

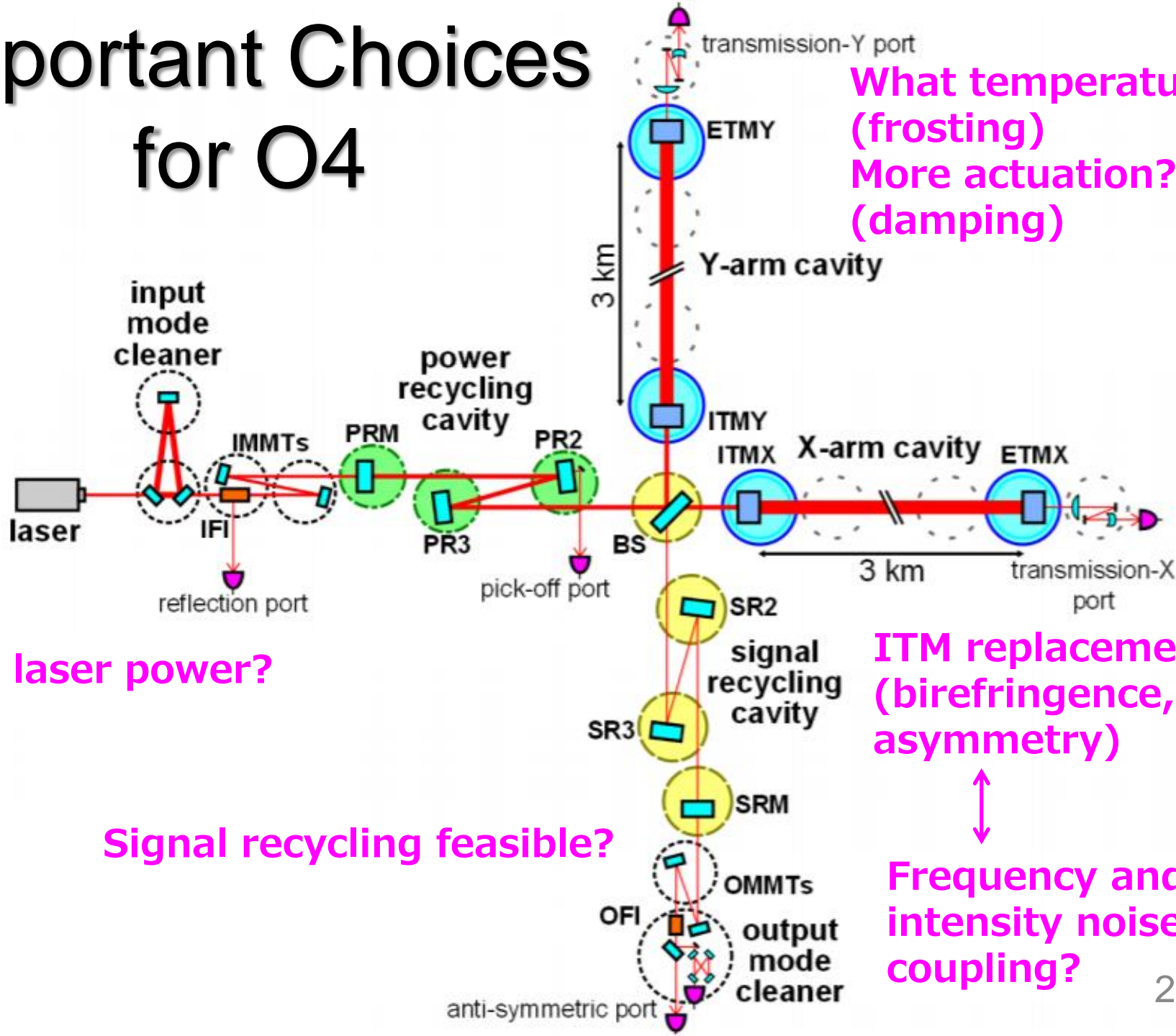
Summary of Sensitivity Estimate for O4 in Various Interferometer Configurations

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Important Choices for O4



What temperature?
(frosting)
More actuation?
(damping)

What laser power?

Signal recycling feasible?

ITM replacement?
(birefringence,
asymmetry)

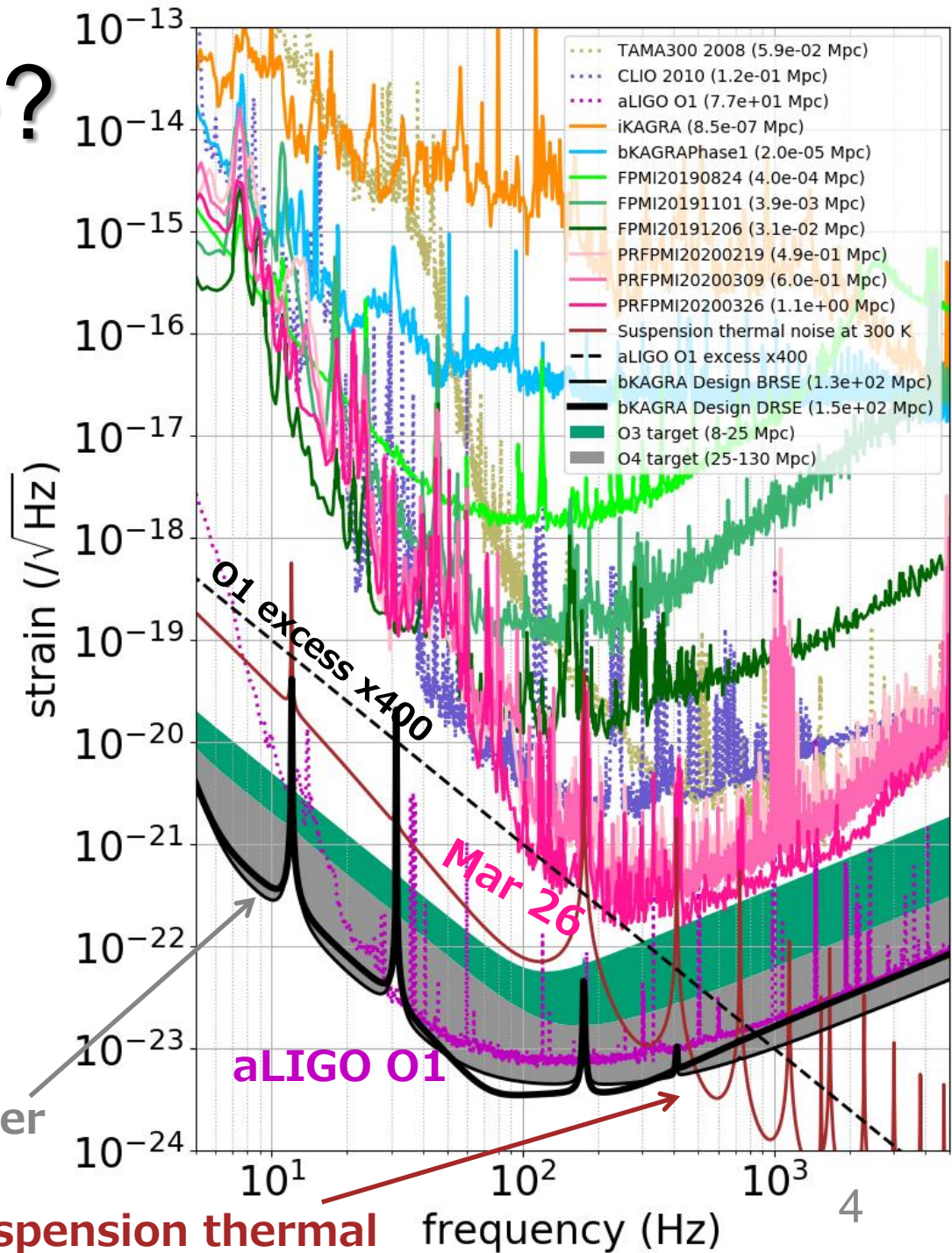
↕
Frequency and
intensity noise
coupling?

Assumptions for Estimation

- IFO configuration: PRFPMI with 0% SRM or DRFPMI with 70% SRM, upto 300 W at BS (no shot noise coupling considered)
- Temperature: 22 K to 300 K (heat extraction capability not considered); see [JGW-P2011614](#)
- Frequency and intensity noise: current level or estimated noise using Optickle (see, also, [JGW-T1910352](#))
 - Assume ITMs are not replaced (see [JGW-G2011541](#))
- Actuator noise: Not significant for O4 if we do it right, with whitening filters (see [JGW-T2011661](#))

Where Are We?

- ~1 Mpc at best
- PRFPMI with 70% SRM tilted, 3-5 W to PRM, ~250 K, DC readout
- O1 excess x400
- Almost shot noise limited at high freq. (klog [#13475](#))



O4 target on Obs. Scenario Paper
25-130 Mpc by ~2021

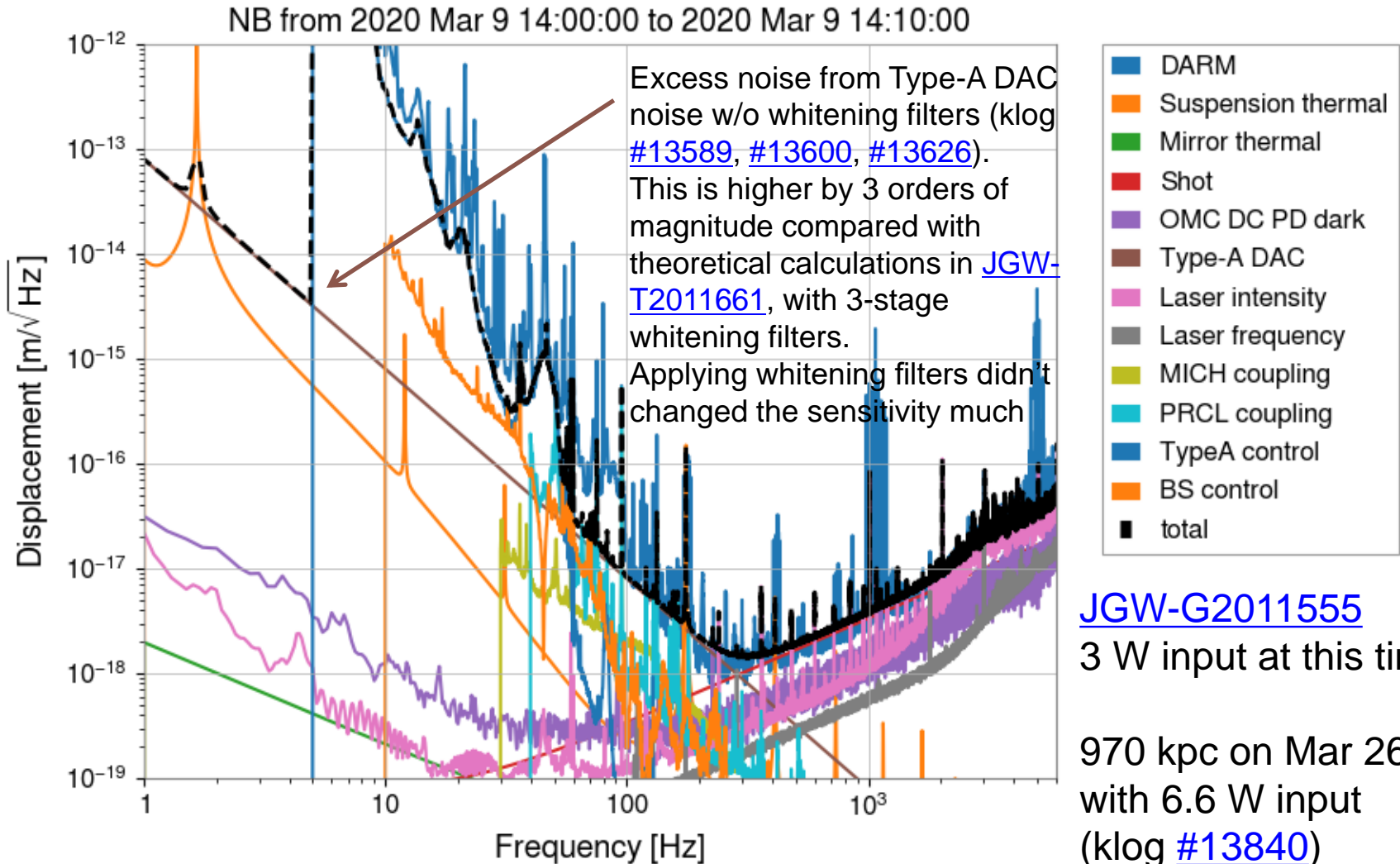
O3 best and O4 Target

	Mirror temp.	Power at BS	SRM reflectivity	Detuning angle	Homodyne angle	Excess noise
O3 best	~250 K	30-50 W	70% tilted	~90 deg (PRFPMI)	~90 deg (conventional)	O1 x 400
O3 low	22 K	10 W	0 %	90 deg (PRFPMI)	90 deg (conventional)	O1 x 20
O3-15Mpc	22 K	10 W	70 %	90 deg	90 deg	O1 x12
O3 high / O4 low	22 K	33 W	70 %	90 deg (BRSE)	90 deg (conventional)	O1 x 8
O4 80Mpc	22 K	404 W	85 %	90 deg	90 deg	O1 x 2
O4 high	22 K	673 W	85 %	90 deg (BRSE)	90 deg (conventional)	no excess
Design	22 K	673 W	85 %	86.5 deg	135.1 deg	no excess

