CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Using gravitational-wave detectors to probe quantum gravity

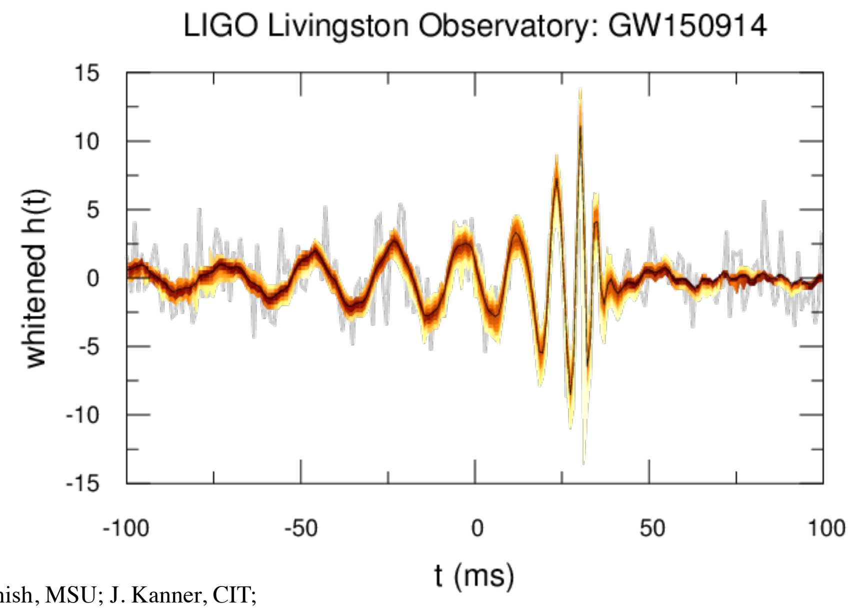
Mikhail Korobko

University of Hamburg

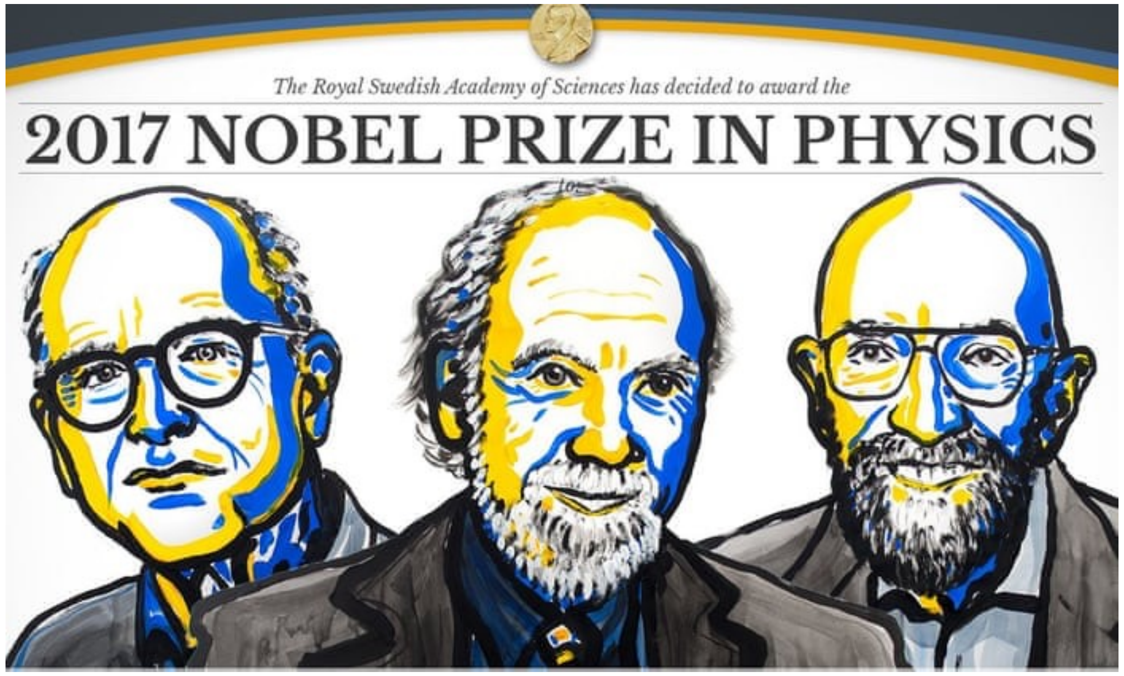
"Gravity and entanglement" workshop, Hamburg 2024

15 September 2014

First detection of gravitational waves



credits: N. Cornish, MSU; J. Kanner, CIT; T. Littenberg, UAH; M. Millhouse, MSU



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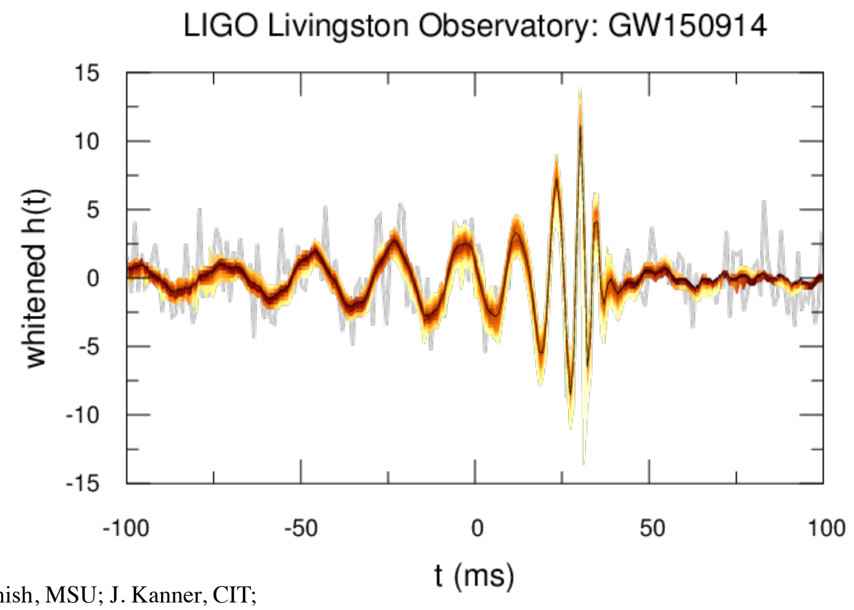

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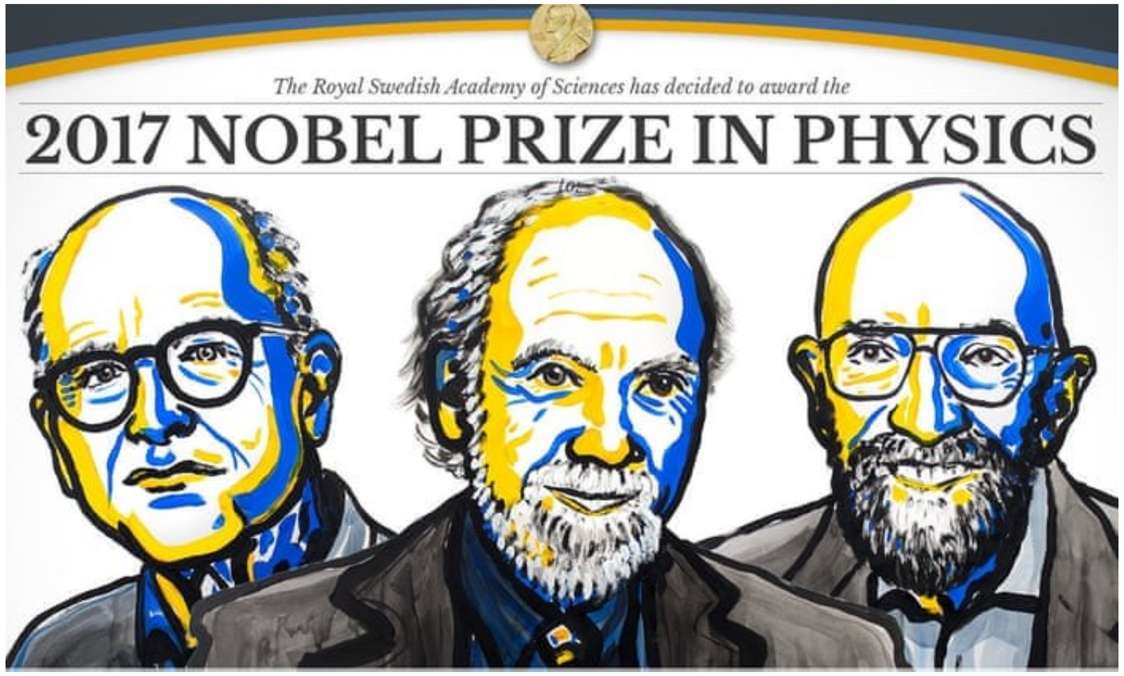
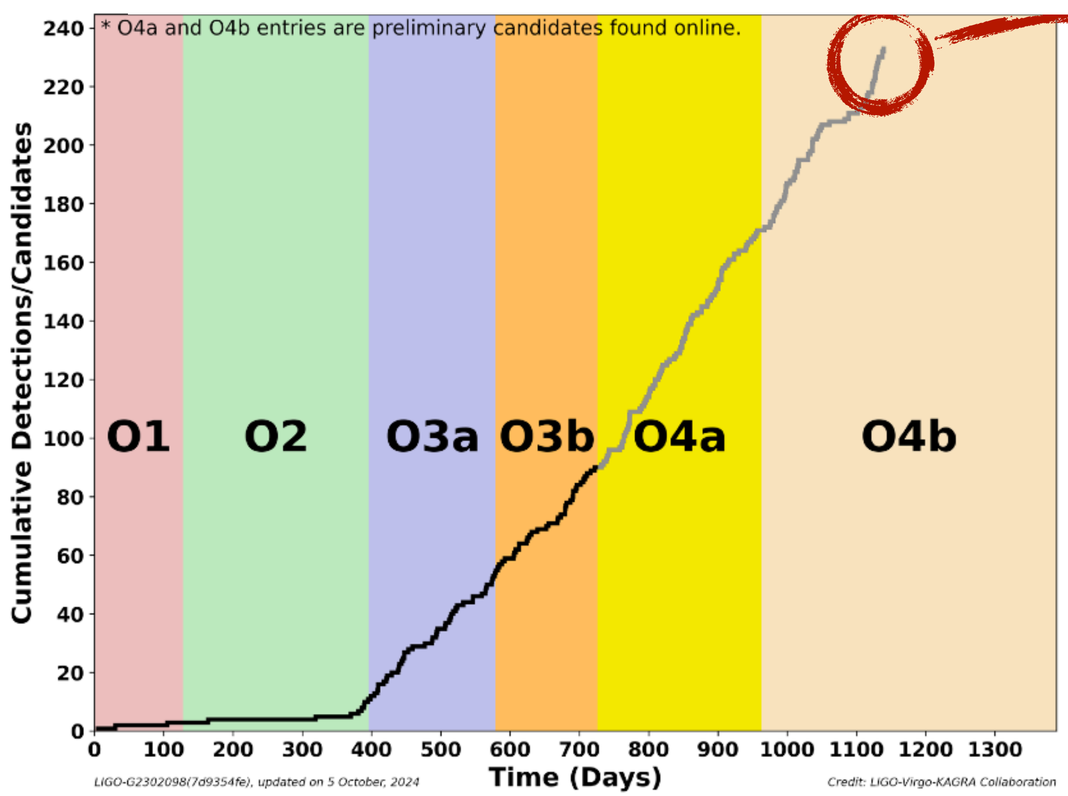
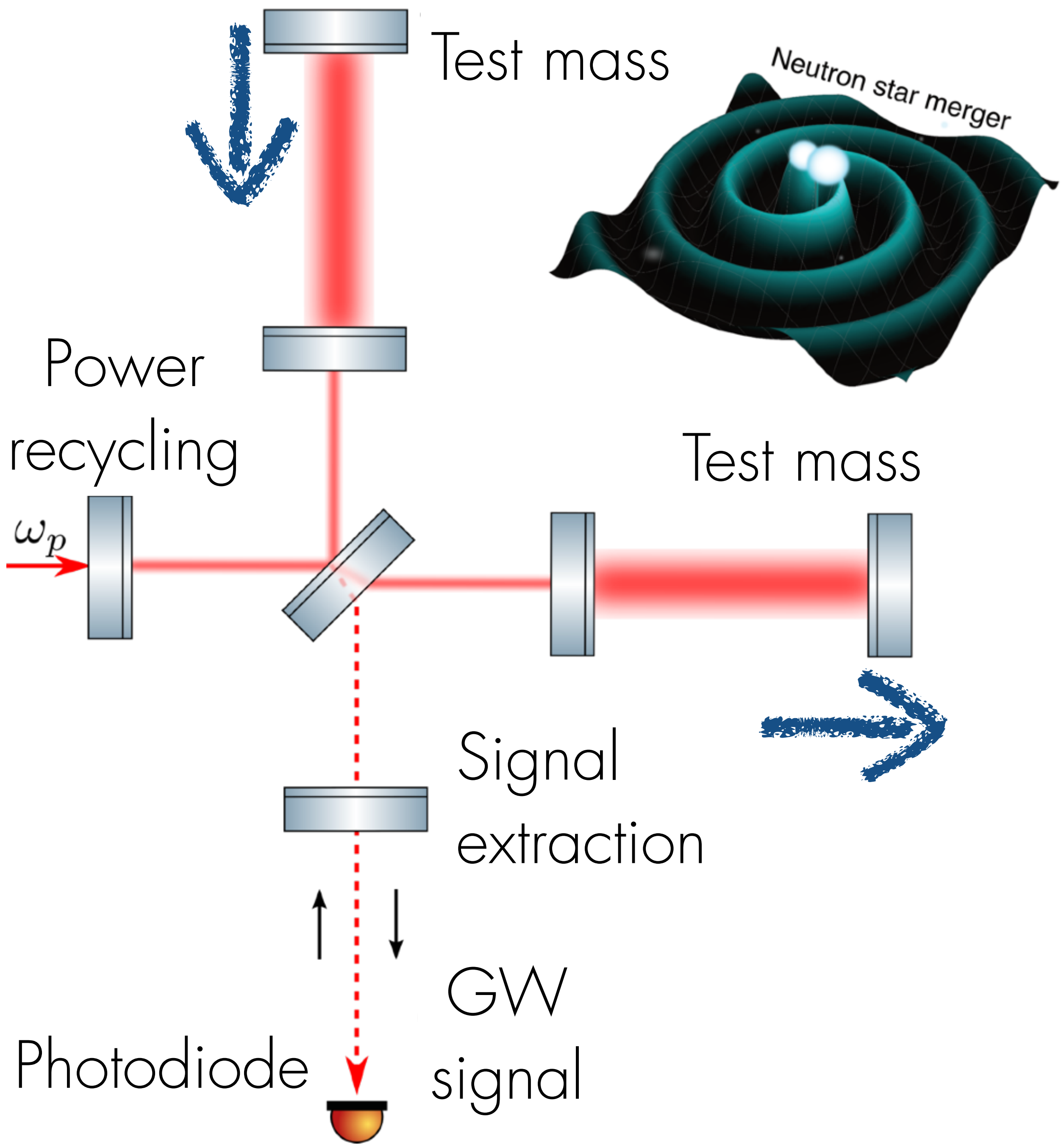
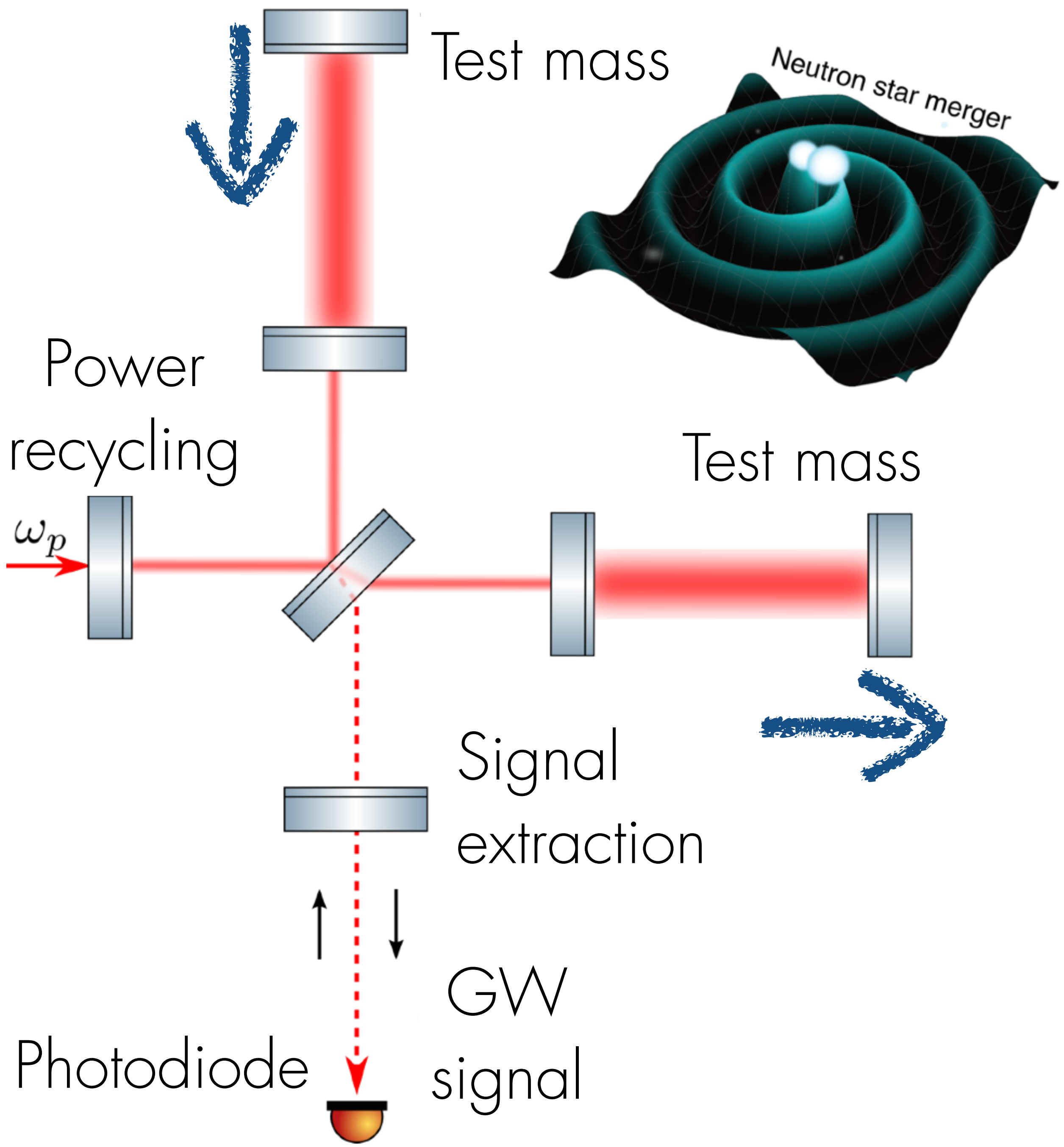


Observed events



Total events:
>230


Test mass
Neutron star merger
Power
recycling
ω_p
Test mass
Signal
extraction
GW
signal
Photodiode



Exceptional sensitivity +
+ lots of data +
great expertise and understanding of the detector

Can we use these detectors to probe quantum gravity?

Outline

1. QG background from an experimentalist perspective
2. Detecting quantum gravity in the lab
3. Gravitational-wave detectors: overview
4. Detecting QG in modern and future detectors

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[1]

PHYSICAL REVIEW D **107,** 024002 (2023)

Interferometer response to geontropic fluctuations

Dongjun Li,[1,2,*] Vincent S. H. Lee,[1,†] Yanbei Chen,[2,‡] and Kathryn M. Zurek[1,§]
[1]*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*
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(Received 25 October 2022; accepted 14 December 2022; published 4 January 2023)

[2]

PHYSICAL REVIEW D **108,** 064038 (2023)

Quantum gravity background in next-generation gravitational wave detectors

Mathew W. Bub,[1,*] Yanbei Chen,[2,†] Yufeng Du,[1,‡] Dongjun Li,[1,2,§] Yiwen Zhang,[1,∥] and Kathryn M. Zurek[1,¶]
[1]*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, California 91125, USA*

(Received 9 June 2023; accepted 31 August 2023; published 20 September 2023)

1. QG background from an experimentalist perspective

Observational signatures of quantum gravity in interferometers

Erik P. Verlinde [a,*], Kathryn M. Zurek [b]

[a] *Institute of Physics, University of Amsterdam, Amsterdam, the Netherlands*
[b] *Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA, USA*

On vacuum fluctuations in quantum gravity and interferometer arm fluctuations

Kathryn M. Zurek

Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA, USA

Quantum fluctuations of space-time appear at the Plank length $\sim 10^{-34}$m

How can we ever detect them? (Our detectors ar 10^{-21} at best)

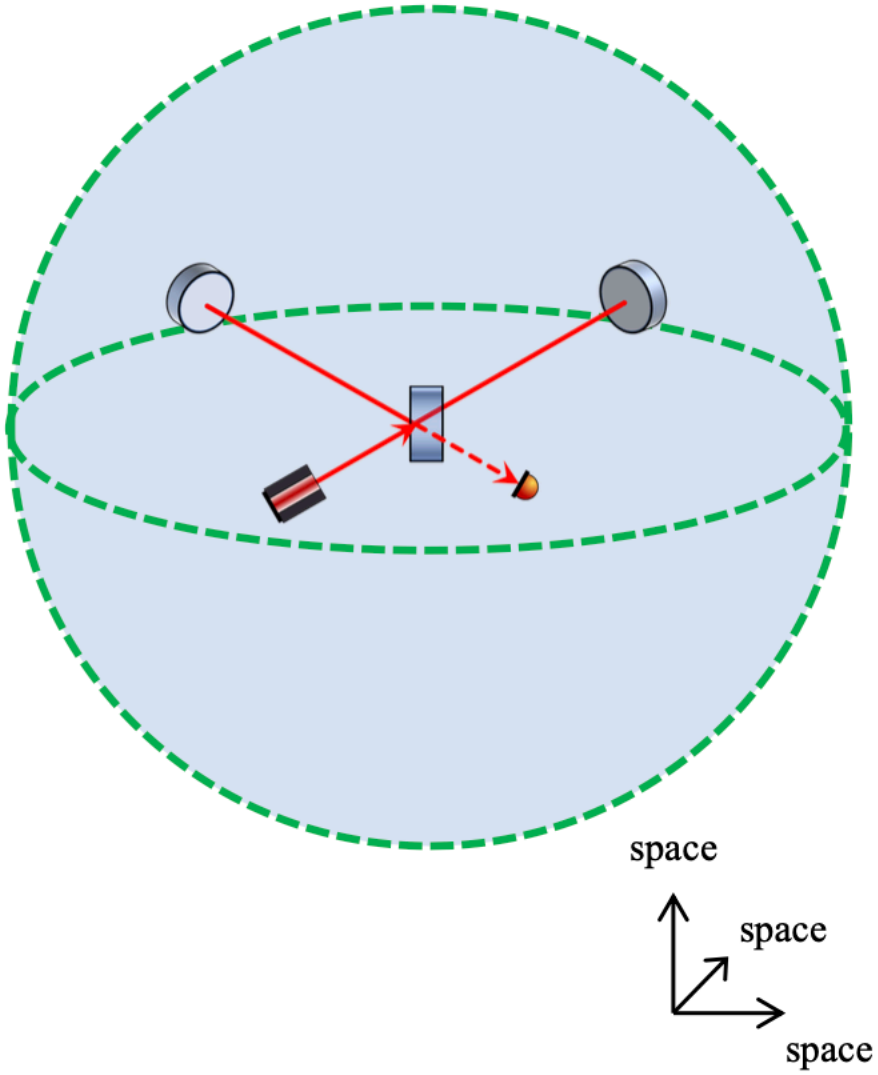
Quantum fluctuations of space-time appear at the Plank length $\sim 10^{-34}$m

