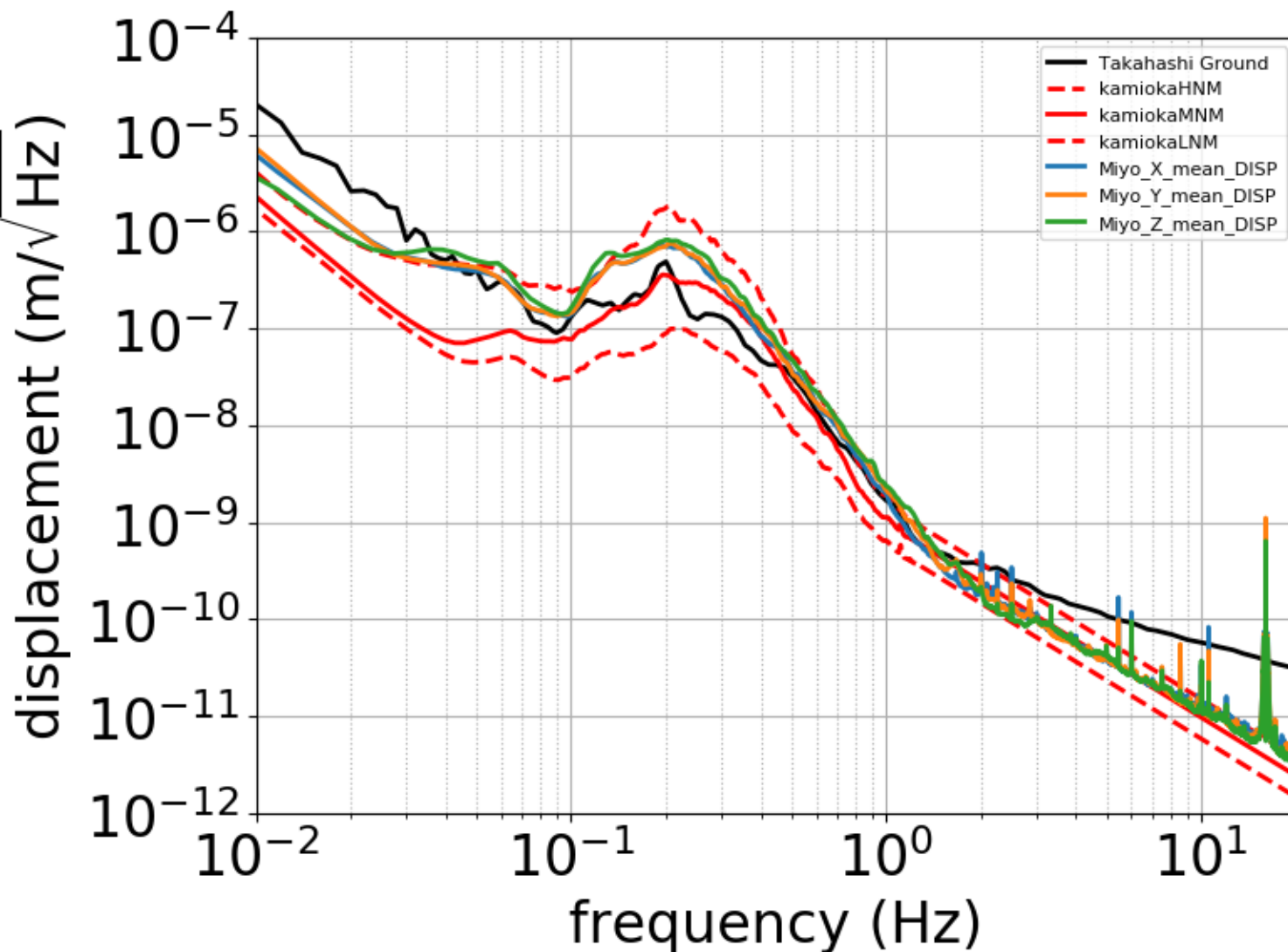
Medium Noise Model
from [JGW-T1402971](https://www.jgwg.org/jgwg-t1402971)



Model from T. Sekiguchi
(used for actuator modeling in
[JGW-P1707051](https://www.jgwg.org/jgwg-p1707051))

Seismic Noise Spectra

- Let's just use [JGW-T1402971](#) MNM for simplicity



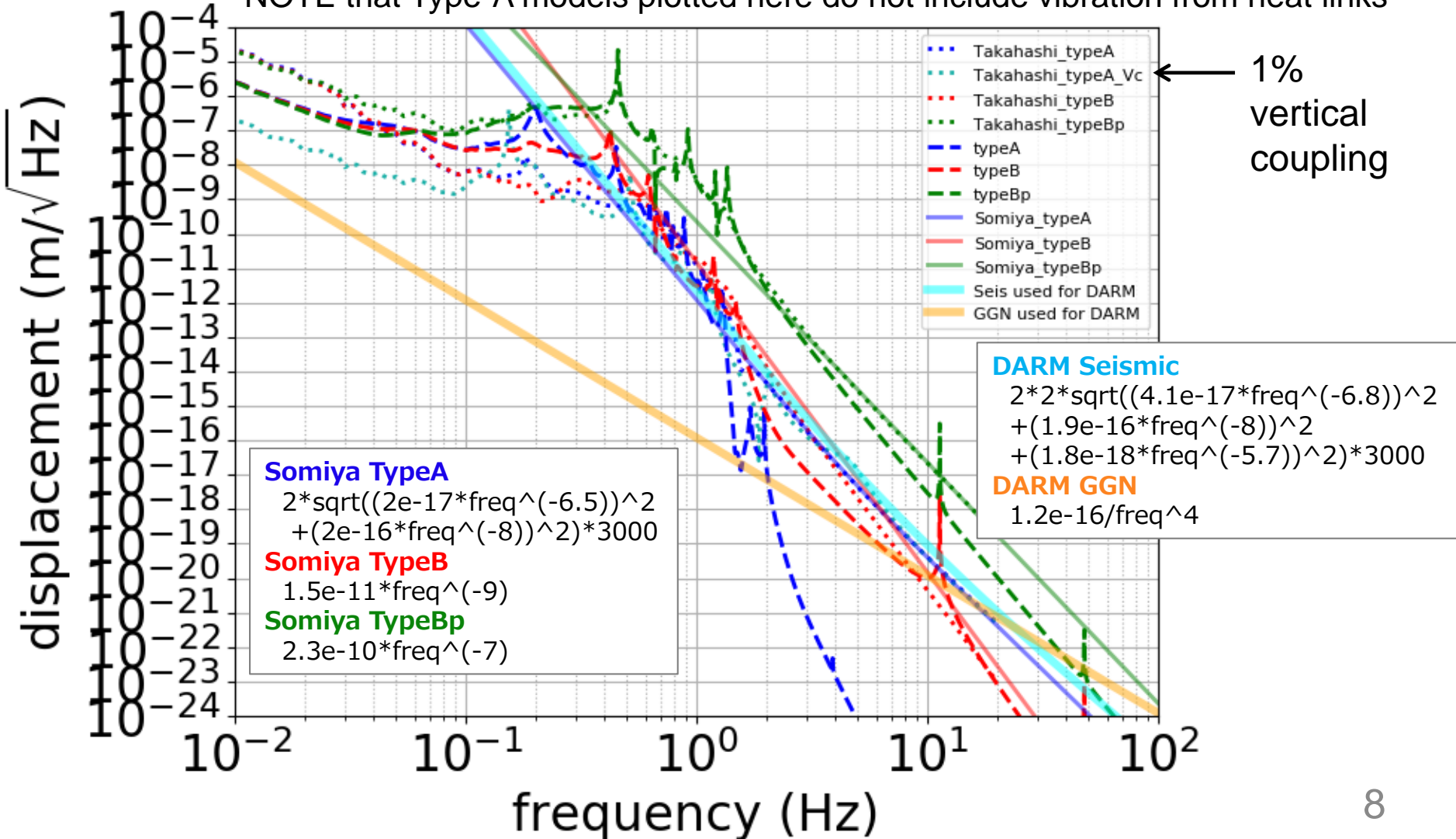
By Sekiguchi
[JGW-T1402971](#)

By Miyo
[JGW-T1910436](#)

Comparison Between Models

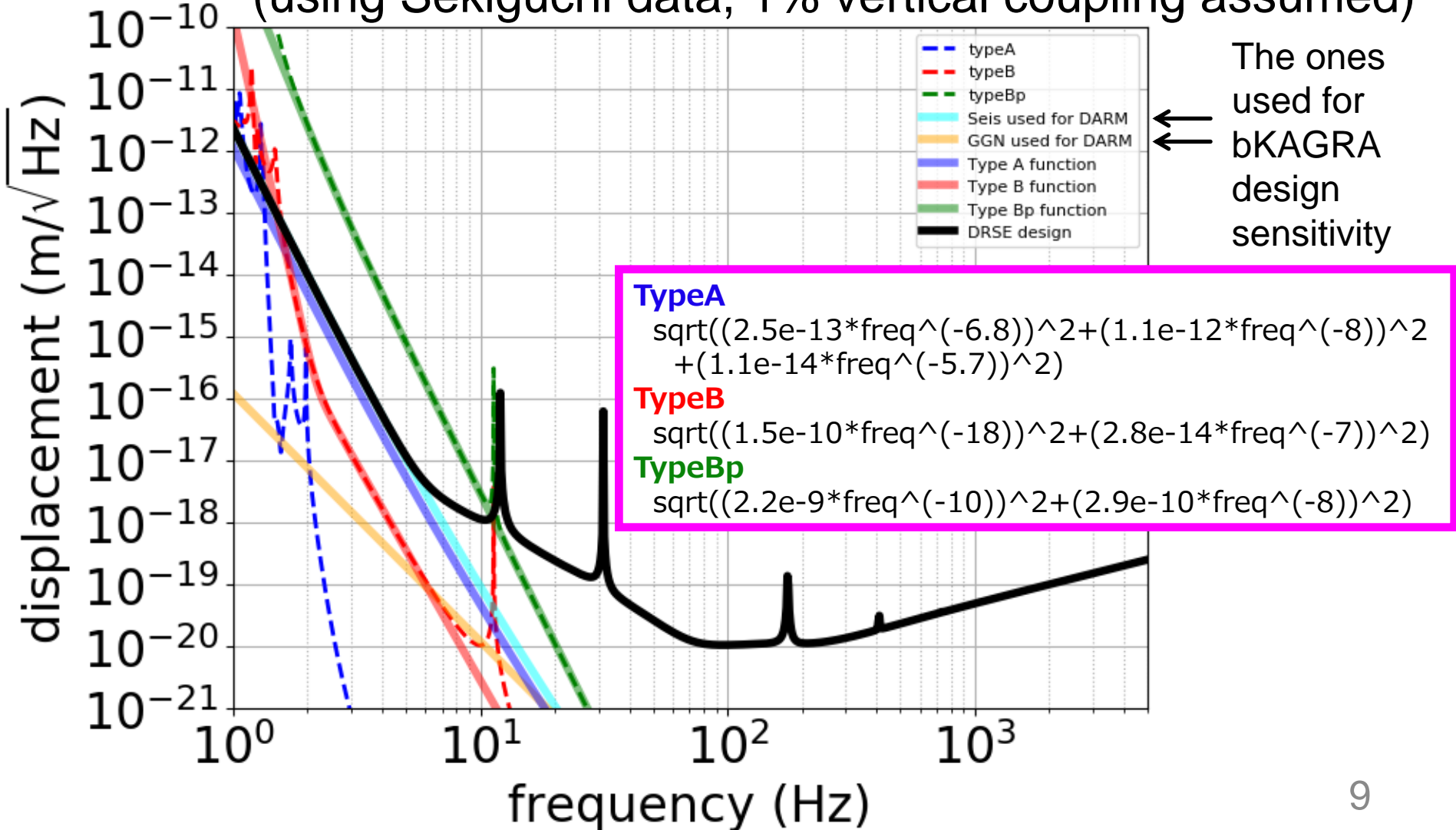
- Fitting function by Somiya based on Takahashi model

NOTE that Type-A models plotted here do not include vibration from heat links



New Seismic Function

- Function for one optic that work above ~3 Hz
(using Sekiguchi data, 1% vertical coupling assumed)



Suspension thermal noise

Type-A Payload Configuration

[CQG 34, 225001 \(2017\)](#)