For details, see [JGW-T1809078](#)

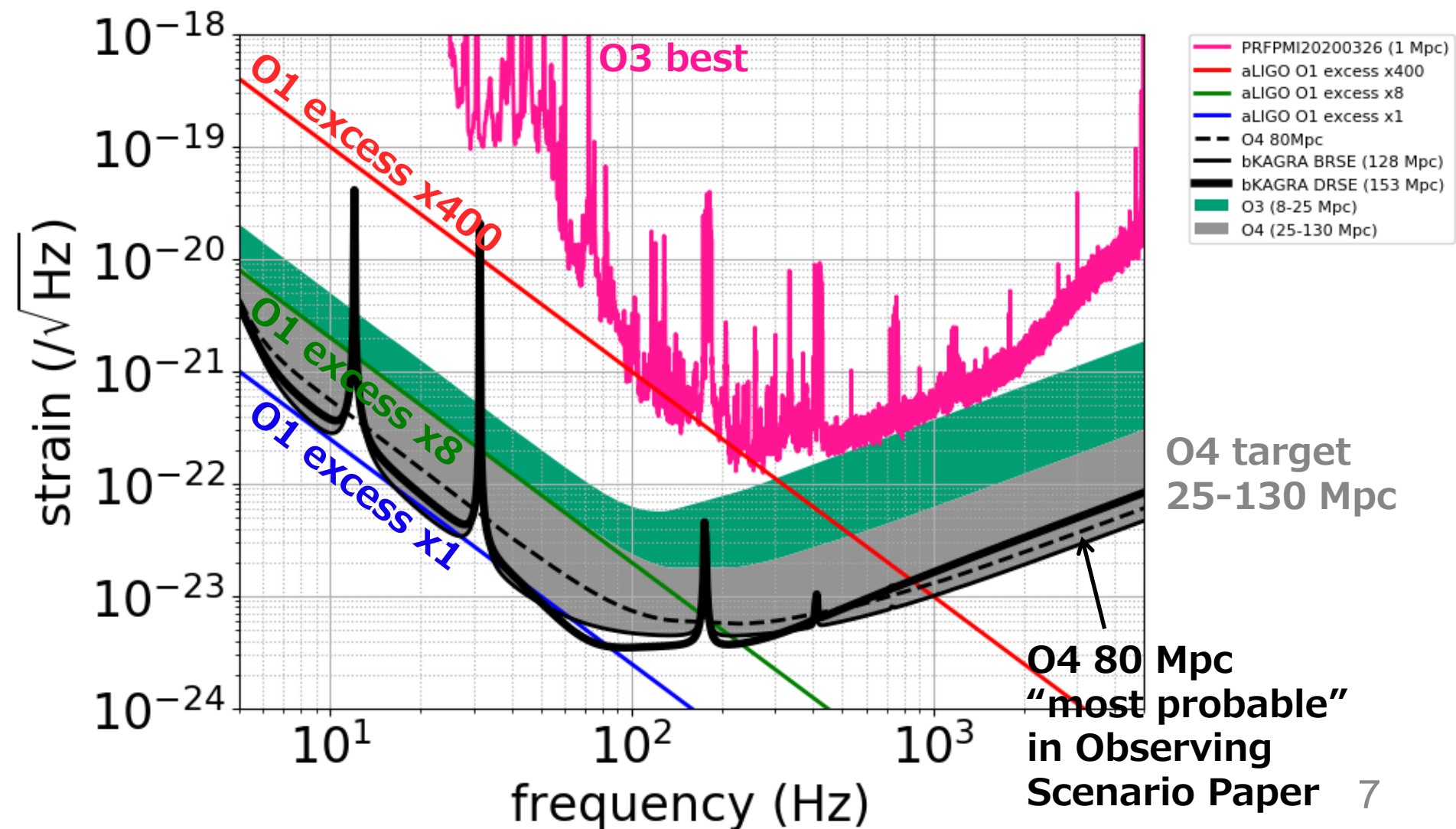
Noise Budget (for 0.6 Mpc 20200309)