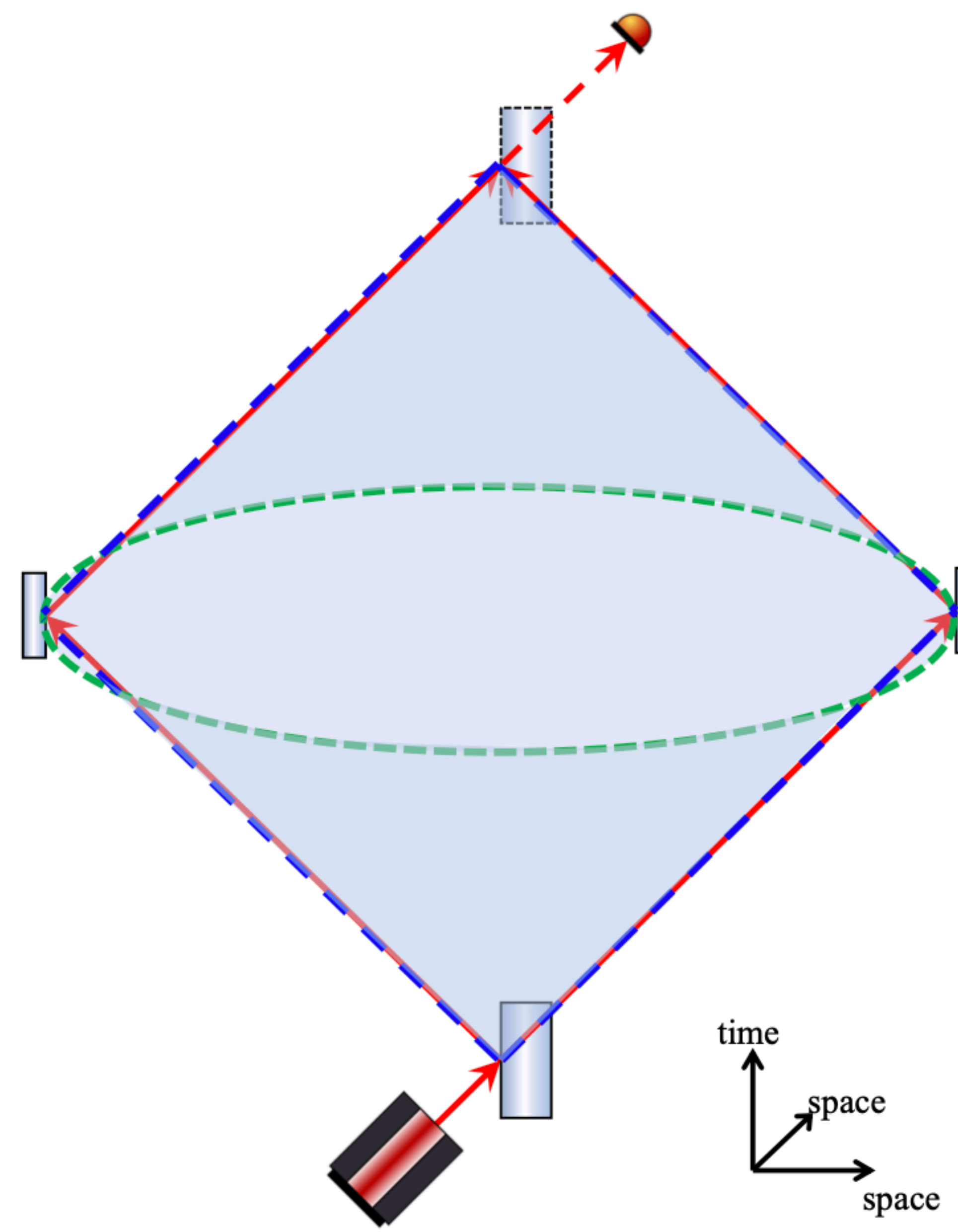
How can we ever detect them? (Our detectors ar 10^{-21} at best)

May be the standard effective field theory GR doesn't work

Using tools from holography

Light bouncing in the interferometer defines the holographic boundary (causally related region of space-time)

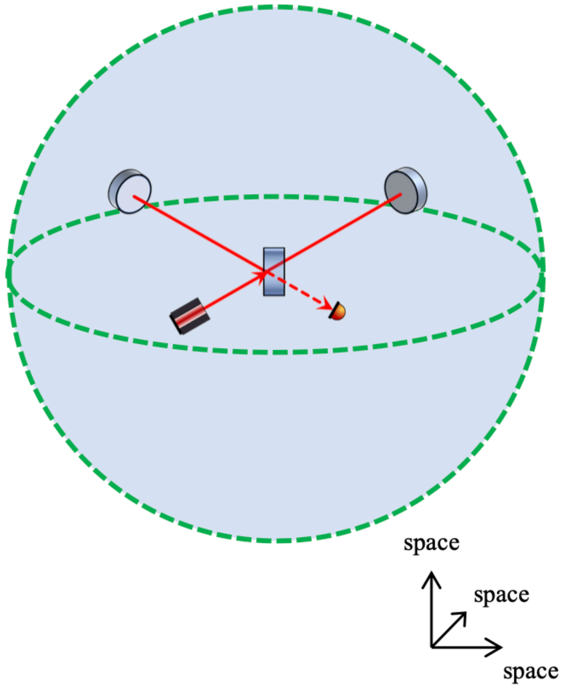




S.Vermeulen, PhD thesis

Hand-wavy argument

- Vacuum fluctuations at the horizon
  → entanglement between inside and outside
- We only access inside → looks like thermal fluctuations



Hand-wavy argument

- Vacuum fluctuations at the horizon
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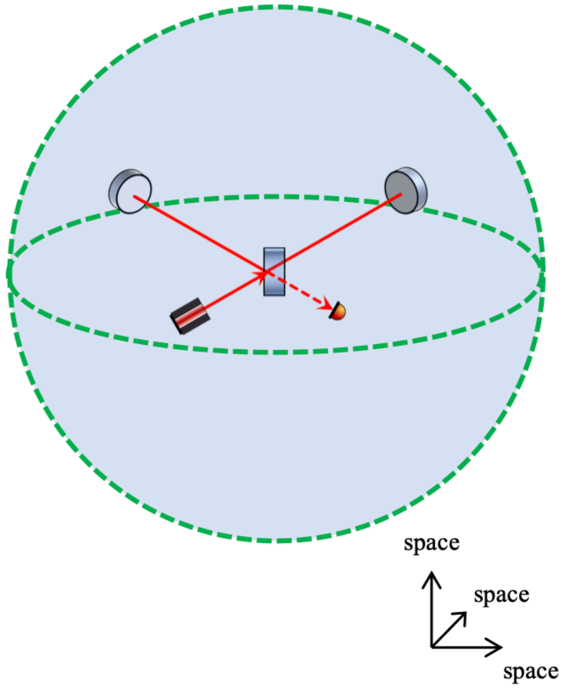
- Entropy of entanglement (holography)

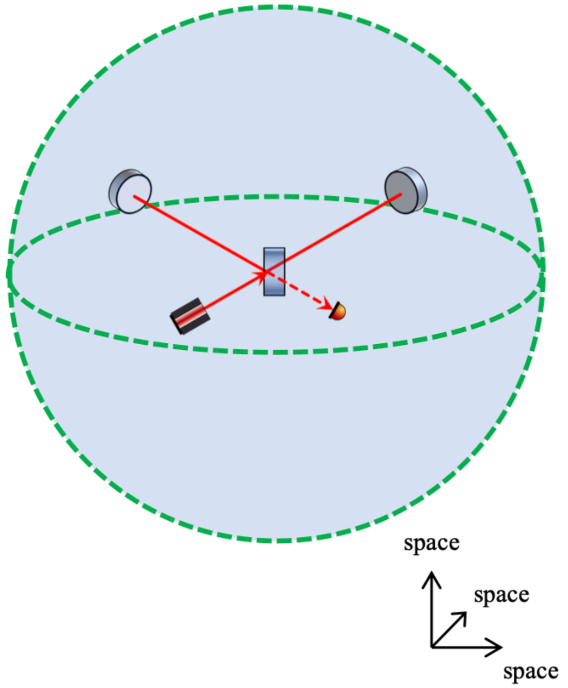


surface area, arm length

$$S_{\text{ent}} = \frac{A}{4G} = \frac{8\pi^2 L^2}{l_p^2}$$

gravitational constant, Planck length

Hand-wavy argument



- Vacuum fluctuations at the horizon
  → entanglement between inside and outside
- We only access inside → looks like thermal fluctuations
- Entropy of entanglement → statistical mechanics

$$N_{\mathrm{d.o.f}} \propto S_{\mathrm{ent}} \propto \frac{L^2}{l_p^2}$$

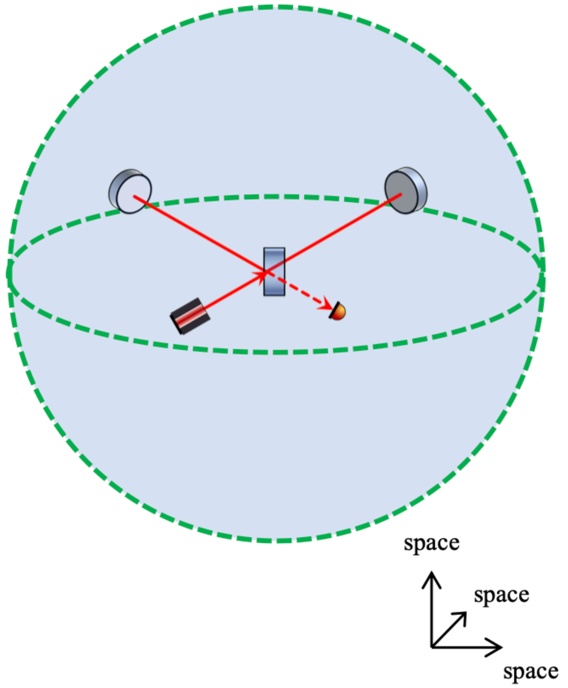
- Each degree of freedom is QM → fluctuations in energy

$$\frac{\delta E}{E} \propto \frac{\sqrt{N_{\mathrm{d.o.f.}}}}{N_{\mathrm{d.o.f.}}}$$

- From GR: length fluctuations depend on energy

$$\frac{\delta L}{L} \propto \sqrt{\frac{\delta E}{E}}$$

Hand-wavy argument



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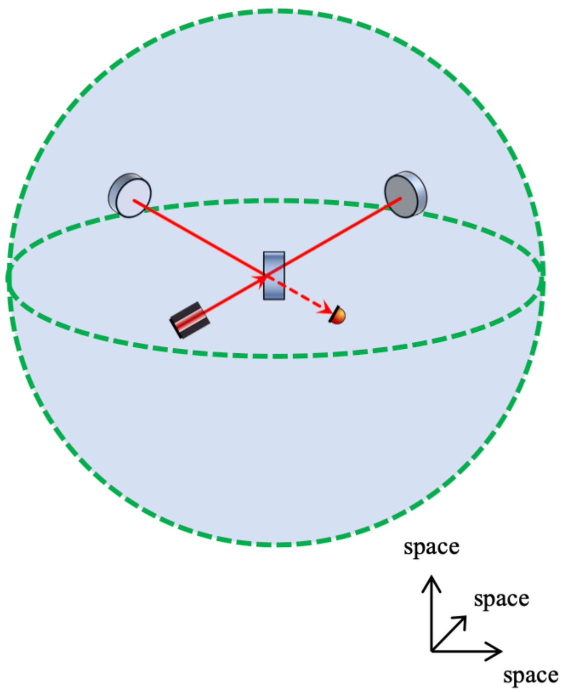
$$\boxed{\delta L \propto \sqrt{l_p L}}$$

Geontoropic fluctuations
— detectable for large L

Pixellon model: ad-hoc model that reproduces the results of the "full" theory

- Scalar field ϕ: a breathing mode of the spherical volume of spacetime



Pixellon model: ad-hoc model that reproduces the results of the full theory

- Scalar field ϕ: a breathing mode of the spherical volume of spacetime
- Bosonic modes that couple to metric

$$ds^2 = -dt^2 + (1-\phi)\left(dr^2 + r^2 d\Omega^2\right)$$

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$$ds^2 = -dt^2 + (1-\phi)\left(dr^2 + r^2 d\Omega^2\right)$$

- They are in a thermal state: have non-zero occupation number

speed of sound

free parameter (~1)

$$\sigma_{\text{pix}}(p) = \frac{\alpha}{2\pi}\frac{c_s^2}{l_p \omega(\mathbf{p})}$$

mode frequency (**momentum**)

Pixellon model: ad-hoc model that reproduces the results of the full theory

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$$ds^2 = -dt^2 + (1-\phi)\left(dr^2 + r^2 d\Omega^2\right)$$

- They are in a thermal state: have non-zero occupation number
- Macroscopically correlated across space-time

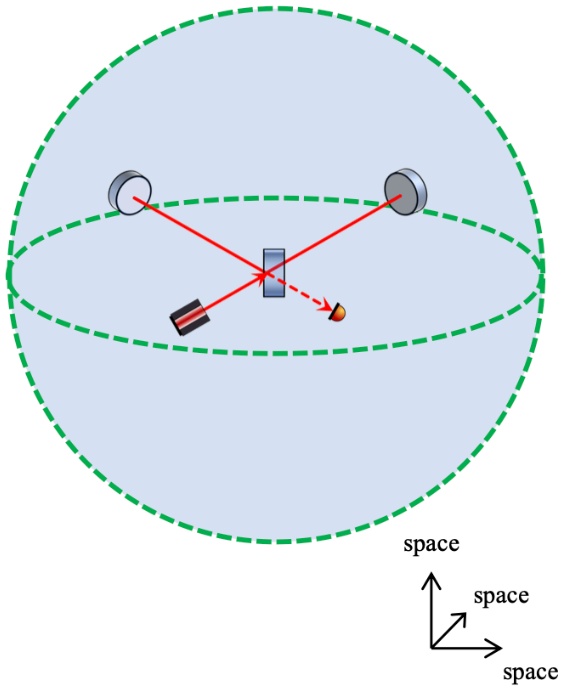
$\downarrow$

We can detect them using interferometers!

Outline

Main properties:

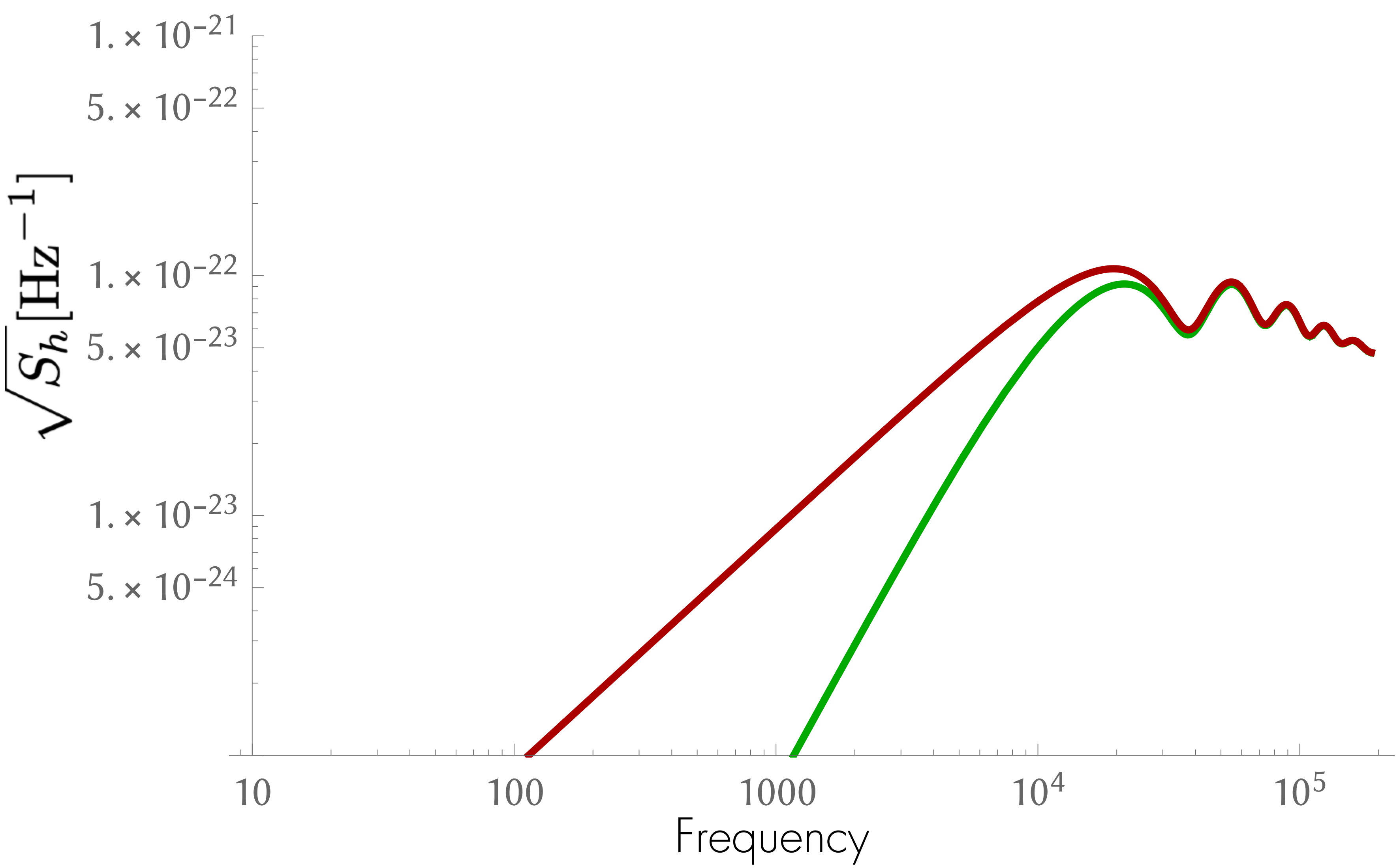
- Signal accumulates along the arm → longer arms
- Correlations over macroscopic distances
- Strong dependence on the angle between arms



Correlation function defines noise spectrum:

$$S_h(\omega) = \frac{\alpha l_p}{4\pi^2 c_s L^2} \int_0^L dr_1 \int_0^L dr_2 \left(\mathrm{sinc}\left[\omega\sqrt{(r_1 - r_2)^2}/c\right] - \mathrm{sinc}\left[\omega\sqrt{r_1^2 + r_2^2}/c\right] \right) \times \cos\left[\omega(L - r_1)/c\right] \cos\left[\omega(L - r_2)/c\right]$$

For L-shape detector



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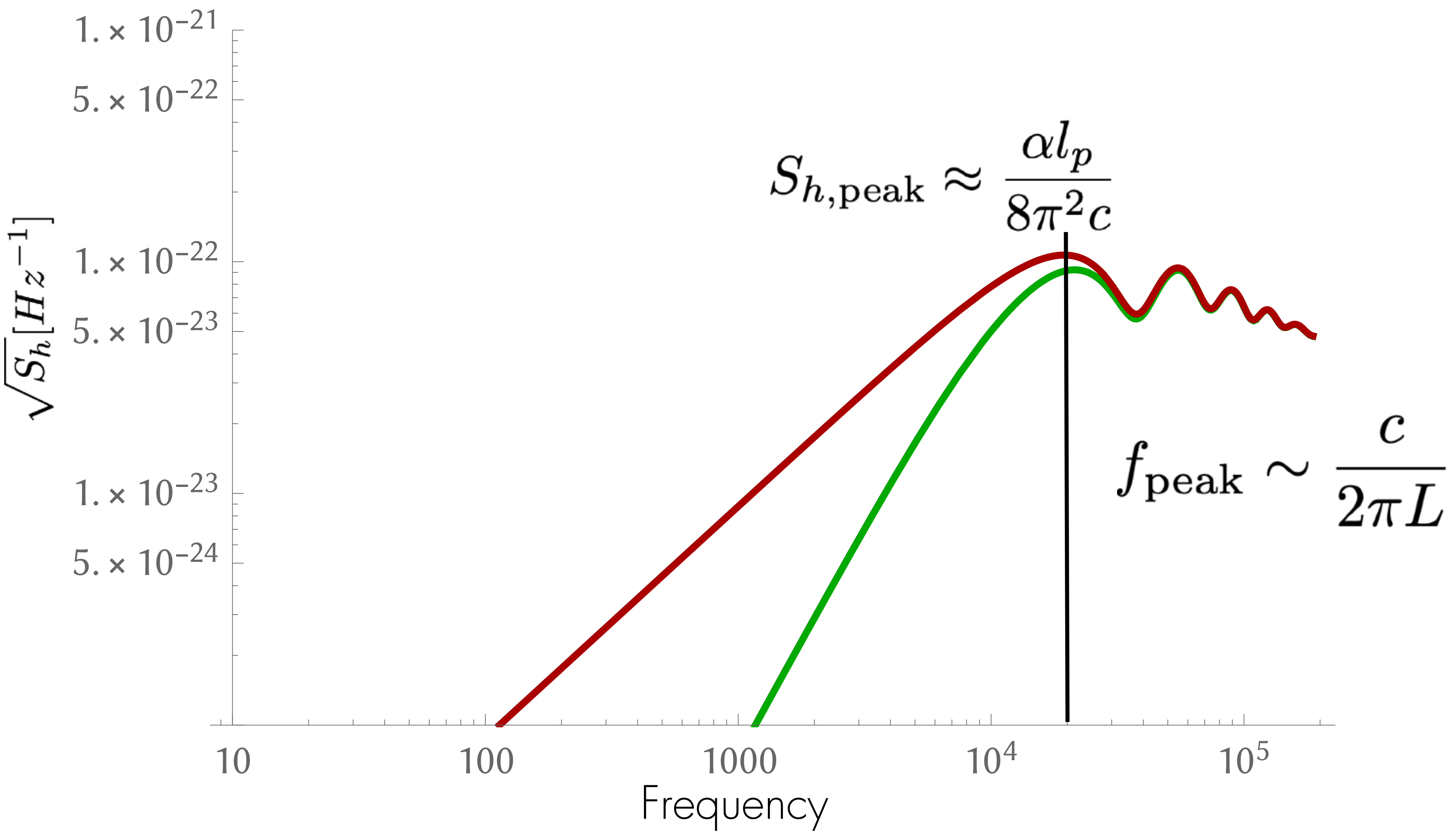

