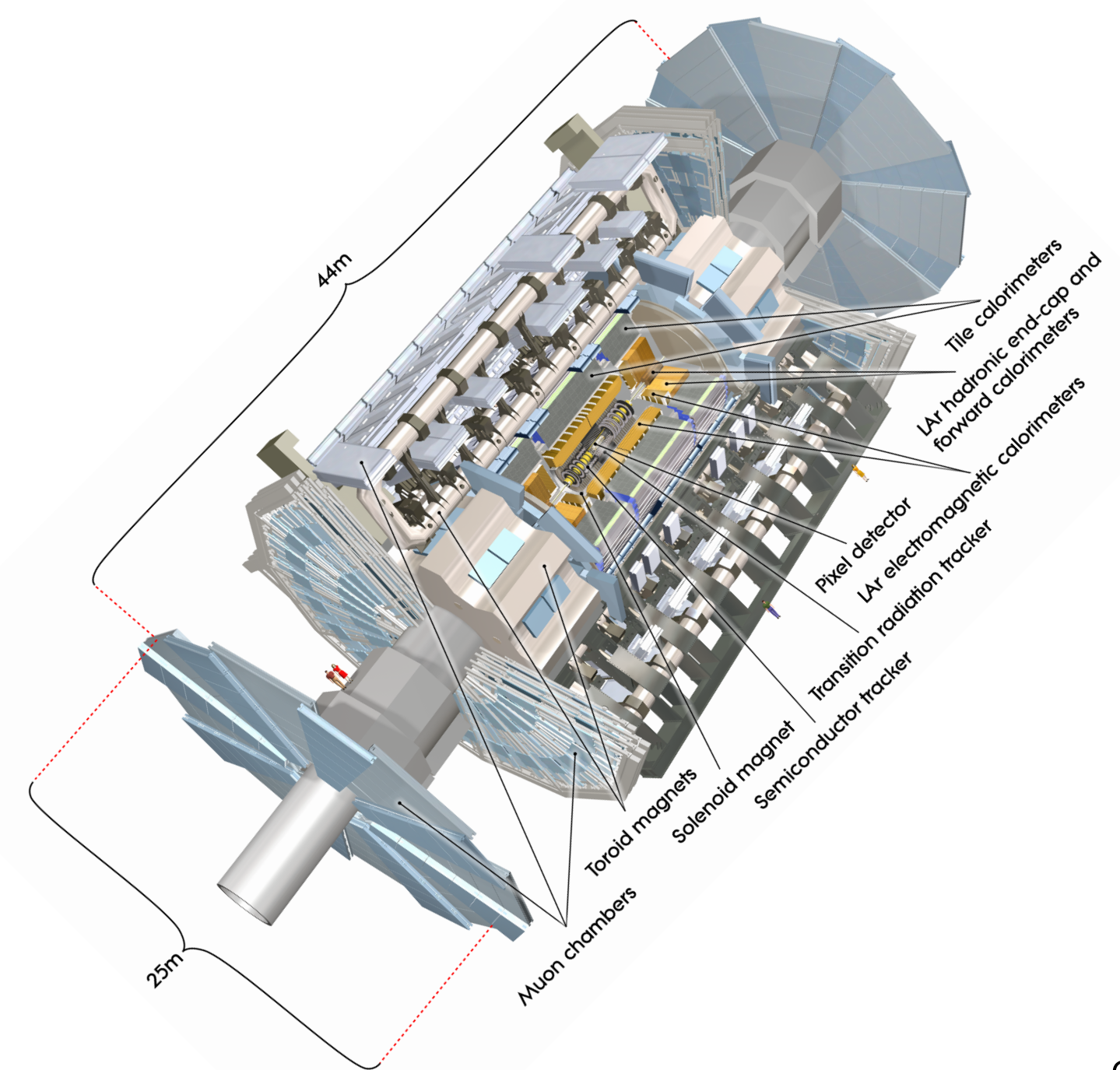


The hunt for high frequency gravitational waves — GravNet —

Kristof Schmieden, PP Seminar Bonn, 17/07/2025



- Phd: **ATLAS**
 - Pixel Detector, Muon System
 - Standard model precision measurements
 - Weak mixing angle
- CERN Fellow + 5 year Staff (until 2020)
- **ATLAS**
 - Central Trigger
 - Operations
- SM precision, Higgs- $\rightarrow\gamma\gamma$
- Light-by-Light scattering
 - **Axion Like particles**
- **FASER**
 - DAQ
- Junior Faculty (2015-2020)
- **ALPs, Axions, Gravitational Waves**
 - ATLAS
 - FASER
 - Supax + GravNet

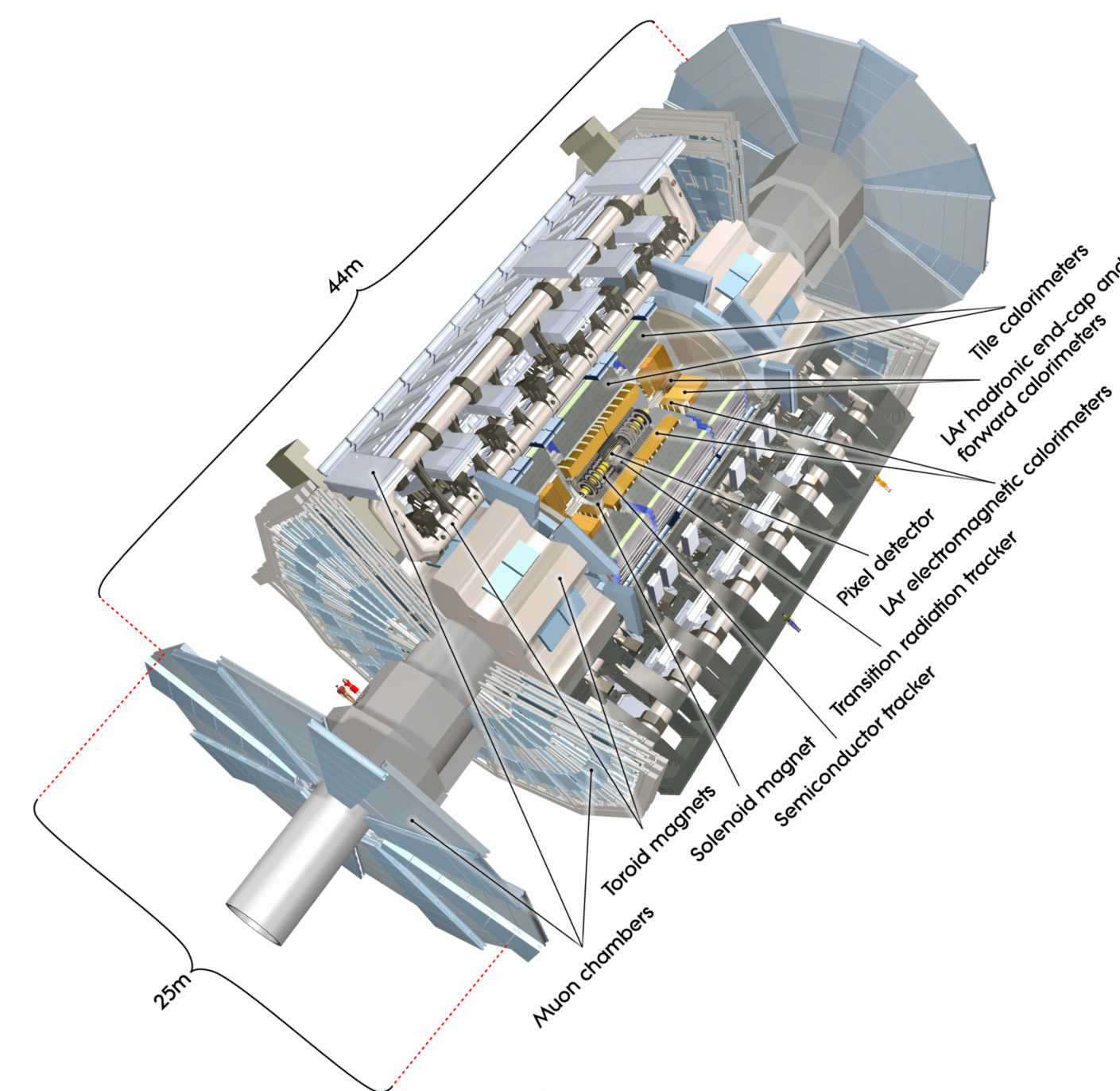




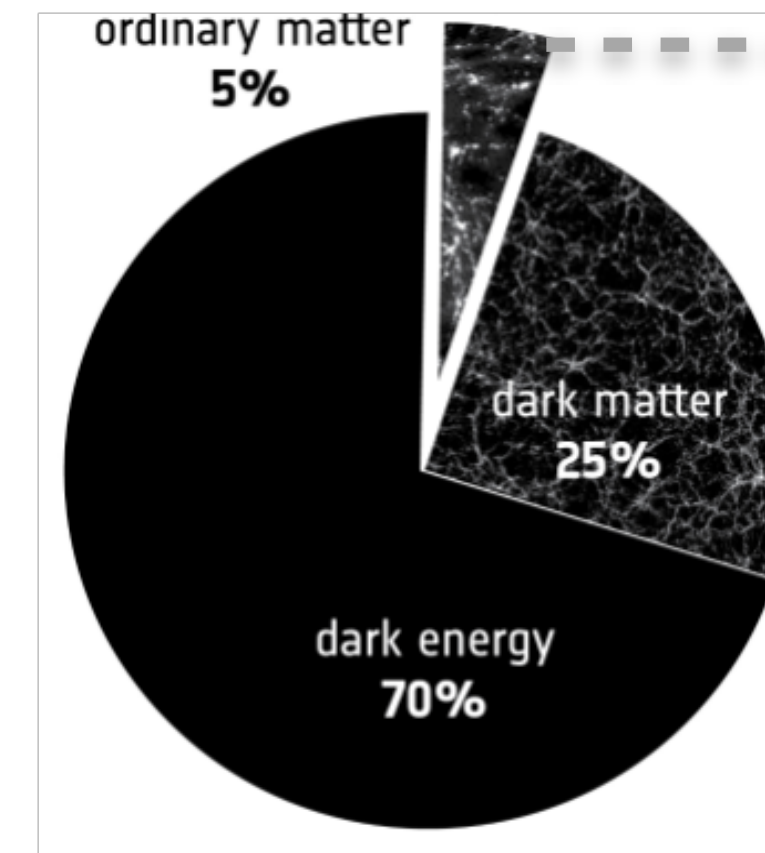
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- Scientific staff @ Bonn since April
- **GW + Axions**
- **GravNet**
- ATLAS

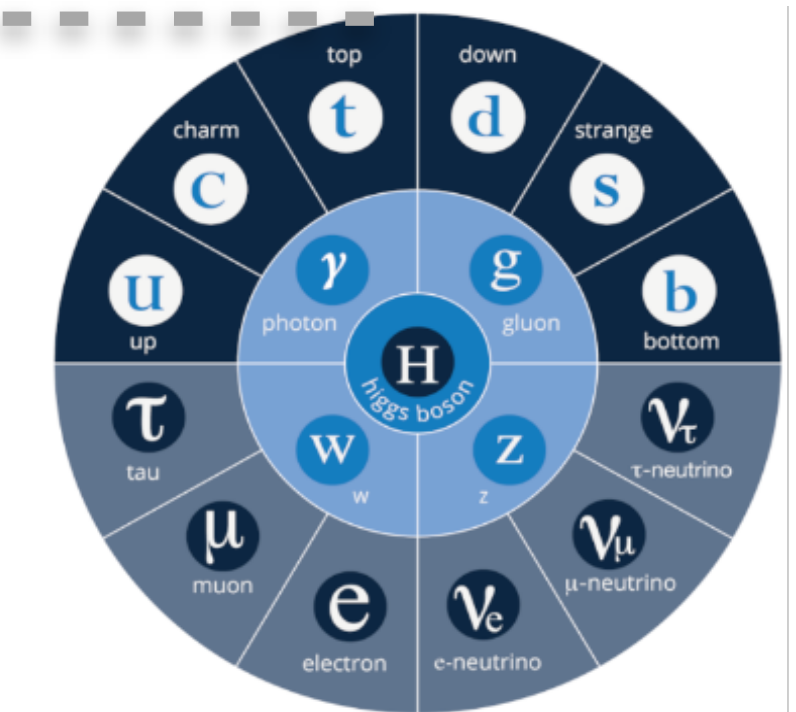
Focus of this talk



Our (incomplete) view of the universe



95% not detectable
with **light**

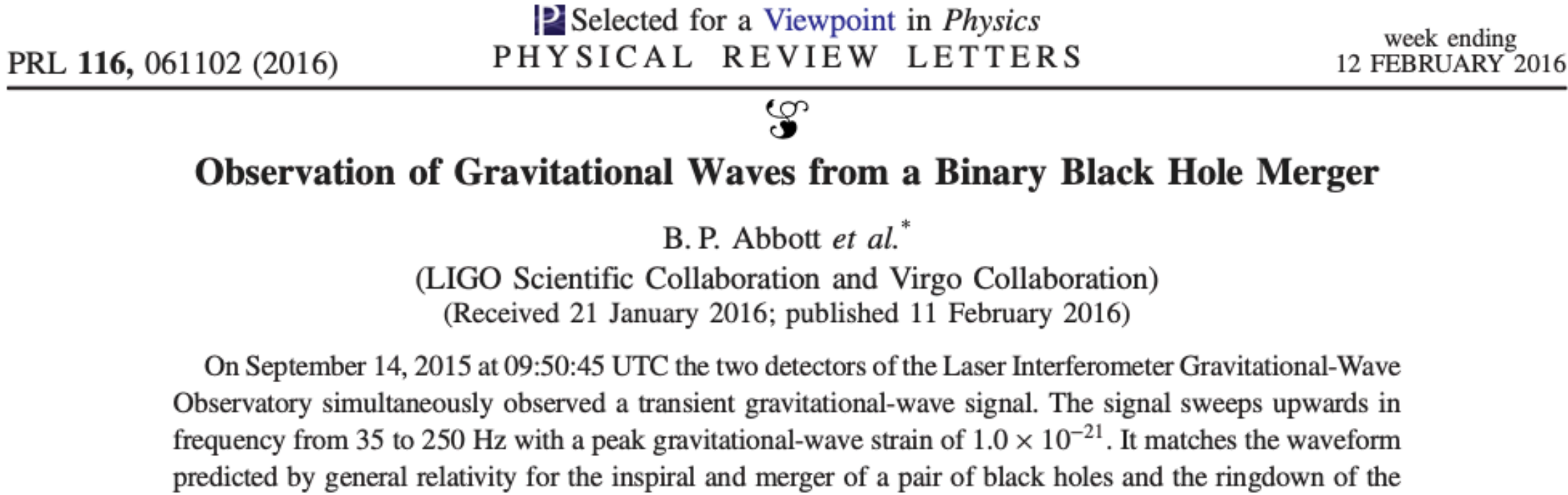


incomplete
at **high energy**

Gravitational waves

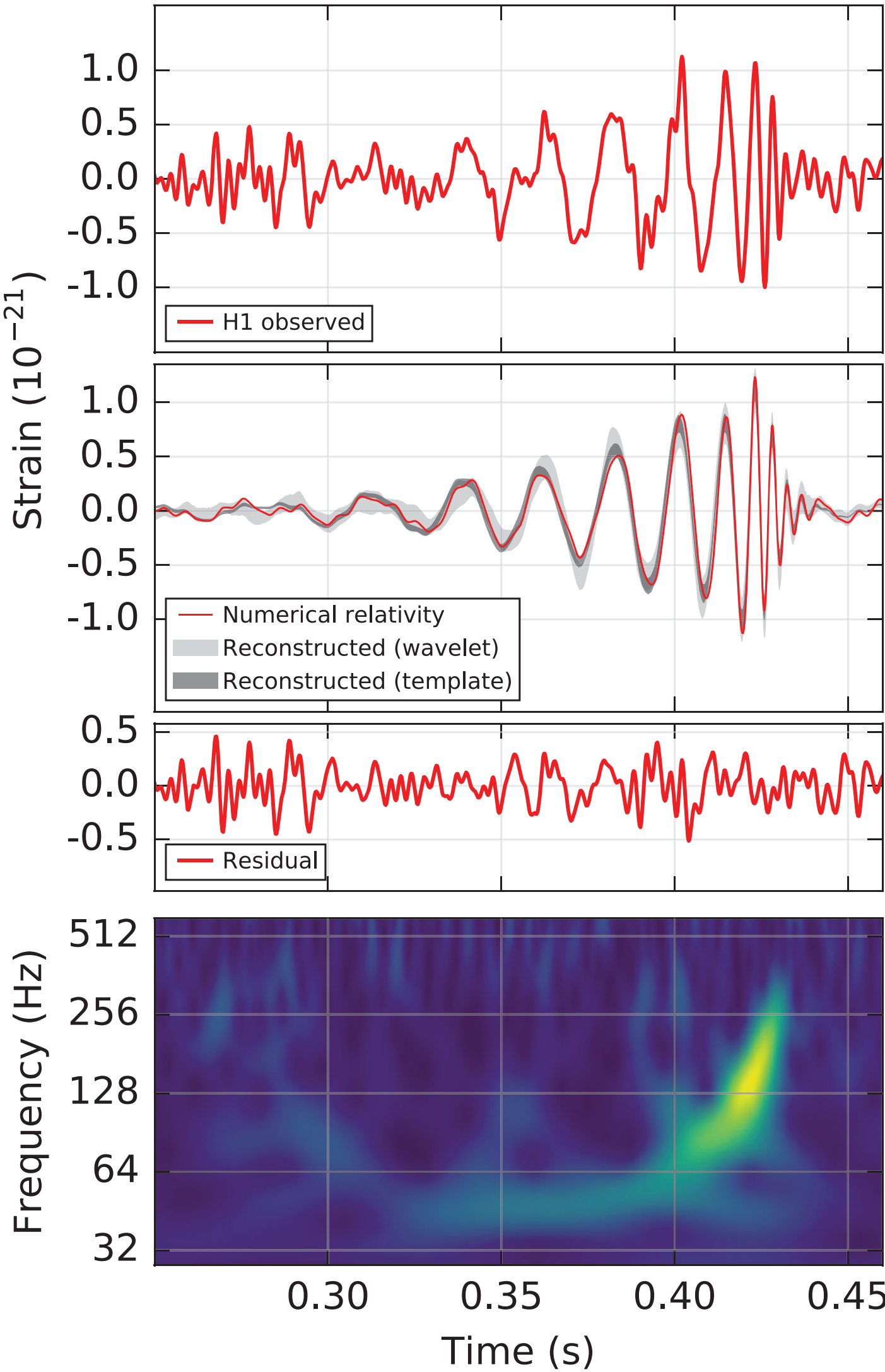
probe all components and may come from the early universe