- Some excess noises at mid freq, shot noise at high freq



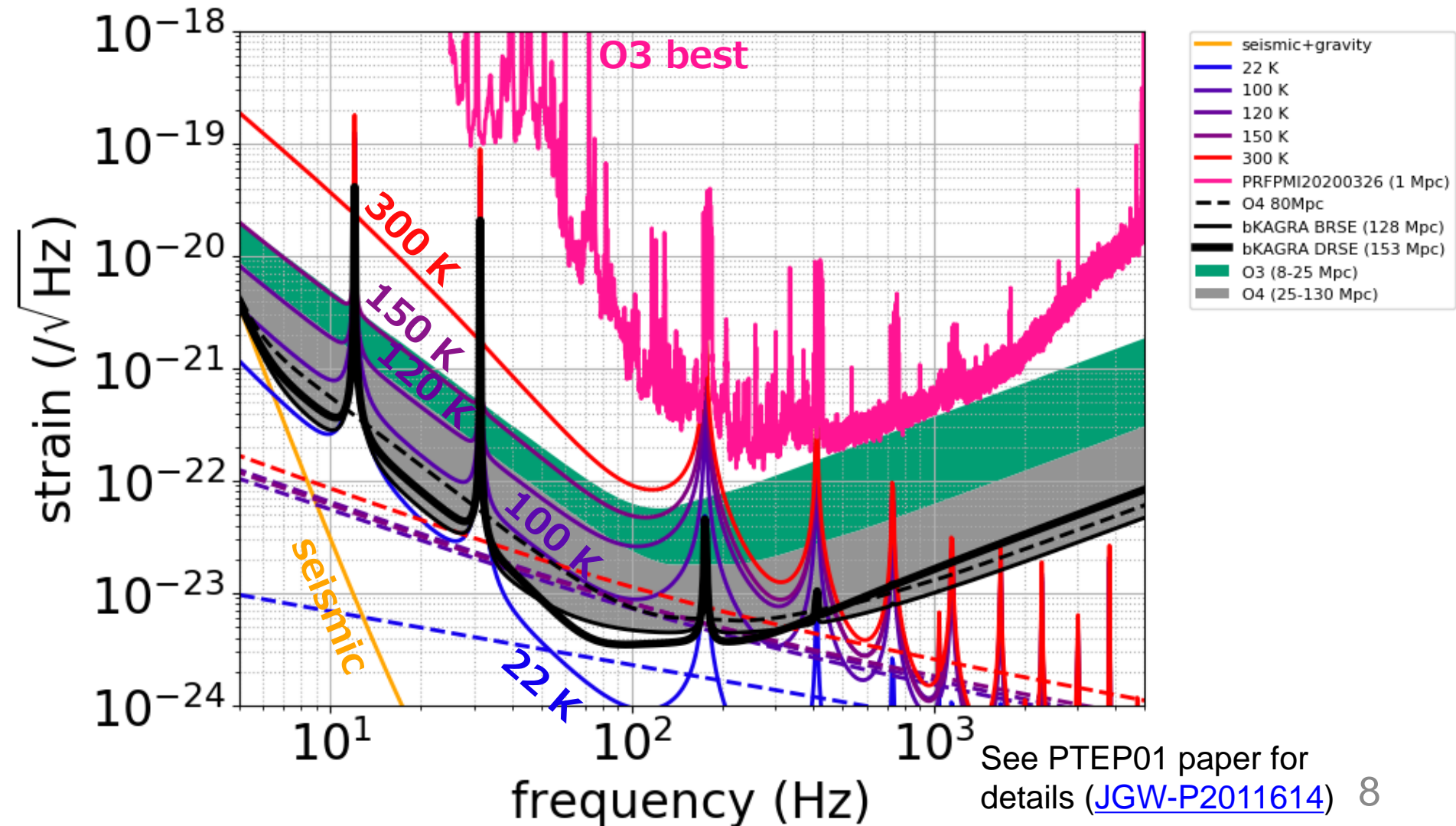
O3 best and O4 Target

- Excess noise should be reduced by at least $\sim 1/20$



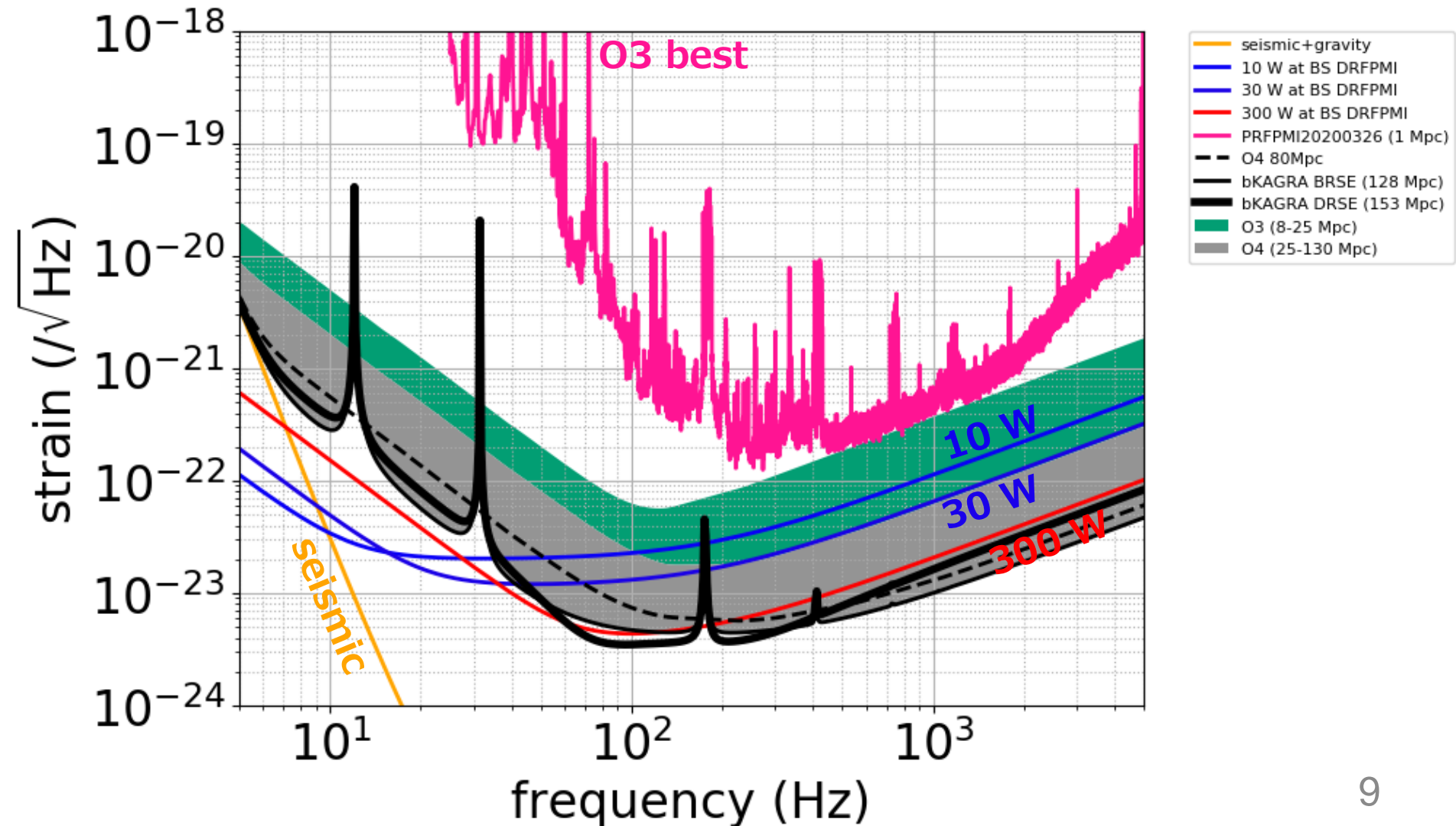
Various Thermal Noise

- 120 K thermal is comparable to x8 O1



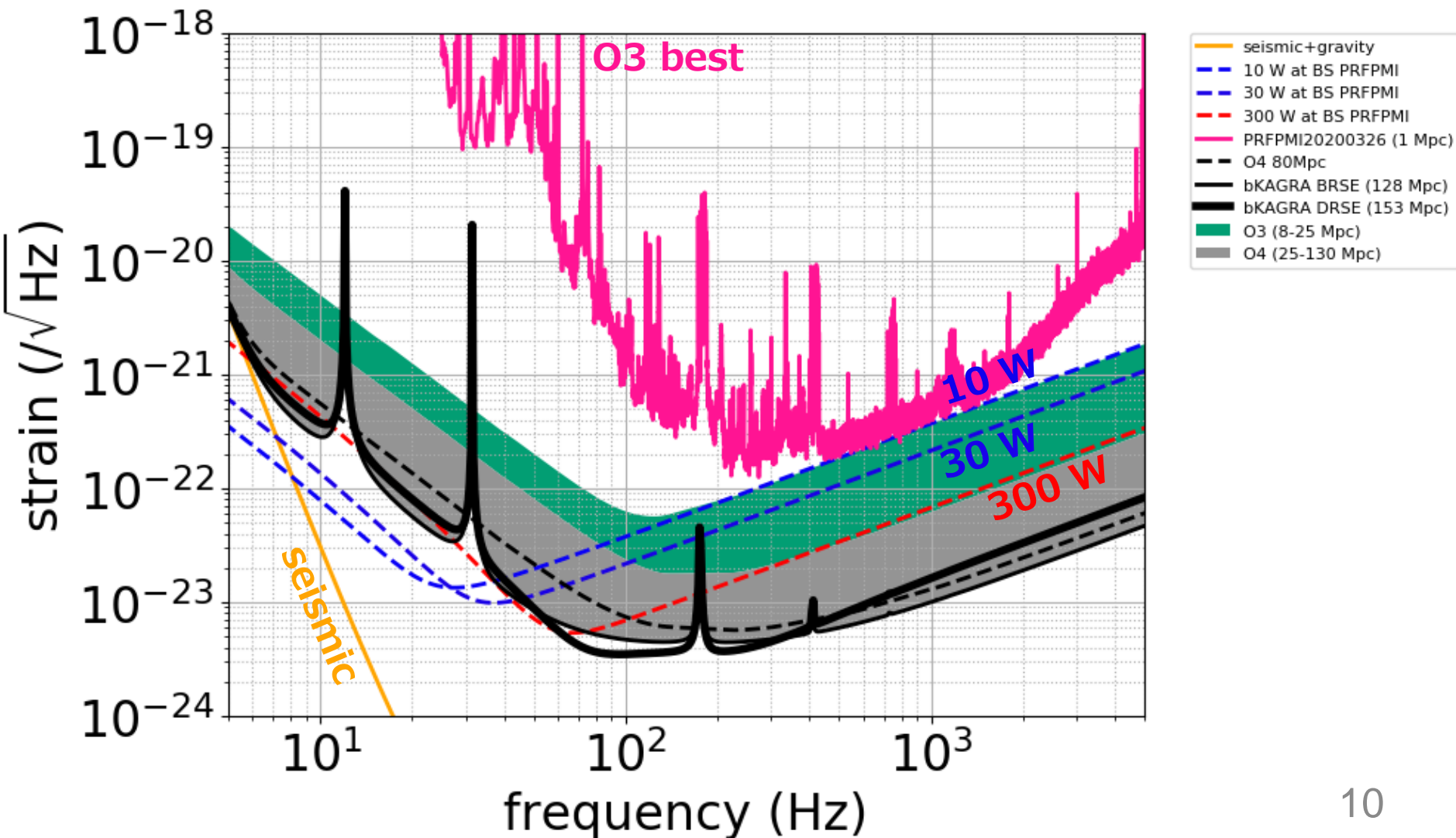
Various Quantum Noise (DR)

- 30 W at BS would be OK



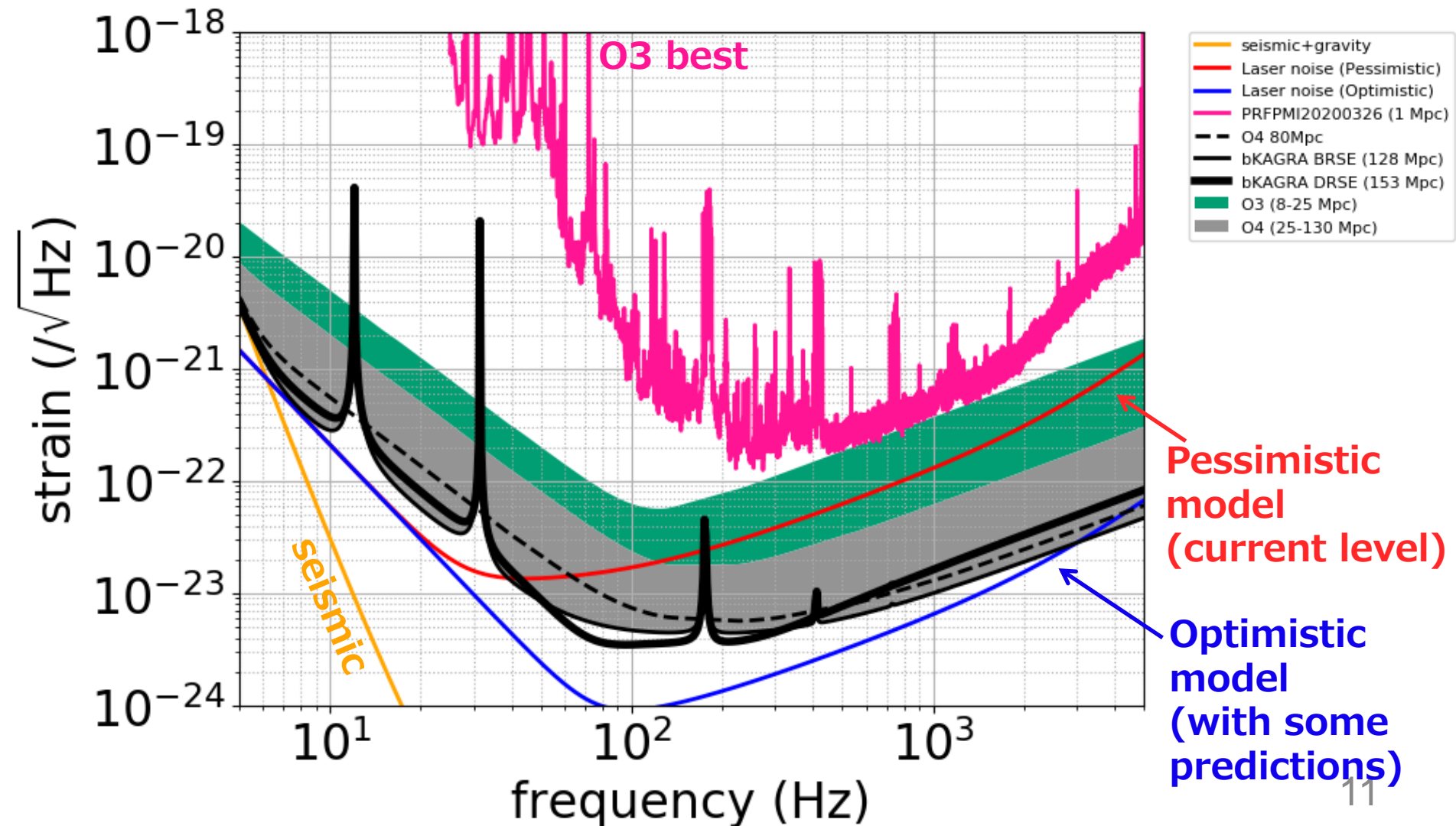
Various Quantum Noise (PR)

- DR necessary if excess noise is more than x8 O1



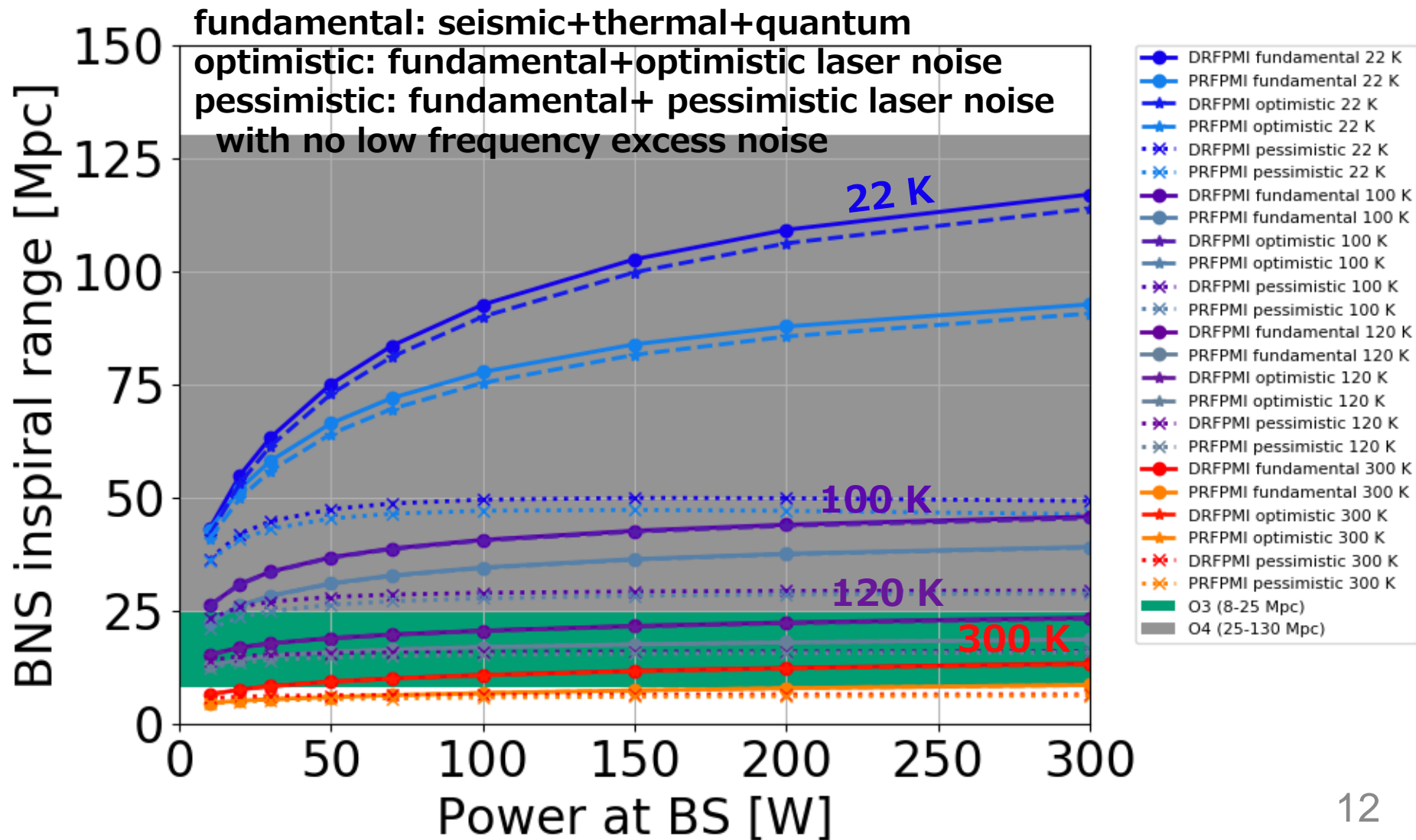
Laser Noises (Frequency + Intensity)

