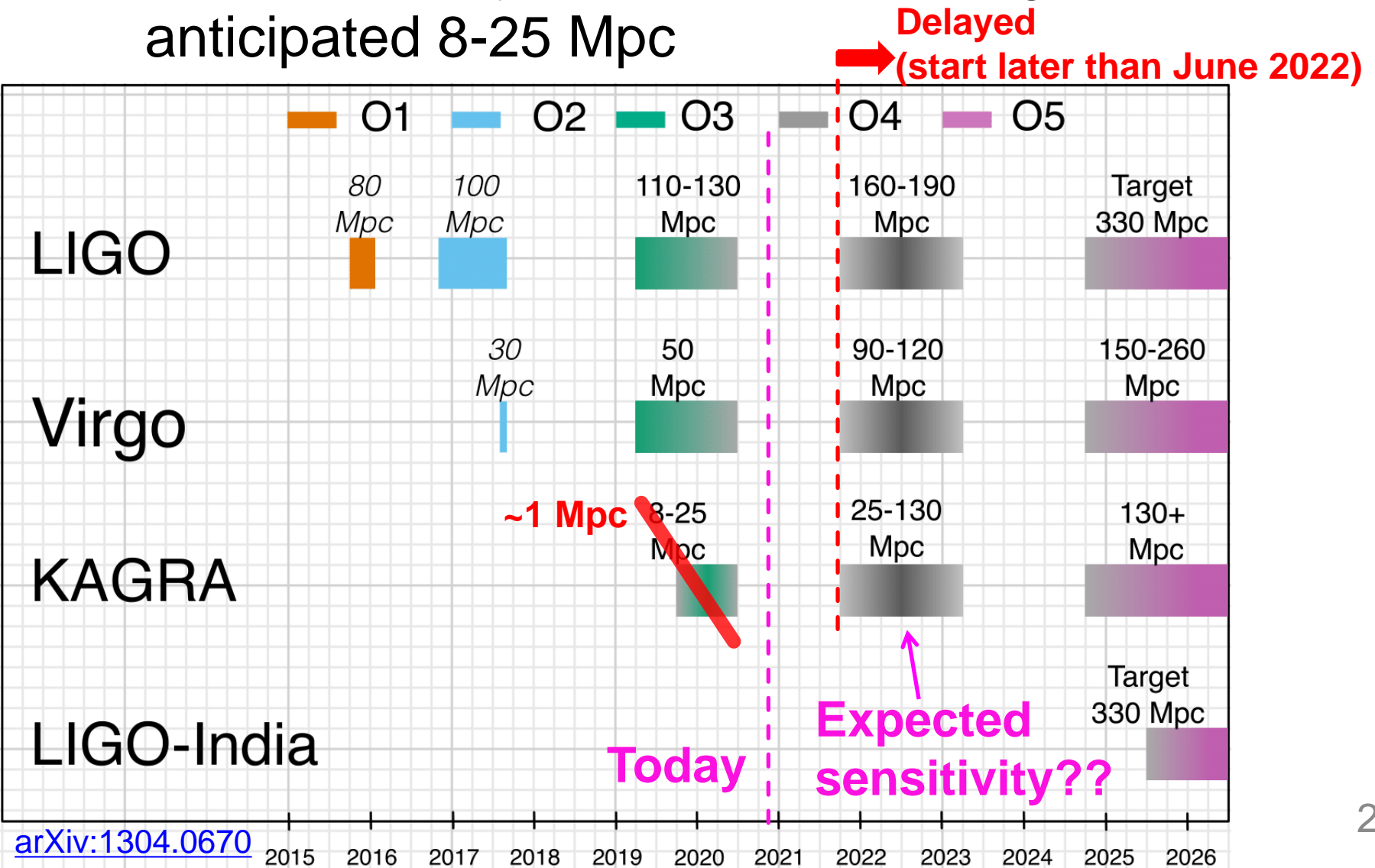December 20, 2020

Expectations for Sensitivity of KAGRA in O4
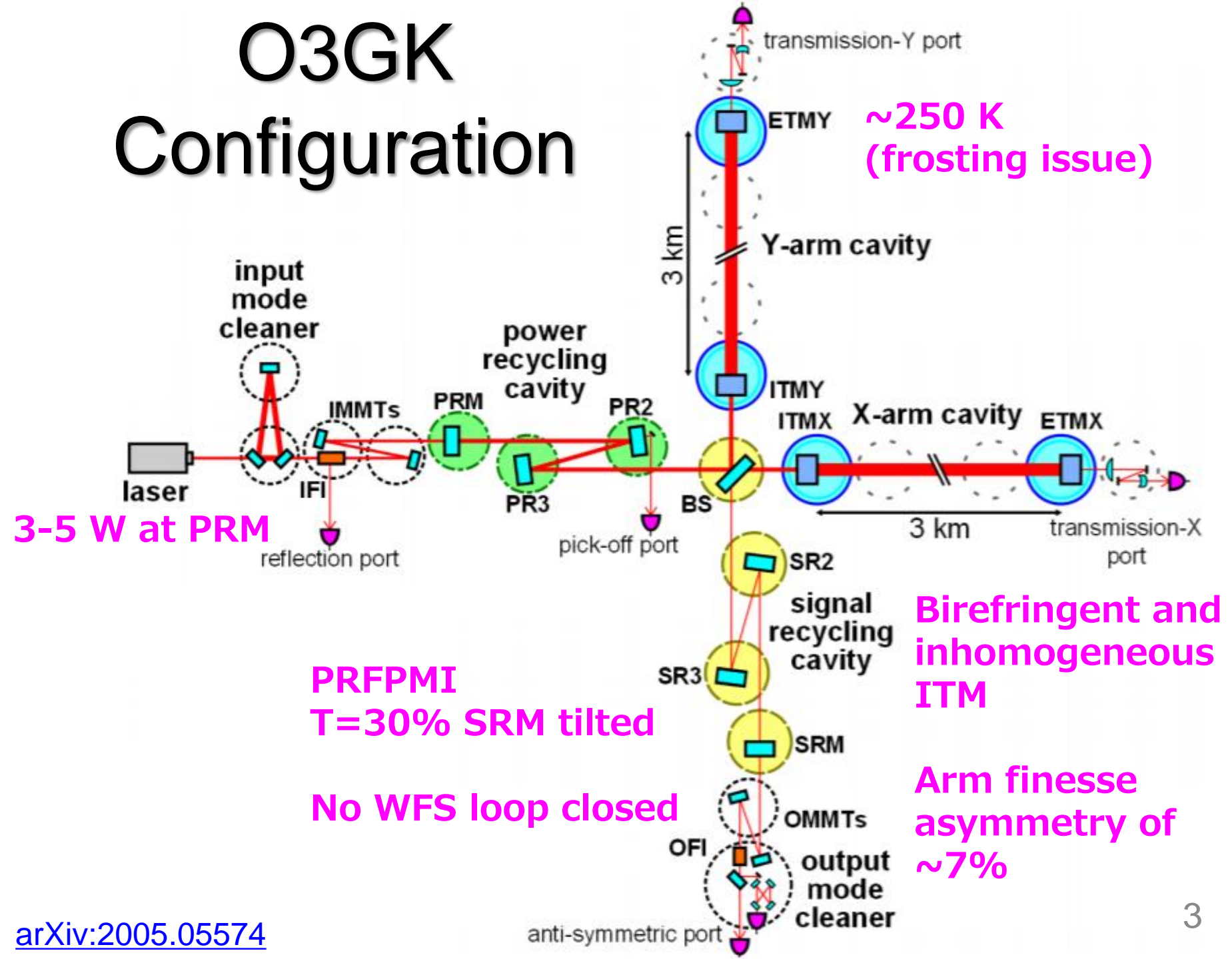
Yuta Michimura

Observing Scenario of LVK

- Best sensitivity was ~1 Mpc although we anticipated 8-25 Mpc
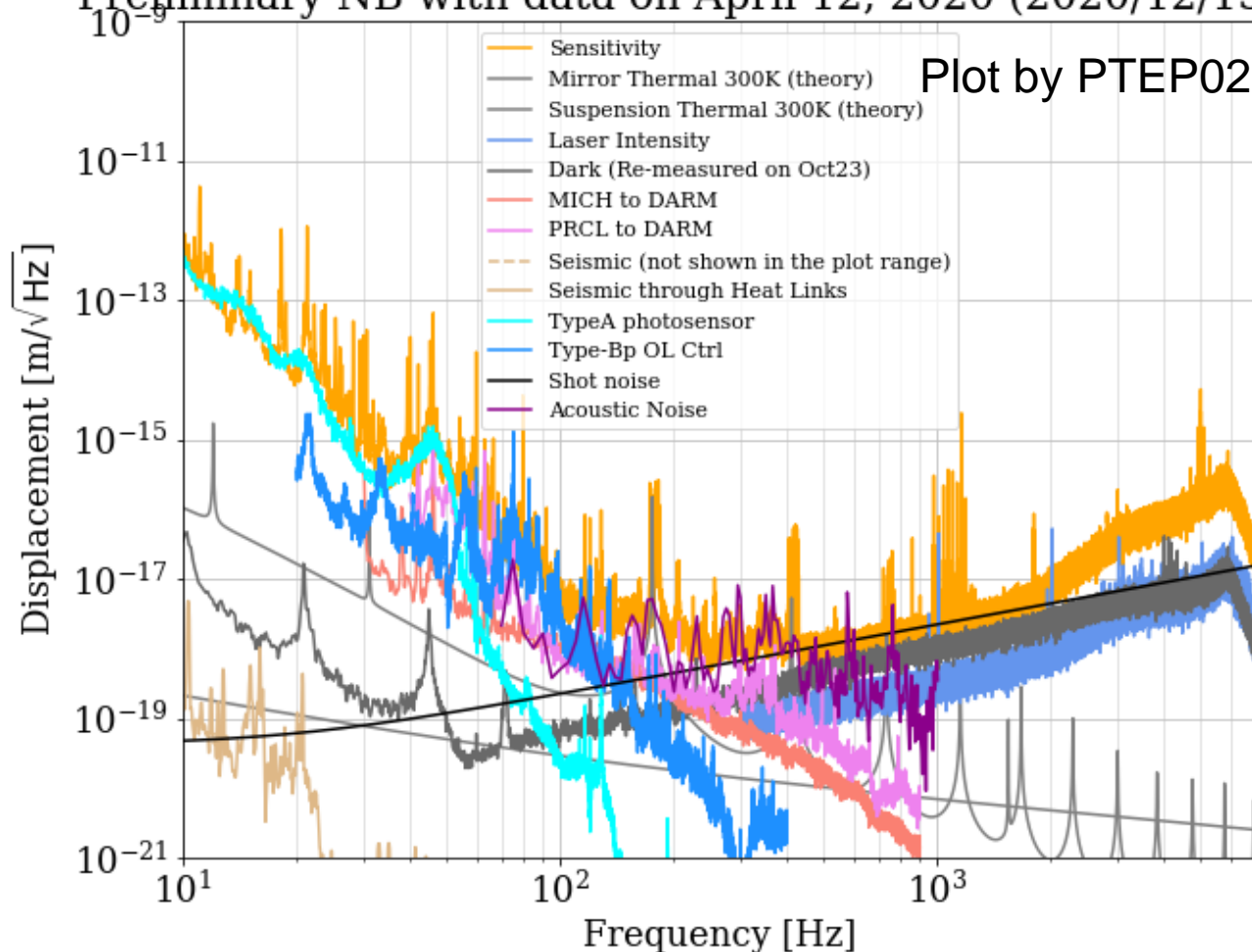
2

