JGW-T2011755

July 1, 2020

Estimated sensitivity for auxiliary degrees of freedom of KAGRA interferometer

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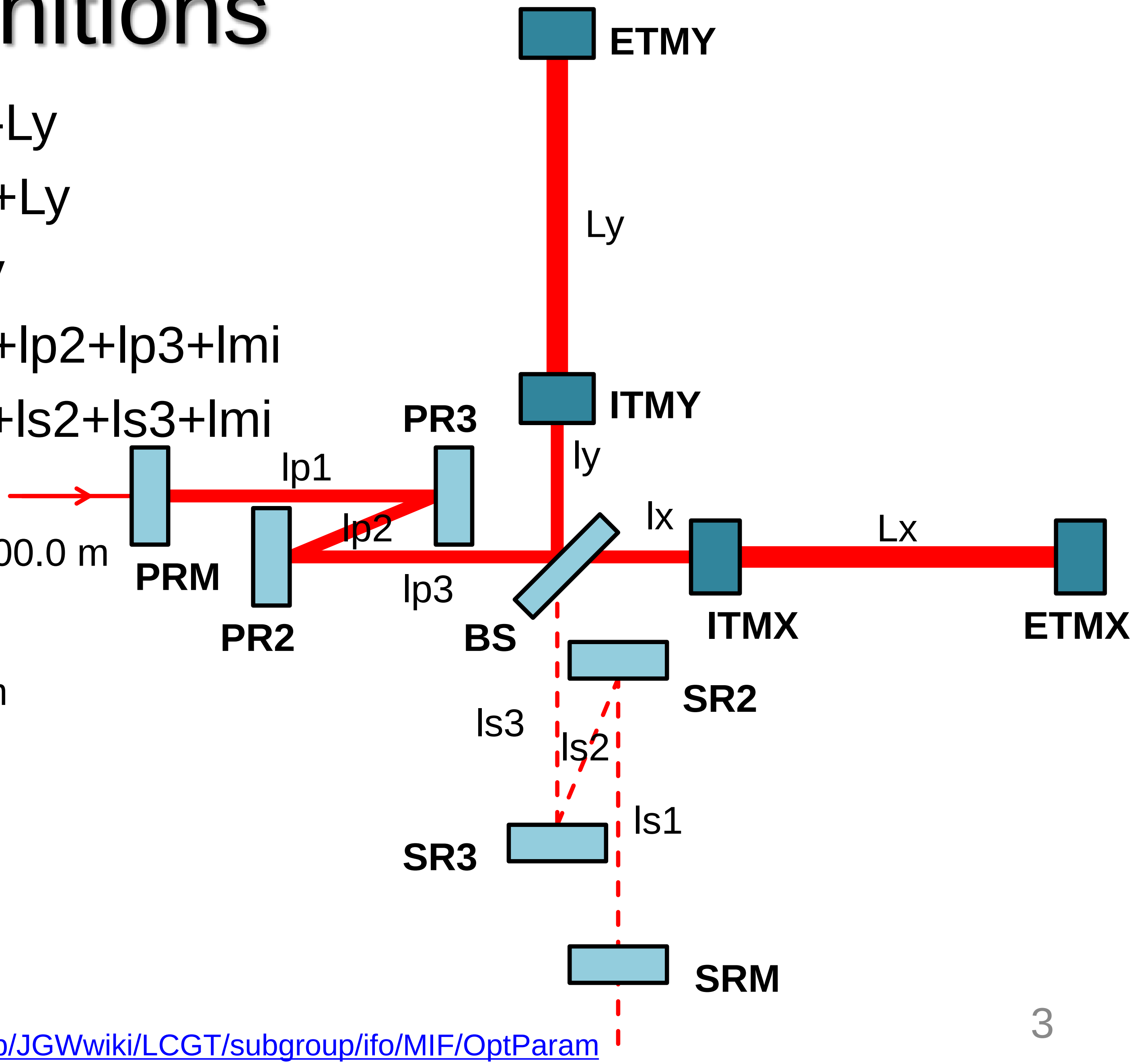
Scope

- 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: Lx-Ly
- CARM: Lx+Ly
- MICH: lx-ly
- PRCL: lp1+lp2+lp3+lmi
- SRCL: ls1+ls2+ls3+lmi

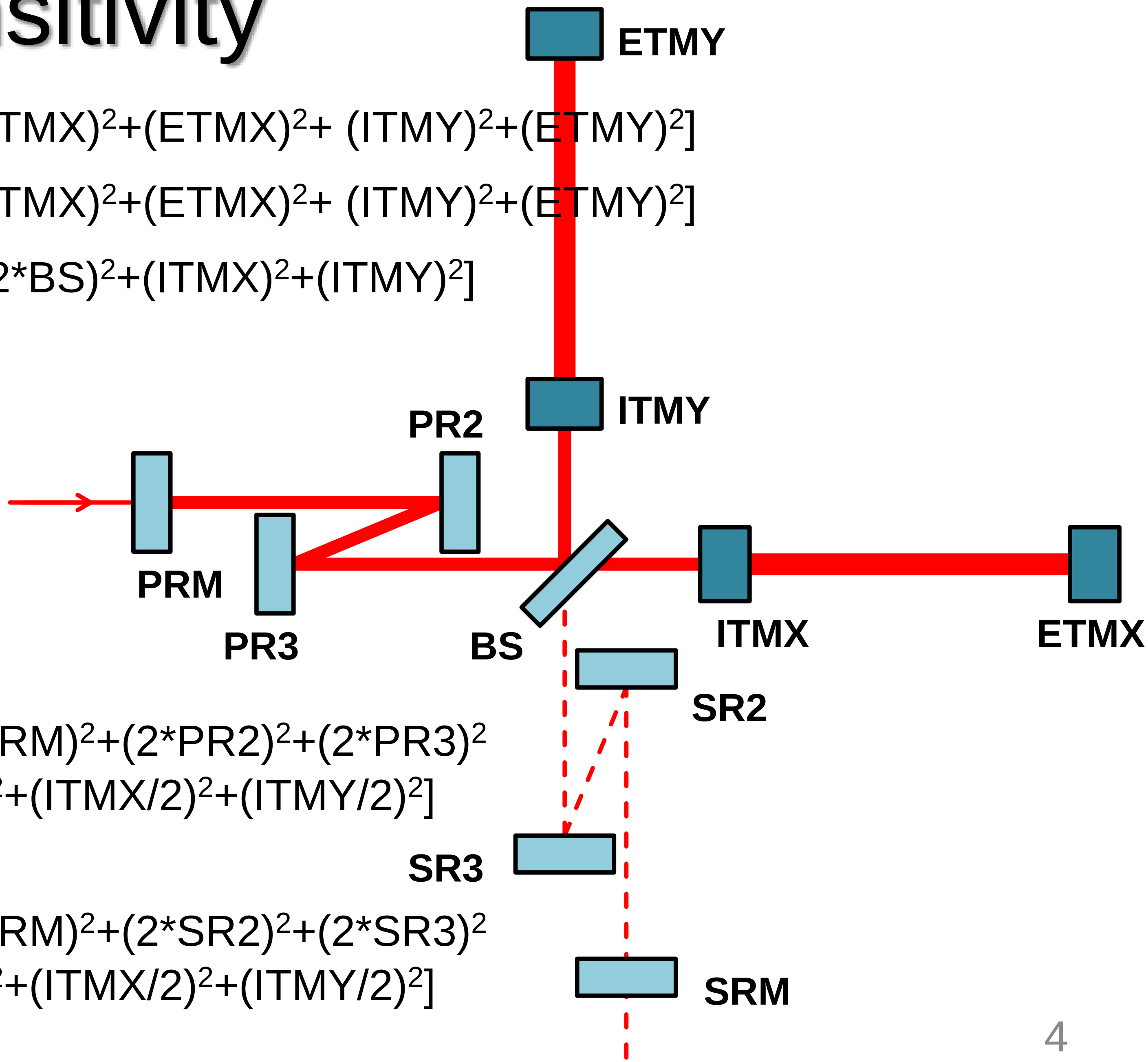


Lx = Ly = Larm = 3000.0 m
Lx = 26.6649 m
ly = 23.3351 m
lmi = (lx+ly)/2 = 25 m
lp1 = 14.7615 m
lp2 = 11.0661 m
lp3 = 15.7638 m
ls1 = 14.7412 m
ls2 = 11.1115 m
ls2 = 15.7386 m

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

Sensitivity

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



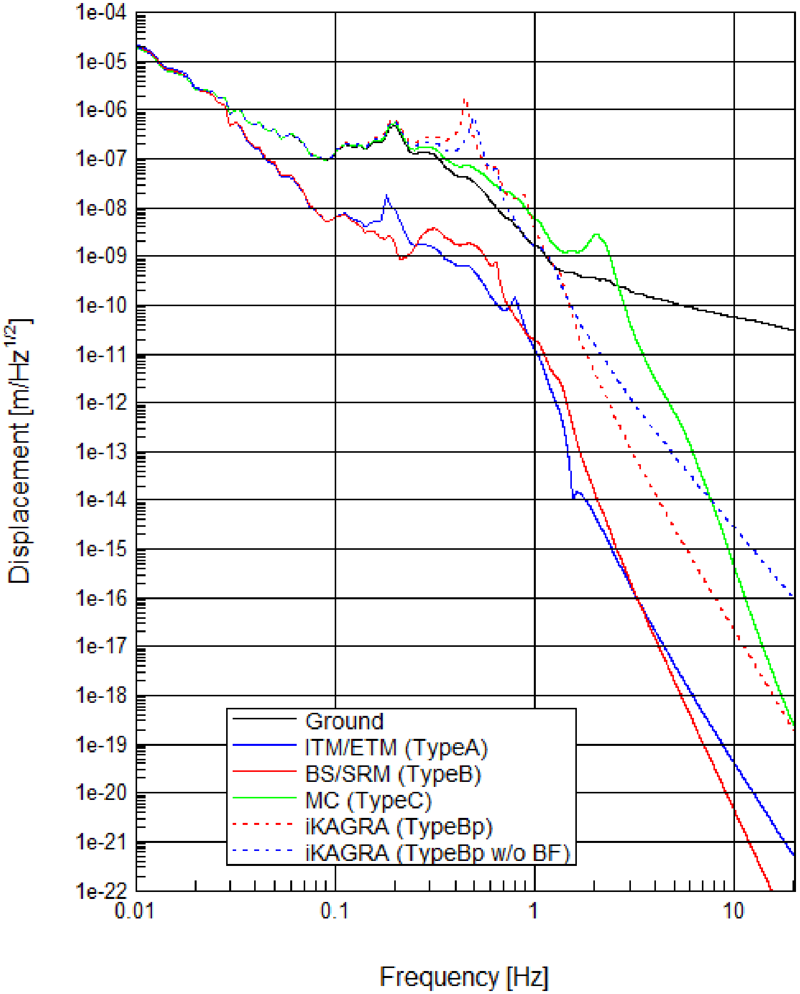
- PRCL: $\sqrt{[(PRM)^2+(2*PR2)^2+(2*PR3)^2 +(\sqrt{2}/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]}$
- SRCL: $\sqrt{[(SRM)^2+(2*SR2)^2+(2*SR3)^2 +(\sqrt{2}/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]}$

Seismic noise

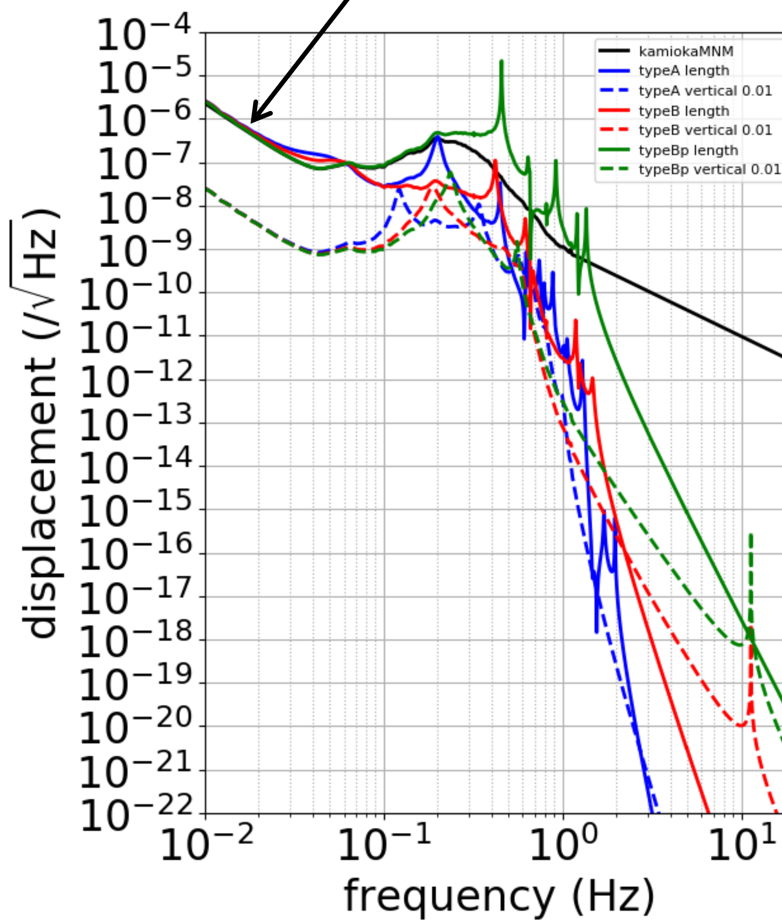
Models

- There exists several models

Medium Noise Model from [JGW-T1402971]



