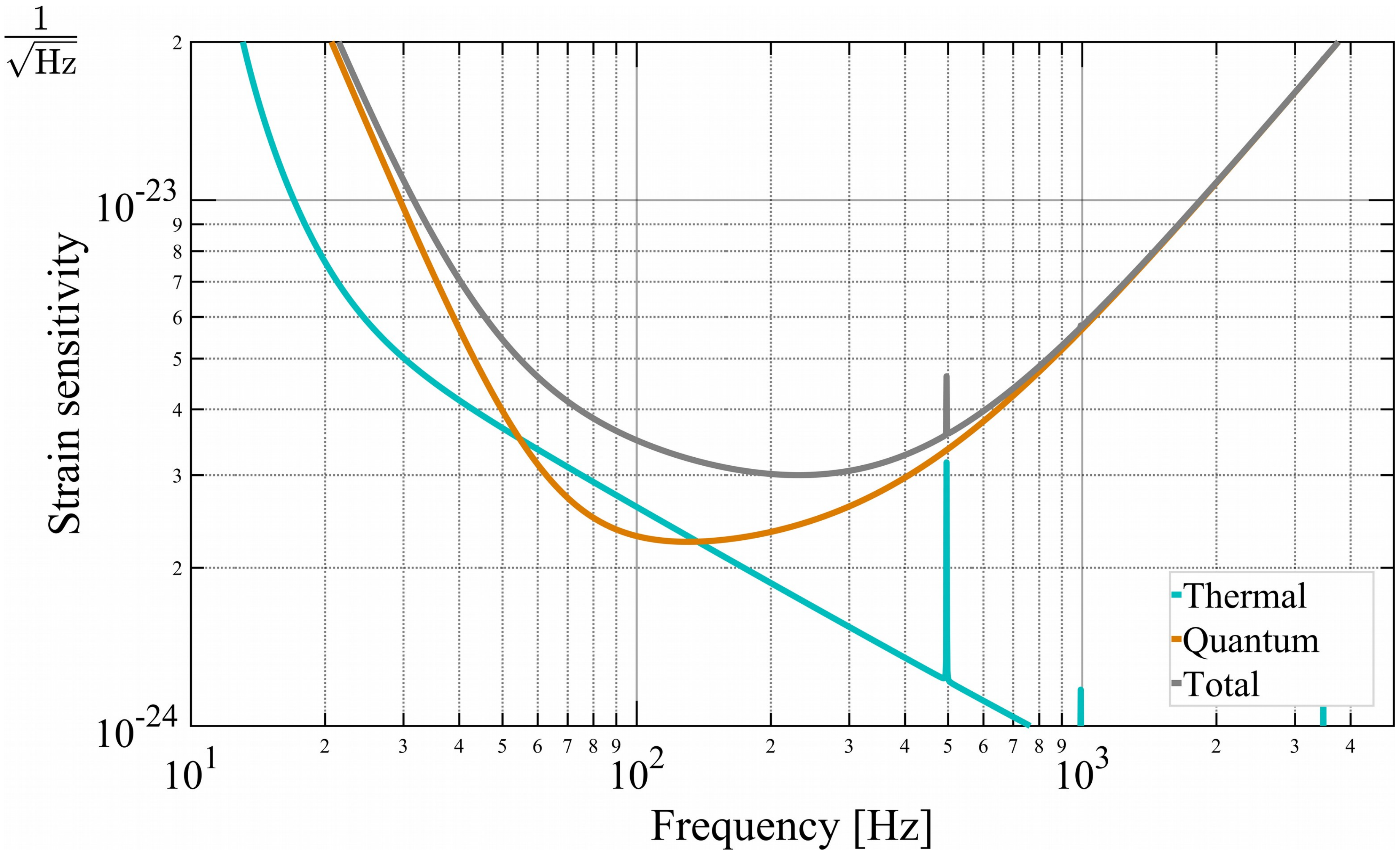
Squeezed states of light for Advanced LIGO and beyond

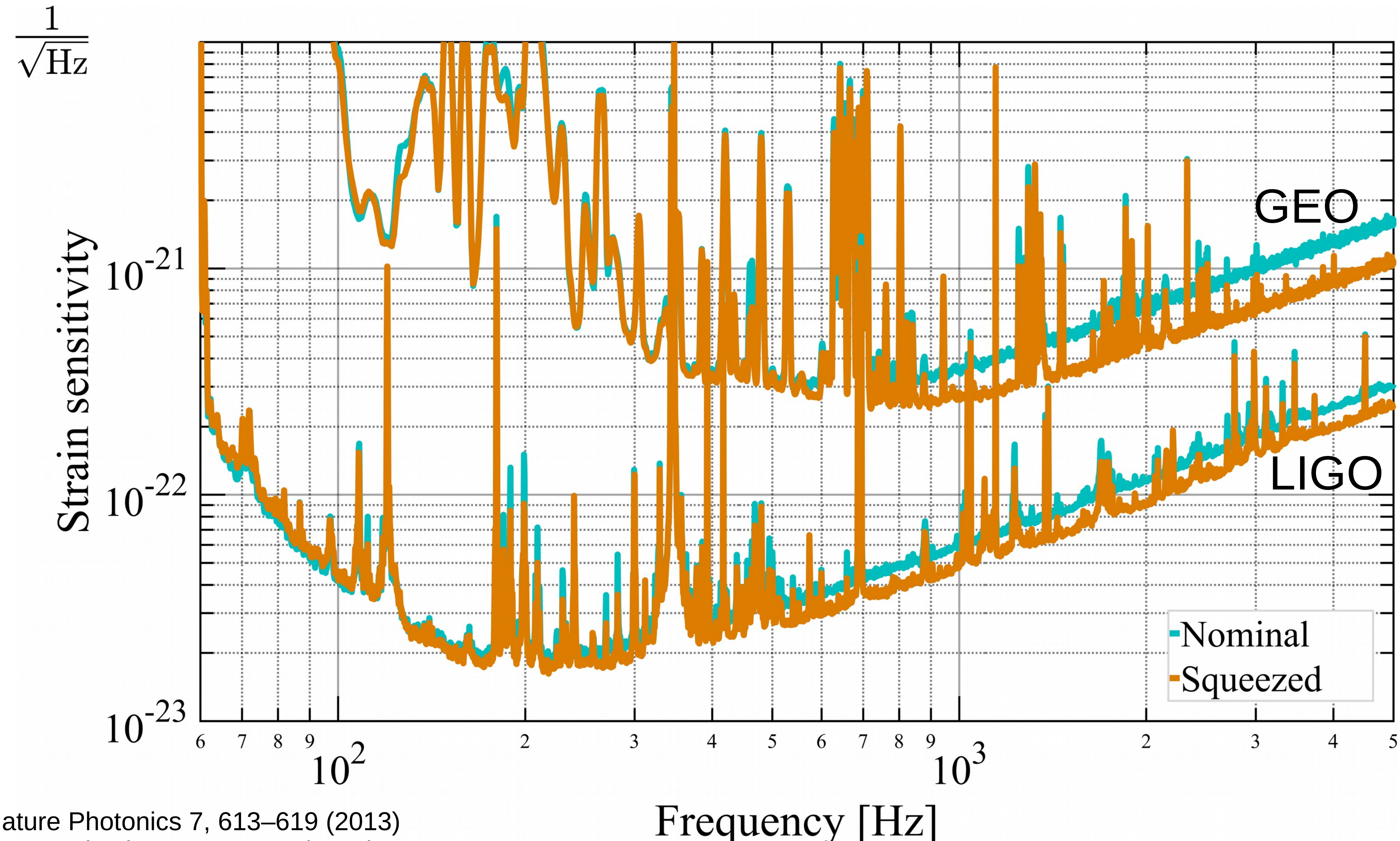
John Miller et al.
LIGO Laboratory, MIT

GR21, 14 July 2016

Quantum noise dominates



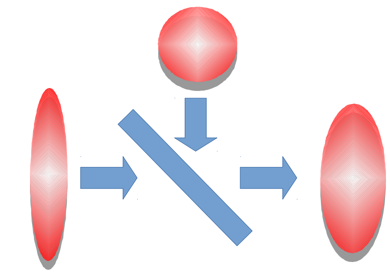
Squeezing works...



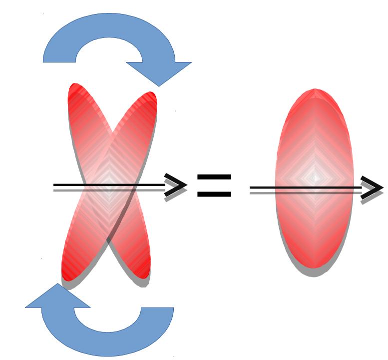
Nature Photonics 7, 613–619 (2013)
Nature Physics 7, 962–965 (2011)

...but

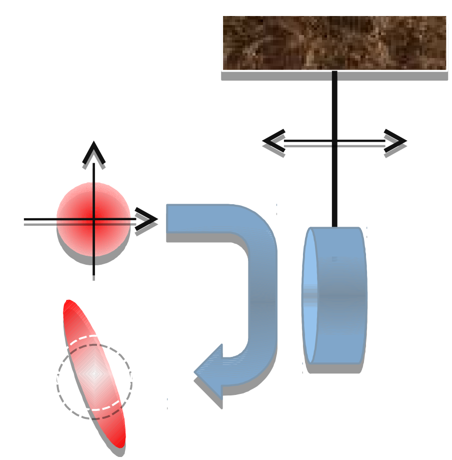
- Losses
  - OPO, Faraday isolators (backscatter), alignment, mode matching, OMC, photodiodes