O3GK Configuration

~250 K
(frosting issue)

3-5 W at PRM

PRFPMI
T=30% SRM tilted

No WFS loop closed

Birefringent and inhomogeneous ITM

Arm finesse asymmetry of ~7%

arXiv:2005.05574

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O3GK Noise Budget

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)

Plot by PTEP02 paper team

O3GK Noise Budget

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)

Plot by PTEP02 paper team

Test mass suspension (Type-A) damping noise

Shot noise

Laser noises

Suspension thermal noise

Acoustic noise

Coupling from auxiliary degrees of freedom

Legend:
- Sensitivity
- Mirror Thermal 300K (theory)
- Suspension Thermal 300K (theory)
- Laser Intensity
- Dark (Re-measured on Oct23)
- MICH to DARM
- PRCL to DARM
- Seismic (not shown in the plot range)
- Seismic through Heat Links
- TypeA photosensor
- Type-Bp OL Ctrl
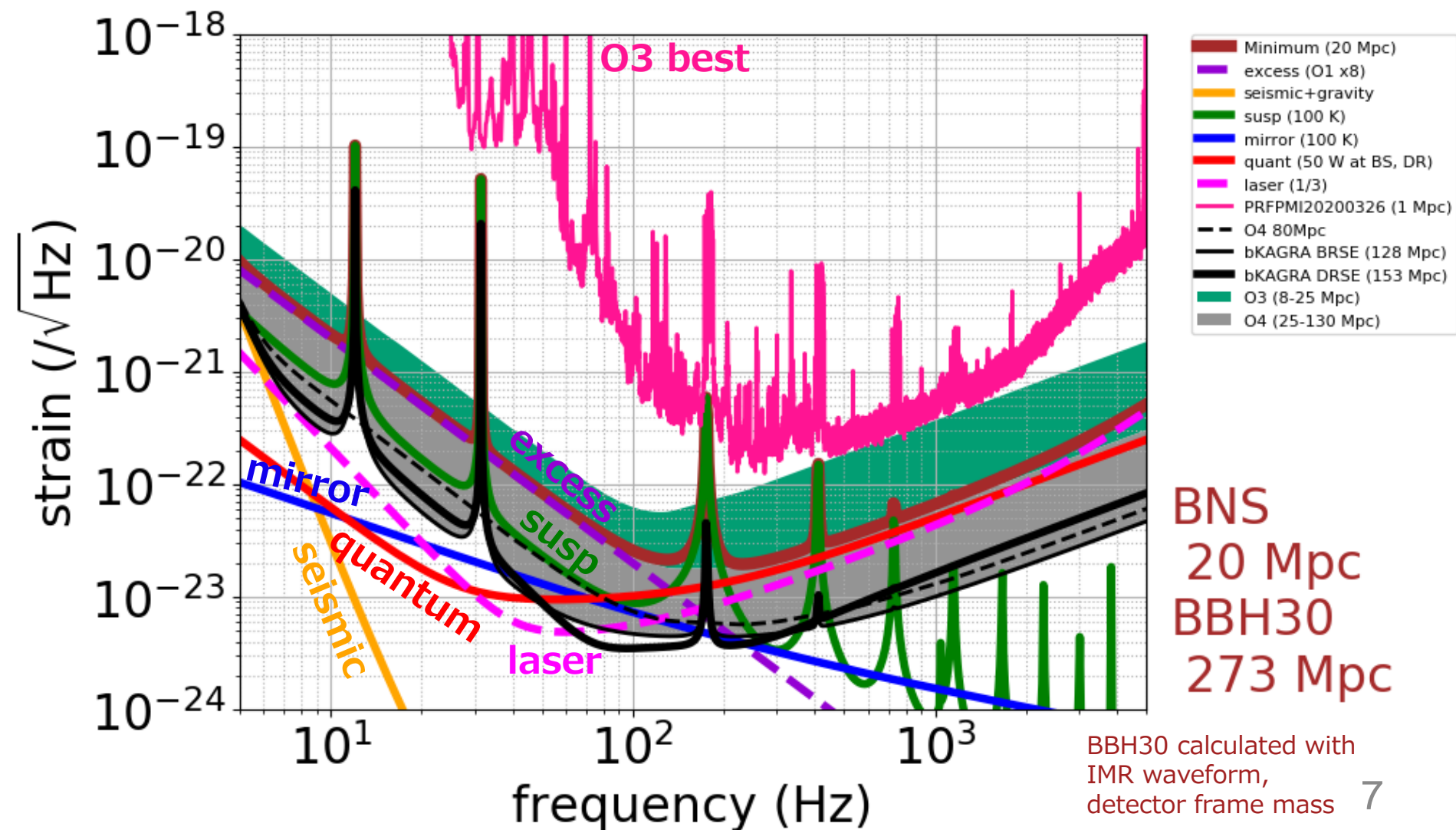- Shot noise
- Acoustic Noise

Displacement [m/√Hz] vs Frequency [Hz]
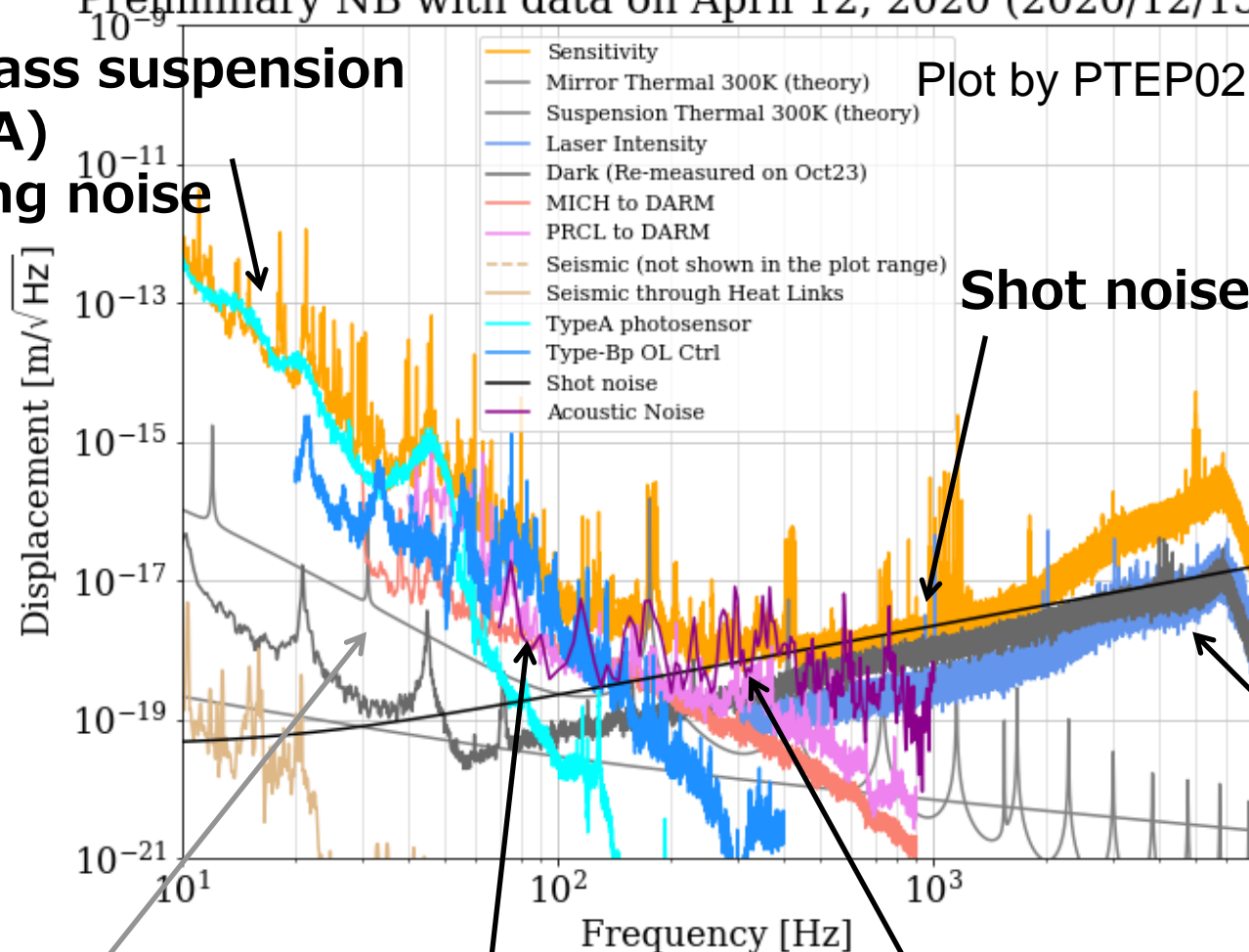
O4 Target

- We need to reduce excess noise at ~100 Hz at least by a factor of 50
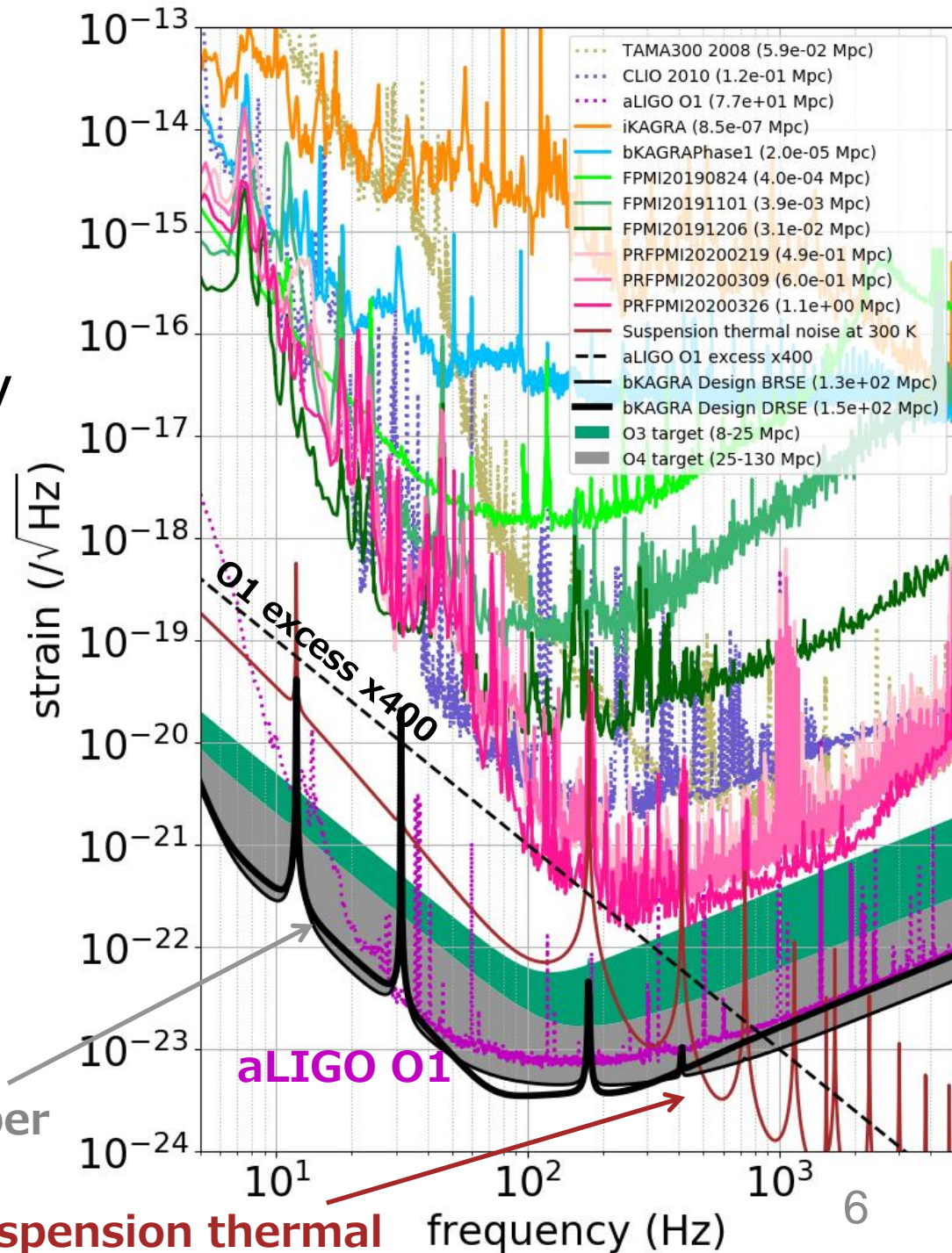
O4 target on Obs. Scenario Paper
25-130 Mpc