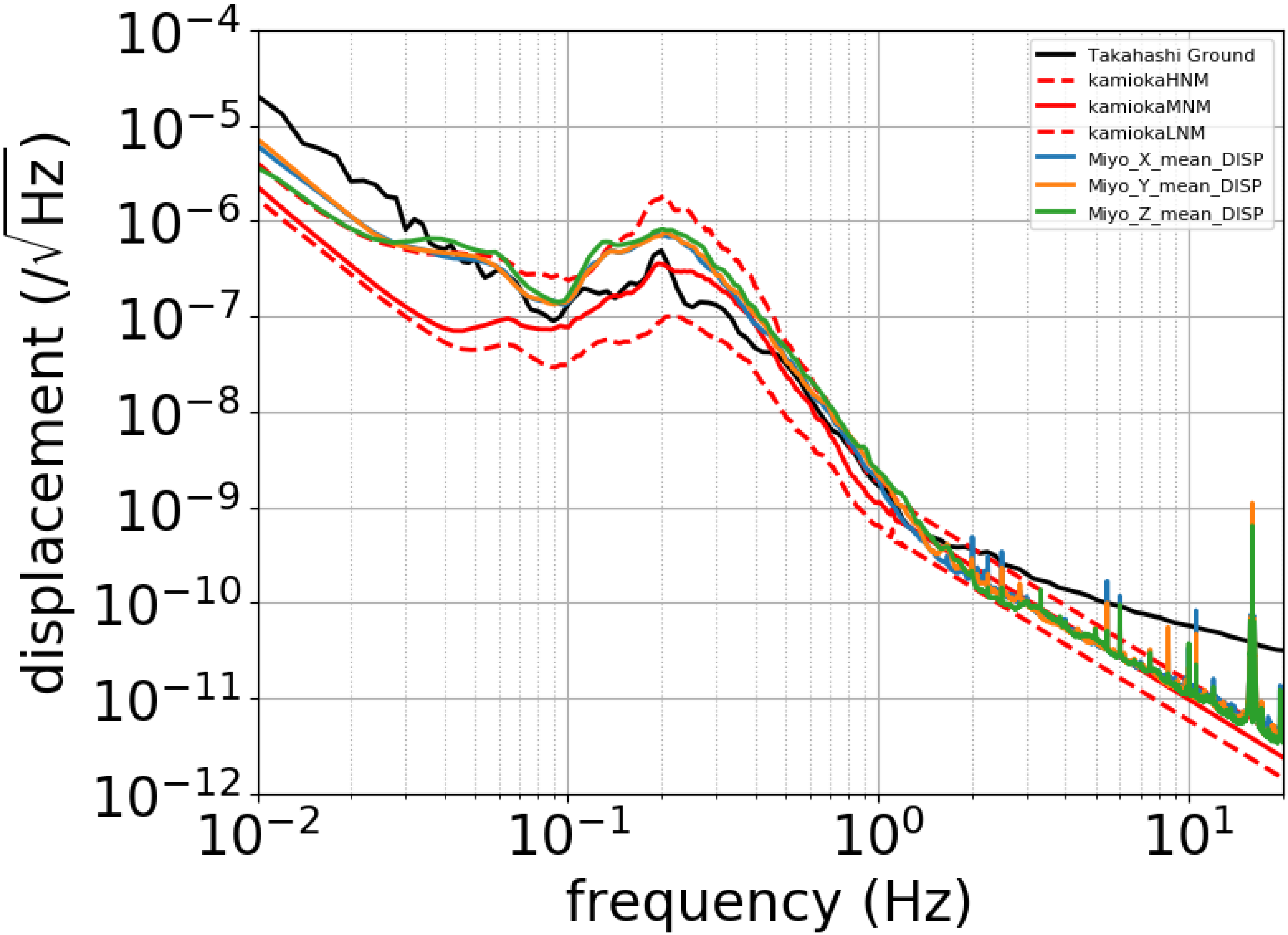
TypeA-C rev3.png
from R. Takahashi
(used for K. Somiya's fitting)



Model from T. Sekiguchi
(used for actuator modeling in [JGW-P1707051])

Seismic Noise Spectra

- Let's just use JGW-T1402971 MNM for simplicity



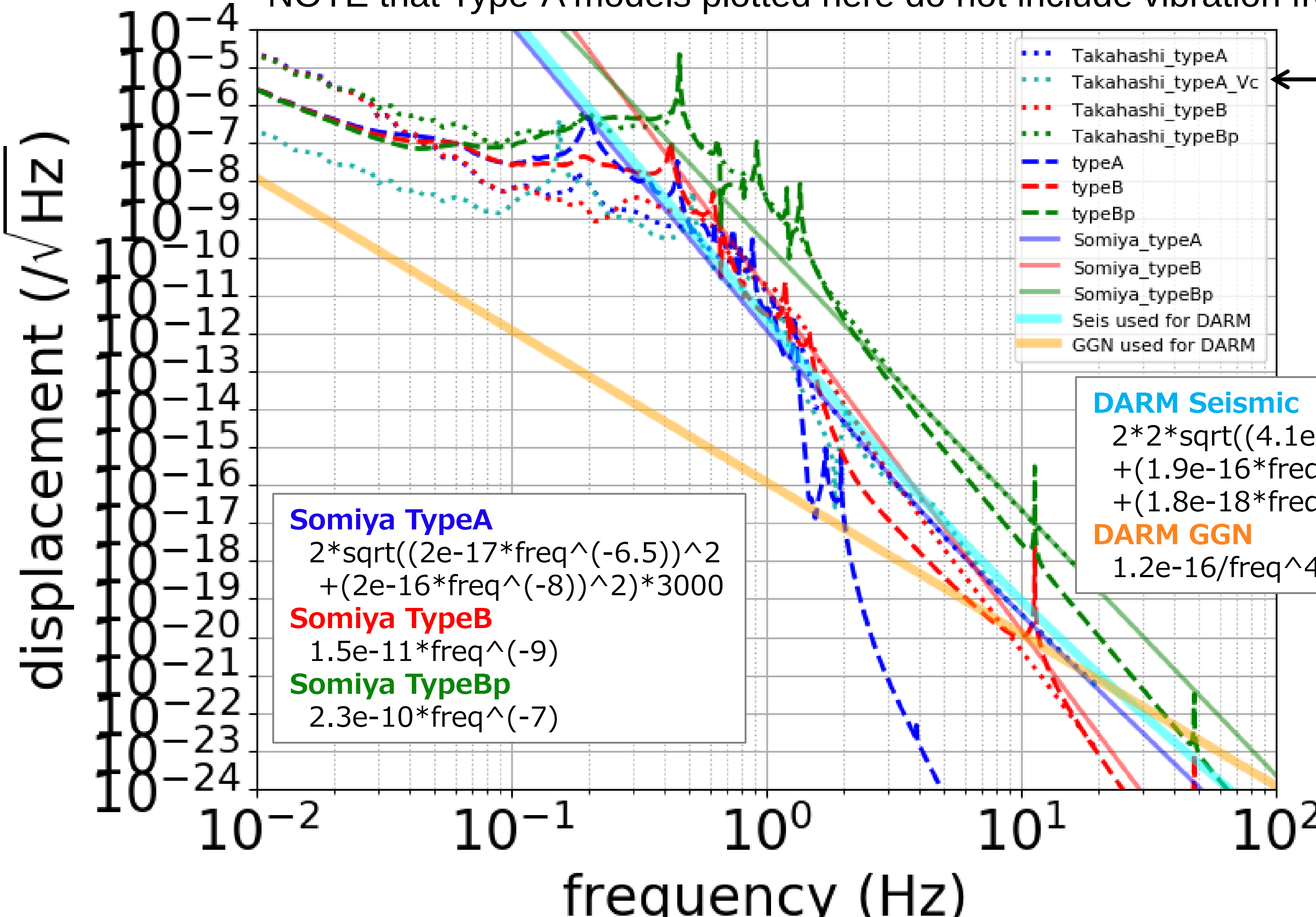
By Sekiguchi
JGW-T1402971

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



Somiya TypeA
2*sqrt((2e-17*freq^(-6.5))^2
+(2e-16*freq^(-8))^2)*3000

Somiya TypeB
1.5e-11*freq^(-9)

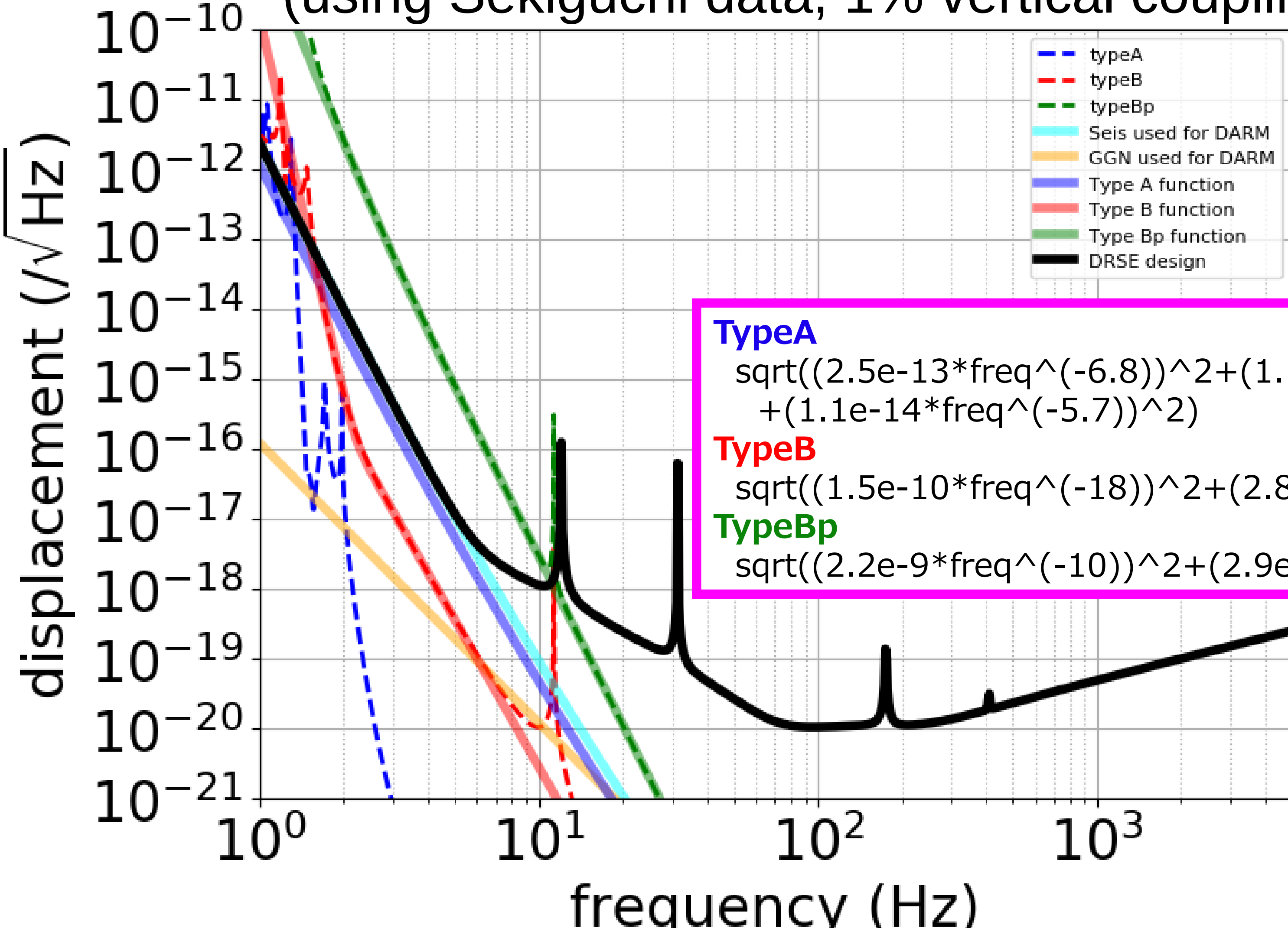
Somiya TypeBp
2.3e-10*freq^(-7)

DARM Seismic
2*2*sqrt((4.1e-17*freq^(-6.8))^2
+(1.9e-16*freq^(-8))^2
+(1.8e-18*freq^(-5.7))^2)*3000

DARM GGN
1.2e-16/freq^4

New Seismic Function

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



The ones used for bKAGRA design sensitivity

TypeA
sqrt((2.5e-13*freq^(-6.8))^2+(1.1e-12*freq^(-8))^2
+(1.1e-14*freq^(-5.7))^2)

TypeB
sqrt((1.5e-10*freq^(-18))^2+(2.8e-14*freq^(-7))^2)

TypeBp
sqrt((2.2e-9*freq^(-10))^2+(2.9e-10*freq^(-8))^2)

Suspension thermal noise

Type-A Payload Configuration

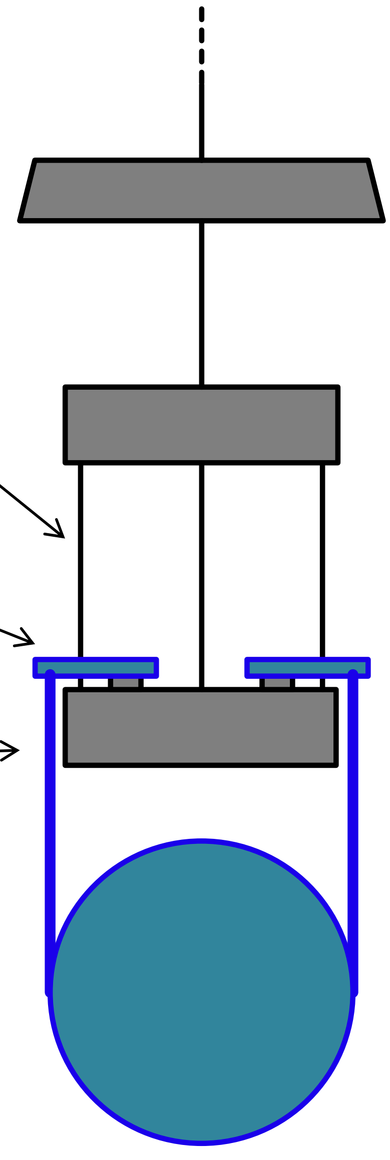
CQG 34, 225001 (2017)

