The hunt for high frequency gravitational waves — GravNet —

Kristof Schmieden, CPPS Seminar Siegen, 10/06/2025

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About Me

- Phd: **ATLAS**
  - Pixel Detector, Muon System
  - Standard model precision measurements
    - Weak mixing angle

- Junior Faculty (2015-2020)
- **ALPs, Axions, Gravitational Waves**
  - ATLAS
  - FASER
  - Supax + GravNet

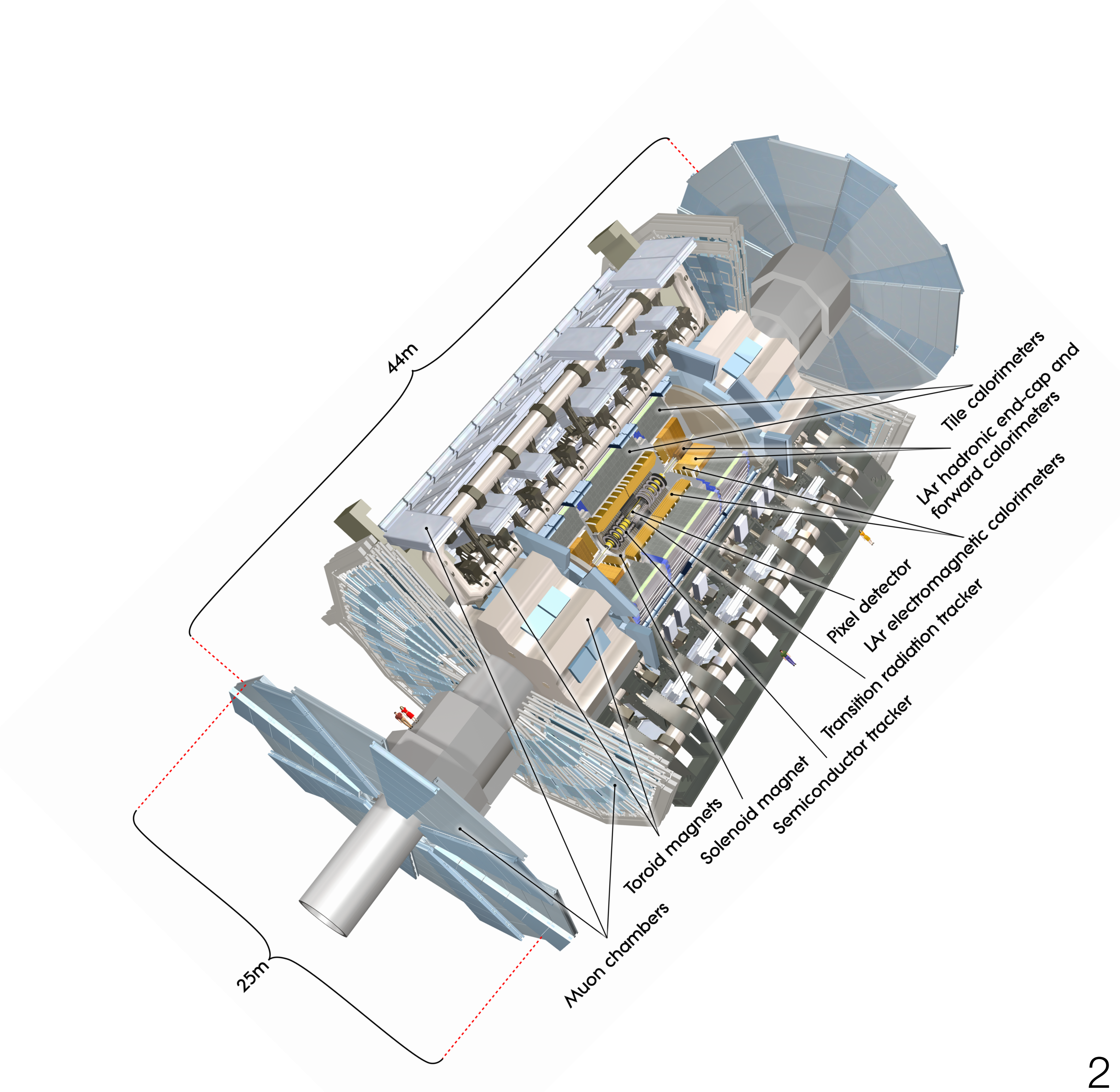
- CERN Fellow + 5 year Staff (until 2020)
- **ATLAS**
  - Central Trigger
  - Operations

- SM precision, Higgs->$\gamma\gamma$
- Light-by-Light scattering
  - **Axion Like particles**

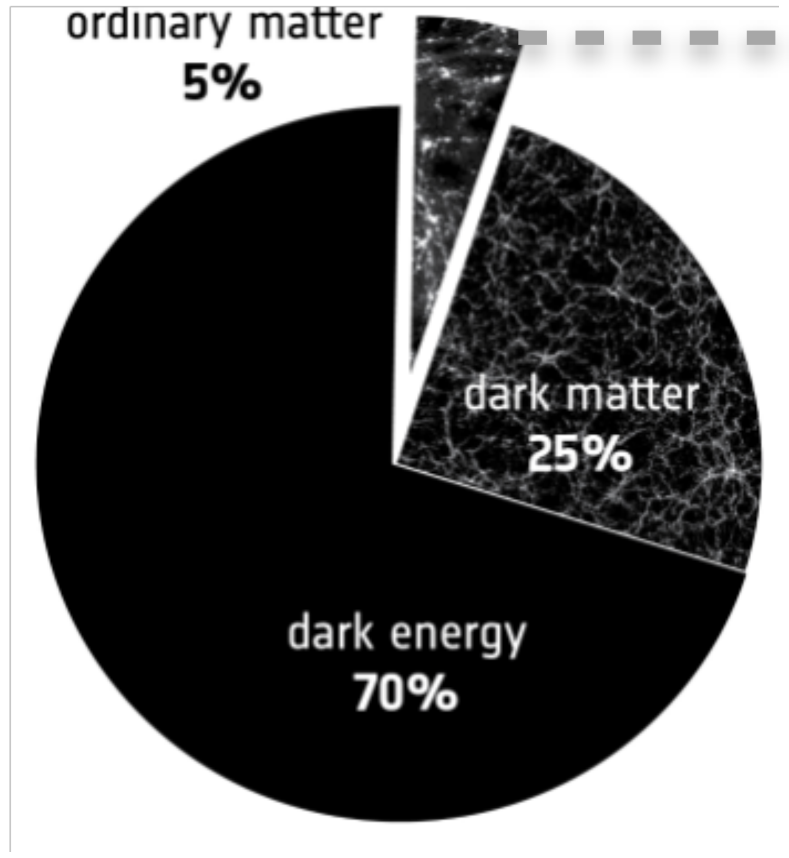
- **FASER**
  - DAQ

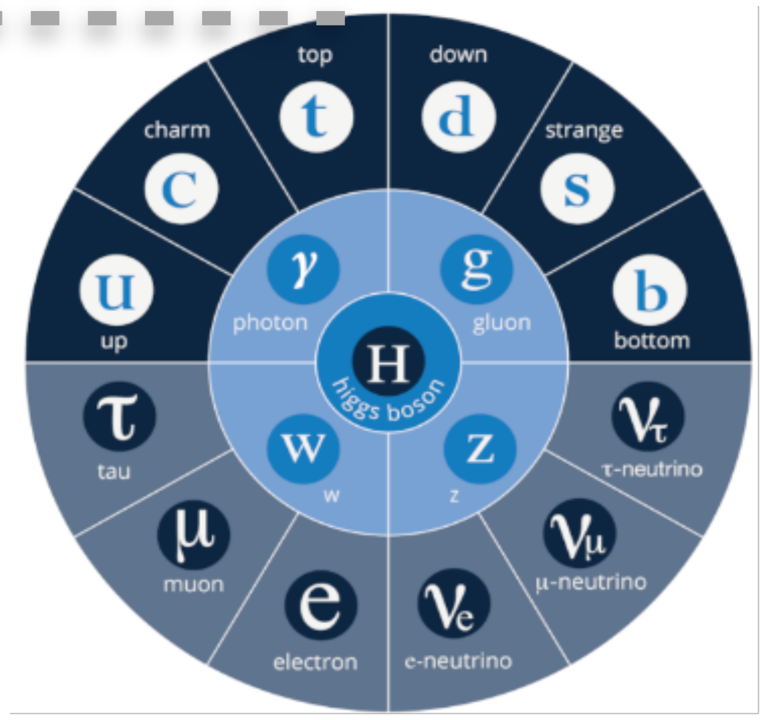
- Scientific staff (recently)
  - **GW + Axions**
    - **GravNet**
  - ATLAS

Focus of this talk



Our (incomplete) view of the universe





95% not detectable with **light**

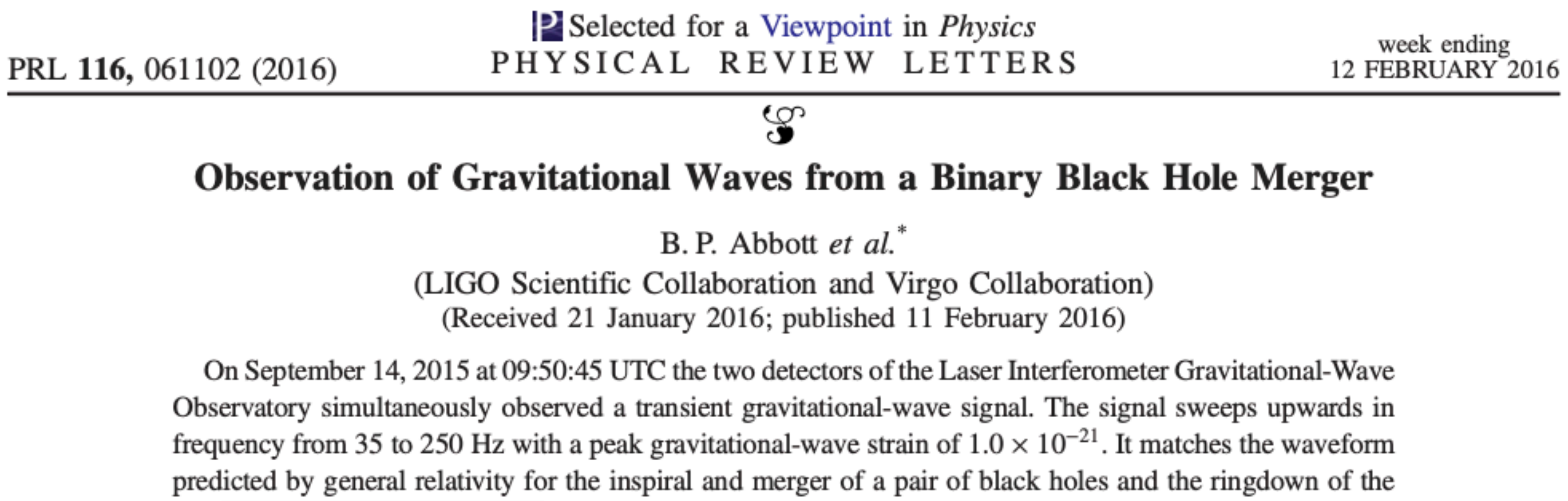
incomplete at **high energy**

Gravitational waves

probe all components and **may come from the early universe**

Gravitational Waves

- 2016 breakthrough in fundamental physics:
  - Observation of gravitational waves by LIGO / Virgo



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the

The New York Times

OUT THERE

Gravitational Waves Detected, Confirming Einstein's Theory

Culture Lifestyle

The Guardian

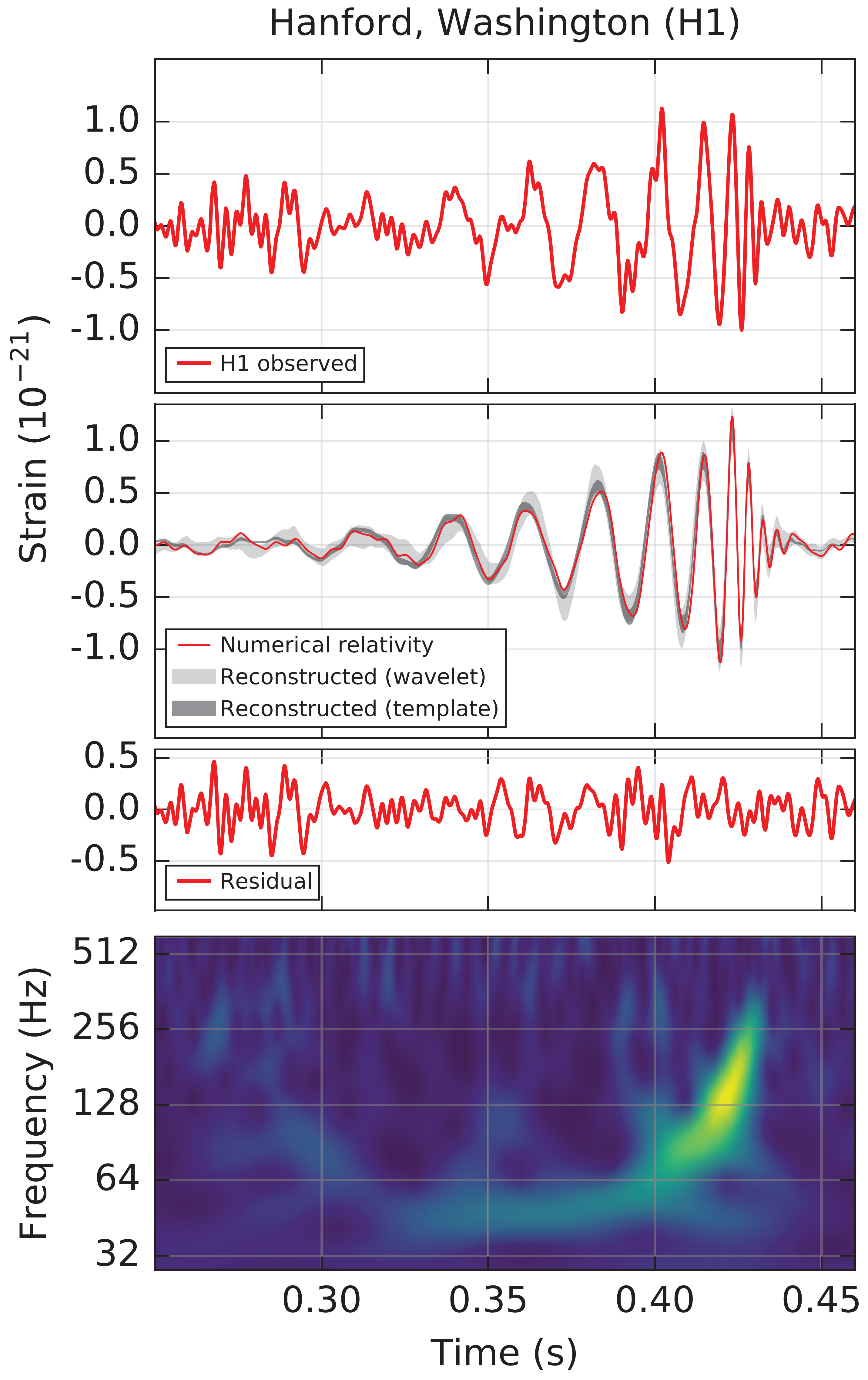
Eur

Science Global development Football Tech Business Obituaries

Gravitational waves: breakthrough discovery after a century of expectation

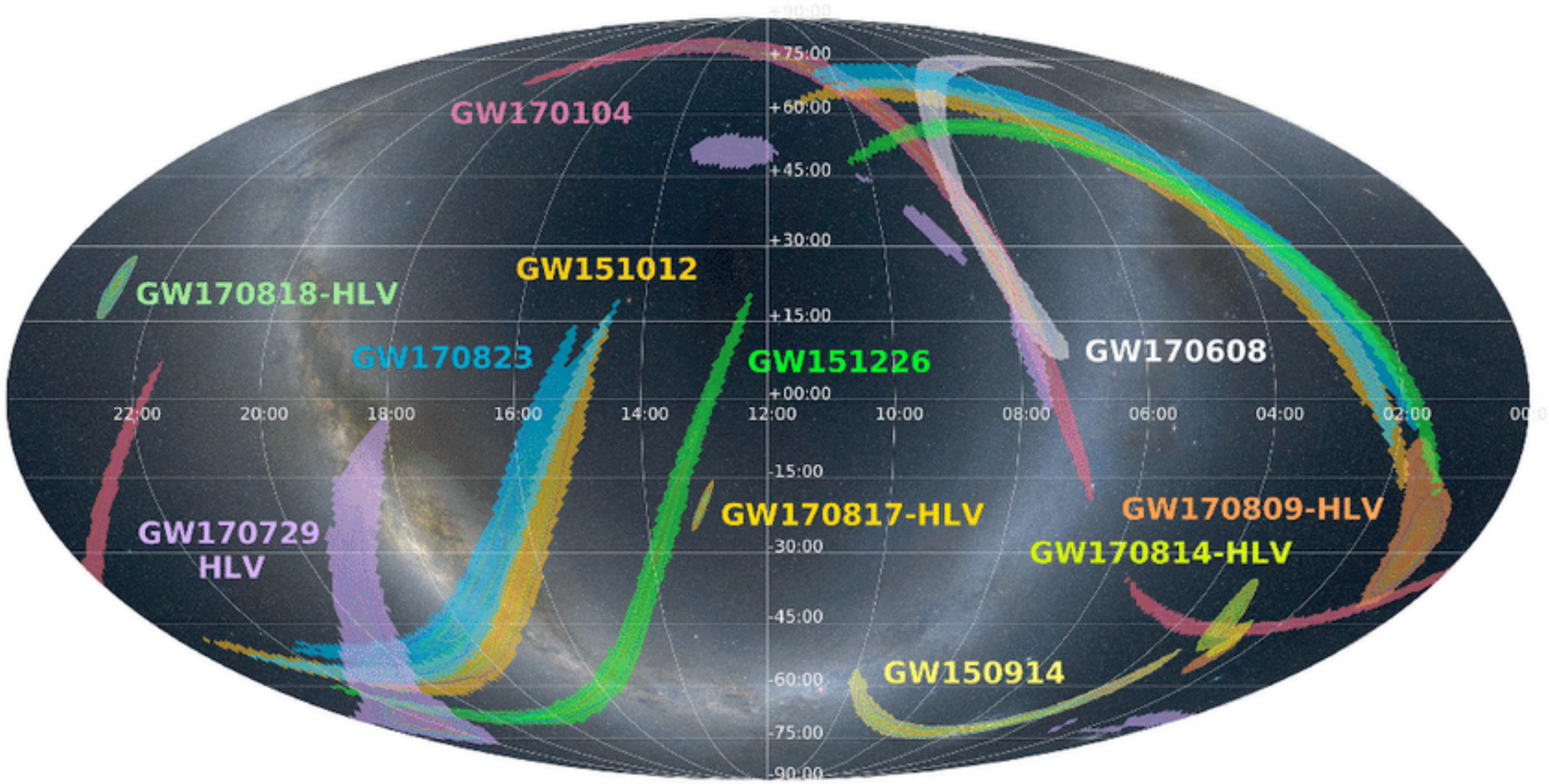
Scientists announce discovery of clear gravitational wave signal, ripples in spacetime first predicted by Albert Einstein

- Frequency range: 10-1000 Hz

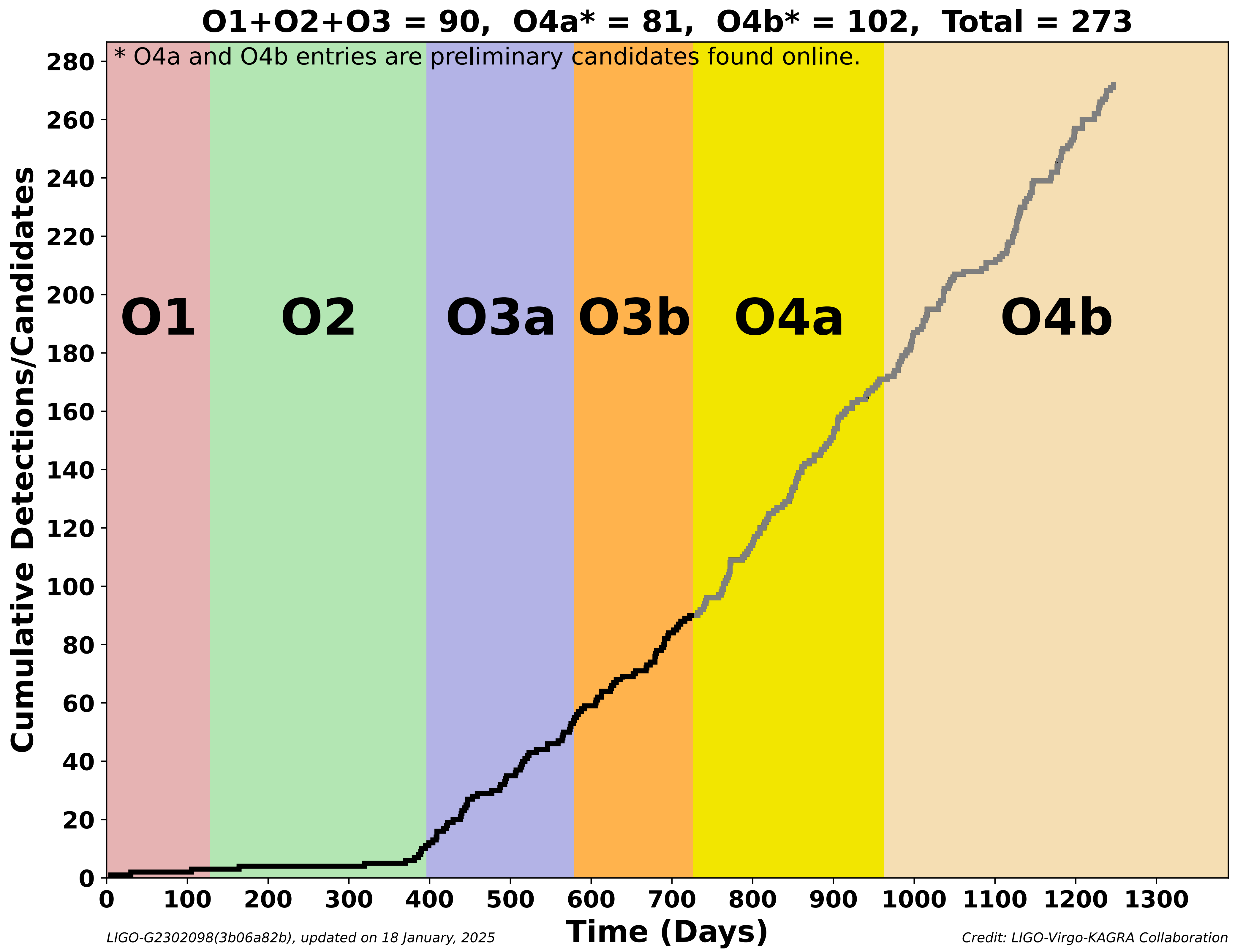


Introduction - Gravitational Waves

- 9 years later:
  - 90 observed GW events, > 200 Candidate events
  - Able to start statistical analysis
  - New observational window into the universe established



[DOI:10.1007/s41114-020-00026-9], O1 + O2 events



[https://dcc.ligo.org/LIGO-G2102395/public]

Introduction - Gravitational Waves

- 2023: First observation of GW in pulsar timing array data
  - Very low frequency: 10^{-8}Hz

[Gabriella Agazie et al 2023 ApJL 951 L8]

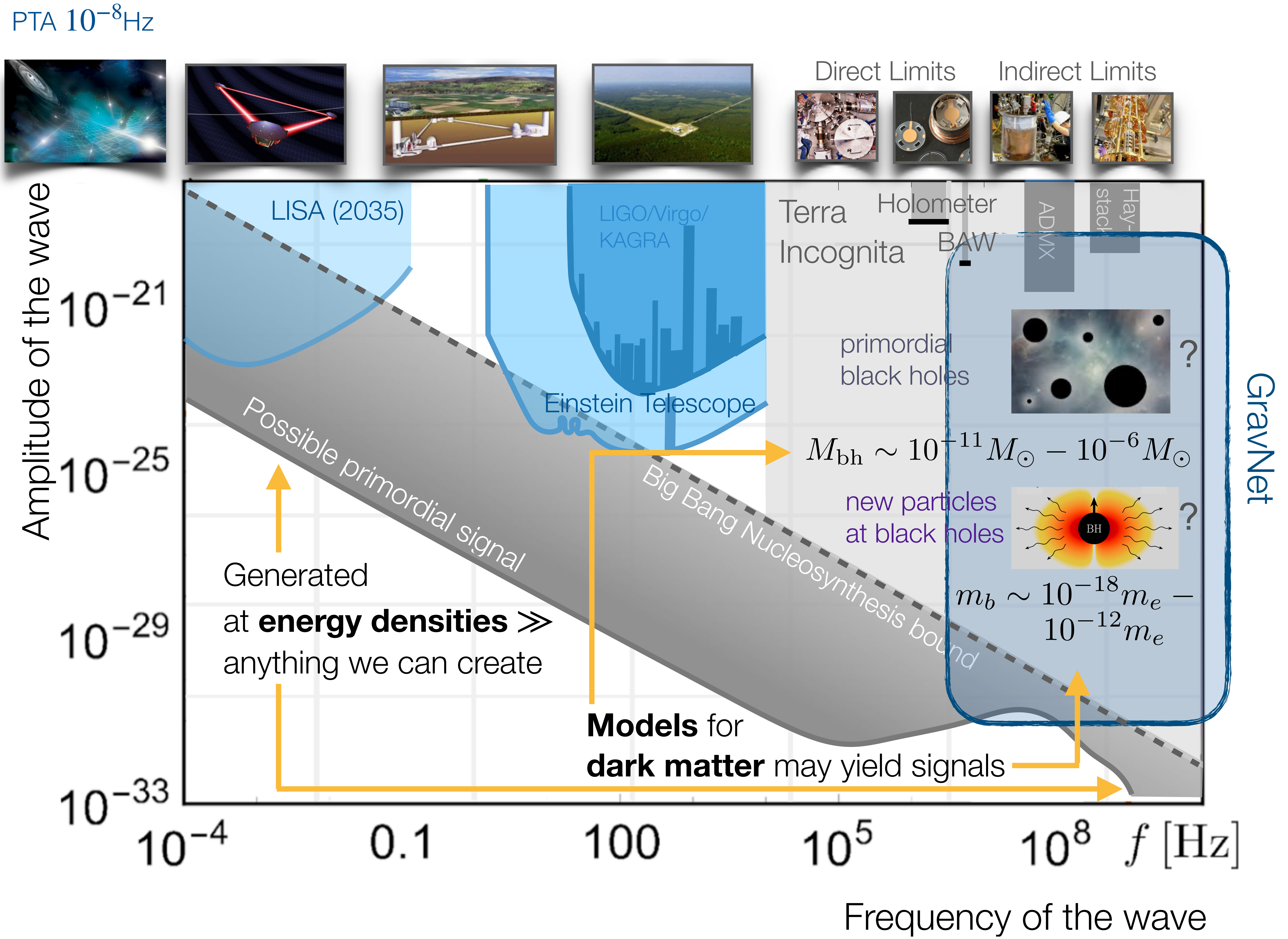
The Astrophysical Journal Letters, 951:L8 (24pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdac6
© 2023. The Author(s). Published by the American Astronomical Society.
OPEN ACCESS

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

Gabriella Agazie[1], Akash Anumarlapudi[1], Anne M. Archibald[2], Zaven Arzoumanian[3], Paul T. Baker[4], Bence Bécsy[5], Laura Blecha[6], Adam Brazier[7,8], Paul R. Brook[9], Sarah Burke-Spolaor[10,11], Rand Burnette[5], Robin Case[5], Maria Charisi[12], Shami Chatterjee[7], Katerina Chatziioannou[13], Belinda D. Cheeseboro[10,11], Siyuan Chen[14]

What about **high frequency** GWs?

Introduction - Gravitational Waves



- High frequency gravitational wave (HFGW) **sources**
  - Could explain dark matter
  - No astrophysical backgrounds
  - (No known sources)

- Very weak existing limits for
  - f = 1 MHz … 10 GHz

GravNet:

Dedicated effort probing high frequency gravitational waves using **cavity resonators**

What are gravitational waves?

