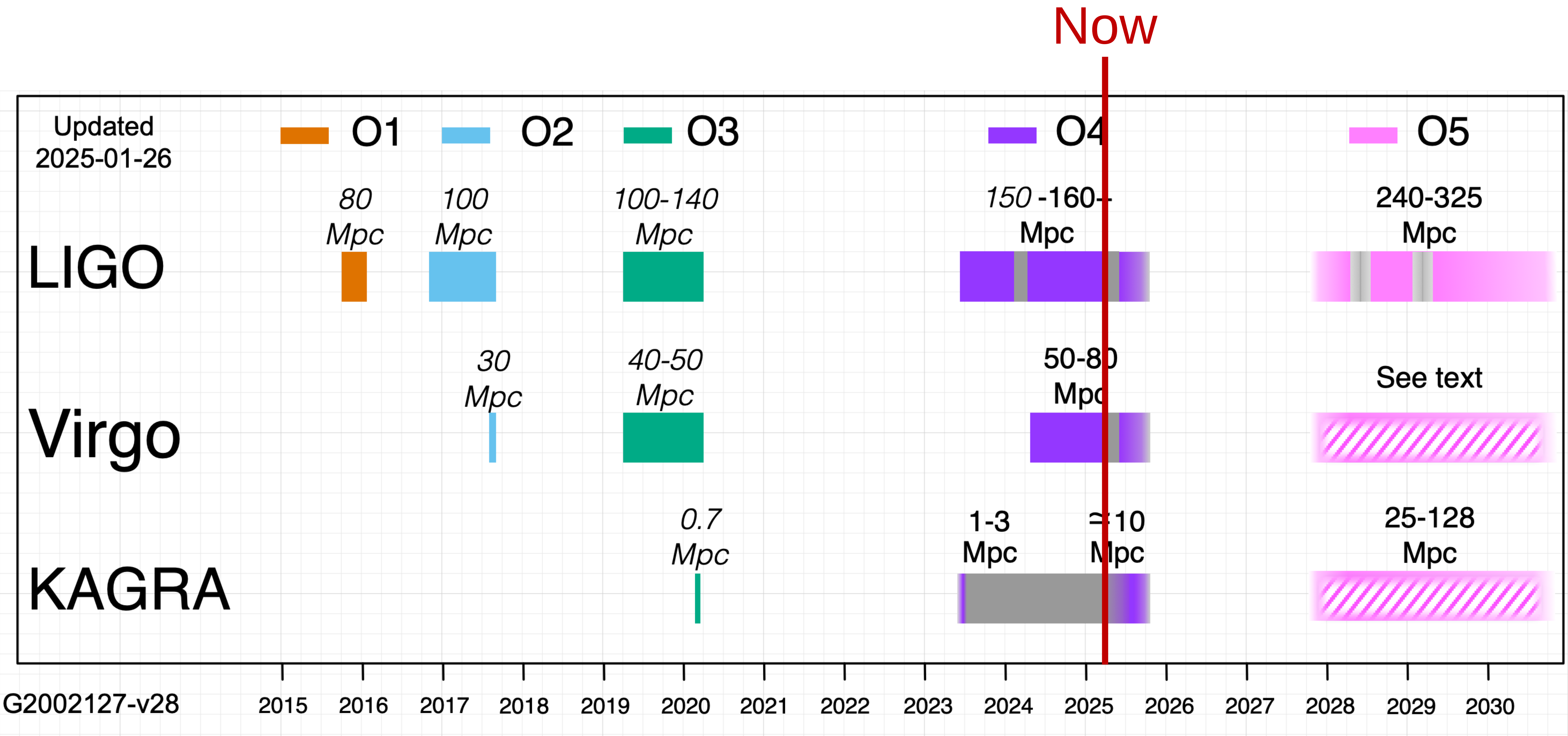
Possible High Frequency Upgrade of KAGRA

2025/4/24
National Astronomical Observatory of Japan
Yoichi Aso on behalf of KAGRA

Context

アメリカ
LIGO
ワシントン州
4km
ルイジアナ州
4km
ドイツ・イギリス
GEO600
ハノーバー 600m
ピサ 3km
VIRGO
フランス・イタリア
計画中
LIGO-India
インド
日本
KAGRA
岐阜県・飛騨市
3km


Now
Updated
2025-01-26
O1
O2
O3
O4
O5
LIGO
80
Mpc
100
Mpc
100-140
Mpc
150 -160+
Mpc
240-325
Mpc
Virgo
30
Mpc
40-50
Mpc
50-80
Mpc
See text
KAGRA
0.7
Mpc
1-3
Mpc
≃10
Mpc
25-128
Mpc
G2002127-v28
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030

Plan toward O5

Advanced LIGO+: 240-325Mpc

- Replacement of mirrors (better coating)

Virgo+: 200Mpc?

- Major reconstruction of recycling cavities

KAGRA: 25-128Mpc

- New mirrors (less birefringence)
- OMC vibration isolation

Post-O5 era (2030s)

Advanced LIGO#: 500Mpc?

- High power laser
- Larger Mirrors

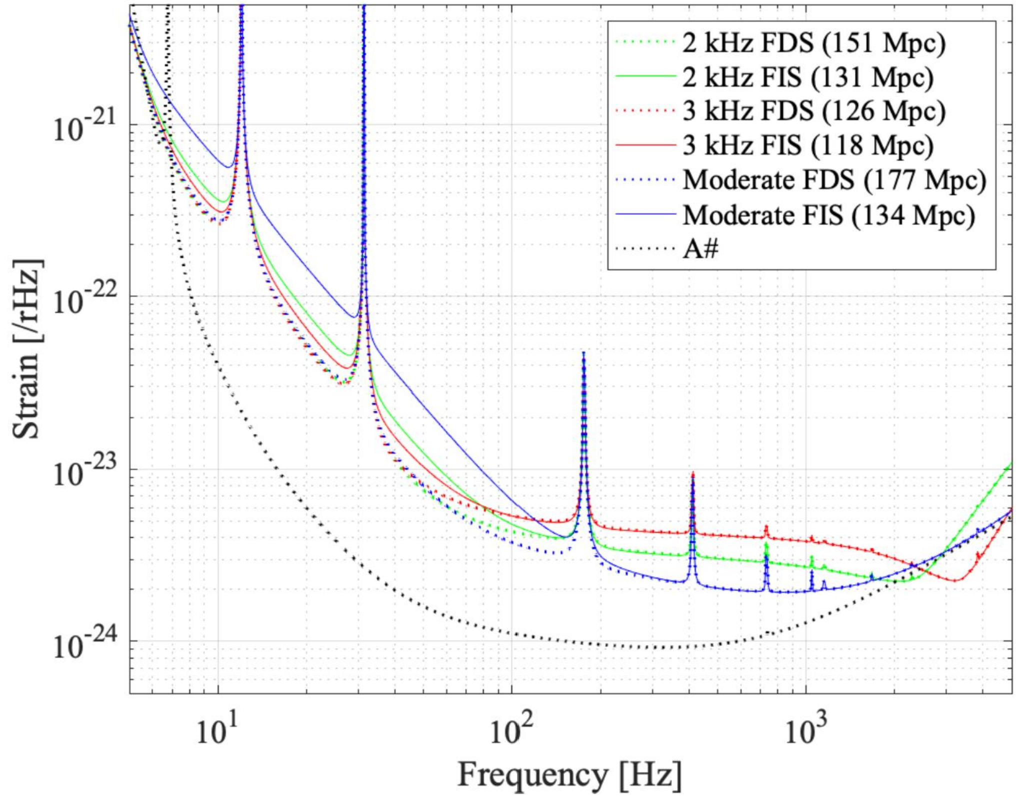
LIGO India: 300Mpc?

- Copy of A+?

VirgoNext: 400Mpc?

- Similar to A#

Broad Band Detectors



KAGRA-HF: High Frequency Optimized Detector

- Long-SRC to optimize the sensitivity around kHz

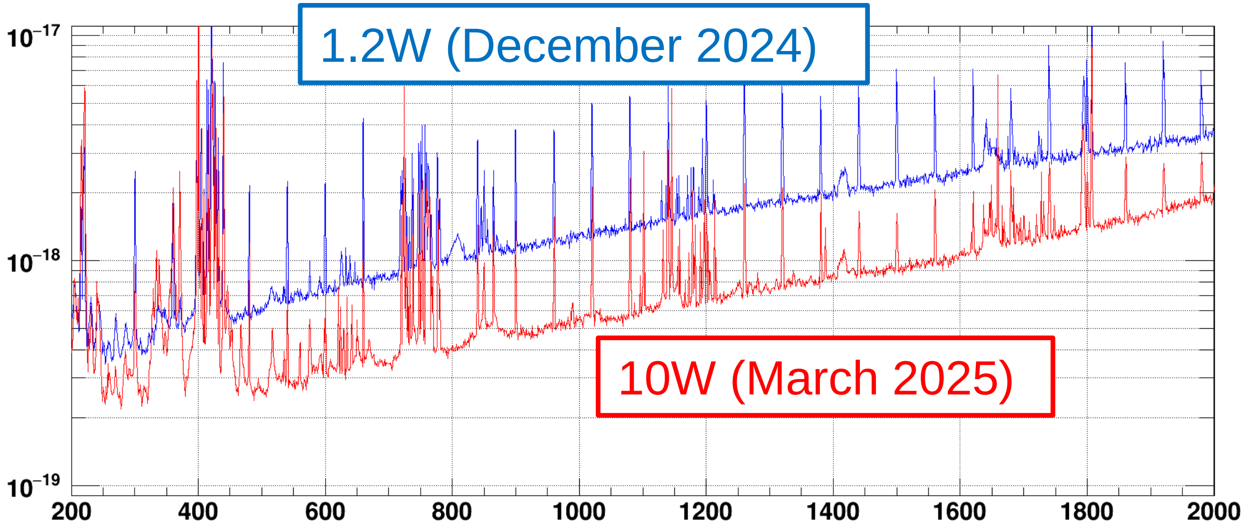
Why do we consider high frequency?

Post O5 era

- 4 broadband GW detectors with >300Mpc
- Can KAGRA compete with them?
- Scientific benefit of having the 5th BB detector?
- Uniqueness of KAGRA in the network is necessary

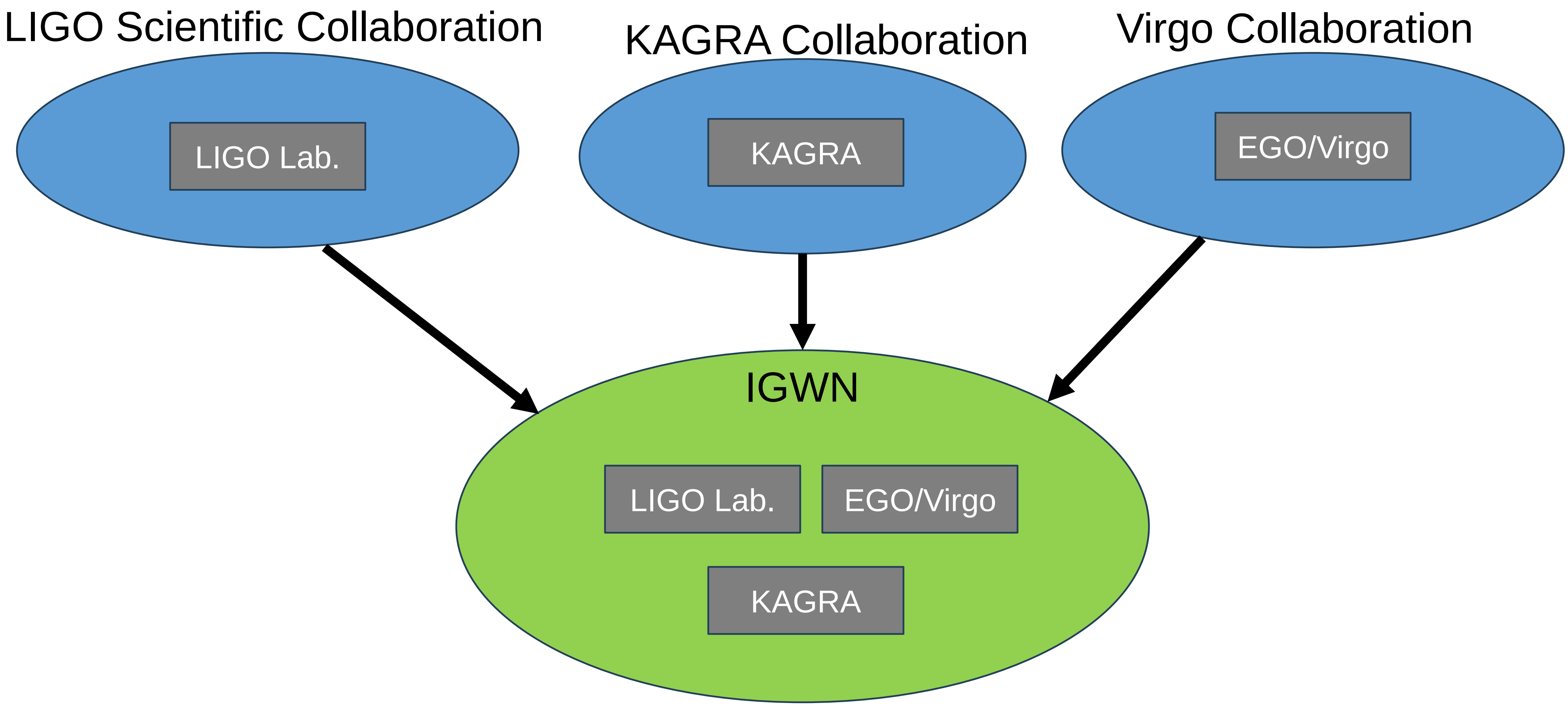
High Frequency Detector

- Mostly limited by the quantum noise
  - Noise reduction is straightforward
- Lower commissioning cost
- Post merger waveform of NS-NS binary
  - Ultra-dense nuclear matter
- Provide unique information in the GW detector network



Formation of IGWN

IGWN = International Gravitational Wave observatory Network



Formation of IGWN

Advantages

- Better coordination of strategies among the observatories
  - Observation scheduling
  - Upgrade planning
- Shared and efficient use of resources (manpower)
- Stricter check of contributions to the collaboration
- Coordinated proposals to funding agencies

Implications for KAGRA upgrades

- Strategic distribution of responsible frequency bands among detectors
- Smoother collaboration for hardware development