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



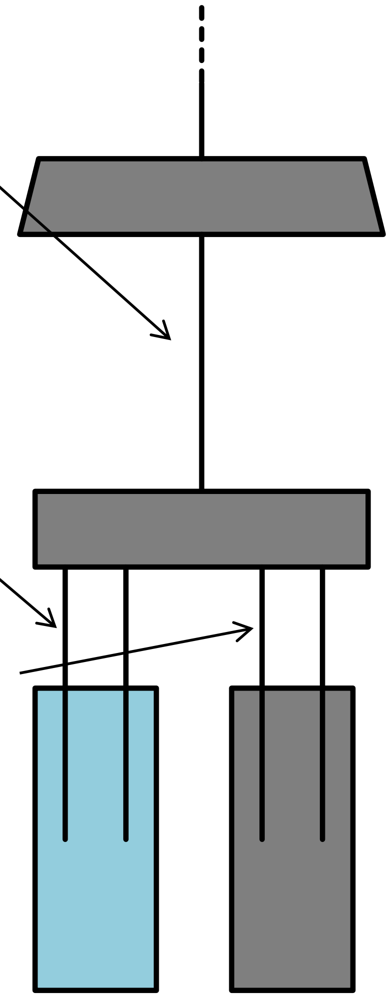
Type-B Payload Configuration

[CQG 34, 225001 (2017)](#)
Type-B info from Fabian
Type-B maraging rod JGW-D1605614
BS mass budget JGW-E1604966

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

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



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

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

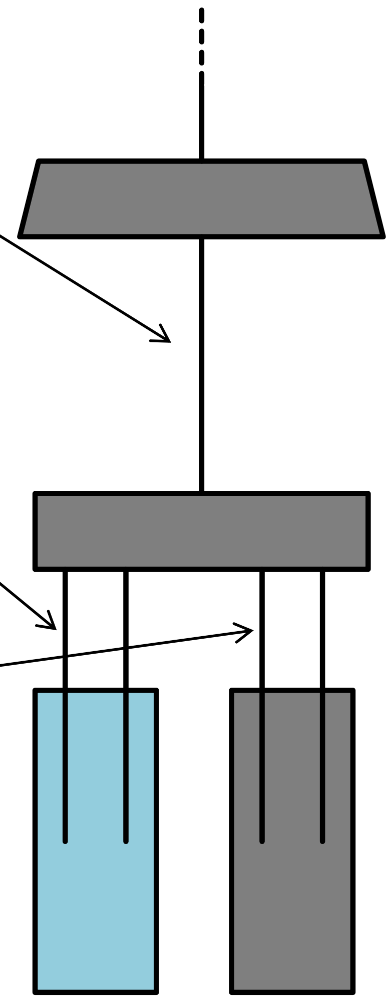
Type-Bp Payload Configuration

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



Bottom filter

Intermediate mass
15.6 kg for PRs

Test mass
10.71 kg for PRs

Recoil mass
12.036 kg for PRs

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

Material Properties of Wires

- Sapphire (see JGW-T1707038)
  - density: 4.0e3 kg/m^3
  - Young's modulus: 4.0e11 Pa
  - loss angle: 2e-7
- Piano wire (Nilaco 711267)
  - density: 7.83e3 kg/m^3 (W. R. Bennett Jr., Science of Musical Sound: Volume 1)
  - Young's modulus: 2e11 Pa (W. R. Bennett Jr., Science of Musical Sound: Volume 1)
  - loss angle: 2e-4 (RSI 86, 084501 (2015))
- Tungsten wire (Nilaco 461406)
  - density: 19.3 kg/m^3 (matweb)
  - Young's modulus: 4.0e11 Pa (matweb)
  - loss angle: 1.7e-4 (PLA 255, 230 (1999))
- Maraging steel rod (Daido MAS-1)
  - density: 8.02 kg/m^3 (see right)
  - Young's modulus: 1.82e11 Pa (see right)
  - loss angle: 2e-4 (N. A. Robertson 2001)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8 マルエージング鋼 MAS-1 (MAS-1 は大同特殊鋼の商標名)

■概　要　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靭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、精密バネ、ダイヤフラム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おります。

■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、靭性もあり、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) 比較的良い溶接性や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)

■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/m³ 8.02	J/(kg・K) 335	μΩ・cm 60～70	N/mm² 182,000	(20～480℃) 10.1×10⁻⁶/K	W/(m・K) 19.7 (25℃)

■ご使用上の注意事項
(1) 固溶化熱処理は 820～870℃で数分～30 分保持した上冷却します。Ms 点が 150℃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。このため靭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℃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。

Maraging steel spec sheet from R. Takahashi

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

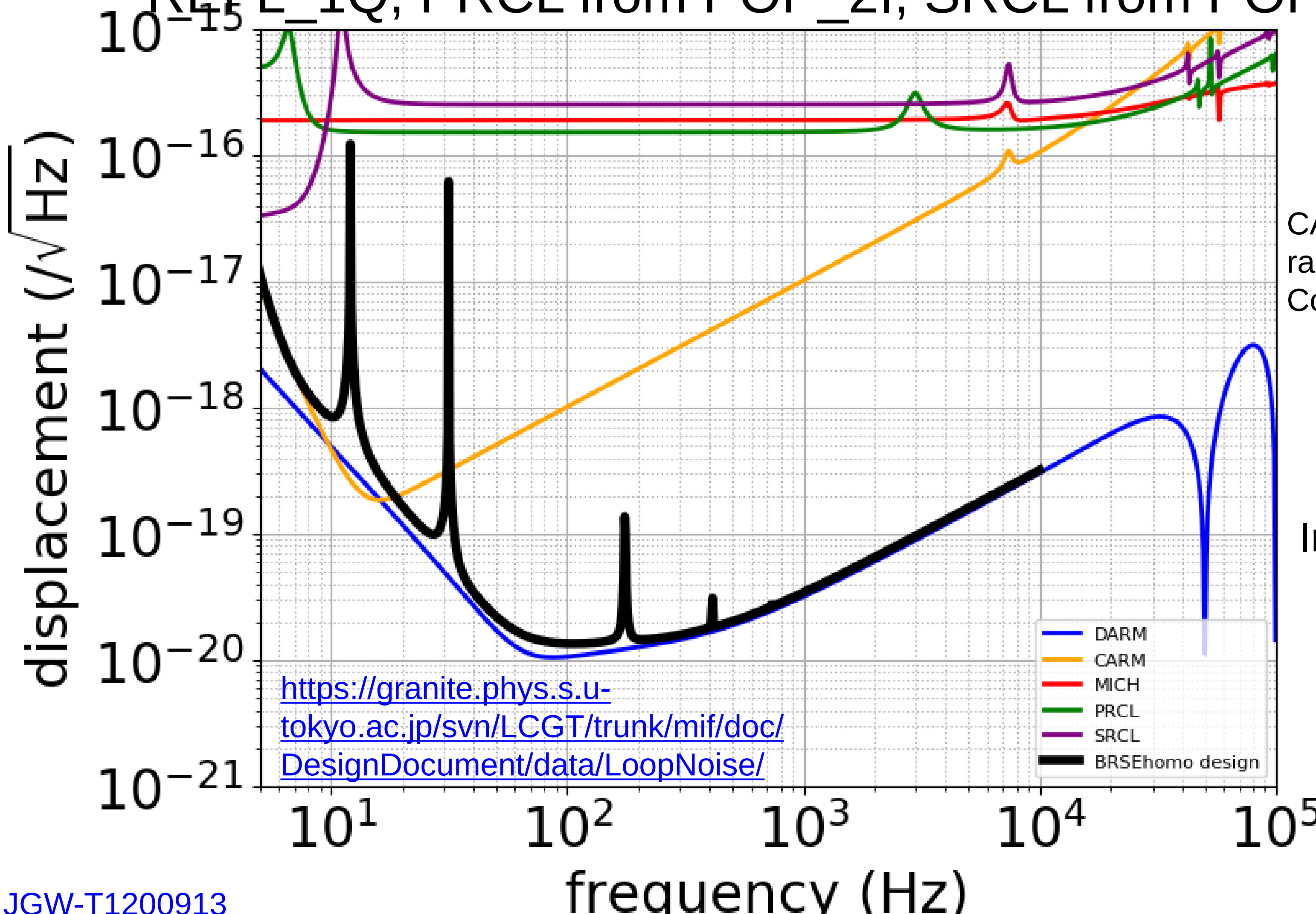
Number of coating layers for fused silica mirrors are derived from calculation using reflectivity. Coating thermal noise of Type-B/Bp suspensions are not very important since quantum noises for auxiliary DOFs are quite high.
BS thermal noise is tricky (LIGO-T0900209) but not considered carefully here.

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



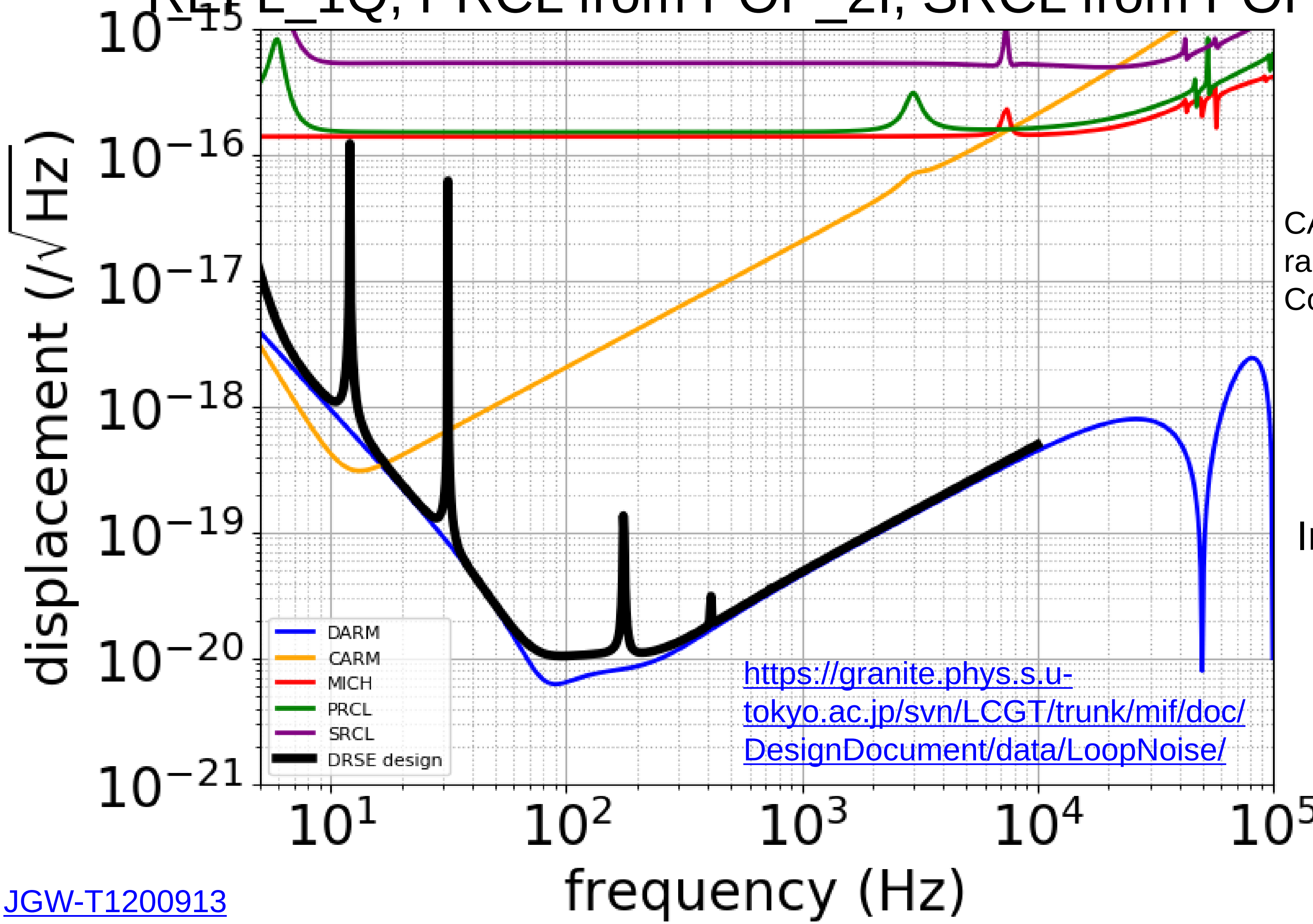
CARM originally in rad/rtHz.
Corrected to m/rtHz

Input power:
?? W

JGW-T1200913

Optickle Simulation (DRSE Aso)

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



CARM originally in rad/rtHz.
Corrected to m/rtHz

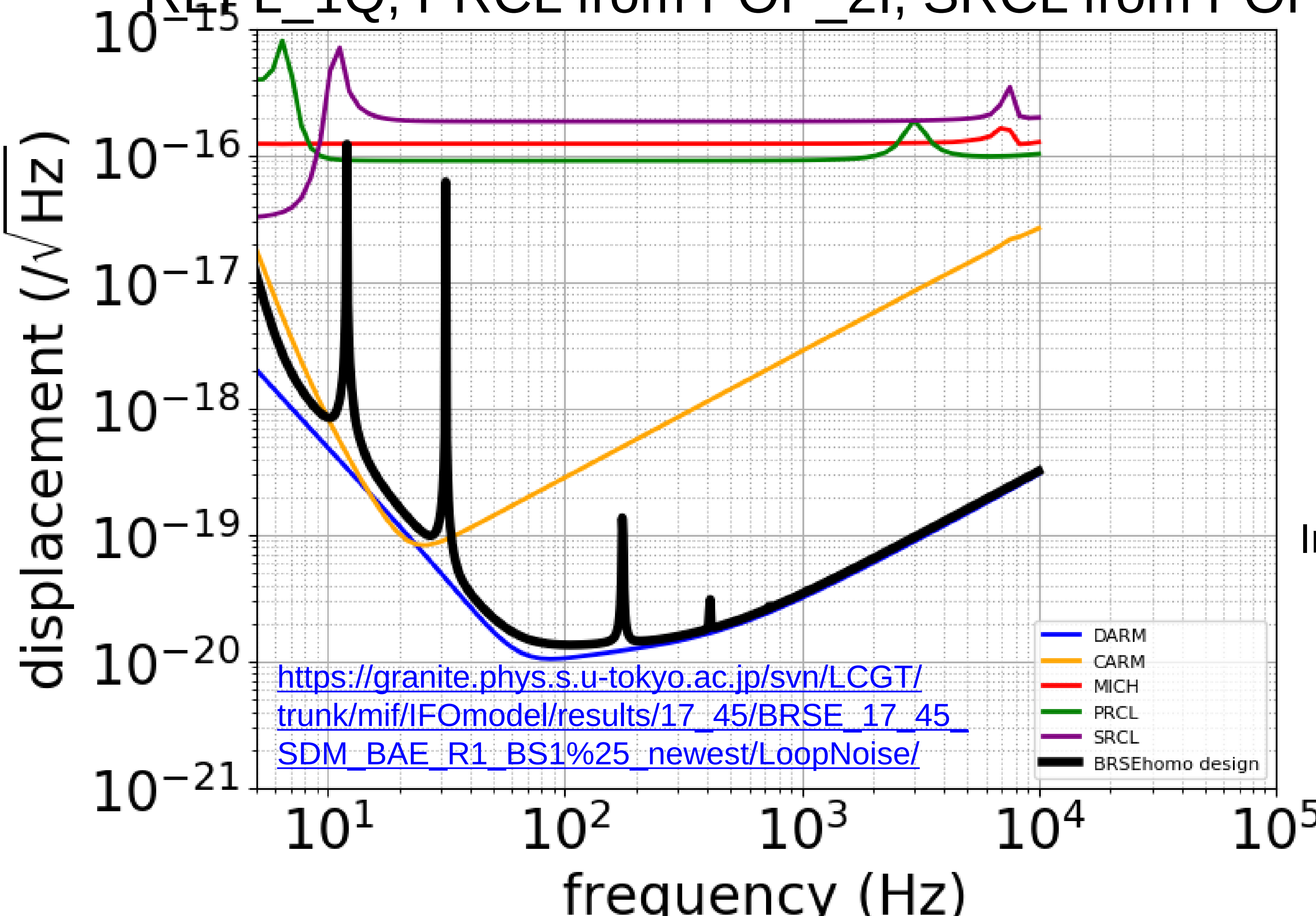
https://granite.phys.s.u-tokyo.ac.jp/svn/LCGT/trunk/mif/doc/DesignDocument/data/LoopNoise/

