CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

LIGO VIRGO KAGRA

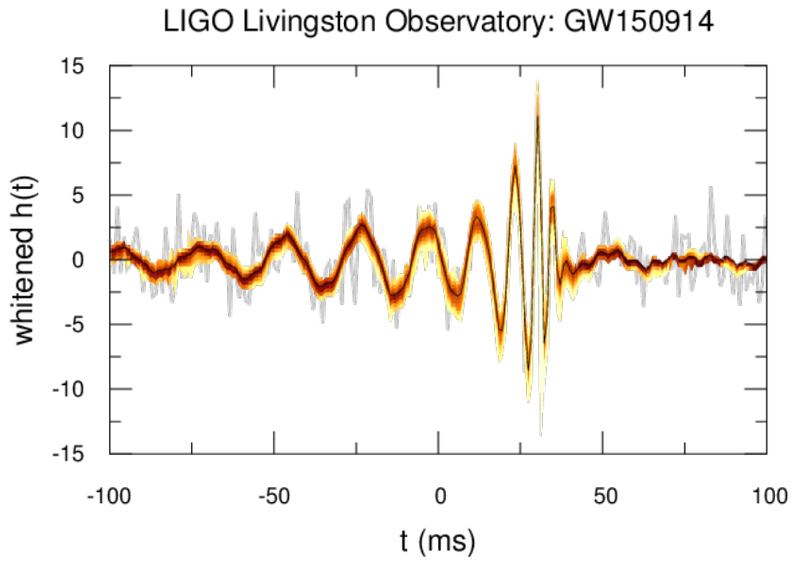
EINSTEIN TELESCOPE

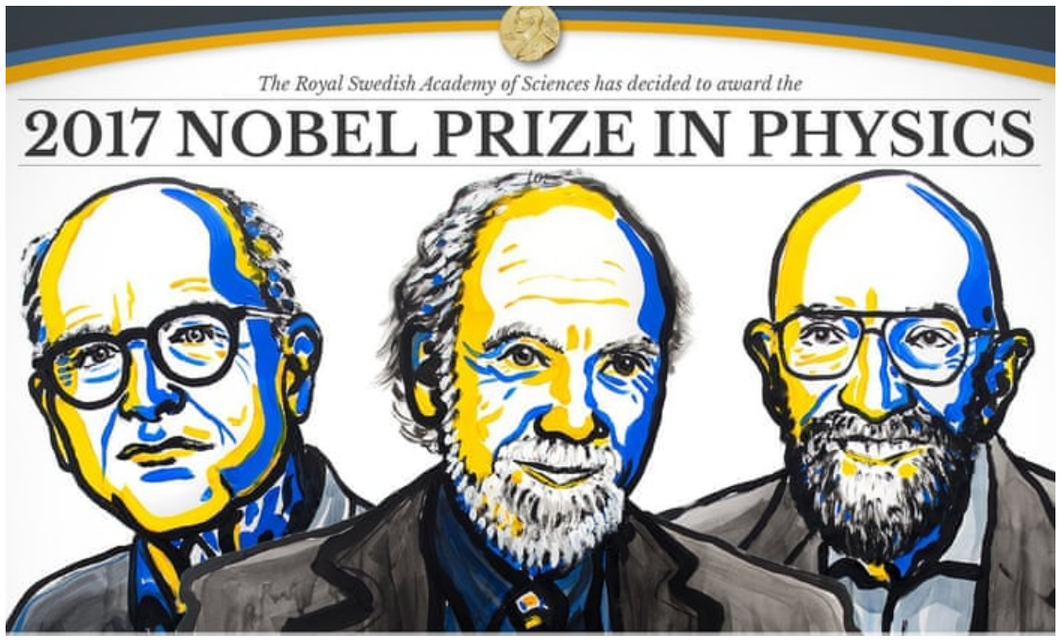
Detection of high-frequency gravitational waves with current GW detectors

Mikhail Korobko
University of Hamburg

DESY/UHH May 2025

15 September 2014
First detection of gravitational waves





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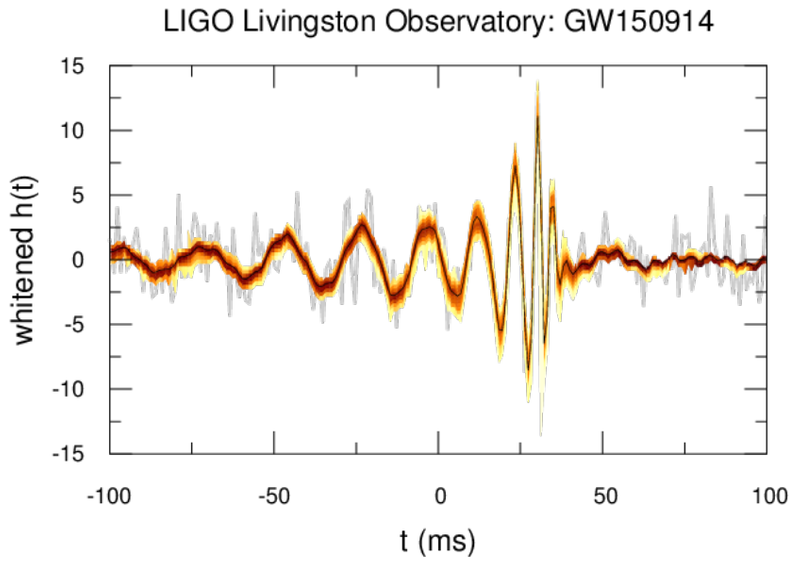
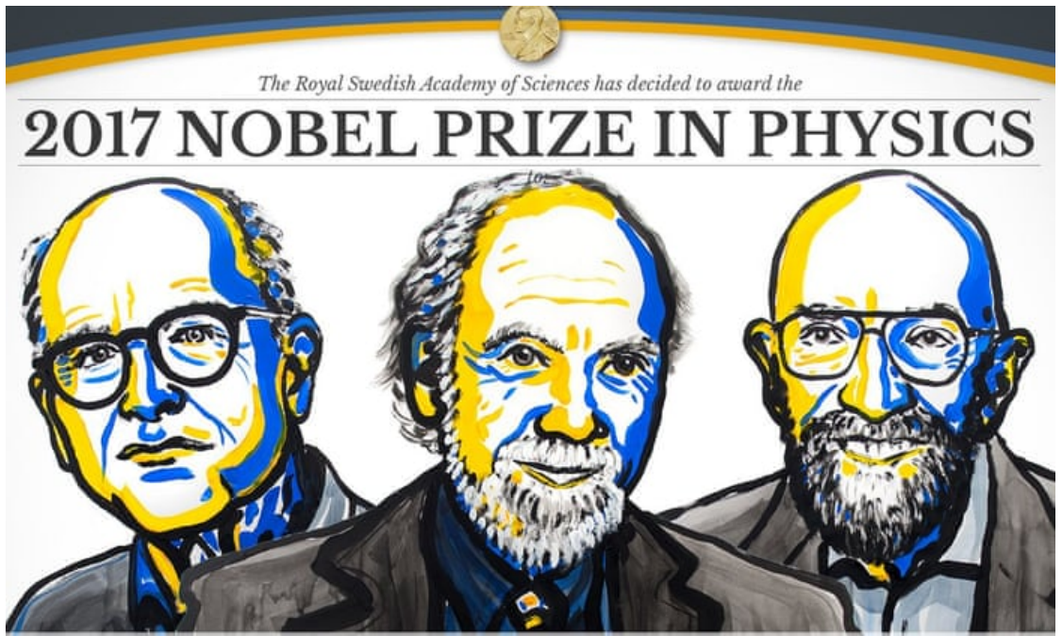
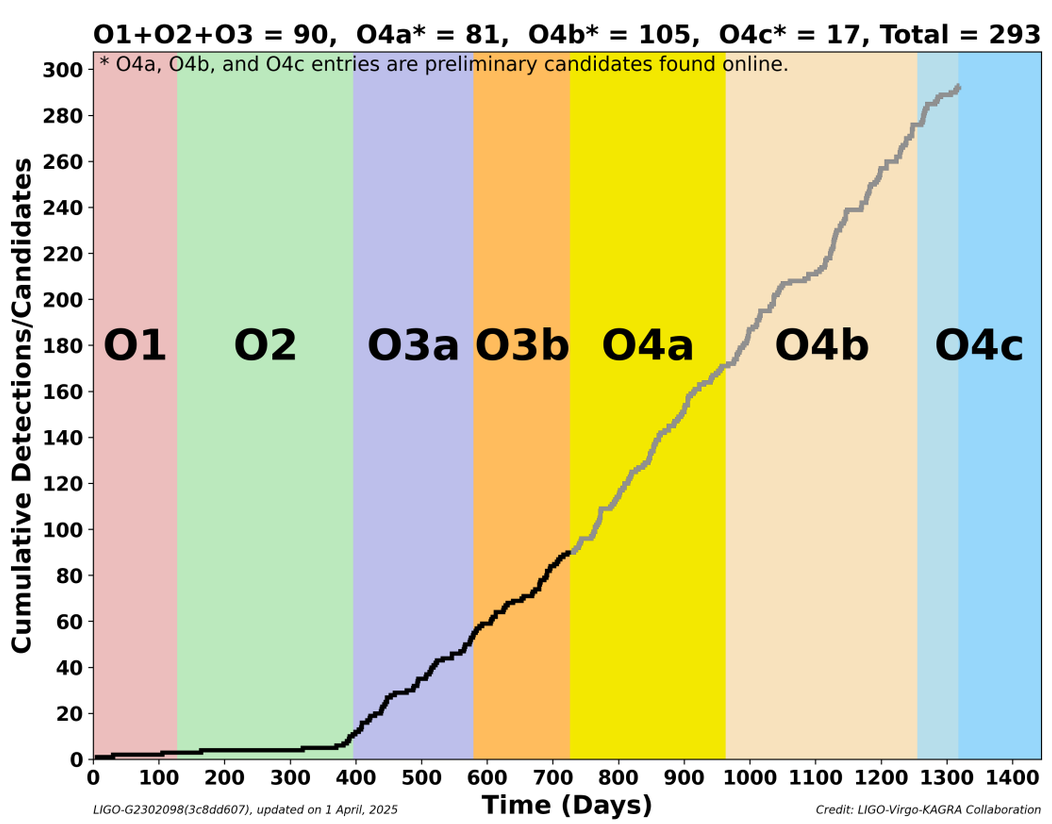
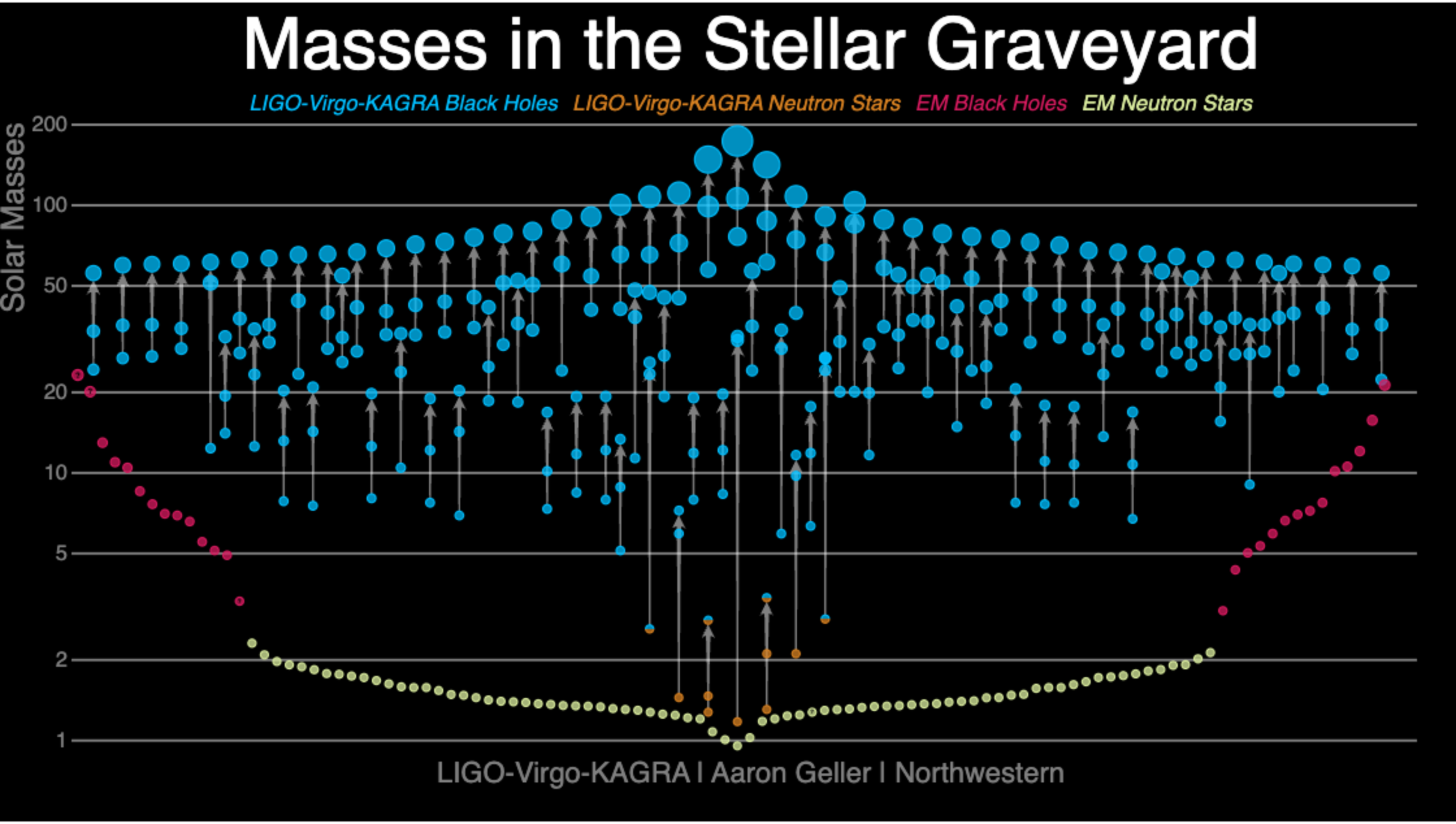
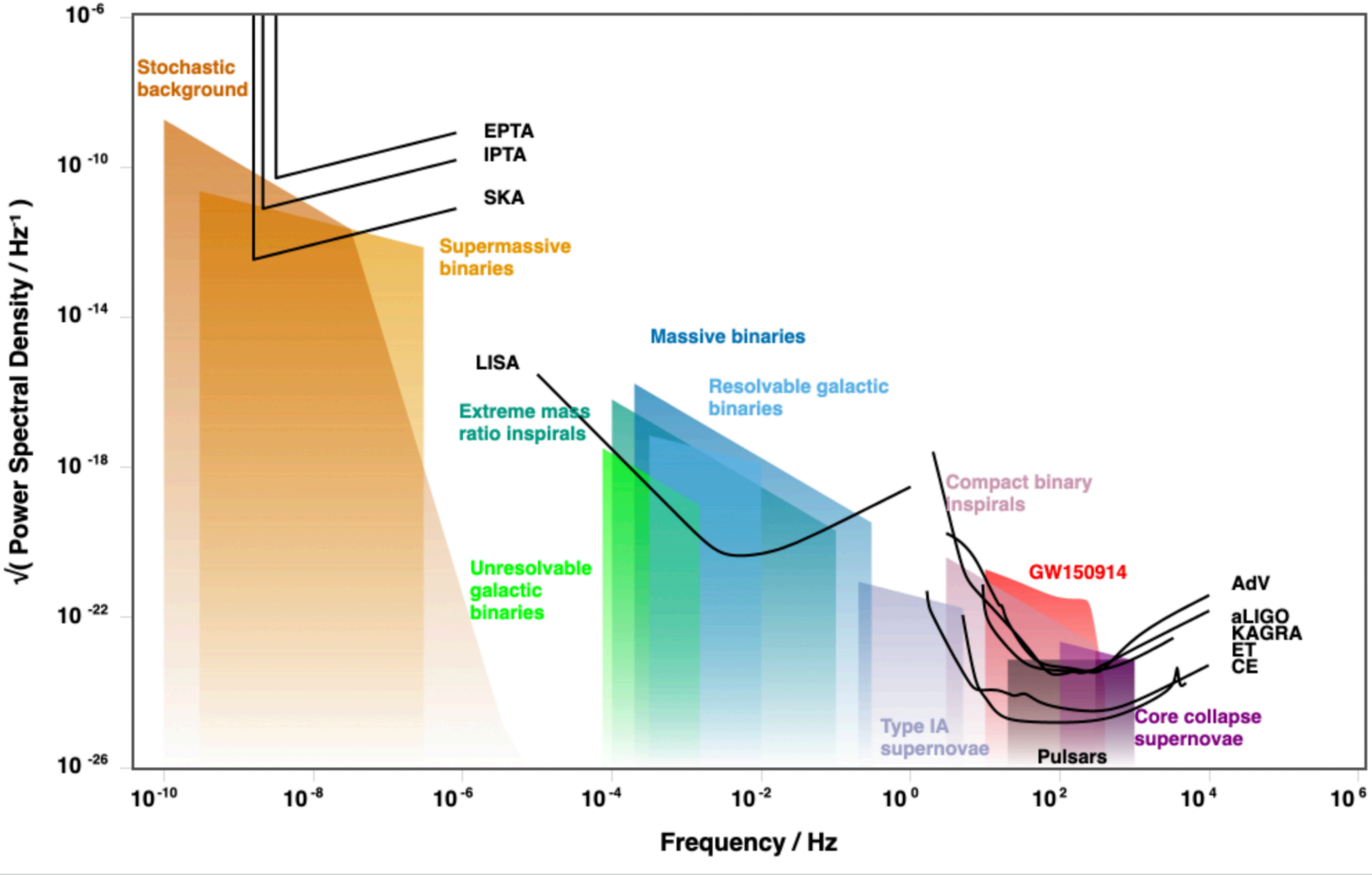


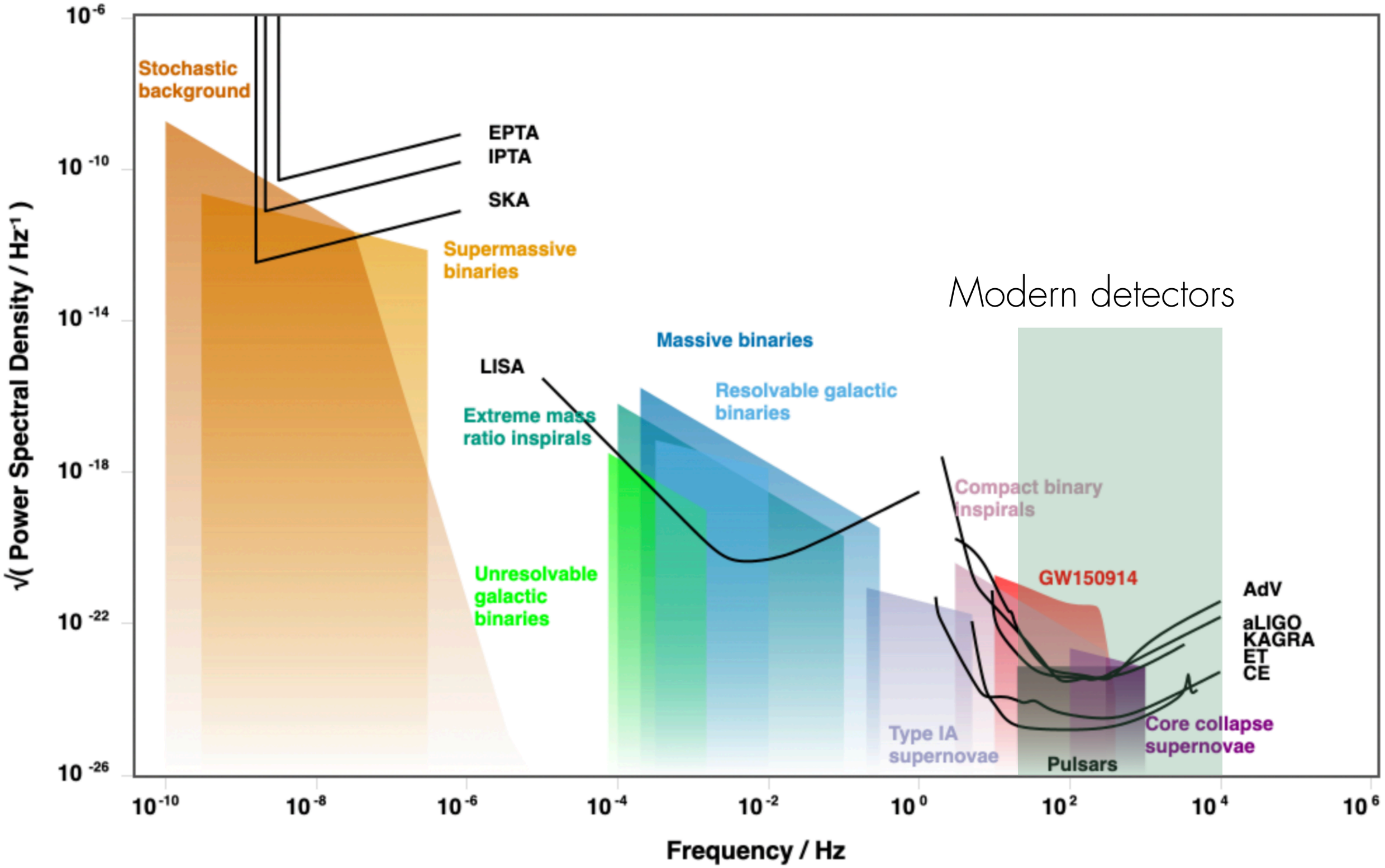




293 detections!


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


√(Power Spectral Density / Hz⁻¹)
10 -6
10 -10
10 -14
10 -18
10 -22
10 -26
Stochastic background
EPTA
IPTA
SKA
Supermassive binaries
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Compact binary inspirals
GW150914
AdV
aLIGO
KAGRA
ET
CE
Type IA supernovae
Pulsars
Core collapse supernovae
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6
Frequency / Hz


Modern detectors
Stochastic background
EPTA
IPTA
SKA
Supermassive binaries
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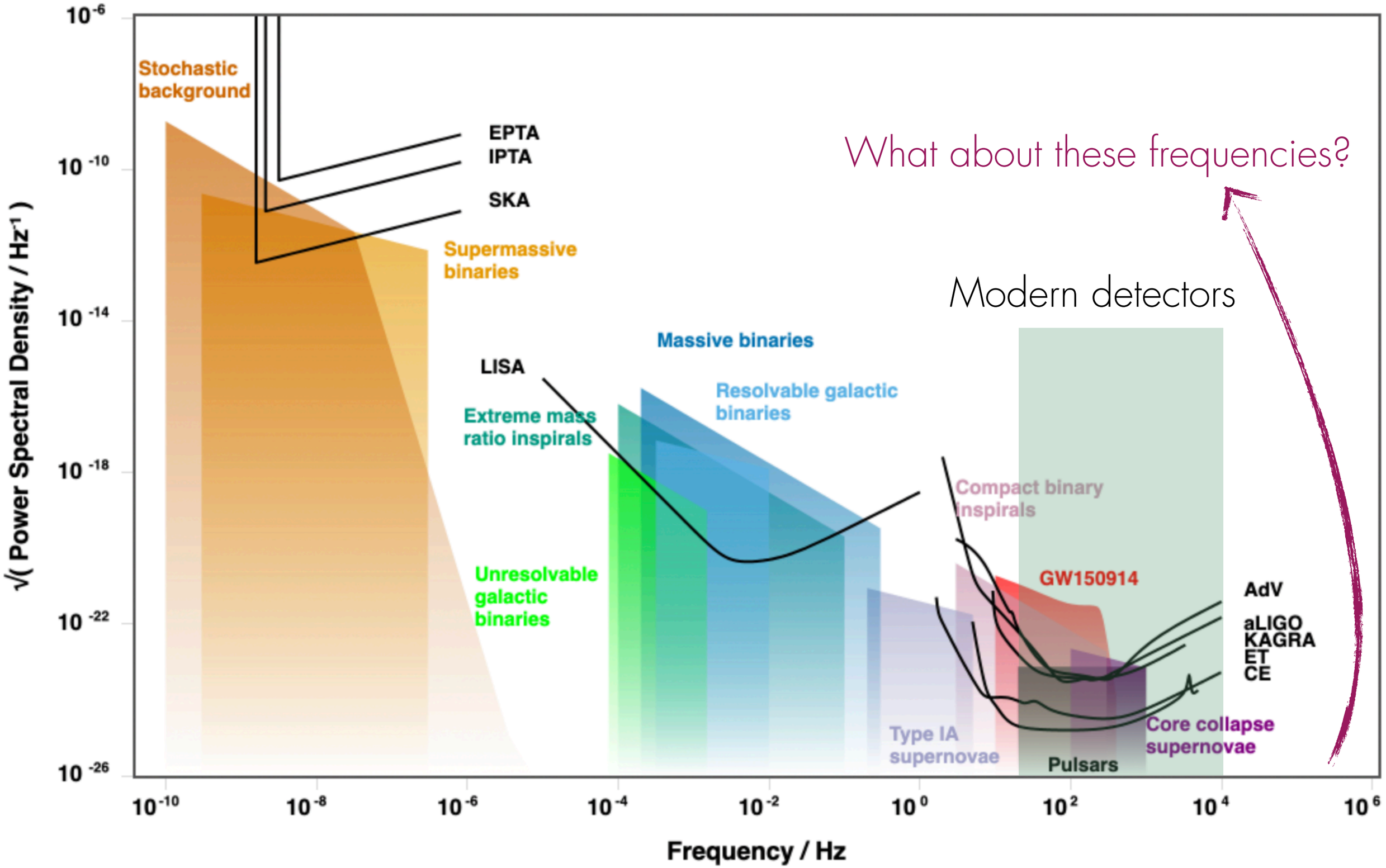
Type IA supernovae
Core collapse supernovae
Pulsars
√(Power Spectral Density / Hz⁻¹)
Frequency / Hz
10⁻⁶
10⁻¹⁰
10⁻¹⁴
10⁻¹⁸
10⁻²²
10⁻²⁶
10⁻¹⁰
10⁻⁸
10⁻⁶
10⁻⁴
10⁻²
10⁰
10²
10⁴
10⁶


What about these frequencies?
Modern detectors
Stochastic background
EPTA
IPTA
SKA
Supermassive binaries
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
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GW150914
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CE
Type IA supernovae
Core collapse supernovae
Pulsars
√(Power Spectral Density / Hz⁻¹)
Frequency / Hz
10⁻⁶
10⁻¹⁰
10⁻¹⁴
10⁻¹⁸
10⁻²²
10⁻²⁶
10⁻¹⁰
10⁻⁸
10⁻⁶
10⁻⁴
10⁻²
10⁰
10²
10⁴
10⁶

- No known coherent sources

- No known coherent sources (Q-balls, boson stars, oscillatons, oscillons, gravastars, fermion–boson stars, anisotropic stars, gravitino stars, dark quark stars, etc)

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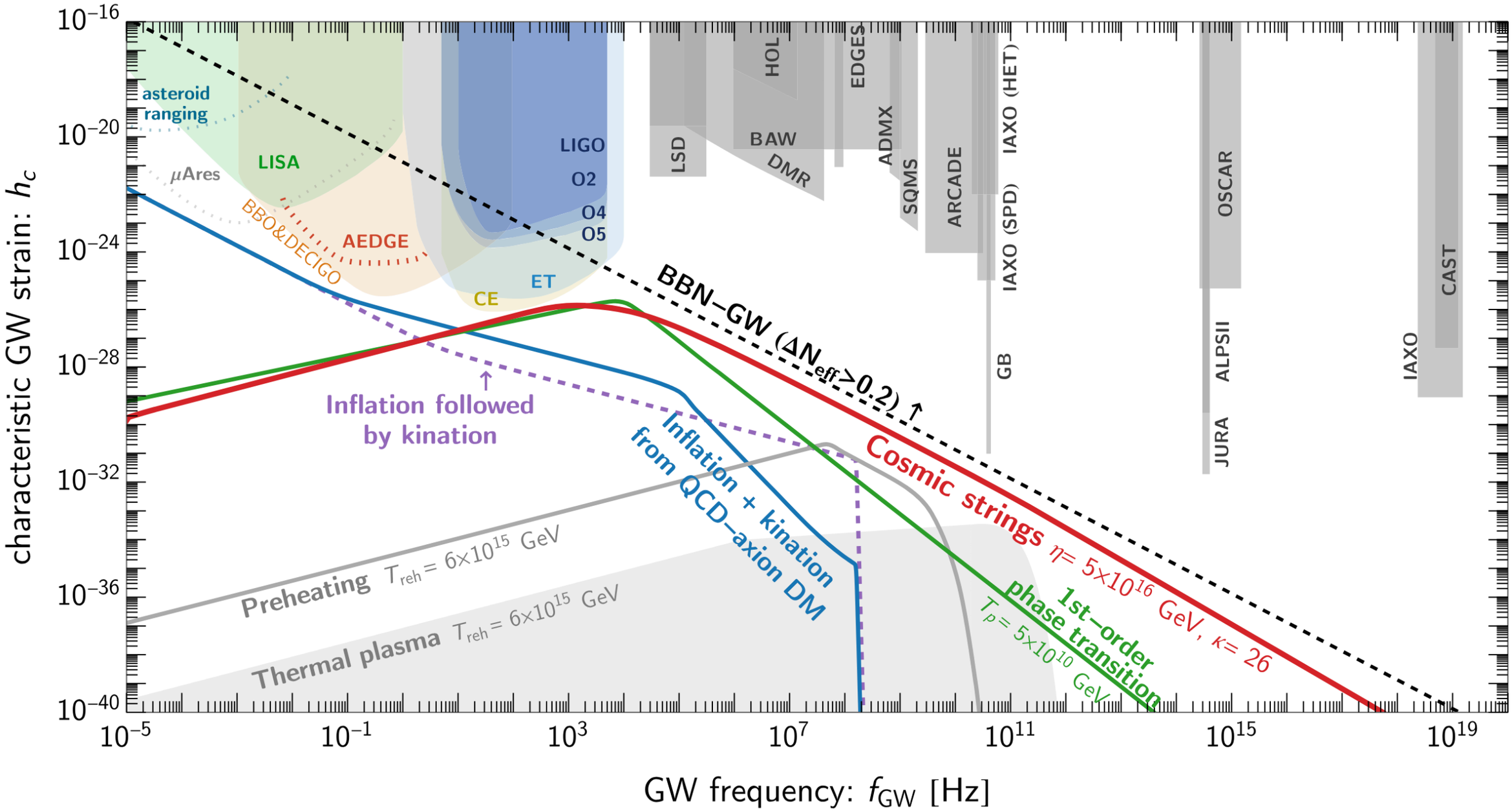

Servant, G., & Simakachorn, P. (2024). Ultrahigh frequency primordial gravitational waves beyond the kHz: The case of cosmic strings. *Physical Review D*, *109*(10), 103538.

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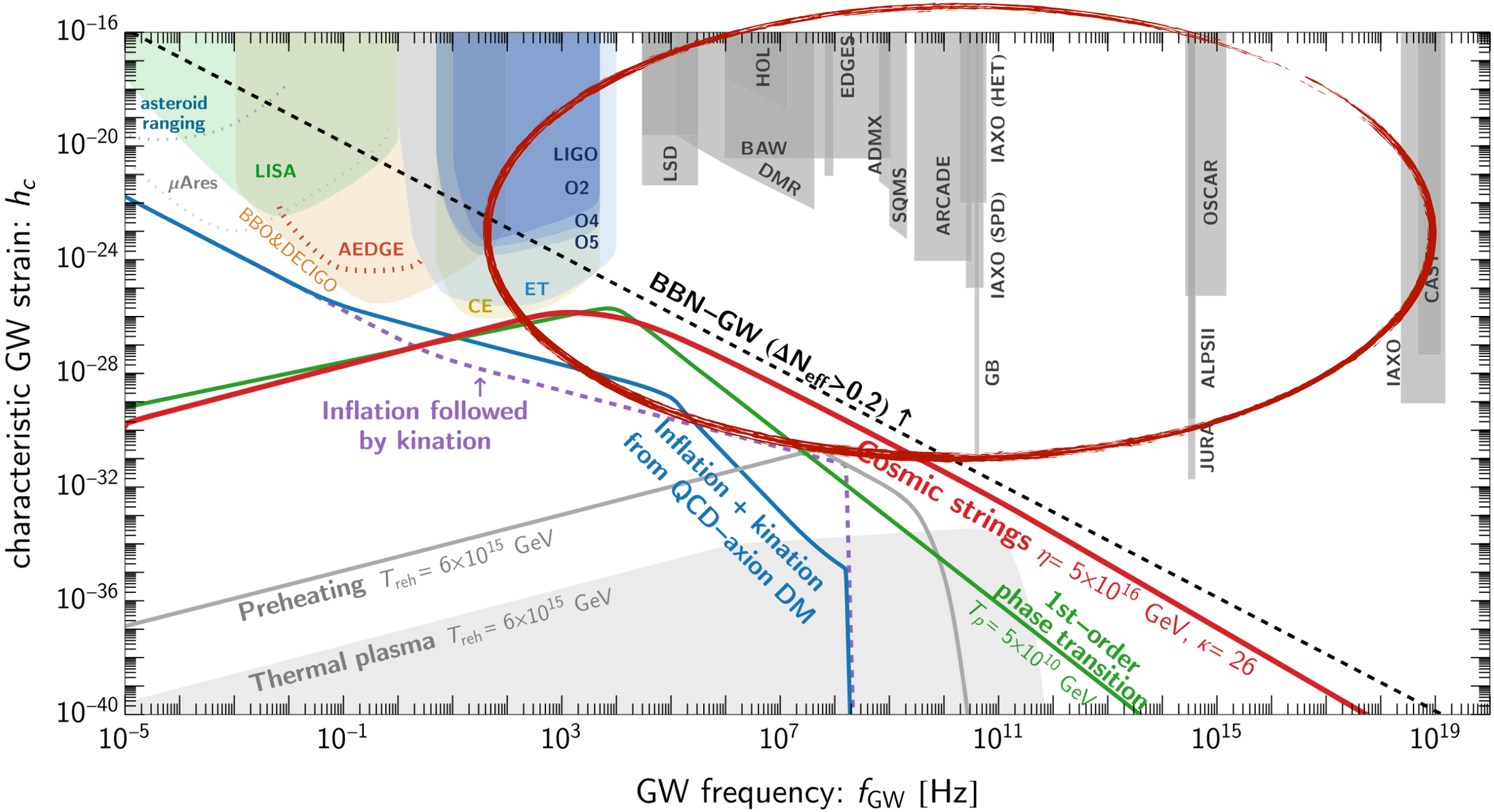
Many dedicated detectors



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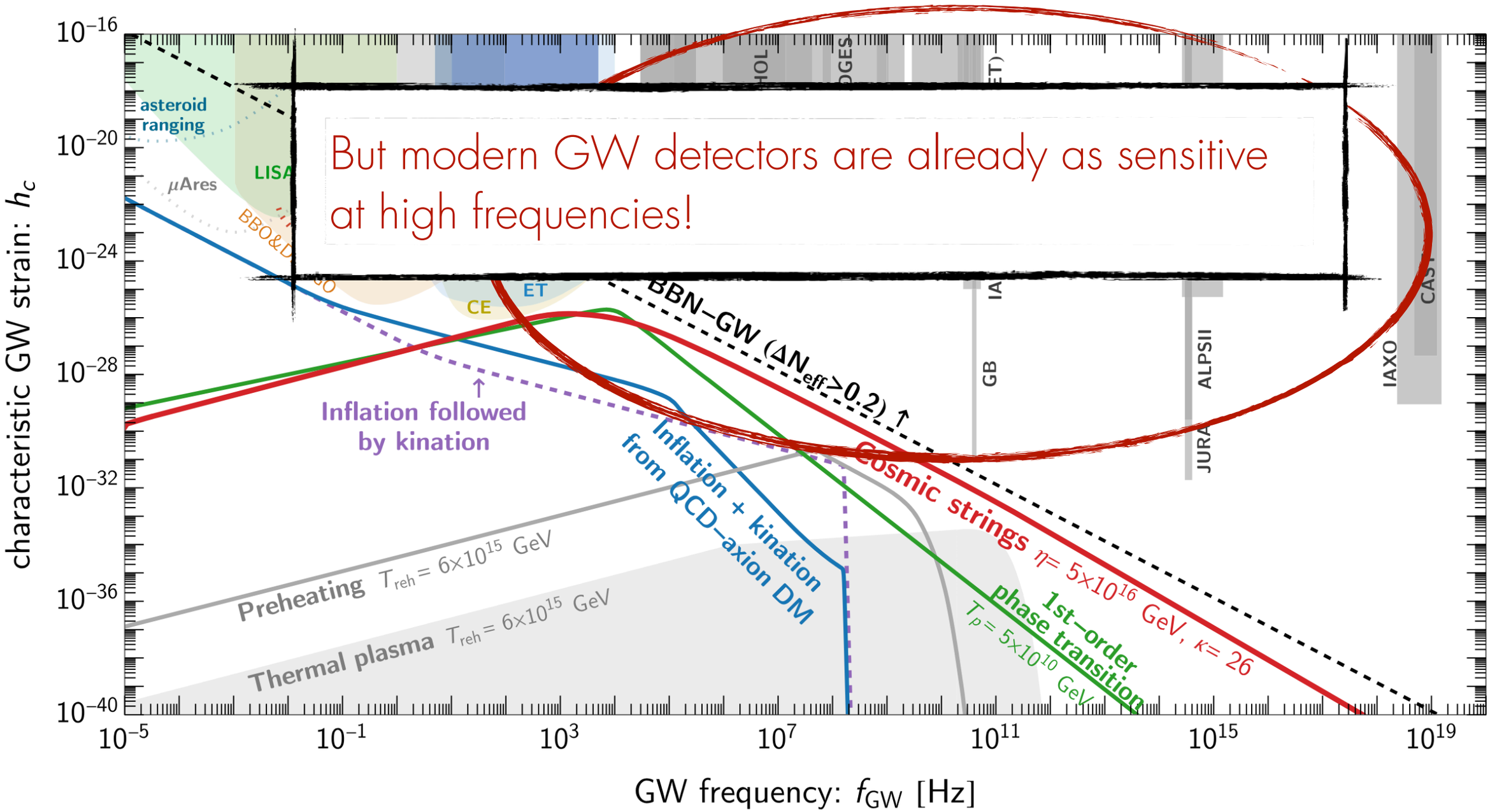

Servant, G., & Simakachorn, P. (2024). Ultrahigh frequency primordial gravitational waves beyond the kHz: The case of cosmic strings. *Physical Review D*, *109*(10), 103538.