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



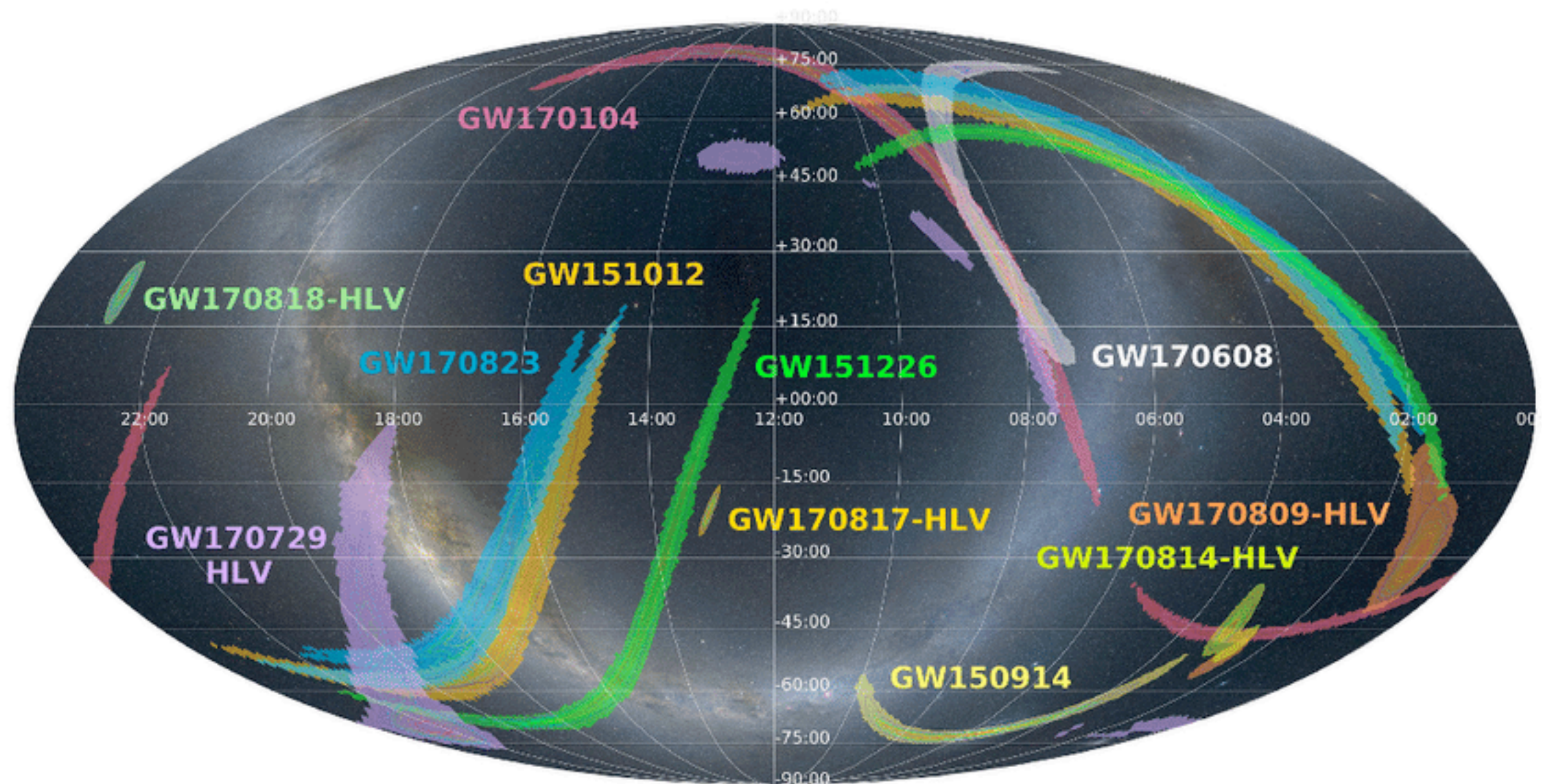
- Frequency range: 10-1000 Hz

Hanford, Washington (H1)

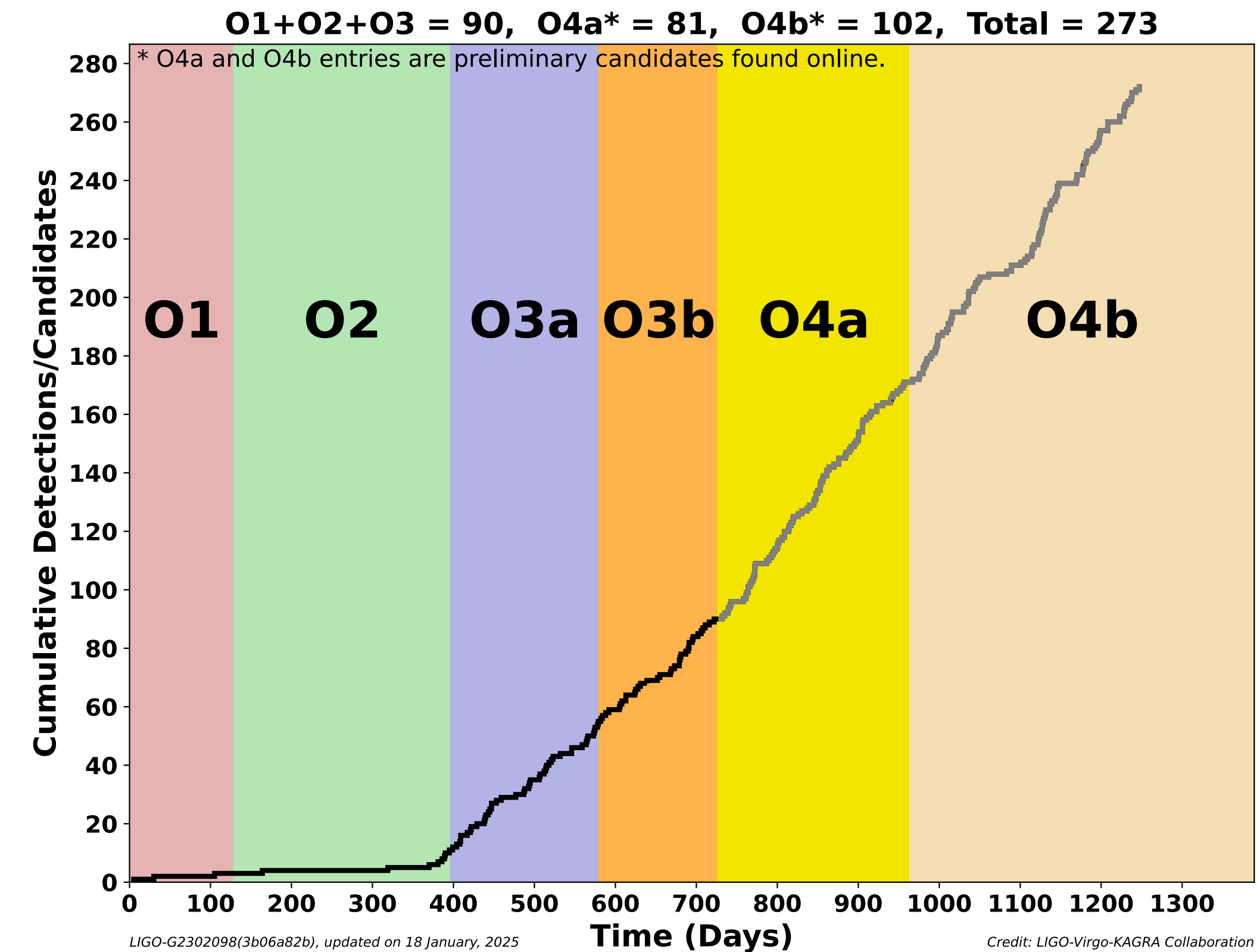


Introduction - Gravitational Waves

- 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>]

- 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>

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OPEN ACCESS



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

Gabriella Agazie¹ , Akash Anumalapudi¹ , Anne M. Archibald² , Zaven Arzoumanian³, Paul T. Baker⁴ , Bence Bécsey⁵ , Laura Blecha⁶ , Adam Brazier^{7,8} , Paul R. Brook⁹ , Sarah Burke-Spolaor^{10,11} , Rand Burnette⁵, Robin Case⁵, Maria Charisi¹² , Shami Chatterjee⁷ , Katerina Chatziananou¹³ , Belinda D. Cheeseboro^{10,11}, Siyuan Chen¹⁴



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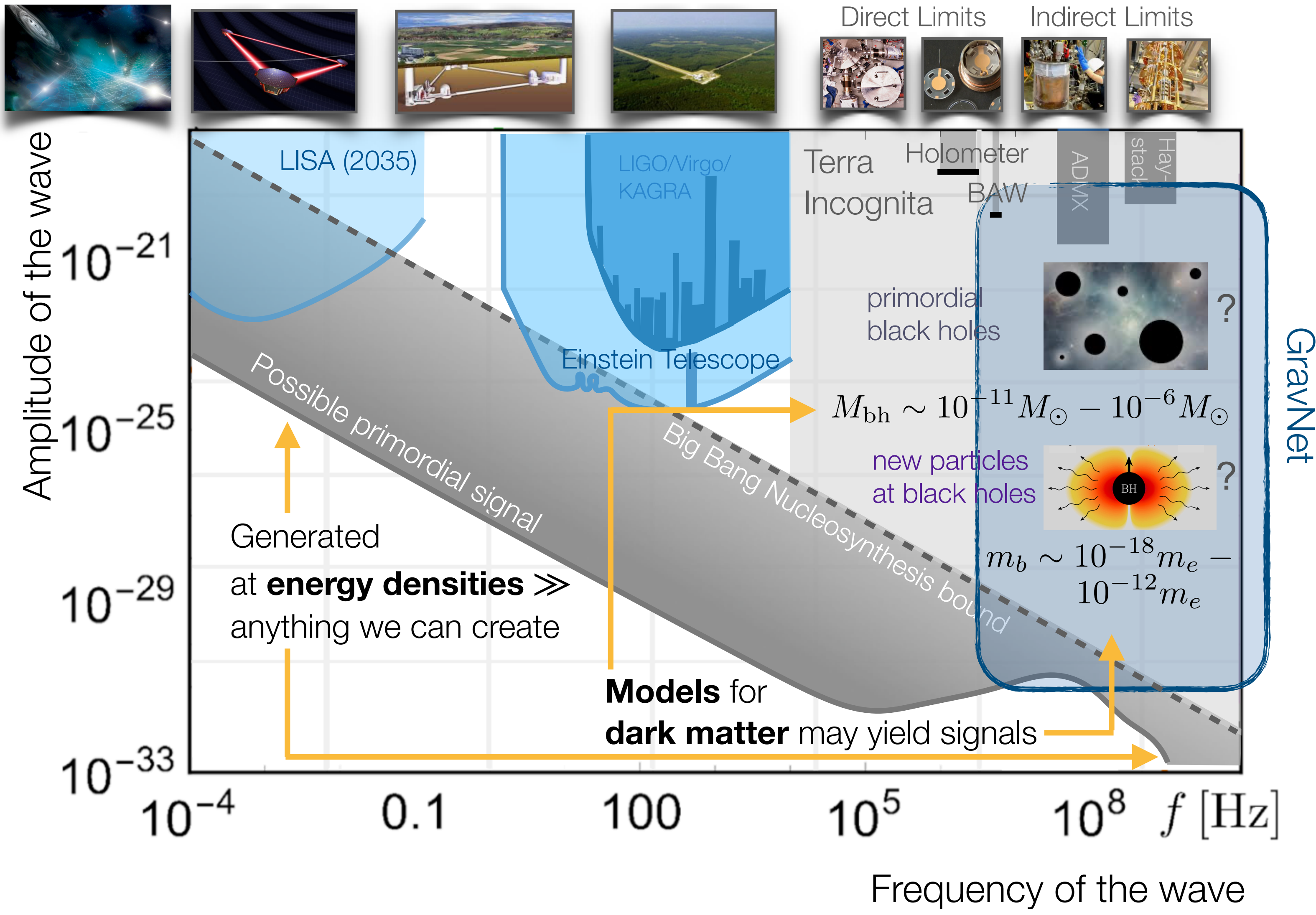


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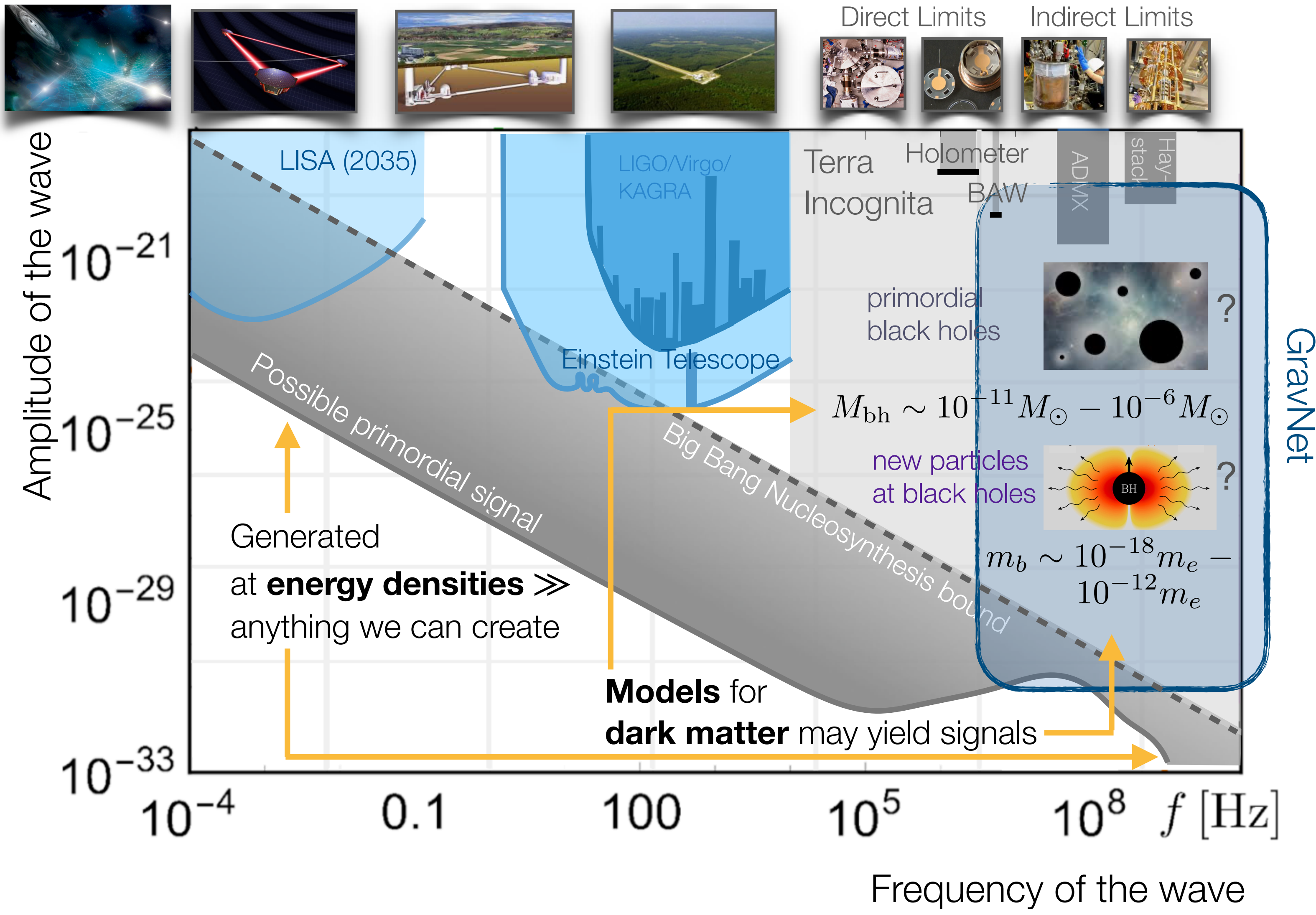
What about high frequency GWs?

PTA 10^{-8}Hz



- High frequency gravitational wave (HFGW) **sources**
 - Could explain dark matter
 - No astrophysical backgrounds
 - (No known sources)
- Very weak existing limits for
 - $f = 1\text{ MHz} \dots 10\text{ GHz}$

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GravNet:

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

What are gravitational waves?