- Hard to predict; see “Details” attached for details



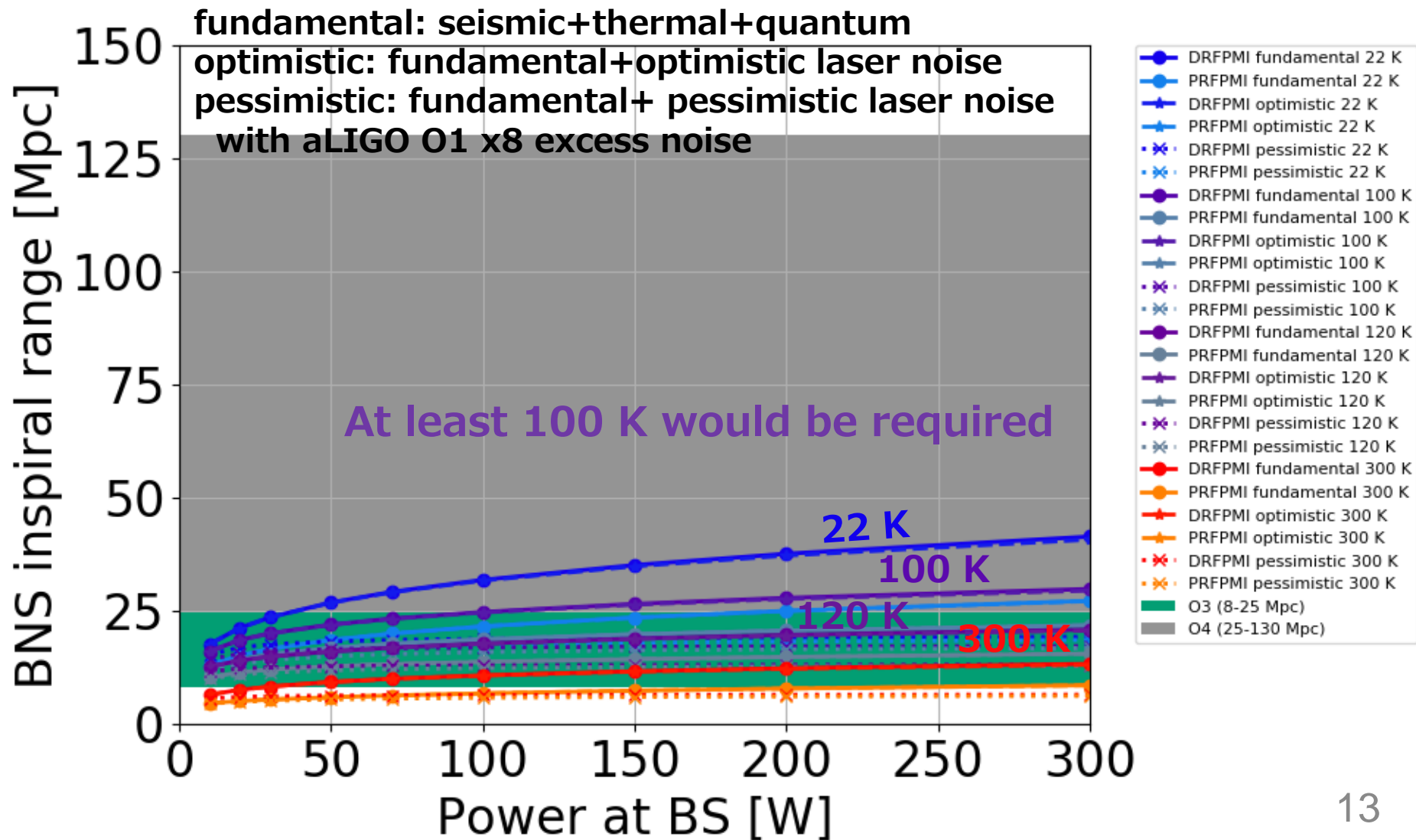
Inspiral Range vs Power (x0 O1)

- Power change not so significant with other noises



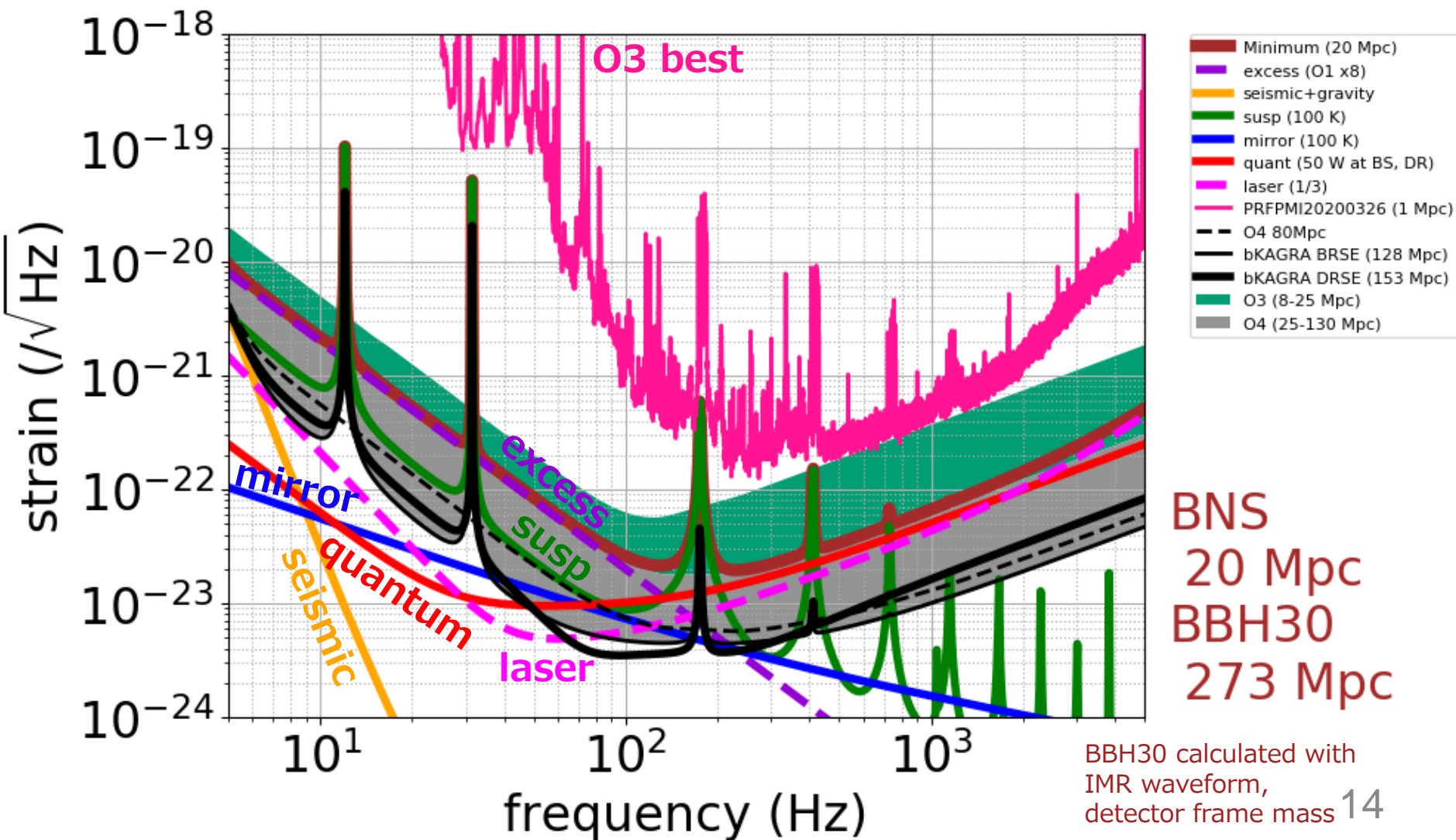
Inspiral Range vs Power (x8 O1)

- Power change not so significant with other noises



O4 "Minimum" Example

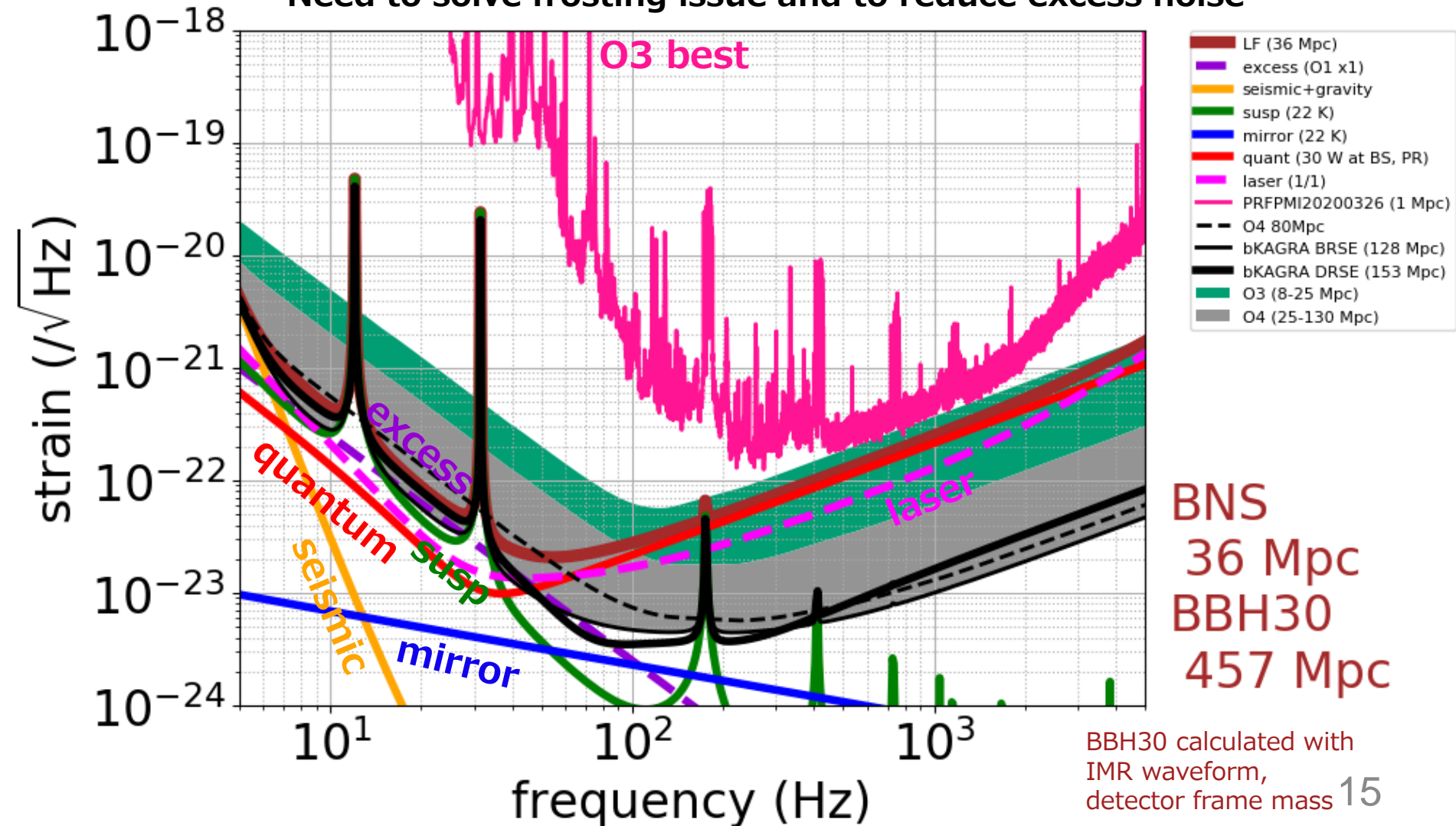
- x8 O1, 100 K, 50 W at BS, DR, 1/3 laser noise