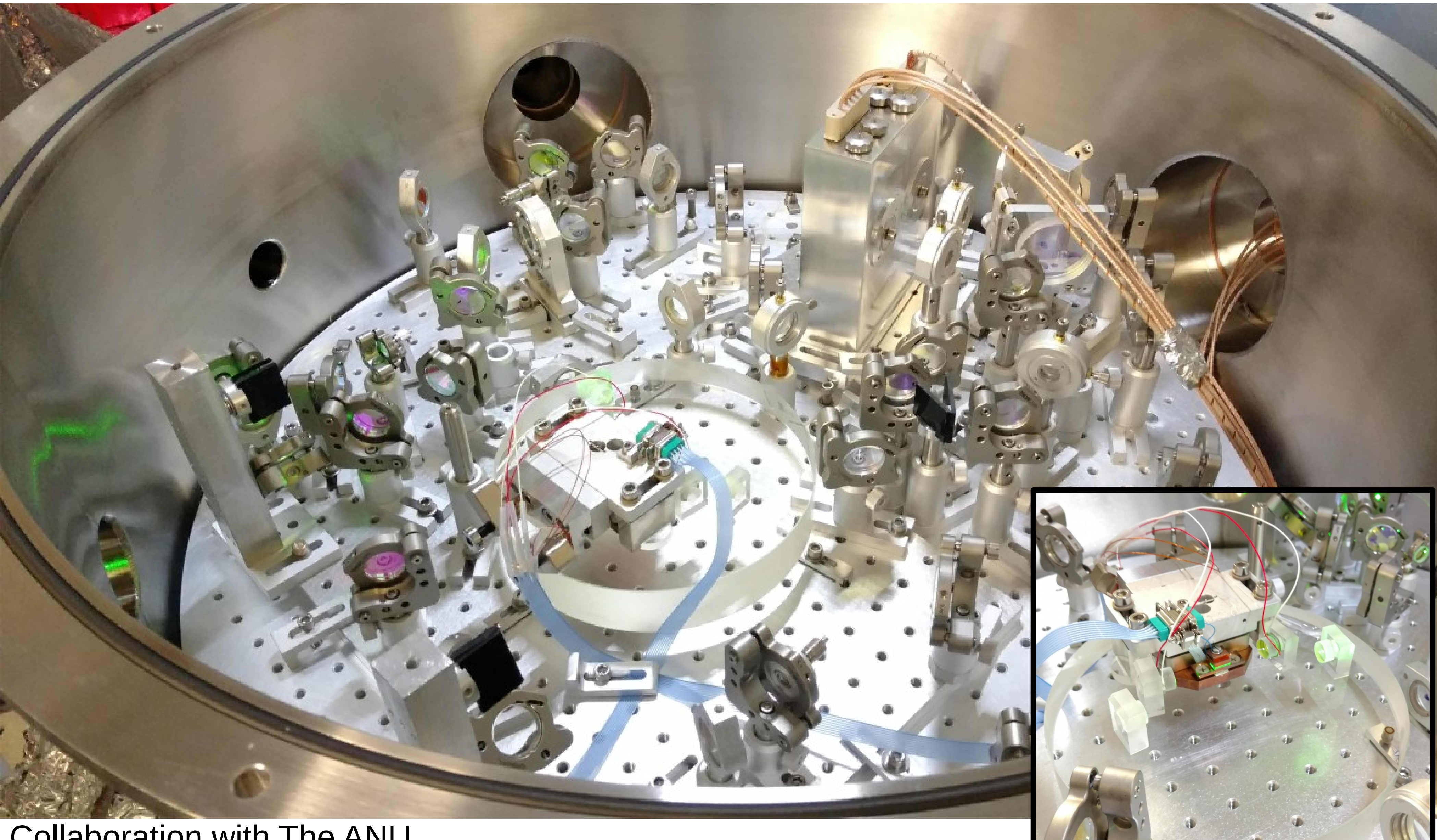
- Phase noise
  - Unwanted/residual motion of optics, PLL, CLF offset in frequency, finite bandwidth



- Control issues
  - Long term drifts, alignment,...
- Radiation pressure noise
  - Squeezed quadrature must rotate with frequency