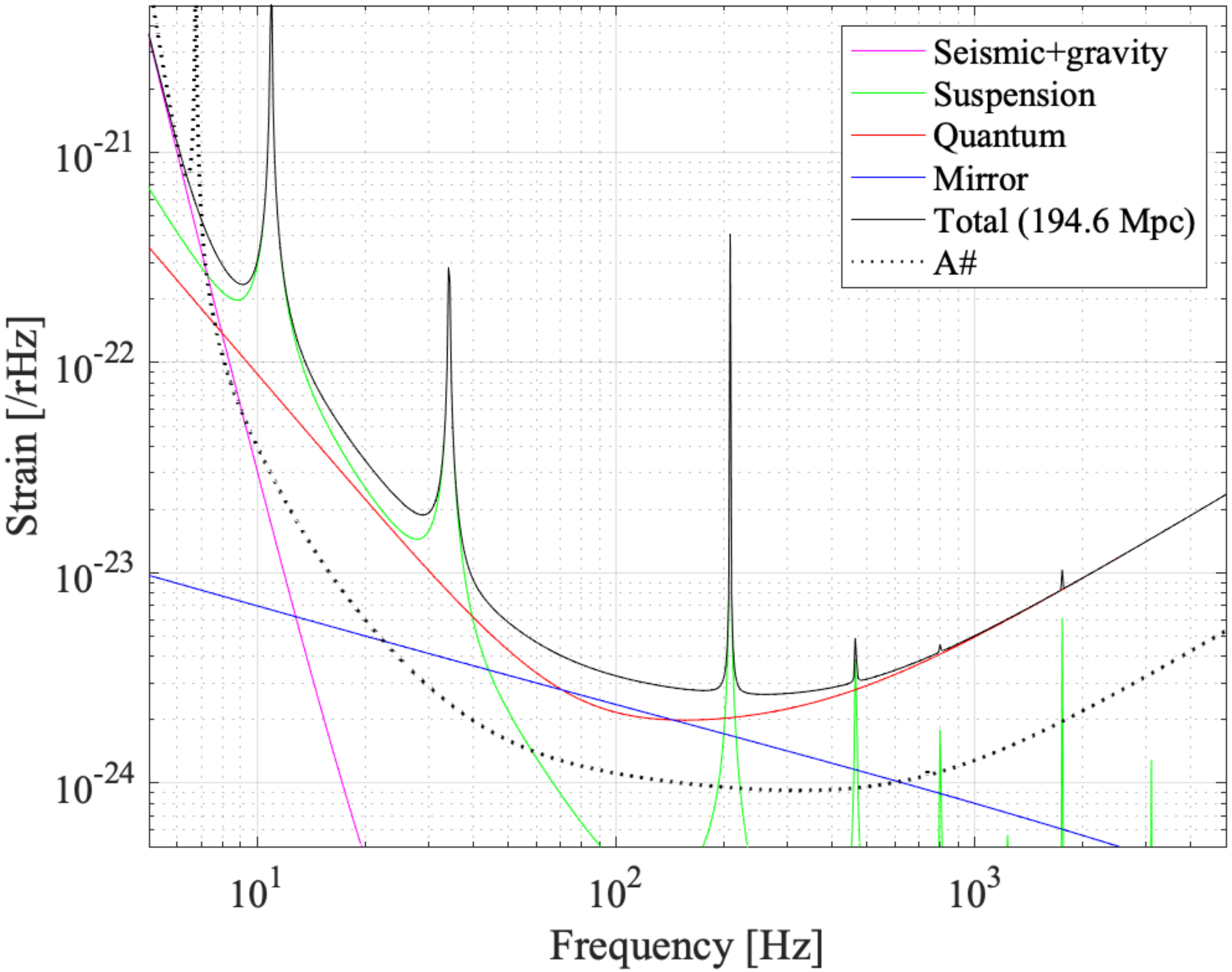
Broad Band Upgrades

Broad Band Upgrade

BB40FDS-HQS

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB

Binary Range: ~195Mpc

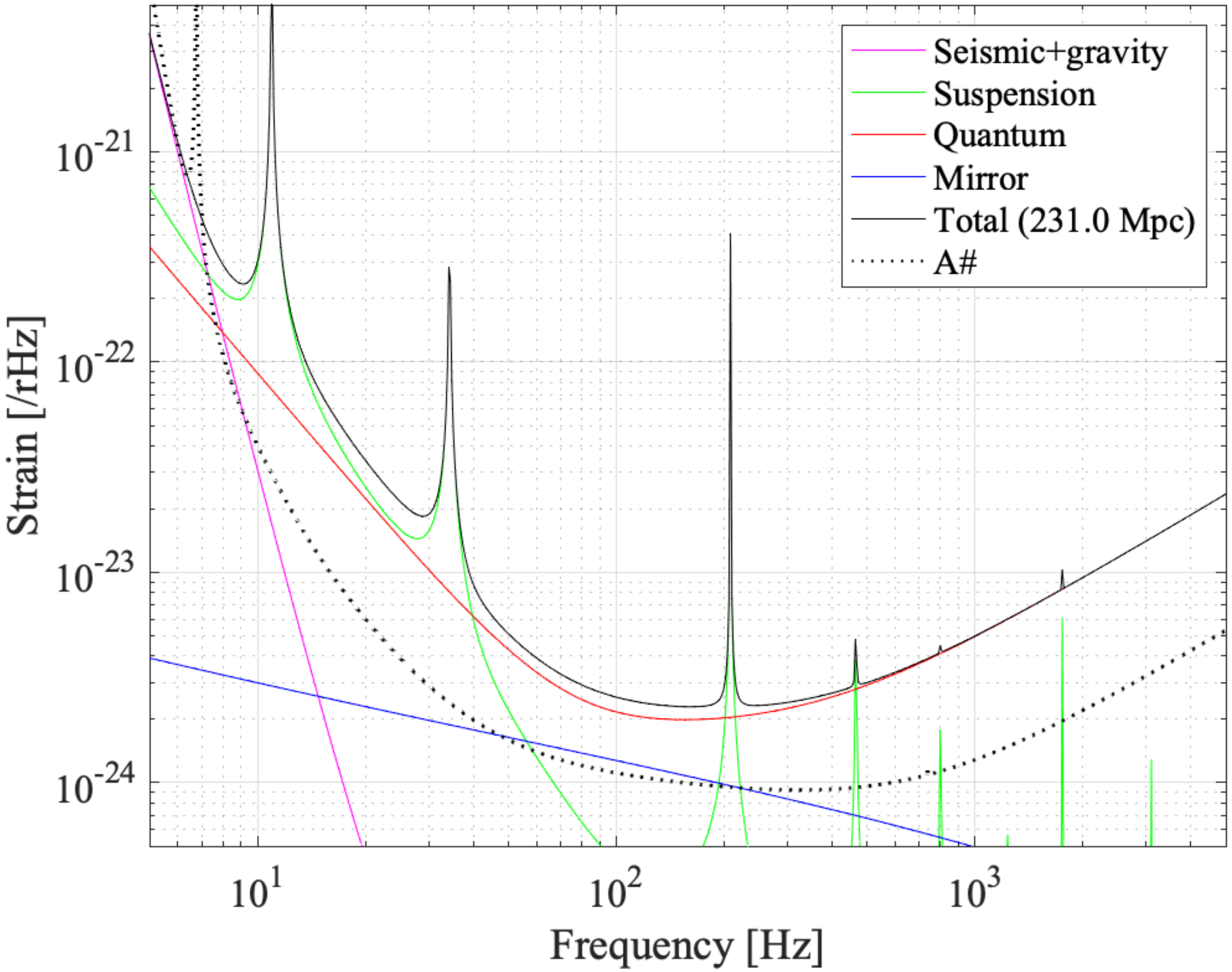


Better coating?

BB40FDS-HQS-BC

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB
AlGaAs Coating: Φ=1e-5

Binary Range: ~231Mpc



Bad Suspension Q

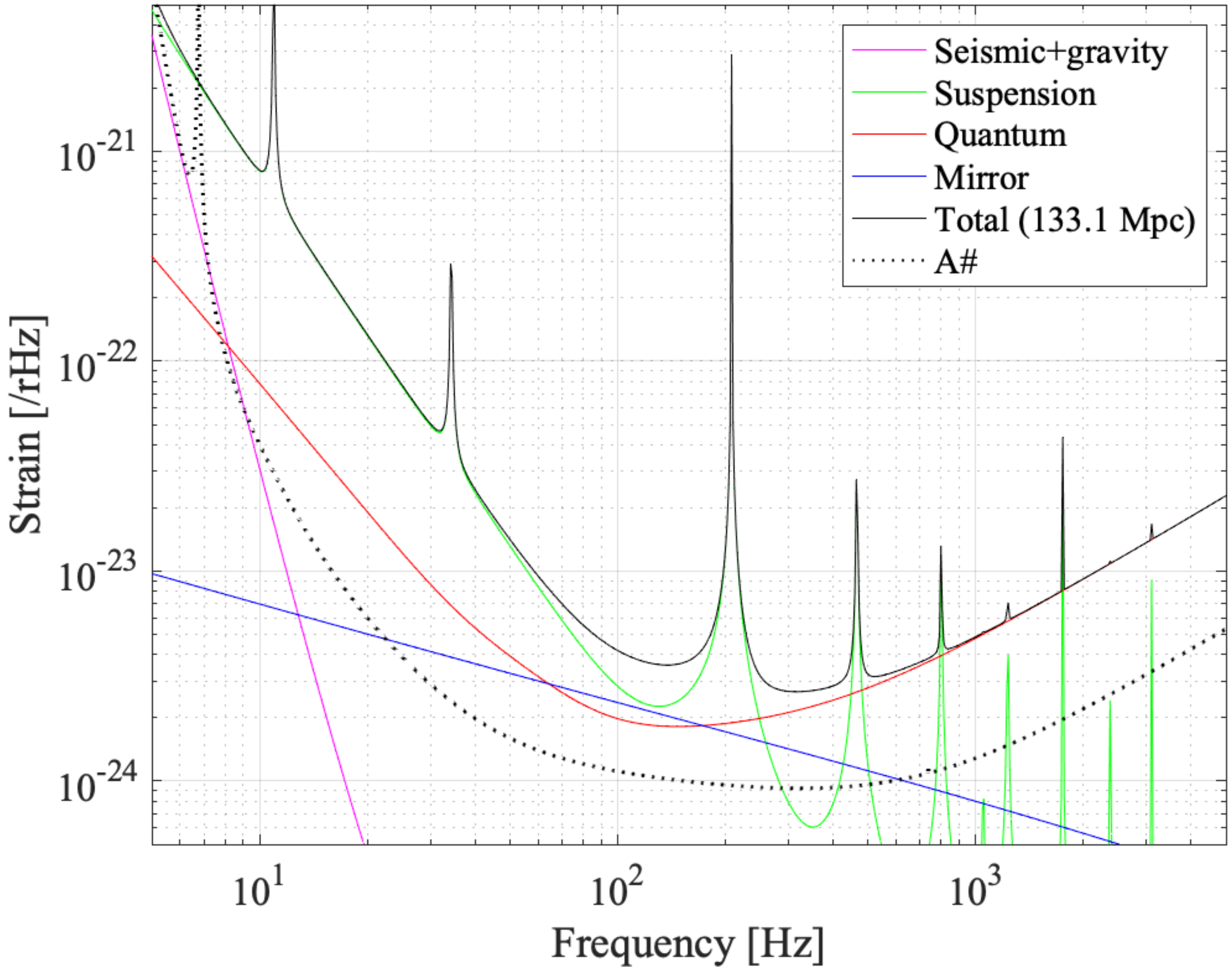
Current sapphire suspension seem to have larger than expected loss