Outline

1. Introduction to GW detection
2. Status of current GW detectors
3. Into the deep: how GWDs really work
4. Response of the detectors to high-frequency GWs
5. Challenges & perspectives

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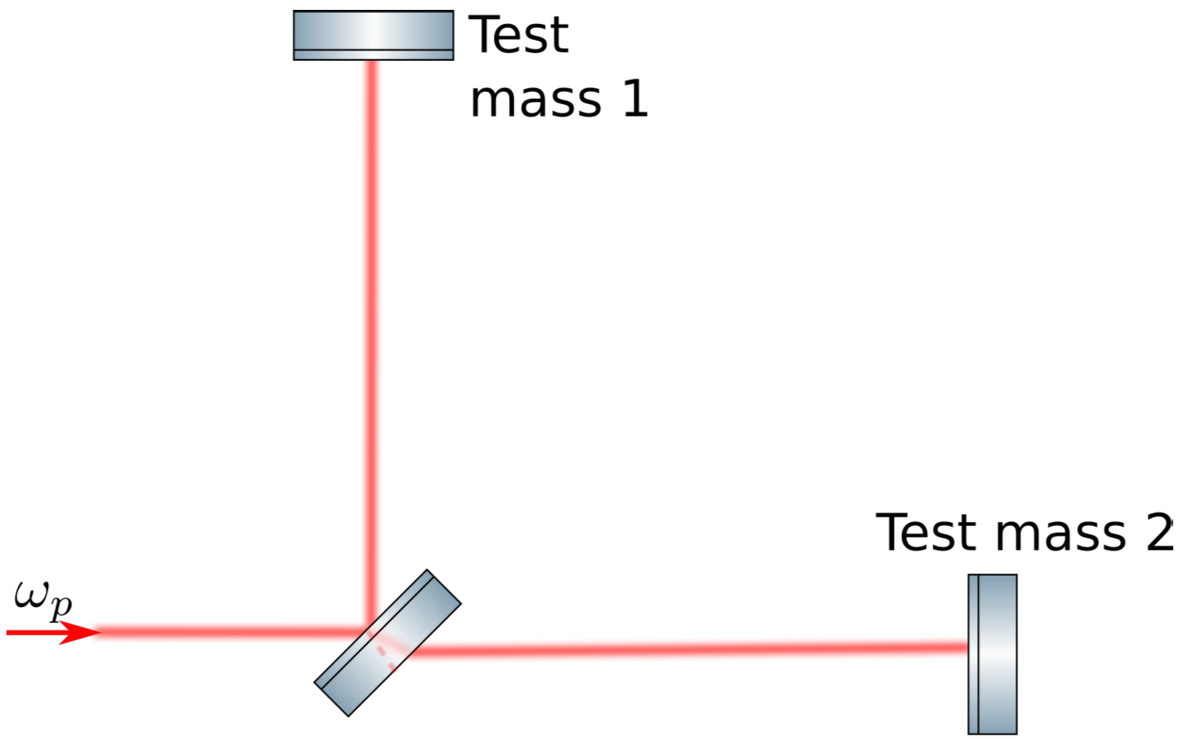
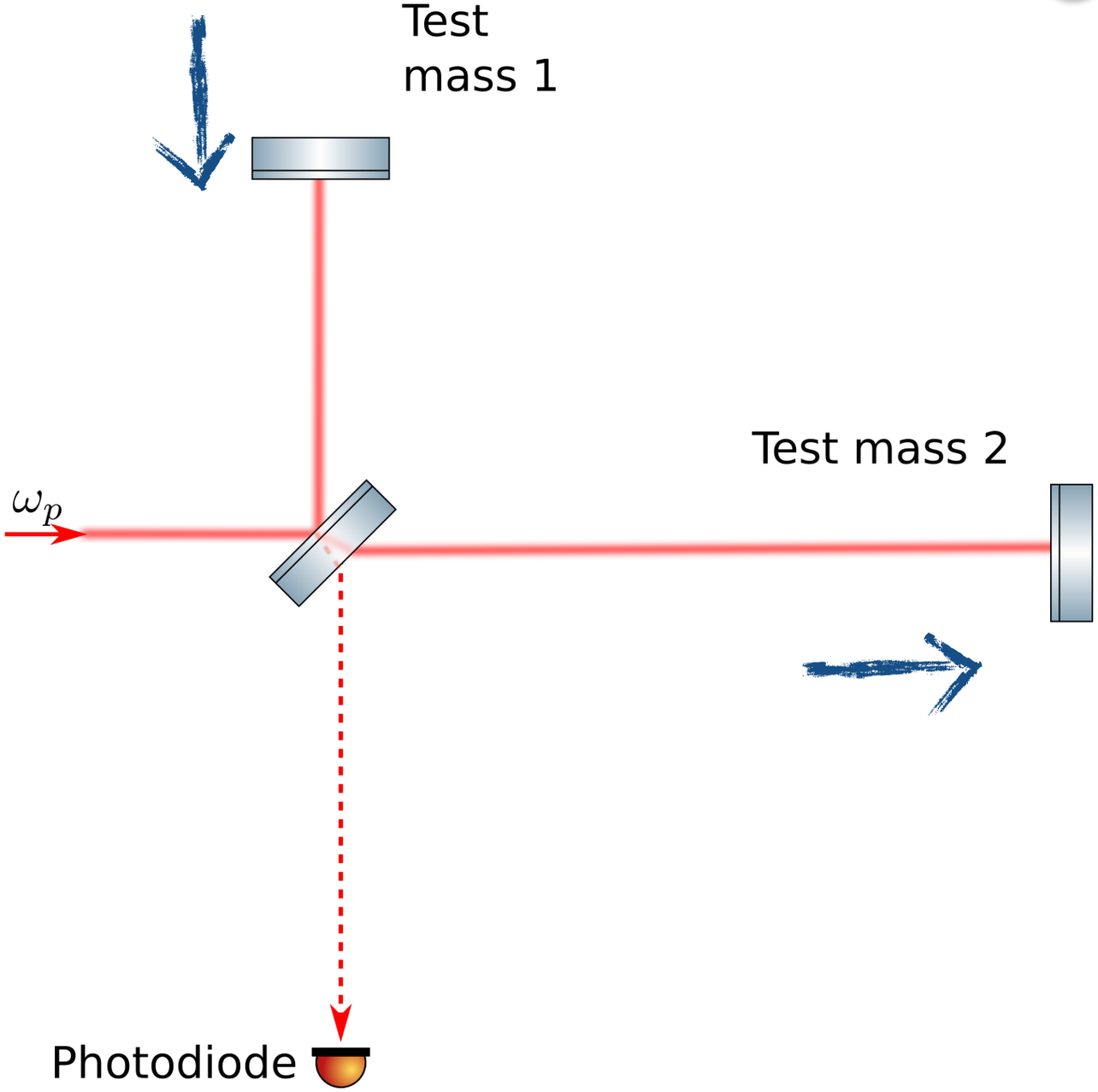


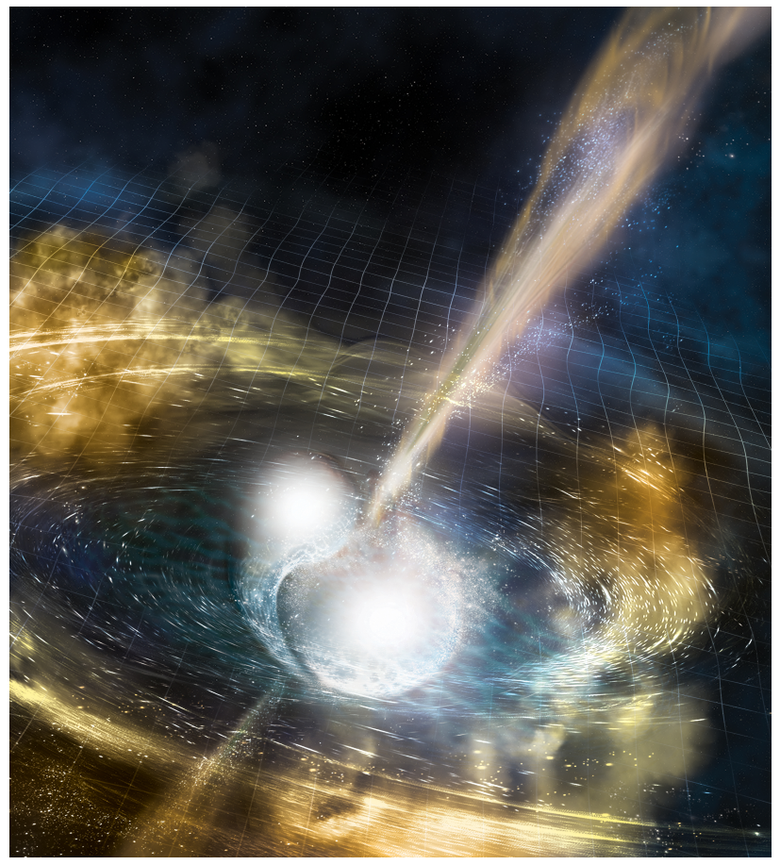
No Signal

Photodiode

Introduction

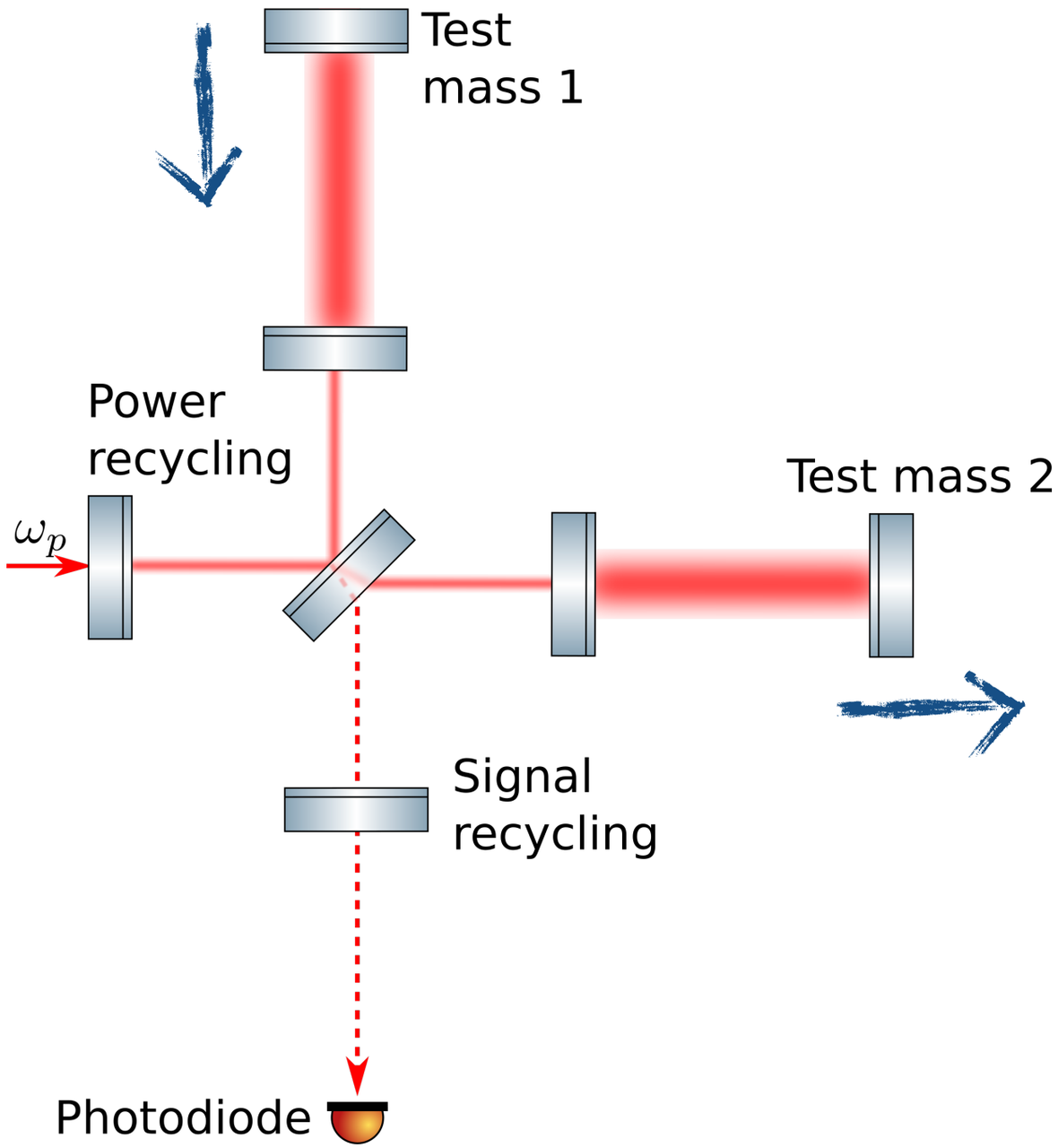


Detecting weak forces



GW strain = ΔLength/Length

Introduction

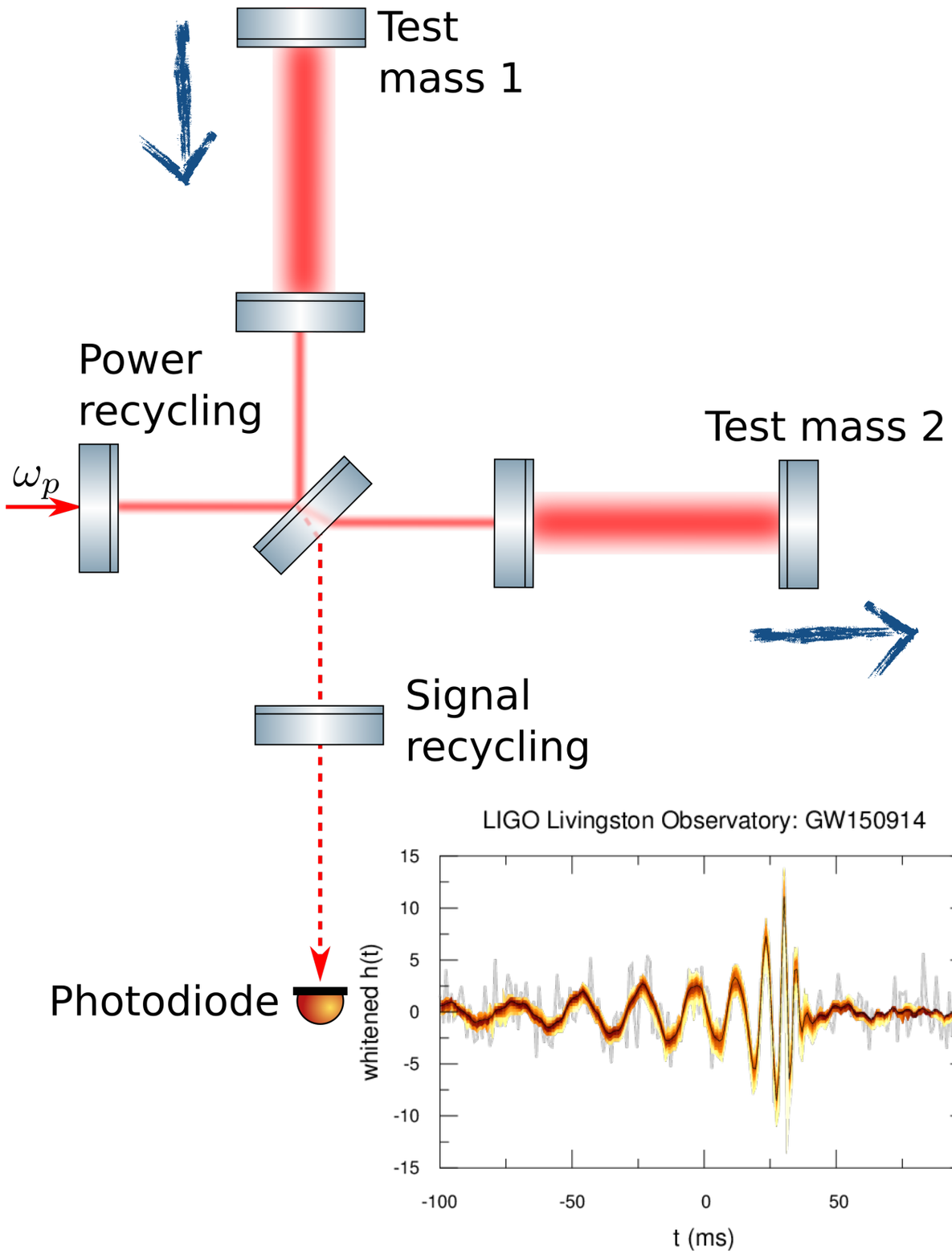


Cavity-enhanced detector

Advanced LIGO

GW signal = (cavity gain)^2 ΔLength/Length

Introduction



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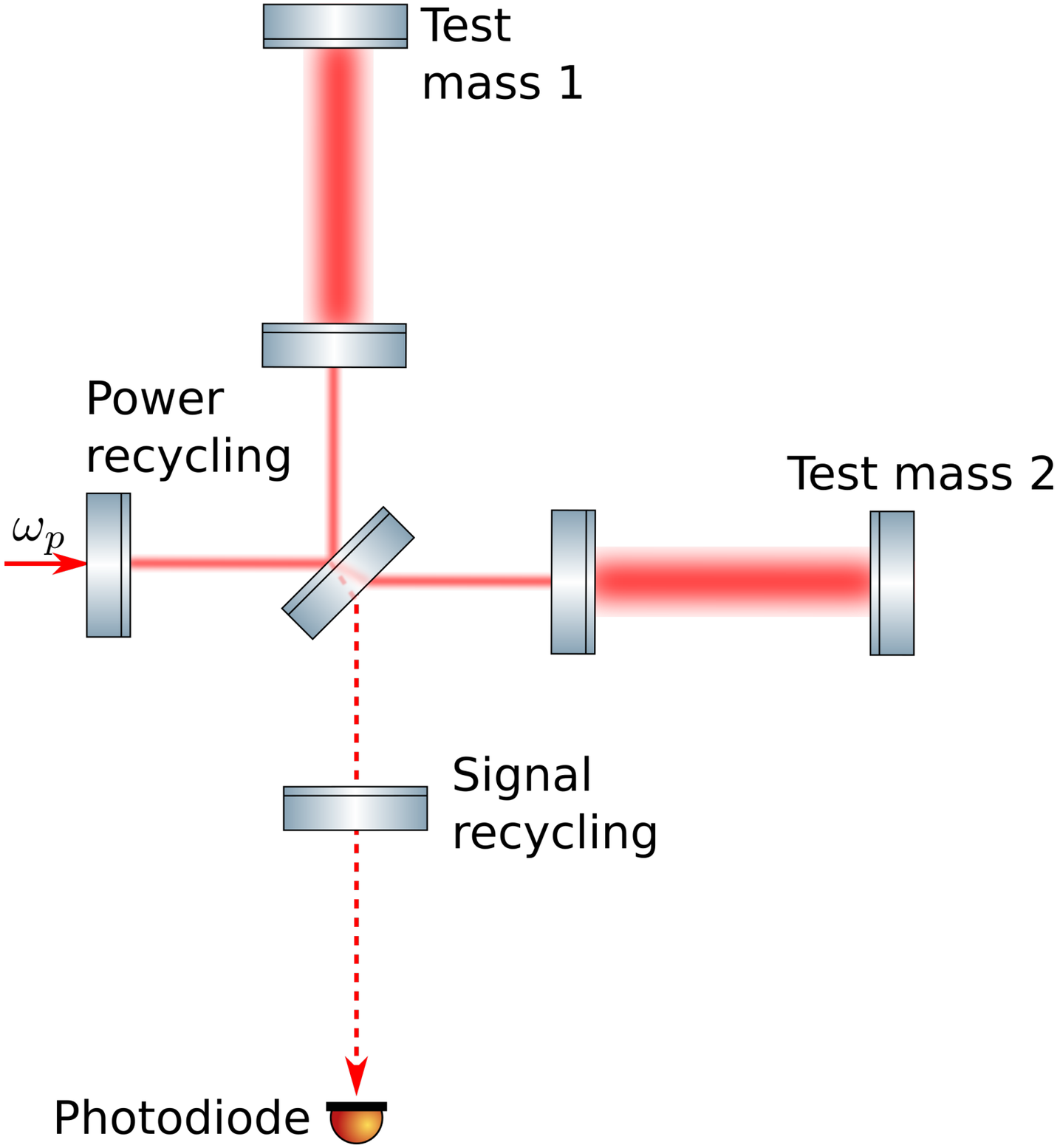
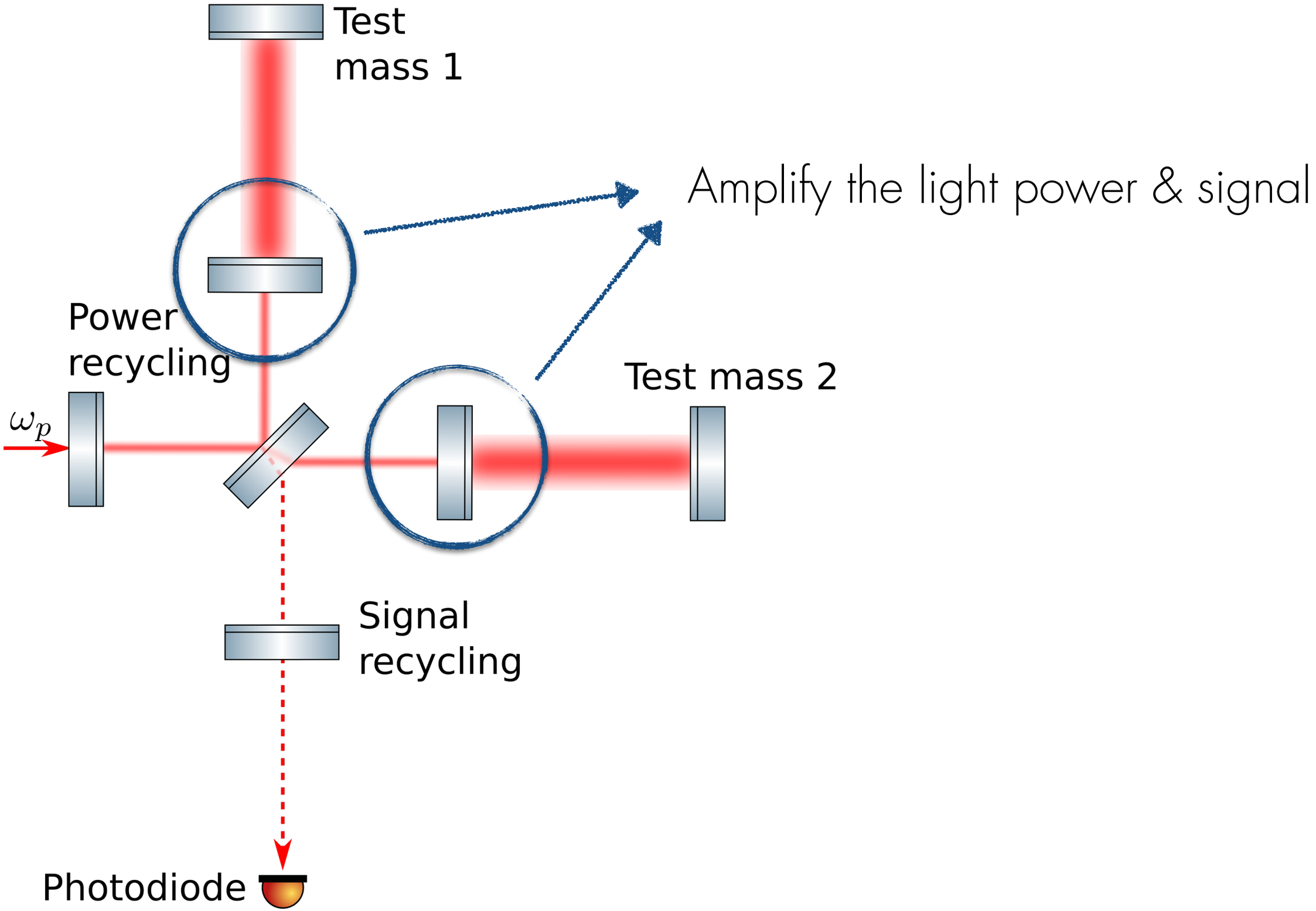
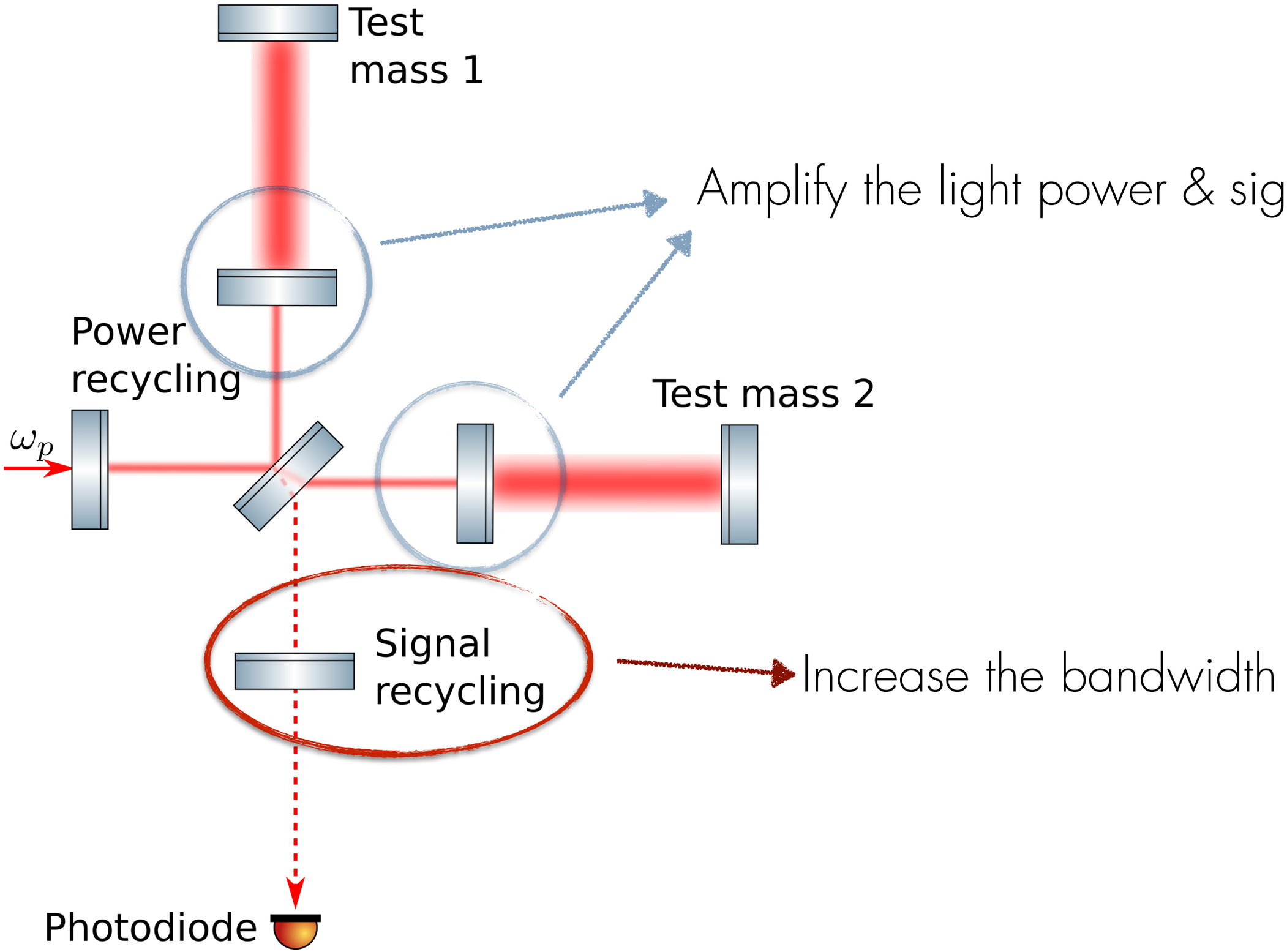

Test
mass 1
Power
recycling
Test mass 2
ω_p
Signal
recycling
Photodiode

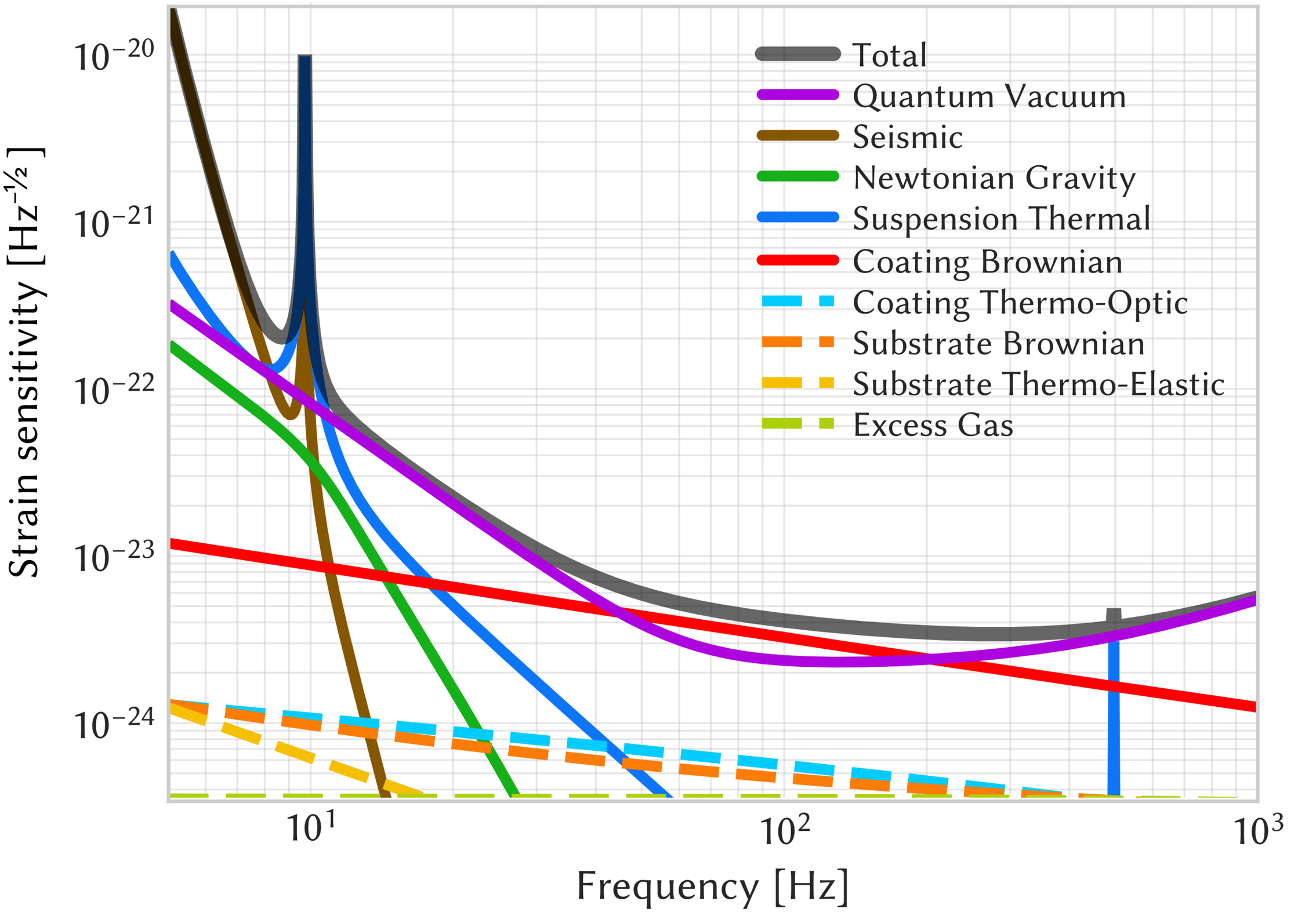

Test
mass 1
Amplify the light power & signal
Power
recycling
Test mass 2
ω_p
Signal
recycling
Photodiode

Cavity-enhanced detector



Amplify the light power & signal

Increase the bandwidth


Strain sensitivity [Hz$^{-½}$]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Frequency [Hz]
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermo-Elastic
Excess Gas

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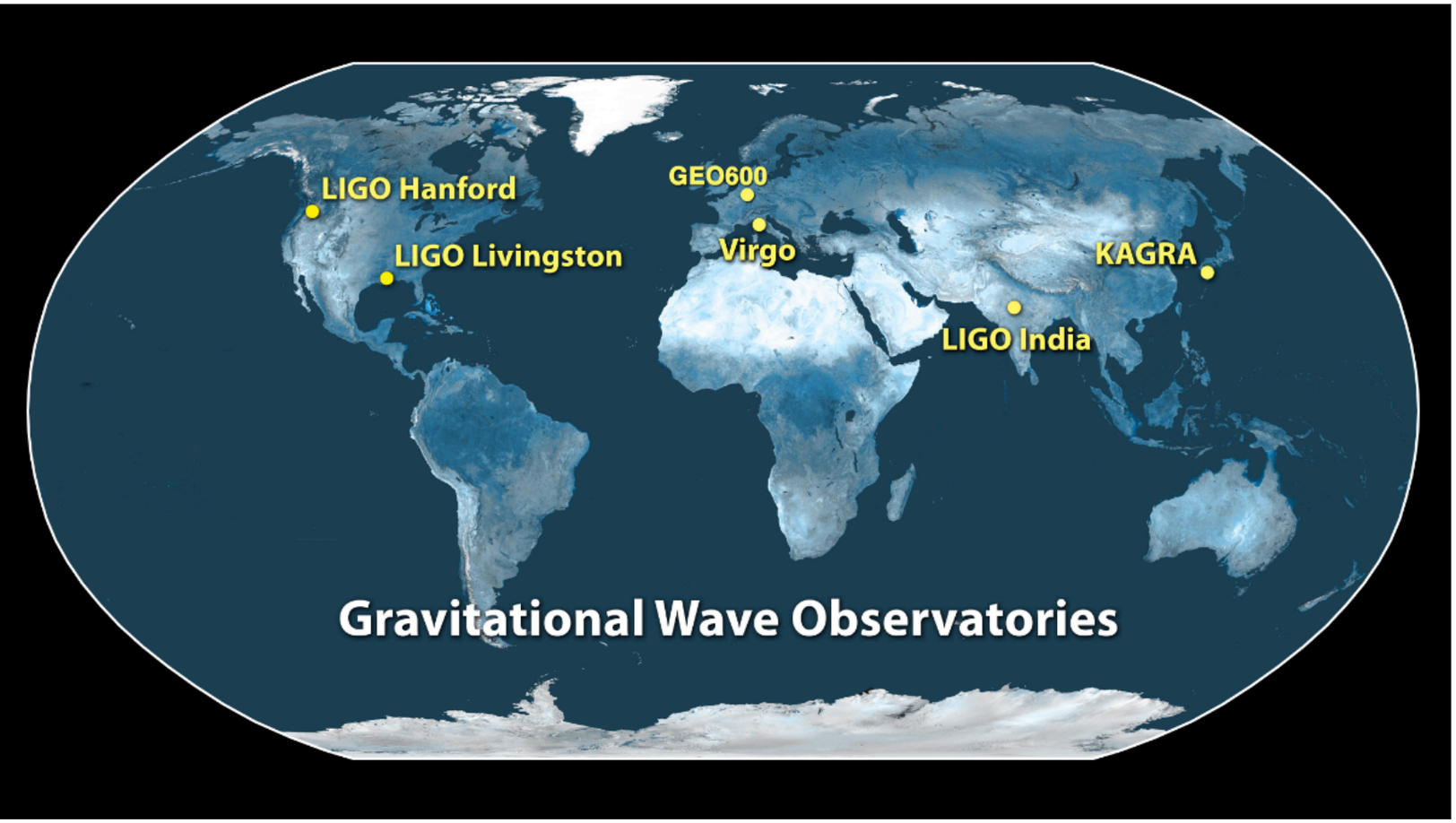
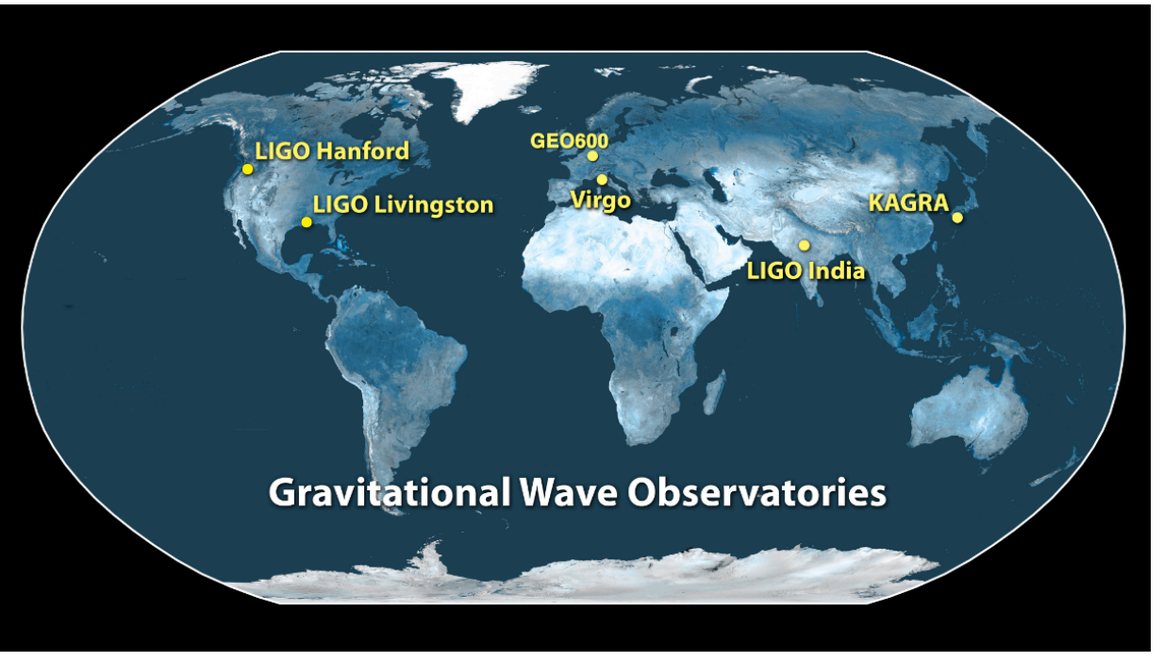
Status of the detectors