Input power:
?? W

JGW-T1200913

Optickle Simulation (BRSE Enomoto)

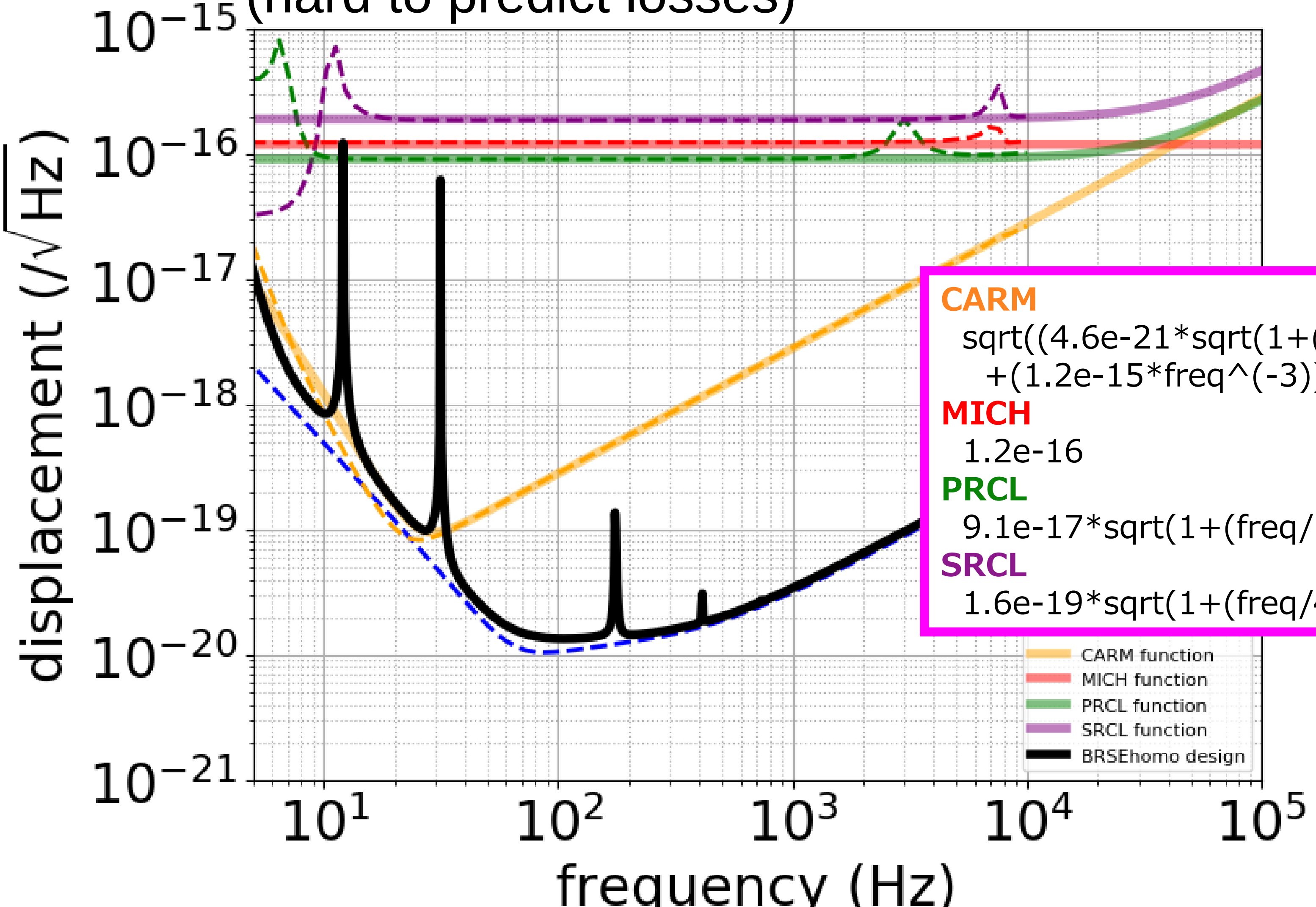
- DARM from AS_DC, CARM from REFL_1I, MICH from REFL_1Q, PRCL from POP_2I, SRCL from POP_1I



Input power: 77 W

Quantum Function

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



CARM
sqrt((4.6e-21*sqrt(1+(freq/1.6)^2))^2
+(1.2e-15*freq^(-3))^2)

MICH
1.2e-16

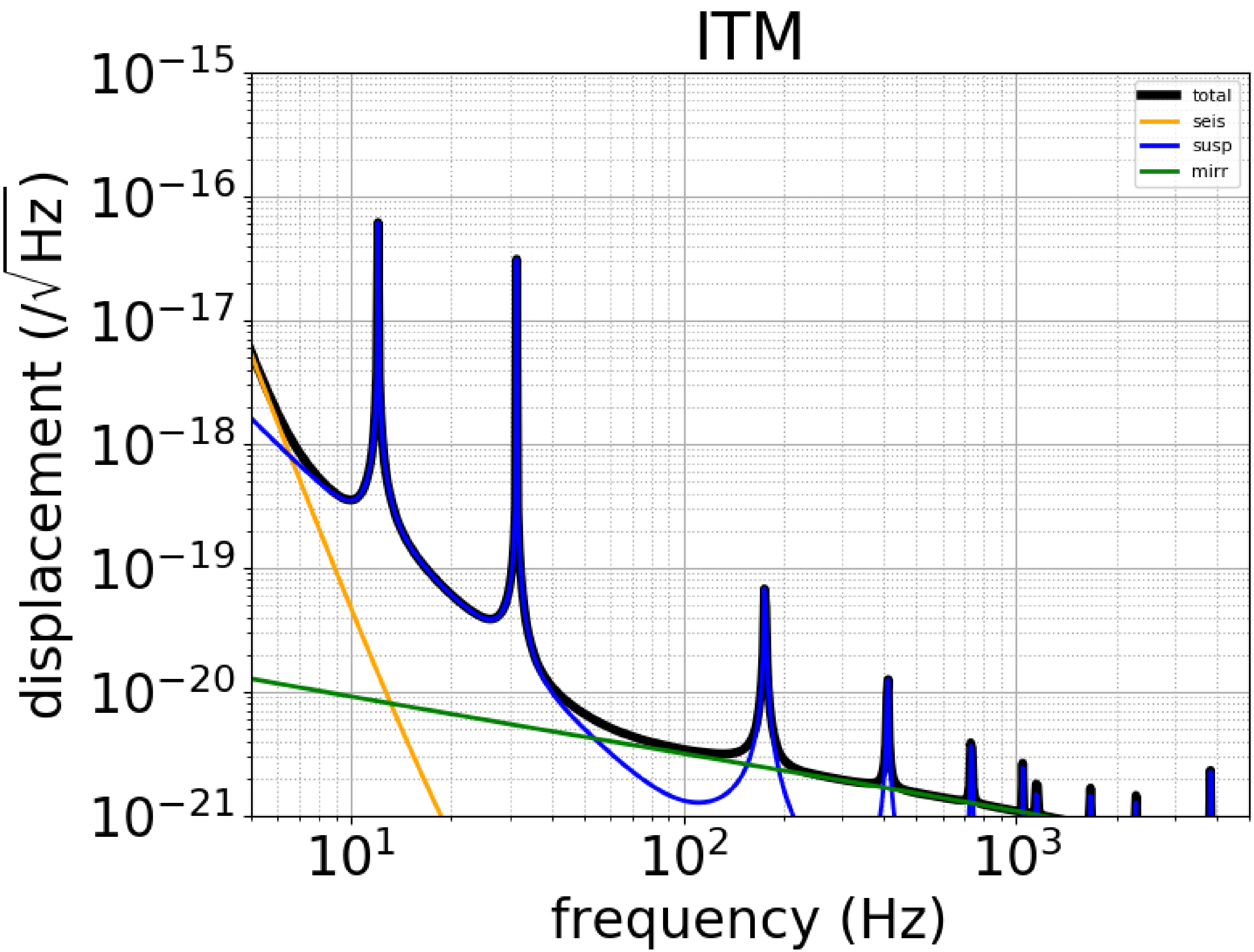
PRCL
9.1e-17*sqrt(1+(freq/3.6e4)^2)

SRCL
1.6e-19*sqrt(1+(freq/4.5e4)^2)