IM suspension

4 CuBe wires
16 K
26.1 cm long, 0.6 mm dia.
loss angle $5e-6$

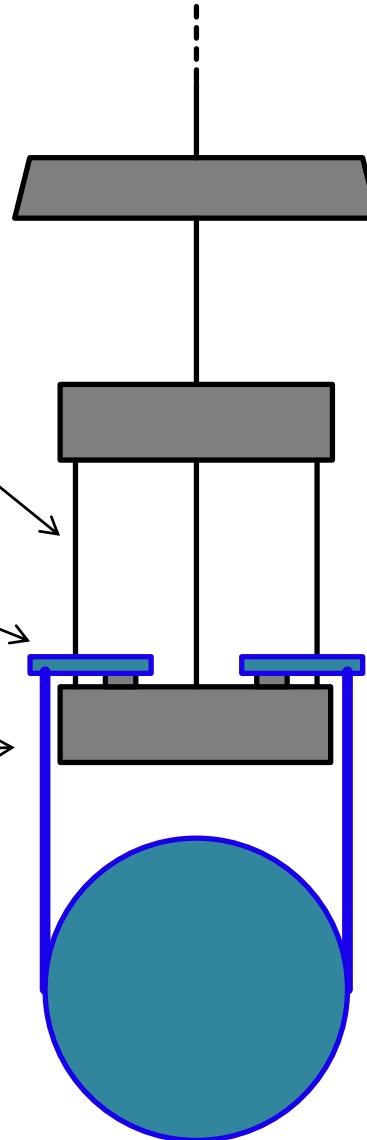
Blade springs

4 Sapphire
55 g each
16 K
loss angle $7e-7$

TM suspension

4 Sapphire fibers
19 K (average of 16 K and 22 K)
35 cm long, 1.6 mm dia.
loss angle $2e-7$

Vertical to horizontal coupling 1/200



Platform

Marionette

16 K

Intermediate mass

16 K

20.5 kg

Test mass

22 K

22.8 kg

Type-B Payload Configuration

IM suspension

1 maraging steel rod
62.5 cm long, 3.6 m dia. body for BS
59.85 cm long, 2.5 mm dia. body for SRs
(neck 2.65 cm long, 2 mm dia.)
loss angle $2e-4$

[CQG 34, 225001 \(2017\)](#)

Type-B info from Fabian

Type-B maraging rod [JGW-D1605614](#)

BS mass budget [JGW-E1604966](#)

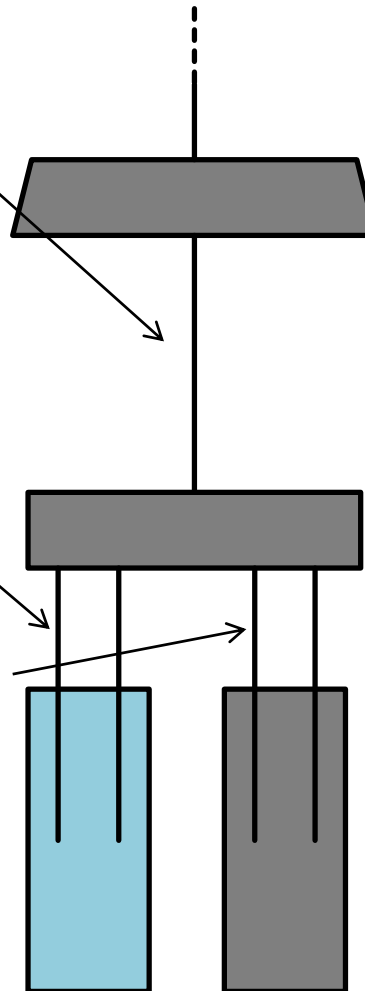
TM suspension

4 piano wires
55.1 cm long, 0.3 mm dia. for BS
58.7 cm long, 0.2 mm dia. for SRs
loss angle $2e-4$

RM suspension

4 tungsten wires
55.1 cm long, 0.65 mm dia. for BS
58.7 cm long, 0.6 mm dia. for SRs
loss angle $1.7e-4$

Vertical to horizontal coupling $1/200$
("neck" is ignored in the calculation)
OK since vertical thermal noise is dominating



Bottom filter

Intermediate mass

34.6 kg for BS
15.6 kg for SRs

Test mass

18.71 kg for BS
10.71 kg for SRs

Recoil mass

22.3 kg for BS
12.036 kg for SRs

Type-Bp Payload Configuration

IM suspension

1 maraging steel rod
59.85 cm long, 2.5 mm dia. body for PRs
(neck 2.65 cm long, 2 mm dia.)
loss angle $2e-4$

[CQG 34, 225001 \(2017\)](#)

Type-Bp info from Shoda (same as SRs)

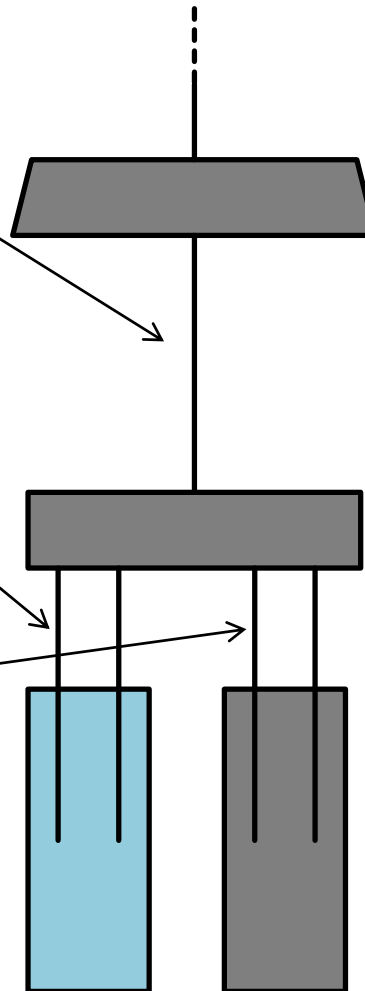
TM suspension

4 piano wires
58.7 cm long, 0.2 mm dia. for PRs
loss angle $2e-4$

RM suspension

4 tungsten wires
58.7 cm long, 0.6 mm dia. PRs
loss angle $1.7e-4$

Vertical to horizontal coupling $1/200$
("neck" is ignored in the calculation)
OK since vertical thermal noise is dominating



Bottom filter

Intermediate mass
15.6 kg for PRs

Test mass
10.71 kg for PRs

Recoil mass
12.036 kg for PRs

Material Properties of Wires

- Sapphire (see [JGW-T1707038](#))
 - density: $4.0 \times 10^3 \text{ kg/m}^3$
 - Young's modulus: $4.0 \times 10^{11} \text{ Pa}$
 - loss angle: 2×10^{-7}
- Piano wire (Nilaco 711267)
 - density: $7.83 \times 10^3 \text{ kg/m}^3$ ([W. R. Bennett Jr., Science of Musical Sound: Volume 1](#))
 - Young's modulus: $2 \times 10^{11} \text{ Pa}$ ([W. R. Bennett Jr., Science of Musical Sound: Volume 1](#))
 - loss angle: 2×10^{-4} ([RSI 86, 084501 \(2015\)](#))
- Tungsten wire (Nilaco 461406)
 - density: 19.3 kg/m^3 ([matweb](#))
 - Young's modulus: $4.0 \times 10^{11} \text{ Pa}$ ([matweb](#))
 - loss angle: 1.7×10^{-4} ([PLA 255, 230 \(1999\)](#))
- Maraging steel rod (Daido MAS-1)
 - density: 8.02 kg/m^3 (see right)
 - Young's modulus: $1.82 \times 10^{11} \text{ Pa}$ (see right)
 - loss angle: 2×10^{-4} ([N. A. Robertson 2001](#))

Maraging steel spec sheet from R. Takahashi

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マルエージング鋼 MAS-1 (MAS-1は大同特許)

要 旨 MAS-1は低炭素 18%Ni 鋼に時効硬化元素として Co, Mo, Ti, Al 等を加えた材料で、時効硬化処理によって 1960N/mm² 以上の強度を得られると共に靱性も持ち合わせた代表的な超強力鋼で時計部品、電算機部品、精密パネ、ダイヤモンドその他の極めて高度の信頼性を要求される部品等に使用されています。

特 長 (1) 比較的簡単な時効硬化処理のみによって 1960N/mm² 以上の引張強さが得られます。この強度は冷間加工を施すと更に上昇し、例えば 50%圧延材の時効硬化後の引張強さは 2110N/mm² 以上になります。
 (2) この高強度の上、靱性もあり、高い切欠強度や疲労強度を有しております。
 (3) 熱処理が急冷等の必要もなく簡単で、熱処理による歪も極小です。
 (4) 比較的良い溶接性と切削性を有しております。
 (5) 冷間加工による硬化がわずかです。(50%圧延でHV40 前後の増加程度)

組成化学成分

	%								
C	Si	Mn	P-S	Ni	Co	Mo	Ti	Al	
≤0.03	≤0.10	≤0.10	≤0.010	18.00~ 19.00	8.50~ 9.50	4.70~ 5.20	0.50~ 0.70	0.05~ 0.15	

物理的性質

密度	比熱	電気抵抗	ヤング率	熱膨張係数	熱伝導率
Mg/m ³	J/(kg·K)	μΩ·cm	N/mm ²	(20~480°C)	W/(m·K)
8.02	335	60~70	182,000	10.1×10 ⁻⁶ /K	19.7 (25°C)

取扱い上の注意事項 (1) 固溶化熱処理は 820~870°C で数分~30 分保持した上冷却します。Ms 点が 150°C 近辺であるため、常温で低炭素マルテンサイト相になり 300~330HV 位になっています。このため靱性はあるものの一般軟質材のような加工はできません。
 (2) 標準的な時効硬化処理条件は 480°C 3h ですが、多少の温度・時間の組合せを変えることは可能です。
 (3) 熱処理の雰囲気は、水素または AX ガスが適当です。
 (4) 高合金鋼のため一見ステンレス鋼のように錆びにくい材料と思われがちですが、不銹成分であるクロムを含まないため、一般鉄鋼に準じた防錆処置が必要です。

Mirror thermal noise

Mirror and Coating Parameters

- Coating: silica/tantala (loss angle: $3e-4$ / $5e-4$)

	ITM/ETM	BS	SRM/2/3	PRM/2/3
Material	Sapphire	Fused silica	Fused silica	Fused silica
Diameter	22 cm	37 cm	25 cm	25 cm
Thickness	15 cm	8 cm	10 cm	10 cm
Mass	22.8 kg	18.9 kg	10.8 kg	10.8 kg
Temperature	22 K	290 K	290 K	290 K
Substrate loss angle	$1e-8$	$1/(6.5e-12/thickness+7.6e-12*f^{0.77})$ Physics Letters A 352, 3 (2006)		
Coating layers	22 / 40	tantala/silica/tantala (see p.10 of JGW-T1503347)	4 / 18 / 18	4 / 18 / 18
Beam radius	3.5 cm	3.62 cm	0.43 / 0.43 / 3.67 cm	0.46 / 0.46 / 3.66 cm

Number of coating layers for fused silica mirrors are derived from calculation using reflectivity. Coating thermal noise of Type-B/Bp suspensions are not very important since quantum noises for auxiliary DOFs are quite high.

BS thermal noise is tricky ([LIGO-T0900209](#)) but not considered carefully here.

[JGW-T1707038](#)

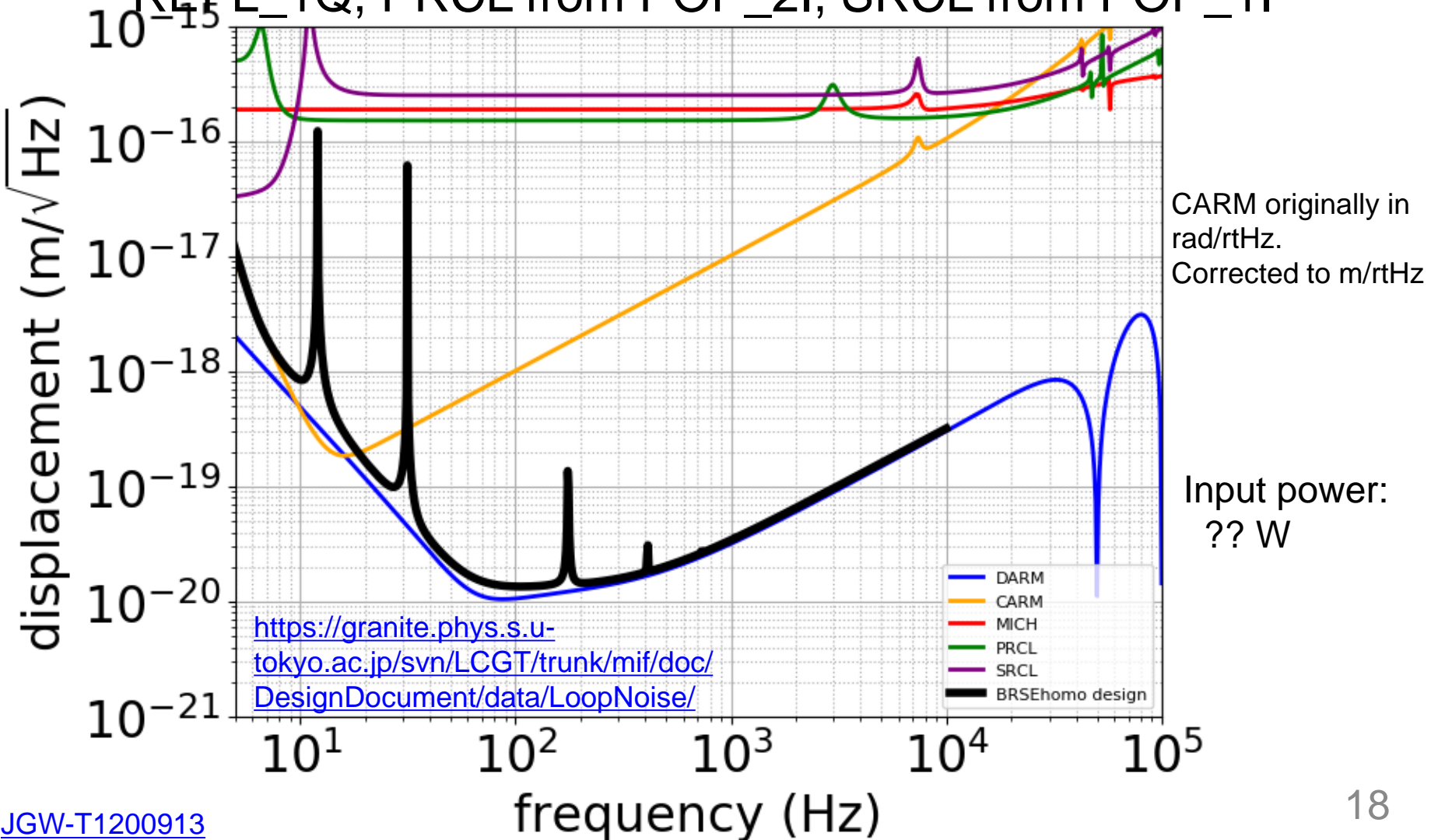
[Classical and Quantum Gravity 34, 225001 \(2017\)](#)