BB40FDS

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB
Larger suspension TN

Fiber loss angle: 2e-7 -> 1e-5

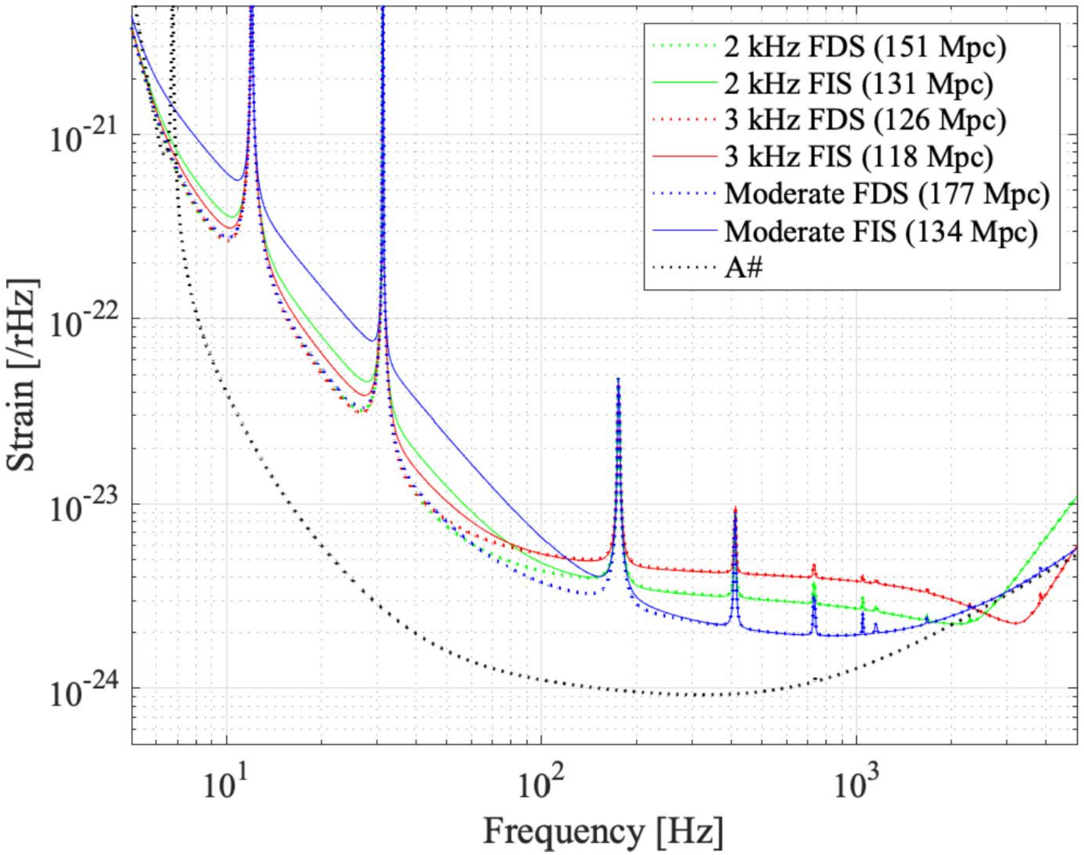
Binary Range: ~133Mpc

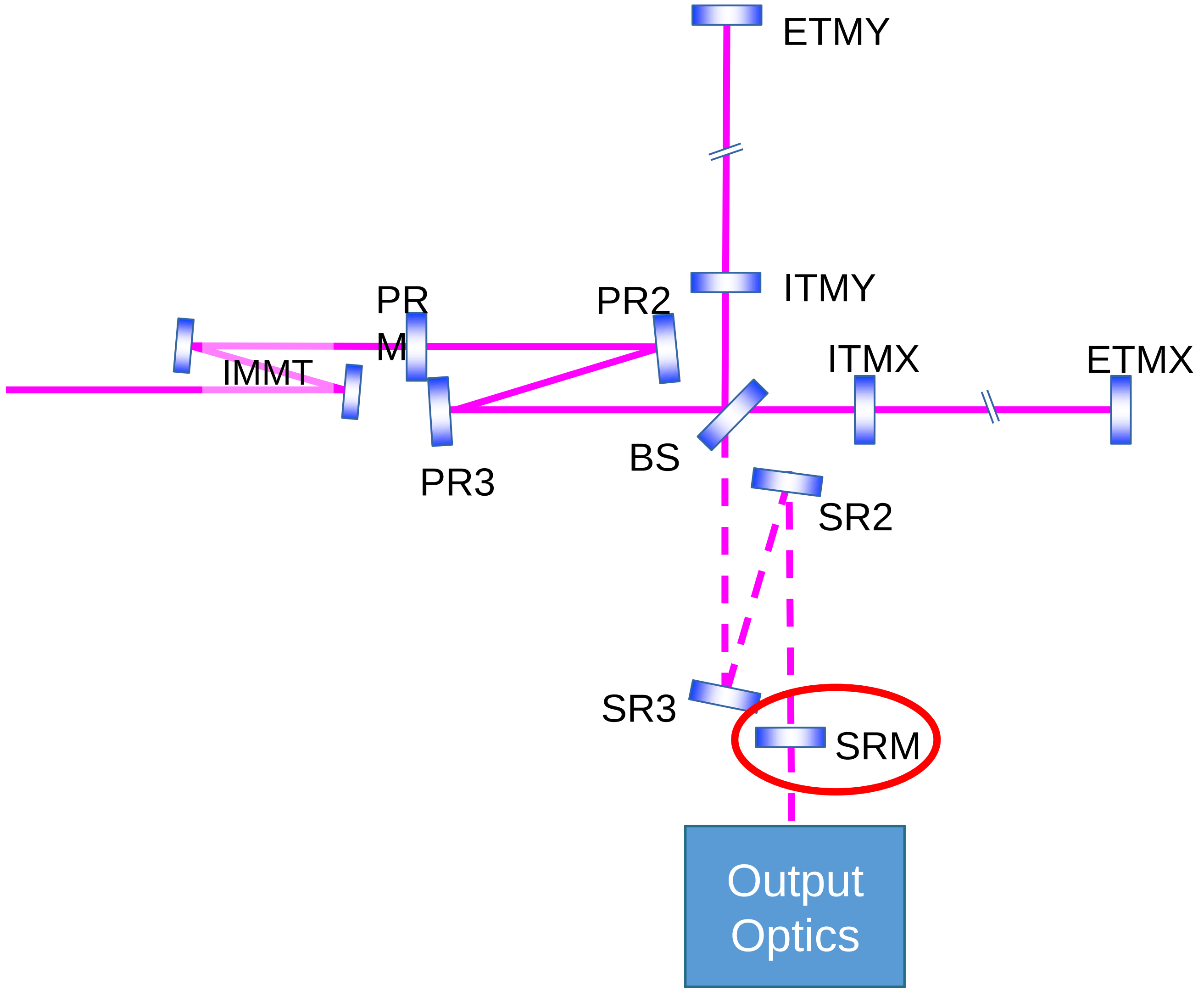


High Frequency Upgrades

How to optimize the detector to kHz?

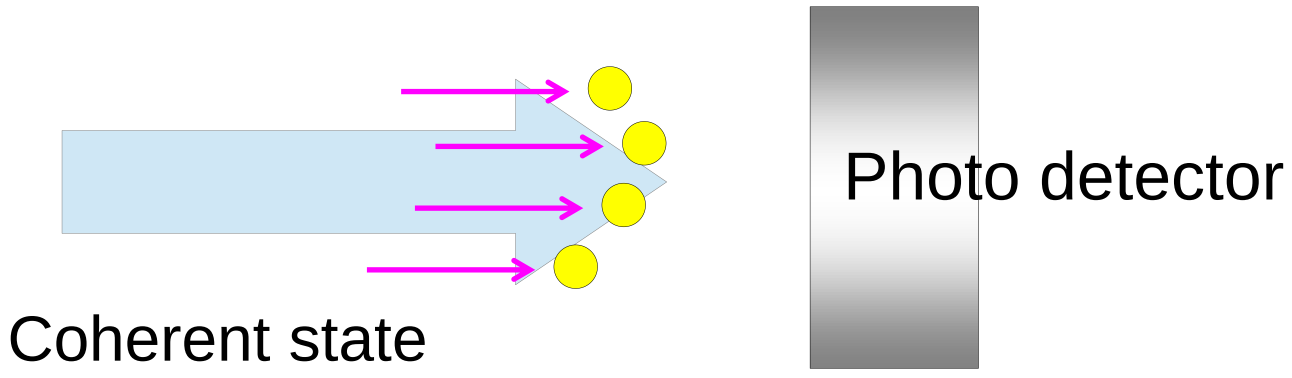
Various HF options



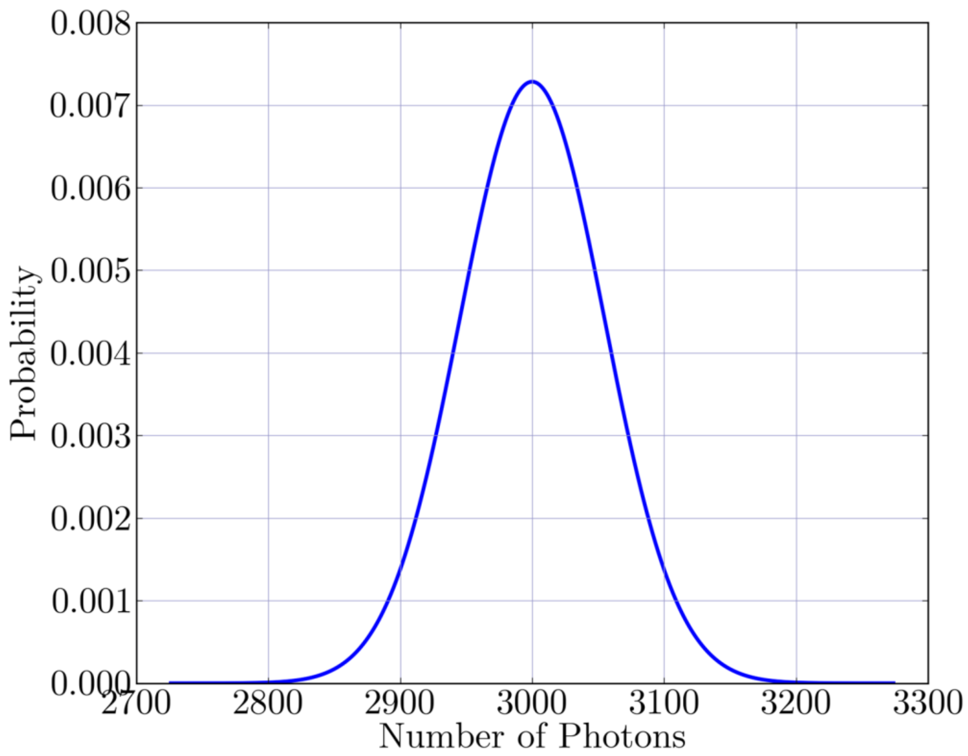


High Power Laser for Reduction of Shot Noise

Shot noise

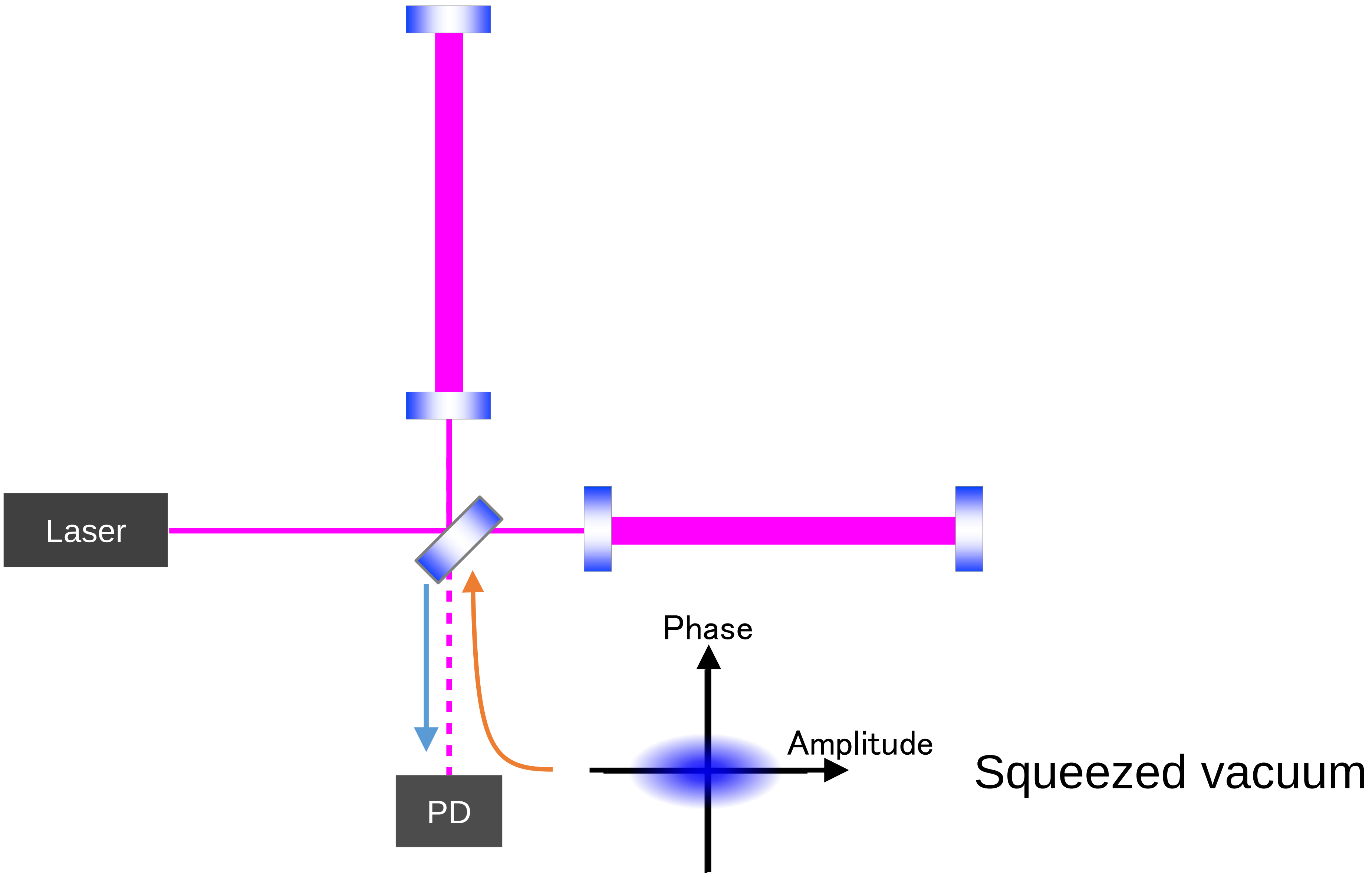


Poisson Distribution



$$\frac{\text{Signal} \propto P}{\text{Noise} \propto \sqrt{P}} \propto \sqrt{P}$$

Injection of squeezed vacuum



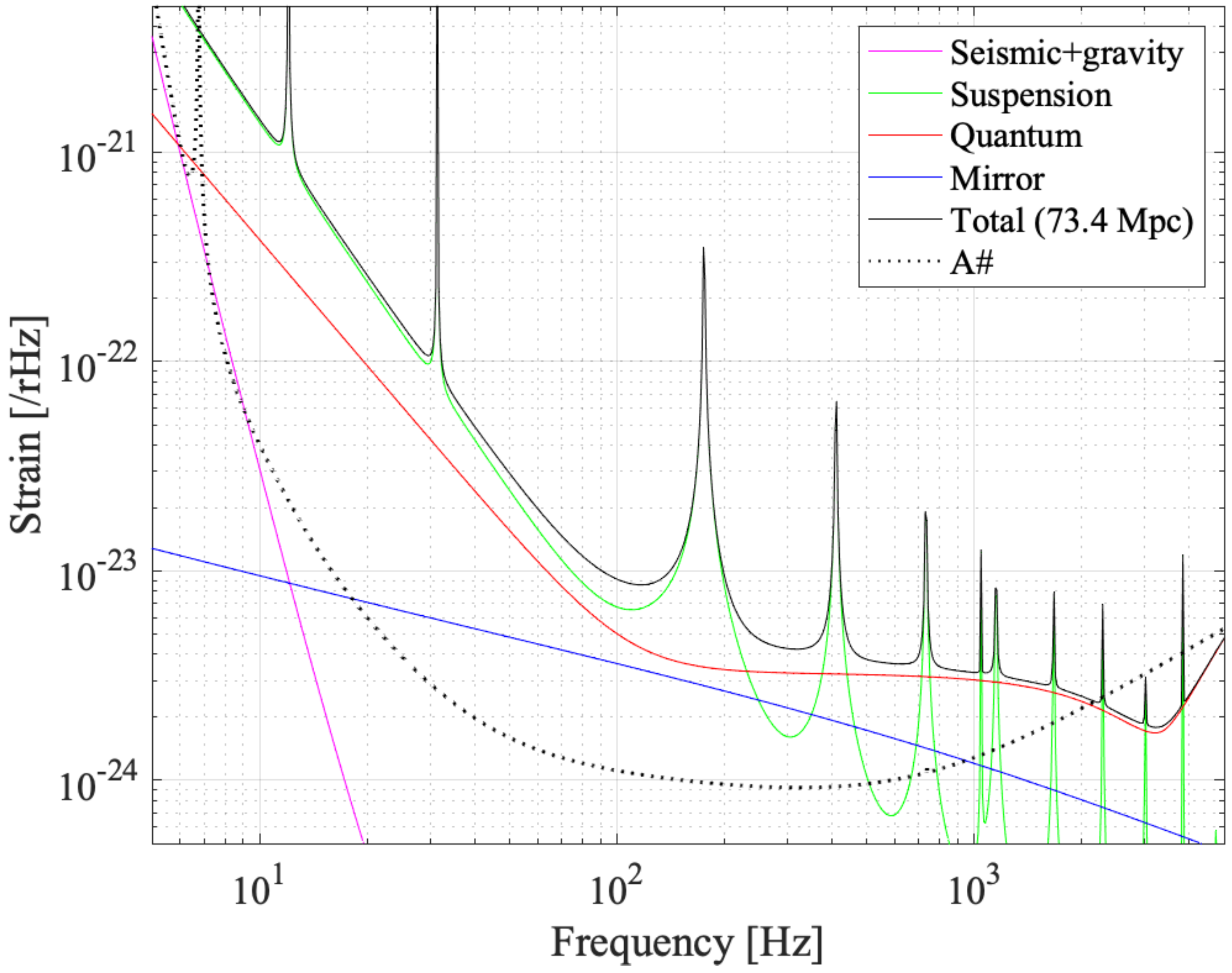
KAGRA HF 3kHz

Note:
Binary range is calculated up to the ISCO frequency. Including the merger and post-merger signals may increase the range.

