UHFGW @ Supax

Cosmic Whipers WG4, 05/03/2024

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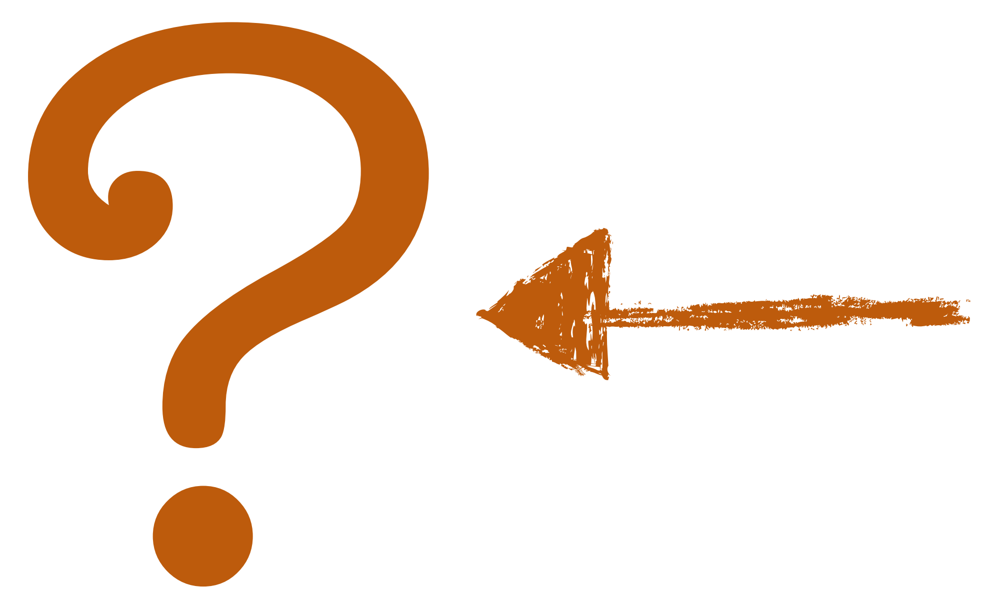
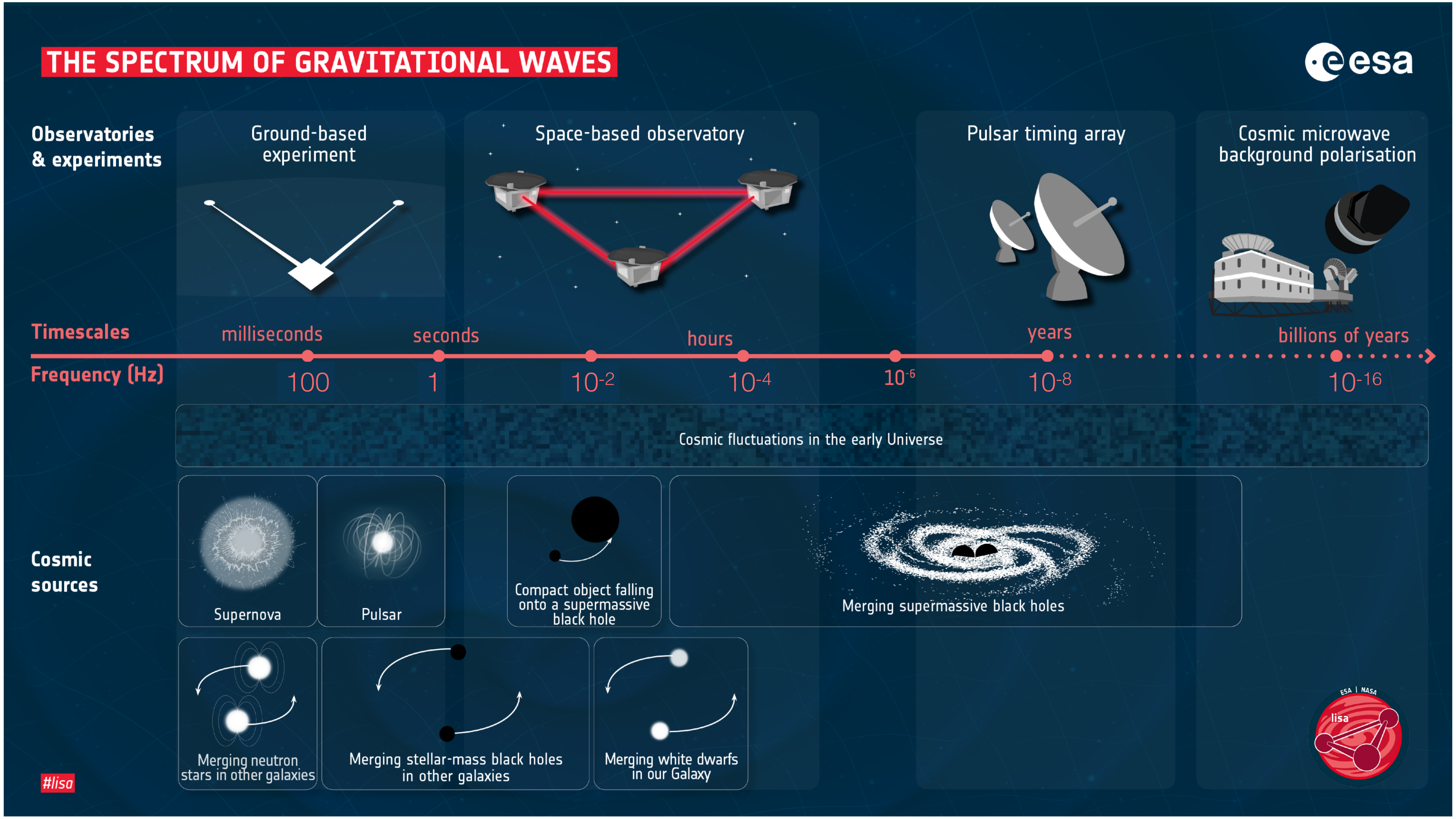
*: University of Mainz, **: University of Bonn

a RADES experiment

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

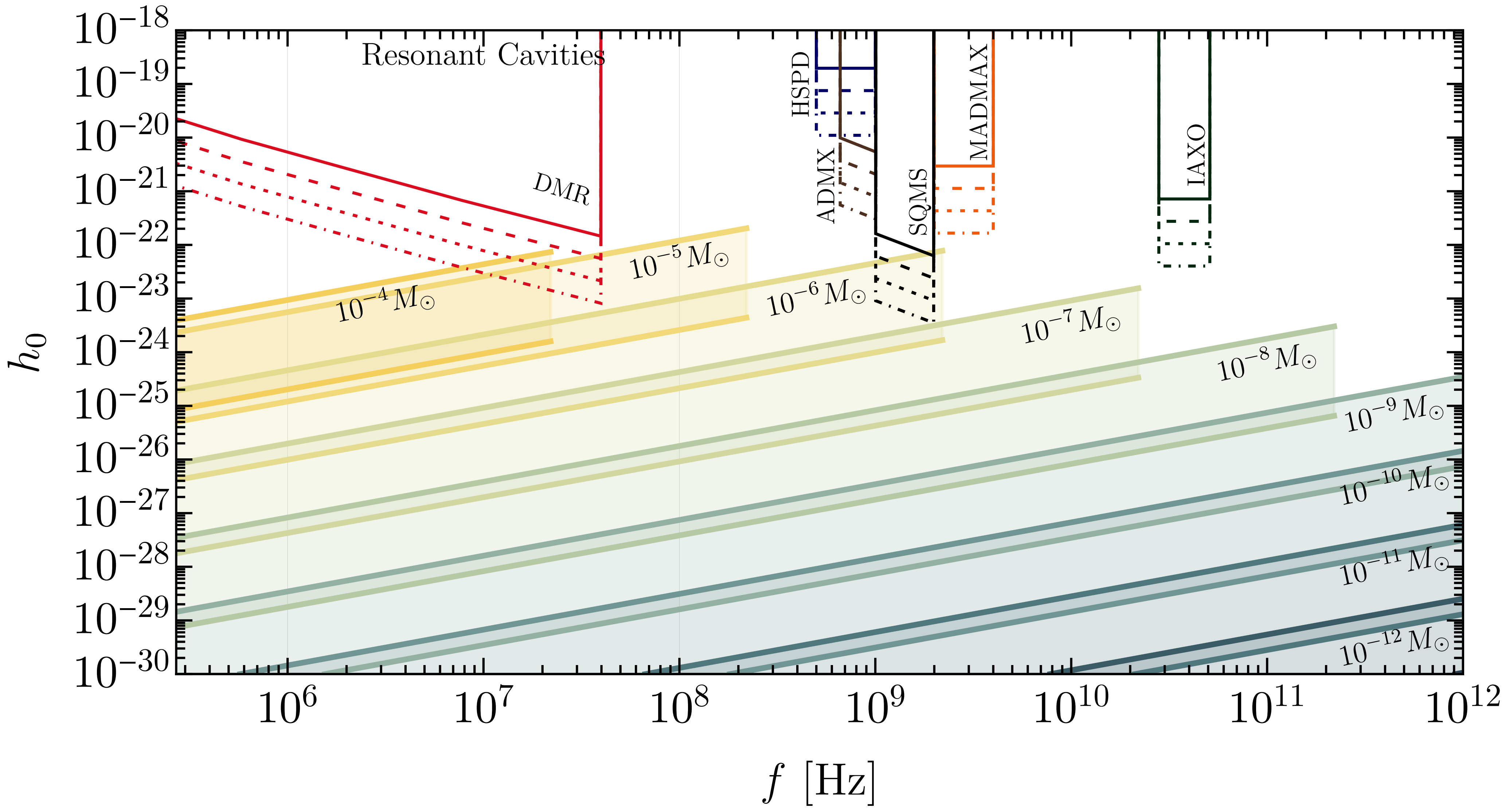




[https://www.esa.int/]

High Frequency Gravitational Waves Sources

- Several well motivated beyond the standard model sources:
  - Primoridal black hole mergers
    - Chirp signals
  - GW from boson clouds around BHs
    - **BH super radiance**
    - Monochromatic over long timescales



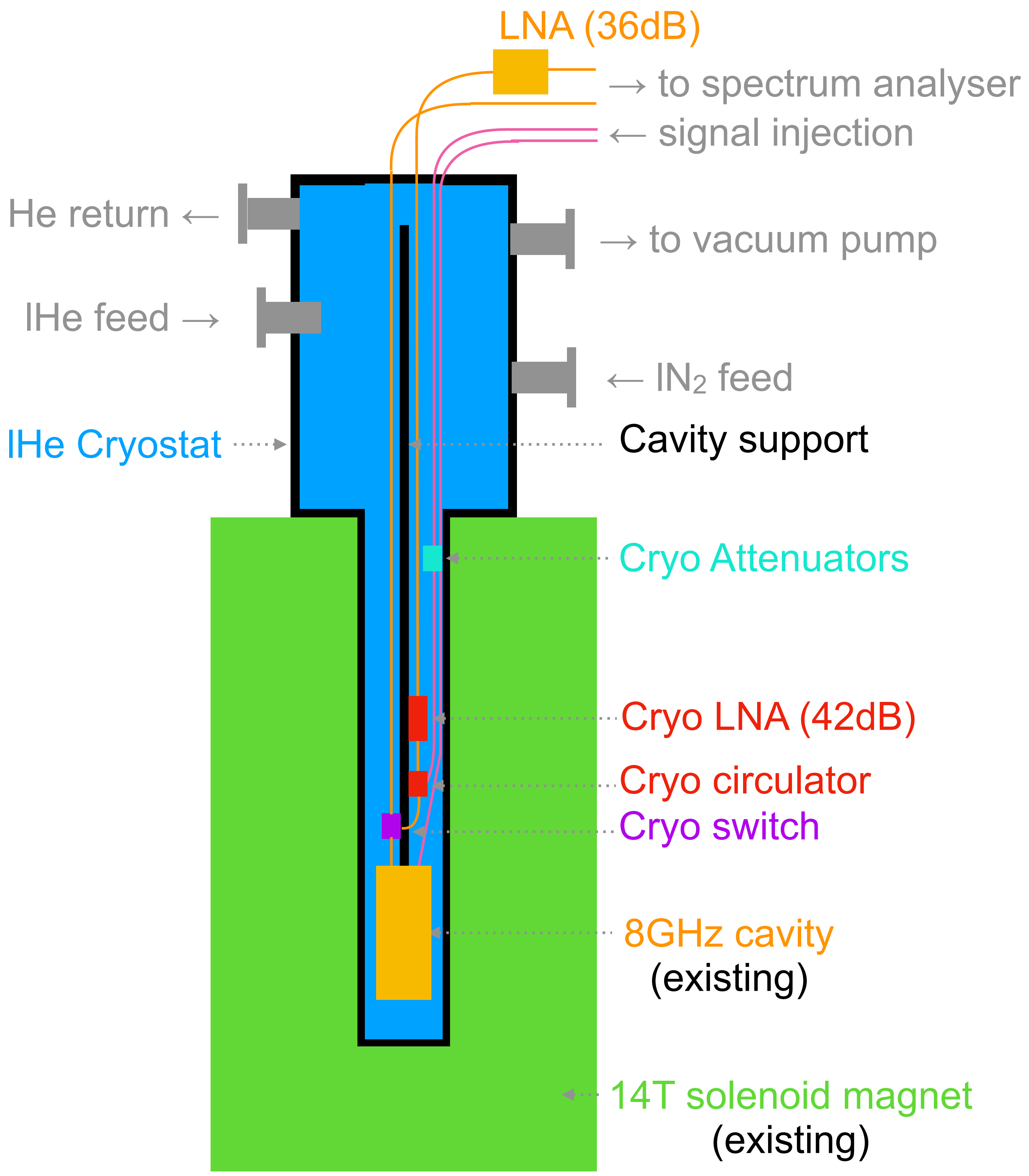
[Gabriele Franciolini, Anshuman Maharana, Francesco Muia; arXiv:2205.02153v1]