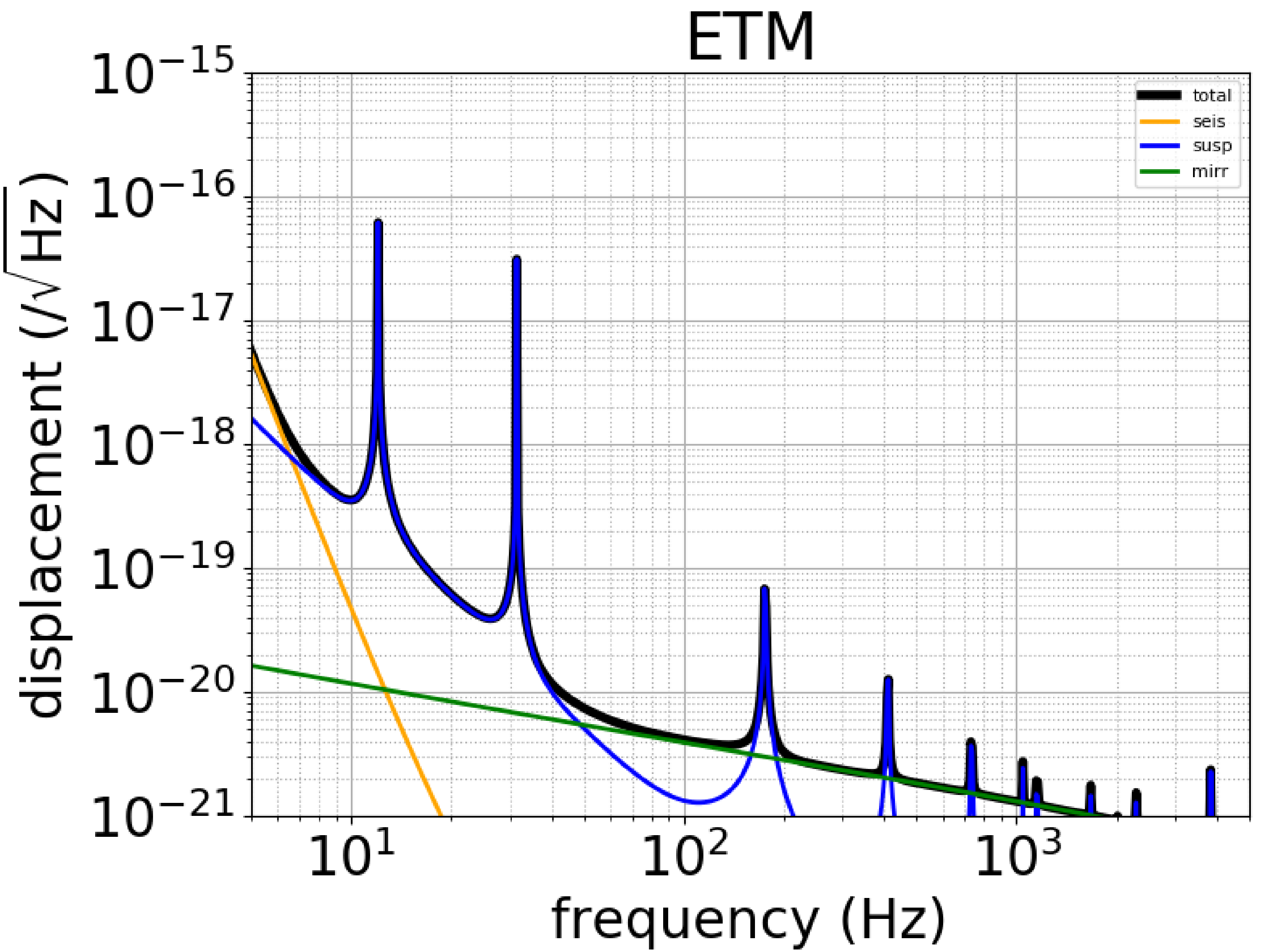
Displacement sensitivity

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

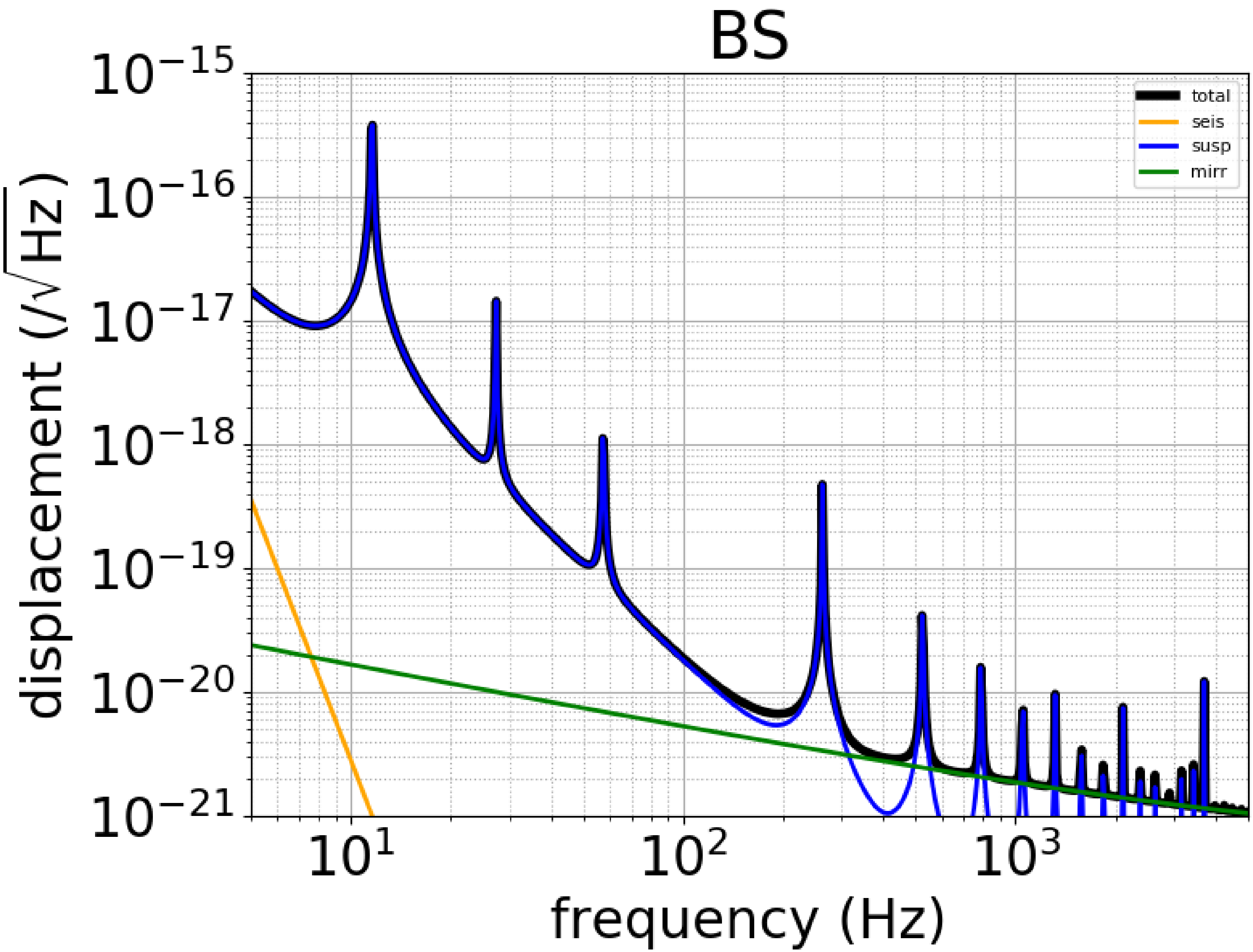
Displacement Noise: ITM



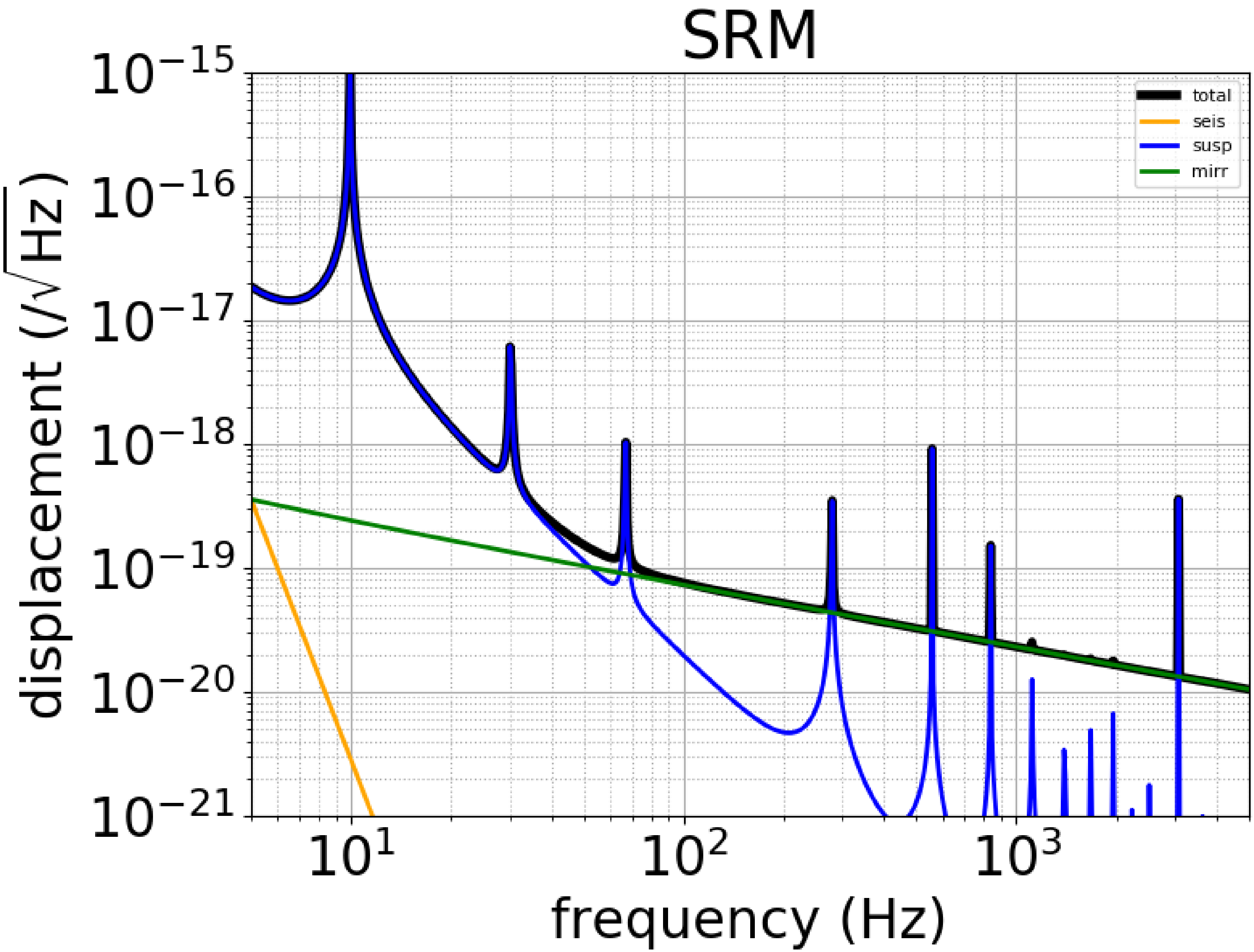
Displacement Noise: ETM



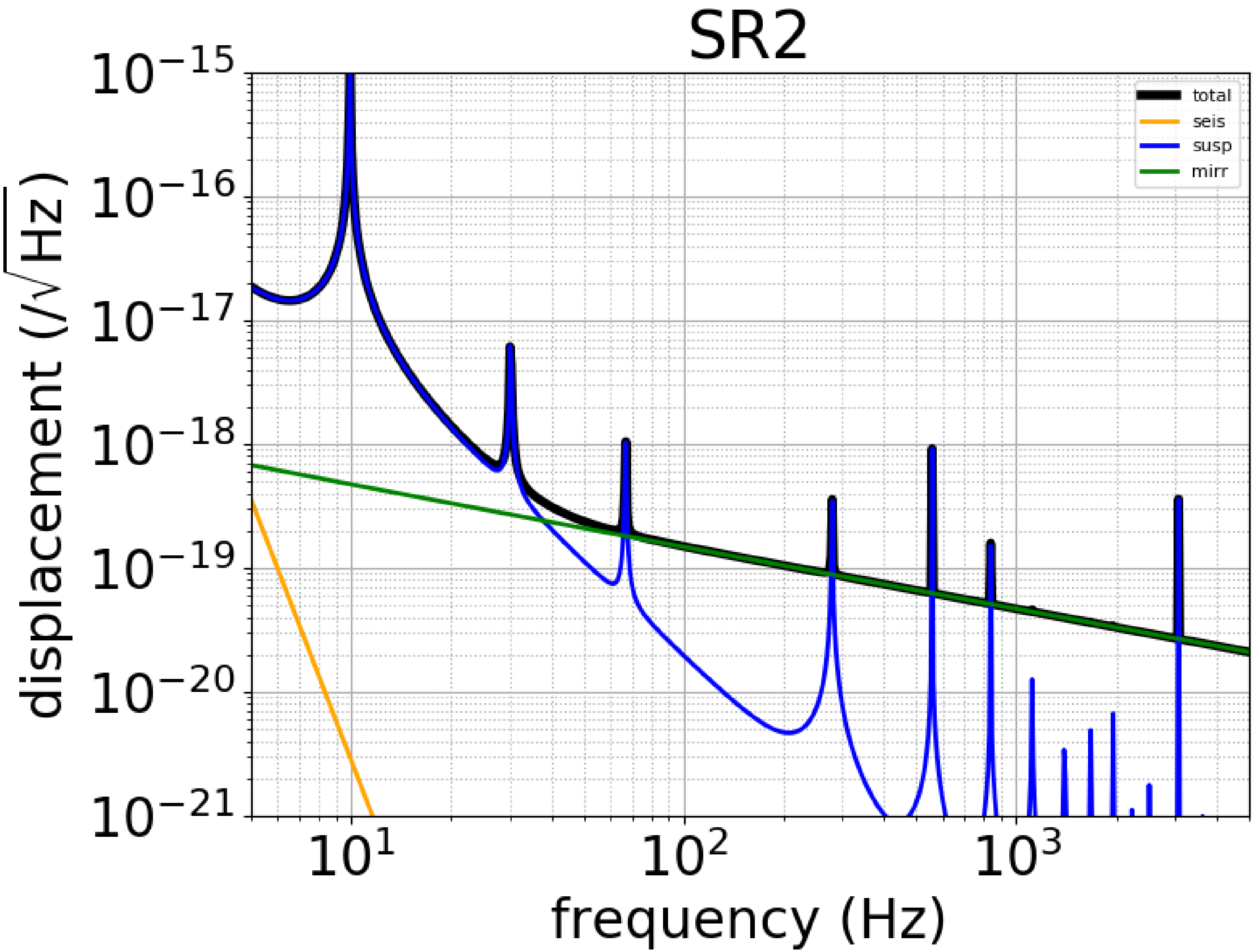
Displacement Noise: BS



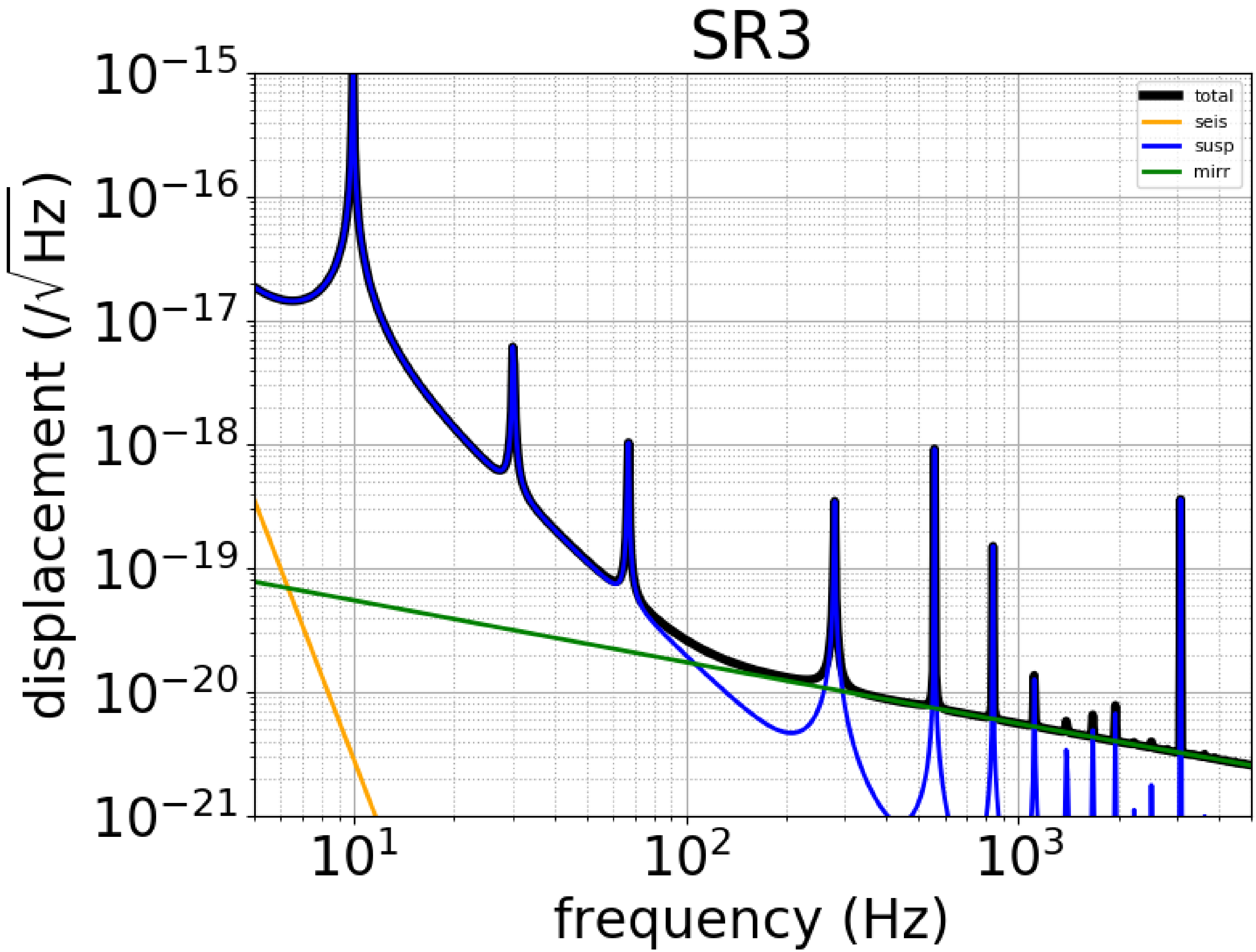