Create a dip in sensitivity around 3kHz

- SRM reflectivity: 85% -> 99.5%
- Mirror temperature: 22K -> 30K
- Suspension loss: 2e-7->1e-5
- Input power: 4x (1.3MW in arm)
- 10dB non-FD squeezing

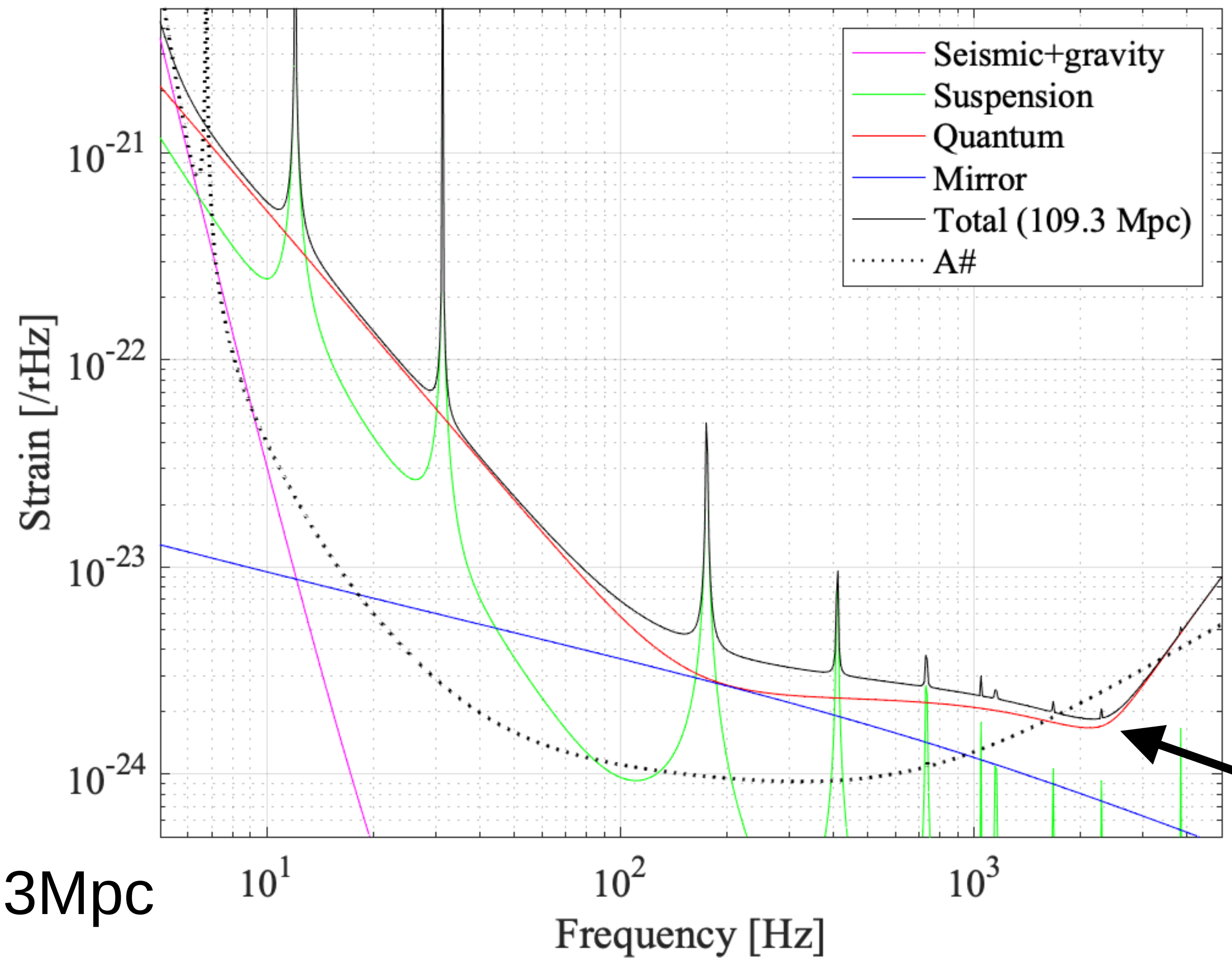
Binary Range: 73.4Mpc



What if we lower the dip frequency?

- Suspension loss: 2e-7
- 10dB non-FD squeezing
- Higher ITM reflectivity: 99.6% -> 99.8%

HF2kFIS-HQS



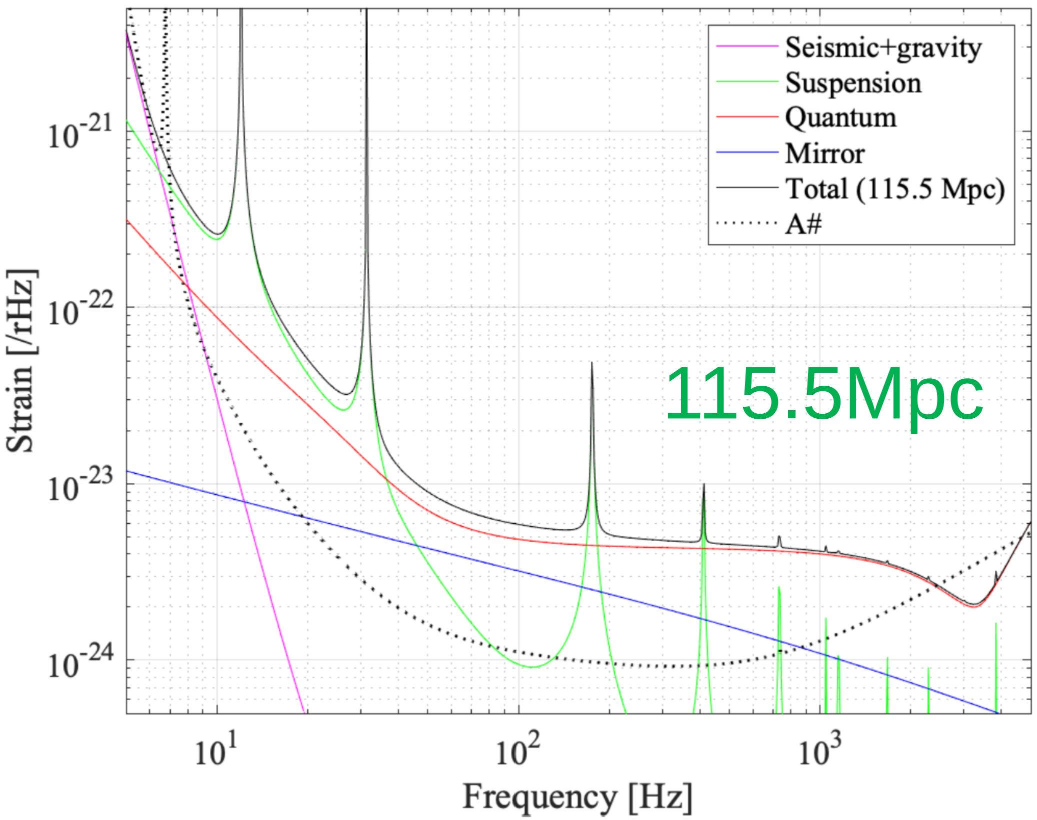
2kHz dip

Binary Range: 109.3Mpc

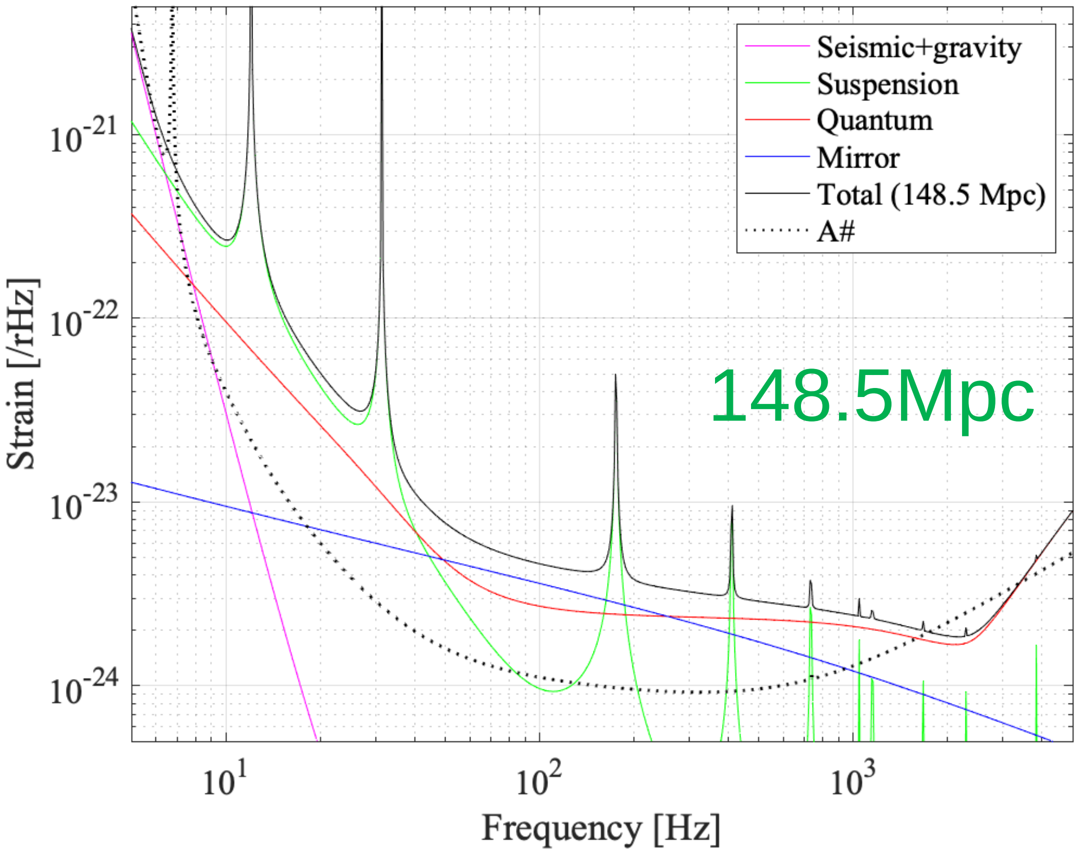
Need more binary range?