300 K suspension thermal

Legend:
- TAMA300 2008 (5.9e-02 Mpc)
- CLIO 2010 (1.2e-01 Mpc)
- aLIGO O1 (7.7e+01 Mpc)
- iKAGRA (8.5e-07 Mpc)
- bKAGRAPhase1 (2.0e-05 Mpc)
- FPMI20190824 (4.0e-04 Mpc)
- FPMI20191101 (3.9e-03 Mpc)
- FPMI20191206 (3.1e-02 Mpc)
- PRFPMI20200219 (4.9e-01 Mpc)
- PRFPMI20200309 (6.0e-01 Mpc)
- PRFPMI20200326 (1.1e+00 Mpc)
- Suspension thermal noise at 300 K
- aLIGO O1 excess x400
- bKAGRA Design BRSE (1.3e+02 Mpc)
- bKAGRA Design DRSE (1.5e+02 Mpc)
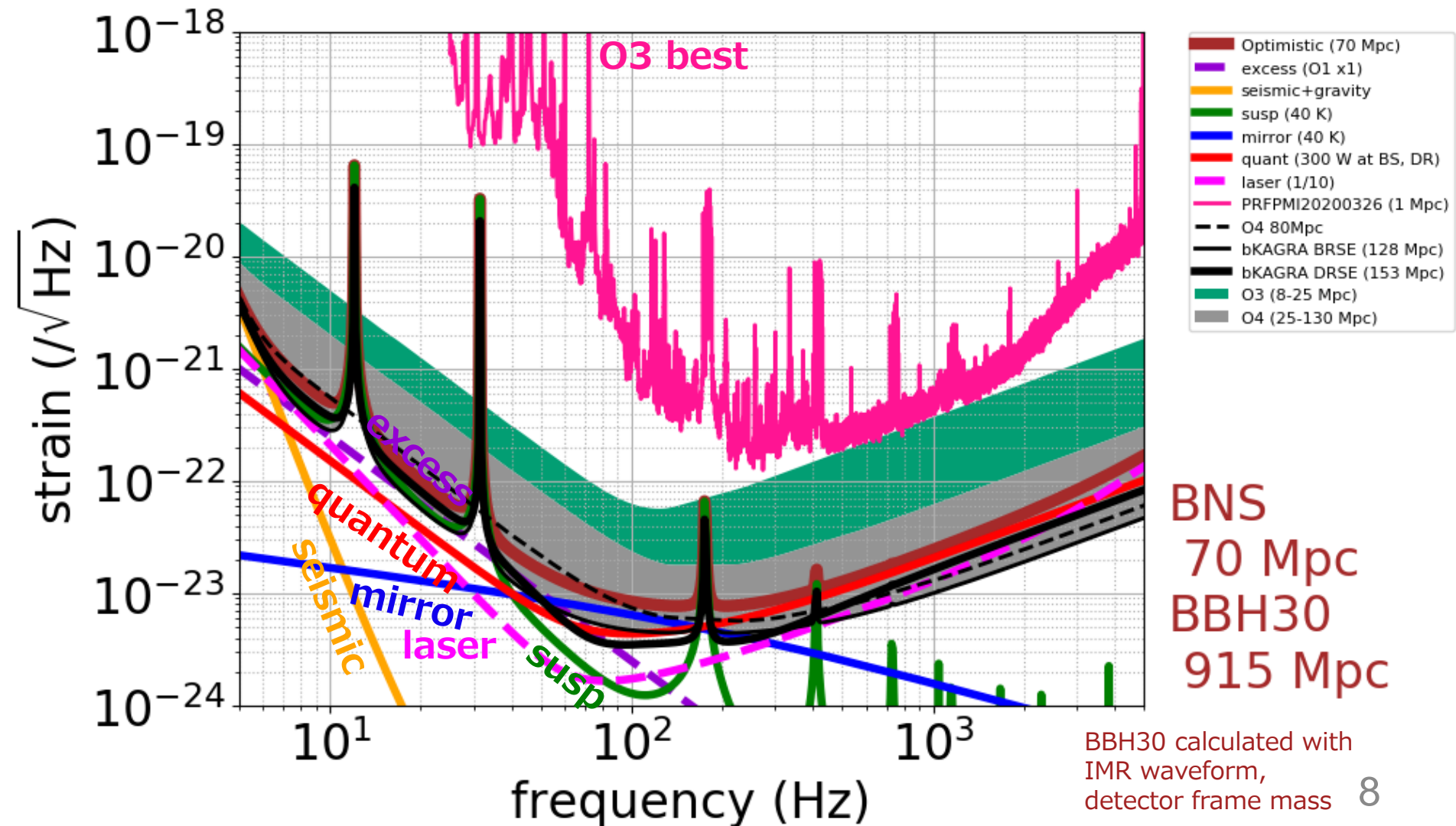- O3 target (8-25 Mpc)
- O4 target (25-130 Mpc)

O4 "Minimum" Example

- 1/40 excess, 100 K, 50 W at BS, DR, 1/3 laser noise

O4 "Optimistic" Example

- 1/400 excess, 40 K, 300 W at BS, DR, 1/10 laser noise
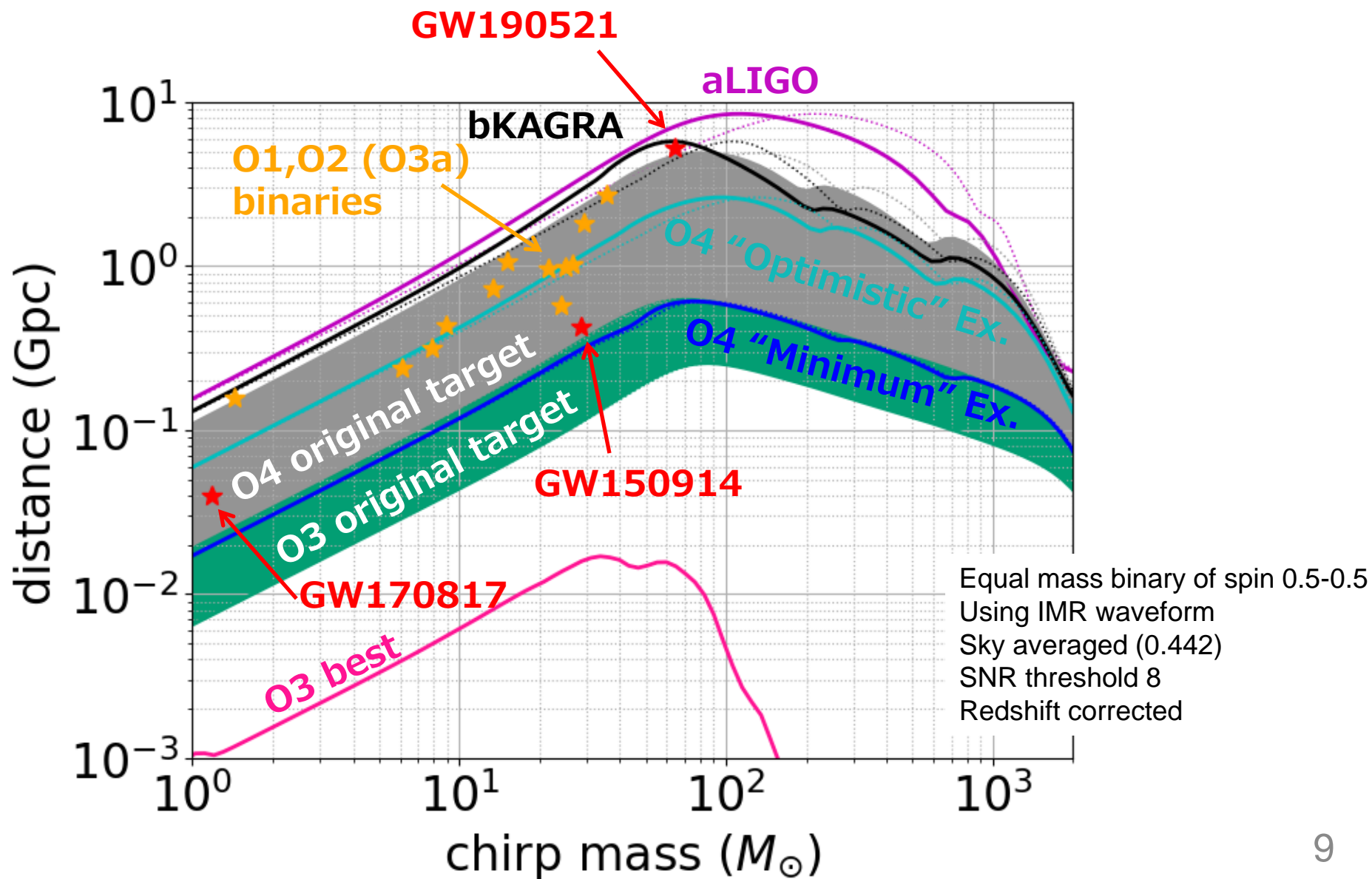
BBH30 calculated with IMR waveform, detector frame mass

Inspiral Range

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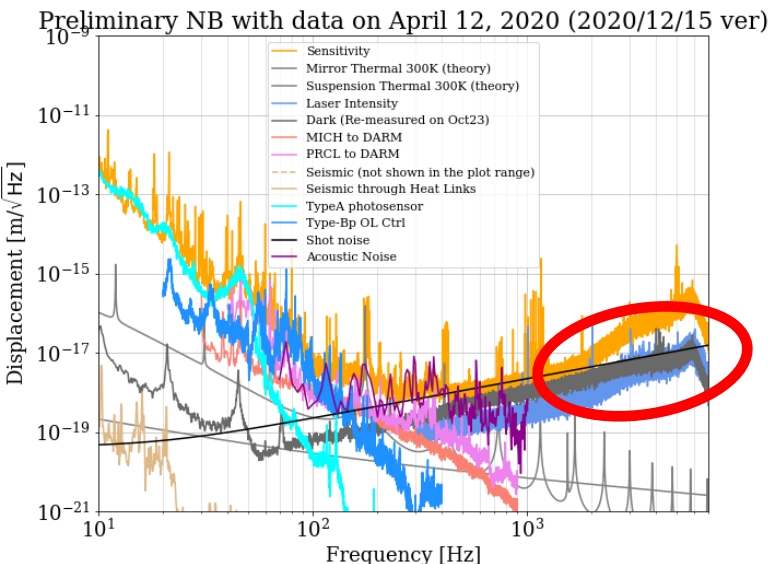SNR threshold 8
Redshift corrected

