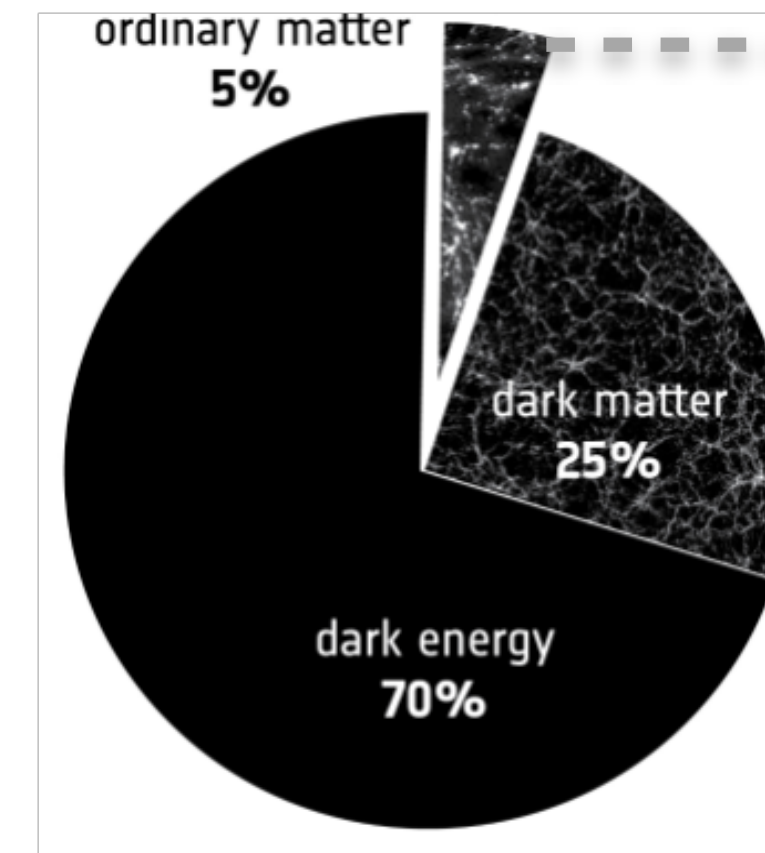


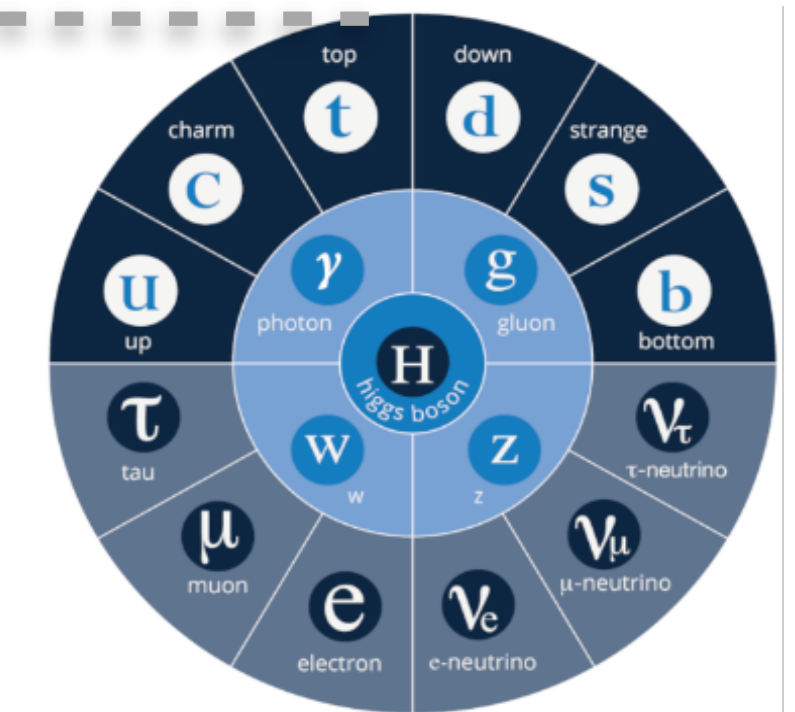
GravNet: A Network of High Frequency Gravitational Wave Detectors

Identification of Dark Matter 2026
02/06/2026 - Zaragoza

Our (incomplete) view of the universe



95% not detectable
with **light**

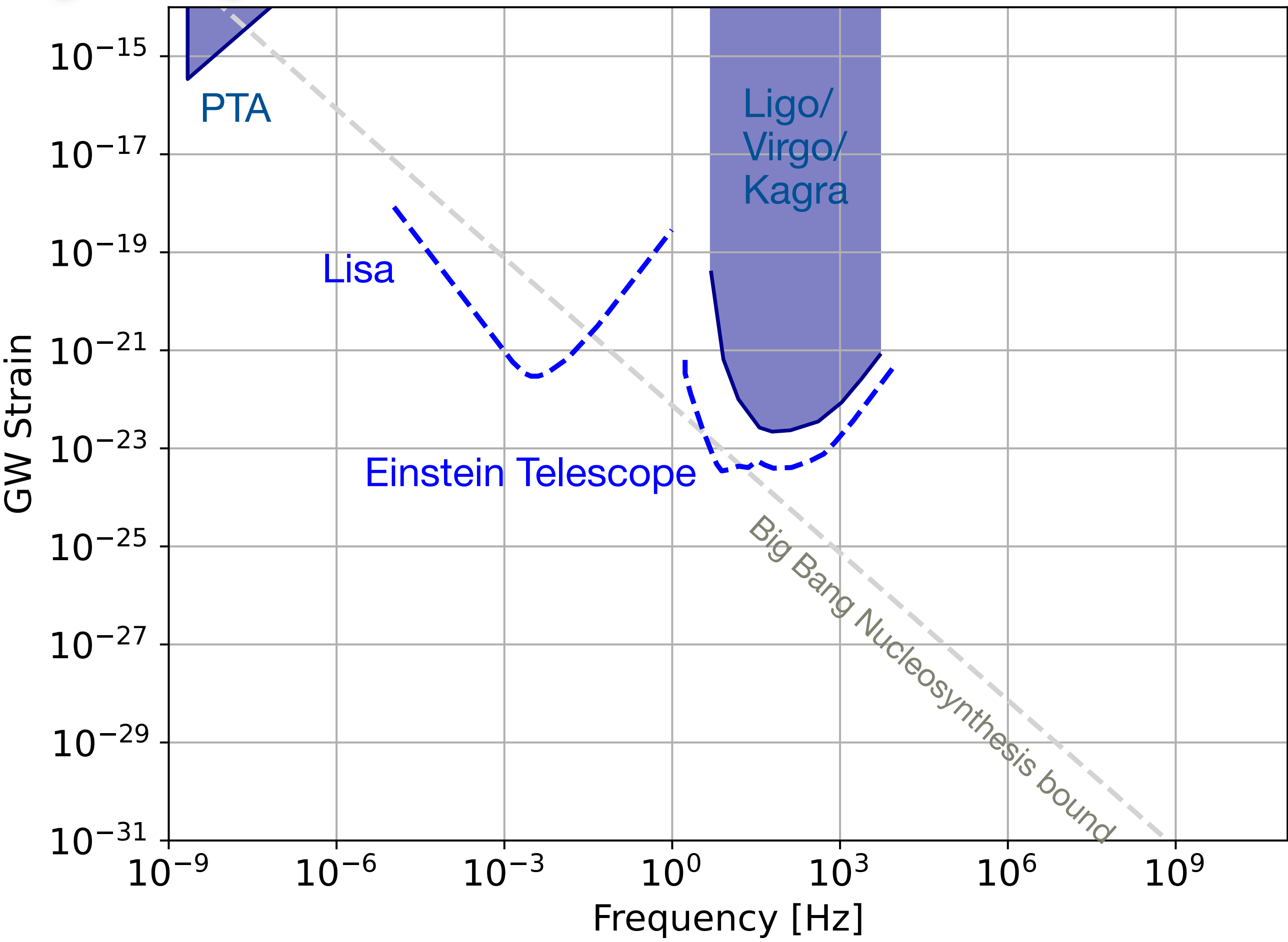
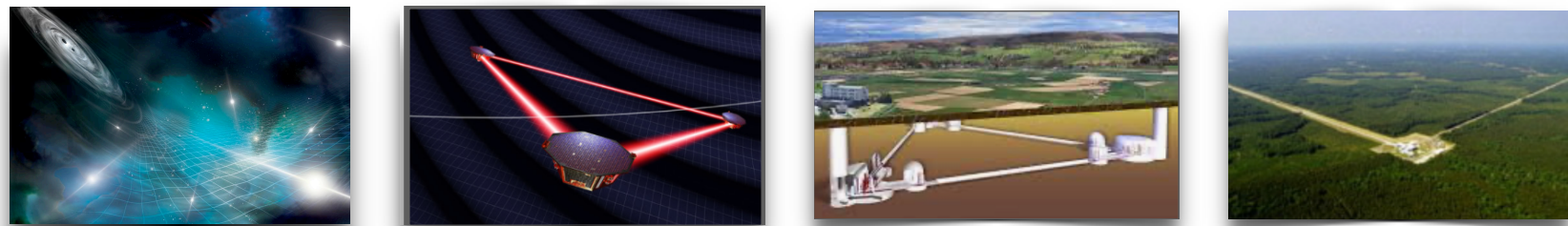


incomplete
at **high energy**

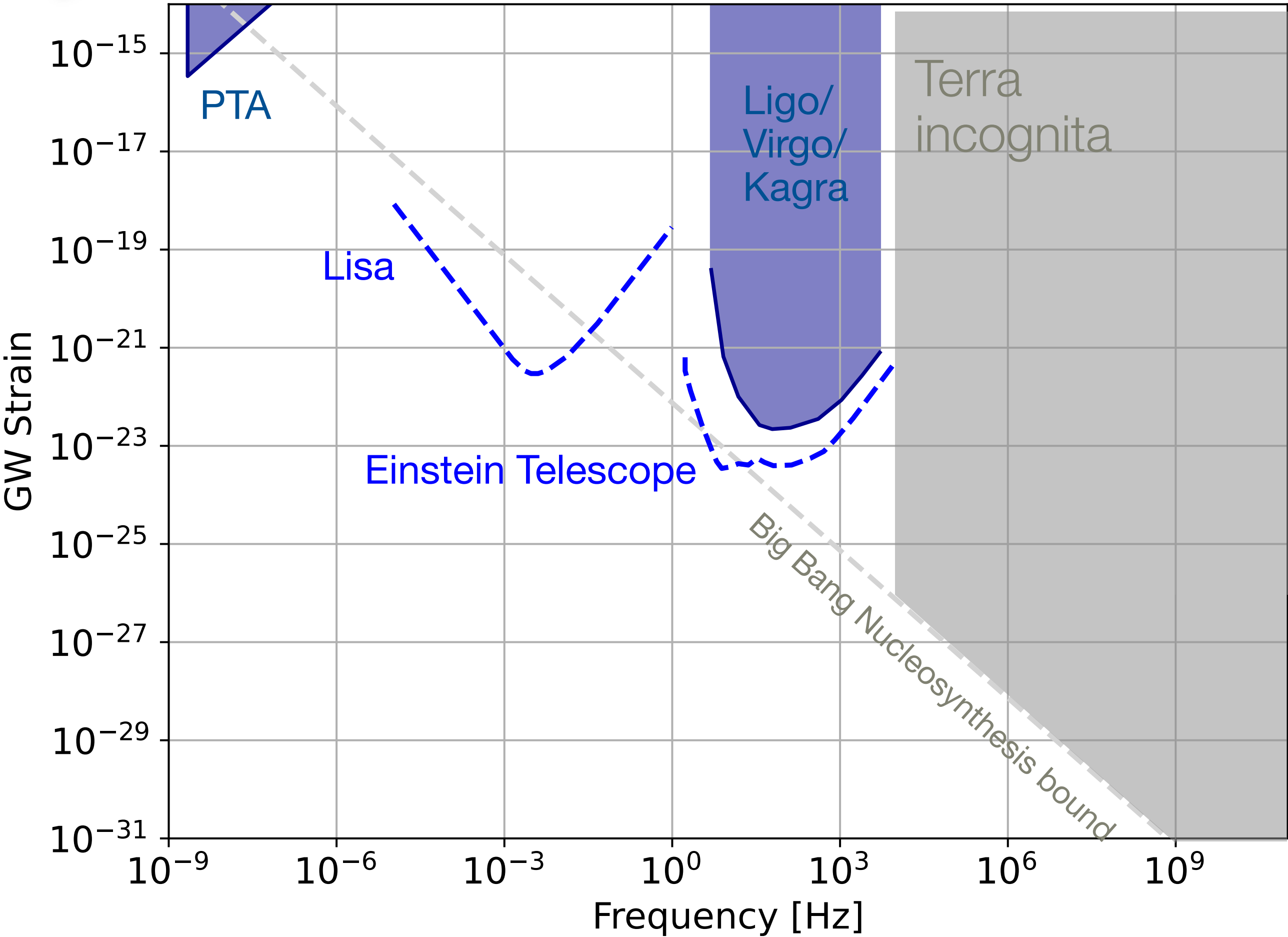
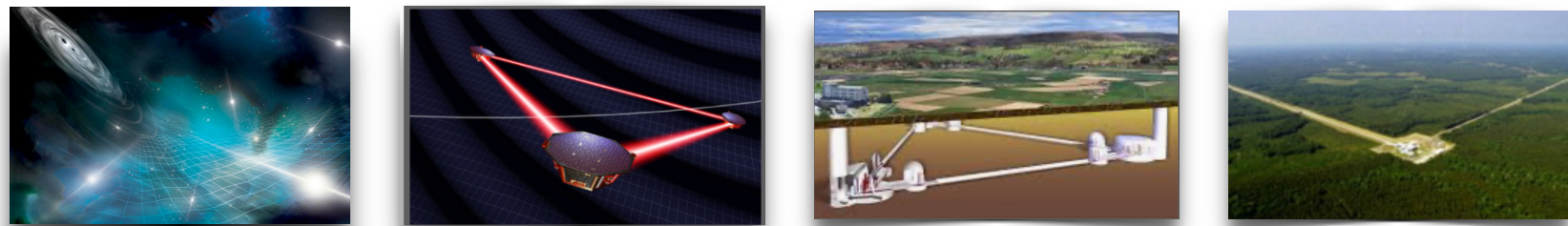
Gravitational waves

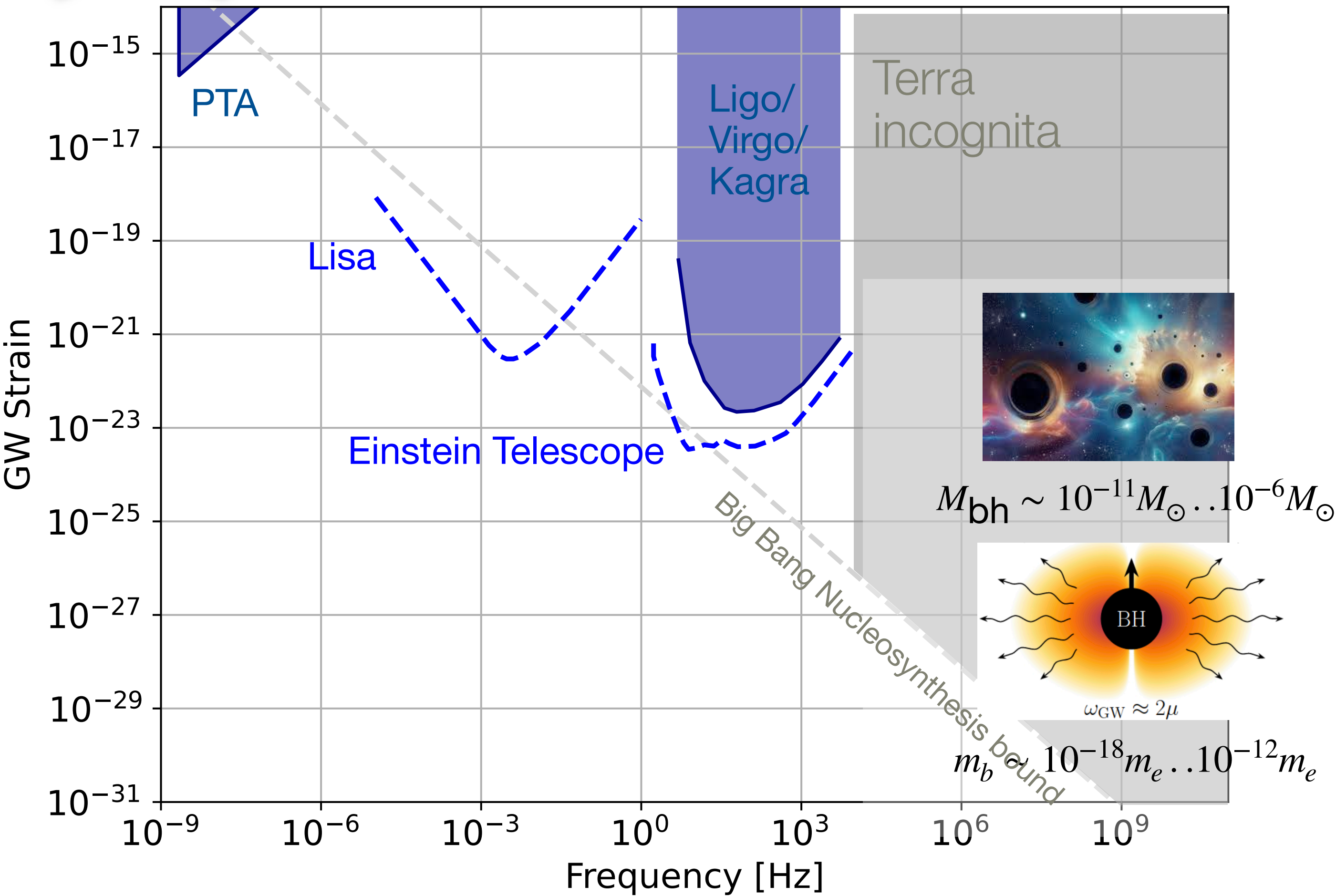
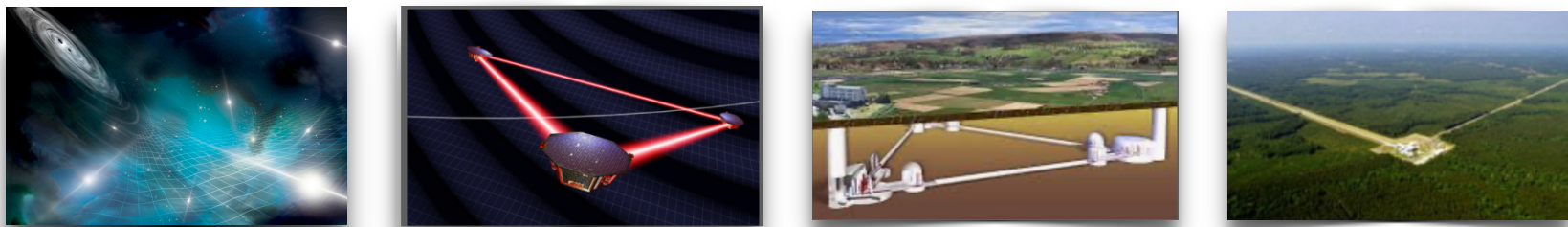
probe all components and may come from the early universe