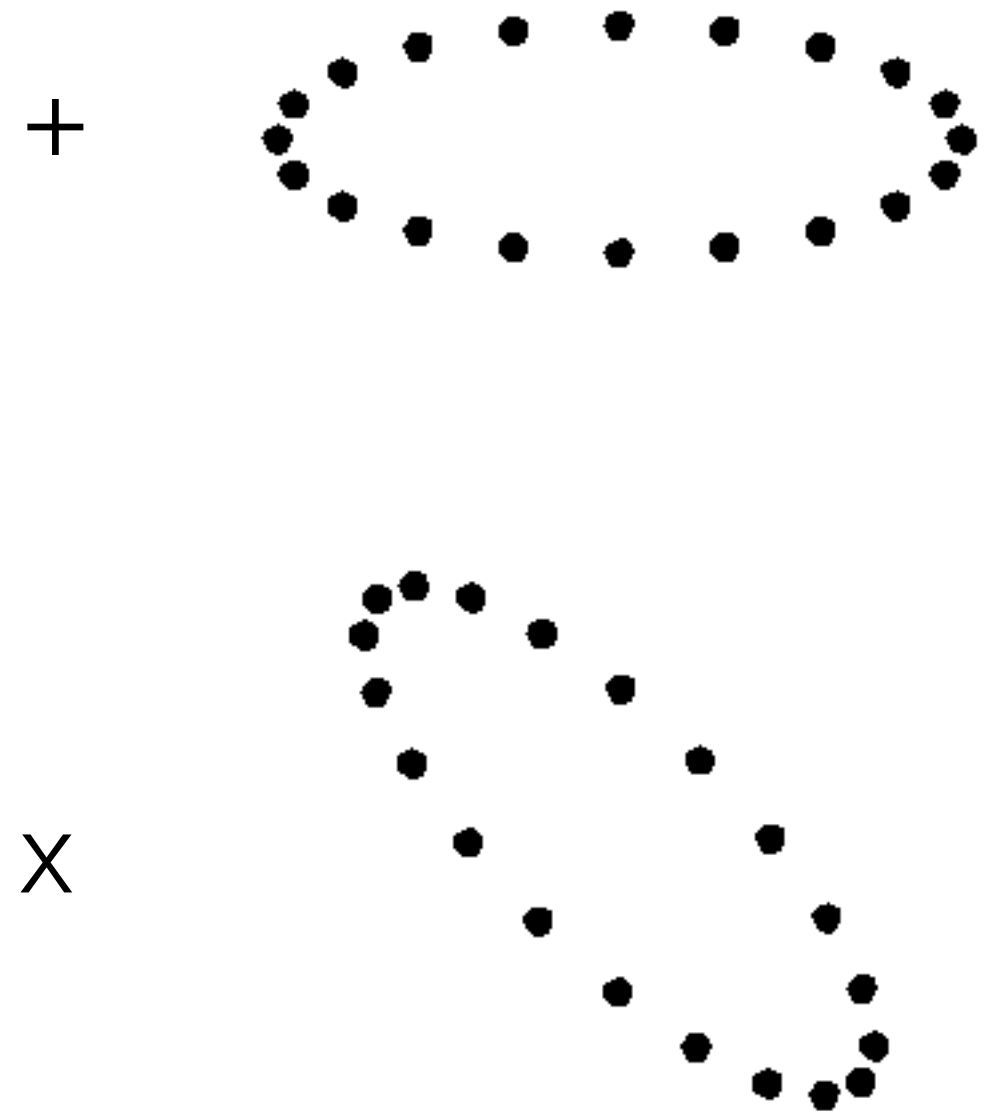
Introduction - Gravitational Waves

Cosmological constant * metric tensor

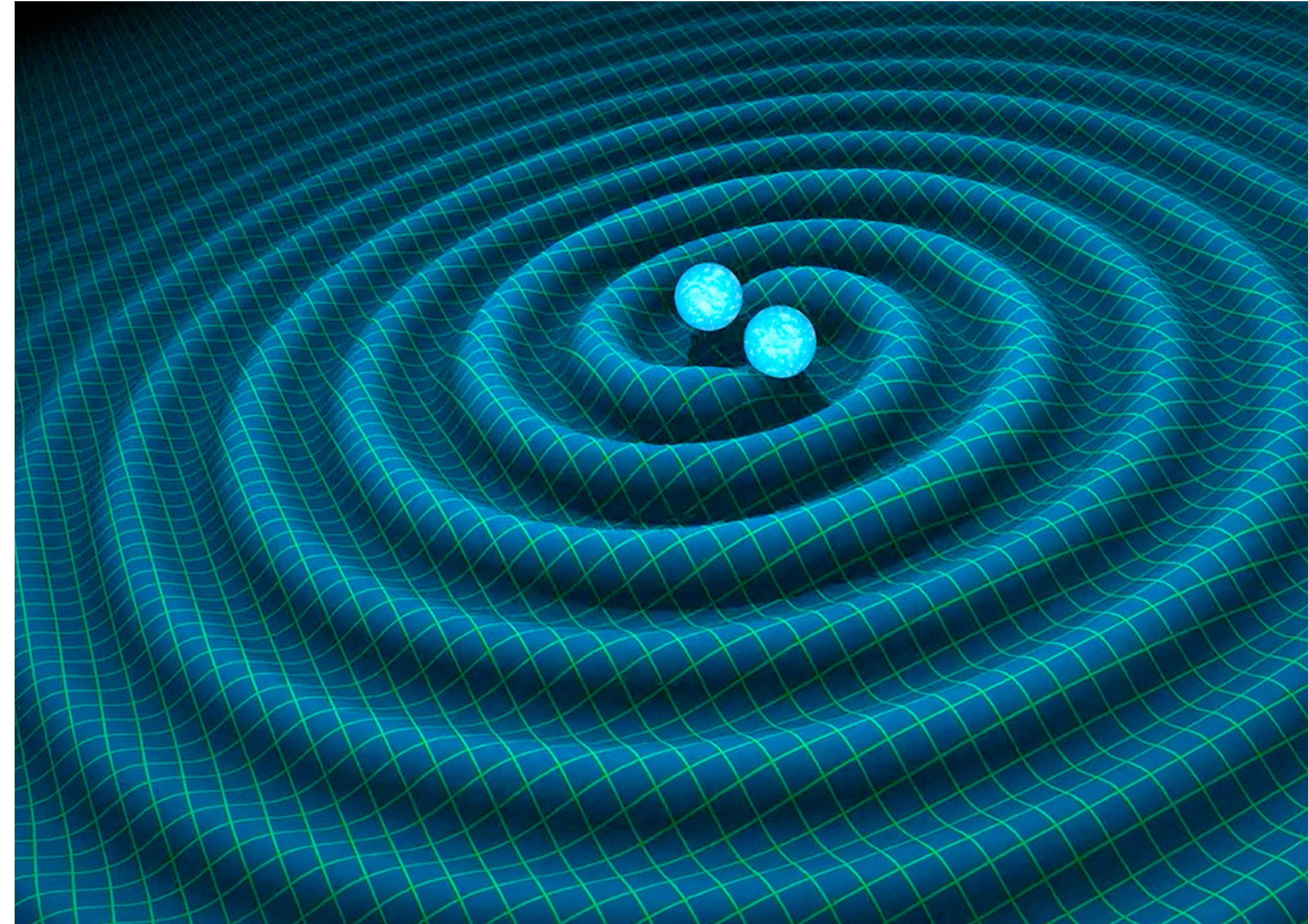
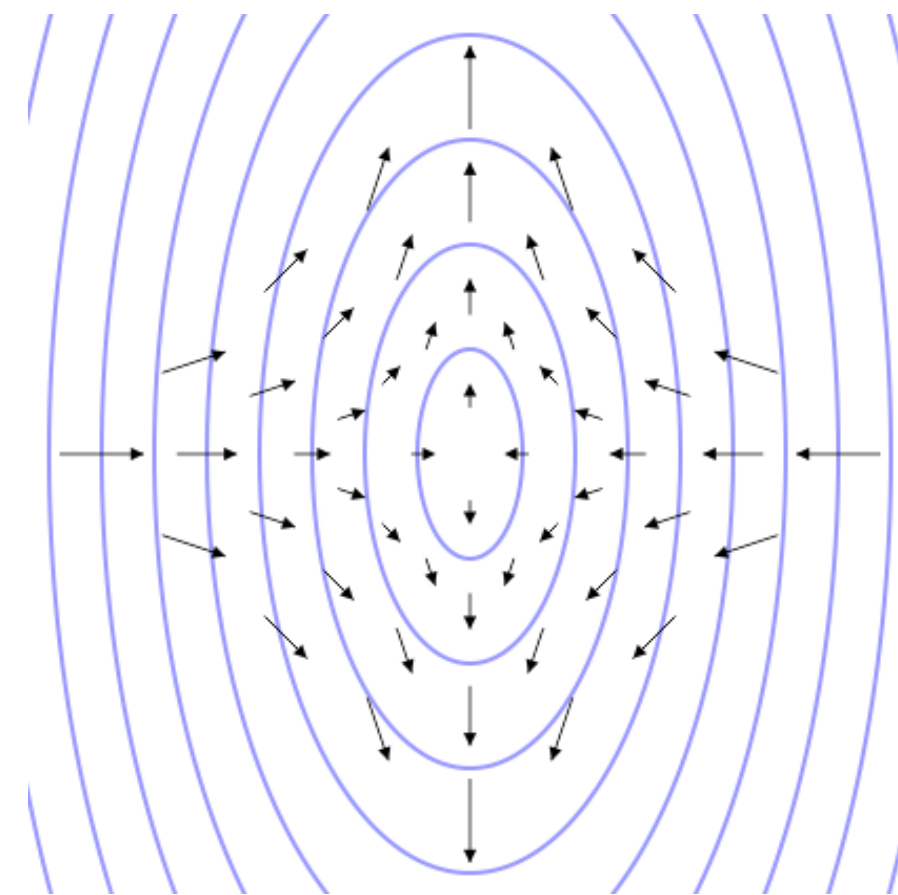
$$\overset{\text{Einstein tensor}}{G_{\mu\nu}} + \overset{\text{Cosmological constant * metric tensor}}{\Lambda g_{\mu\nu}} = \kappa \overset{\text{Energy-Momentum tensor}}{T_{\mu\nu}}$$

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

- Wave solution of Einstein equations:
 - 2 Polarisations



Quadrupole structure



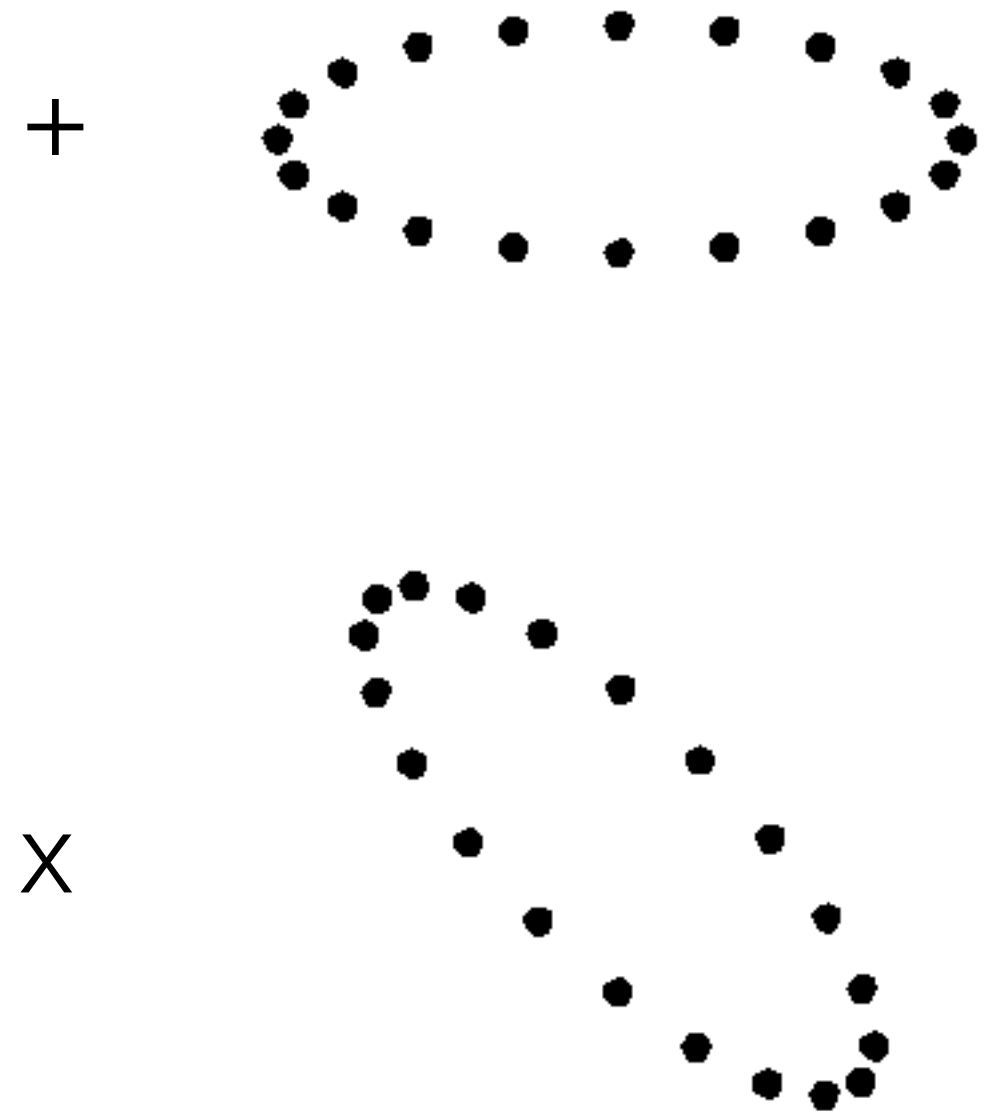
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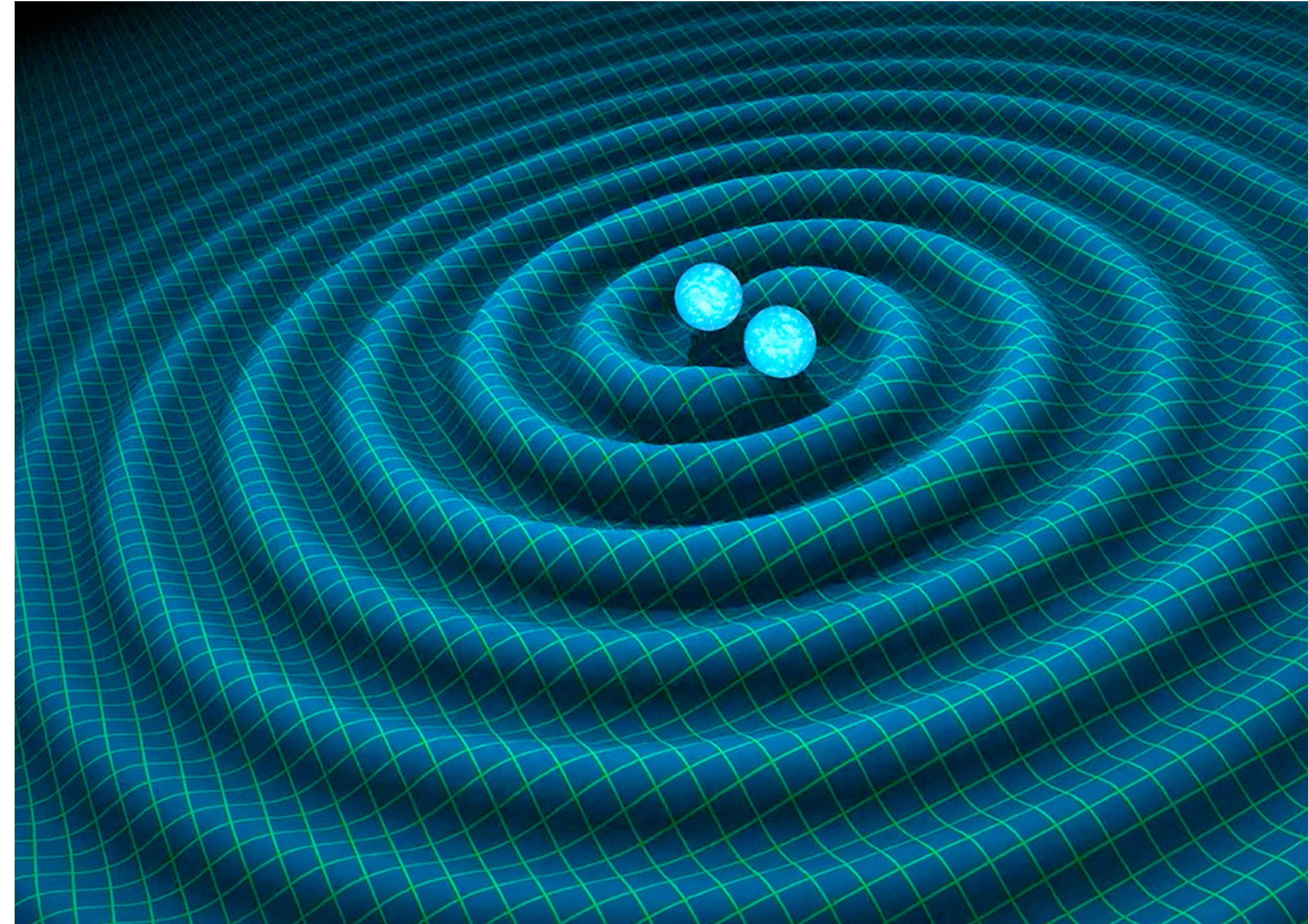
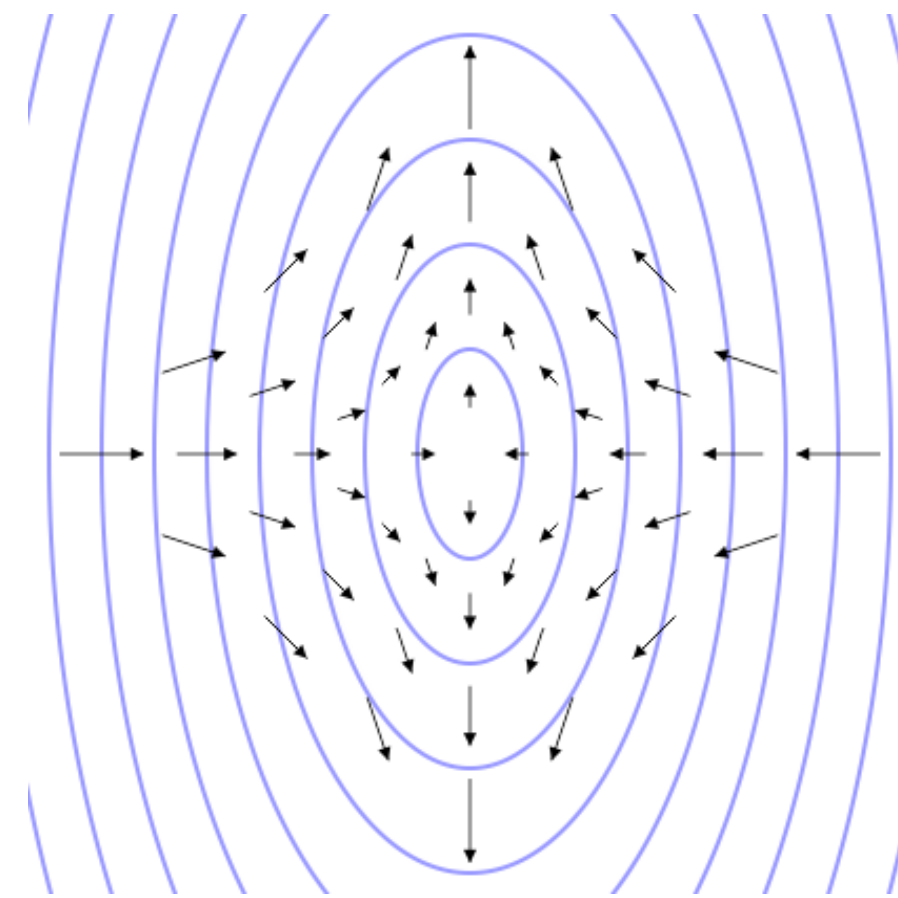
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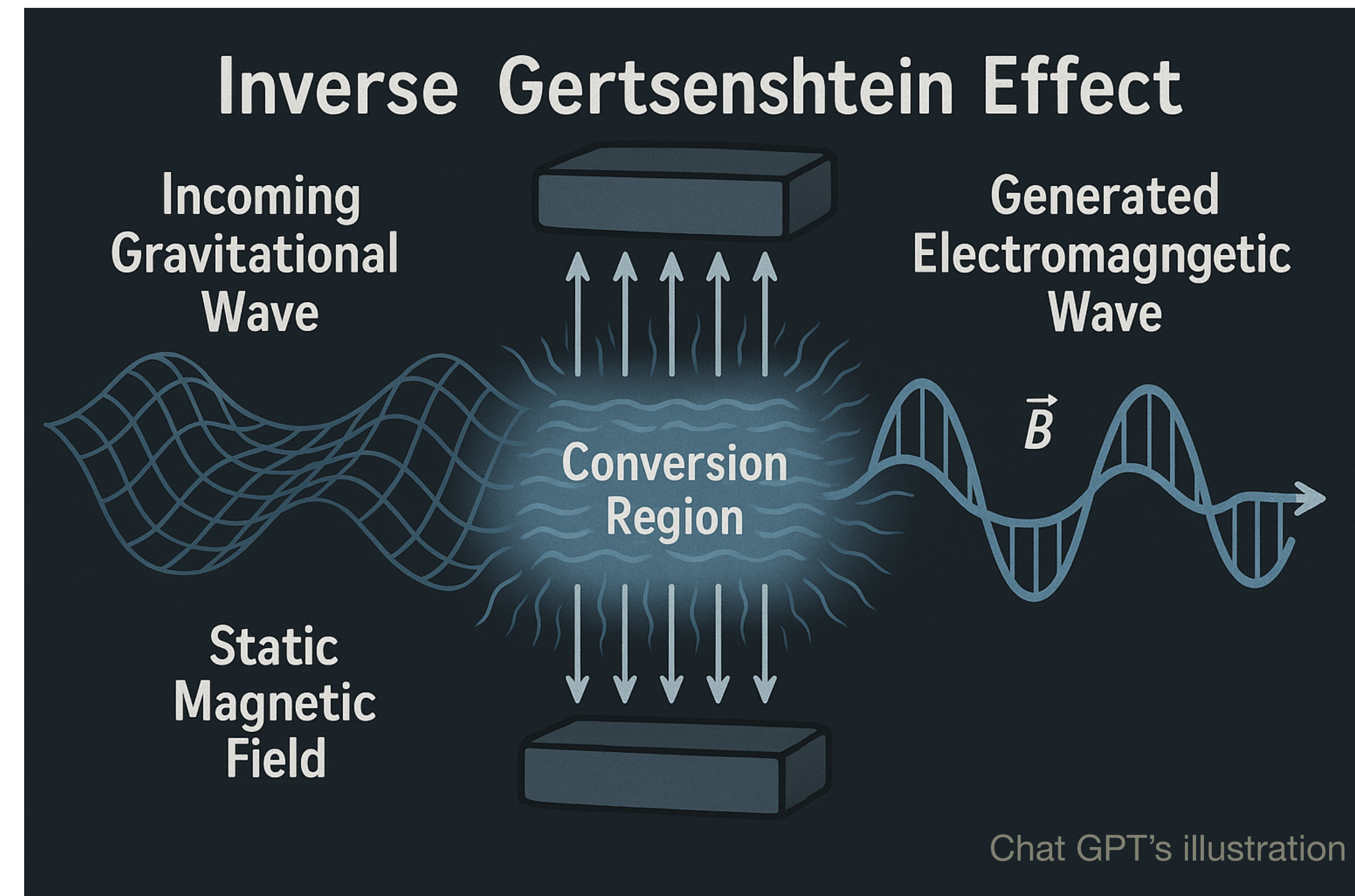
- Periodic compression of B-field $\propto hB$