Introduction - Gravitational Waves

Cosmological constant * metric tensor

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

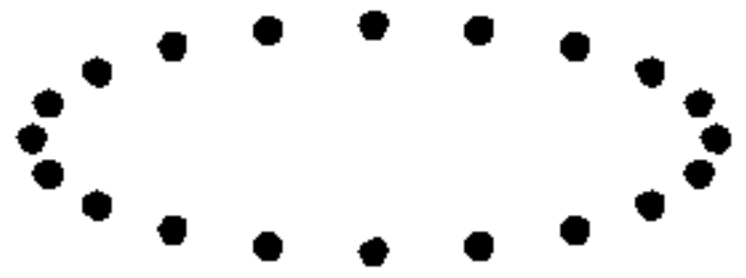
Energy-Momentum tensor

Einstein tensor

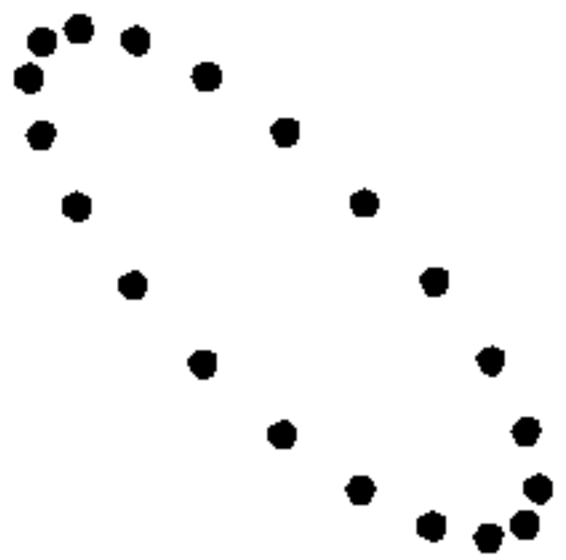
$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu}$$

- Wave solution of Einstein equations:
  - 2 Polarisations

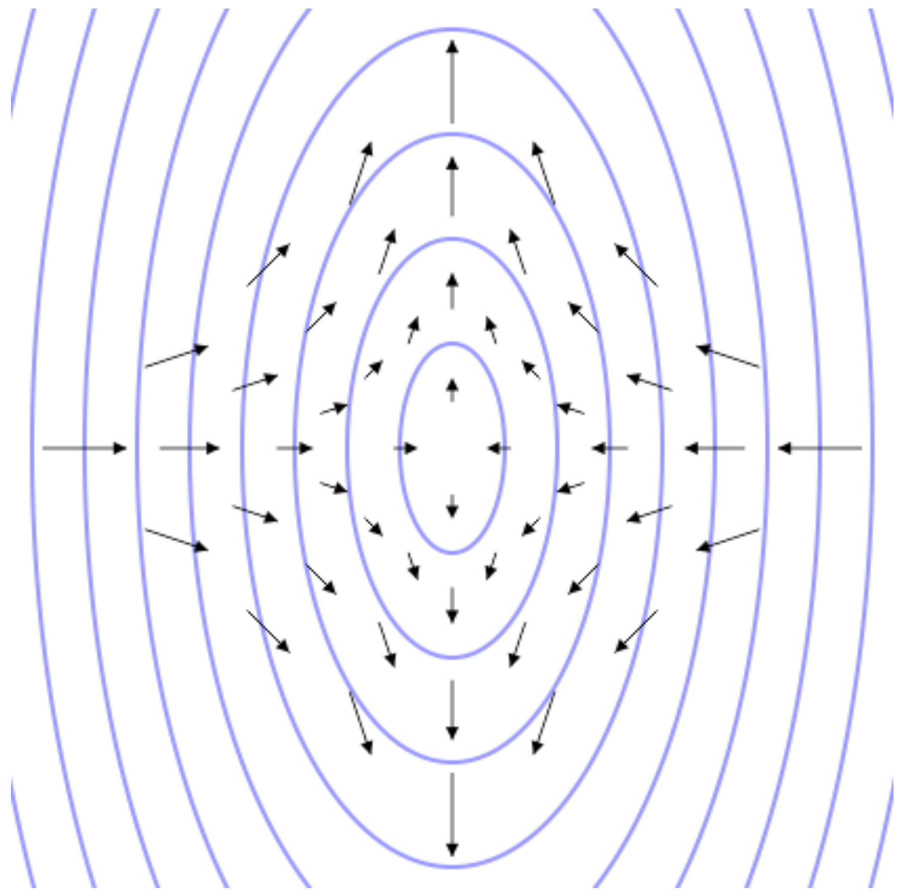
+

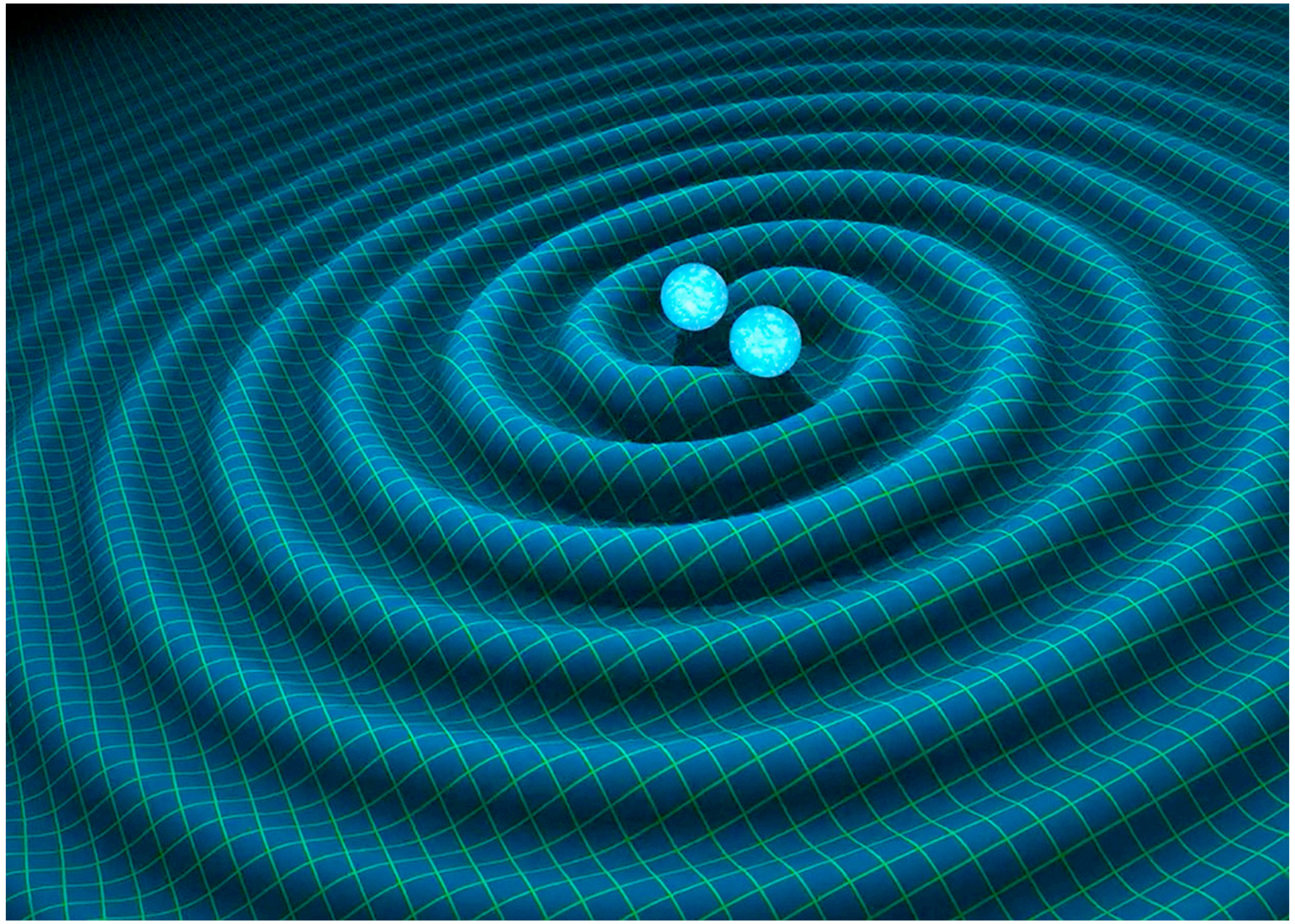


X



Quadrupole structure





Maxwell equations on variably curved space time

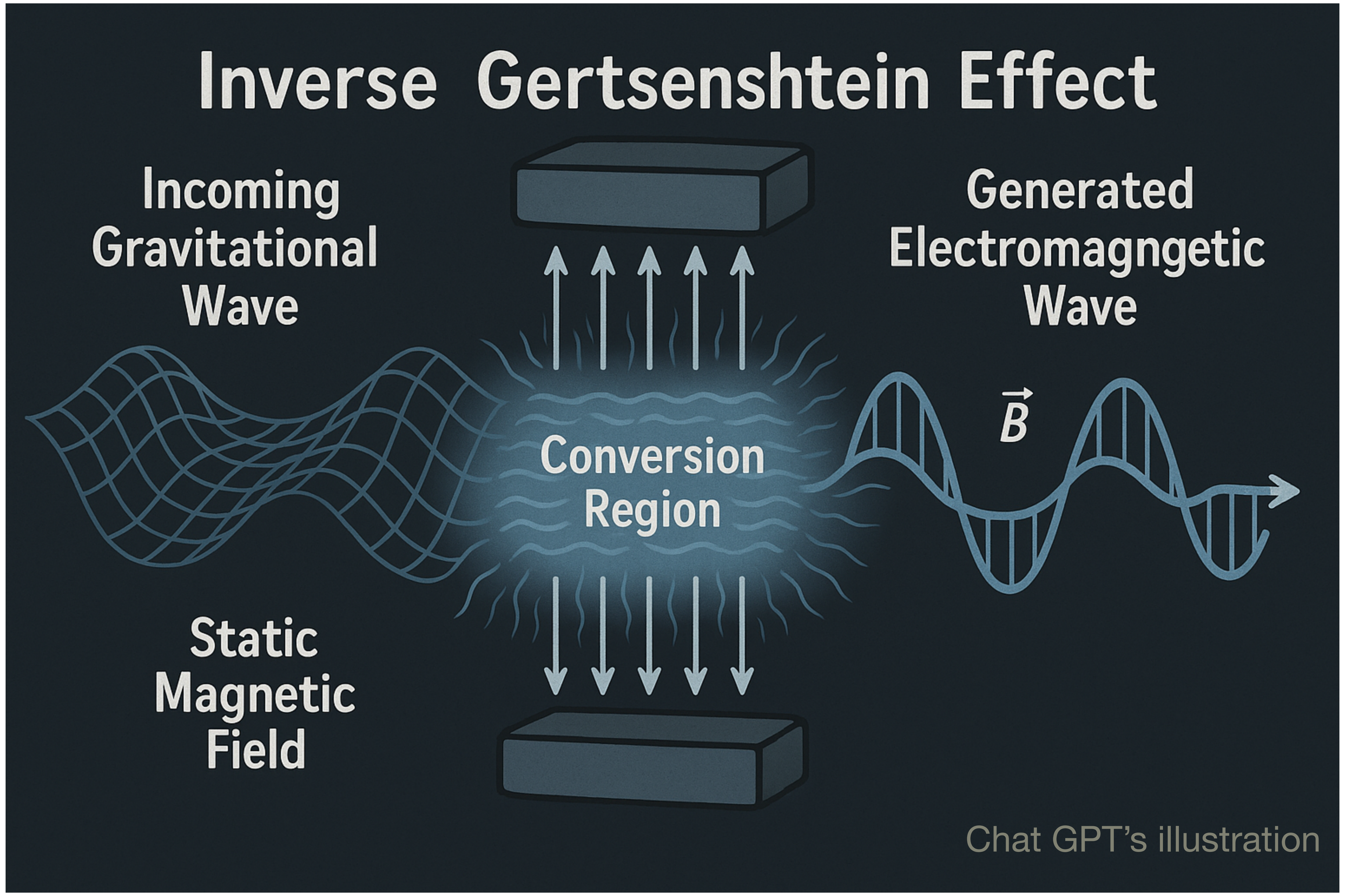
- Periodic compression of B-field $\propto hB$

$$\rightarrow \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \neq 0$$

$$E_x \simeq = \frac{A_+}{2} B_y^0 e^{i(k_g z - \omega_g t)} = \frac{h_+}{2} B_y^0$$

- Two polarisations of GW

$$h_+ = A_+ \, e^{i(k_g z - \omega_g t)}, h_\times = i A_\times \, e^{i(k_g z - \omega_g t)}$$



Gravitational & Electromagnetic Waves

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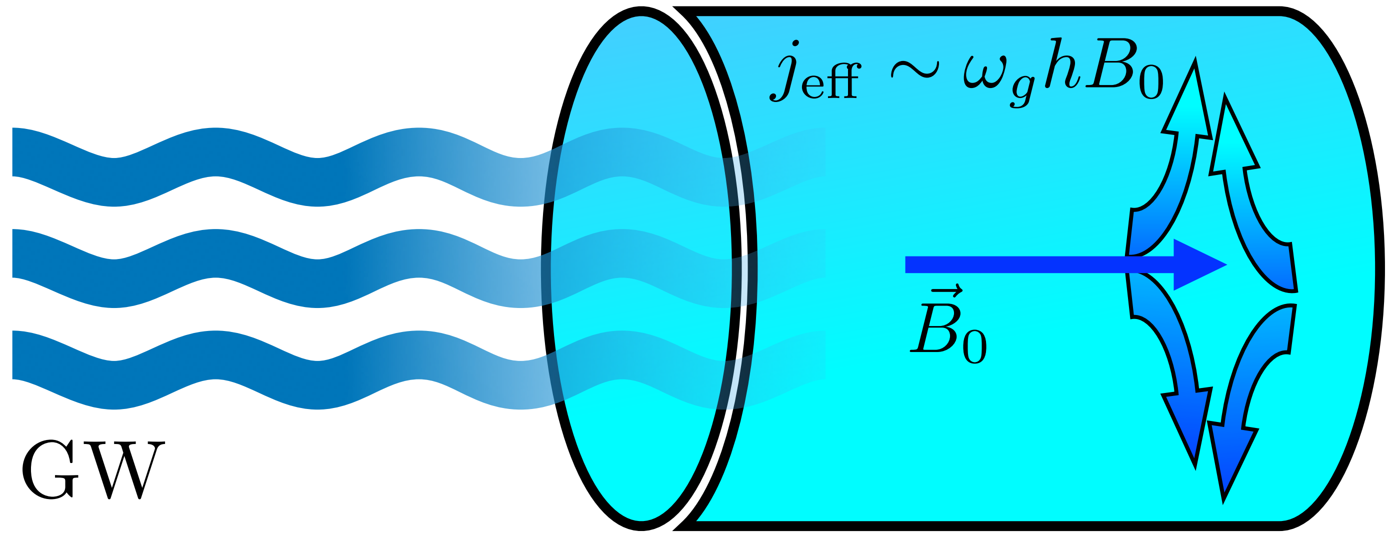
- GW leads to source of **effective current** in Maxwell's equation

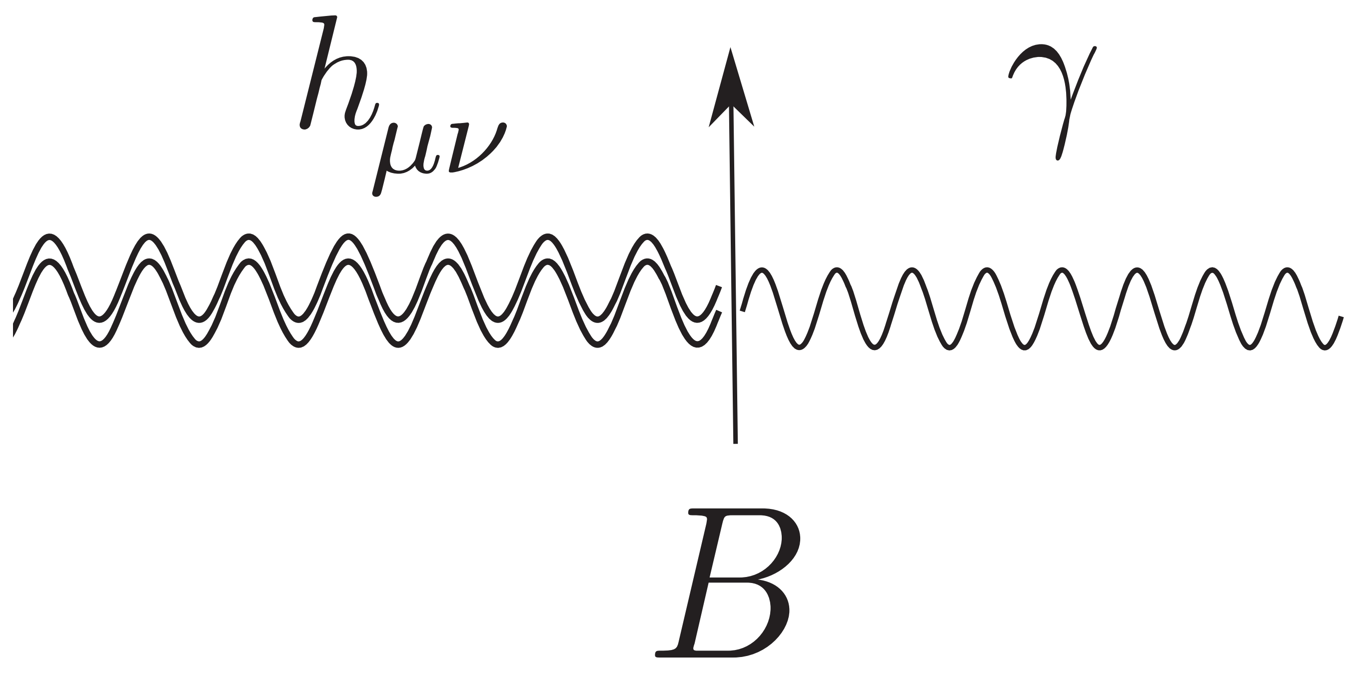
$$j_{eff} \propto \omega_g h B_0 e^{i(k_g z - \omega_g t)}$$



- Conversion of GW energy into Photons and vice-versa!
- => **GW can excite EM field** within RF resonator!
- If signal duration long enough: exploit **resonance enhancement**

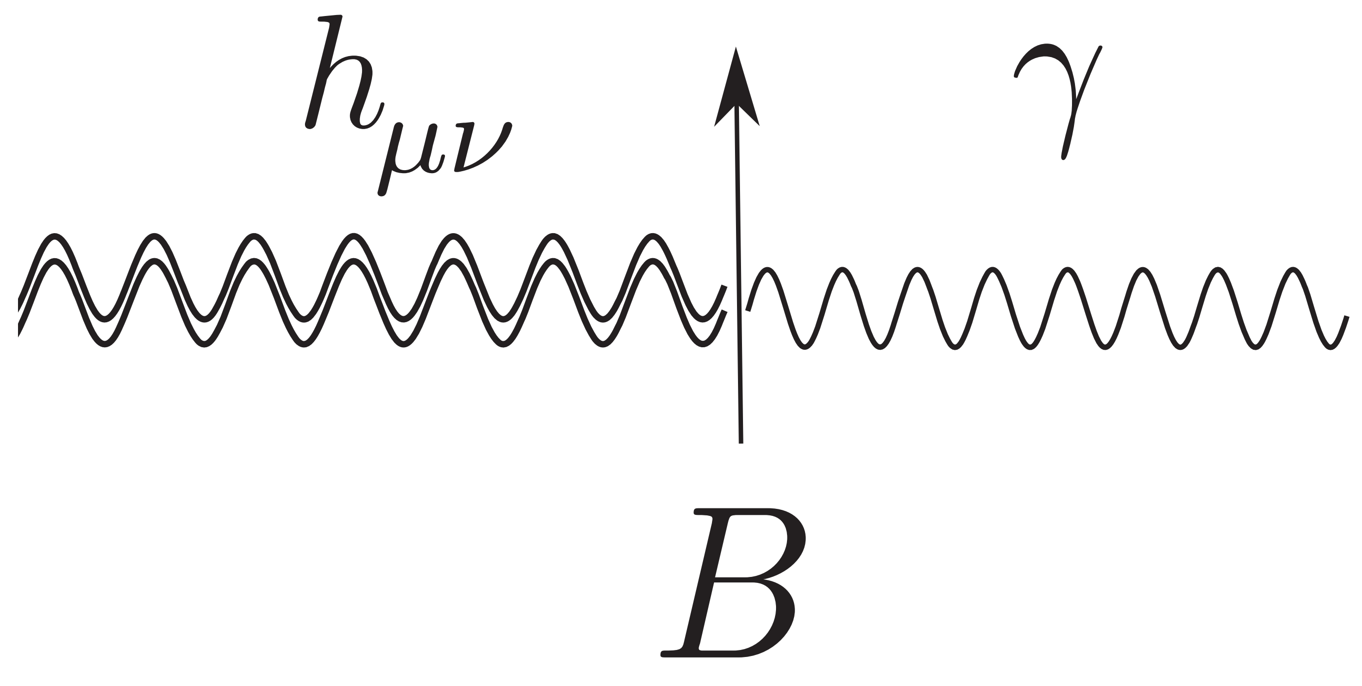
Gravitational Waves & Haloscopes

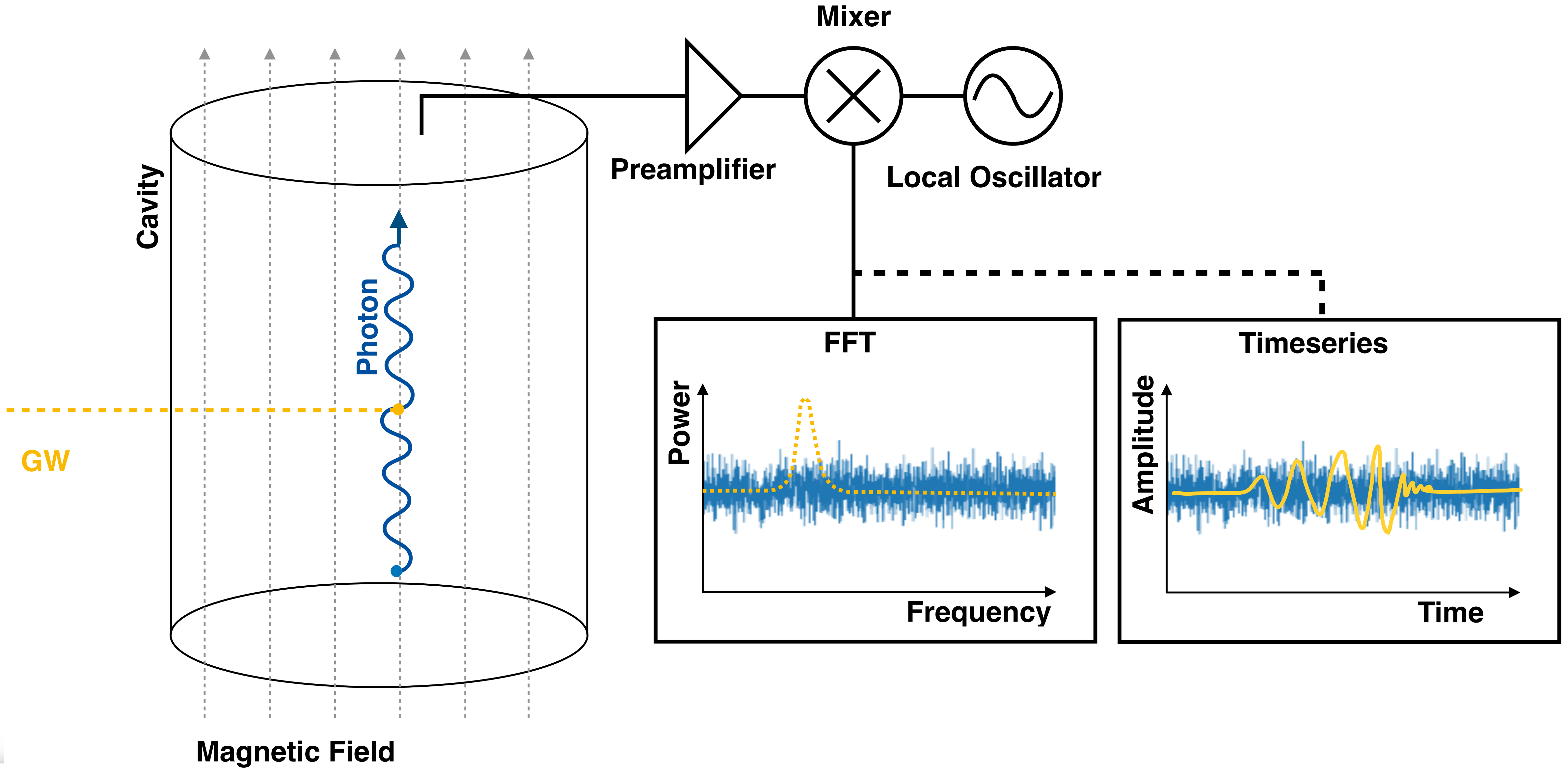
- Direct conversion of GW to photons: **inverse Gertsenshtein effect**
  - Gertsenshtein effect described 1962
  - Inverse effect calculated in 70ies
    [Ya. B. Zel'dovich]
  - White-paper on HFGW detection: 2020
    [Living Rev. Rel. 24 (2021) no.1, 4]
    Update 2025: arXiv:2501.11723



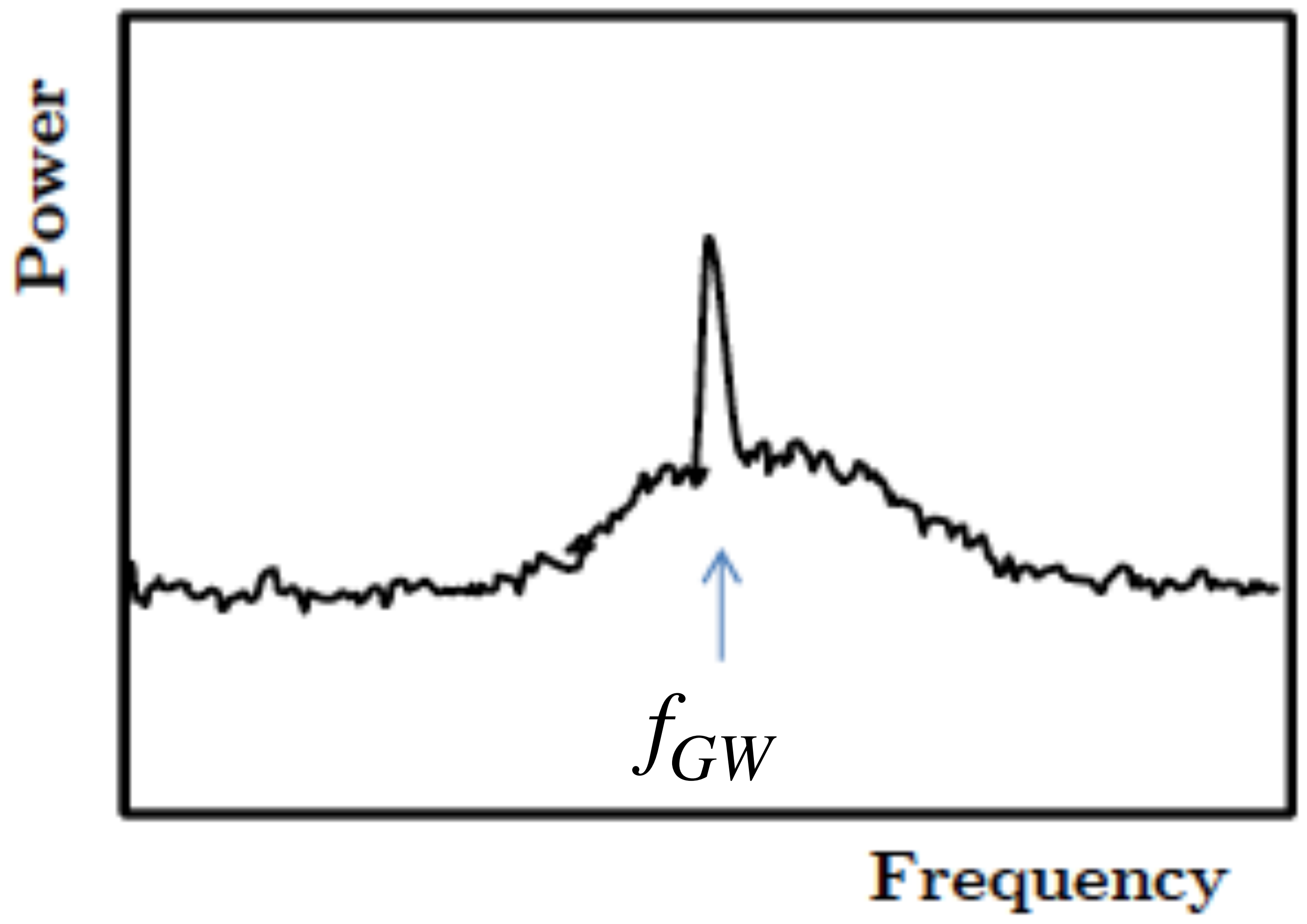
How can this be used to detect GWs ?