Introduction - Gravitational Waves

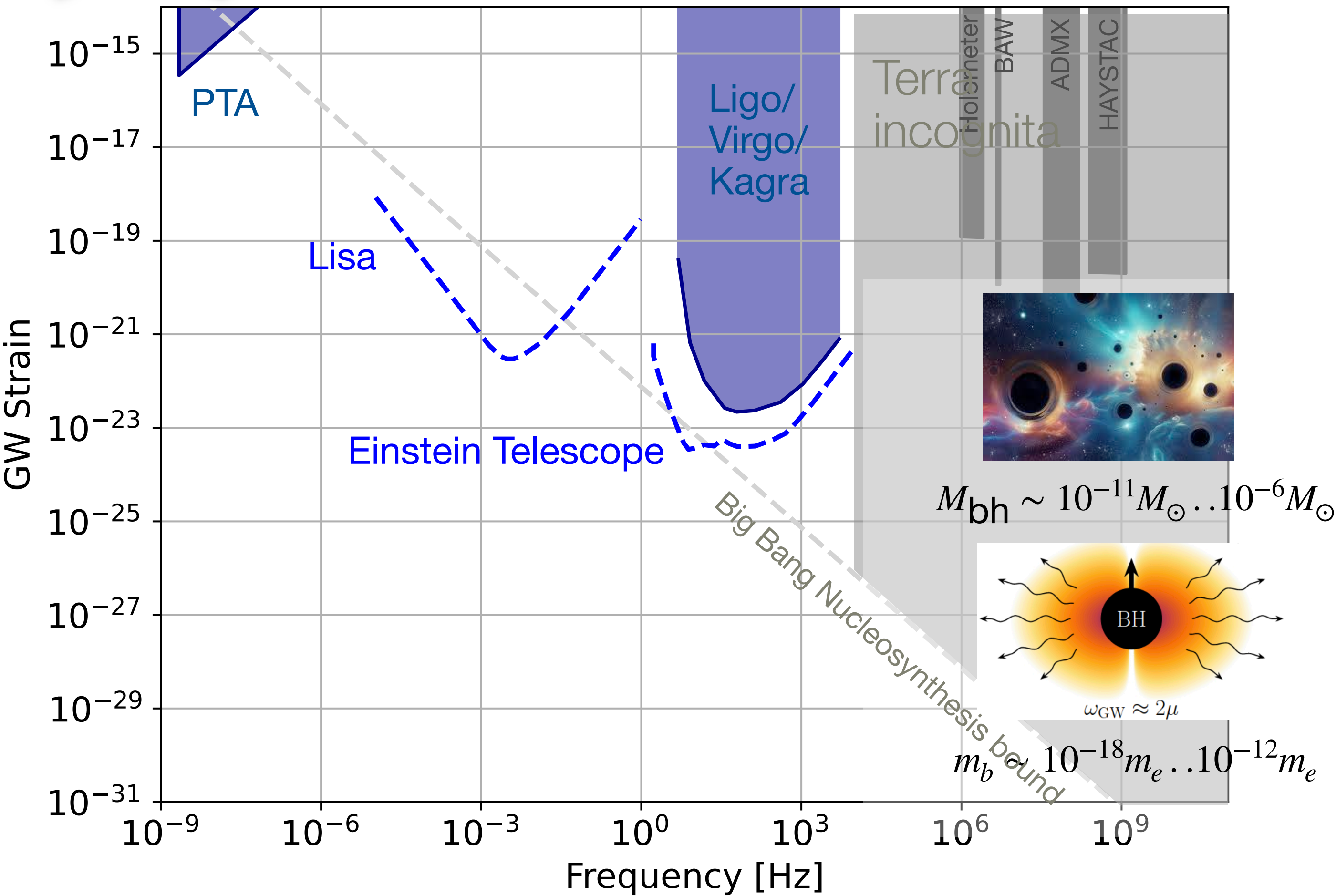


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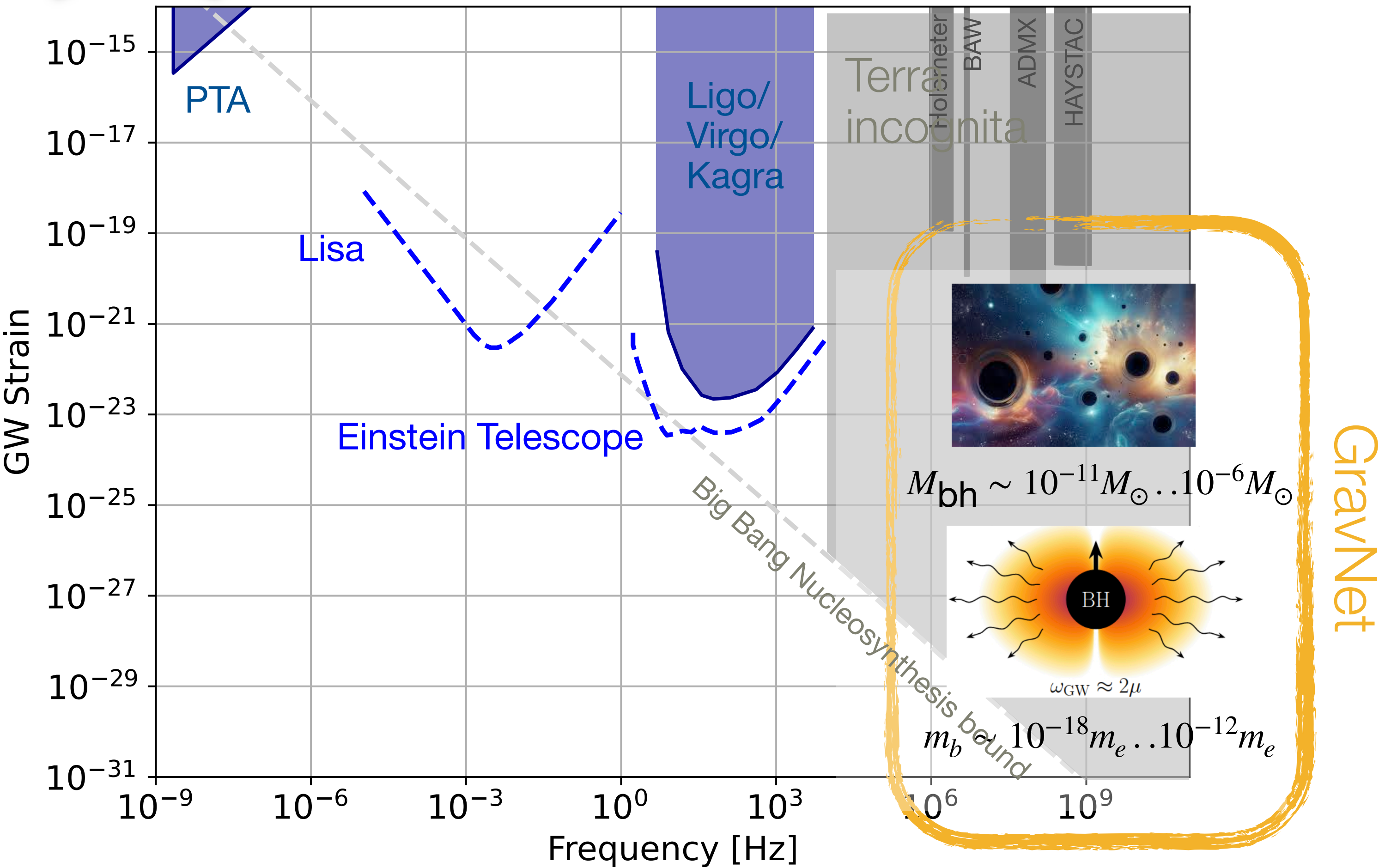




- High frequency gravitational wave (HFGW) **sources**
 - Could explain dark matter
 - No astrophysical backgrounds
 - (No known sources)



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GravNet:

Dedicated effort probing high frequency gravitational waves

Primordial black holes:

- Black holes created in the early universe
 - Not limited to the mass range of stellar BHs
 - Expected Mass range: $10^{-10} - 10^{-16} M_{\odot}$
 - Density unknown
- Merging events expected
 - Low mass $\rightarrow$ High frequency
 - Fast transients

Why are PBH interesting objects?

Primordial black holes:

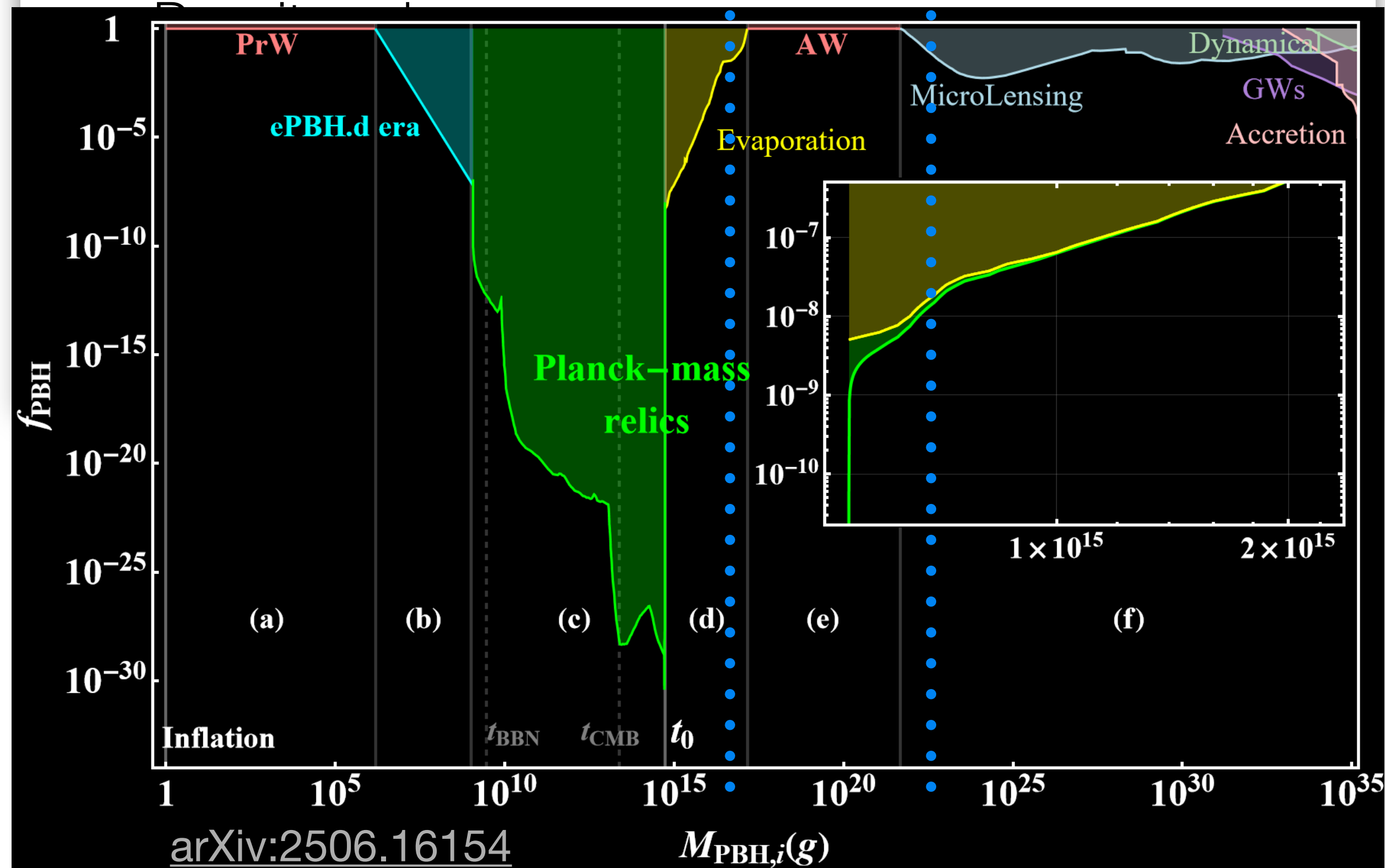
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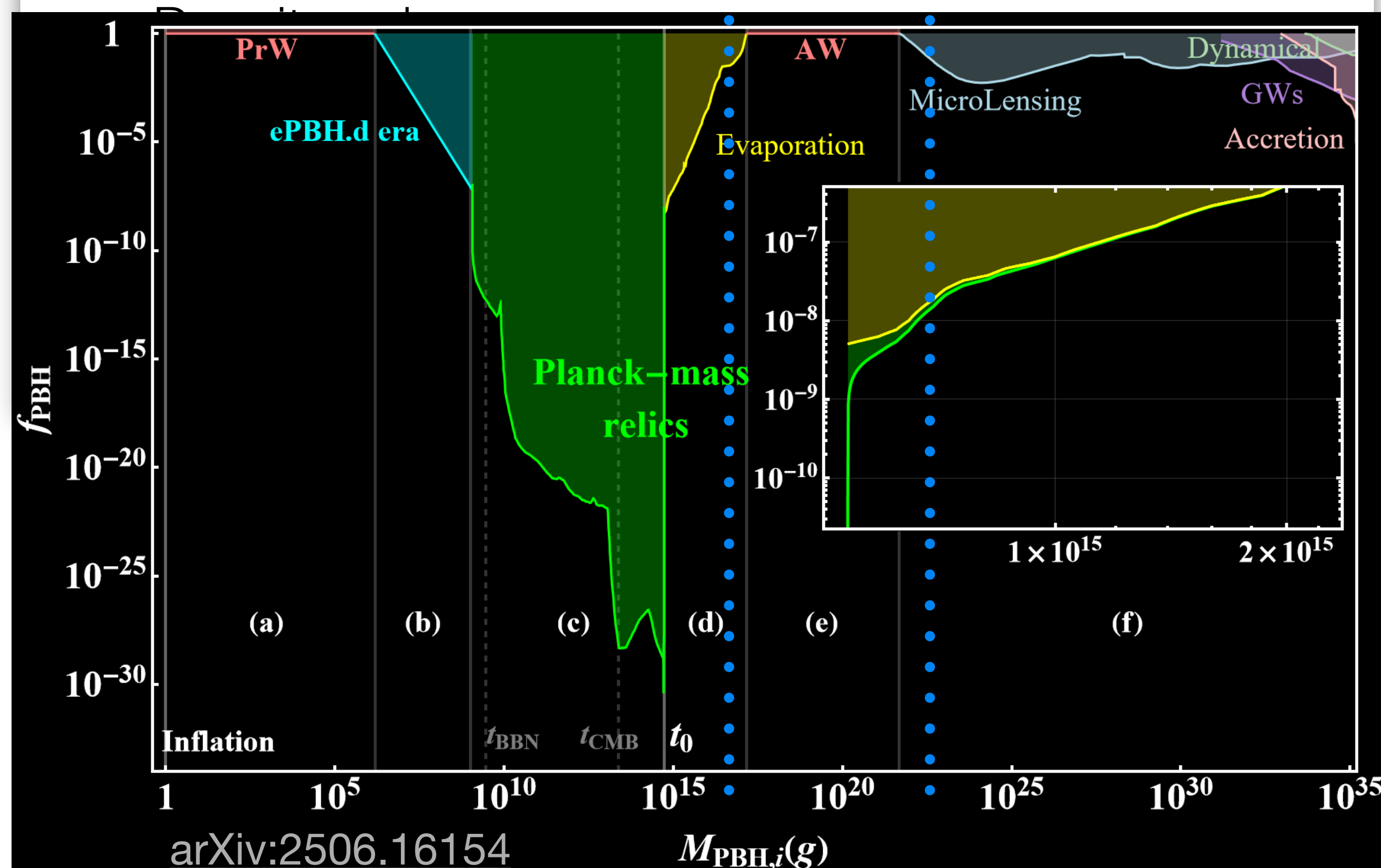


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Why are PBH interesting objects?

Could be dark matter

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

Detecting High Frequency GWs

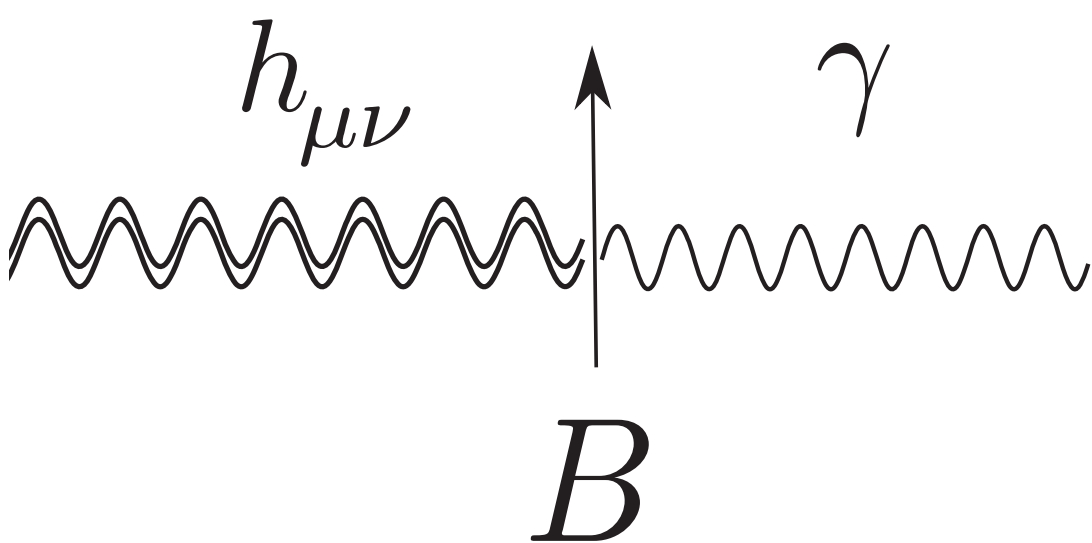
- Large range of experimental approaches tackling HFGW
- Three Categories:
 - Spin interaction
 - Something is mechanically deformed
 - **Conversion of GWs (gravitons) into Photons**

[arXiv: [2501.11723](#)]

4.2	Detection at frequencies beyond current detectors	31	
4.2.1	Optically levitated sensors	31	
4.2.2	Inverse Gertsenshtein effect	32	GravNet [arXiv: 2603.24645]
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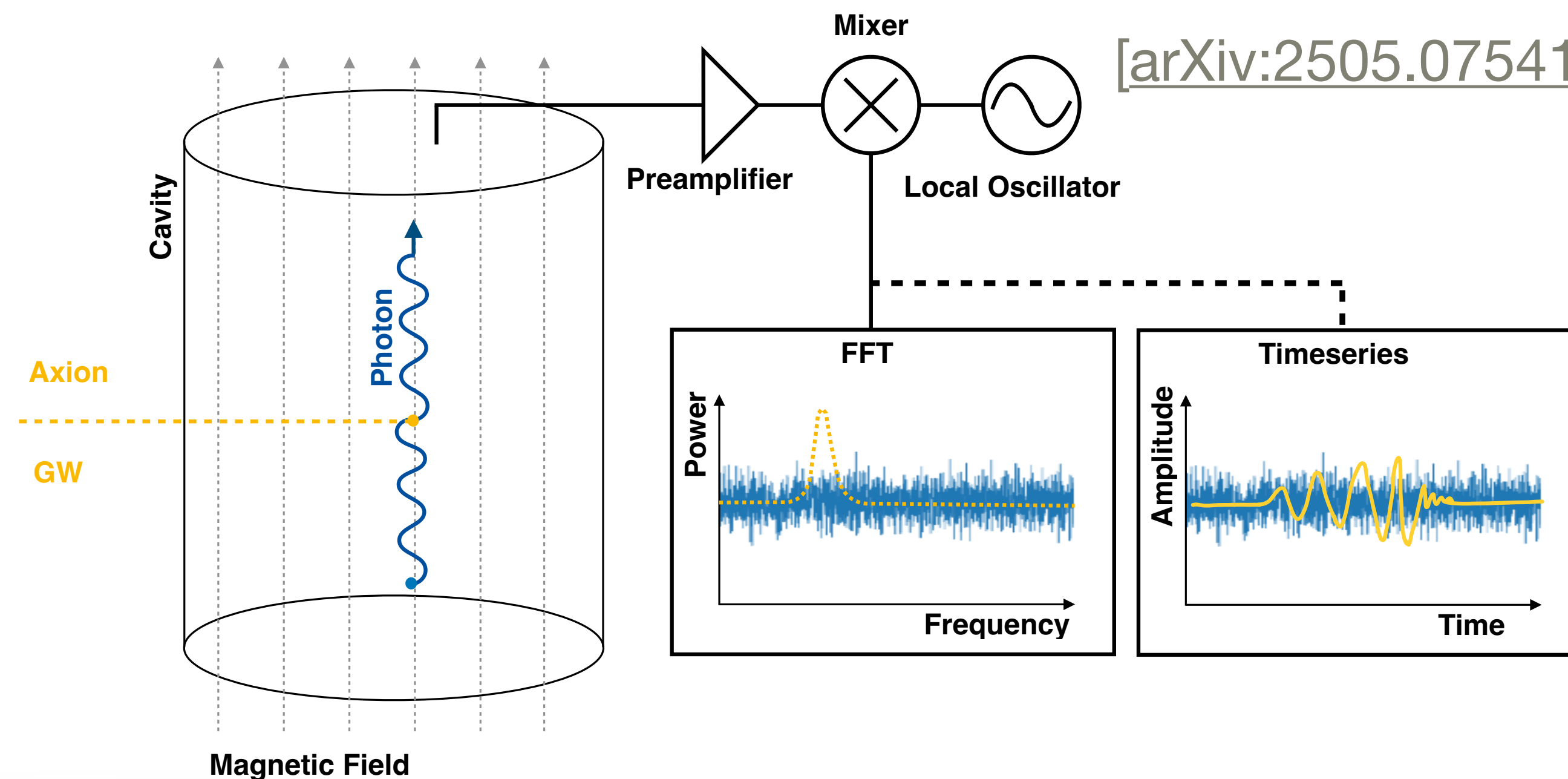
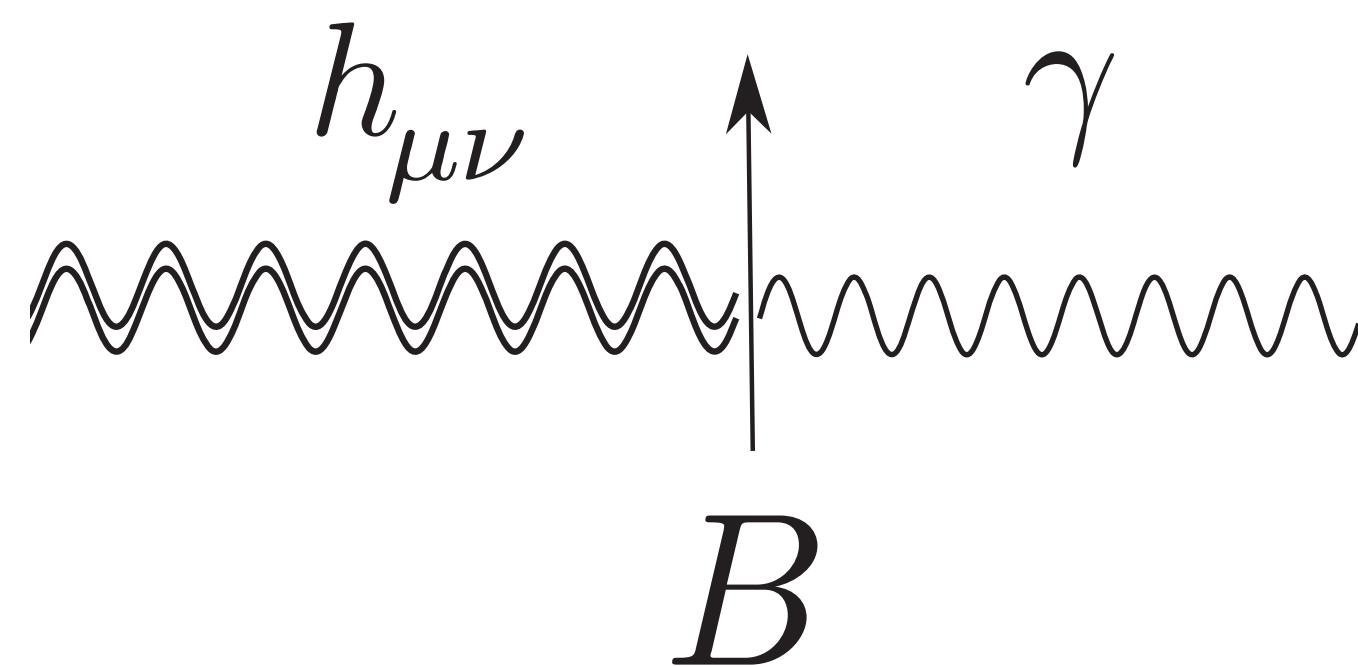
- GW leads to source of **effective current** in Maxwell's equation