<http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam>

Quantum noise

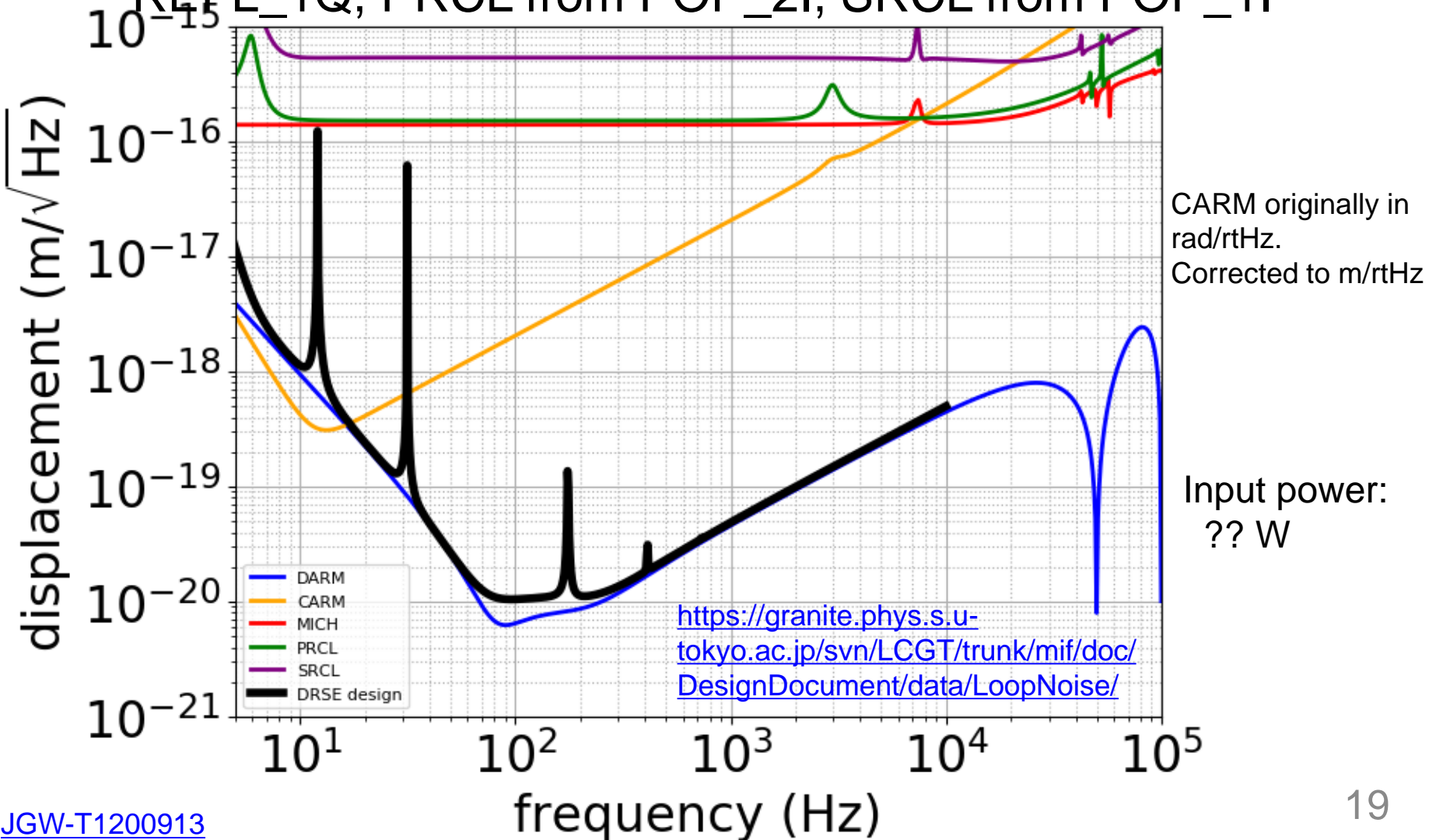
Optickle Simulation (BRSE Aso)

- DARM from AS_DC, CARM from REFL_1I, MICH from REFL_1Q, PRCL from POP_2I, SRCL from POP_1I



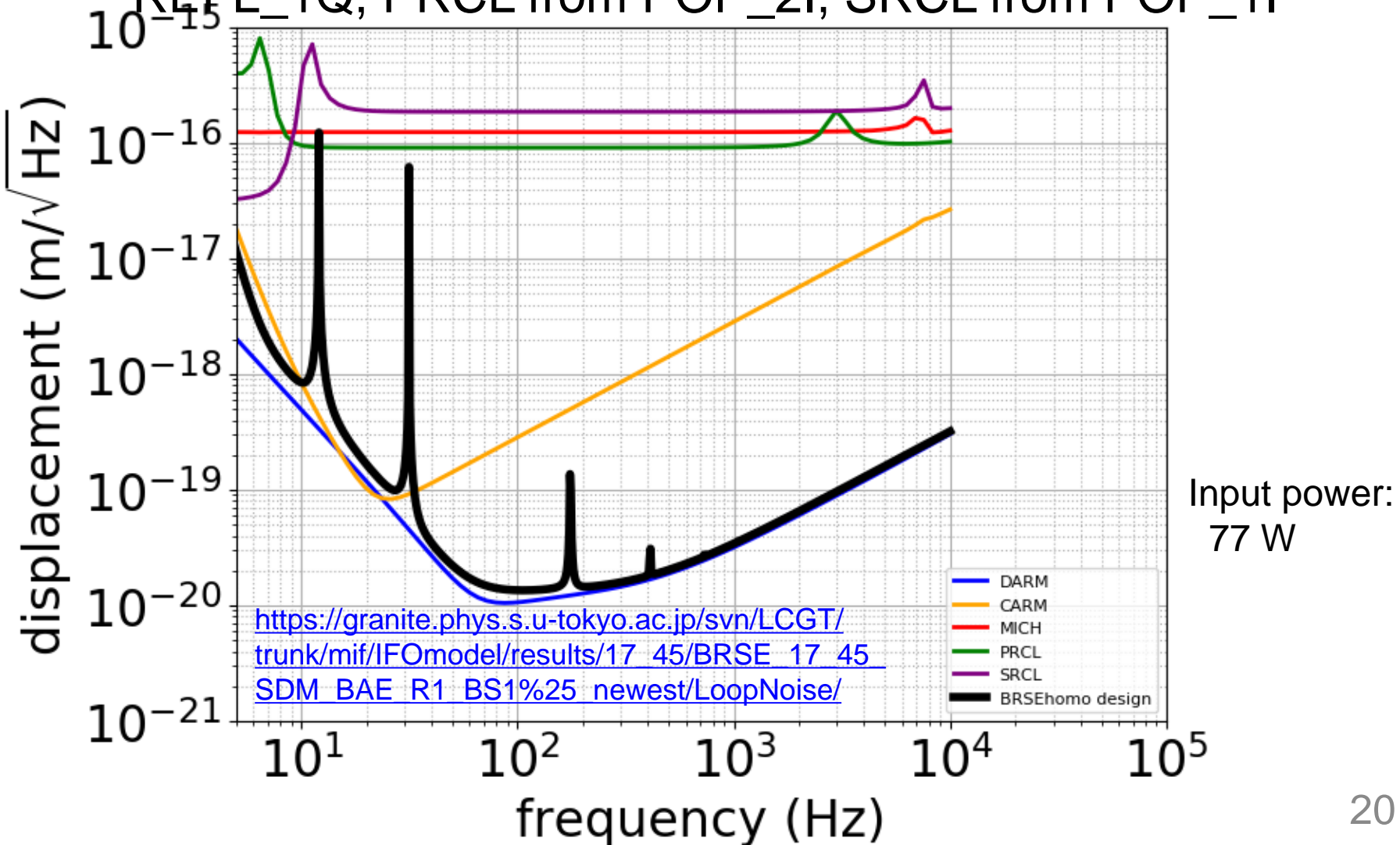
Optickle Simulation (DRSE Aso)

- DARM from AS_DC, CARM from REFL_2I, MICH from REFL_1Q, PRCL from POP_2I, SRCL from POP_1I



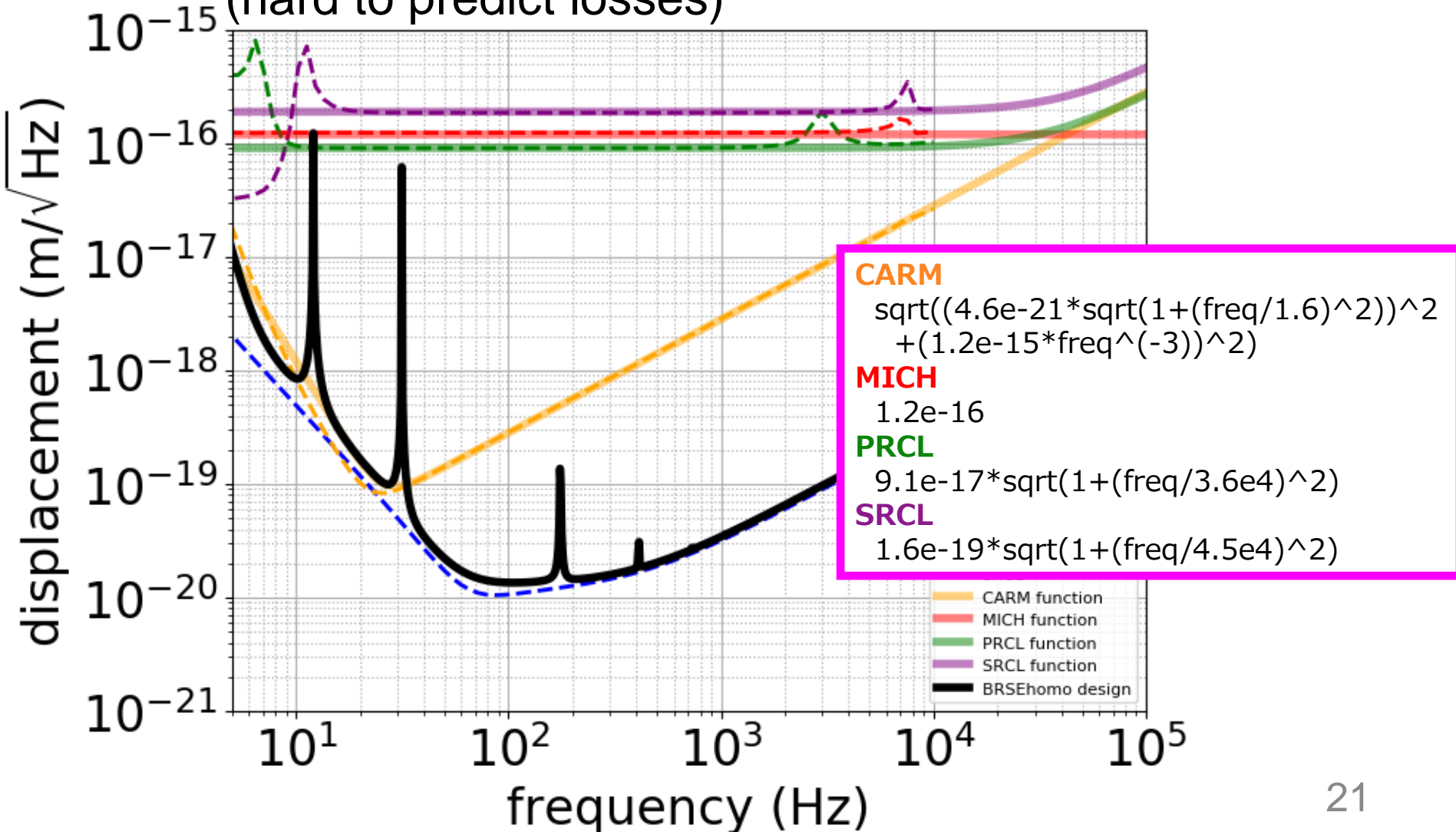
Optickle Simulation (BRSE Enomoto)