- Low suspension thermal assumed
- 10dB Frequency Dependent squeezing

HF3kFDS-HQS



HF2kFDS-HQS

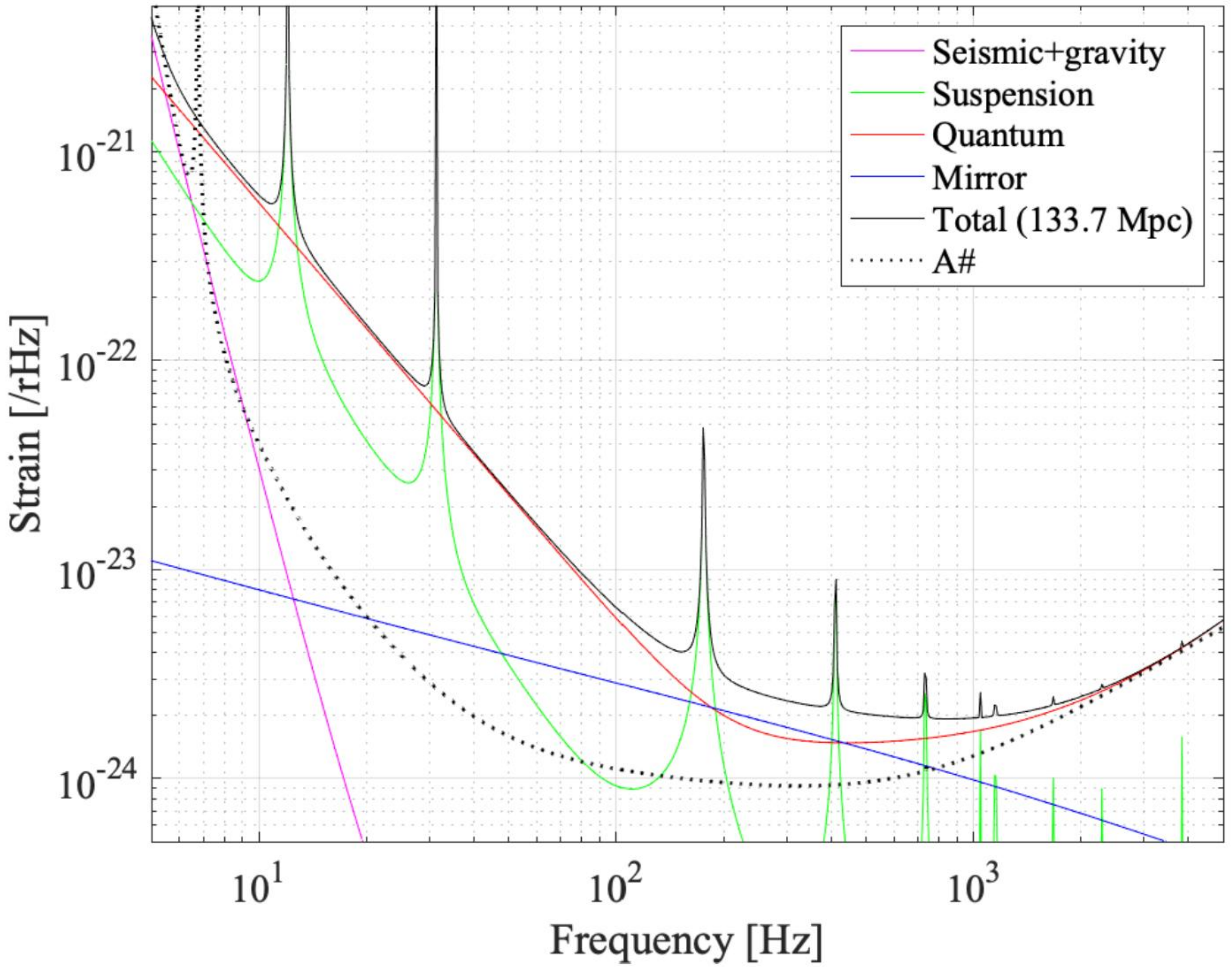


Moderate HF option

HFmodFIS-HQS

Laser Power: 68W -> 150W
SRM: 85% -> 96%
Squeezing: 10dB FIS

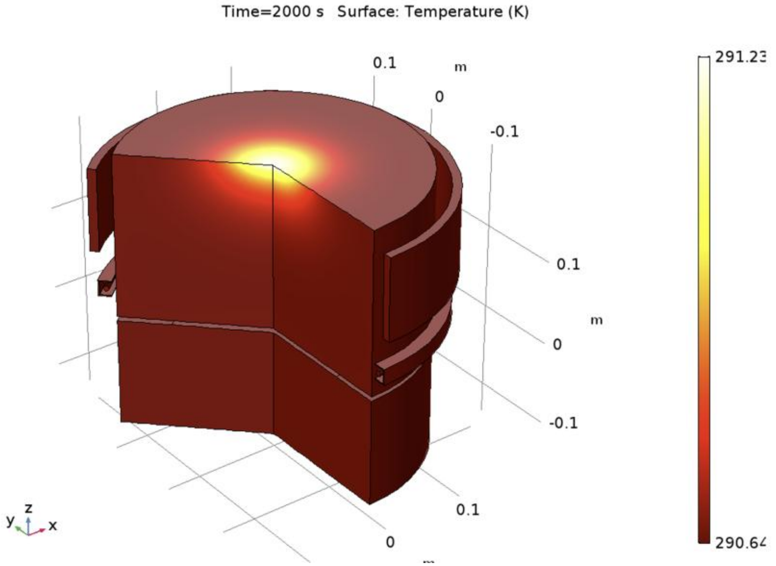
Binary Range: 133.7Mpc



Advantages

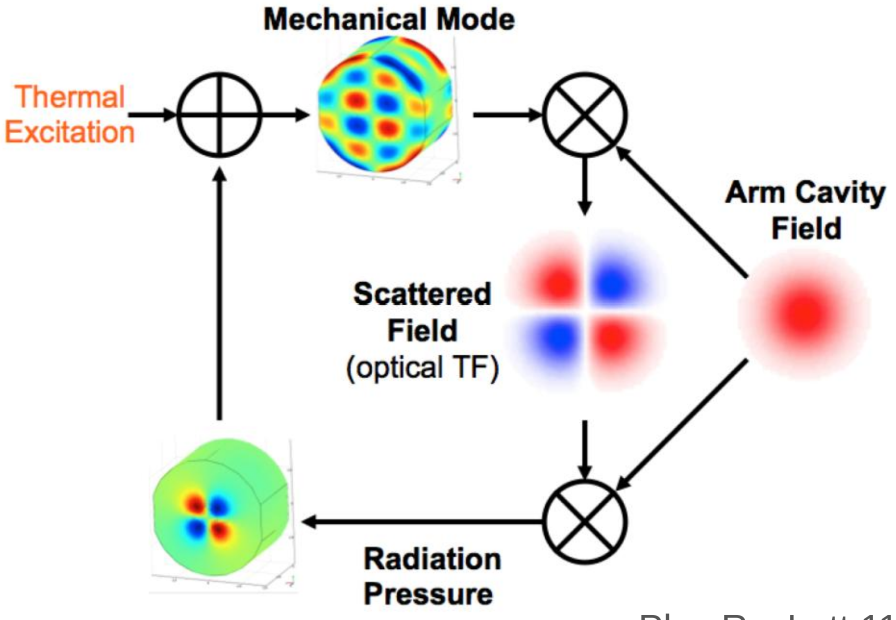
Low Cost

- Small number of upgrade items
  - SRM replacement
  - High Power Laser
  - 10dB squeezing



Low Risk

- High frequency noise is predictable
- Common technologies with A#
  - High Power Laser, Squeezing
- Cryogenic mirrors
  - Negligible thermal lensing
  - Less parametric instability



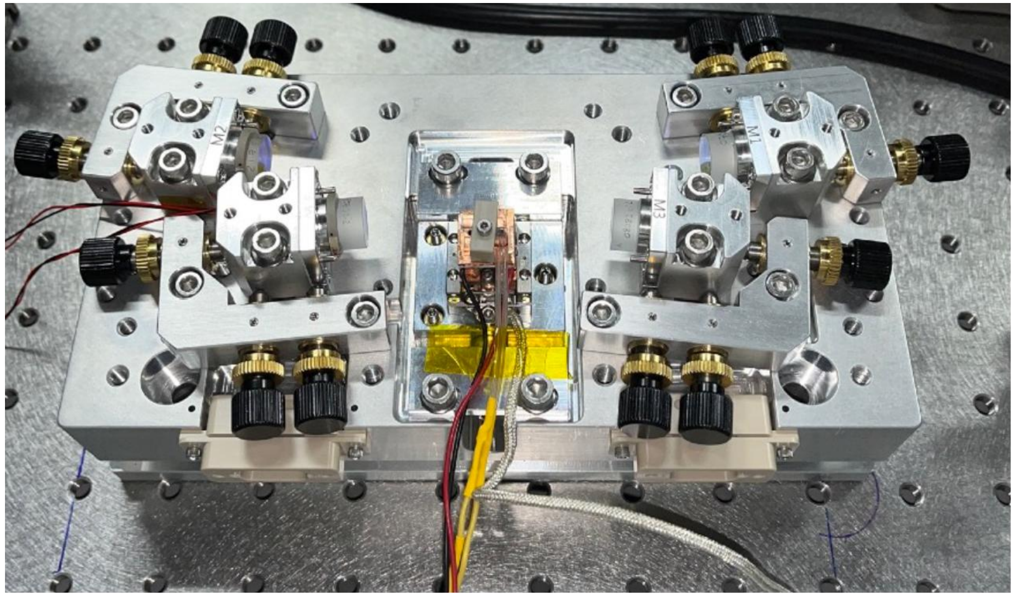
PhysRevLett.114.161102

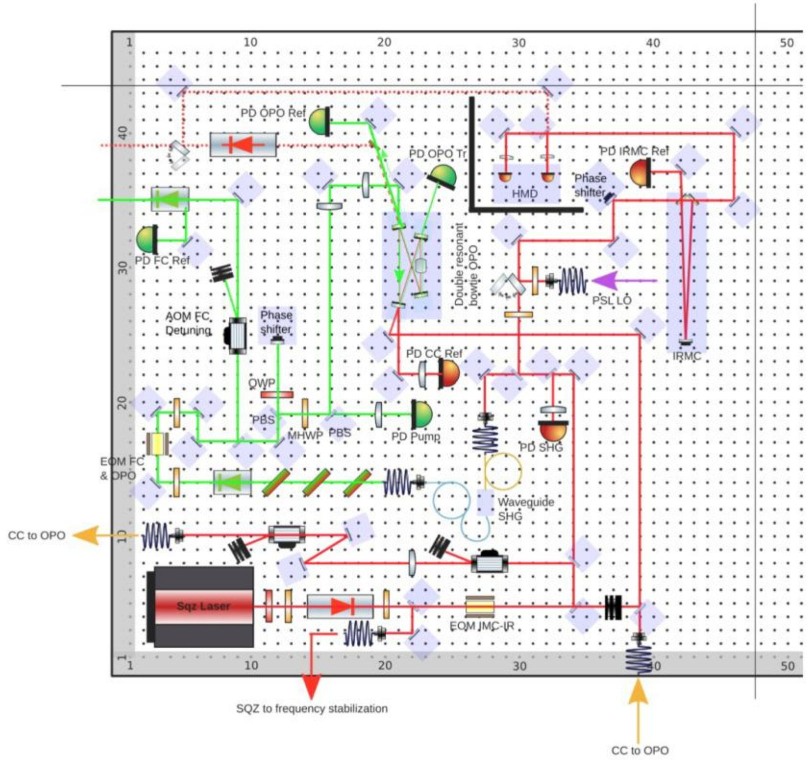
Necessary R&Ds

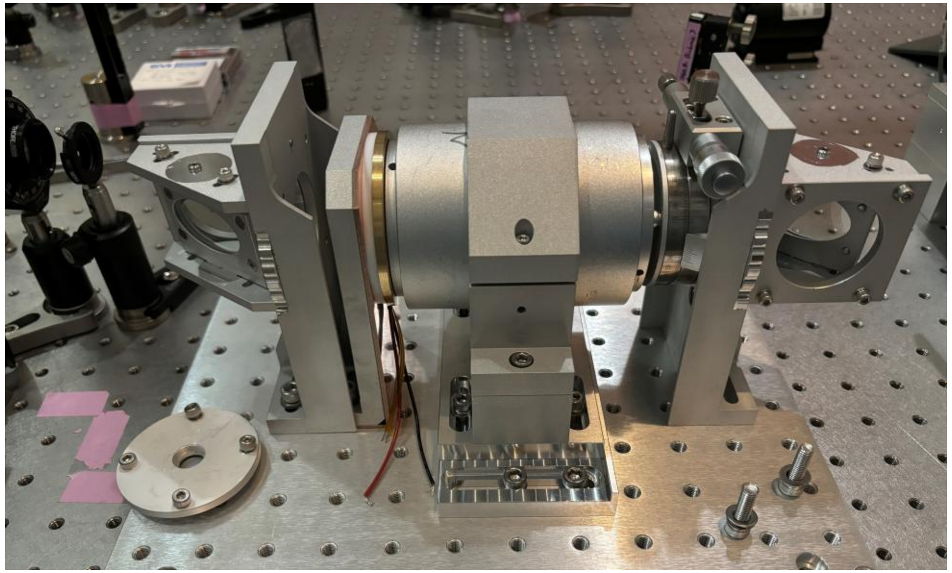
Squeezer

10dB squeezing

- Currently up to 6dB has been realized
- Lower loss and alignment control are the keys to achieve 10dB
- Test using TAMA300







High Power Operation

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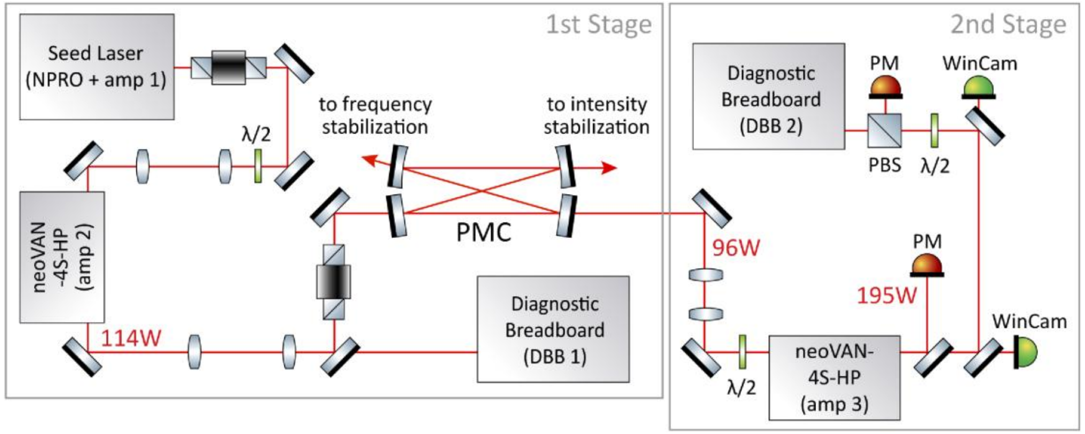


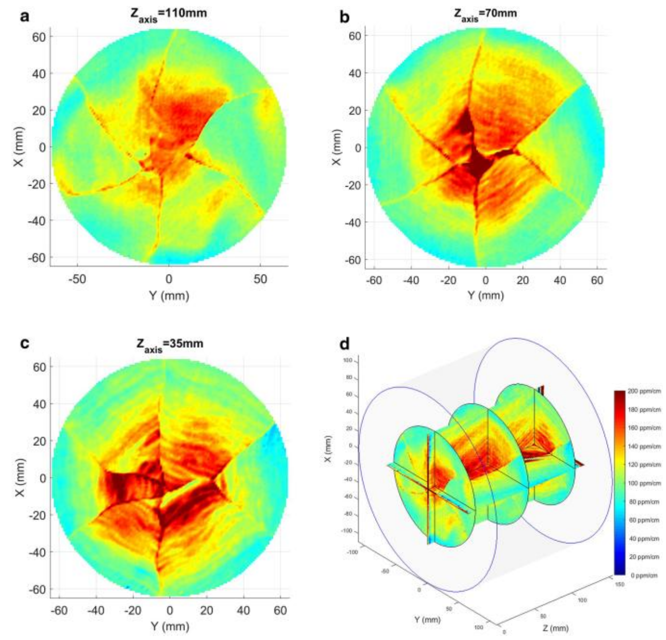
300W Laser

- 195W commercially available
- A little more push necessary

How to cope with 1.3MW circulating power?