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

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Requirement

- **Electromagnetic field**

=> B-Field

- **Resonant enhancement** of signal => RF-resonator
 - Narrow band experiment

- Noise suppression

=> Cryogenic setup

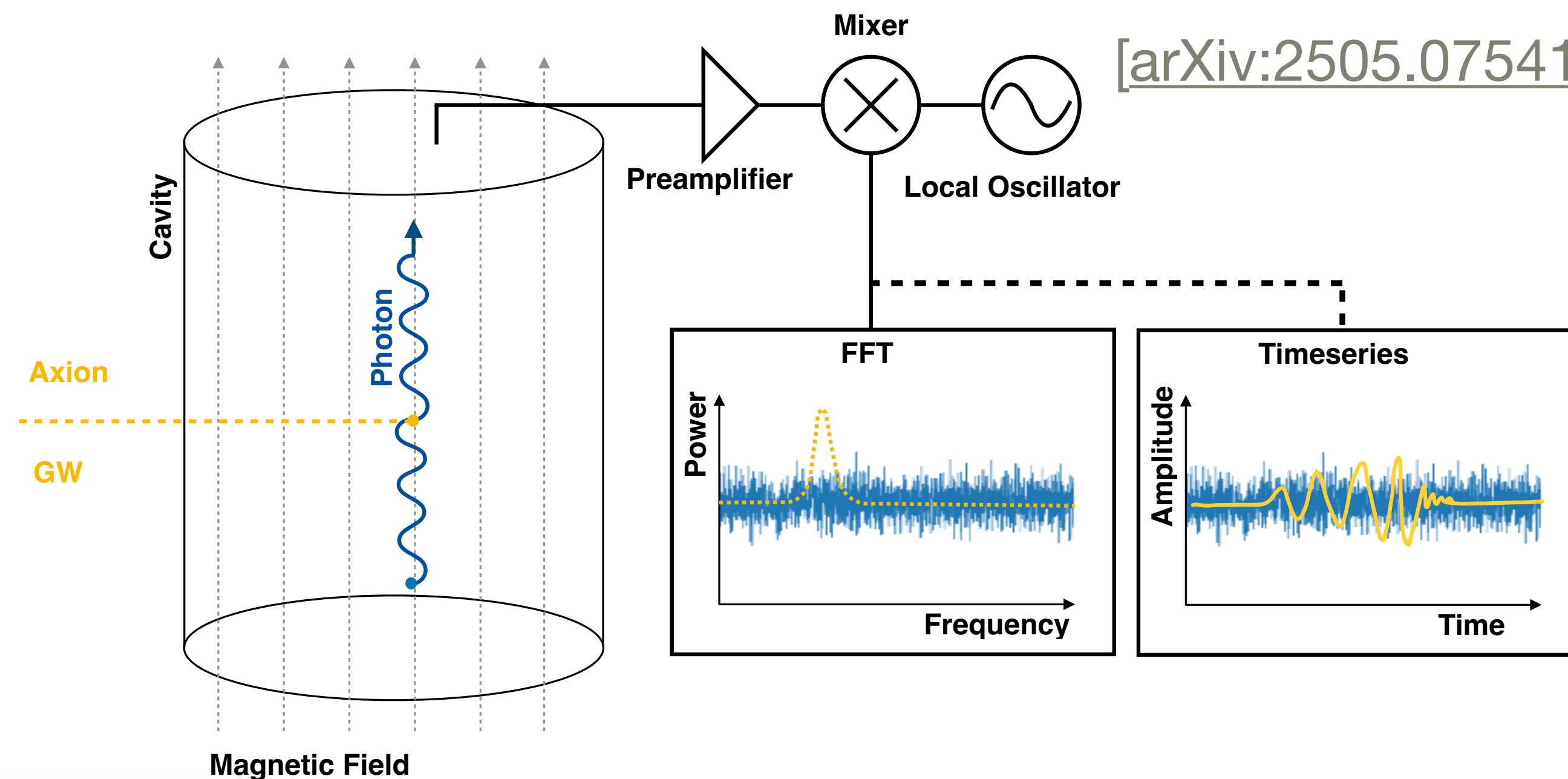
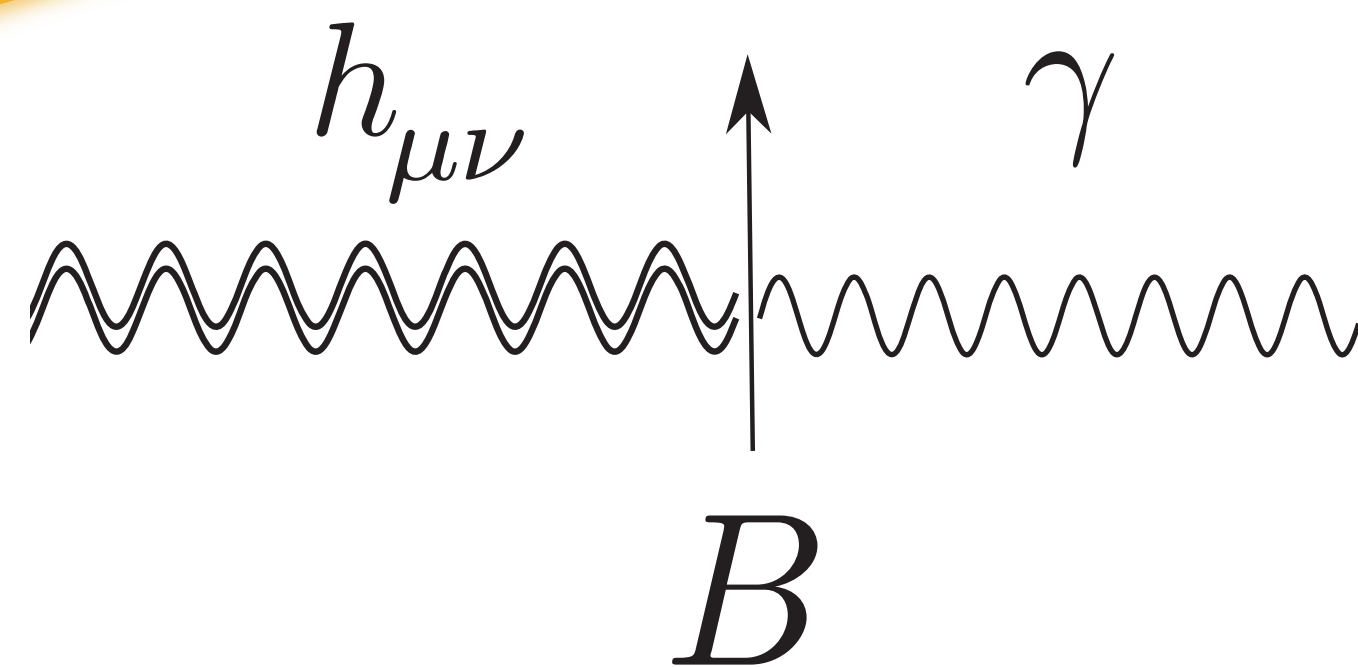
- High sensitivity

=> Low Noise, high gain DAQ

Typical setup

See **Poster** by **Stefan Horodenski** on the Axion program (Supax)

[arXiv:2505.07541]



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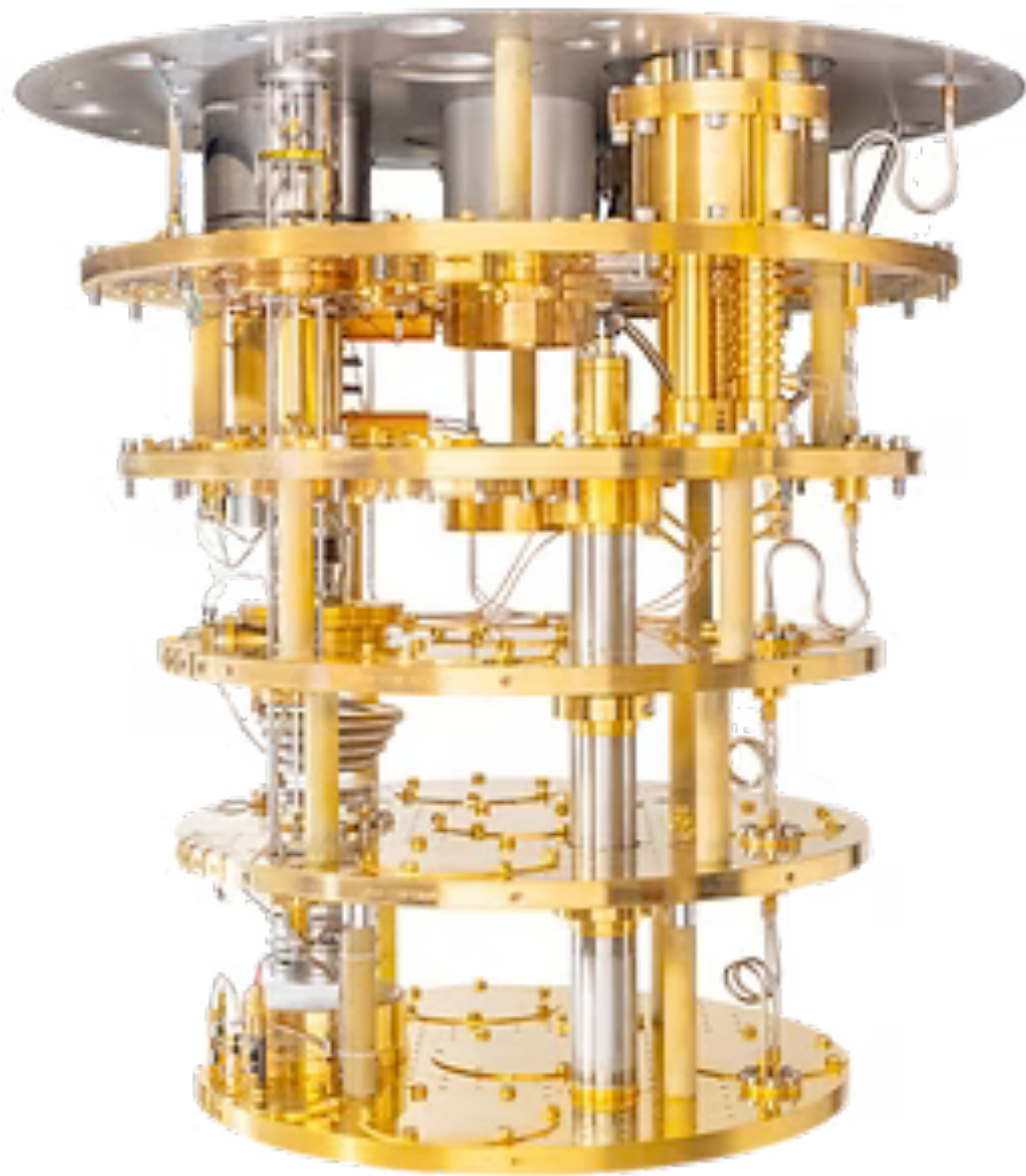
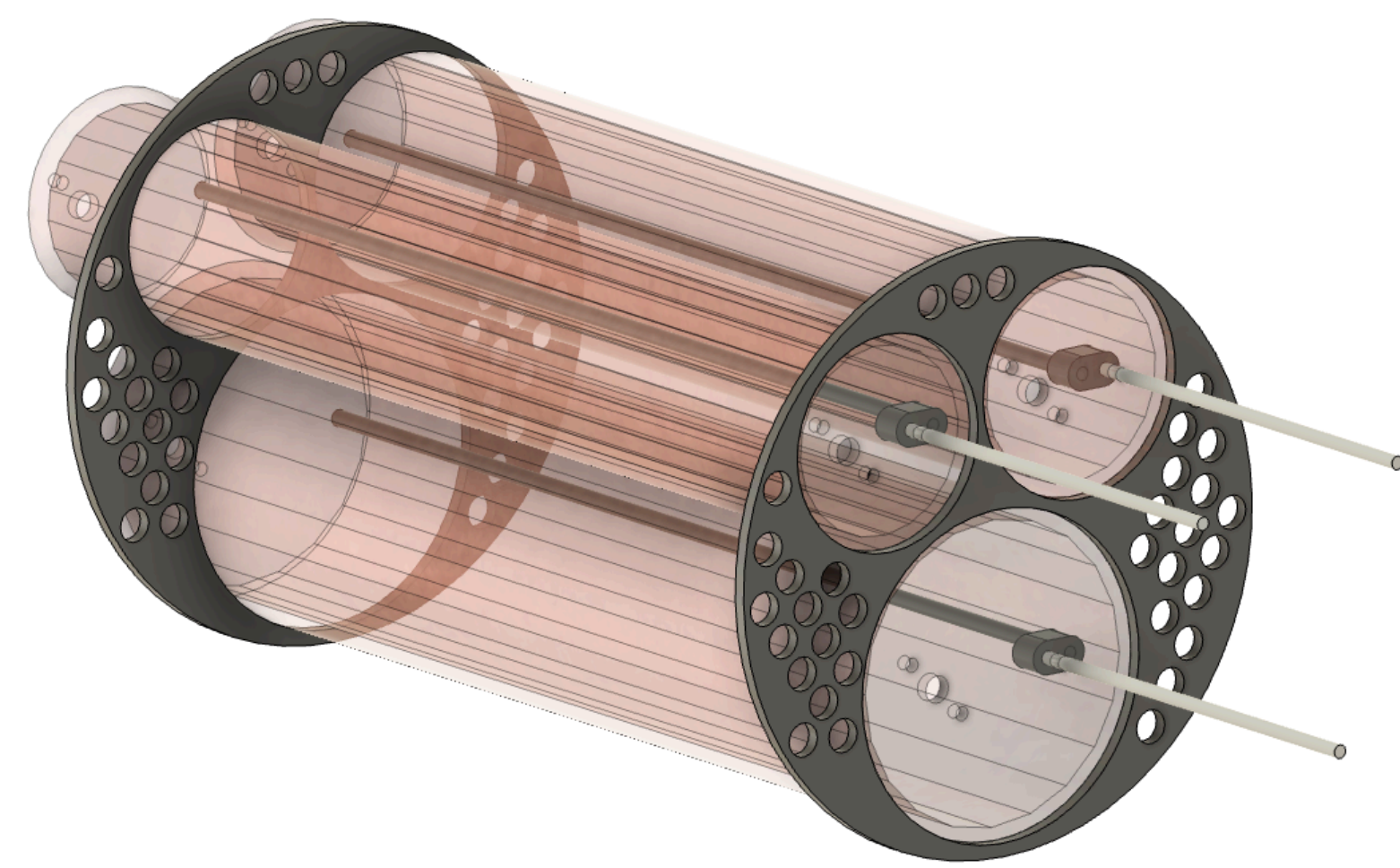
Technical implementation

- => B-Field
- => RF-resonator
- => Cryogenic setup
- => Low Noise, high gain DAQ

Sound like an ...
axion haloscopes

The *NEW* Supax Experiment @ Bonn

- **Axions & GWs** [[arXiv: 2603.24645](#)]
- Temperature: **10 mK**
- B-field: 12 T
- Usable volume: $\varnothing = 9 \text{ cm} \times 20 \text{ cm}$
- Freq. range: 2 GHz - 7GHz
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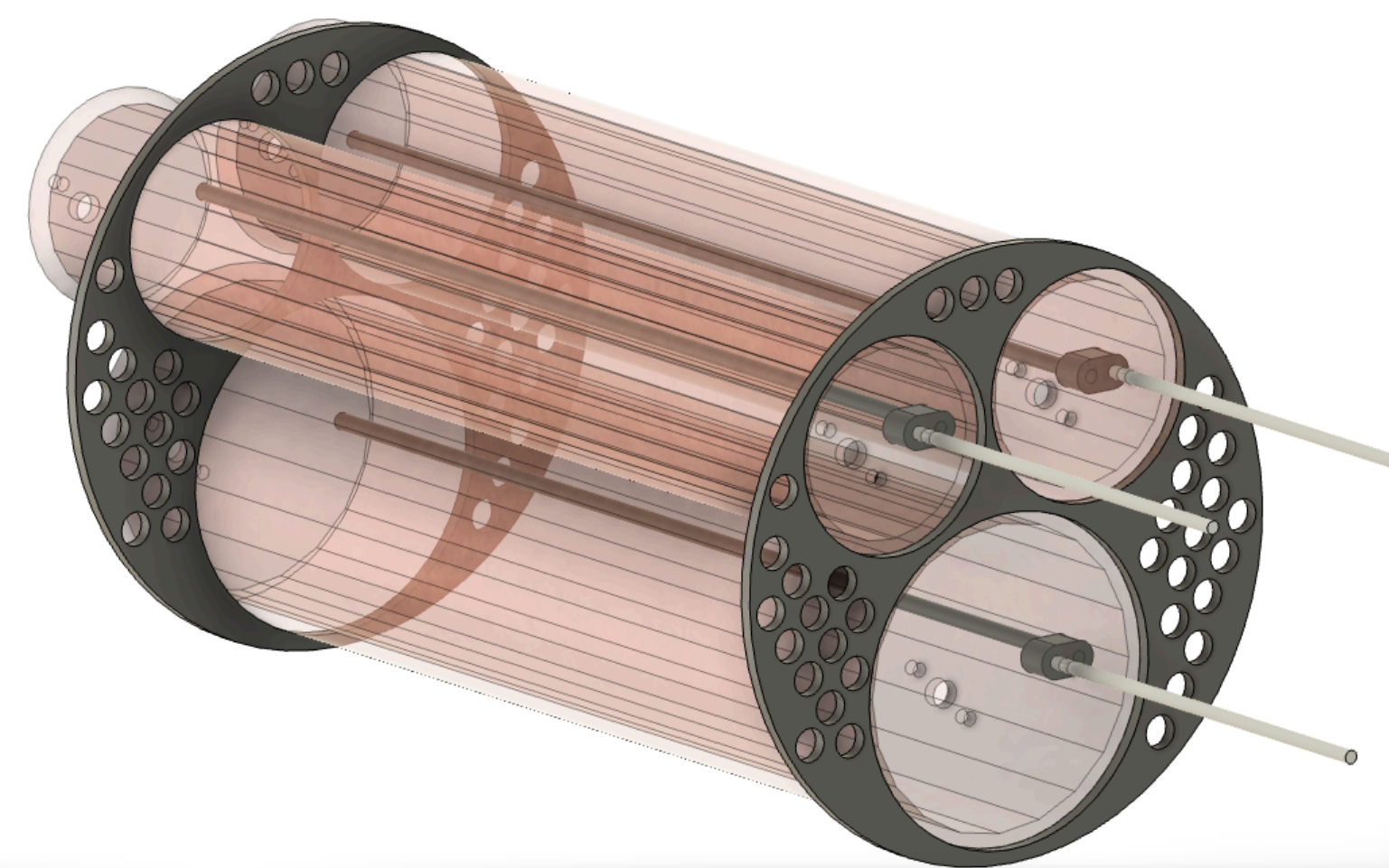