O4 “Low Frequency” Example

- x1 O1, 22 K, 30 W at BS, PR, same laser noise

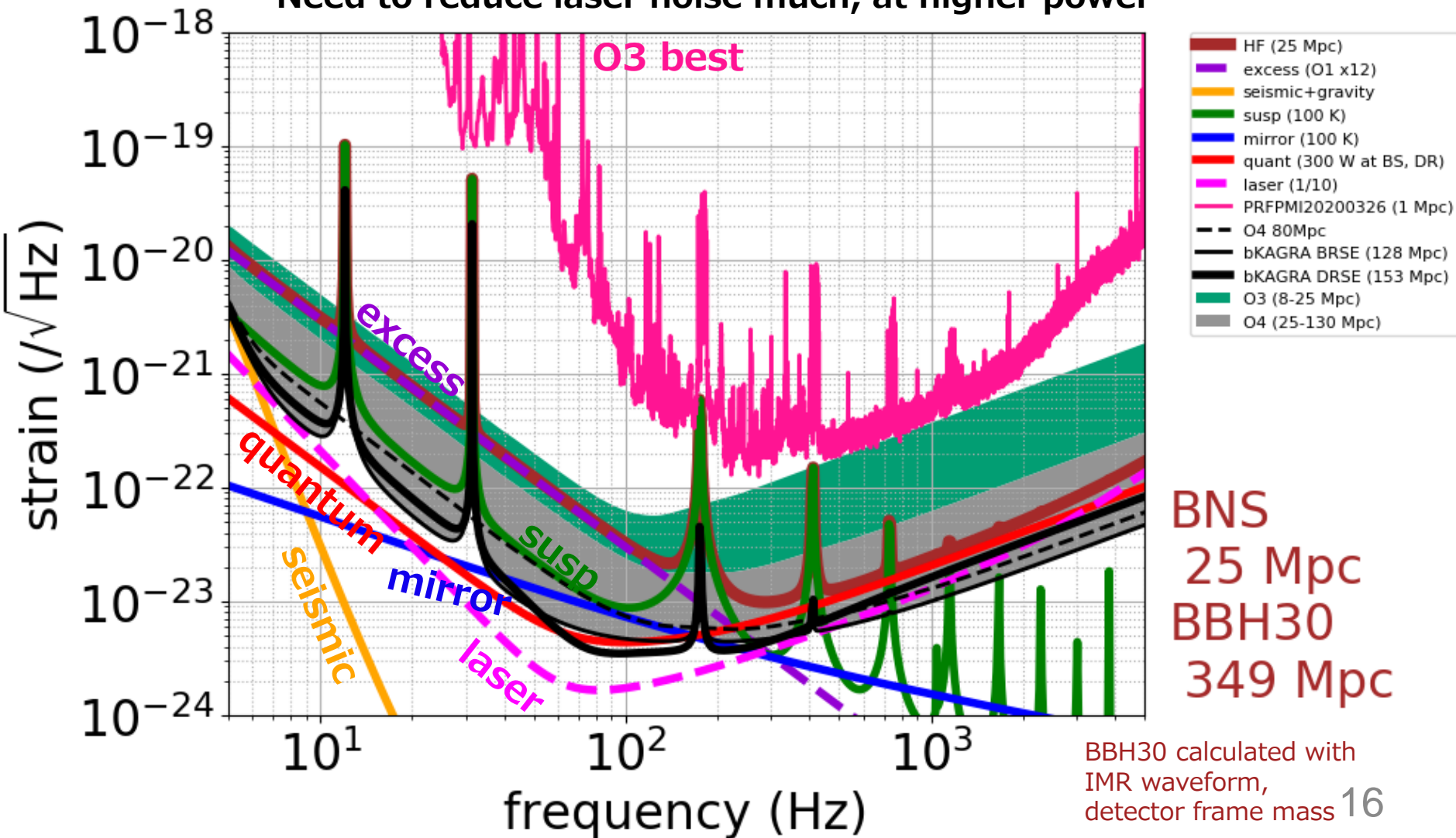
Need to solve frosting issue and to reduce excess noise



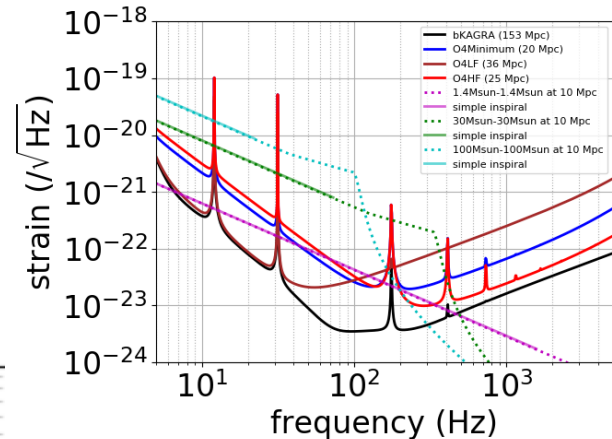
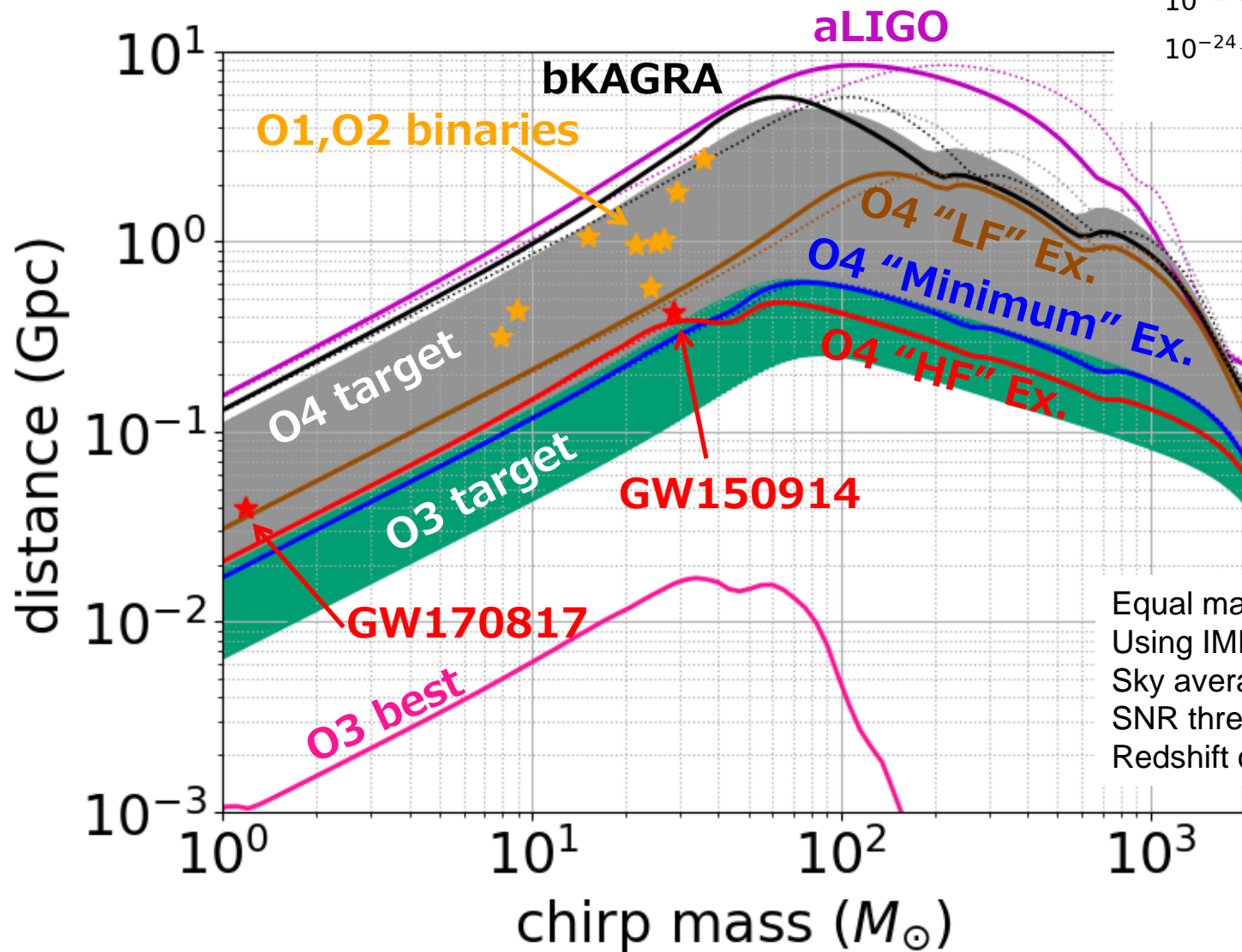
O4 “High Frequency” Example

- x12 O1, 100 K, 300 W at BS, DR, 1/10 laser noise

Need to reduce laser noise much, at higher power



Inspiral Range (IMR)



The ratio between BNS range and BBH30 range is almost constant for different sensitivity curves since the bucket is at ~ 100 Hz

Equal mass binary of spin 0.5-0.5
 Using IMR waveform
 Sky averaged (0.442)
 SNR threshold 8
 Redshift corrected