Thermal lensing

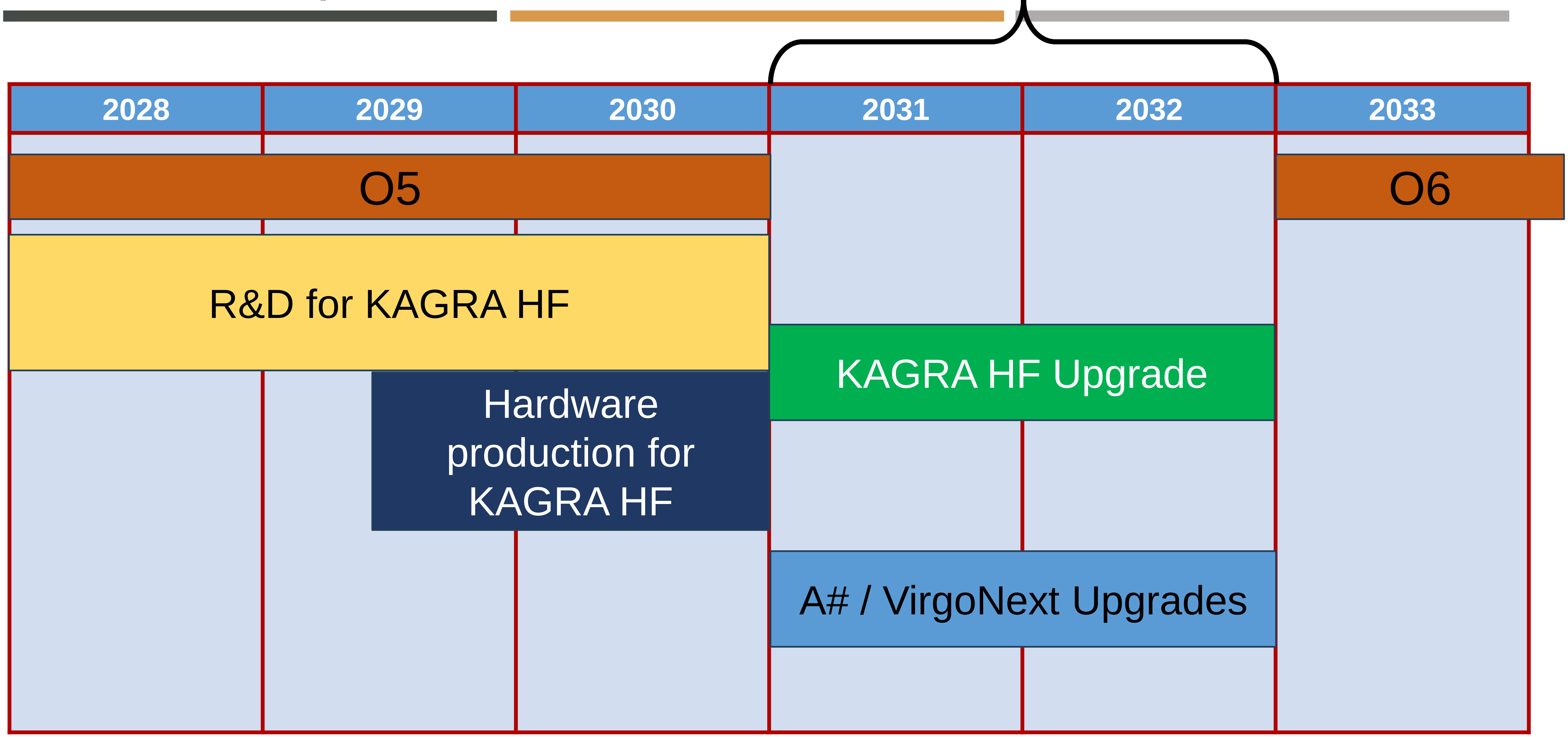
- No problem for cryogenic mirrors
- Room temp. mirrors need attention



Cooling

- Low absorption sapphire crystals
- Thicker fibers -> higher thermal noise
  - Low loss suspension fibers

Roadmap


Highly uncertain
2028
2029
2030
2031
2032
2033
O5
O6
R&D for KAGRA HF
KAGRA HF Upgrade
Hardware production for KAGRA HF
A# / VirgoNext Upgrades