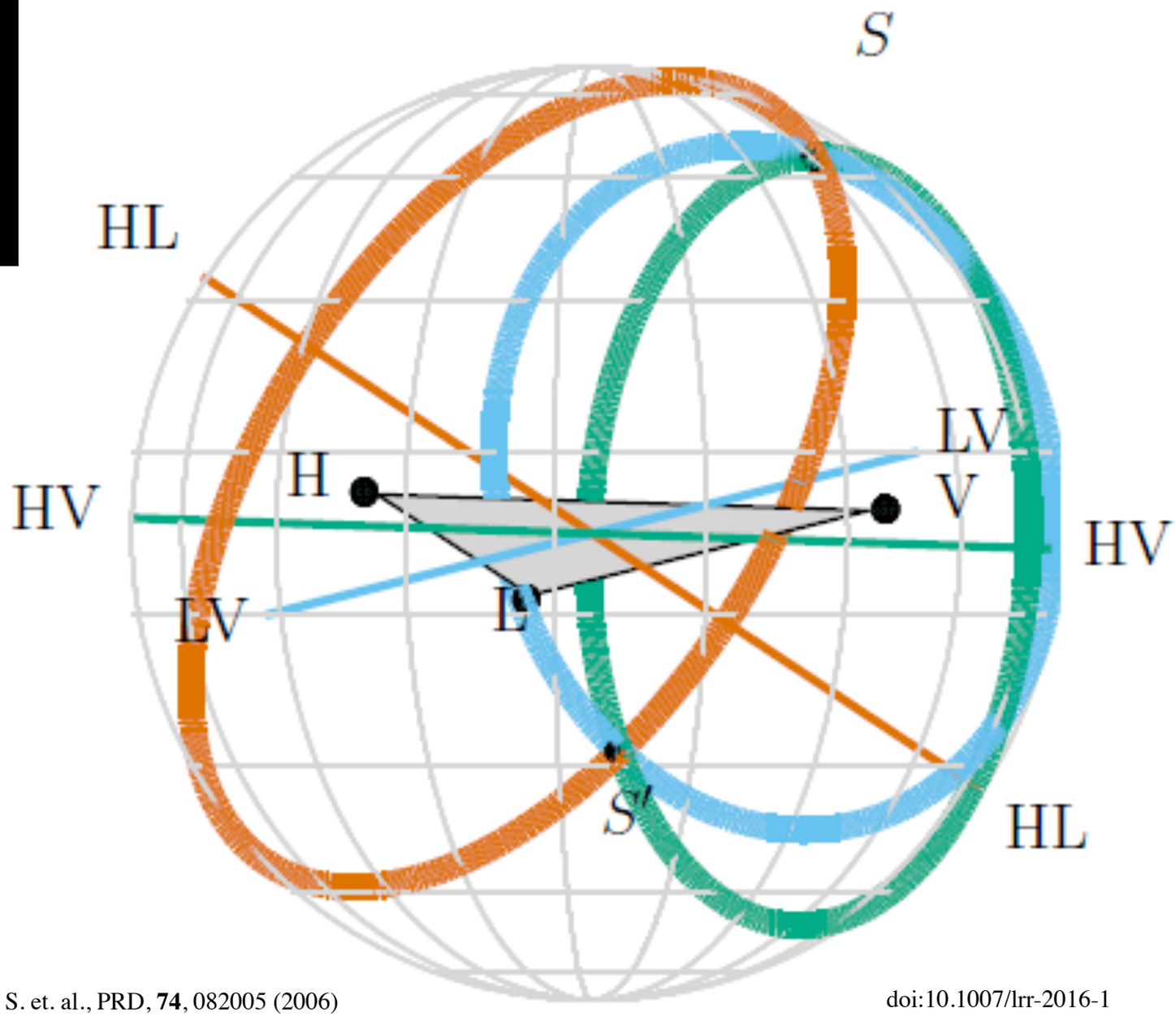
Detector network



Status of the detectors



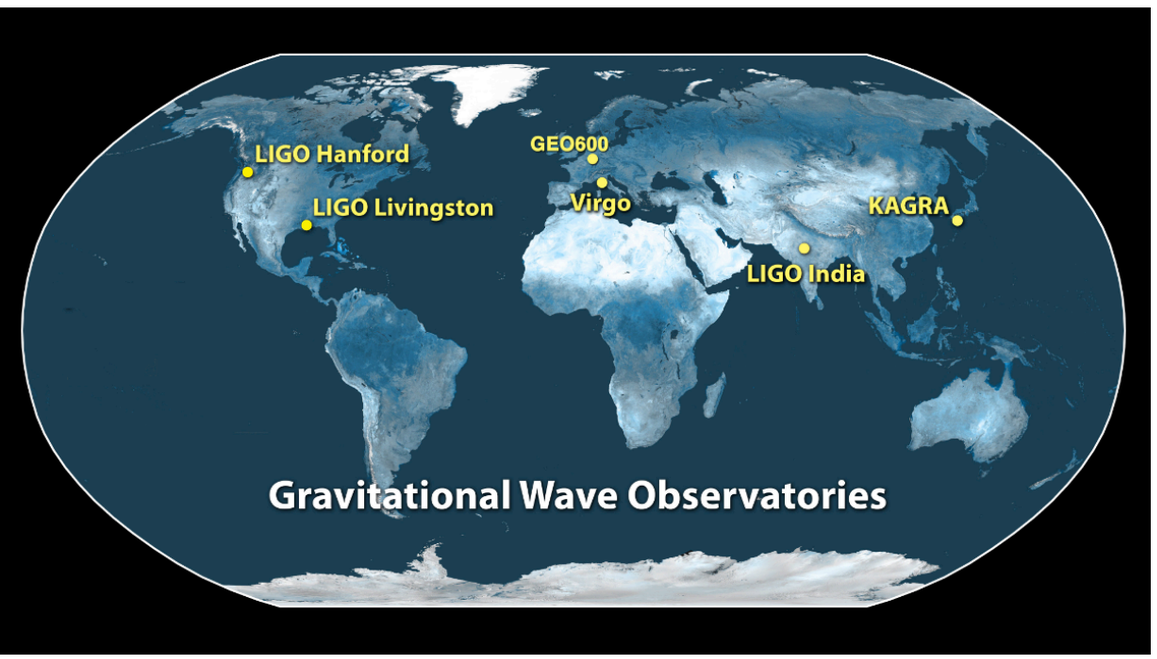
Detector network



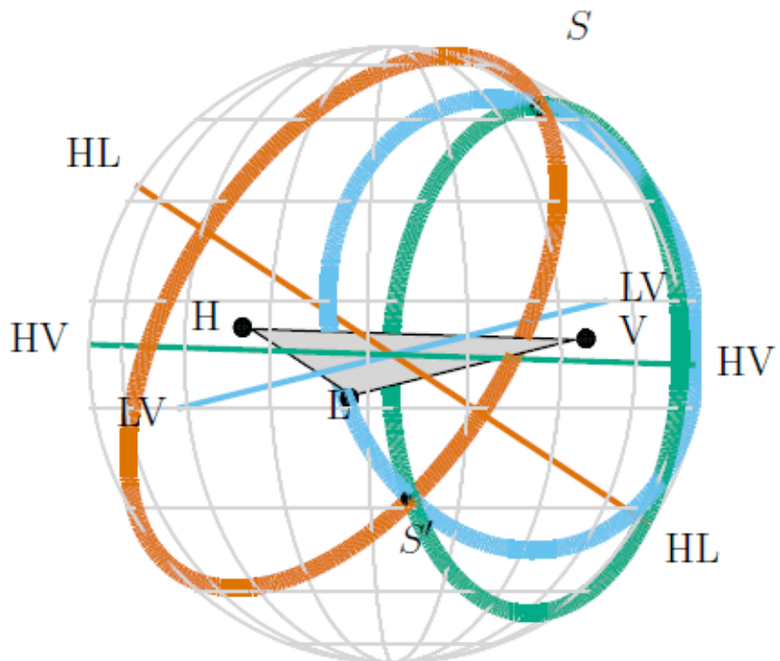
Chatterji, S. et. al., PRD, **74**, 082005 (2006)

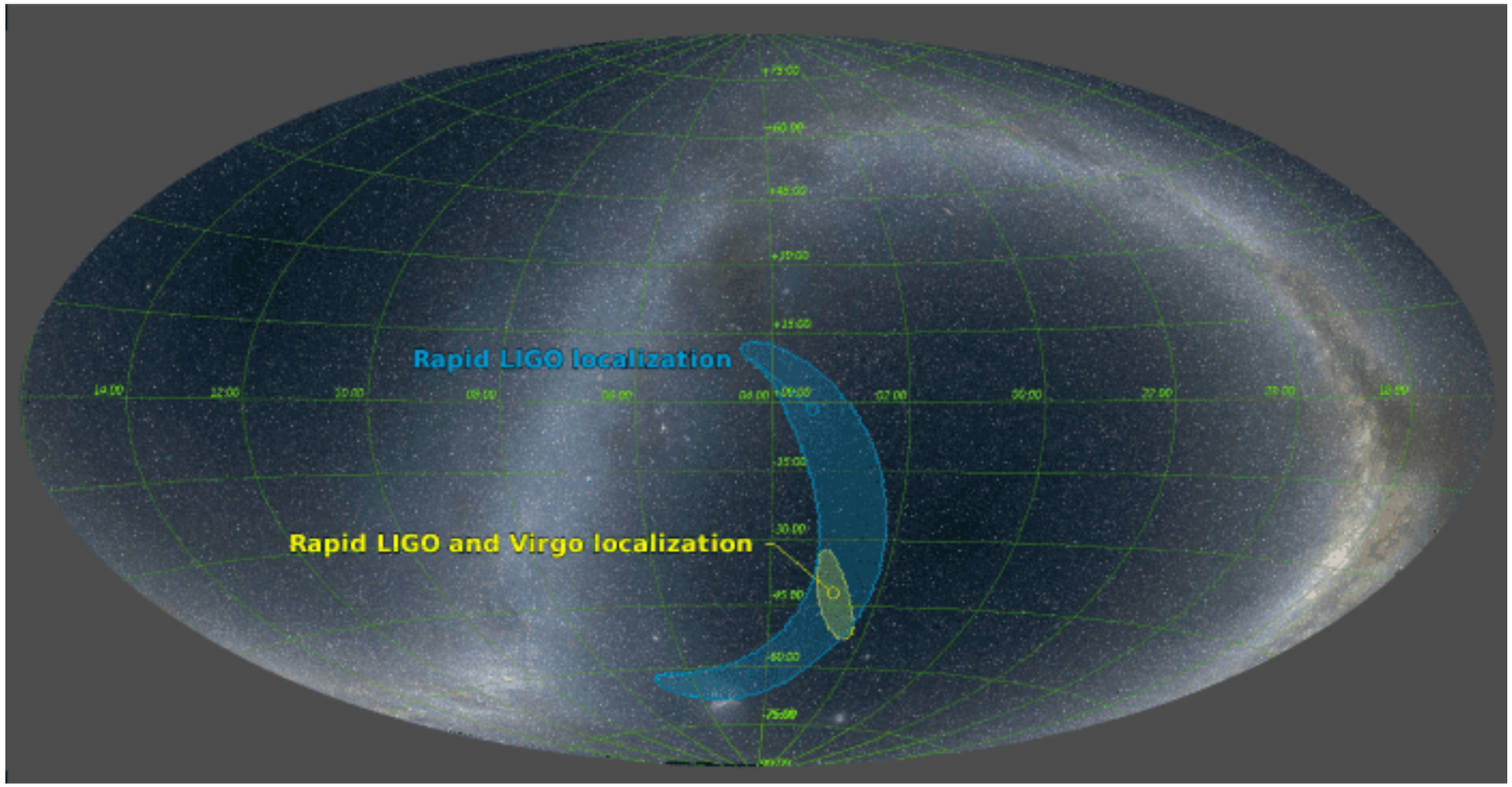
doi:10.1007/lrr-2016-1

Status of the detectors



Detector network





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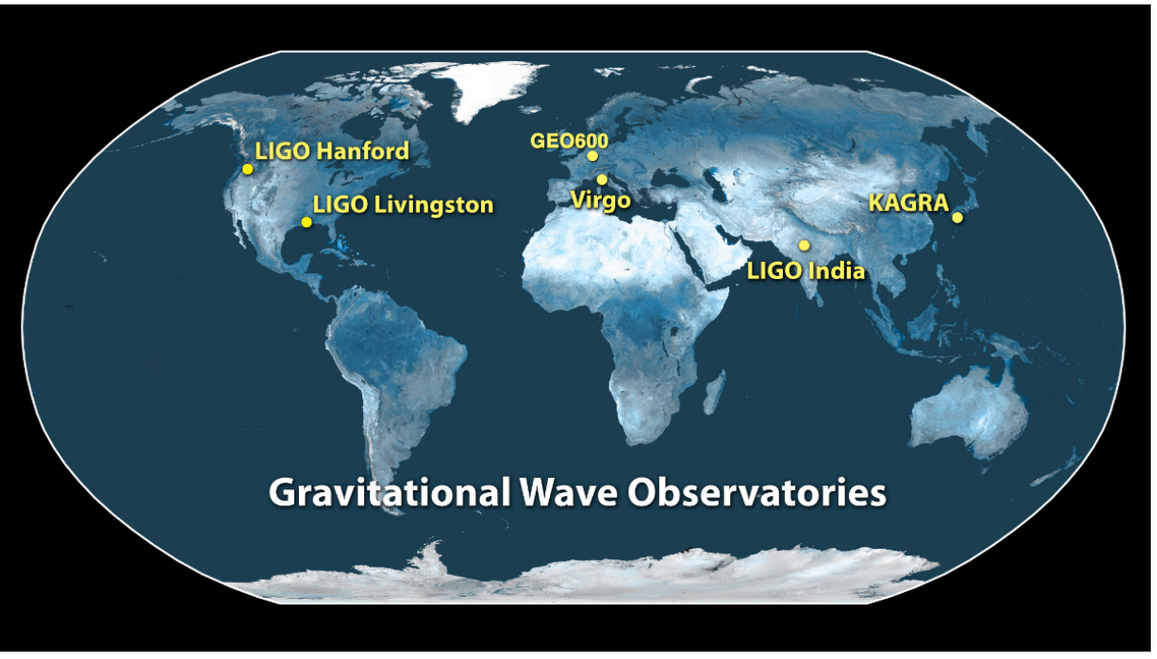
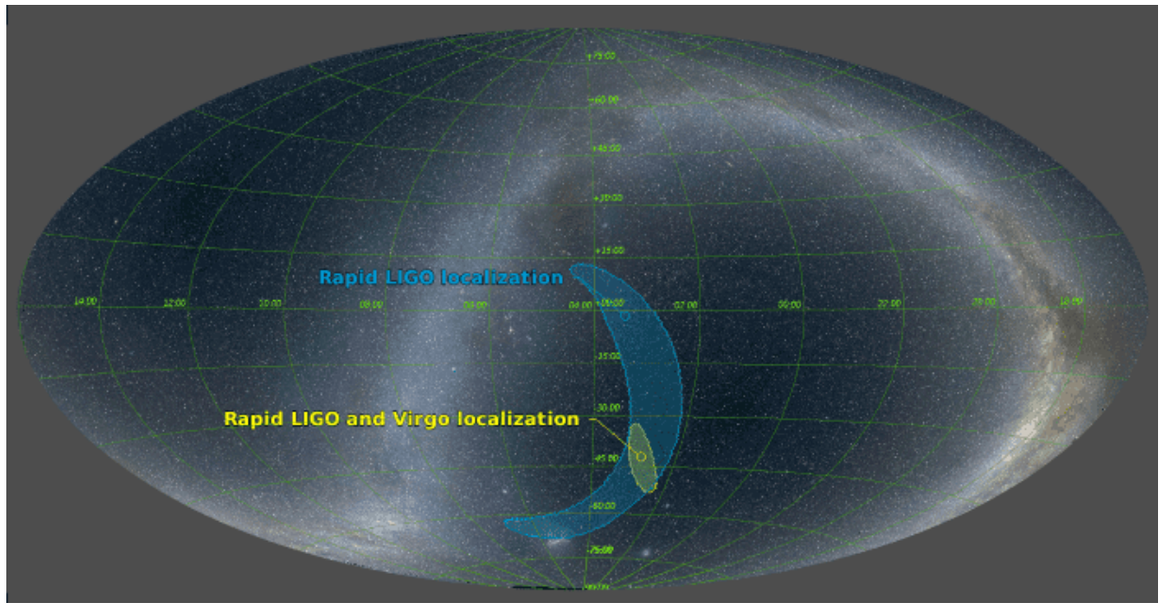
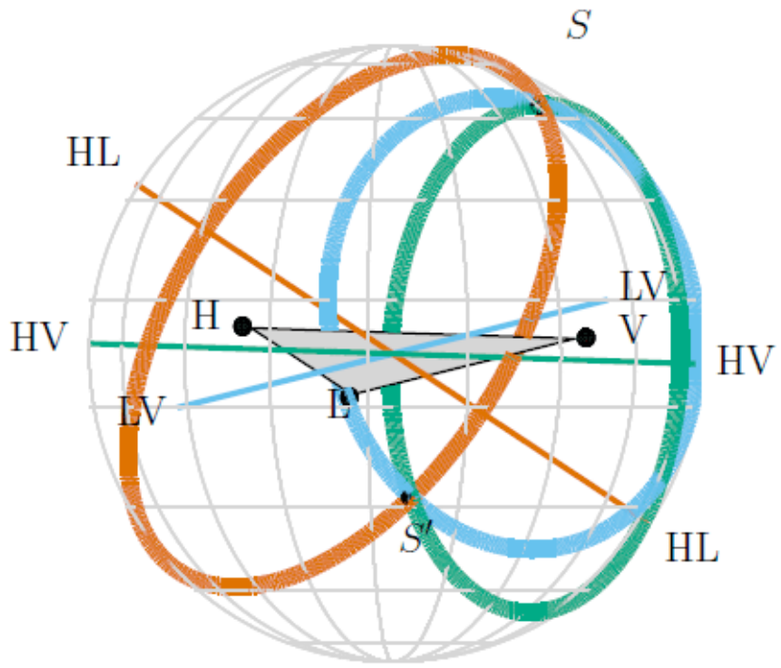
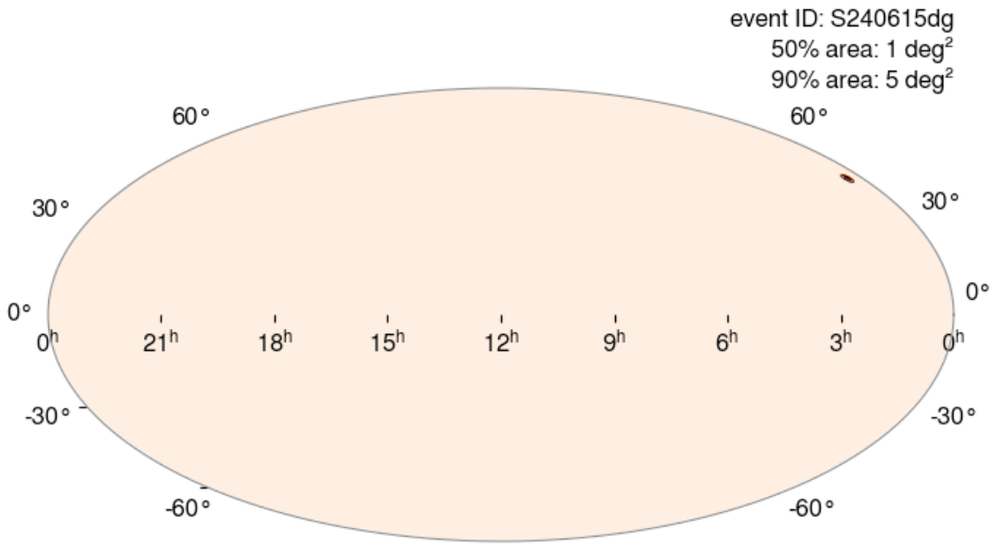


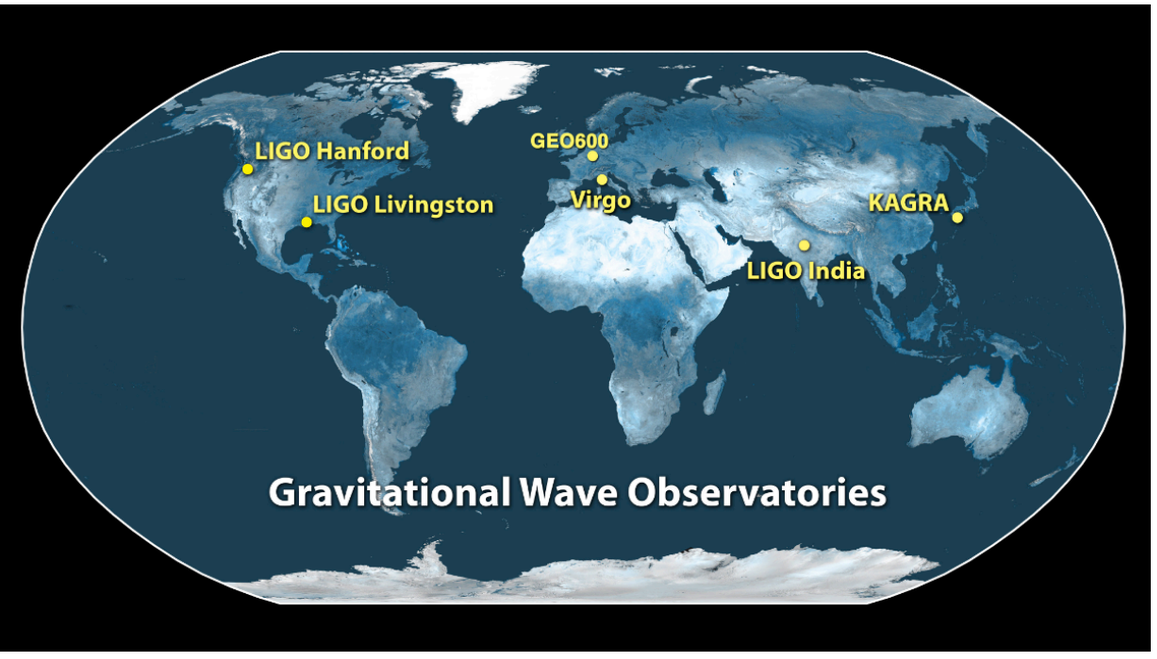


Detector network

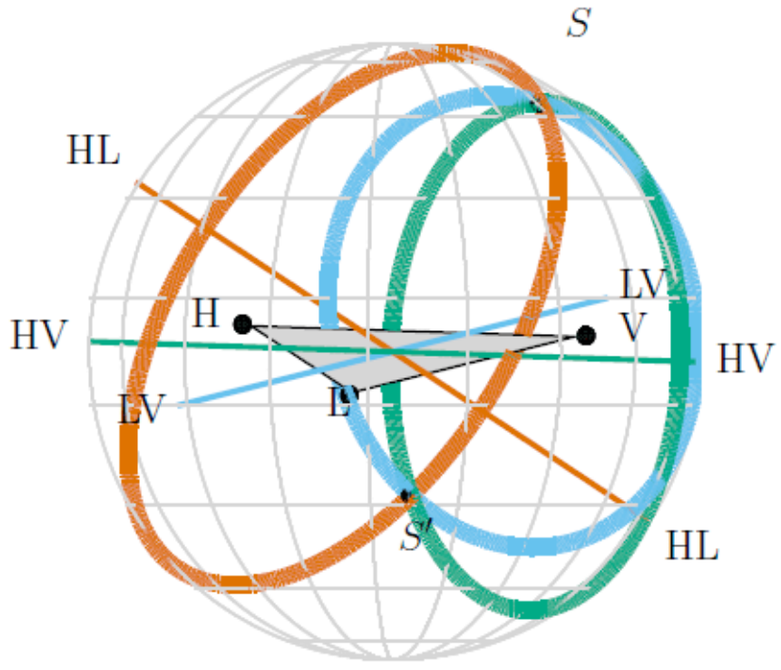


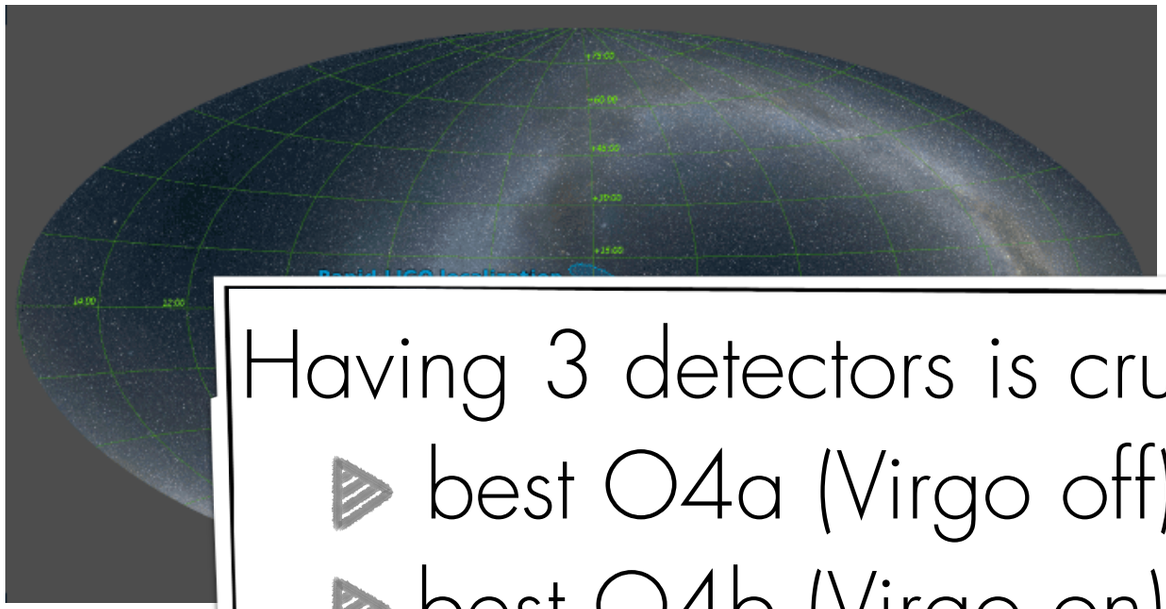


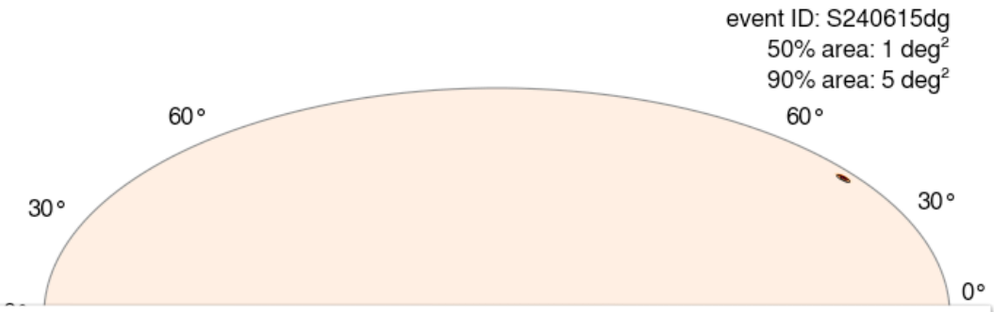
Status of the detectors



Detector network





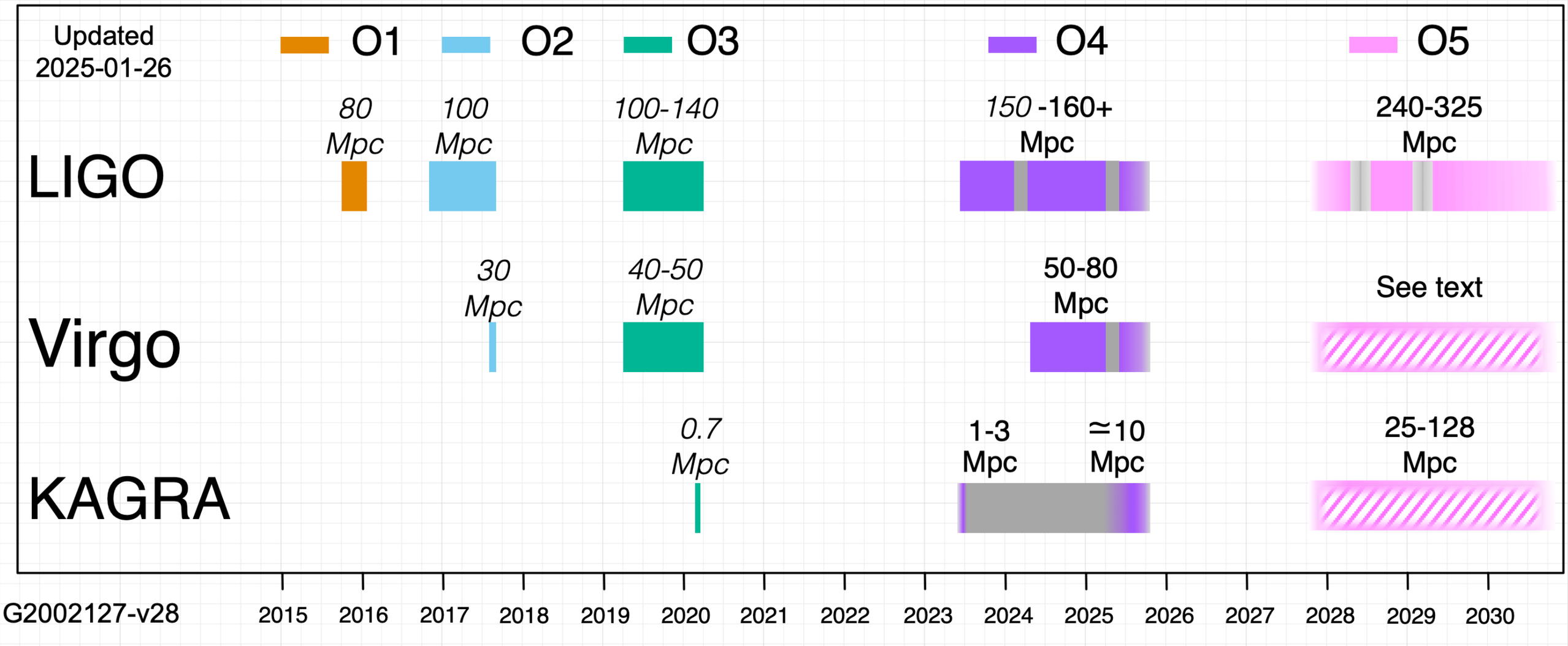


Having 3 detectors is crucial for good localisation:

- best O4a (Virgo off) is 80deg^2
- best O4b (Virgo on) is 5deg^2

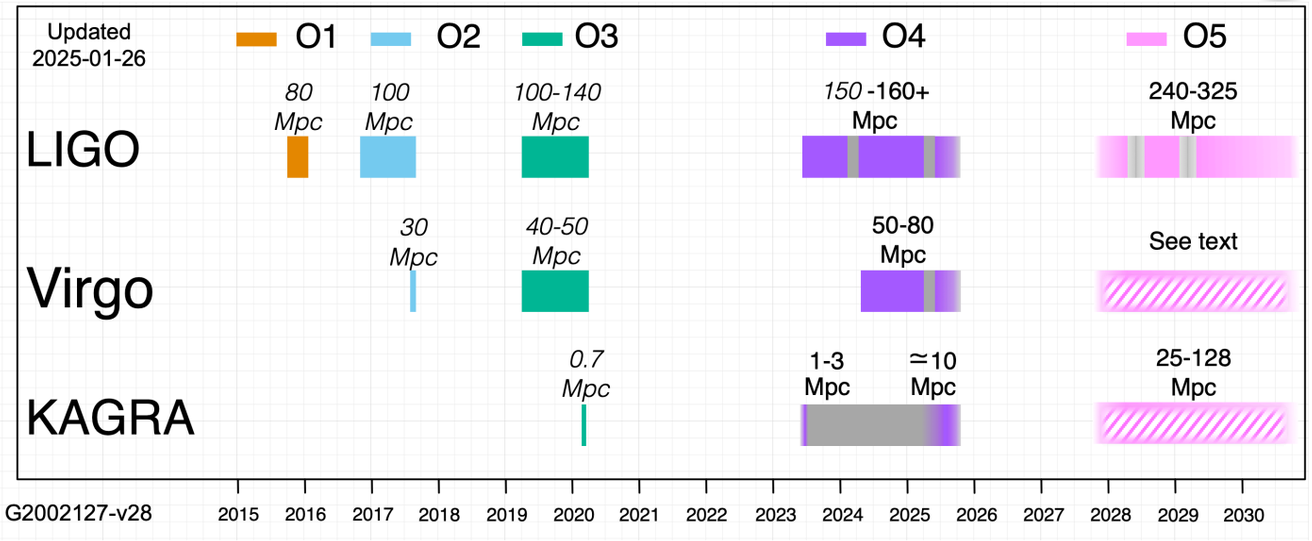
Status of the detectors

Observation plan



https://observing.docs.ligo.org/plan/

Status of the detectors



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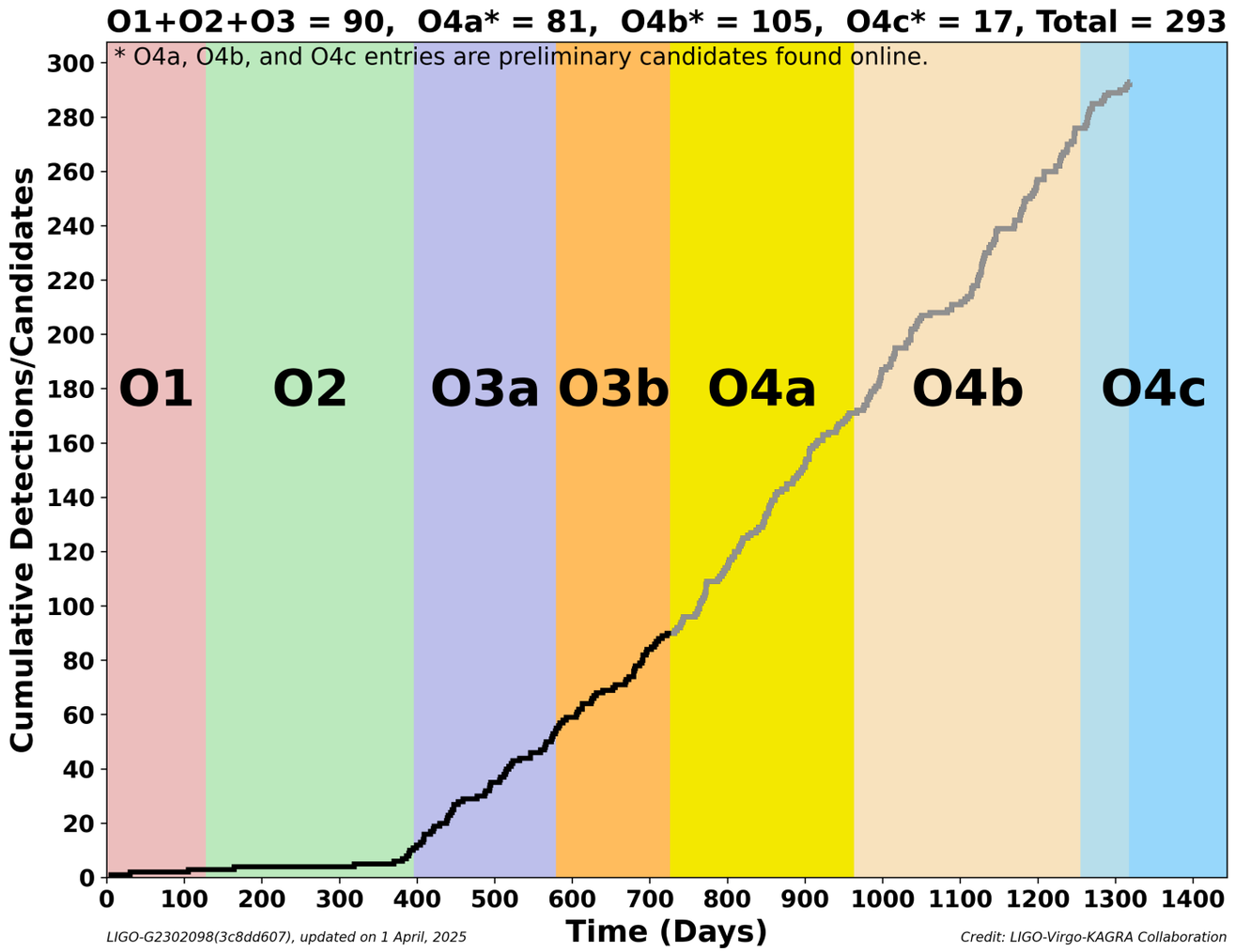

https://observing.docs.ligo.org/plan/

The key component is public alerts & live information on parameters

This enables EM follow-up, immediate science response

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(and it's fun and engaging!)

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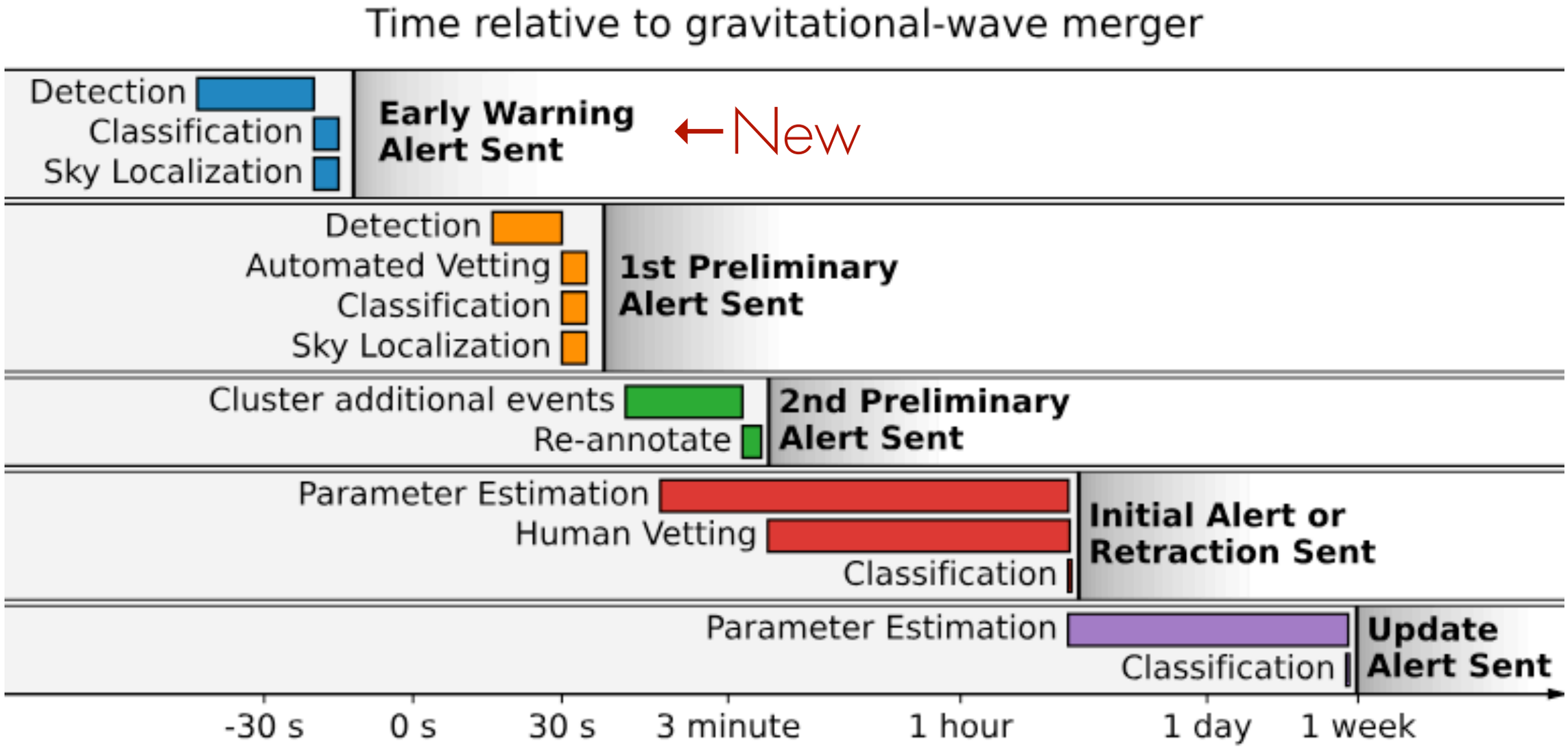

https://emfollow.docs.ligo.org/userguide/analysis/index.html

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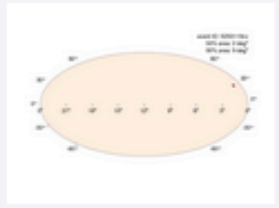
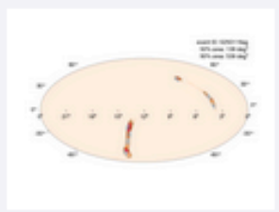
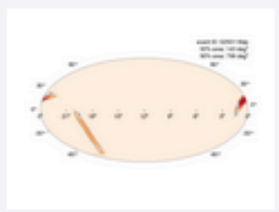
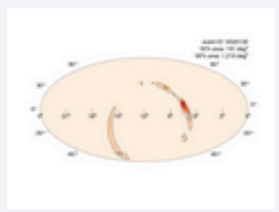
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S250119cv	BBH (>99%)	Yes	Jan. 19, 2025 19:02:38 UTC	GCN Circular Query Notices | VOE		1 per 7.9146e+11 years	
S250119ag	BBH (>99%)	Yes	Jan. 19, 2025 02:51:38 UTC	GCN Circular Query Notices | VOE		1 per 94621 years	
S250118dp	BBH (>99%)	Yes	Jan. 18, 2025 17:05:23 UTC	GCN Circular Query Notices | VOE		1 per 5.7028e+16 years	
S250118az	BBH (99%)	Yes	Jan. 18, 2025 05:58:02 UTC	GCN Circular Query Notices | VOE		1 per 3.2435 years	