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Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
- Thermal noise
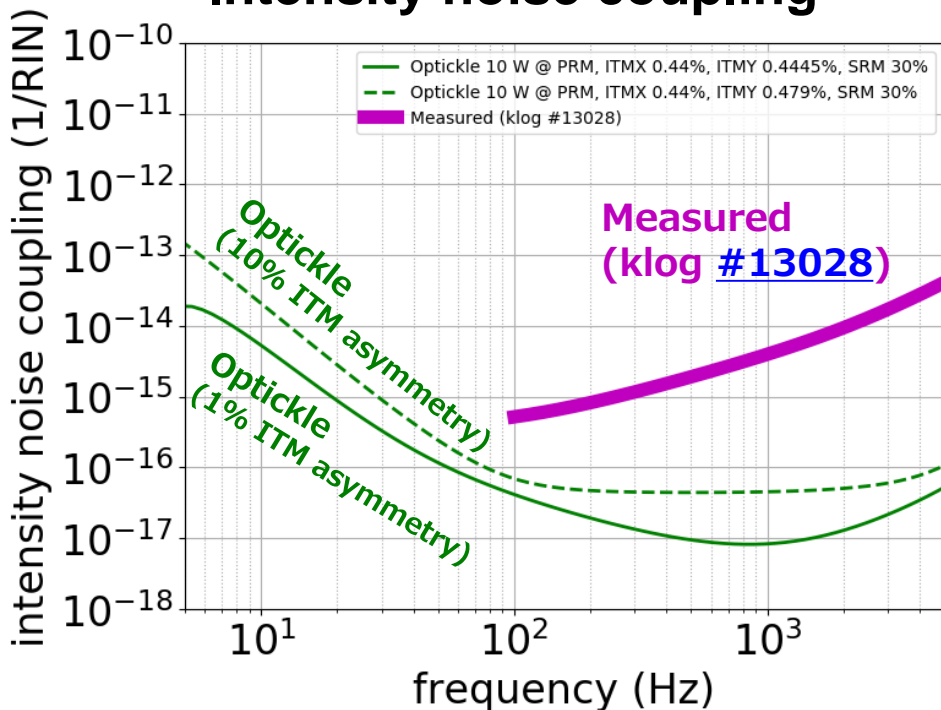- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)

Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
- Thermal noise
- Test mass suspension damping noise

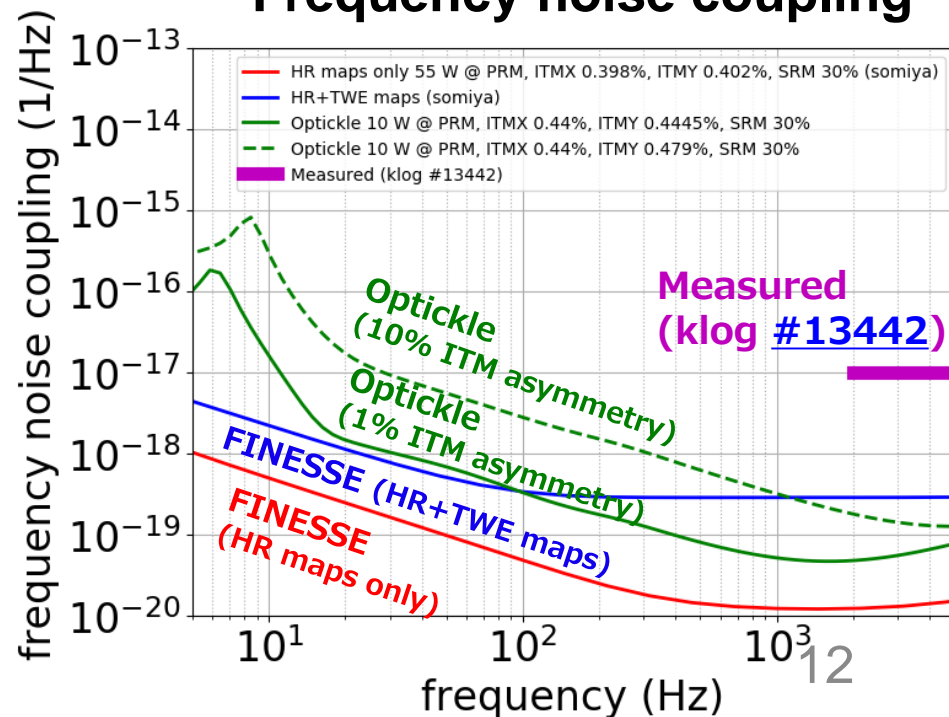Preliminary NB with data on April 12, 2020 (2020/12/15 ver)

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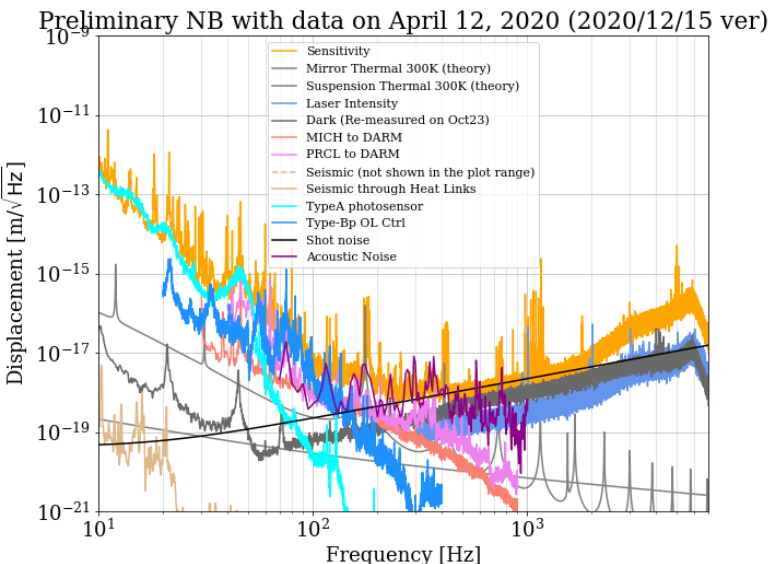
Laser Noises

- Coupling was larger than expected by 1-2 orders of magnitude (probably due to birefringence)
- Better interferometer alignment would reduce the coupling (with WFS)

JGW-T2011662

Intensity noise coupling

Legend:
- Optickle 10 W @ PRM, ITMX 0.44%, ITMY 0.4445%, SRM 30%
- Optickle 10 W @ PRM, ITMX 0.44%, ITMY 0.479%, SRM 30%
- Measured (klog #13028)

Measured (klog #13028)

Optickle (10% ITM asymmetry)

Optickle (1% ITM asymmetry)

Frequency noise coupling

Legend:
- HR maps only 55 W @ PRM, ITMX 0.398%, ITMY 0.402%, SRM 30% (somiya)
- HR+TWE maps (somiya)
- Optickle 10 W @ PRM, ITMX 0.44%, ITMY 0.4445%, SRM 30%
- Optickle 10 W @ PRM, ITMX 0.44%, ITMY 0.479%, SRM 30%
- Measured (klog #13442)

Measured (klog #13442)

Optickle (10% ITM asymmetry)

Optickle (1% ITM asymmetry)

FINESSE (HR+TWE maps)
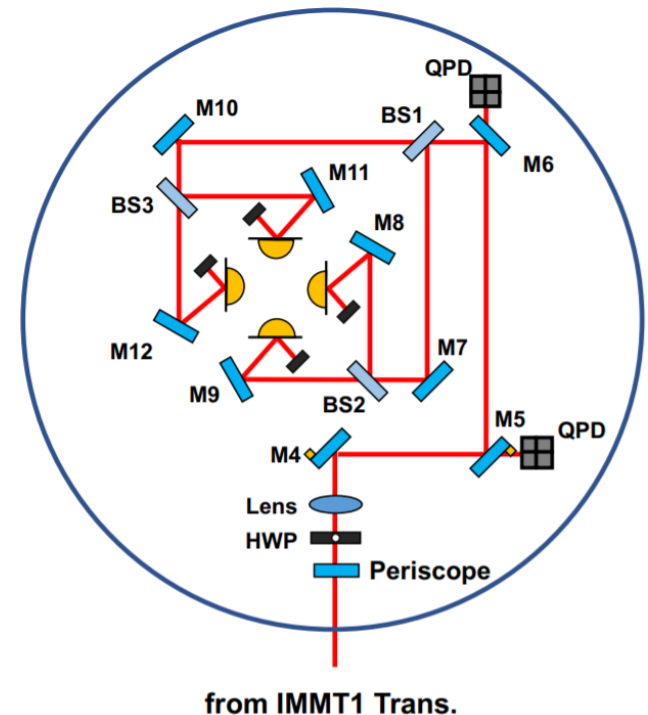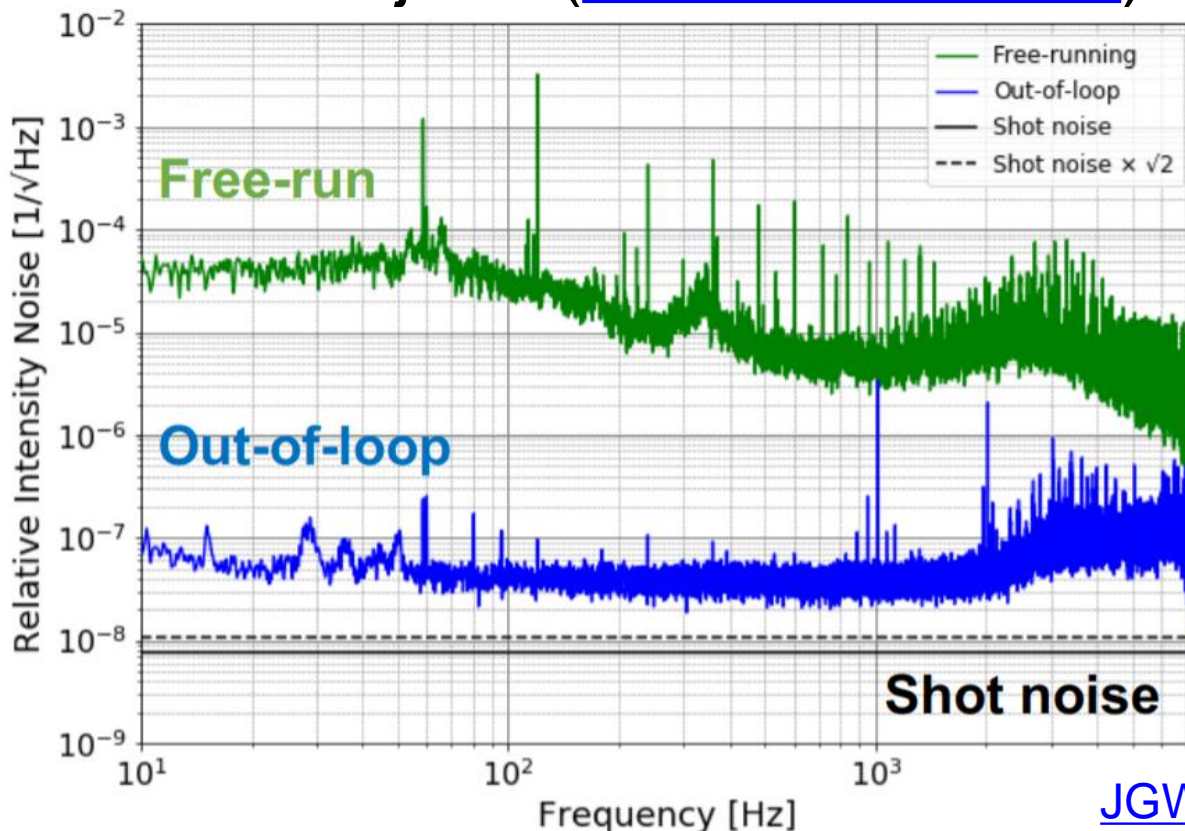
FINESSE (HR maps only)