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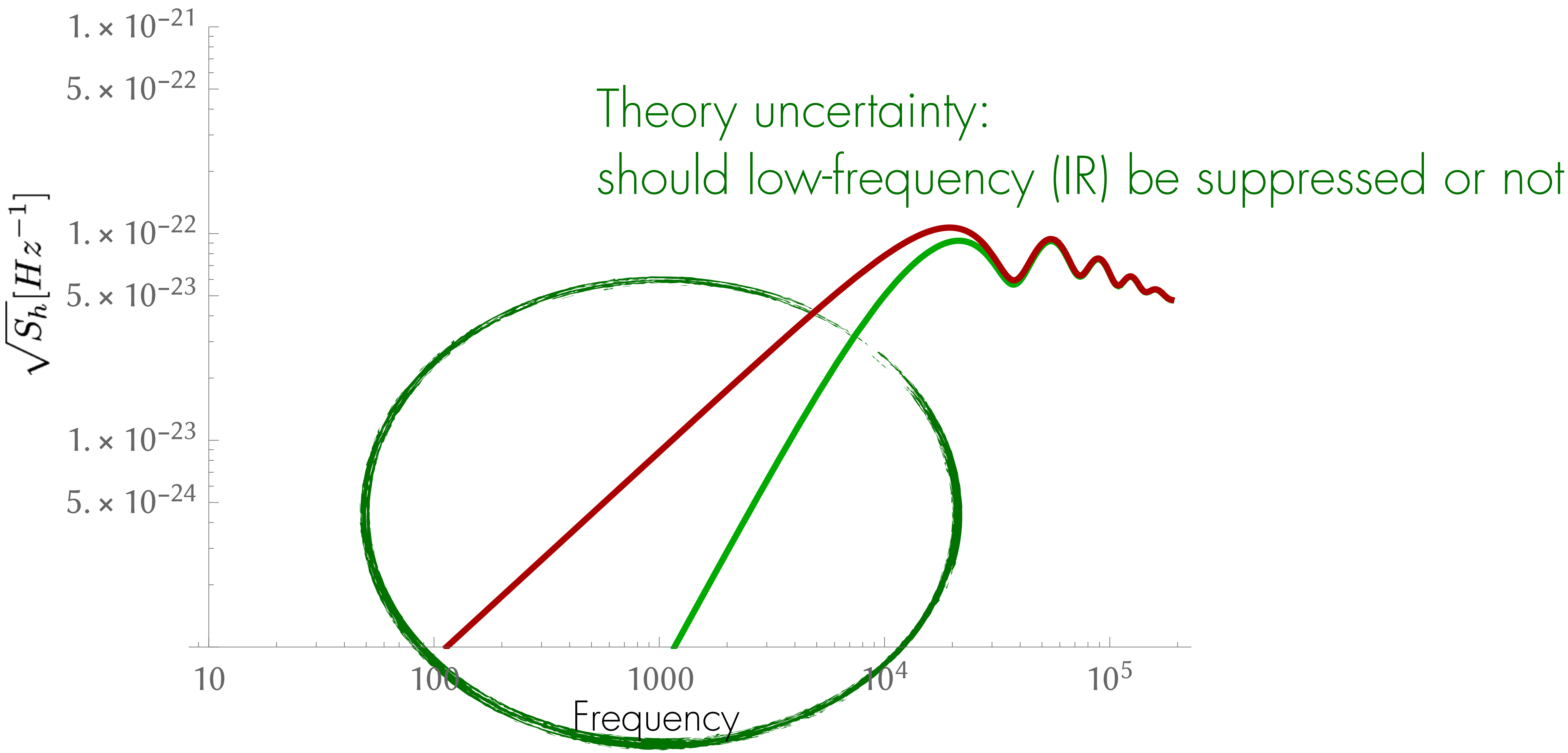

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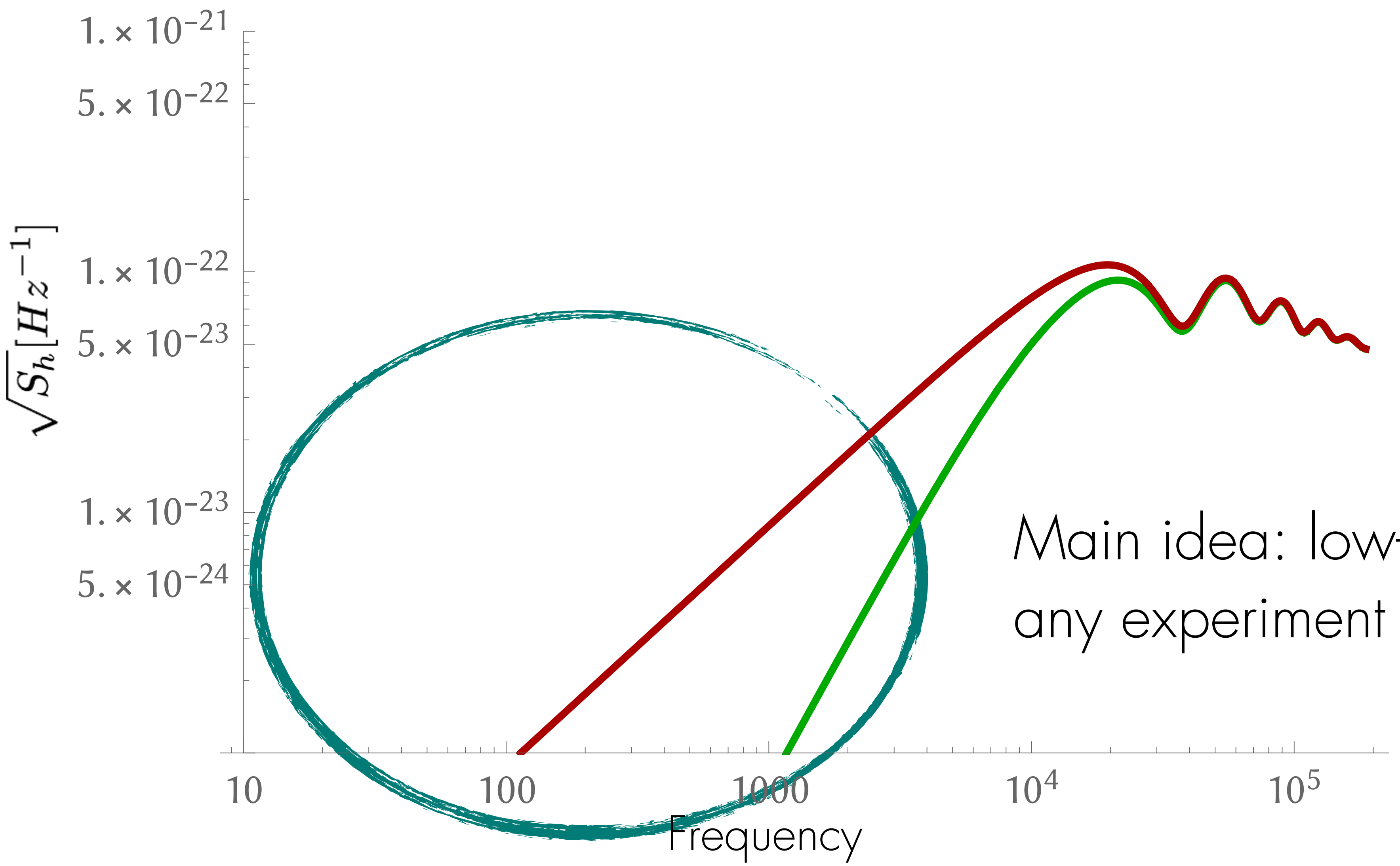

Main idea: low-frequency scaling is bad, any experiment should look at high frequency

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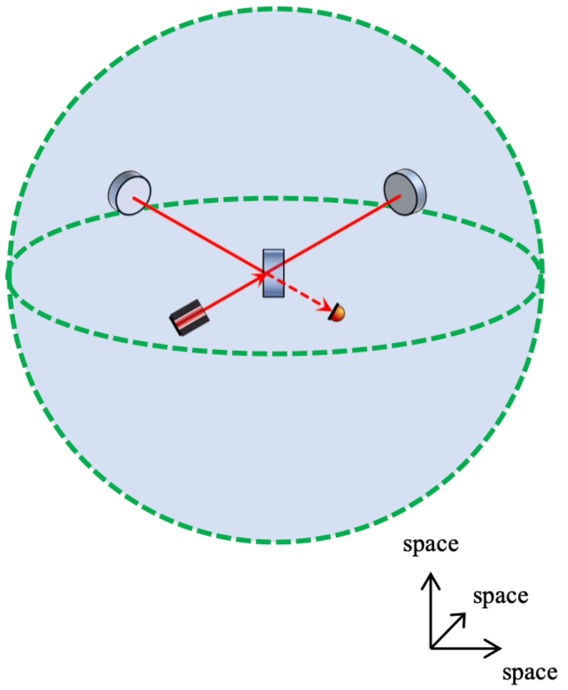

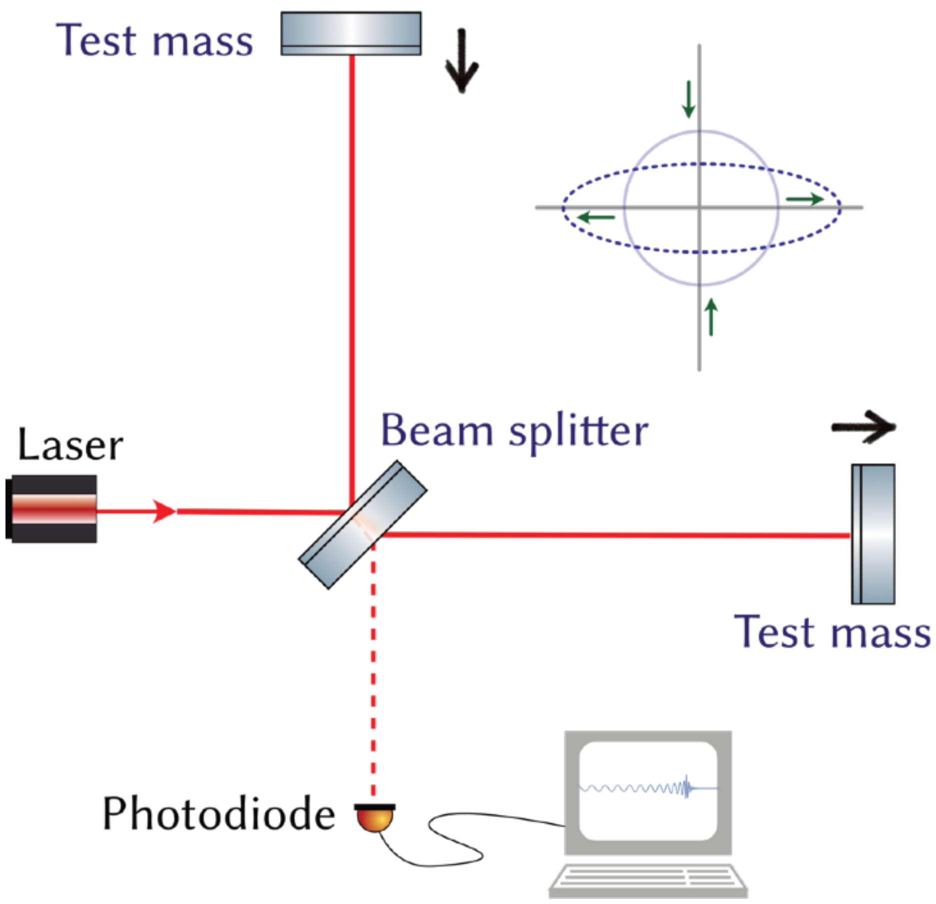

What limits the sensitivity?

- Laser noise
- Thermal noise of the mirrors
- Seismic fluctuations
- Gas, control noise, etc.
- Quantum shot noise

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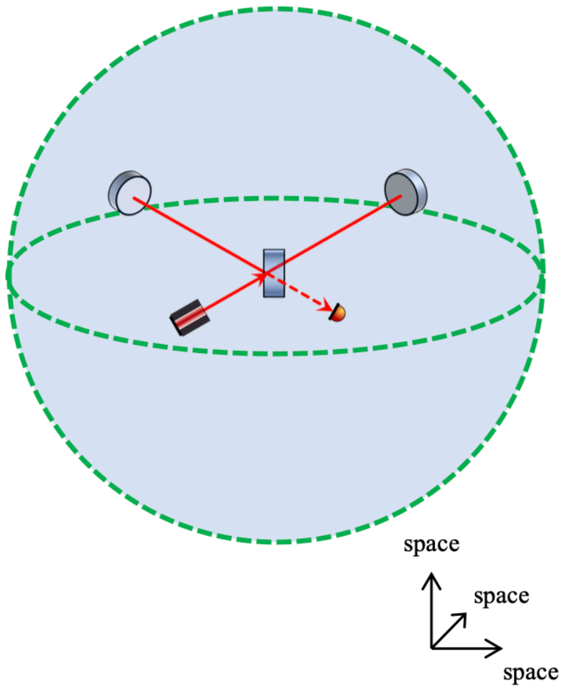

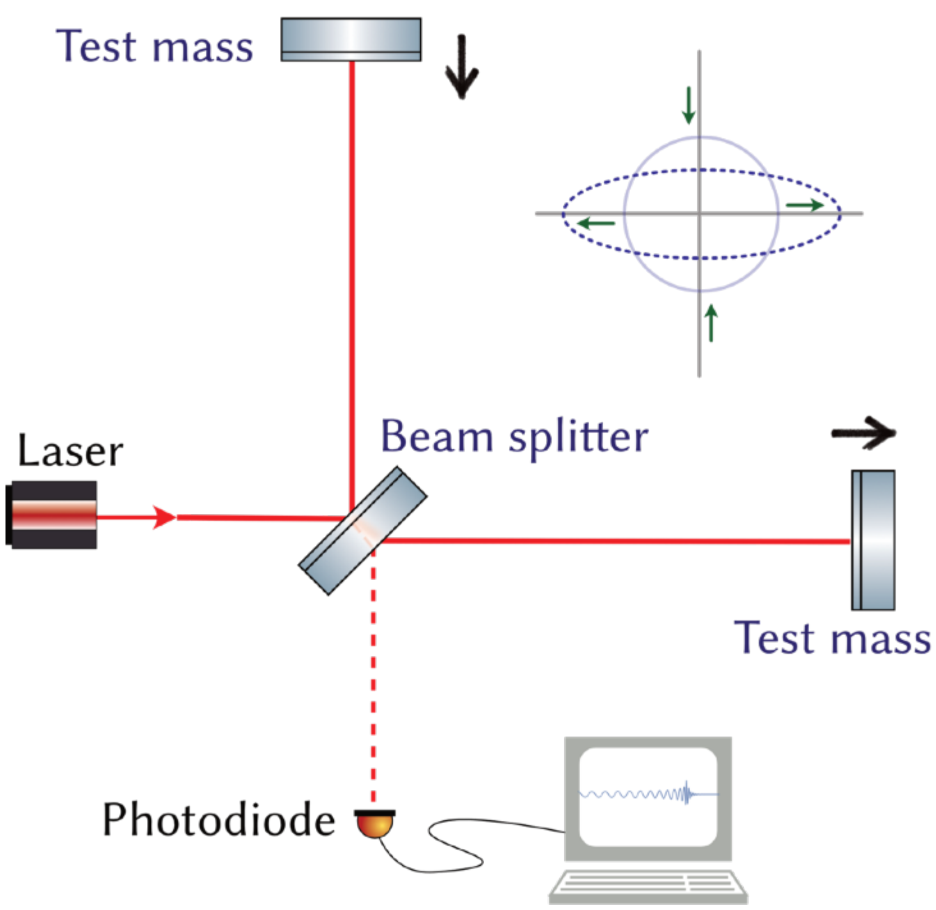

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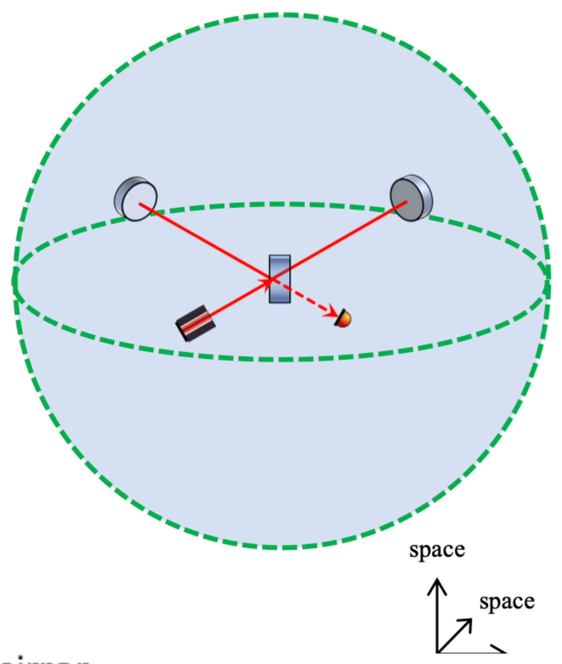
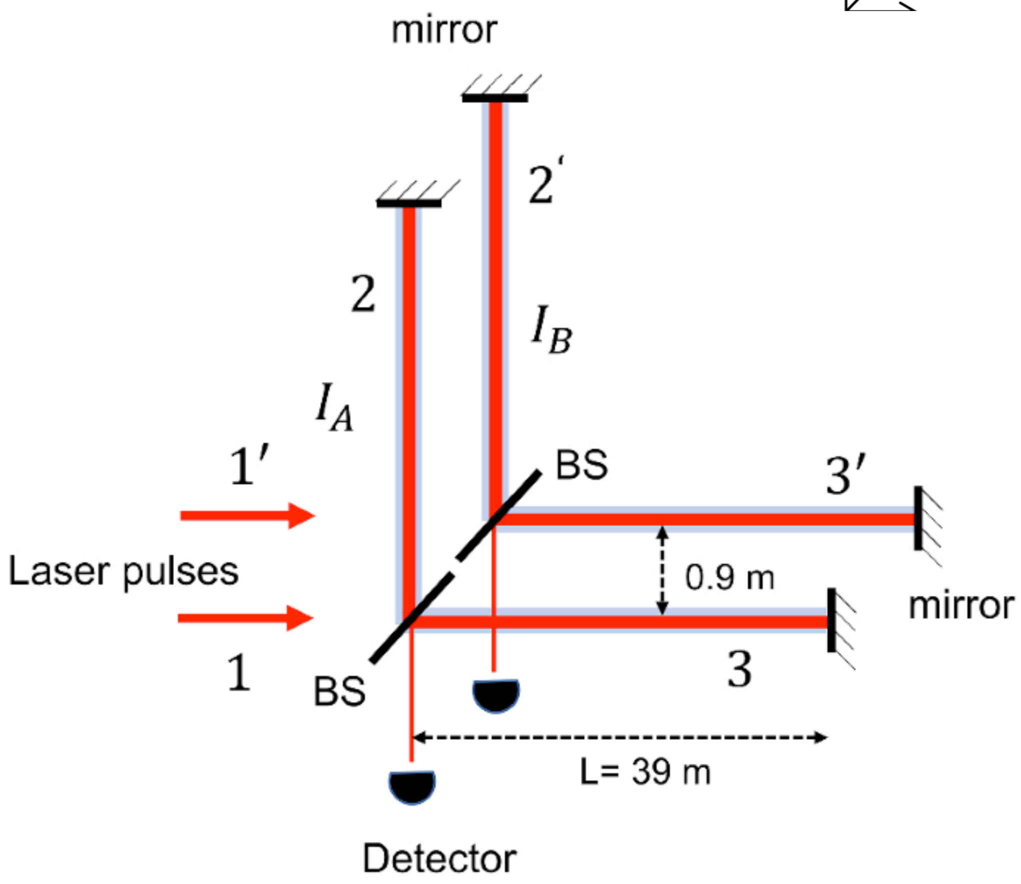


↓

- Ideally have several co-located interferometers
- All technical noises are not correlated for them
- Correlating them will only bring the QG (or other) background



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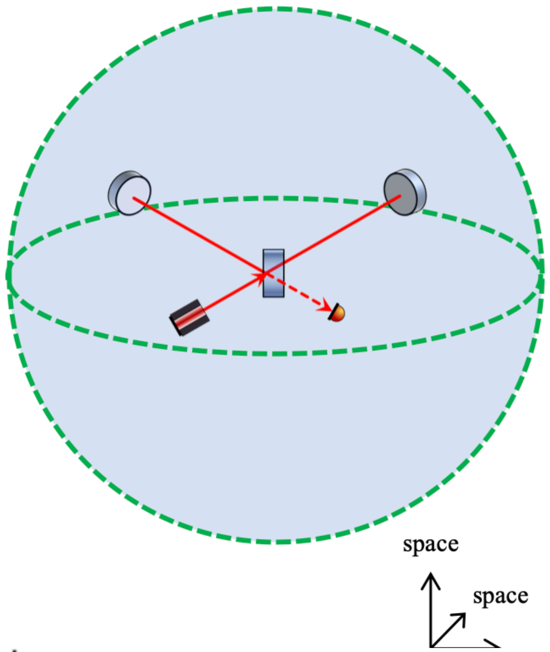

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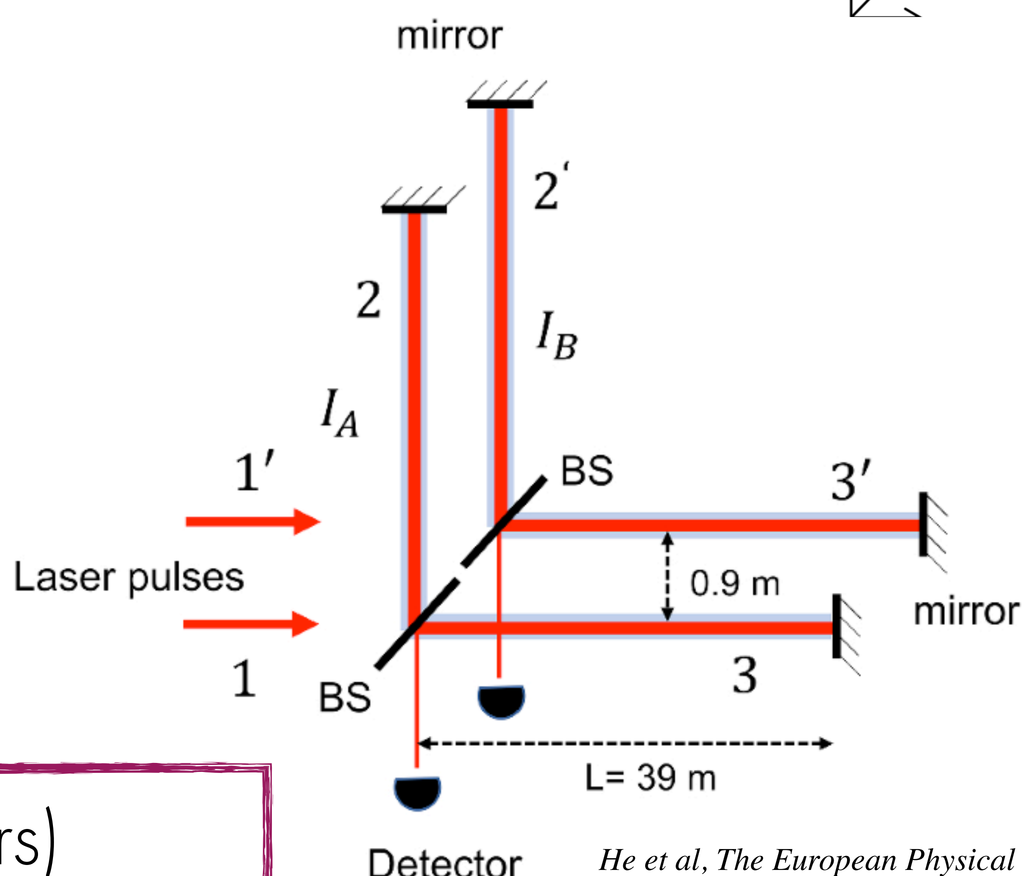
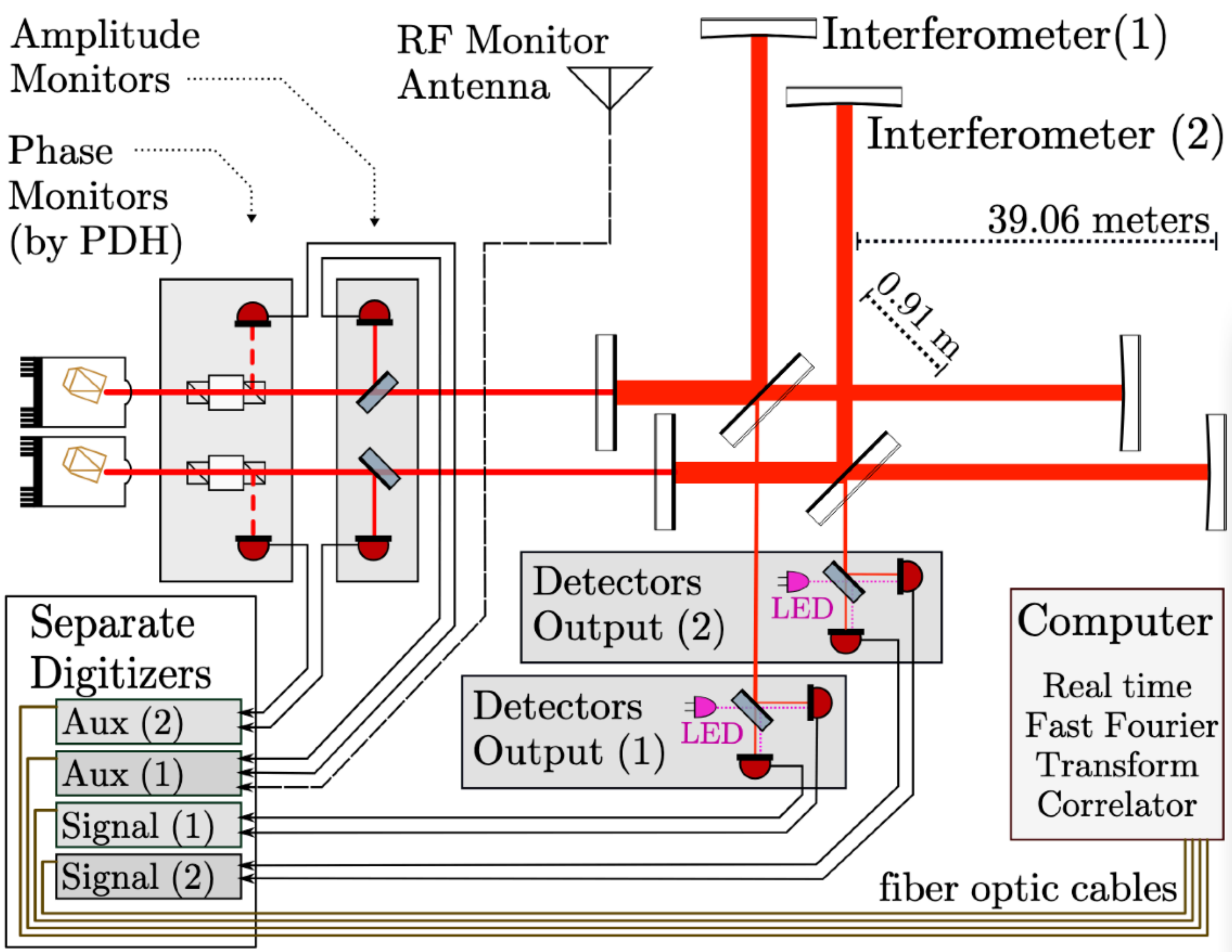


He et al, The European Physical Journal Plus 138.2 (2023): 141.