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

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

- Two polarisations of GW

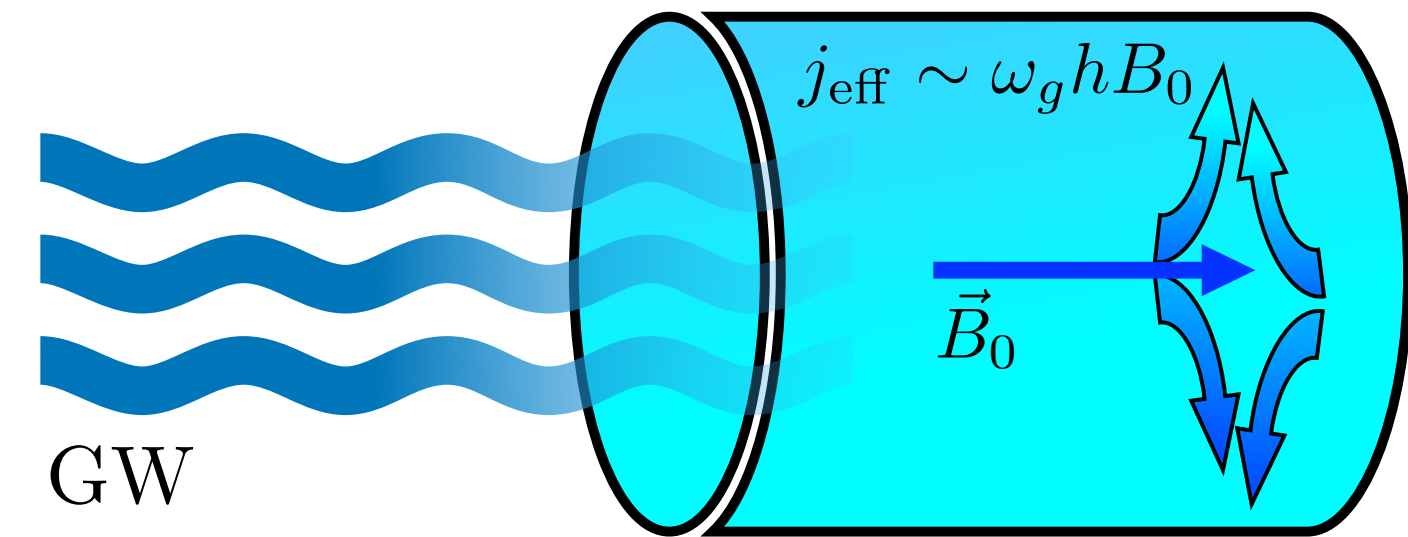
$$h_+ = A_+ e^{i(k_g z - \omega_g t)}, h_\times = iA_\times e^{i(k_g z - \omega_g t)}$$



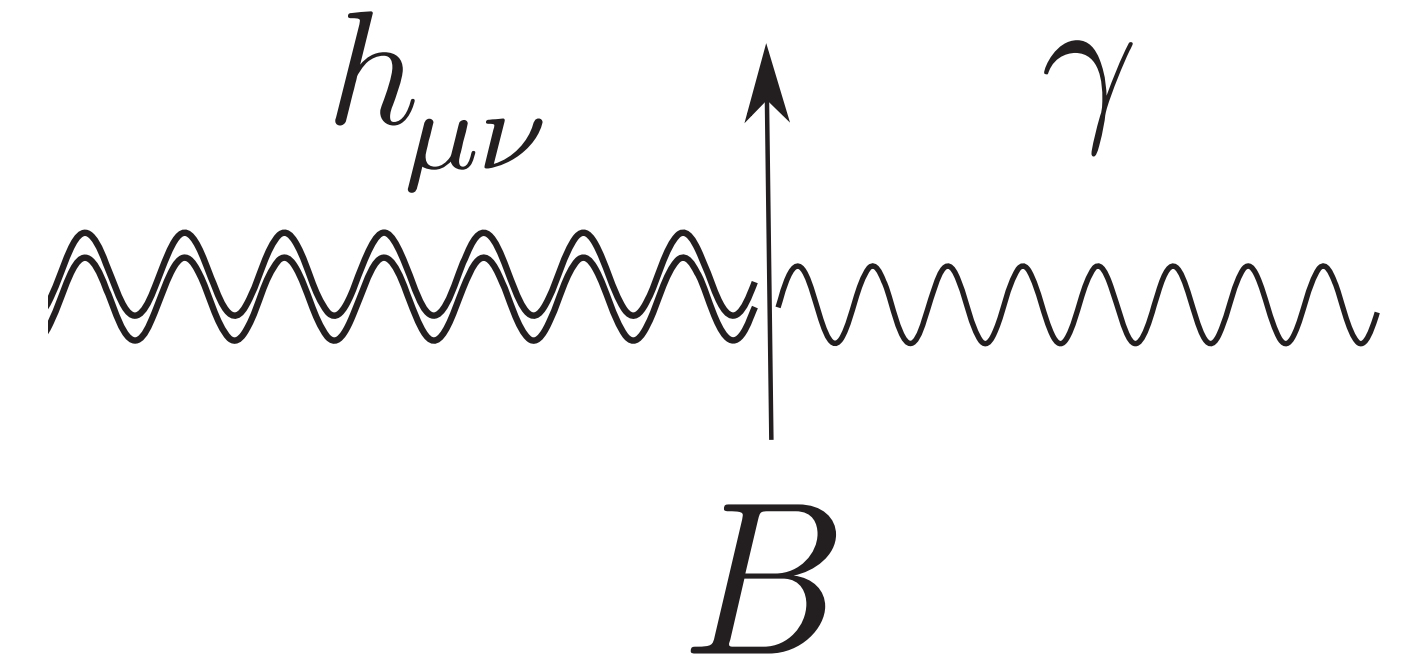
- GW leads to source of **effective current** in Maxwell's equation

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

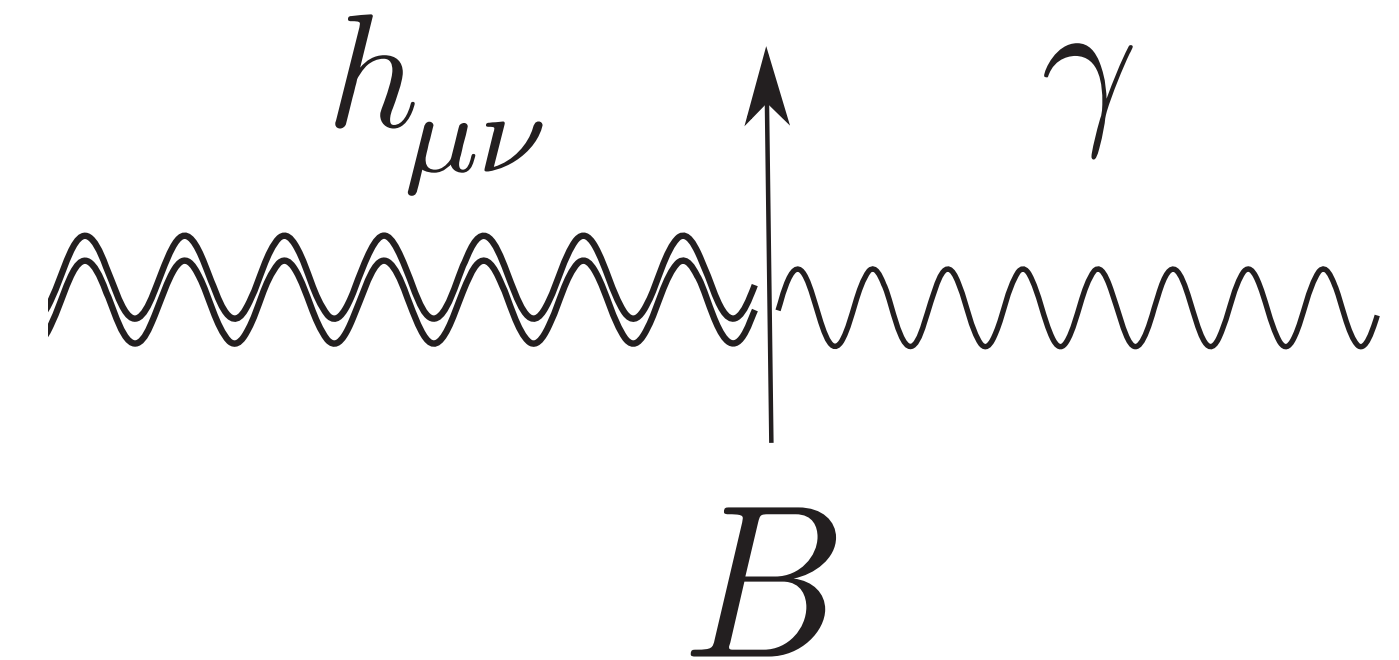
- Conversion of GW energy into Photons and vice-versa!
- => **GW can excite EM field** within RF resonator!
- If signal duration long enough: exploit **resonance enhancement**



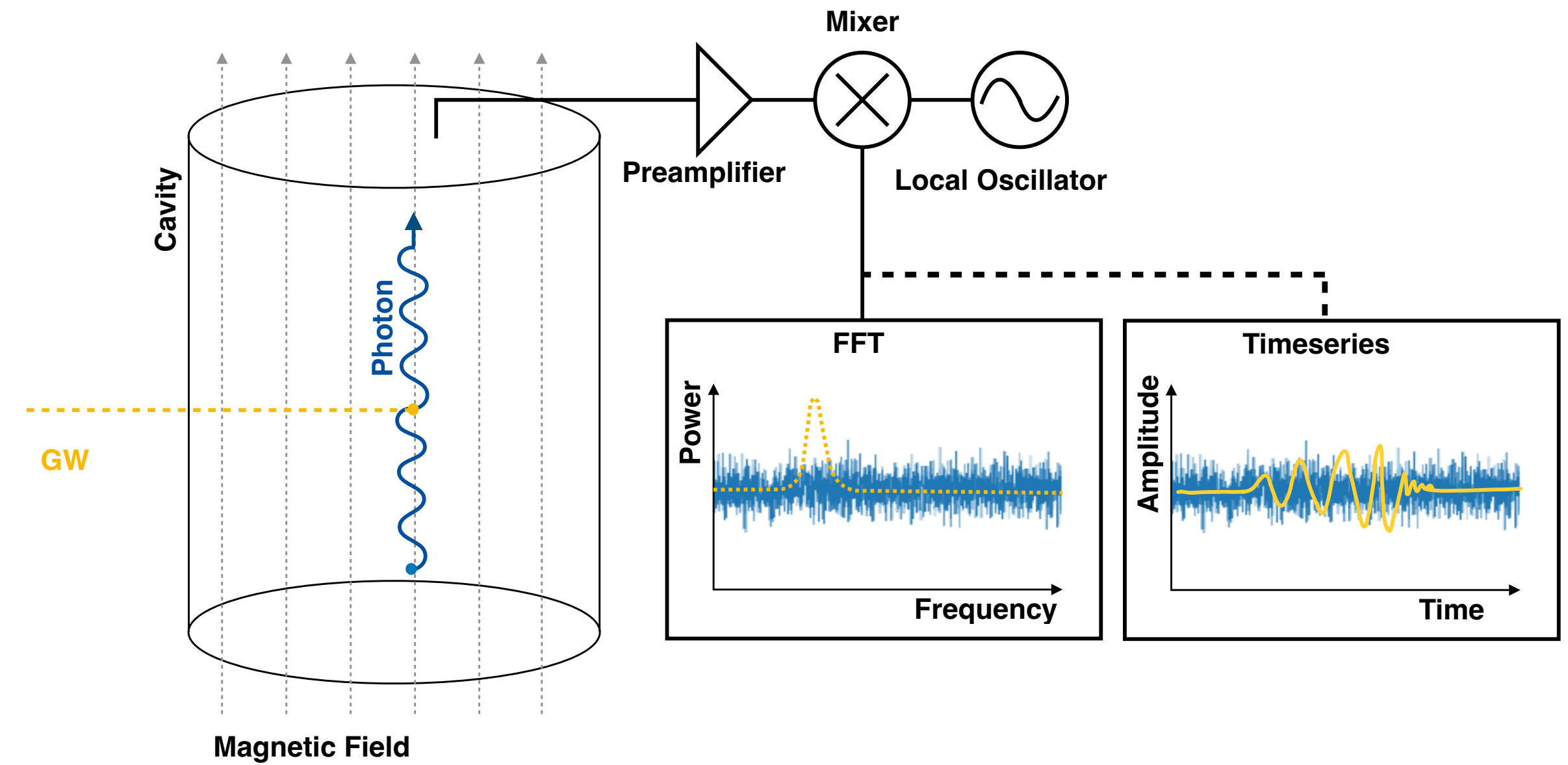
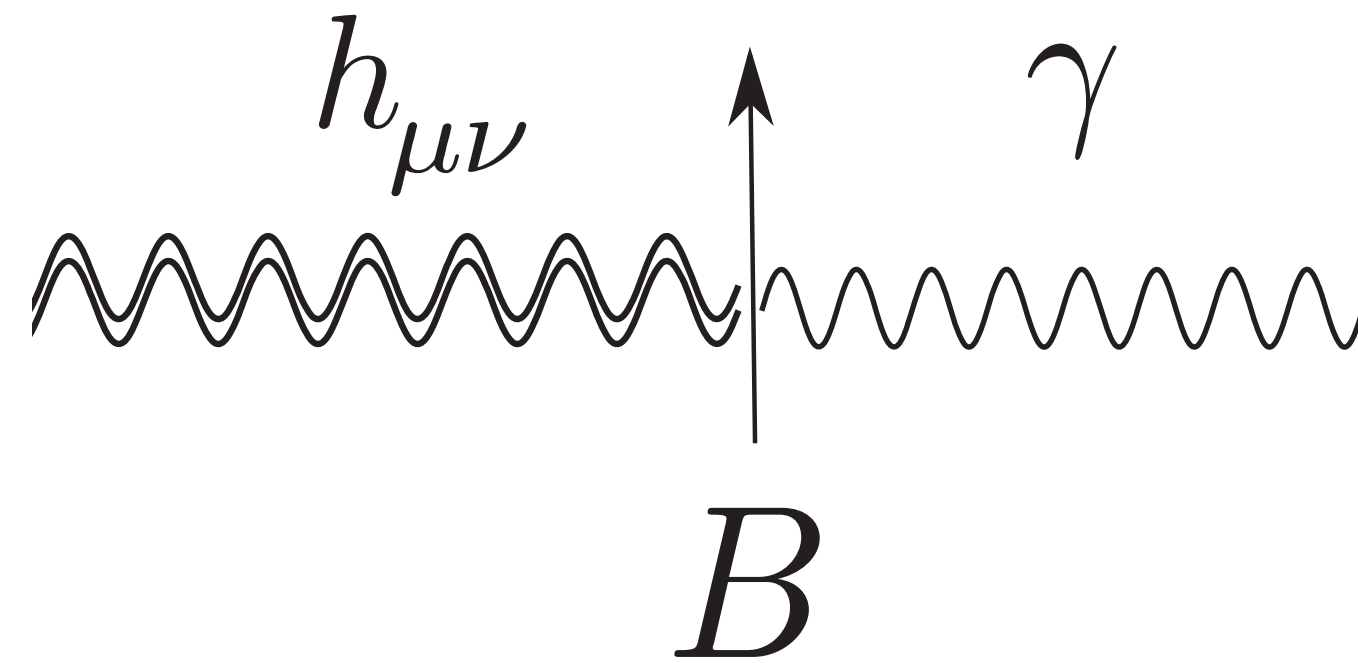
- **Direct conversion** of GW to photons: **inverse Gertsenshtein effect**
 - Gertsenshtein effect described 1962
 - Inverse effect calculated in 70ies
[Ya. B. Zel'dovich]
 - White-paper on HFGW detection: 2020
[Living Rev. Rel. 24 (2021) no.1, 4]
Update 2025: [arXiv:2501.11723](https://arxiv.org/abs/2501.11723)



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How can this be used to detect
GWs ?