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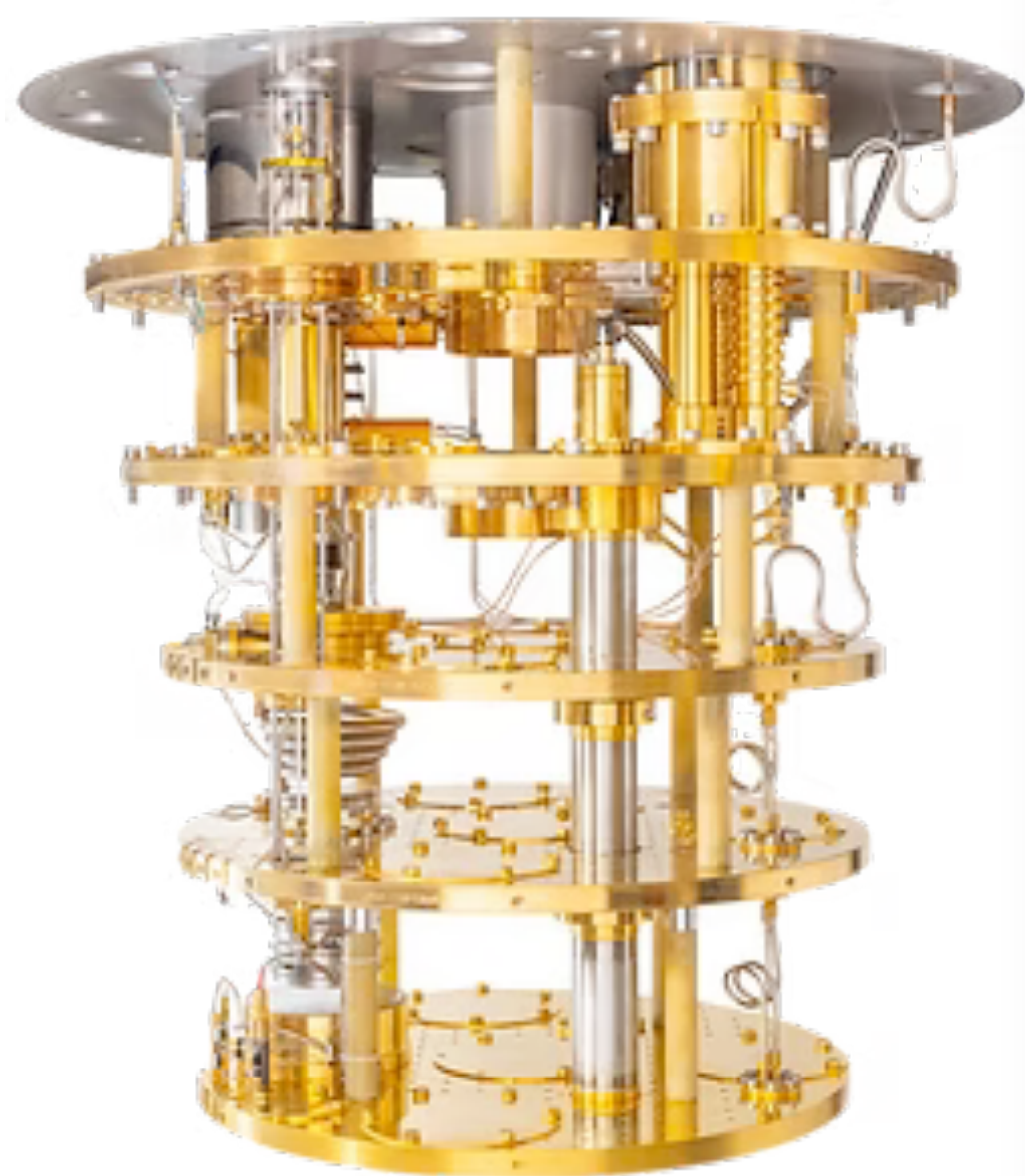
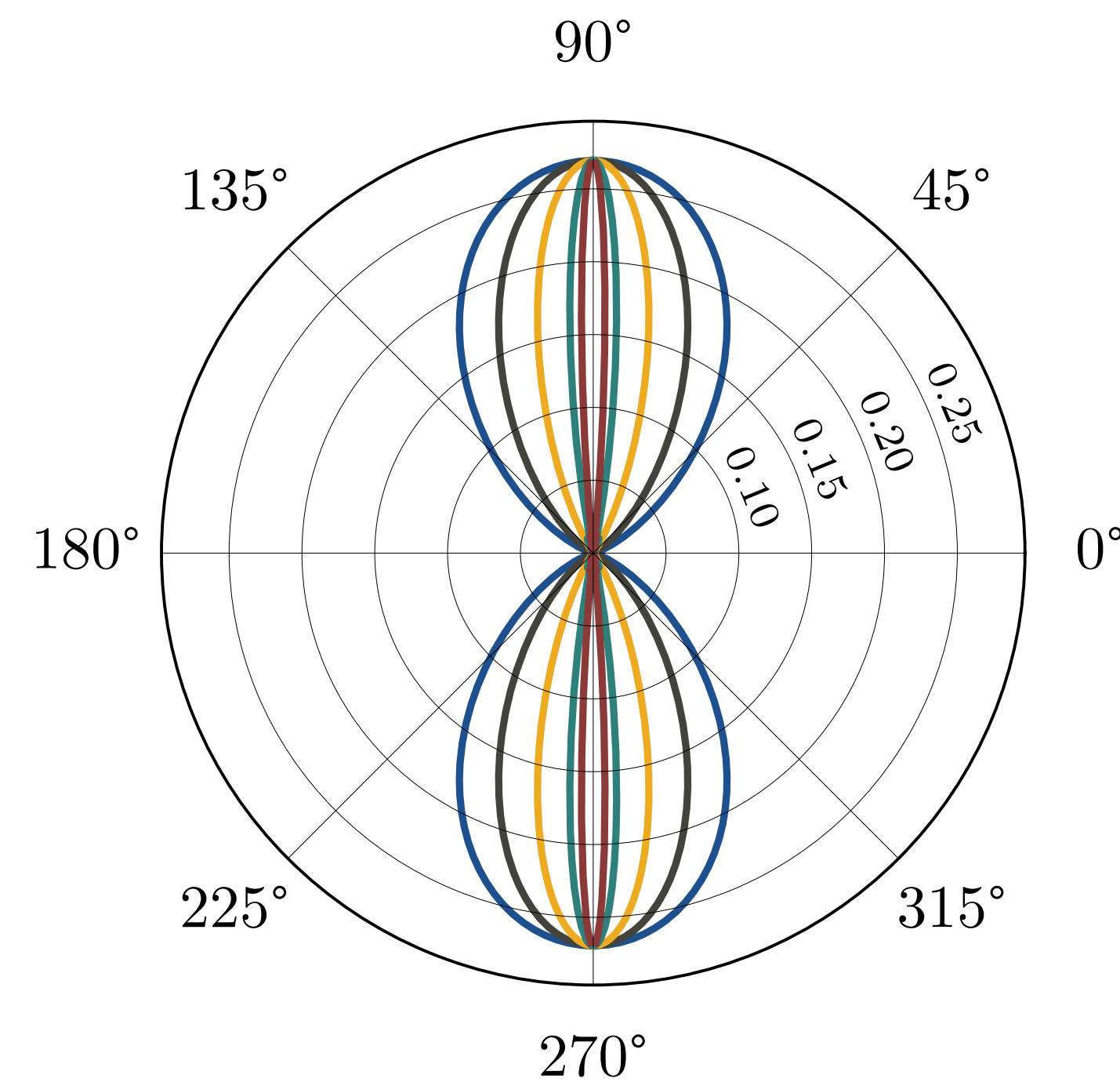
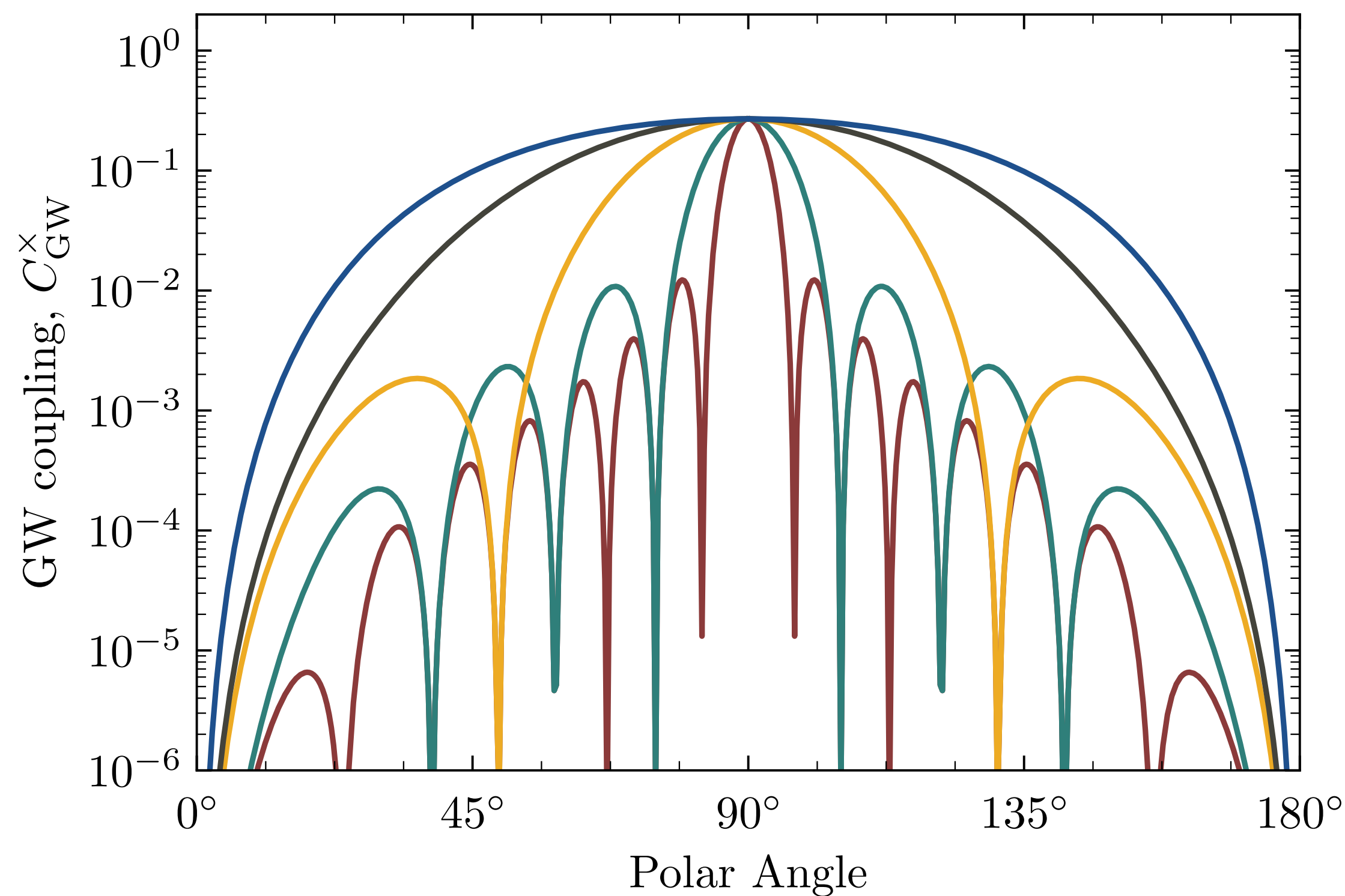
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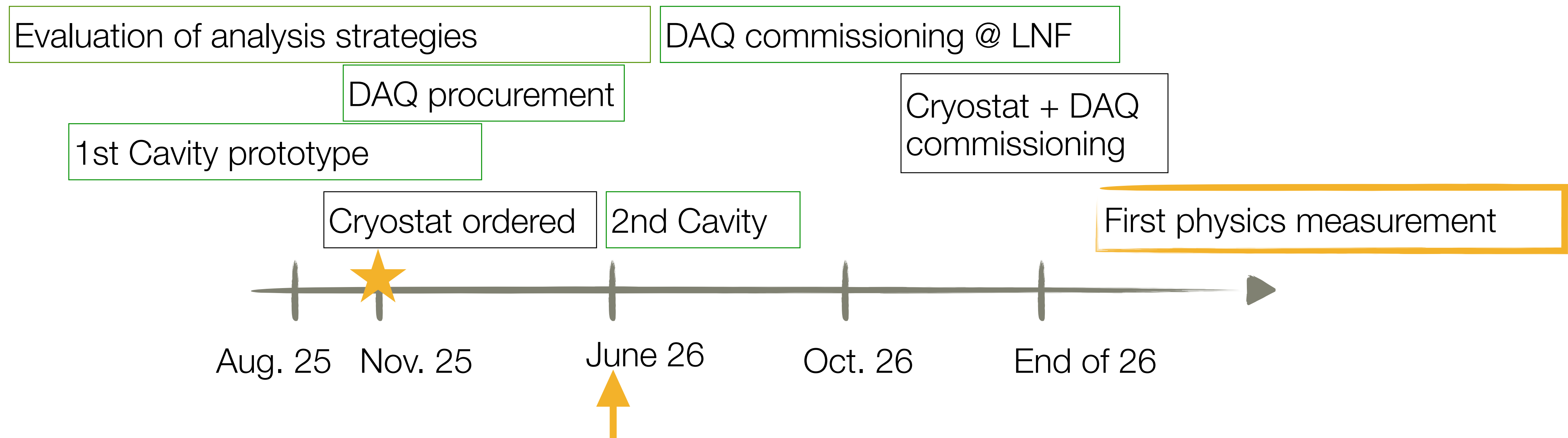
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— $R = 1.0 \text{ cm}$ — $R = 2.0 \text{ cm}$ — $R = 5.0 \text{ cm}$ — $R = 10.0 \text{ cm}$ — $R = 30.0 \text{ cm}$

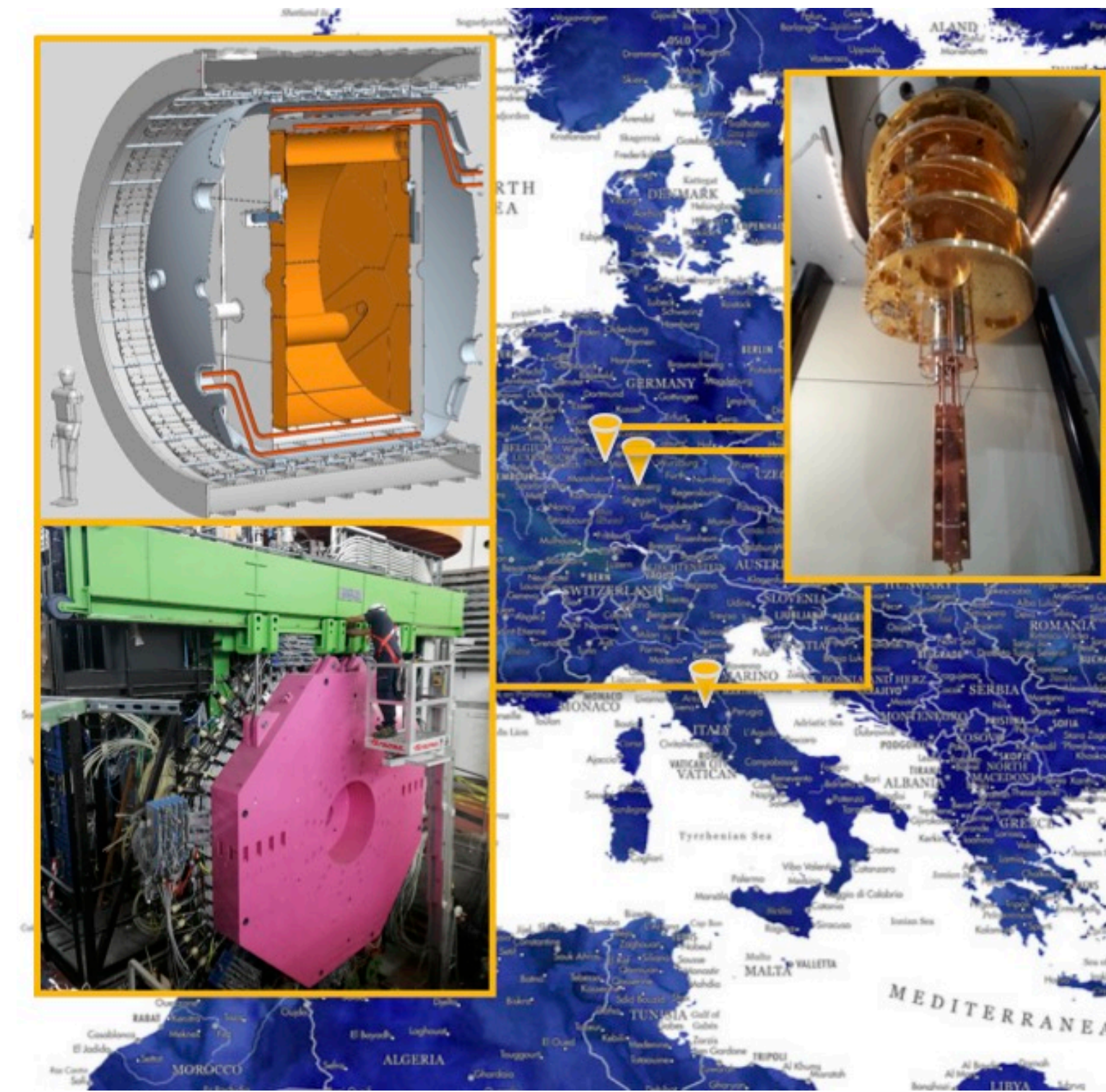




Readout system

TWPA → HEMT → RSA

- Initial proposal with 3 experimental sites: Bonn, Mainz, Frascati (Flash, QUAX)
- Up to nine small resonant cavities (5-8 GHz)
- Collaboration is growing :-)
- Time-Synchronised detection of GW in multiple detectors
 - Coincidence Experiment: Each site can produce 'triggers'
 - Combined analysis of data from all sites
- Requirement on synchronization:
 - Max. distance between sites / speed of light $\Rightarrow \sim \text{ms}$
 - Better time-resolution for triangulation required
 - Will use **GPS time-stamping**: cheap commercial hardware



