GEO 600 VHF

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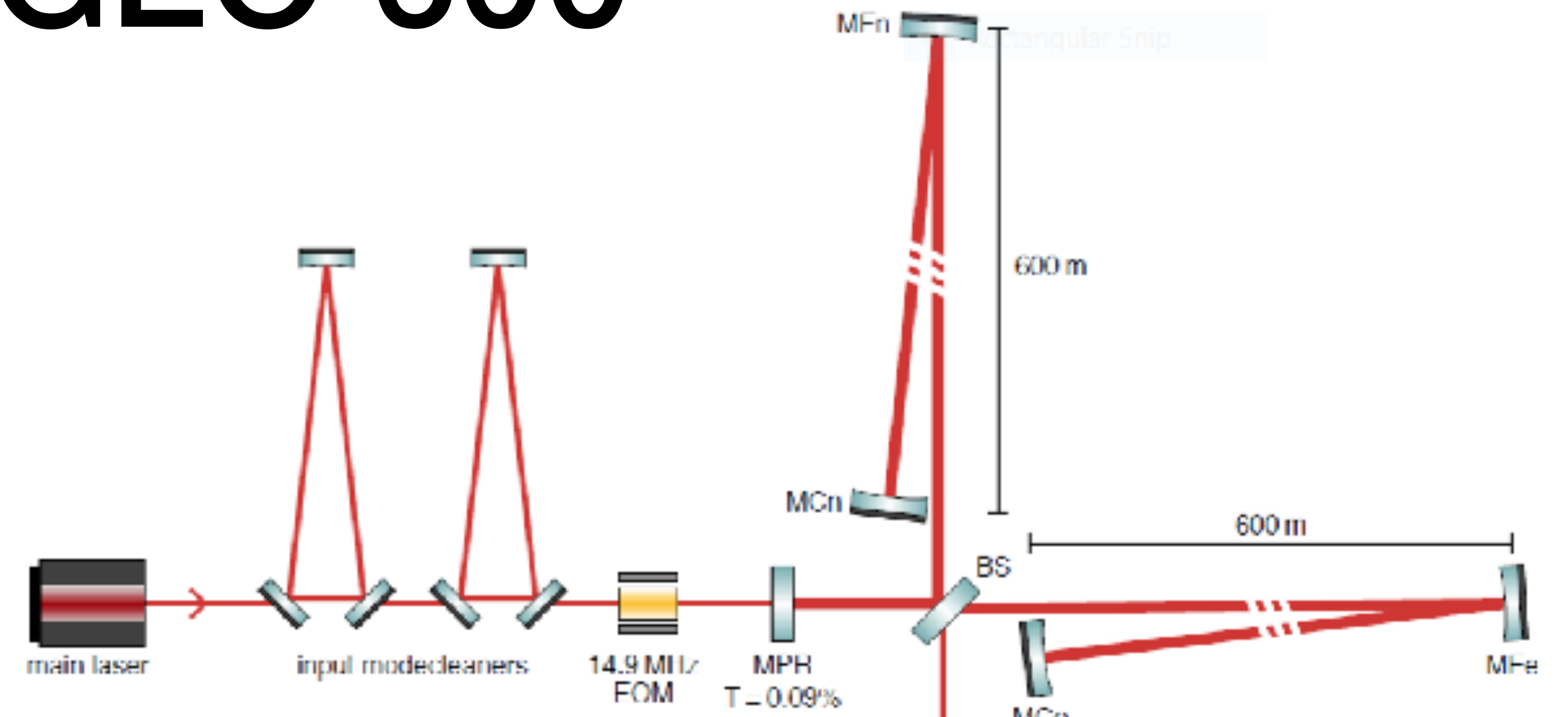
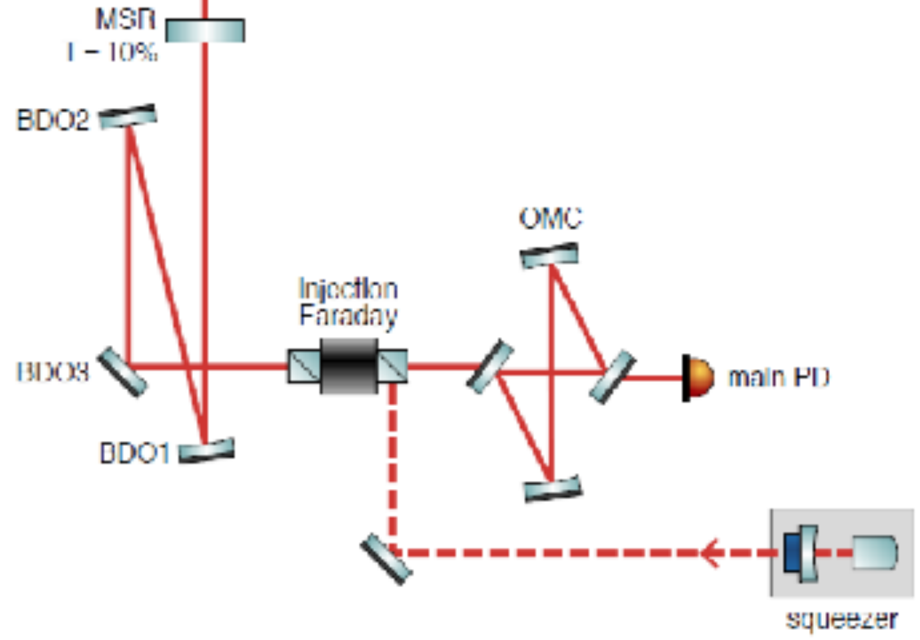
Karsten Danzmann

GEO 600





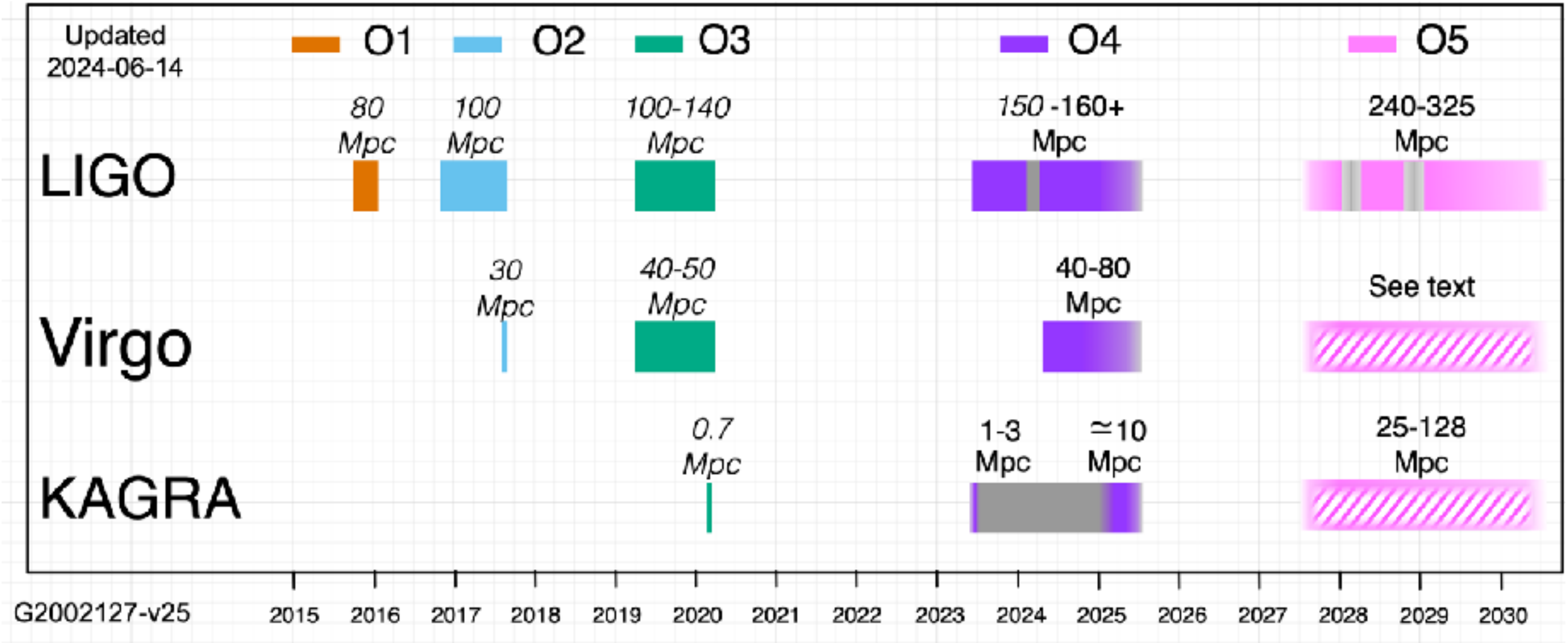
Above: GEO layout
Left: GEO central buildings