- DARM from AS_DC, CARM from REFL_1I, MICH from REFL_1Q, PRCL from POP_2I, SRCL from POP_1I



Quantum Function

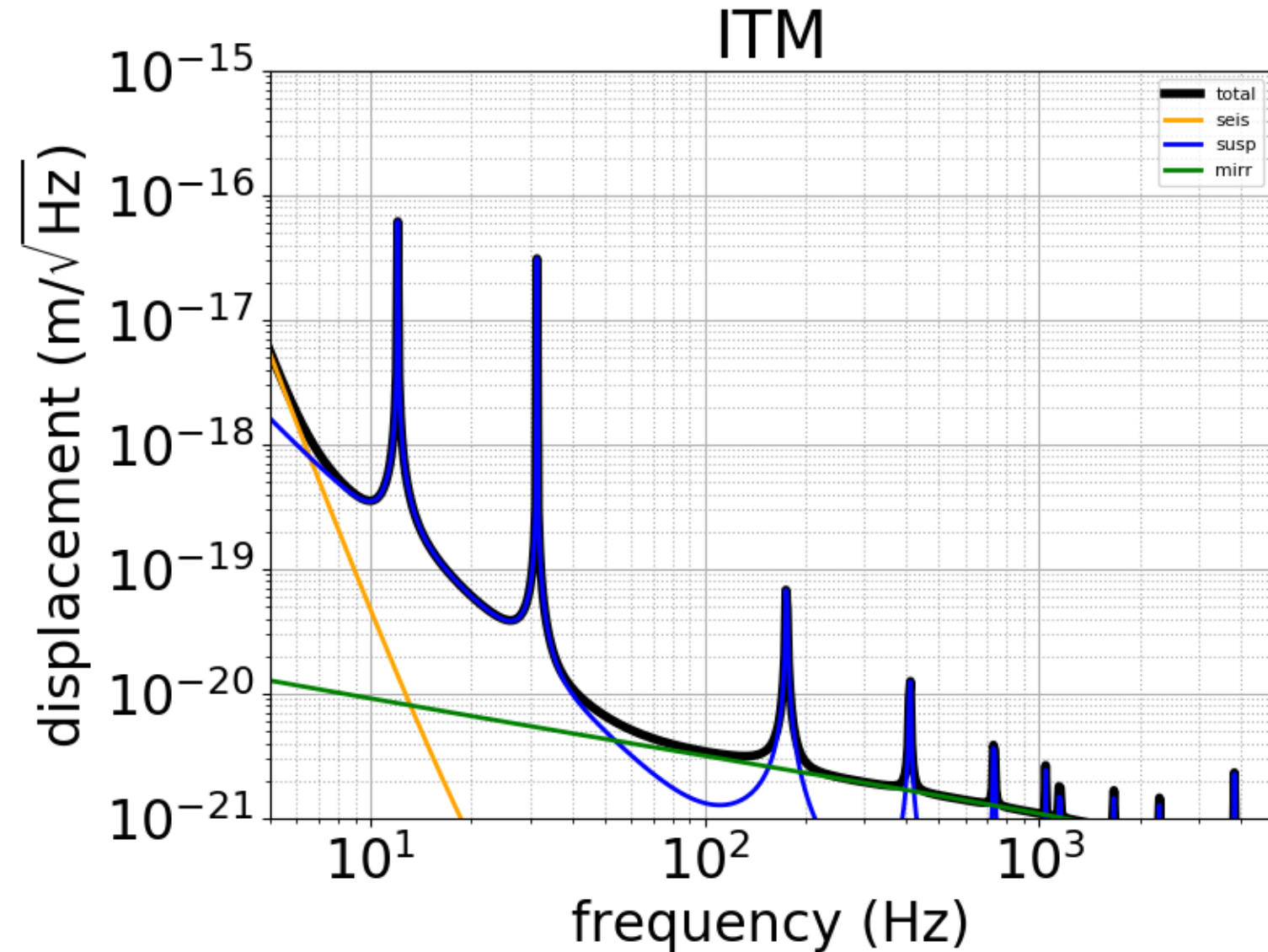
- Use fitted function instead of doing analytical calculation (hard to predict losses)



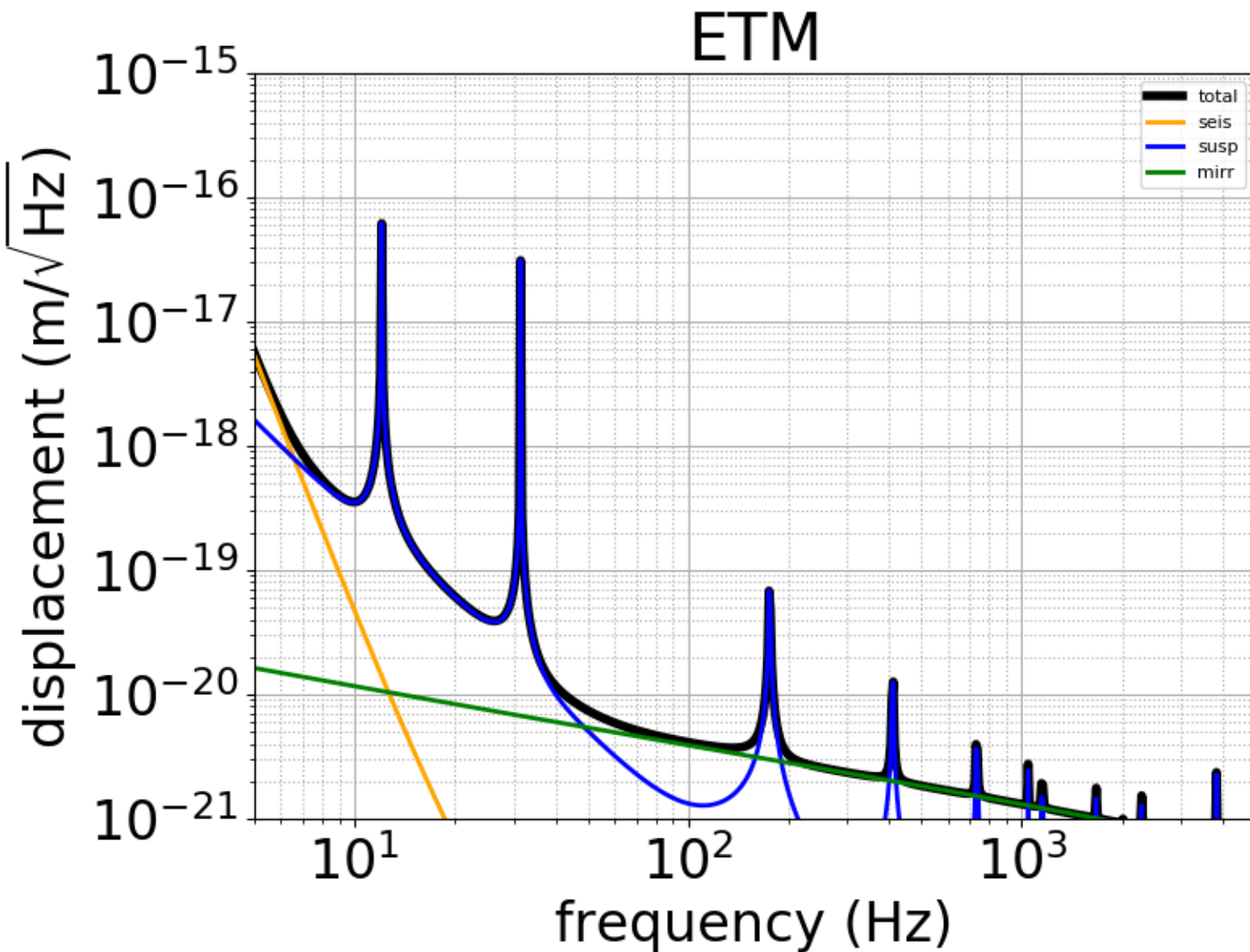
Displacement sensitivity

Codes for plotting these sensitivity curves lives in the zip file of [JGW-T2011755](#)