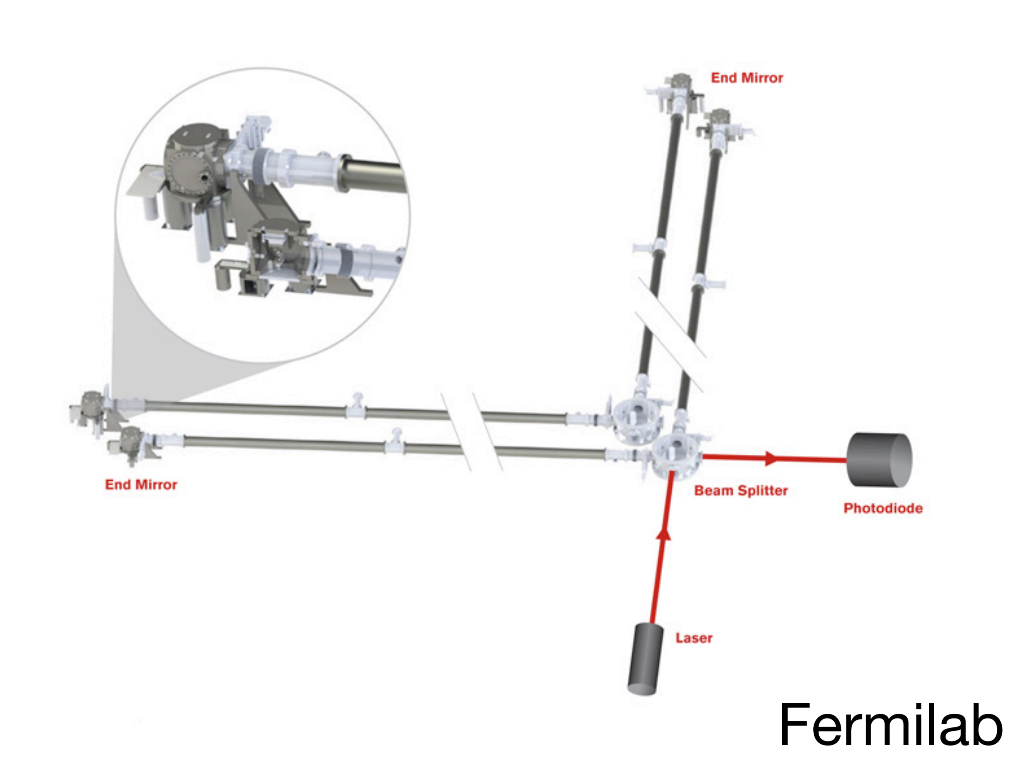
Note: detector networks (with far-separated detectors) don't work

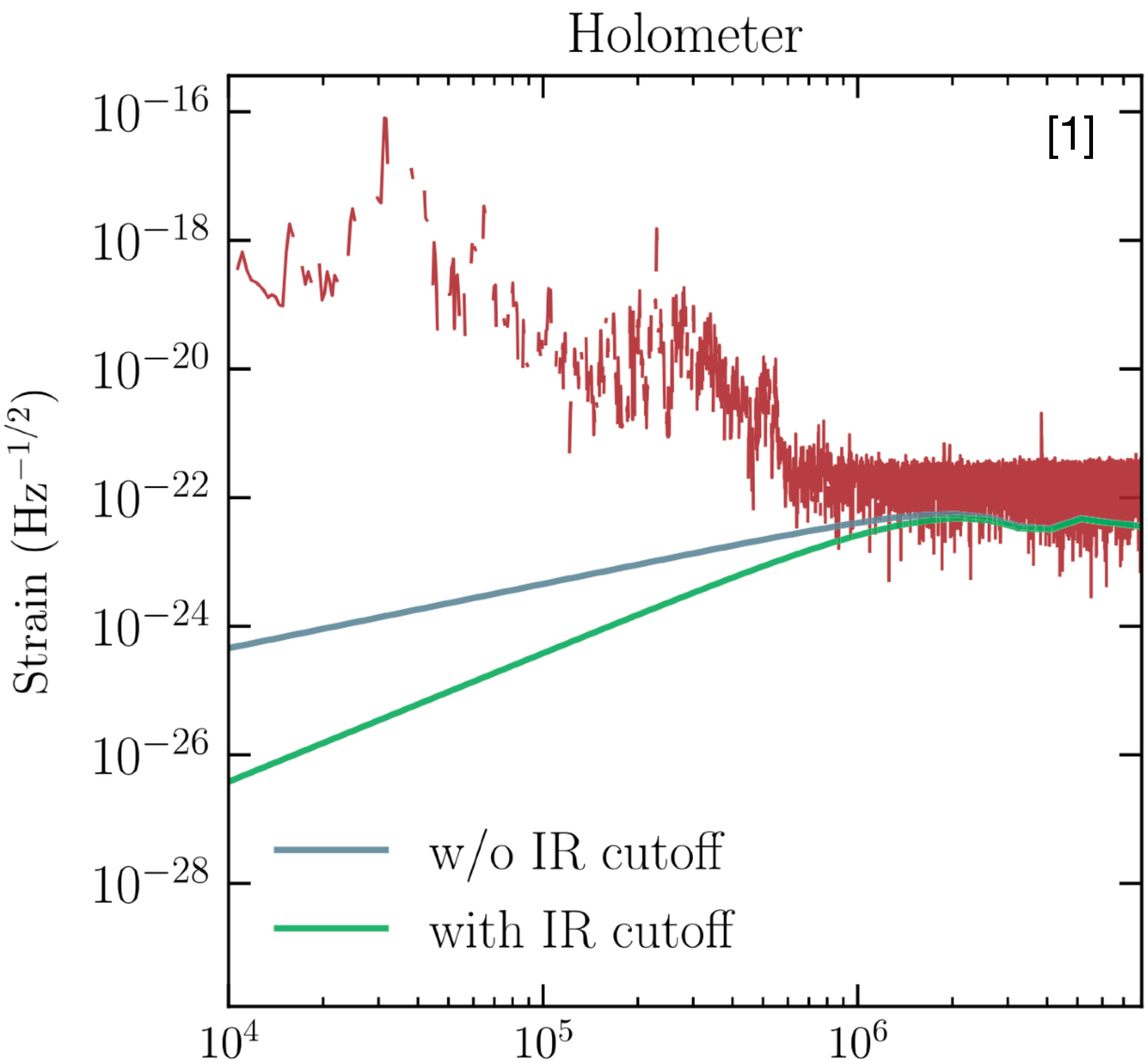
One of the first detectors: Holometer in Fermilab

- Two co-located interferometers, about 40m each.
- Averaging for a long time
- Finished its work in ~2015, ruling out one of the types of holographic noise



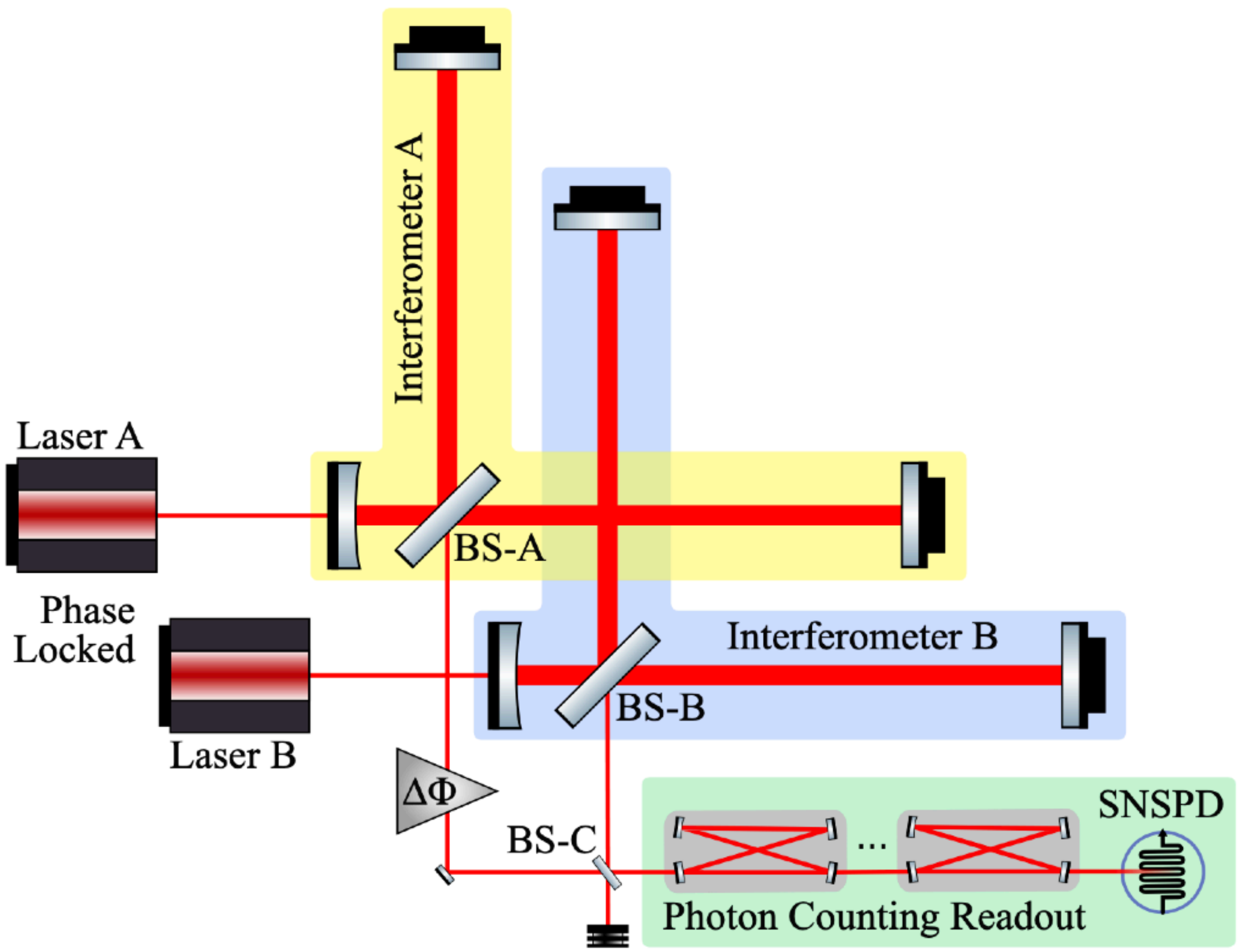
arXiv: 1512.01216

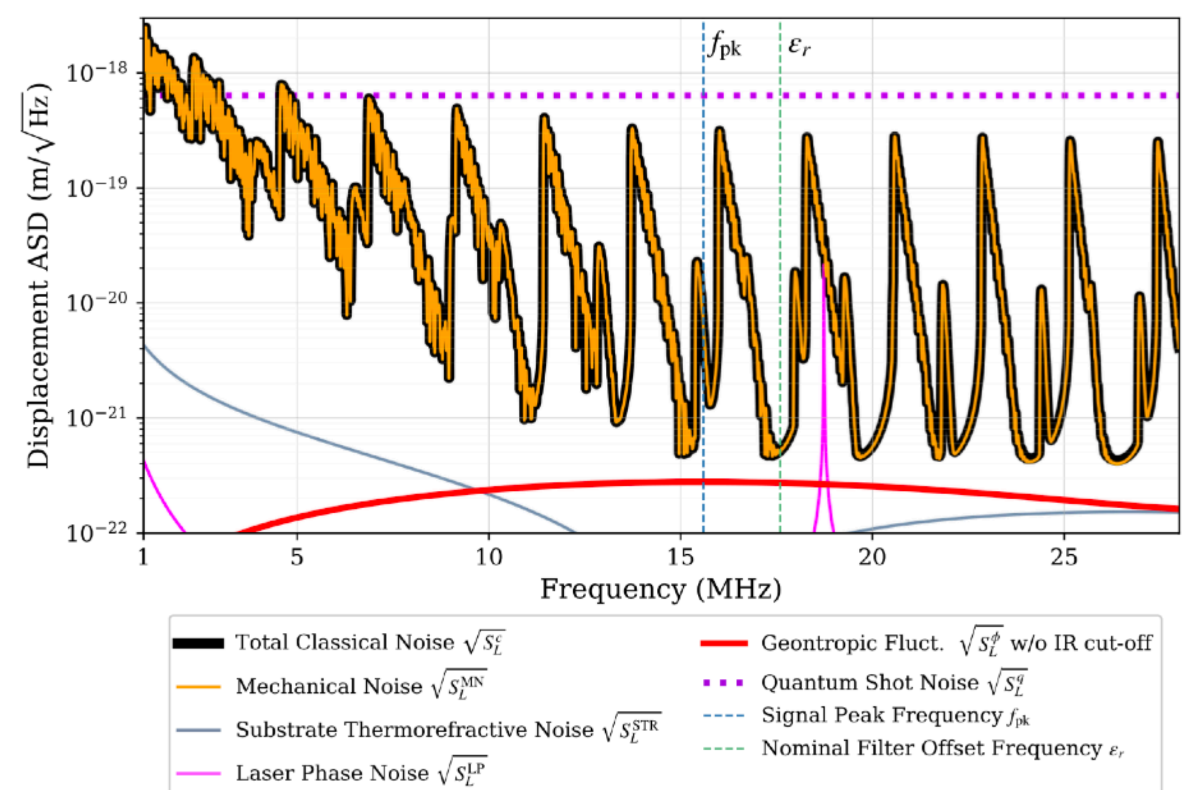



Holometer
[1]
Strain $(\mathrm{Hz}^{-1/2})$
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{4}
10^{5}
10^{6}
w/o IR cutoff
with IR cutoff

A "follow-up" to the Holometer

- Two co-located interferometers, about 5m each.
- Photon counting instead of usual PD: novel approach to gain high SNR

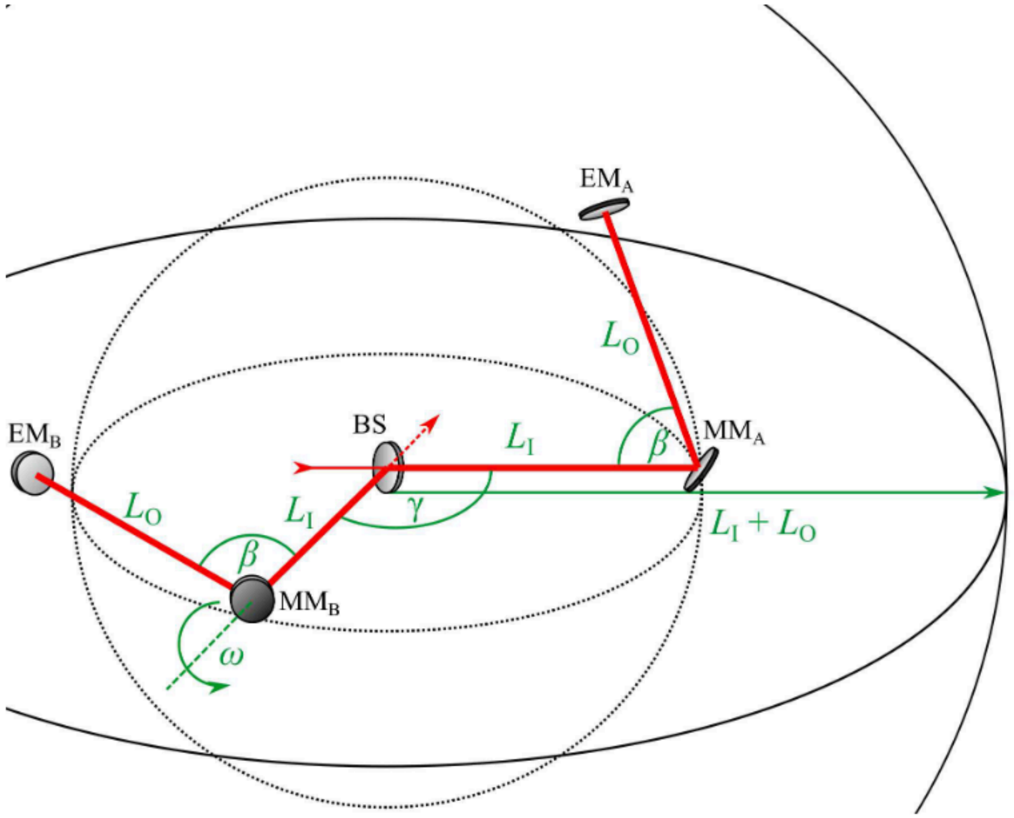




arXiv: 2404.07524

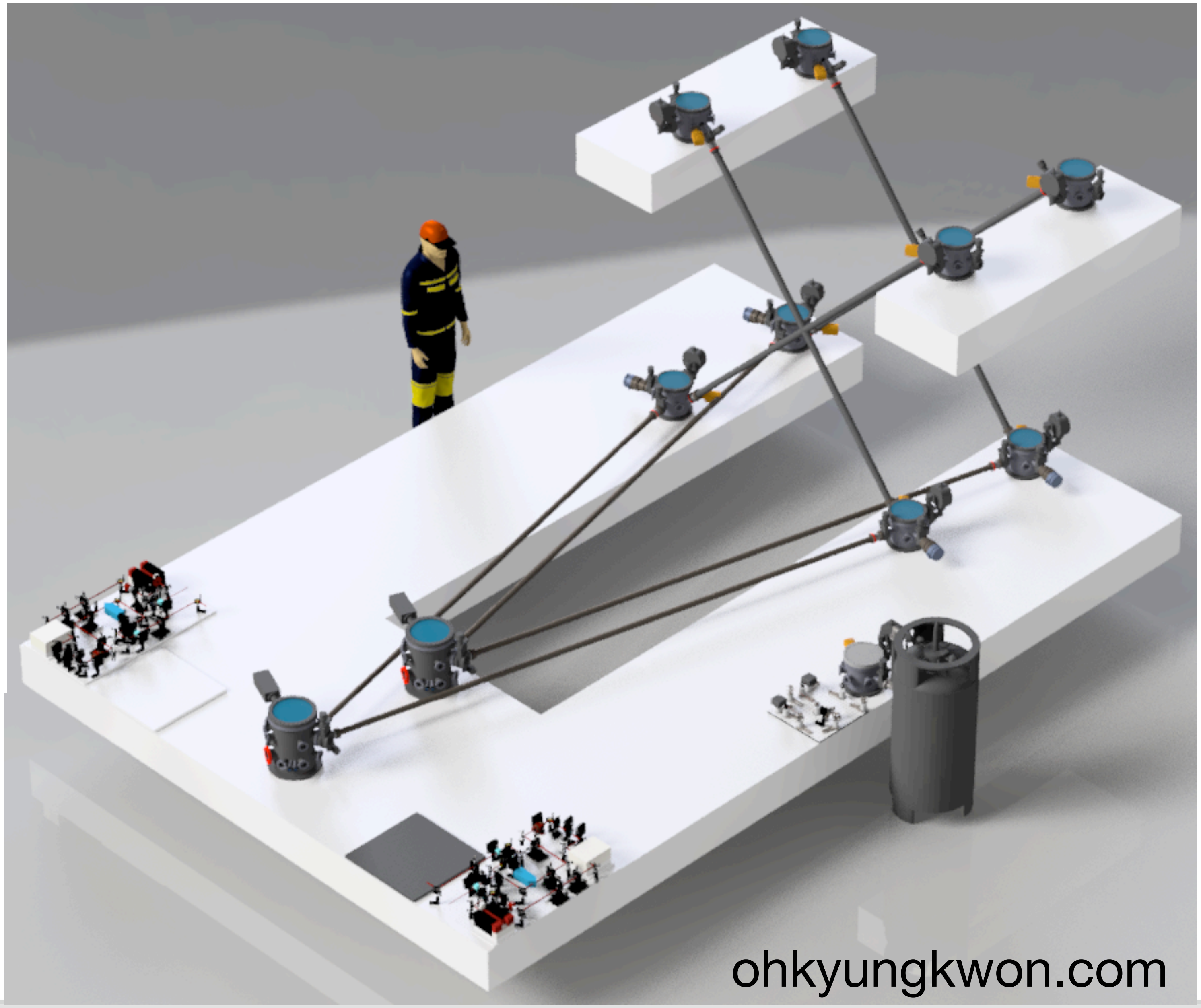
Another "follow-up" to the Holometer in Cardiff:

- Two co-located interferometers with different angles arranged in 3d.
- Should probe different breathing modes of pixellon field
- Unclear if the model is compatible with that