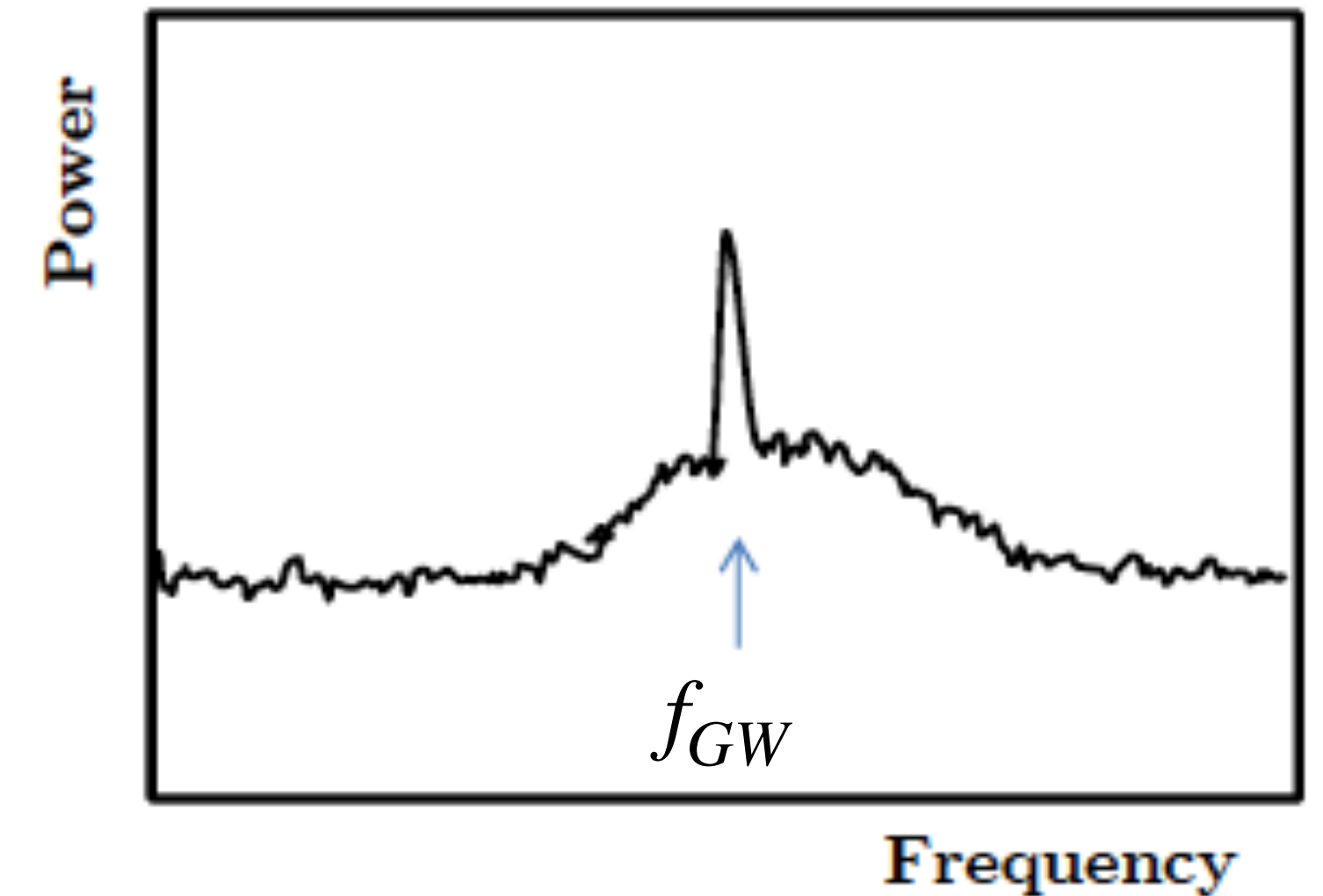


Requirement

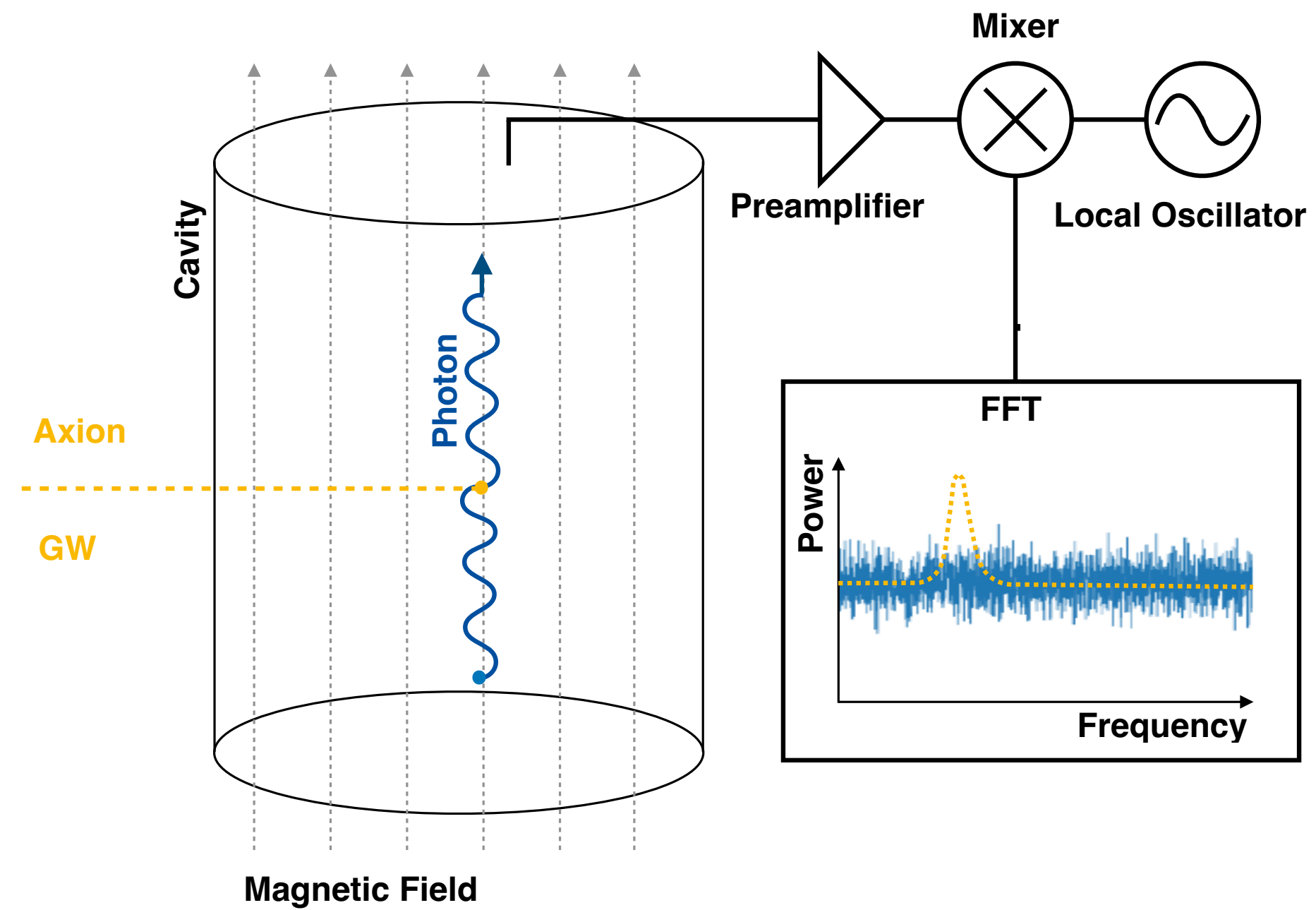
- Electromagnetic field
- Resonant enhancement of signal
 - Narrow band experiment
- Noise suppression
- High sensitivity

Technical implementation

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



Typical setup - Connection to Axion searches



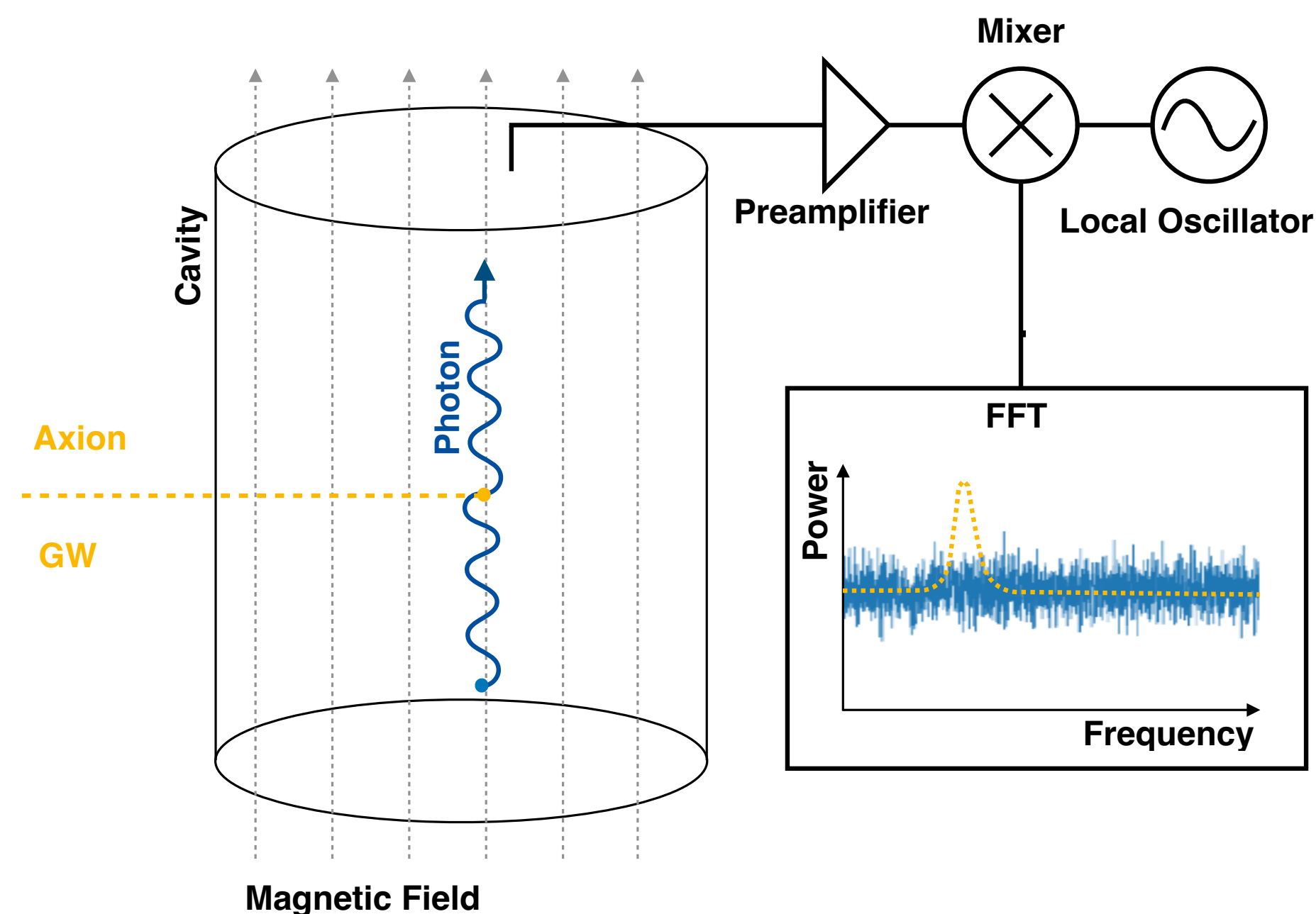
- Suspicious similarity with **axion haloscopes**
- Indeed: Identical setup

- **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



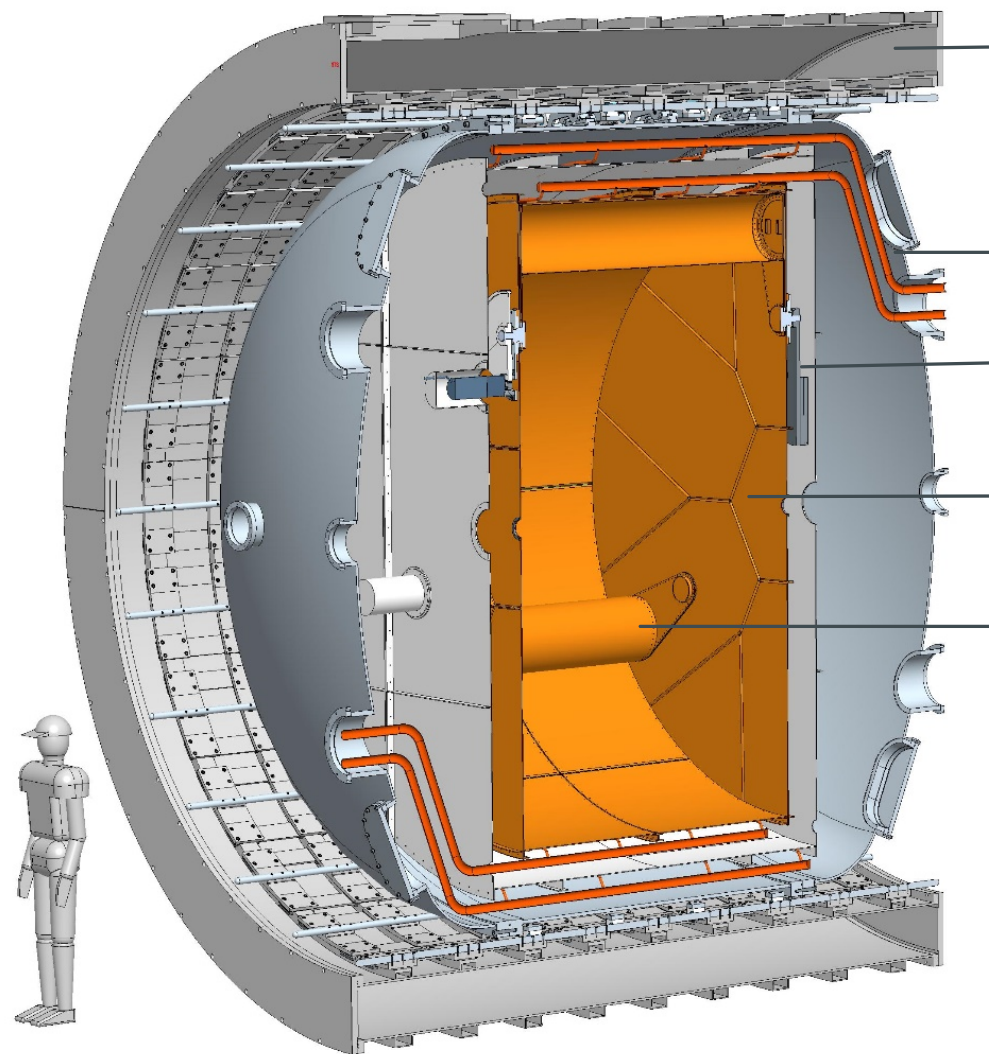
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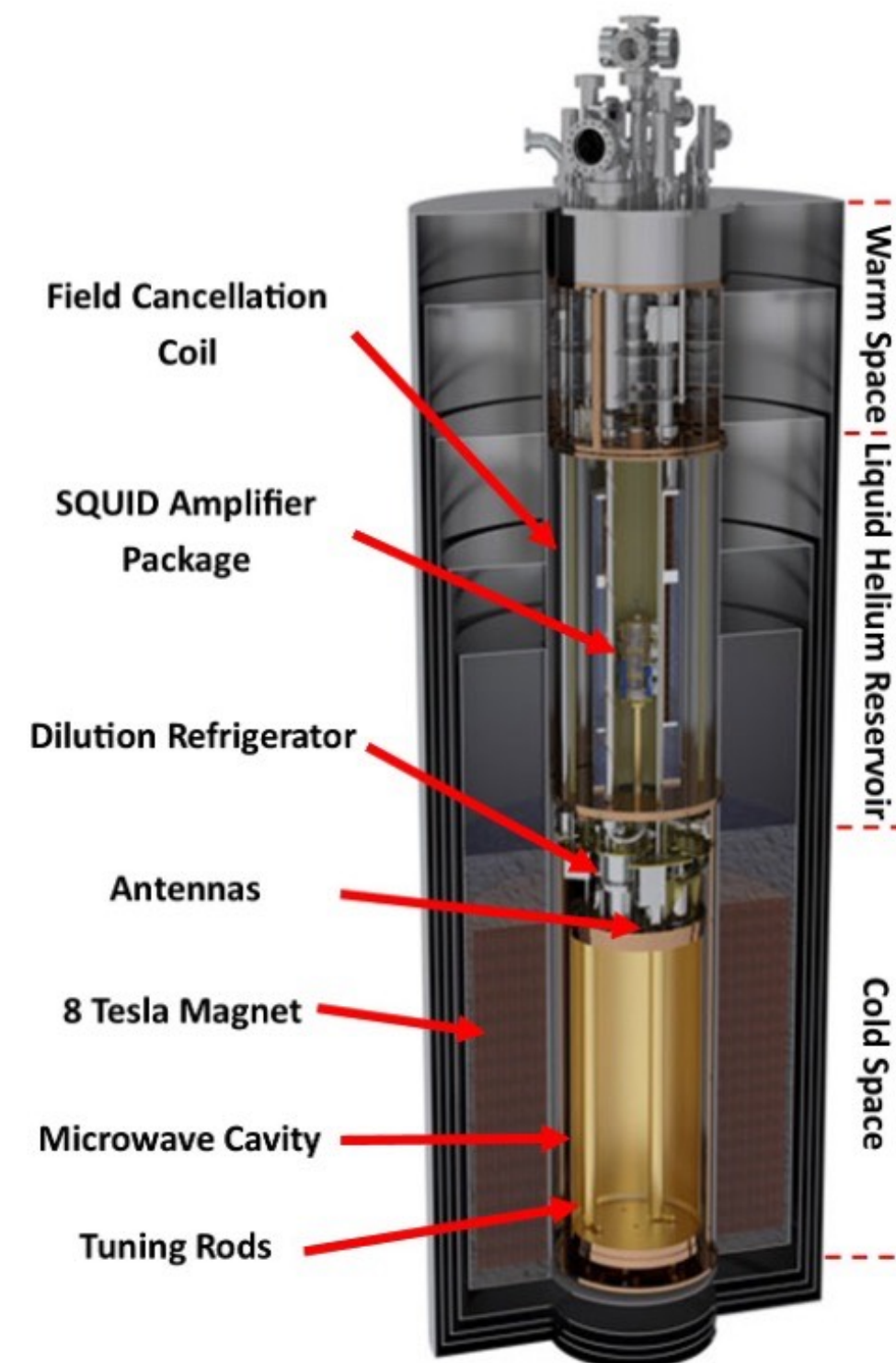
Well established experimental method

Flash

100 MHz



ADMX 1 GHz



Organ

100 GHz

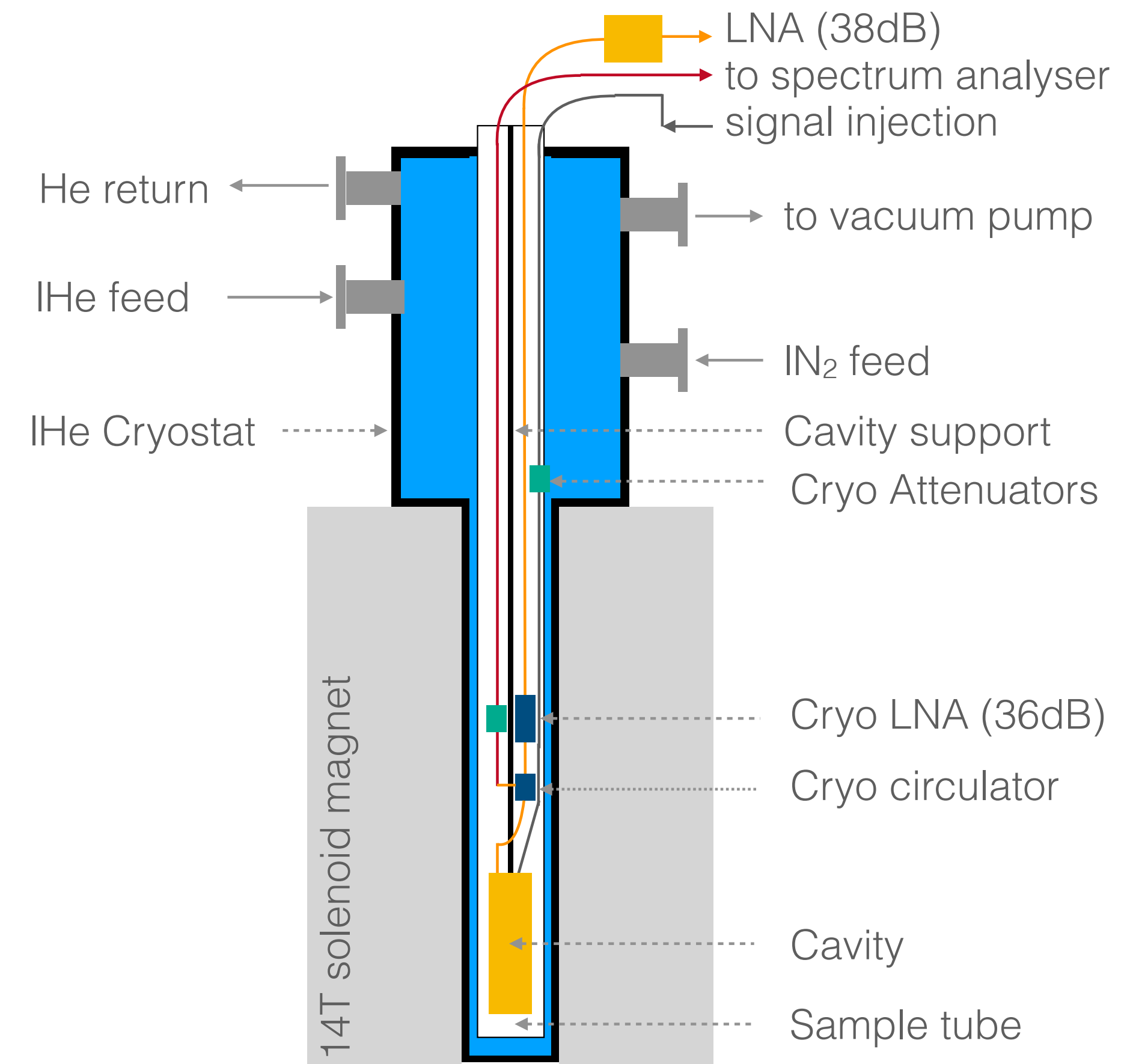


What was done at Mainz

[arXiv:2308.08337]