GEO Astrowatch

~1 Mpc

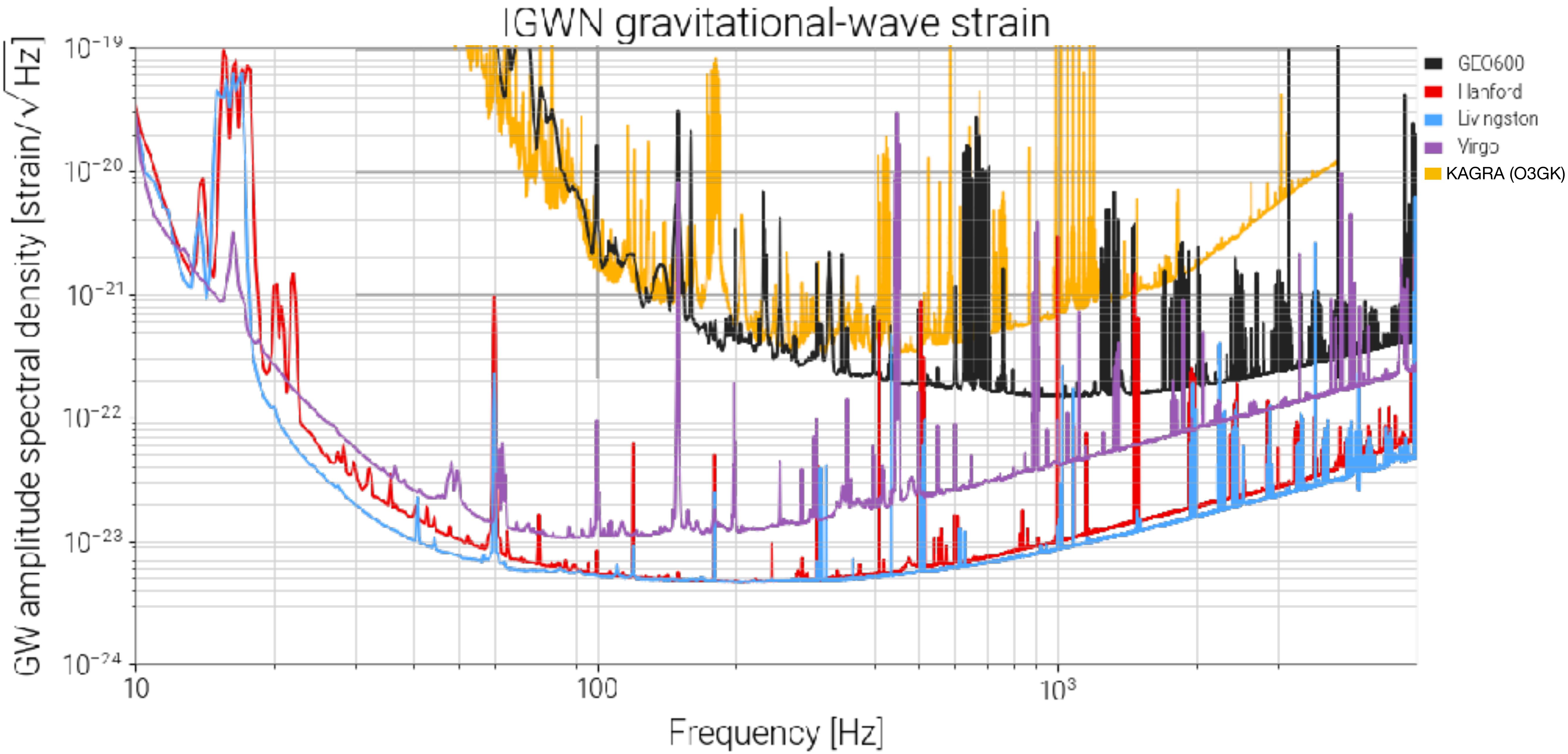
GEO

70% duty cycle while also doing instrument science



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

O3 Sensitivity



Last day of O3b: 27 March 2020

https://www.gw-openscience.org/detector_status/day/20200327/

O3GK: April 2020

https://www.gw-openscience.org/O3/O3GKspeclines/

GEO Data Usage

- GW170817 BNS post merger search

Properties of the Binary Neutron Star Merger GW170817
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X **9**, 011001 – Published 2 January 2019