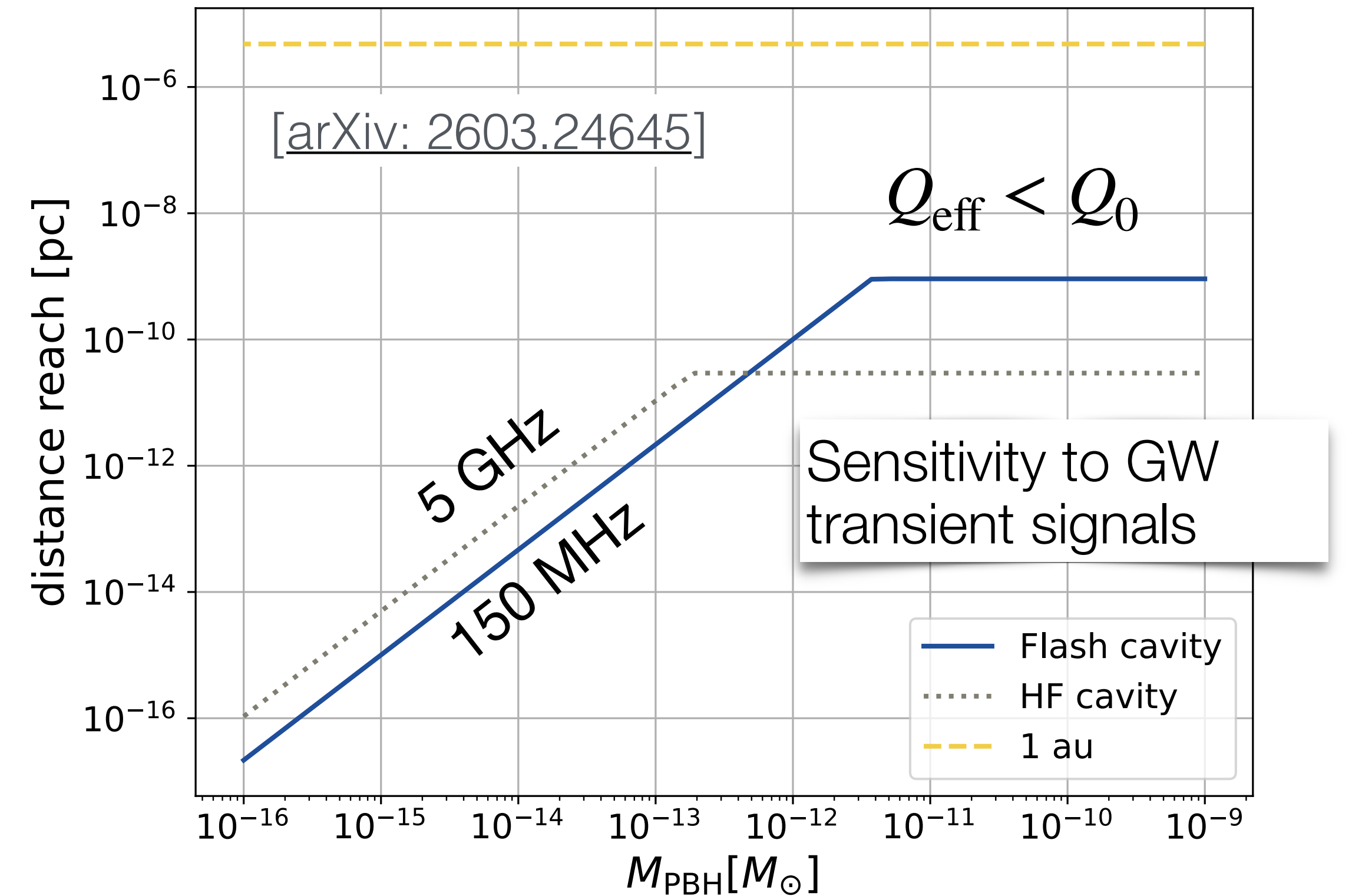
Expected Sensitivities - single cavity

- Search for **transient** signals
- **Duration:**
 - $< \text{ns} \dots \text{s}$, depending on signal source
- **Strain sensitivity:**
 - Depends on energy deposited within signal duration;
- Showing **distance to detectable source**

$$h_0^{\min} = 2 \cdot 10^{-21}$$

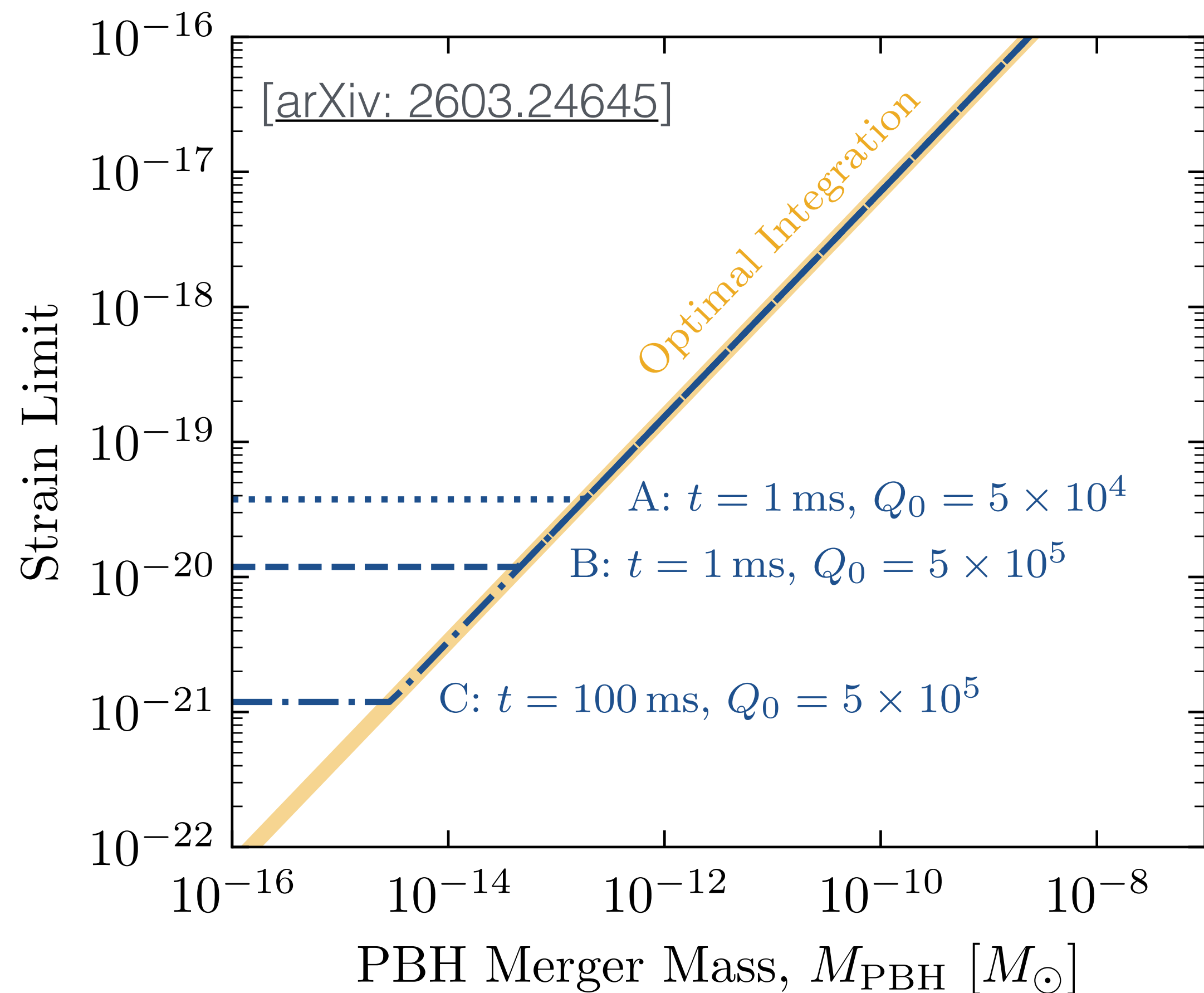
Assuming:

- At least Q cycles within cavity bandwidth
- Optimal readout time
- 95% CL limit & optimal filtering (SNR = 0.08)



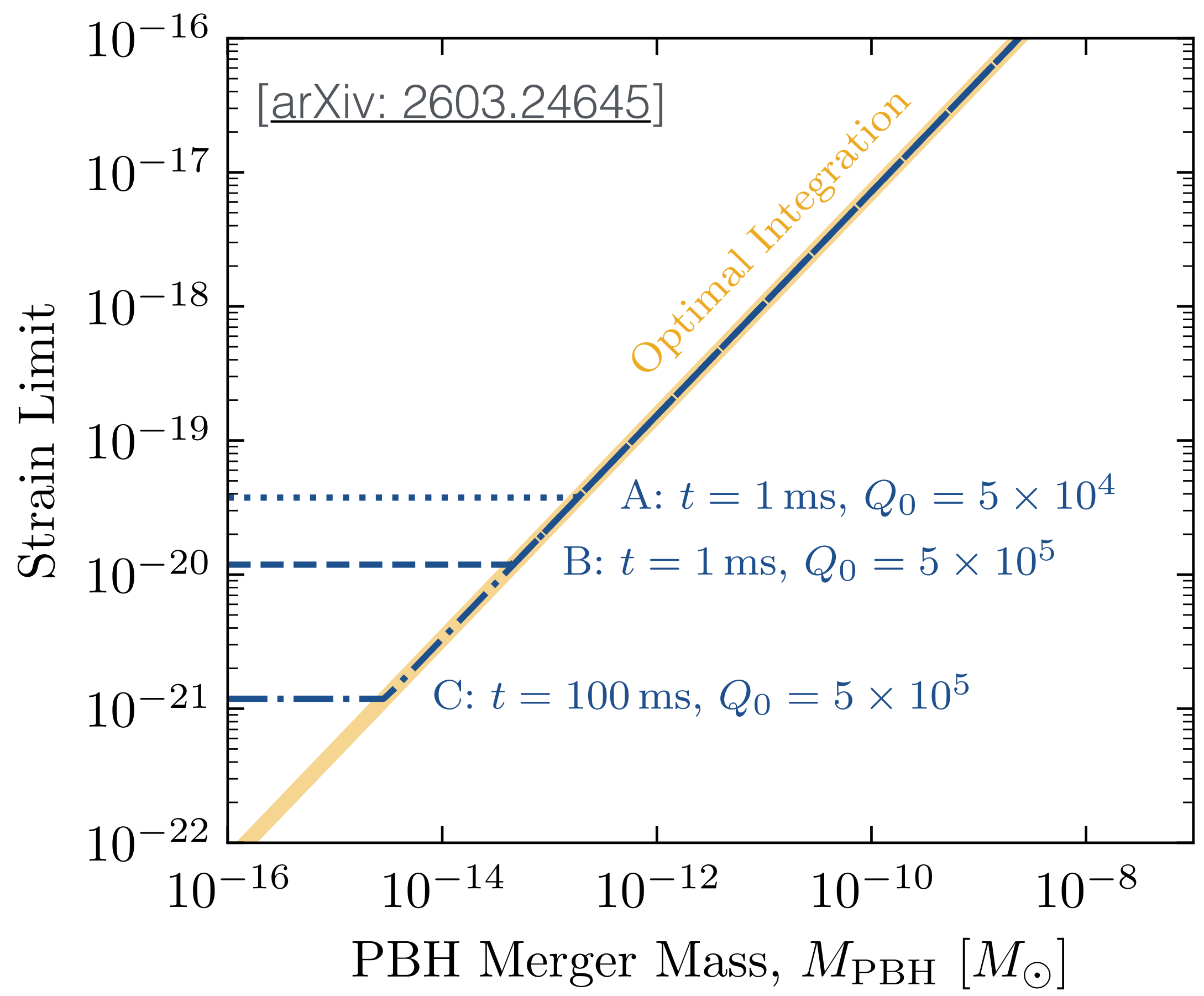
$$m_{PBH} = \begin{matrix} 10^{-15} M_{\odot} \\ t = 6 s^* \end{matrix} \quad \begin{matrix} 10^{-13} M_{\odot} \\ t = 2.7 ms \end{matrix} \quad \begin{matrix} 10^{-9} M_{\odot} \\ 6 \cdot 10^{-10} s \end{matrix}$$

Faster transient



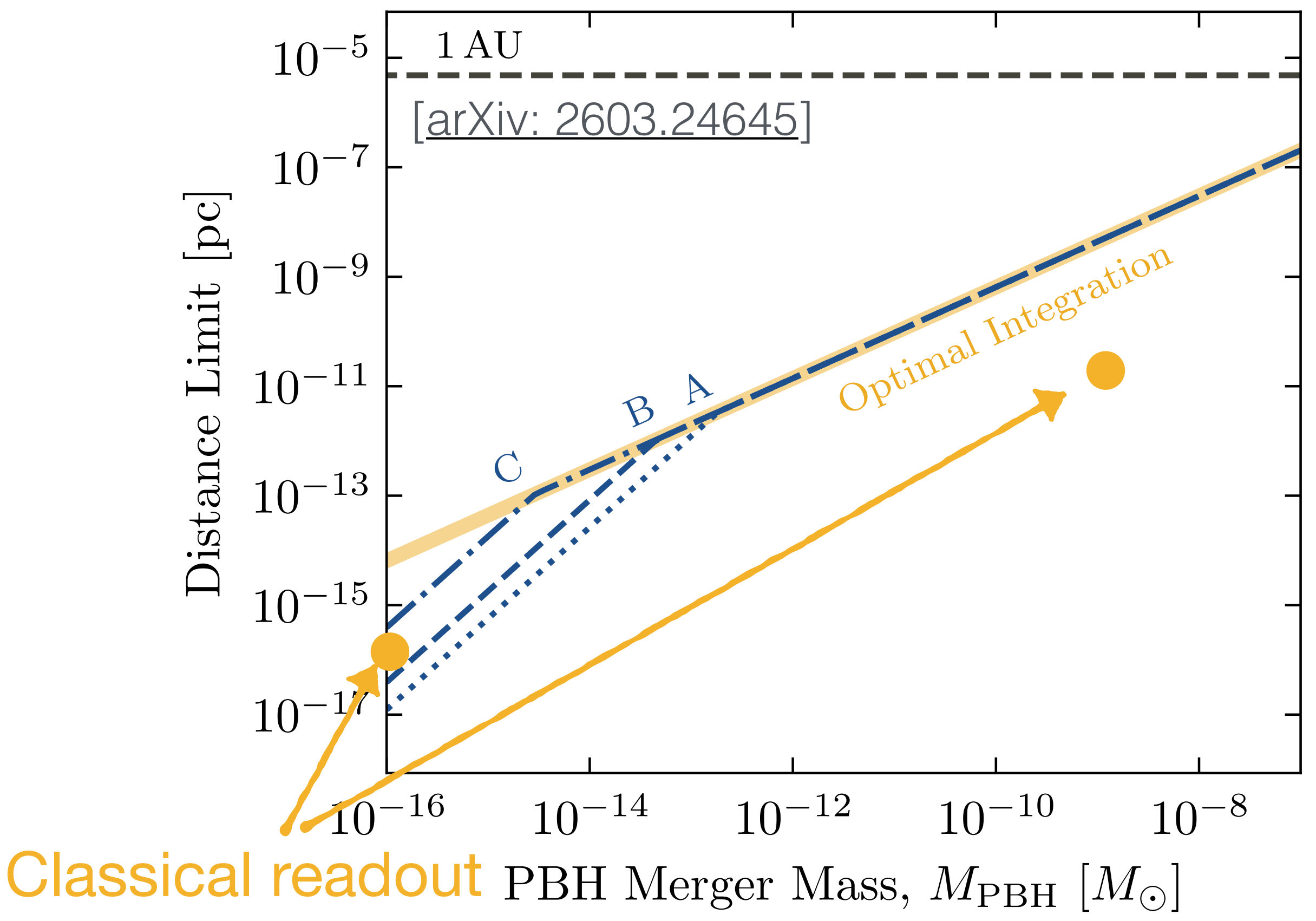
- **Coincidence setup:** using 9 cavities
 - Dark count rate: $< 10 \text{ Hz}$
 - Energy deposited within bandwidth: $\geq 1 \gamma$

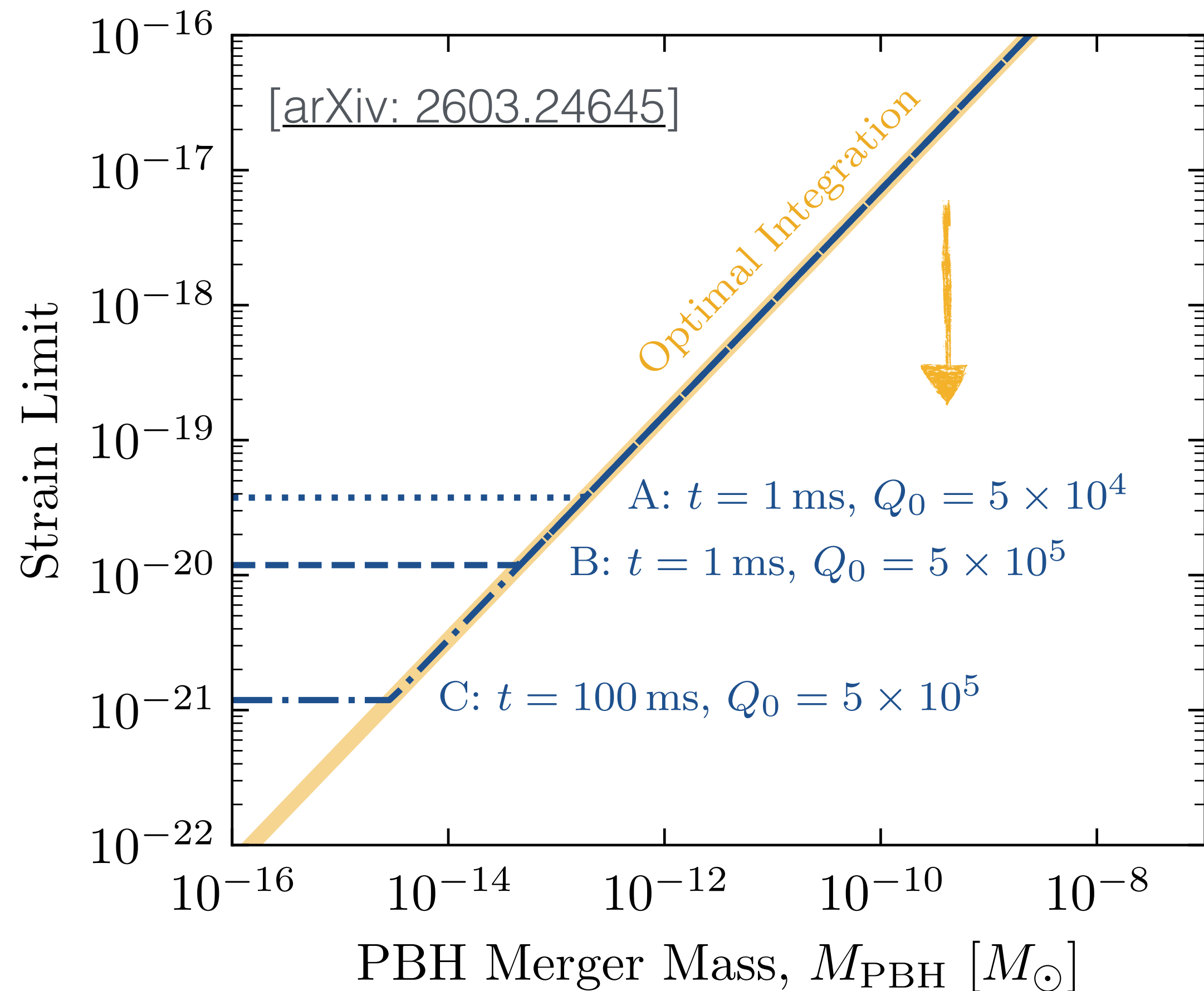
- **PBH merger signals**, assuming thermal background only
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- Target: $h < 10^{-24}$
 - Only few orders of magnitude missing!