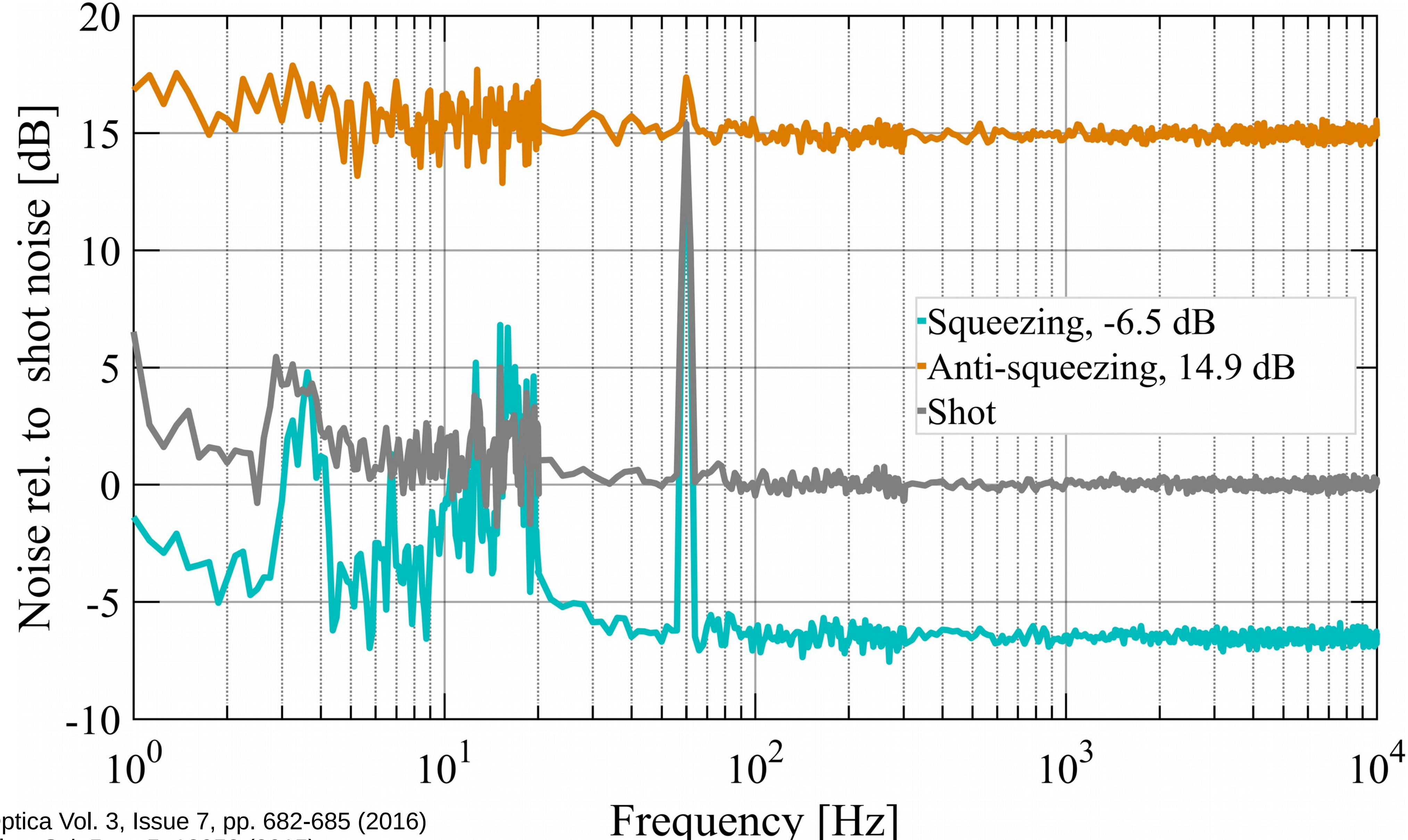


Current status



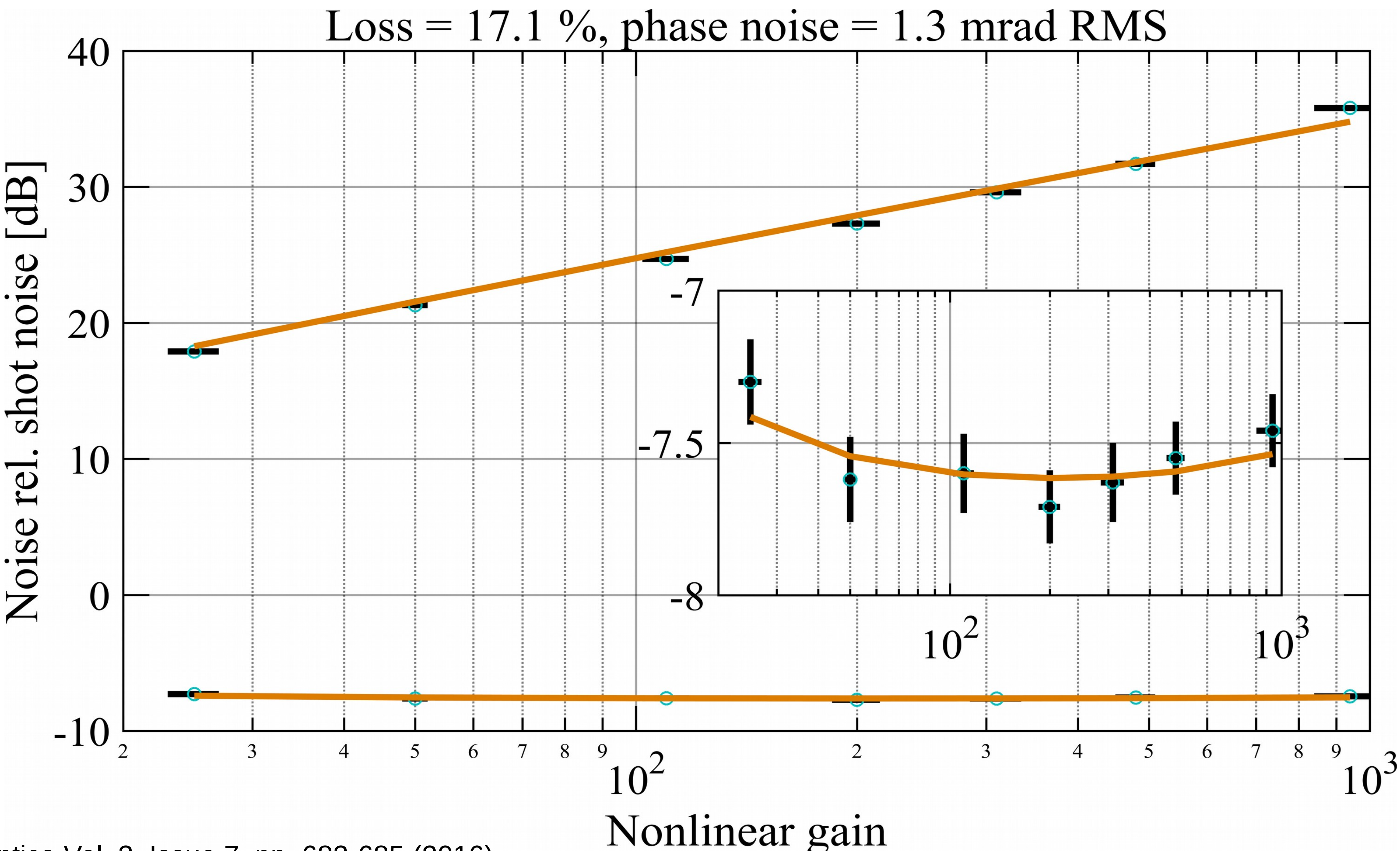
Collaboration with The ANU

In-vacuum squeezing



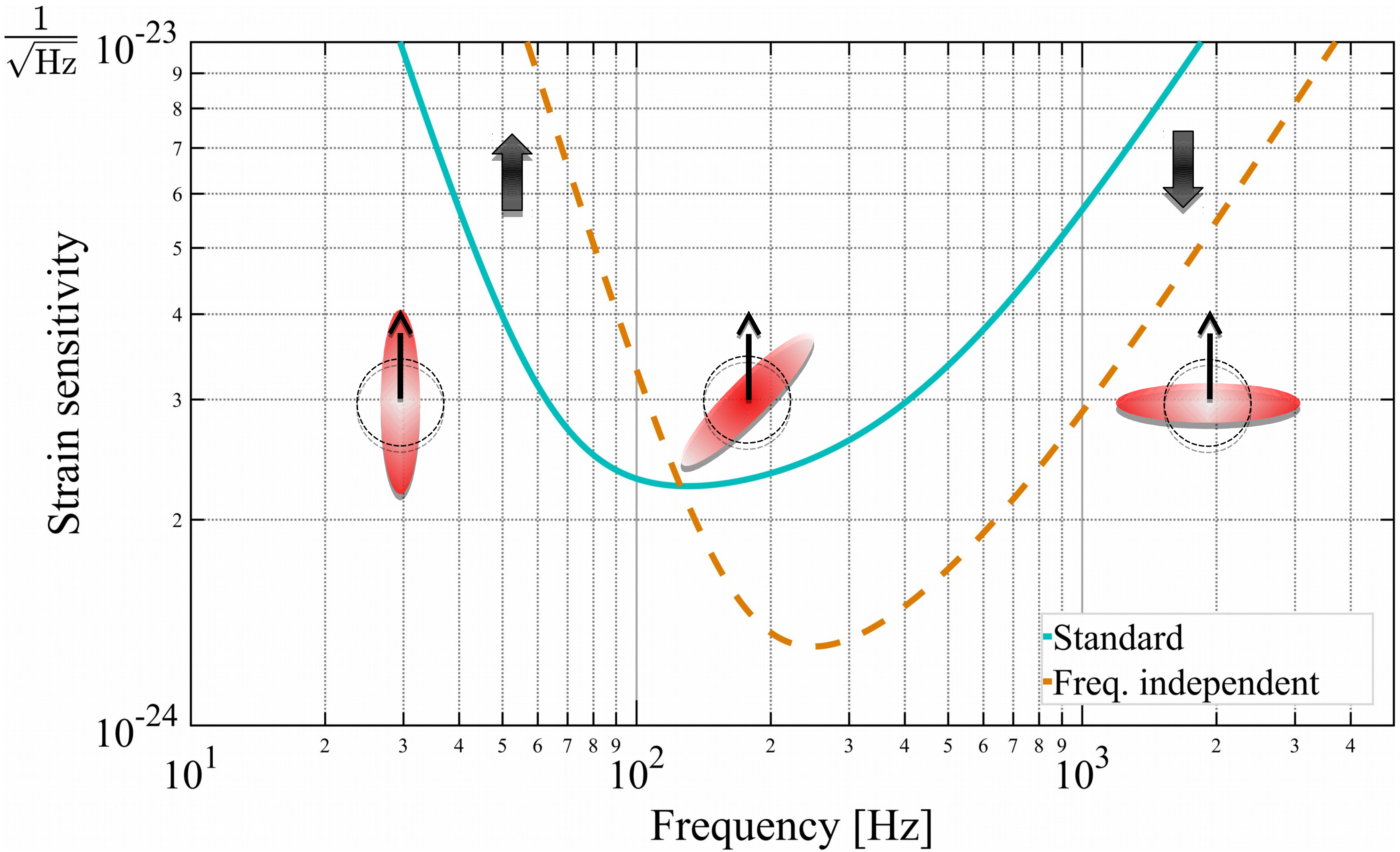
Optica Vol. 3, Issue 7, pp. 682-685 (2016)
Also, Sci. Rep. 5, 18052 (2015)

Ultra-low phase noise (in air)

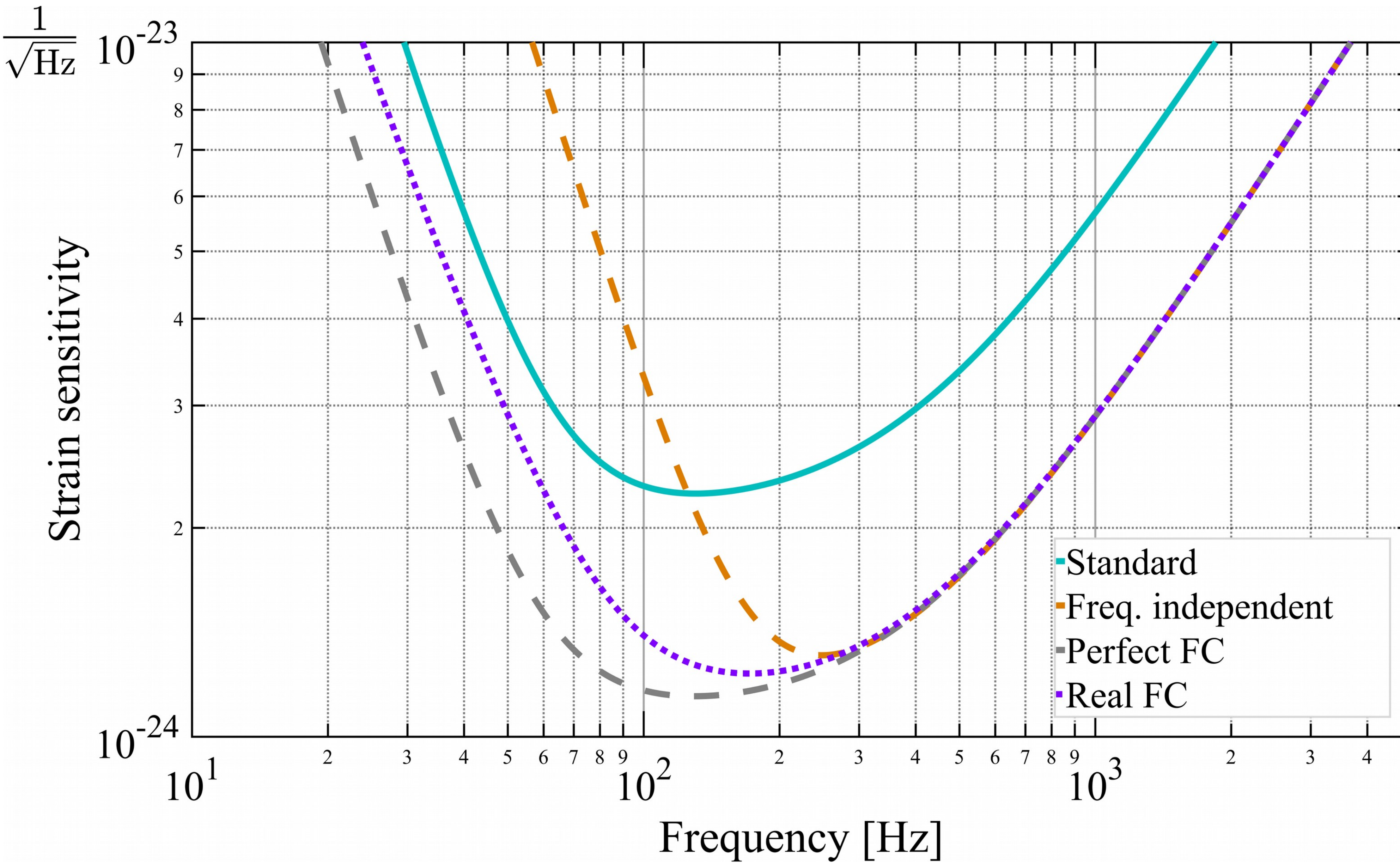


Optica Vol. 3, Issue 7, pp. 682-685 (2016)