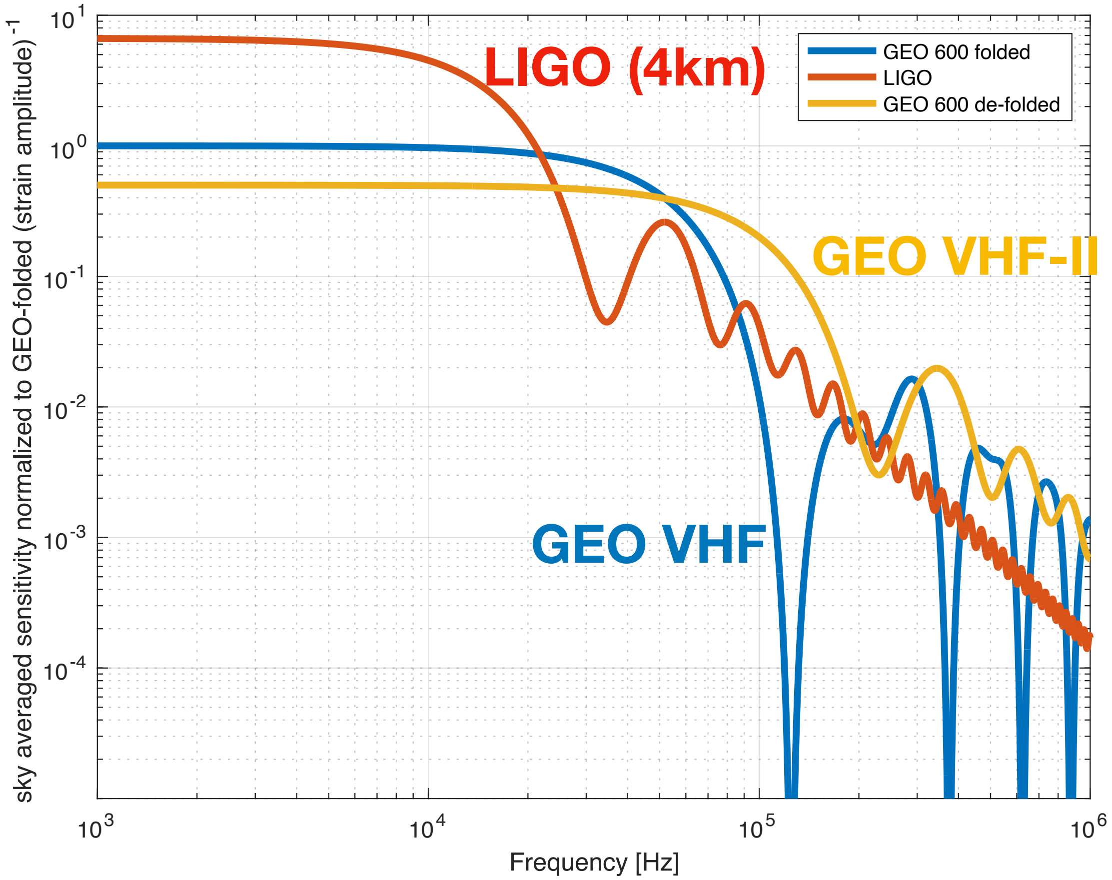
- O3GK science run with KAGRA

First joint observation by the underground gravitational-wave detector KAGRA with GEO 600
Progress of Theoretical and Experimental Physics, Volume 2022, Issue 6, June 2022, 063F01

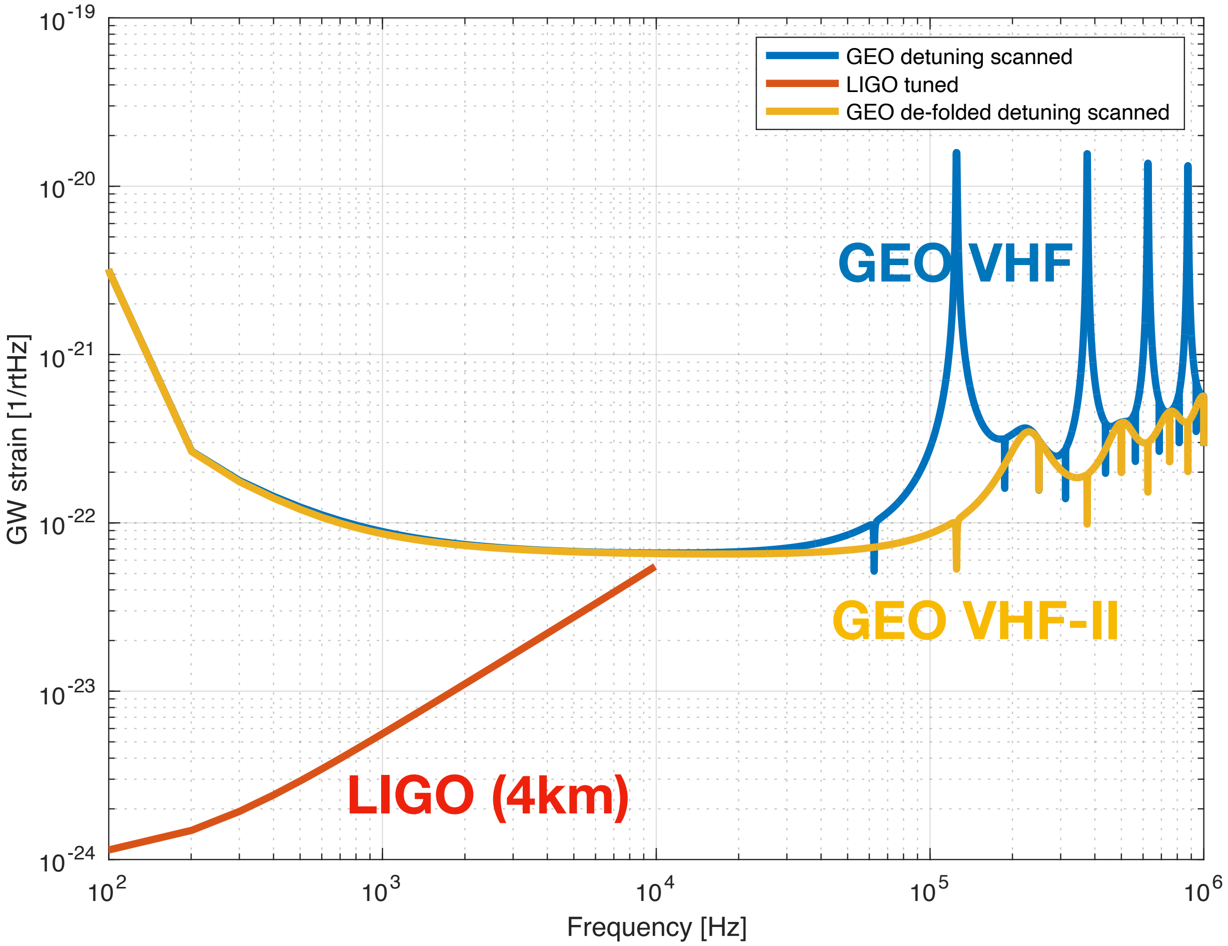
- Dark matter search

Direct limits for scalar field dark matter from a gravitational-wave detector
Vermeulen et al *Nature* **volume 600**, pages 424–428 (2021)

High frequency GW interaction



- interaction (antenna pattern) falls off for short (relative to detector size) wavelength GWs
- shorter is better at high frequencies