- **How to increase sensitivity?**
 - Need to be able to measure sub-photon energy deposits
 - Photon number is wrong observable
 - Need to measure
 - **Phase or Amplitude**

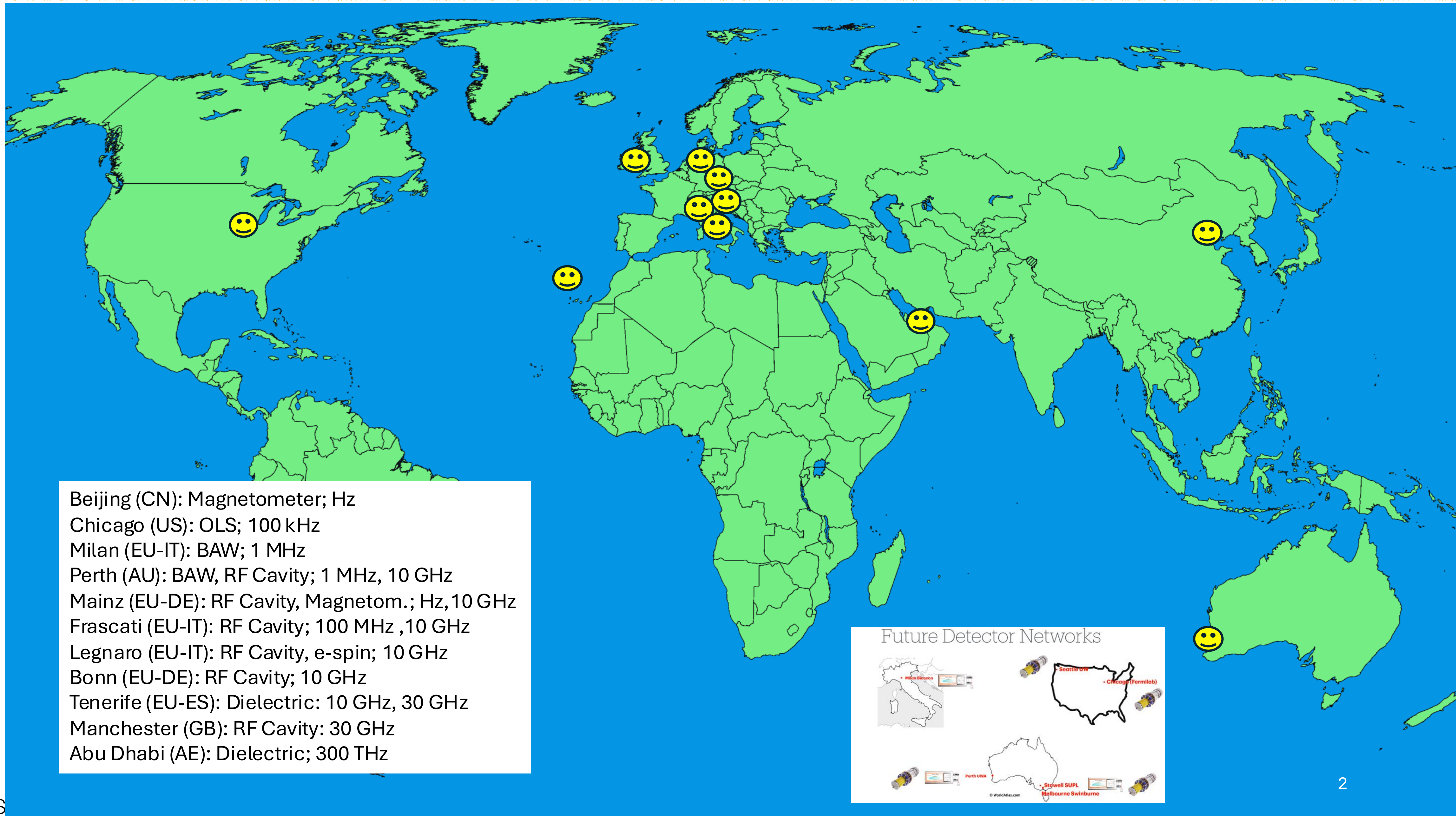
- Searching for HFGW is a very intriguing new research topic
 - Lots of challenges, **lots of opportunities**
 - Combination of data from different detector technologies
- **New haloscope at Bonn**
- GravNet CDR: [[arXiv: 2603.24645](https://arxiv.org/abs/2603.24645)]



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

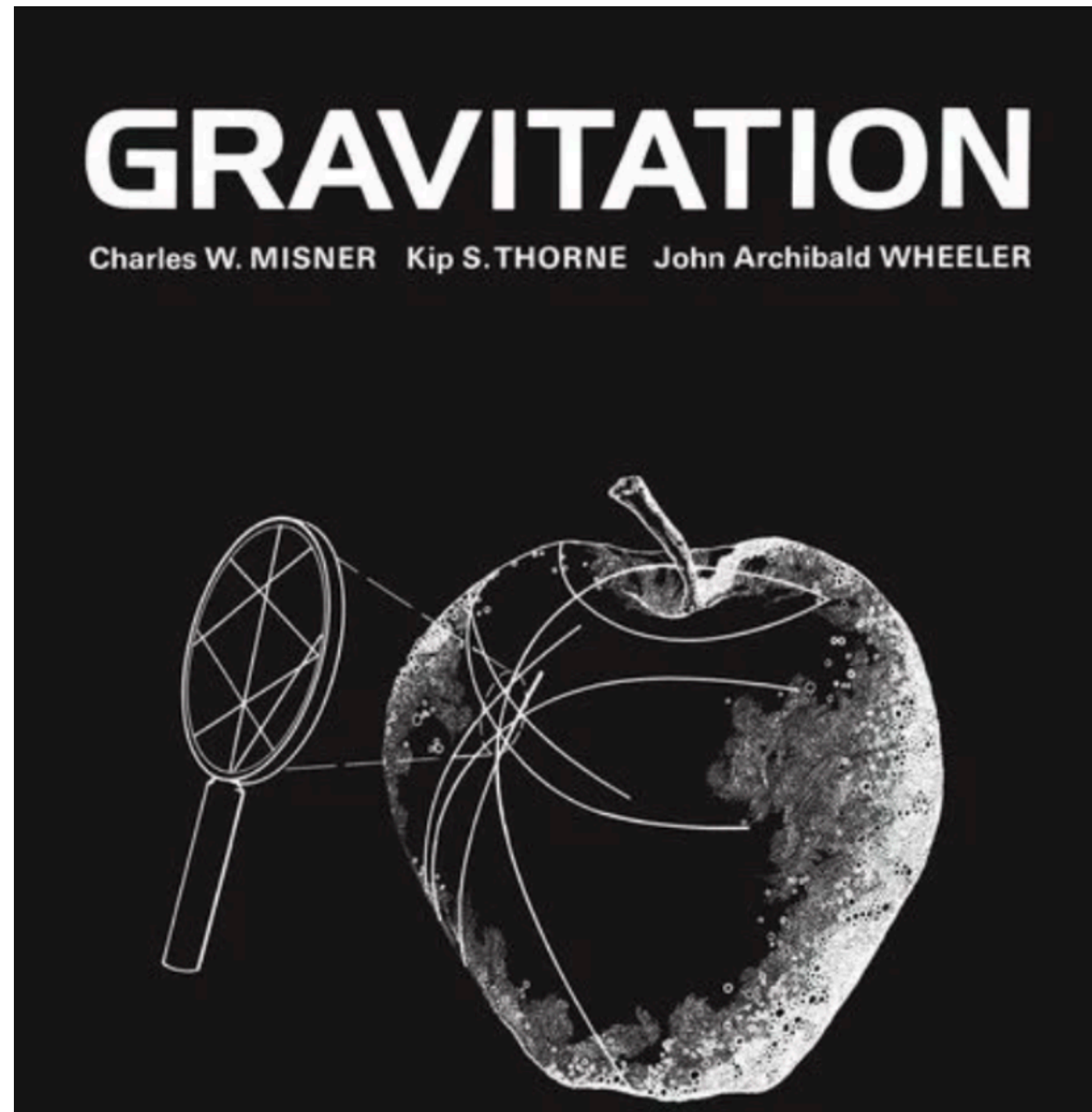
BACKUP SLIDES

Interested Parties in first combined Data Taking



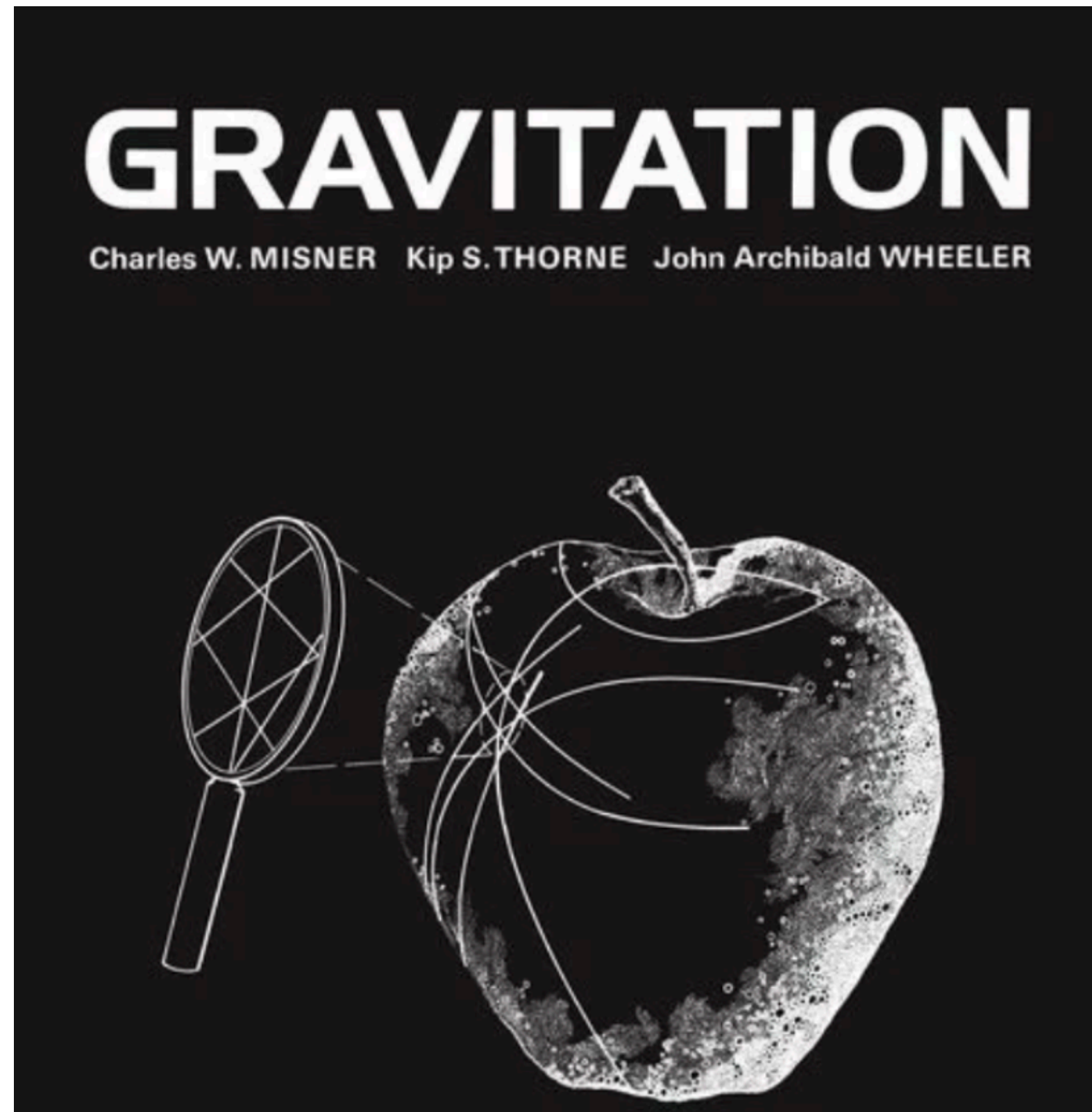
Ambitious, but rewarding goal

Misner, Thorne, Wheeler, 1973



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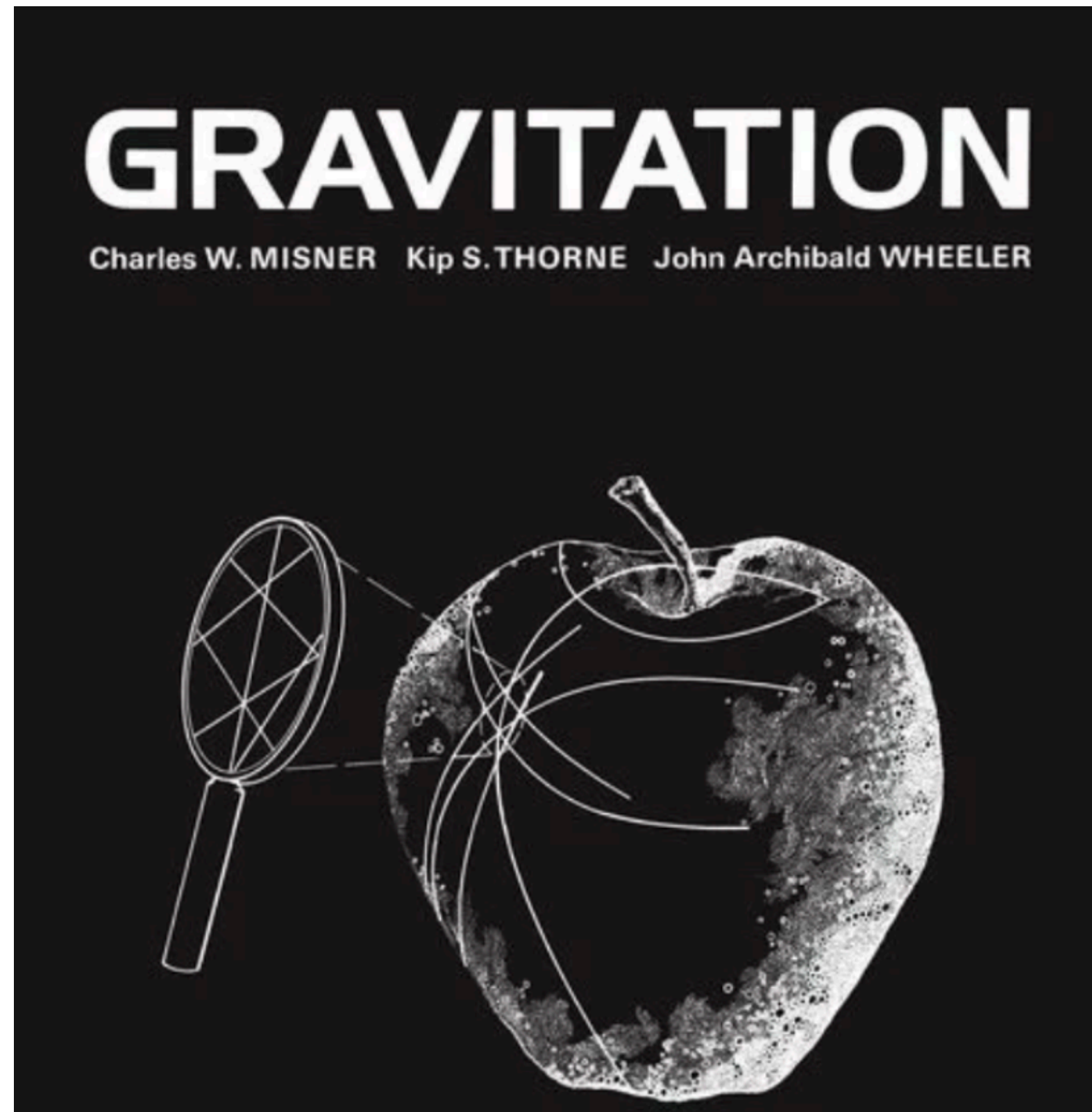


“ [interferometers] have so low sensitivity that they are of little experimental interest”

p. 1014

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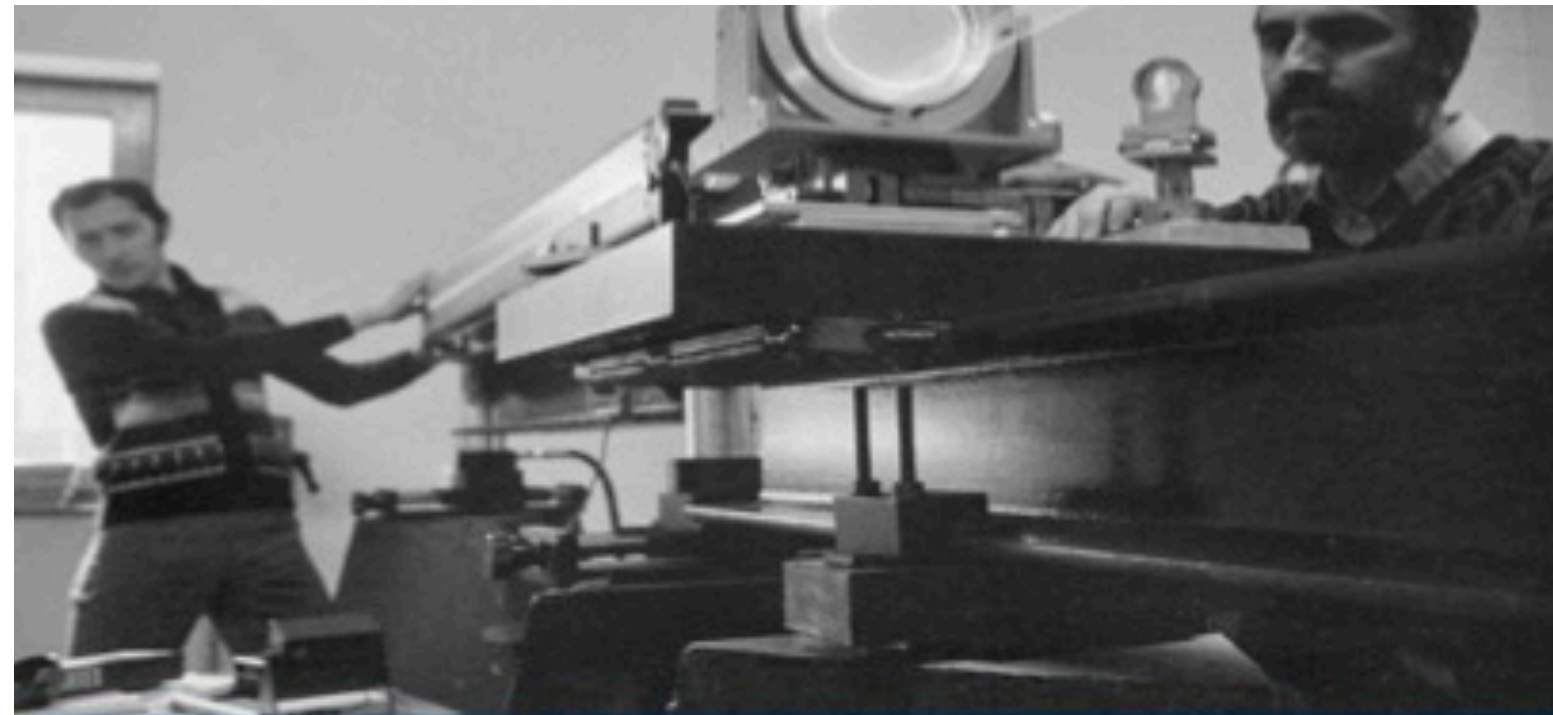