- Displayed expected experimental sensitivities for PBHs:
  - Assuming GW signal long enough to ring up cavity
  - E.g.: given for ADMX,SQMS @ $m_{PBH} \approx 10^{-10} M_\odot$

What we do at Mainz: Typical setup

[arXiv:2308.08337]

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



What we do at Mainz: Typical setup

[arXiv:2308.08337]

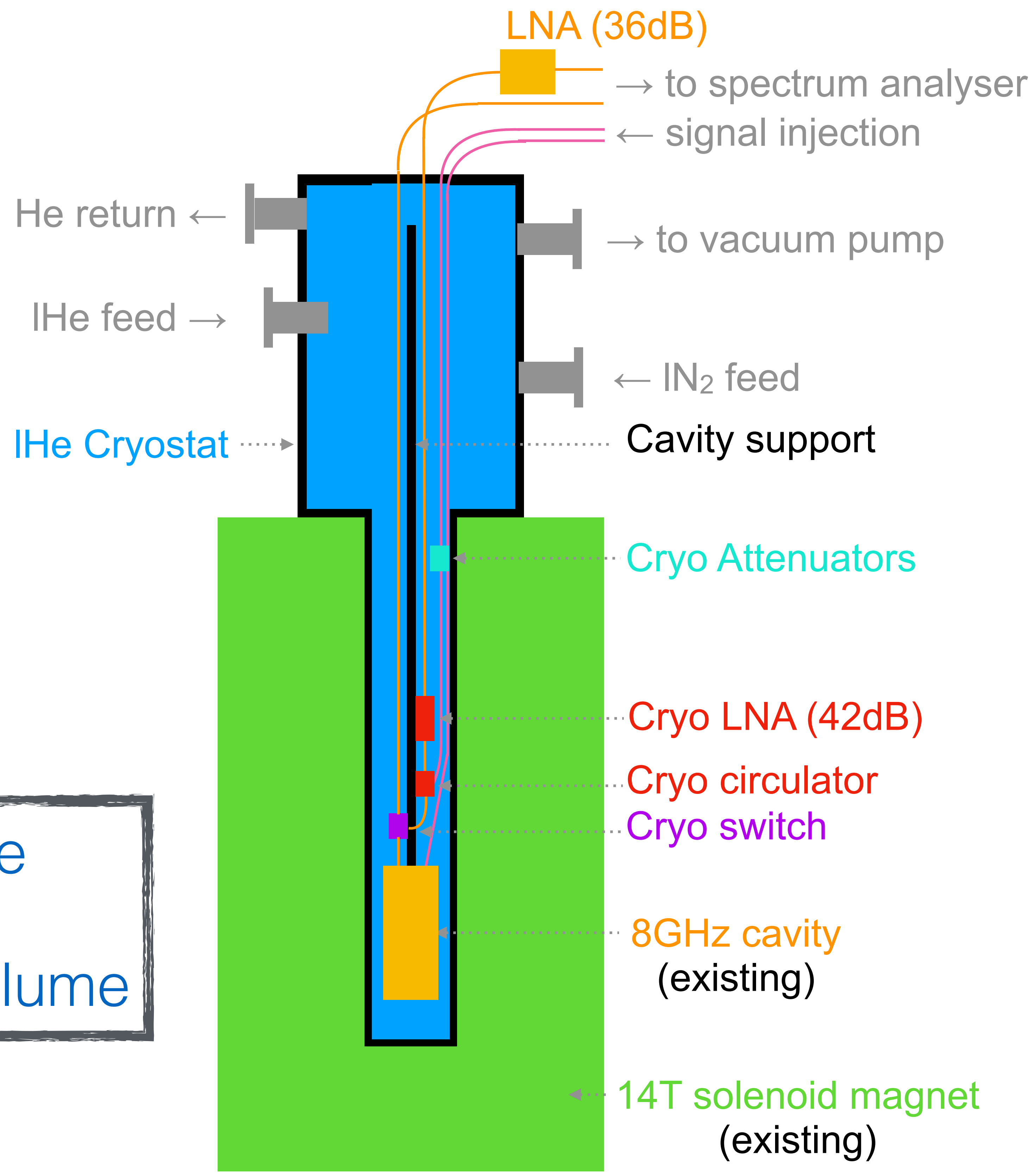
Metamaterials

Geometries

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

- Depends on cavity material:
  - High purity copper: ~5·10⁴
  - Superconducting: difficult in high magnetic field!
    - Target: 10^6
    - Achieved: $3 \cdot 10^5$ (non tunable)
      - HTS arXiv: 2002.08769
      - Di-electric arXiv: 2208.12670
    - Materials under study: Nb_3Sn, HTS materials (YBCO)
    - New: **NbN**

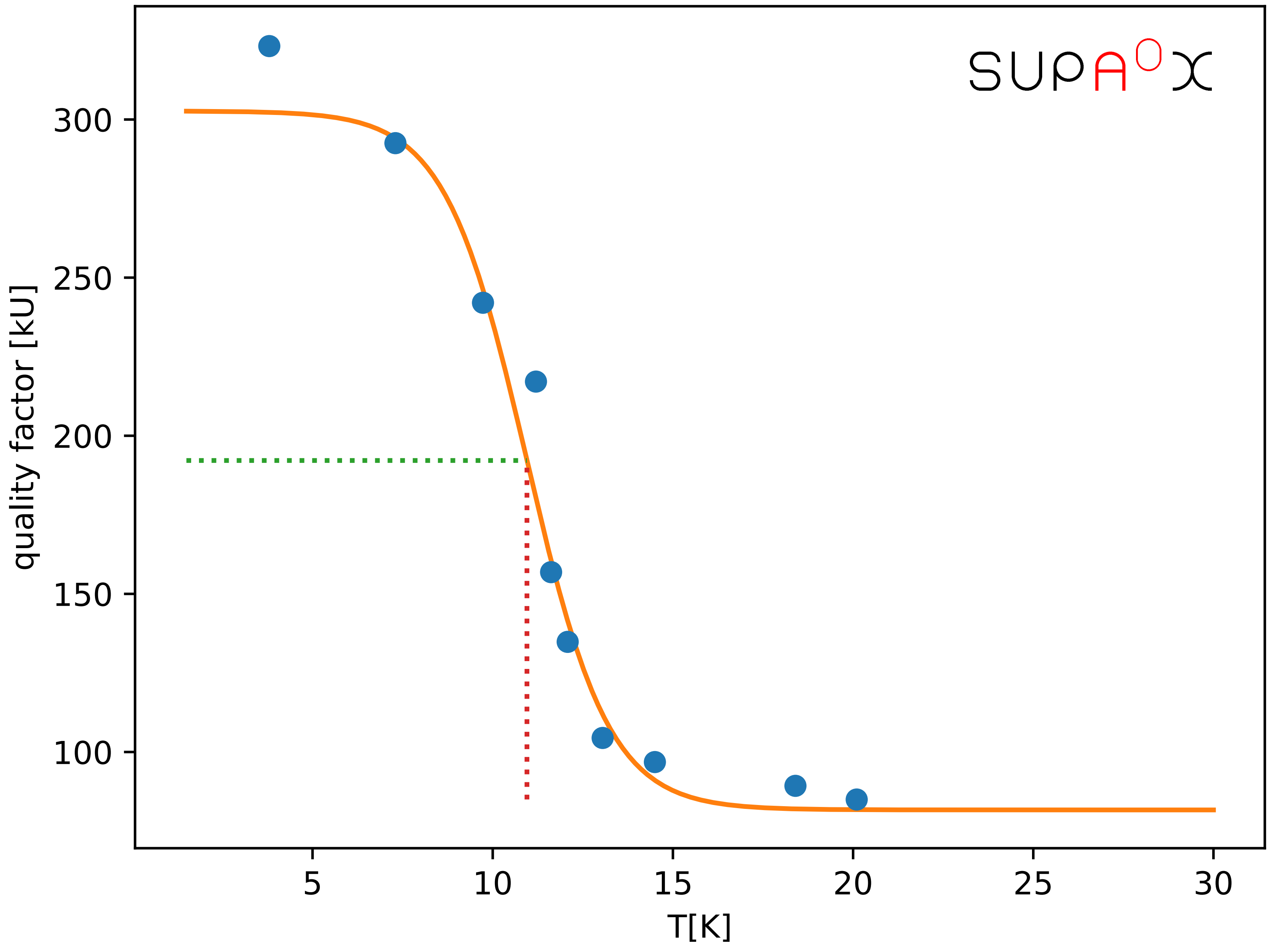
- Up to 14T magnets in use
  - Up to 20T envisioned
- Larger fields - smaller volume



Supax SRF cavity

- **Supax:** new superconducting material for RF cavities:
  - **NbN**
  - $Q_0 = 3.1 \cdot 10^5$ @ 8.4 GHz, 4 K
  - Measurements within B-field finished last Friday

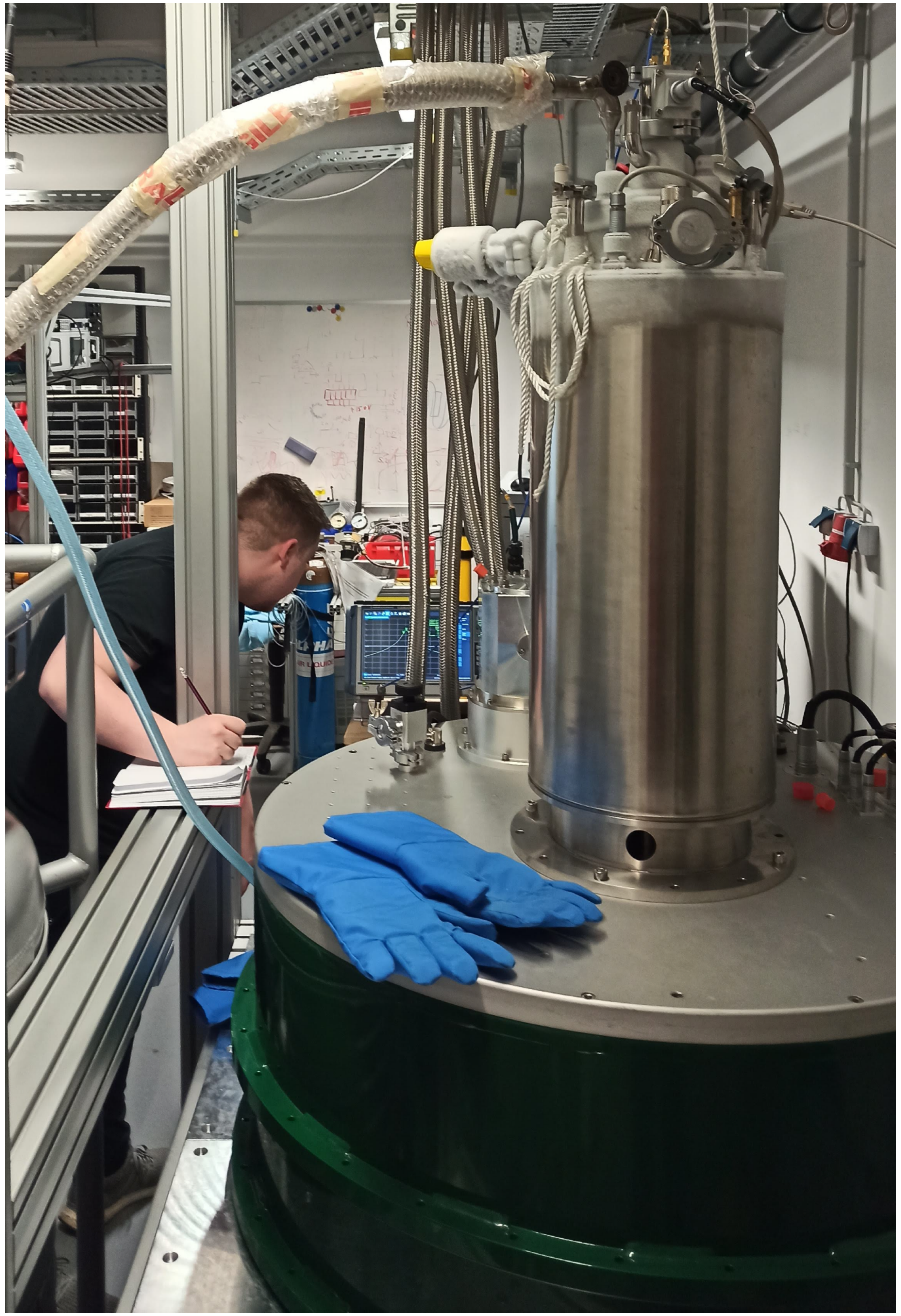
Cu cavity, coated with NbN at university of Siegen