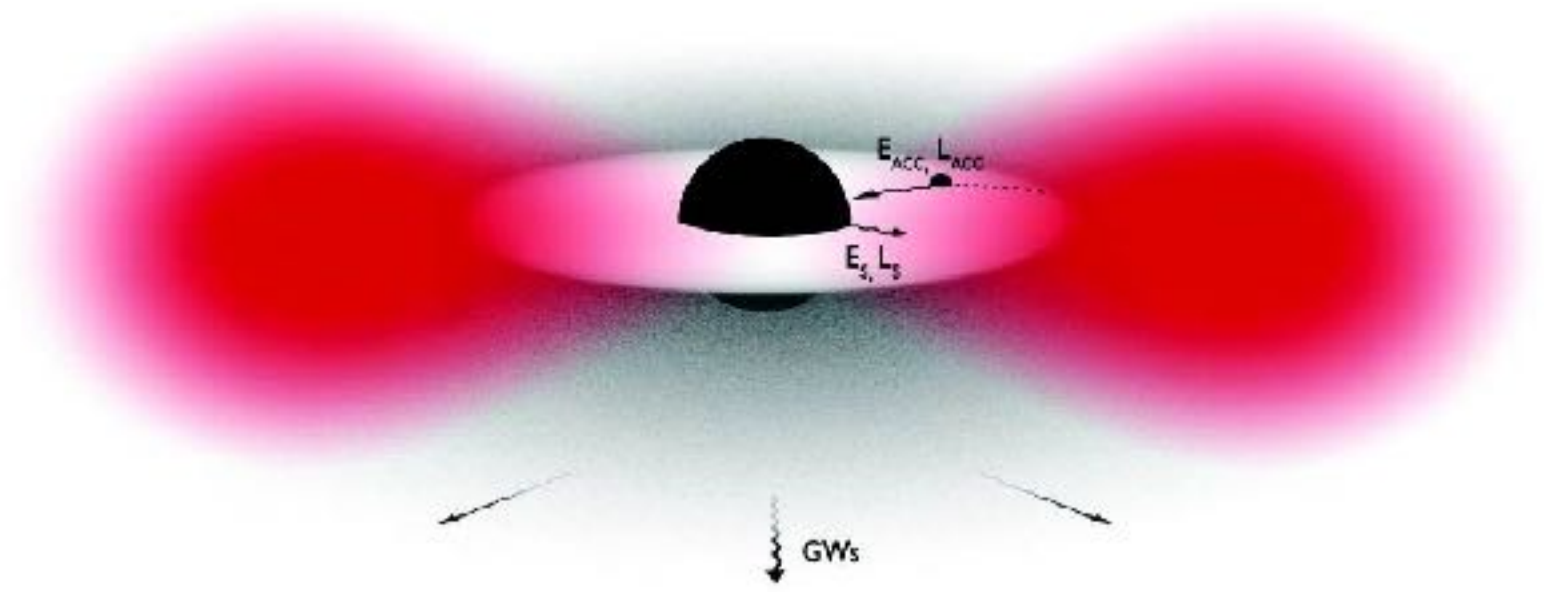
- interaction combined with interferometer response
- GEO is not tuning restricted

Black hole superradiance

- black hole interaction with ultralight bosons
- spinning black holes can enter a superradiant instability, coherently amplifying the boson field orbiting the BH
- black hole spin energy converted to gravitational waves
- signal is quasi-continuous (process will stop)
- frequency linearly proportional to boson mass
- superradiance efficiency ties black hole mass inversely proportional to boson mass
- BH spin needs to be >~0.7

example 1 Msol BH:

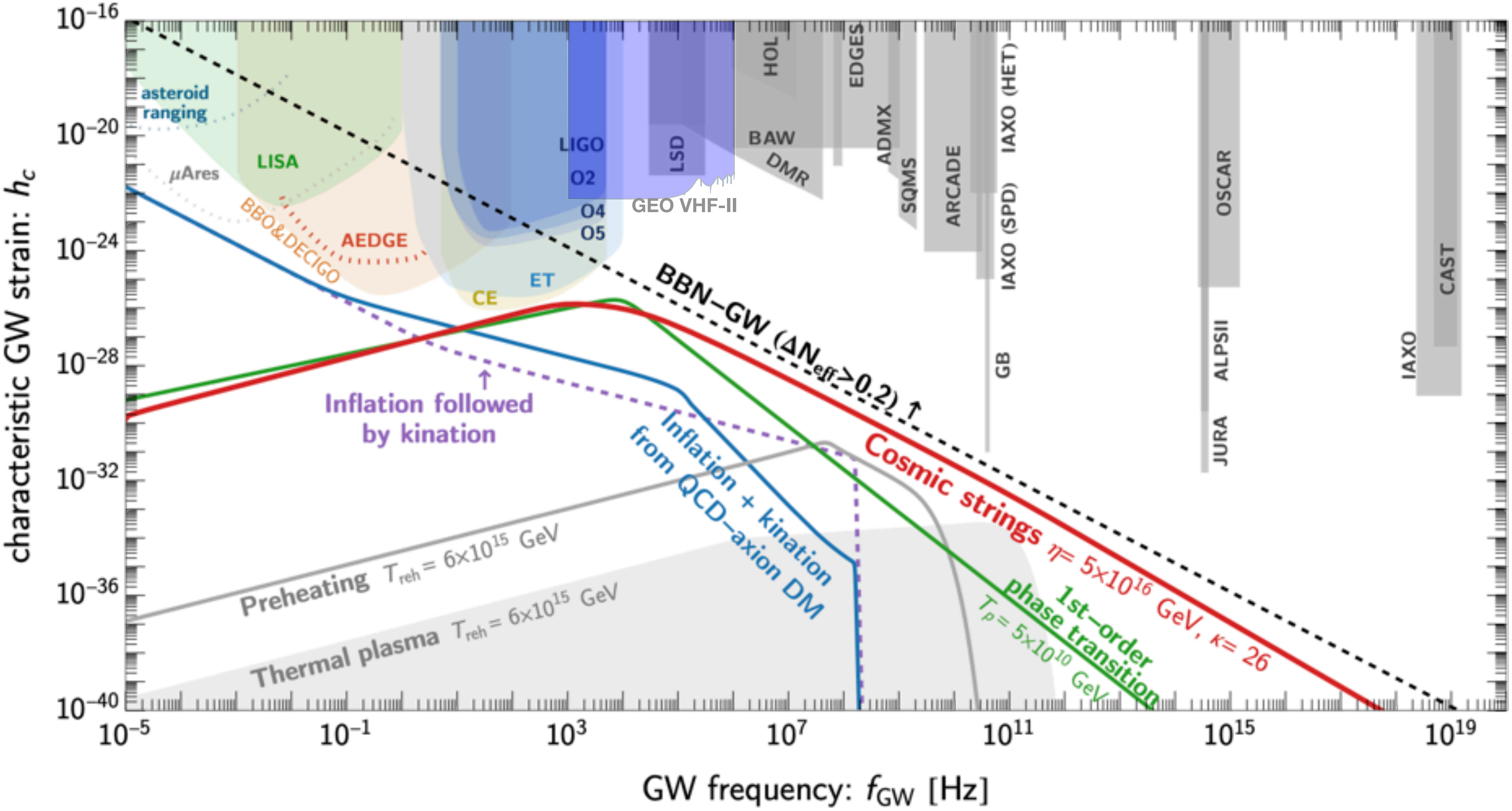
- $3.74 \times 10^{-11}\mathrm{eV}$
  spin-1 boson
- ~9 kHz GW



Maximiliano Isi, Ling Sun, Richard Brito, and Andrew Melatos. Directed searches for gravitational waves from ultralight bosons. Phys. Rev. D, 99:084042, Apr 2019.