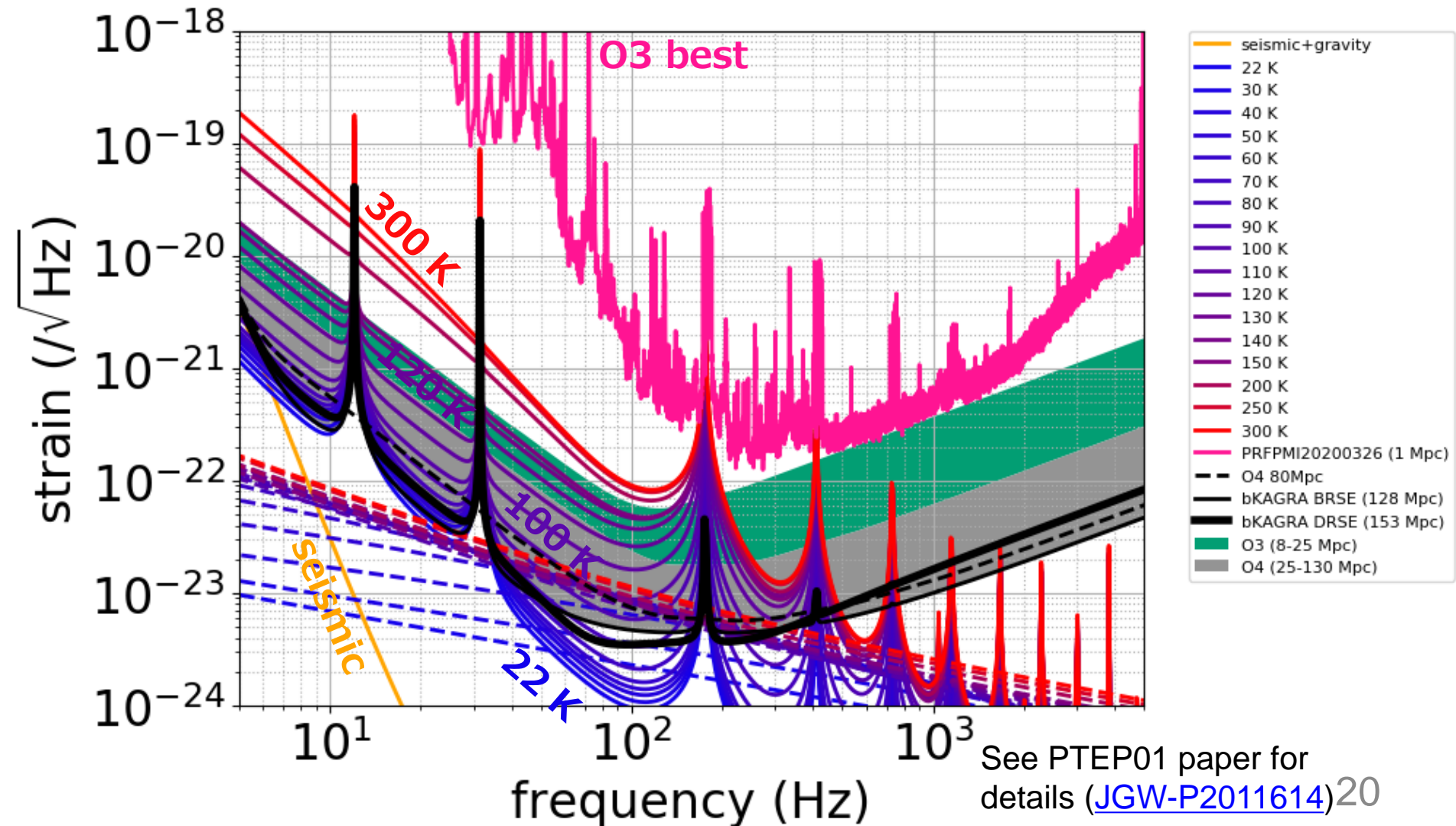
Conclusions So Far

- Should be **below ~100 K** (achieving O4 target **above 120 K is not possible**)
- Low-mid frequency noise should be reduced at least by a factor of **~20** (more at low frequencies)
- **DR necessary** if excess noise is more than x8 O1
- Higher power is better, but not so important especially when other noises are high (**~30 W at BS could be enough**)
- **Laser noise should be reduced** (by subtraction, better alignment, further stabilization etc.)
- *As we have been keep saying, investigations on current noises and noise coupling mechanisms are very important (low frequency noise; laser intensity and frequency noise) for estimating the sensitivity in O4*

Details

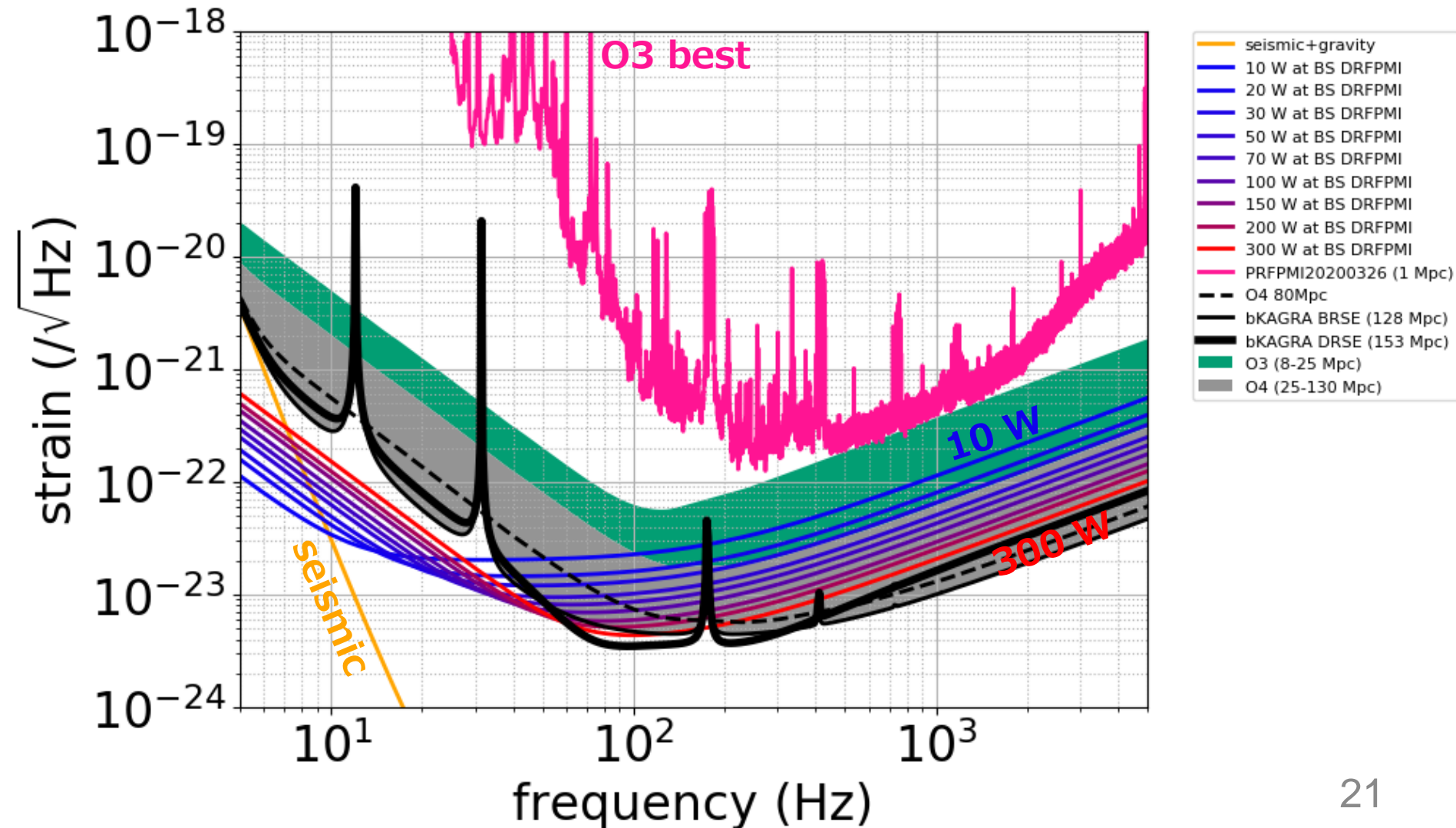
Various Thermal Noise

- All temperatures



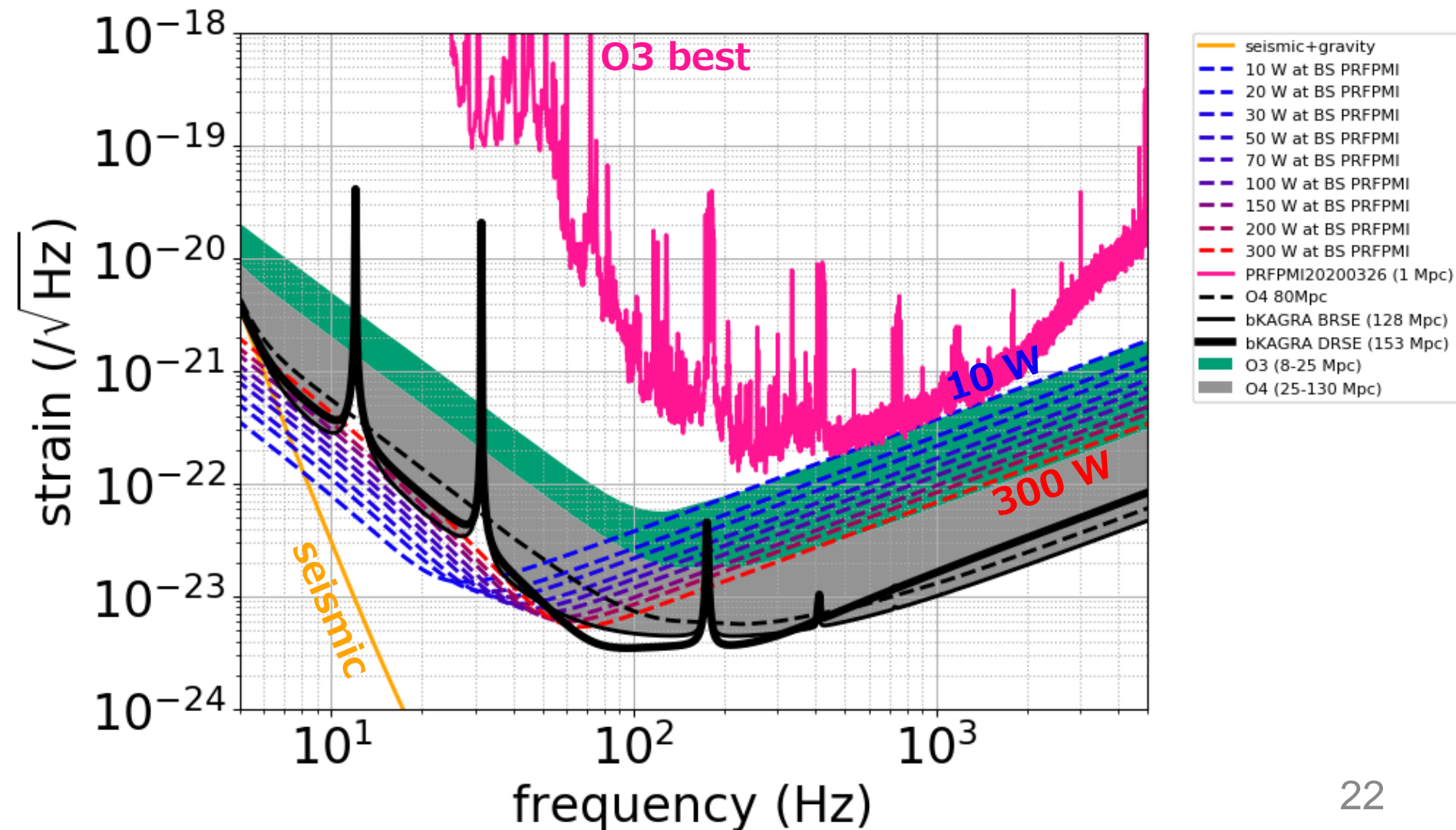
Various Quantum Noise (DR)

- All powers



Various Quantum Noise (PR)

- All powers



How to Realize 100 K ?