Displacement Noise: SRM



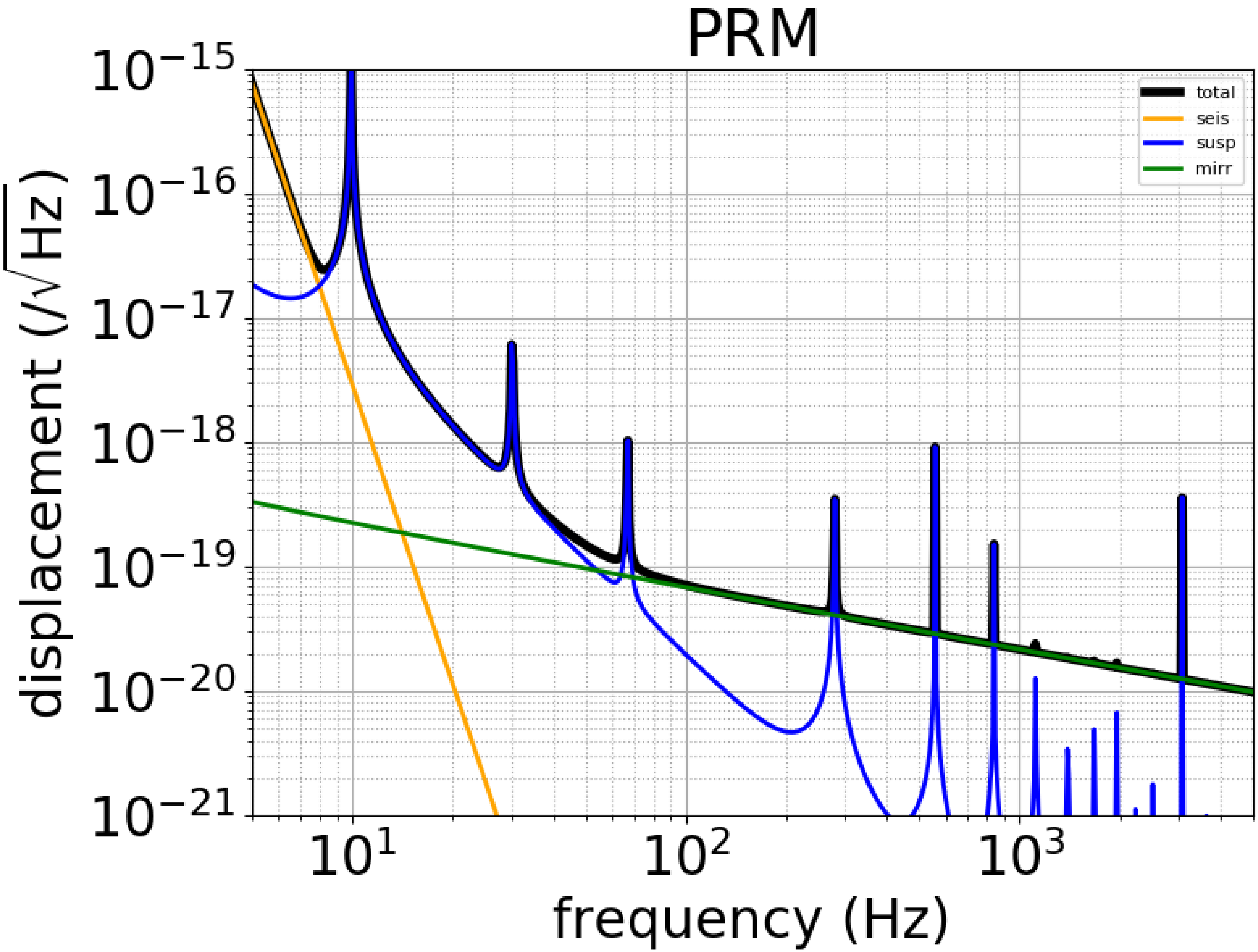
Displacement Noise: SR2



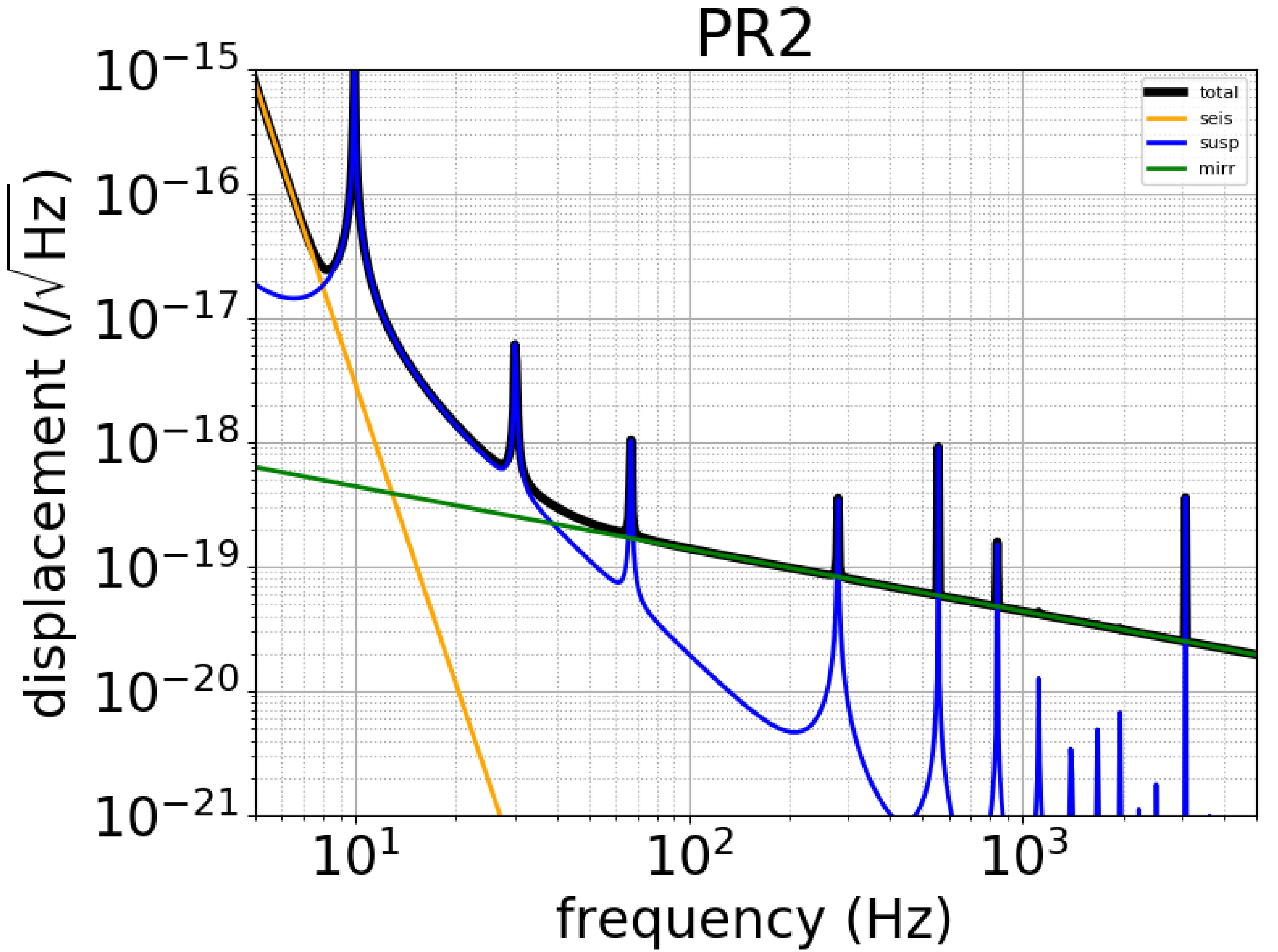
Displacement Noise: SR3



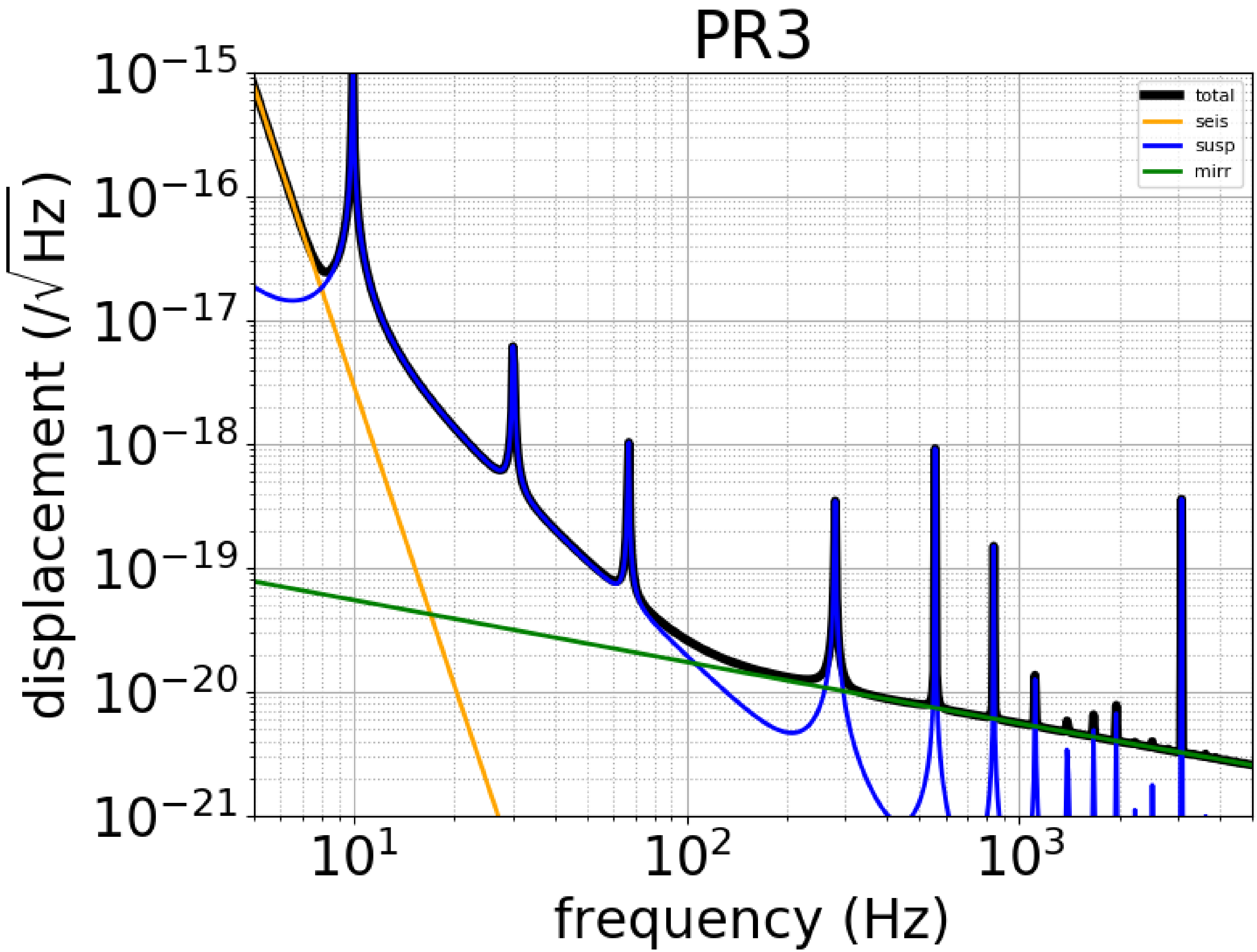
Displacement Noise: PRM



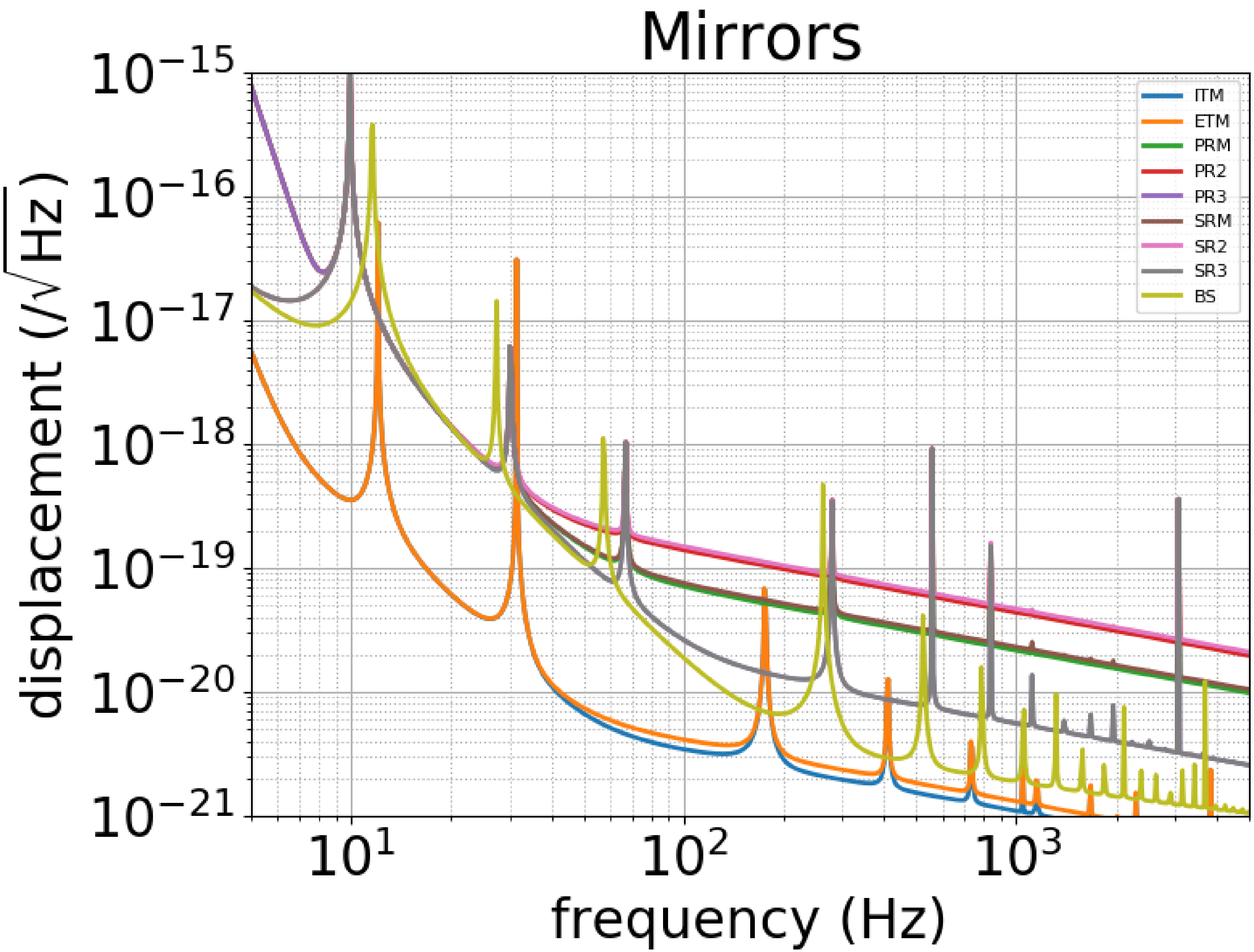
Displacement Noise: PR2



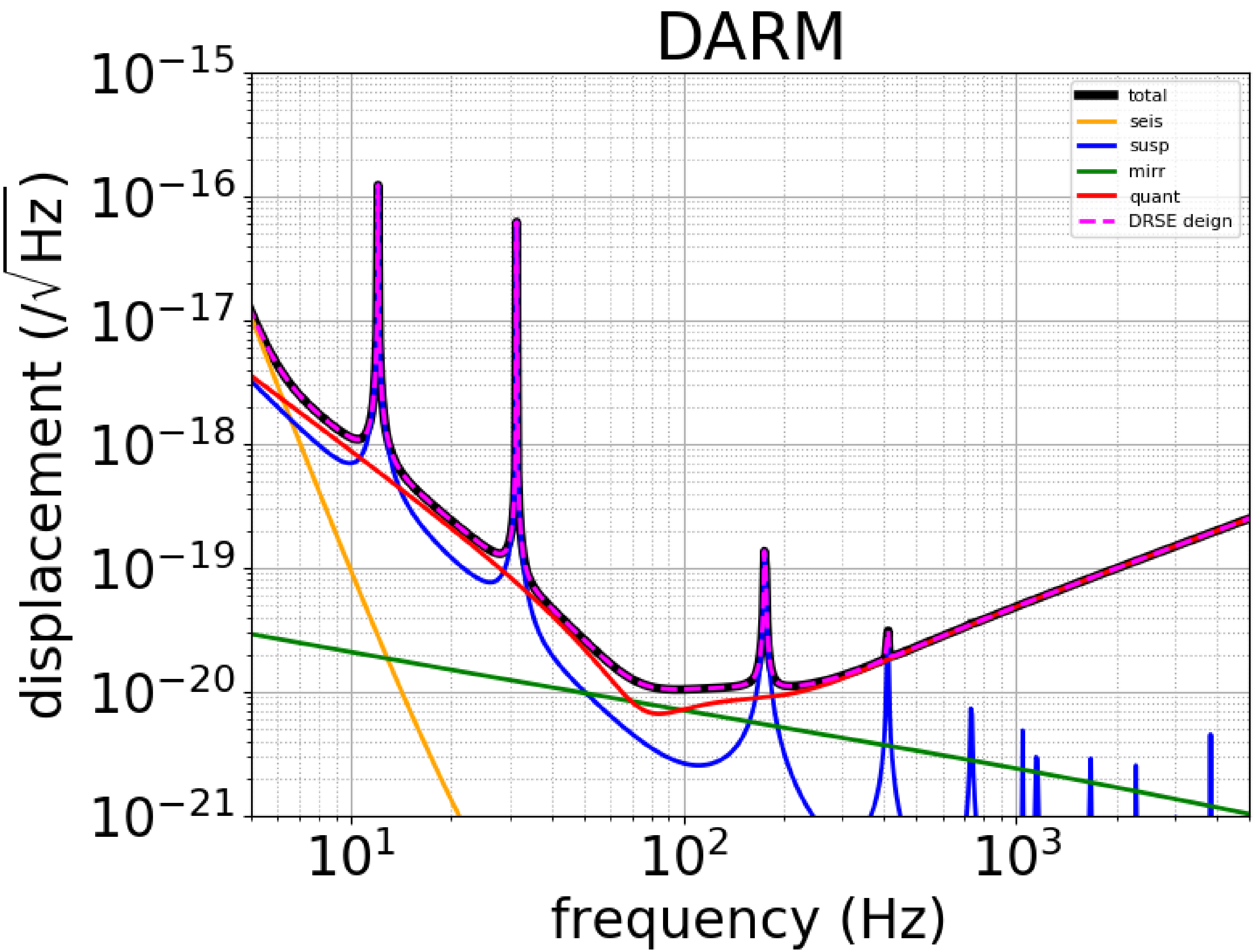