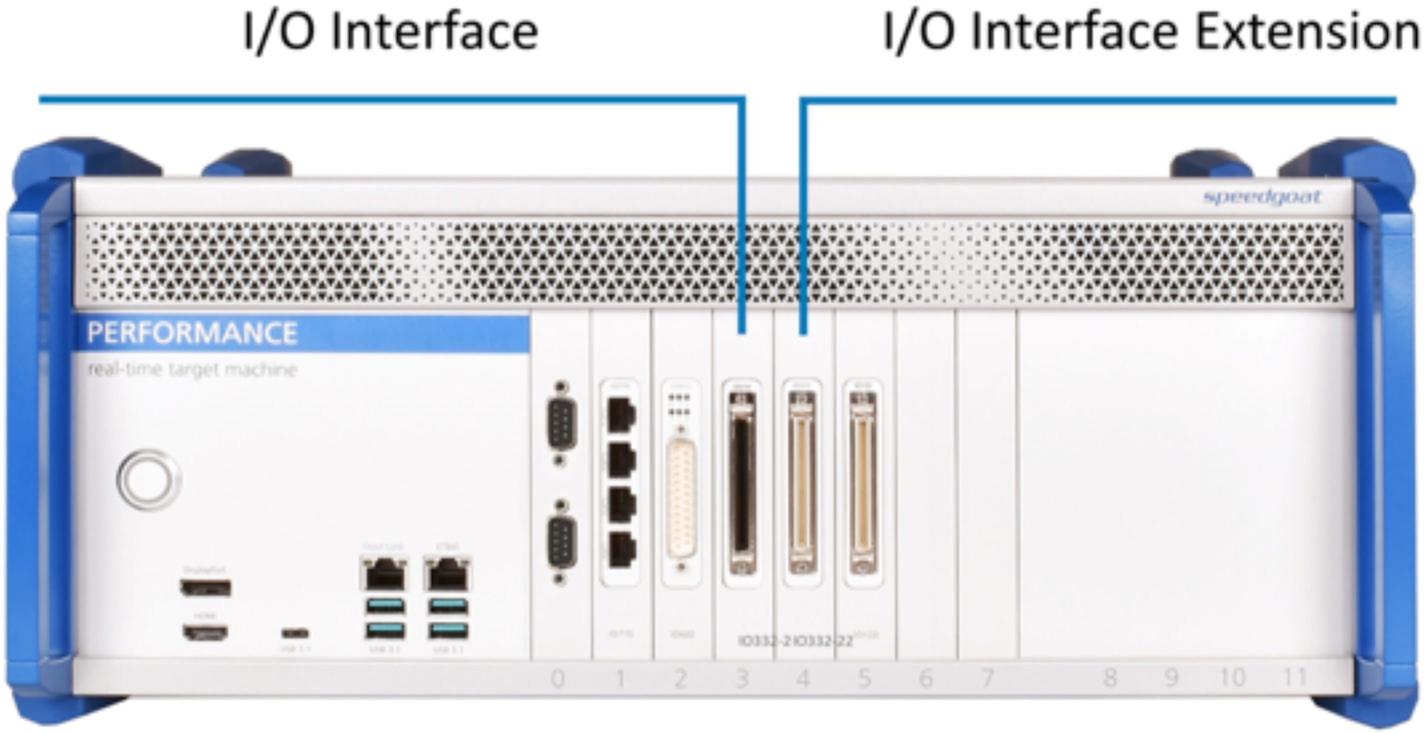
credit: Ana Sousa
https://cqgplus.com/2015/06/11/black-hole-superradiance-and-the-hunt-for-dark-matter/

Primordial gravitational waves



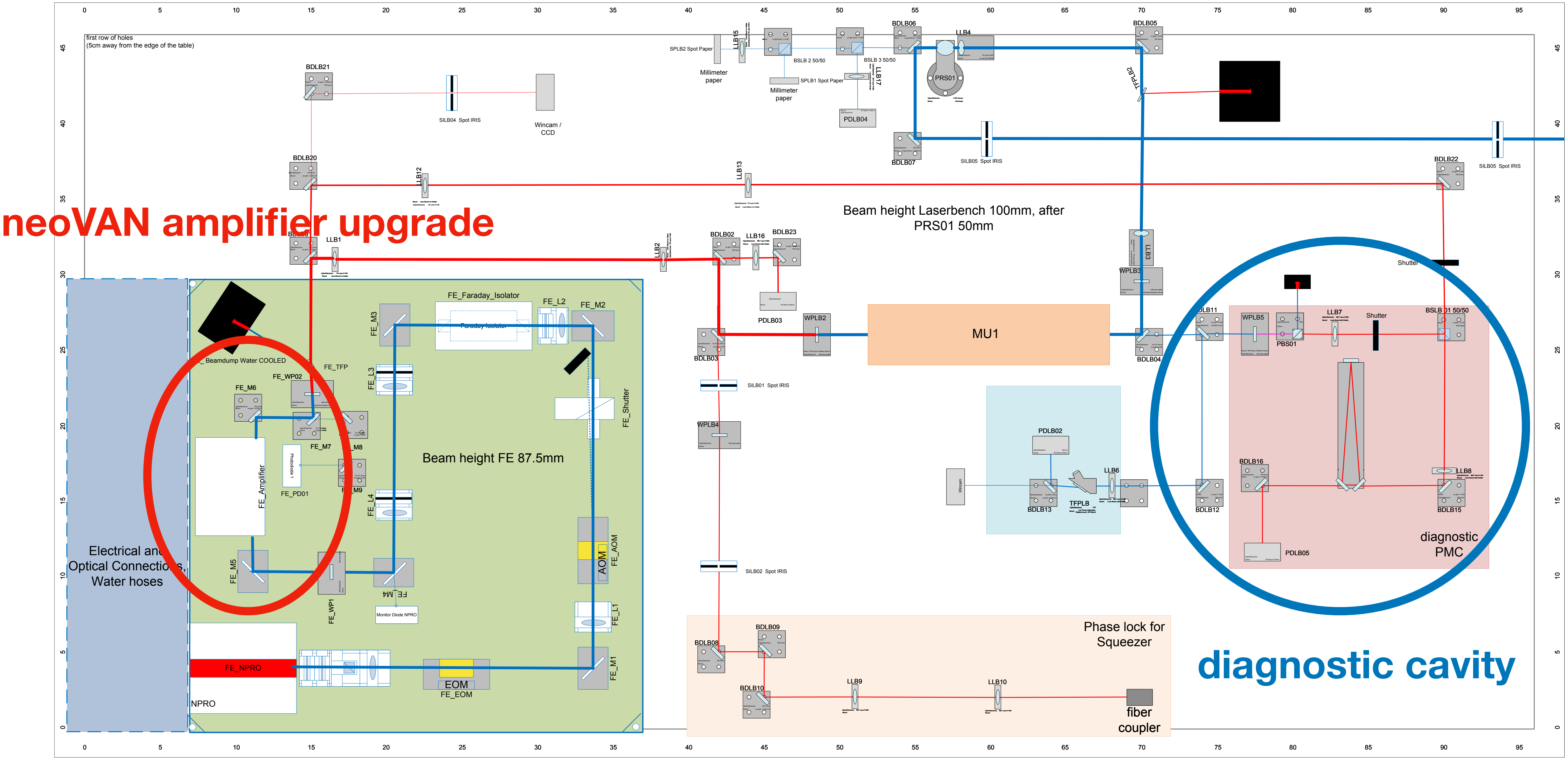
Géraldine Servant and Peera Simakachorn,
https://doi.org/10.48550/arXiv.2312.09281
https://doi.org/10.1103/PhysRevD.109.103538