https://gracedb.ligo.org

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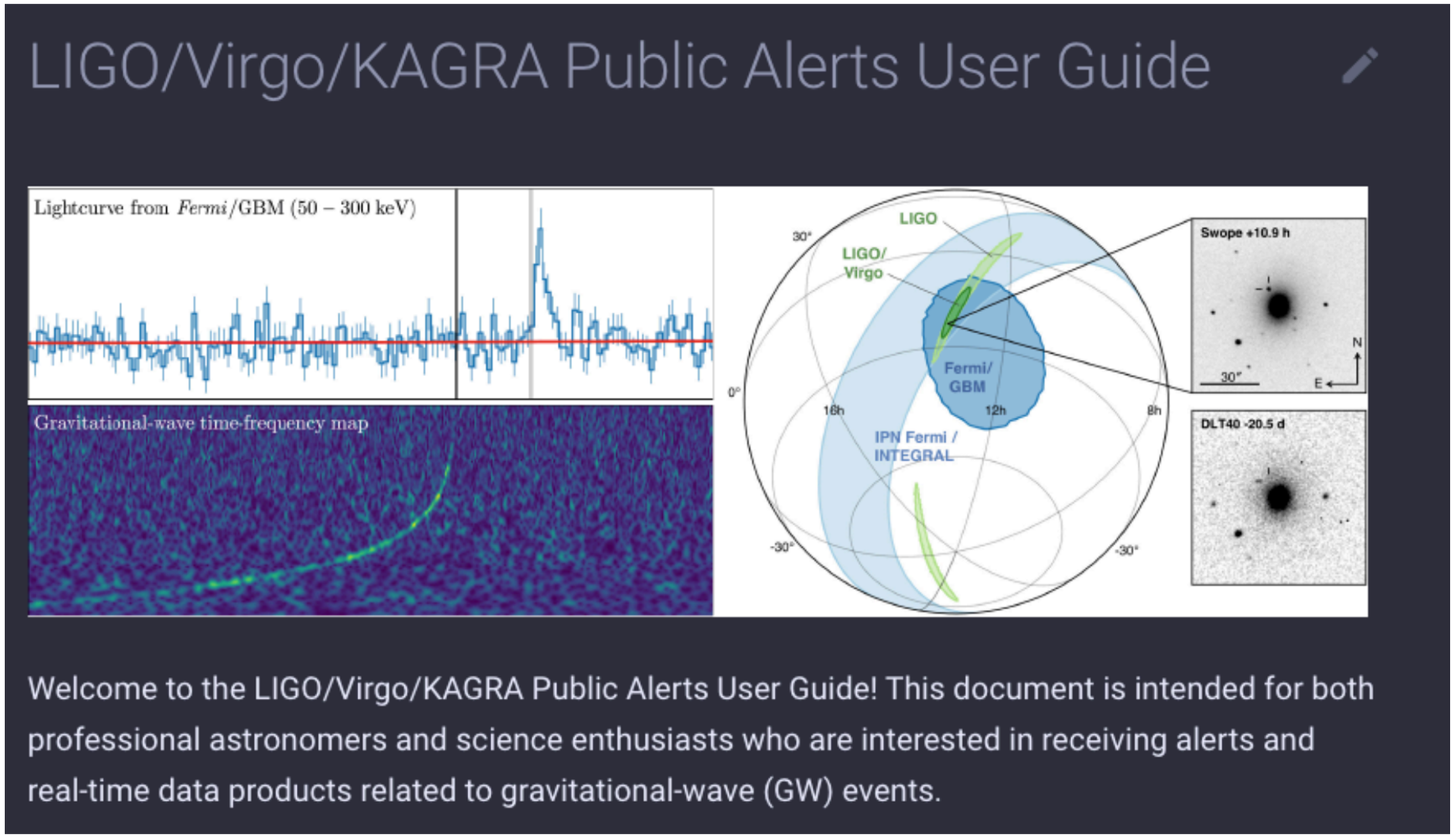
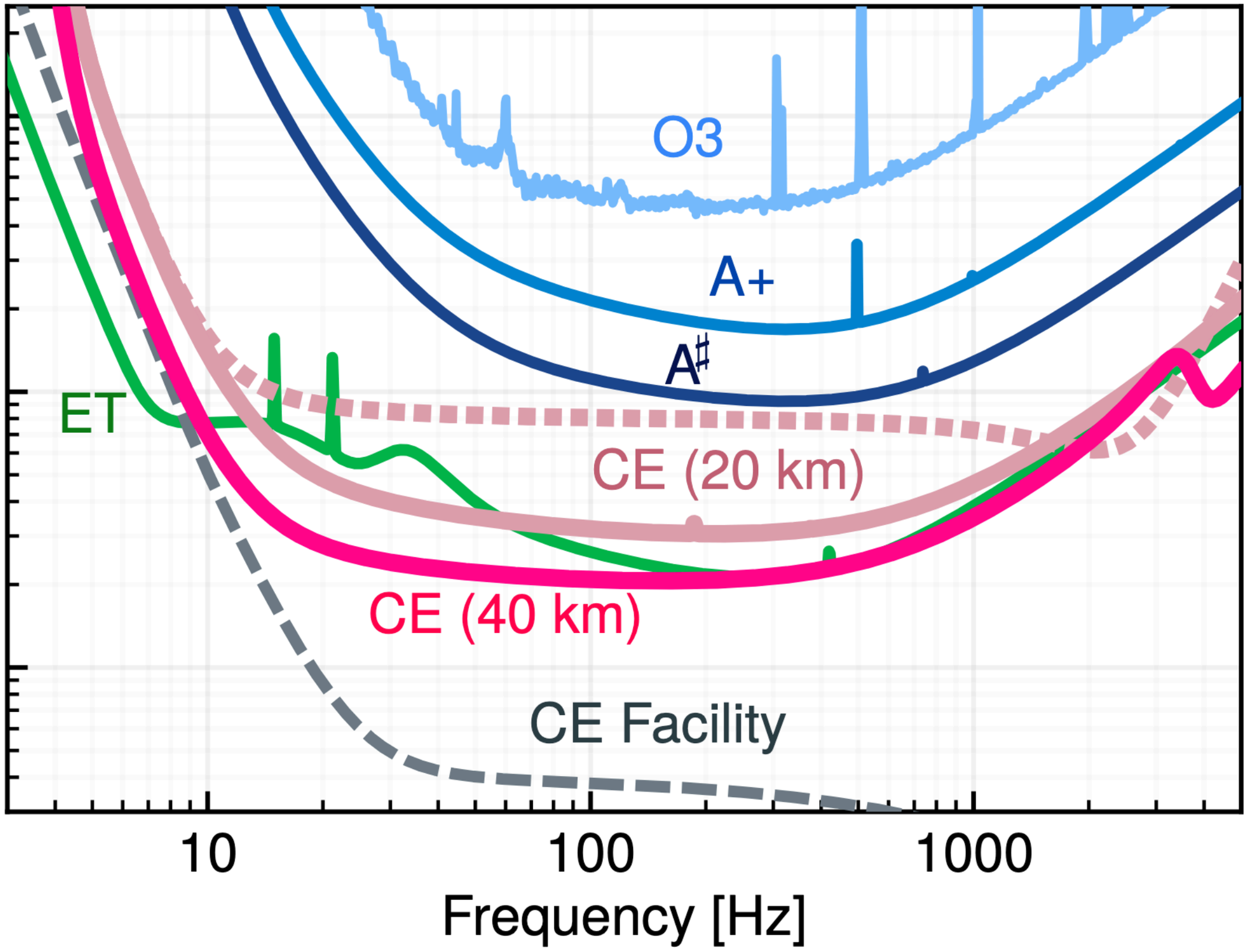
This enables EM follow-up, immediate science response

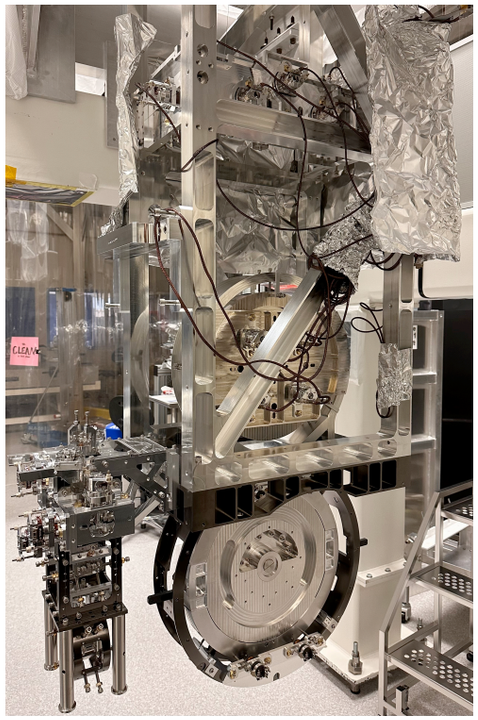
(and it's fun and engaging!)



https://emfollow.docs.ligo.org/


O3
A+
A♯
ET
CE (20 km)
CE (40 km)
CE Facility
10
100
1000
Frequency [Hz]

Status of the detectors



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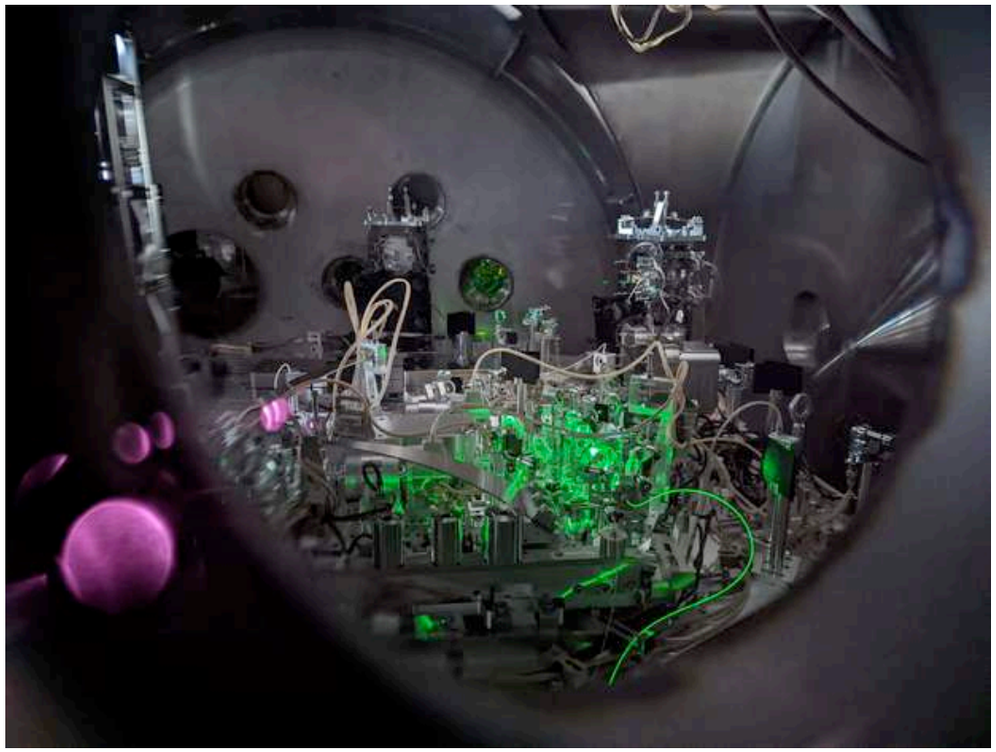
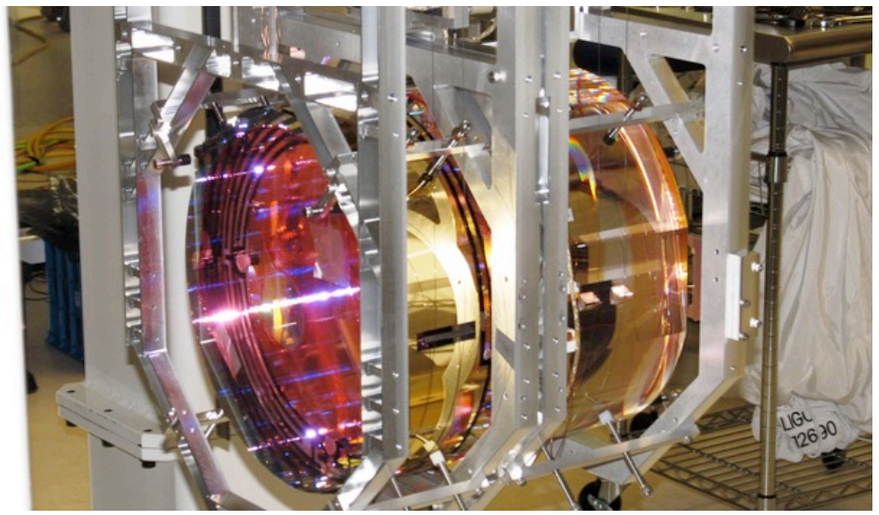
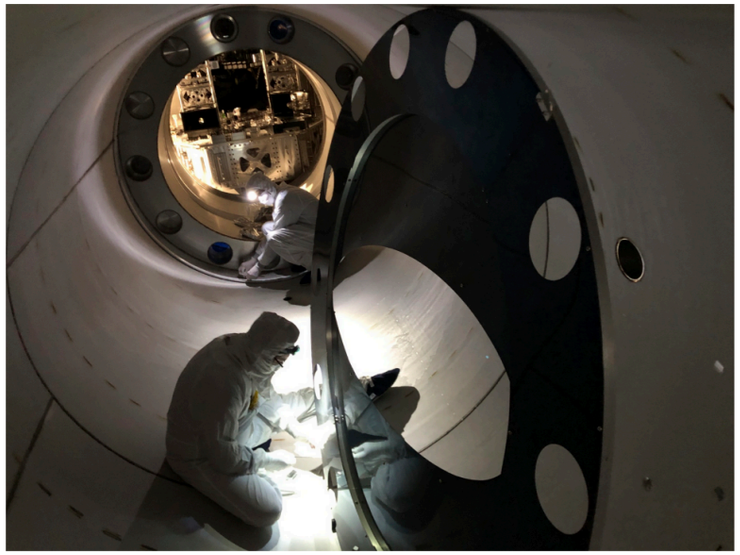


https://www.ligo.caltech.edu



https://www.ligo.caltech.edu

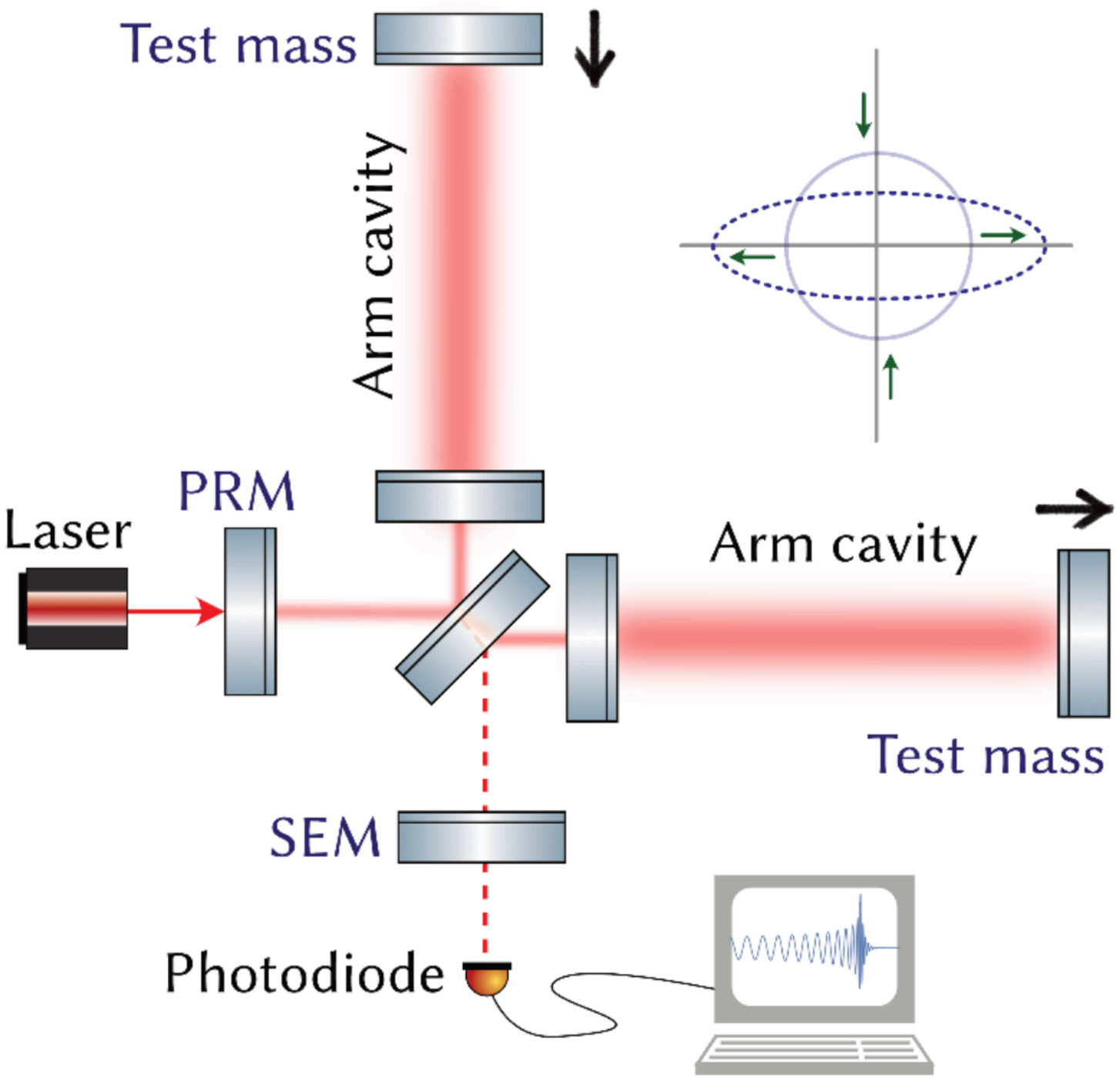
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=75529



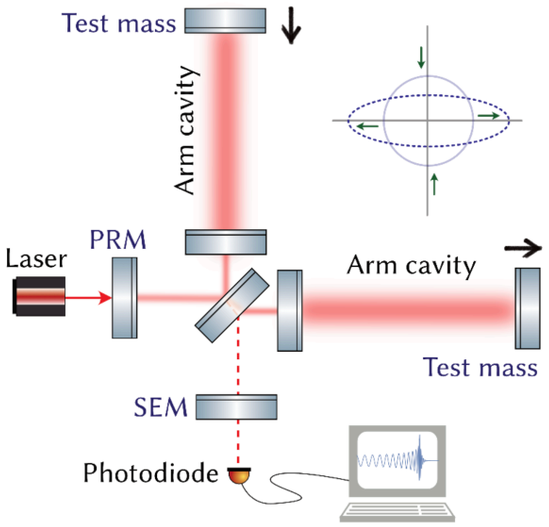
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=75654

Outline

1. Introduction to GW detection
2. Status of current GW detectors
3. Into the deep: how GWDs really work
4. Response of the detectors to high-frequency GWs
5. Challenges & perspectives

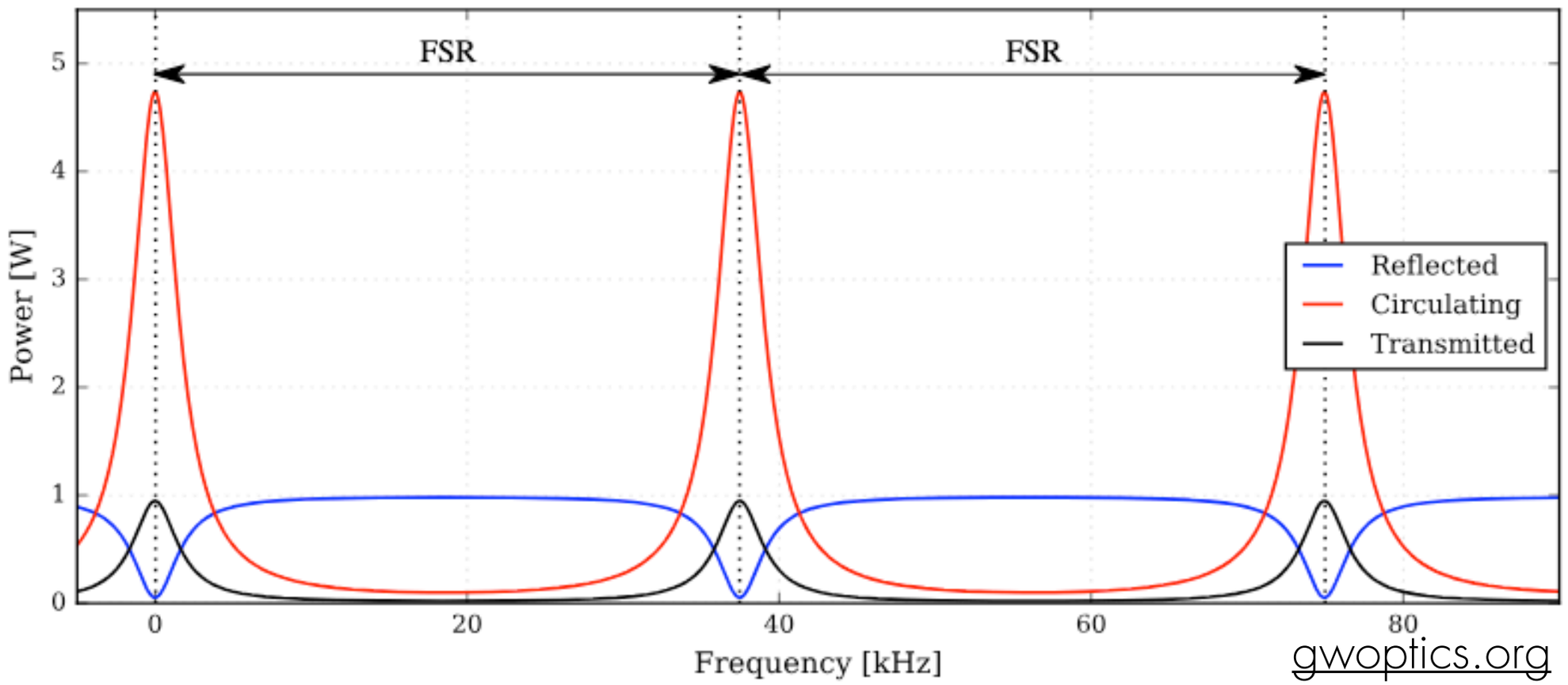

Test mass
Arm cavity
PRM
Laser
Arm cavity
Test mass
SEM
Photodiode

GW response



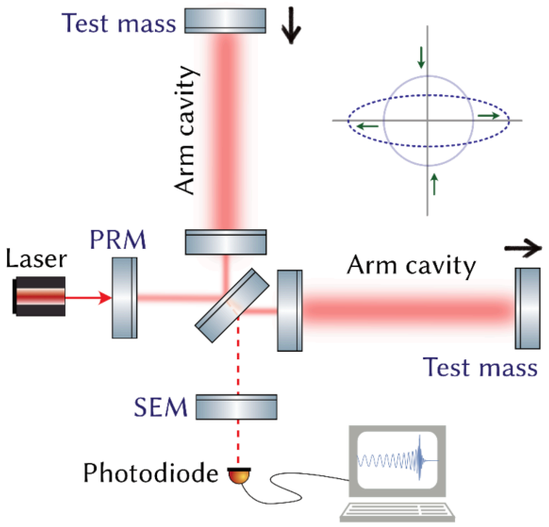
Optical cavity

Cavities become resonant every free spectral range!



gwoptics.org

GW response



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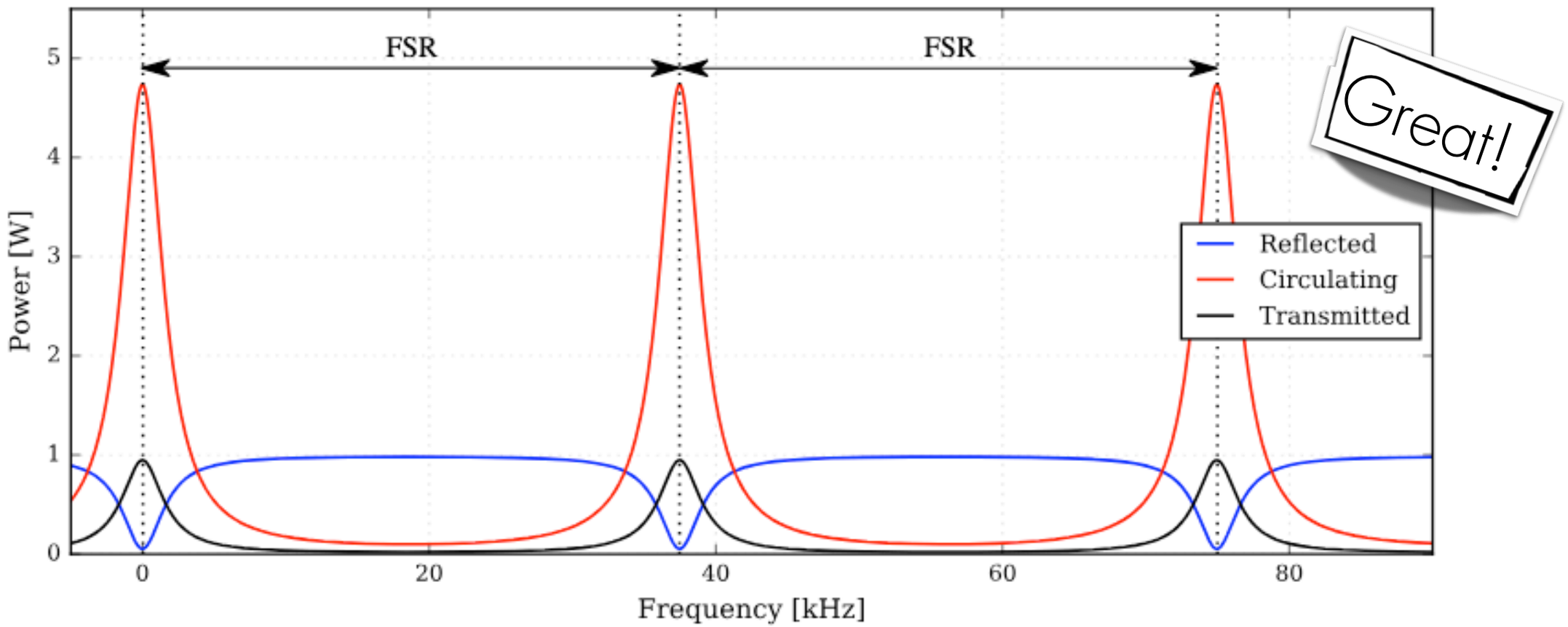
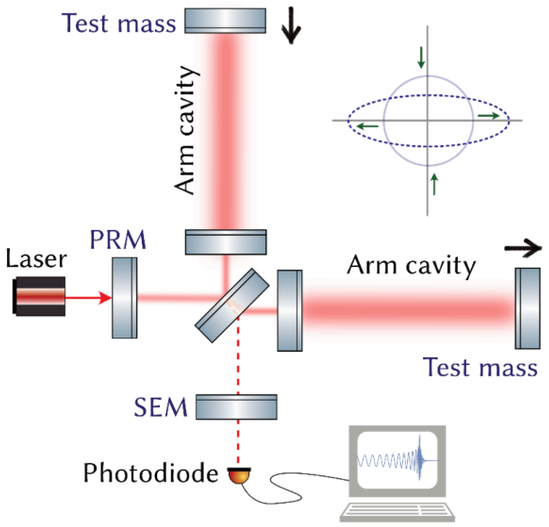


GW response



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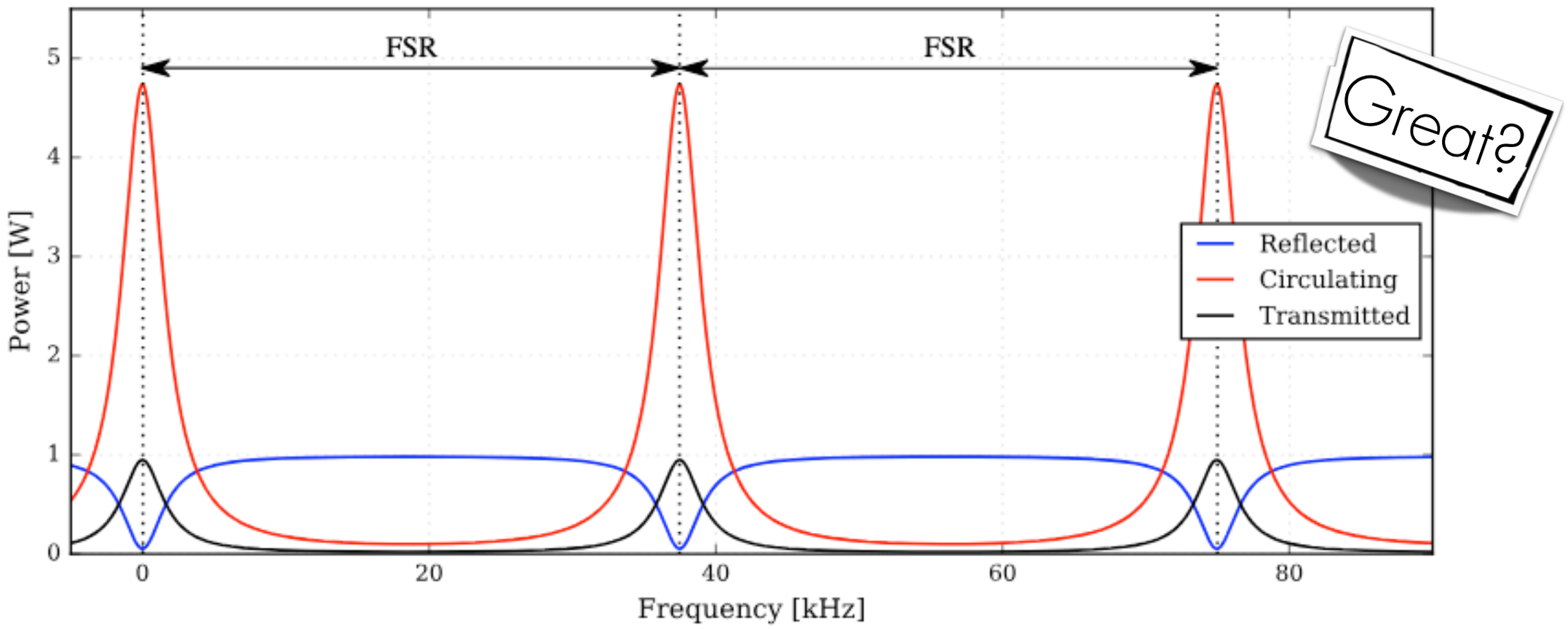
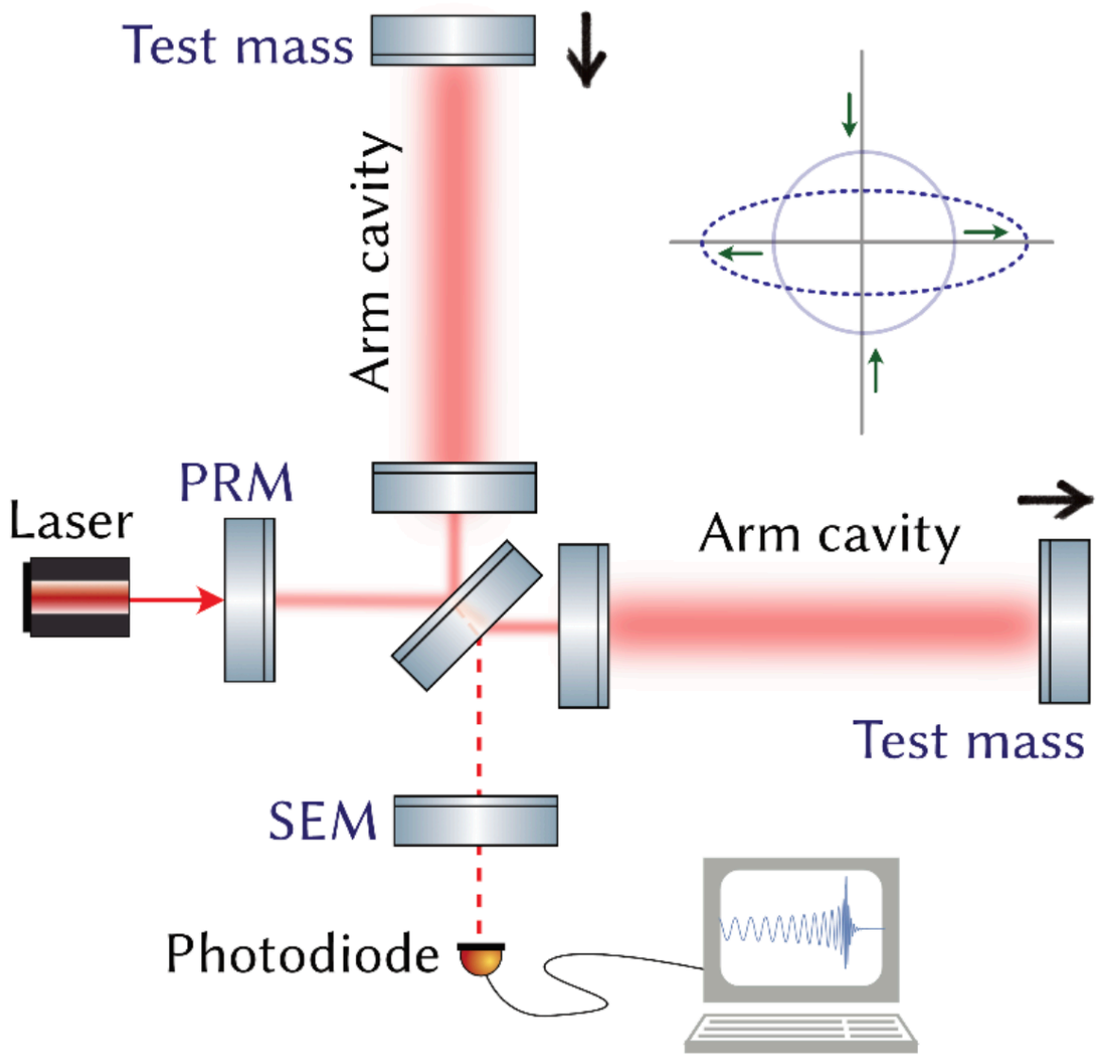


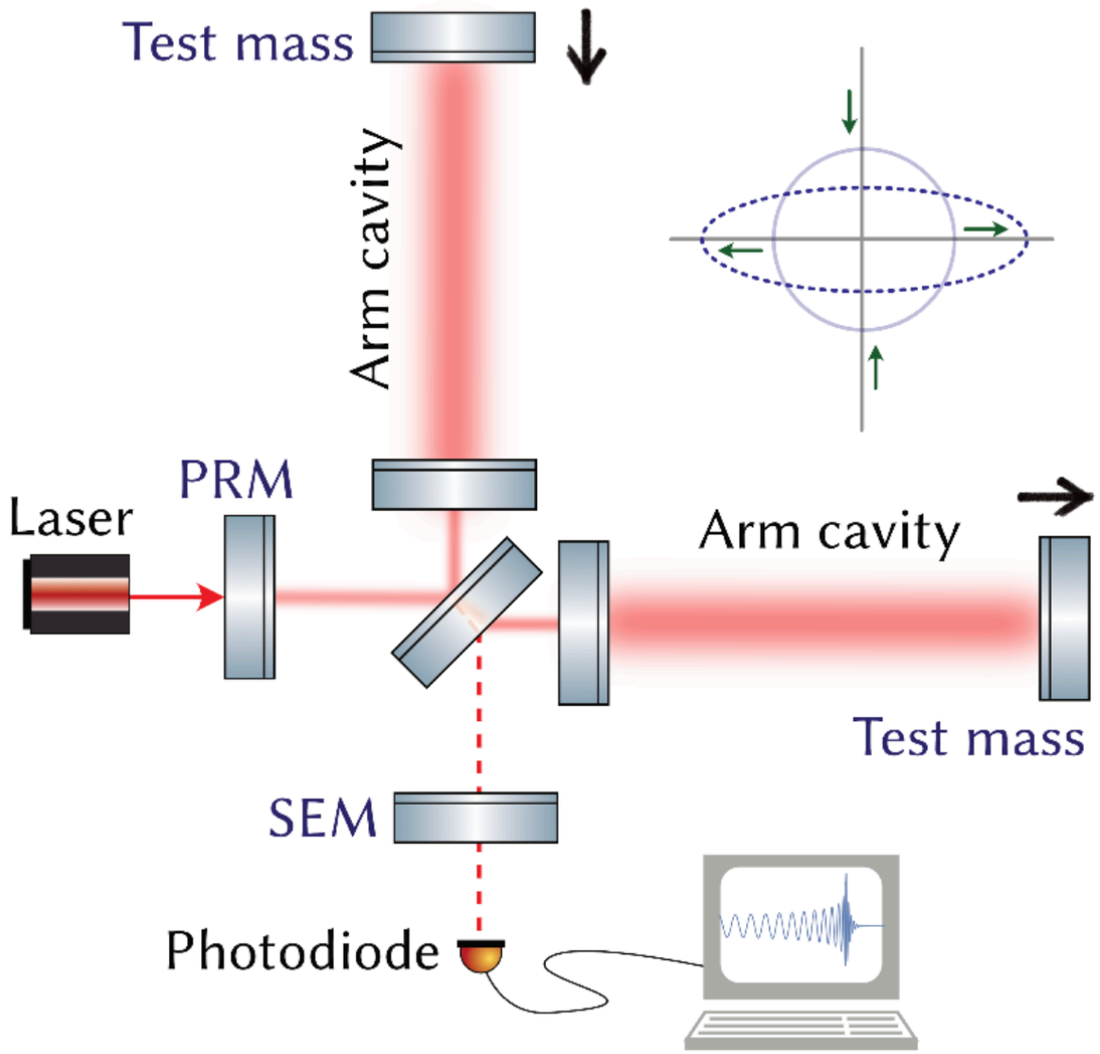
GW response



GW wavelength

For low-frequency GWs, wavelength is » arm length

GW response

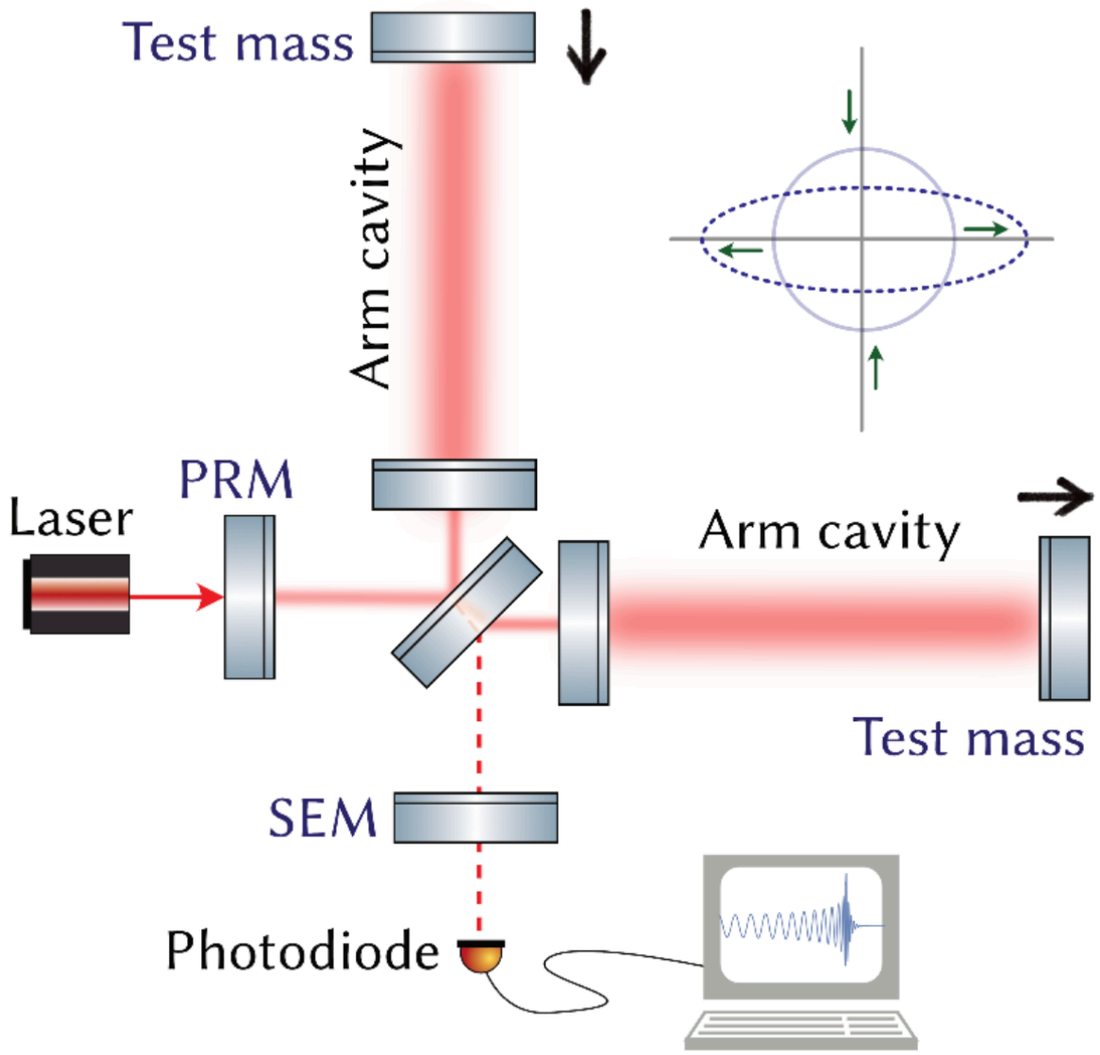


GW wavelength

For low-frequency GWs,
wavelength is » arm length

For high-frequency GWs,
the response changes:
if the half wave fits
exactly into the arm length