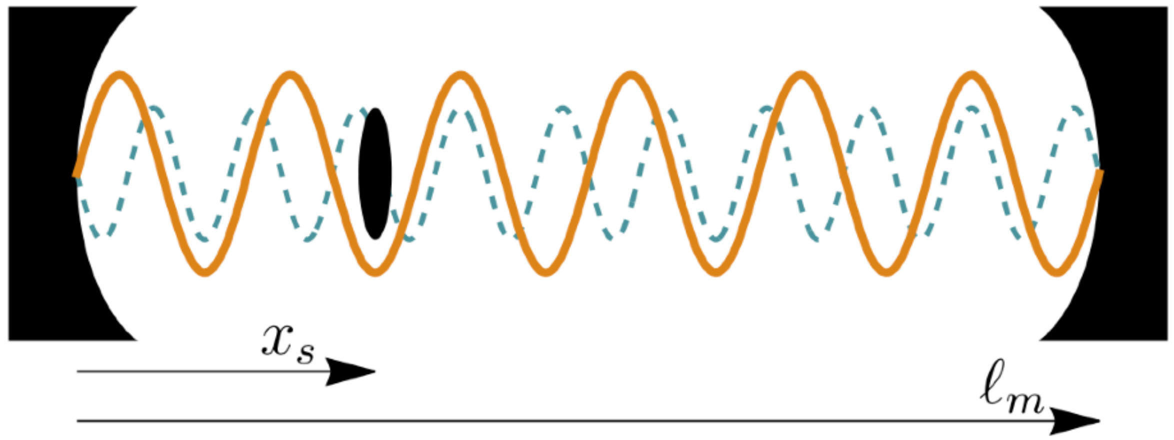


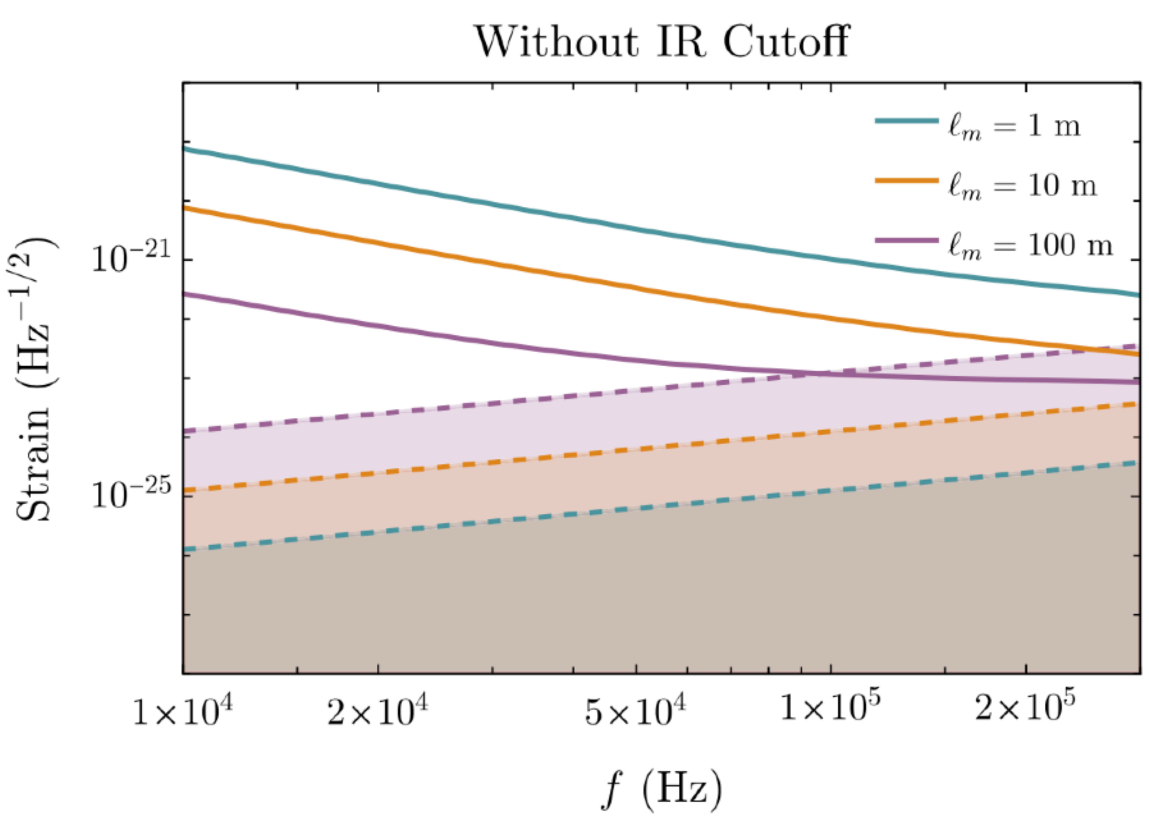
(a)

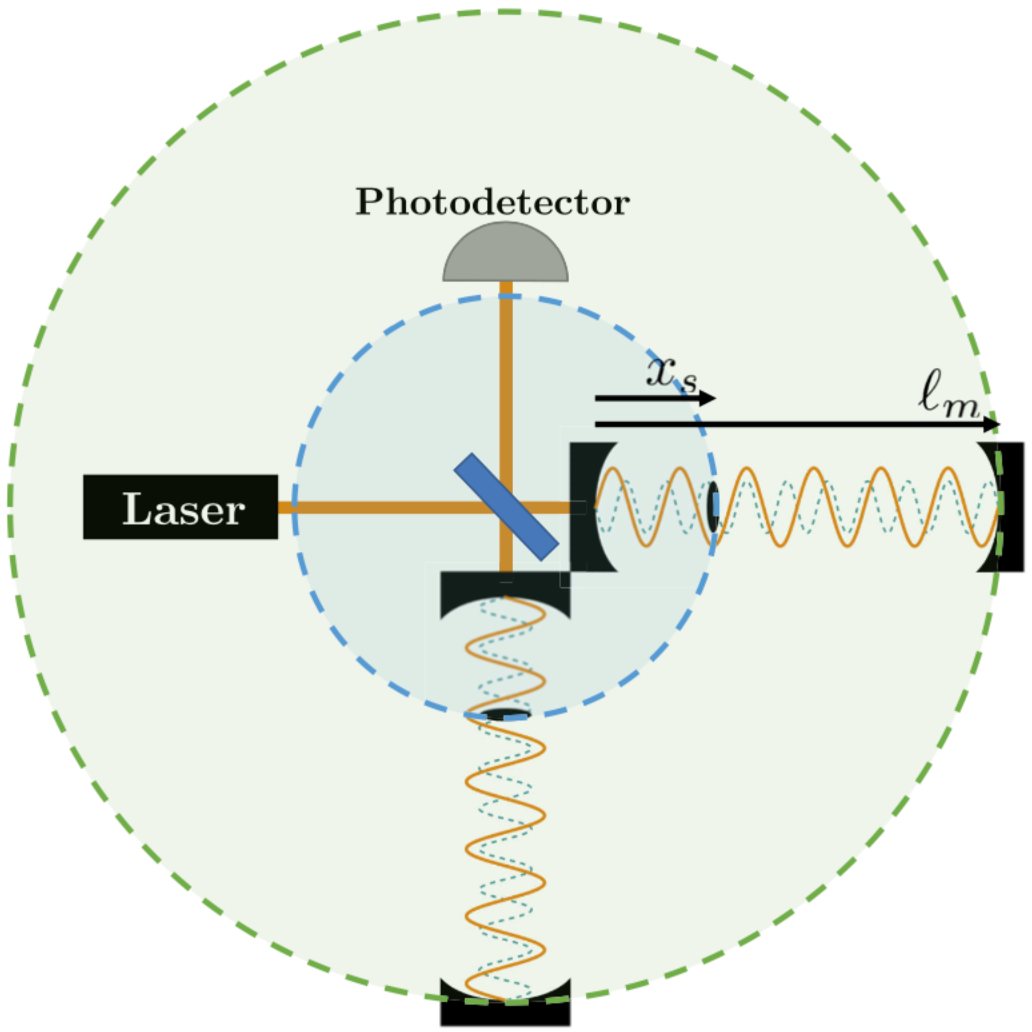
arXiv: 2008.04957



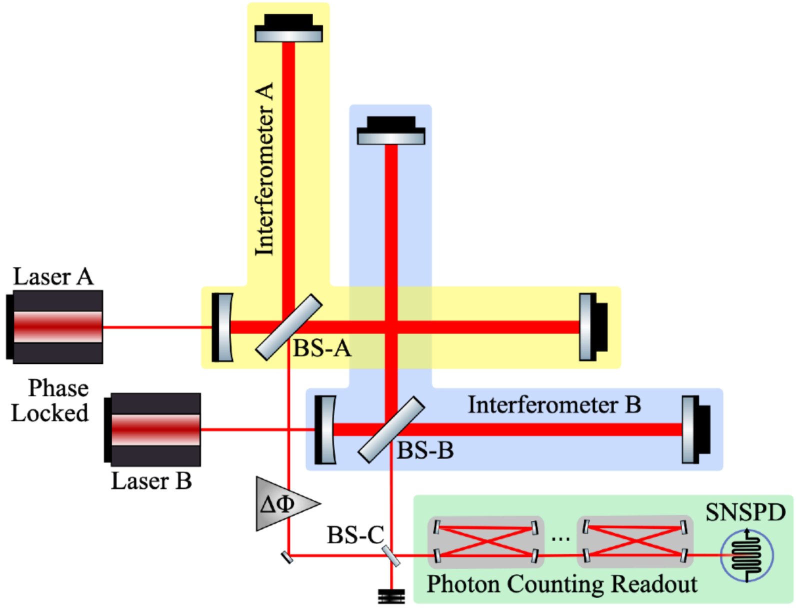
Using the dielectric disc optically levitated allows to make a “free” test mass
Target: any high-frequency GWs in the ~10-100 kHz region.

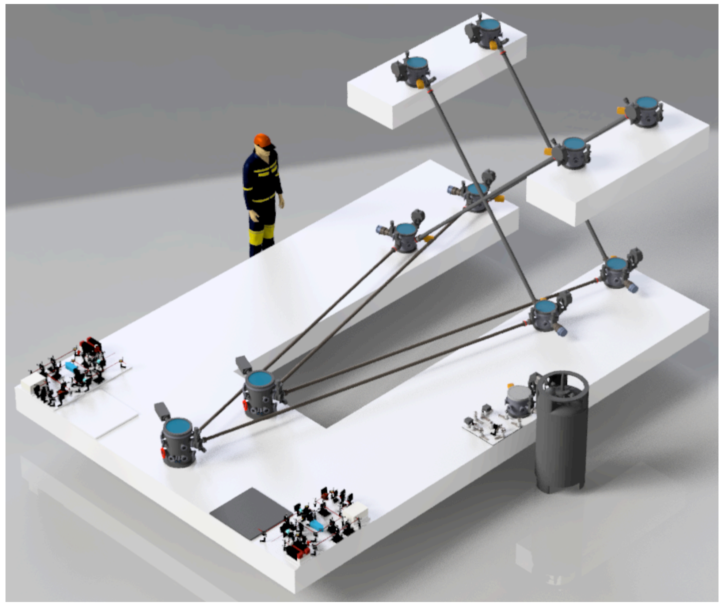




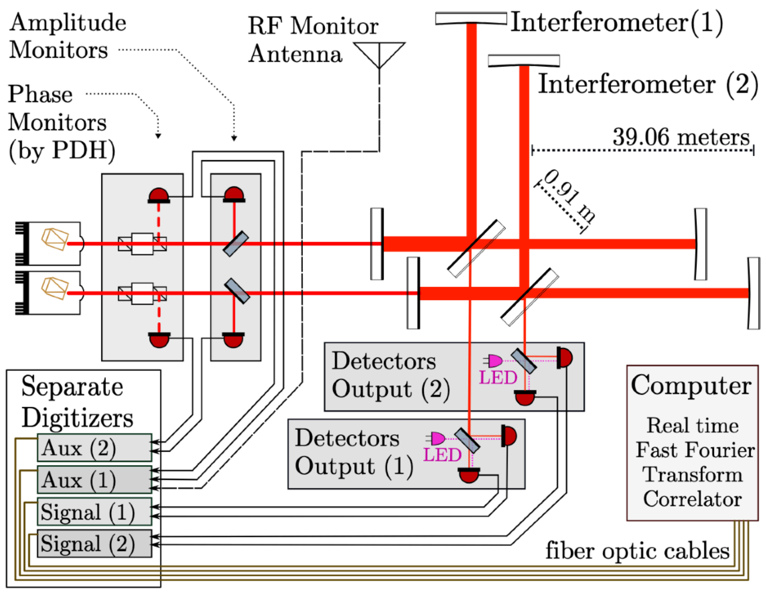


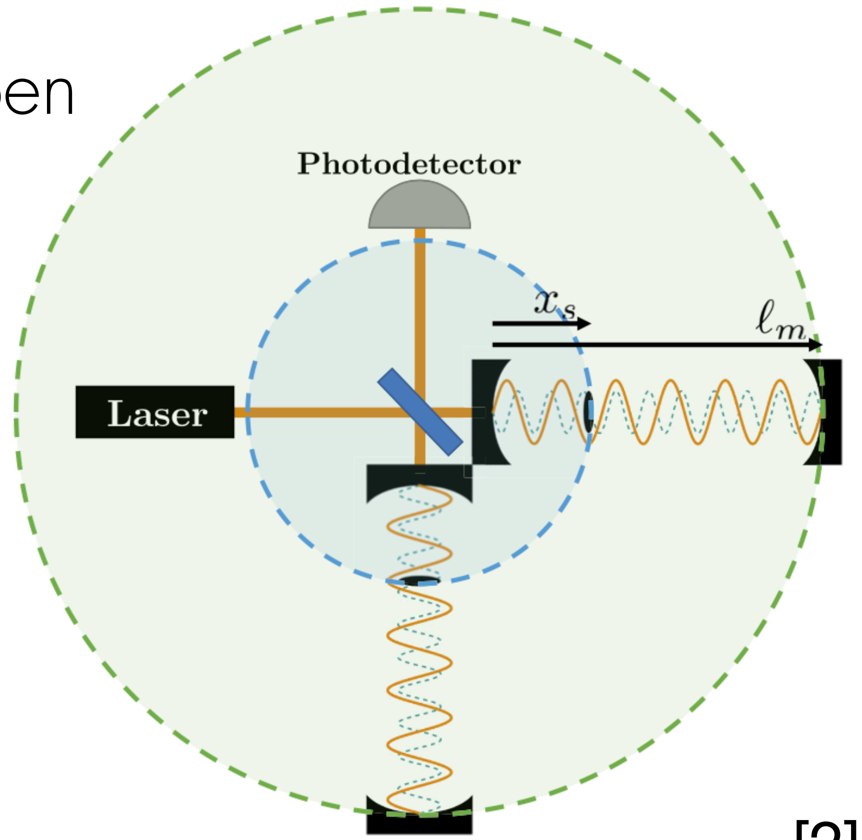
[2]





More development needed
before any detection could happen

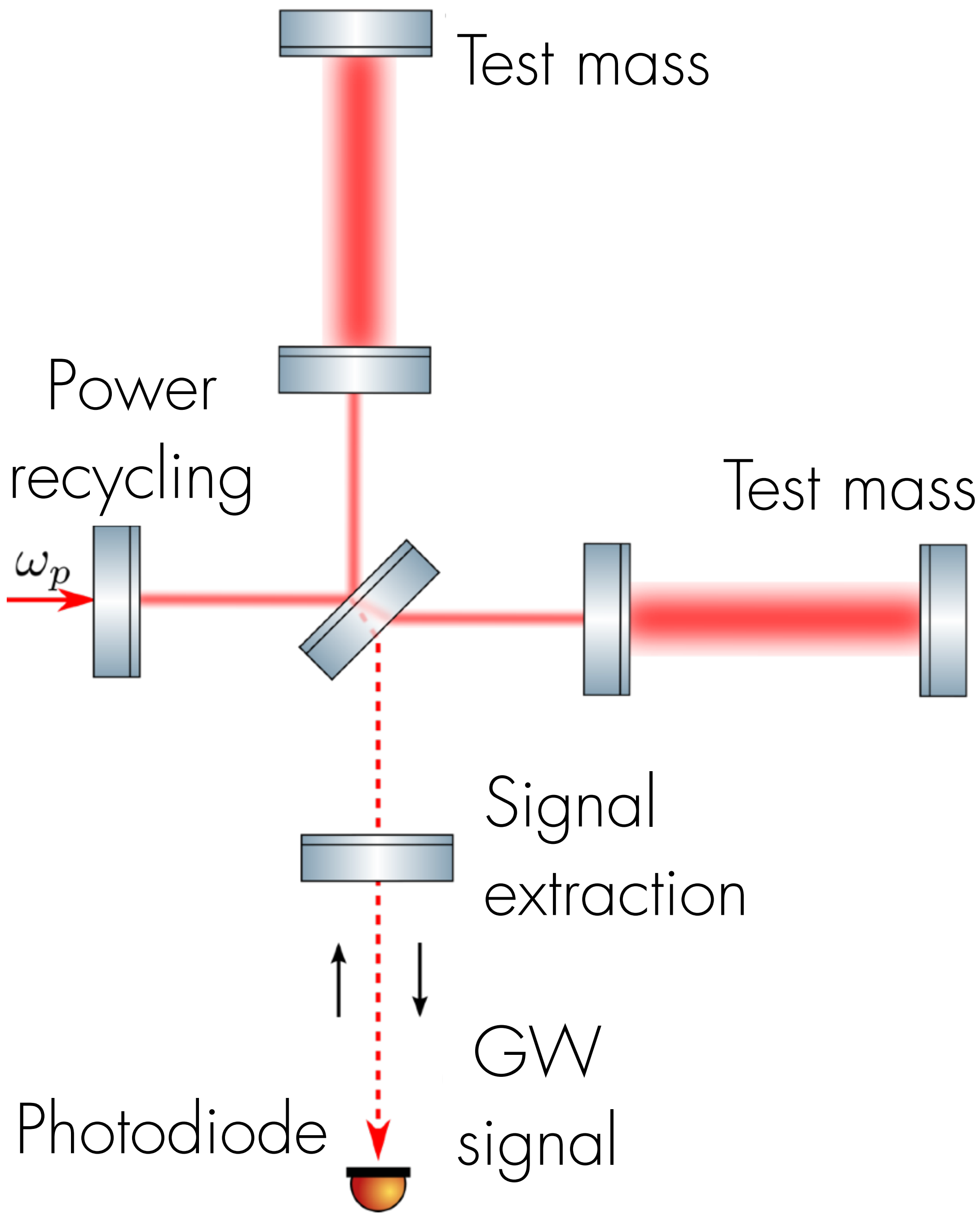




[2]

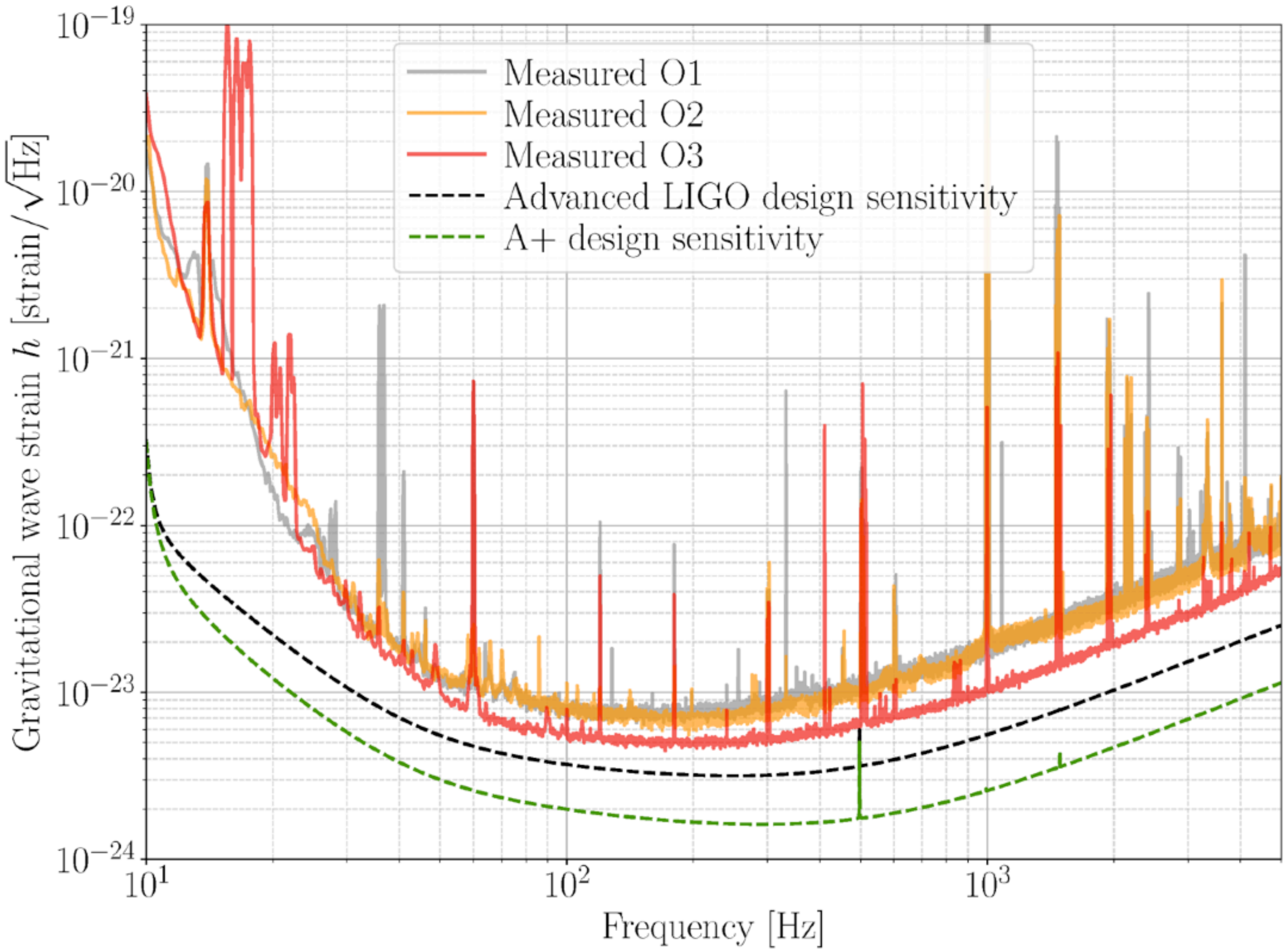
Outline

GW detection

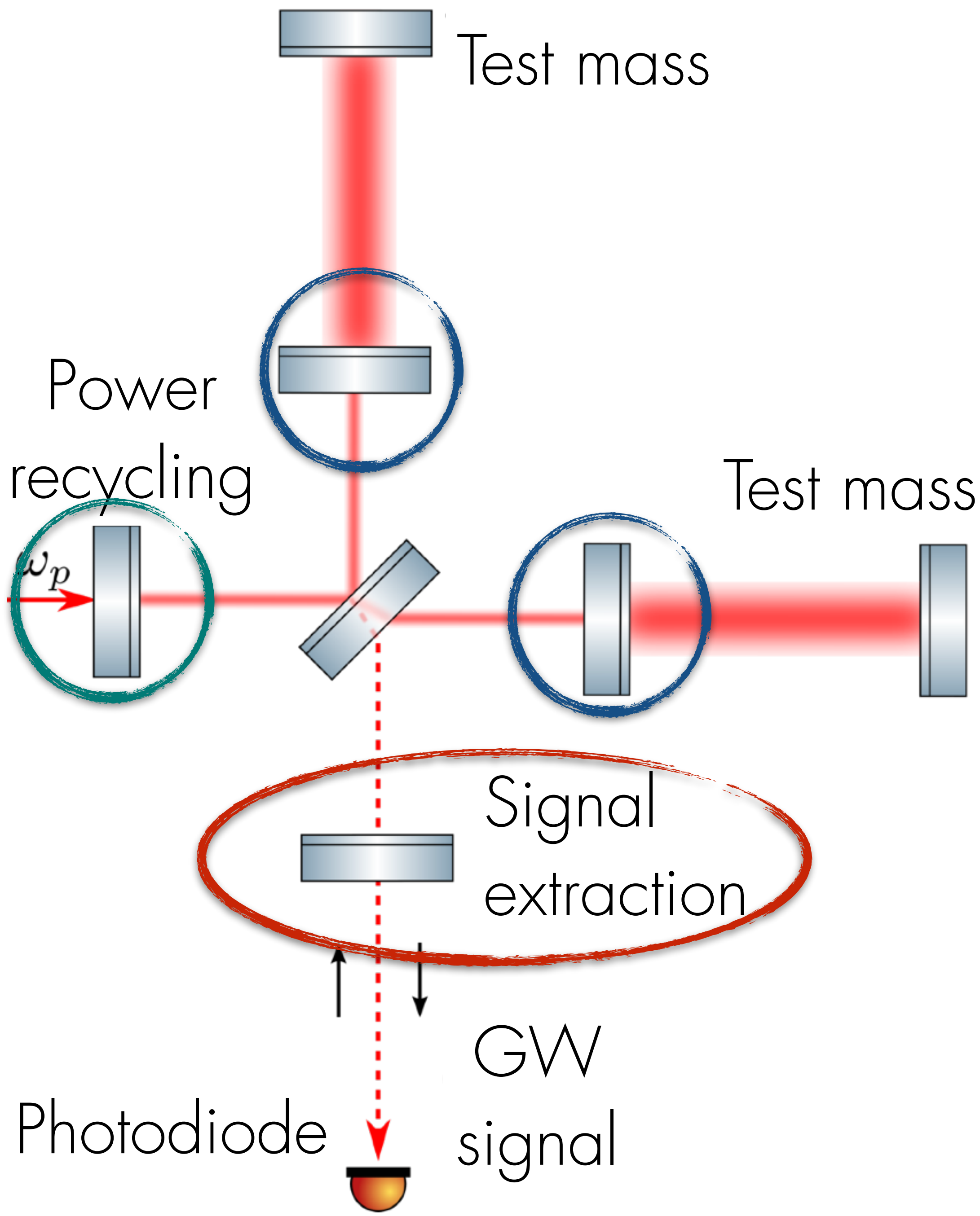


Sensitivity of the detector

Cahillane, C., & Mansell, G., *Galaxies*, *10*(1), 36. (2022).