Typical setup





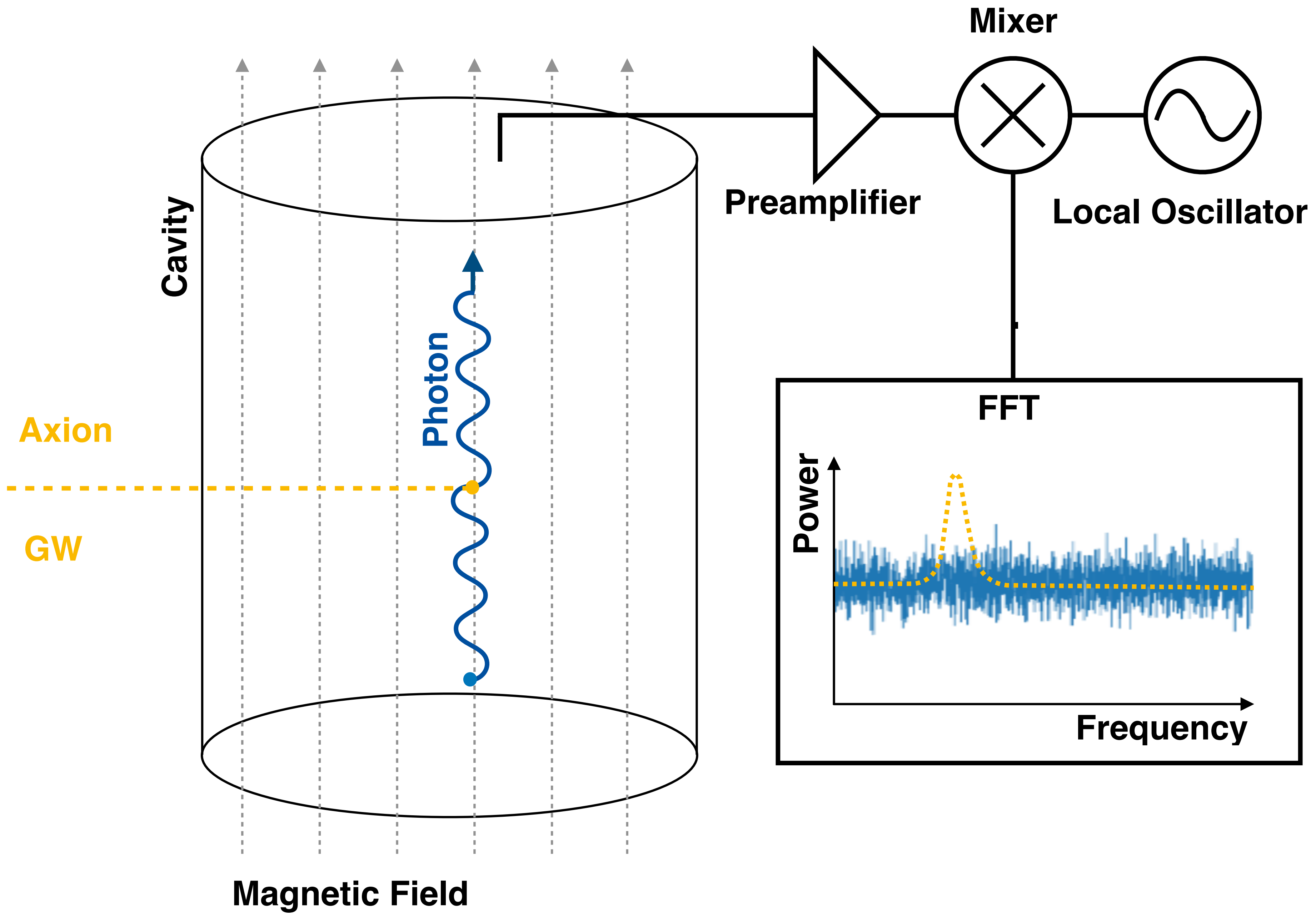
- Electromagnetic field => B-Field
- Resonant enhancement of signal => RF-resonator
  - Narrow band experiment
- Noise suppression => Cryogenic setup
- High sensitivity => Low Noise, high gain DAQ



Typical setup - Connection to Axion searches

- **Same technological challenges**
  - High field magnets
  - Ultra low noise amplifier
  - Highly sensitive readout systems

- **Fundamentally different signal properties**
  - Duration
  - Coupling of GW and B-field:
    - Orientation
    - Cavity geometry
    - Sensitive Mode



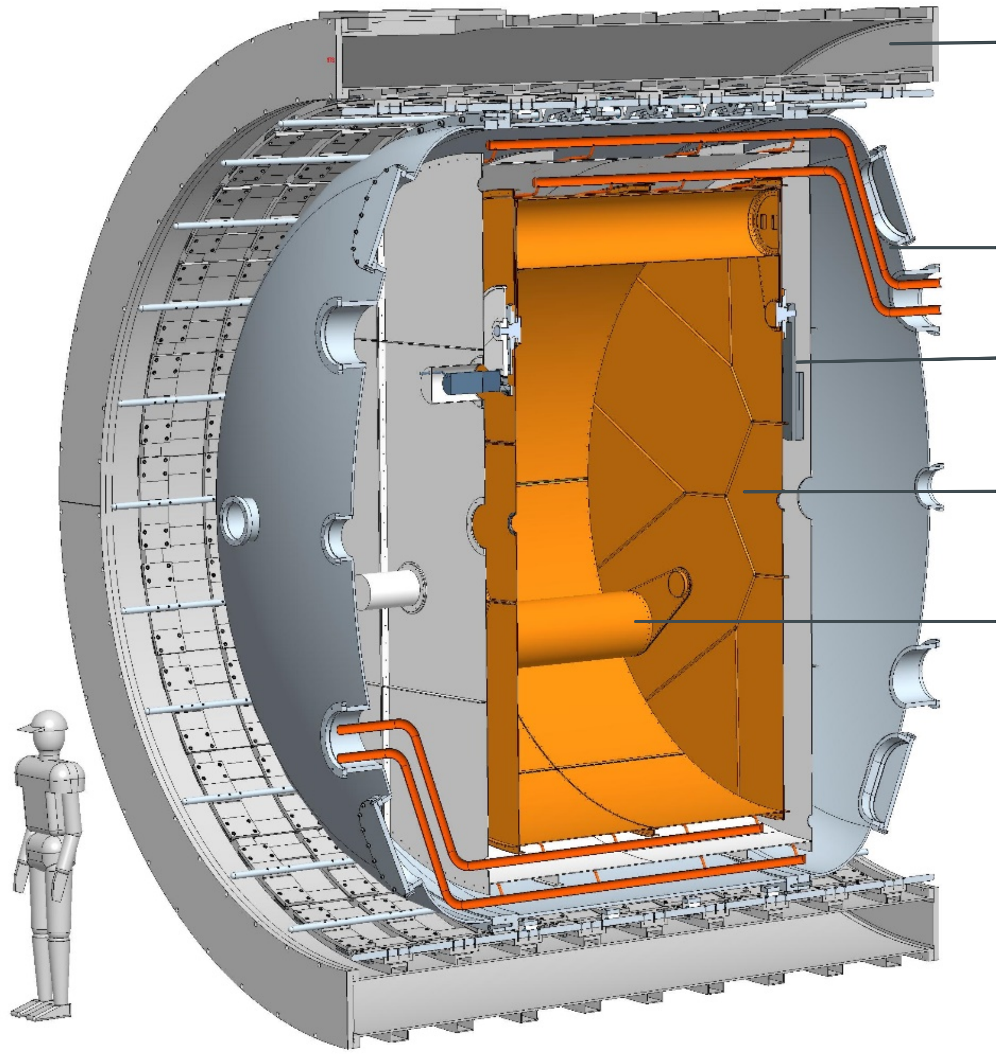
- Suspicious similarity with **axion haloscopes**
  - Indeed: Identical setup

Typical setup - Connection to Axion searches

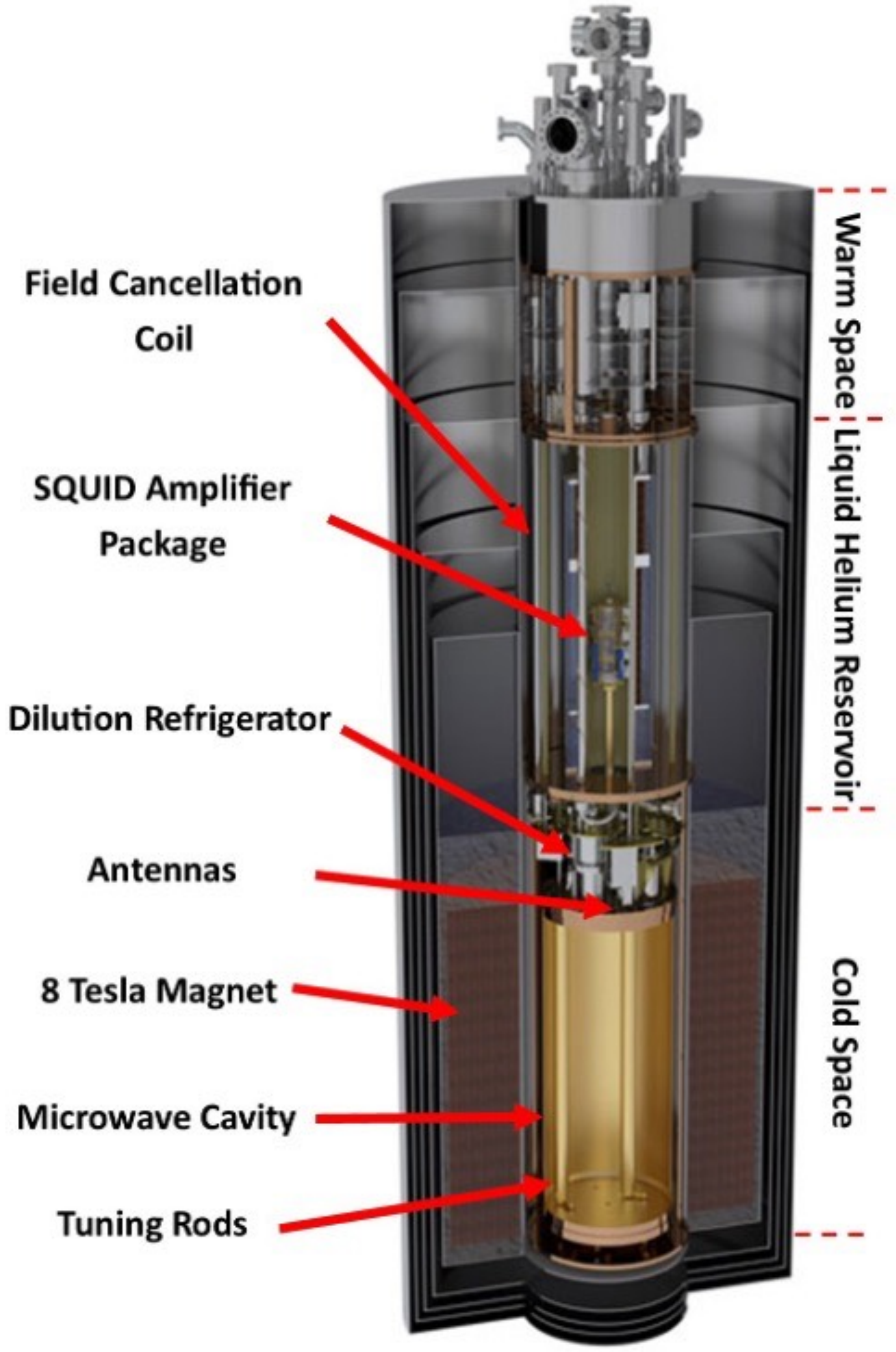
Well established experimental method

Flash

100 MHz



ADMX 1 GHz



Organ

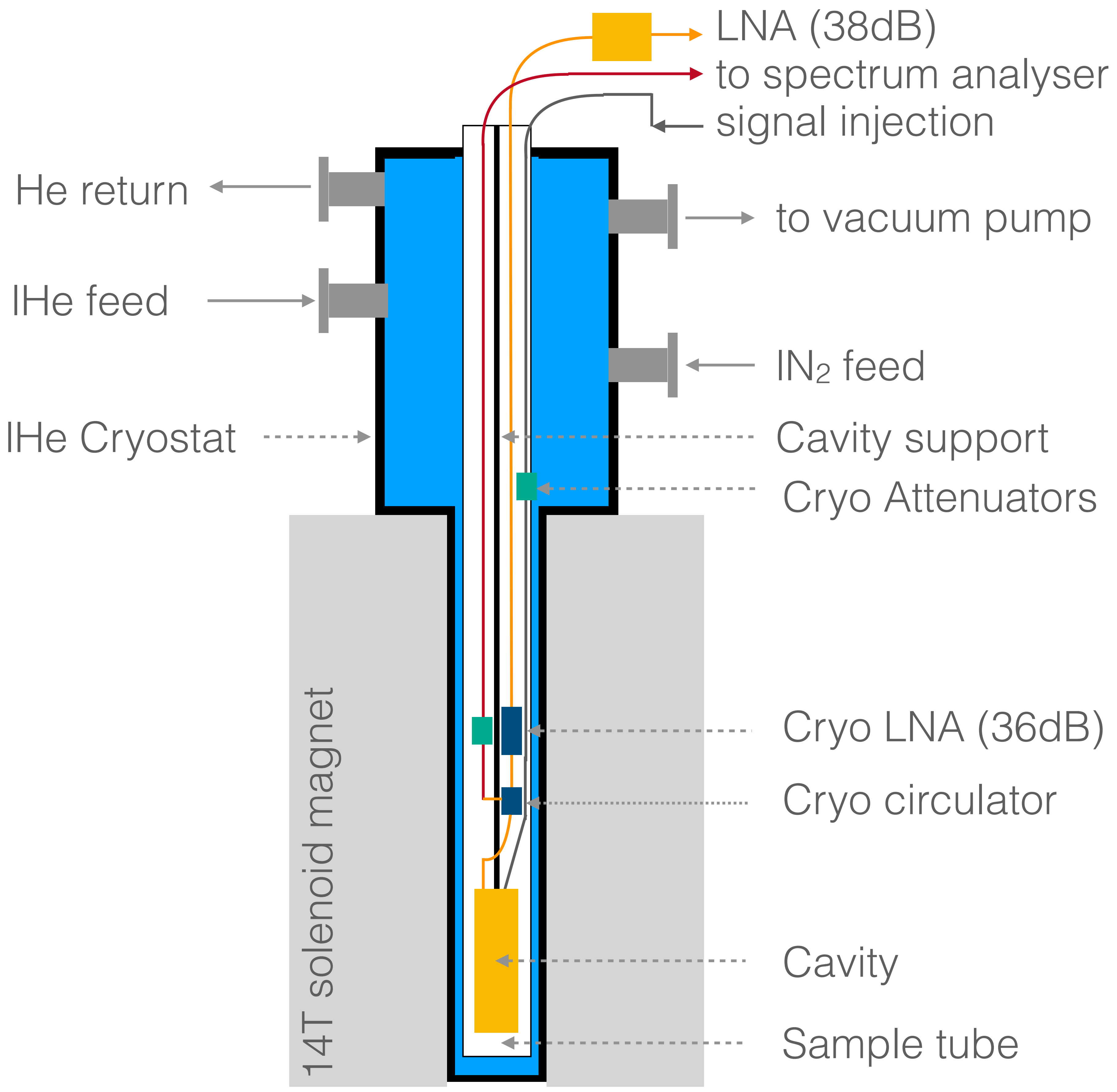
100 GHz

What was done at Mainz

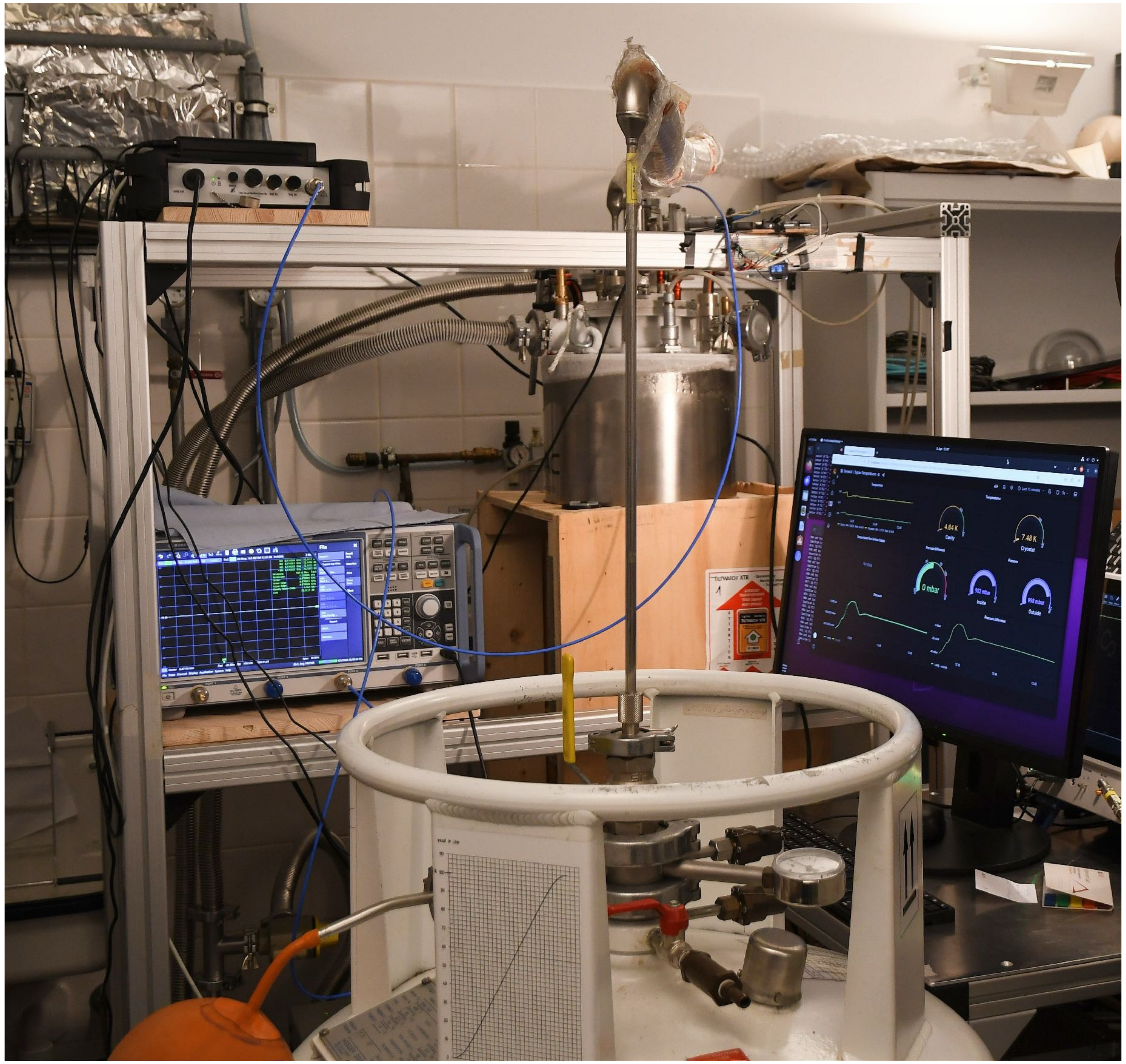
[arXiv:2308.08337]

- **Setup at Mainz (finished):**
  - 13T B-field, 2K, SC cavity, HEMT amplifier
  - Data taken in 2024
  - Dark Photon & Axion results

- **Supax:** superconducting axion search @ Mainz
  - First results on dark photons (~commissioning) [arXiv:2308.08337]
  - **Goals**:
    - Study of new **SC materials** for resonant cavity experiments
    - Study of **cavity geometries** optimised for **GW** searches
      - Together with Mainz theory section (P. Schwaller)



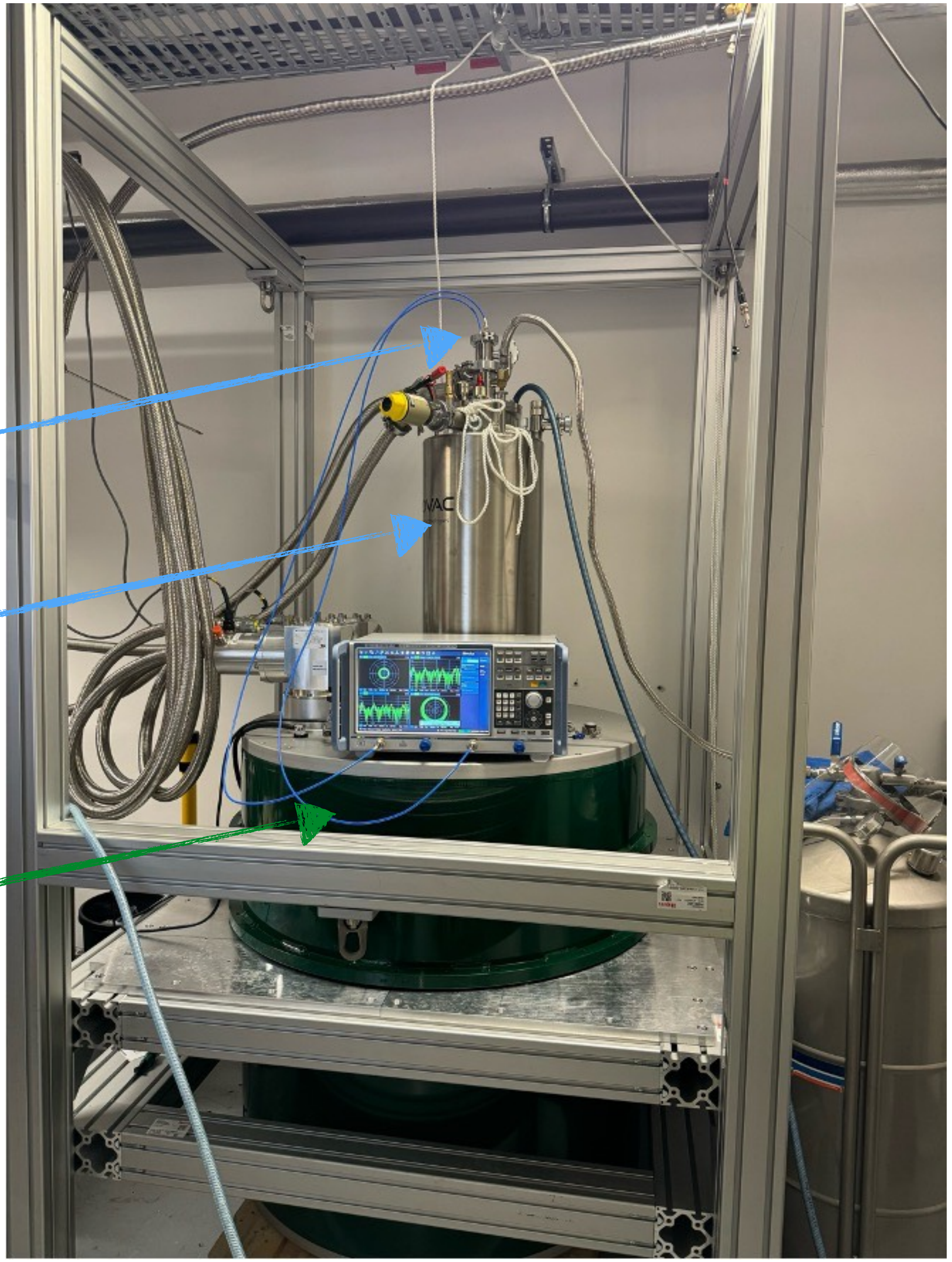
Supax / GravNet - Measurements



Inset Top

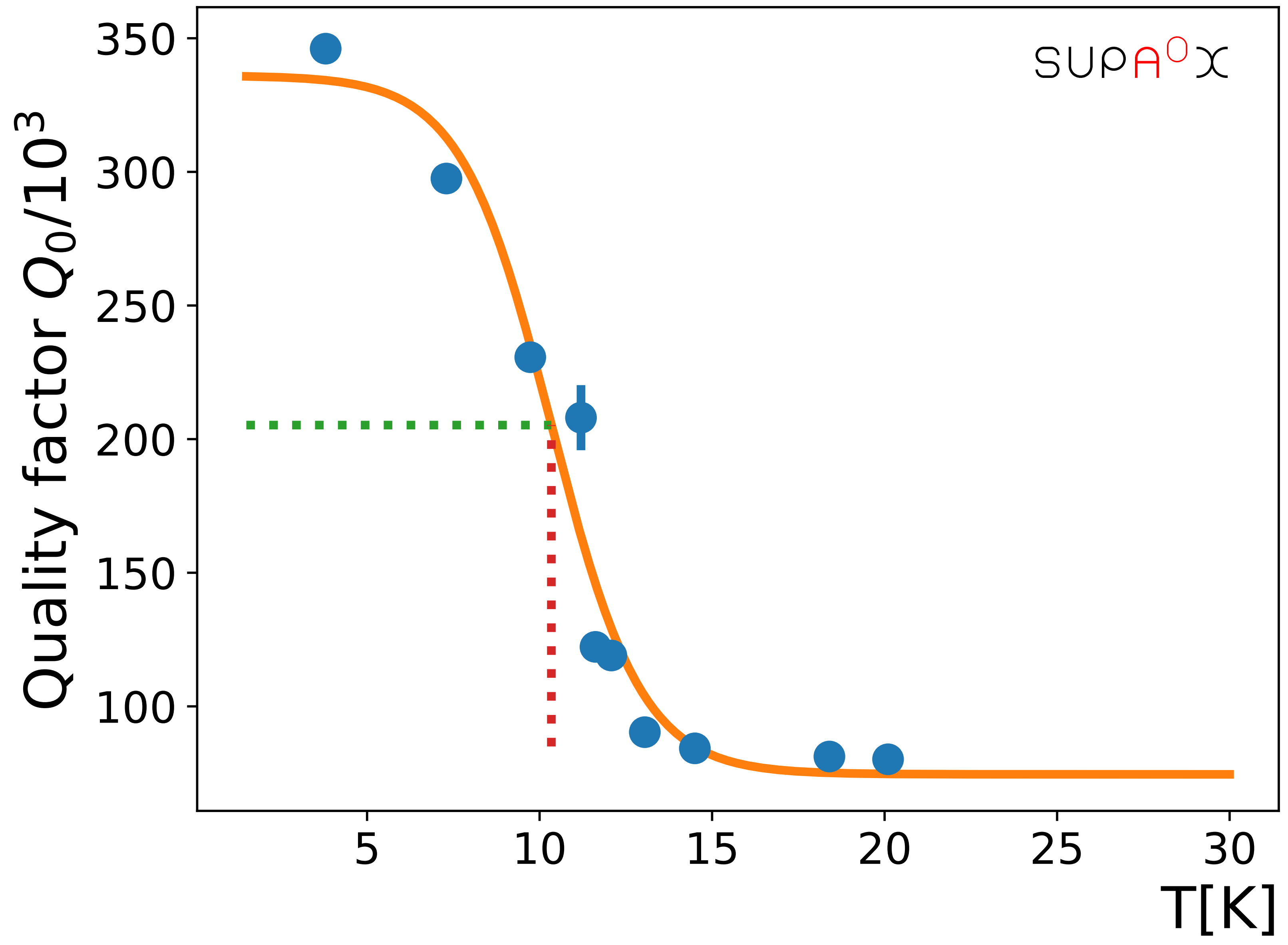
Cryostat

Magnet
(warm bore)

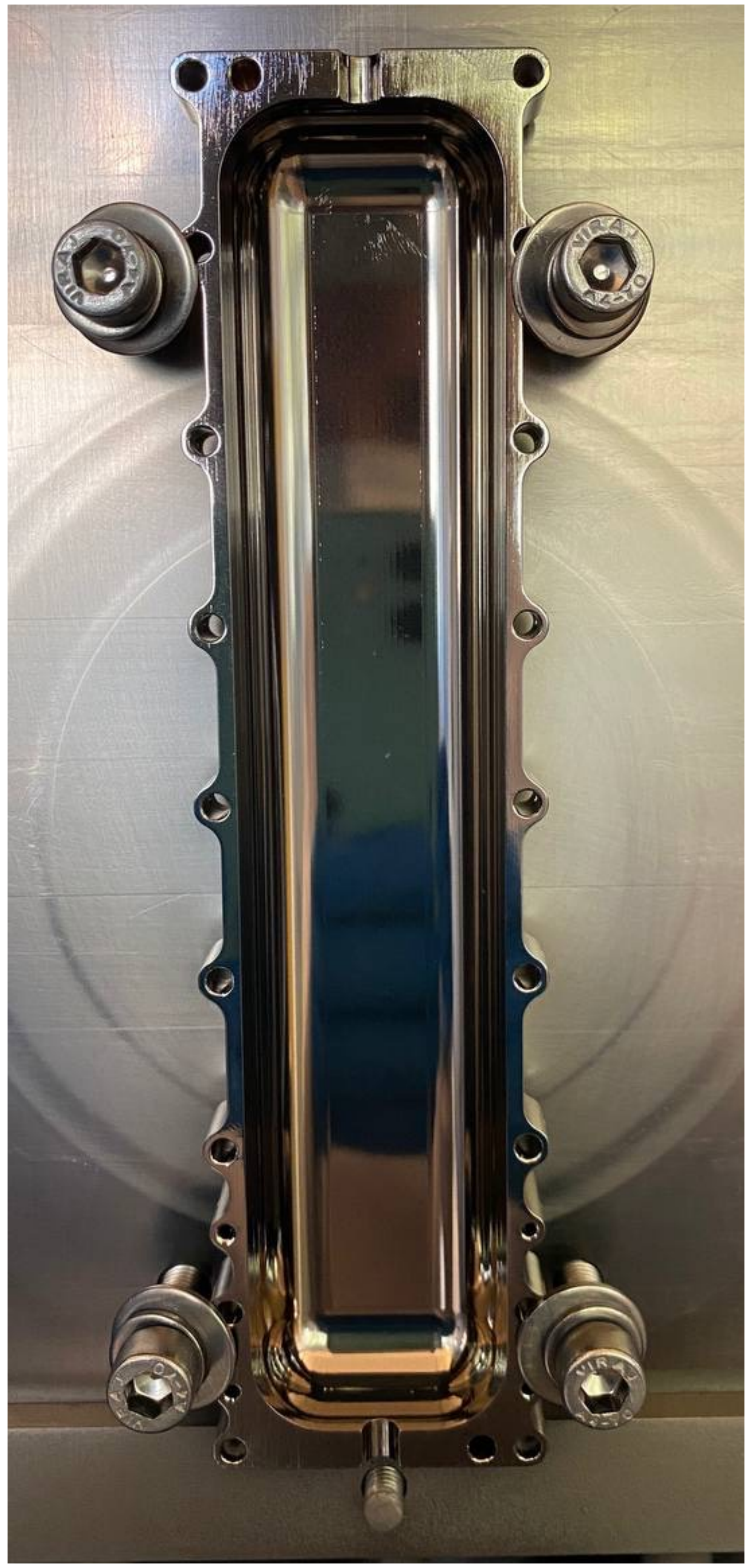


Supax / GravNet - Cavities

- Test of various cavity geometries and coatings



Cu coated with NbN
Coating by Zubtsovskii @ Uni Siegen



Sources of HF GW

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- **Working setup**
- Sensitive to HFGW (~ GHz)
- Which **sources** can be seen?
- Is there anything emitting GHz gravitational waves?