Displacement Noise: PR3



Mirrors Summary

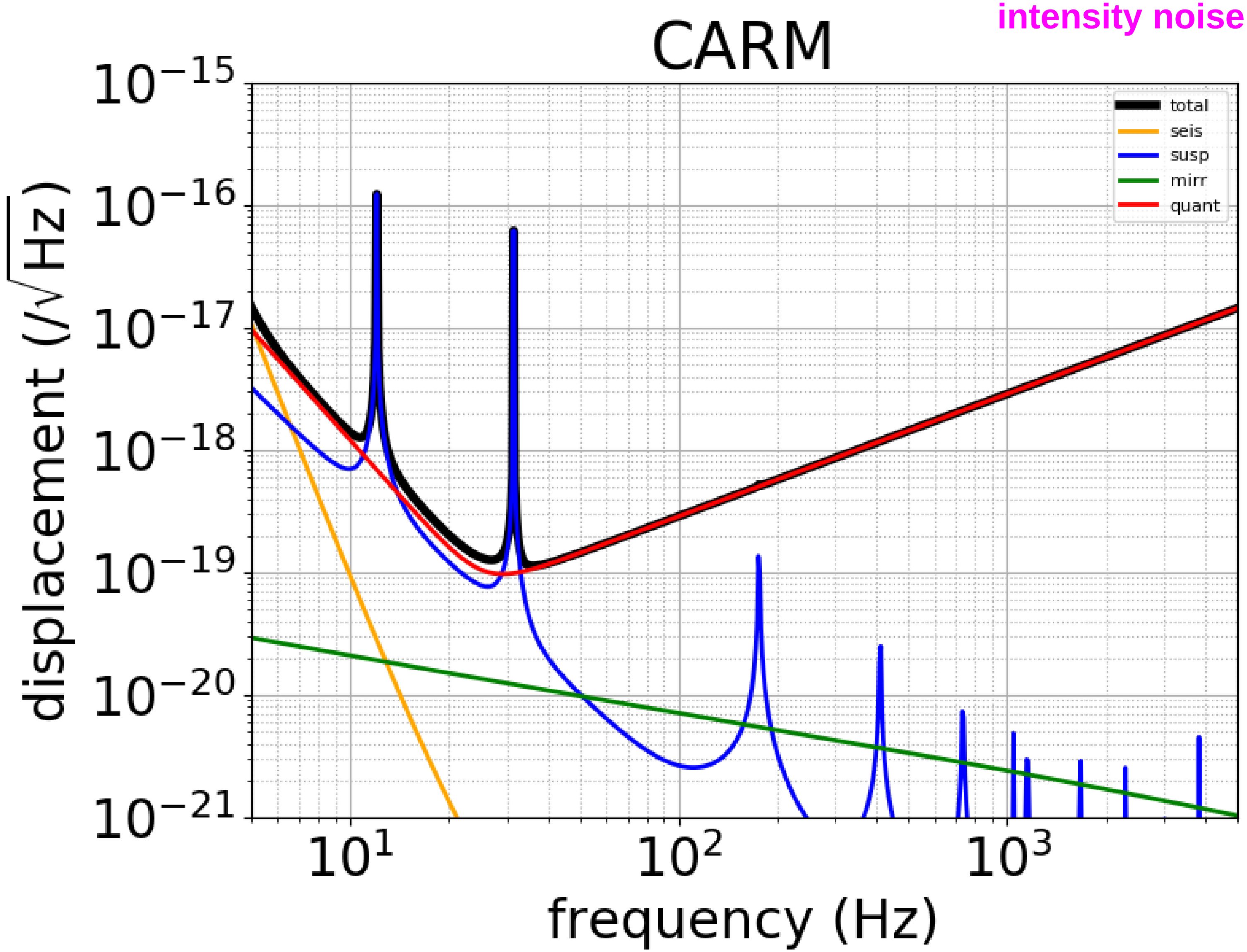


Displacement Sensitivity: DARM

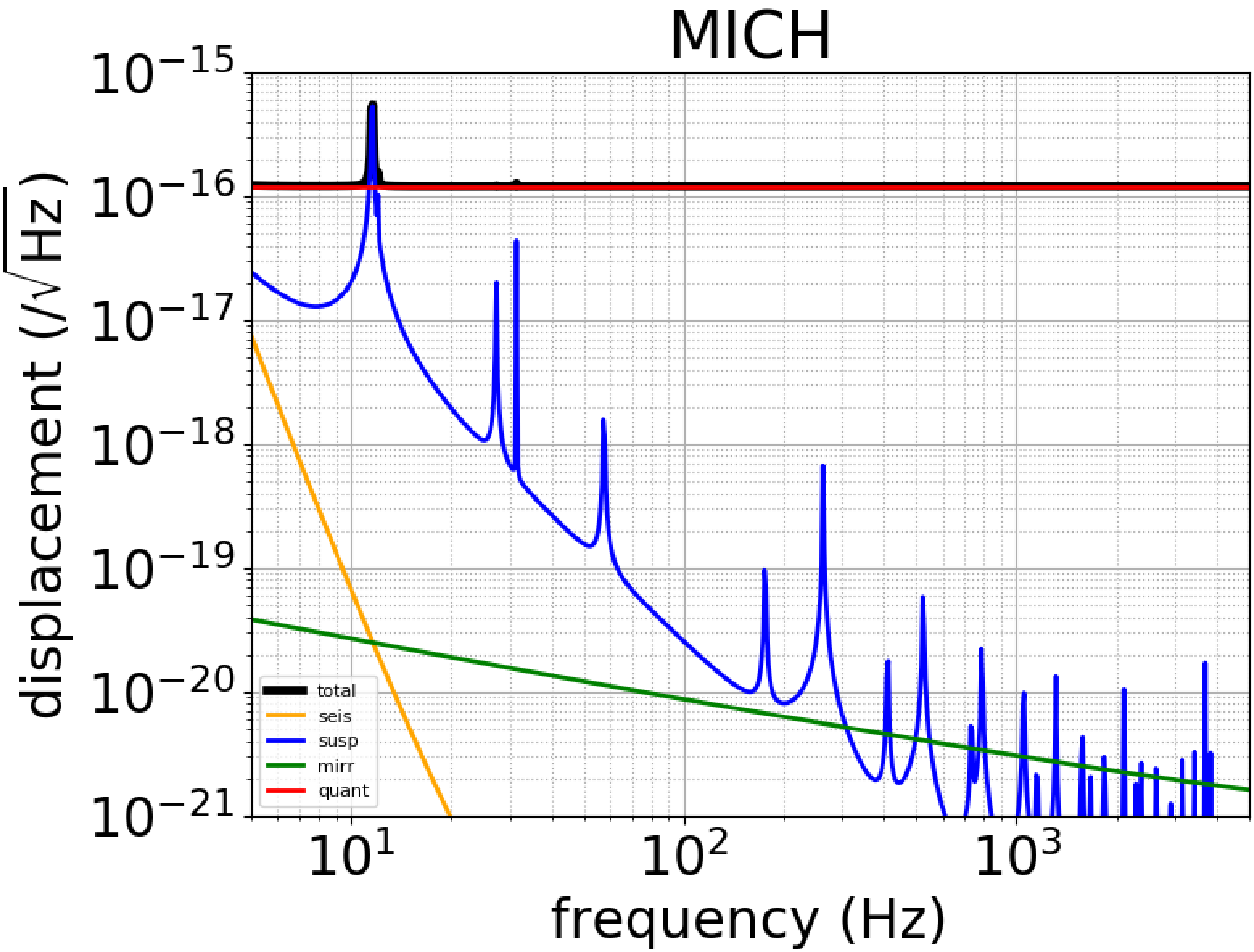


Displacement Sensitivity: CARM

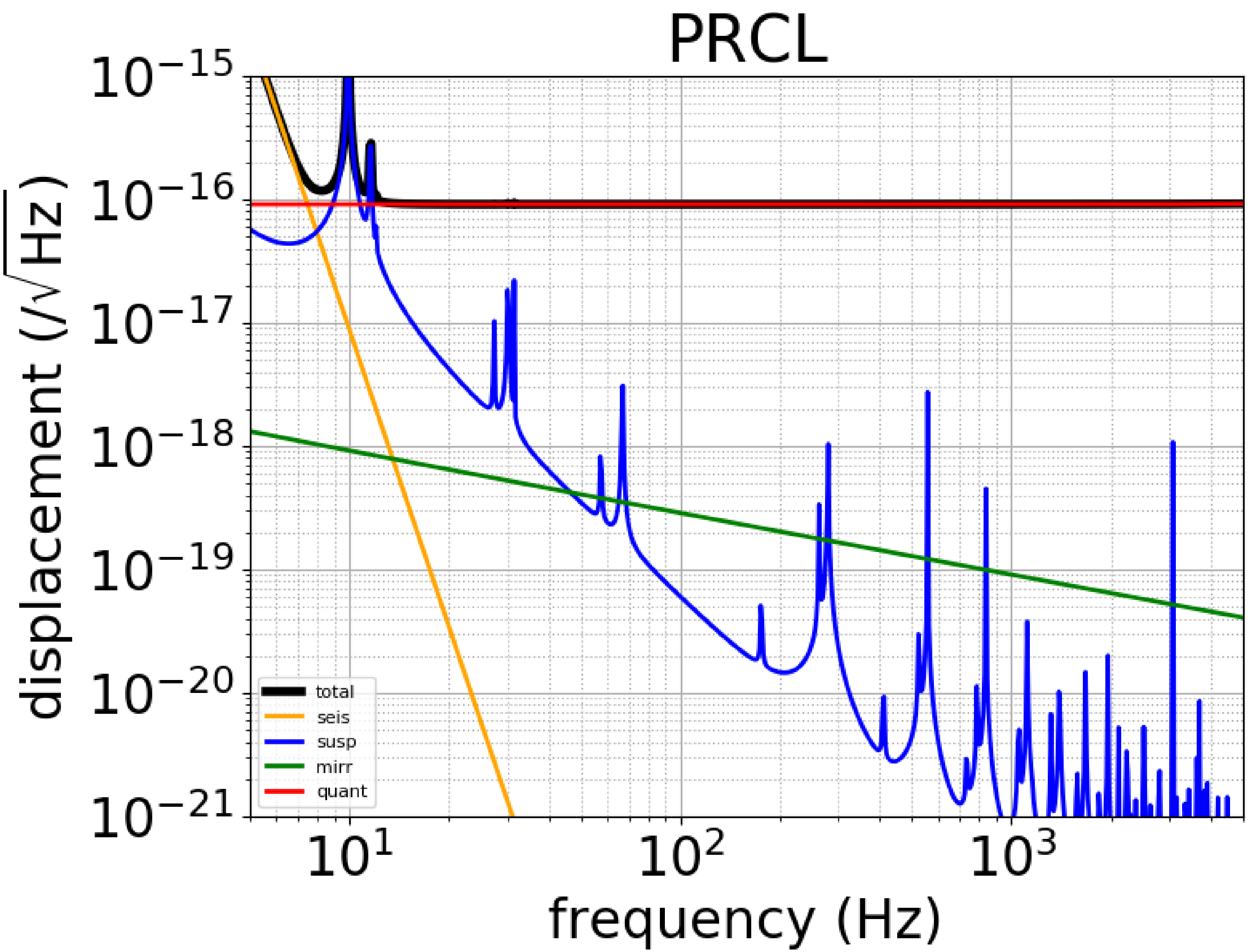
NOTE: frequency noise and intensity noise not considered



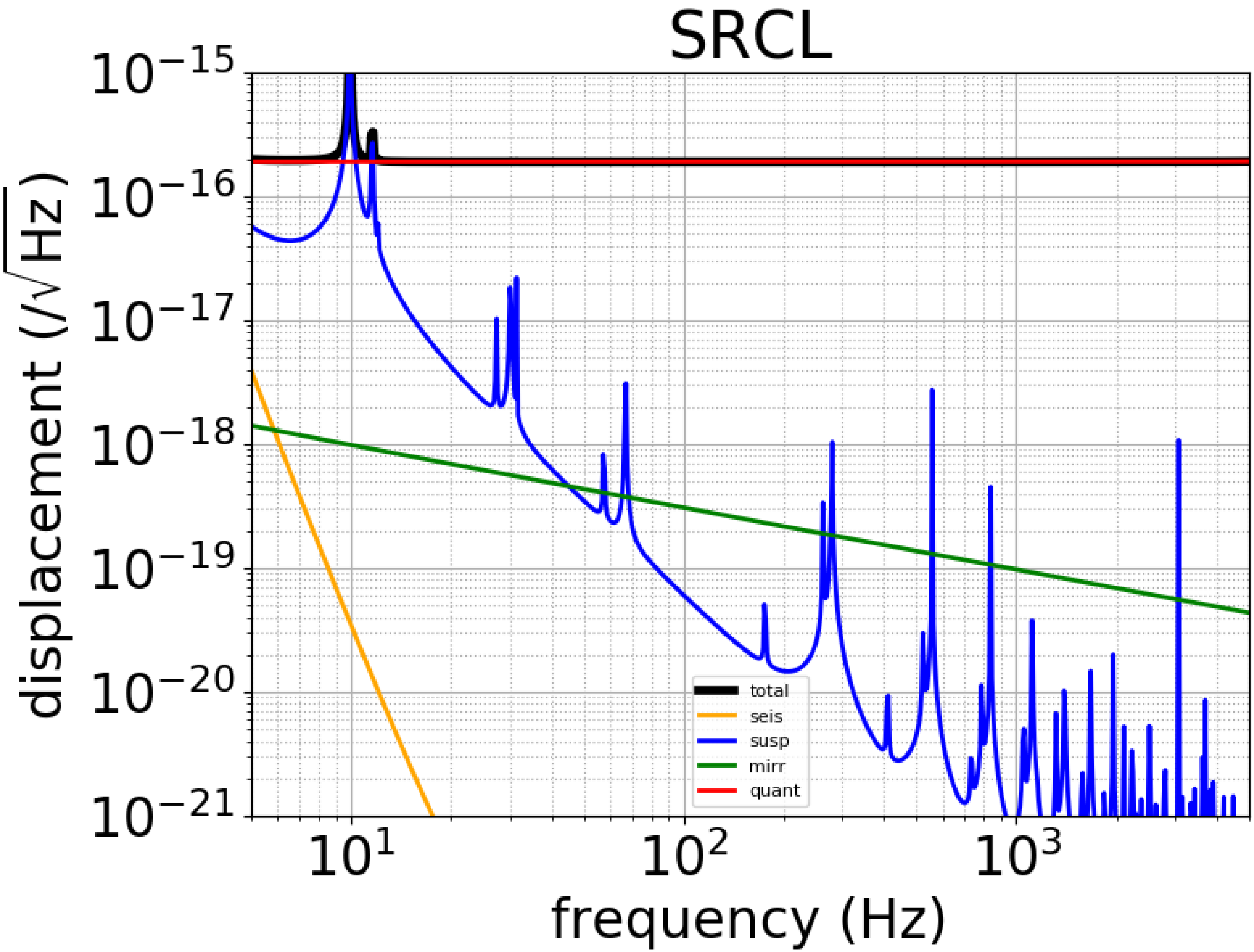