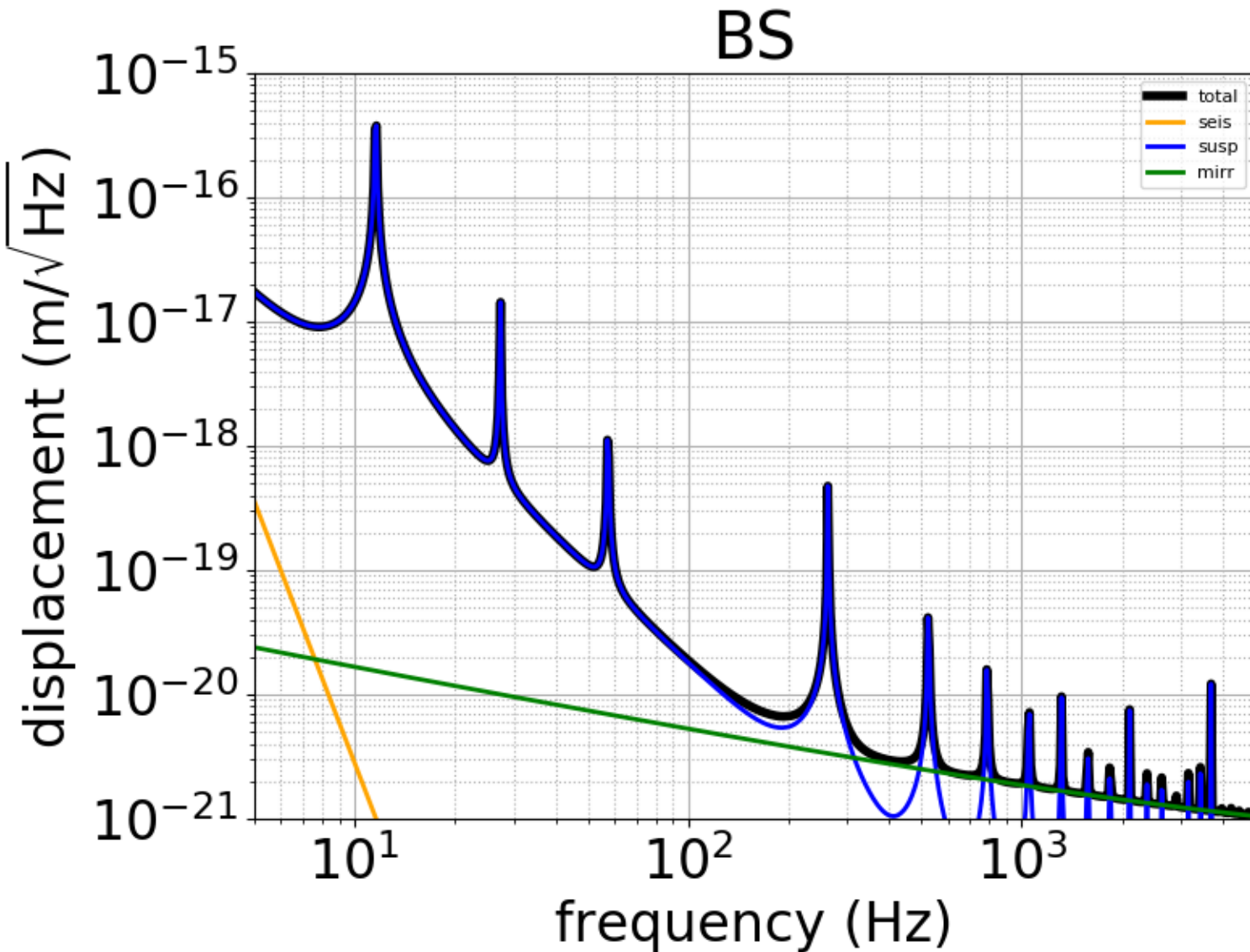
Displacement Noise: ITM



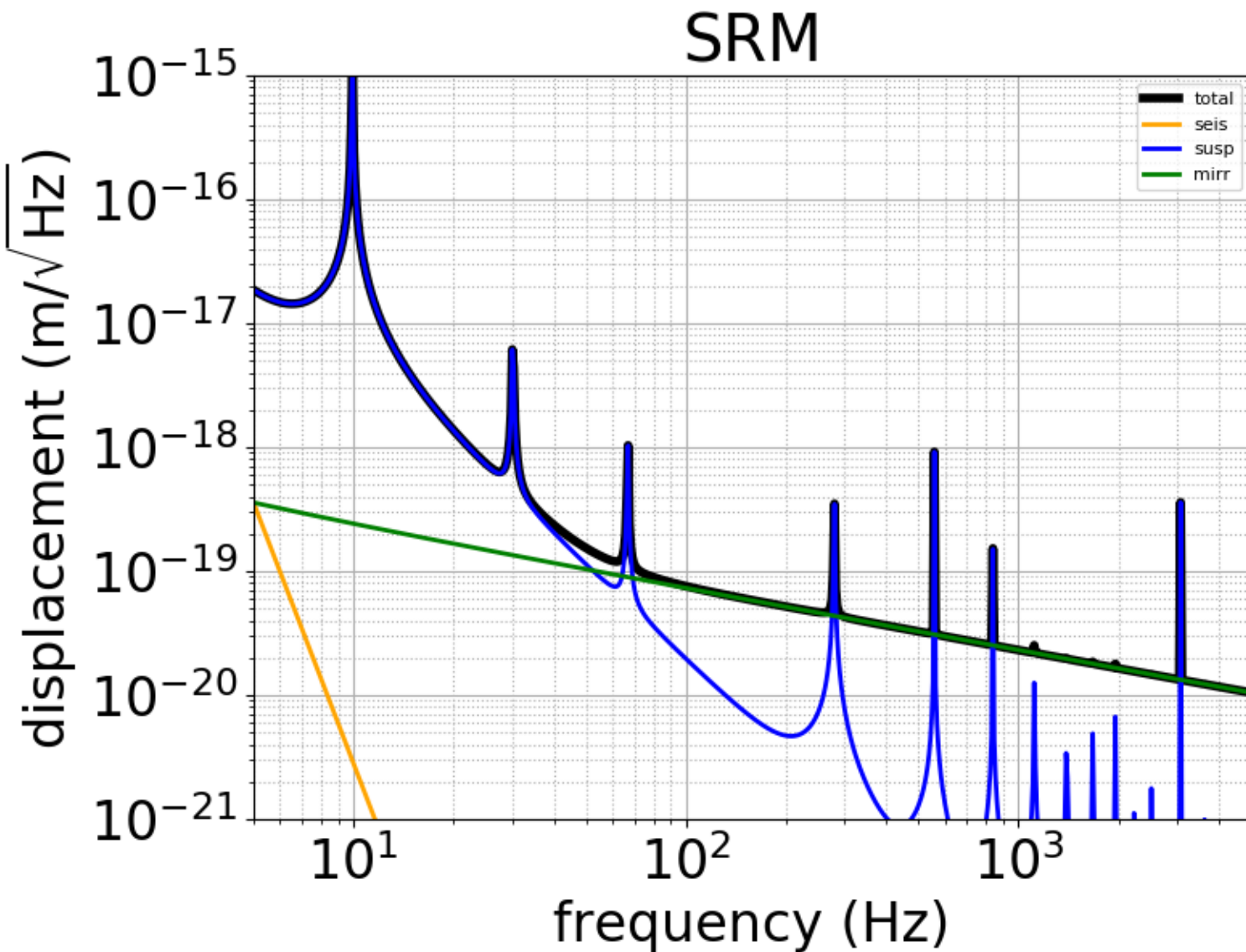
Displacement Noise: ETM



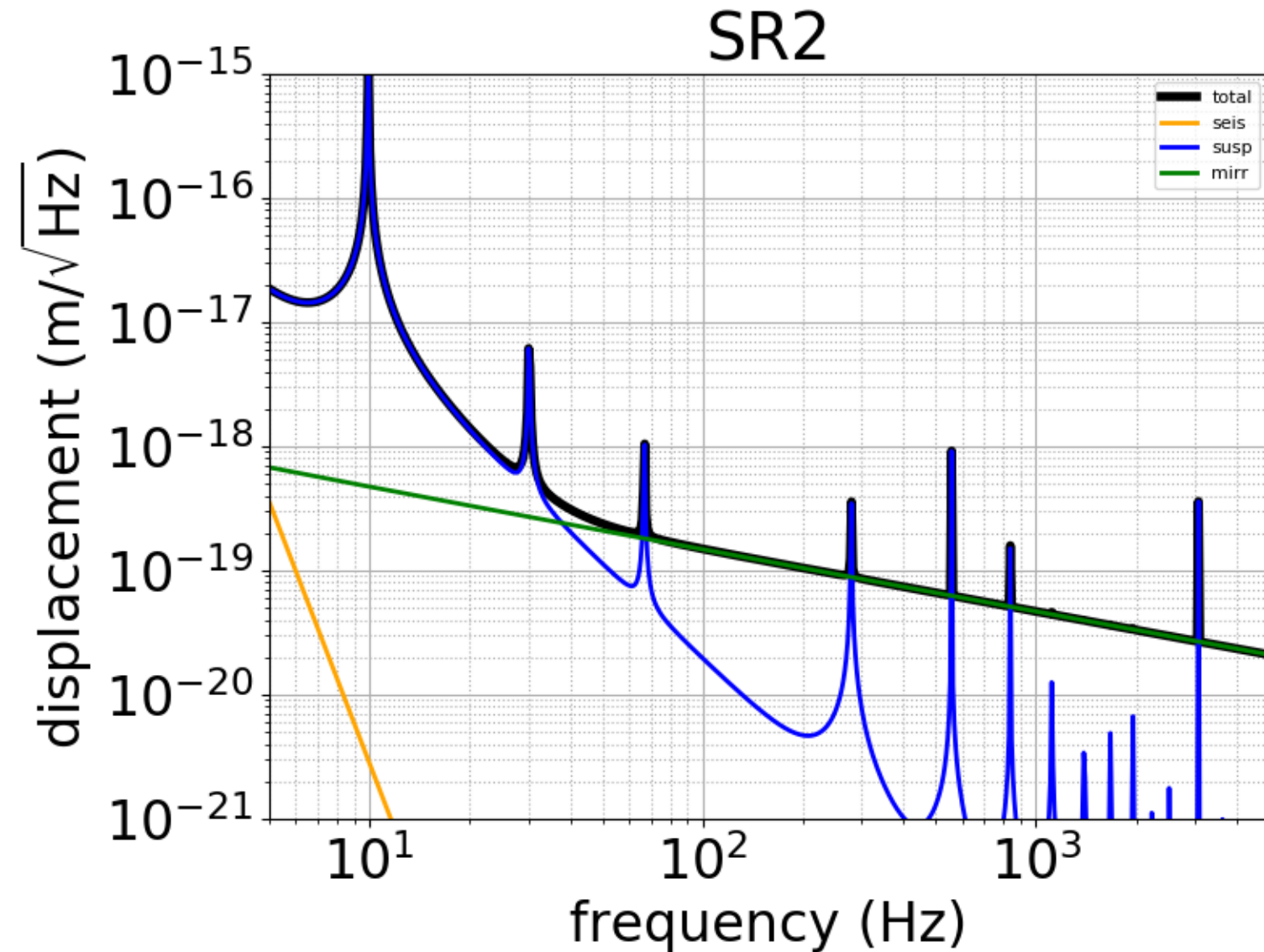
Displacement Noise: BS



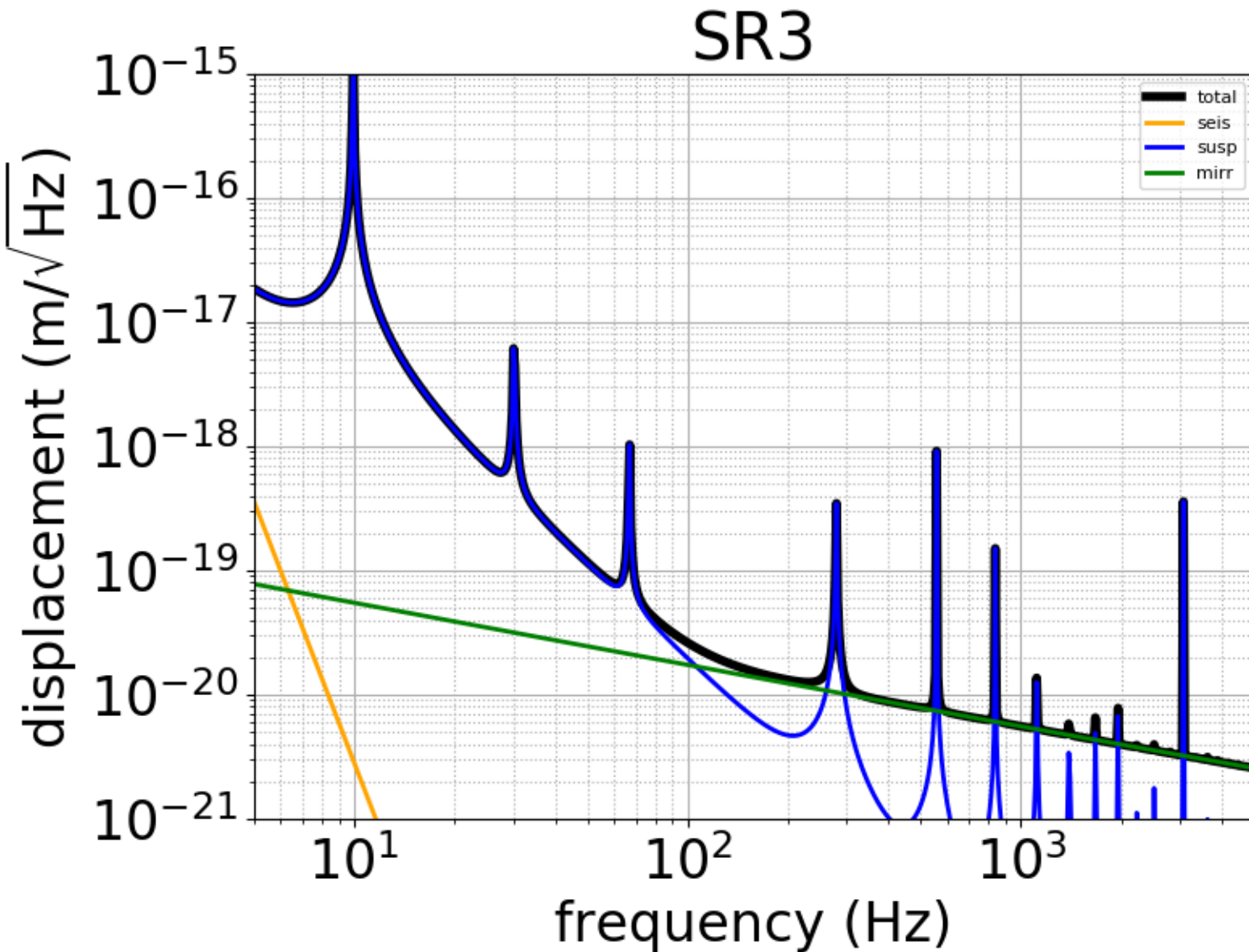
Displacement Noise: SRM



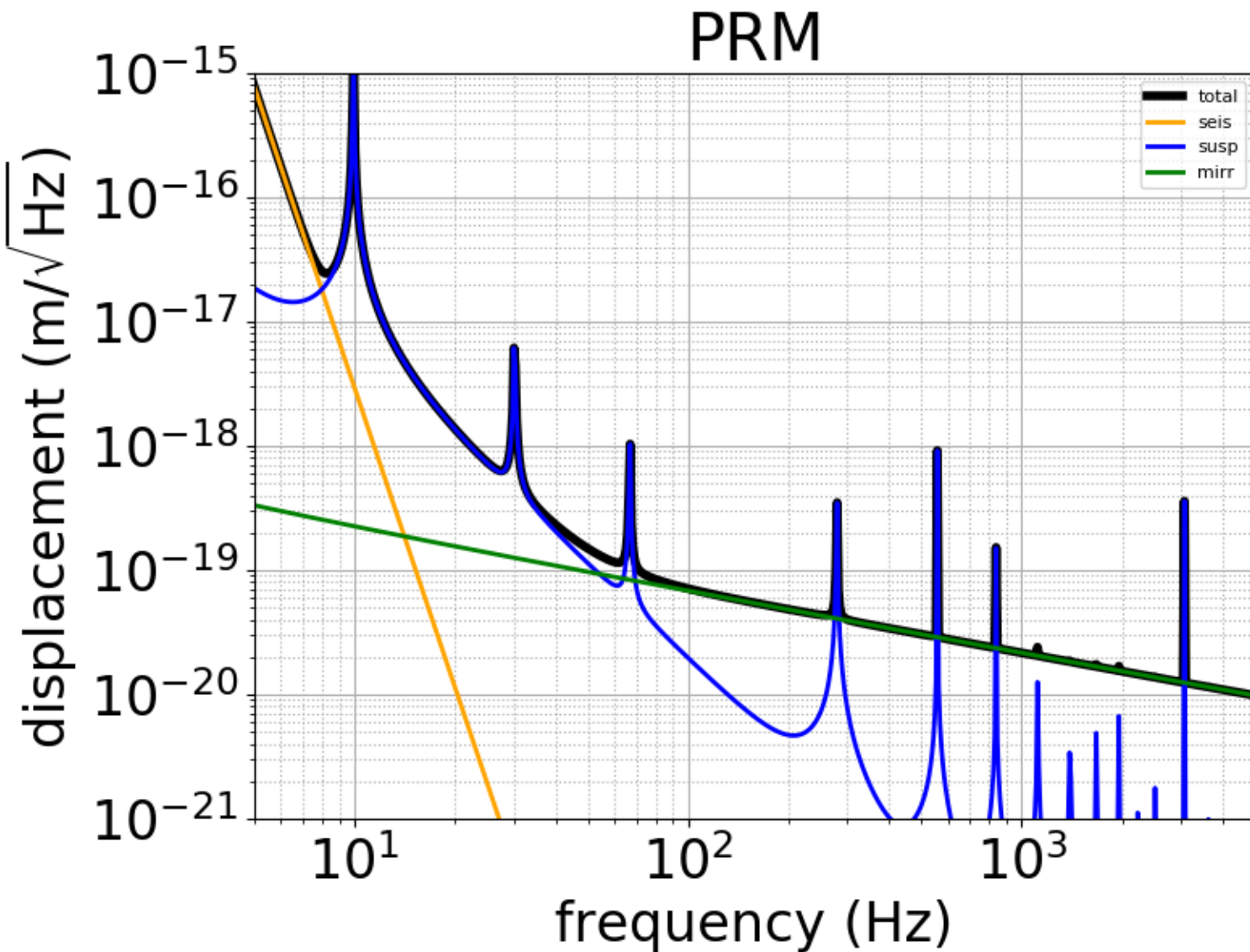