The anti-squeezing problem

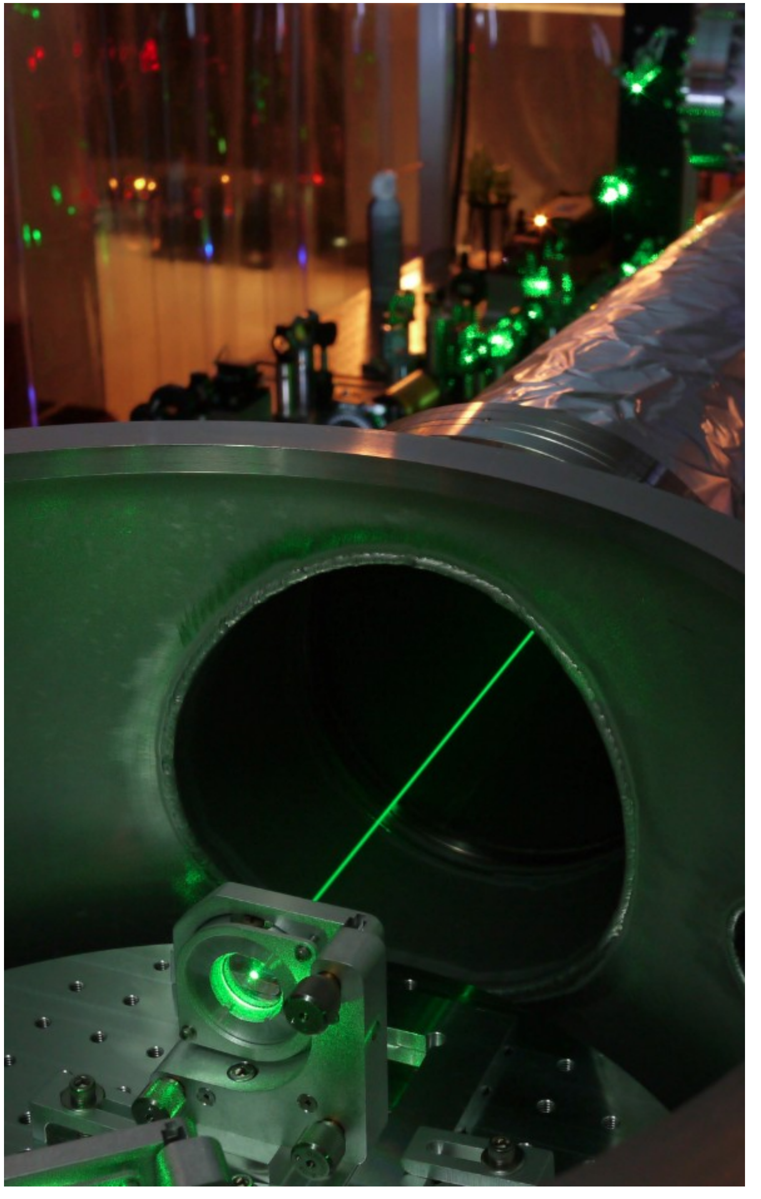


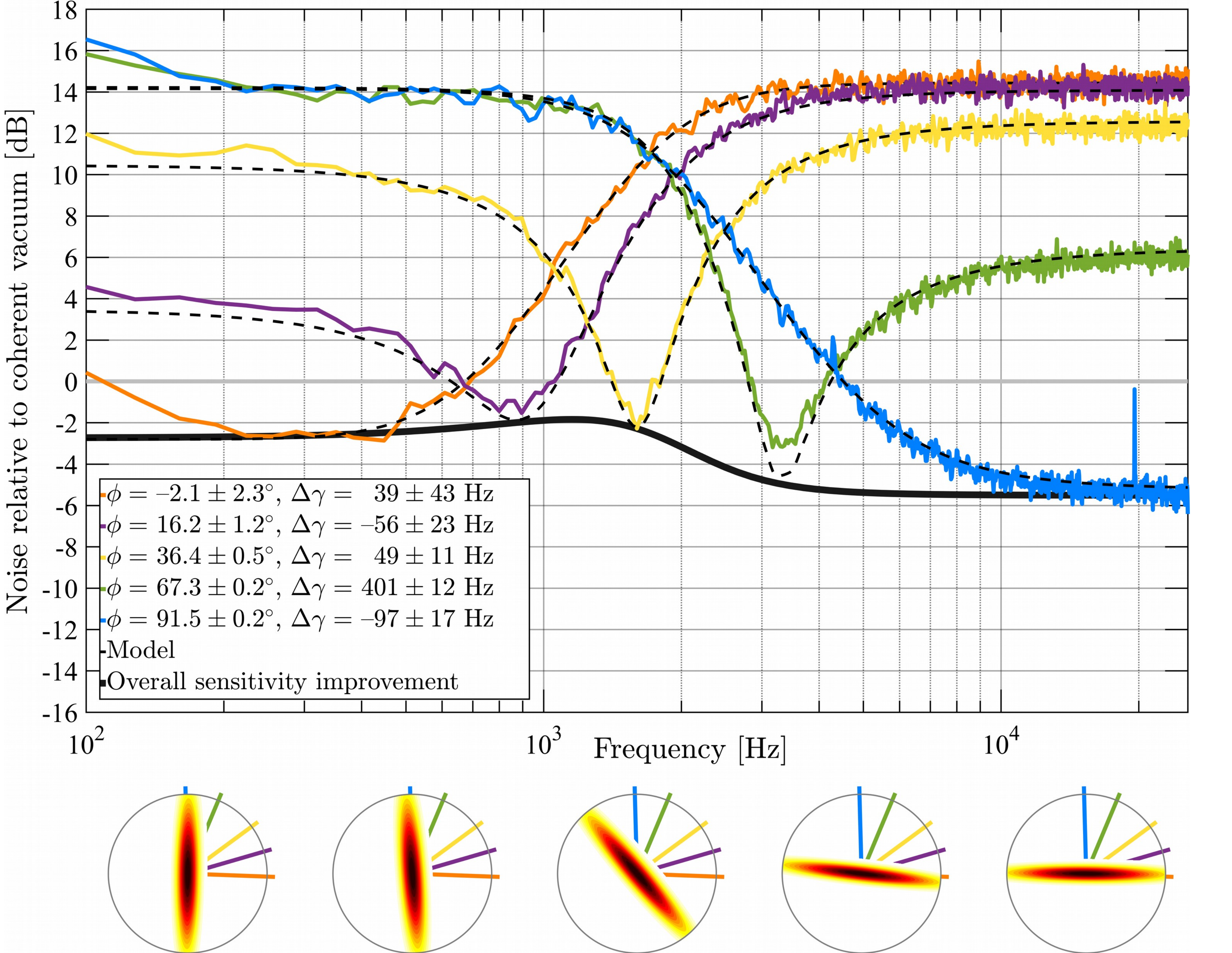
The anti-squeezing problem



Filter cavity

- Quantify and extrapolate losses
    - Isogai et al., Opt. Exp. Vol. 21, Issue 24, pp. 30114 (2013)
- Modelled noise sources
    - Kwee et al. Phys. Rev. D 90, 062006 (2014)
- Audio-band rotation with 2m cavity
    - Oelker et al. PRL 116, 041102 (2016)

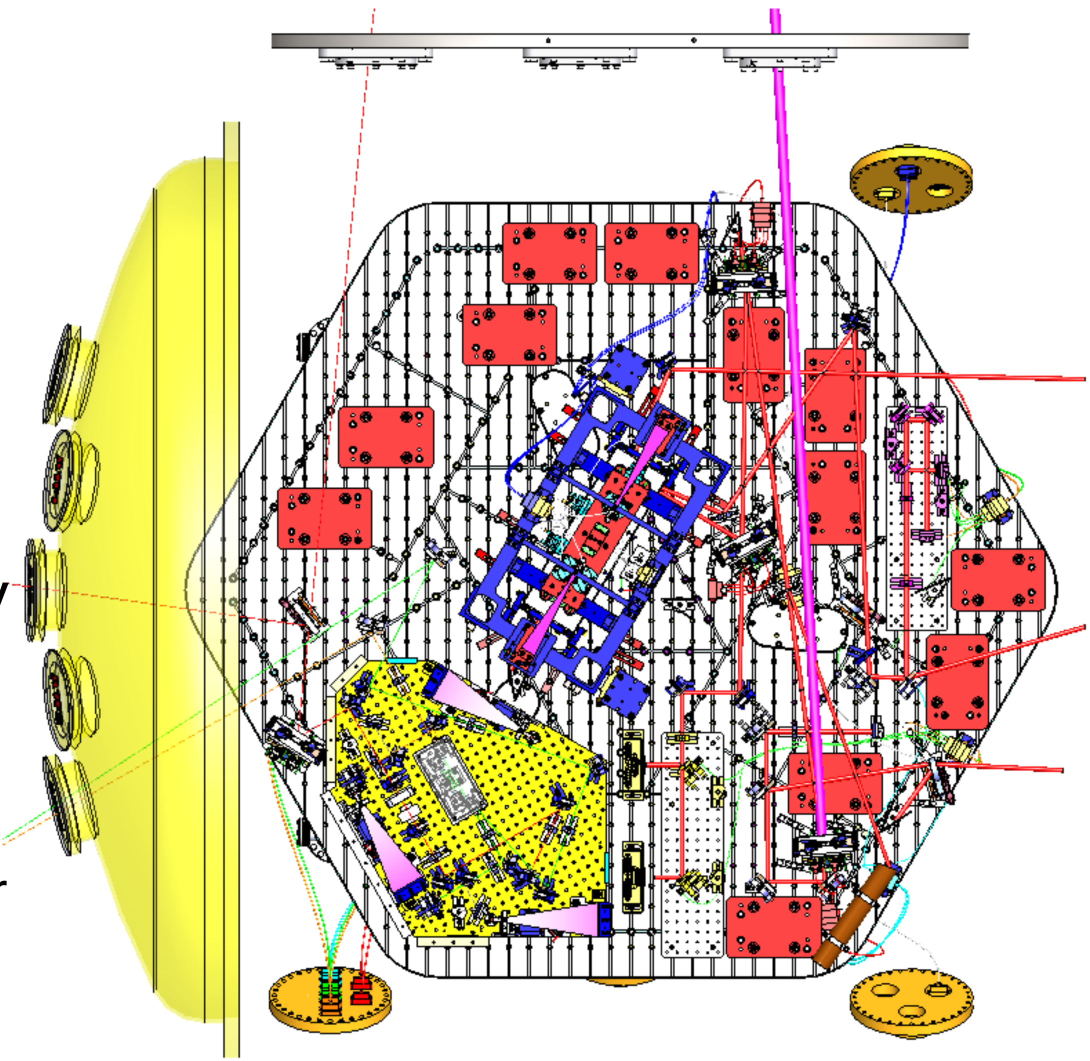




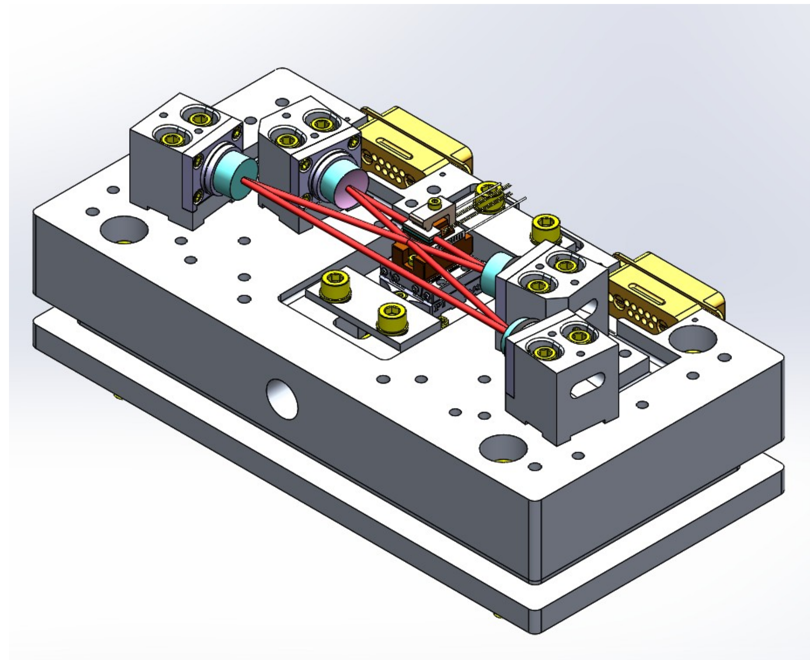
Noise relative to coherent vacuum [dB]
Frequency [Hz]
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
10^2
10^3
10^4
$\phi = -2.1 \pm 2.3°$, $\Delta\gamma = 39 \pm 43$ Hz
$\phi = 16.2 \pm 1.2°$, $\Delta\gamma = -56 \pm 23$ Hz
$\phi = 36.4 \pm 0.5°$, $\Delta\gamma = 49 \pm 11$ Hz
$\phi = 67.3 \pm 0.2°$, $\Delta\gamma = 401 \pm 12$ Hz
$\phi = 91.5 \pm 0.2°$, $\Delta\gamma = -97 \pm 17$ Hz
Model
Overall sensitivity improvement

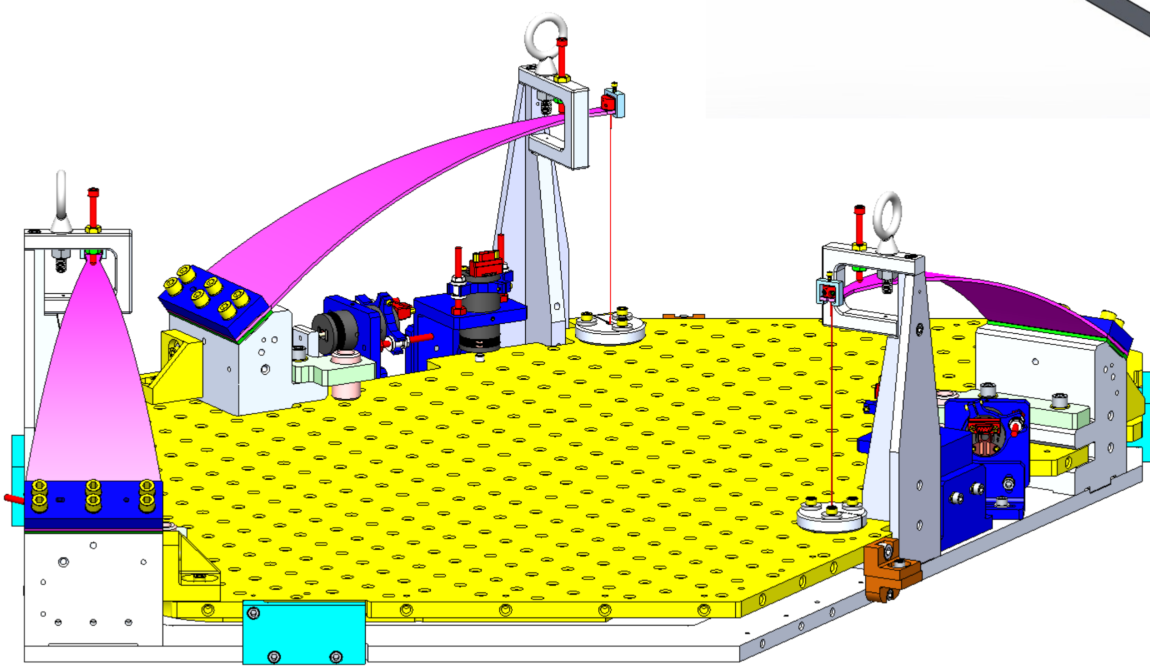
Toward squeezing in aLIGO

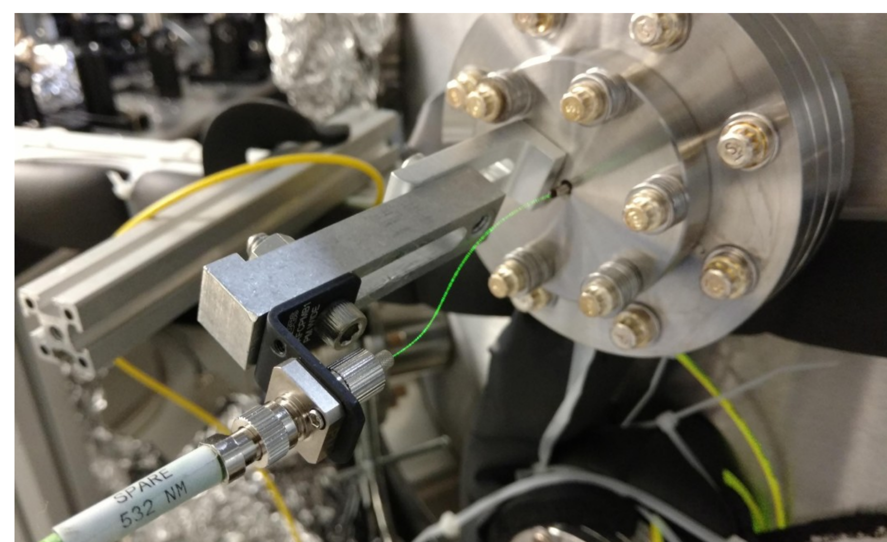
- Three activities
  - A new squeezed light source
    - In vacuum
    - Suspended
    - Fibre coupled
  - Investigating 16 m filter cavity
    - Accommodated within existing vacuum system
    - No low-f improvement but research is applicable to longer cavities
    - Integrate with squeezer
  - Active wavefront control