Laser Frequency noise

- Almost shot noise limited (~10 mW at PD) at 100 Hz
- Not very critical for BNS range
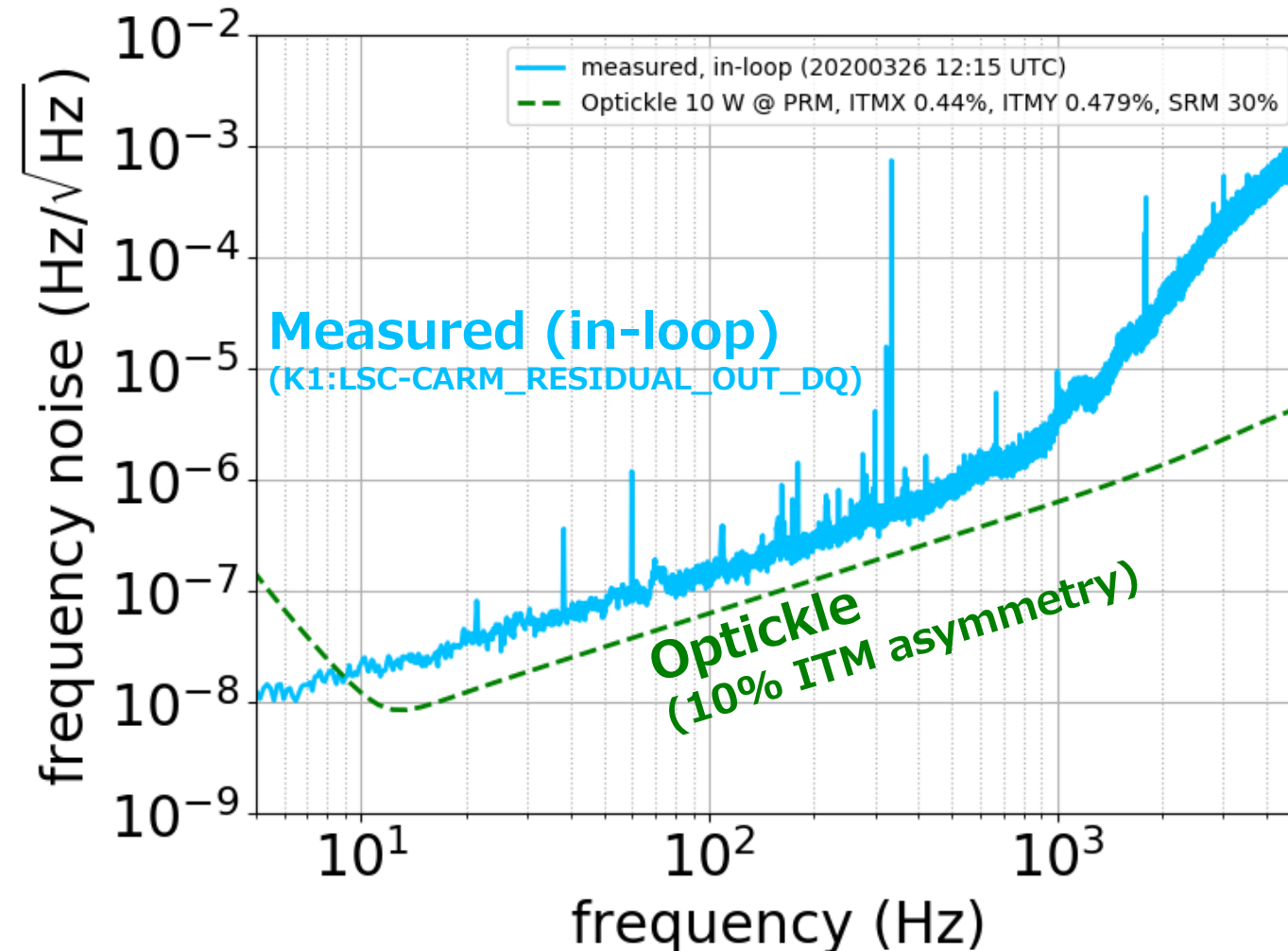
Laser Intensity noise

- A factor of ~3 to shot noise limit
- Some noise from beam jitter ?
- There is a plan to increase power and to reduce beam jitter (JGW-G2012322)
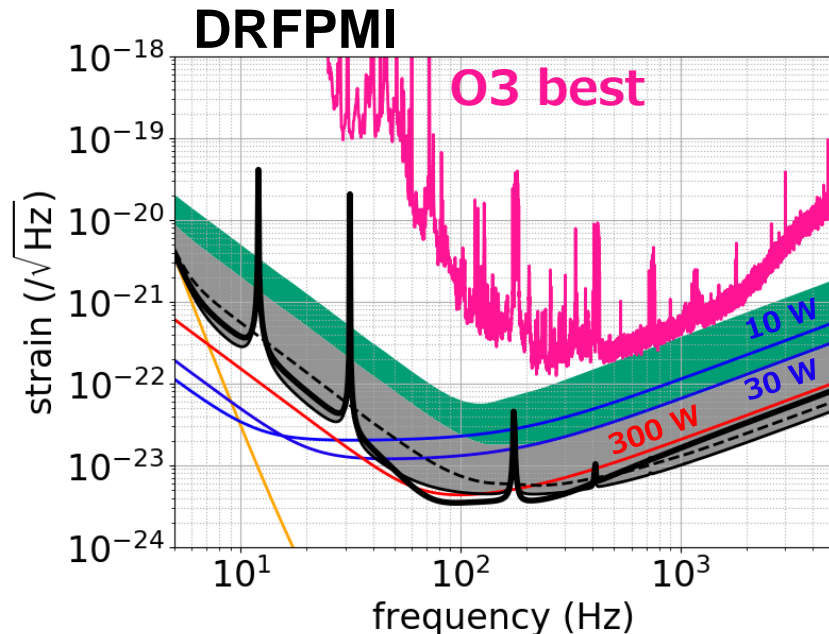

JGW-G2012322

Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
- Thermal noise
- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)
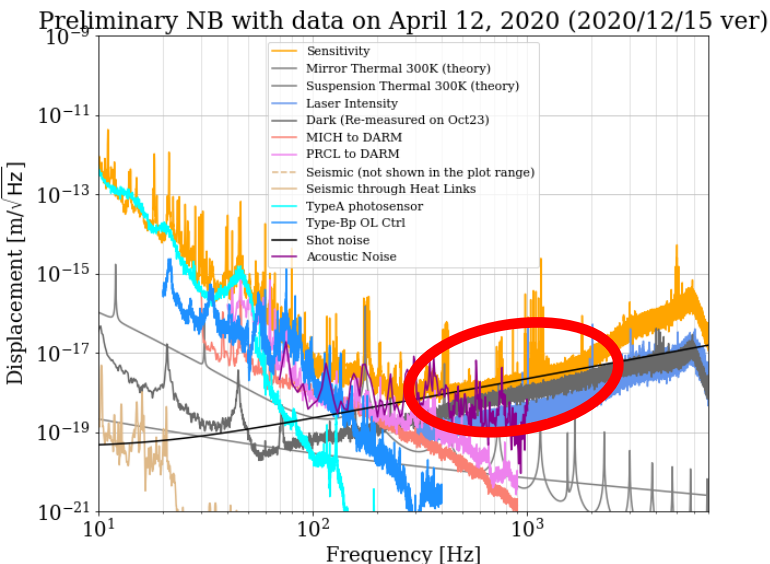
Shot Noise