GW strain = ΔLength/Length



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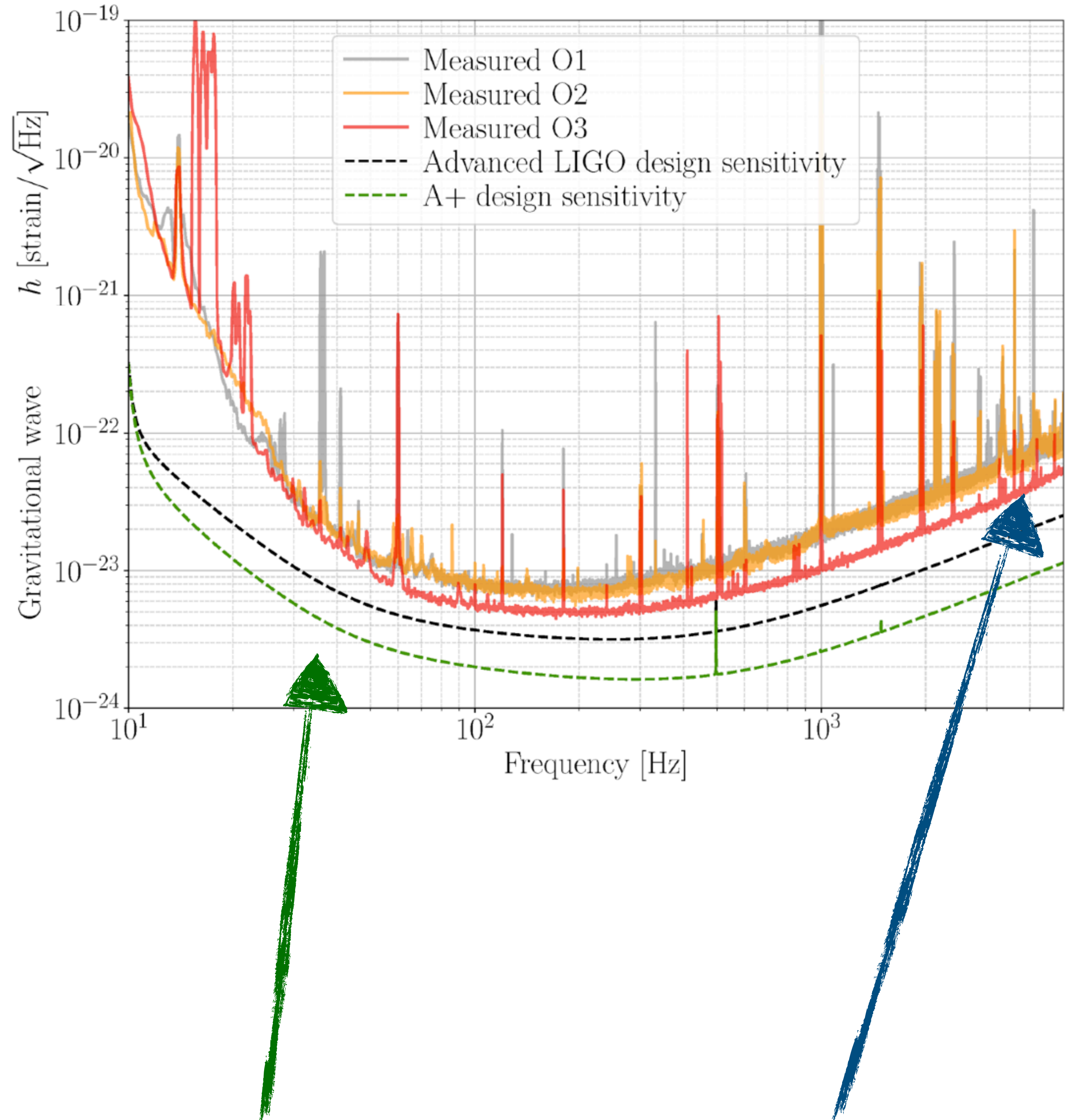
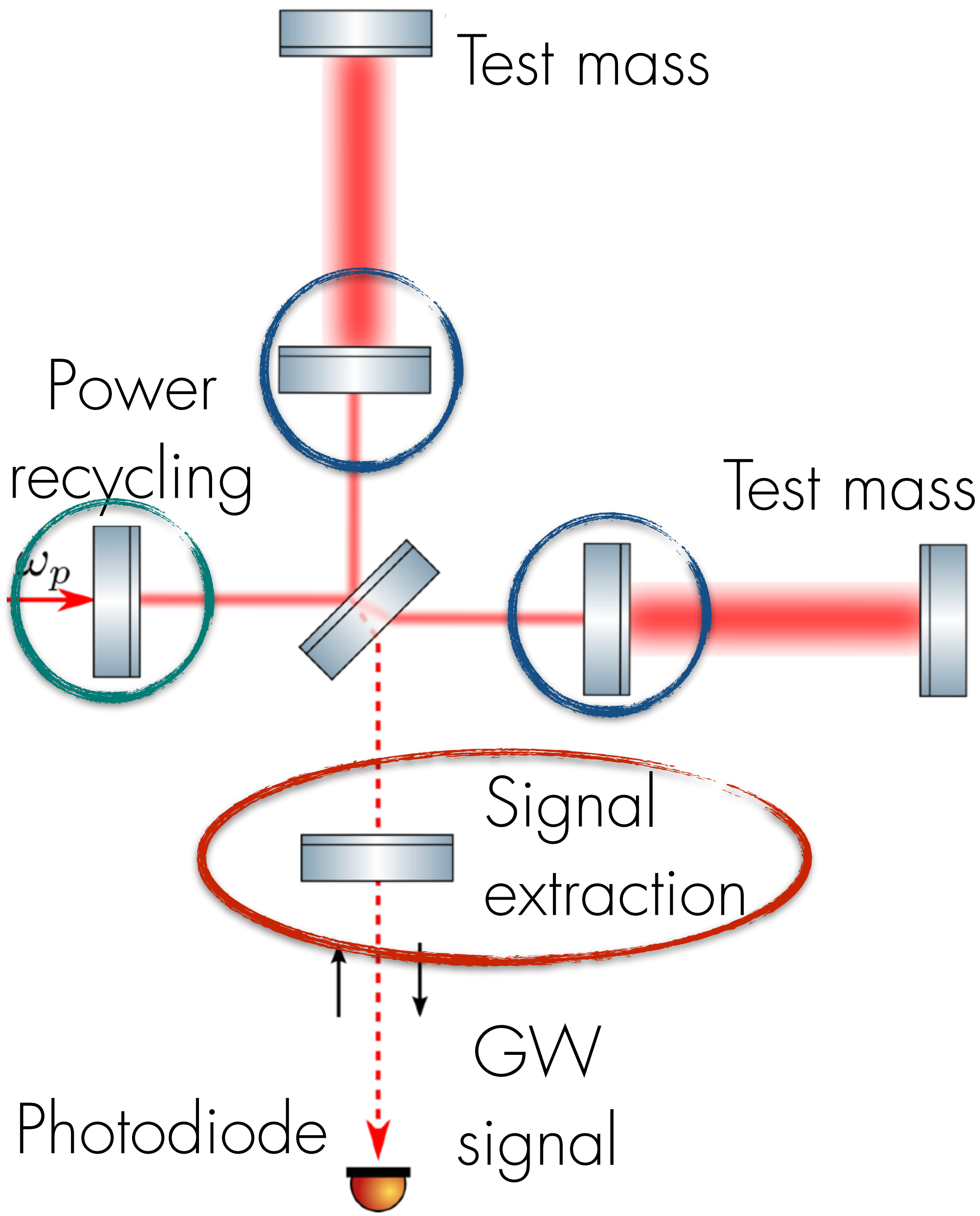


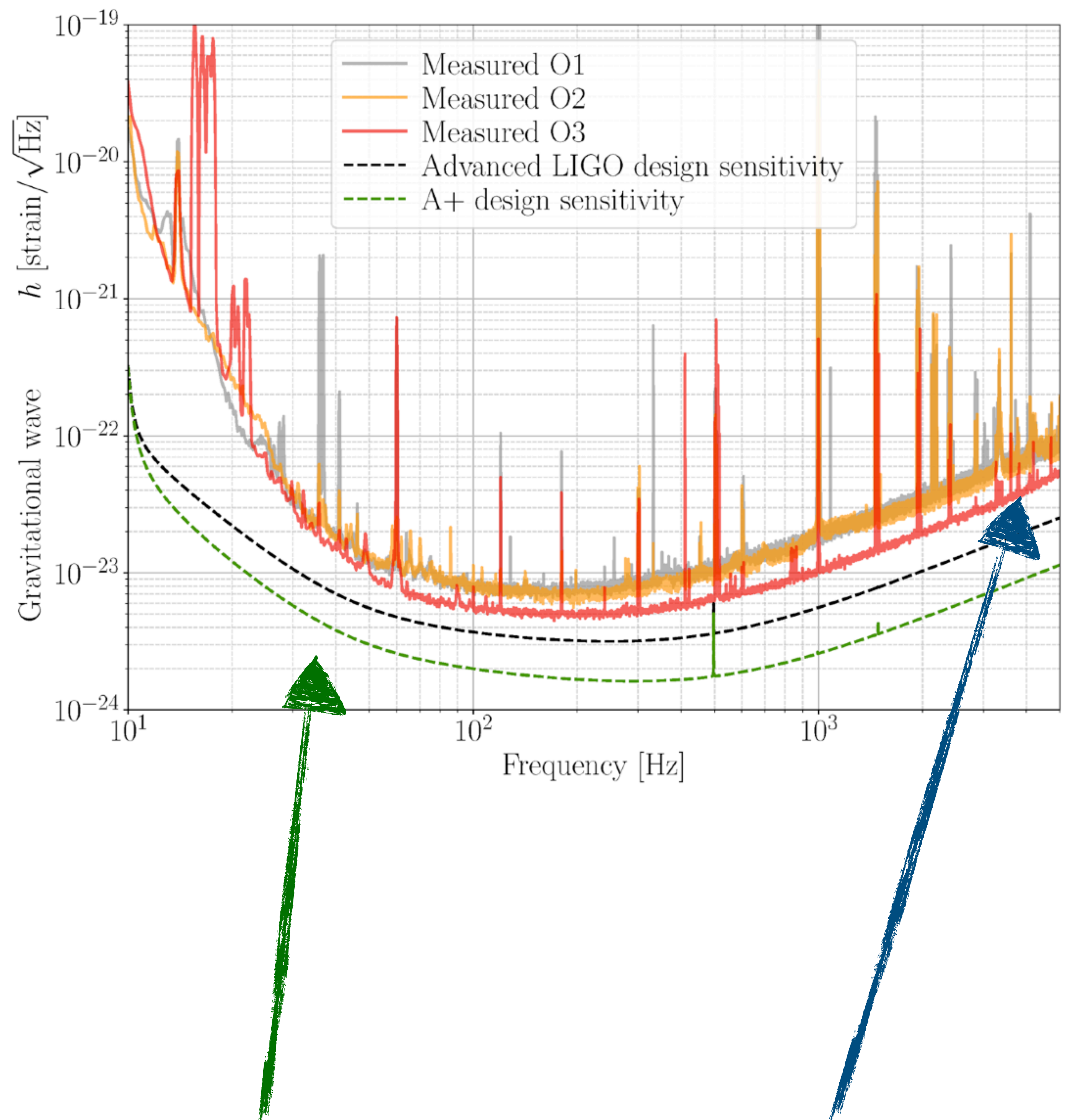
Role of cavities: amplify power and signal on resonance & increase bandwidth

GW detection



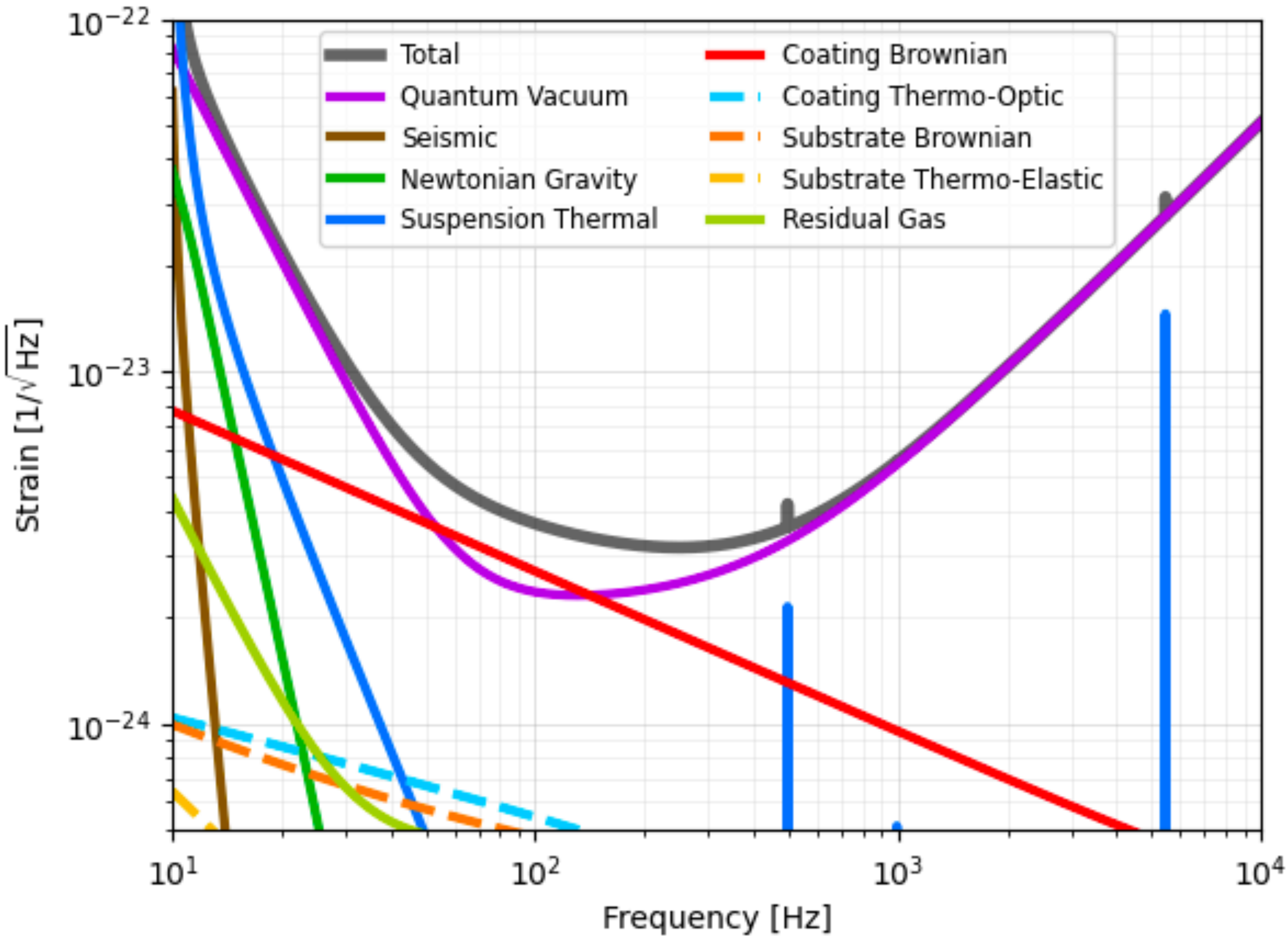
Sensitivity of the detector

Cahillane, C., & Mansell, G., *Galaxies*, *10*(1), 36. (2022).

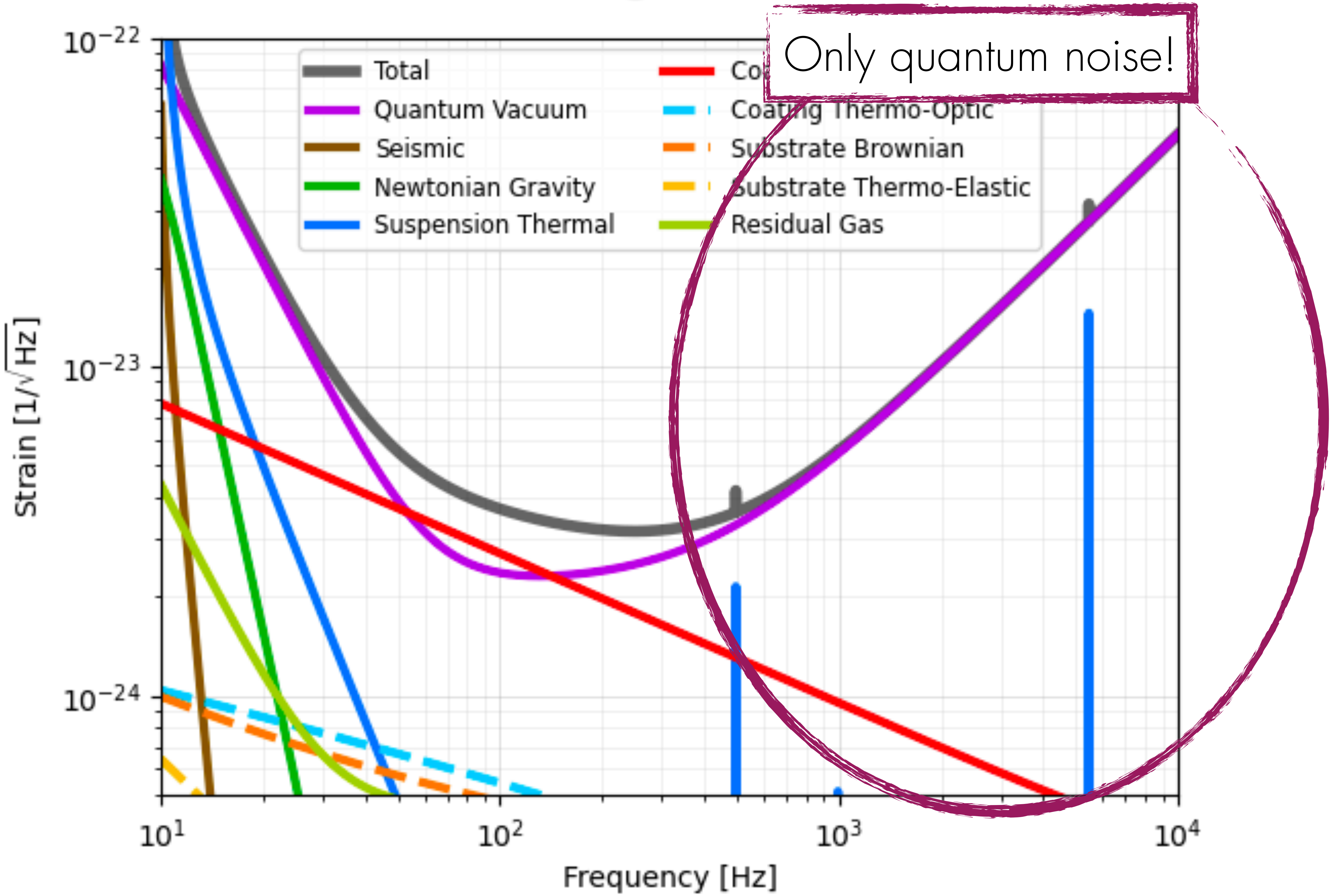


Role of cavities: amplify power and signal on resonance & increase bandwidth

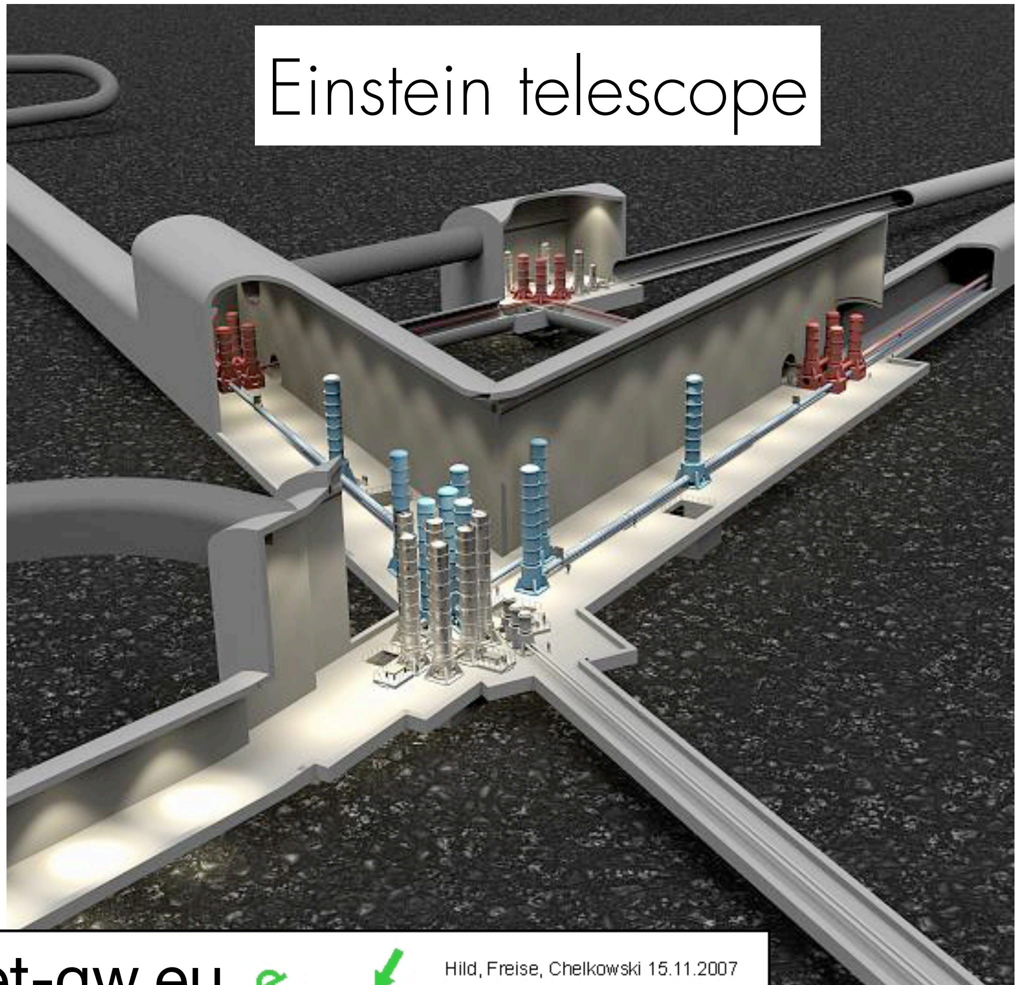
Cavities don't affect the geontropic noise detection (probably)