Sources of HF GW

- What about: **Black hole merging events**
  - Chirp signals
    - $m_{BH} \sim O(10 M_\odot)$: frequency in acoustic range

$$f \approx 100\,Hz \rightarrow m_{BH} \approx 30\,M_\odot$$, Duration: $0.1s$

- Lighter BHs => higher frequencies

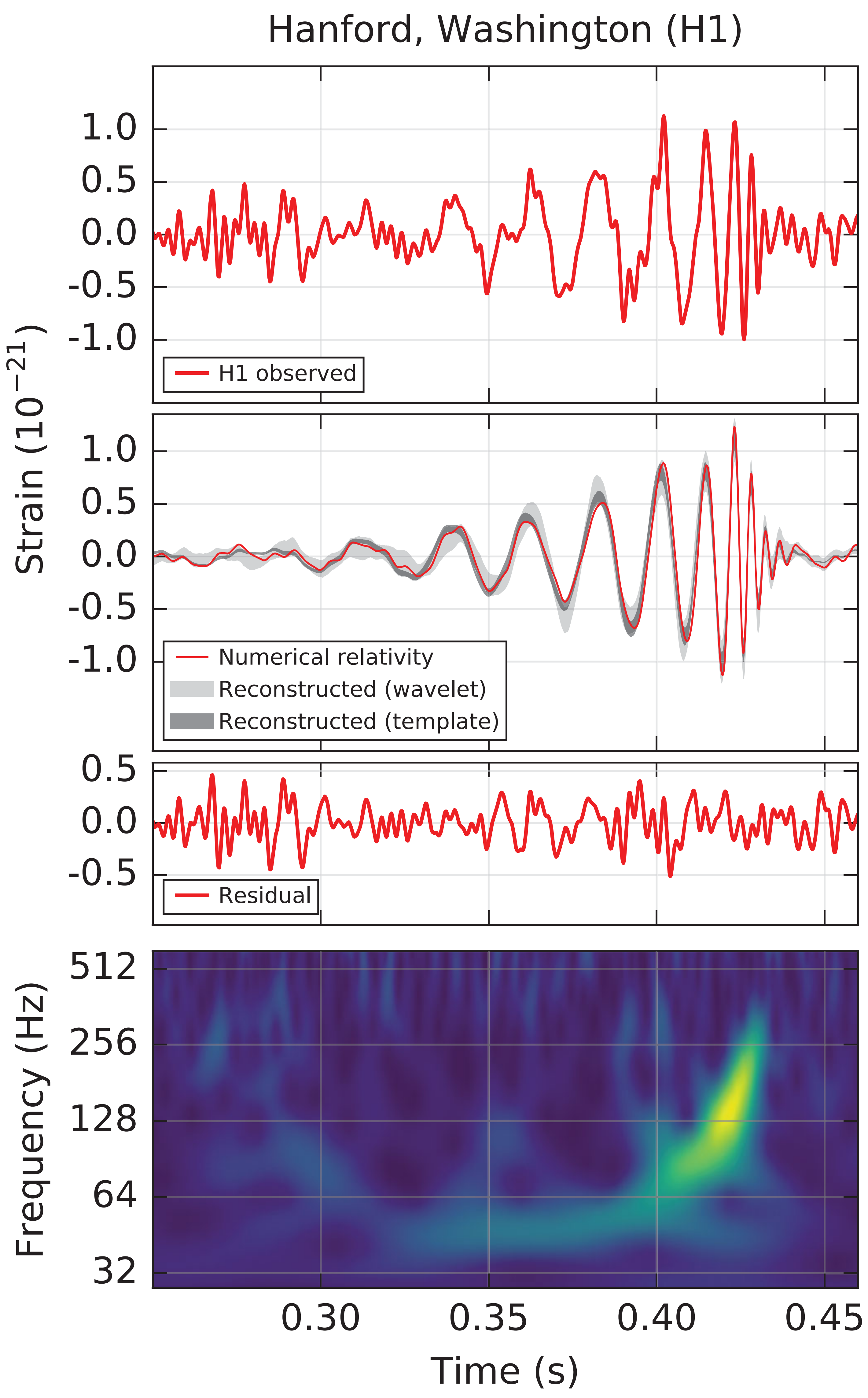
Lower BH **mass**

Lower merger **duration**

Higher GW **frequency**

$$f \approx GHz \rightarrow m_{BH} < 10^{-6} M_\odot$$, Duration: $< \mu s$

- Frequency range: 10-1000 Hz



PRL 116, 061102 (2016)

Sources of HF GW

Any issues with black hole masses of $10^{-6} M_\odot$?

- Chandrasekhar limit: Up to 1.4 $M_\odot$ white dwarfs are stable
- Tolman–Oppenheimer–Volkoff limit: Neutron stars stable up to 2 - 3 $M_\odot$
  - Corresponding to stellar progenitor masses O($10 M_\odot$)

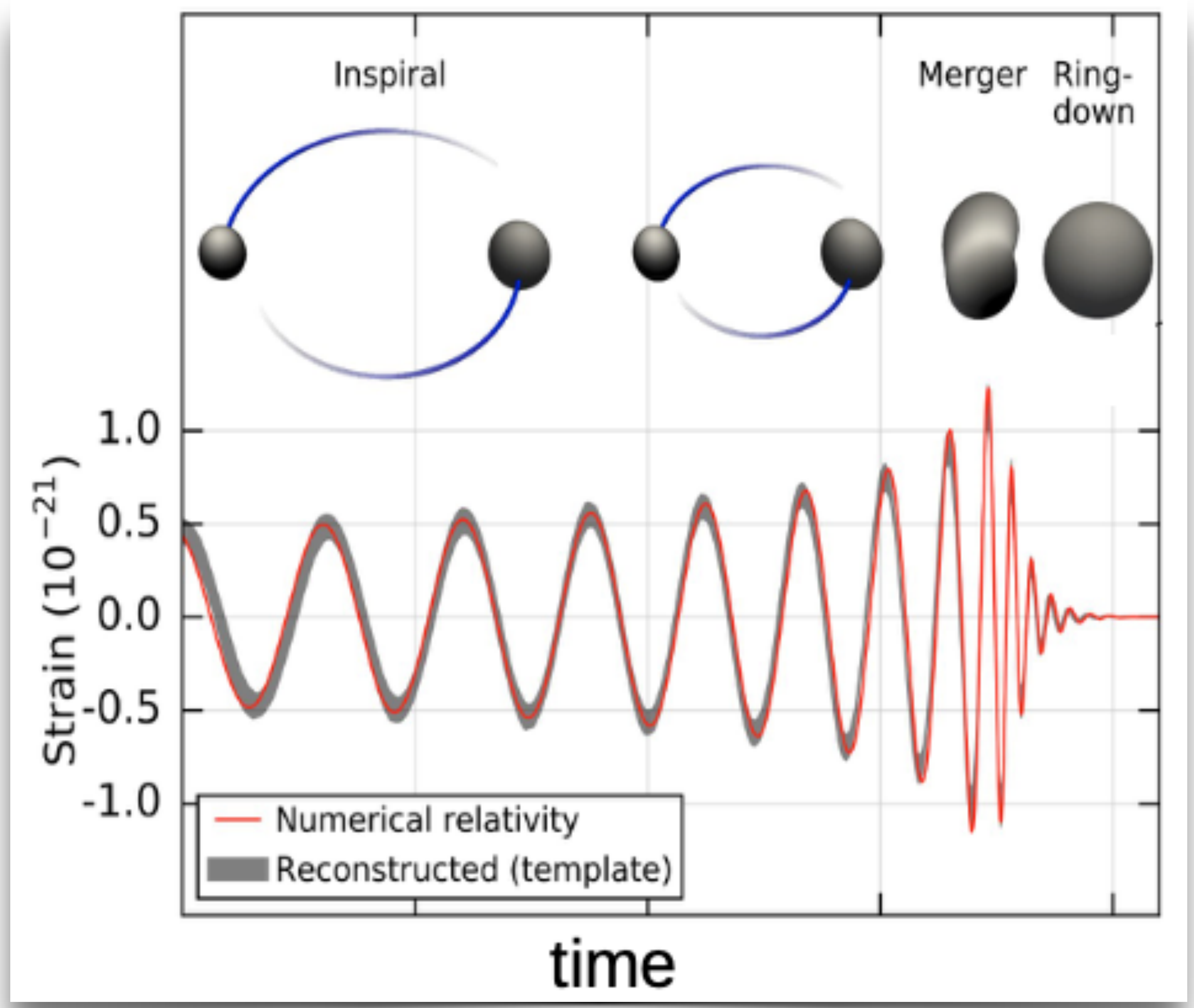
Lightest BH should be around $2 - 3\, M_\odot$

(Lightest currently observed: $3\, M_\odot$)

Sources of HF GW

- **Primordial black hole mergers**
    - Hypothetical BHs created shortly after the big bang, before the first stars were formed
    - Not limited to the mass range of stellar BHs
- **Formation**:
    - Small scale perturbation in early universe
    - Amplitude of space-time curvature perturbations enhanced by some mechanism
    - Perturbation freeze in during inflation
    - Post-inflation collapse if larger than some threshold
        - Population of PBHs
        - Masses controlled by energy in one Hubble volume

- Merging event very short, unknown frequency
- Focus on inspiral:
    - Sweep of huge frequency span



Sources of HF GW - Primordial Black Holes

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- Sources for HFGWs:
  - **Primordial black hole mergers**
  - Boson clouds (BH superradiance)
  - …

Primordial black holes:

- Black holes created in the early universe
  - Unlike stellar BH: No minimum mass requirement
  - Expected Mass range: 10^{-10} - 10^{-16} $M_\odot$
  - Density unknown
- Merging events expected
  - Low mass -> High frequency
  - Fast transients (μs - ms)

Why are PBH interesting objects?

Could be dark matter

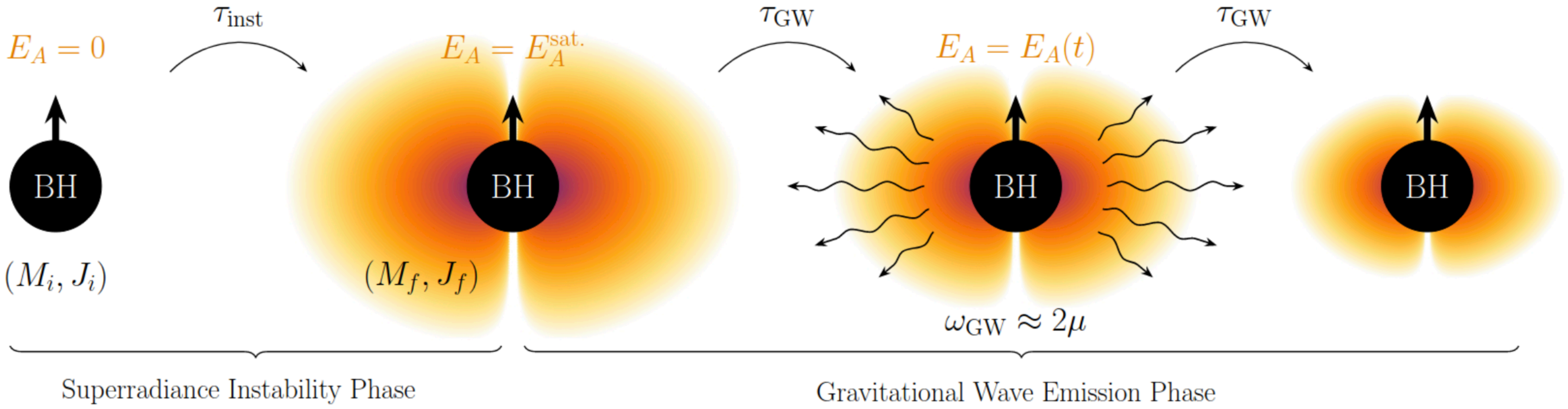
- Expected Strain: $< 10^{-24}$
  - (If all of DM is PBH, one event per year)

Sources of HF GW - Axion Superradiance

- Sources for HFGWs:
  - Primordial black hole merges
  - **Boson clouds (BH superradiance)**
  - …

Axion superradiance:

- Compton wavelength of boson = size of BH
  - Boson accumulates outside BH event horizon
  - Annihilation into gravitons if mass > threshold
    - $\omega_a < m\Omega_H$



Sources of HF GW - Axion Superradiance

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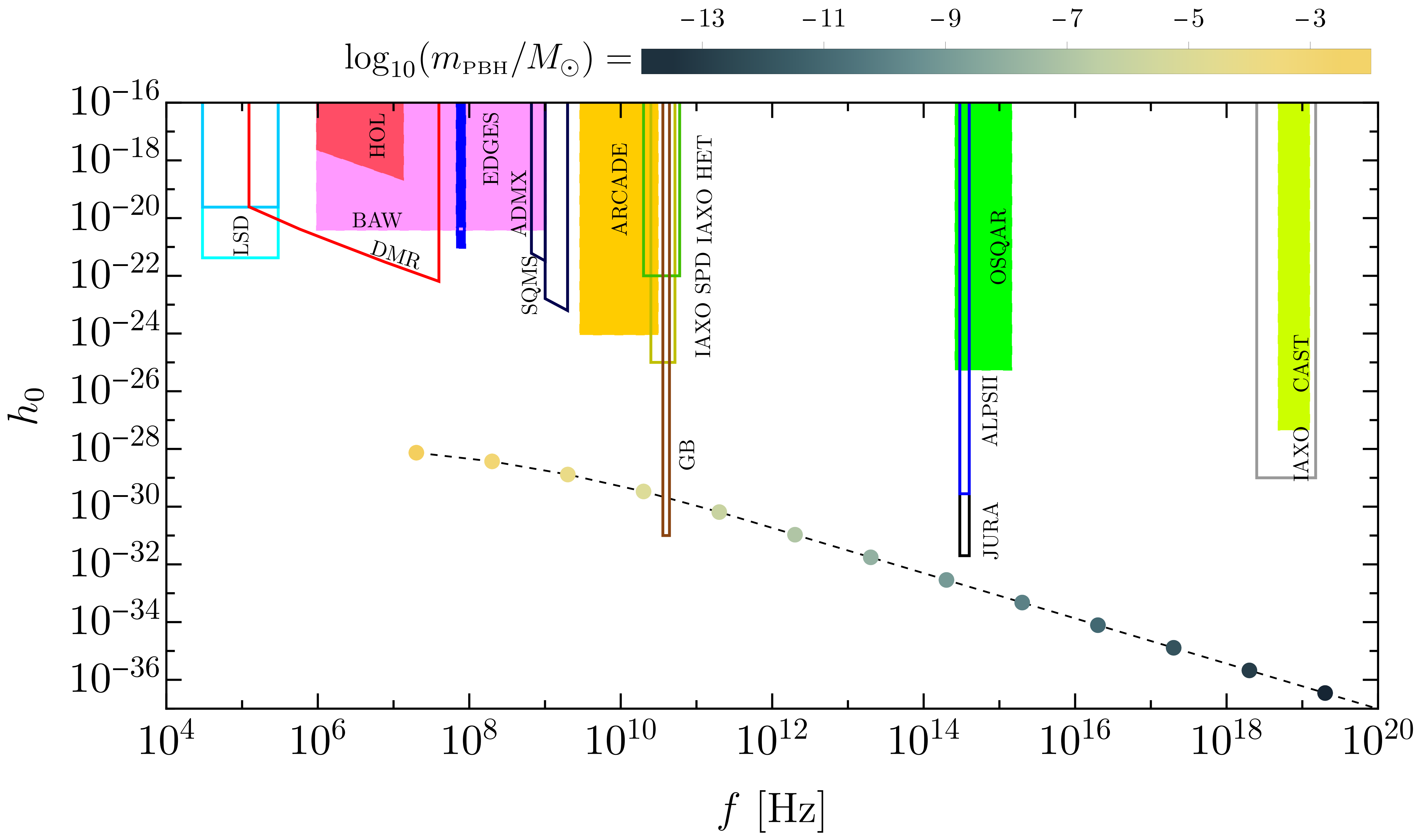
- Sources for HFGWs:
  - Primordial black hole merges
  - **Boson clouds (BH superradiance)**
  - …

Axion superradiance:

- Compton wavelength of boson = size of BH
  - Boson accumulates outside BH event horizon
  - Annihilation into gravitons if mass > threshold
- Requires **light, spinning BHs**
- Requires **axion (-like) bosons**

- **Monochromatic**, coherent signal!
- **Decay times of min. to years** (depending on BH mass)
- Strain assuming distance = radius of sphere with one event per year



Sources of HF GW - Stochastic Background

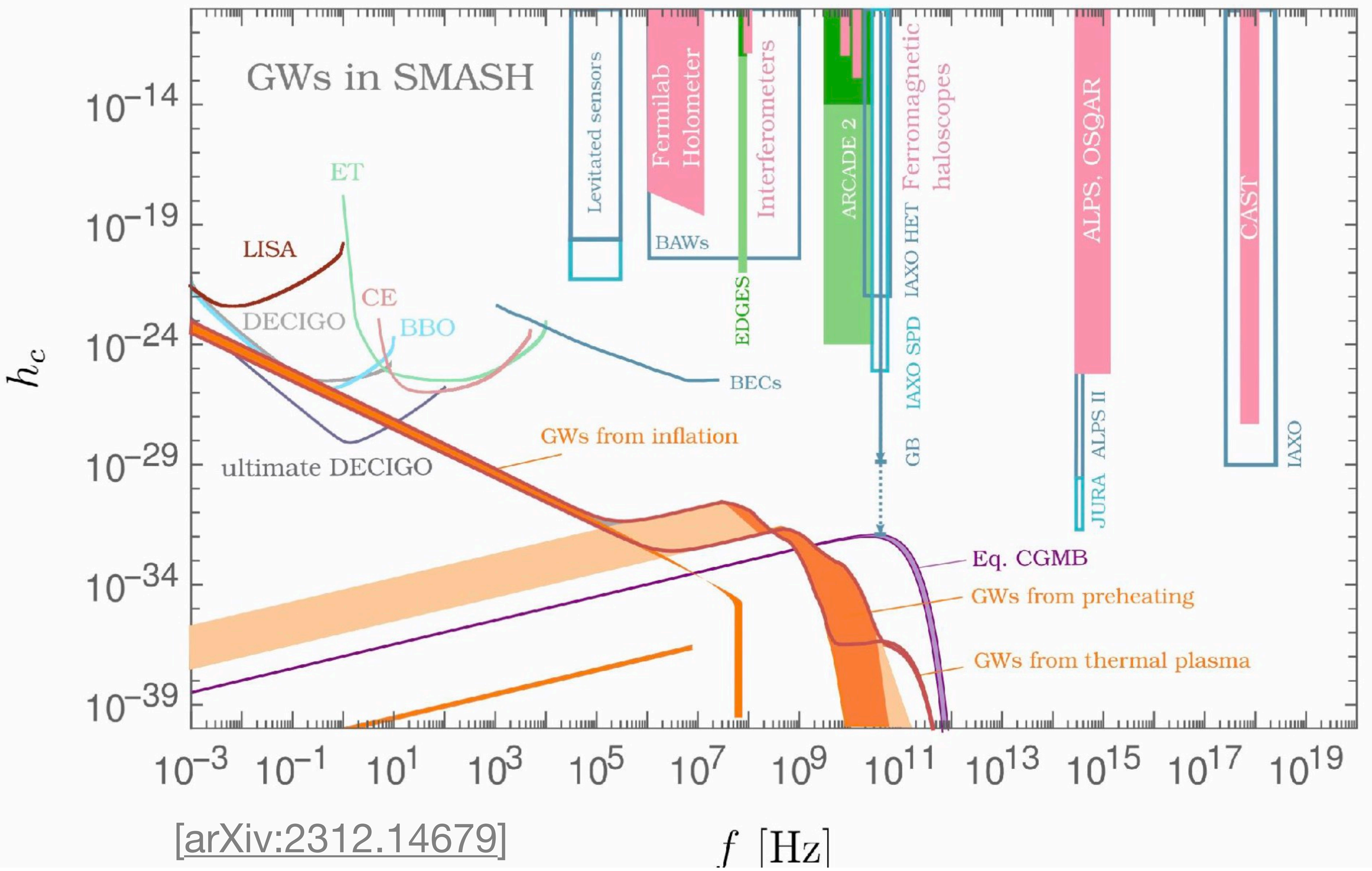
- Sources for HFGWs:
  - Primordial black hole merges
  - Boson clouds (BH superradiance)
  - **Stochastic GW sources**

Very low strain expected:

$$h_0 < 10^{-32}$$

Several sources possible:

- Phase transitions in the early universe
- Dynamics of inflation and subsequent (p-)reheating
- Fluctuations in the thermal plasma
- Cosmic strings



[arXiv:2312.14679]

High Frequency Gravitational Wave - Strains

Expected Strain

- Primoridal black hole mergers
  - Chirp signals
- $h_0 < 10^{-24}$

- GW from boson superradiance
  - Monochromatic over long timescales
- $h_0 < 10^{-29}$

- Stochastic GW background
  - Even lower strains …
- $h_0 < 10^{-32}$

Observed Strain

- Ligo / Virgo Signals
  - BH mergers
- $h_0 < 10^{-21}$

Expected Sensitivity:

- 1 cavity
- T = 100 mK
- B = 12 T
- f_0 = 8 GHz

$$h_0 > 10^{-21}$$

How to improve the sensitivity?

GravNet in the next years

A Global Network of HFGW Detectors

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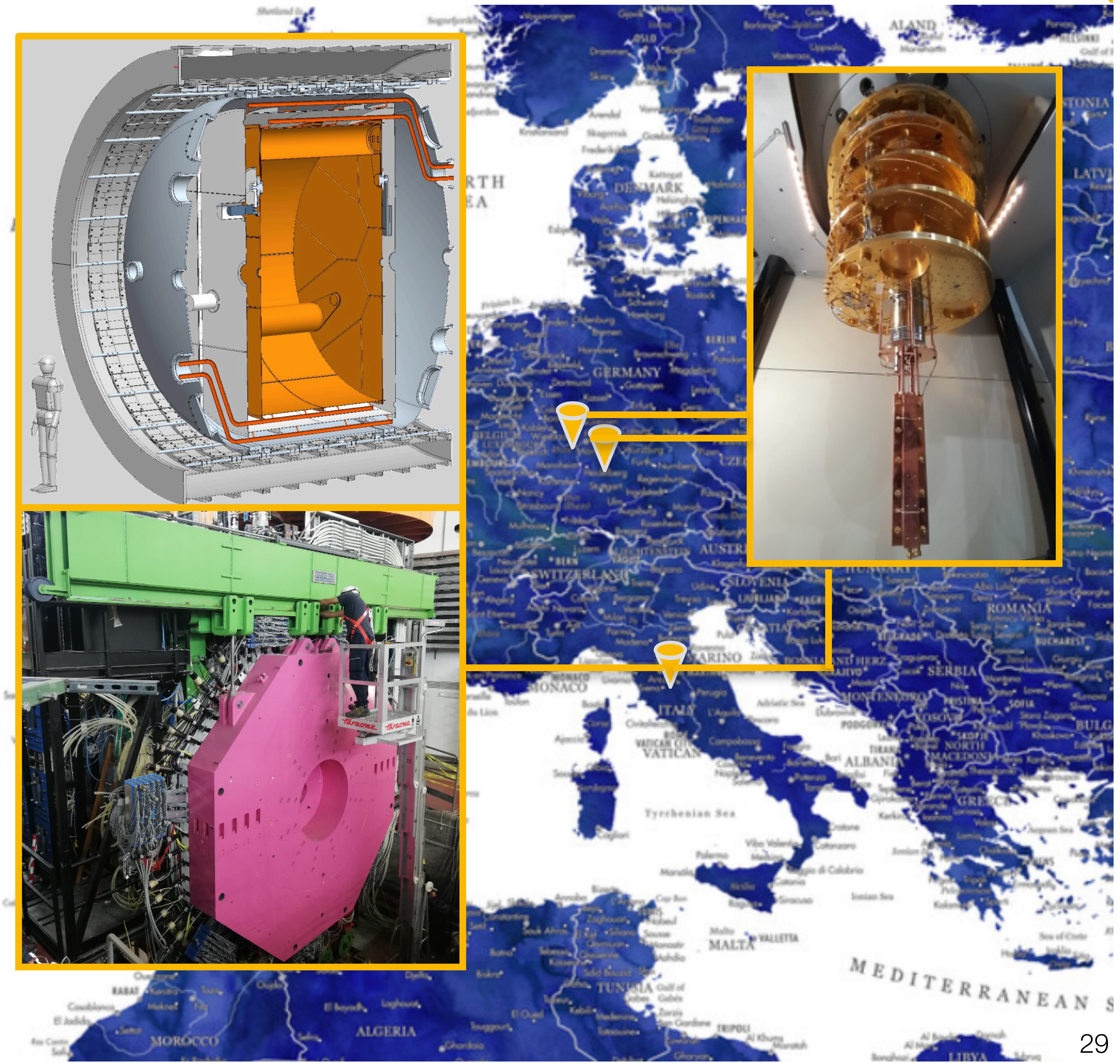
- Starting point of GravNet
  - Initial sites: Bonn, Mainz, Frascati
  - Technical synergies: magnets and local infrastructure already available
- GPS based data-acquisition scheme
  - Experience from GNOME Network
- Nine small resonant cavities (5-8 GHz)
  - Operation of three cavities in one magnet
- One large resonant cavities (100 MHz)