Supax SRF cavity in B-Field

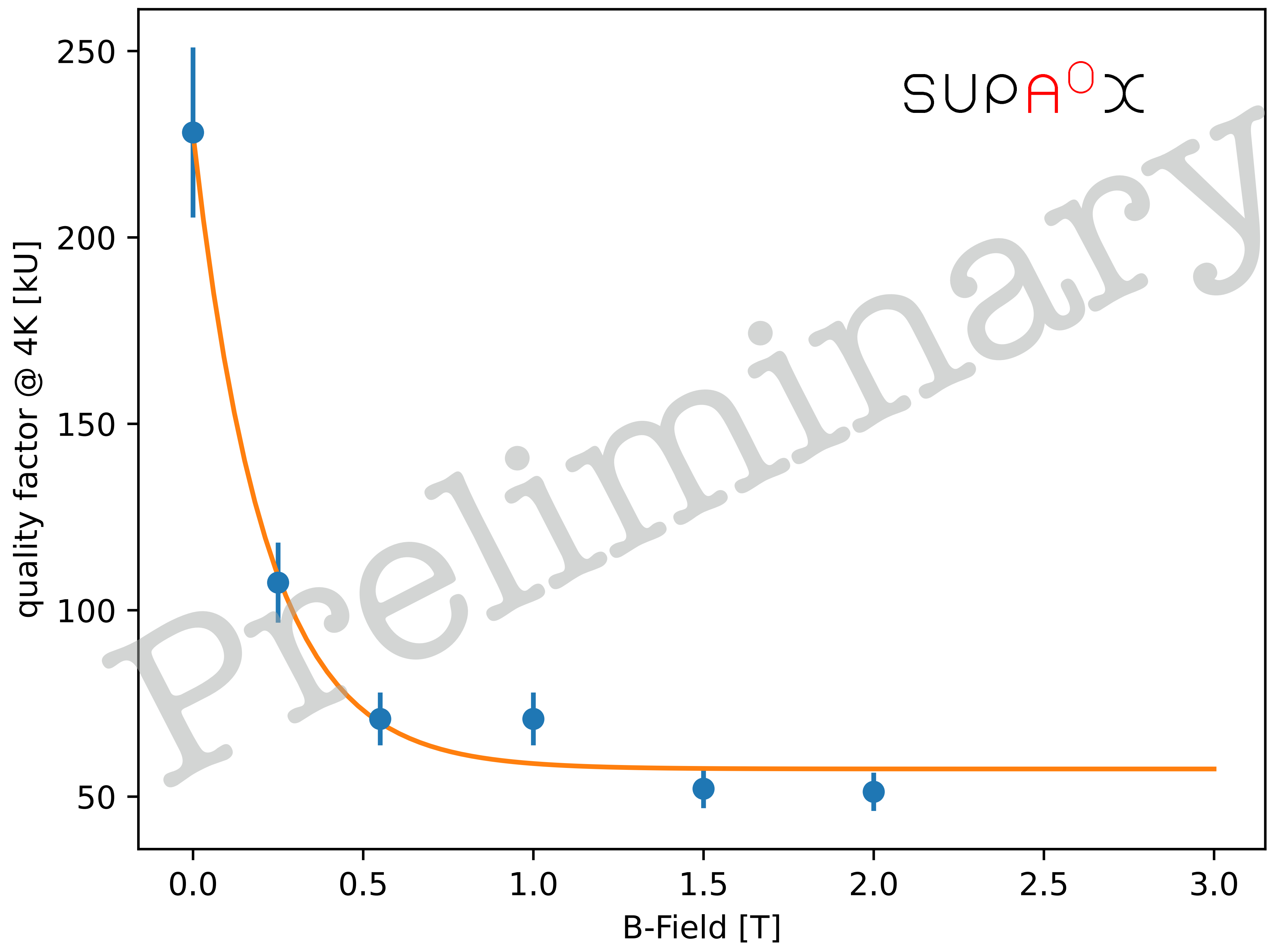
•Measurement at D. Budkers lab in Mainz

- **Supax:** new superconducting material for RF cavities:
  - **NbN**
  - $Q_0 = 3.1 \cdot 10^5$ @ 8.4 GHz, 4 K
  - Measurements within B-field finished last Friday
  - Analysis in progress. Preliminary results



Supax SRF cavity in B-Field

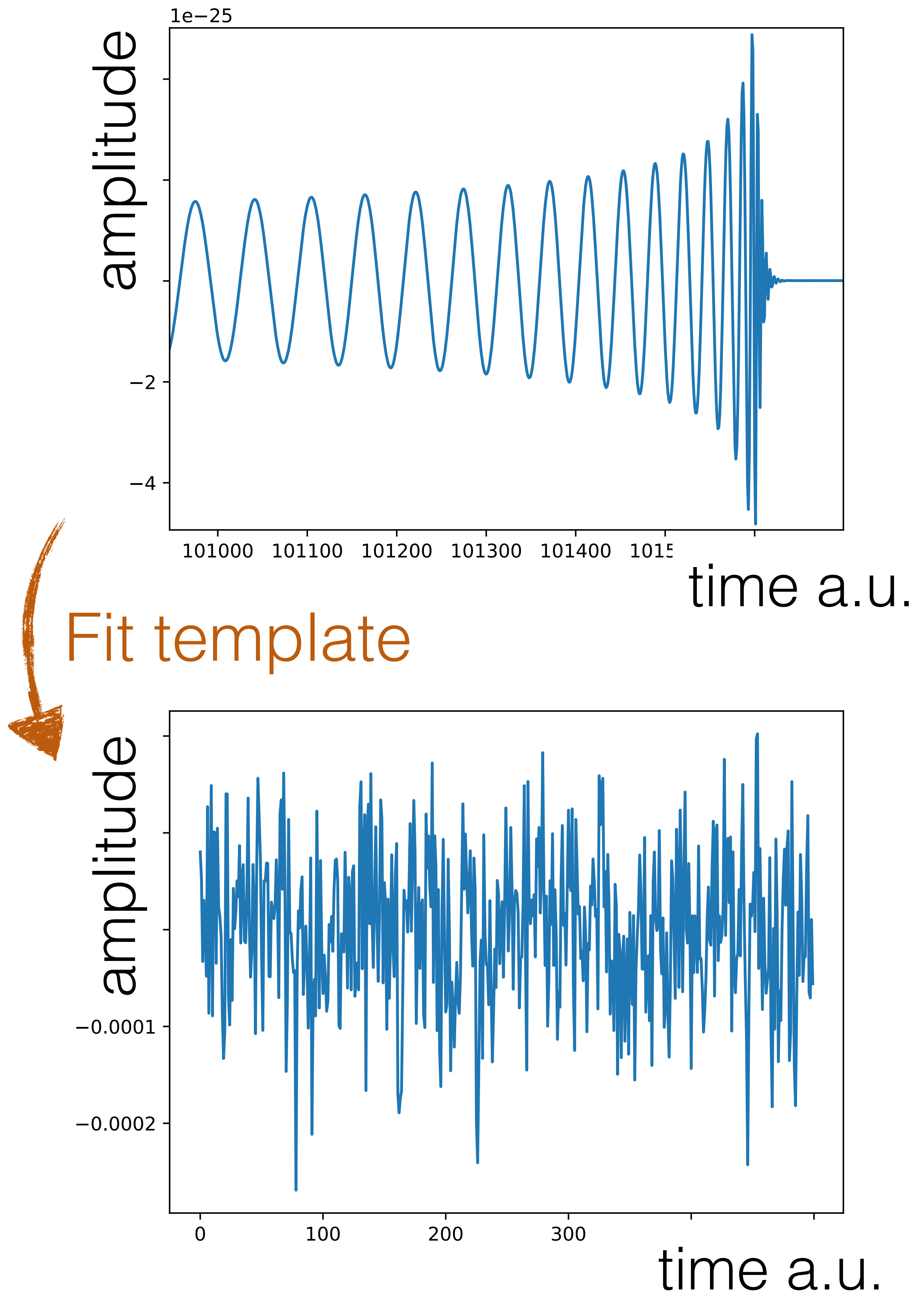
- **NbN**
  - Cavity largely over coupled during measurement
  - Q0 around $3 \cdot 10^5$ in previous measurement
  - Q0 ~exponentially decaying with increasing B-field
    - Suggest reduction of Q max by factor 4.5 at 2T field
    - Seems NbN not suitable for this purpose …



Next Steps

- **Spherical cavity:**
  - Prototype spherical cavity produced (4cm diameter, Cu)
  - To be characterised
- **MgB2 as SC material:**
  - Investigating coating possibilities
- **Timeseries analysis of multiple cavity signals:**
  - Analysis of pseudo-data is currently in development
  - Targeting transient signals with O(10ms) duration

- Similar approach as for low frequency BH mergers:
  - Analysis in **time domain**
  - Data rates: ~100MB/s per channel for 10MHz bandwidth
- Simultaneous fit of expected signal shape in all data streams
  - Exploiting all available information
    - + Increased sensitivity compared to time domain analysis
    - - Significant increase in storage & CPU requirement
  - **Sensitive to** **short transient** signals



Estimated Sensitivity Combining Cavities

- Phase aligned combination voltages from of N cavities
  - RF amplitude (voltage):

$$V_{comb} = \frac{it\omega}{\sqrt{N}} \sum_i V_i e^{i\phi_i} \propto \sqrt{N} V_0$$

$$V_i = V, \phi_i = \phi$$

- Hence the **signal power scales linearly in N**!

- Assumed single setup
  - 14T B-field, about 10cm diam., 30cm long
  - 3 spherical cavities @ 5GHz, SC, high Q
  - 1s integration time

Setup	Supax	GravNet
Shape	cyl.	spher.
f_0 [GHz]	8.3	5.0
Volume [l]	0.128	0.21
Q_0	39600	10^6
η	0.08	0.6
T_{sys} [K]	5	0.1
B [T]	14	
int. time	1 s	
n cavities	1	3
noise power [W]	$1.5 \cdot 10^{-21}\, W$	$6.2 \cdot 10^{-23}\, W$
$h_0(P_{sig} = P_{noise})$	$7.1 \cdot 10^{-21}$	$5.2 \cdot 10^{-23}$

- Results in table for power integrating measurement

- **Timeseries analysis**
  - Sensitive to shorter signals
  - Expected to increase sensitivity by factor 2 - 4

Long Term Goal: GravNet [arXiv:2308.11497]