SUPA⁰X

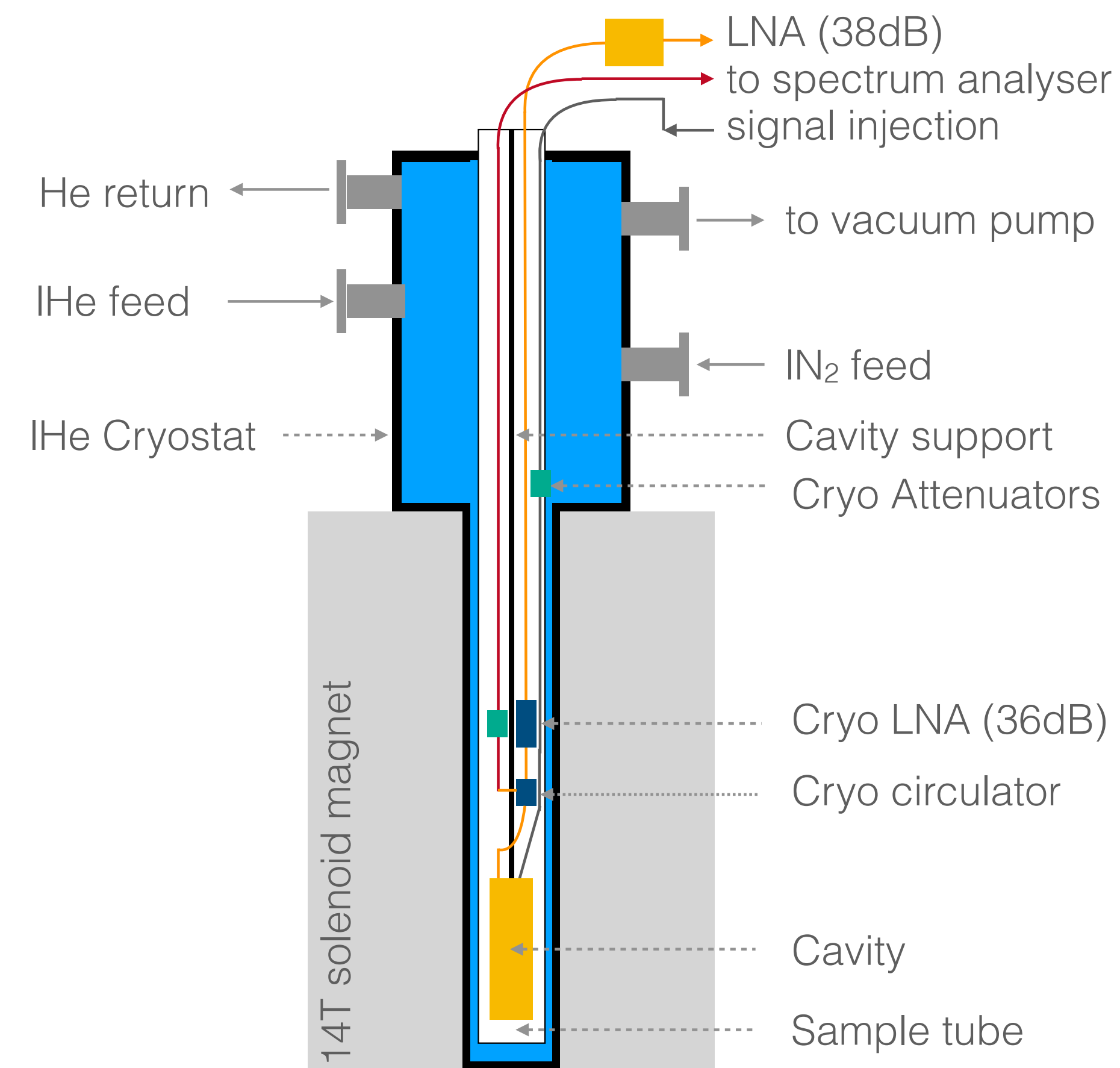
- Setup at Mainz (finished):
 - 14T B-field, 2K, SC cavity, HEMT amplifier
 - Data taken in 2024
 - Dark Photon & Axion results

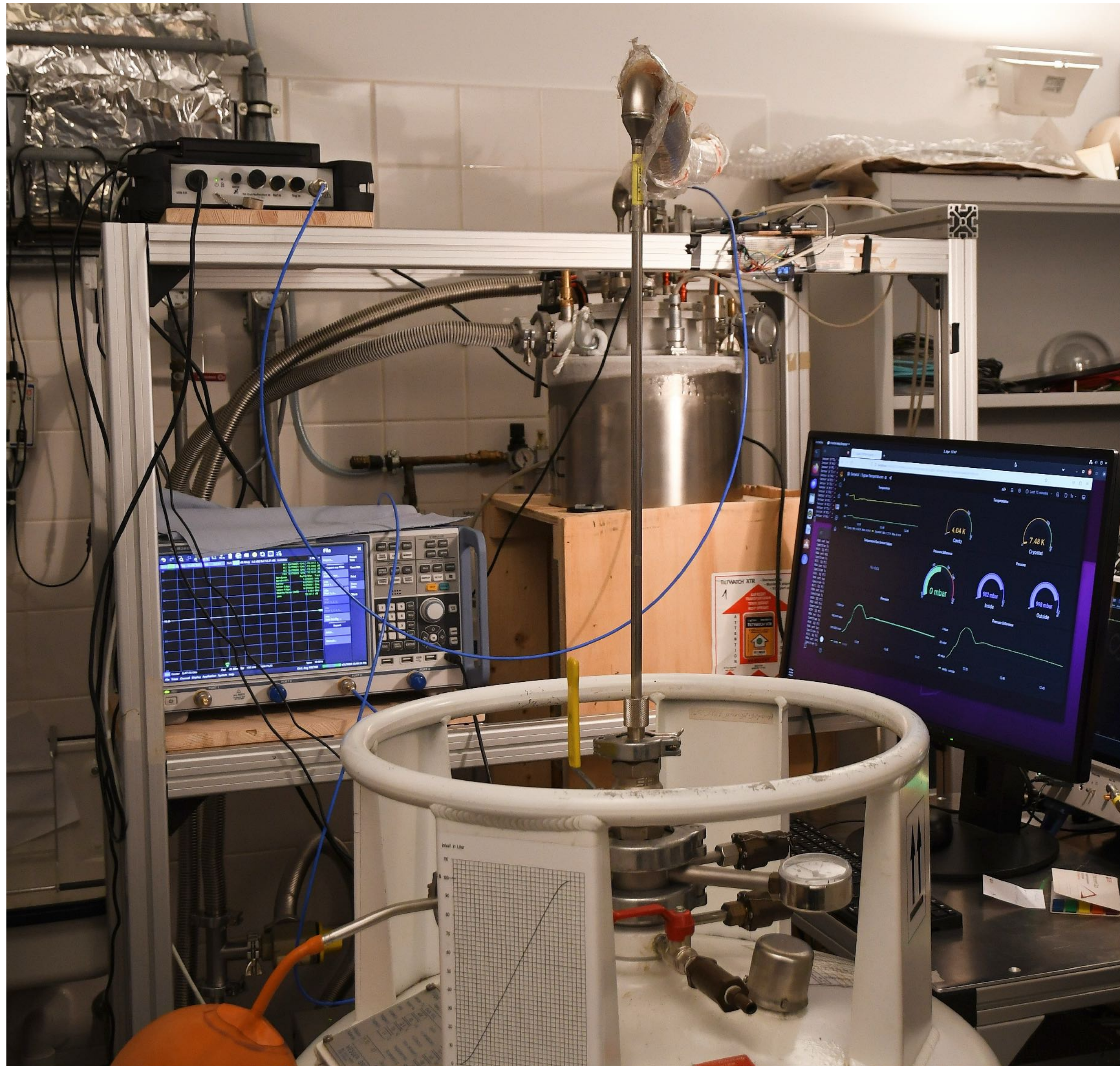


SUPA⁰X

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 - 14T 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

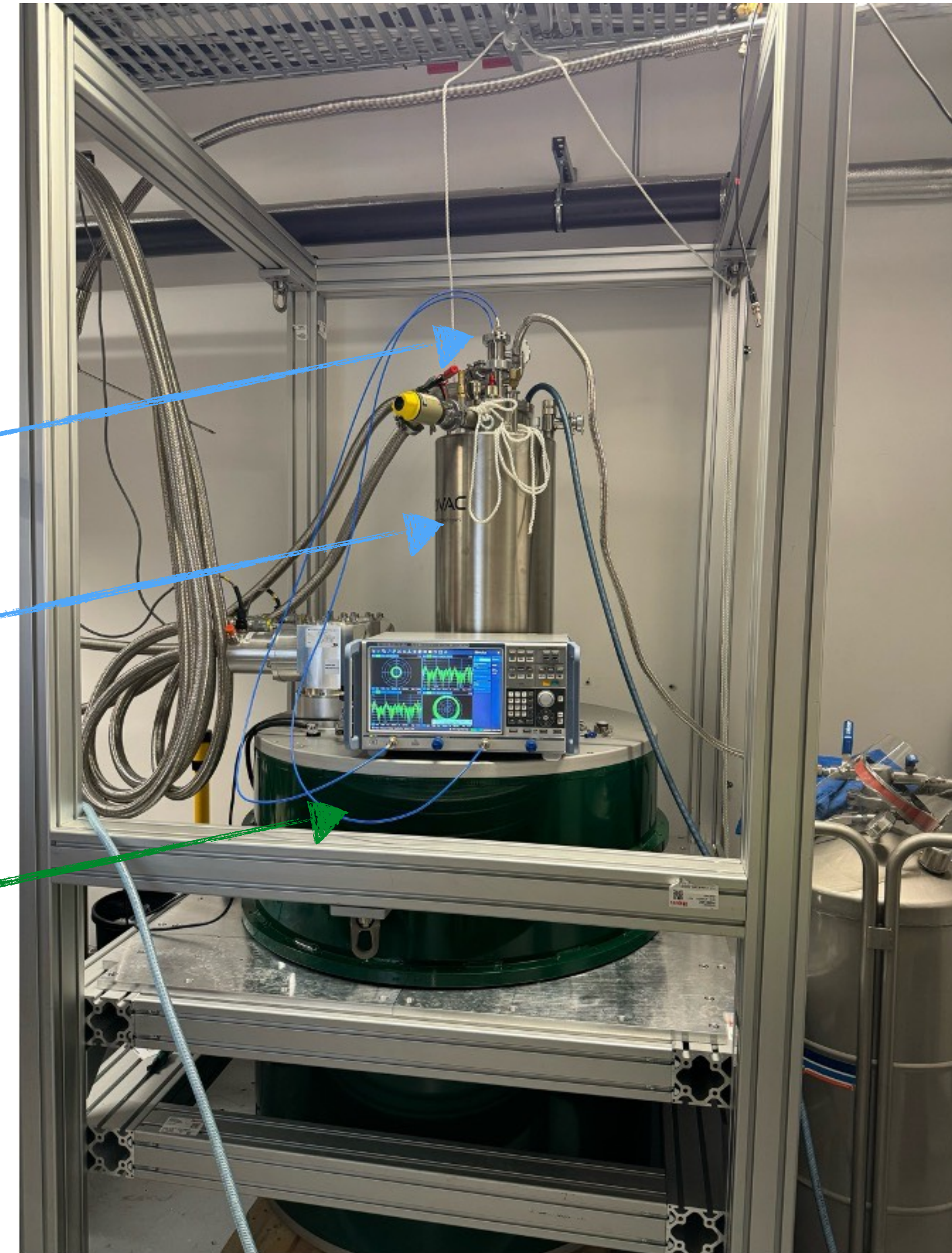




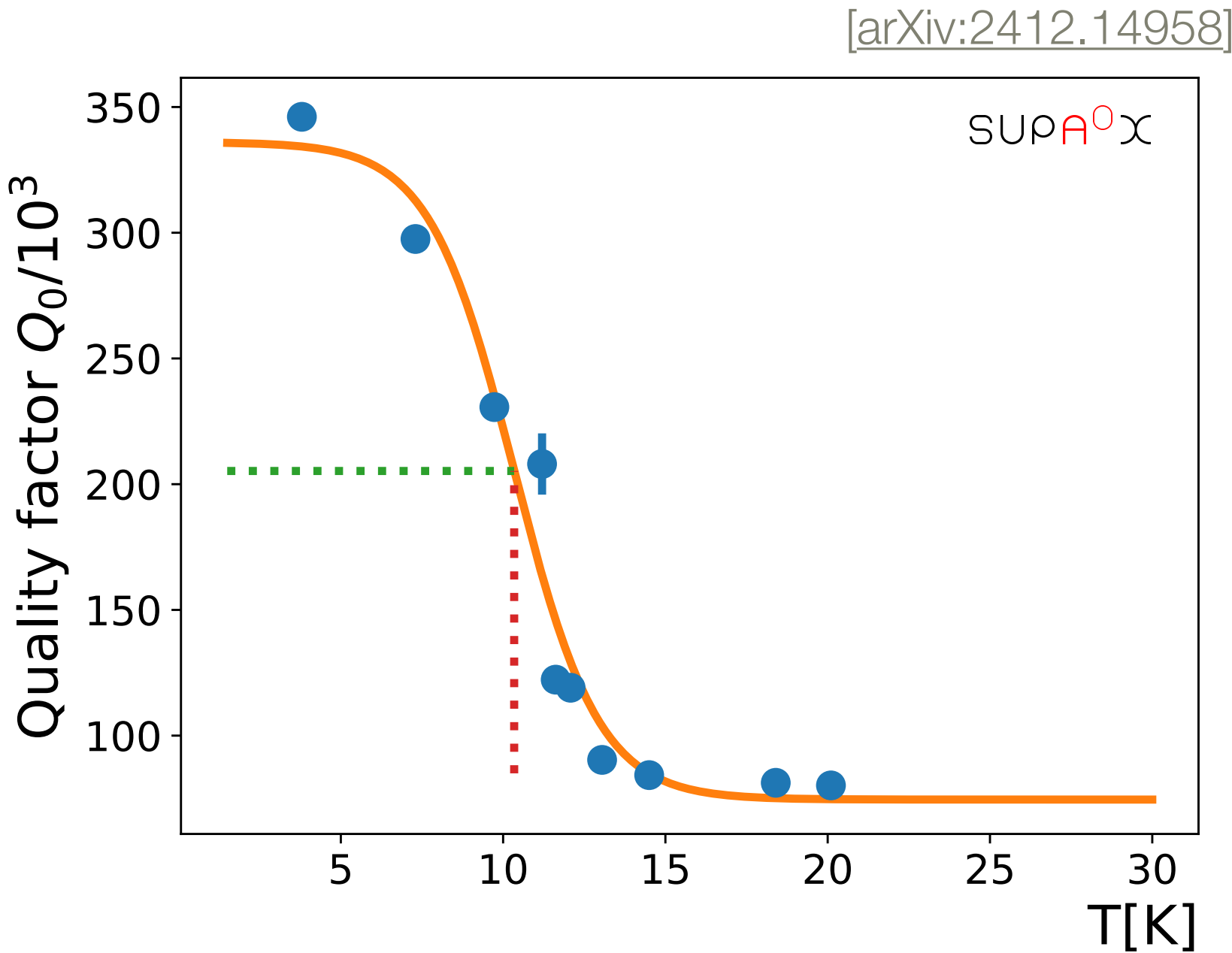
Inset Top

Cryostat

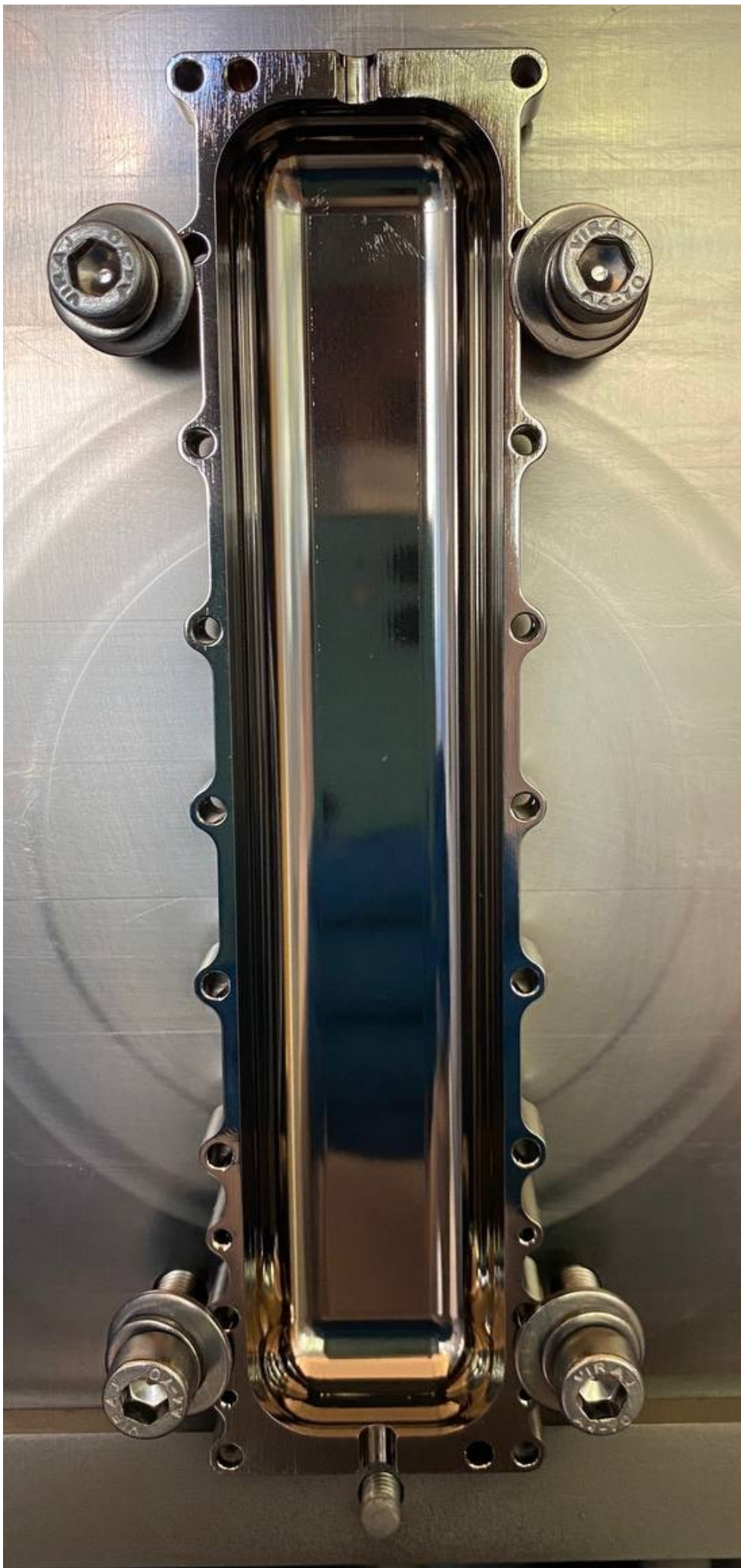
Magnet
(warm bore)