End

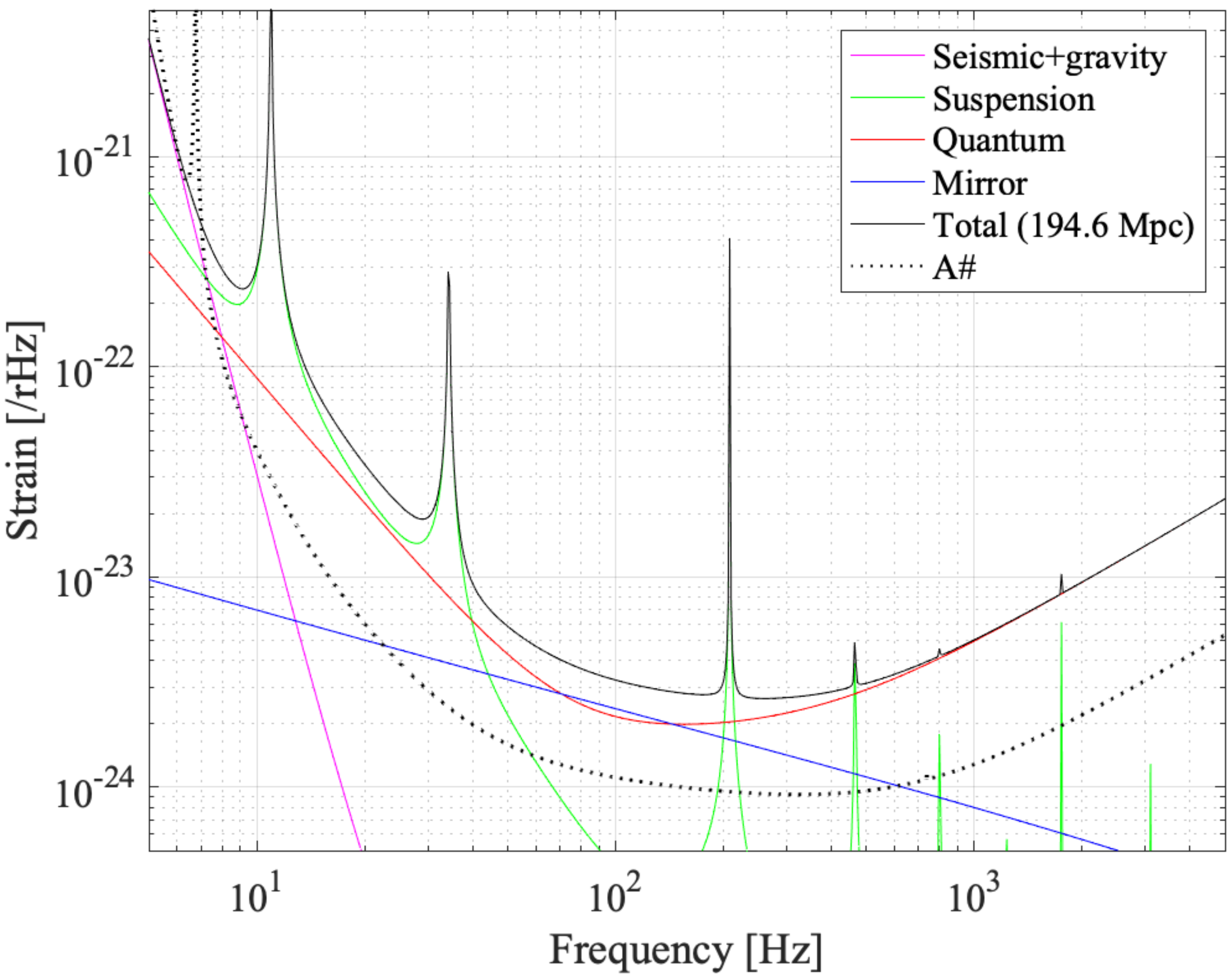
Spare Slides

Broadband Upgrade

BB40FDS-HQS

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB

Binary Range: ~195Mpc

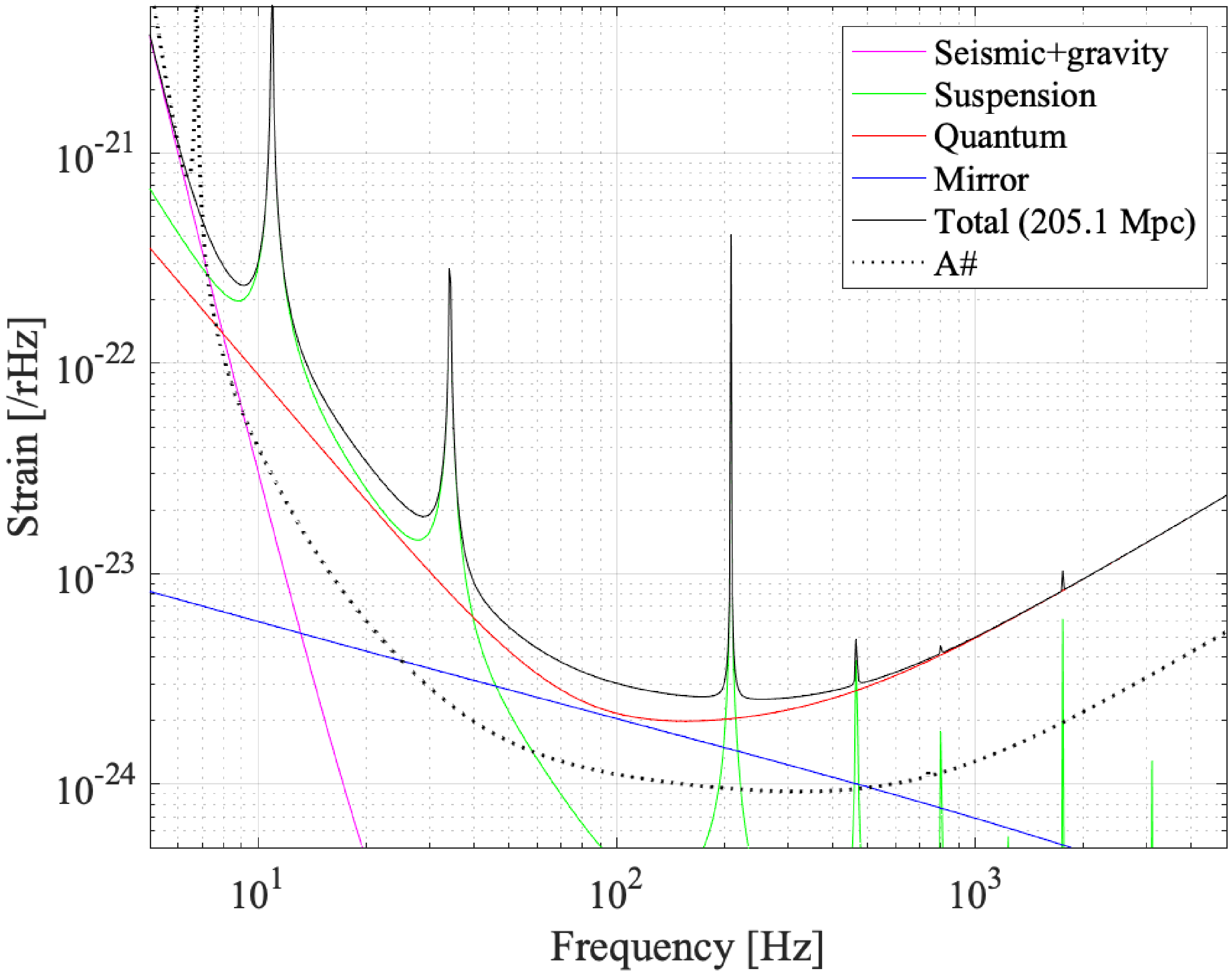


Larger Beam Size

BB40FDS-LB-HQS

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB
Larger Beam: 1.2x

Binary Range: ~205Mpc

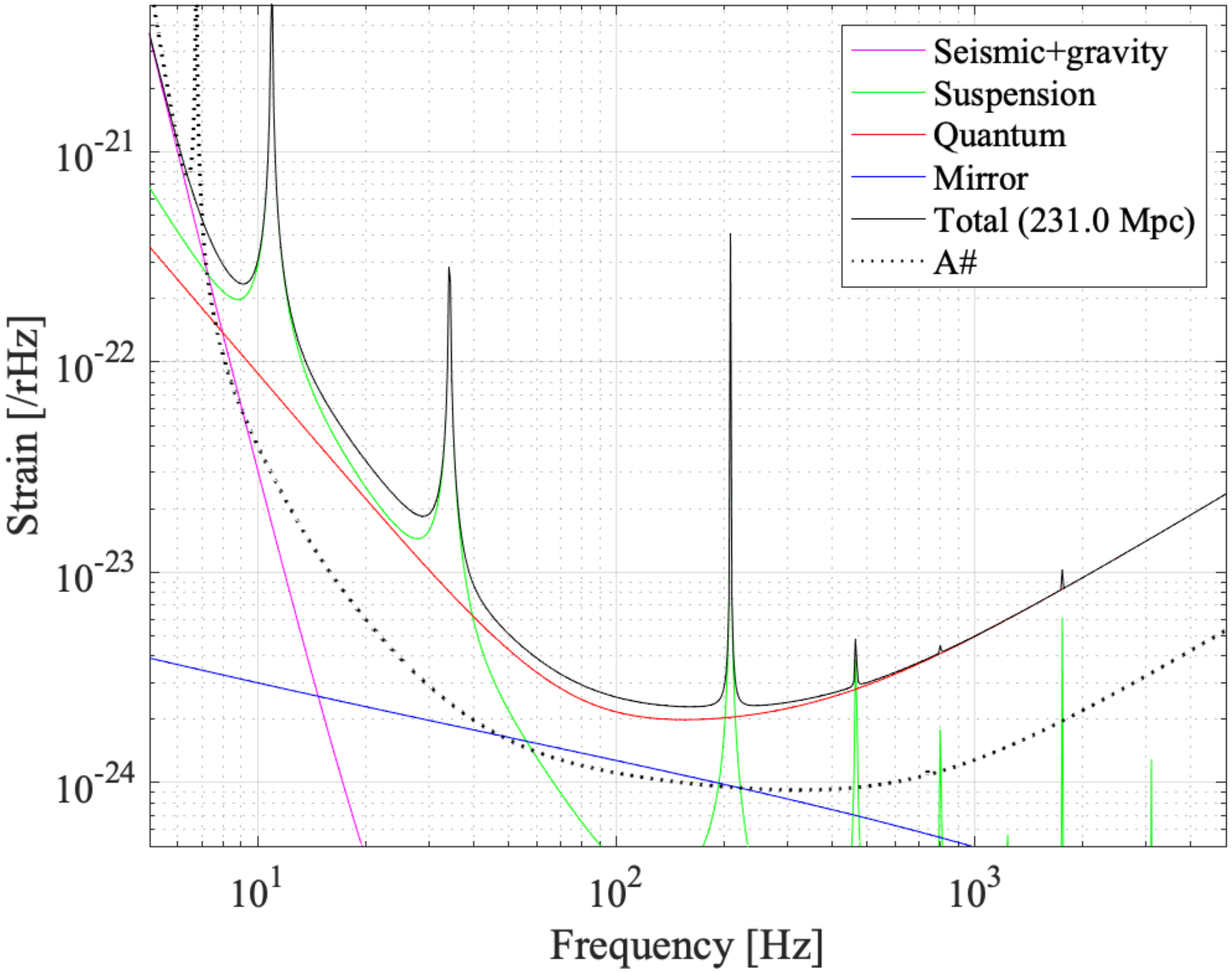


Better Coating

BB40FDS-HQS-BC

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB
AlGaAs Coating: Φ=1e-5

Binary Range: ~231Mpc



What happens with a bad suspension Q

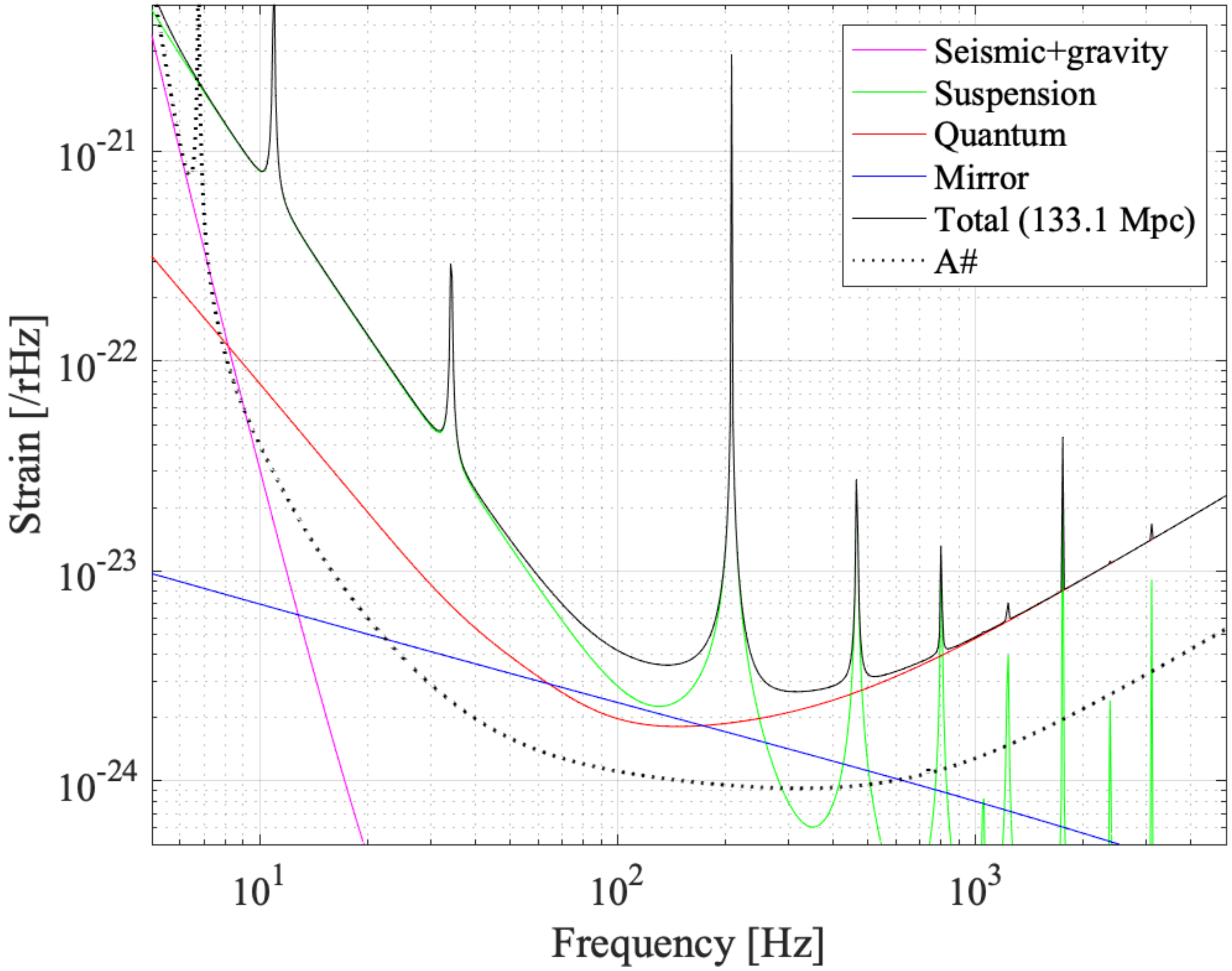
Current sapphire suspension seem to have larger than expected loss

BB40FDS

Larger mirrors: 40kg
Frequency Dependent Squeezing: 6dB
Larger suspension TN

Fiber loss angle: 2e-7 -> 1e-5

Binary Range: ~133Mpc



HF3k

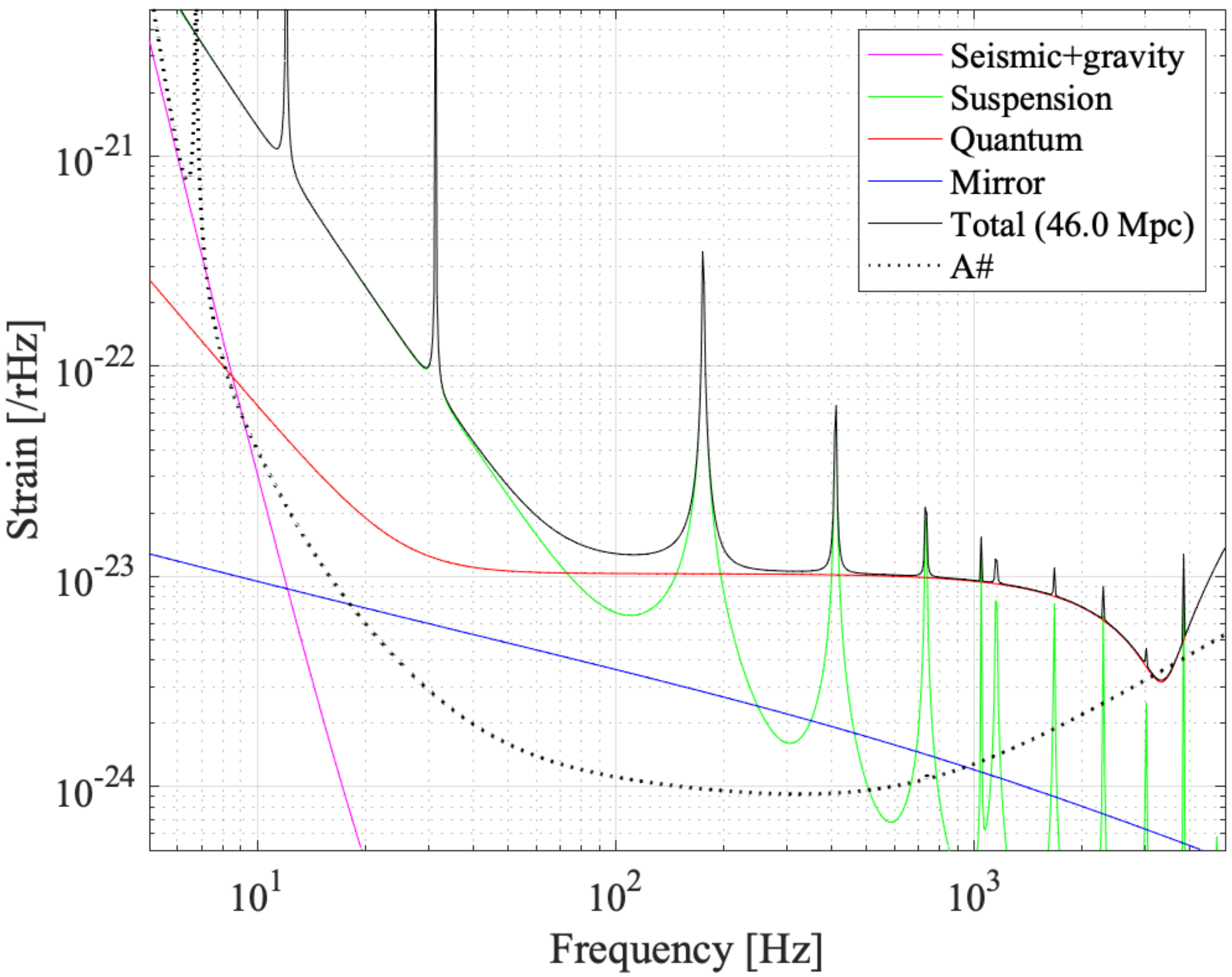
Create a dip in sensitivity around 3kHz

- SRM reflectivity: 85% -> 99.5%
- Mirror temperature: 22K -> 30K
- Suspension loss: 2e-7->1e-5
- Input power: 4x (1.3MW in arm)
- No squeezing

Comparison with A#

- A# assumes AlGaAs coating
  - KAGRA-HF is conventional one
- A# assumes 1.5MW arm power
  - KAGRA-HF: 1.3MW
- A# assumes 10dB FD squeezing

Note:
Binary range is calculated up to the ISCO frequency. Including the merger and post-merger signals may increase the range.



HF3kFIS

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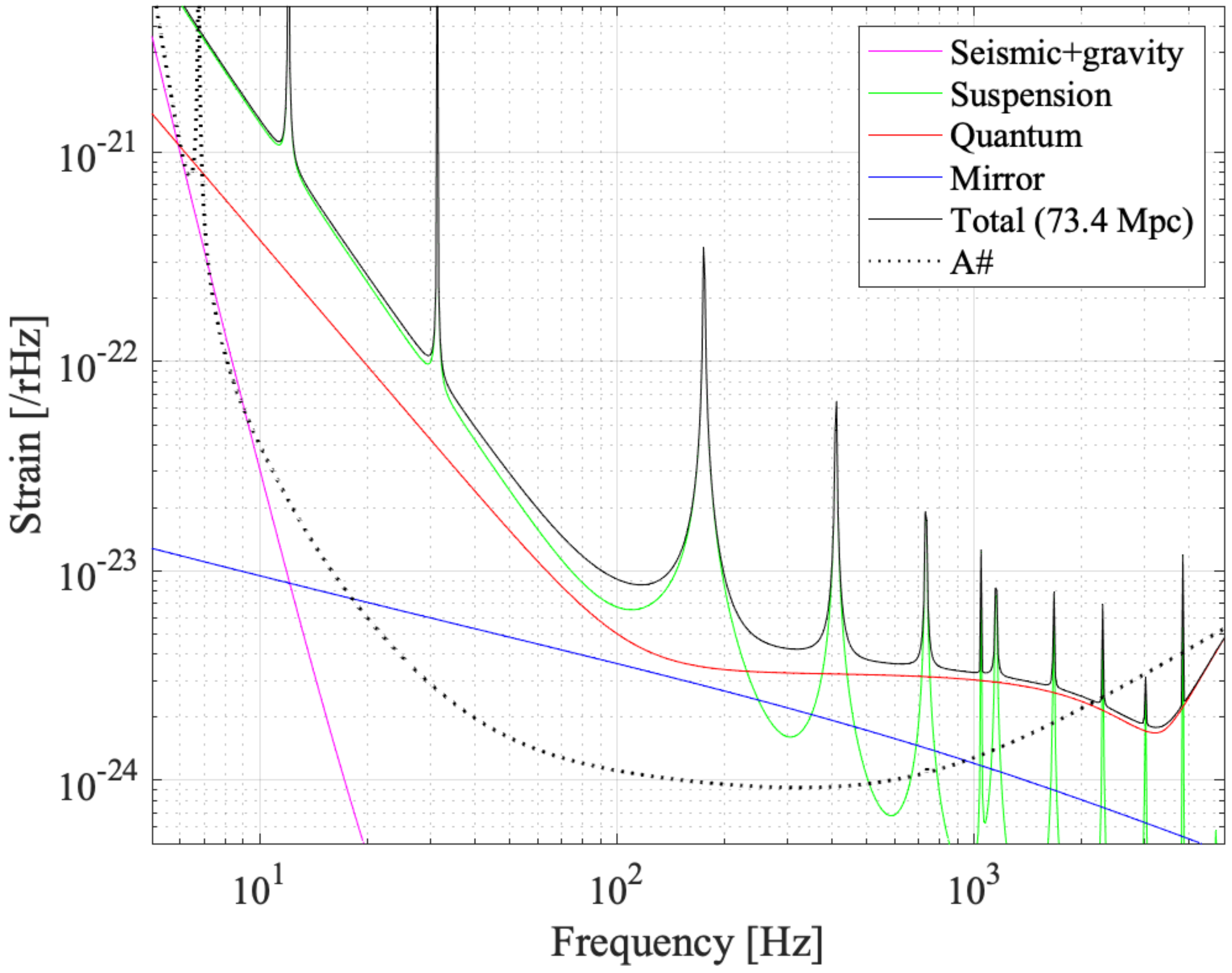
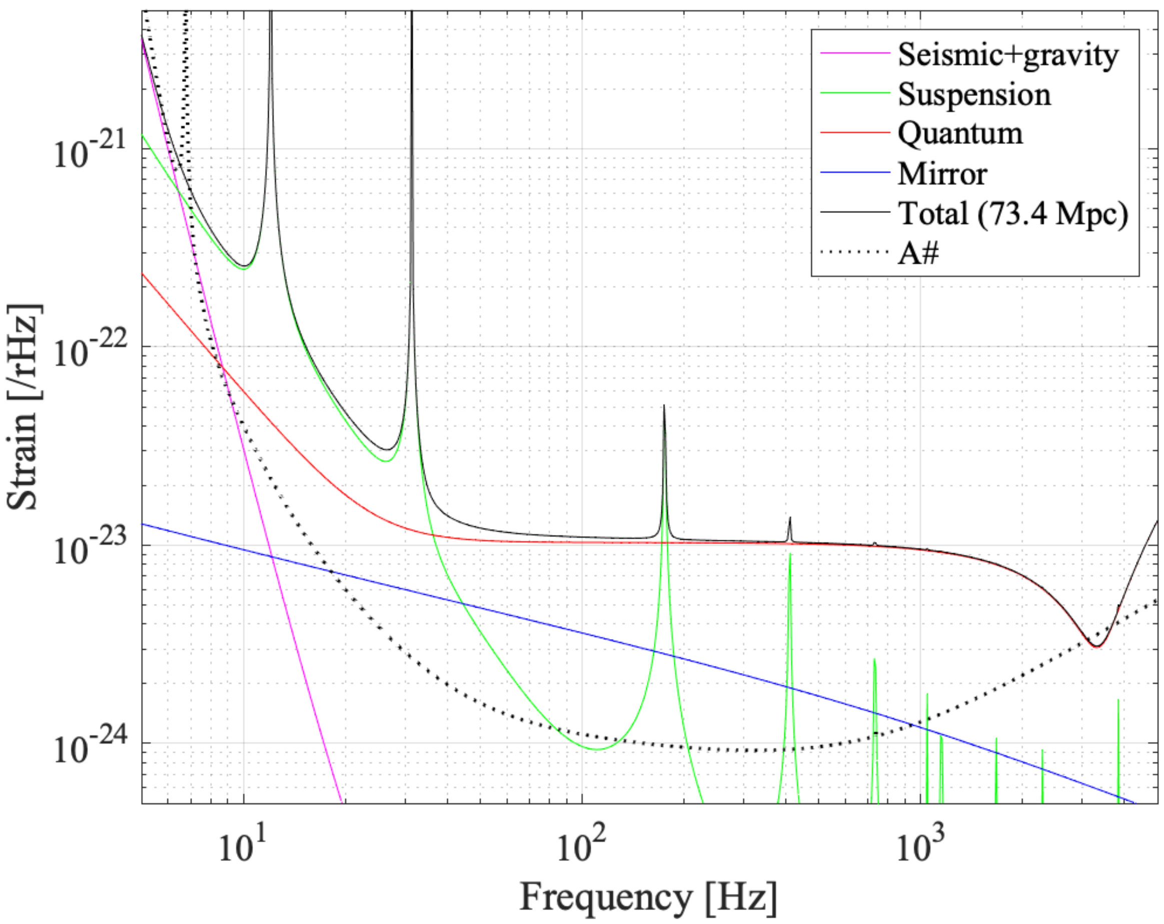
- Suspension loss: 2e-7->1e-5
- Input power: 4x (1.3MW in arm)
- 10dB non-FD squeezing



What if we assume a low suspension loss?