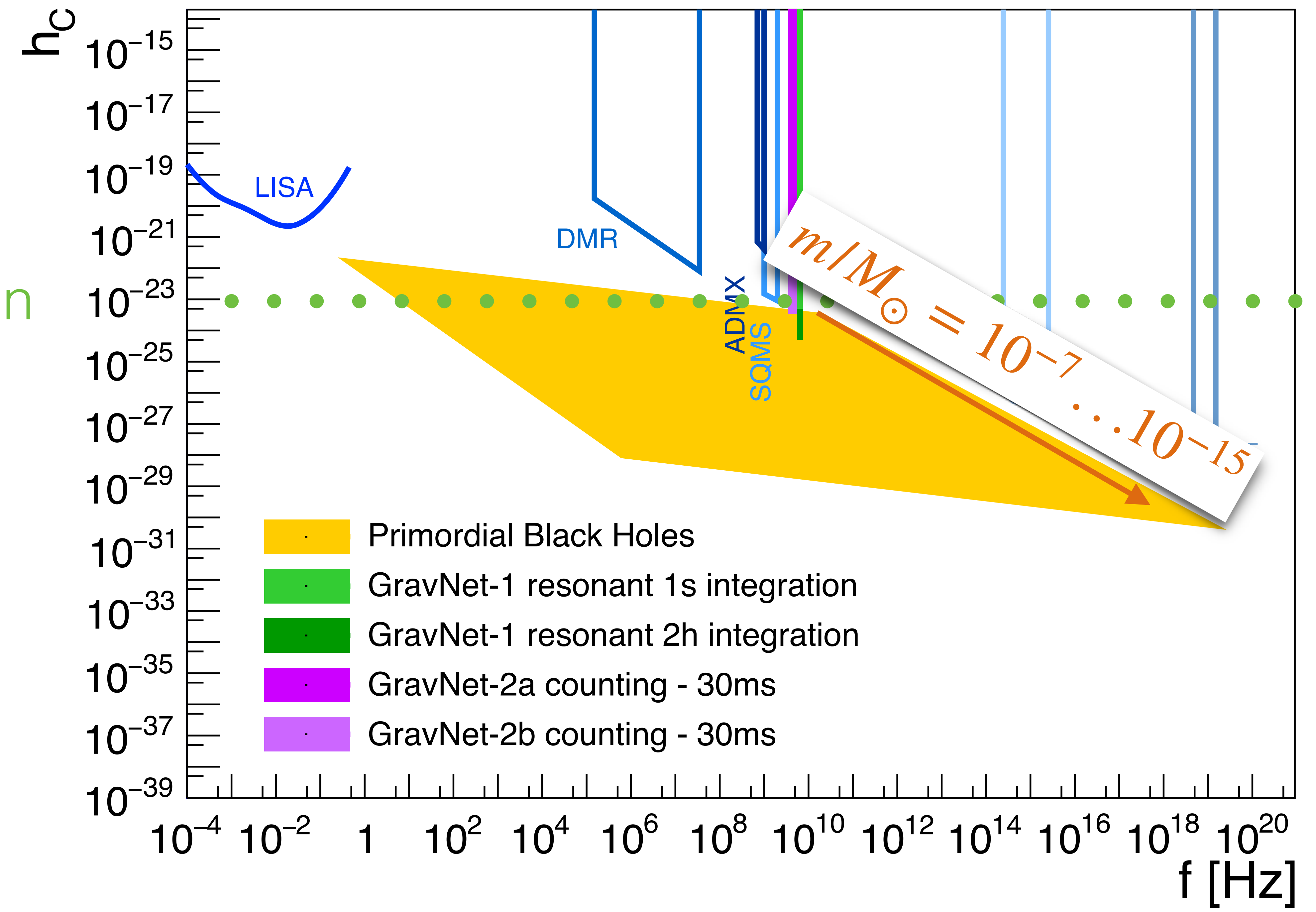
- How sensitive can we get with **10 setups**, scattered around the globe

- Assumptions:
  - Sampling of Waveform -> offline combination of phase aligned IQ data
  - Setups as shown before
    - Effective signal power increased by factor 10
    - Strain sensitivity increased by factor $\sqrt{10} \approx 3$

$$h_0 < 10^{-23}$$, 1 second integration time

- No frequency tuning needed:
  - PBH signals are fast transients
    - Single frequency sufficiency

1s integration



- Phase alignment for distributed setups:
  - If signal seen in 3 cavities:
    - Direction of GW can be reconstructed
  - Otherwise:
    - Scan through all possible directions and repeat combinations

Long Term Goal: GravNet [arXiv:2308.11497]

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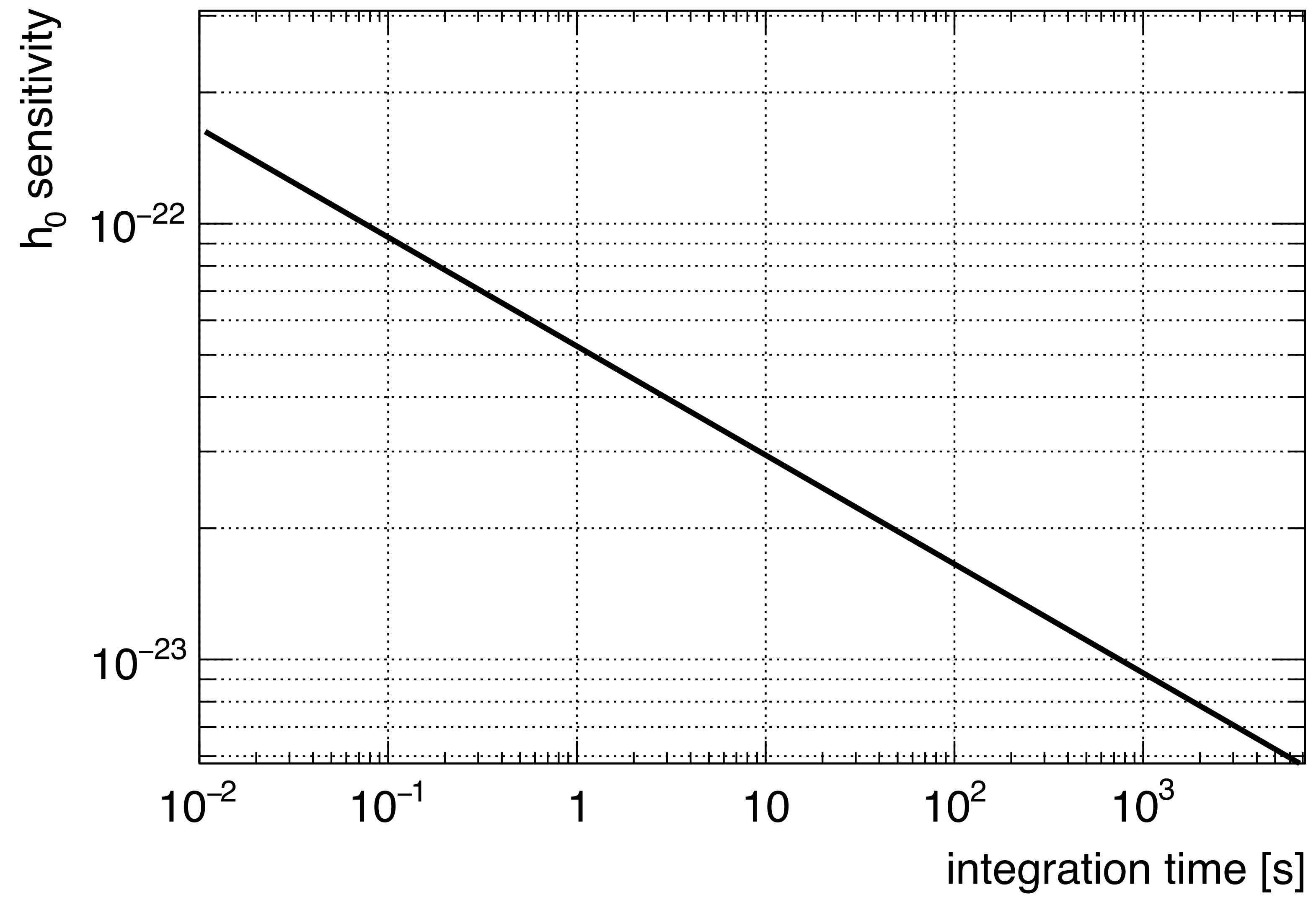
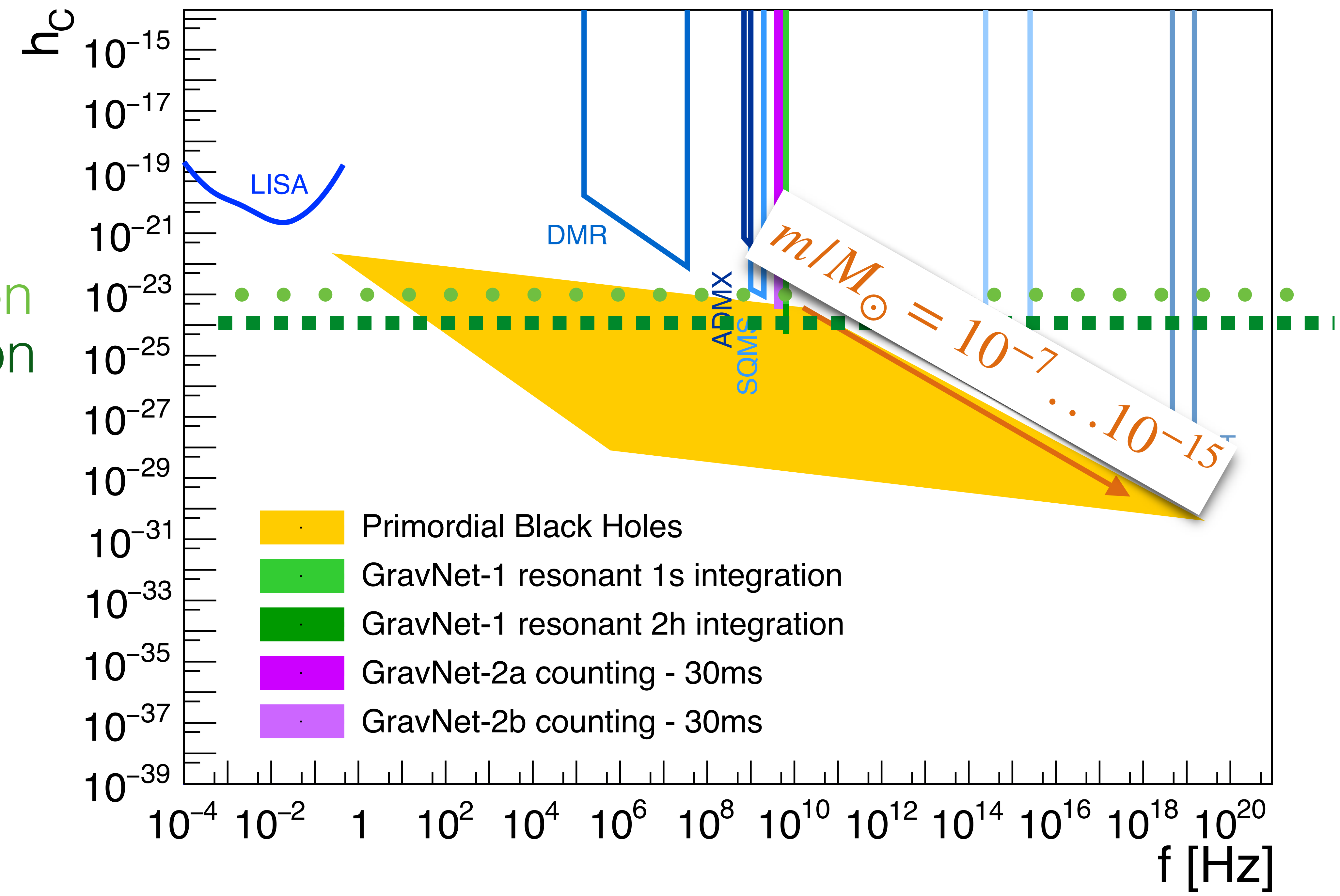