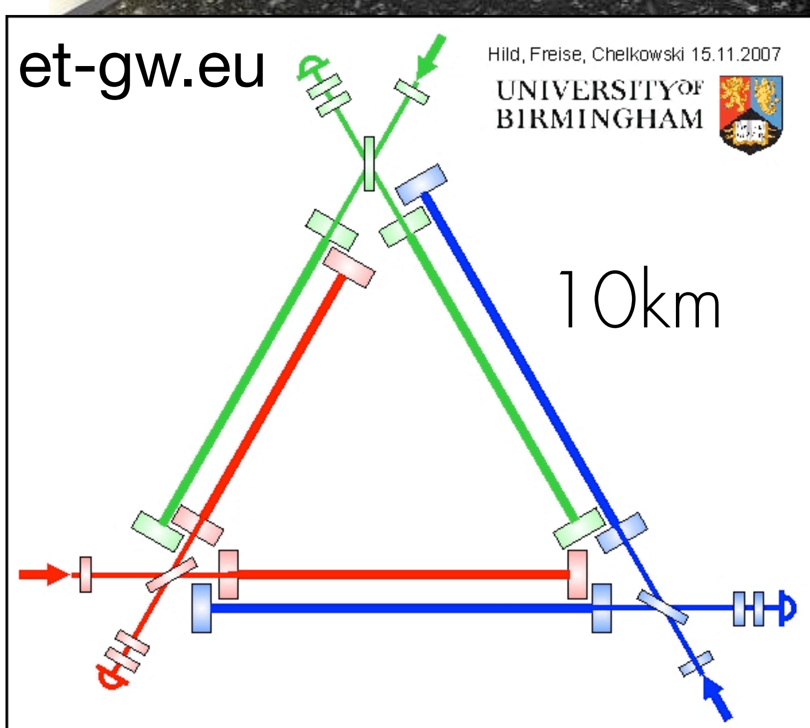

Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermo-Elastic
Residual Gas
10^{-22}
10^{-23}
10^{-24}
Strain [$1/\sqrt{\mathrm{Hz}}$]
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

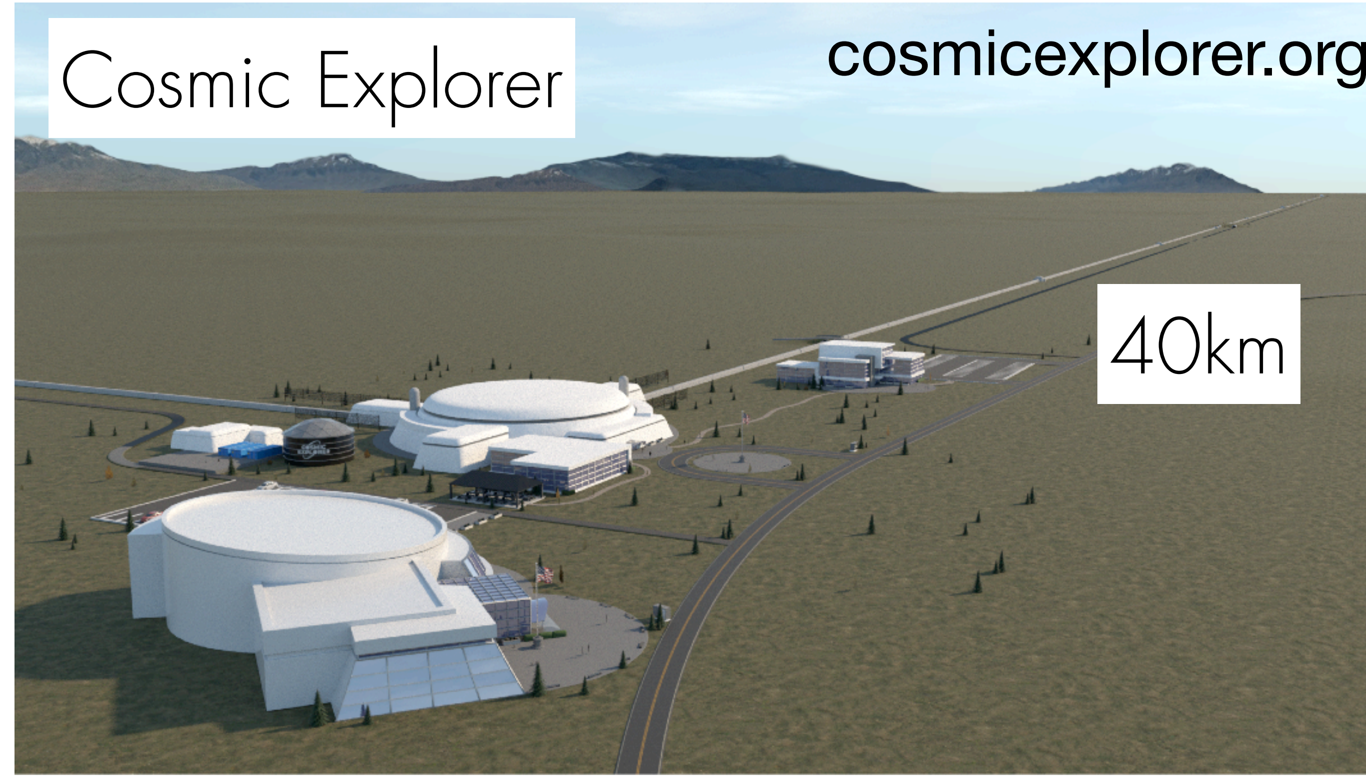
Sensitivity of the detector

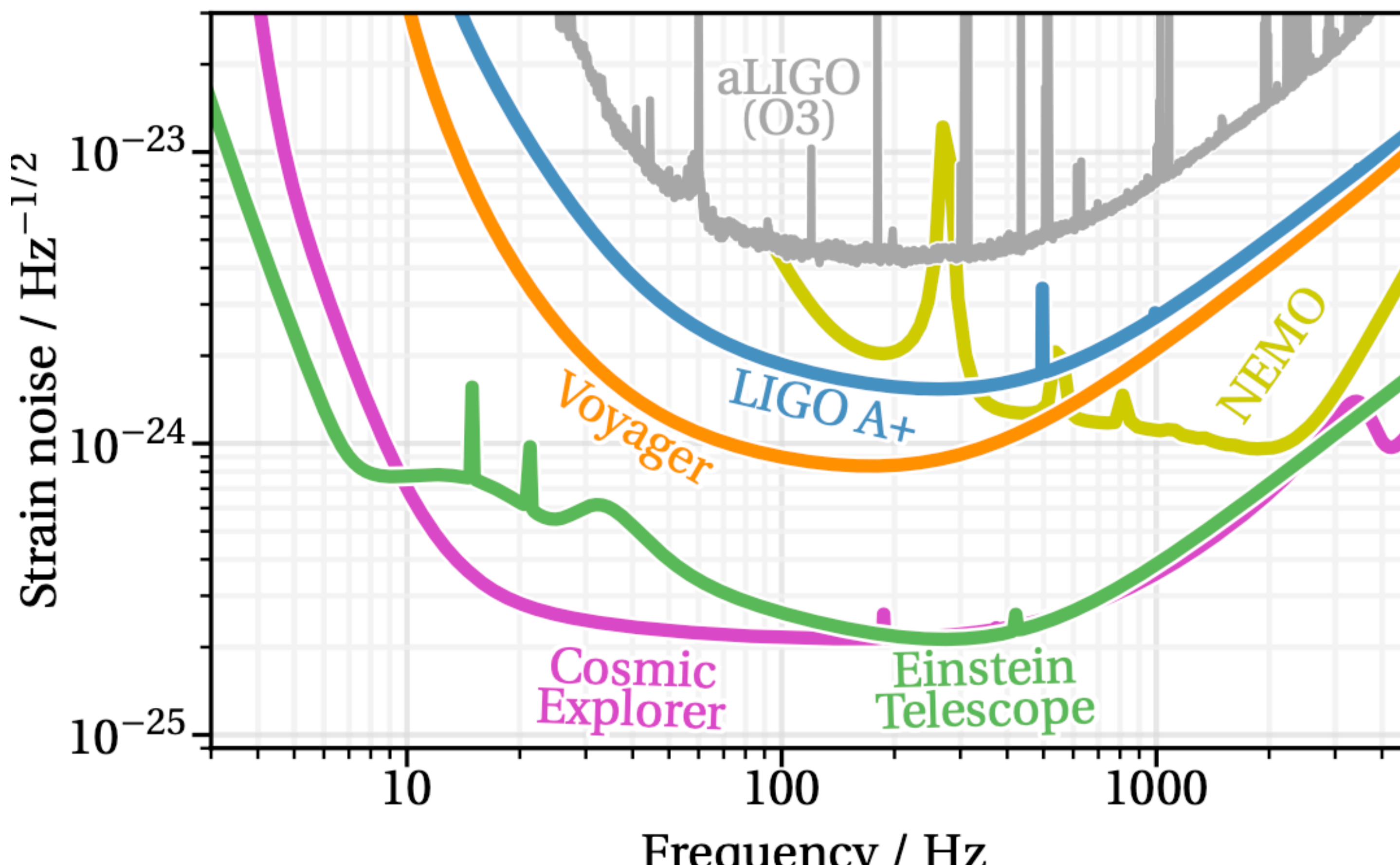


GW detection — Future detectors





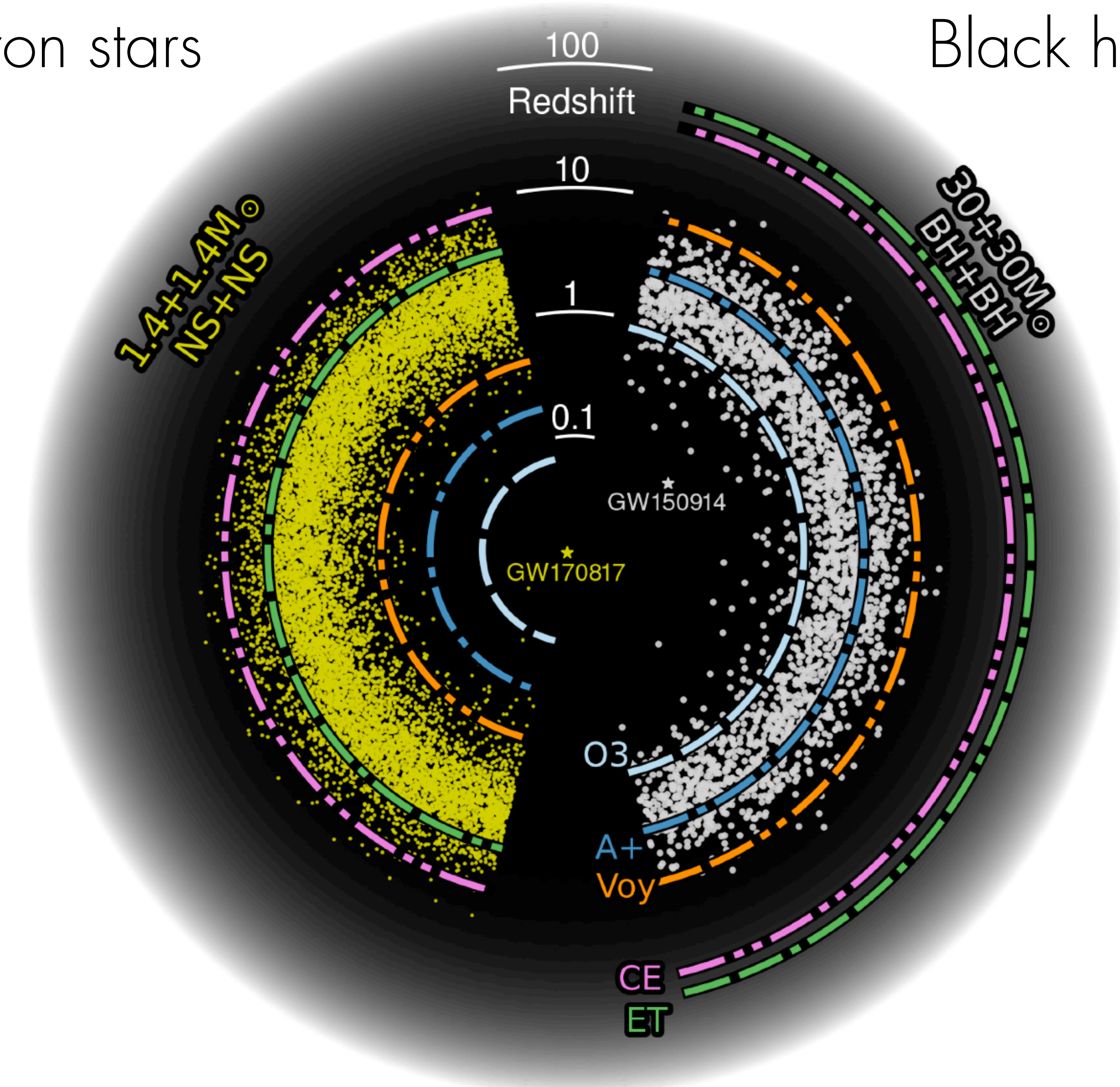




We will see most of the Universe!