Displacement Noise: SR2



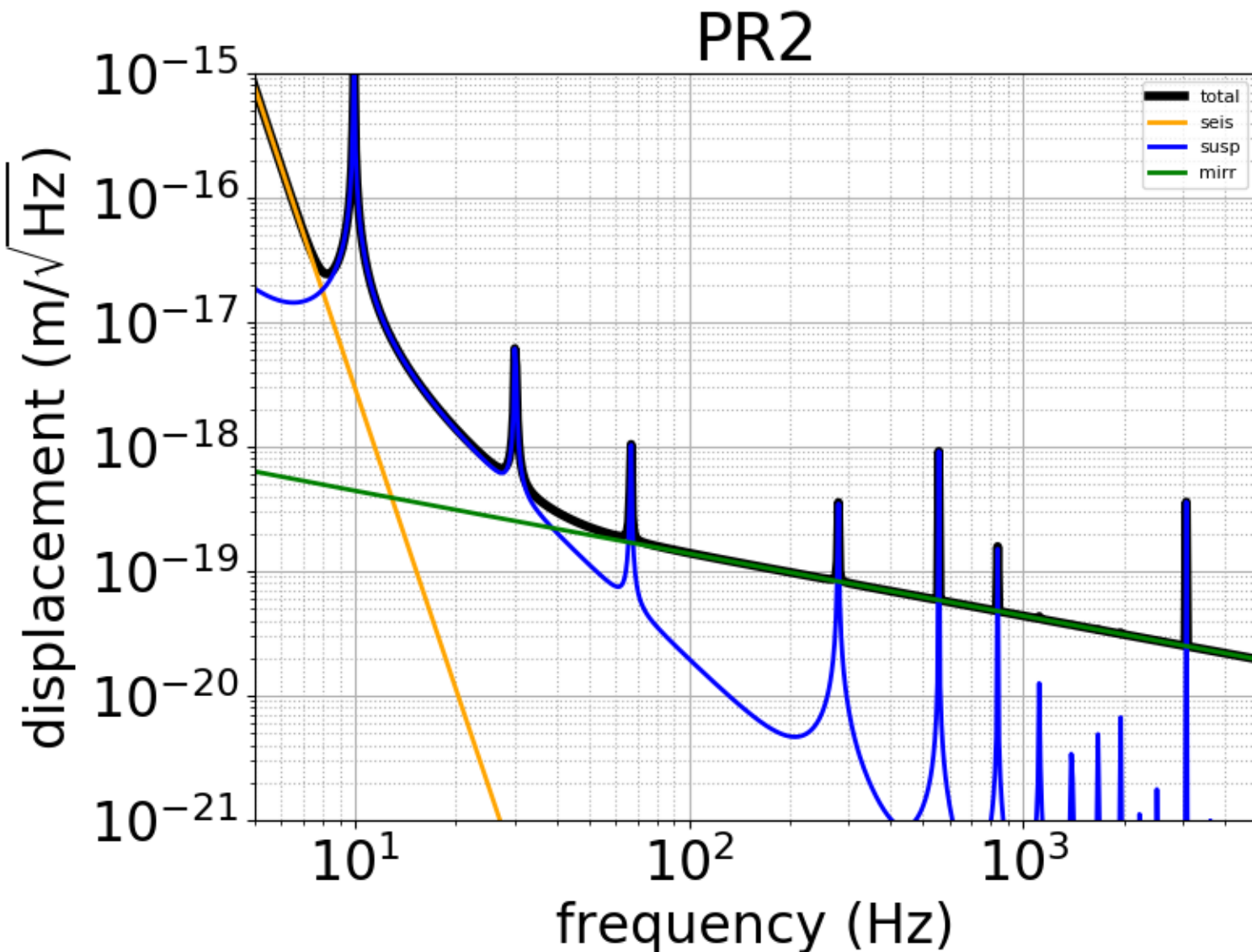
Displacement Noise: SR3



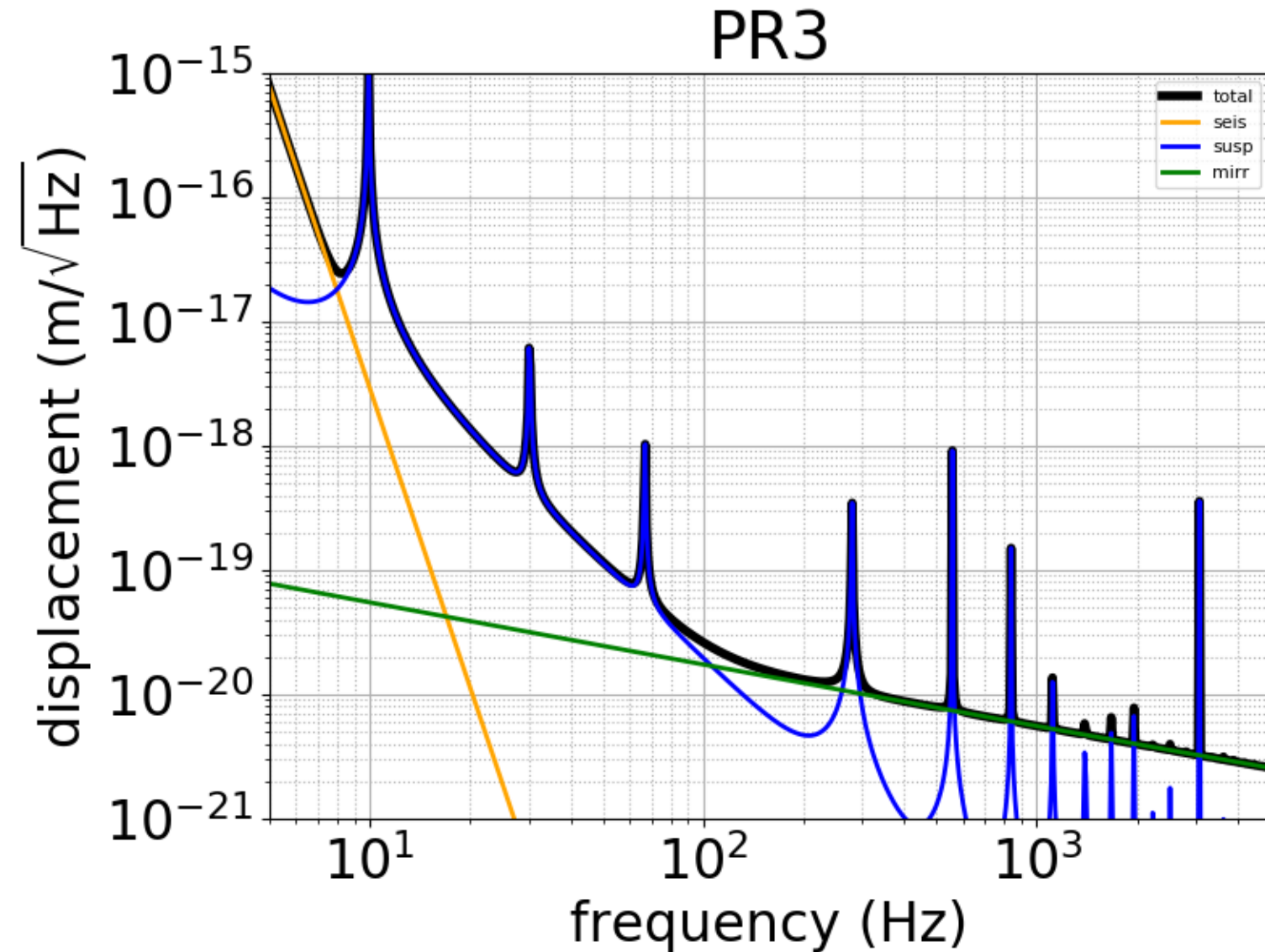
Displacement Noise: PRM



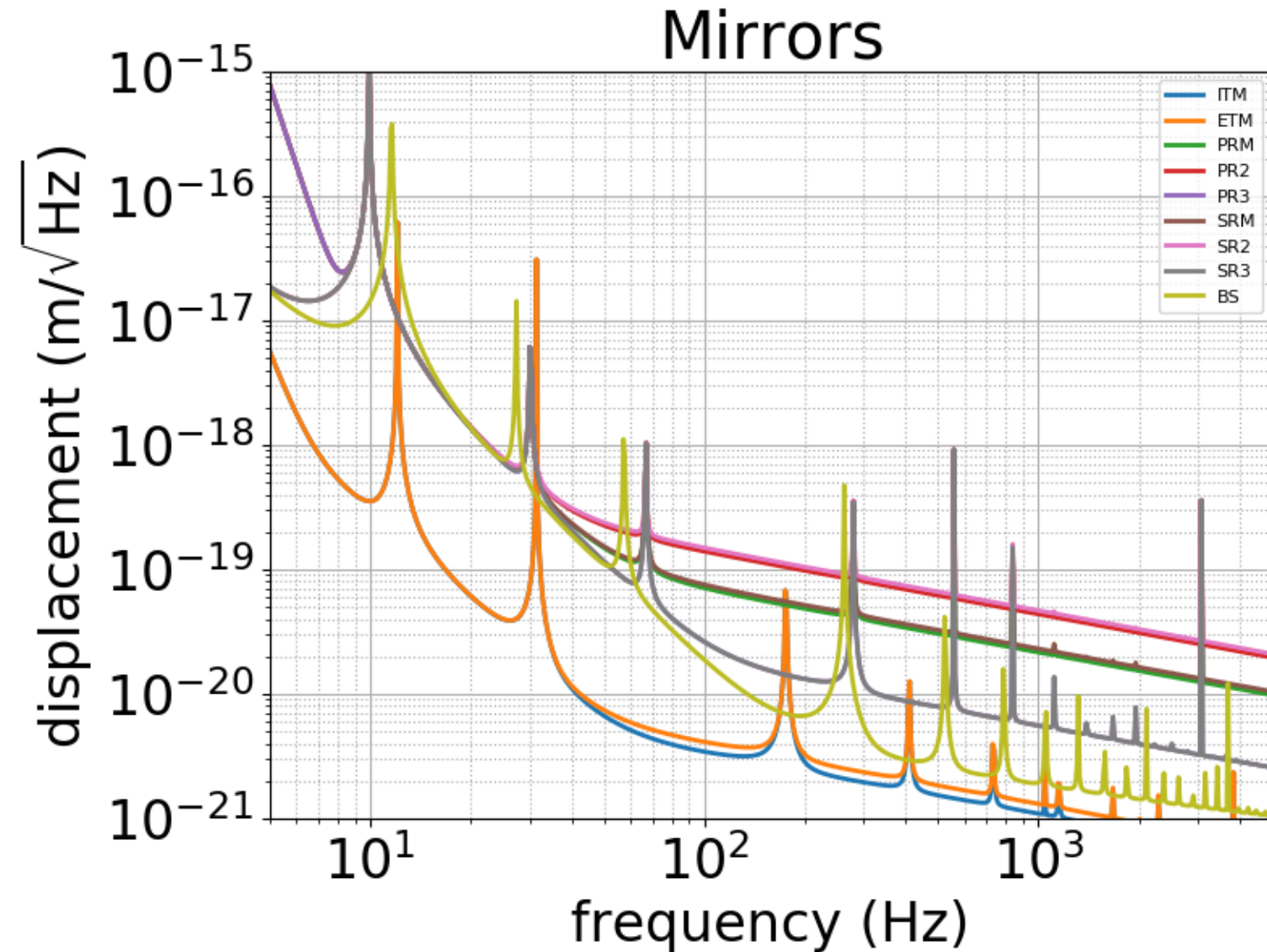
Displacement Noise: PR2



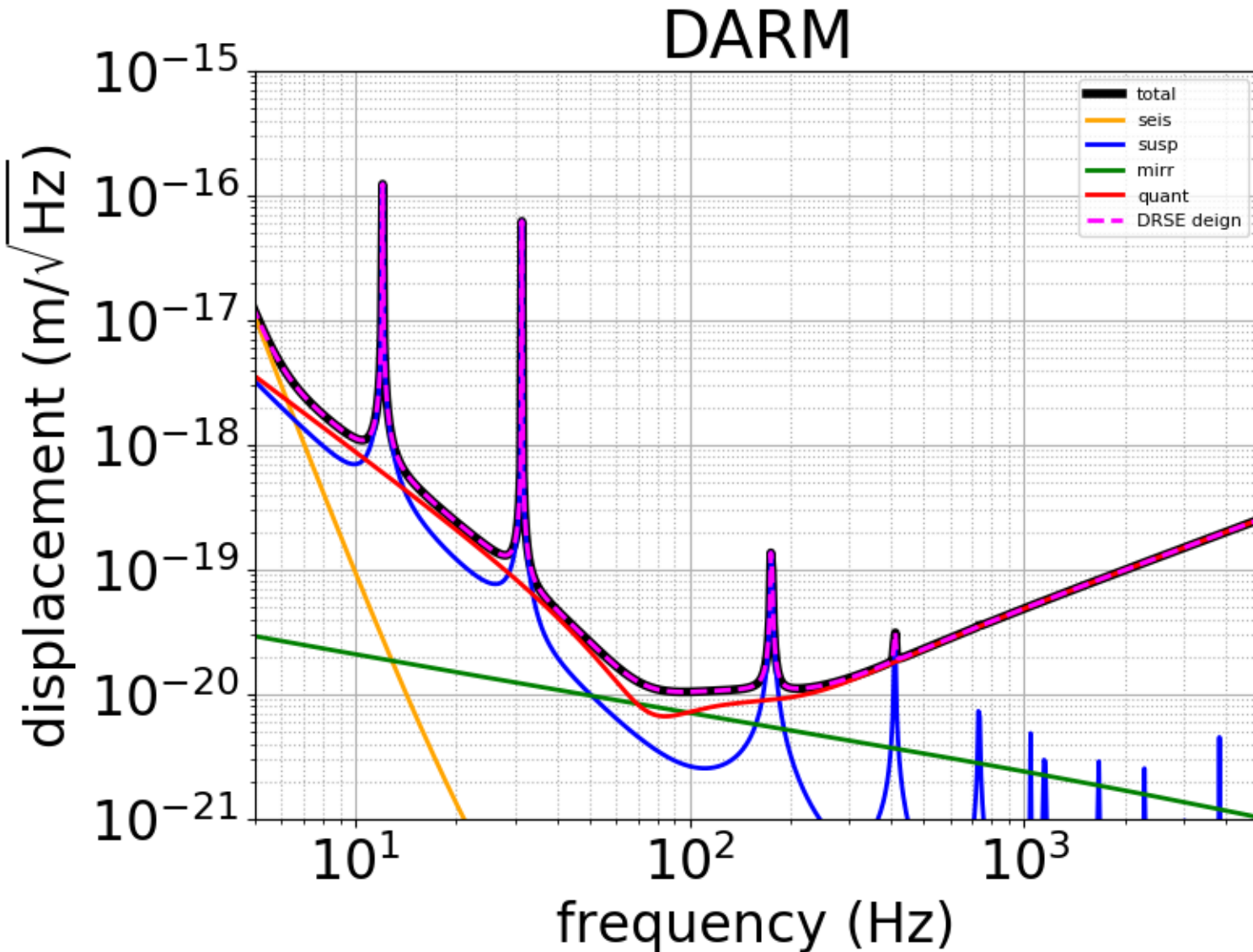