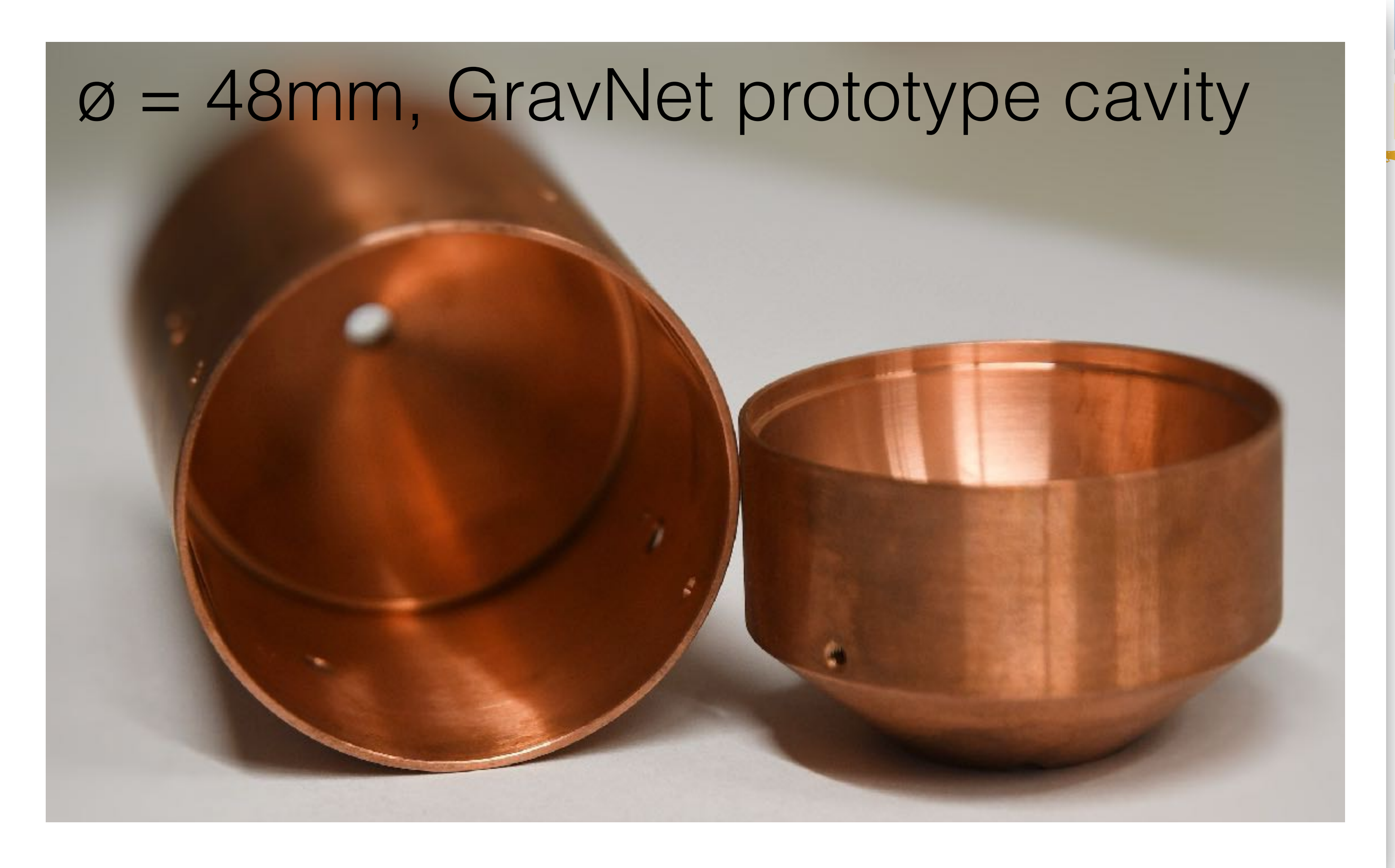
A Global Network of HFGW Detectors

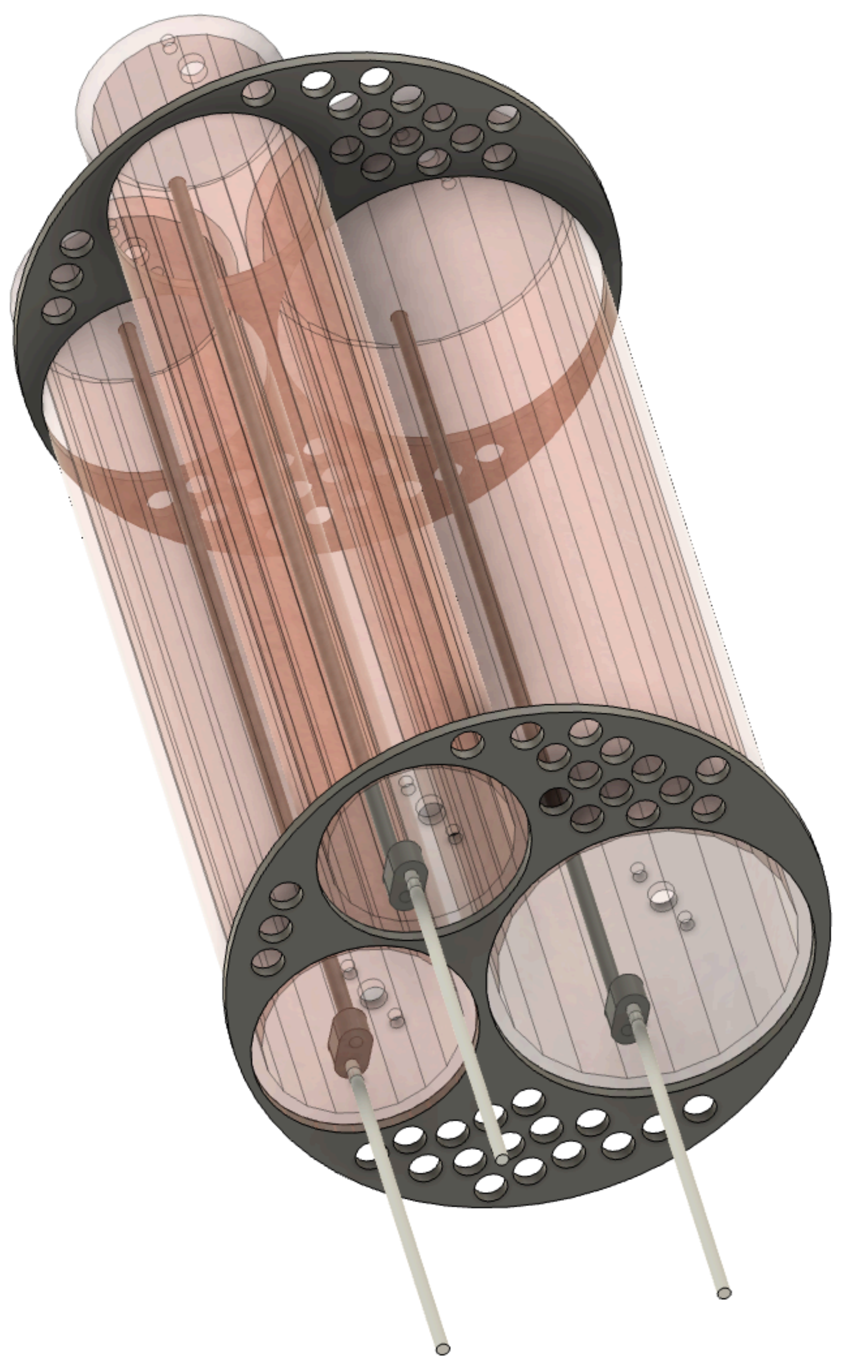
- **Example**: 8 GHz corresponds to a sphere of diameter ≈ 5cm
  - High frequencies typically correspond to small volumes

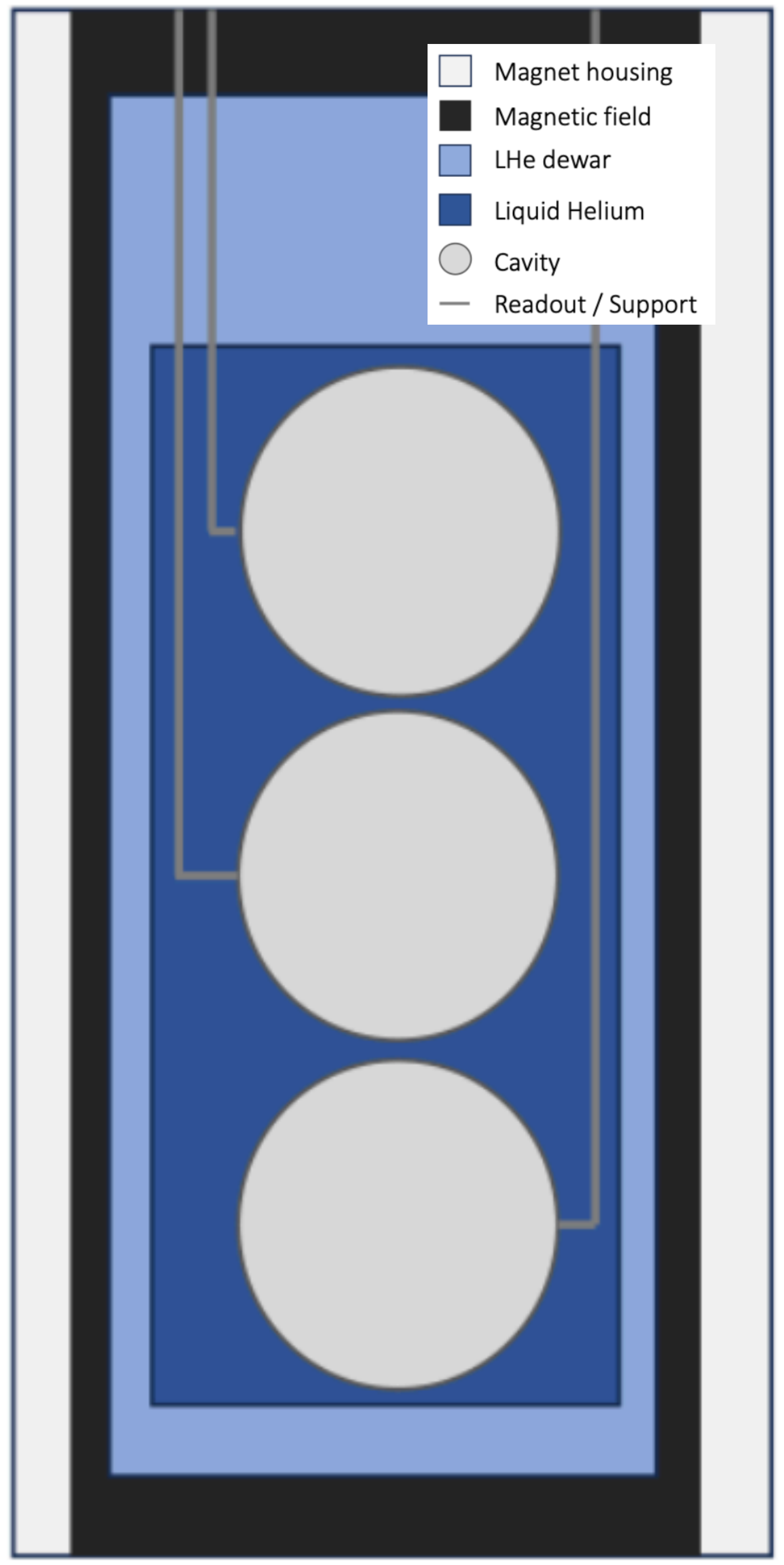
- **Challenge**: Signal power depends nearly quadratically on volume V

$$P_{sig} = \frac{1}{2} Q \omega_g^3 V^{5/3} (\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$$

- **Advantages**:
  - Higher magnetic fields
  - Single photon readout
  - Operation of several cavities in parallel







The FLASH cavity

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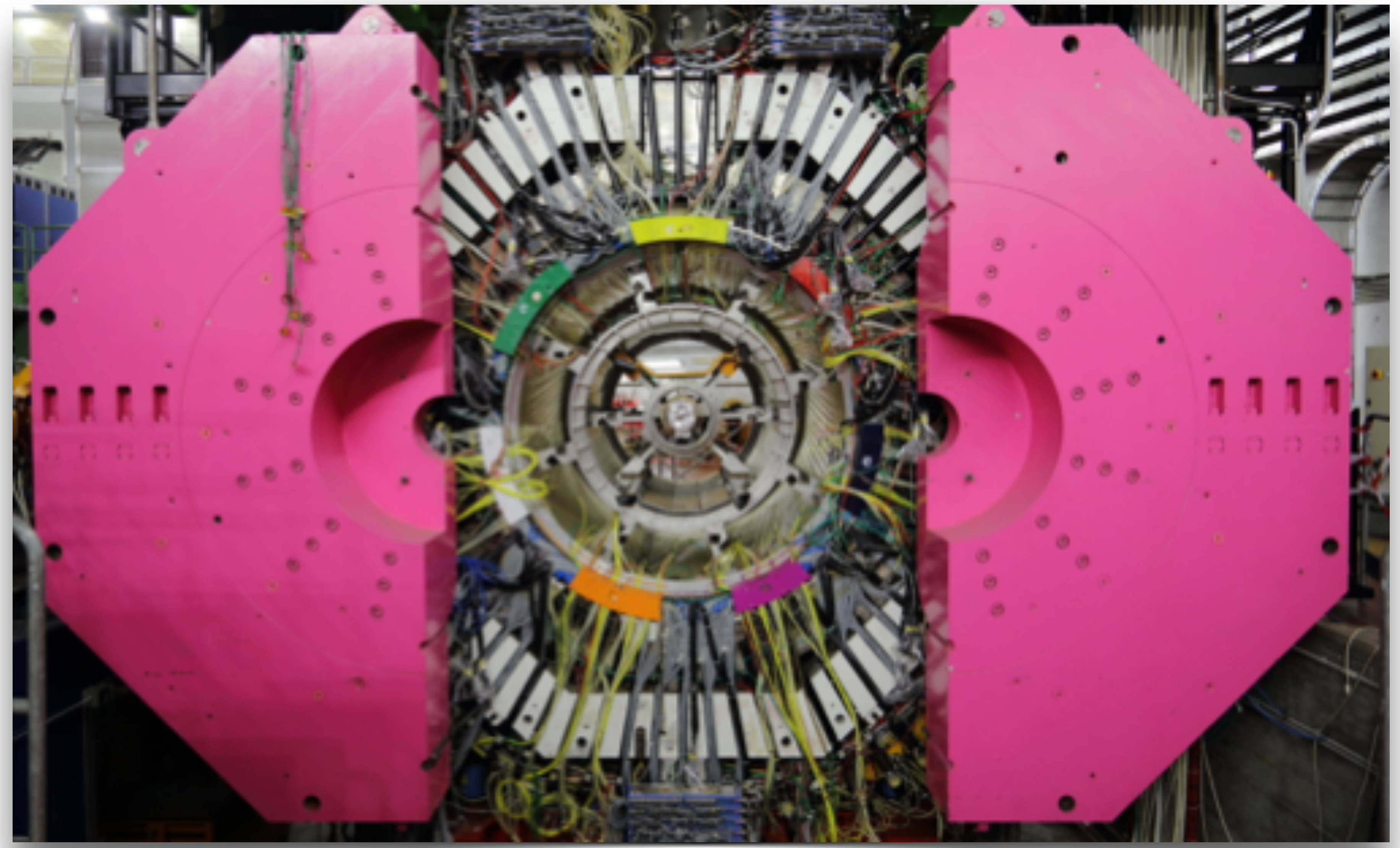
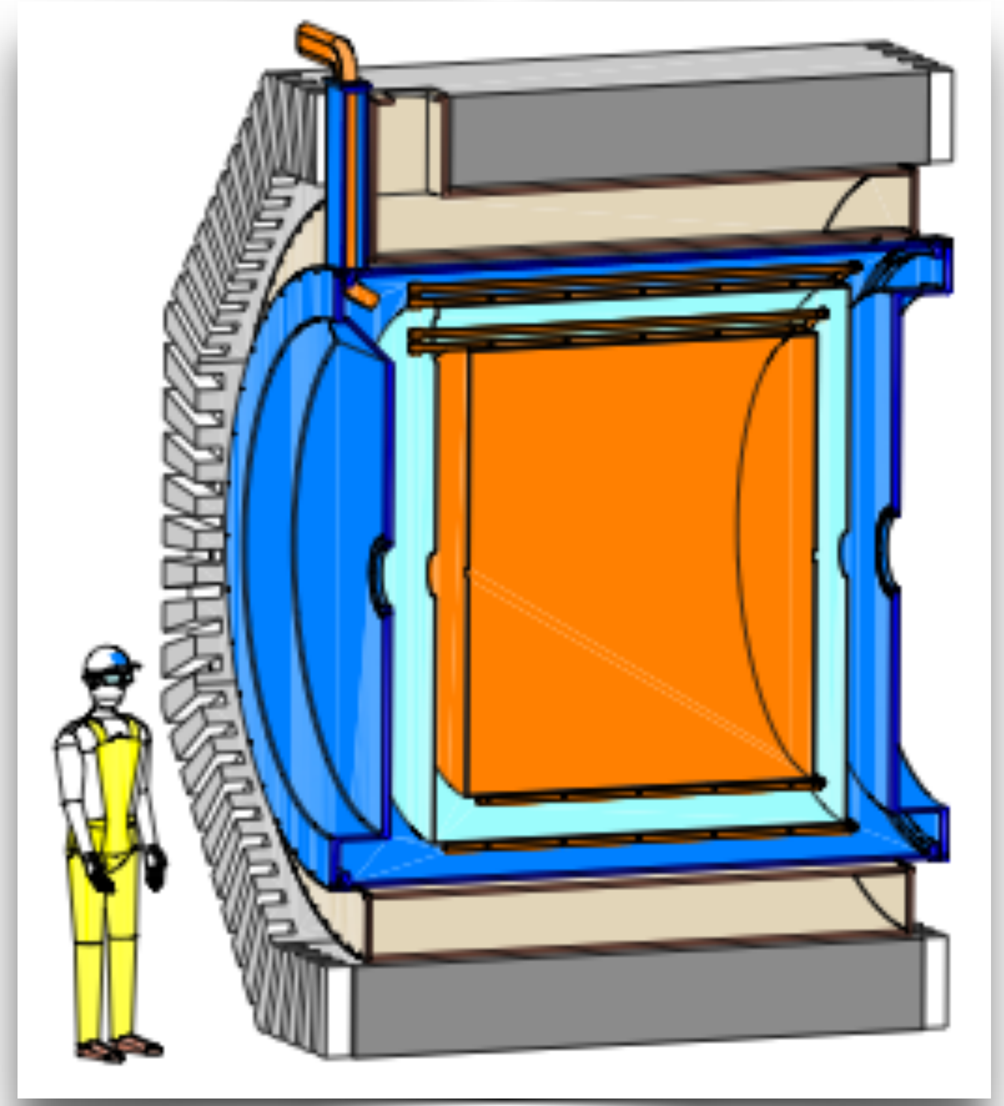
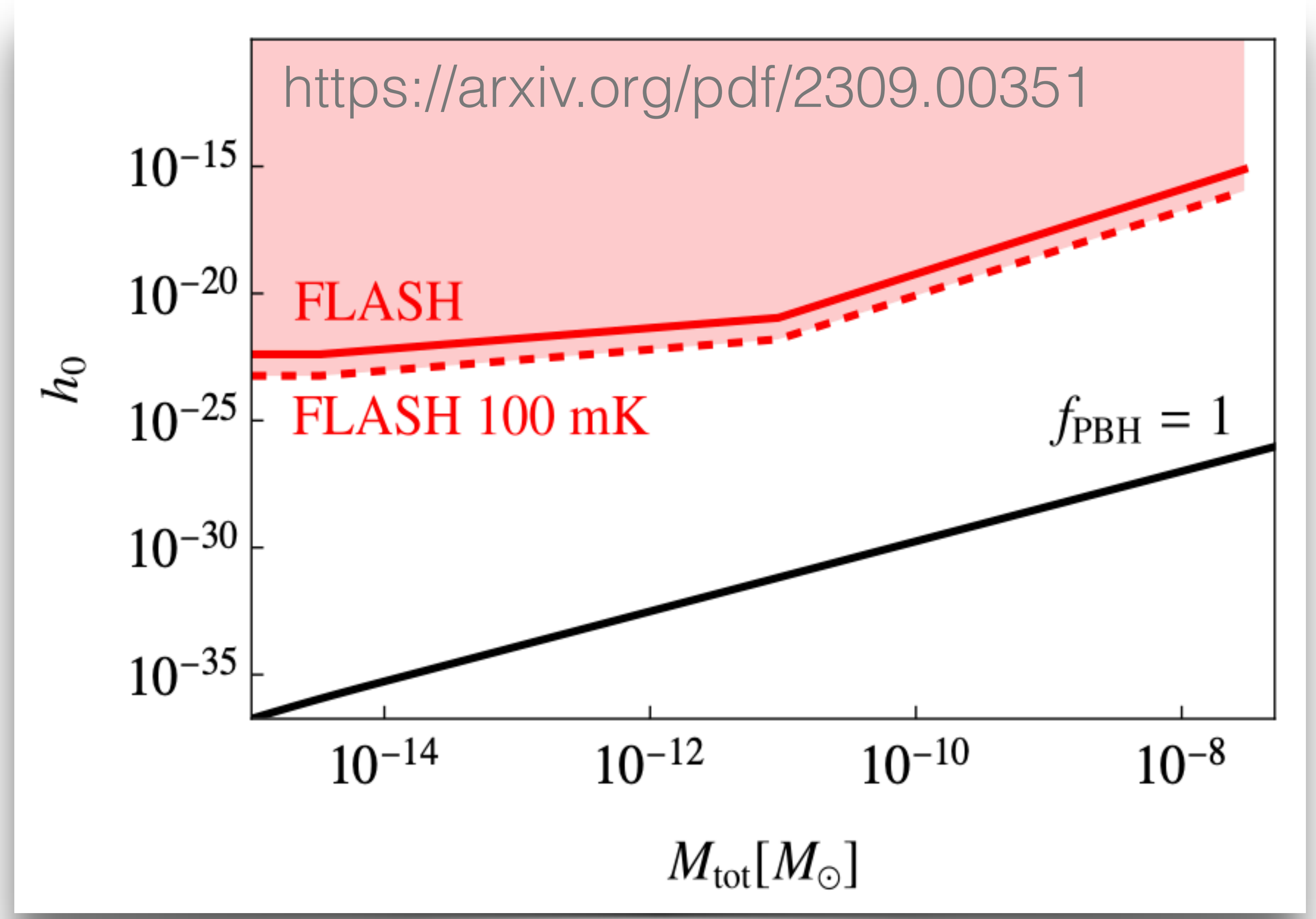






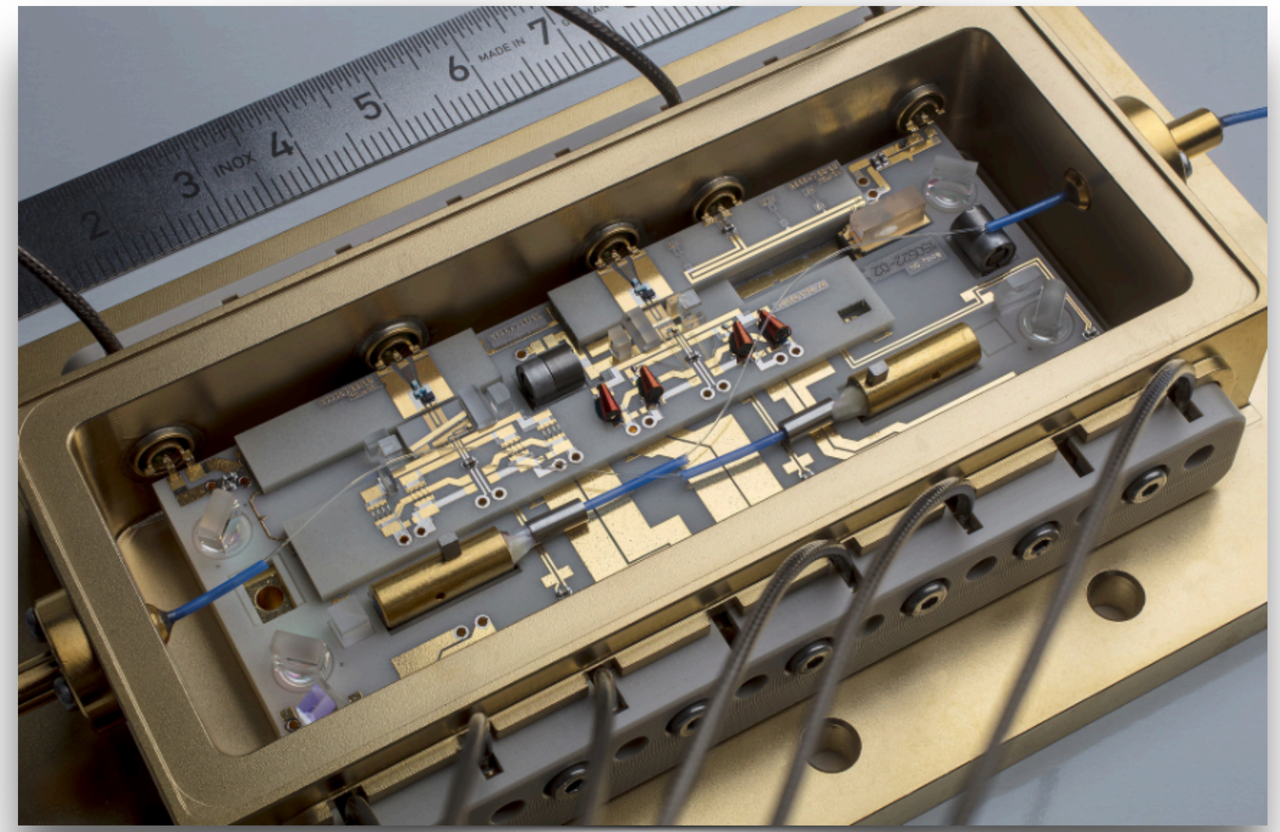
- Reuse of the FIDUNA magnet system at INFN Frascati within the FLASH Experiment:
  - Axion Search (0.49-1.49 µeV)
  - Res. Frequency: 100-300 MHz

- System properties:
  - $V = 4.15\ m^3$
  - $B = 1.1T$
  - $Q_L = 1.4x10^5$
  - Tsys = 4.9K

- Readout:
  - SQUID readout
  - Limited by thermal noise

R&D Efforts

Drastically reduce noise in readout

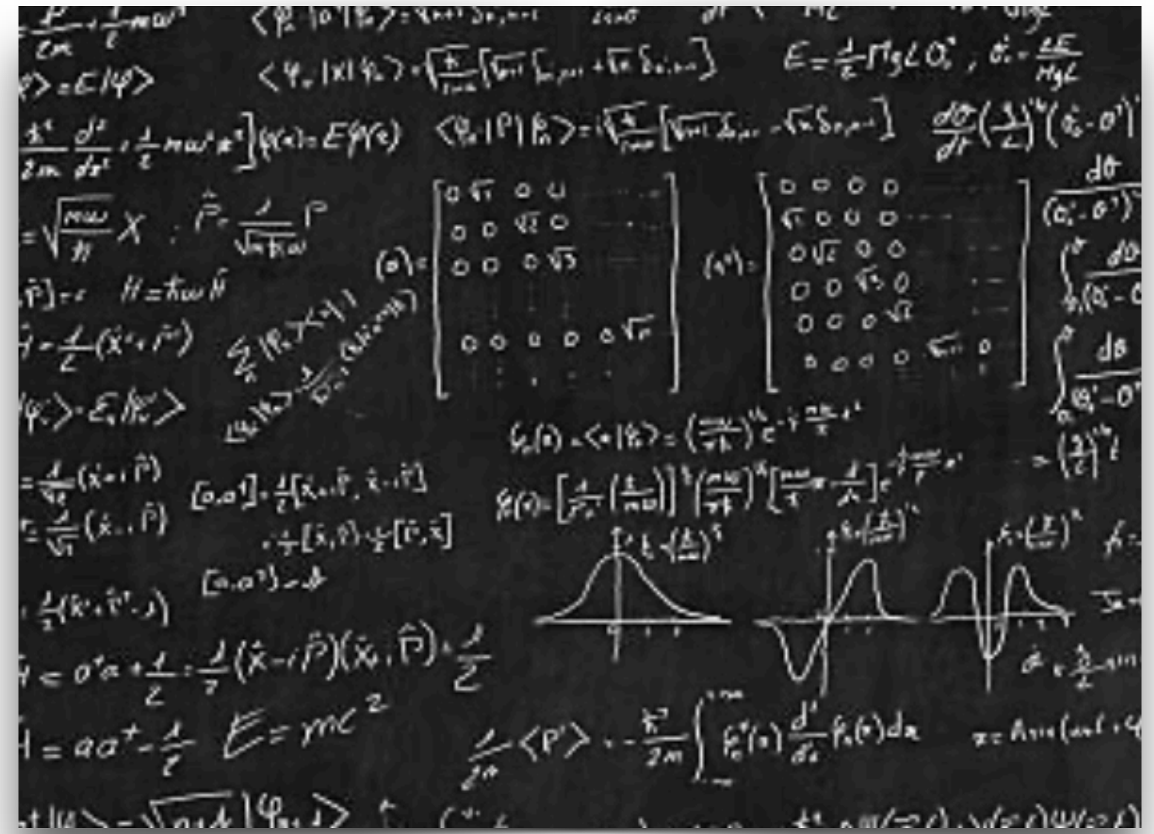


- Use of quantum sensing
- Single RD photon detection
- Quantum non-demolition measurements

Optimize Cavity

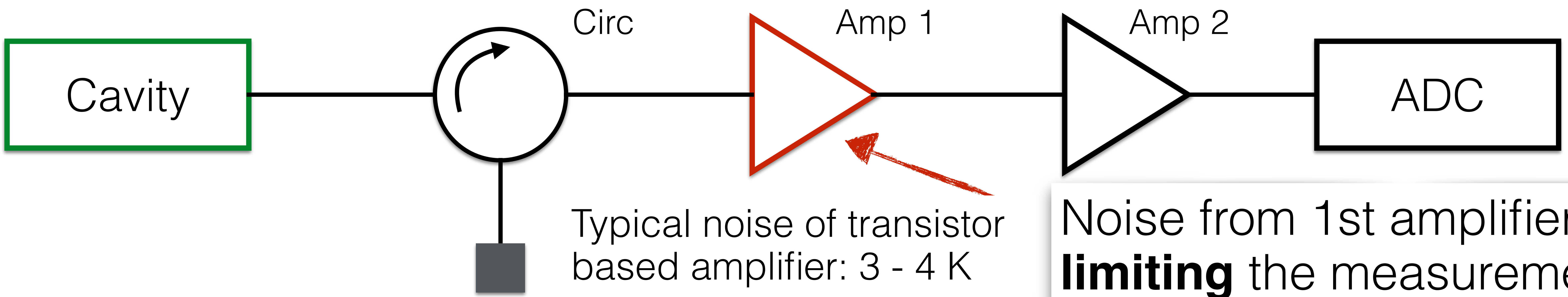
- Optimise shape to improve coupling to GW:
- Enhance quality factor using superconductors

Optimize Data Analysis



- Combination of data from distributed detectors
- Usage of advanced machine learning tool
- Signal modeling

Readout Noise



Typical noise of transistor based amplifier: 3 - 4 K

Noise from 1st amplifier is **limiting** the measurement!