- **Possible cooling process?**

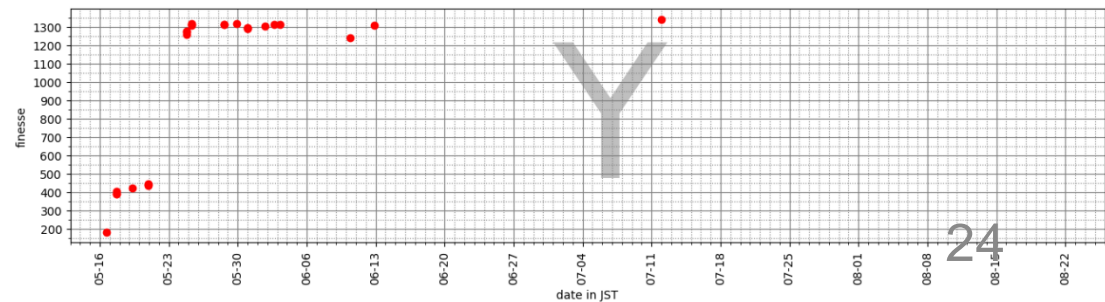
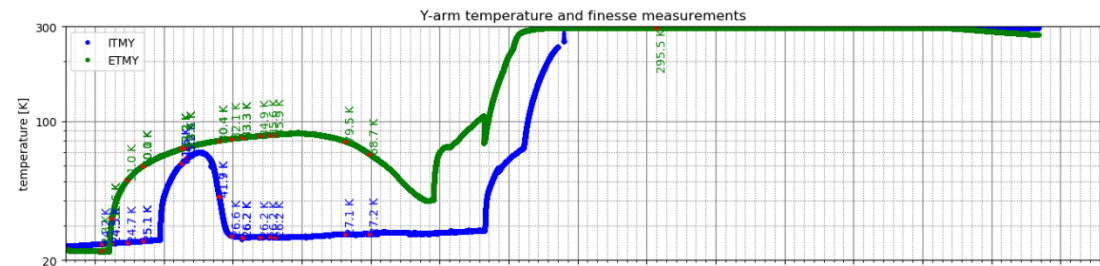
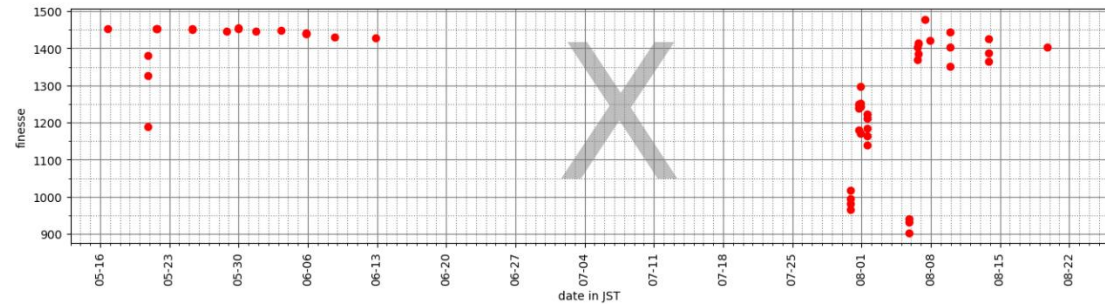
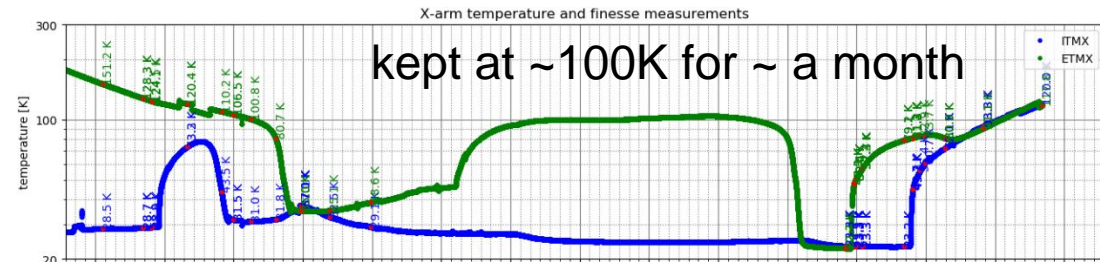
- First cool the test mass with four cryocooler
- When reached below ~ 100 K, turn off two cryocoolers for cryopayload (shields have to be kept cooled); as we have done in July 2019, we can keep the temperature at ~ 100 K (klog [#10033](#))
- Turn on two cryocoolers occasionally to keep the temperature ~ 100 K

- **Maximum input power?**

- Thermal lensing: At 100 K, thermal lensing is smaller by $1/100 \sim 1/300$ than 300 K, but larger by 4 orders of magnitude than 20 K. Thermal lensing would be OK below ~ 130 K (See [JPCS 32, 062 \(2006\)](#)).
- Cooling power (with 4 cryocoolers): 67 K can be achievable with 0.8 W heat load to the test mass, with current thermal resistance of 70 K/W (according to [JGW-G1910569](#)). < 300 W at BS would be OK.
- Cooling power (with 2 cryocoolers): According to the cooling curve from bKAGRA Phase 1 (7 K/day at around 100 K), 0.2 W heat load makes the mirror temperature at steady state (around 100 K, thermal conductivity of sapphire fibers are low). Absorption from light will be $\sim 0.001 \cdot P_{BS}$ where P_{BS} is the power at BS. Therefore, $P_{BS} = 200$ W is good to keep ~ 100 K.

Frosting of the Test Mass

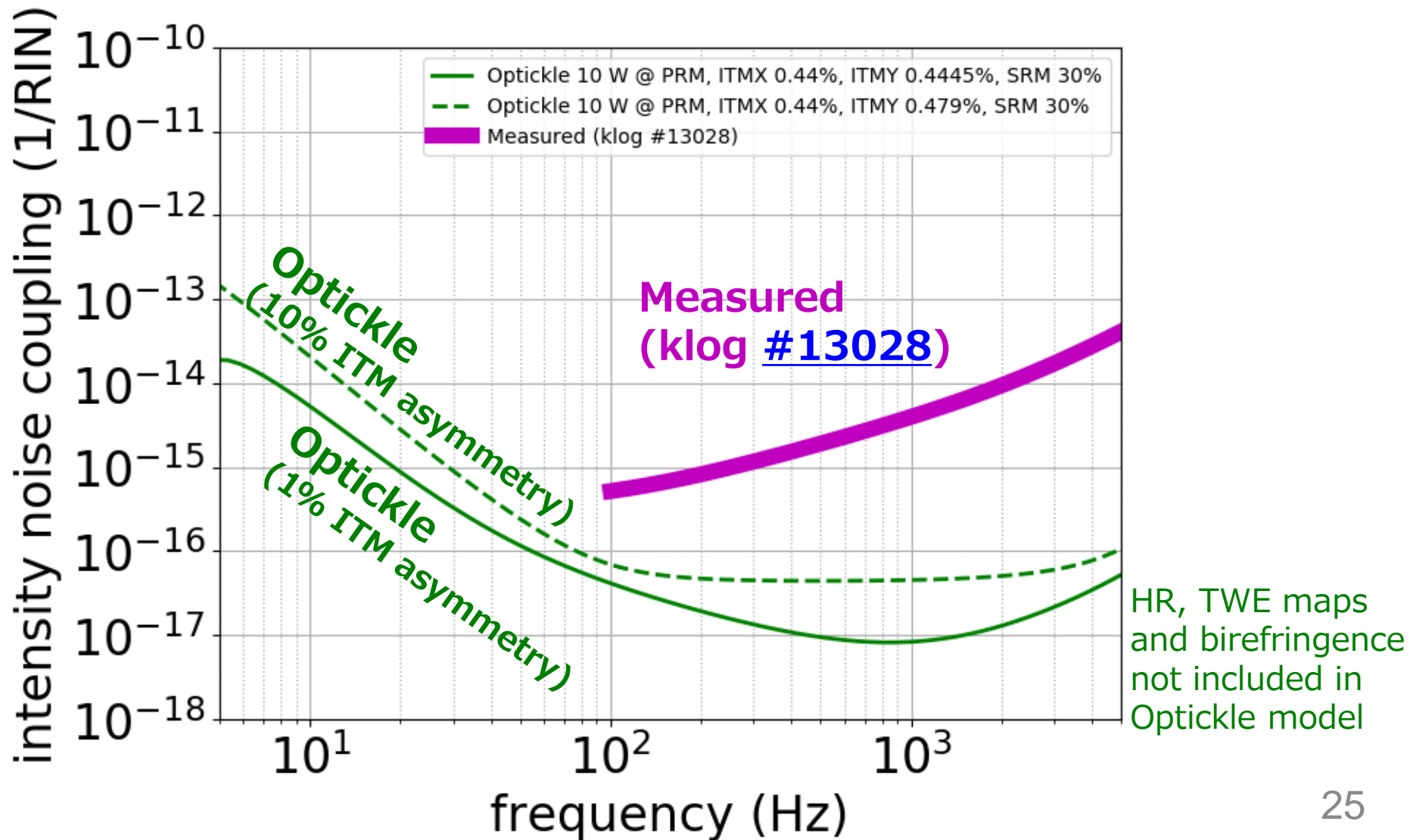
- Finesse drop observed when one of the test mass temperature is below ~ 30 K



klog [#10033](#)