Displacement Noise: PR3



Mirrors Summary

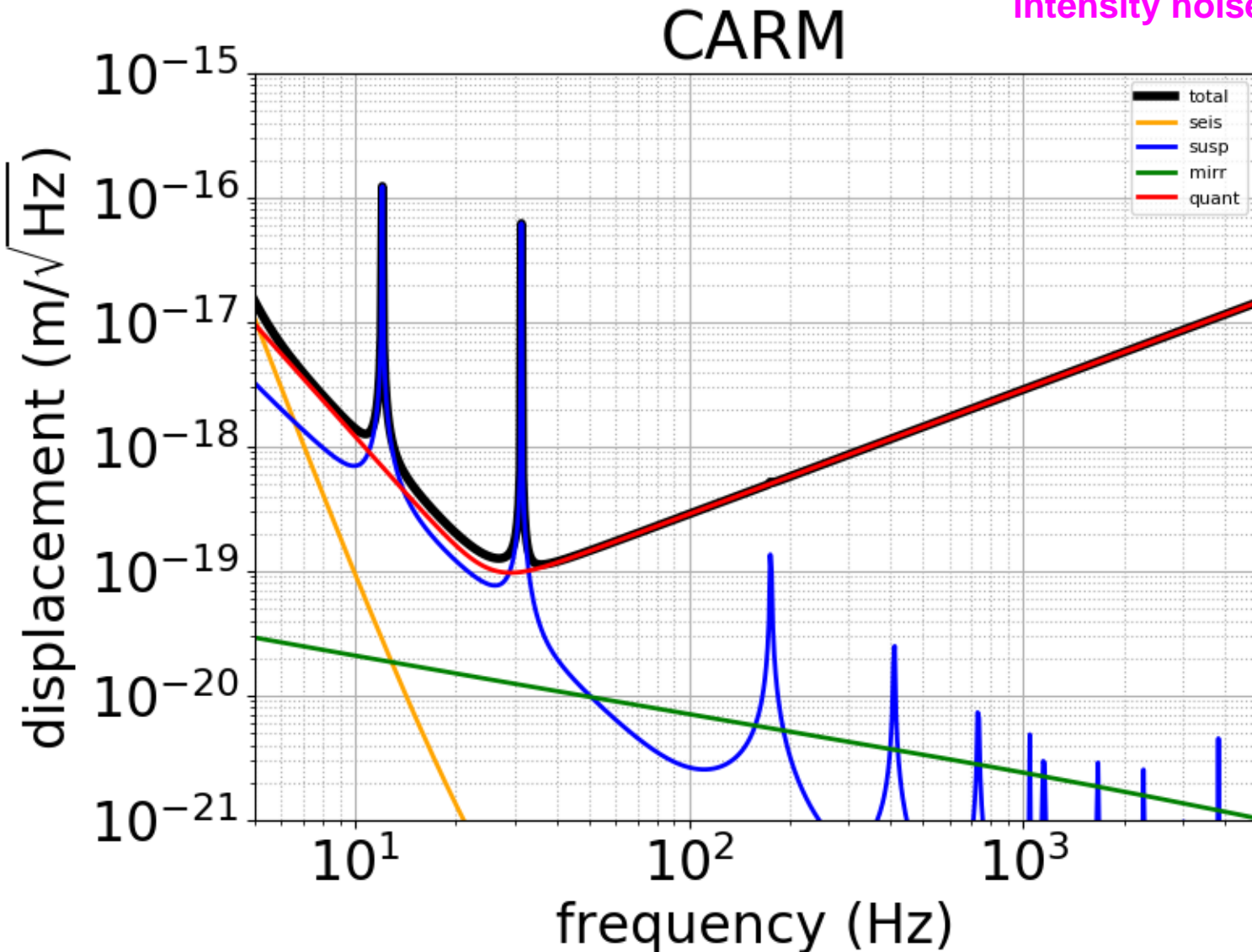


Displacement Sensitivity: DARM

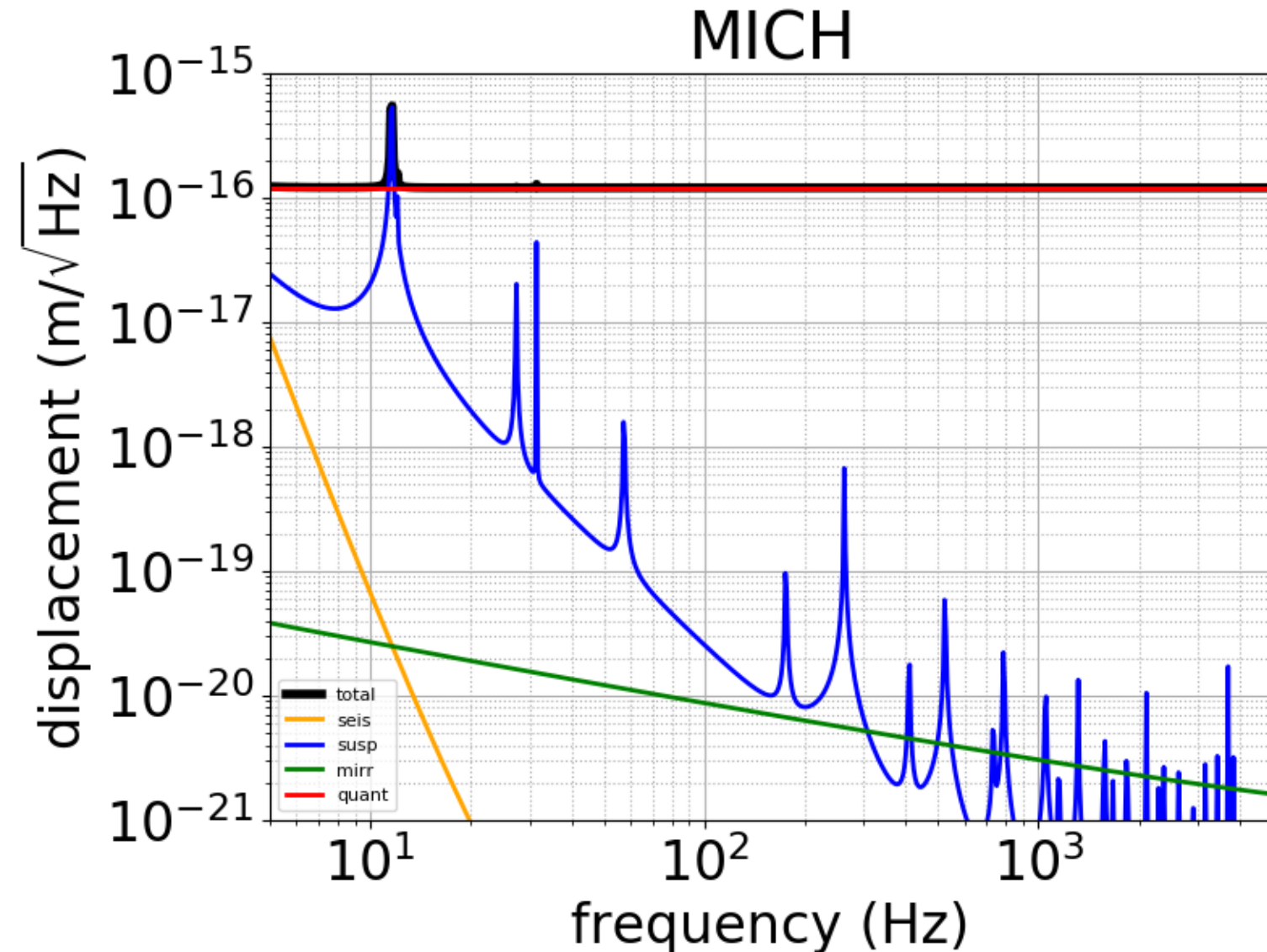


Displacement Sensitivity: CARM

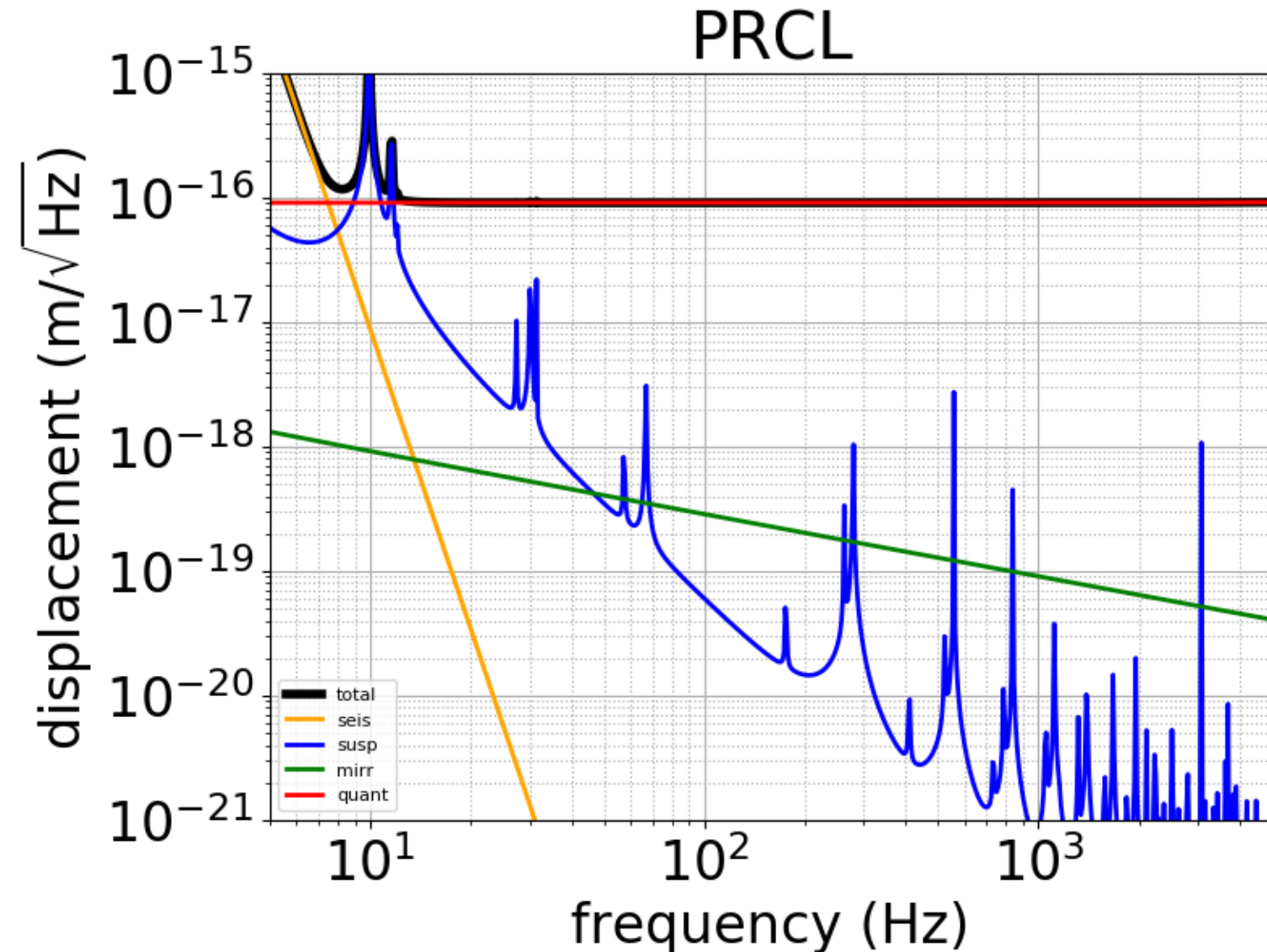
NOTE: frequency noise and intensity noise not considered