- Longer integration times
  - Sensitivity gain with integration time $t^{1/4}$

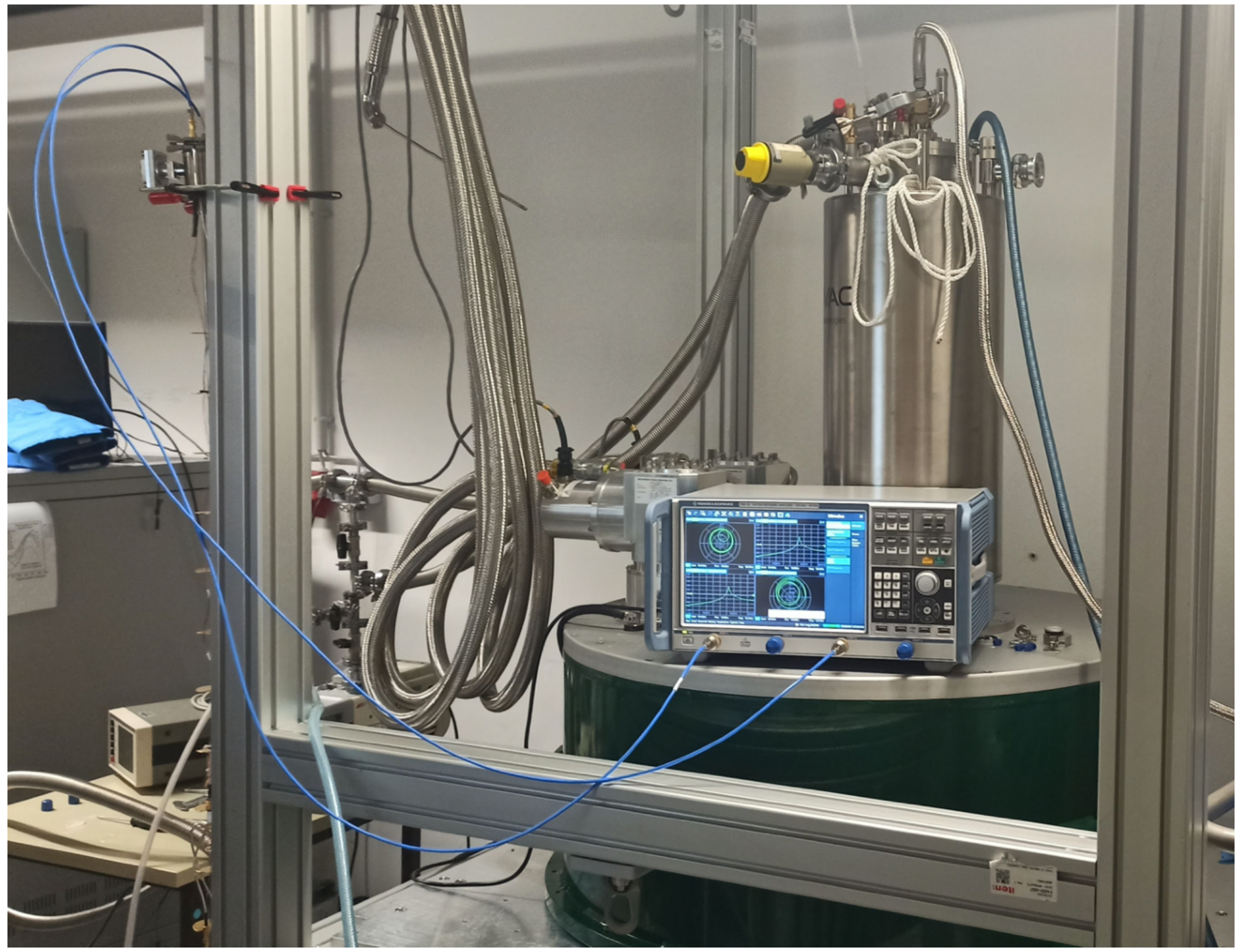
$h_0 < 10^{-24}$, 2h integration time

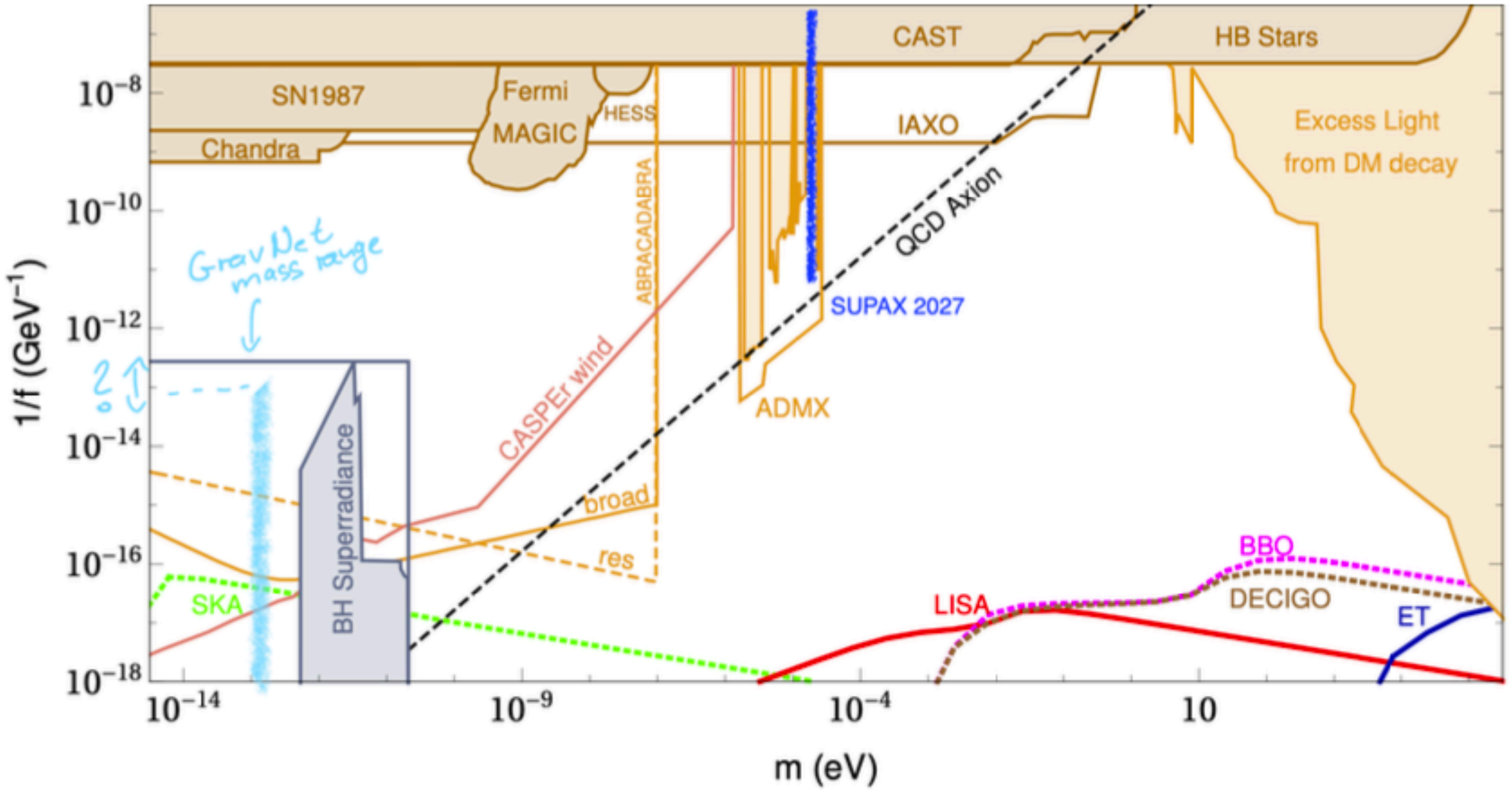
1s integration
2h integration



Summary

- Working **4K setup @ Mainz** with **14T** magnet
- R&D on SC high Q cavities in B-field ongoing
  - **First results on NbN**
- Optimisation of cavity geometry for GW started
- Combination of multiple cavities next
- **Target sensitivity:**
  - Strain **< 10^{-23}** for 1s integration times
- Ultimately working towards a network of GW detectors reaching strains of 10^{-24} for transient signals O(10ms)





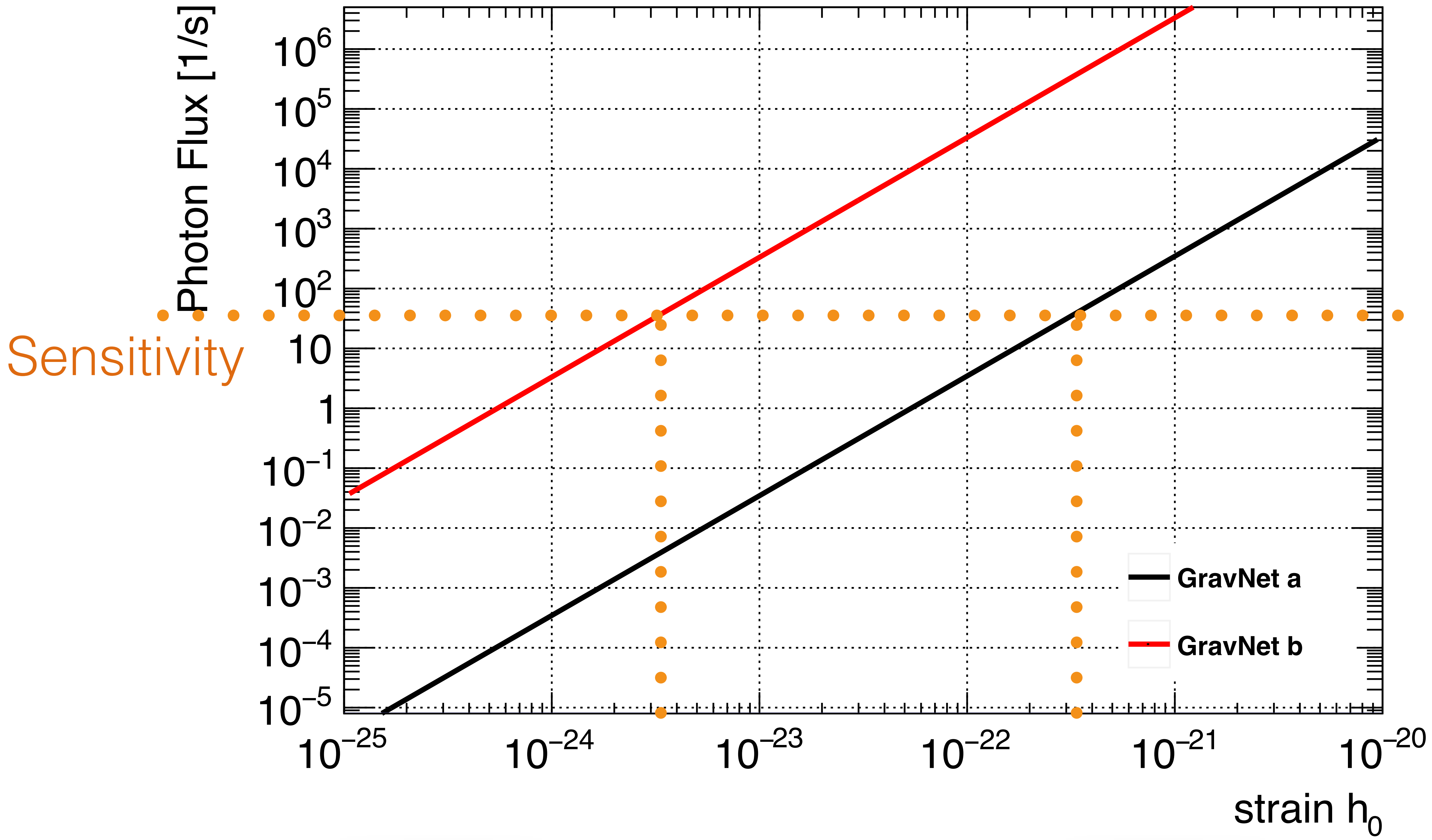
BACKUP

Far Future: Photon Counting

- With 20 detectors a photon flux of 40 Hz can be detected with an efficiency of 1 within a coincidence interval of 32ms

- Signal photon flux depends on conversion region:
  - a) Magnet dimensions as before (9cm diameter), B = 14T
  - b) Assuming large NMR magnet (80cm diameter), B = 9T

Setup	GravNet-a	GravNet-b
radius	40 mm	40 cm
length	12cm	50 cm
Volume $[m^3]$	6×10^{-4}	0.25
Q_0	10^6	10^5
$T_{\rm sys}$ [K]	0.1	0.1
B [T]	14	9



- Achievable sensitivity:
  - $h_0 < 3\text{x}10^{-22}$ .... $3\text{x}10^{-24}$
  - With coincidence time of 32ms!

Global network of HFGW detectors will be able to reach into the interesting region for PBH with existing technologies!