Using **parametric** amplifiers (e.g. JPA):

- Added noise ~ 200 mK
  - Below standard quantum limit

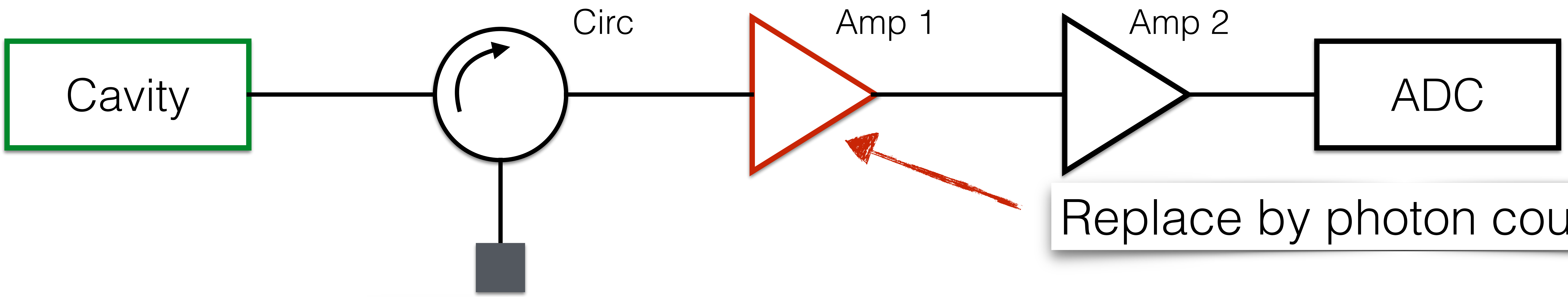
System noise:

$$k_B T_{sys} = h\nu N_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_A \right)$$

SQL: $N_A \geq 1/2 \Rightarrow N_{sys} \geq 1$

(Price for spectral resolution)

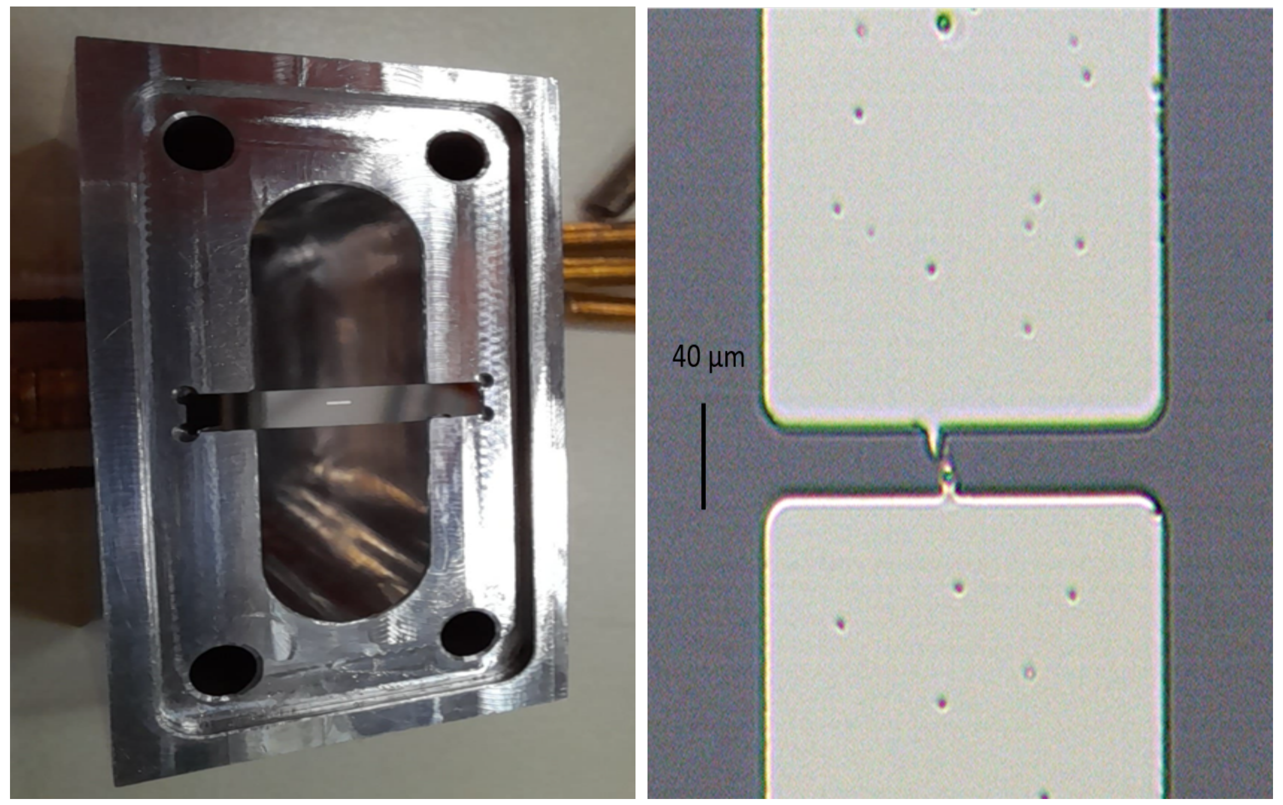
Readout Noise

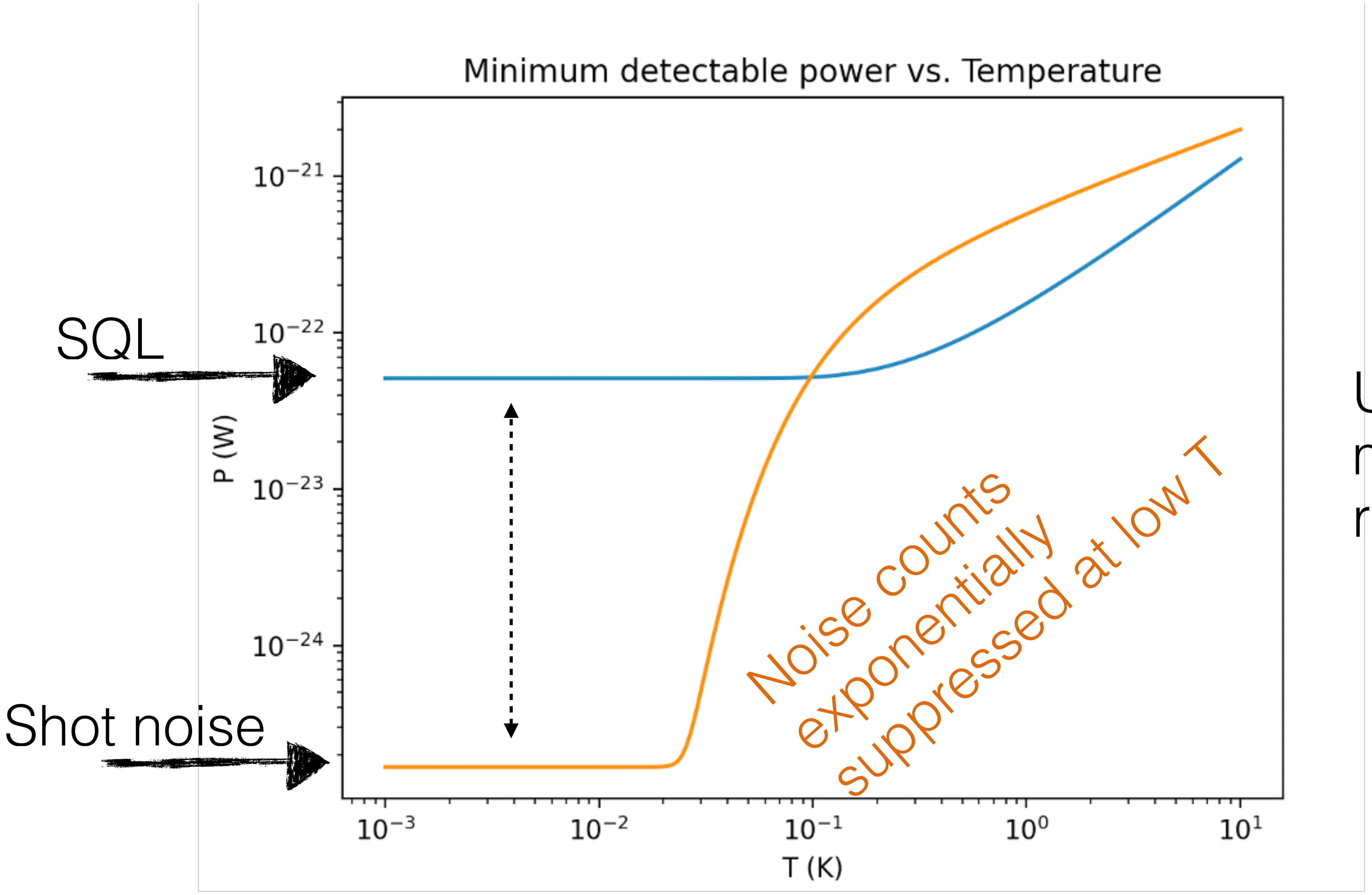


Replace by photon counter

Using **photon counting**:

- Noise below SQL possible!
- Counting experiment
- E.g. using transmon Q-bits





Up to 3 orders of magnitude noise reduction!

Appl. Sci. 2024, 14(4), 1478

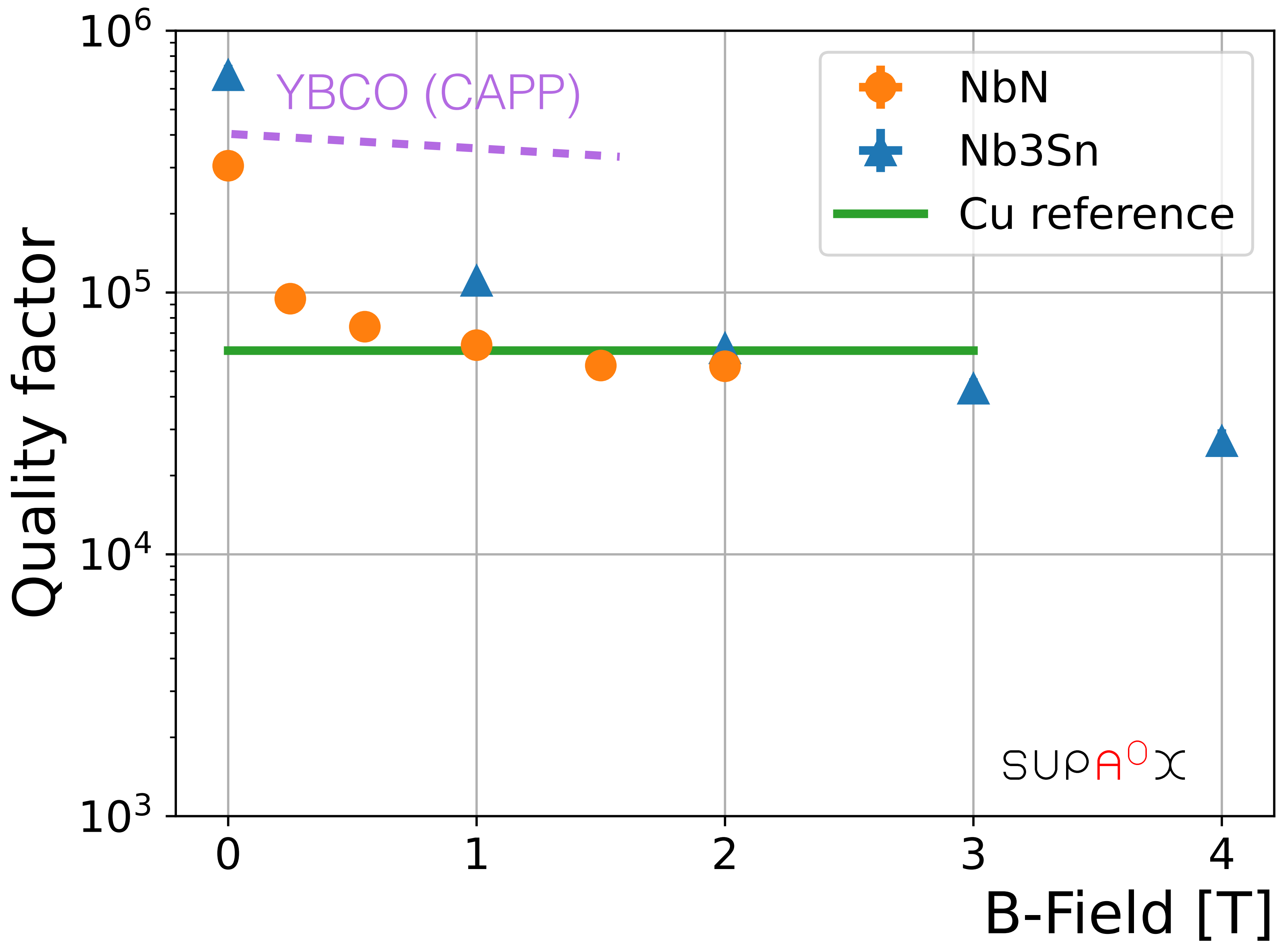
Optimise setup

- High purity copper: ~5·10^4
- Superconducting: difficult in high magnetic field!
  - Target: 10^6
  - Achieved: 3·10^5 (CAPP, non tunable)
    - Materials under study: Nb_3Sn, **NbN**, HTS materials (YBCO)

- Up to 14T magnets in use
  - Up to 20T envisioned
- Larger fields - smaller volume

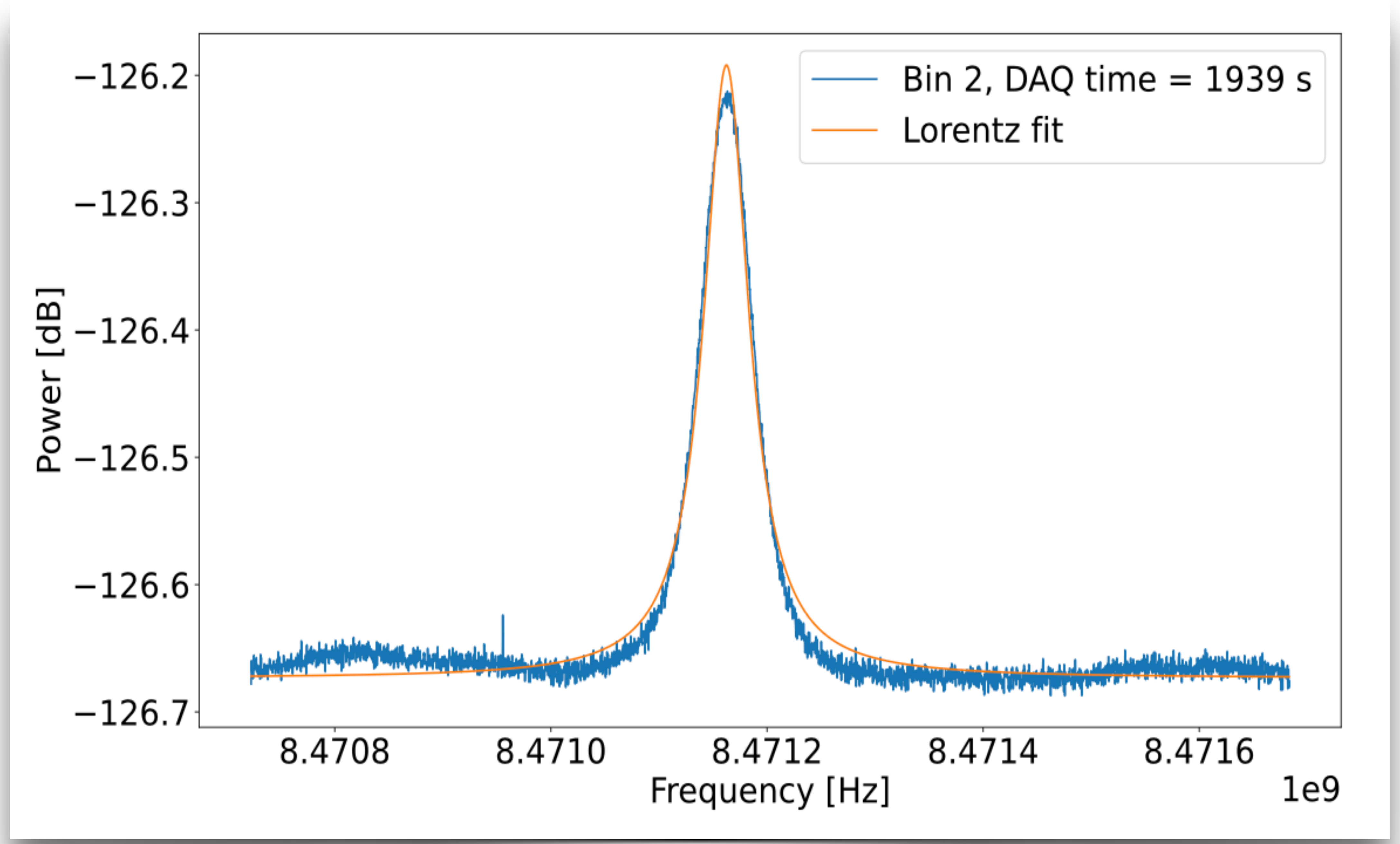
$$P_{sig} = \frac{1}{2} Q \omega_g^3 V^{5/3} (\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$$

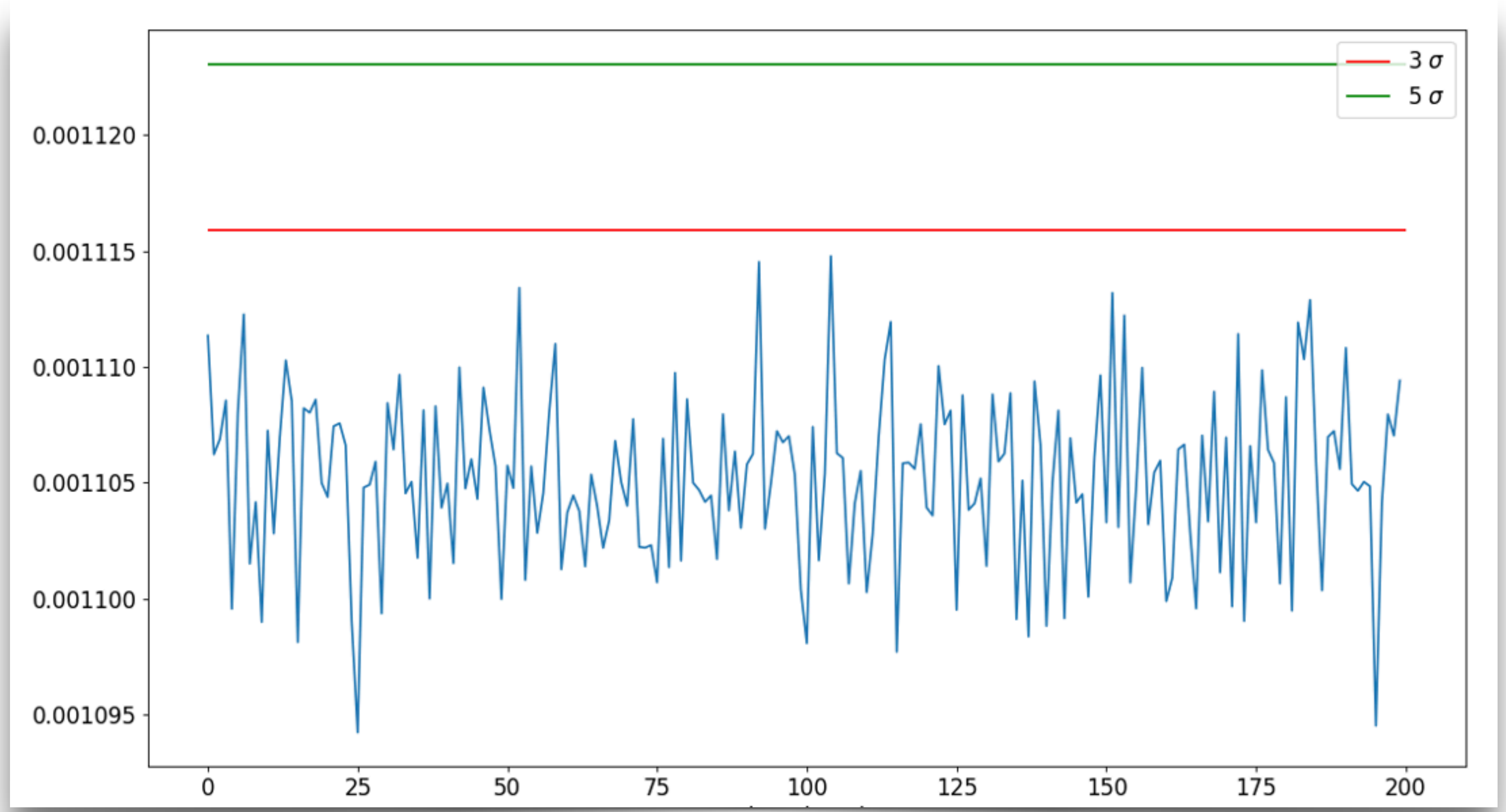
- Volume limited by
  - Magnet aperture
  - Resonance frequency
  - Tuning elements



- Supax measurement [arXiv: 2412.14958]
- D. Ahn et. al (CAPP), ~7 GHz https://arxiv.org/abs/2002.08769
- J. Golm et. al (RADES), ~8 GHz https://arxiv.org/abs/2110.01296

Data Analysis





Naive approach:

- Bump-hunt in frequency domain

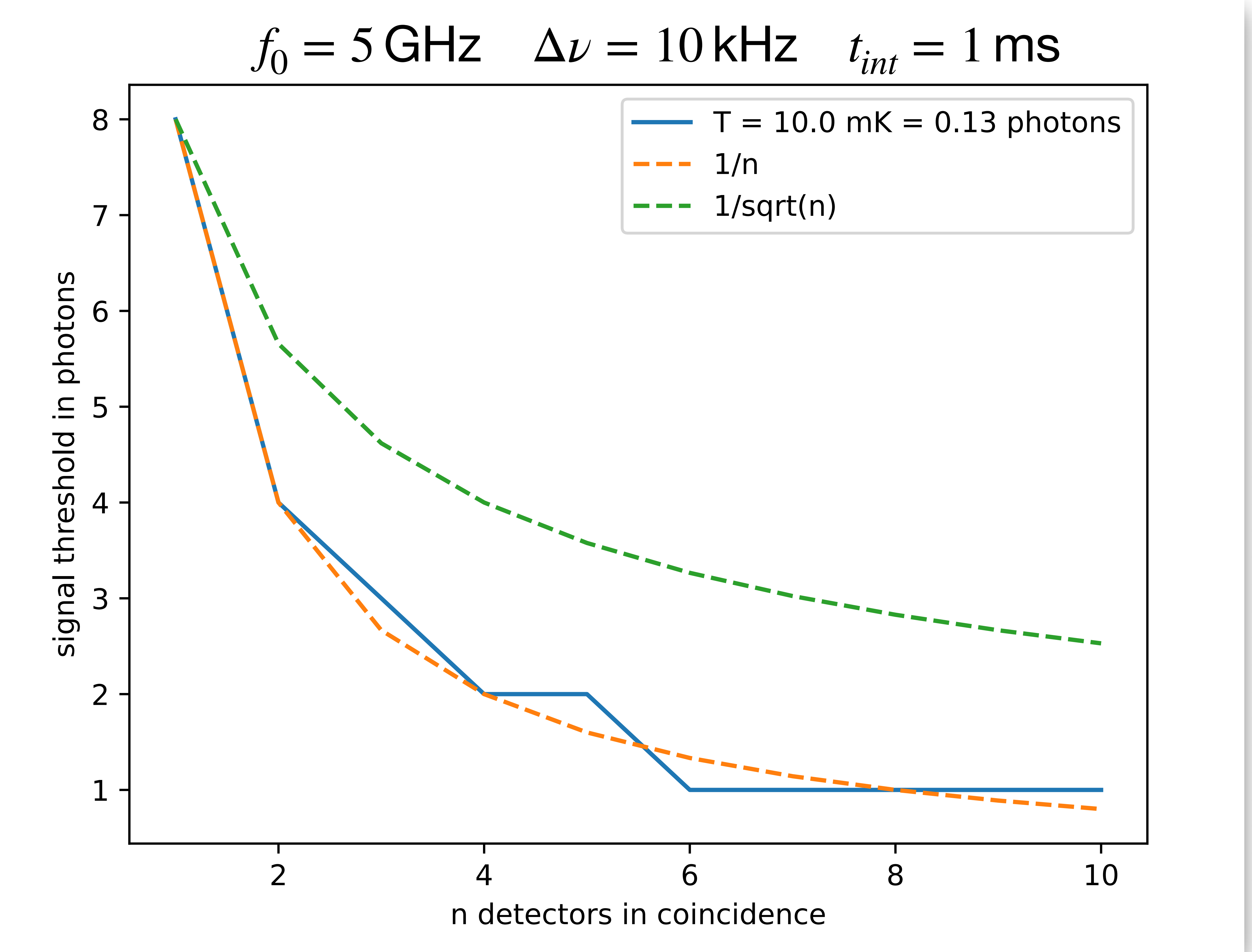
Advance approach:

- Search for signature in time series
- Modern anomaly detection methods

How to Combine Signals

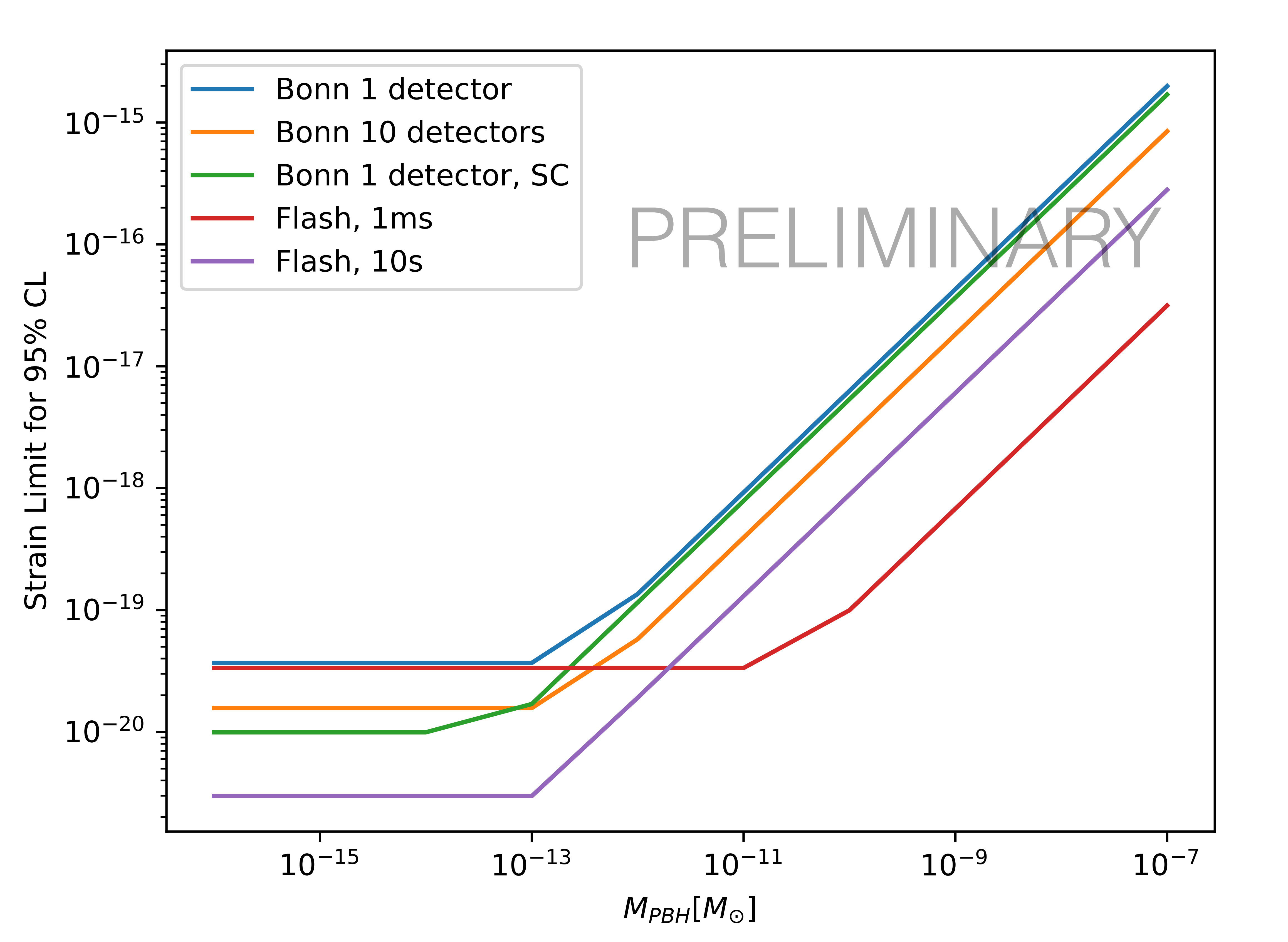
- Adding N coherent signals (in phase) yields an improvement on the SNR of ~N

- Single photon readout:
  - Measurement becomes **counting experiment**
  - Thermal/quantum noise yields a certain **number of photons per time-interval**
  - Expect one signal event per year
  - Additional cavities/experimental sites suppress background (combinatorics)