- Test of various cavity geometries and coatings



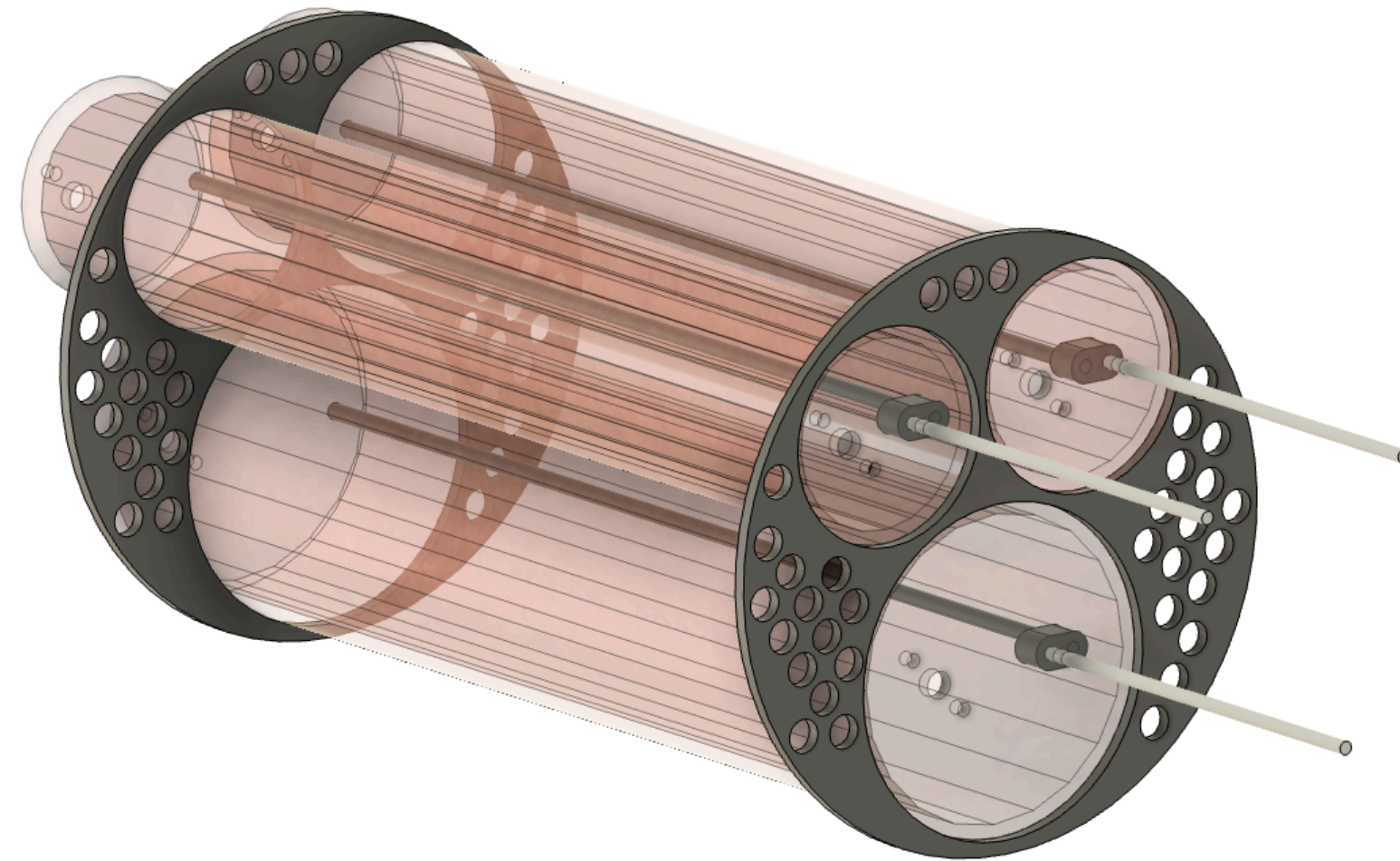
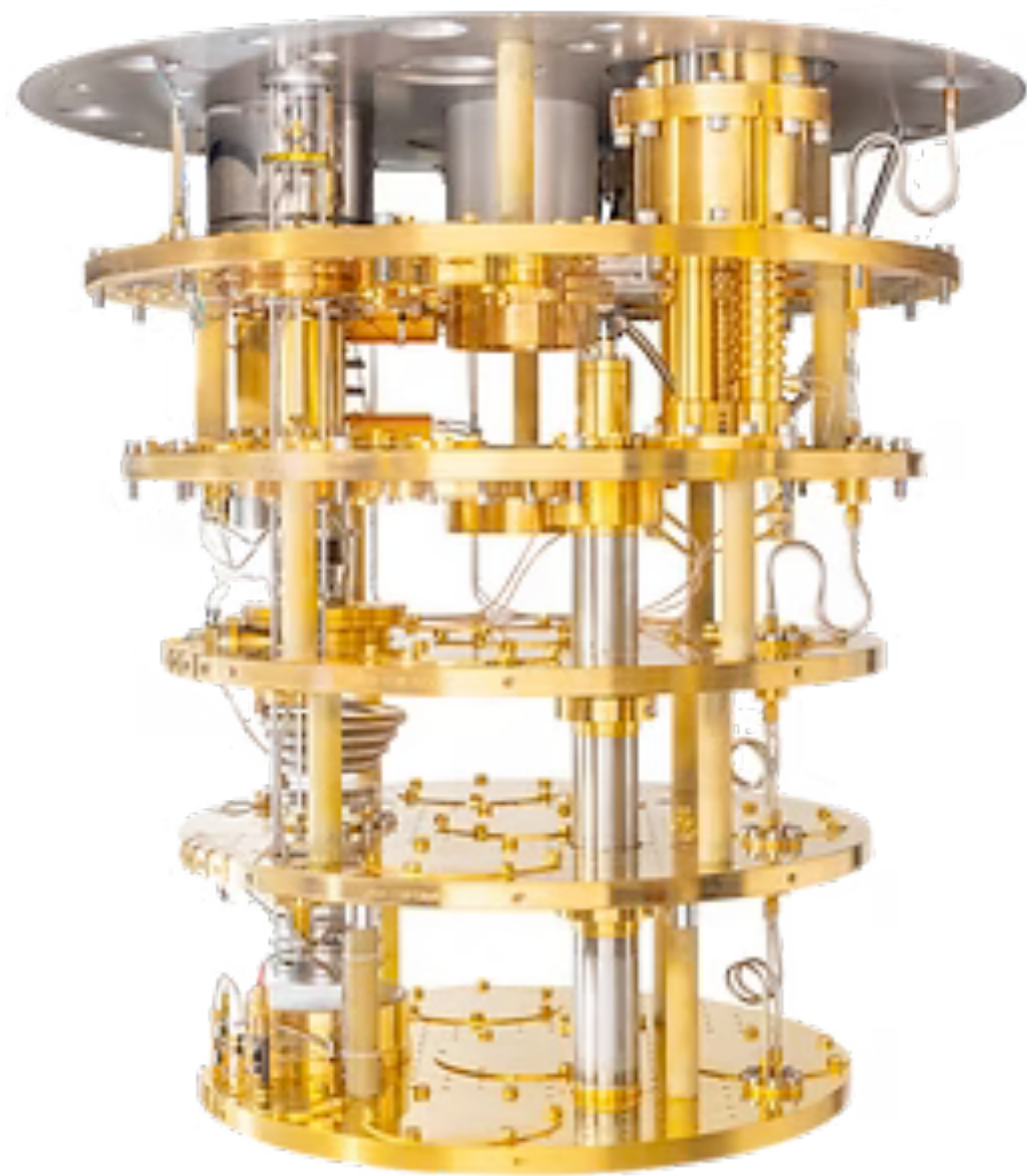
Cu coated with NbN
Coating by Zubtsovskii @ Uni Siegen



Supax gen2 @ Bonn

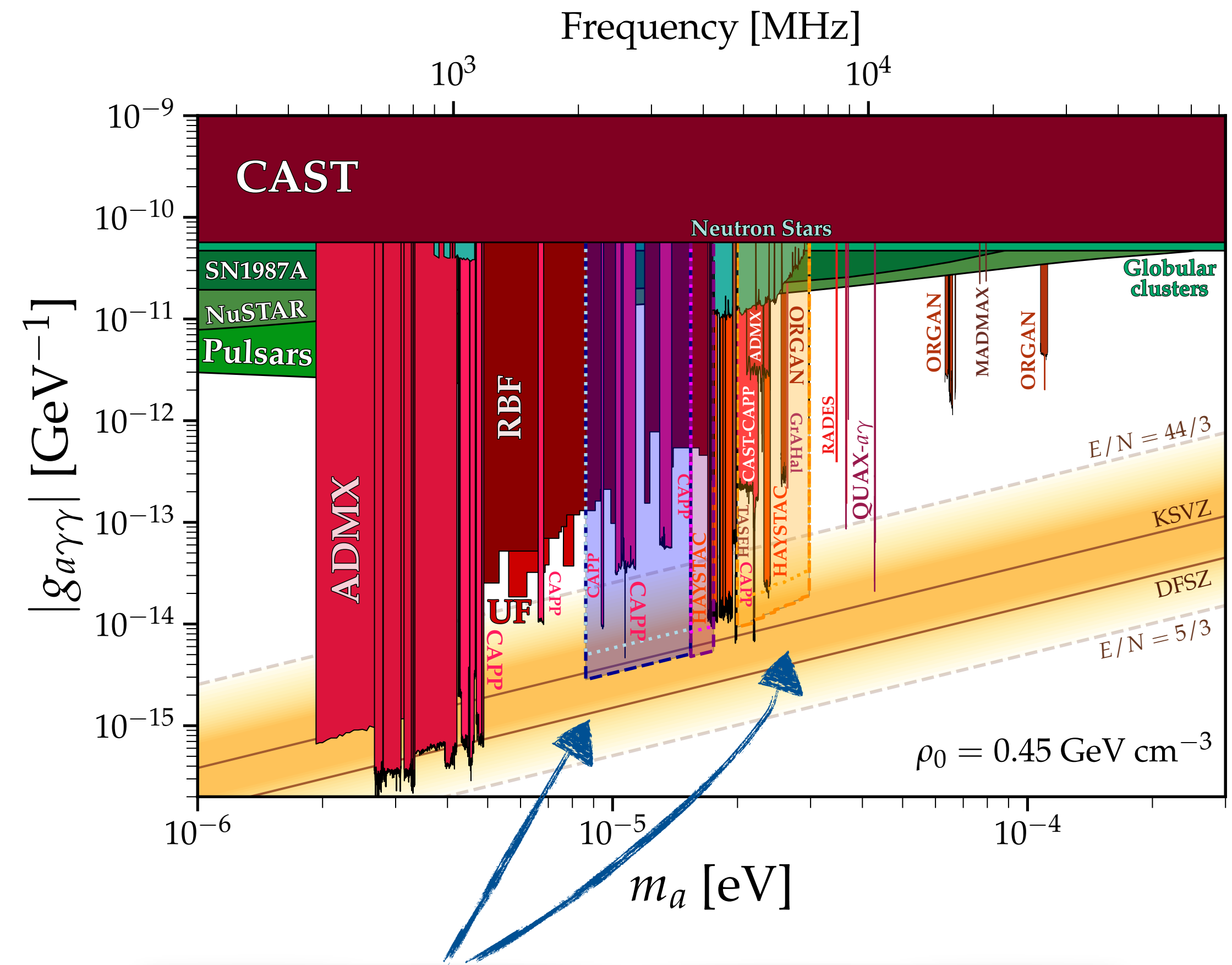
The new Supax Experiment

- Dual use: **Axions** & **GWs**
- Temperature: **10 mK**
- B-field: 12 T
- Usable volume: $\varnothing = 9 \text{ cm} \times 20 \text{ cm}$
- Freq. range: 2 GHz - 7GHz
- Up to 3 cavities in parallel

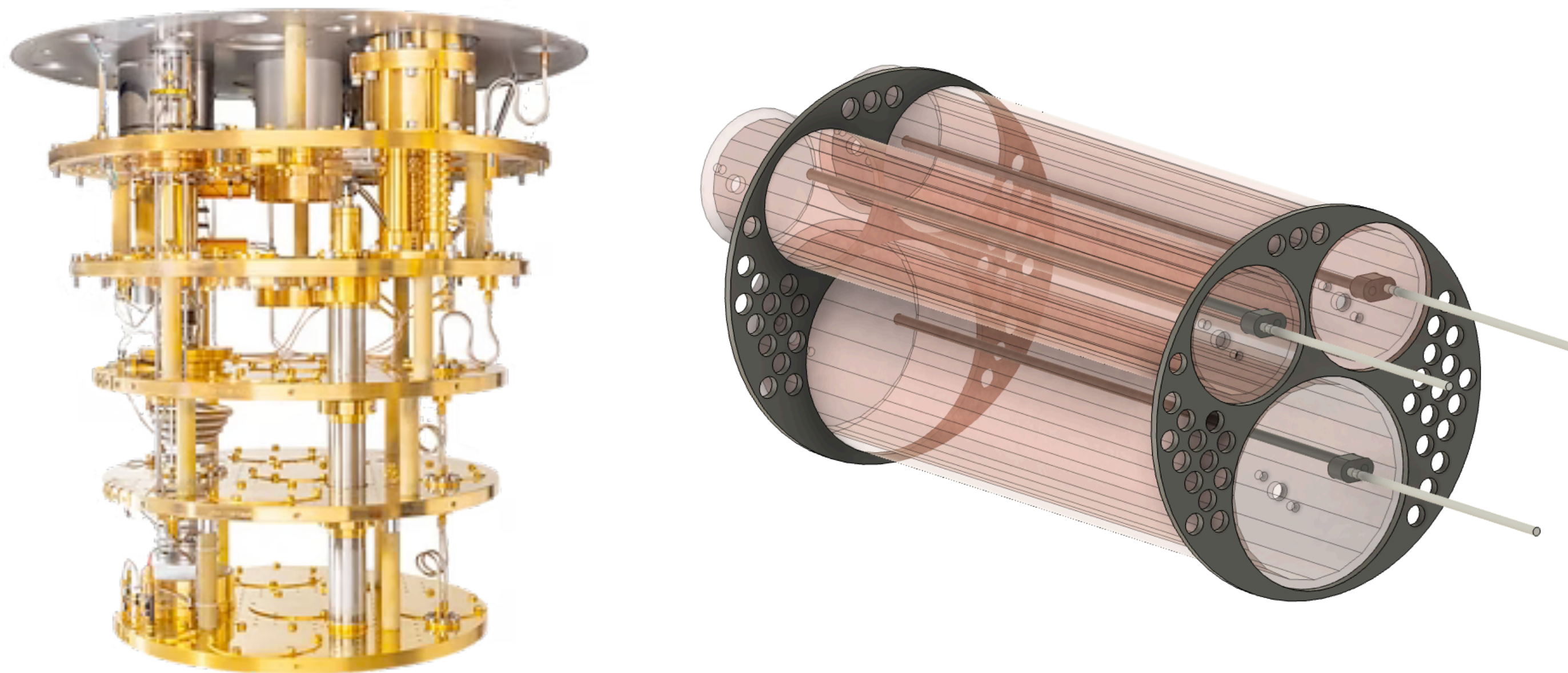


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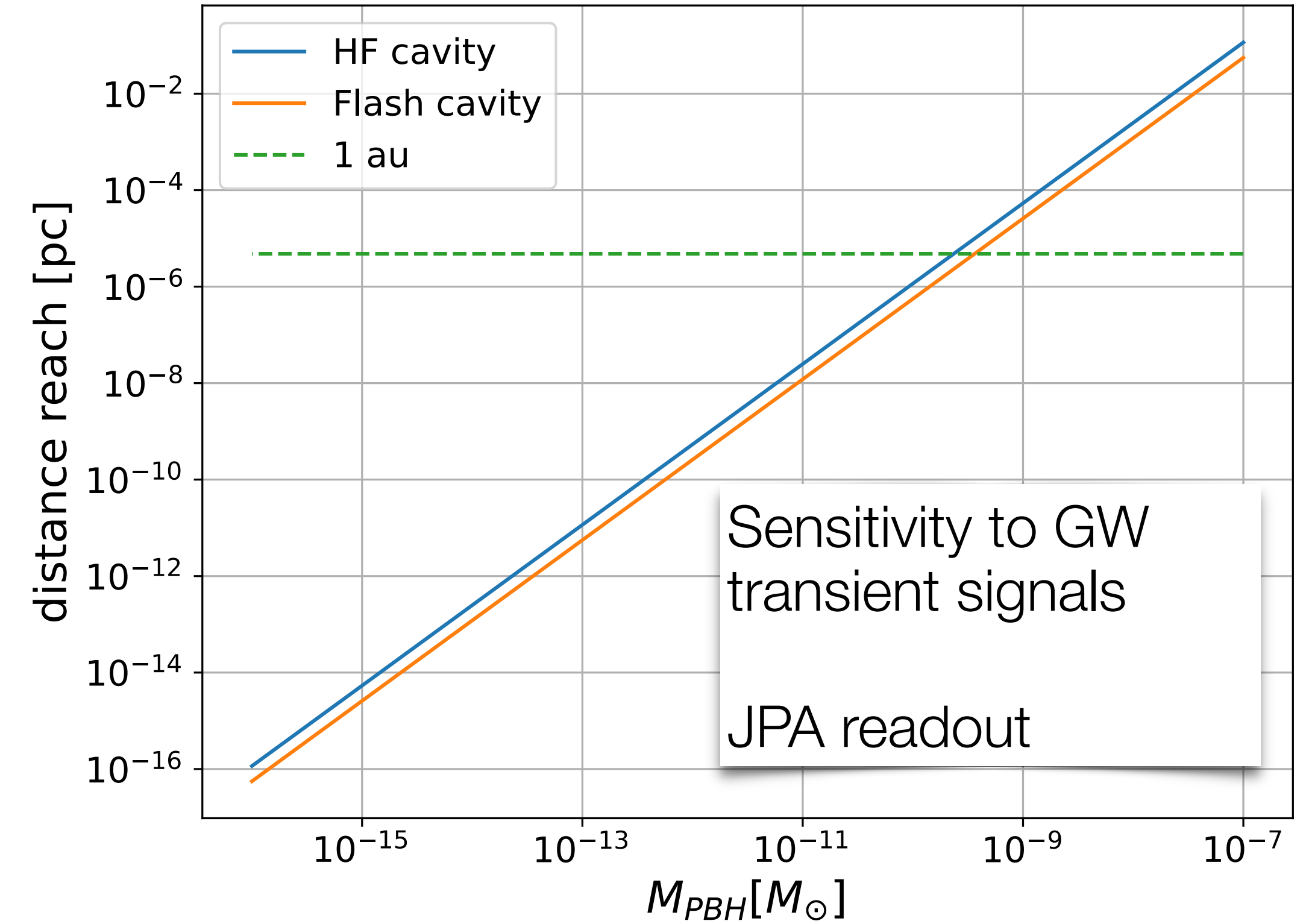
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Sensitivity to axions in
40 weeks measurement time / block