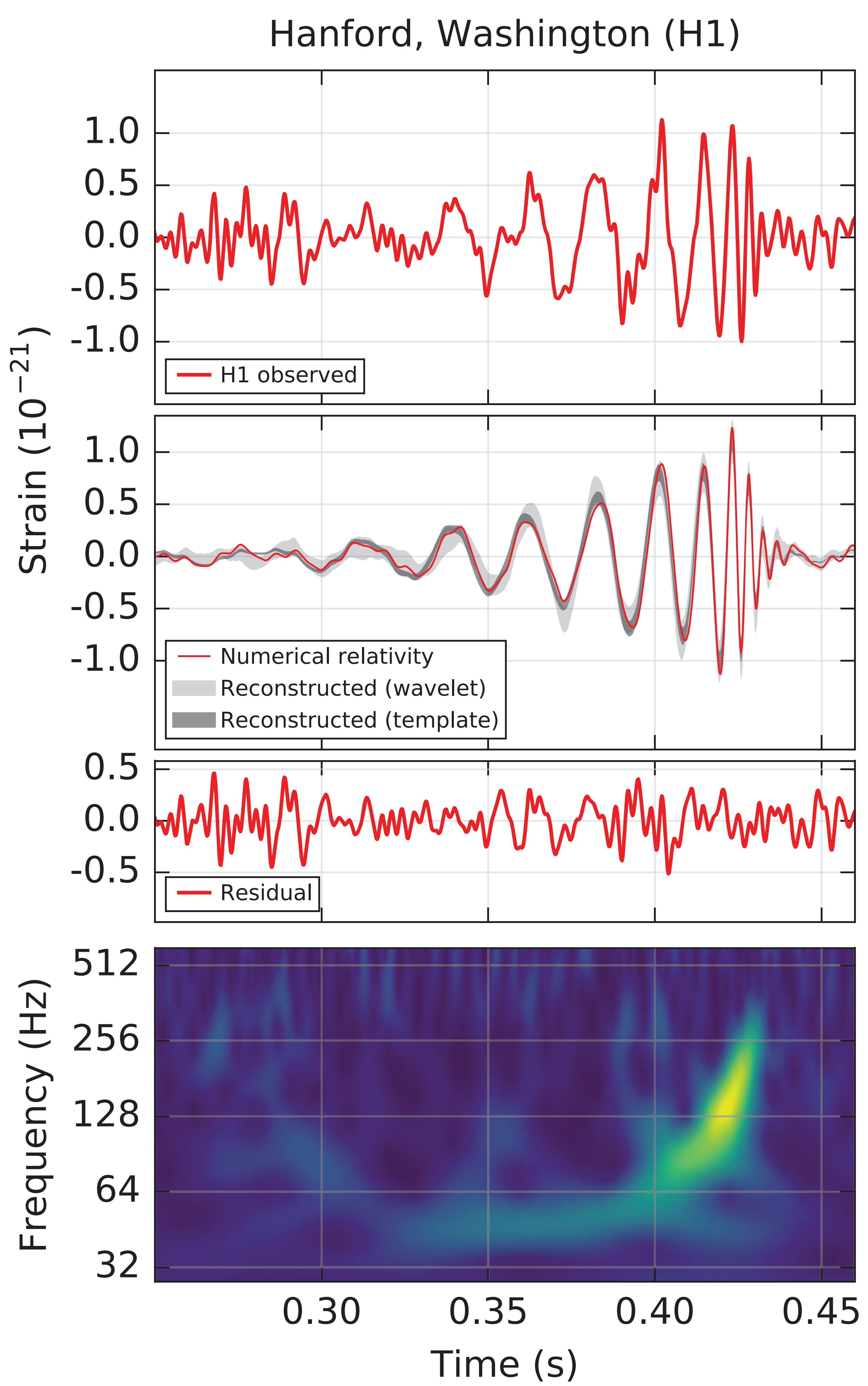
Significant room for improvements:
more detectors, larger volumes, higher detector efficiency

- Observation of gravitational waves by LIGO/Virgo is certainly a breakthrough in fundamental physics!

- However, there should/could be other sources of gravitational waves
  - Primordial black hole merges
  - Boson clouds (BH superradiance)
  - …
- Those GW would have frequencies in the GHz regime
  - **Should search for high frequency GW**

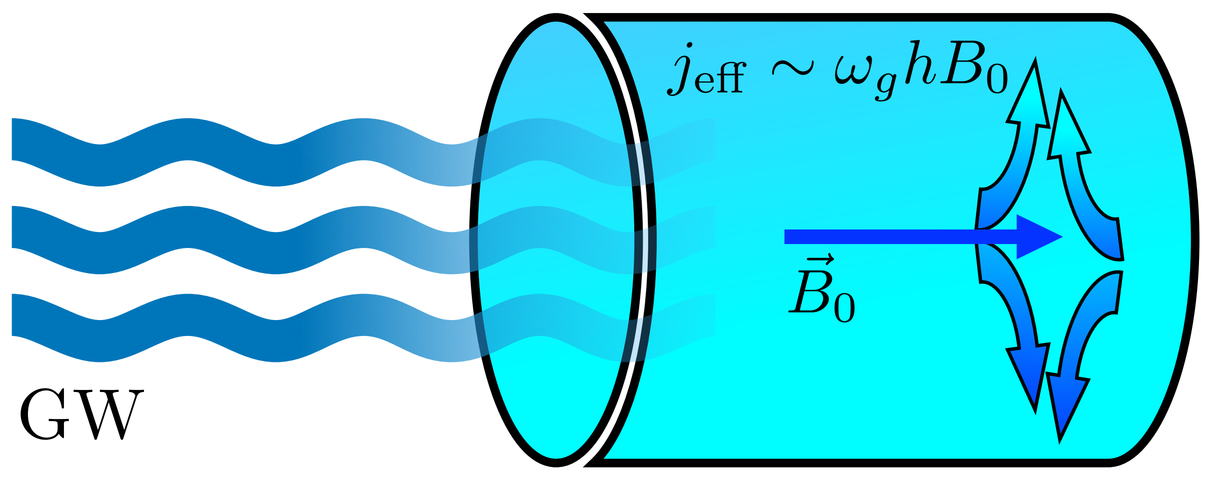
But how?

- Frequency range: 10-1000 Hz



[PRL 116, 061102 (2016)]

[arXiv:2112.11465]



- Two contributing effects
  - Assuming conversion cavity with volume V within static B-Field

- GW deforms cavity
  - Oscillating change of magnetic flux
  - Excitation of EM field

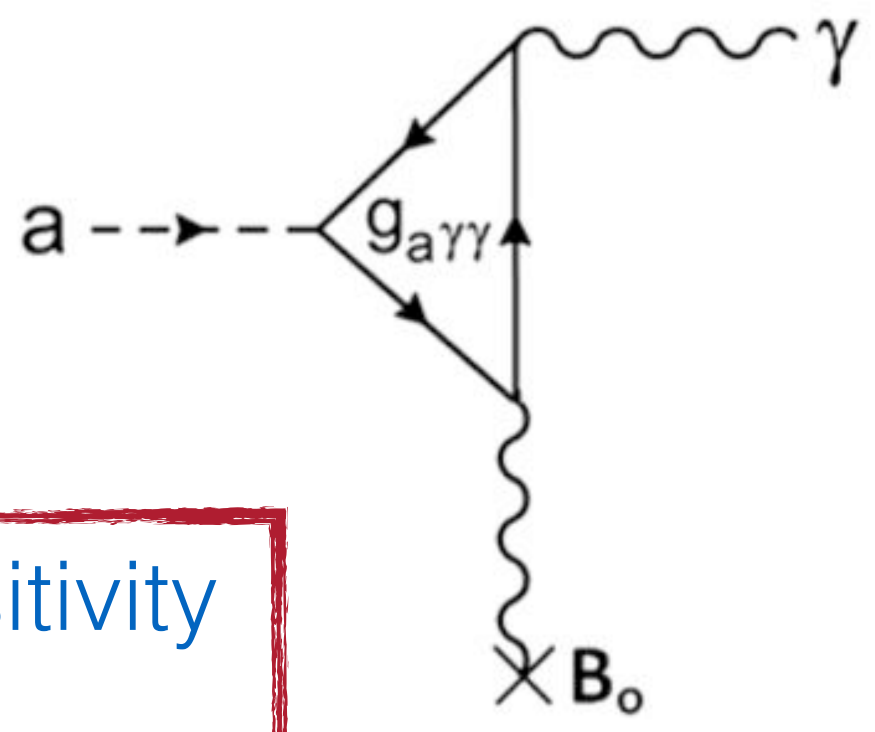
- Direct conversion of gravitons to photons via the inverse Gertsenshtein effect

- Resonant excitation of EM field in Cavity
  - Produced EM power given by:

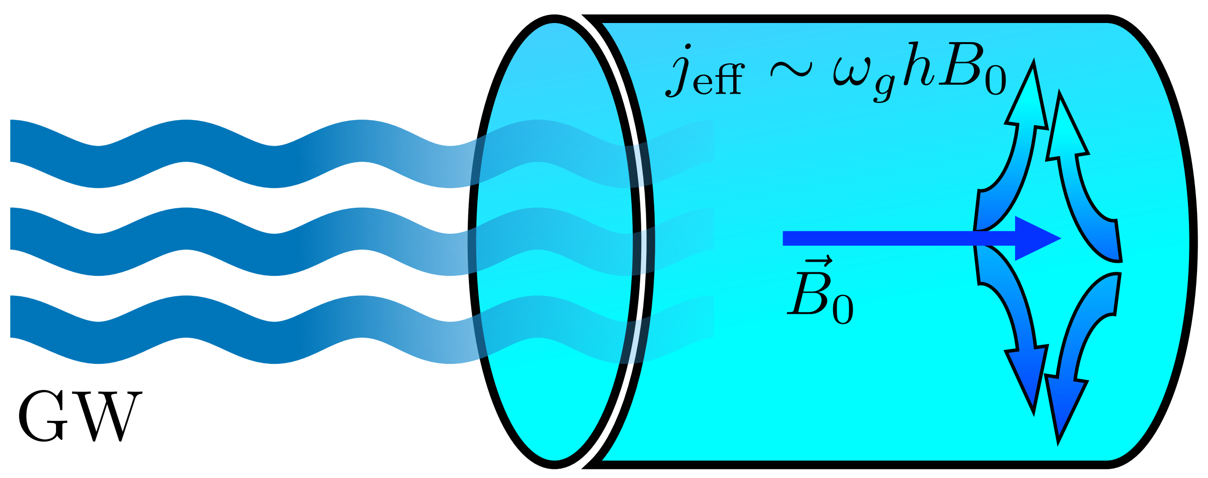
$$P_{sig} = \frac{1}{2} Q \omega_g^3 V^{5/3} (\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$$

Similarity to Axion Searches

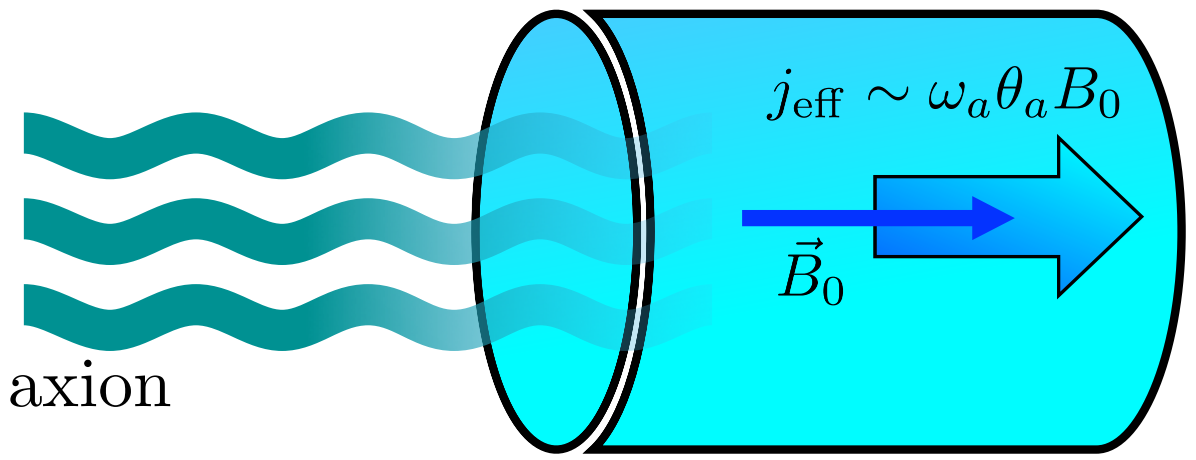
- Axion Haloscopes:



  - RF cavity in magnetic field → Primakov conversion of axions to photons
  - Resonant excitation of cavity mode
  - **Cavity based haloscopes are sensitive to GWs**