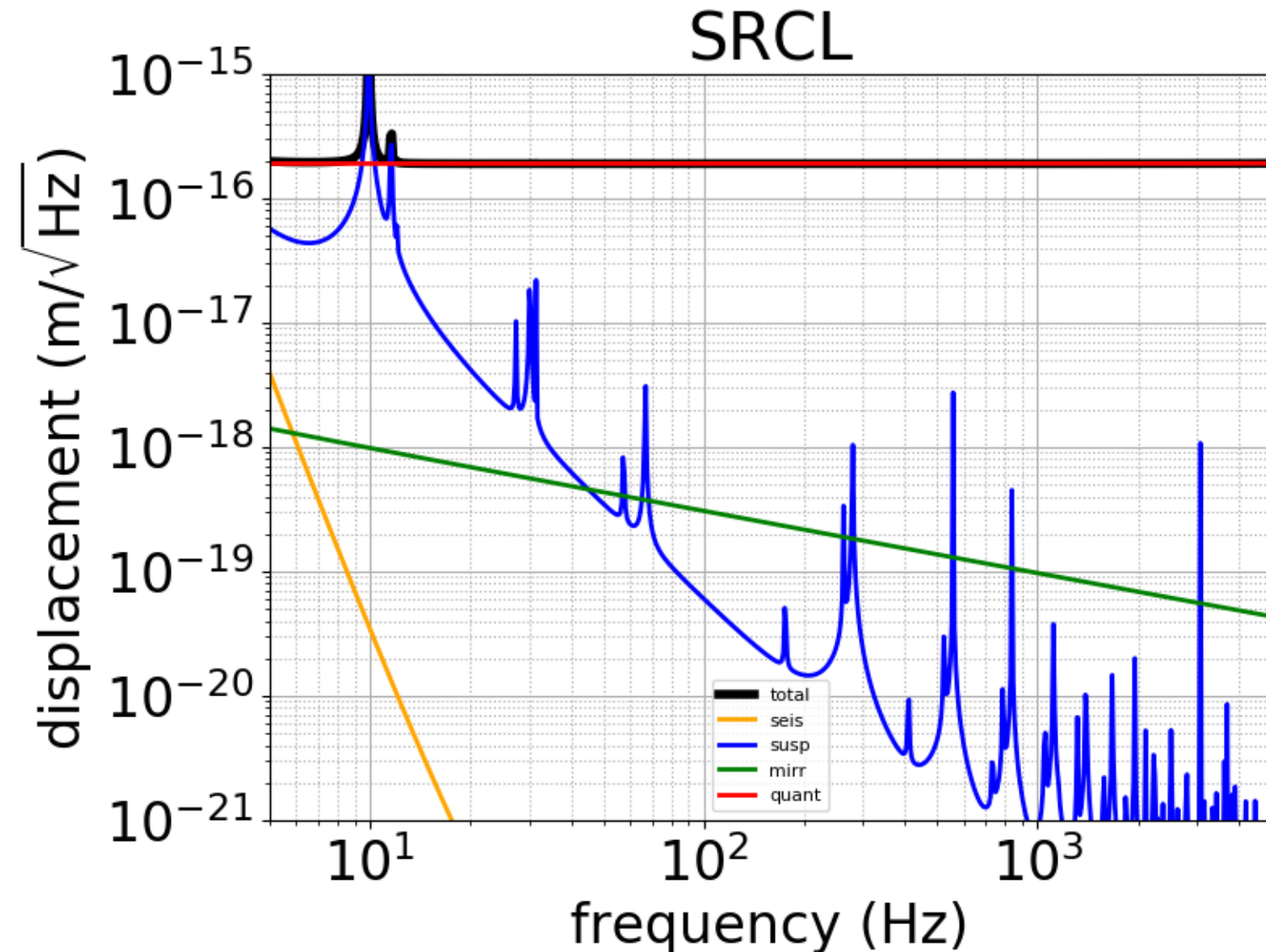
Displacement Sensitivity: MICH



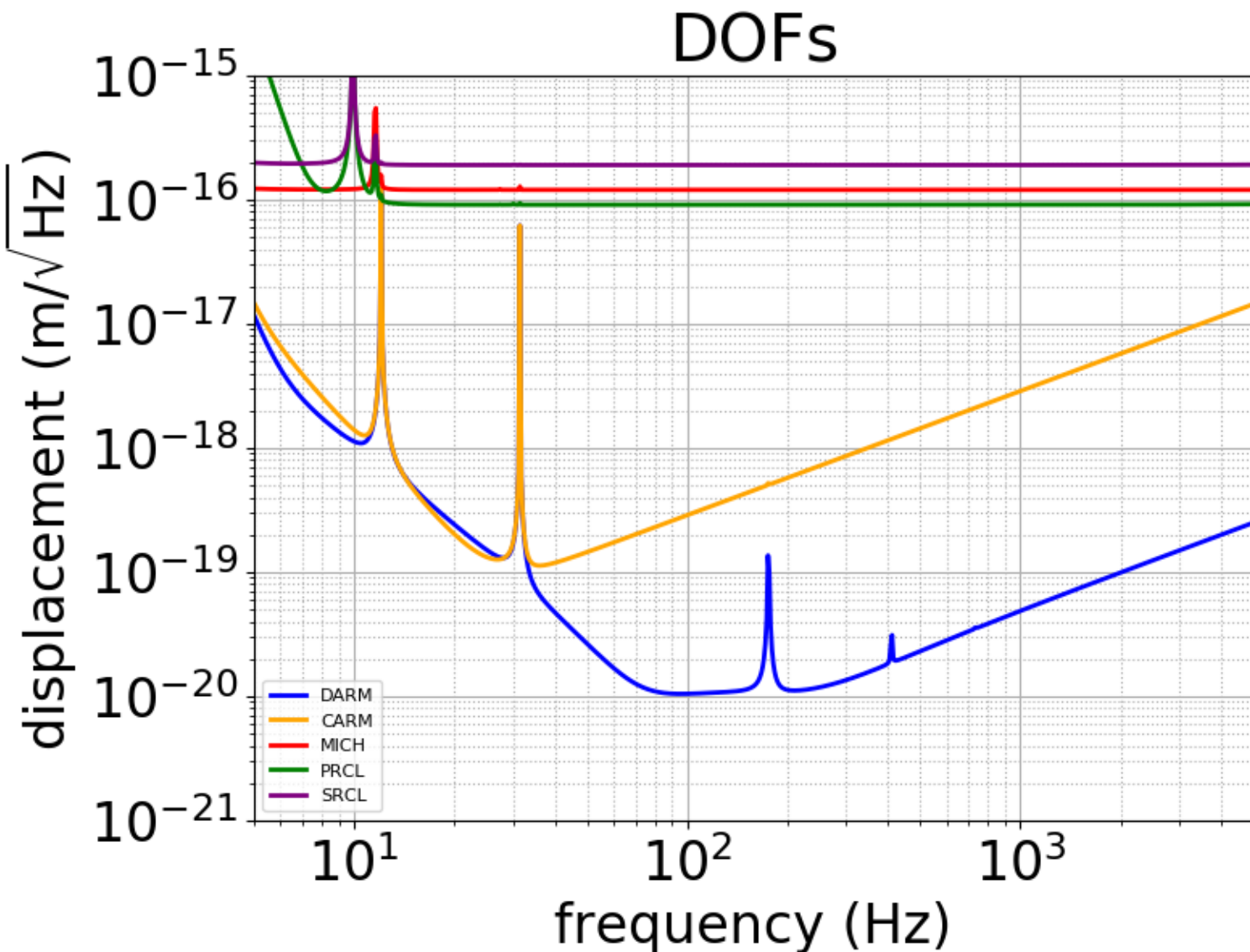
Displacement Sensitivity: PRCL



Displacement Sensitivity: SRCL



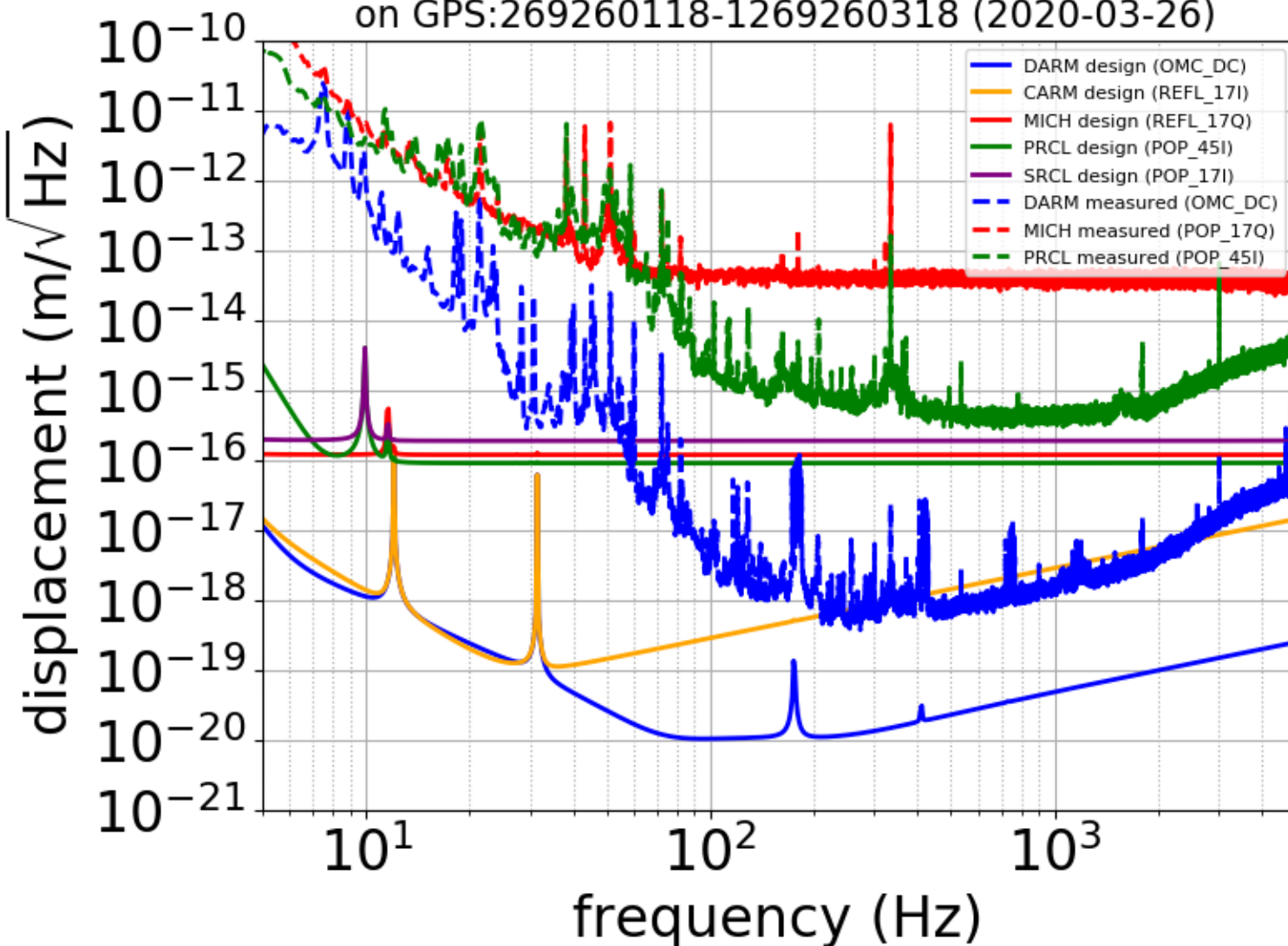
Displacement Sensitivity Summary



NOTE: frequency noise and intensity noise not considered for CARM

Mar 26, 2020 Sensitivity

Designed vs measured sensitivity
on GPS:269260118-1269260318 (2020-03-26)



MICH and PRCL calibrated offline (see [klog #14556](#))