Data Acquisition



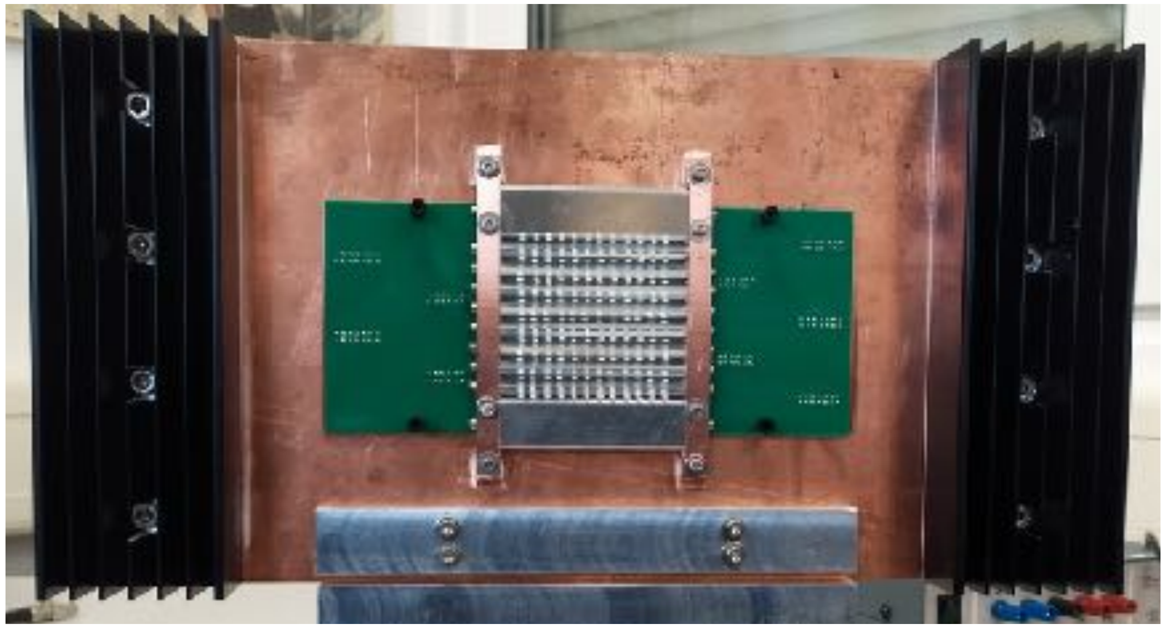
- Speedgoat IO334
- https://www.speedgoat.com/products/simulink-programmable-fpgas-fpga-i-o-modules-io334
- ADC
  - 16-bit, >13 ENOB @1 MHz
  - up to 5 MSPS
- FPGA cycle rate 100MHz
- TTL I/O for timing synchronization

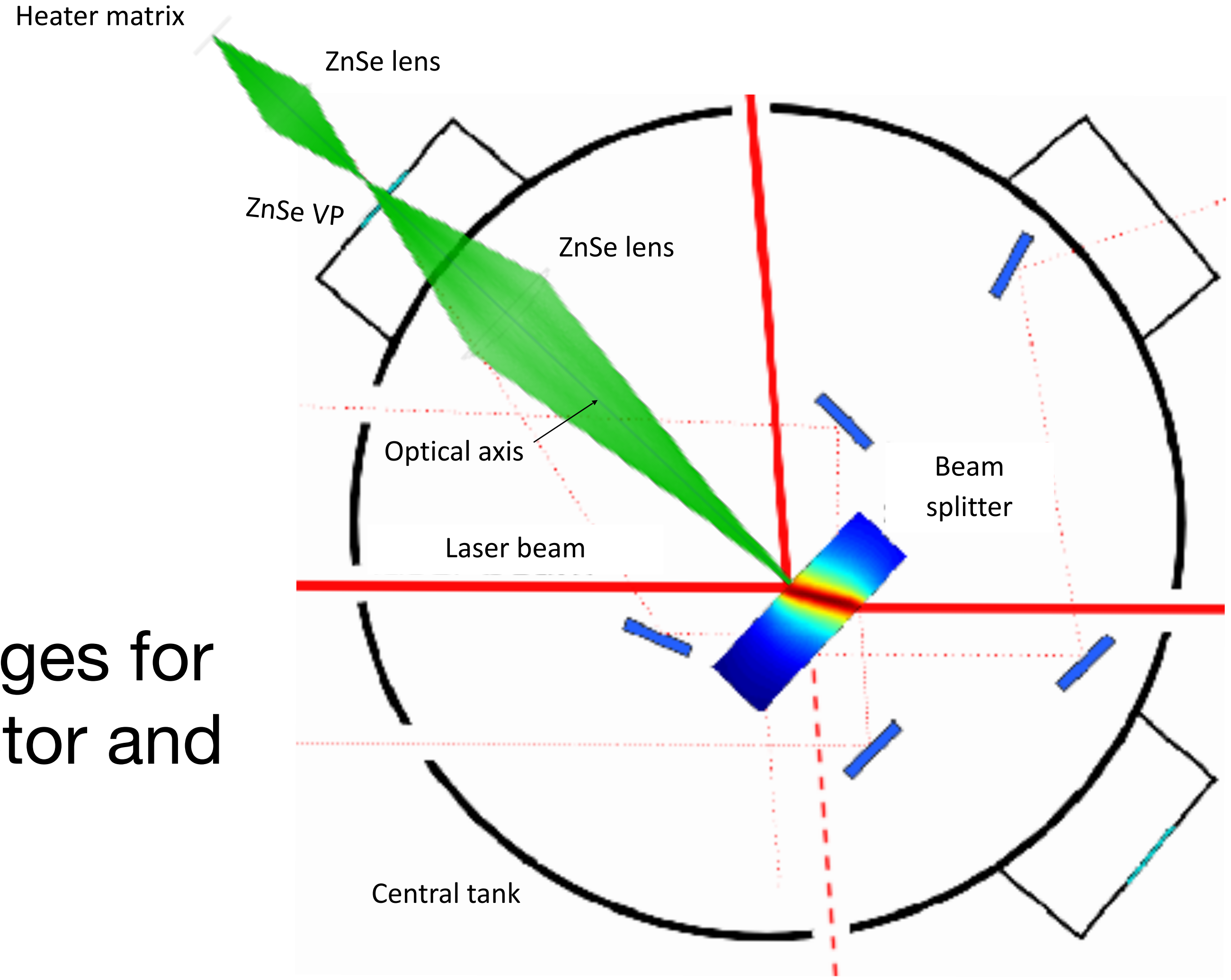
Laser upgrade



- upgrade to new neoVAN-4S-HP for increased stability and power
- New layout with additional diagnostics
- Up to 70 W available

Beamsplitter TCS





- heater and lens on movable stages for adjustment of magnification factor and focus
- controllable remotely
- tuned for thermal lensing astigmatism correction - 2nd order mode reduction by factor 3
- system for power-up assistance

paper in preparation: Severin Nadji, et al

Neural sensing and control

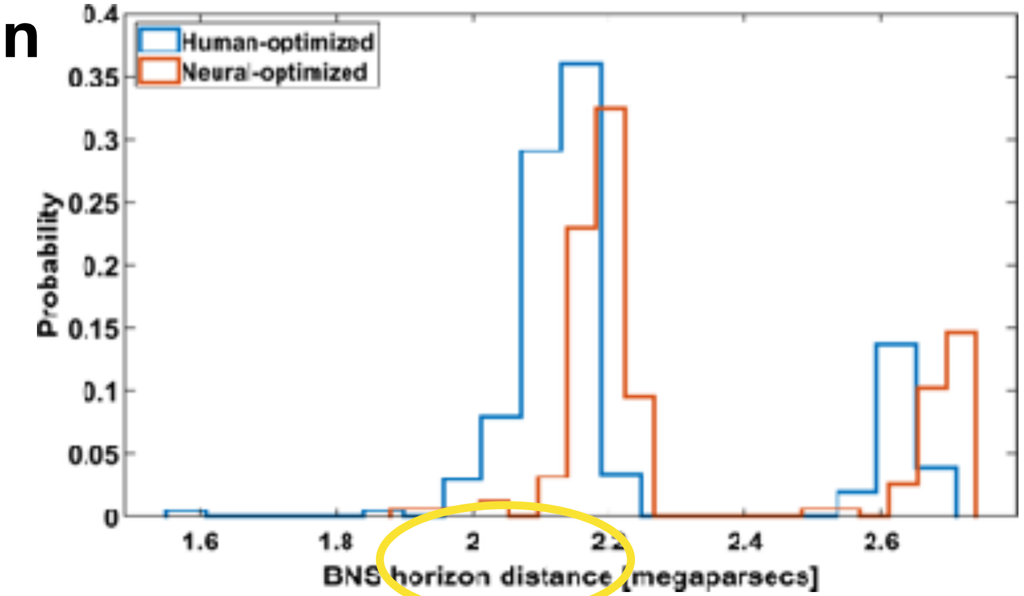
- currently analog camera is digitized and is delivered via ip video server
- neural network running in matlab on a workstation
- continuously running system