Displacement Sensitivity: MICH



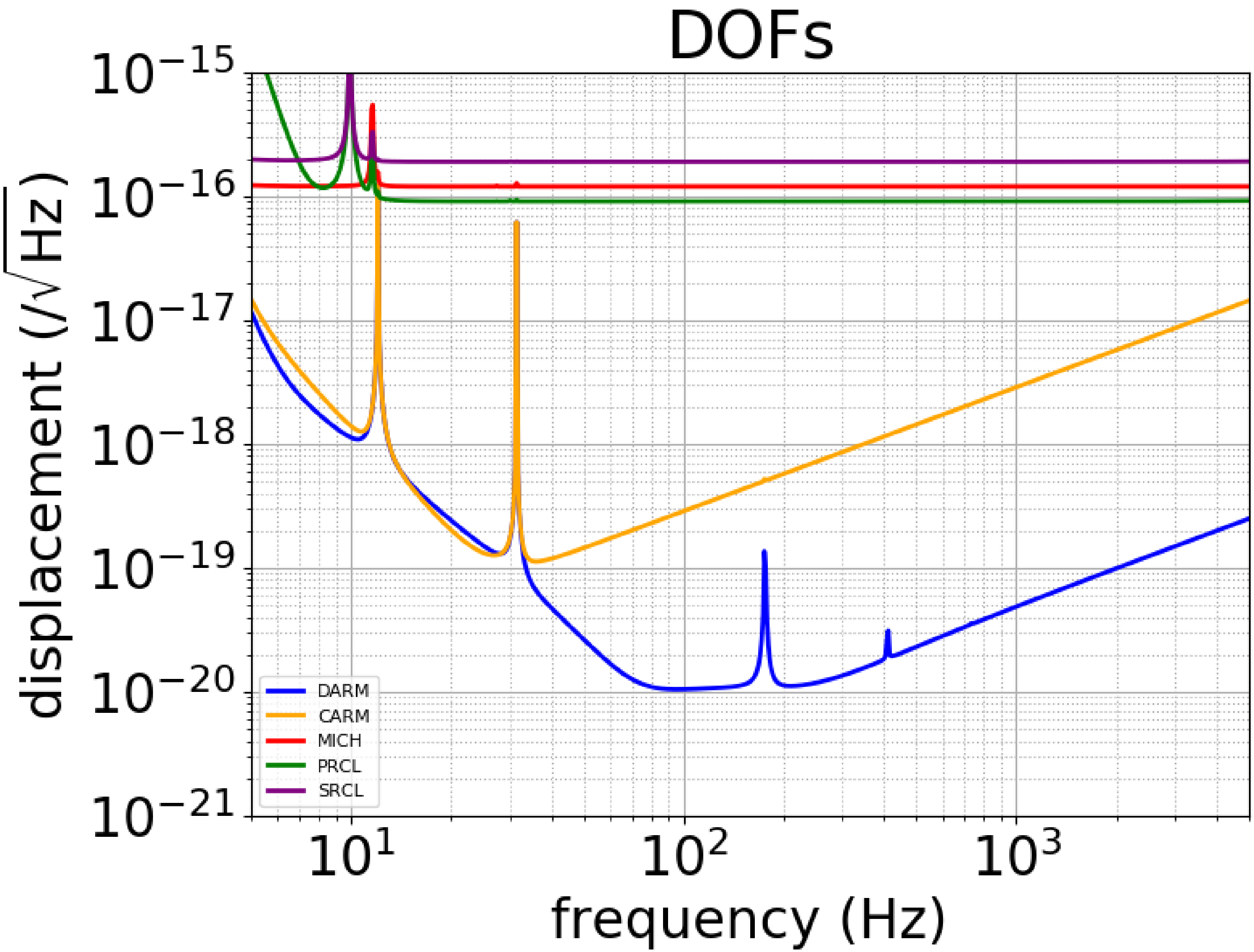
Displacement Sensitivity: PRCL



Displacement Sensitivity: SRCL

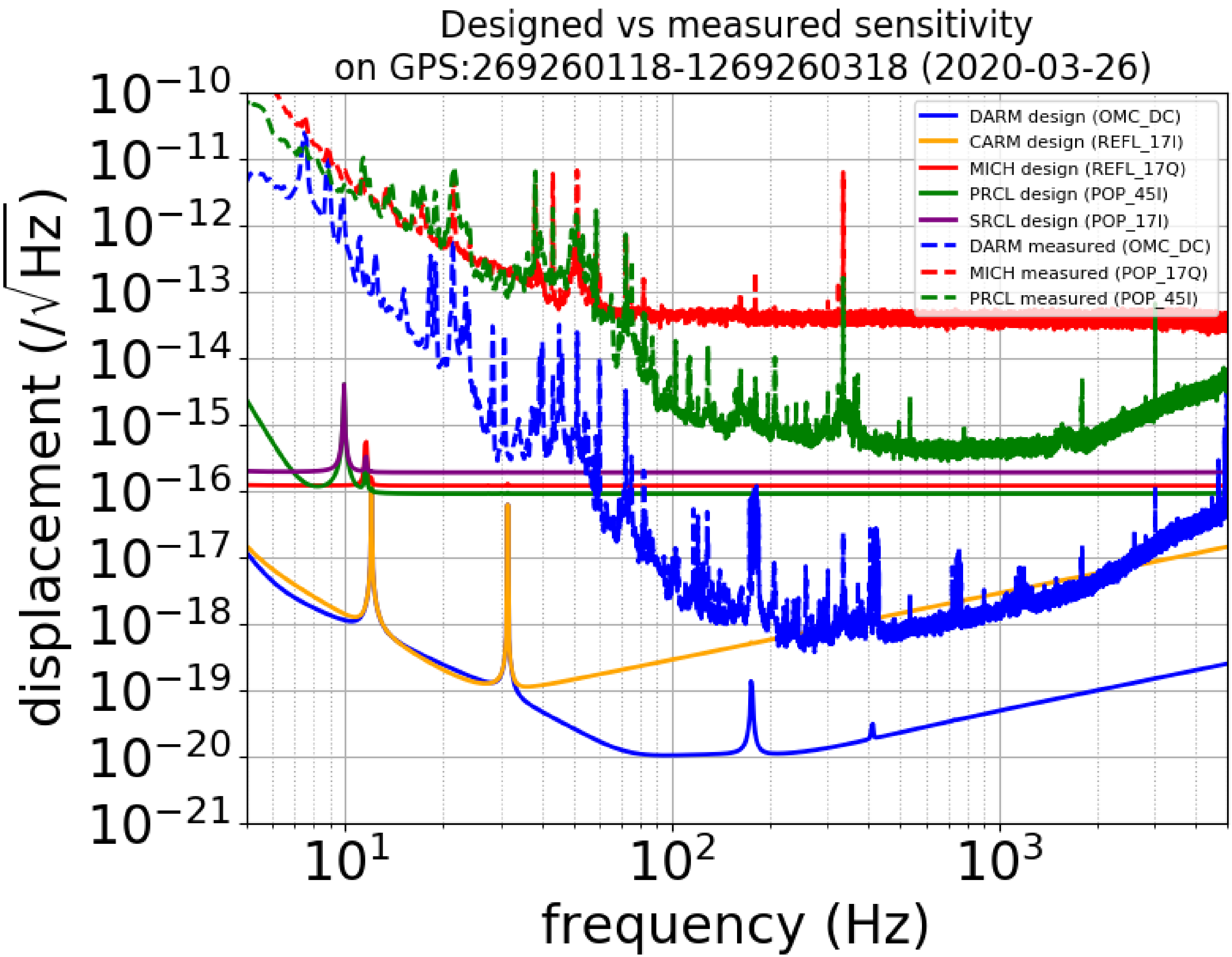


Displacement Sensitivity Summary



NOTE: frequency noise and intensity noise not considered for CARM

Mar 26, 2020 Sensitivity



MICH and PRCL calibrated offline (see klog #14556)