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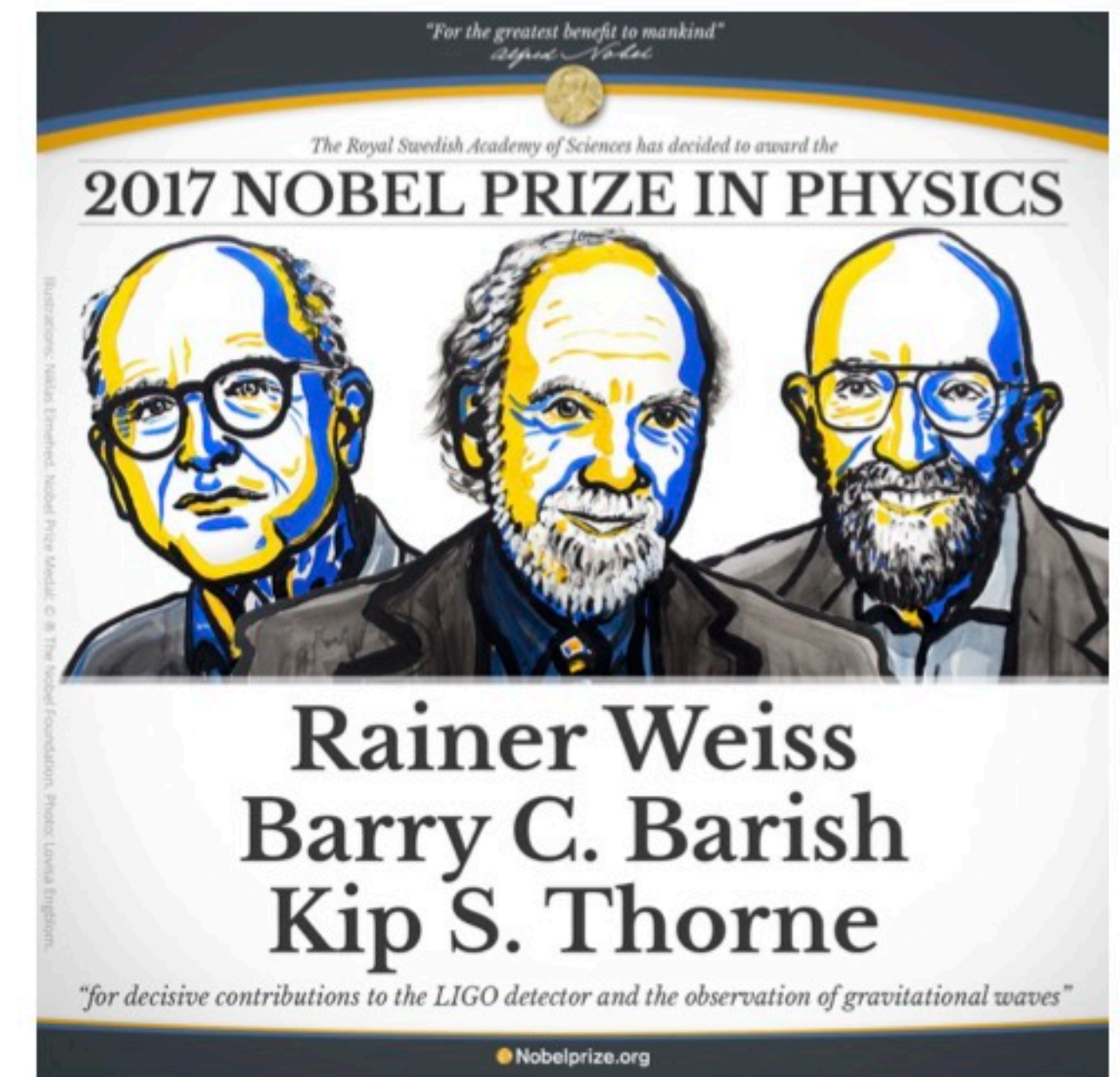
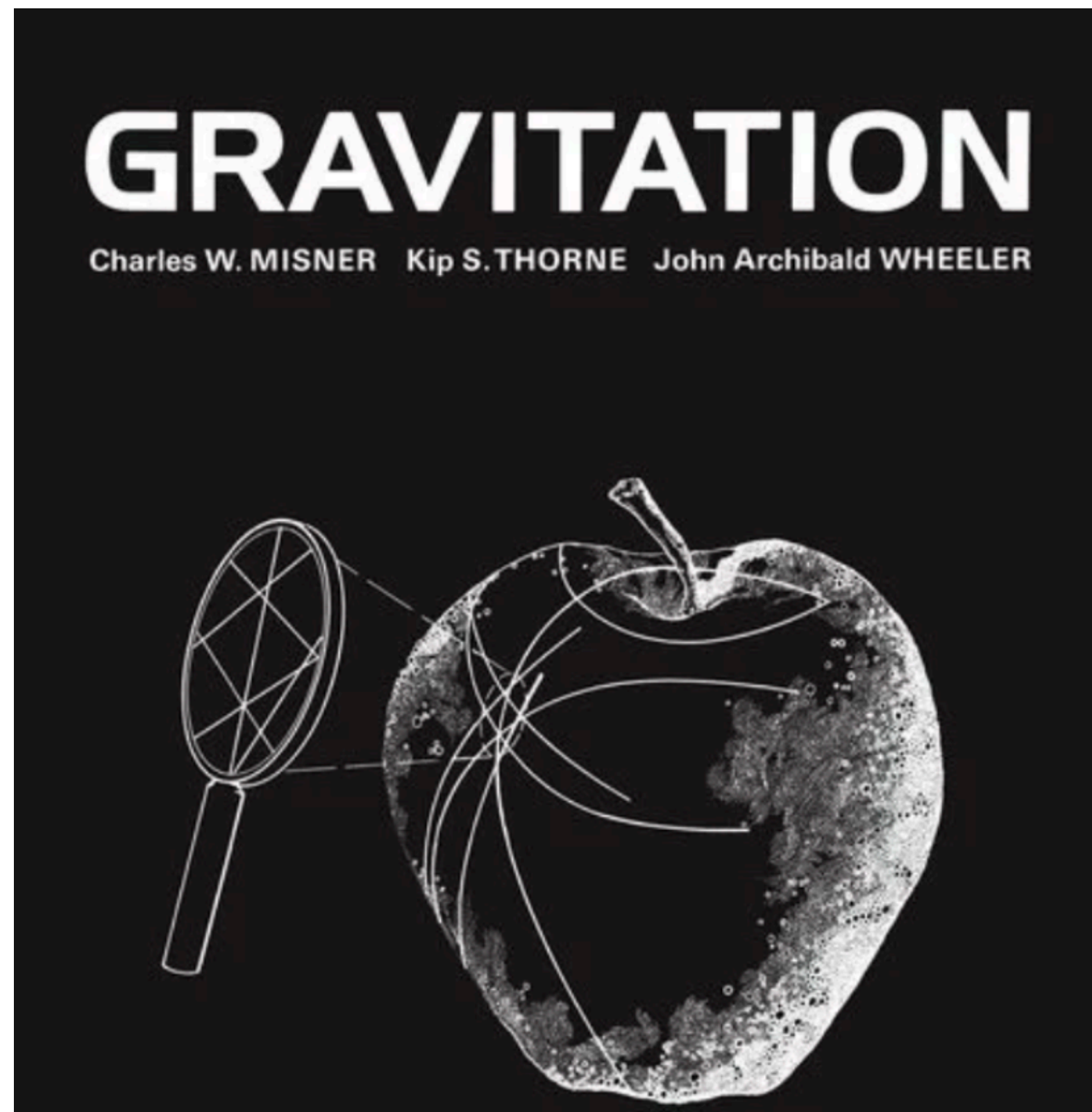
50 years of work, 23 attempts



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 - Post-inflation collapse if energy density large enough
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 - Masses controlled by energy in one Hubble volume

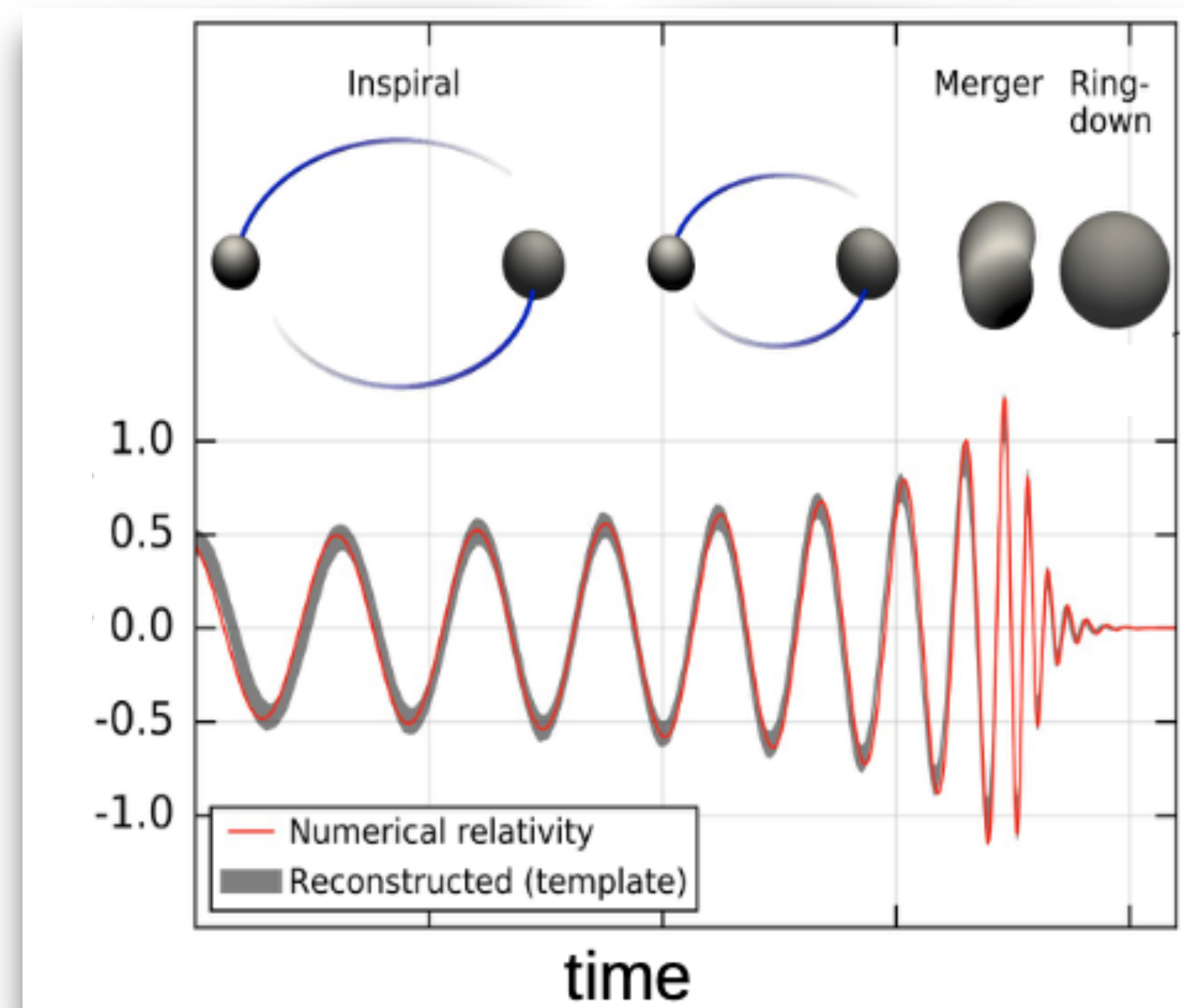
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- Merging frequency depending on PBH mass
- **Focus on inspiral:**
 - Sweep of huge frequency span



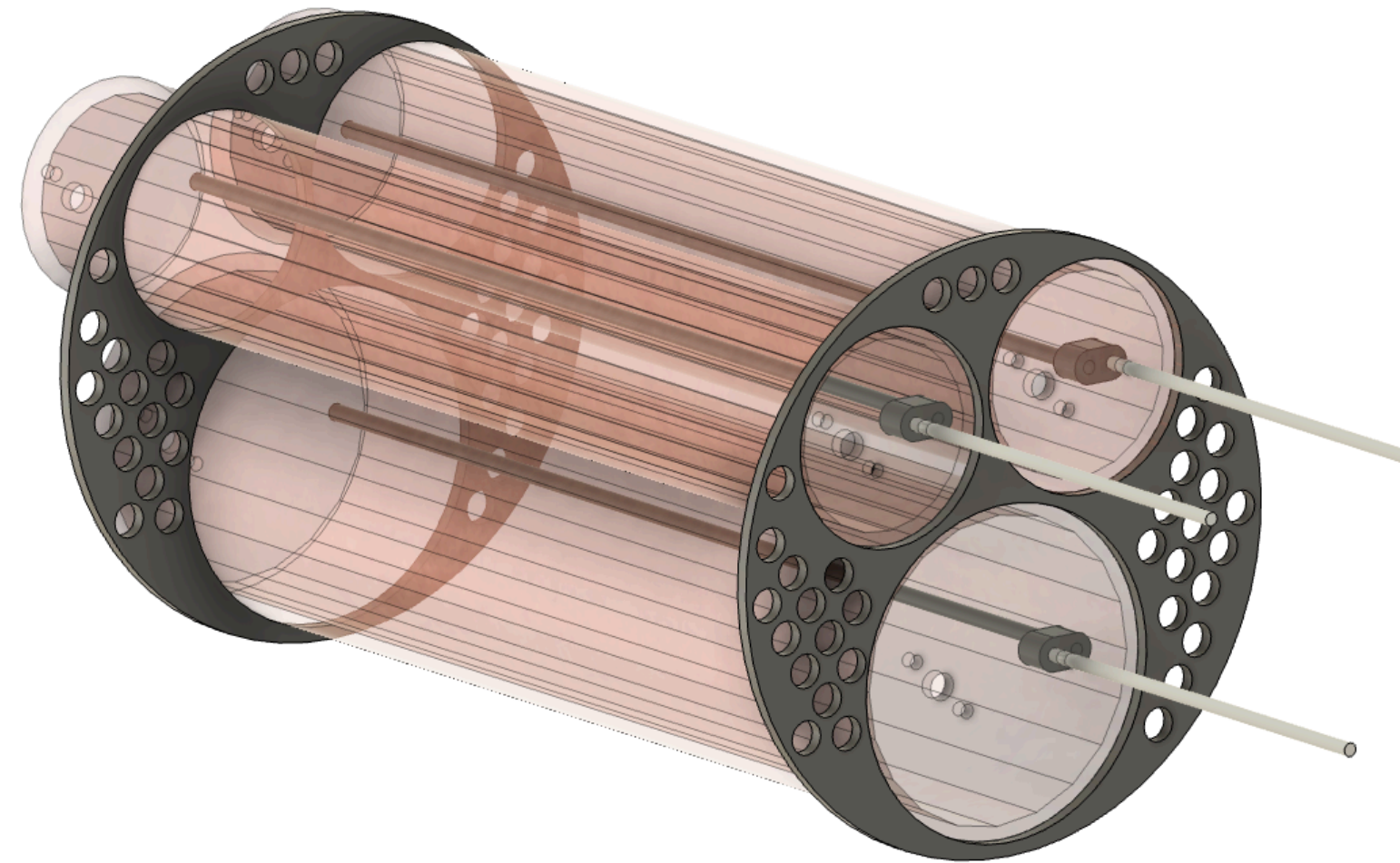
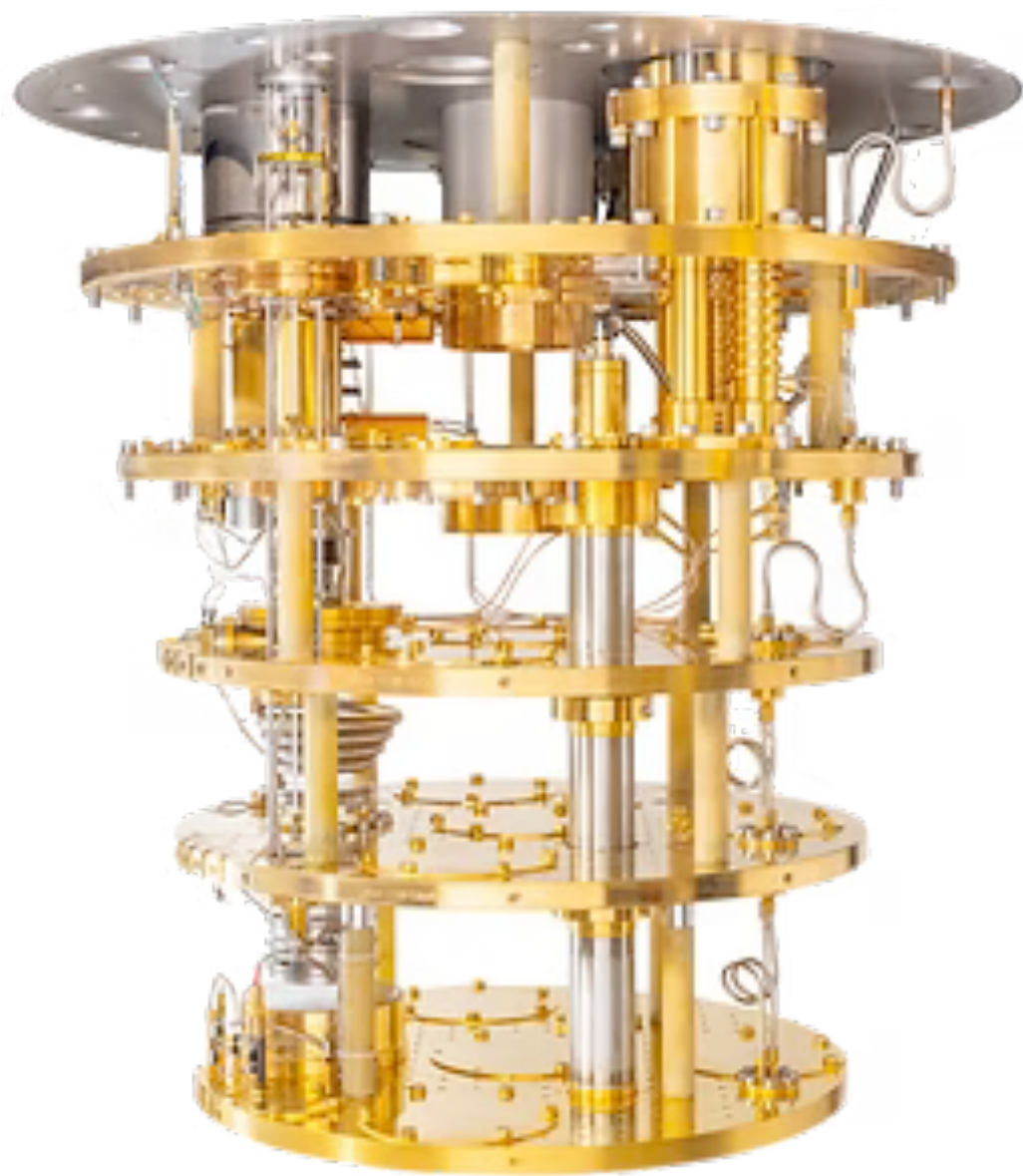
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 - Pick up (short) transient in time-series
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 - Conversion to **frequency domain**
 - Short (ms - 1s) intervals of data
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- **ML techniques** (Anomaly detection, Classifiers in time-domain)
 - Need training data, much less fine grid than above
 - Computationally easy

The **NEW** Supax Experiment

- Dual use: **Axions** & **GWs**
- Temperature: **10 mK**
- B-field: 12 T
- Usable volume: $\varnothing = 9 \text{ cm} \times 20 \text{ cm}$
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Sensitivity to Axions: [\[arXiv:2505.07541\]](https://arxiv.org/abs/2505.07541)