BASLER ACE

NVIDIA Jetson

MSR

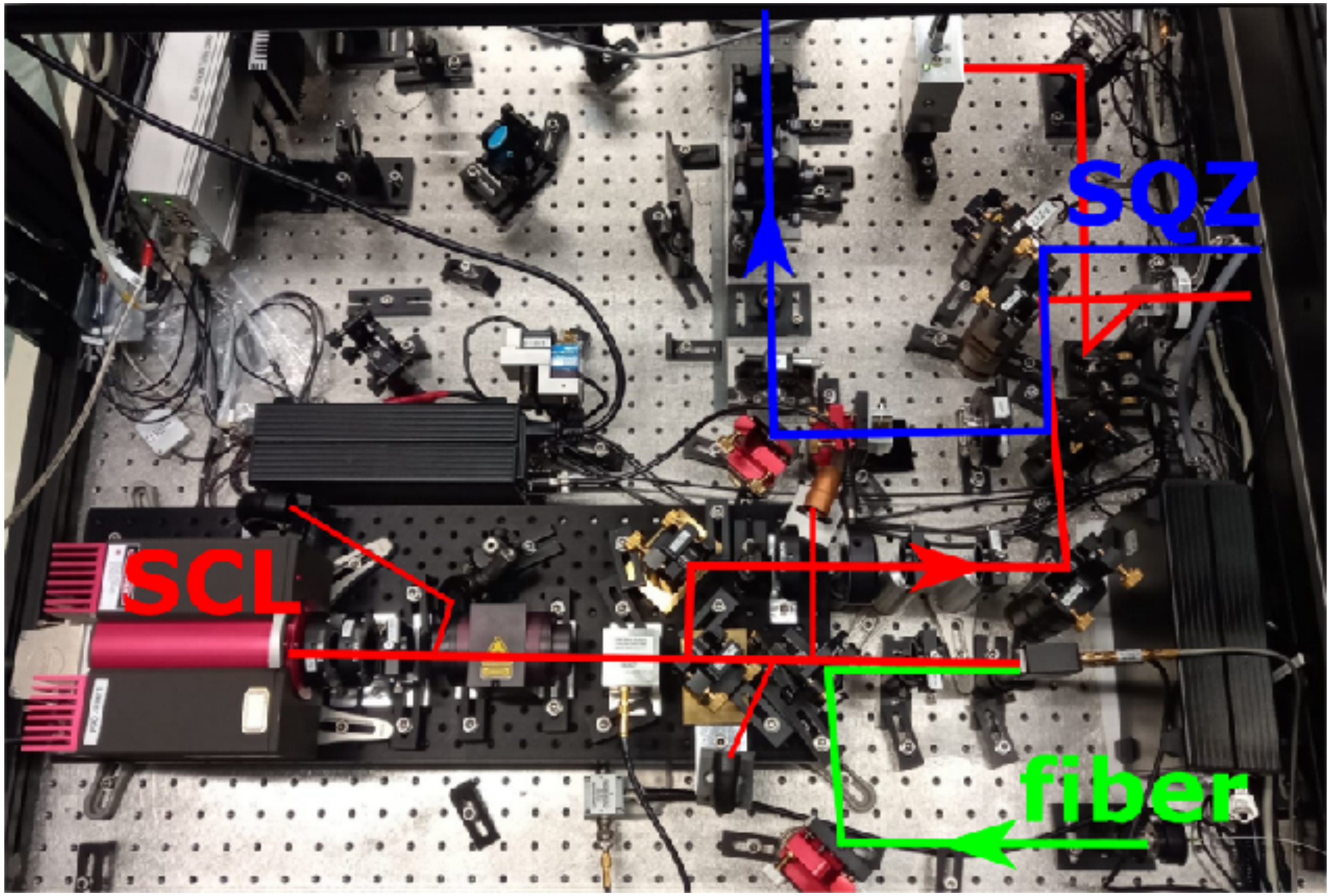
- Demonstration with signal recycling alignment
- Additional alignment signals visible including very clear Michelson differential
- Michelson modulation can potentially be turned off in full lock - reduced un-squeezable shot noise



https://arxiv.org/abs/2301.06221

https://doi.org/10.1103/PhysRevApplied.20.064041

SRC Subcarrier control



- control of signal recycling mirror by pdh lock with auxiliary laser (phase locked with a few GHz offset) from the dark port
- SRC detuning more straightforward: simply change the frequency of the subcarrier laser by way of PLL LO
- Squeezing compatibility: subcarrier overlaps with sqz field

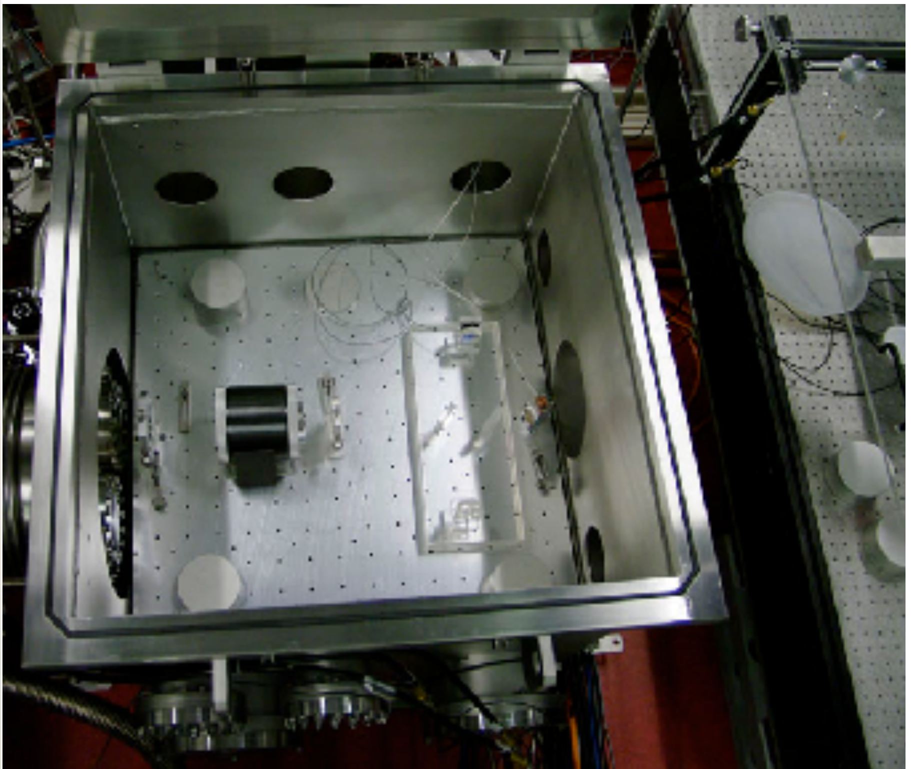
Bergamin, Fabio: Development of a squeezing-compatible signal recycling cavity control at GEO600. Hannover : Gottfried Wilhlem Leibniz Univ., Diss., 2024, xi, 196 S., DOI: https://doi.org/10.15488/17442