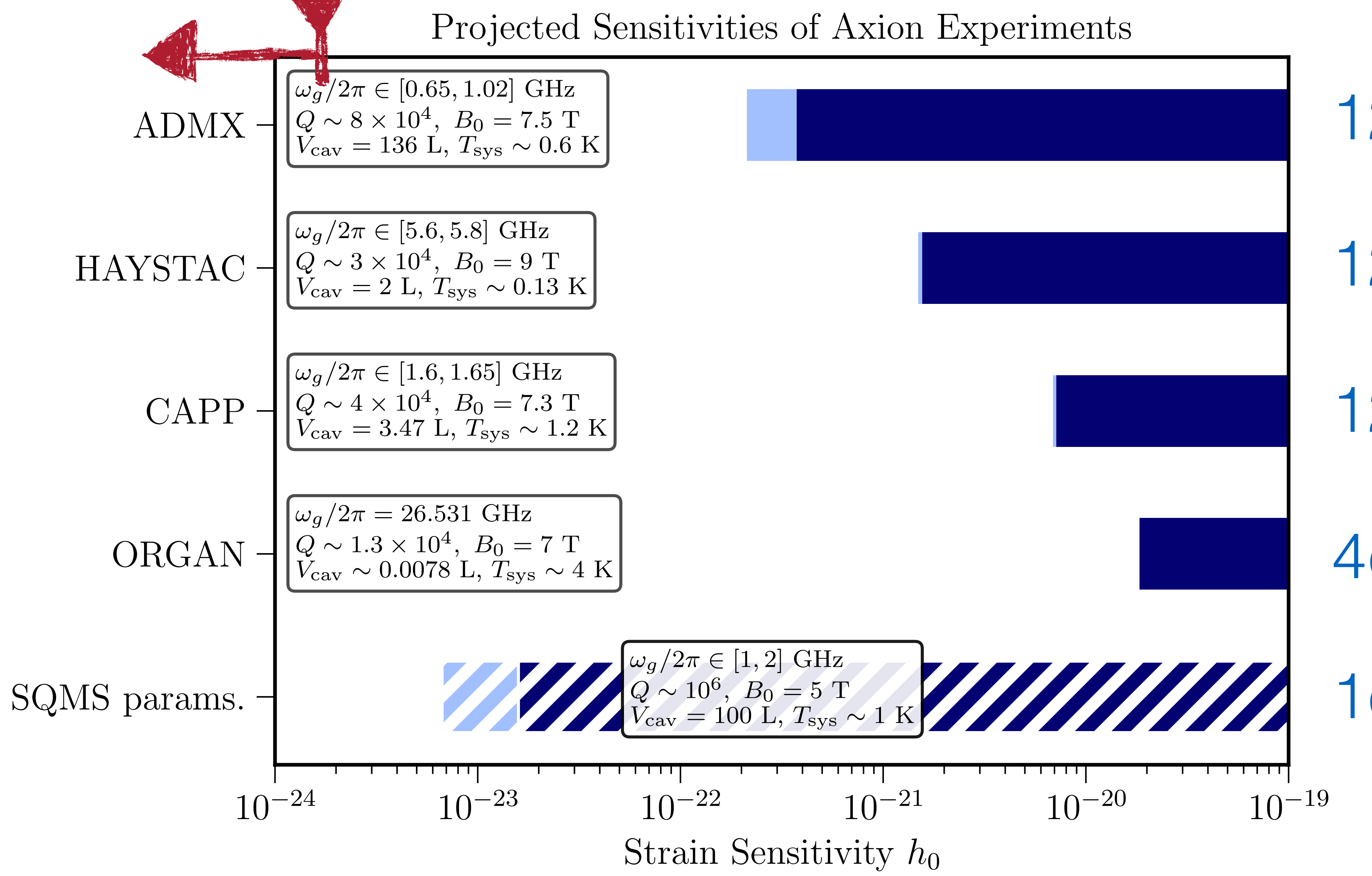
- GW:
  - Typical quadruple structure
  - Preferred mode: TM 020
  - Current direction dependent on GW



- Axions:
  - Preferred mode: TM 010
  - Current dependent on B-field direction
  - Litle overlap with GW mode

[arXiv:2112.11465]

Interesting sensitivity range for PBH



t_int
120s
120s
120s
4d
1d

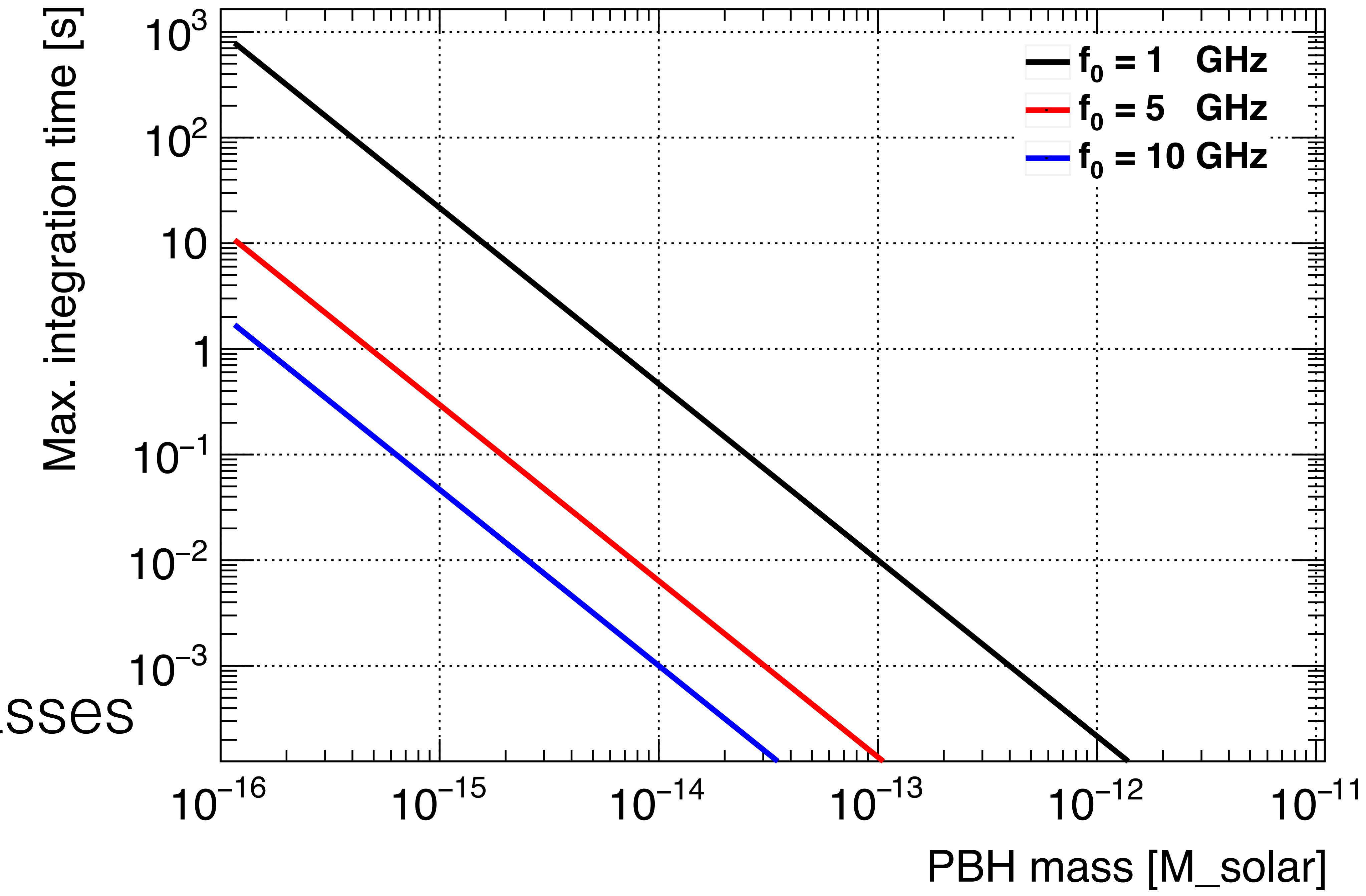
[Detecting high-frequency gravitational waves with microwave cavities
Asher Berlin, Diego Blas, Raffaele Tito D'Agnolo , Sebastian A.R. Ellis
arXiv:2112.11465]

PBH merger & high Q cavities

- GW strain: largest if merging is imminent (closest to innermost stable circular orbit)
  - Frequency drift large

$$\dot{f} = \frac{96}{5}\pi^{8/3} m_c^{5/3} f^{11/3} \simeq 4.62 \times 10^{11}\,\mathrm{Hz}^2 \left(\frac{m_{\mathrm{PBH}}}{10^{-9} M_\odot}\right)^{5/3} \left(\frac{f}{\mathrm{GHz}}\right)^{11/3}$$

- To resonantly excite a cavity:
  - GW frequency must stay within resonator bandwidth
    - $\omega/Q \approx 10^{10} Hz/10^6 = 10 kHz$
  - Very short integration times O(ms) or below for larger PBH masses

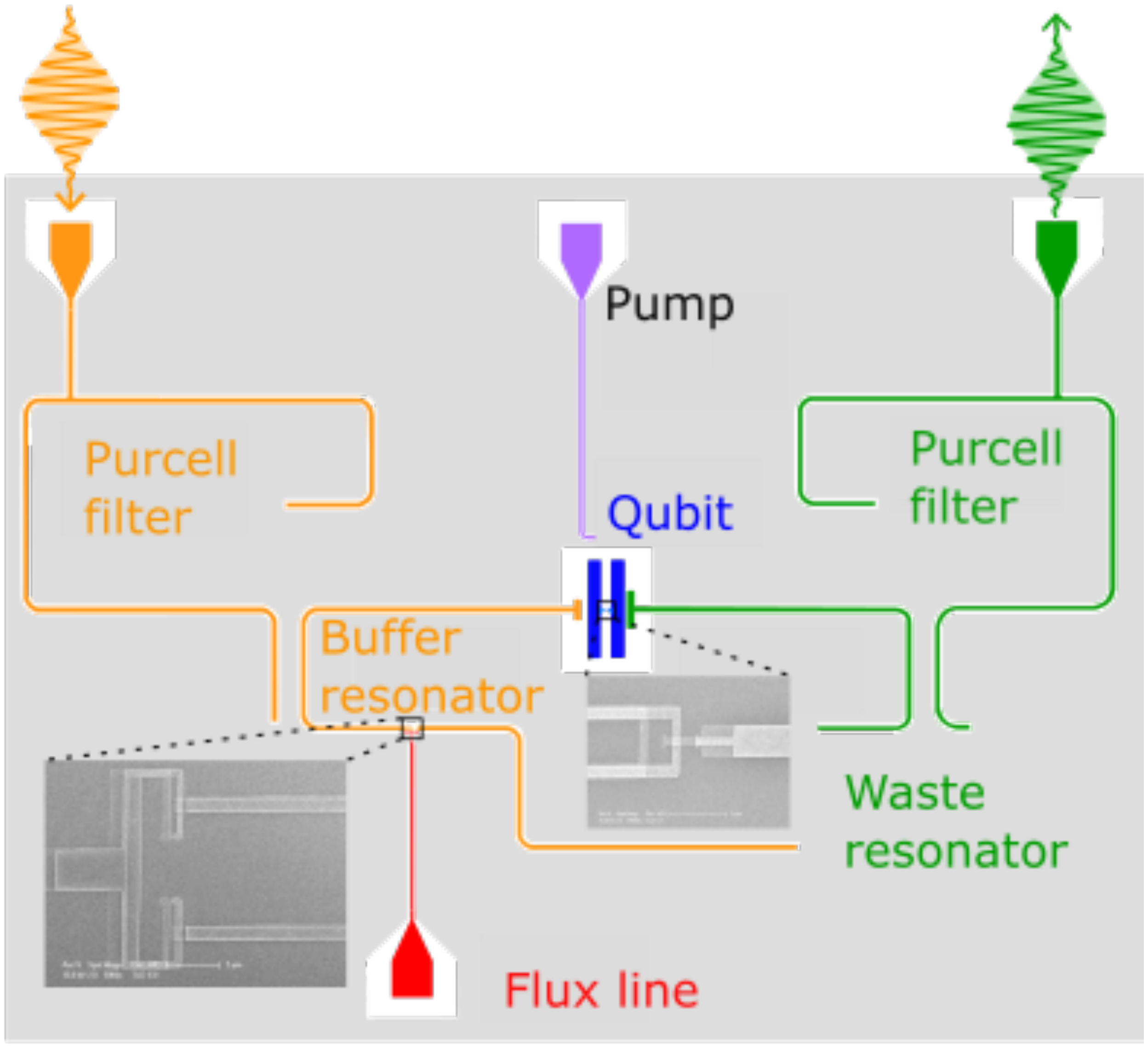


- No improvement with longer integration times!
  - Alternative?