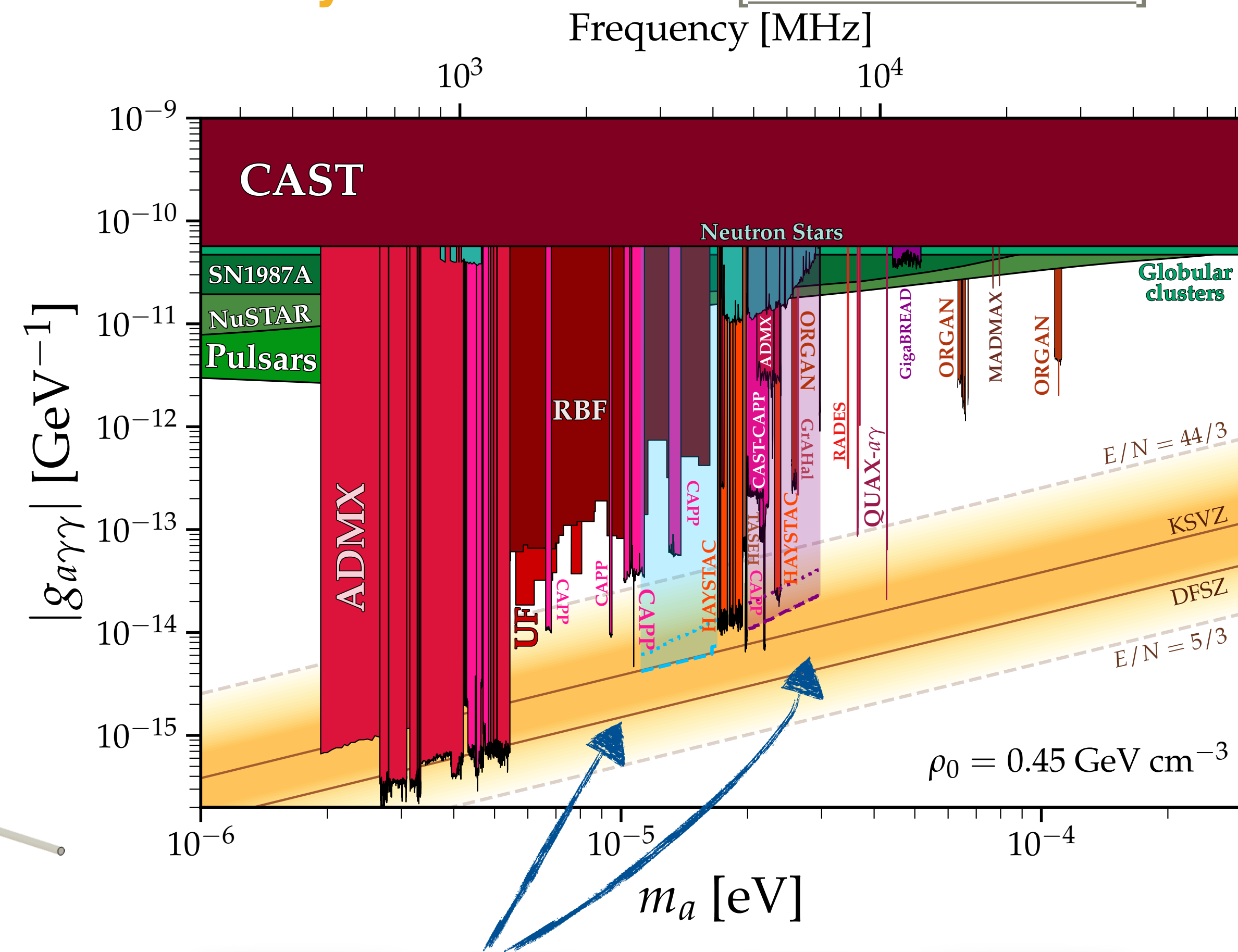


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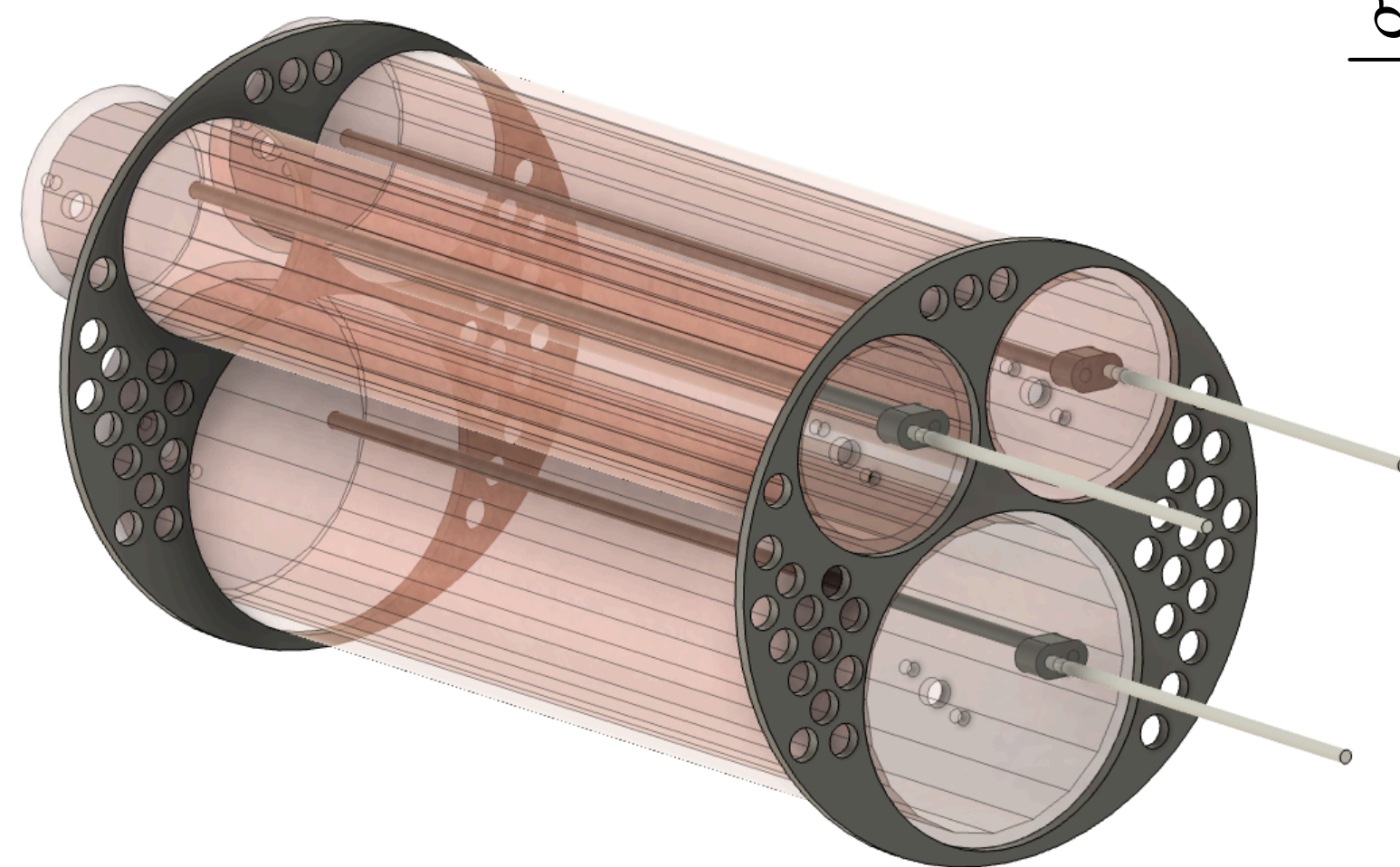
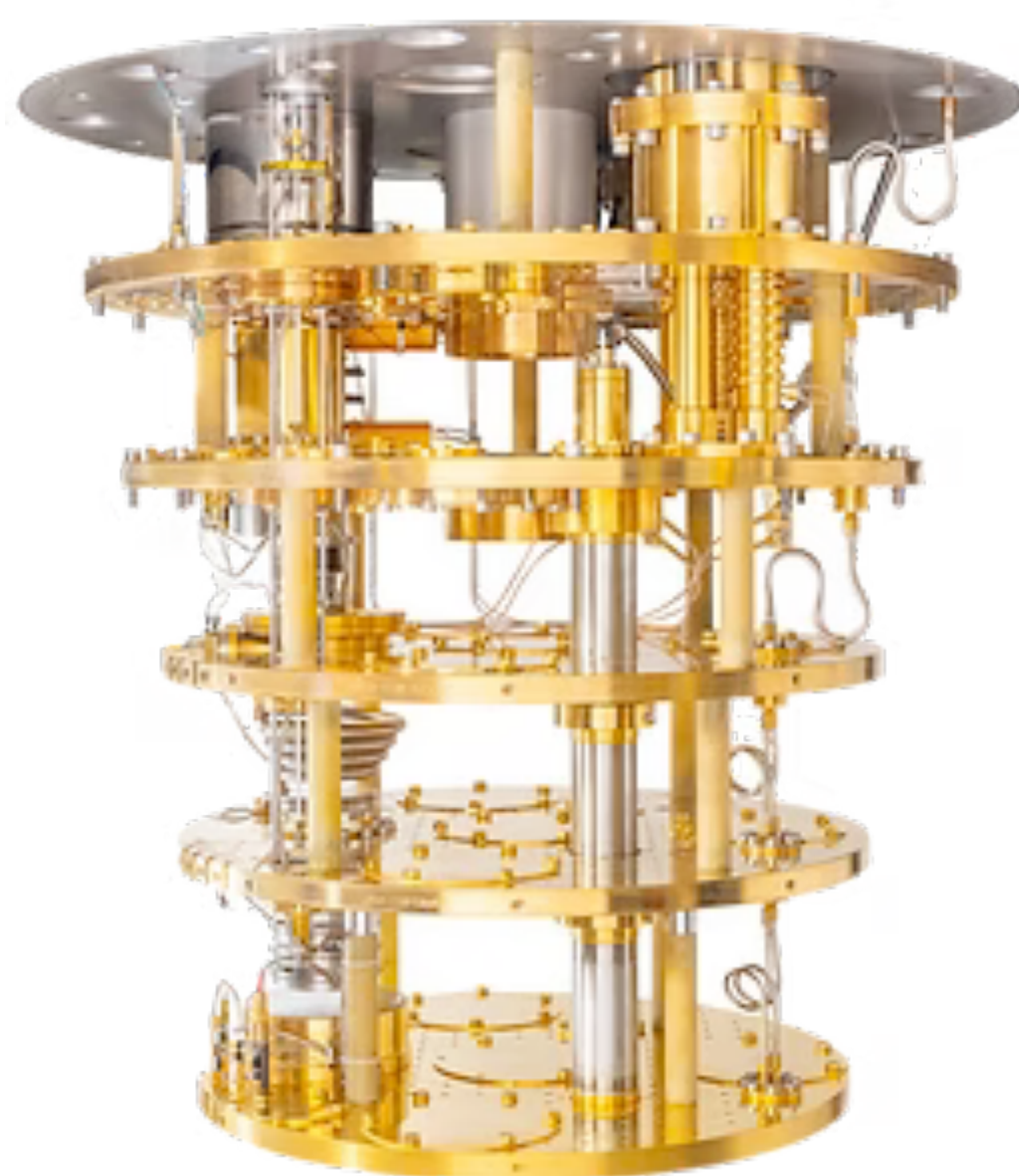
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Sensitivity to axions in
40 weeks measurement time / block

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Maxwell equations on variably curved space time

- Assume GW passing through a static B-field:

$$g_{\alpha\beta} = \text{diag}(1, -1, -1, -1) + h_{\alpha\beta}$$

- Covariant Maxwell equations:

$$\partial_\mu(\sqrt{-g}F^{\mu\nu}) = \partial_\mu(\sqrt{-g}g^{\mu\alpha}g^{\nu\beta}F_{\alpha\beta}) = 0$$

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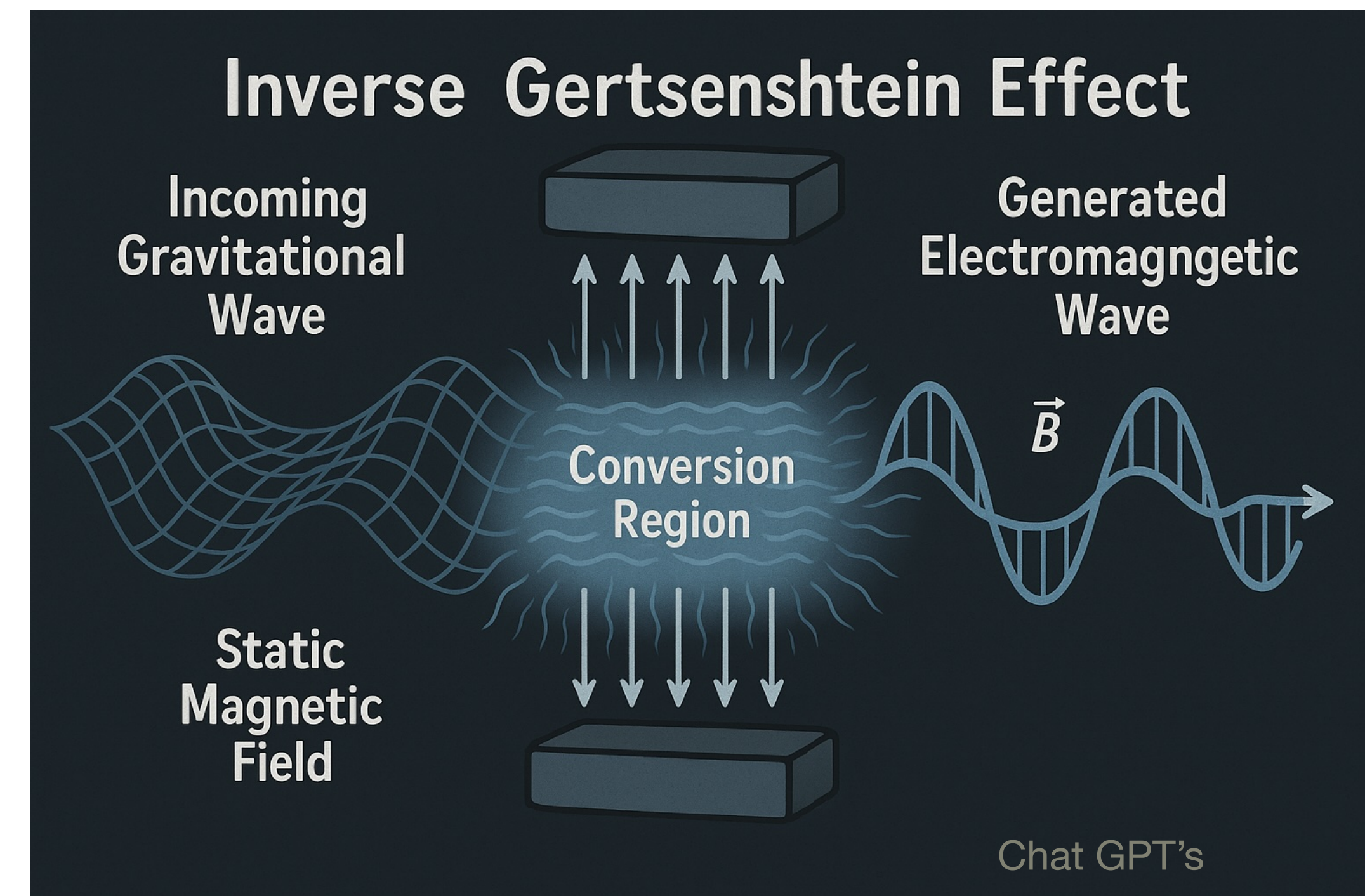
$$E_x \simeq = \frac{A_+}{2}B_y^0 e^{i(k_g z - \omega_g t)} = \frac{h_+}{2}B_y^0$$

- Two polarisations of GW

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

- 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](https://arxiv.org/abs/2501.11723)



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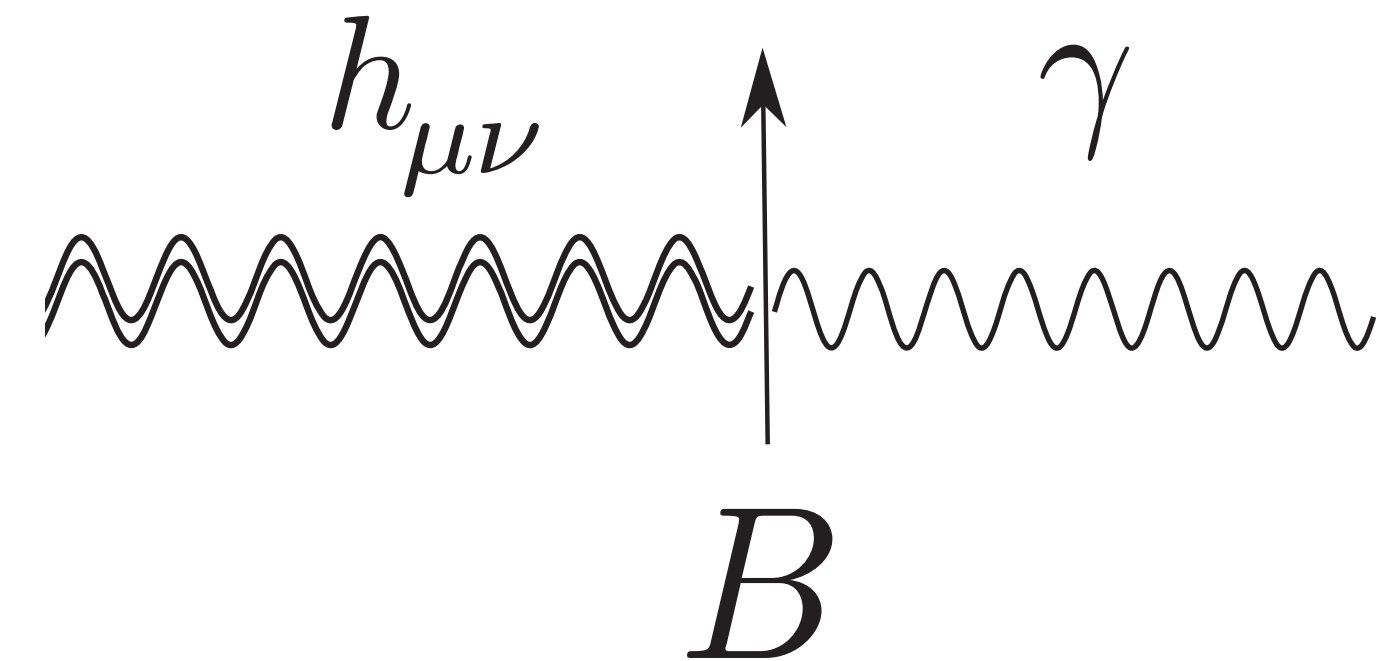
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$$j_{\text{eff}} \propto \omega_g h B_0 e^{i(k_g z - \omega_g t)}$$

- Conversion of GW energy into Photons and vice-versa!



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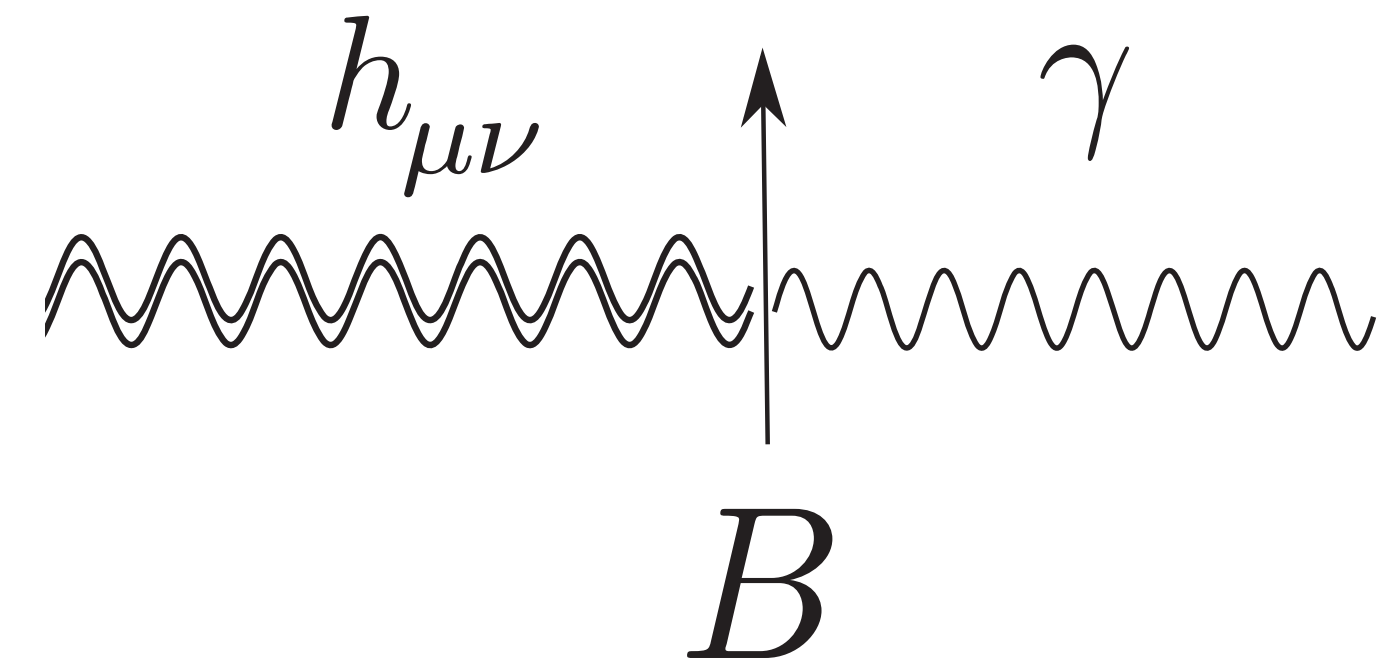
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How can this be used to detect GWs ?

- 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!



- Primordial black hole mergers
 - Chirp signals
- GW from boson superradiance
 - Monochromatic over long timescales
- Stochastic GW background
 - Even lower strains ...

- Ligo / Virgo Signals
 - BH mergers

Needed strain sensitivity

- $h_0 < 10^{-24}$
- $h_0 < 10^{-29}$
- $h_0 < 10^{-32}$

Observed Strain

- $h_0 \sim 10^{-22}$

Expected Sensitivity:

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

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