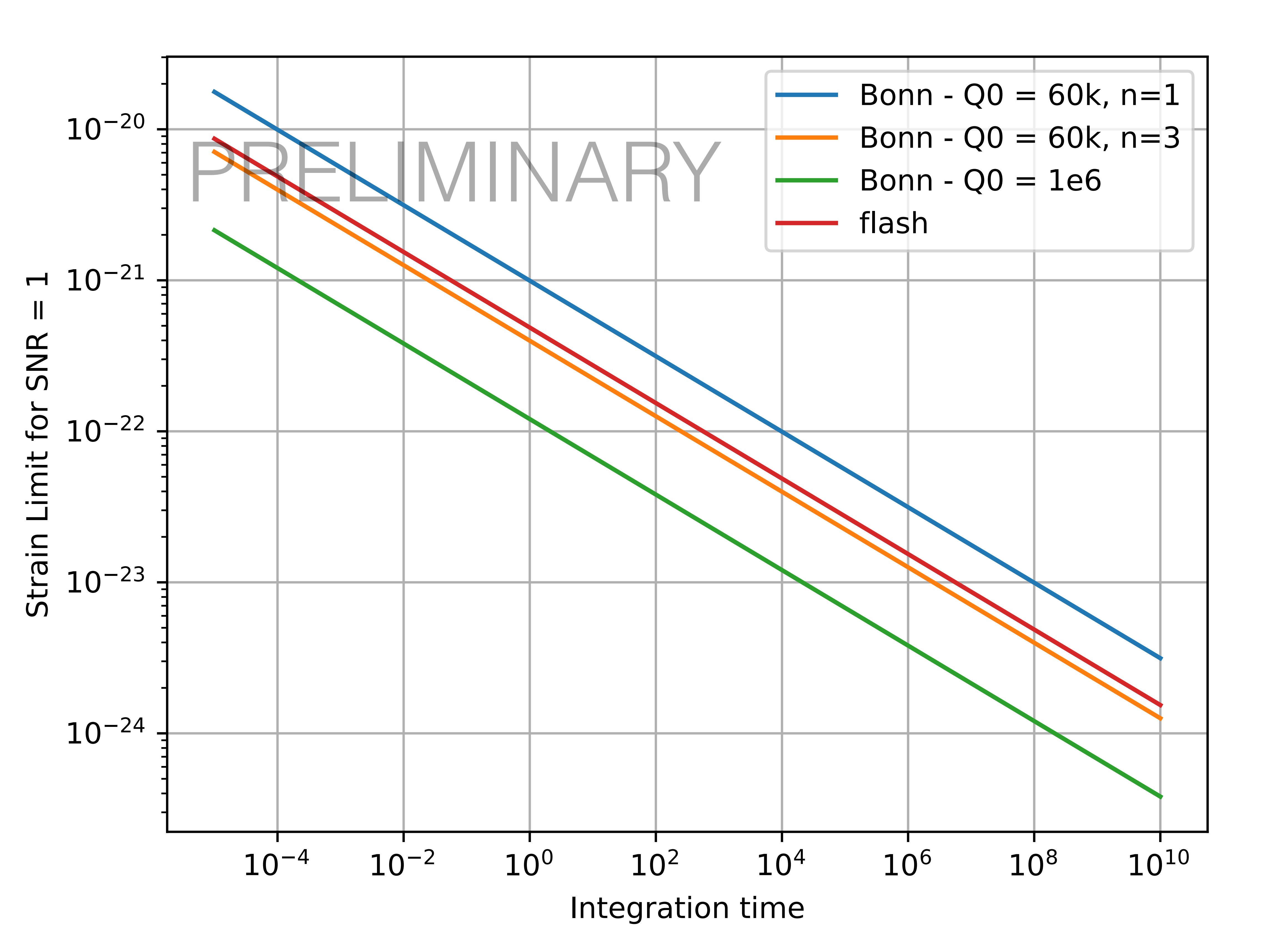


- Relevant quantity: Induced power should be in the order of O(1) photon

GravNet: Expected Sensitvities

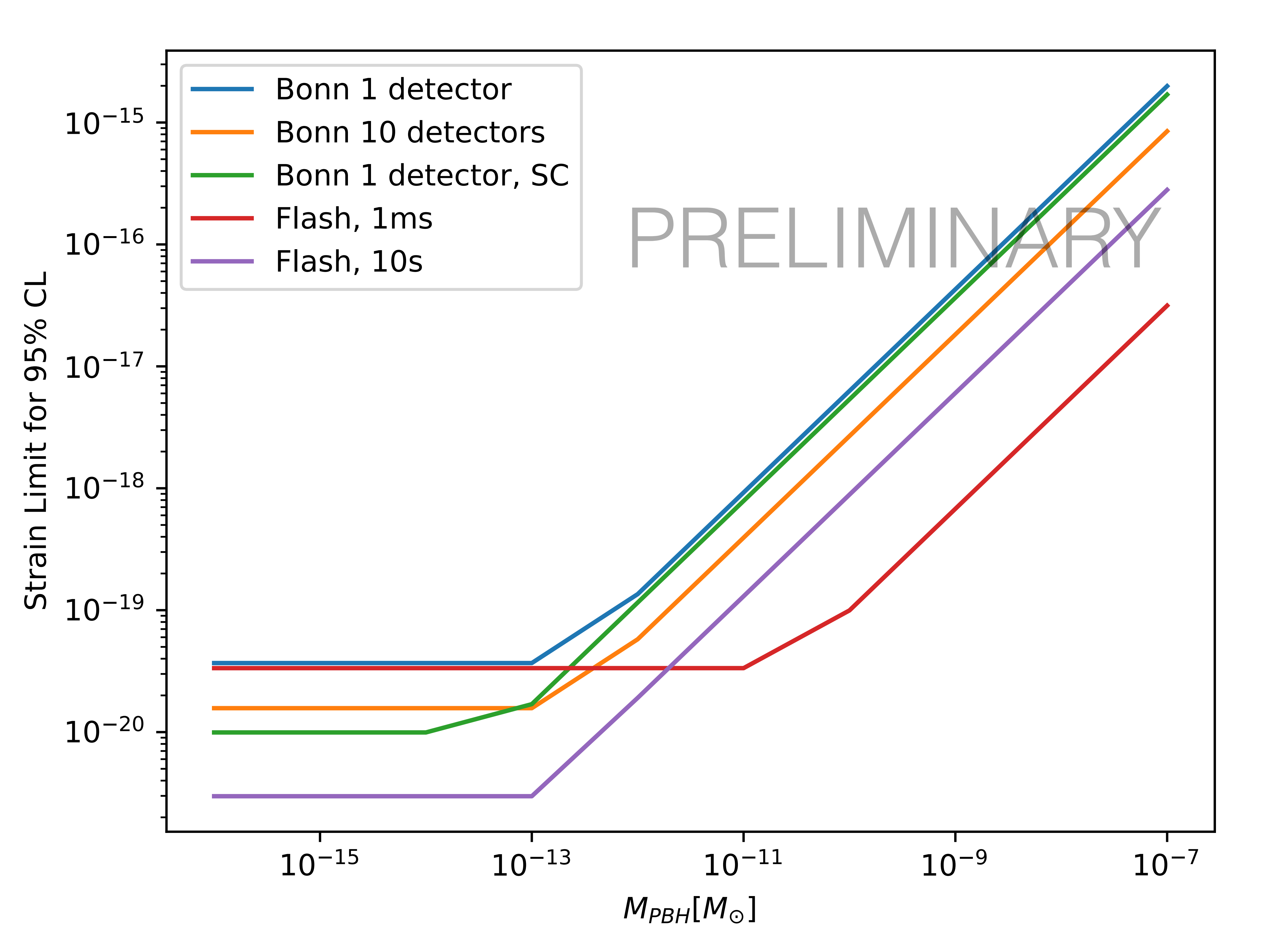


- Limit for monochromatic signals with longer integration times
- General development: go broadband



- PBH merger signals, assuming thermal background only
- Target: h < 10^{-24}
  - Only few orders of magnitude missing!

GravNet: Expected Sensitvities

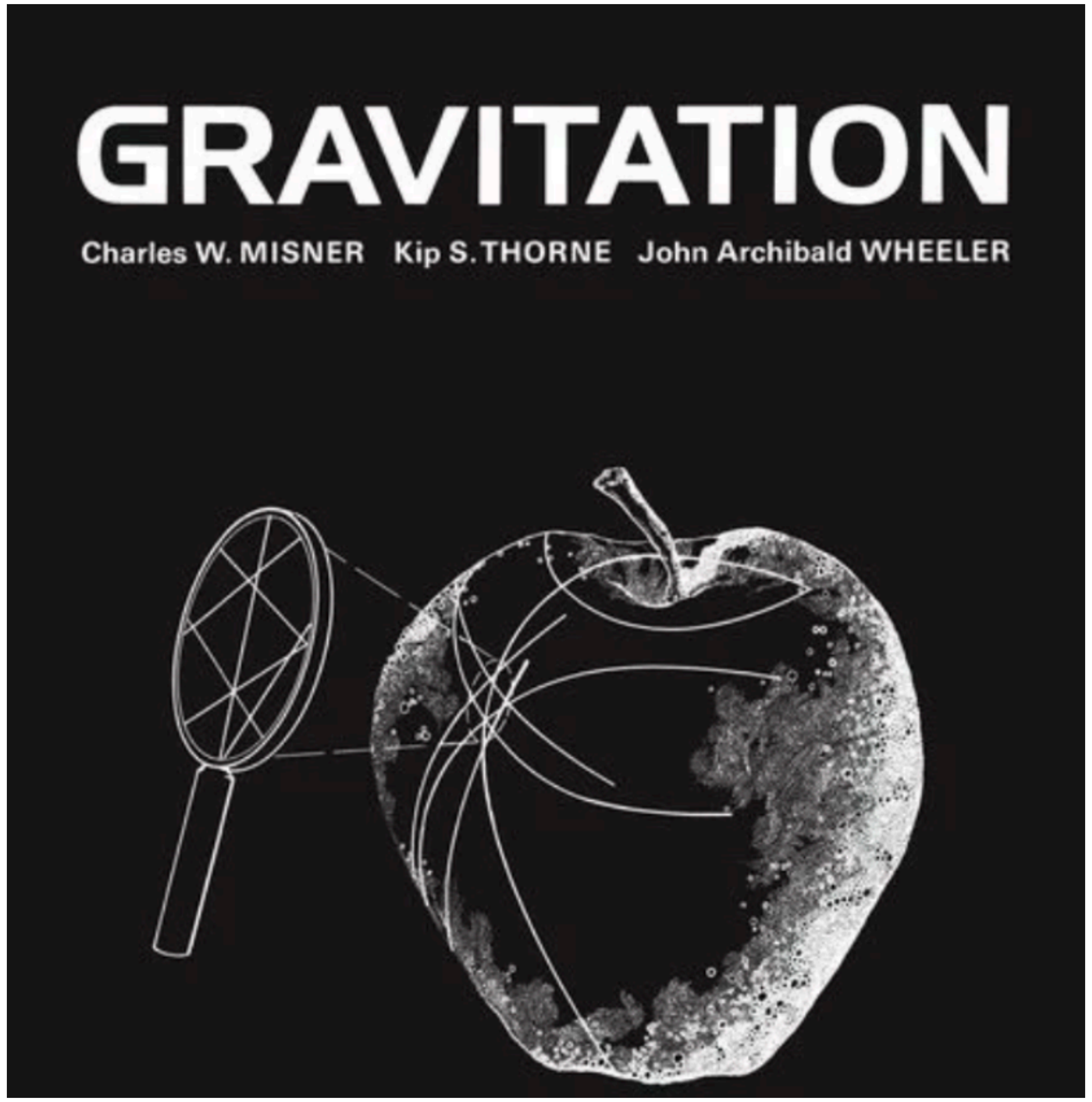


- PBH merger signals, assuming thermal background only
- Target: h < 10^{-24}
  - Only few orders of magnitude missing!

Isn't this depressing?

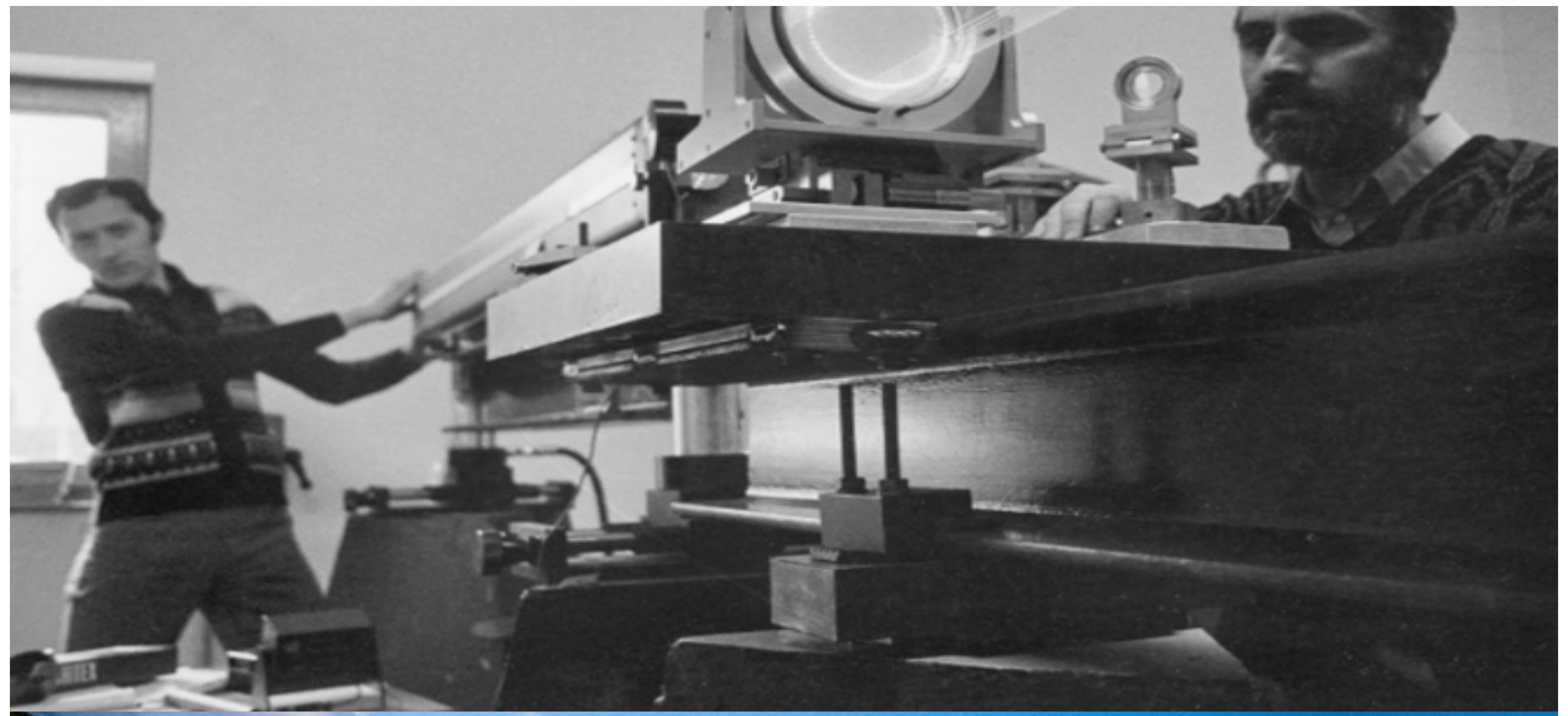
Ambitious, but rewarding goal

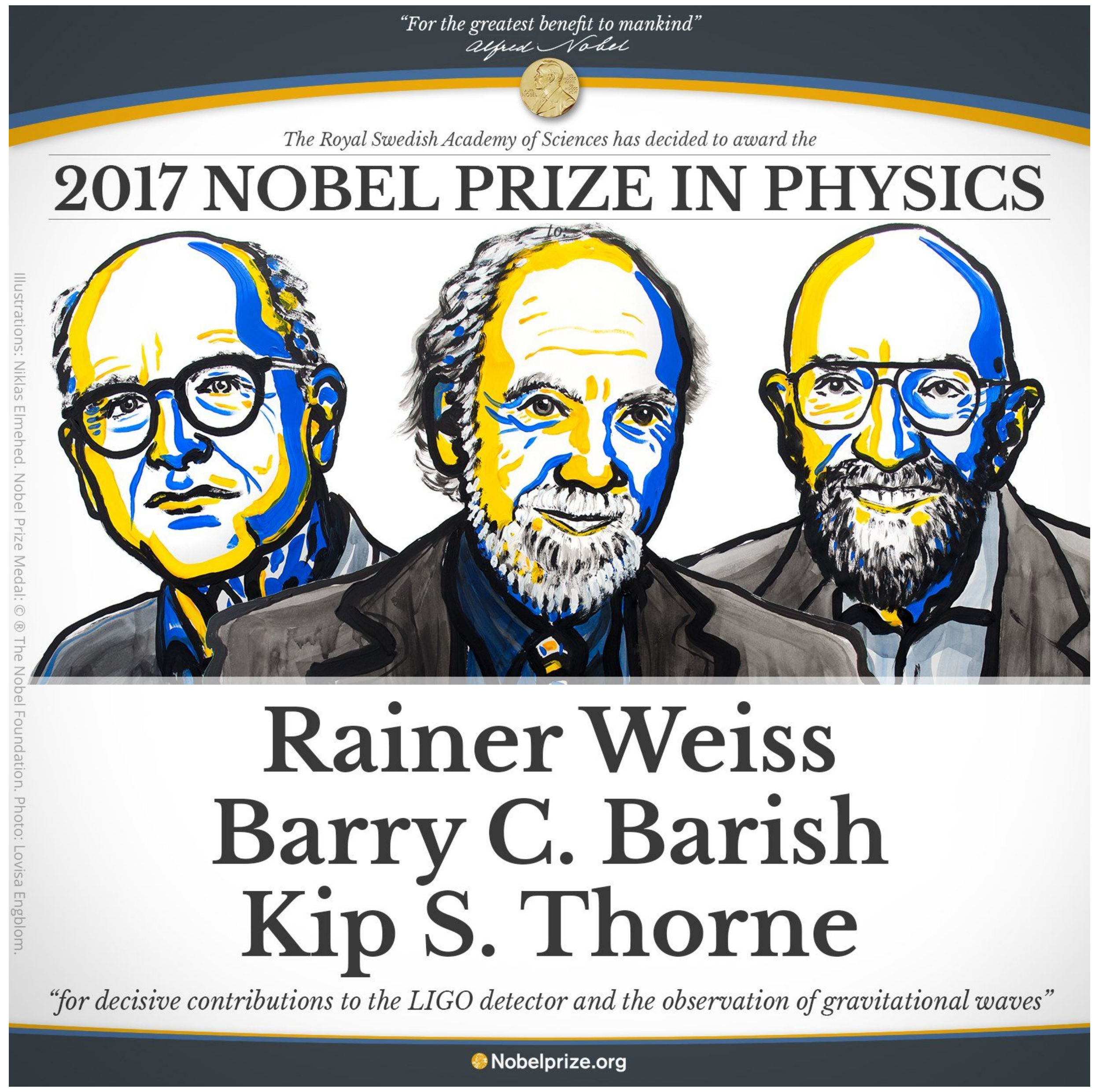
Misner, Thorne, Wheeler, 1973



“ [interferometers] have so low sensitivity that they are of little experimental interest”
p. 1014

50 years of work, 23 attempts





Alternative Technologies

- Large range of experimental approaches tackling HFGW
- Three Categories:
  - Conversion of GWs (gravitons) into Photons
  - Something is mechanically deformed
  - Spin interaction

[arXiv:2011.12414]

- Energy density in E-field about 10^{-6} compared to B-fields due to electron release

Alternative Technologies - Hetrodyne Detection

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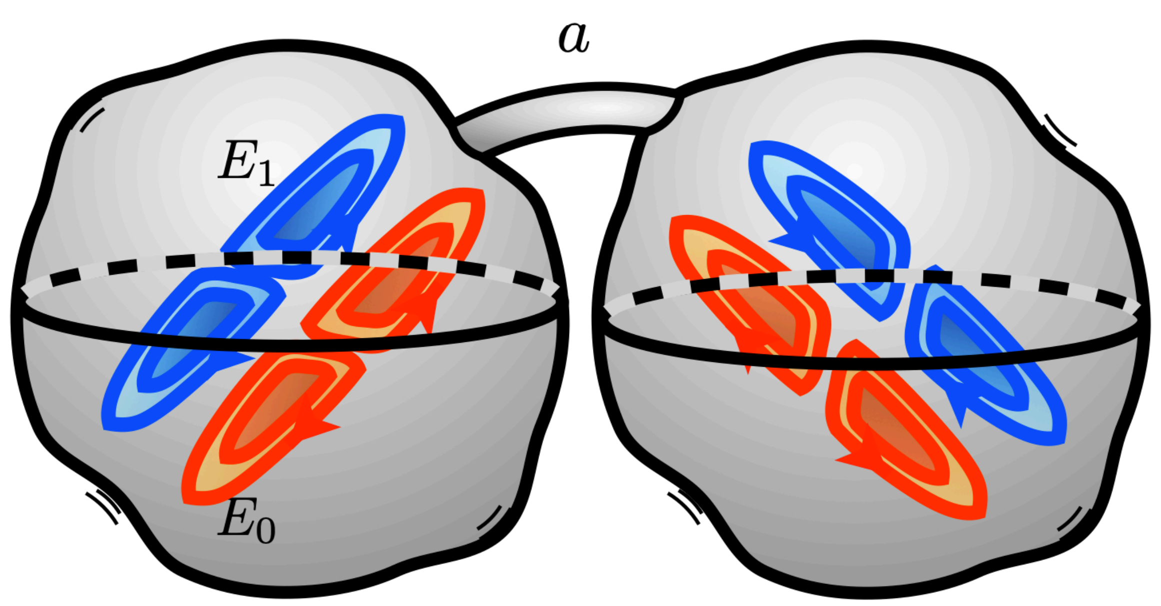
- Heterodyne enhancement of GW signals
  - Coupled resonators: mode splitting
- Pump frequency: ω_s ~ GHz
- Energy transfer to signal mode $\omega_a = \omega_s + 2\Delta\omega$
  - GW frequency: $\Delta\omega$



- **Pro**:
  - Amplification linear in Pump Power
- **Con**:
  - Frequency stability of modes
  - RF leakage into signal mode

- **MAGO experiment @ Desy**

- Sensitivity from 10 kHz - 100MHz (with various cavities)

$$h_0 > 10^{-22} \qquad h_0 > 10^{-21}$$

Alternative Technologies - Mechanical Deformation

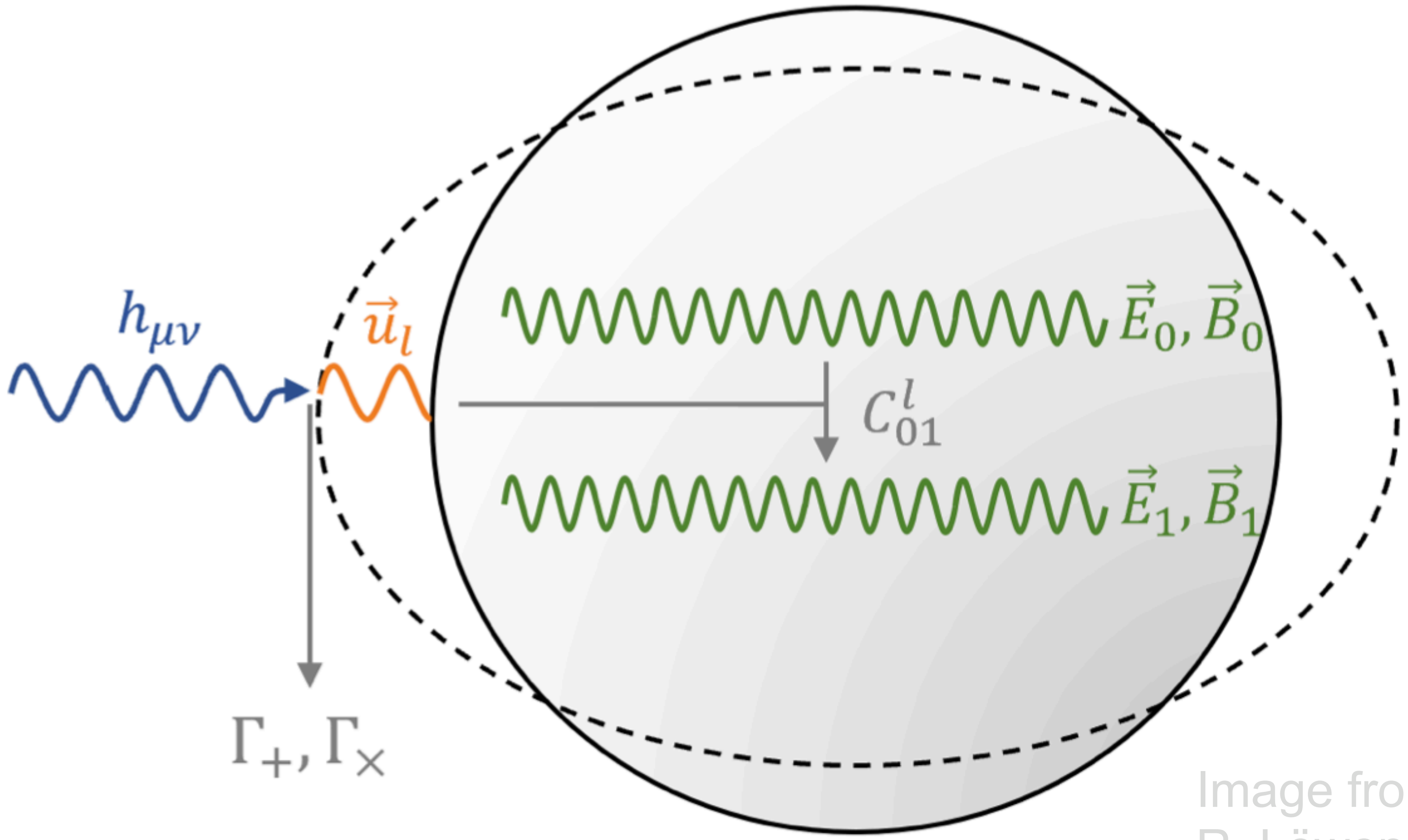
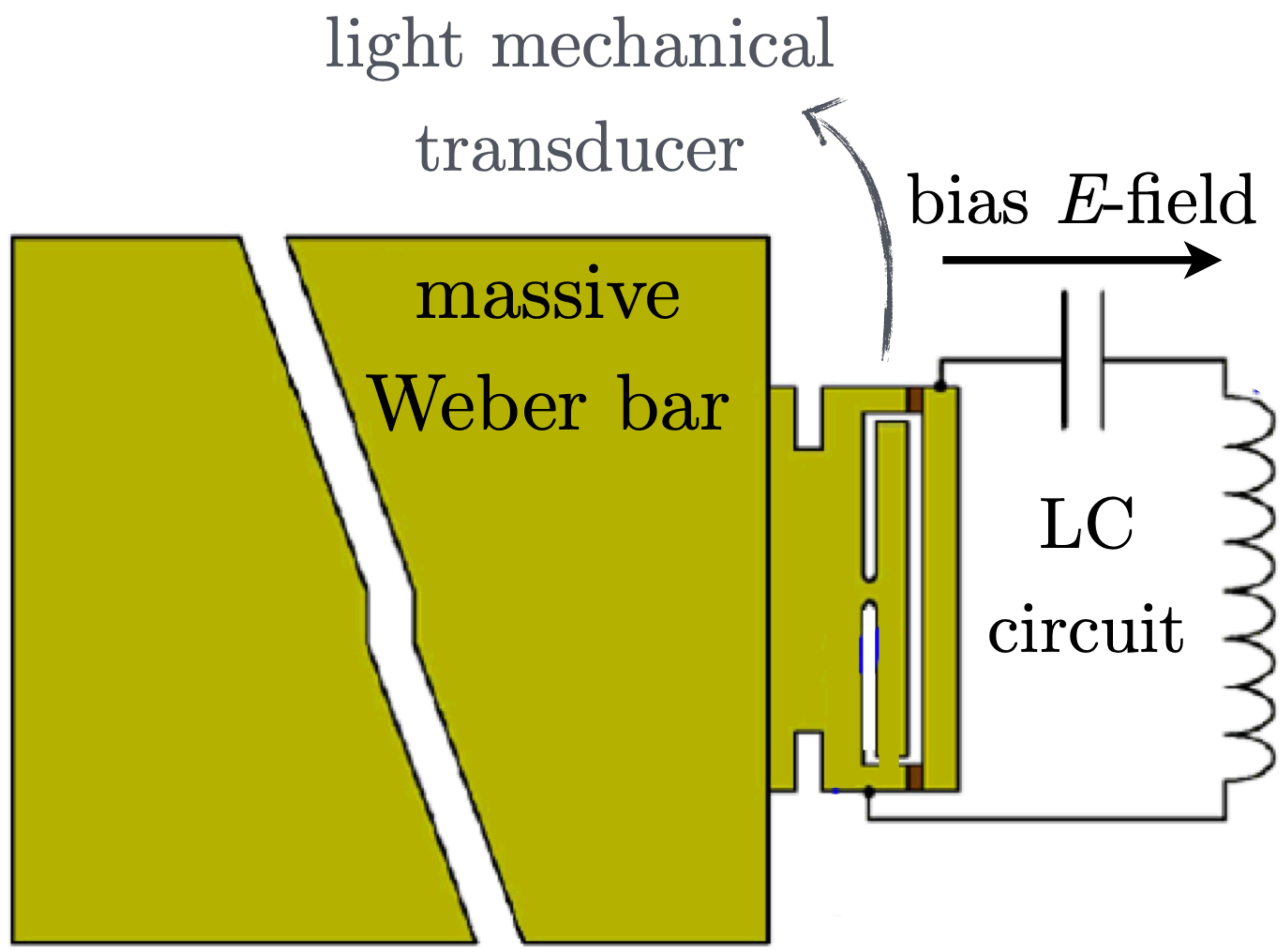


Image from
R. Löwenberg
thesis

- Transfer of mechanical to EM energy
- Competing process for any cavity based detector