Conclusion

- GEO VHF to extend sensitive band beyond current detectors (~6kHz) up to > 500 kHz
- Laser upgrade currently underway
    - ~1 month downtime
- New FPGA-based fast data acquisition
    - tested
    - fully integrated this year
- Sources
    - Black Hole superradiance: sub-solar mass
    - primordial gravitational waves
- direct interaction: dark matter, quantum gravity

Facility overview

- Construction began in 1995 (groundbreaking)
- Installation began in 1998
- same core optics
- HF upgrade 2009, squeezer installed 2010
- switch from 98% to 90% signal recycling mirror in 2011 (increased bandwidth)



History of Pioneering Technologies

- Lasers
- Glasgow suspensions - monolithic triple
- Signal Recycling/ Extraction
- Thermal Compensation
- Electrostatic Actuators
- Squeezing

Superradiance

- boson cloud grows from reflections off the BH horizon taking away angular momentum from the BH
- saturation (BH spin relation to boson frequency), amplification process stops
- gravitational wave emission:

“α<<1”

$$h_0^{(\mathrm{v})} \approx 4 \times 10^{-24} \left(\frac{M}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^5 \left(\frac{\mathrm{Mpc}}{r}\right) \left(\frac{\chi - \chi_f}{0.1}\right) \tag{30}$$

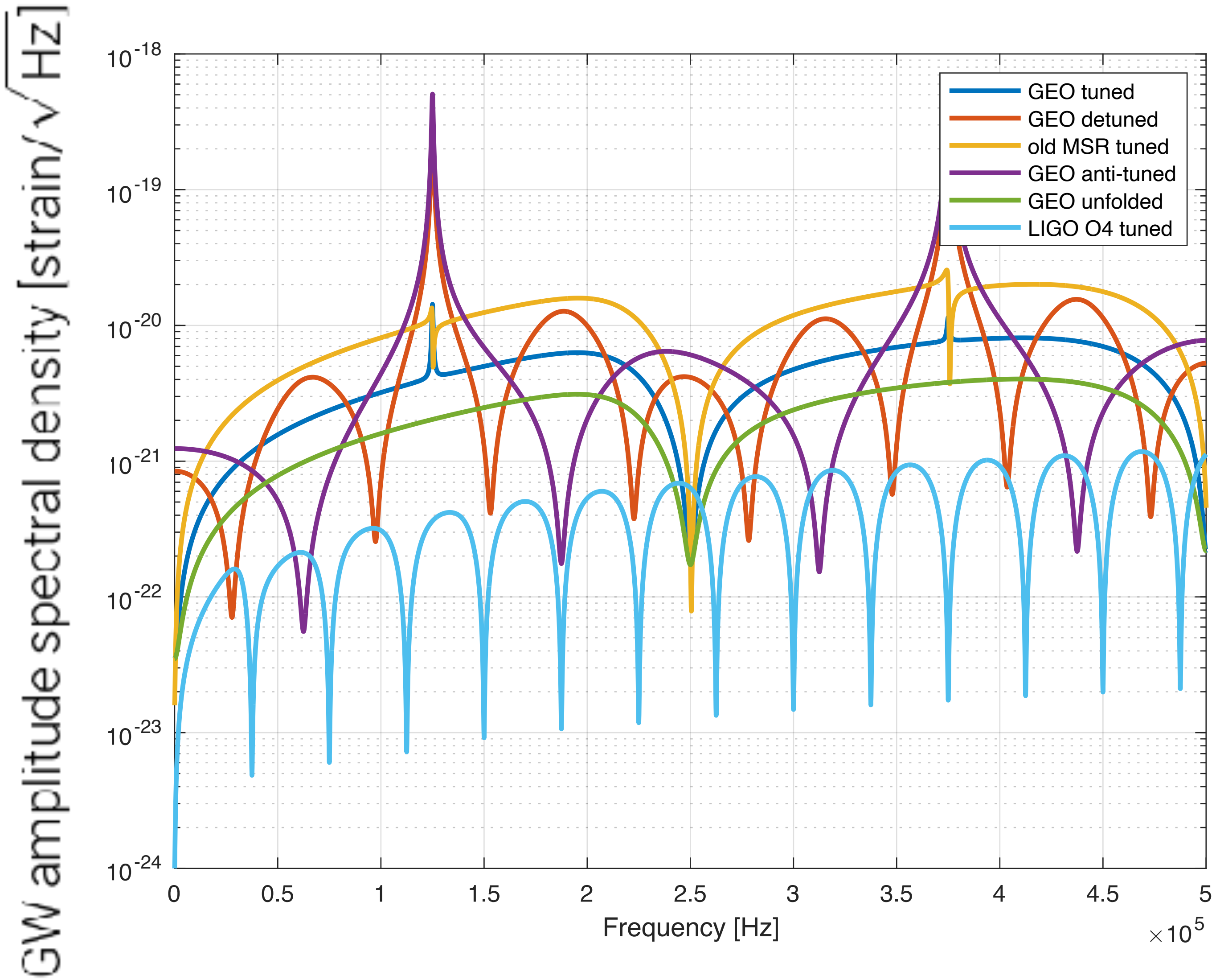
Isi, et al PRD (2019)
LIGO P-1800270

α=μM=0.28, χ=0.7->0.62, M=Msun, boson mass μ=3.74e-11 eV, 1Mpc

-> 9kHz, ~1e-23 “characteristic” strain amplitude

Duration ~some weeks?

Sensitivity



“instantaneous” detector ASD noise floor for different cases

Detectability - VHF

1. most energy from system ~0.1 M_{BH} (most efficient Superradiance)
2. Most efficient Superradiance occurs with ~const. μM
3. $E_{\mathrm{GW}} \propto M_{\mathrm{BH}}$
4. $h_0 \propto M_{\mathrm{BH}}$
5. $\tau_{\mathrm{GW}} \propto M_{\mathrm{BH}}^{-1}$ ***implied from (3) & (4) and conservation of energy***
6. ***only based on 0.1 Msun energy into GW*** SNR ~1000 for detector with $1 \times 10^{-23} [\frac{1}{\sqrt{\mathrm{Hz}}}]$ strain amplitude spectral density, integrated for duration of signal (1 Mpc). i.e. 100 Mpc range for SNR 10.
7. range ~100Mpc * sqrt(9kHz/f_{GW}) for detector with $1 \times 10^{-23} [\frac{1}{\sqrt{\mathrm{Hz}}}]$ strain amplitude spectral density (only requires (1) and (6)
8. e.g. 900kHz: range=10 Mpc (0.001 Msun GW energy)