Neutron stars

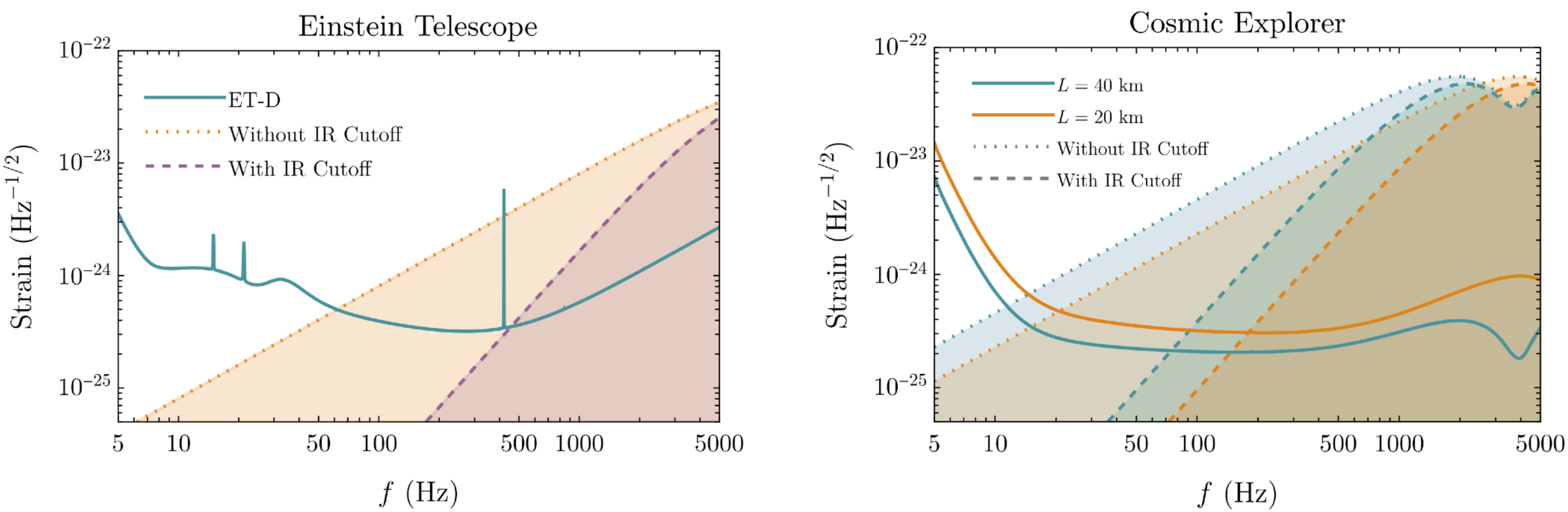
Black holes



cosmicexplorer.org

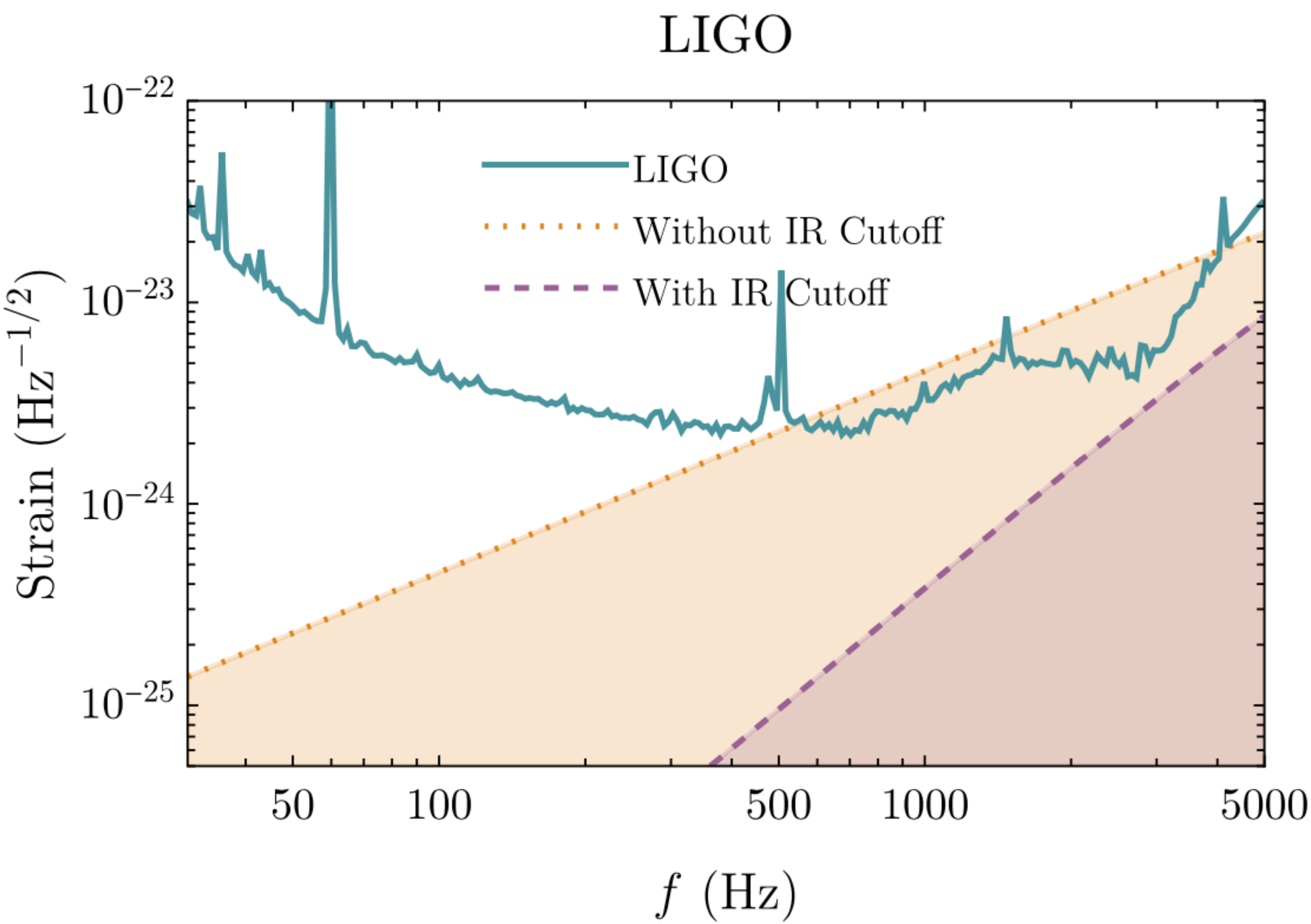
Outline

Future detectors

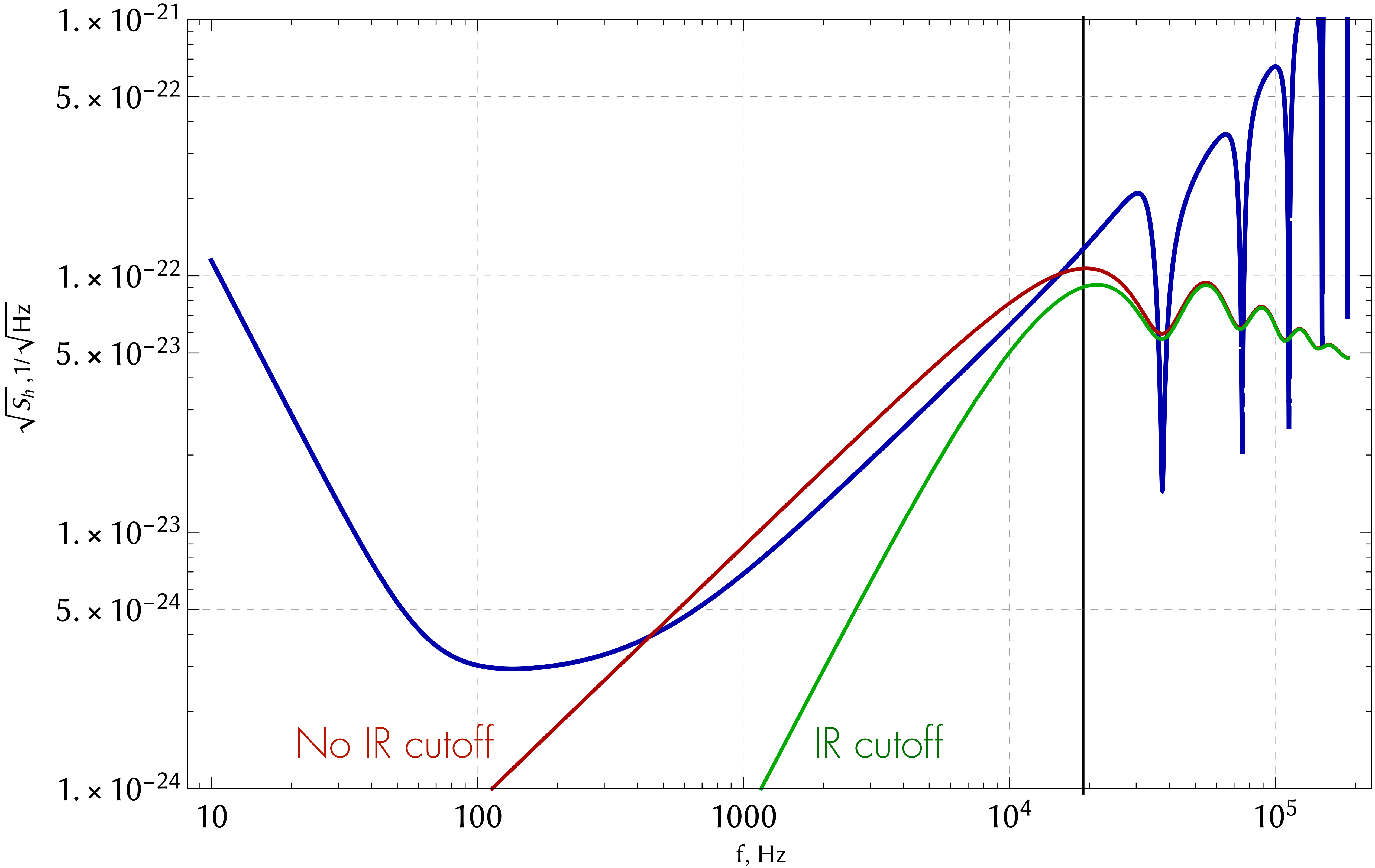


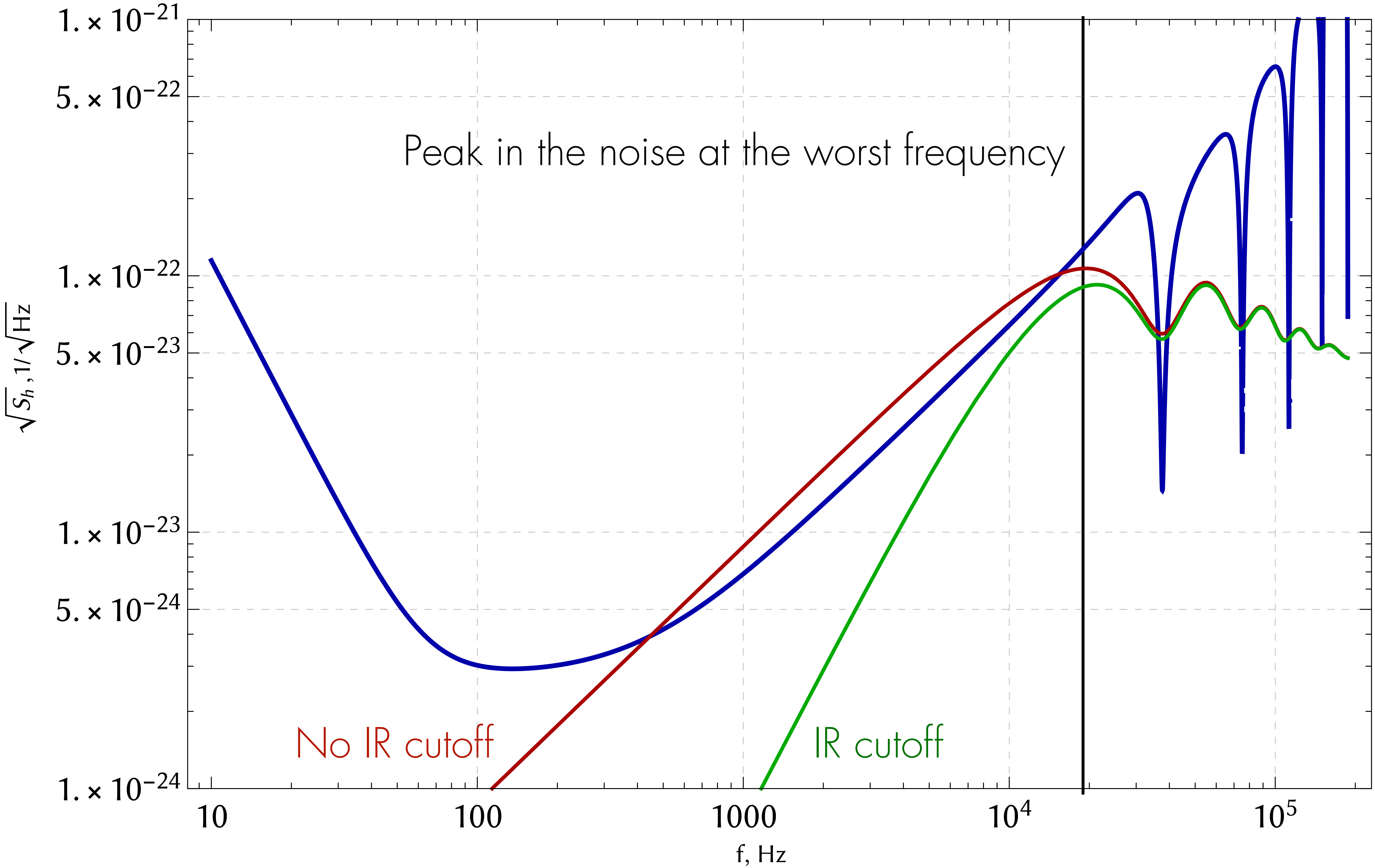
It is…scary!

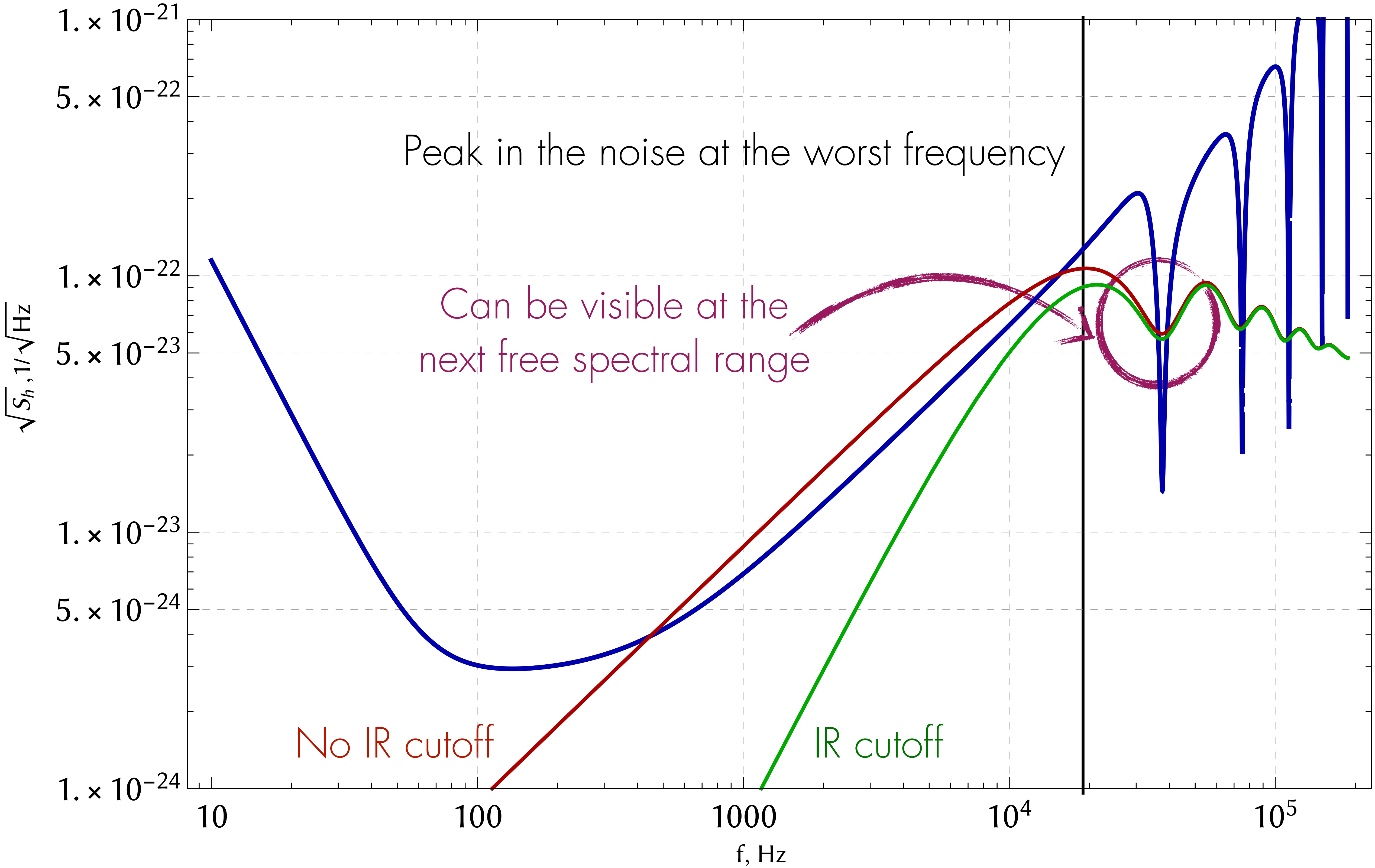
[2]


LIGO
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain $(\mathrm{Hz}^{-1/2})$
LIGO
Without IR Cutoff
With IR Cutoff
50
100
500
1000
5000
f (Hz)

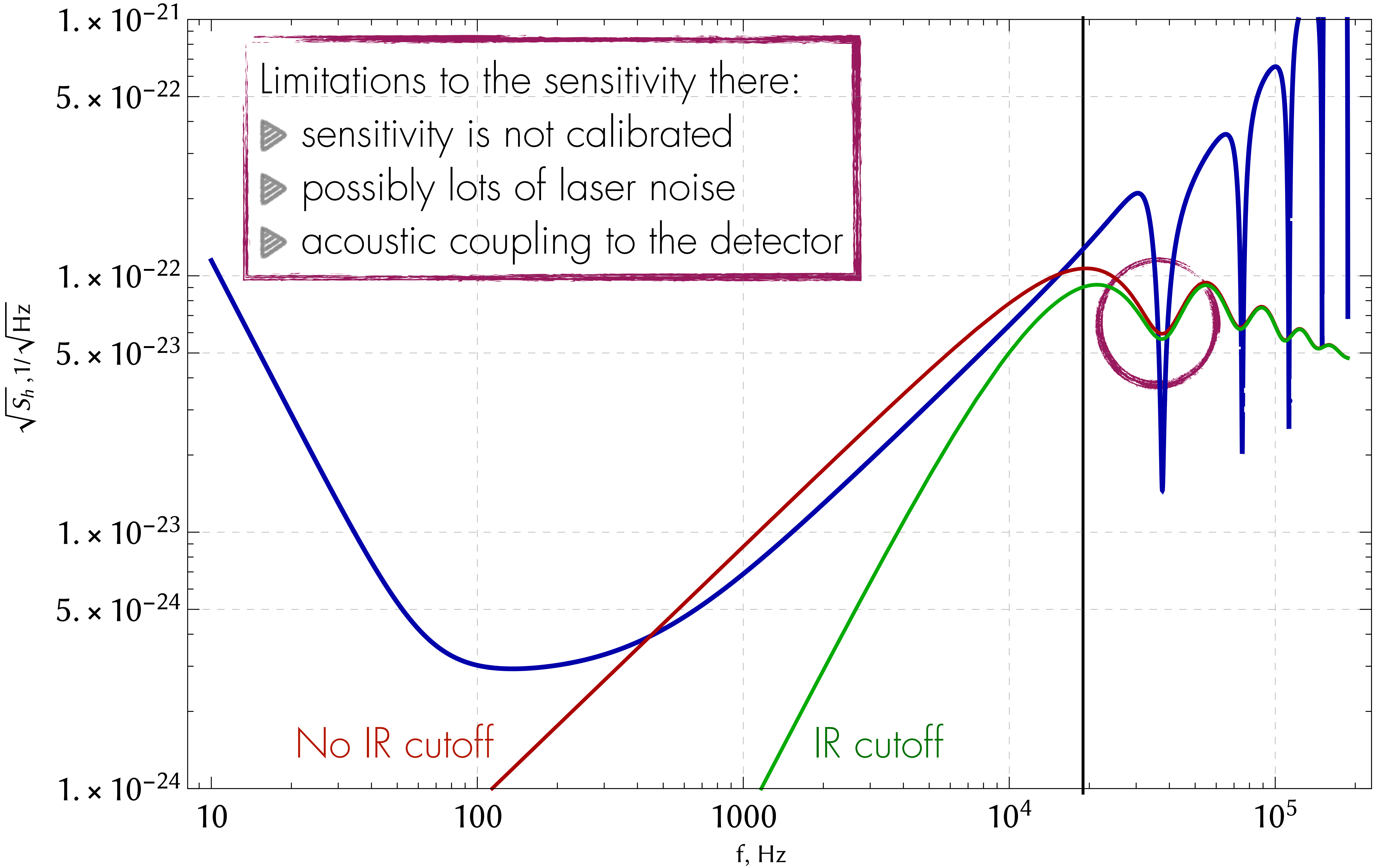
[2]

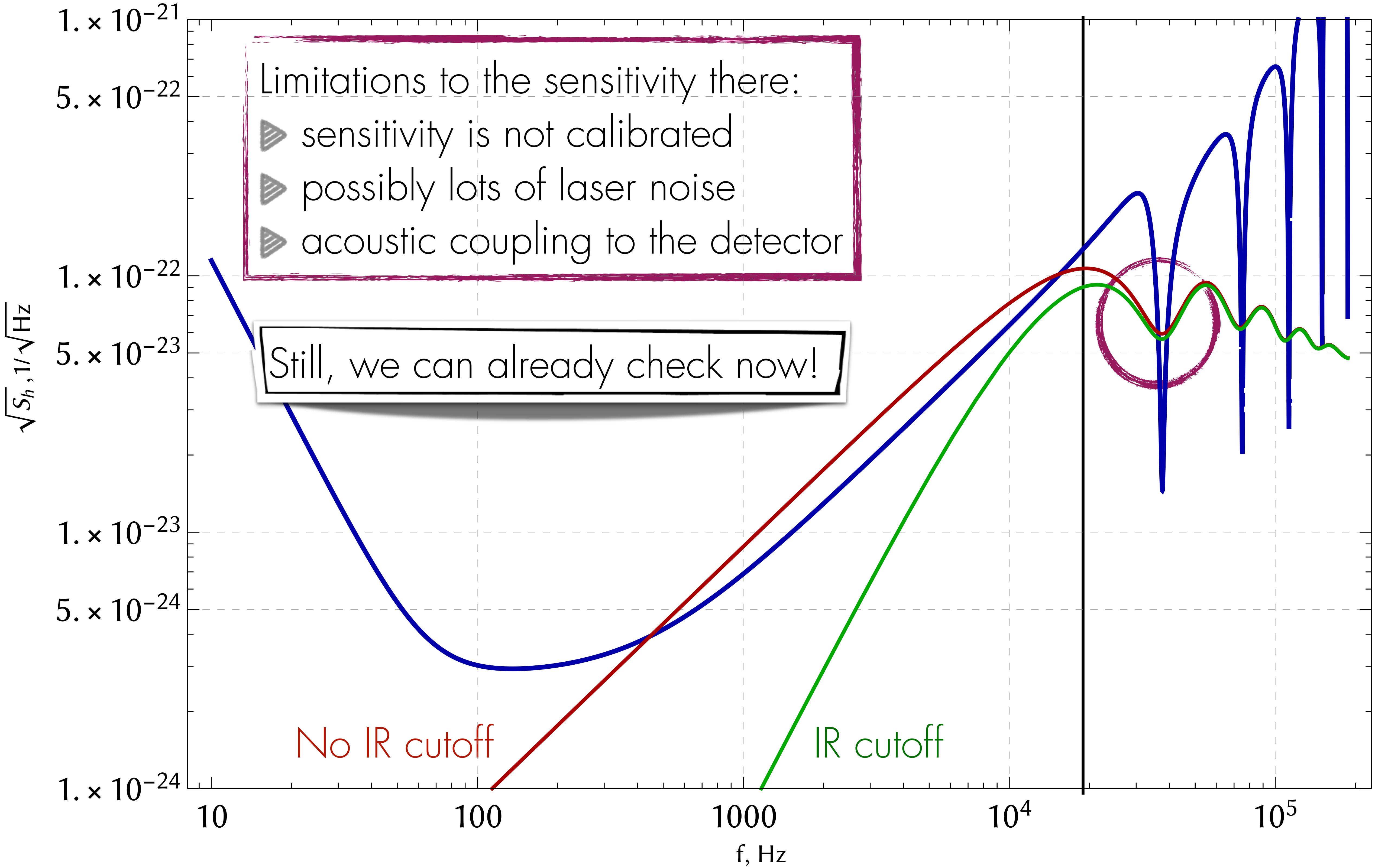

$1. \times 10^{-21}$
$5. \times 10^{-22}$
$1. \times 10^{-22}$
$5. \times 10^{-23}$
$1. \times 10^{-23}$
$5. \times 10^{-24}$
$1. \times 10^{-24}$
$\sqrt{S_h}, 1/\sqrt{\text{Hz}}$
10
100
1000
10^4
10^5
f, Hz
No IR cutoff
IR cutoff


Peak in the noise at the worst frequency
No IR cutoff
IR cutoff
$1. \times 10^{-21}$
$5. \times 10^{-22}$
$1. \times 10^{-22}$
$5. \times 10^{-23}$
$1. \times 10^{-23}$
$5. \times 10^{-24}$
$1. \times 10^{-24}$
$\sqrt{S_h}, 1/\sqrt{\text{Hz}}$
10
100
1000
10^4
10^5
f, Hz



$1. \times 10^{-21}$
$5. \times 10^{-22}$
$1. \times 10^{-22}$
$5. \times 10^{-23}$
$1. \times 10^{-23}$
$5. \times 10^{-24}$
$1. \times 10^{-24}$
$\sqrt{S_h}$, $1/\sqrt{\text{Hz}}$
10
100
1000
10^4
10^5
f, Hz
Peak in the noise at the worst frequency
Can be visible at the
next free spectral range
No IR cutoff
IR cutoff

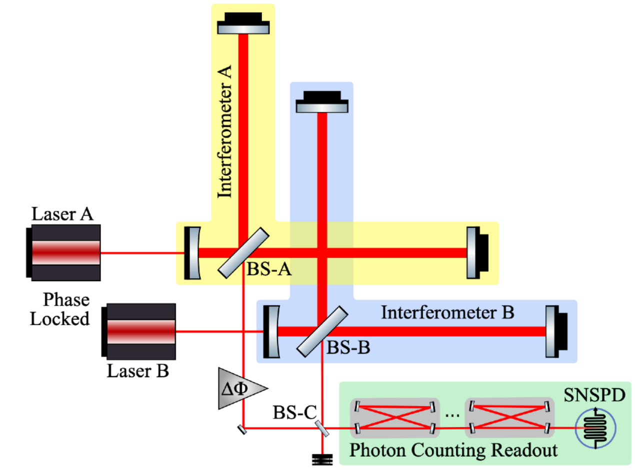

Limitations to the sensitivity there:
sensitivity is not calibrated
possibly lots of laser noise
acoustic coupling to the detector
No IR cutoff
IR cutoff
$1. \times 10^{-21}$
$5. \times 10^{-22}$
$1. \times 10^{-22}$
$5. \times 10^{-23}$
$1. \times 10^{-23}$
$5. \times 10^{-24}$
$1. \times 10^{-24}$
$\sqrt{S_h}, 1/\sqrt{\text{Hz}}$
10
100
1000
10^4
10^5
f, Hz

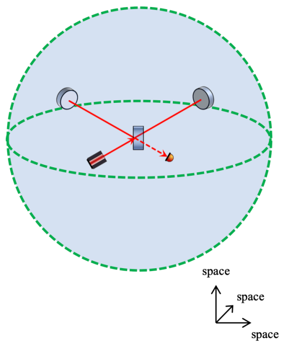

Limitations to the sensitivity there:
sensitivity is not calibrated
possibly lots of laser noise
acoustic coupling to the detector
Still, we can already check now!
No IR cutoff
IR cutoff
$1.\times10^{-21}$
$5.\times10^{-22}$
$1.\times10^{-22}$
$5.\times10^{-23}$
$1.\times10^{-23}$
$5.\times10^{-24}$
$1.\times10^{-24}$
10
100
1000
10^4
10^5
f, Hz
$\sqrt{S_h}, 1/\sqrt{\mathrm{Hz}}$

Conclusions

Geontropic noise is tackled on many fronts

- Theory building stronger foundation
- New dedicated detectors
- Bounds from existing detectors





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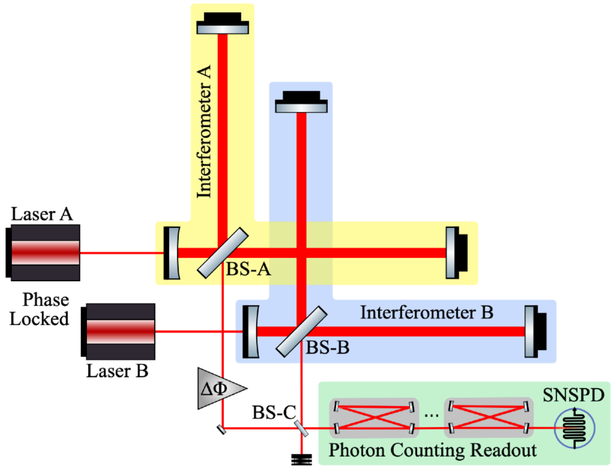
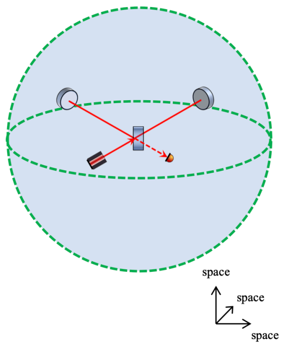
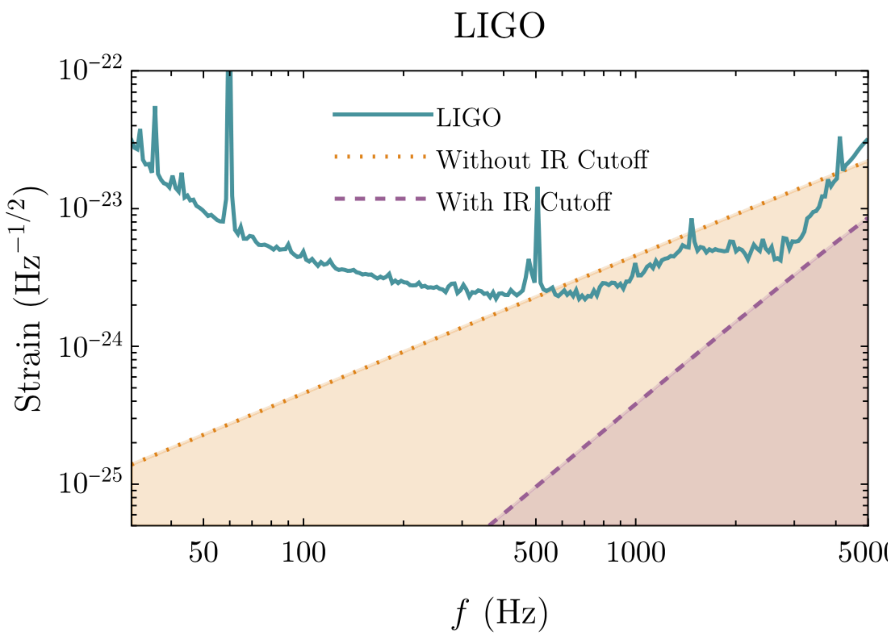




GW detectors are perfect to sense this noise

- Current generation sets a bound
- Future detectors might be swamped with it
- Could we use next-FSR detection?



Conclusions

Geontropic noise is tackled on many fronts

- Theory building stronger foundation
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GW detectors are perfect to sense this noise

- Current generation sets a bound
- Future detectors might be swamped with it
- Could we use next-FSR detection?

Many open questions (to me)

- What is the response to off-axis sourced fields?
- How to take the IFO response into account?
- Are we in trouble with next-generation detectors?
- What can we measure in current detectors?