- Shot noise in O3 was not good due to tilted SRM
- When DRFPMI, at least 30 W at BS is necessary
- When PRFPMI, at least 300 W as BS is necessary
- DR seems to be almost necessary for O4
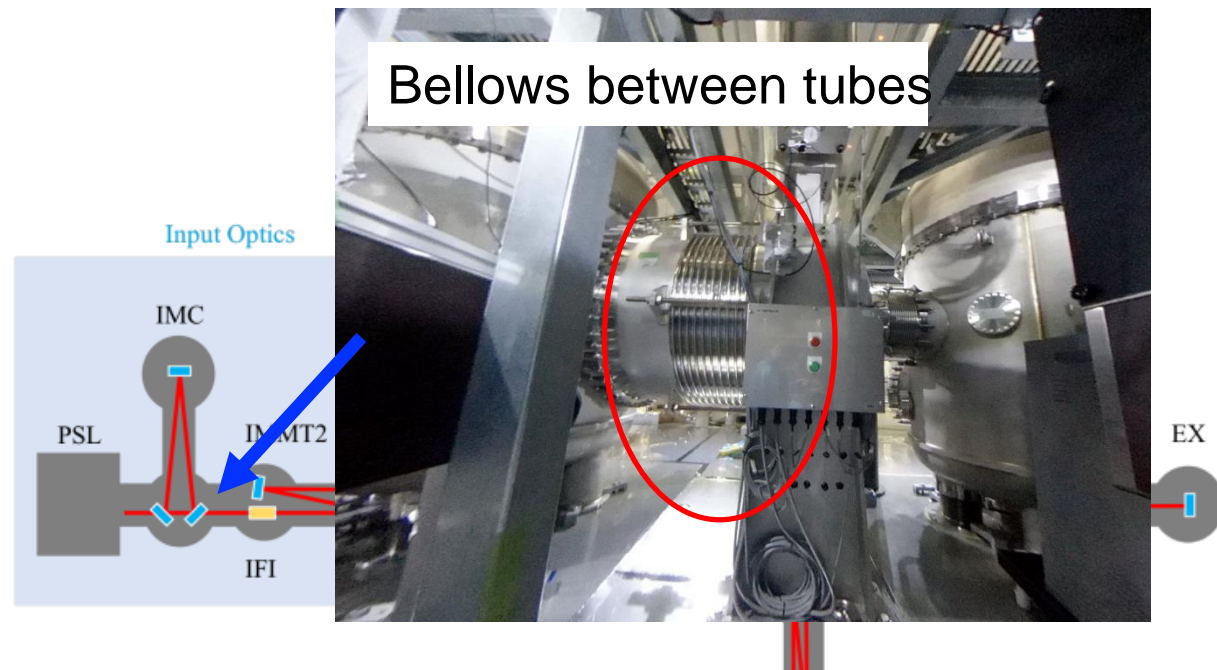
JGW-T2011662
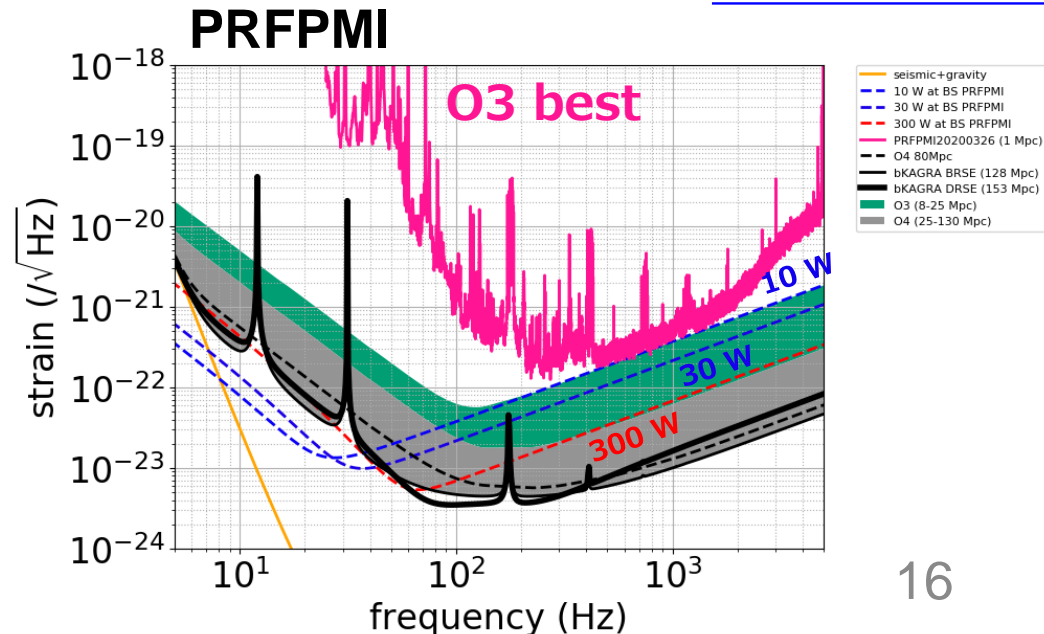
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Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
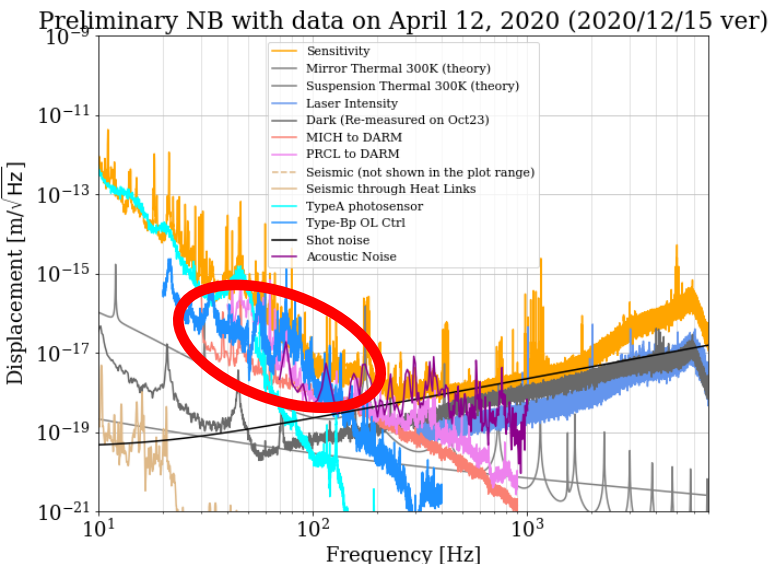- Thermal noise
- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)
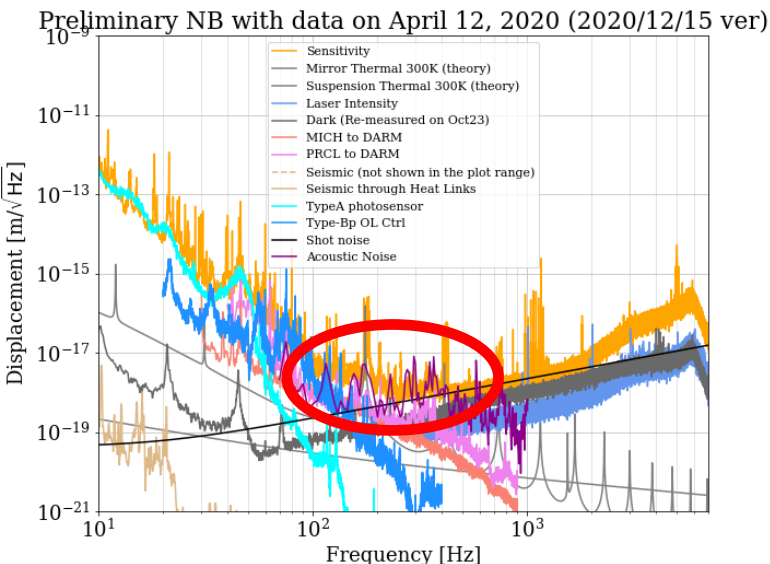
Acoustic Noise

- Most contribution from bellows between IMC-IFI chamber
- Could be reduced by scattered light mitigation

Bellows between tubes

Input Optics

IMC

PSL

IMMT2

IFI

EX

JGW-G2012315
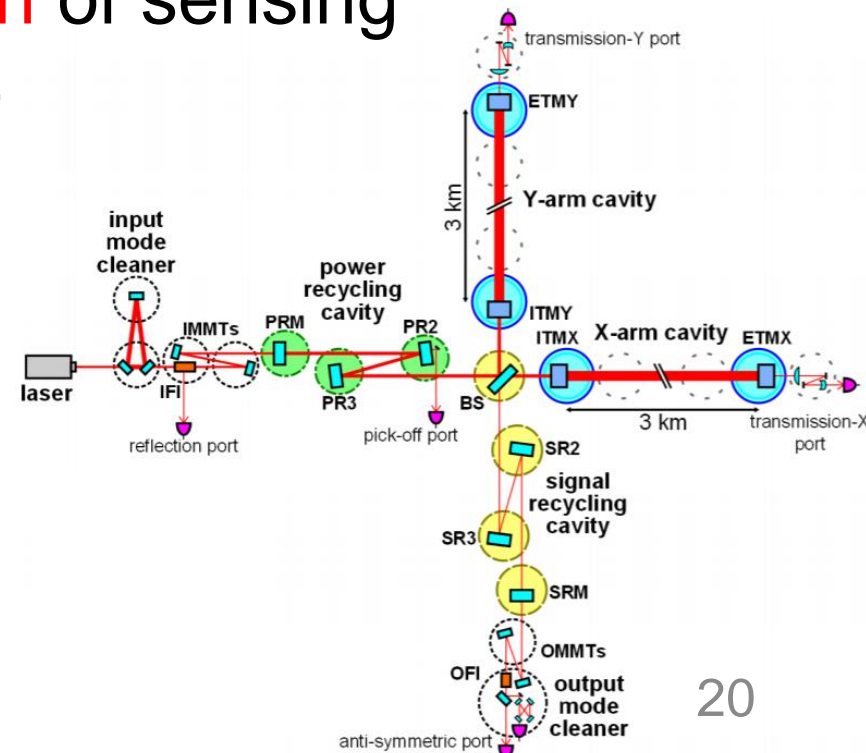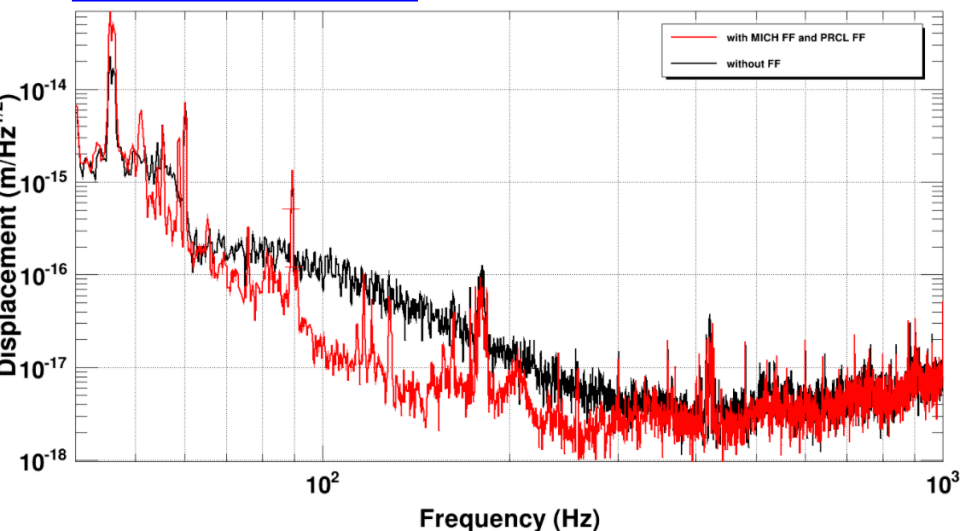
18

Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
- Thermal noise
- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)


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Coupling from Auxiliary DOFs

- Coupling MICH (Michelson) and PRCL (power recycling cavity length)

- Feedforward reduces the coupling by ~1/10 at max

- More feedforward gain necessary

- Also, better diagonalization of sensing matrix can be done for O4
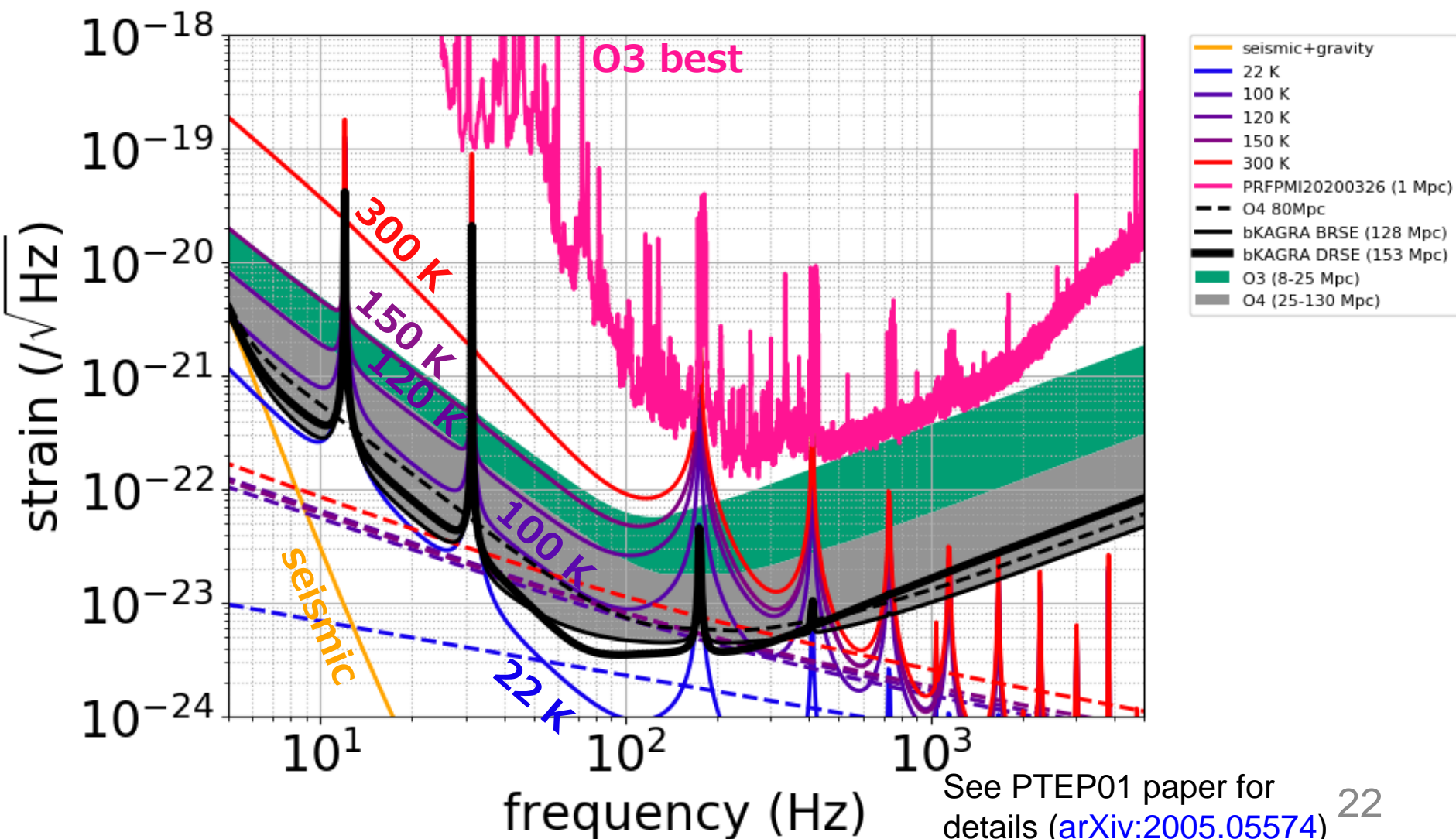
JGW-G2012315

Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
- Thermal noise
- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)
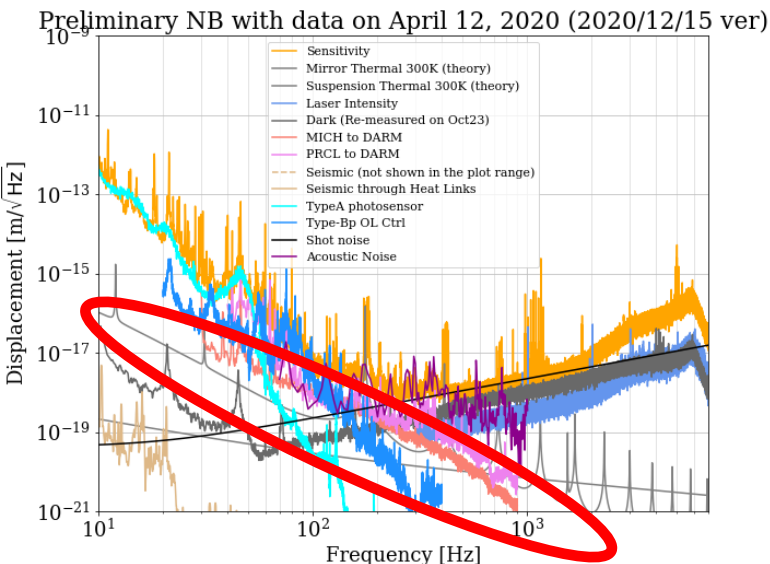
Thermal Noise

- At least below ~100 K is necessary

See PTEP01 paper for details (arXiv:2005.05574)

Expectations for O4

- Laser noises (frequency noise and intensity noise)
- Shot noise
- Acoustic noise
- Coupling from auxiliary degrees of freedom
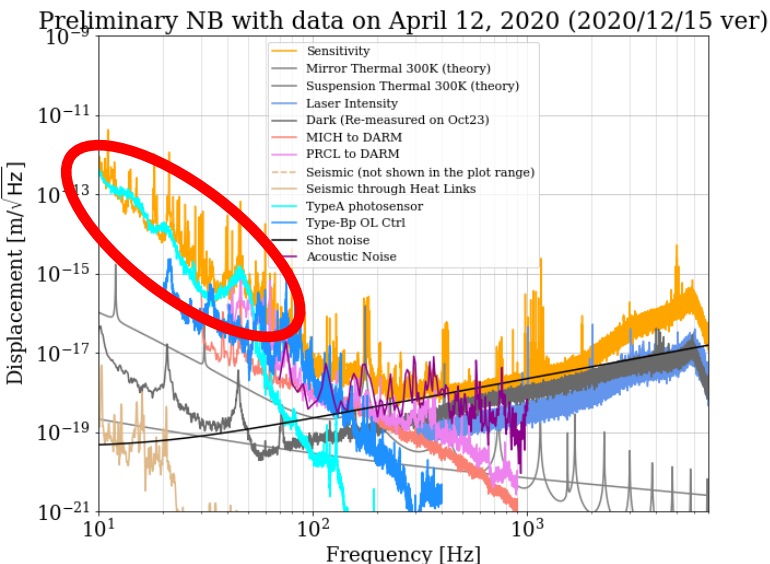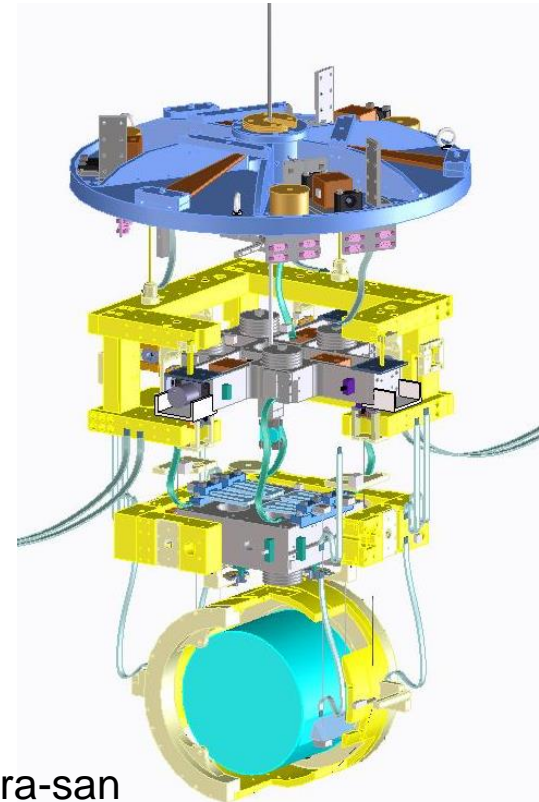- Thermal noise
- Test mass suspension damping noise

Preliminary NB with data on April 12, 2020 (2020/12/15 ver)

Test Mass Suspension Damping

- Noises from marionette damping using photo sensors are limiting
- There is a plan to install optical levers for marionette stages (cannot be used for recoil mass damping)
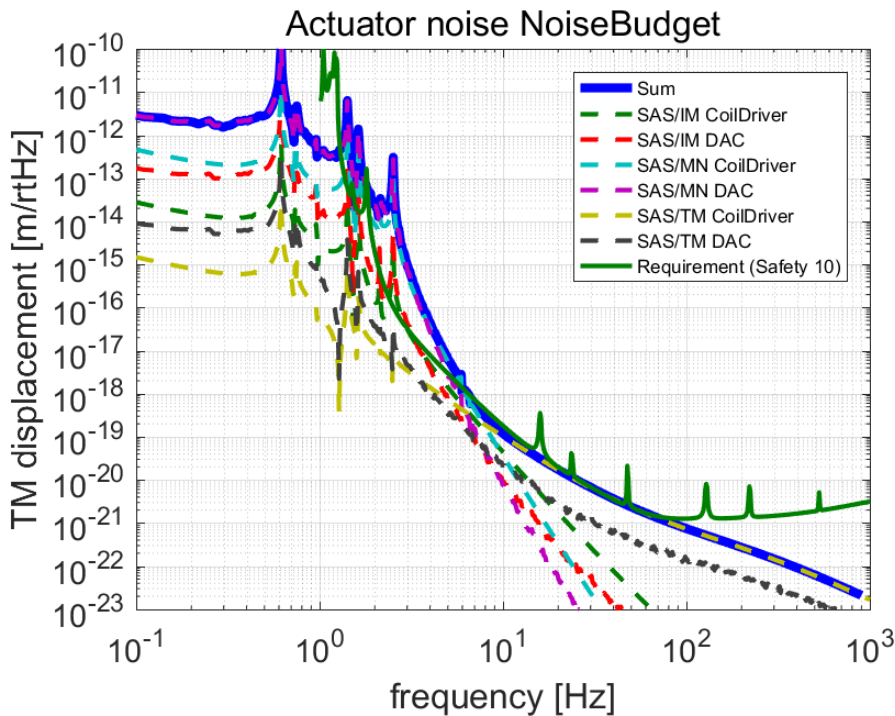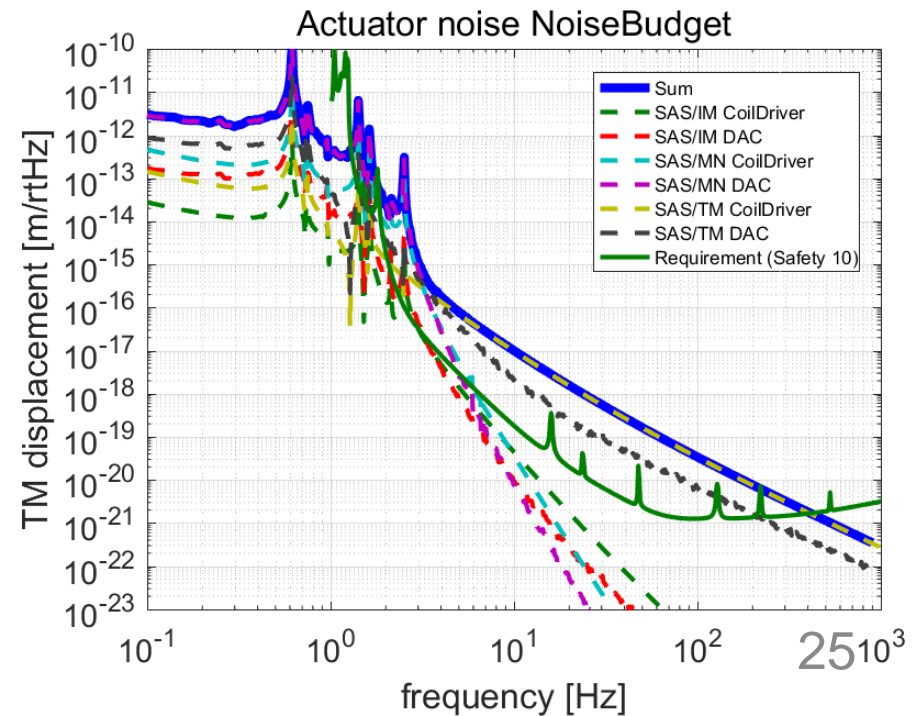
CAD from Hagiwara-san

Actuator Noise

- Noises from high power coil driver used for O3 is not good for O4

- Coil driver switch to turn off high power coil driver after the lock acquisition necessary

JGW-T1910142

Nominal Case

High Power TM Case

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Summary

- O4 sensitivity would be ~70 Mpc at maximum

- Laser noises
  - alignment improvement (with WFS) necessary
  - improvement plan for ISS seems promising

- Shot noise
  - DRFPMI with more than 30 W at BS necessary

- Thermal noise
  - at least ~100 K necessary

- Coupling of auxiliary degrees of freedom
  - more sensing matrix diagonalization necessary
  - more feedforward gain necessary (by ~ x10)

- Suspension damping noises
  - coil driver switch necessary
 - concrete planning based on noise estimates necessary

Details

O4 Considerations

- Temperature ?
  - At least below 100 K required to achieve 25 Mpc (JGW-T2011662)
  - ~40 K seems to be optimum considering the balance between the absorption from the input power and thermal noise (JGW-G2011756)
  - Mirror frosting observed below ~30 K (arXiv:2005.05574)

- PRFPMI or DRFPMI ?
  - lock of DRFPMI not achieved yet, but close (JGW-G2012213)

- Input power ?
  - not very critical at this stage (JGW-T2011662)
  - 300 W at BS feasible from laser preparations and TM cooling

- Laser frequency and intensity noise ?
  - coupling larger than expected due to ITM inhomogeneity (JGW-T2011662)

- Unknown excess noise ?
  - At least a reduction by a factor of 50 necessary to achieve 25 Mpc (JGW-T2011662)