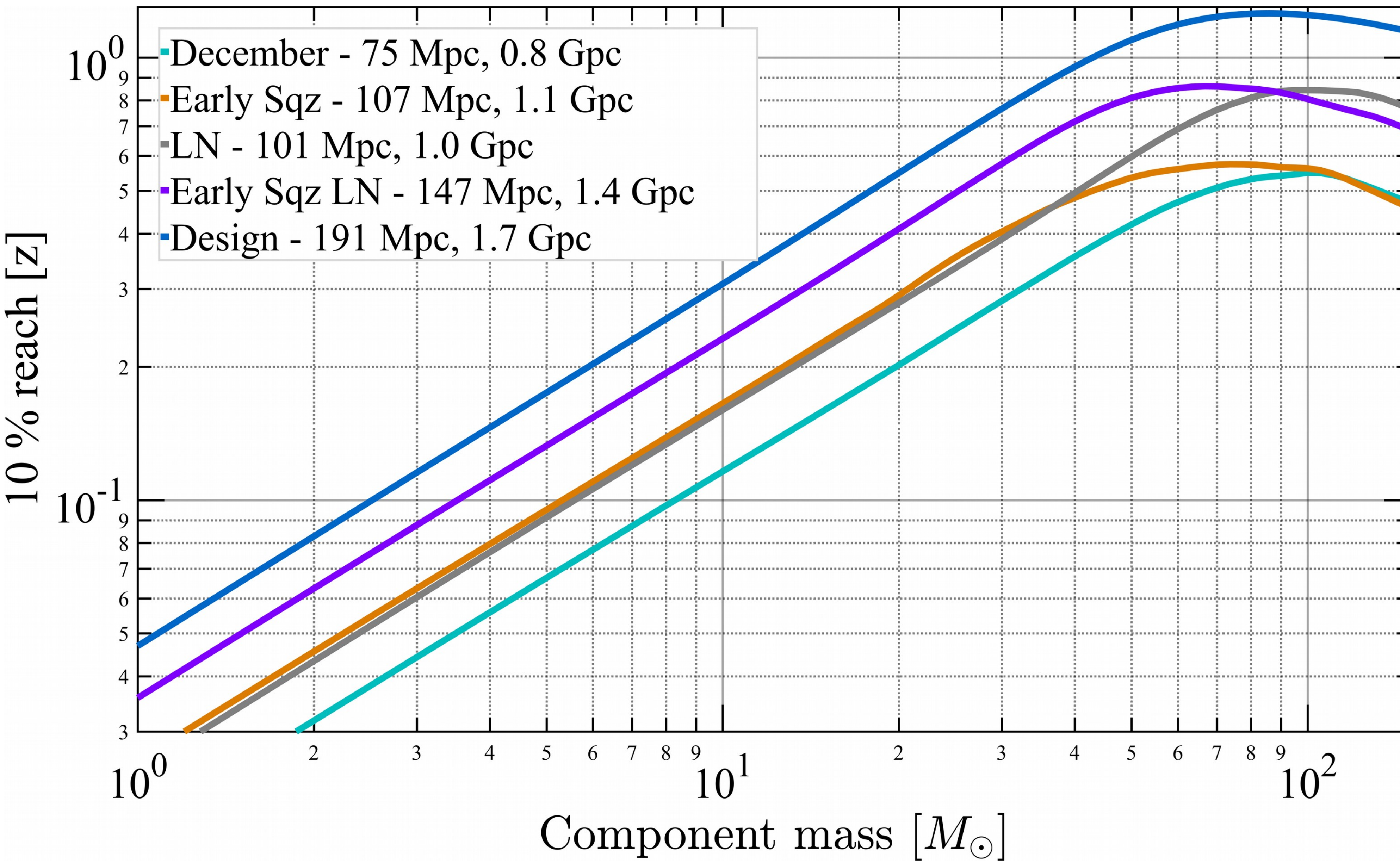
Suspension, OPO & Fibres



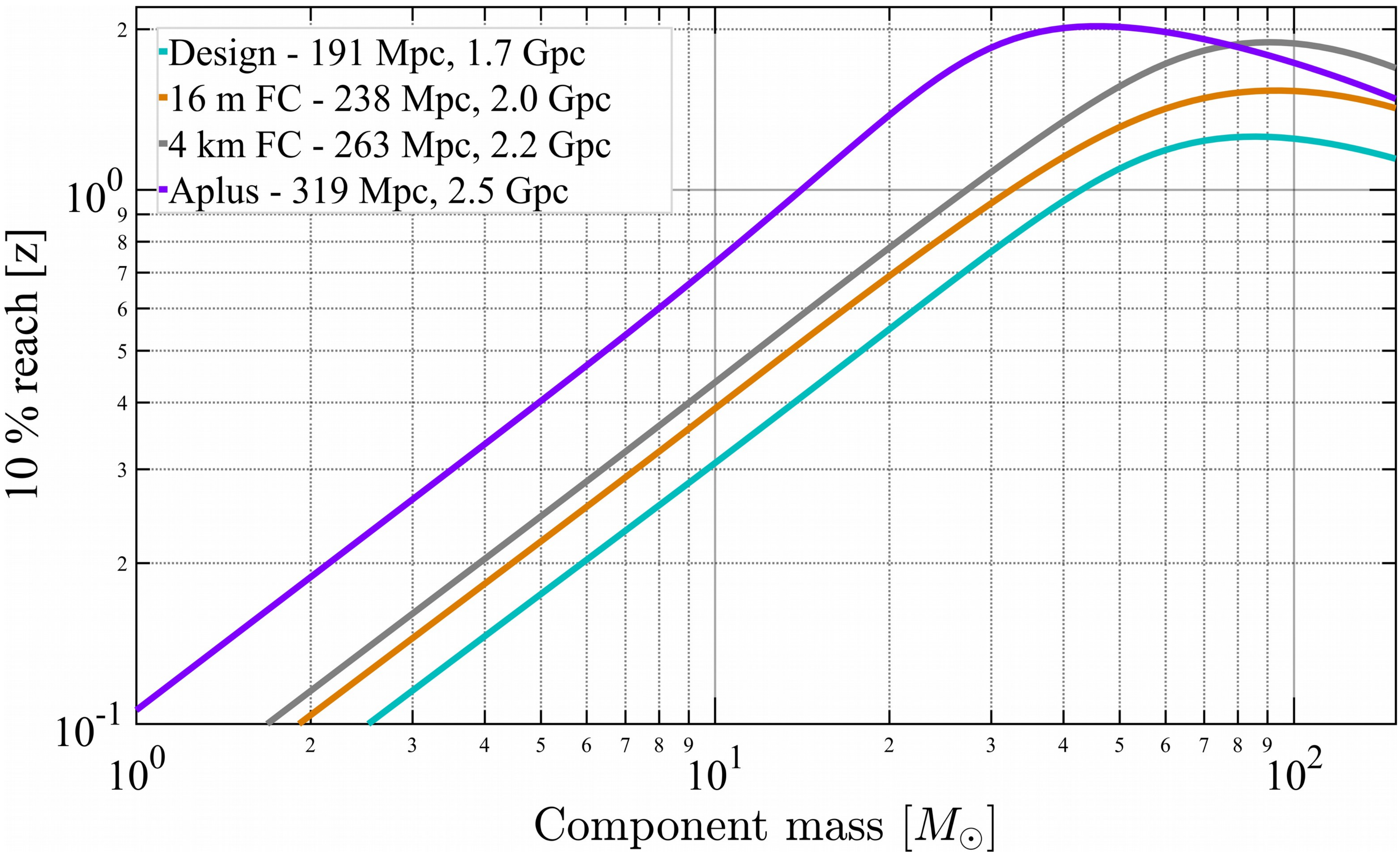




Binary coalescence reach

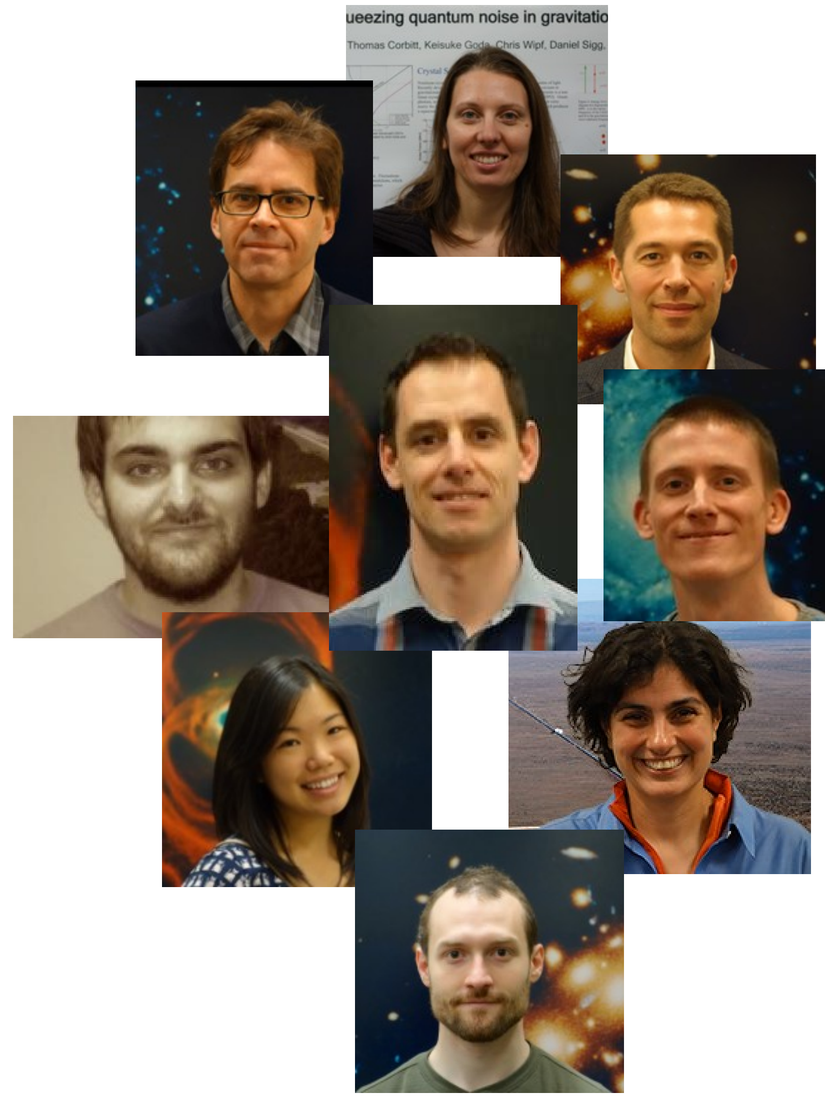


Binary coalescence reach



Summary

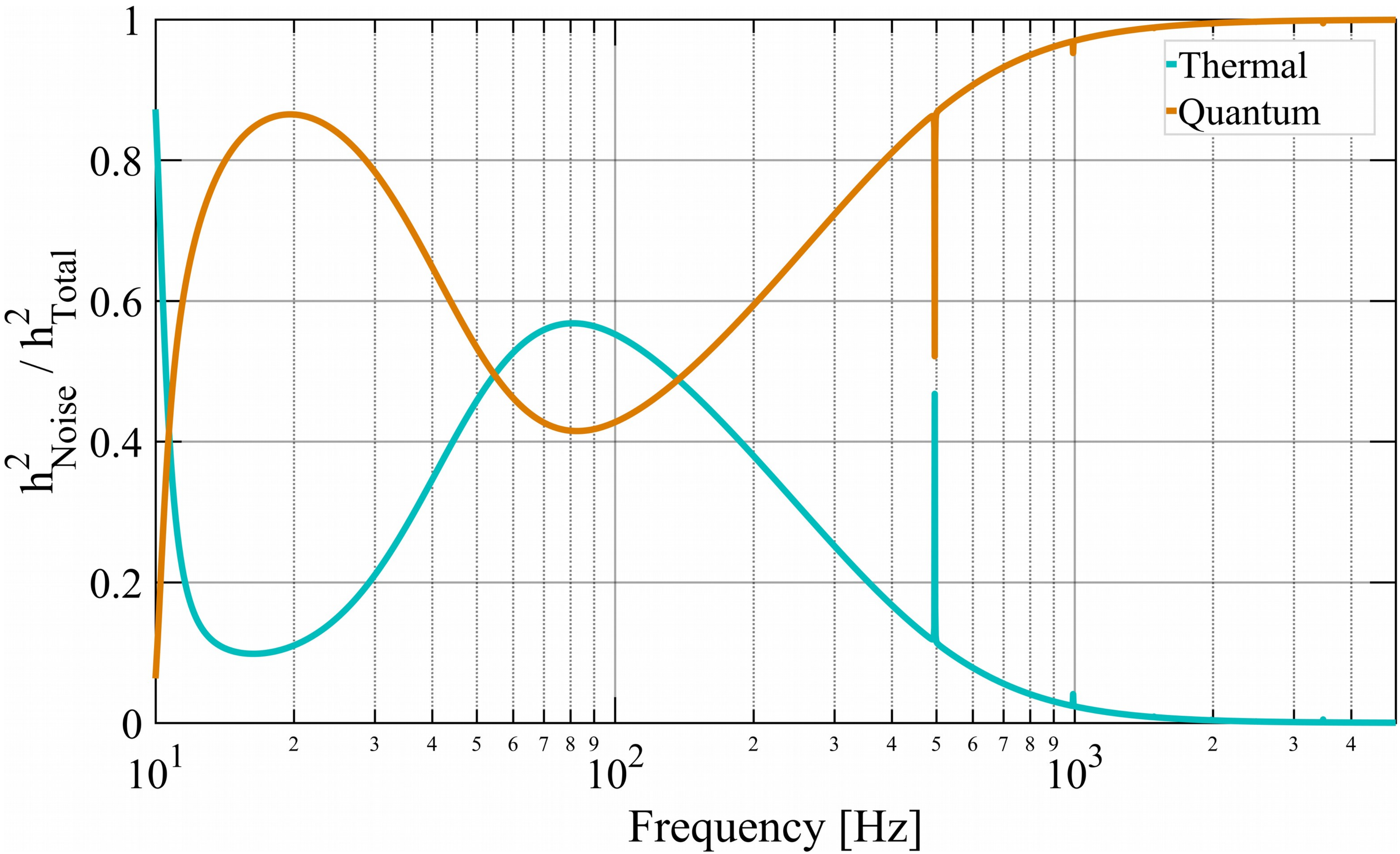
- Squeezing mature
- Enables all other upgrades