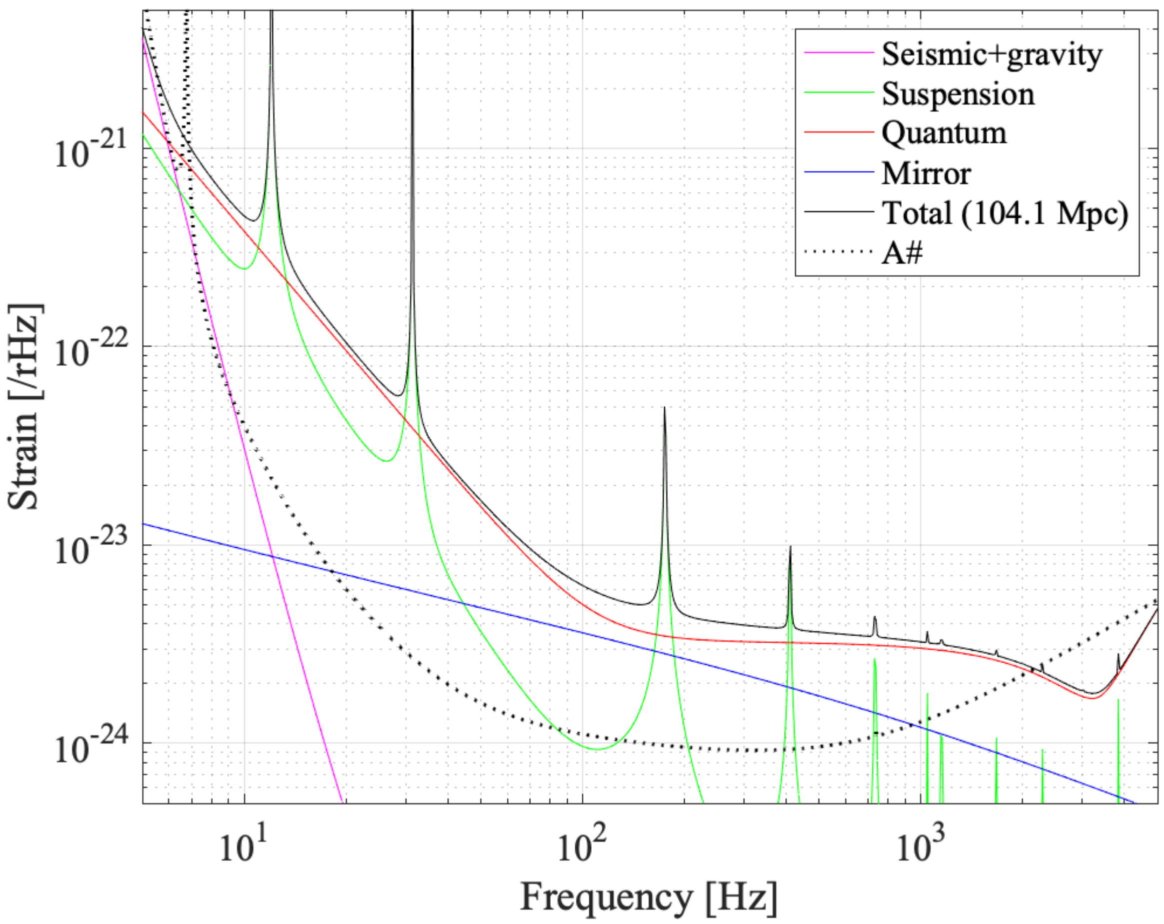
HF3k-HQS

- Suspension loss: 2e-7
- No squeezing



HF3kFIS-HQS

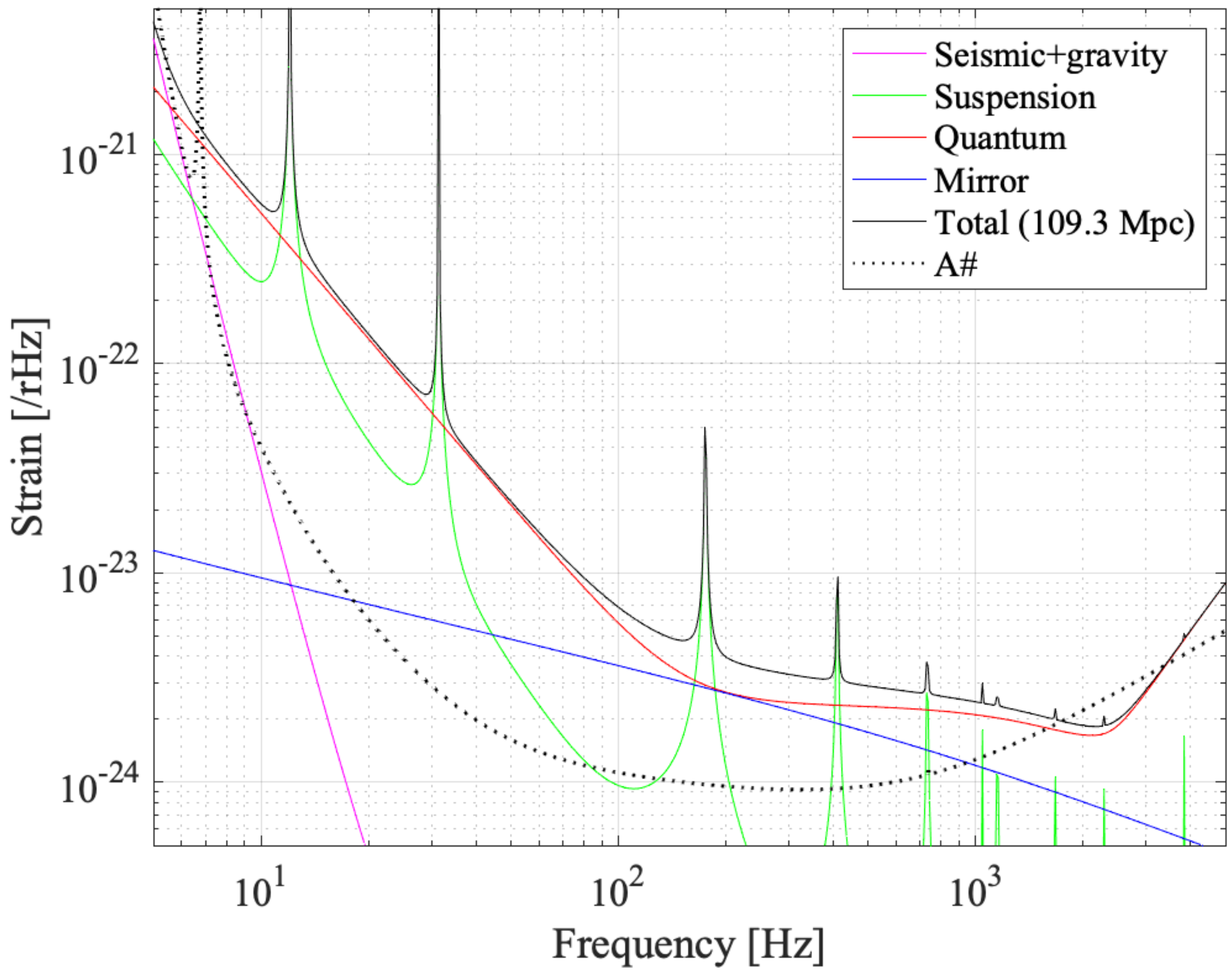
- Suspension loss: 2e-7
- 10dB non-FD squeezing



What if we lower the dip frequency?

- Suspension loss: 2e-7
- 10dB non-FD squeezing
- Higher ITM reflectivity: 99.6% -> 99.8%

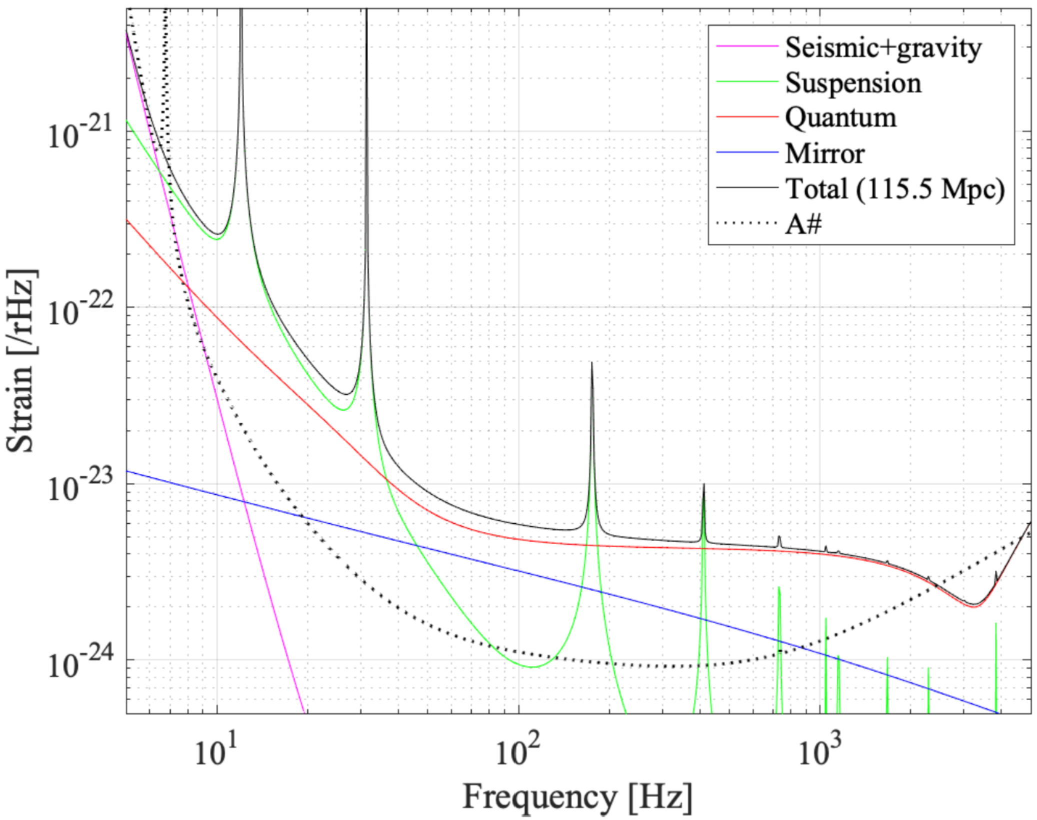
HF2kFIS-HQS



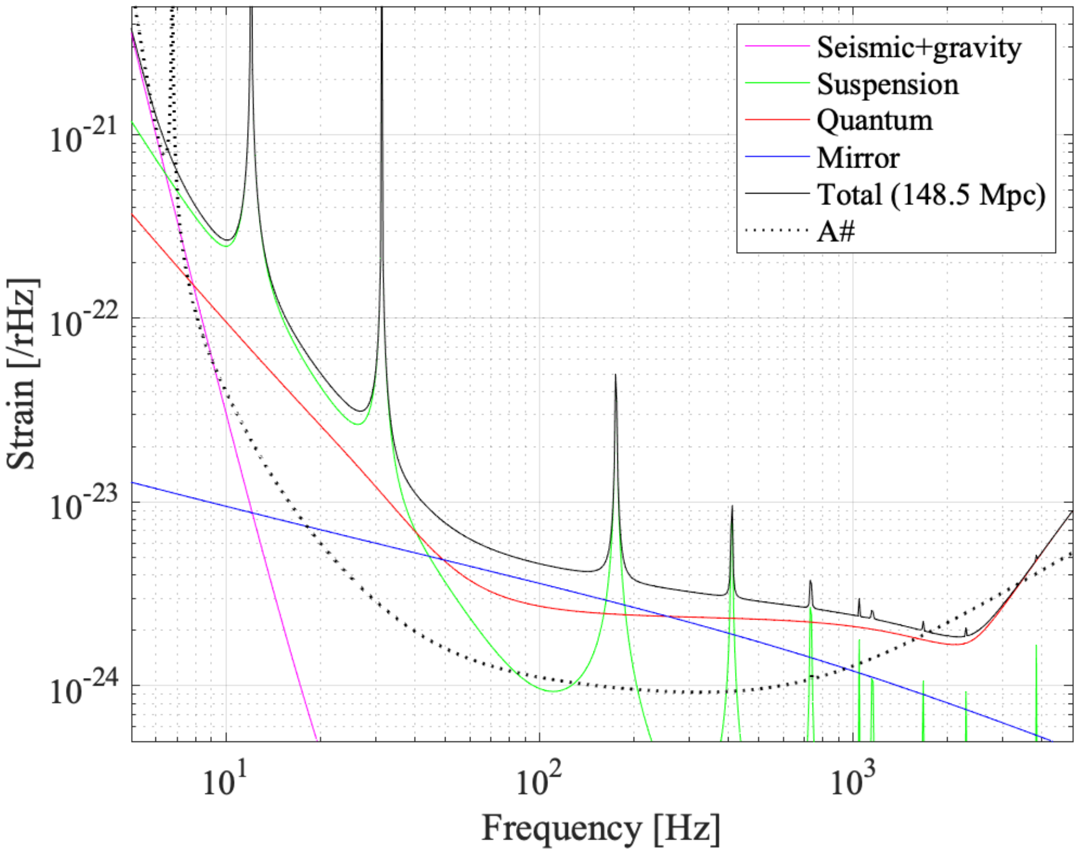
What if we use FD SQZ?

- Low suspension thermal assumed
- 10dB FD squeezing

HF3kFDS-HQS



HF2kFDS-HQS



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Squeezing: 10dB FIS