GW response



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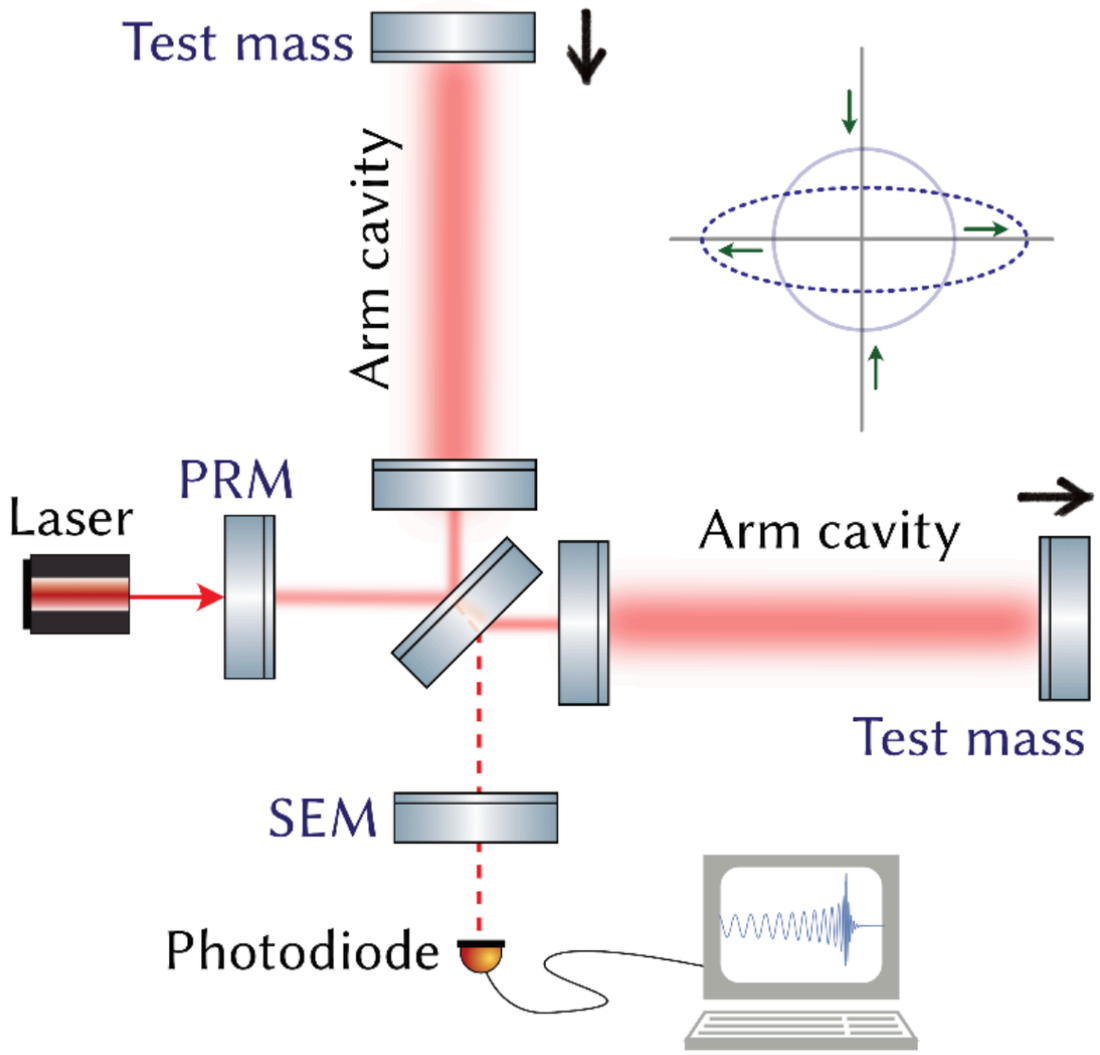
if the half wave fits
exactly into the arm length

$$\text{GW response} \sim h_+ \,\text{sinc}\left(\frac{\pi f}{f_{\text{FSR}}}\right)$$

GW response



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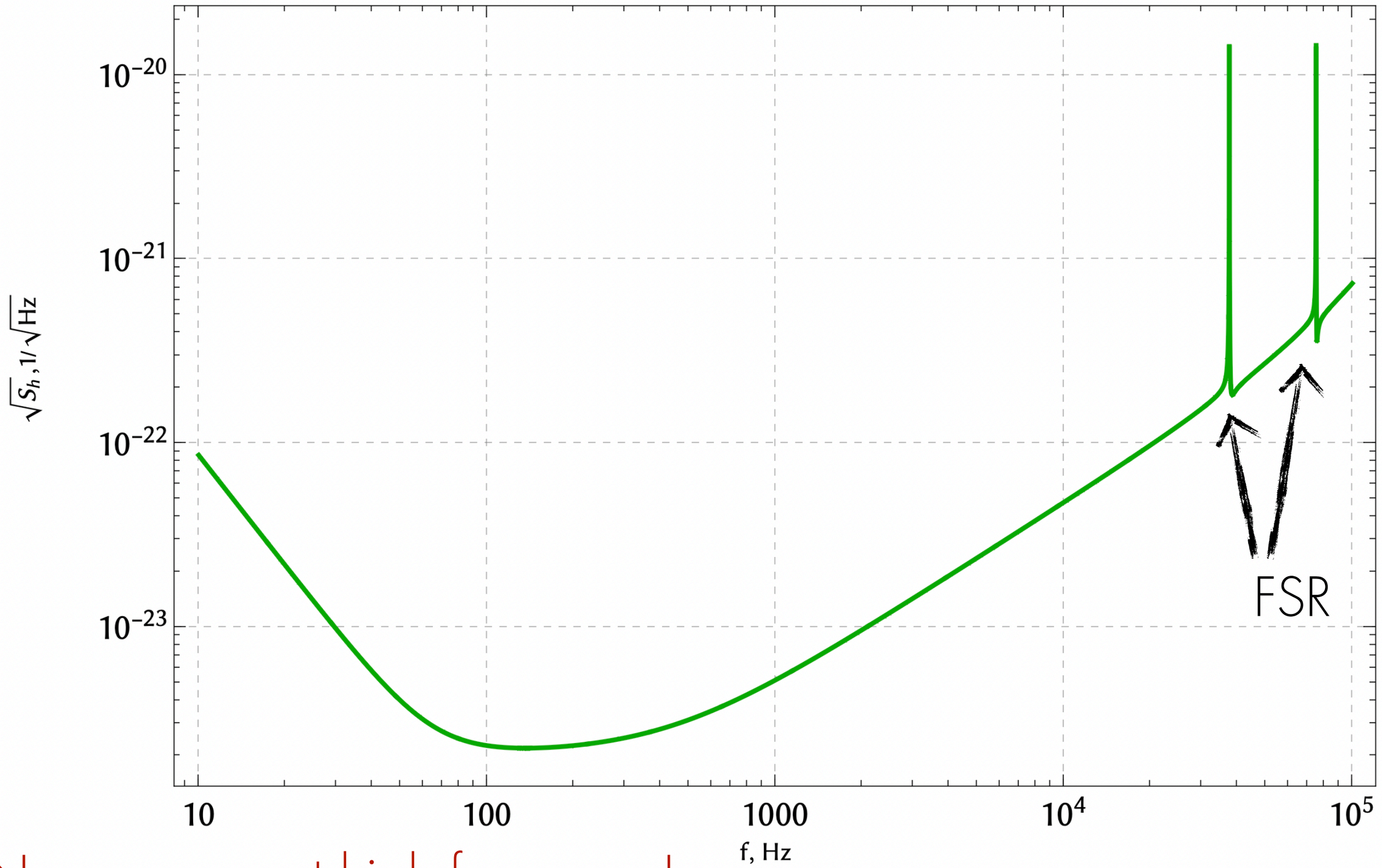
No response at high frequency!

GW response

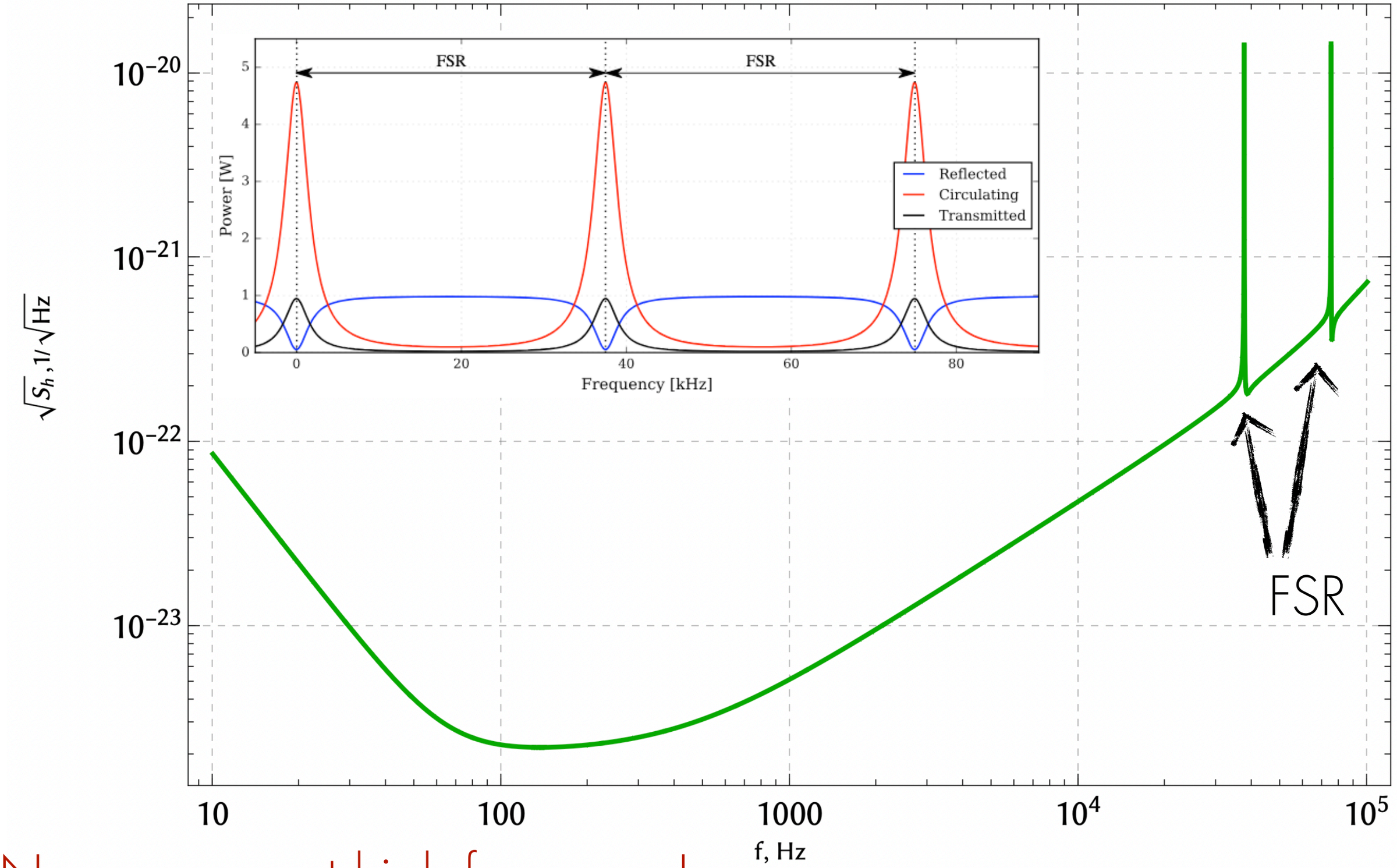
GW wavelength



No response at high frequency!

GW response

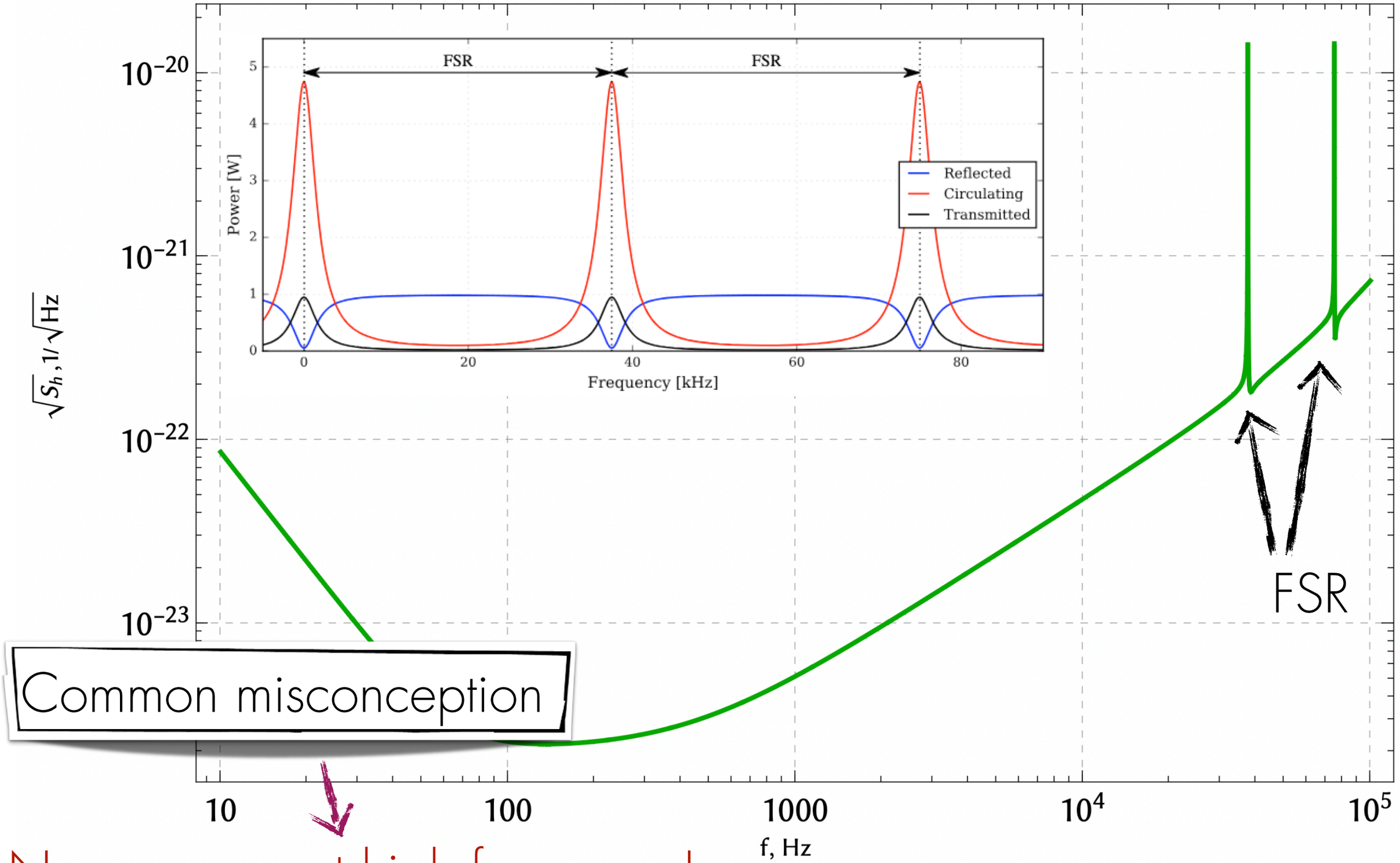
GW wavelength



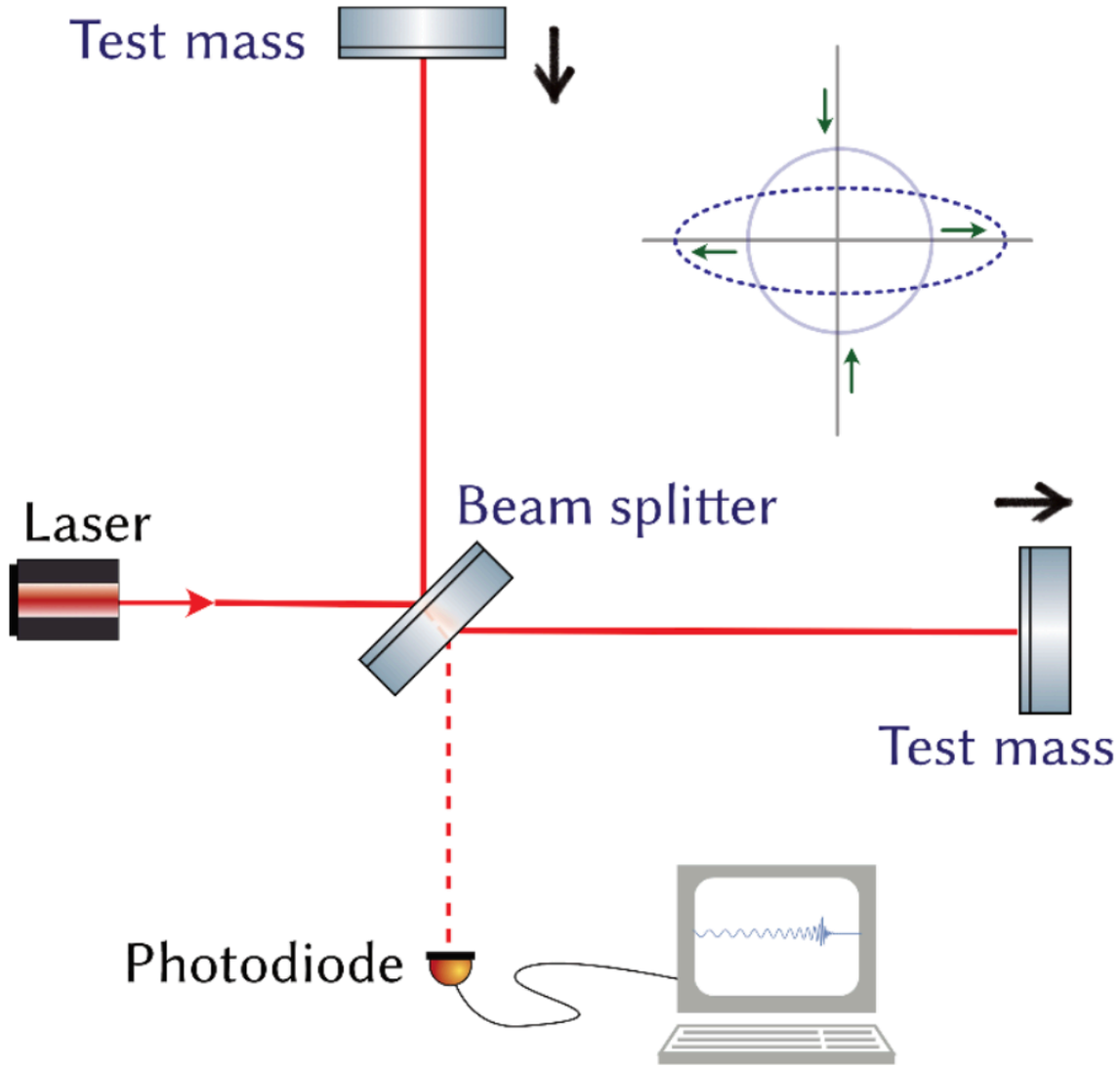
No response at high frequency!