- Clear path forward
- Working to make squeezing available during/after O2



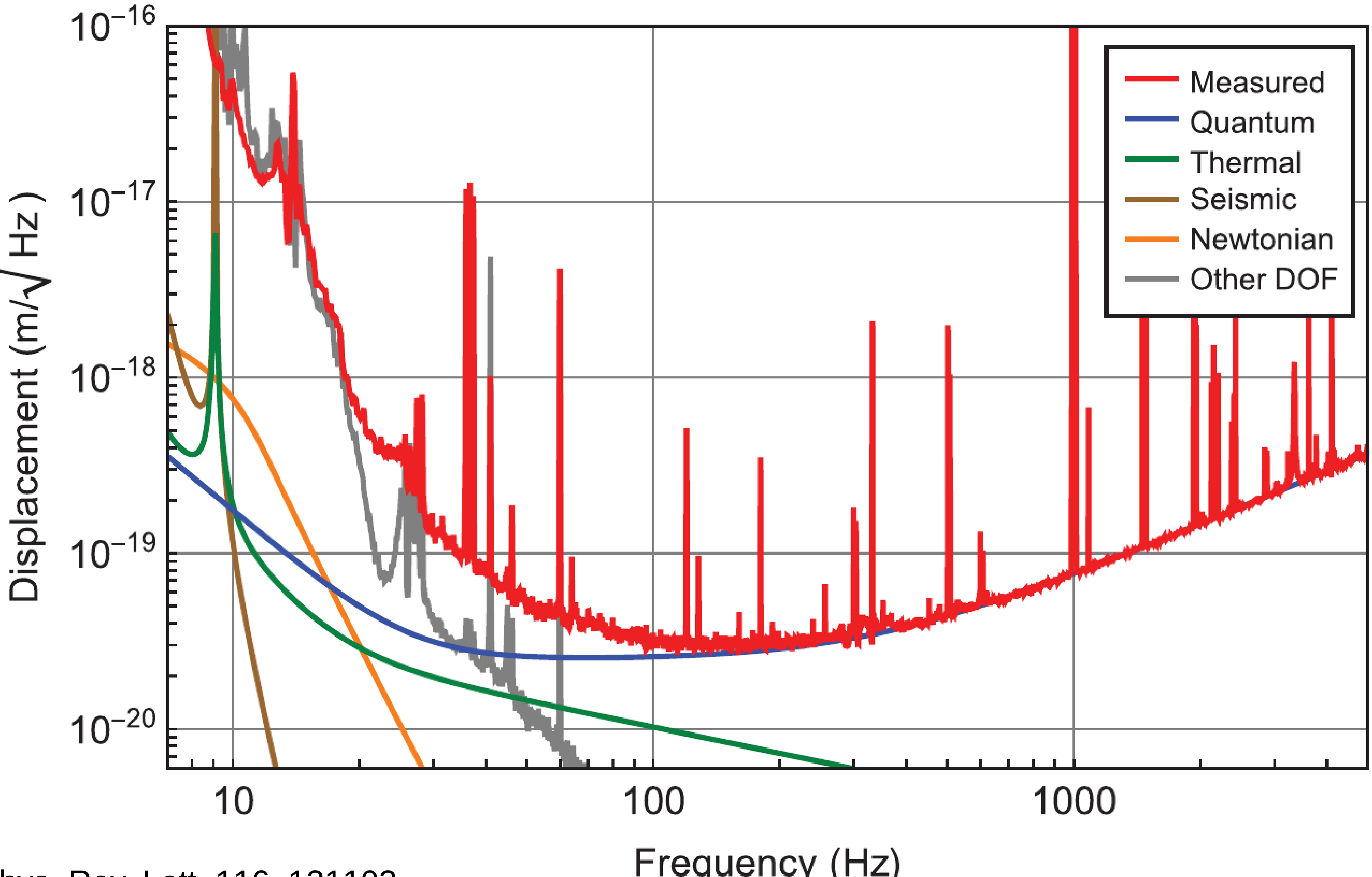
John Miller, Peter Fritschel, Eric Oelker, Lisa Barsotti, Fabrice Matichard, Alvaro Fernandez, Romain Fetick, Nergis Mavalvala, Matthew Evans, Maggie Tse, Lee McCuller