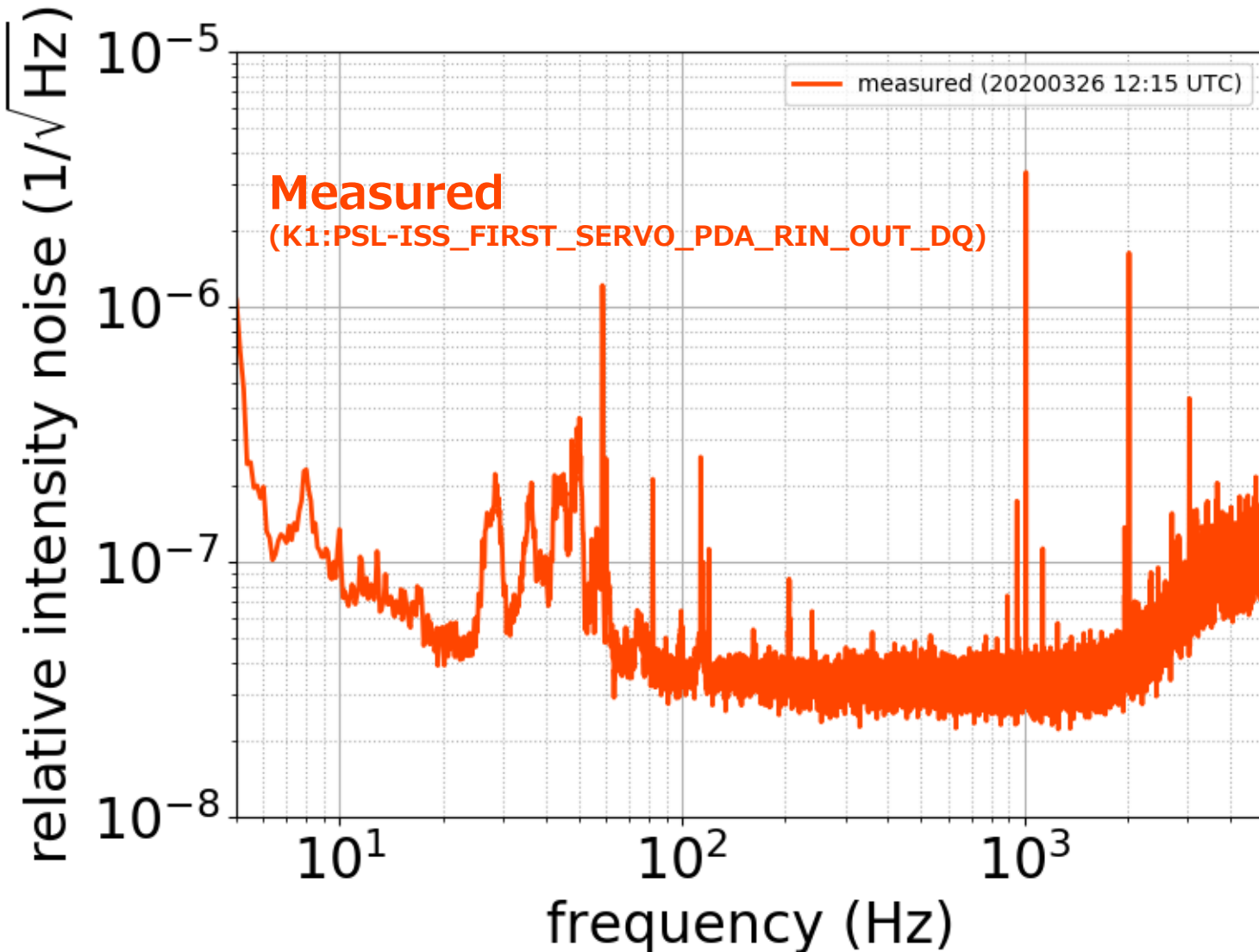
Laser Intensity Noise Coupling

- Measured to be larger than Optickle model



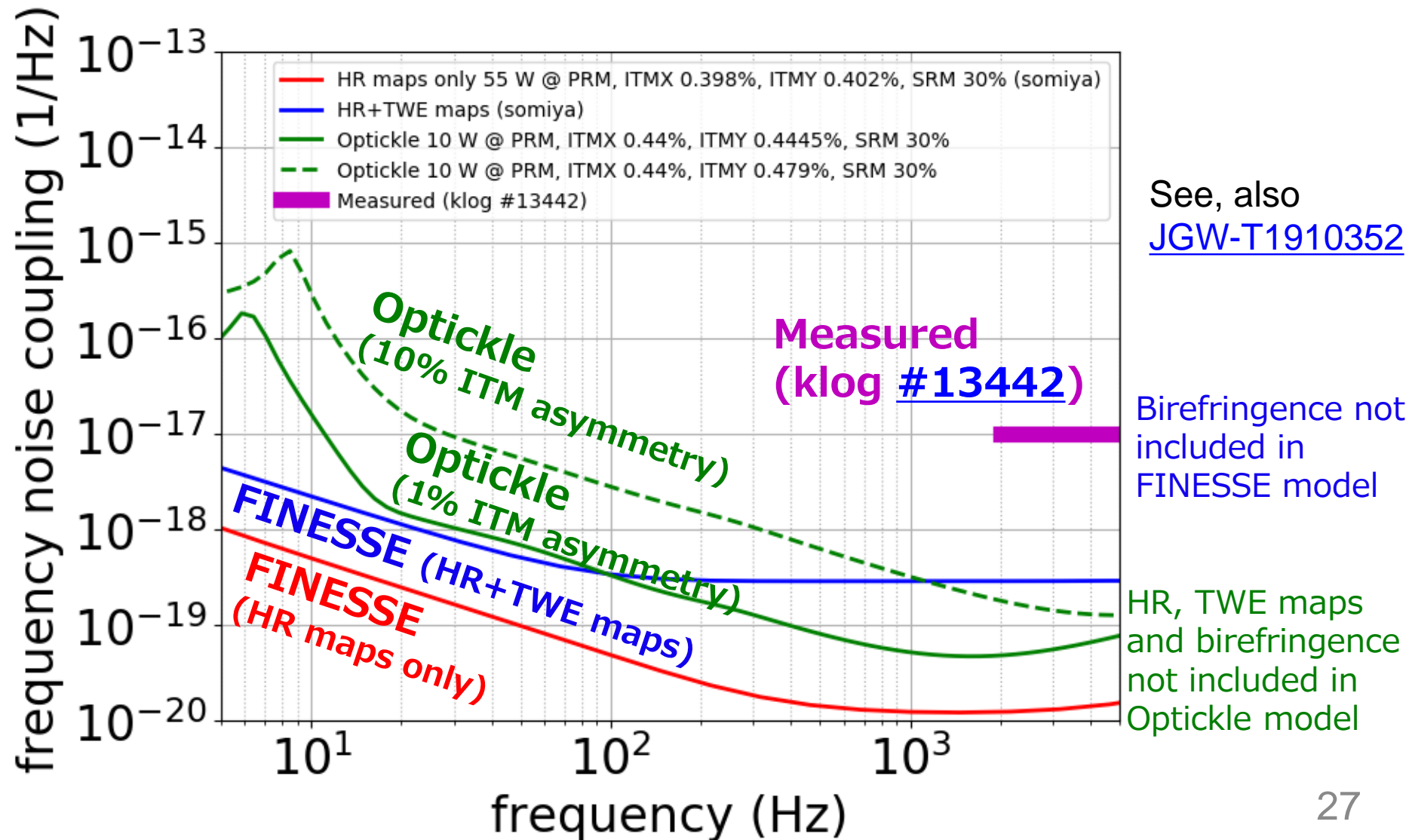
Laser Intensity Noise

- RIN of $3e-8$ /rtHz achieved. $1e-8$ /rtHz possible in O4?



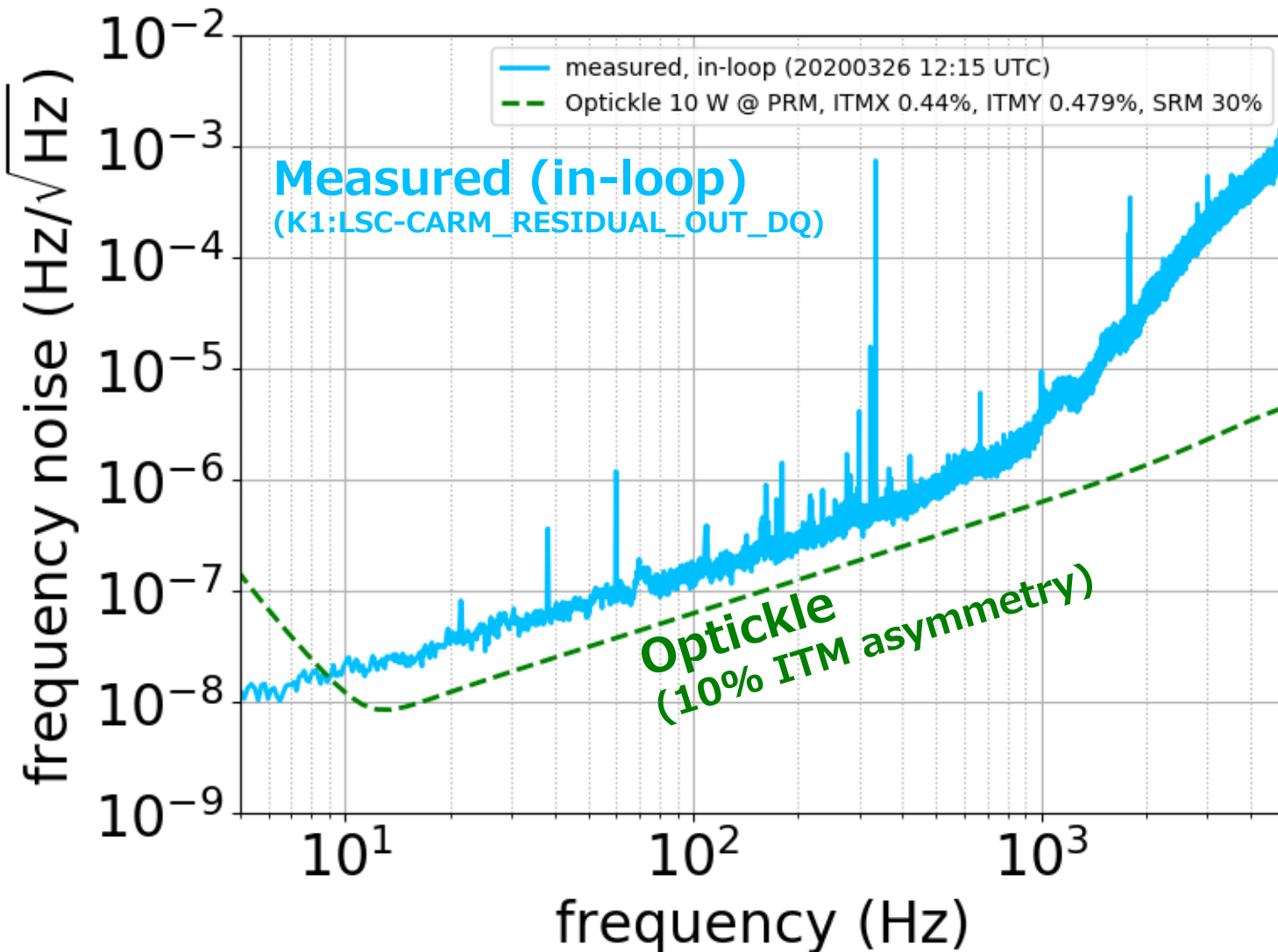
Laser Frequency Noise Coupling

- Measured to be larger than various models



Laser Frequency Noise

- Close to CARM shot noise limit from Optickle



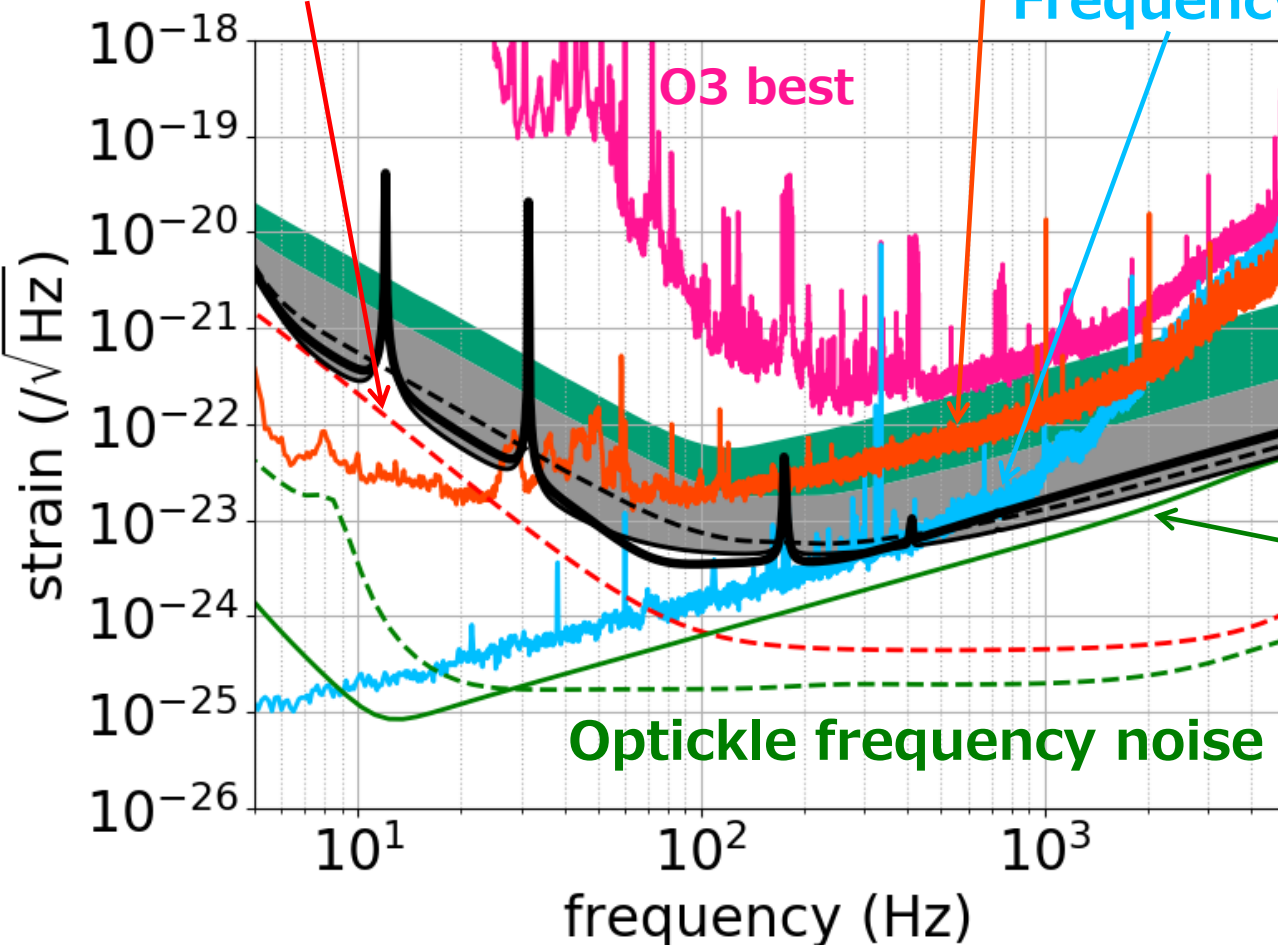
Laser Noise Projections

- Close to CARM shot noise limit from Optickle

RIN 1e-8 /rtHz
x Optickle coupling

Intensity noise projection O3

Frequency noise projection O3



- PRFPMI20200326 (1 Mpc)
- Frequency noise
- Intensity noise
- RIN 1e-8 /rtHz * Optickle coupling
- Freq. noise Optickle 10 W @ PRM, ITMX 0.44%, ITMY 0.479%, SRM 30%
- Optickle shot noise * measured coupling
- O4 80Mpc
- bKAGRA BRSE (128 Mpc)
- bKAGRA DRSE (153 Mpc)
- O3 (8-25 Mpc)
- O4 (25-130 Mpc)

Optickle shot noise
x measured
frequency noise
coupling

Guessing Laser Noise in O4

- Pessimistic case: same as current level
- Optimistic case: RIN of $1e-8$ /rtHz x Optickle coupling and CARM shot noise limited x measured coupling