GW response

GW wavelength

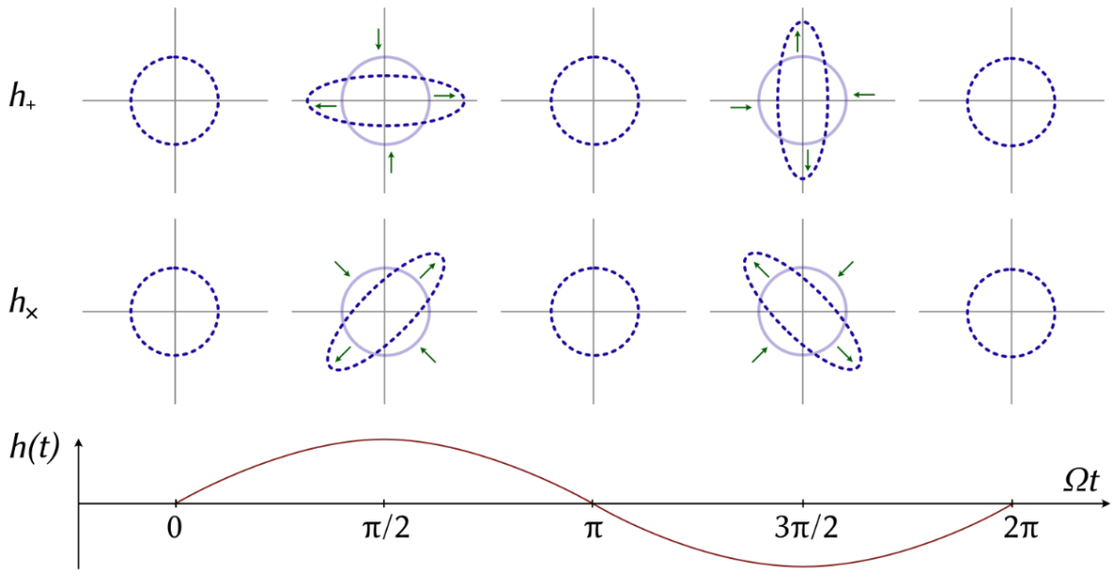


GW response

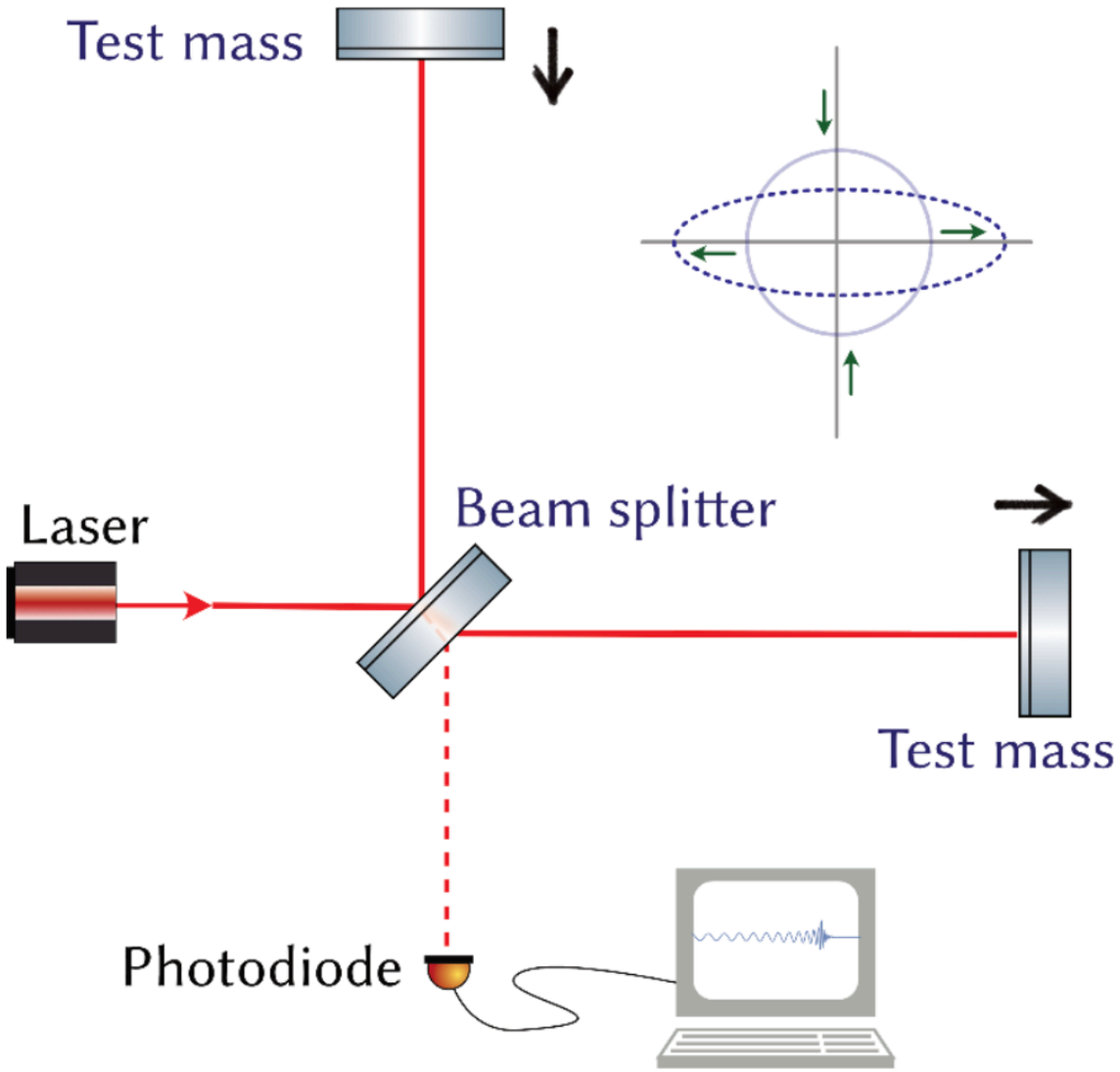


Antennae pattern

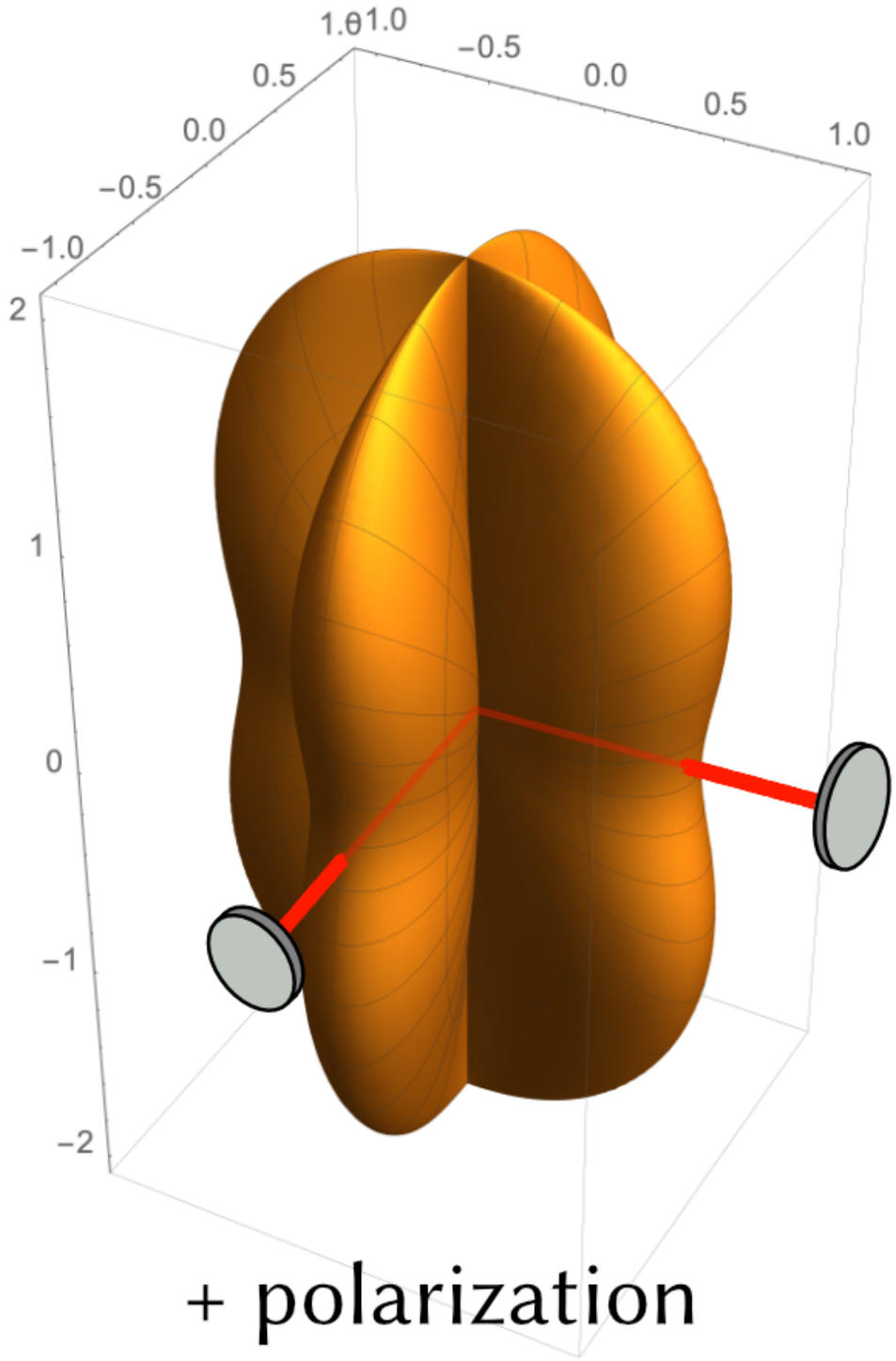
Two polarisations



GW response

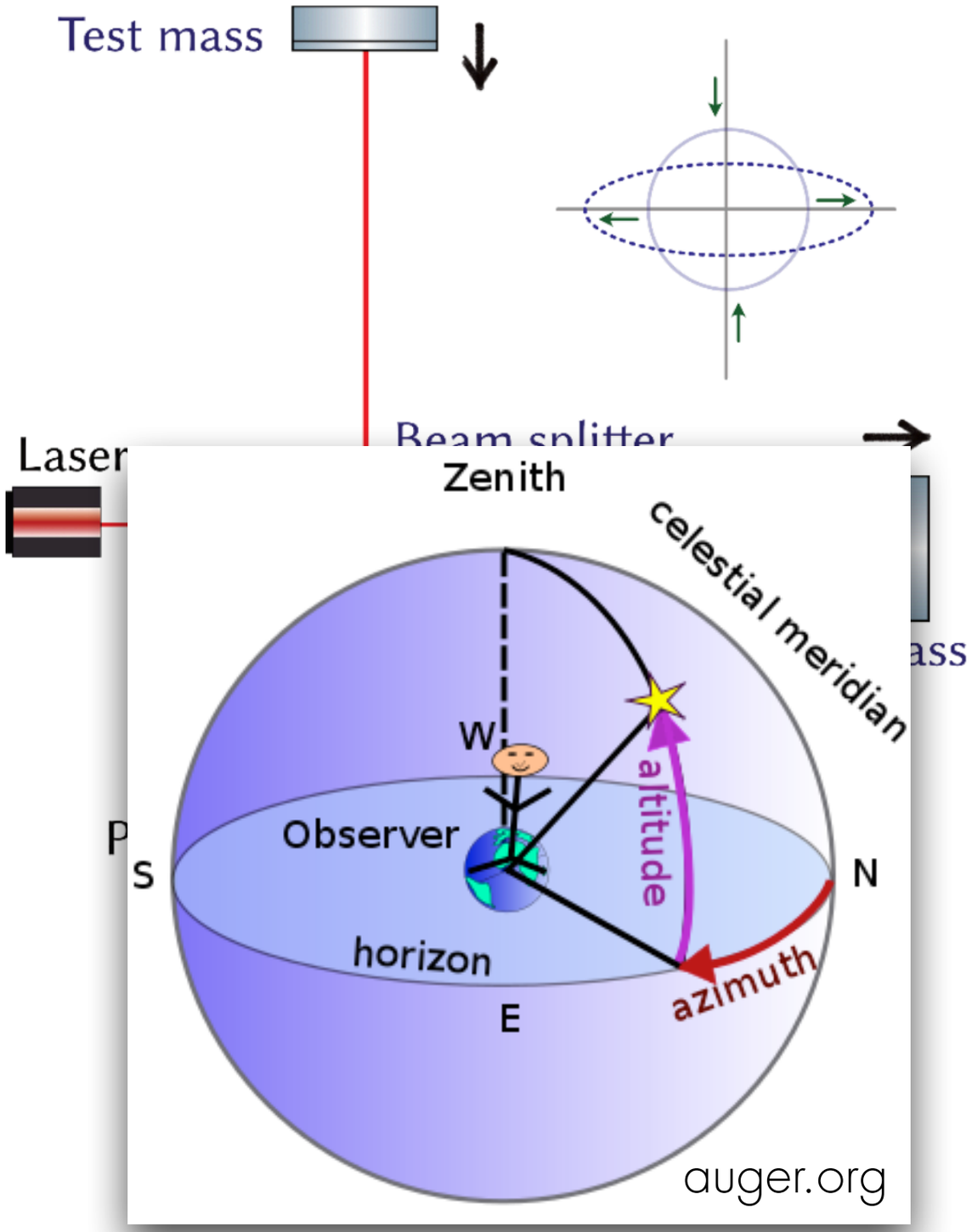


Antenna pattern

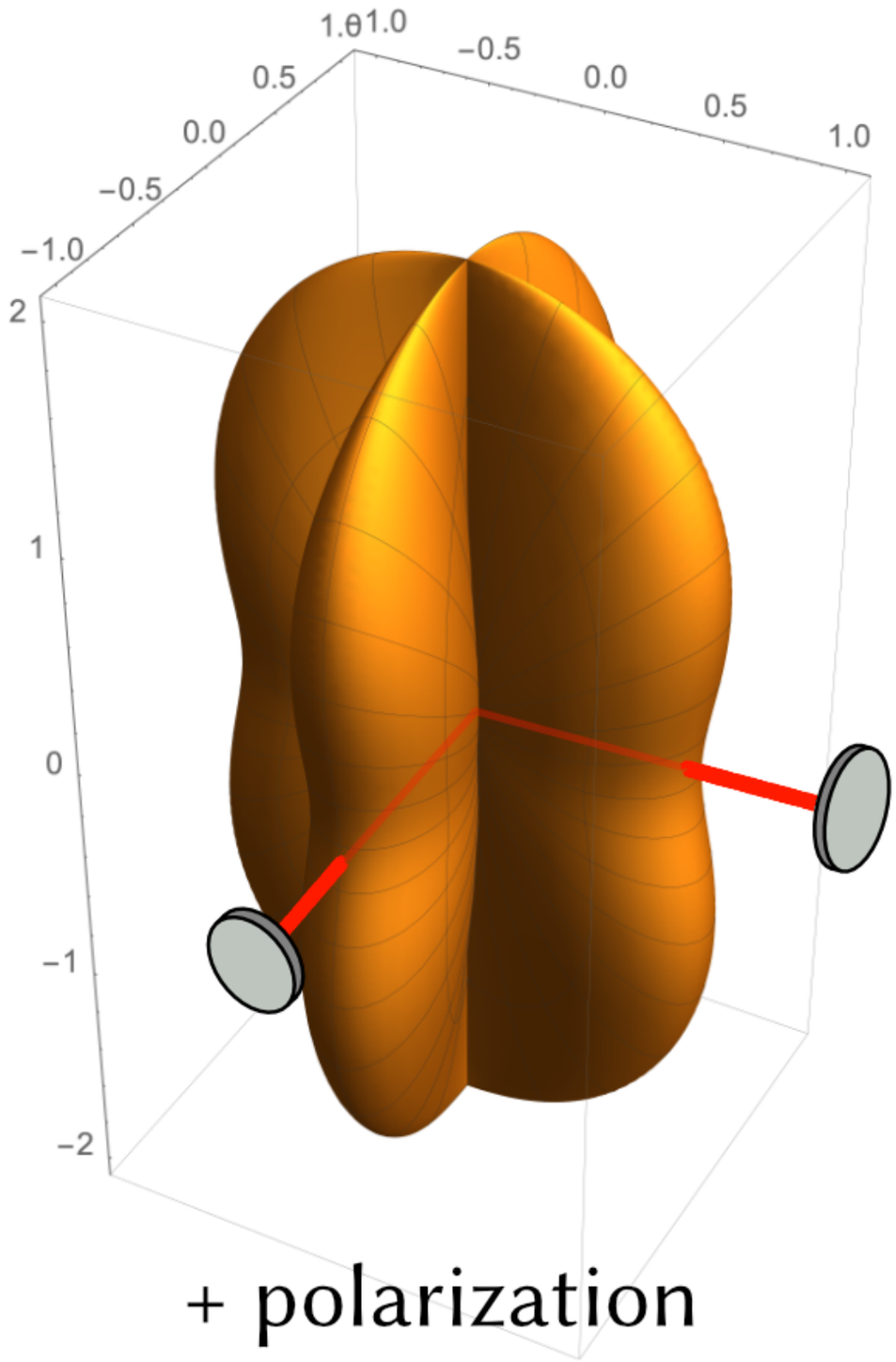


+ polarization

GW response

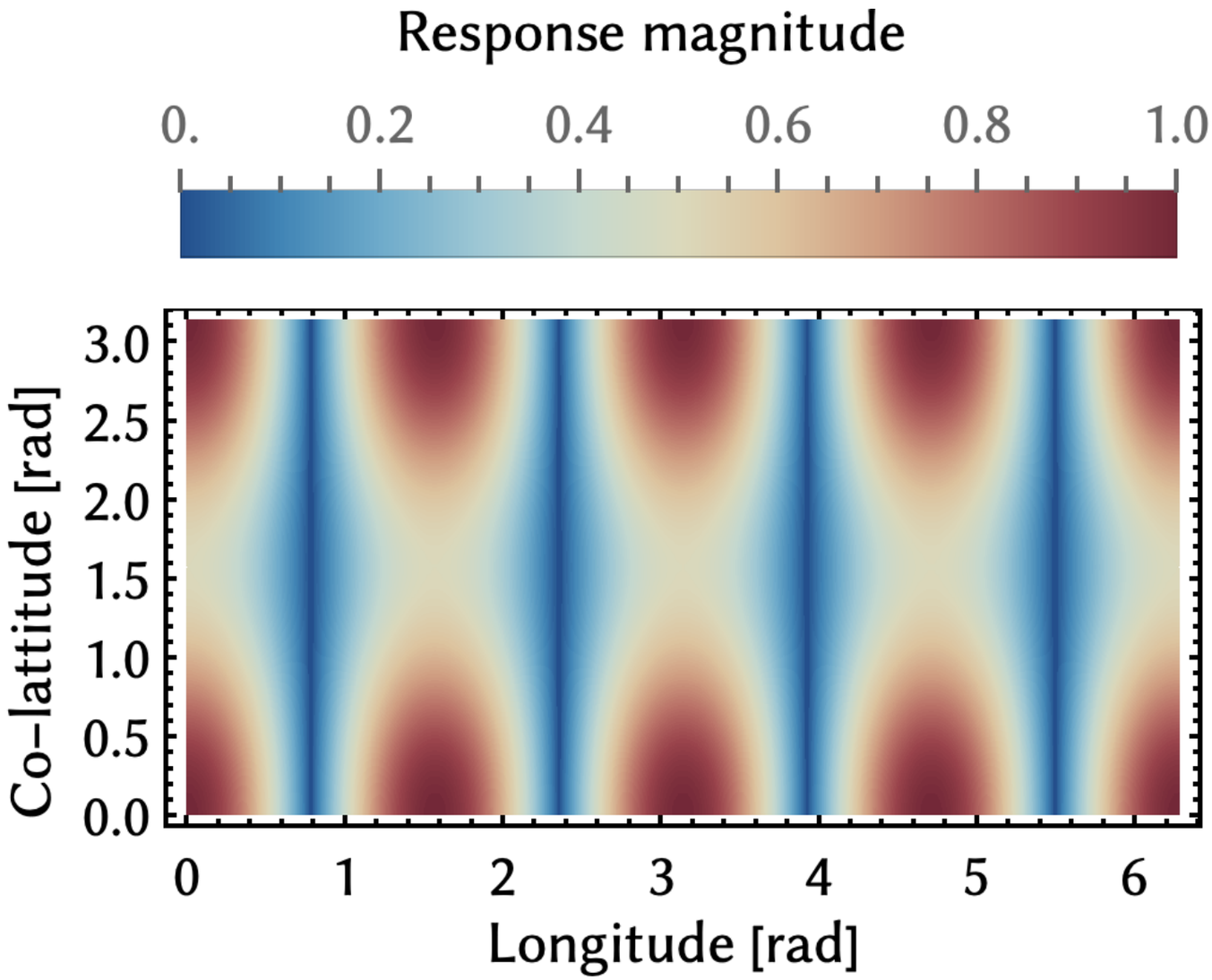


Antenna pattern

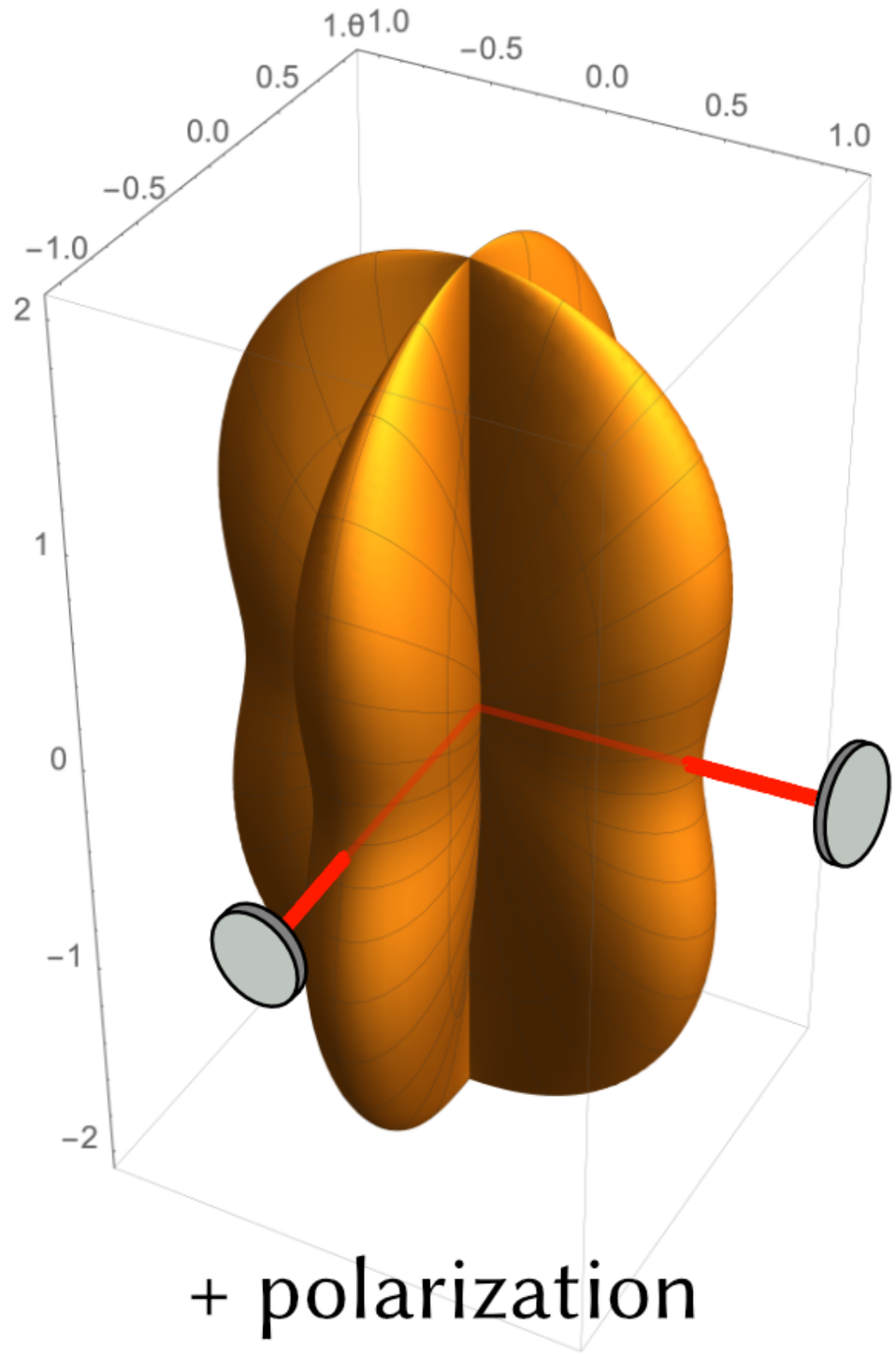


+ polarization

GW response

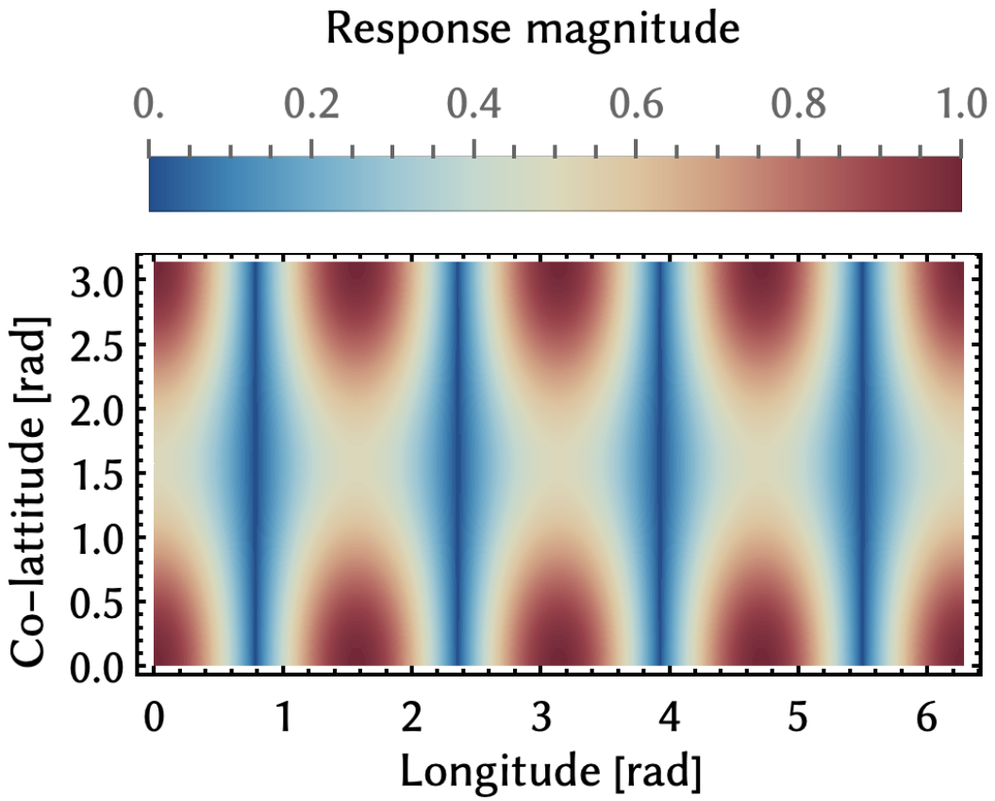


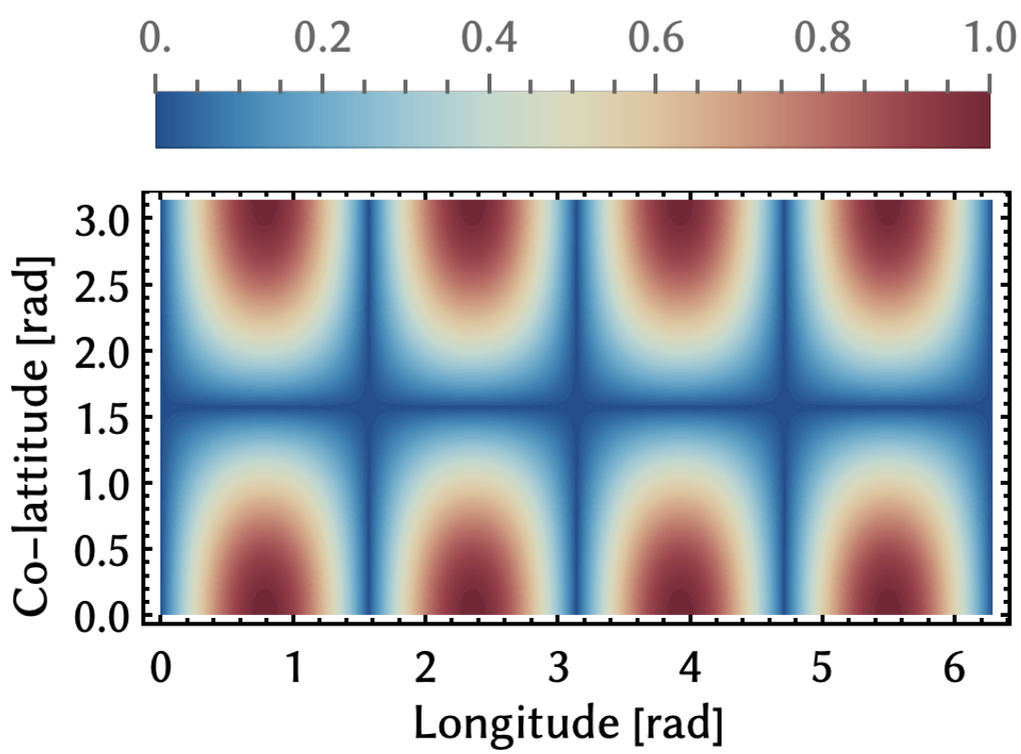
Antenna pattern



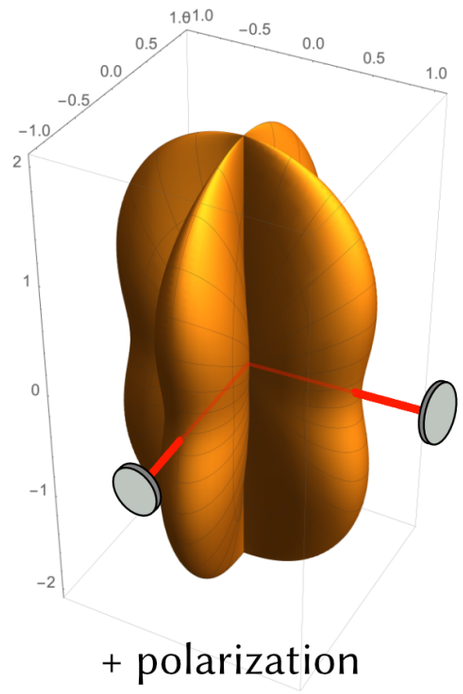
+ polarization

GW response

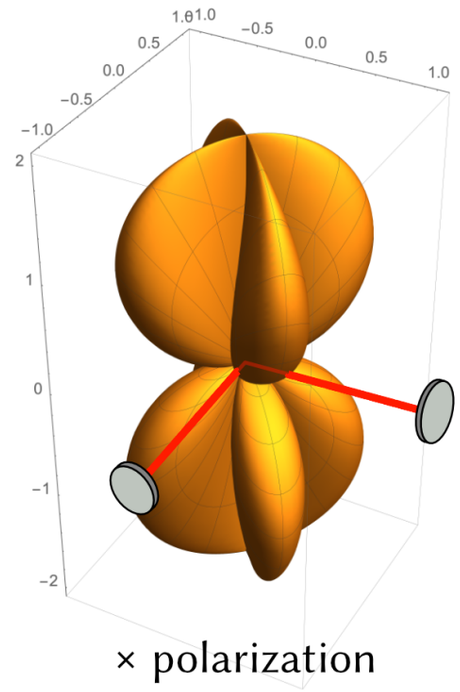




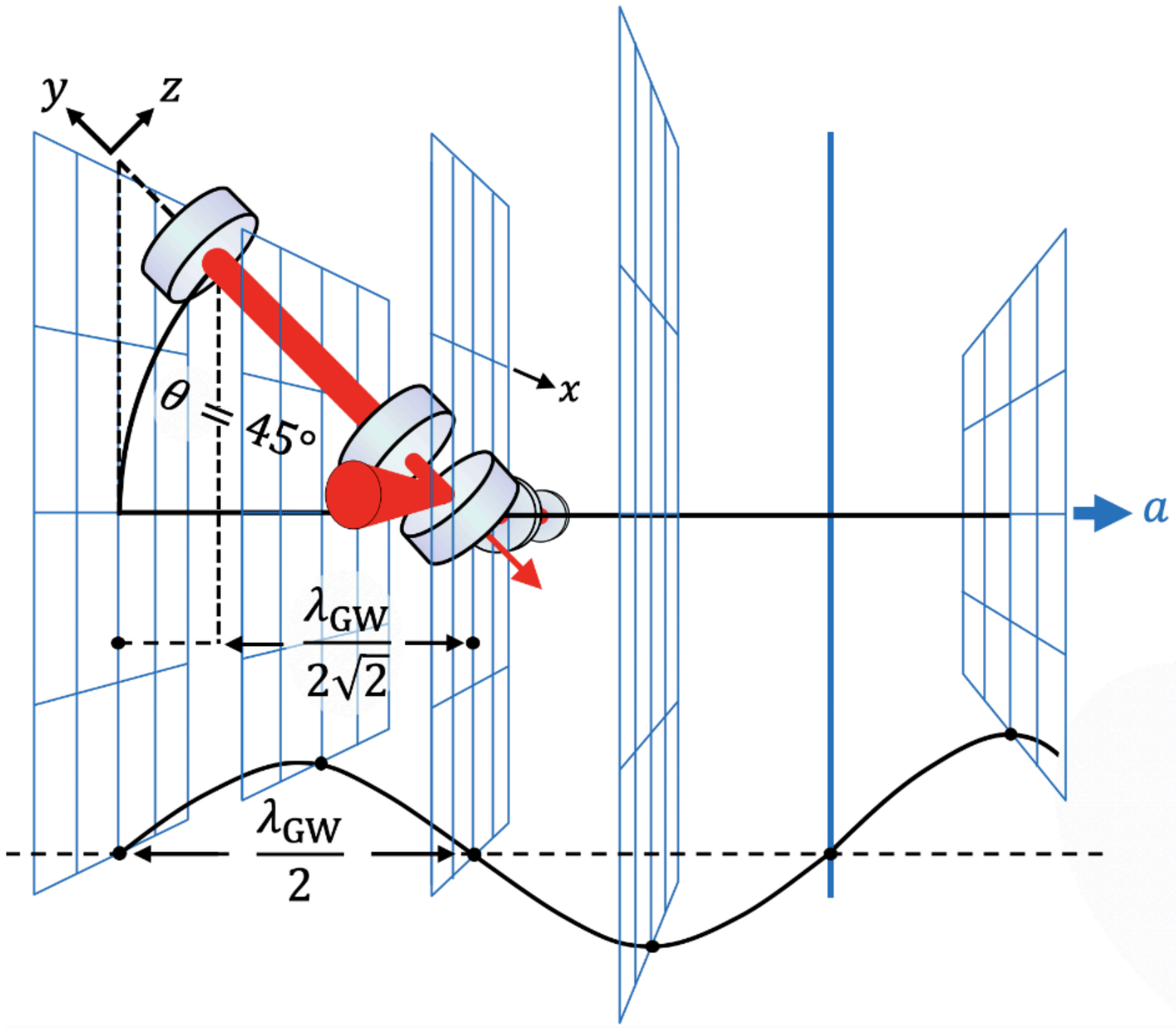
Antenna pattern

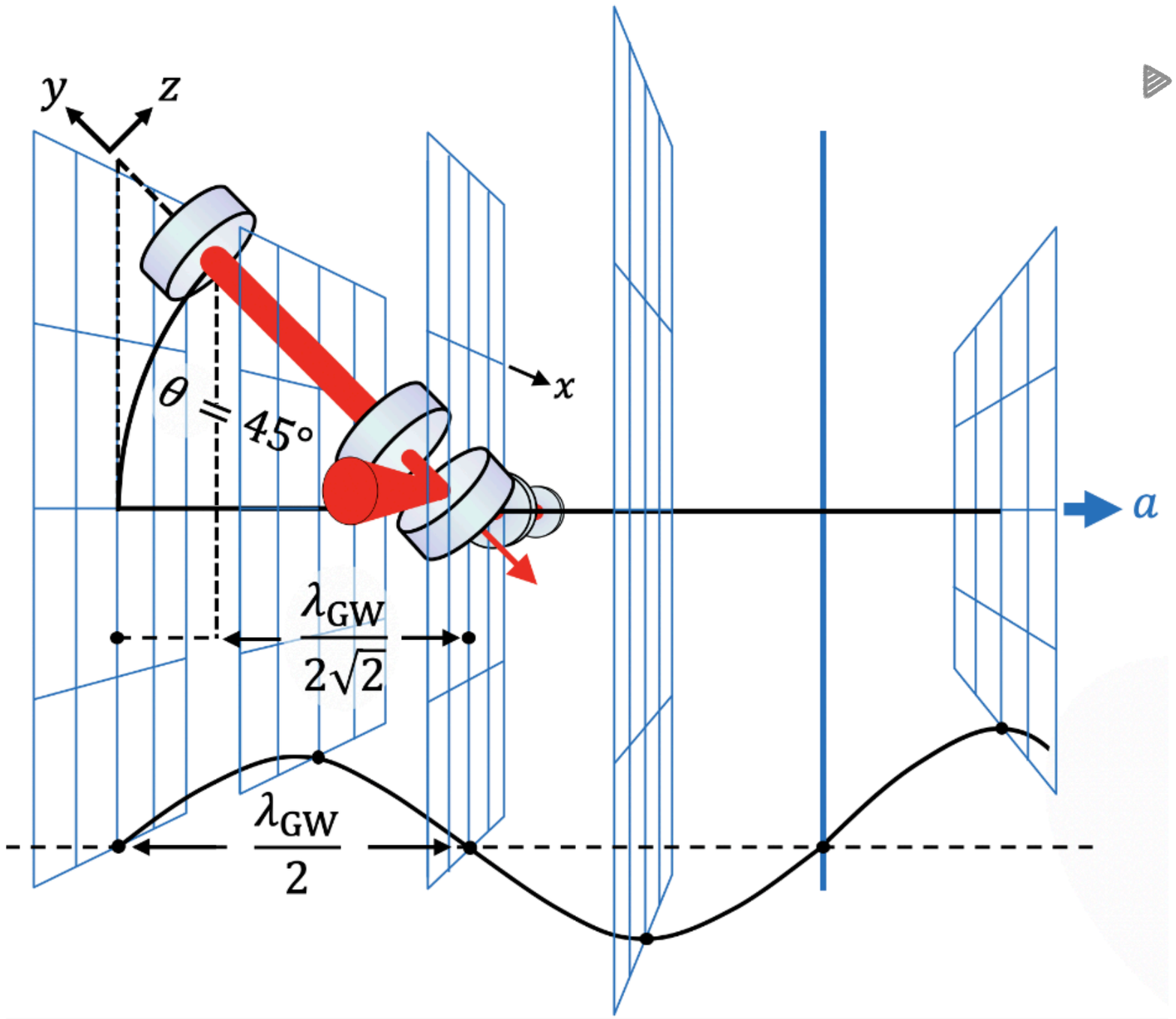


+ polarization

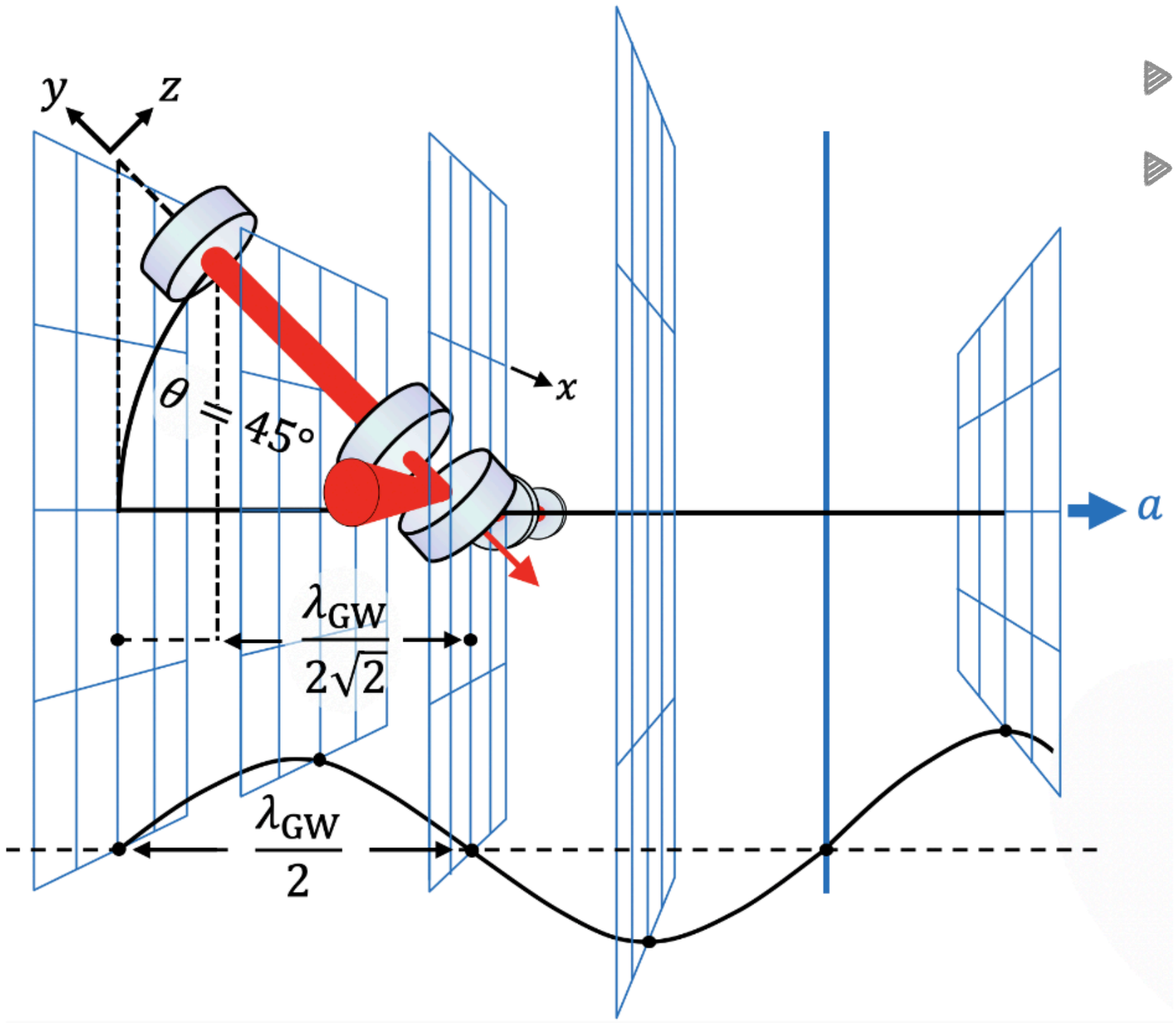


× polarization

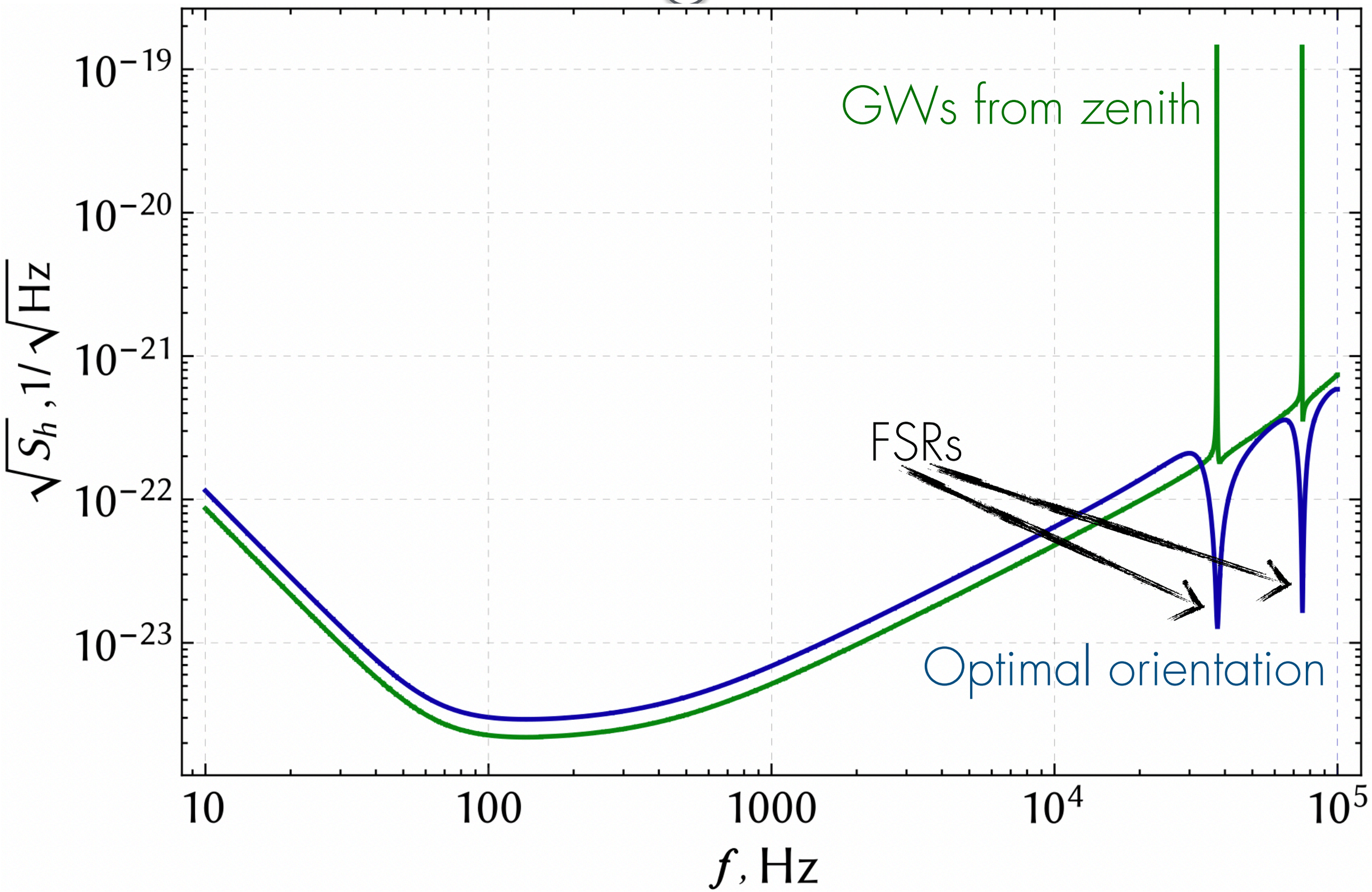

y
z
x
θ
45°
a
λGW
2√2
λGW
2



- x-arm senses no signal

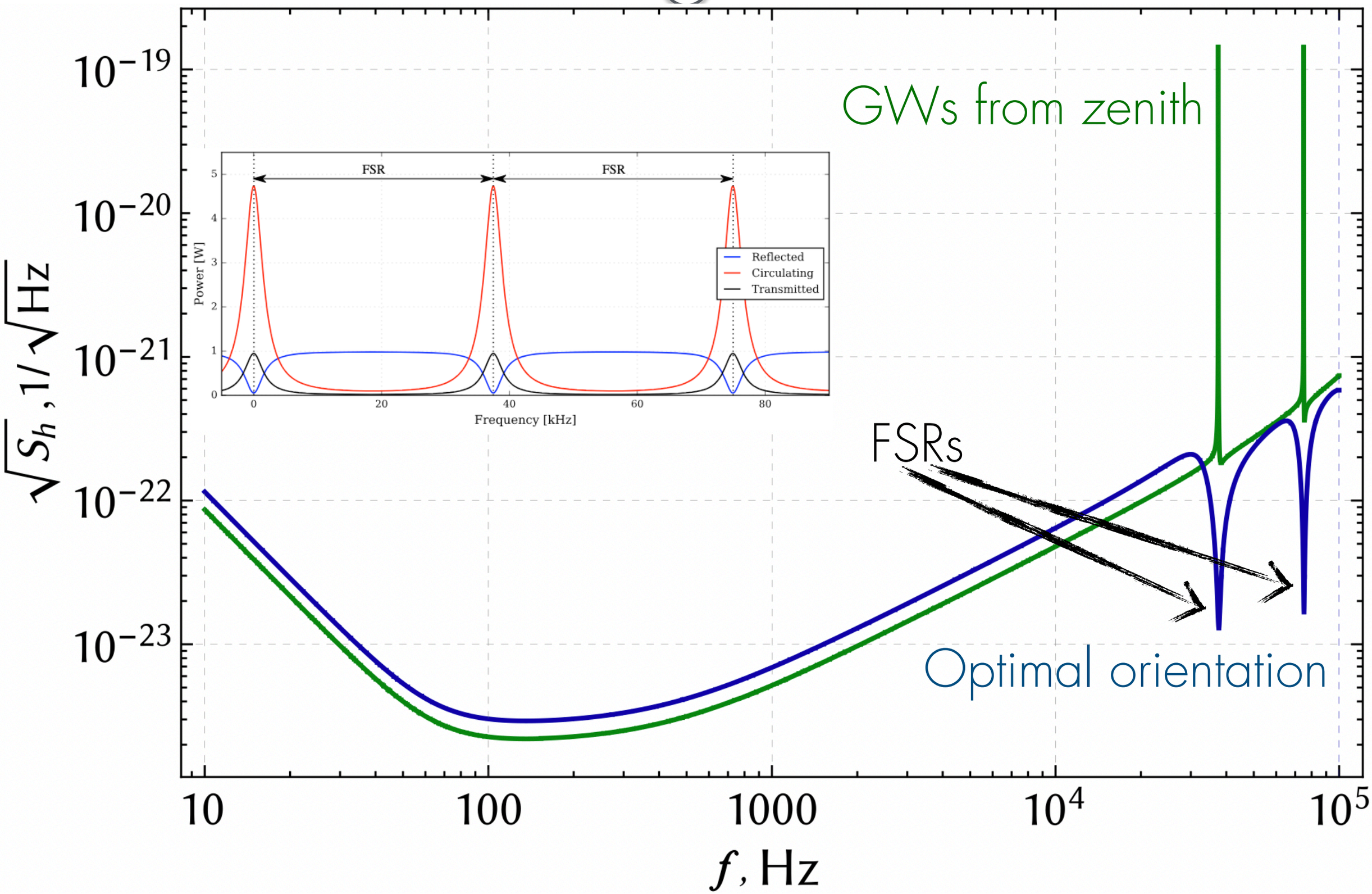


- x-arm senses no signal
- y-arm does sense signal, since effective arm length is shorter!

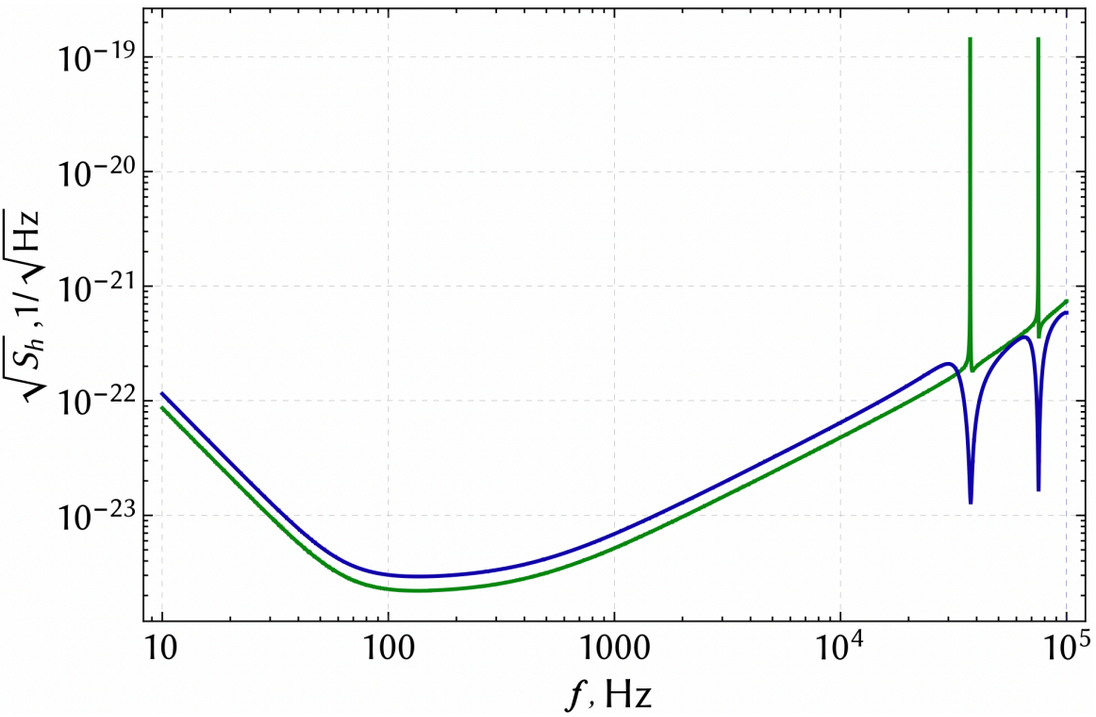

GWs from zenith
FSRs
Optimal orientation
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
$\sqrt{S_h}$, 1/$\sqrt{\text{Hz}}$
10
100
1000
10^4
10^5
f, Hz

GW response

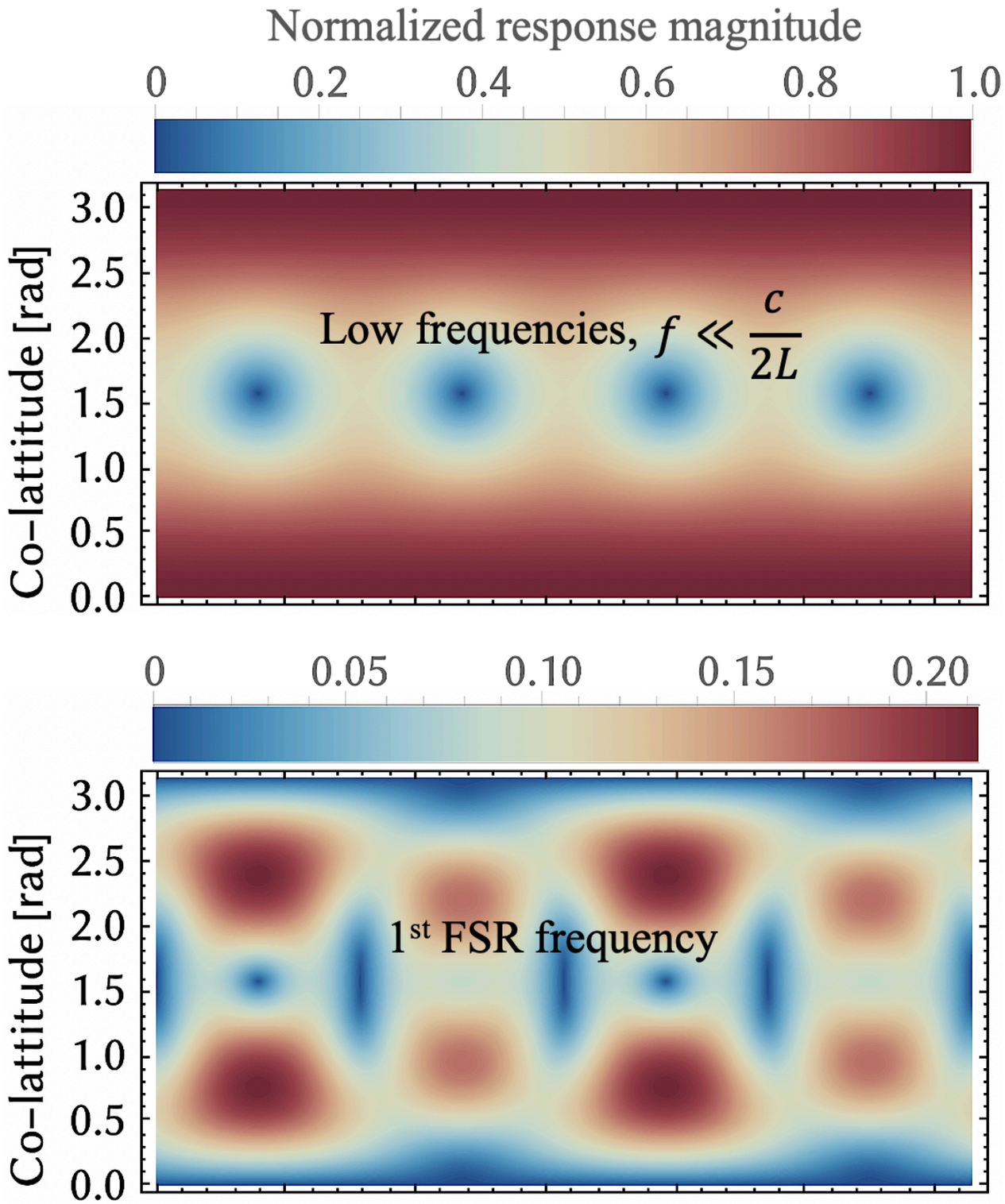
First FSR



GW response



First FSR



GW response

A well-known (in narrow circles) effect, e.g.

Classical and Quantum Gravity

High-frequency corrections to the detector response and their effect on searches for gravitational waves

M Rakhmanov, J D Romano and J T Whelan

Published 2 September 2008 • 2008 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 25, Number 18

Citation M Rakhmanov *et al* 2008 *Class. Quantum Grav.* **25** 184017

DOI 10.1088/0264-9381/25/18/184017

Physical Review D

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Frequency-dependent responses in third generation gravitational-wave detectors

Reed Essick[1,2], Salvatore Vitale[1,2], and Matthew Evans[1,2]

Show more

Phys. Rev. D **96**, 084004 – **Published 3 October, 2017**

DOI: https://doi.org/10.1103/PhysRevD.96.084004

A well-known (in narrow circles) effect, e.g.