Alternative for fast transient signals - Photon Counting

- Recent progress in R&D for single RF photon counters

- Several technologies under study
  - Current Biased Josephson Junctions [arXiv:2302.07556]
  - Kerr Josephon Parametric amplifiers [arXiv:2308.07084]
  - Transmon Q-Bit readout [arXiv:2307.03614]



[arXiv:2307.03614]

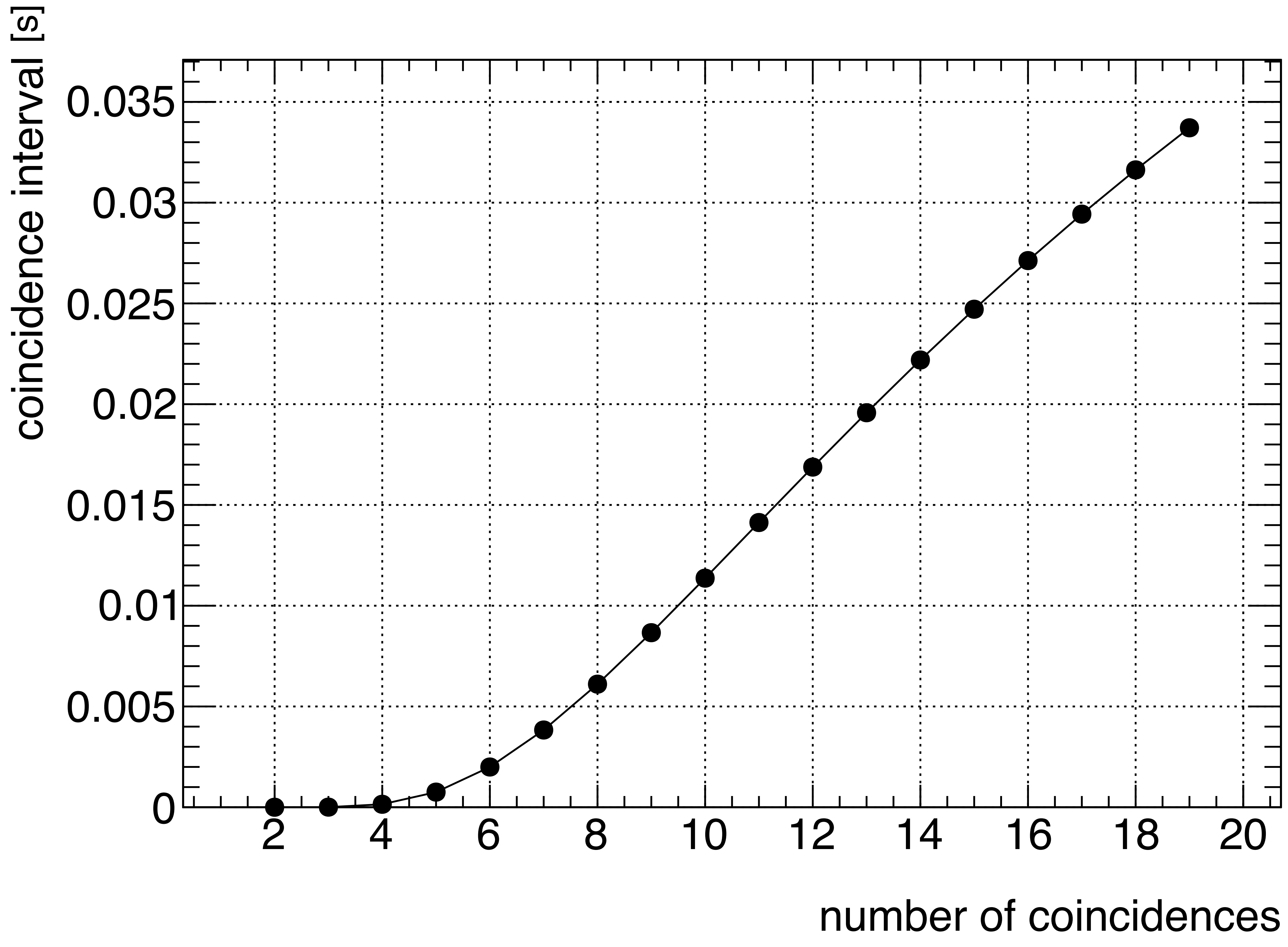
- Shown single photon efficiency: 43% @ 90 Hz dark count rate
  - Big R&D effort ongoing [ERC syn.: "Dark Quantum"]

- Measurement boils down to a **coincidence measurement** !

- Coincidence window and needed number of coincident detectors optimised depending on
  - Background rate (thermal, detector noise)
  - Signal Rate

Photon Counting - Coincidence Interval

- Background rate:
  - Average thermal power in cavity @ 0.1K ~ 4×10^{-23} W, corresponding to 10 photons / s @ 5 GHz
  - Could be lowered going to lower temperatures
  - Assuming advances in the near future on the single photon sensors:
    - Detector dark count rate will drop significantly -> negligible

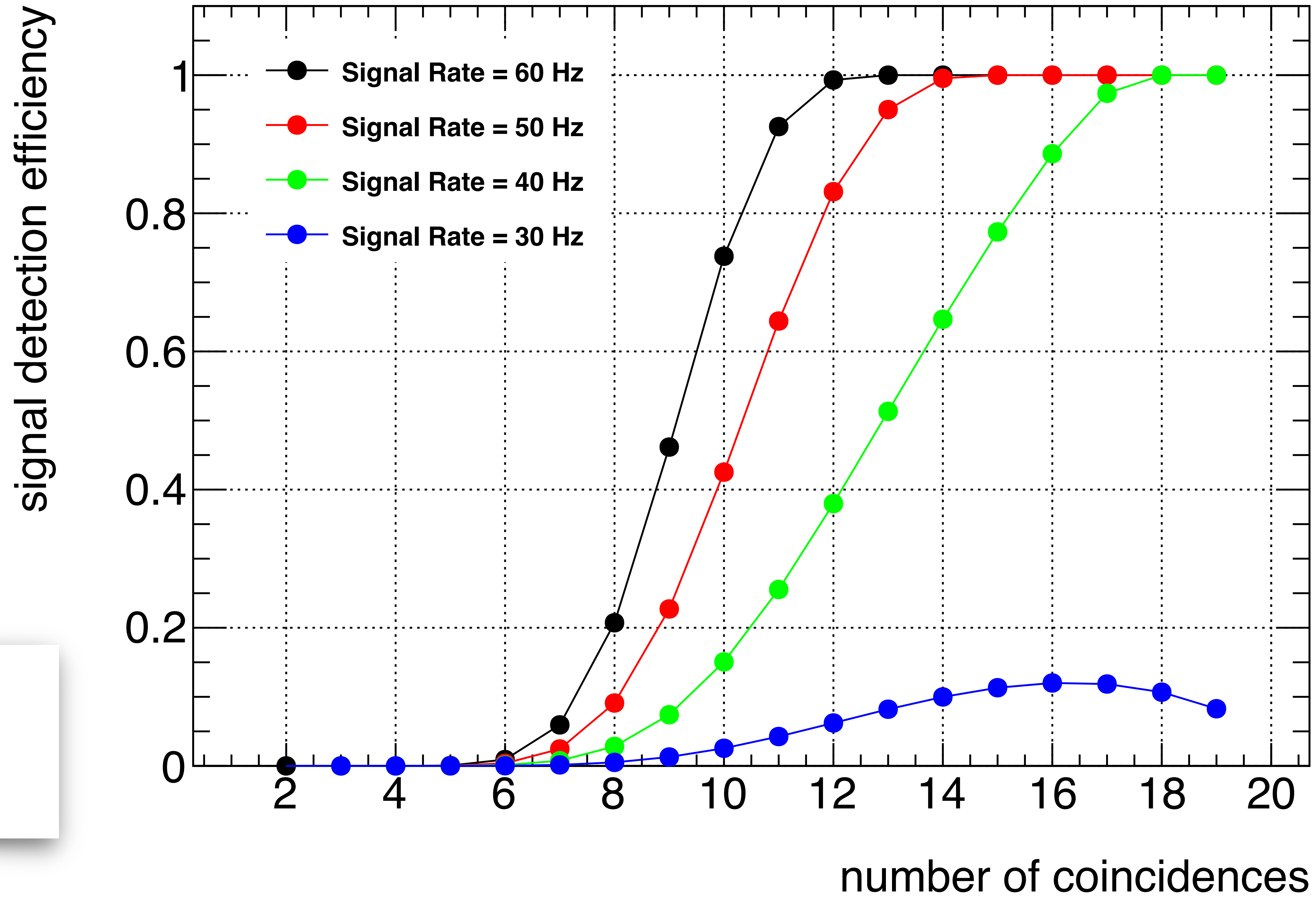


- Parameter used for Calculation:
  - Allowed accidental coincidence rate: <= 1/year
  - Background rate: 10 Hz
  - N detectors: 20

Photon Counting - Signal efficiency

- Overall signal efficiency dependent on detector efficiency, coincidence window and signal photon flux:
  - $\epsilon_{single} = \epsilon_{det} \Delta t_{coincidence} \Phi_{sig}$ Φ_{sig} = signal photon flux
  - $\epsilon_{tot} = \sum_{i>k} \binom{N}{k}, p = \epsilon_{single}$, k = number of required coincidences, N = number of detectors

- Parameter used for Calculation:
  - Allowed accidental coincidence rate: <= 1/year
  - Background rate: 10 Hz
  - N detectors: 20
  - ϵ_{det}: 0.5



- With **20 detectors** a photon flux of **40 Hz** can be detected with an efficiency of 1 within a coincidence interval of **32ms**

- To increase the sensitivity of halo scope style experiments we suggest to build a **global network of detectors**
  - Remember: SNR scales linear with number of detectors!

- Integrating measurement:
  - Sample RF data, combine phase aligned, integrate

- Typical integration times too long to be sensitive to BH merges!

- Single frequency sufficient to hunt for PBH mergers!
  - Could even combine measurements at different frequencies

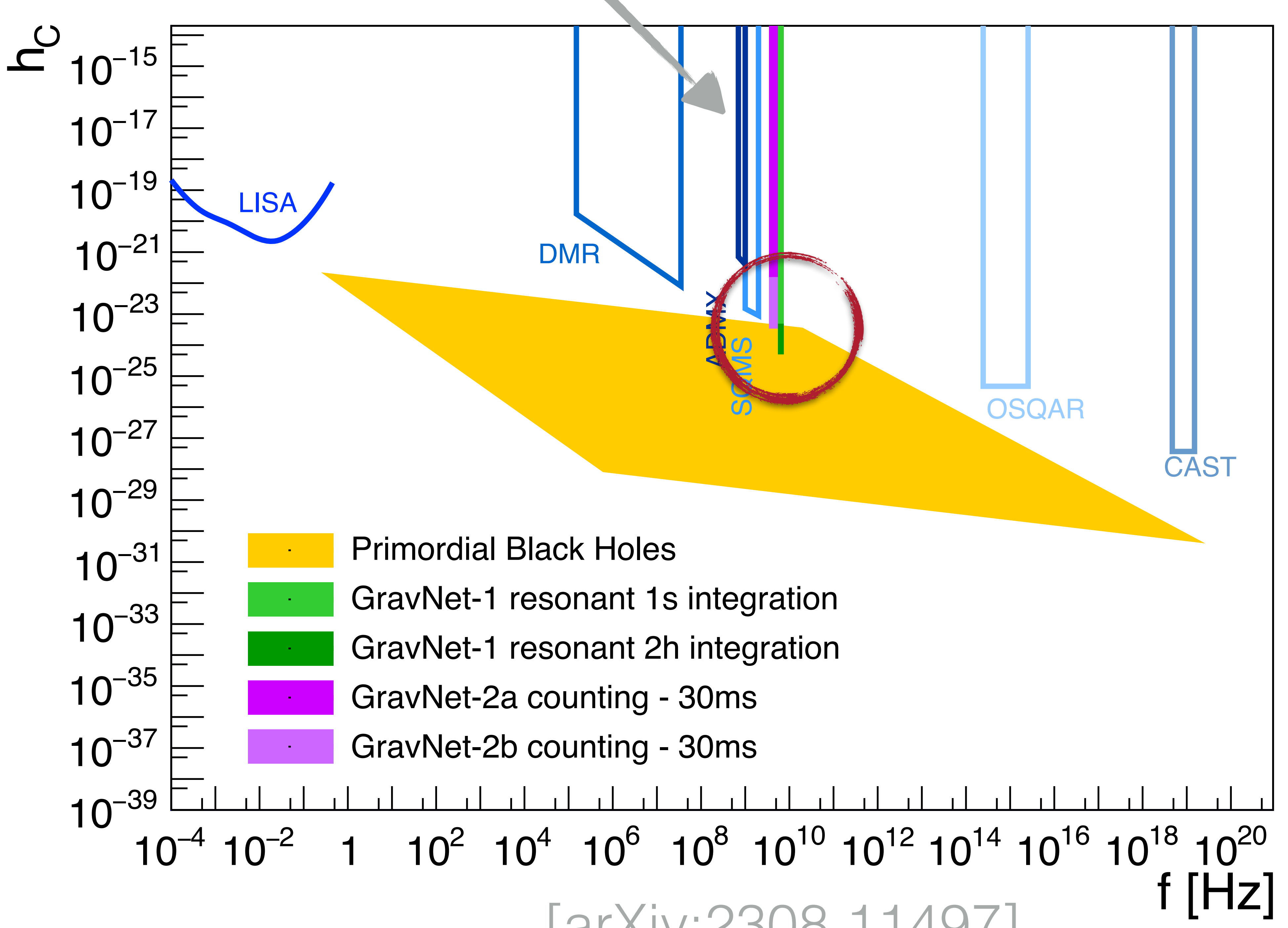
t_{int} > O(100s) [arXiv:2112.11465]

- Photon counting style experiments:
  - Recent advancements in single RF photon detection allows to use coincidences of several detectors

  - Using 20 independent detectors:

    - Sensitivity: $h_0 < 3x10^{-22}$ …. $3x10^{-24}$

Requires large meta material cavities
(high frequency @ large volume)



[arXiv:2308.11497]

Conclusion

GravNet is an idea up for discussion

- Many advantages in **combining efforts searching for UHFGWs** in coordinated way
- GravNet would significantly improve the sensitivity on high frequency gravitational waves
  - Based on commercial magnet systems, which is comparatively cheap
  - Worldwide collaboration would share costs automatically with local lab-based experiments
  - Easy exchange of R&D results and integration at all locations
- Sensitivity to the PBH parameter space with existing technologies!