Extra slides

Fraction of noise power

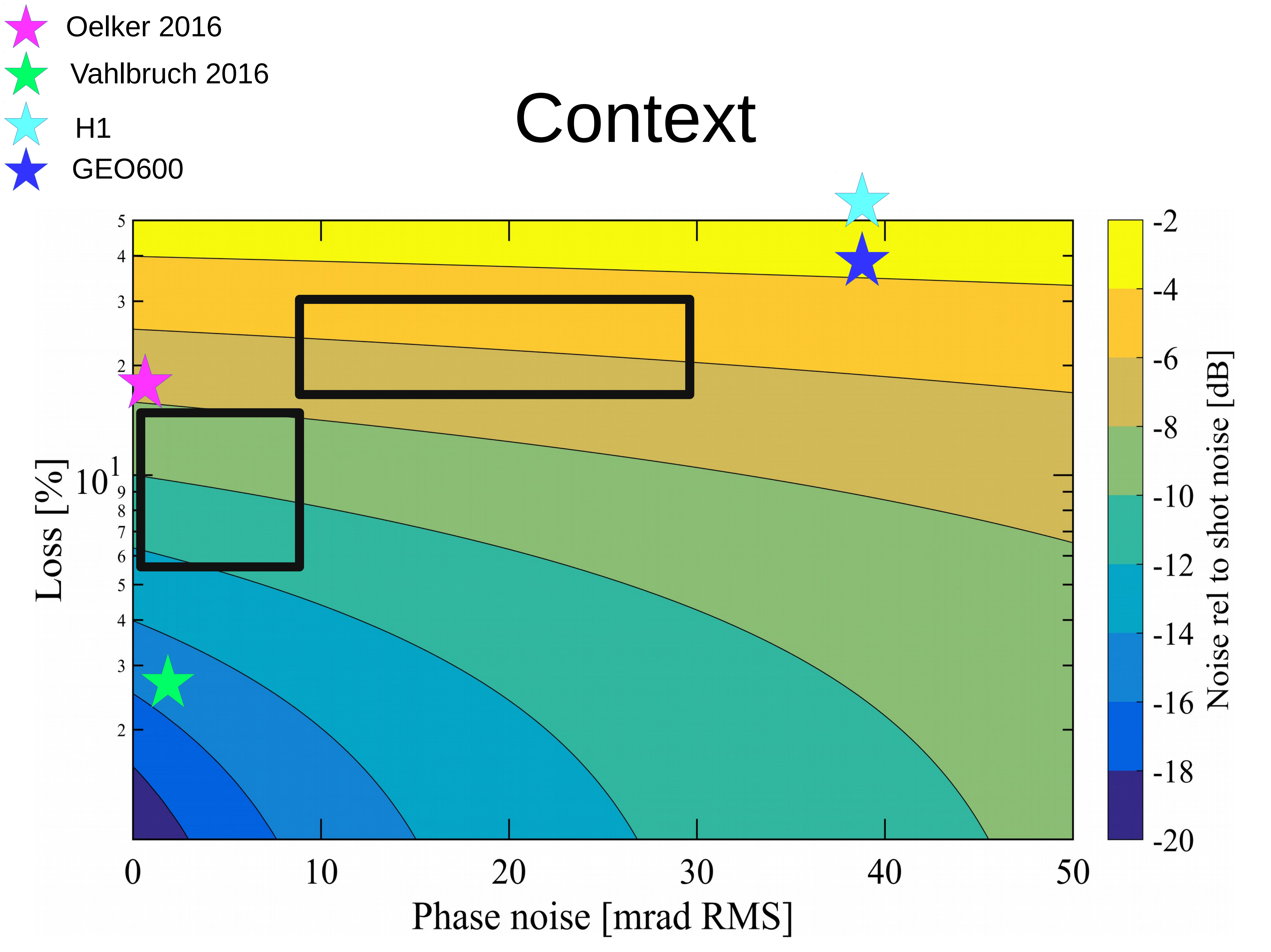


Noise budget



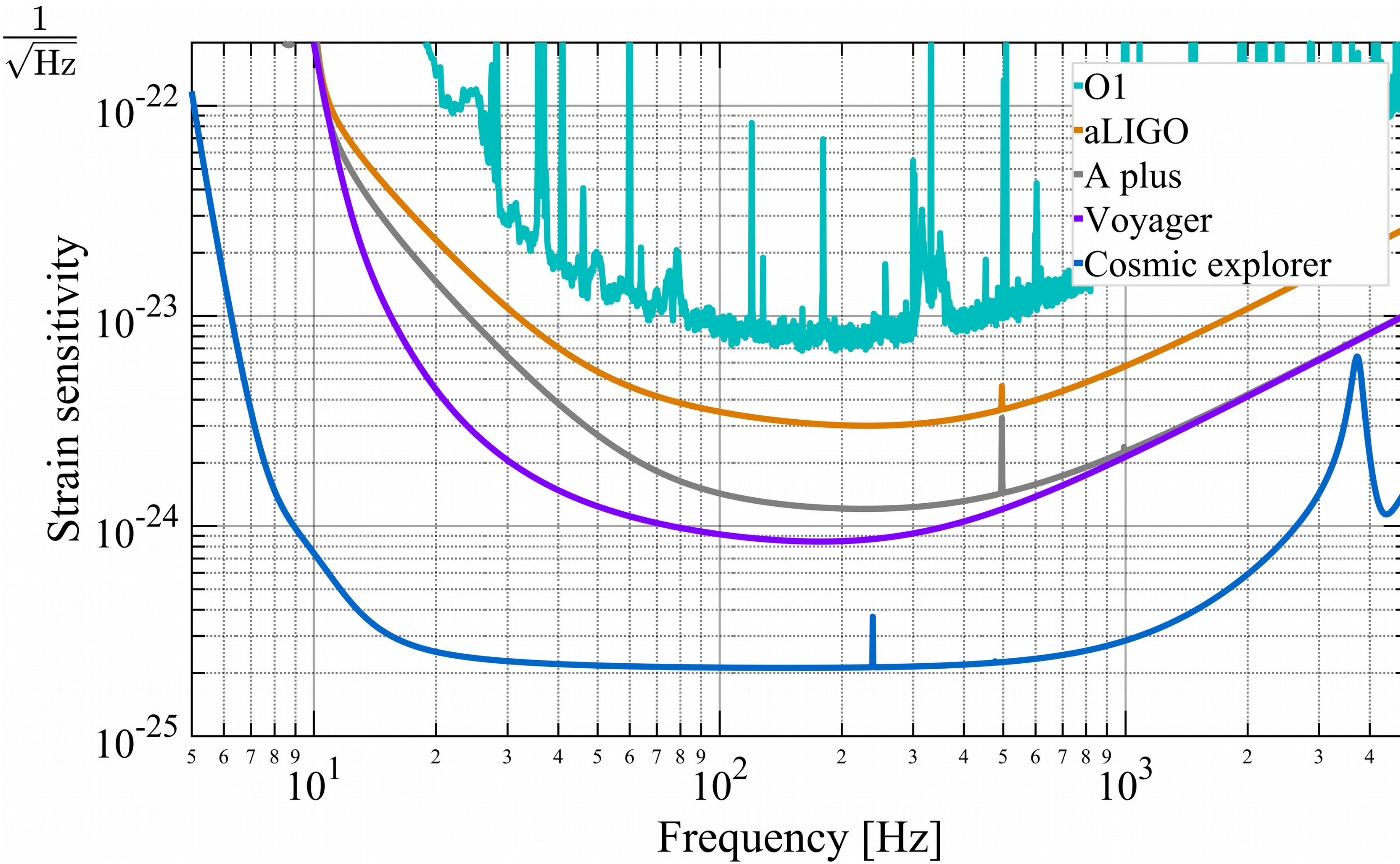
Phys. Rev. Lett. 116, 131103

Context

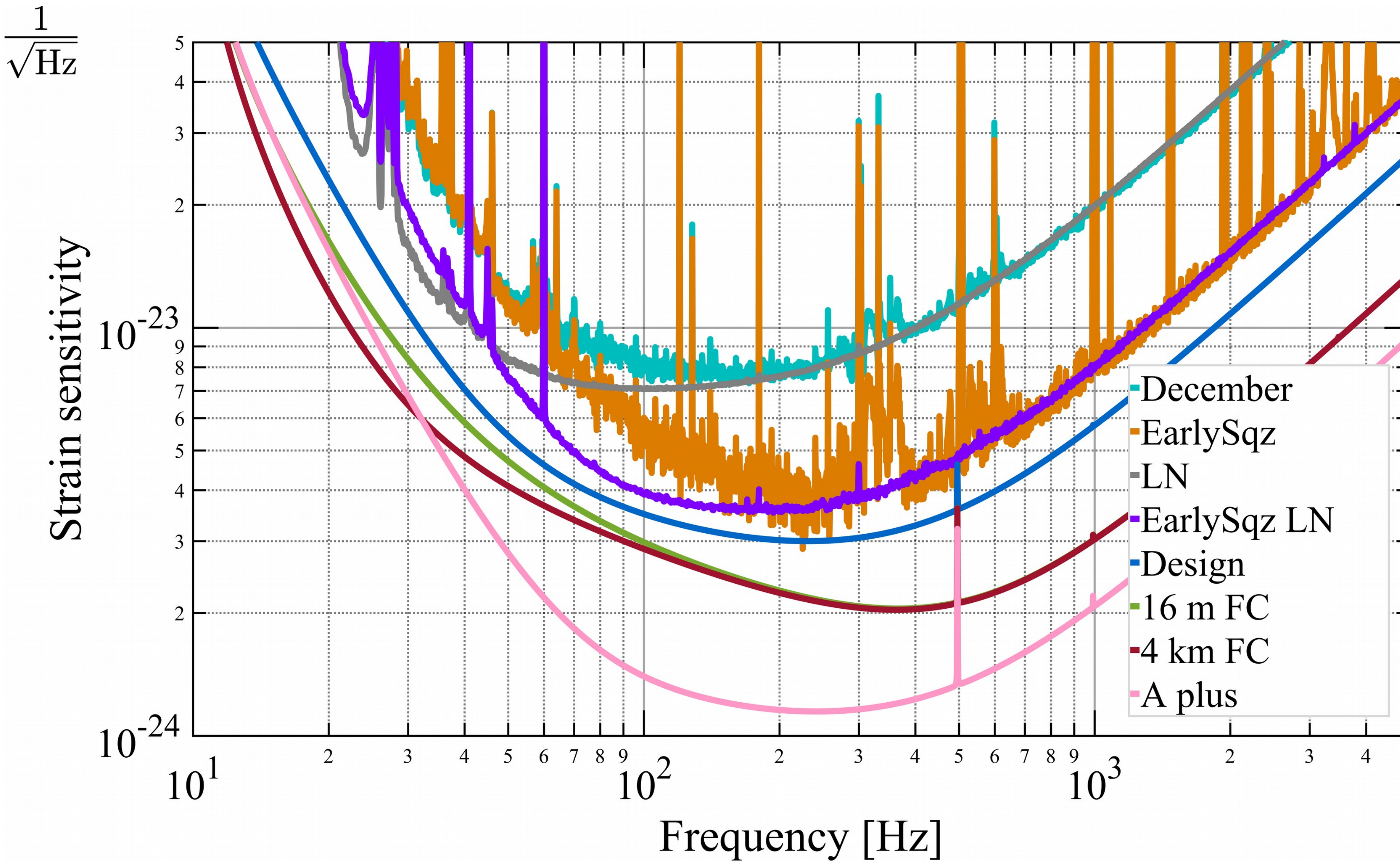


Oelker 2016
Vahlbruch 2016
H1
GEO600
Loss [%]
Phase noise [mrad RMS]
Noise rel to shot noise [dB]
0
10
20
30
40
50
5
4
3
2
10^1
9
8
7
6
5
4
3
2
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20