Our methodological paper (arXiv: 2409.03019)

Optical sensitivities of current gravitational wave observatories at higher kHz, MHz and GHz frequencies

R. Schnabel*[1] and M. Korobko[1]

[1] *Institut für Quantenphysik & Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

Outline

1. Introduction to GW detection
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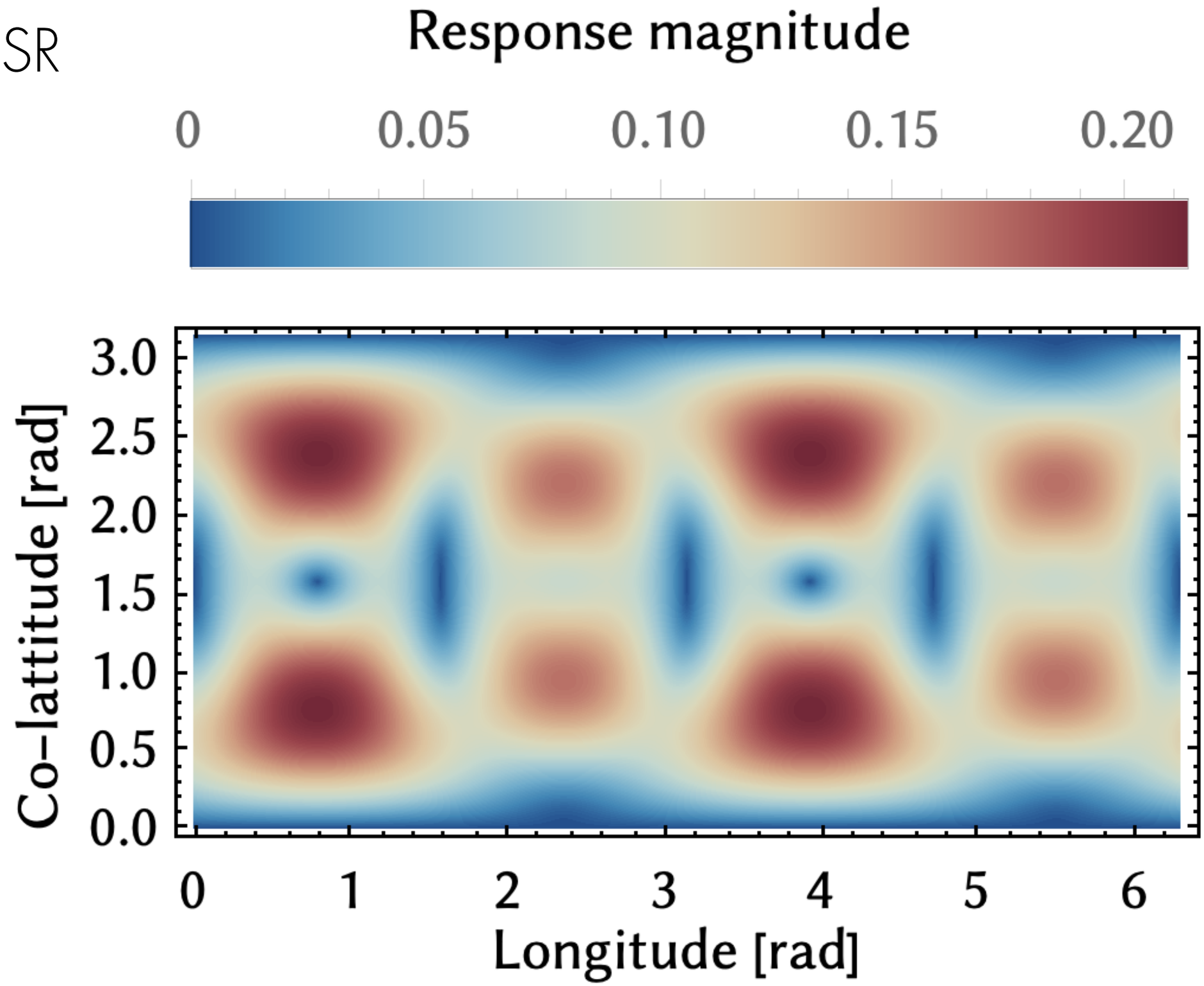
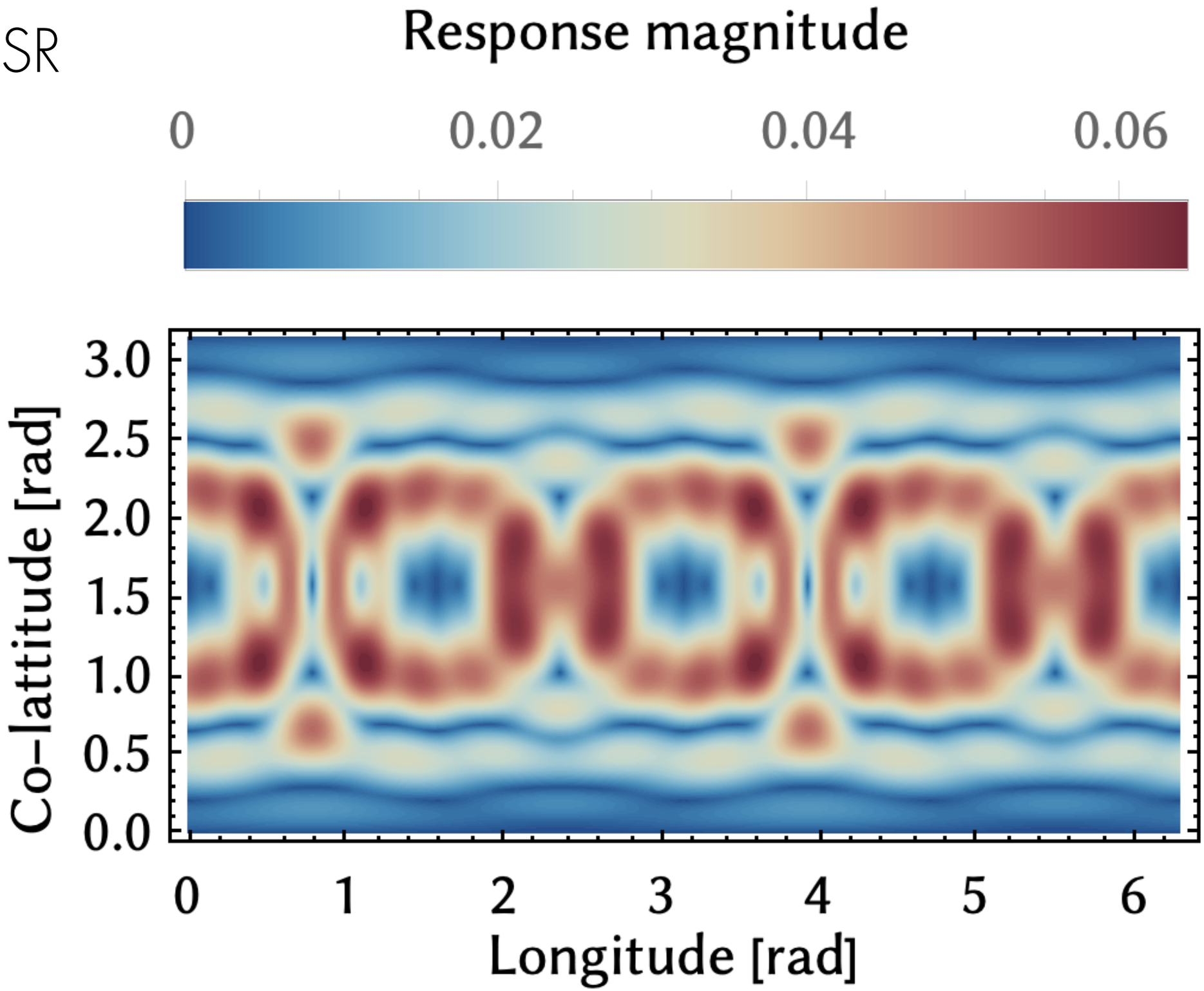
3. Into the deep: how GWDs really work
4. Response of the detectors to high-frequency GWs
5. Challenges & perspectives

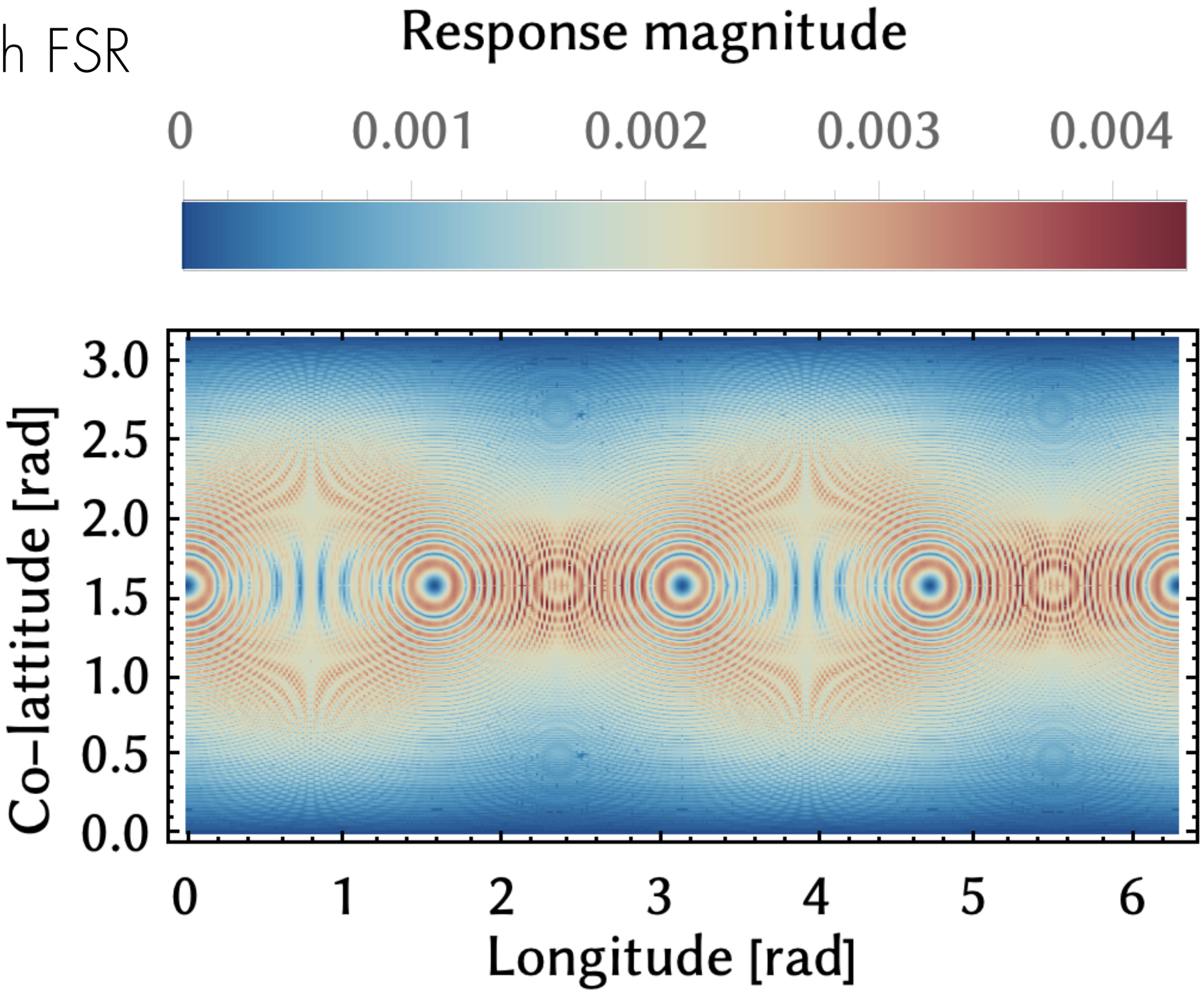
1st FSR


Response magnitude
0
0.05
0.10
0.15
0.20
Co-lattitude [rad]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Longitude [rad]

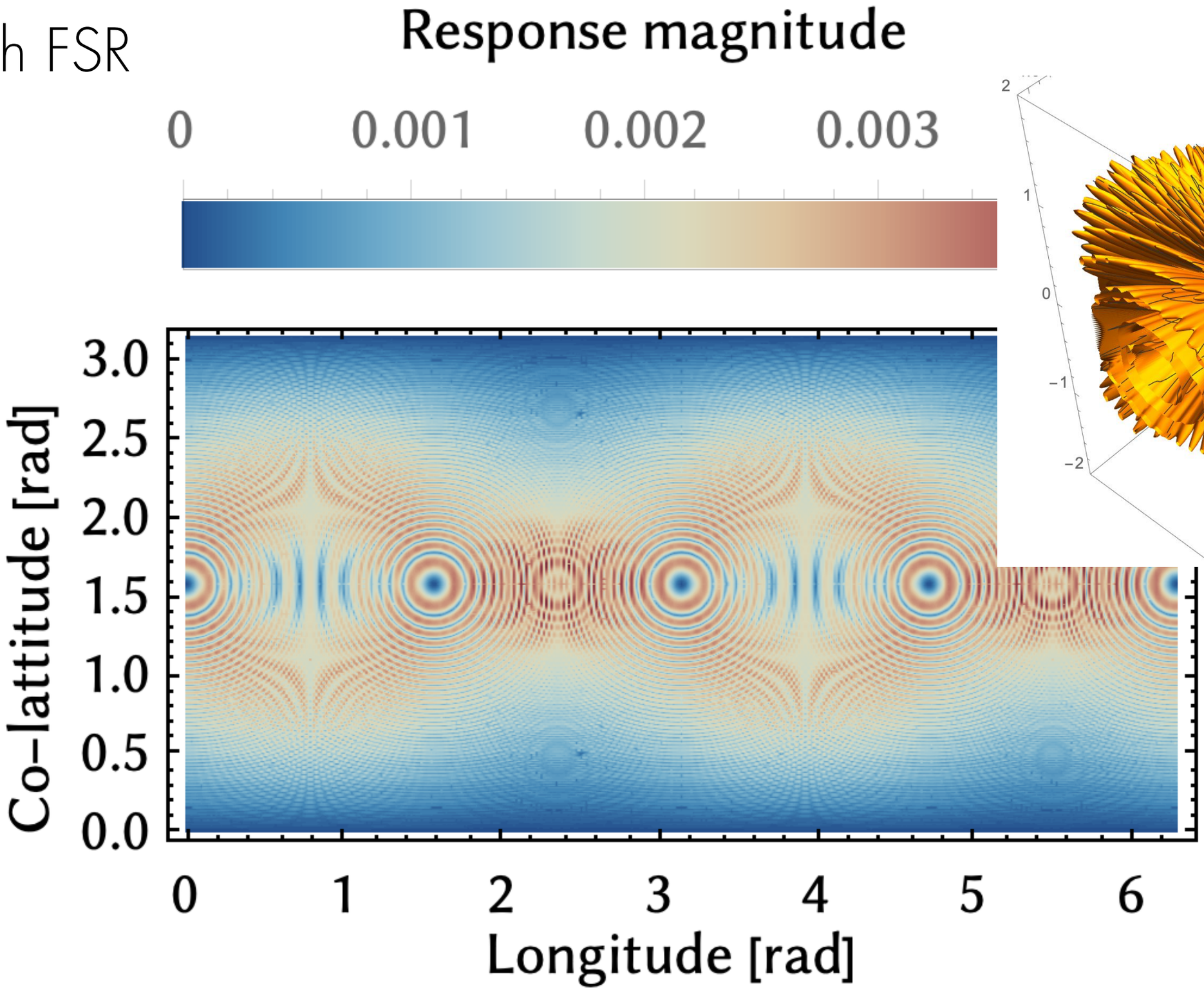
5th FSR

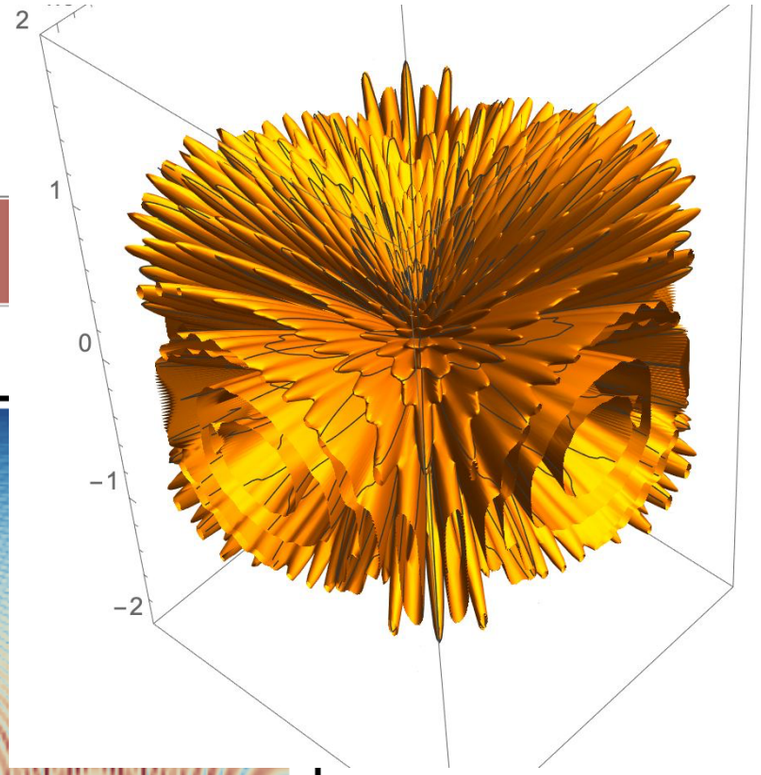

Response magnitude
0
0.02
0.04
0.06
Co–lattitude [rad]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Longitude [rad]

100th FSR

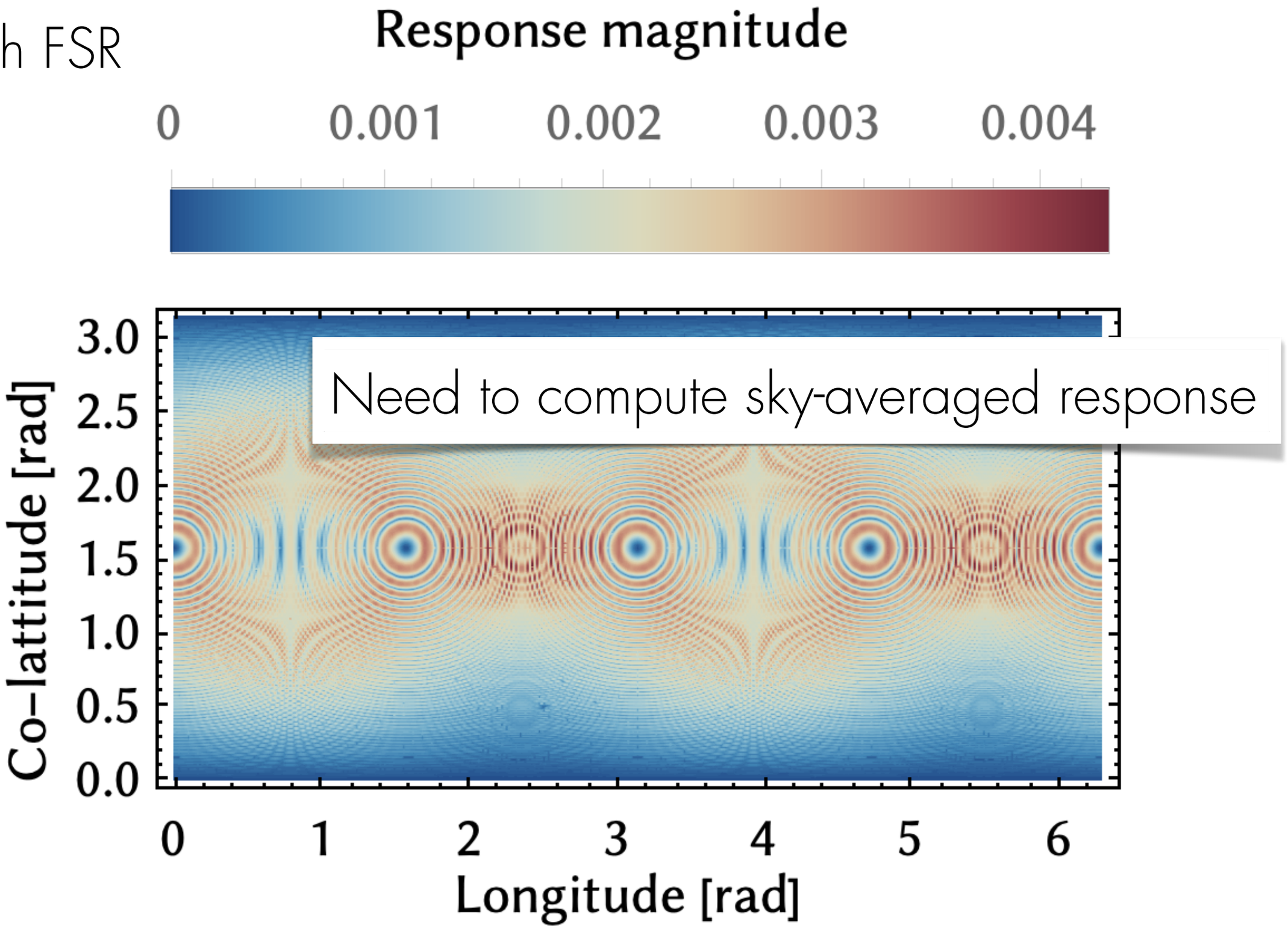

Response magnitude
0
0.001
0.002
0.003
0.004
Co-lattitude [rad]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Longitude [rad]

100th FSR


Response magnitude
0
0.001
0.002
0.003
Co-lattitude [rad]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Longitude [rad]