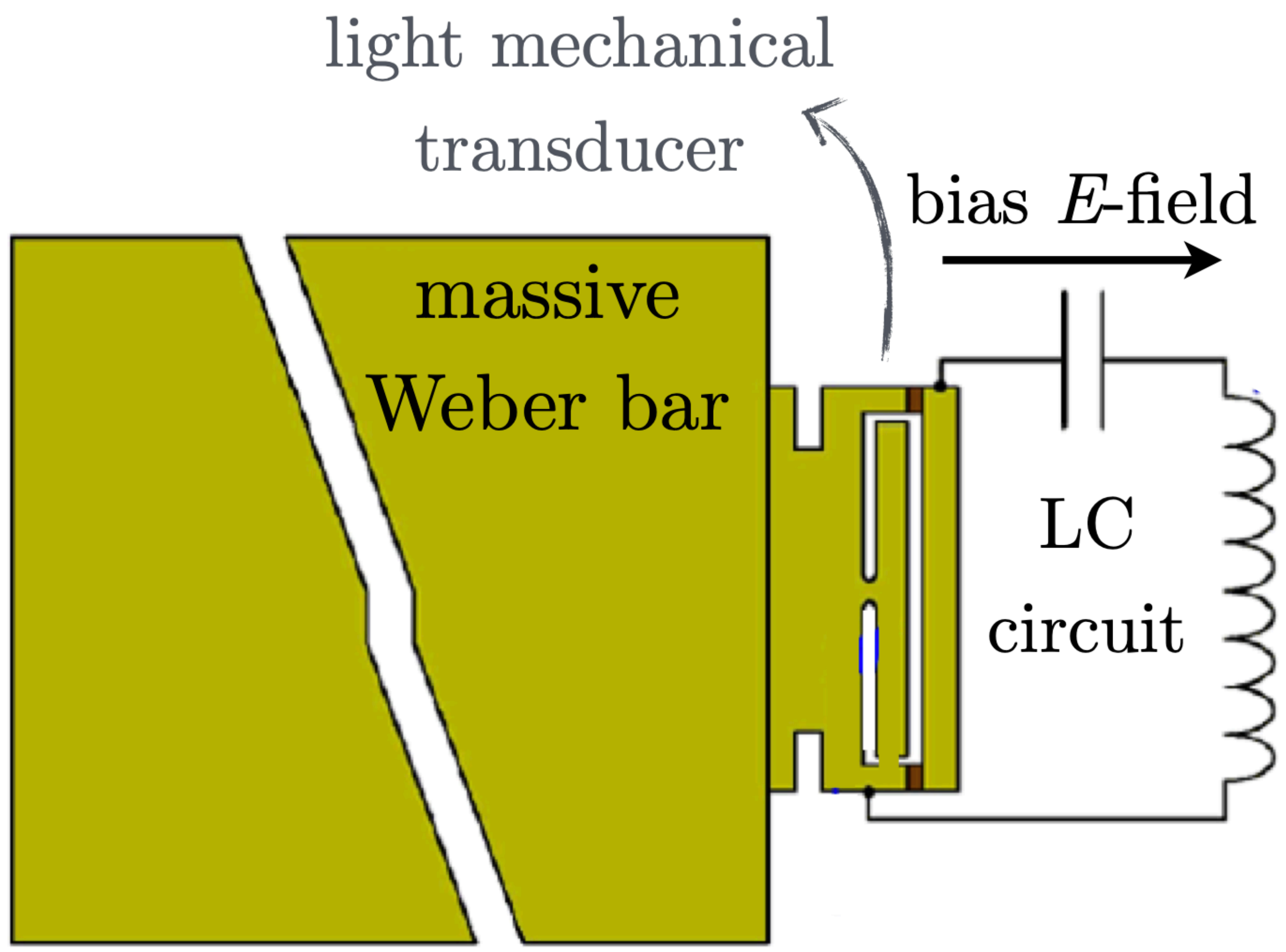
- Exploit mechanical resonances for enhancement
- Noise from environmental vibrations



$$Q_{LC} \sim 10^6 \ll Q_{cav} \sim 10^{11}$$

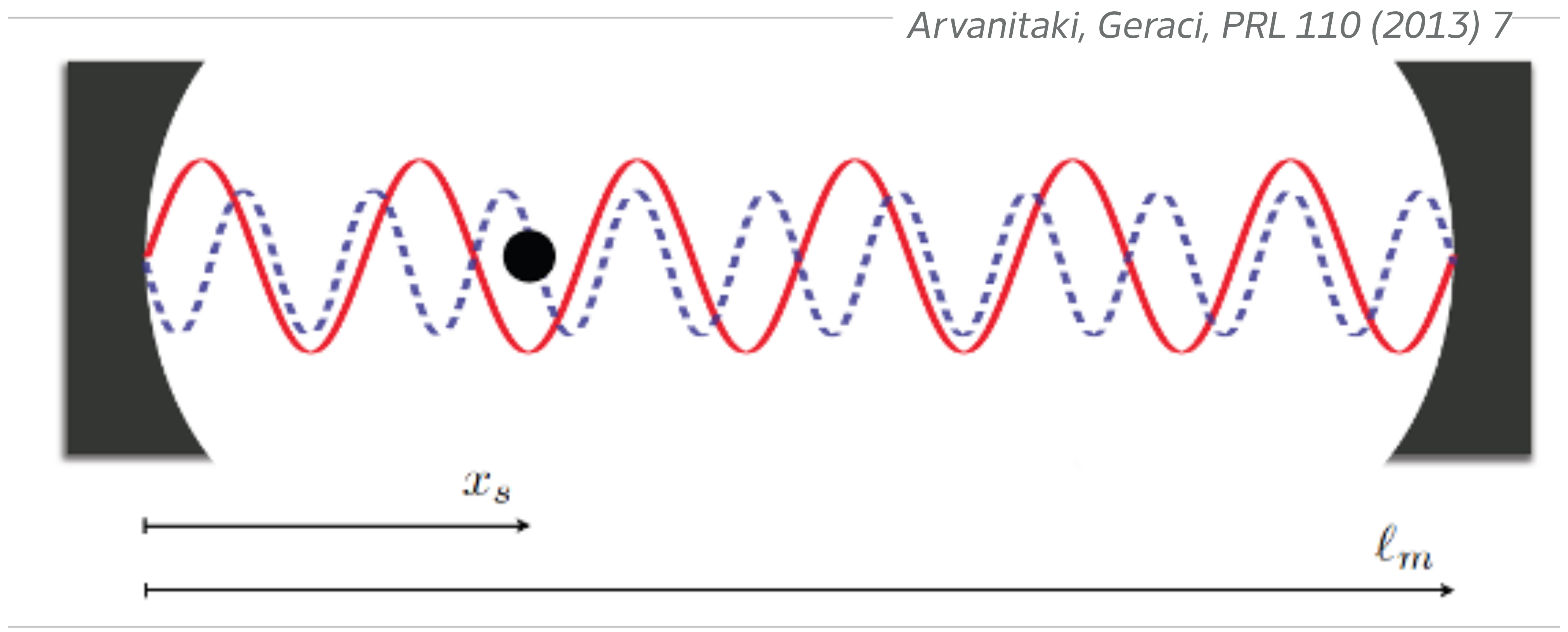
Alternative Technologies - Mechanical Deformation

- Original Idea:
  - Weber bar: 2m x 1m aluminum rod
  - Sensitivity at ~kHz:
    - $h_0 > 10^{-16}$



$$Q_{LC} \sim 10^6 \ll Q_{cav} \sim 10^{11}$$

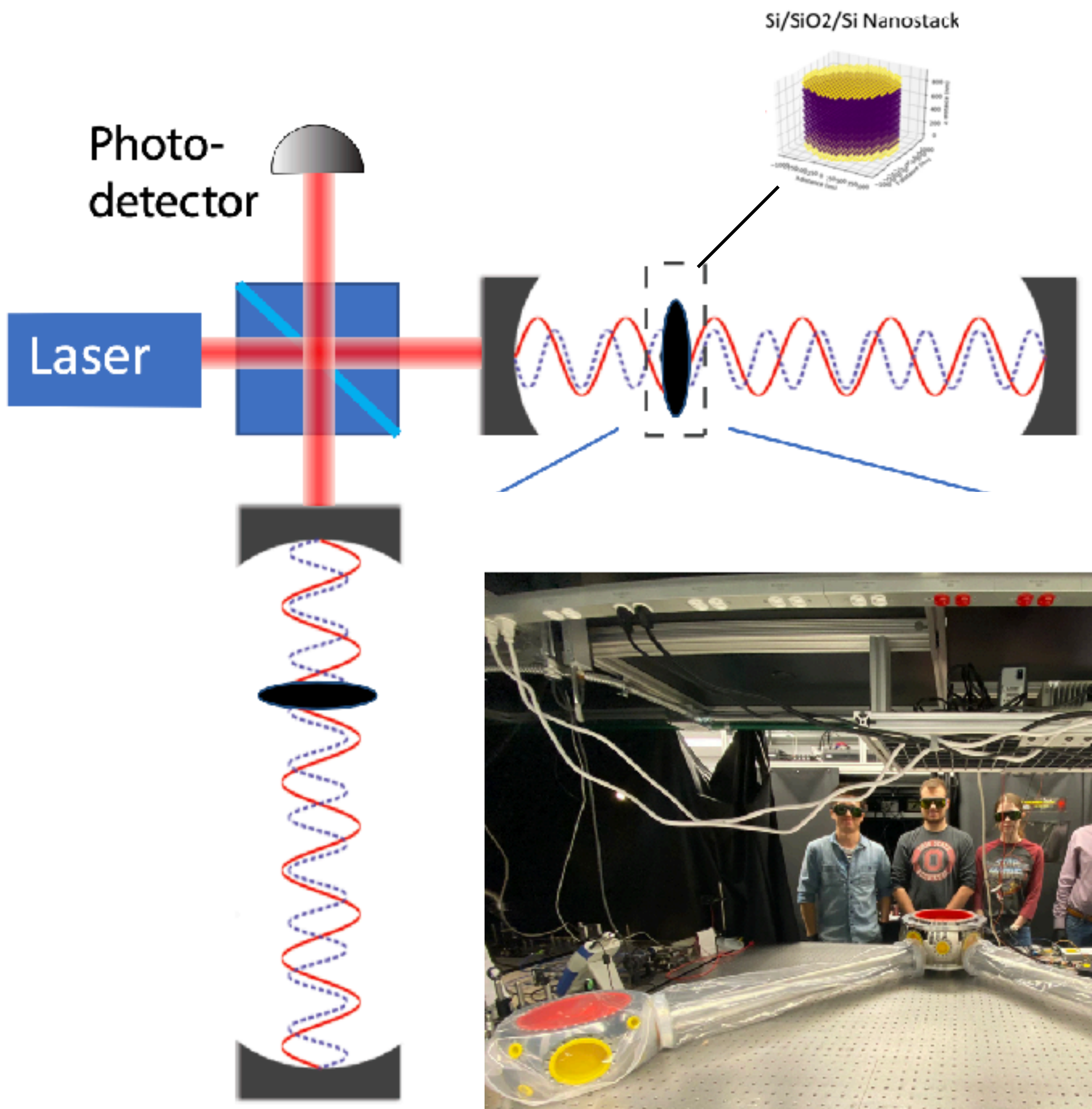
Alternative Technologies - Levitated Sensors

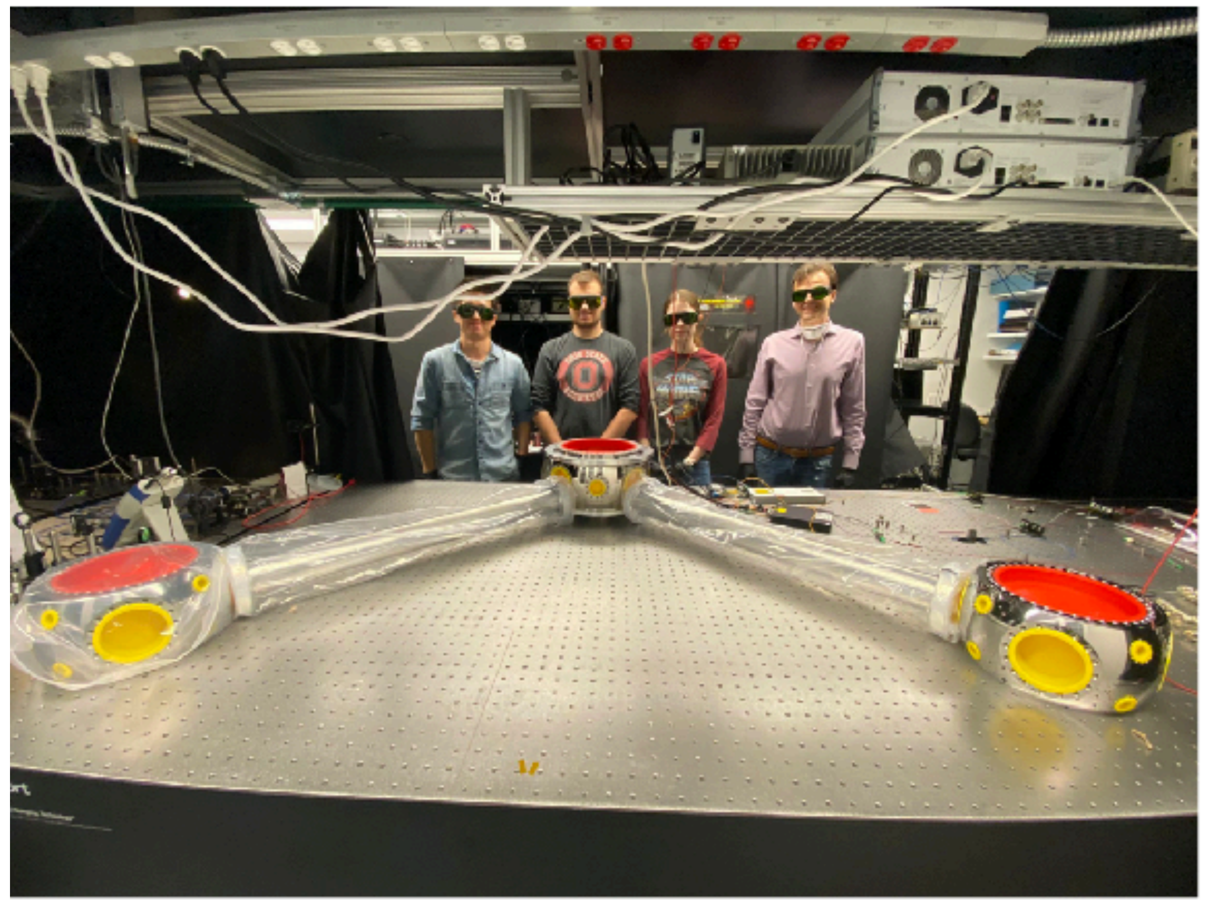


- Limited by thermal noise & Laser heating of levitated particle

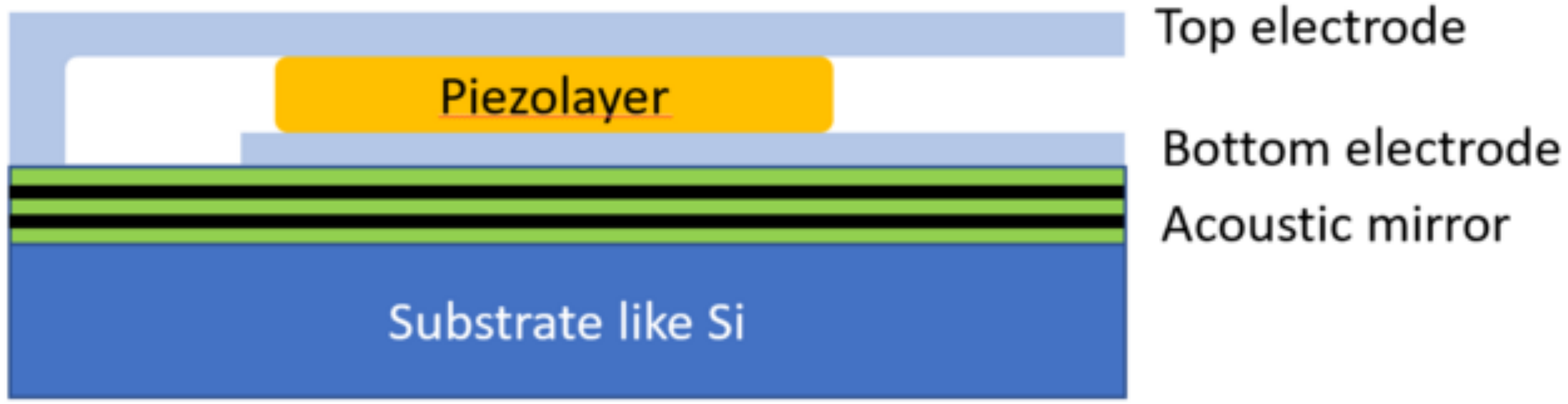
- Sensitivity from 10 kHz - 100kHz
- $h_0 > 10^{-21}$

- Trapping dielectric nano-particles in Laser-field
- Second beam for cooling and readout
- GW displaces nanoparticle w.r.t. trap minimum

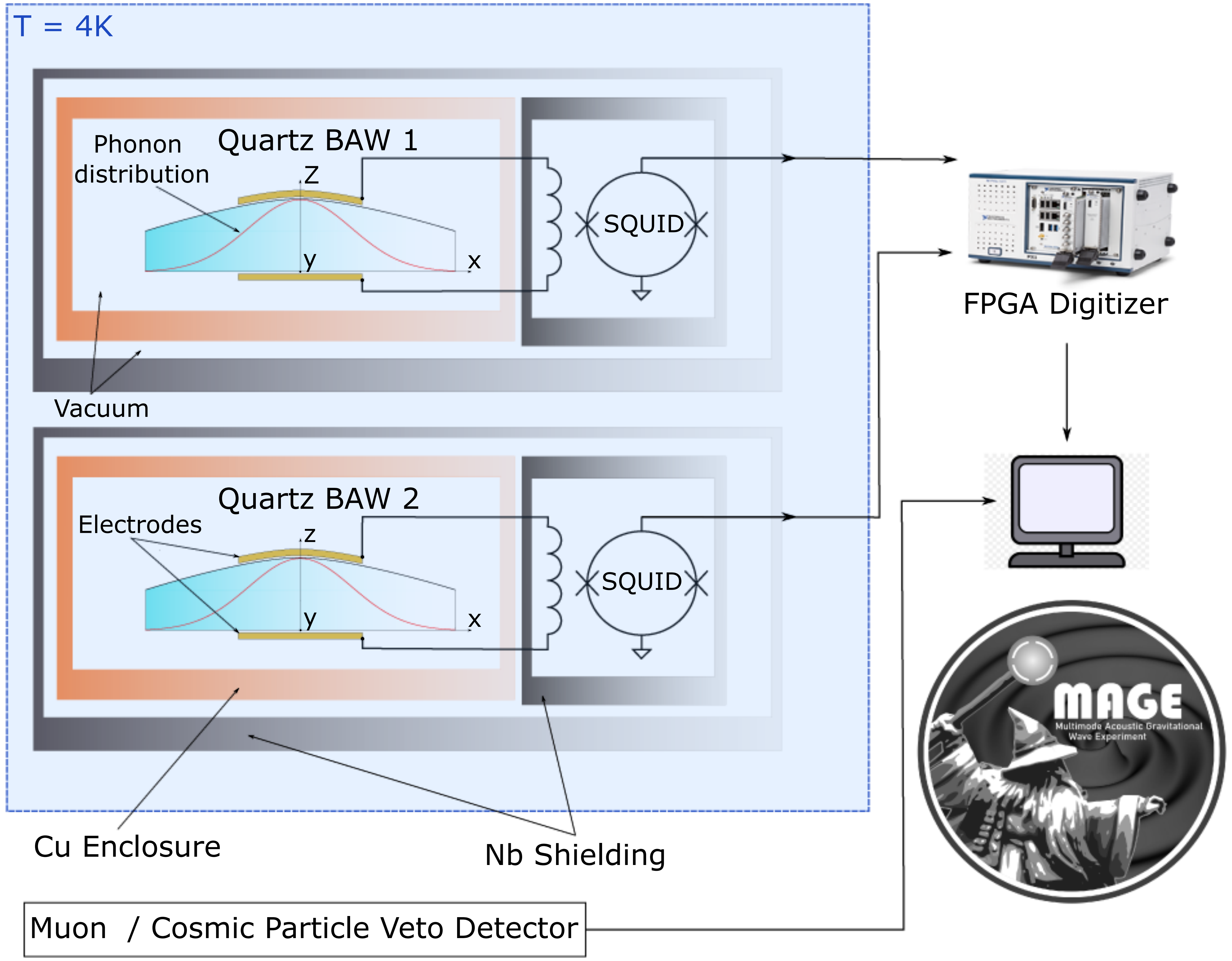




Alternative Technologies - Bulk Acoustic Devices



- Piezoelectric resonator
  - Freq: MHz - GHz
  - Consumer product
- GW deforms resonator
  - Periodically changing resonance frequency

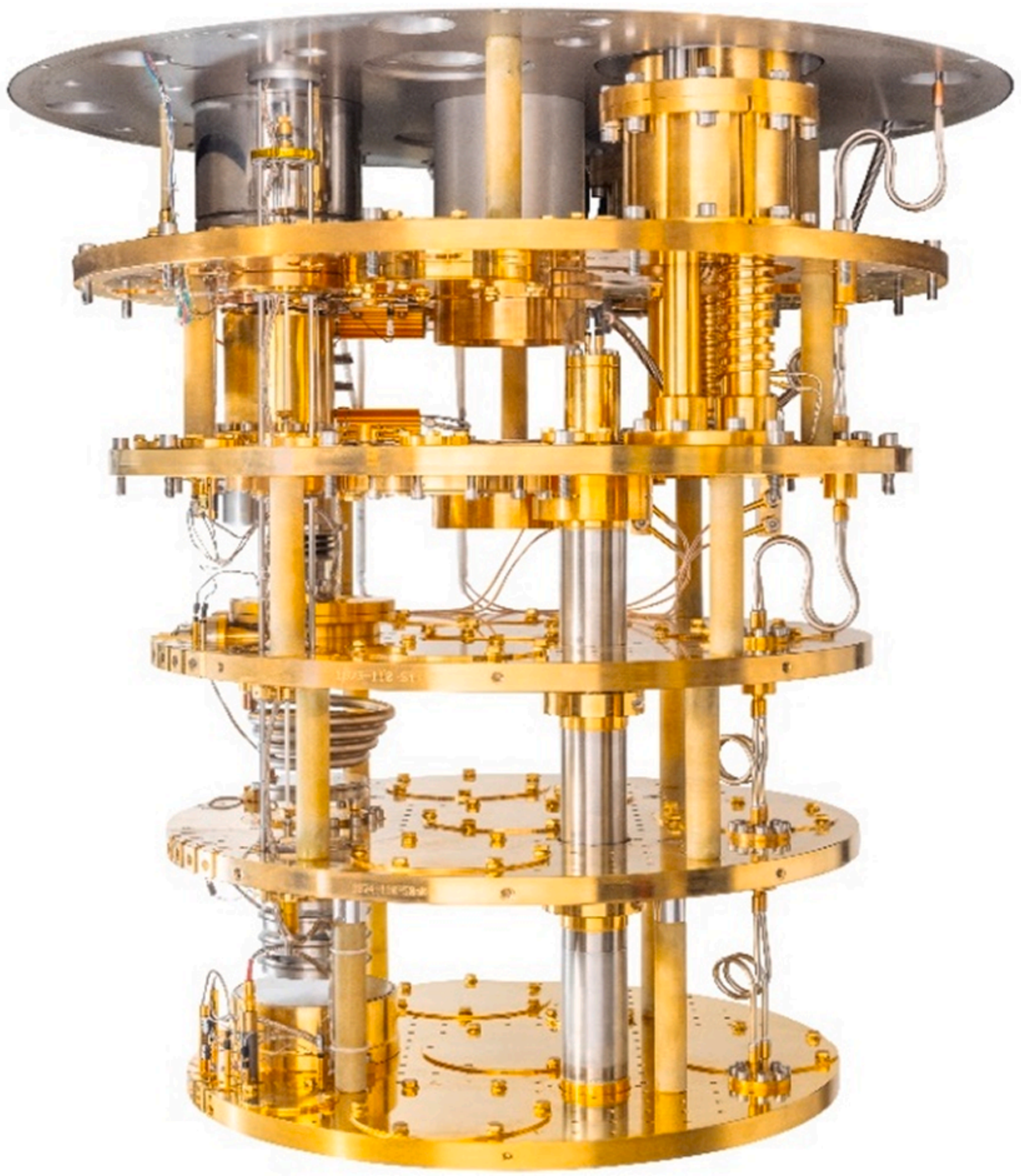


[Sci Rep 13, 10638 (2023). https://doi.org/10.1038/]

- Sensitivity from 5 - 10 MHz
- $h_0 > 10^{-21}$

Which Technology to Choose?

- GravNet will start with cavities since their technology is mature
- Most interesting HFGW sources are transient
  - Any HFGW search will profit from **combining signals**
  - Most developments (**Quantum sensing, Superconducting cavities, analysis**) is of generic use
  - **Magnetic fields** and **ultra cold volumes** are used in several approaches



- We will switch to the most promising experimental approach in the next years

Take Away Messages

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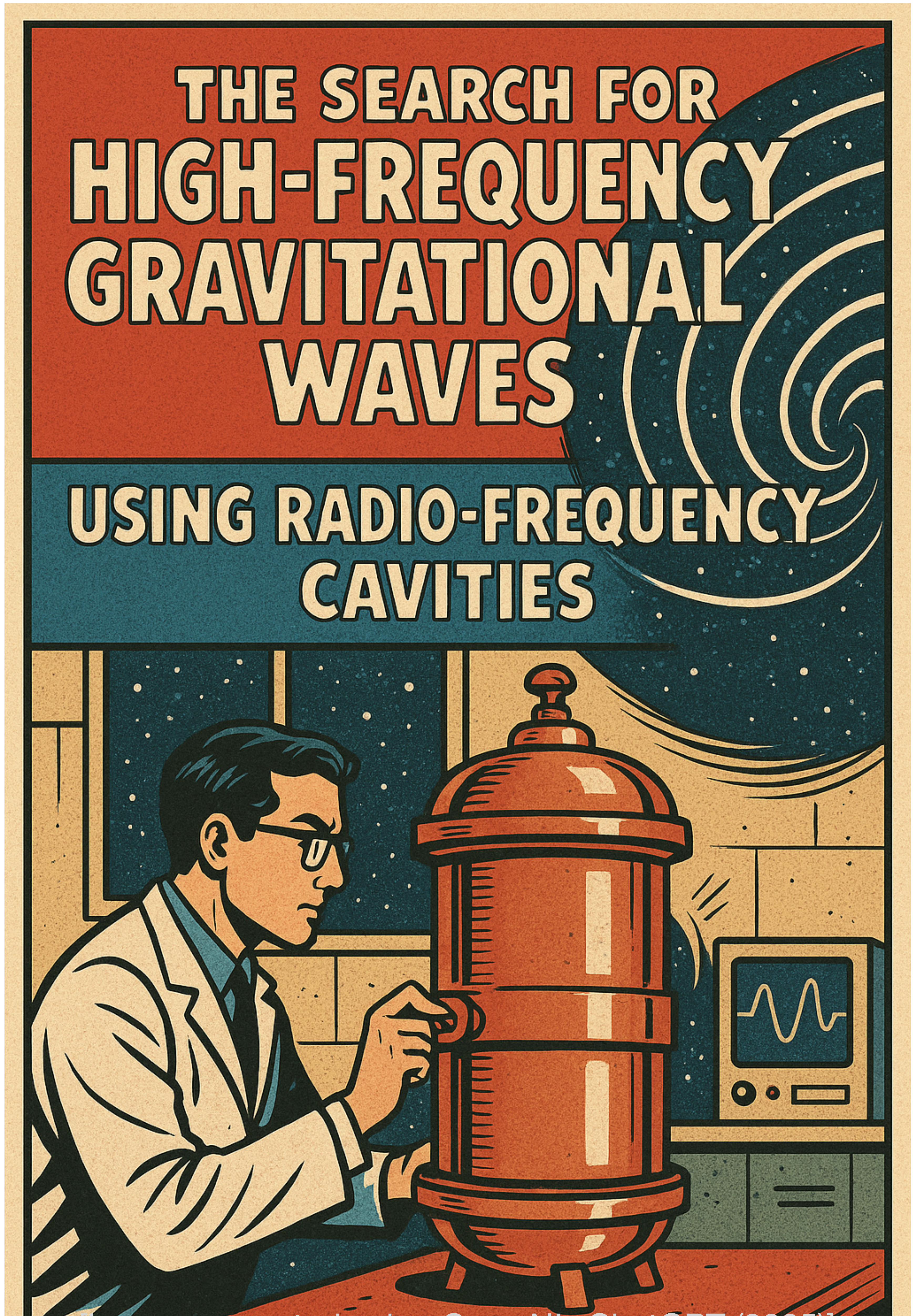
- Searching for HFGW is one of the most intriguing new topics in town
  - Lots of challenges, **lots of opportunities**
- We are looking for new collaborators
  - Kick-off workshop (26/27June)
  - https://indico.him.uni-mainz.de/event/229



[Image generated using OpenAI's ChatGPT (2025)]