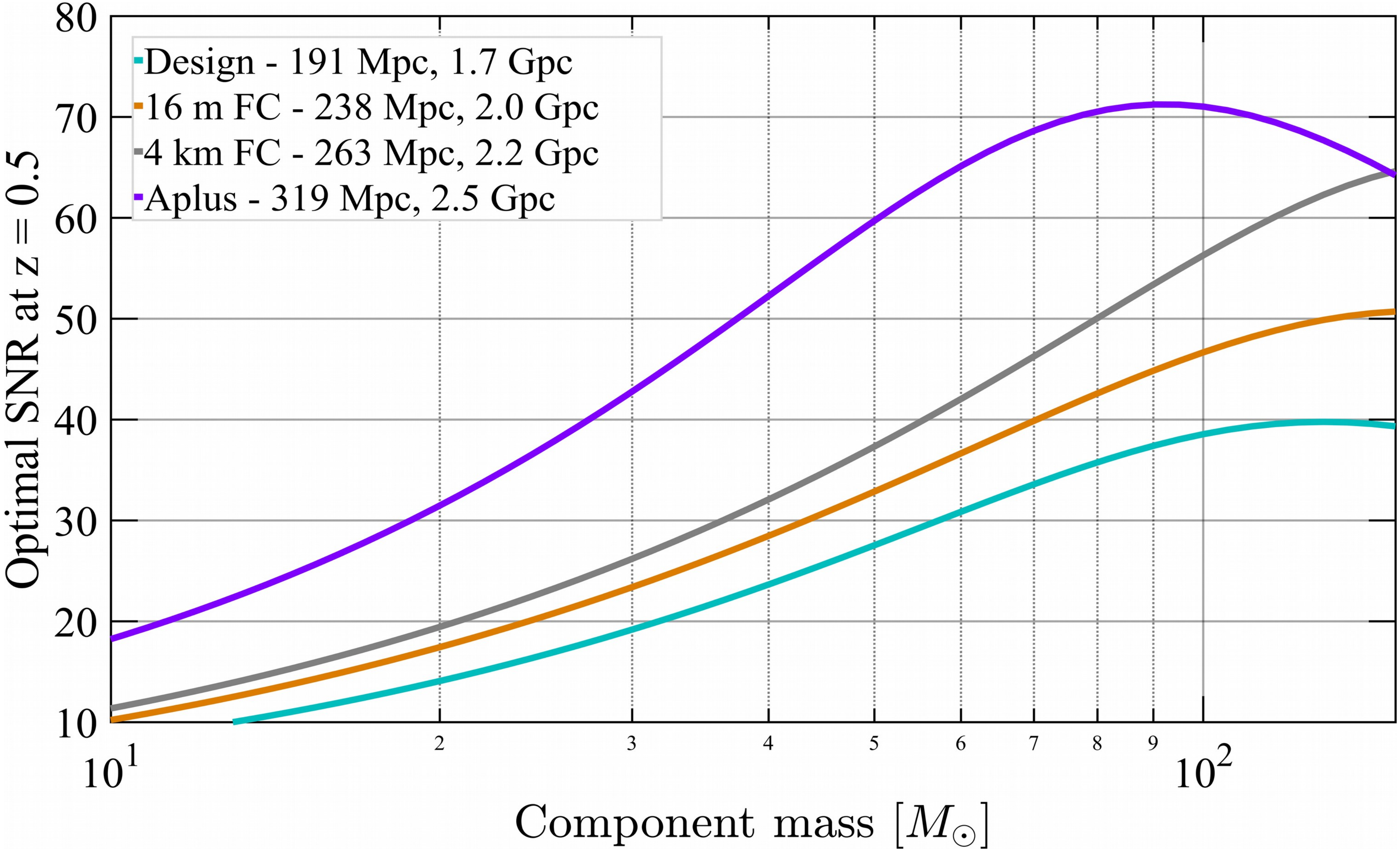
Beyond aLIGO



Equivalent strain noise



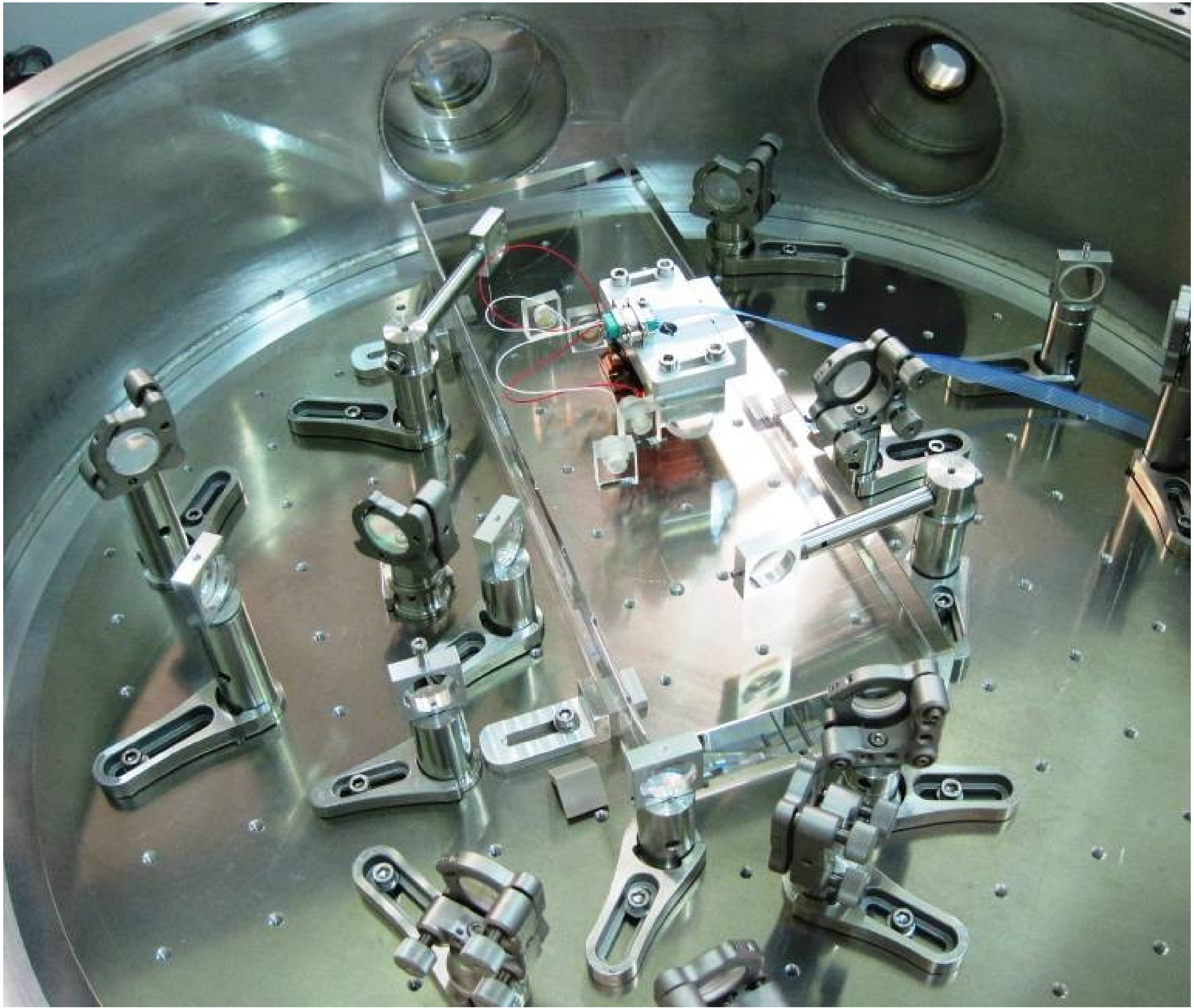
Maximum SNR

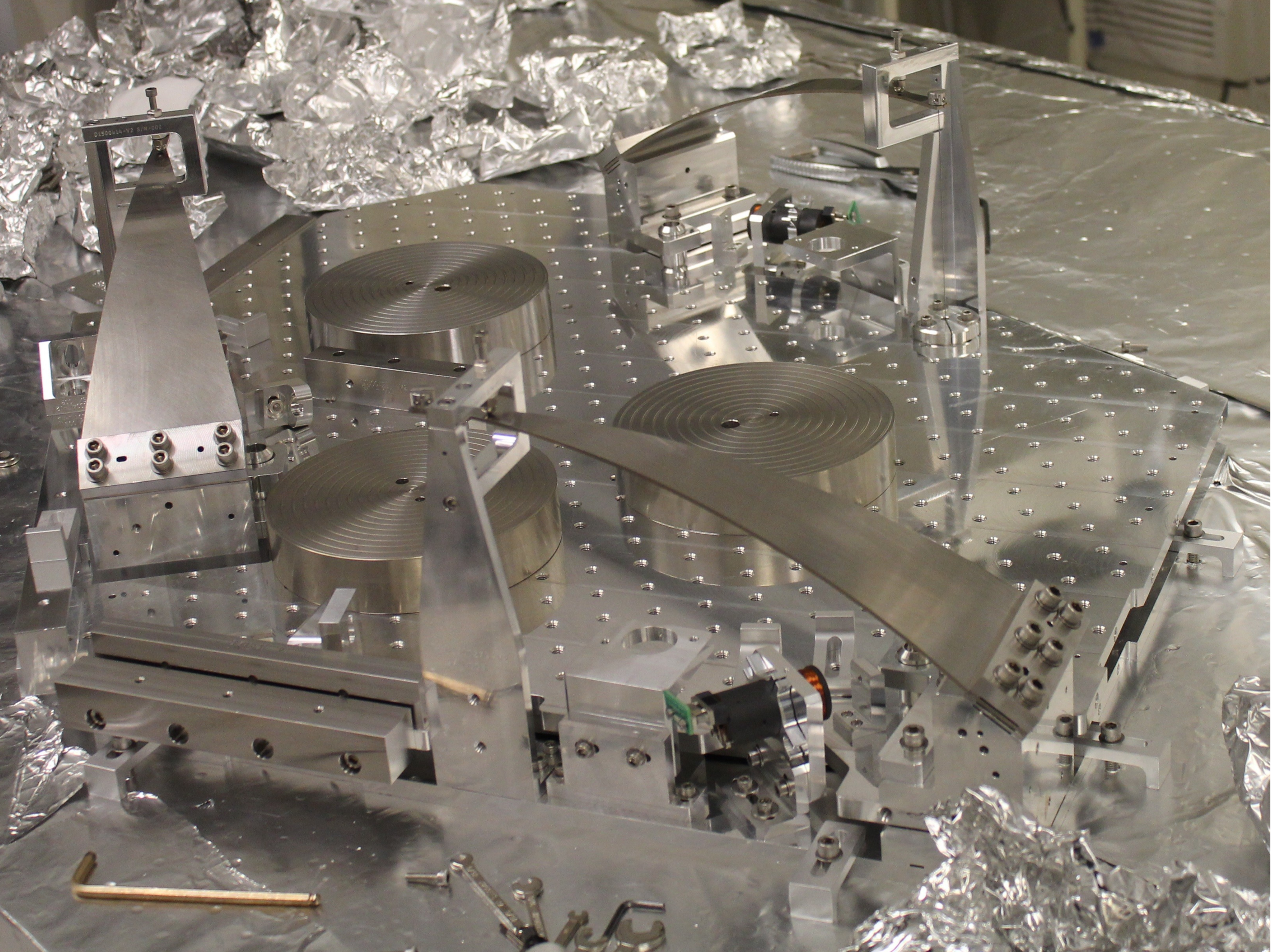

Design - 191 Mpc, 1.7 Gpc
16 m FC - 238 Mpc, 2.0 Gpc
4 km FC - 263 Mpc, 2.2 Gpc
Aplus - 319 Mpc, 2.5 Gpc
Optimal SNR at z = 0.5
80
70
60
50
40
30
20
10
10^1
2
3
4
5
6
7
8
9
10^2
Component mass $[M_\odot]$

Parameter	Symbol	Value
Filter cavity length	L_{fc}	16 m
Filter cavity half-bandwidth	γ_{fc}	$2\pi \times 61.4$ Hz
Filter cavity detuning	$\Delta\omega_{\mathrm{fc}}$	$2\pi \times 48$ Hz
Filter cavity input mirror transmissivity	t_{in}^2	66.3 ppm
Filter cavity losses	Λ_{rt}^2	16 ppm
Injection losses	Λ_{inj}^2	5%
Readout losses	Λ_{ro}^2	5%
Mode-mismatch losses (squeezer-filter cavity)	$\Lambda_{\mathrm{mmFC}}^2$	2%
Mode-mismatch losses (squeezer-local oscillator)	$\Lambda_{\mathrm{mmLO}}^2$	5%
Frequency-independent phase noise (RMS)	$\delta\zeta$	30 mrad
Filter cavity length noise (RMS)	δL_{fc}	0.3 pm
Injected squeezing	σ_{dB}	9.1 dB

- Phys. Rev. D 90, 062006 (2014)

In-vacuum squeezing




D1500414-V2

Loss/phase noise budget

Source of Loss	**Value (%)**
OPO escape efficiency	2 ± 1
Propagation losses	1 ± 0.2
95% homodyne visibility	10 ± 0.5
Photodiode quantum efficiency	5 ± 3
Total efficiency	$\eta = 0.83 \pm 0.03$
Source of Phase Noise	**Value (mrad)**
OPO detuning noise	0.35 ± 0.1
OPO control sidebands	0.35 ± 0.1
SHG length noise	1 ± 0.3
CLF shot noise	0.9 ± 0.3
Total phase noise	$\theta_{\text{rms}} = 1.4 \pm 0.5$

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Loss

Loss Source	**Estimated**	**Projected**
OPO	2%	2%
Squeezing injection optics	1%	1%
Squeezing injection Faraday	3% - 5%	0% - 2%
Output Faraday in Reverse	3% - 5%	1% - 2%
Mode matching (squeezed beam to interferometer)	4% - 6%	1% - 2%
Alignment fluctuations (squeezed beam to interferometer)	0% - 1%	0% - 1%
Total injection losses	10% - 18%	5 % - 9%
Output Faraday	3% - 5%	1% - 2%
OMC transmission	3% - 6%	1% - 2%
Mode matching (interferometer to OMC)	4% - 6%	2% - 3%
Photo-detector	1%	1%
Total readout losses	10% to 17%	5% - 9%
Total losses	**20% - 32%**	**9% - 17%**

Opt. Exp Vol. 22, Issue 17, pp. 21106 (2014)