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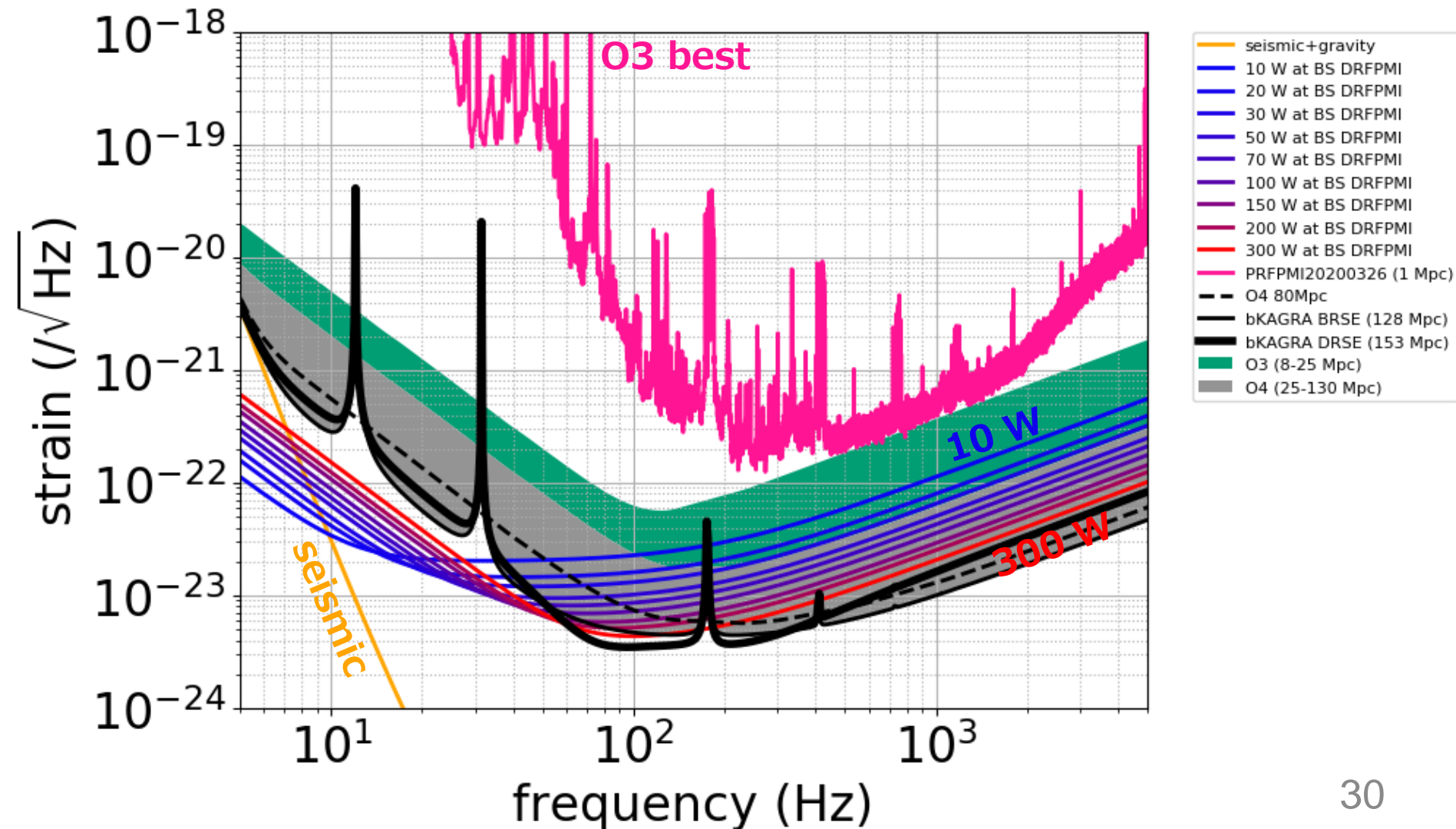# Various Thermal Noise

- All temperatures

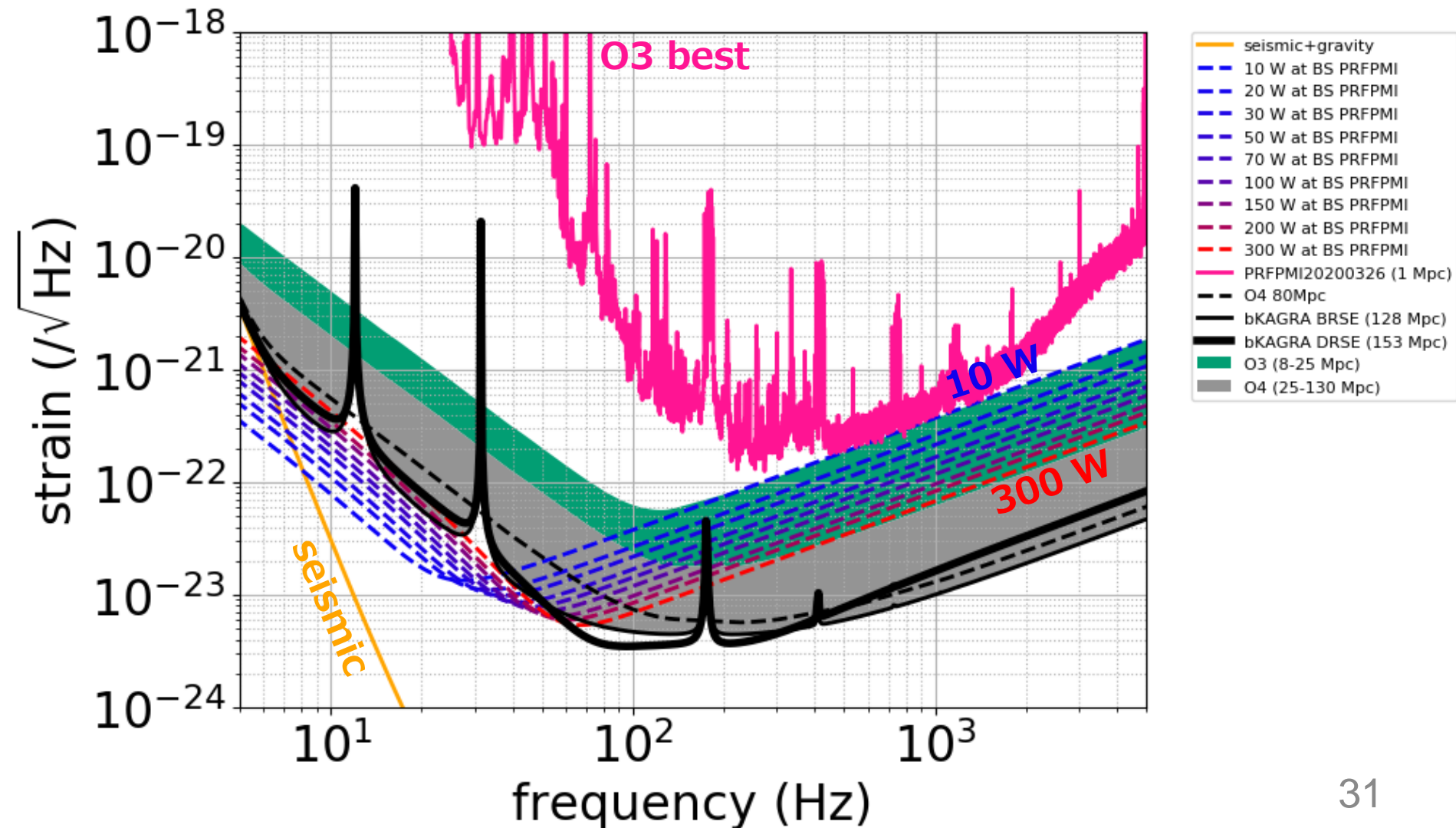See PTEP01 paper for details ([JGW-P2011614](JGW-P2011614))
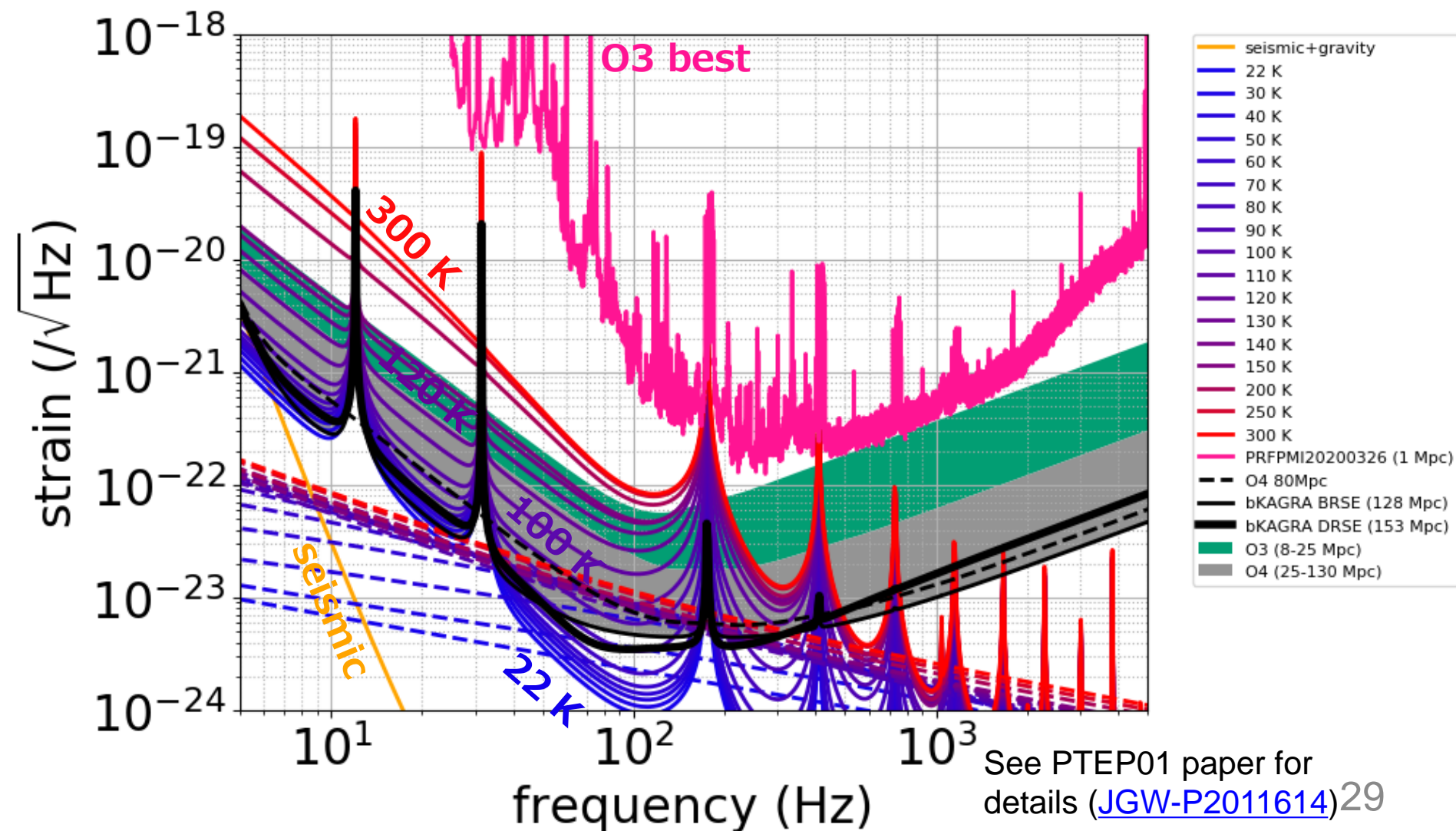
Various Quantum Noise (DR)

- 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 1/100~1/300 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 ~0.001*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