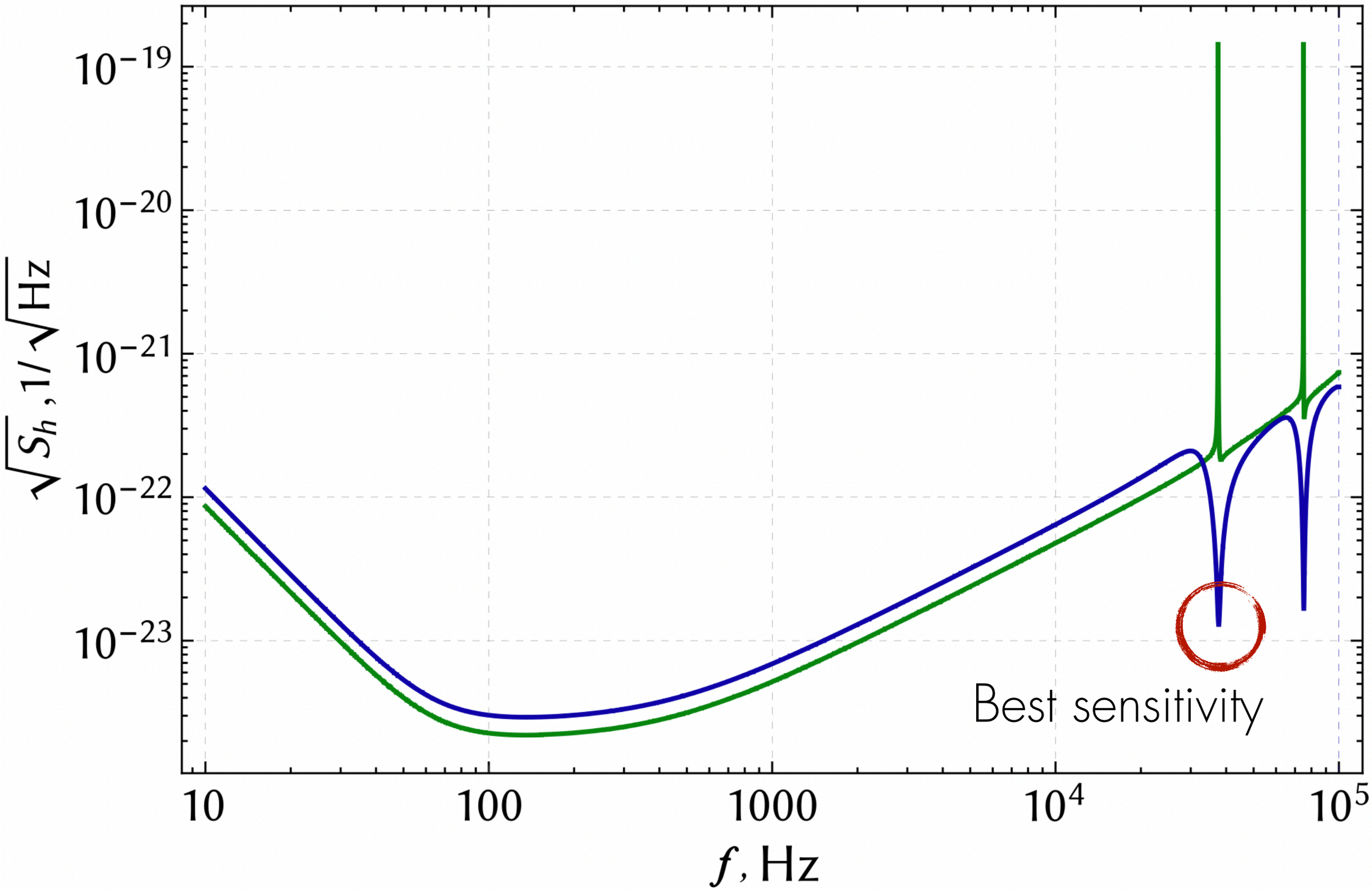

2
1
0
−1
−2

100th FSR



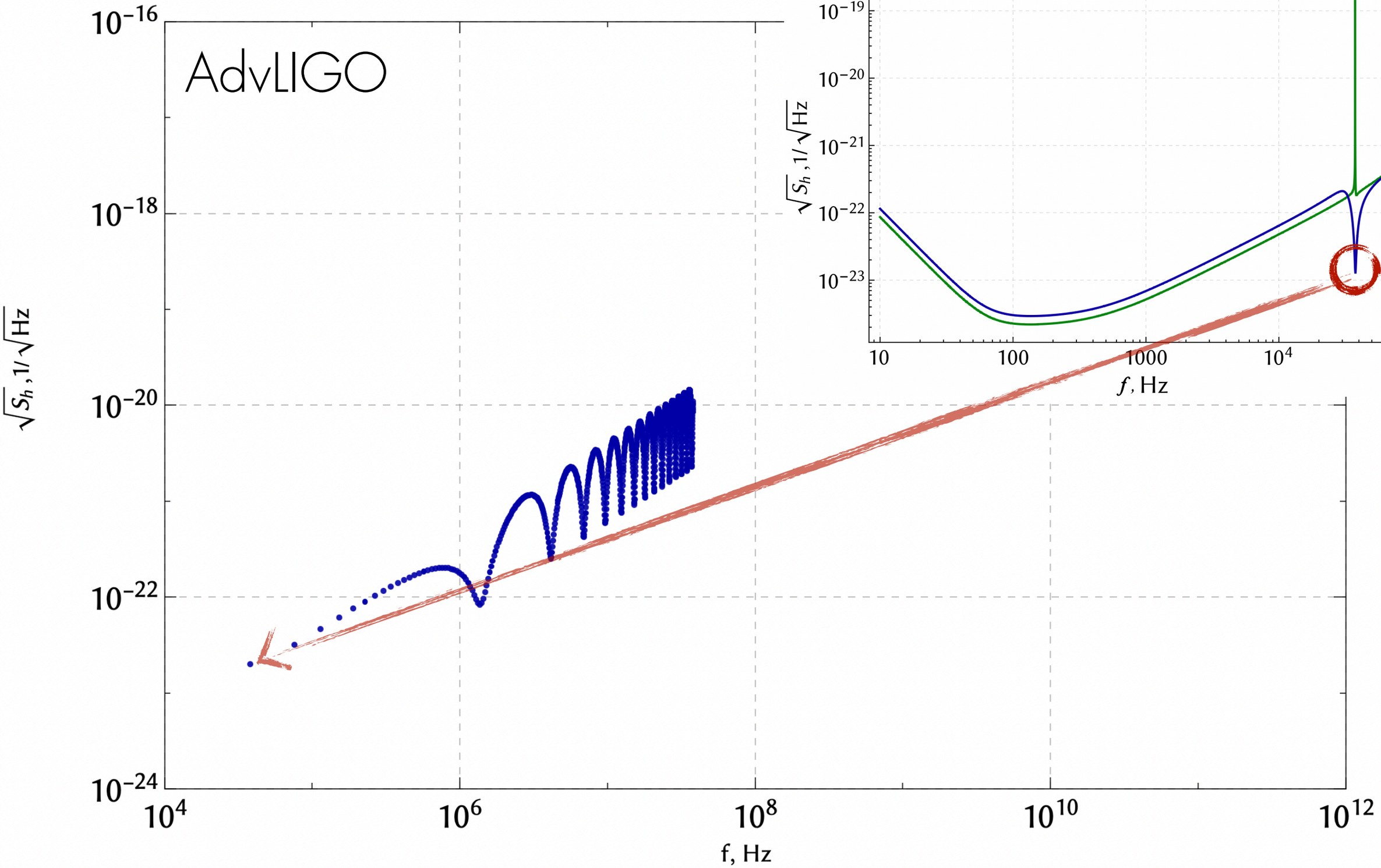
Need to compute sky-averaged response

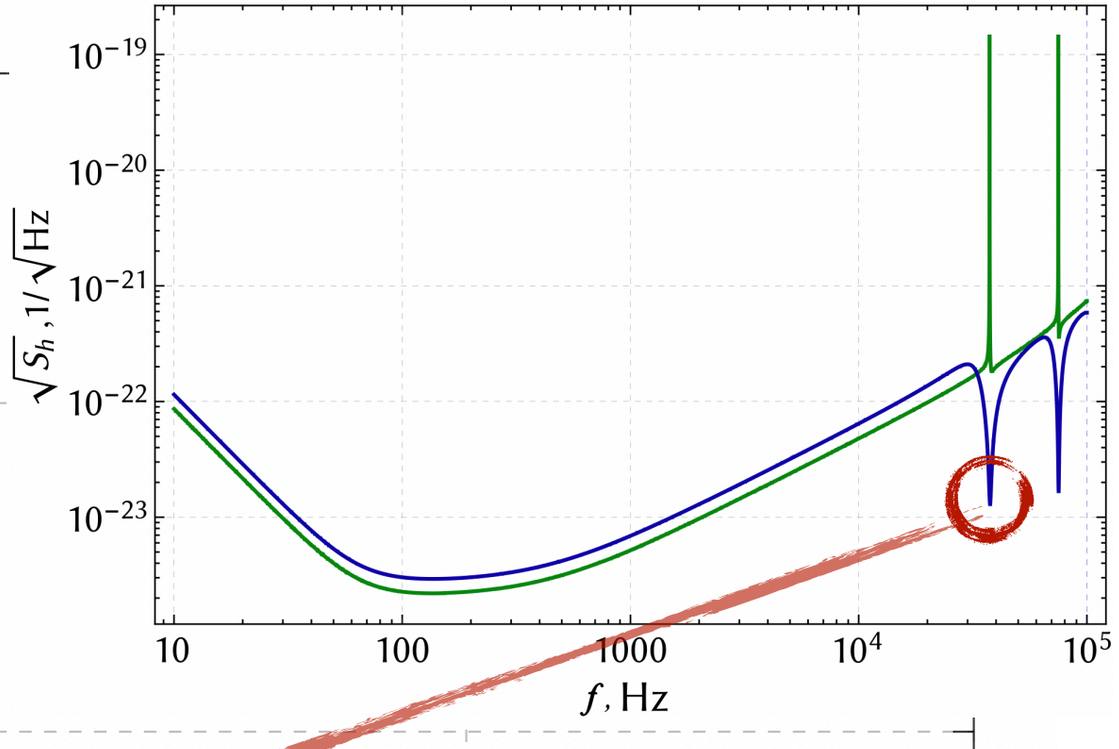
Sensitivity comb

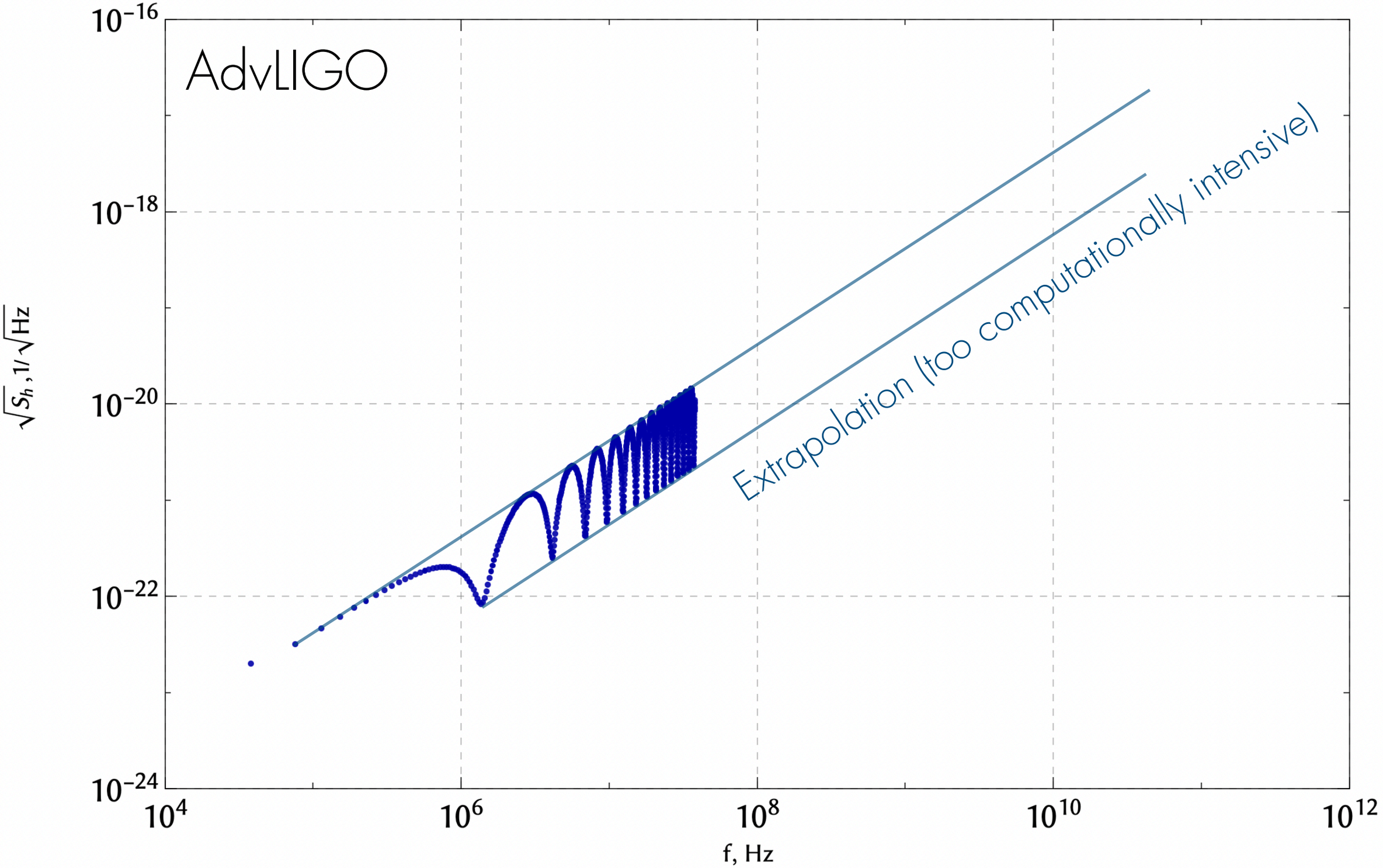


HF GWs

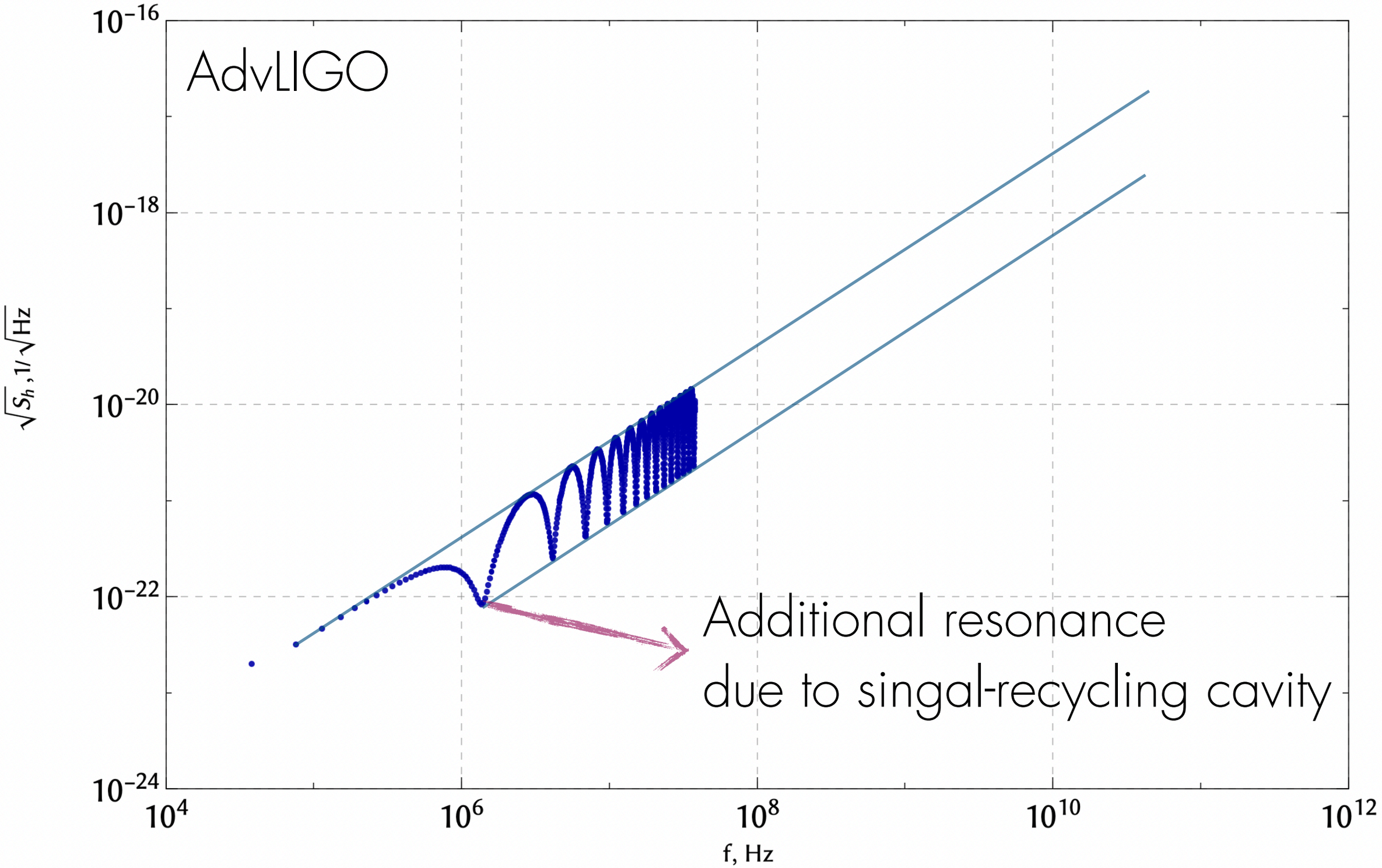
Sensitivity comb

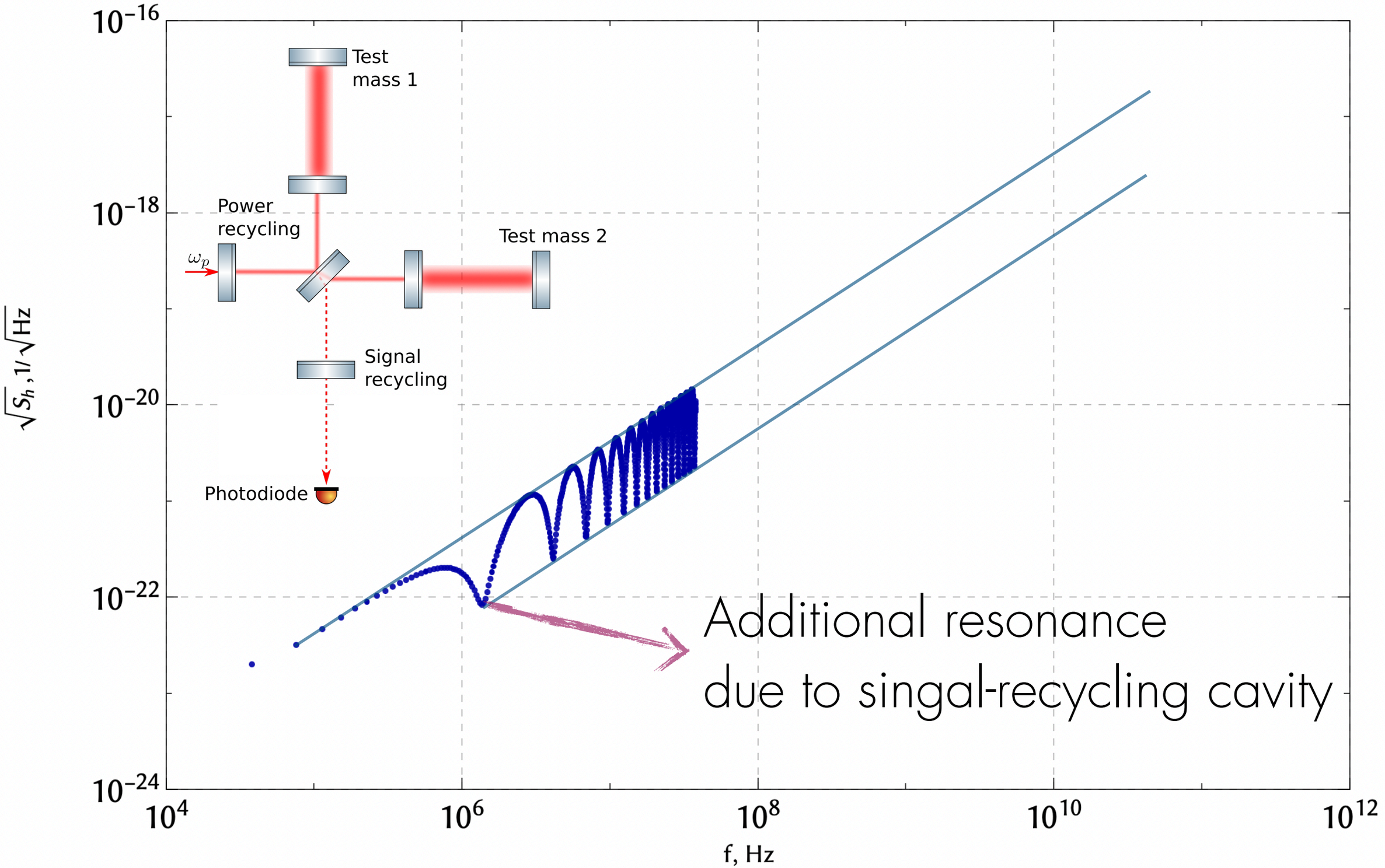


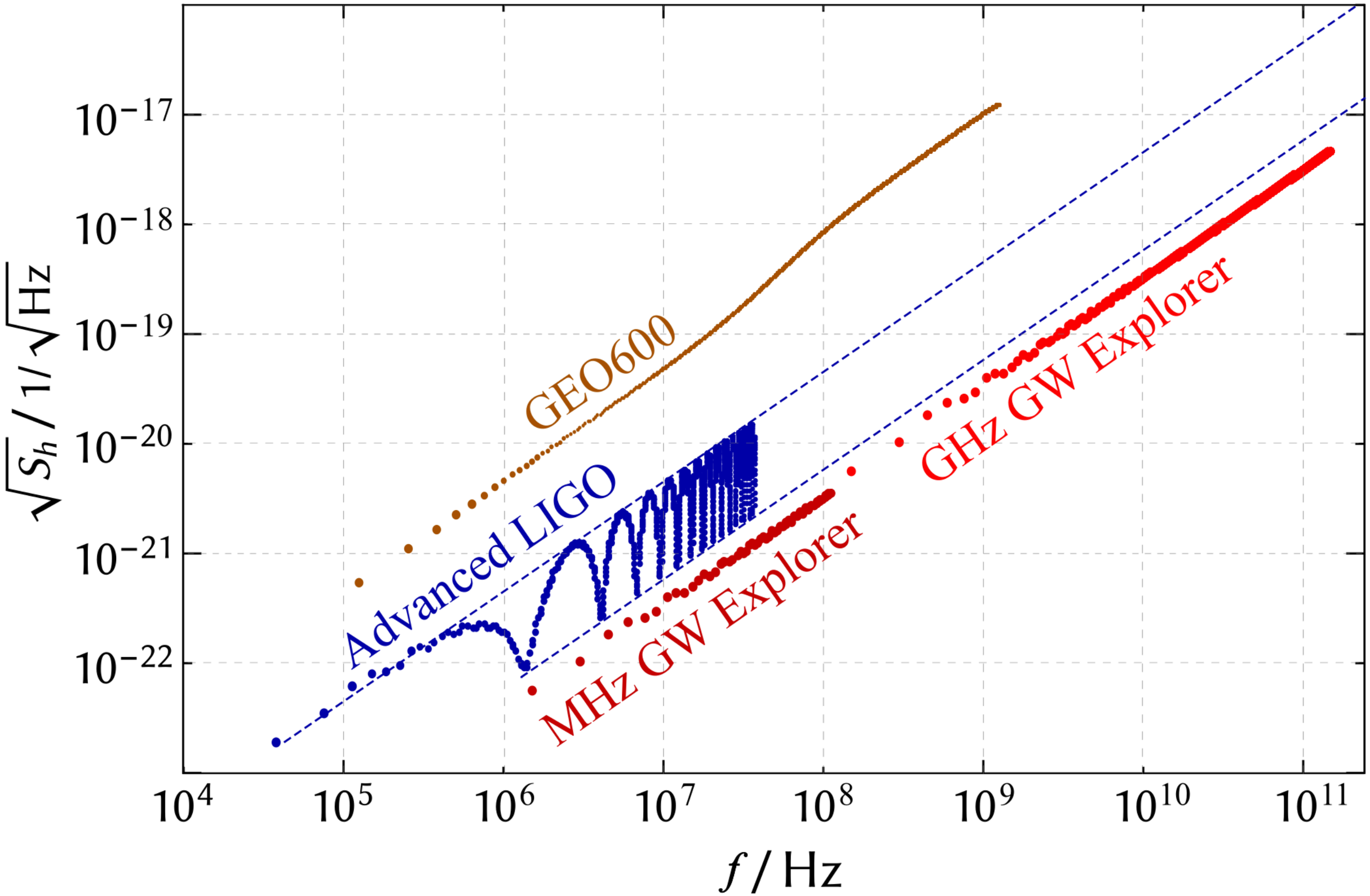


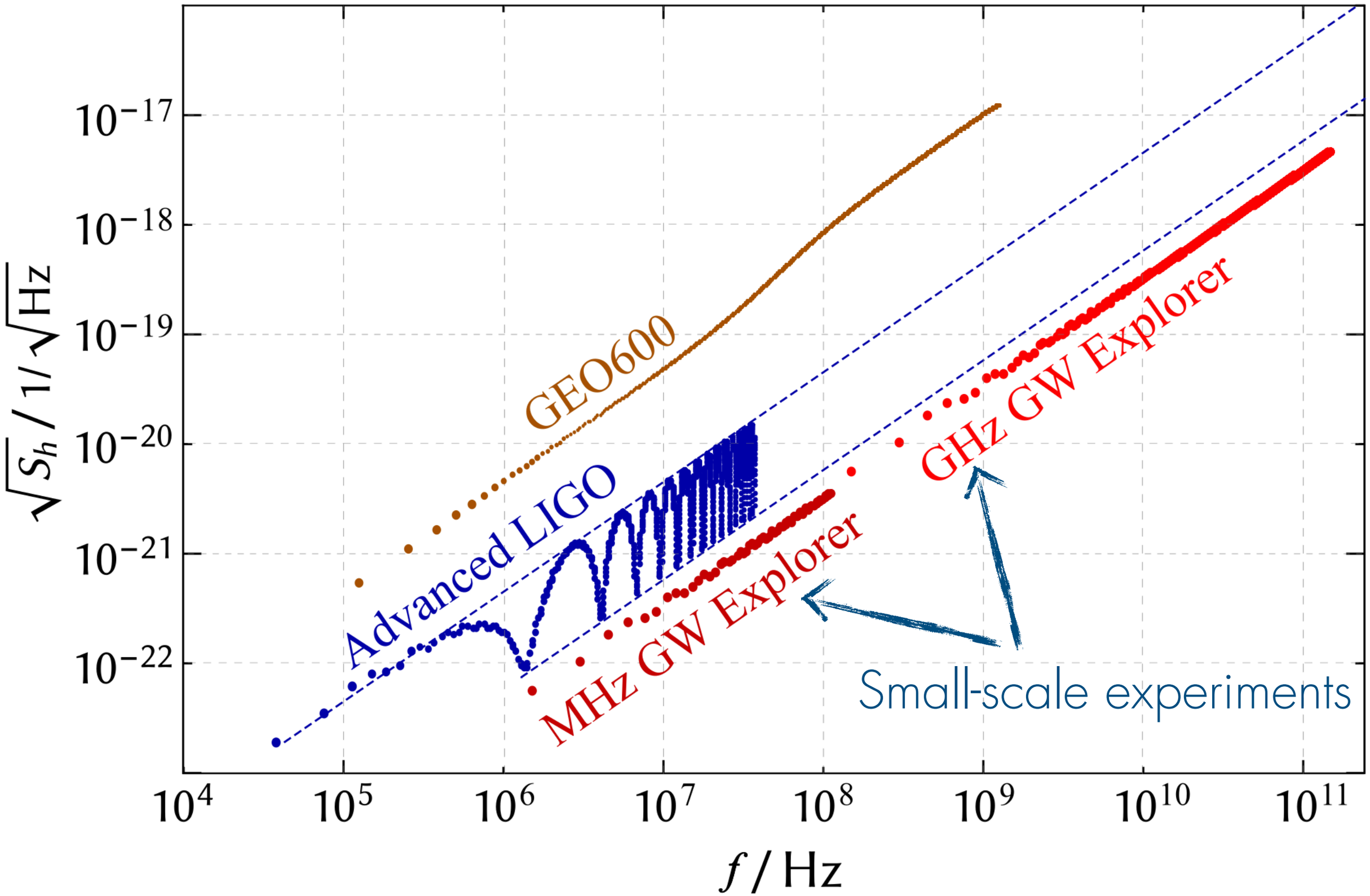

AdvLIGO
Extrapolation (too computationally intensive)
$\sqrt{S_h}, 1/\sqrt{\text{Hz}}$
f, Hz
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}

Sensitivity comb



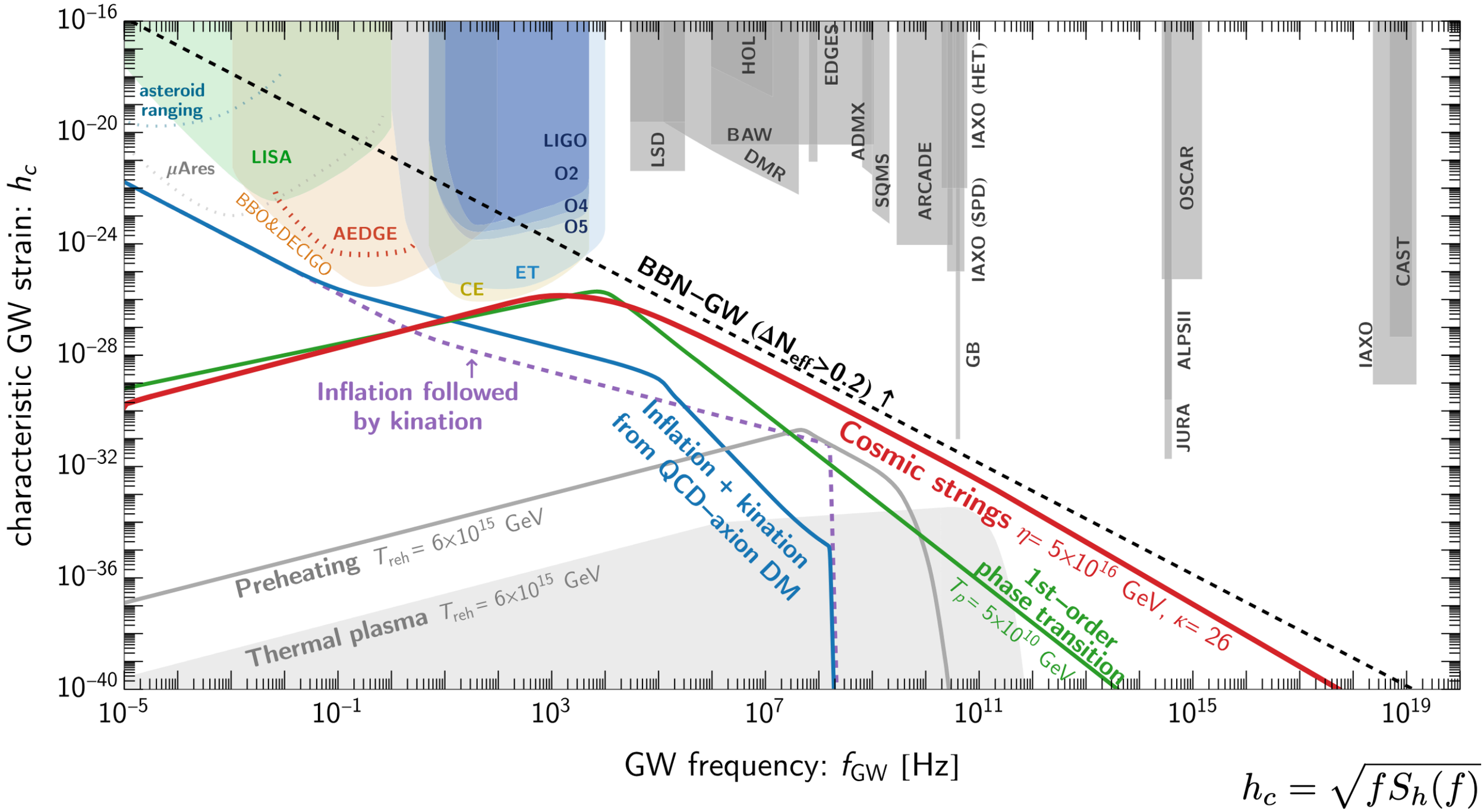

Test mass 1
Power recycling
ω_p
Test mass 2
Signal recycling
Photodiode
$\sqrt{S_h}$, 1/$\sqrt{\text{Hz}}$
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^4
10^6
10^8
10^{10}
10^{12}
f, Hz
Additional resonance
due to singal-recycling cavity


10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
$\sqrt{S_h}$ / 1/$\sqrt{\text{Hz}}$
GEO600
Advanced LIGO
MHz GW Explorer
GHz GW Explorer
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
f / Hz


$\sqrt{S_h}$ / 1/$\sqrt{\text{Hz}}$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
GEO600
Advanced LIGO
MHz GW Explorer
GHz GW Explorer
Small-scale experiments
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
f / Hz

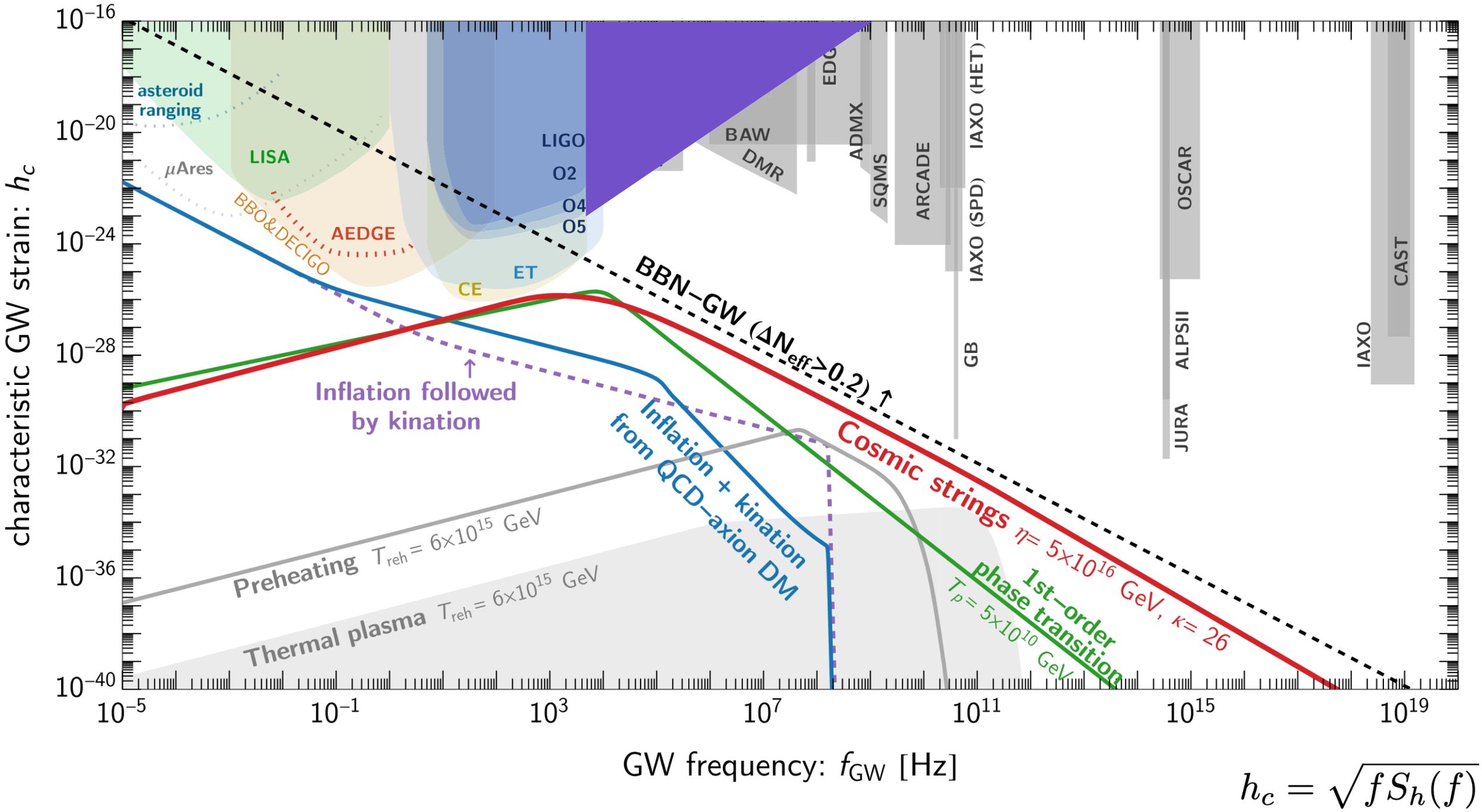
HF GWs

General sensitivity



$$h_c = \sqrt{f S_h(f)}$$

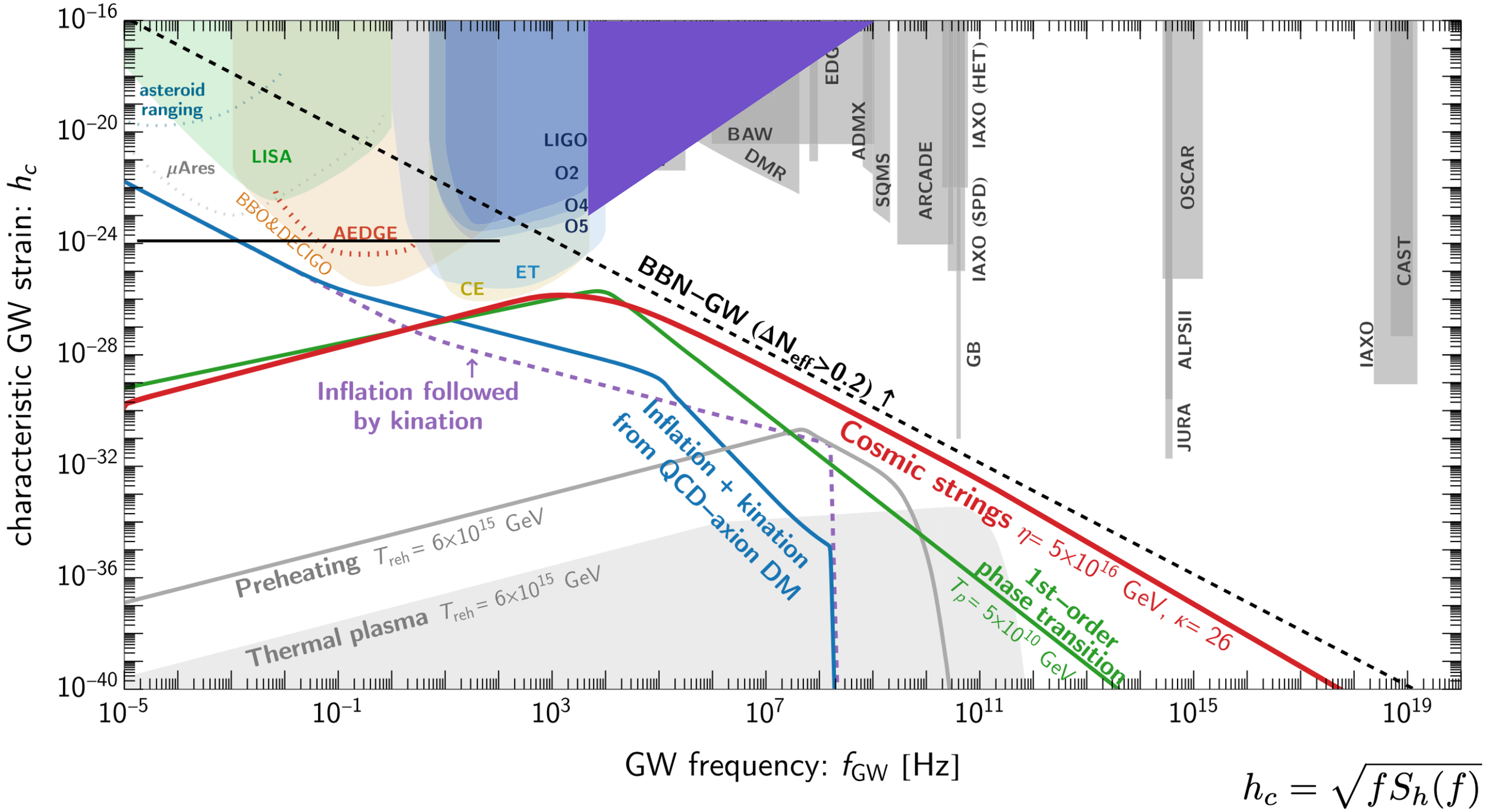
(approximate) scaling of the sensitivity w/o integration



$$h_c = \sqrt{f S_h(f)}$$

General sensitivity

(approximate) scaling of the sensitivity w/o integration with years of averaging, can be substantially lower



$$h_c = \sqrt{f S_h(f)}$$

Outline

1. Introduction to GW detection
2. Status of current GW detectors
3. Into the deep: how GWDs really work
4. Response of the detectors to high-frequency GWs
5. Challenges & perspectives

Challenges

Modern detectors are already sensitive to GWs up to a GHz

Why don't we detect them?

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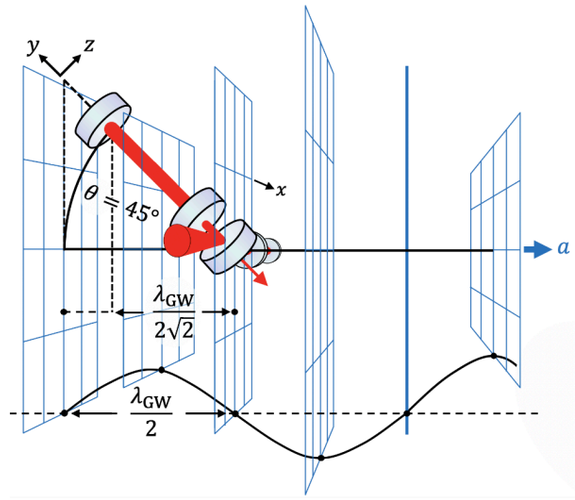
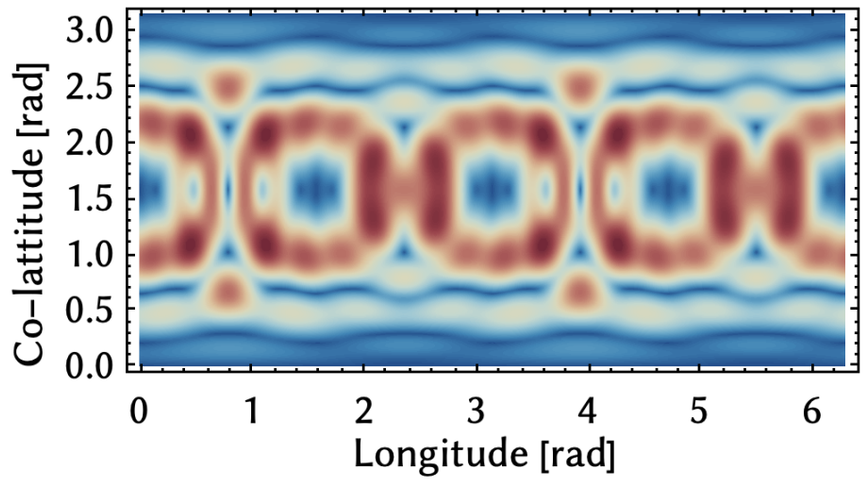
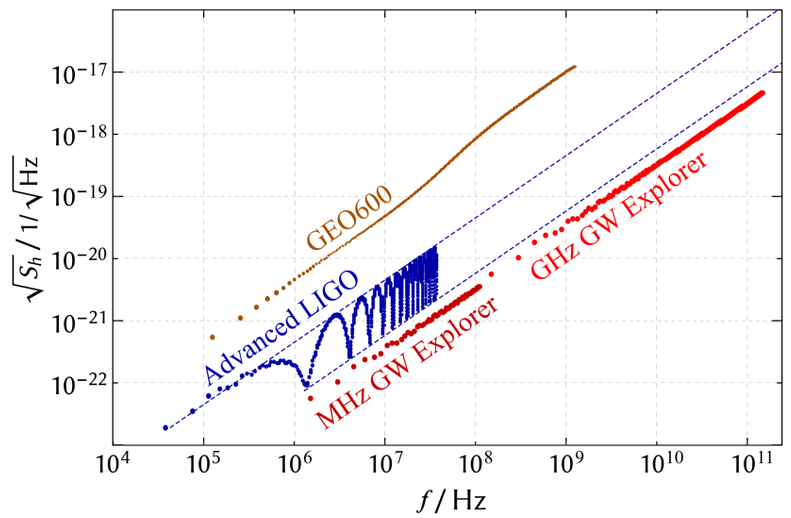
Need a convincing argument to invest time/resources into this

Conclusions

1. Modern GW detectors are developing fast







Conclusions

1. Modern GW detectors are developing fast

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   → but we need to adapt them for that
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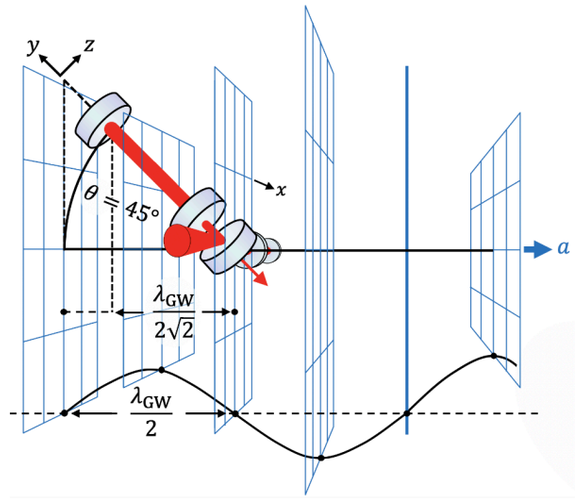

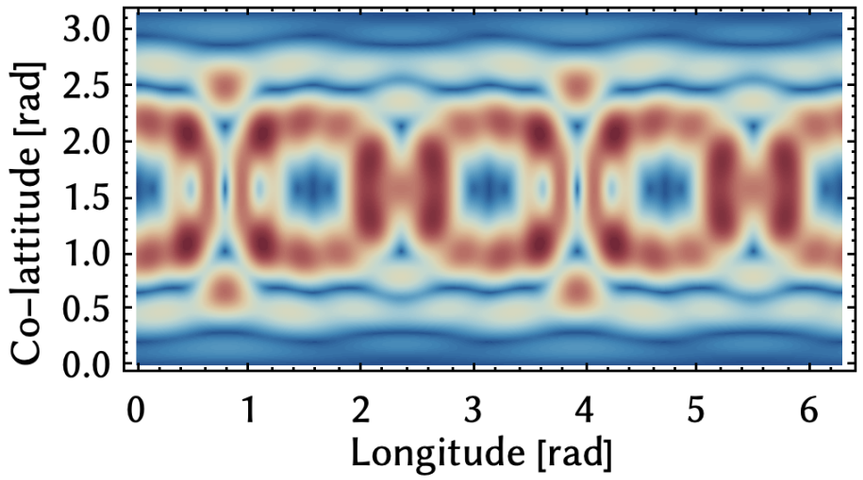

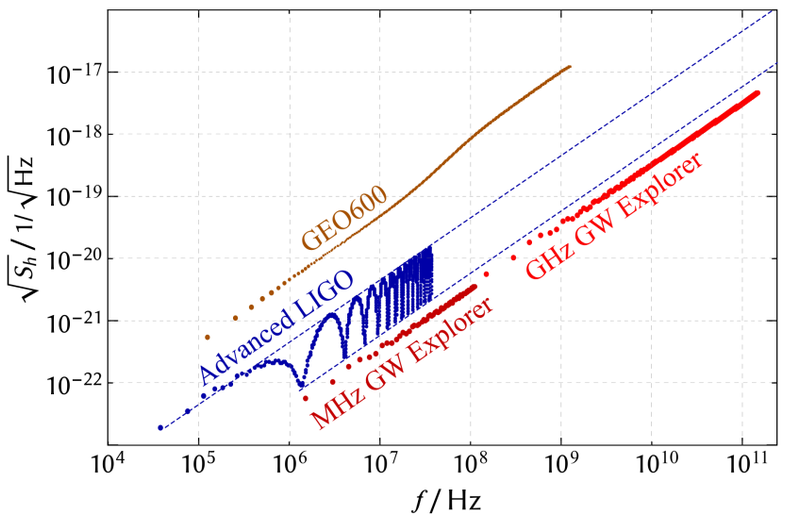

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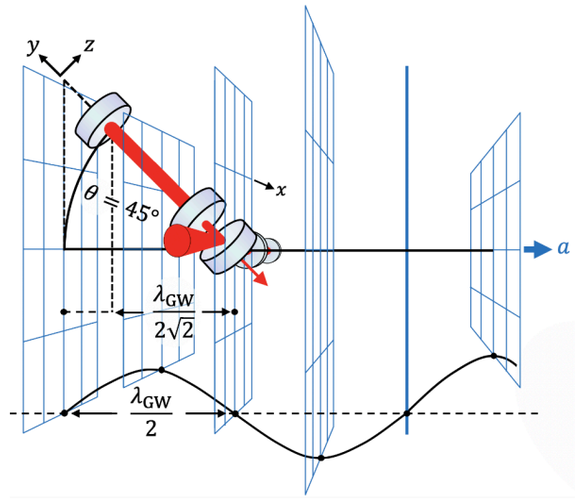
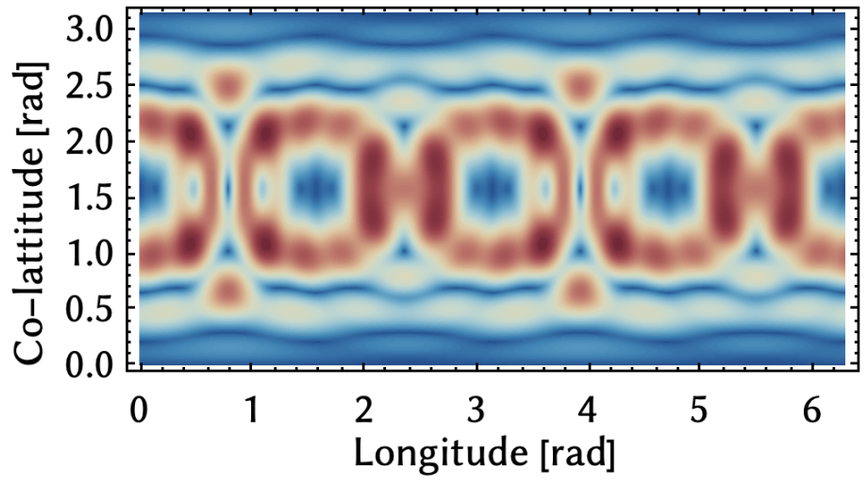
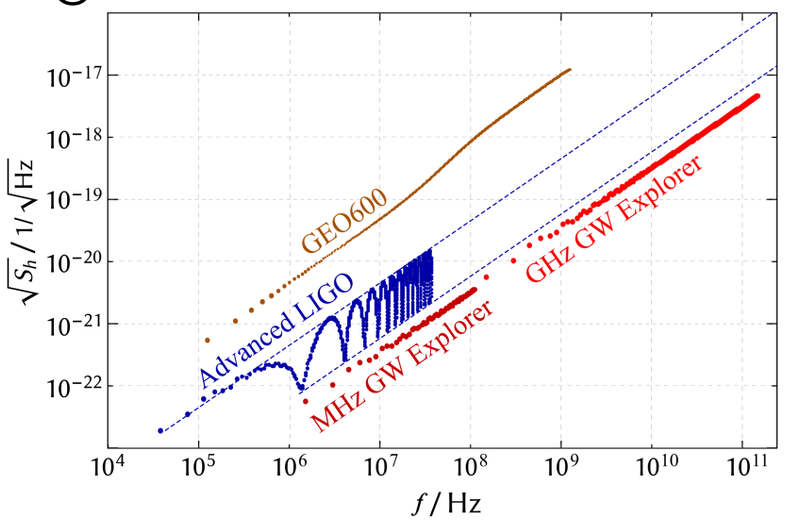
   → well-known technology
   → what is the impact on current HF detector designs?







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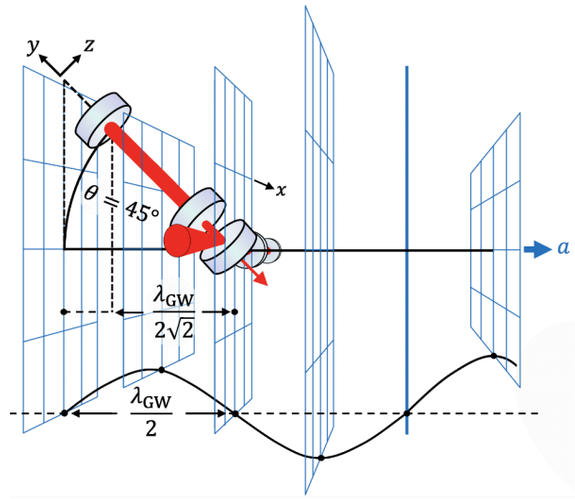

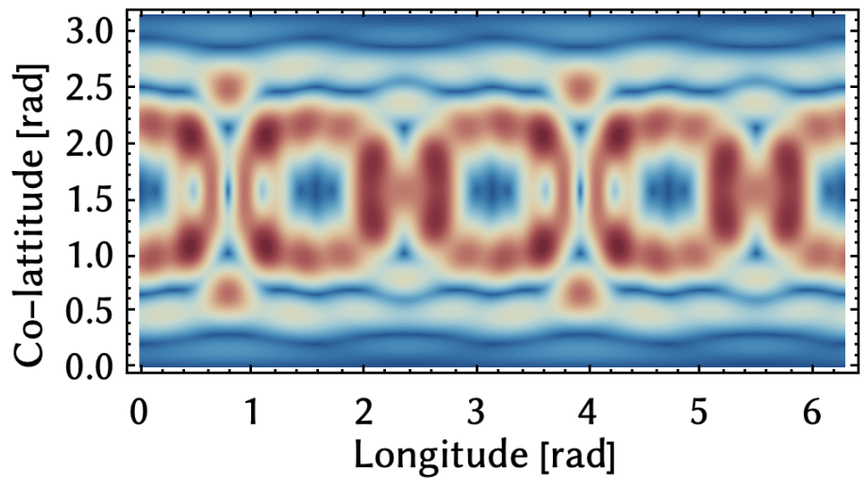

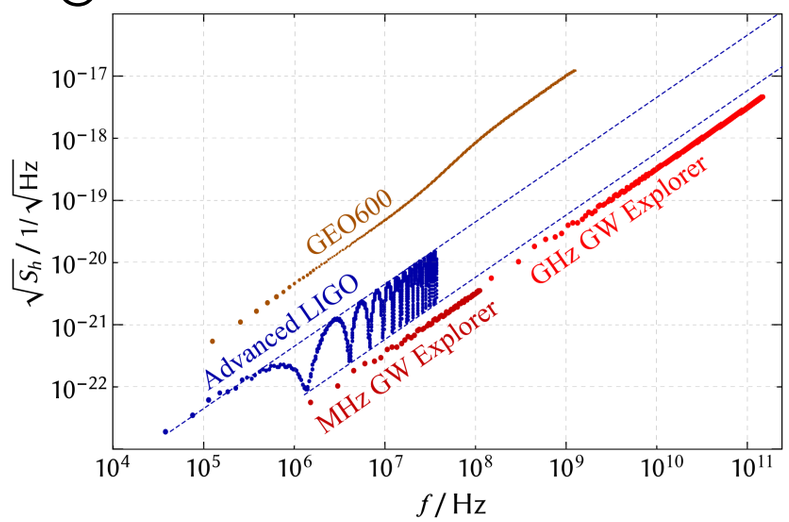

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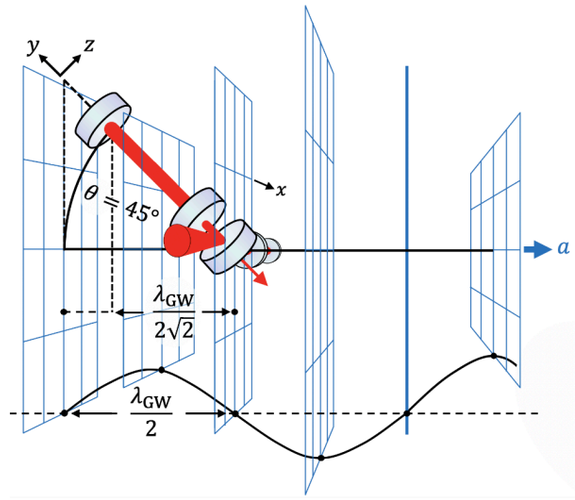

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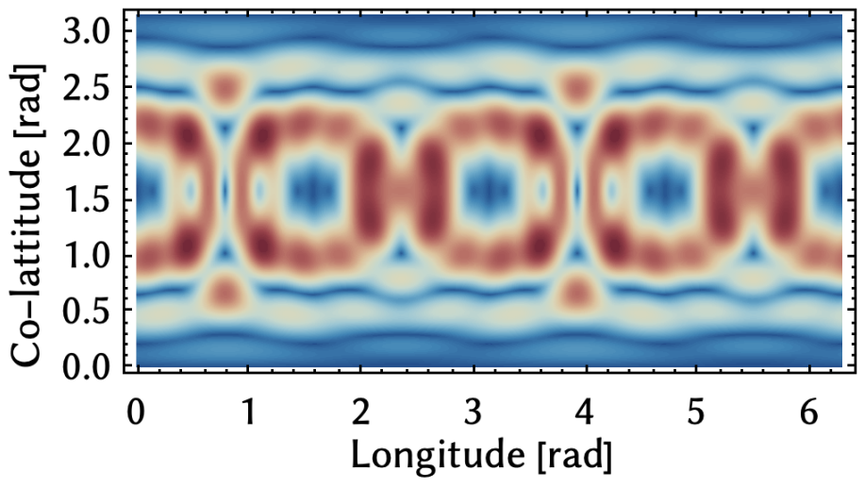

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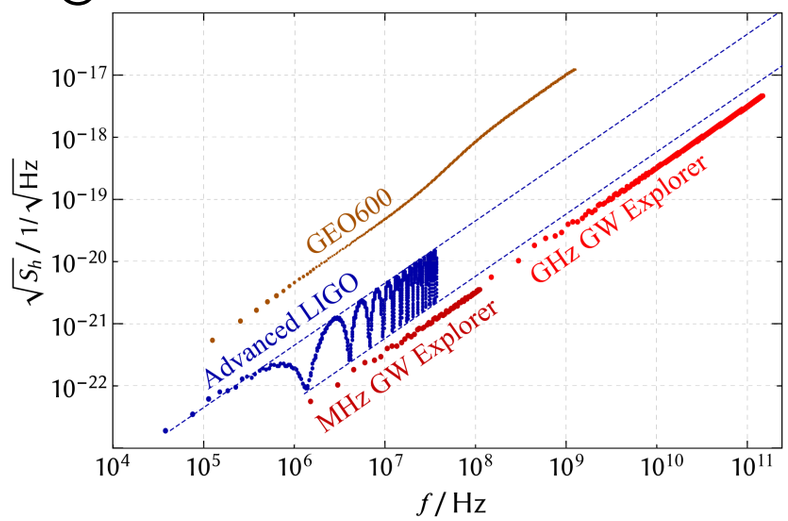

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arXiv:2409.03019 + DOI 10.5281/zenodo.15054036

GW memory

Another approach to detecting HF GWs: memory effects

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- Passing high-frequency GWs leave a permanent distortion to the space-time, extending towards much lower frequency

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Another approach to detecting HF GWs: memory effects

- Passing high-frequency GWs leave a permanent distortion to the space-time, extending towards much lower frequency

- Two types of effects: linear (DC shift) and non-linear (GWs emitting GWSs)

- These signals are detectable even below kHz, but also at higher FSRs