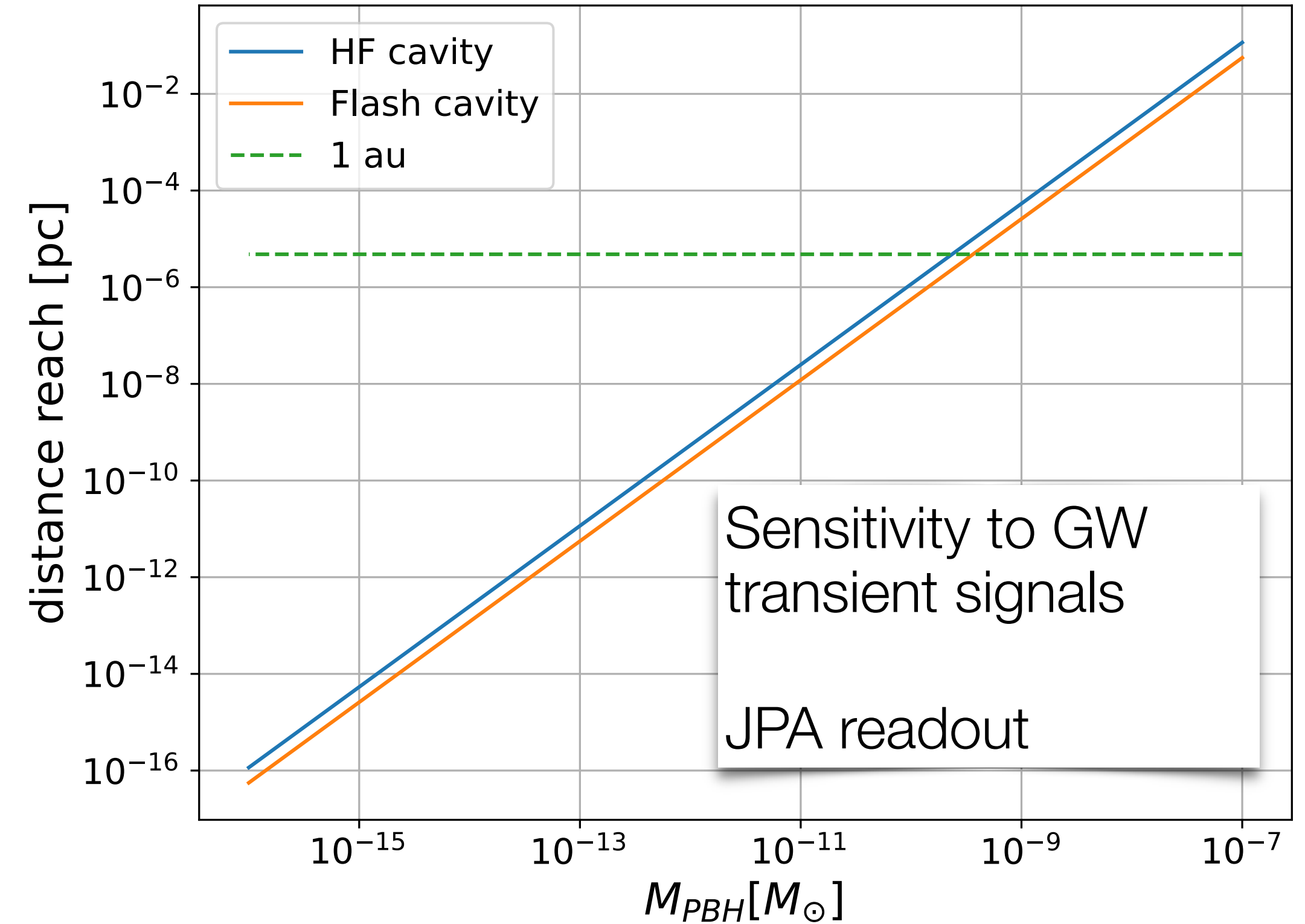


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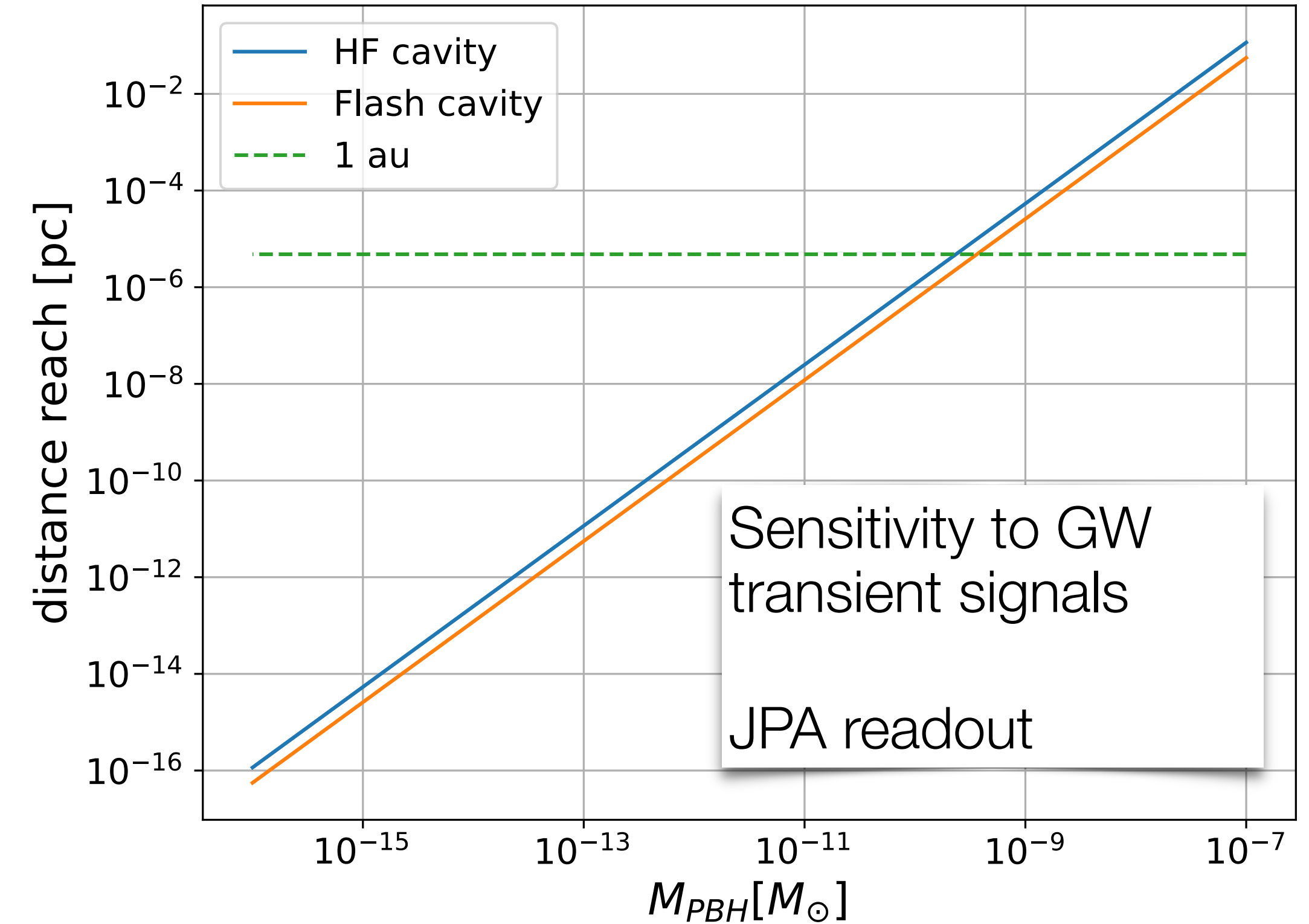
- Currently ongoing activities:

- 2 bachelor projects: Cavity & Analysis
- 1 master project: Analysis strategies
- 1 master project shared with IT: ML for time-series analysis



- Currently ongoing activities:

- 2 bachelor projects: Cavity & Analysis
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Evaluation of analysis strategies

Cavity prototype

Order Cryostat

Cryostat + DAQ
commissioning

First network measurement

Now

August

+ 6 month

Summer 26

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

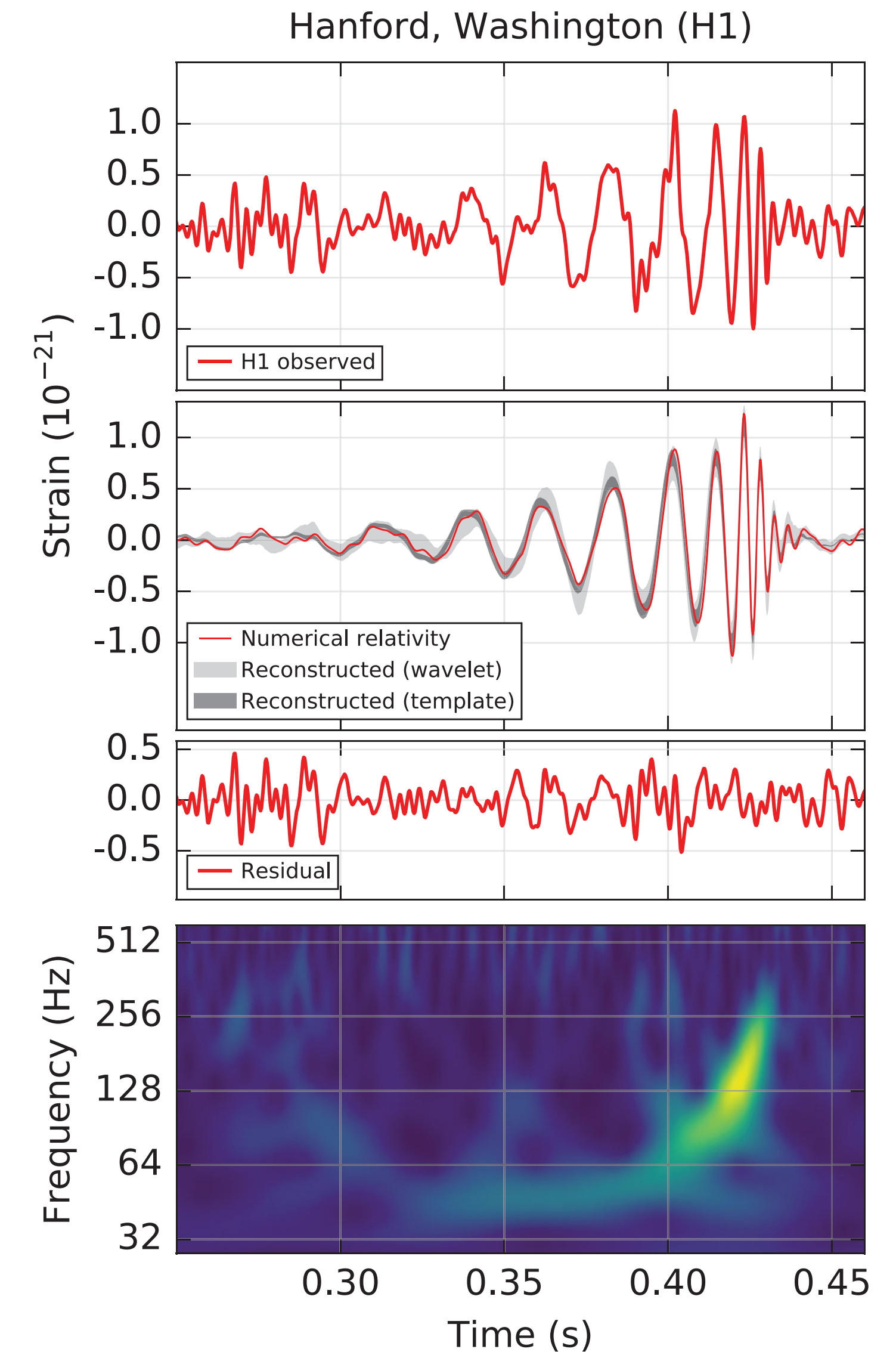
- What about: **Black hole merging events**

- Chirp signals

- $m_{BH} \sim O(10M_{\odot})$: frequency in acoustic range

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

- Frequency range: 10-1000 Hz



PRL 116, 061102 (2016)

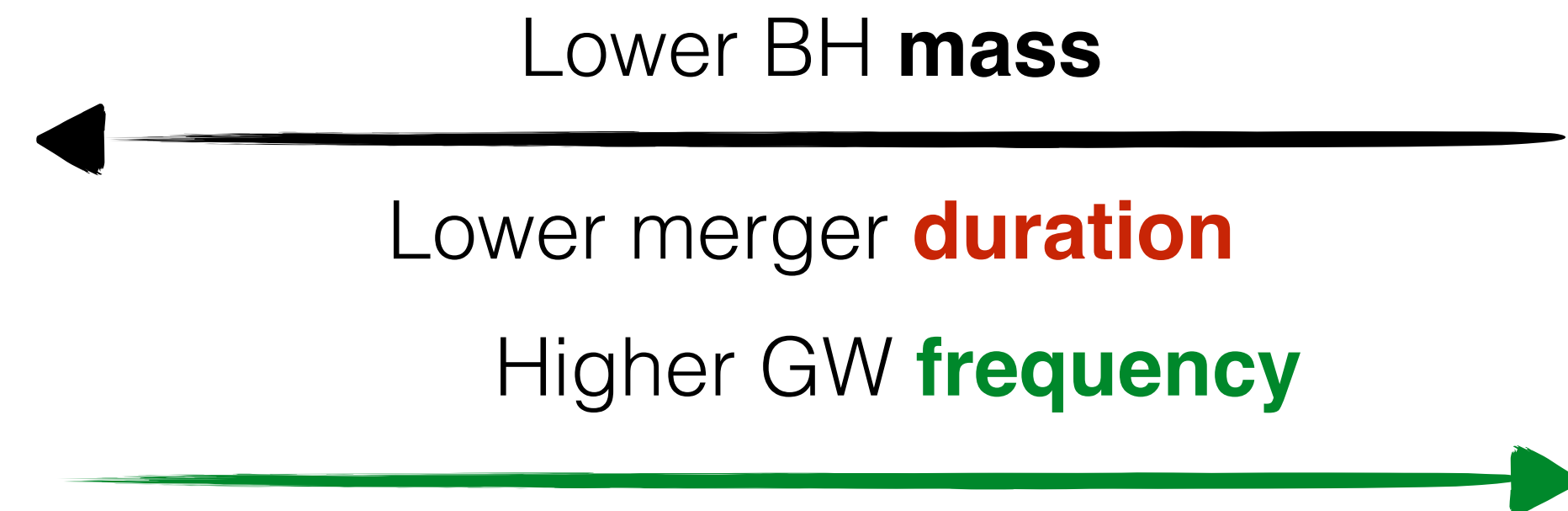
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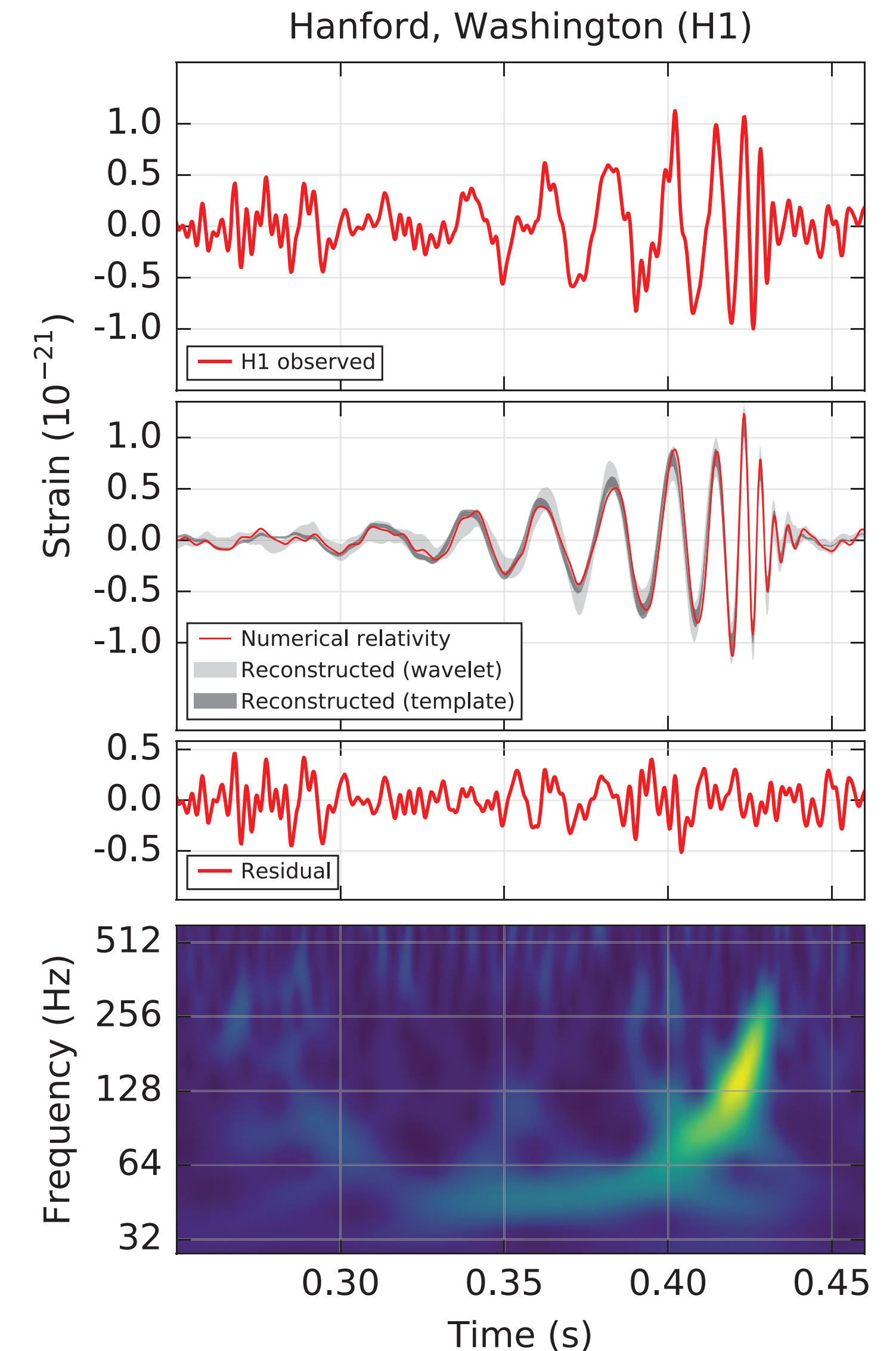
$$f \approx 100 \text{ Hz} \rightarrow m_{BH} \approx 30 M_{\odot}, \text{ Duration: } 0.1s$$

- Lighter BHs => higher frequencies



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

- Frequency range: 10-1000 Hz



PRL 116, 061102 (2016)

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

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- 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 $O(10M_{\odot})$

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- Tolman–Oppenheimer–Volkoff limit: Neutron stars stable up to $2 - 3 M_{\odot}$
 - Corresponding to stellar progenitor masses $O(10M_{\odot})$

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

(Lightest currently observed: $3 M_{\odot}$)

- **Primordial** black hole mergers

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 - **Hypothetical** BHs created shortly after the big bang, before the first stars were formed
 - Not limited to the mass range of stellar BHs

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 - 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

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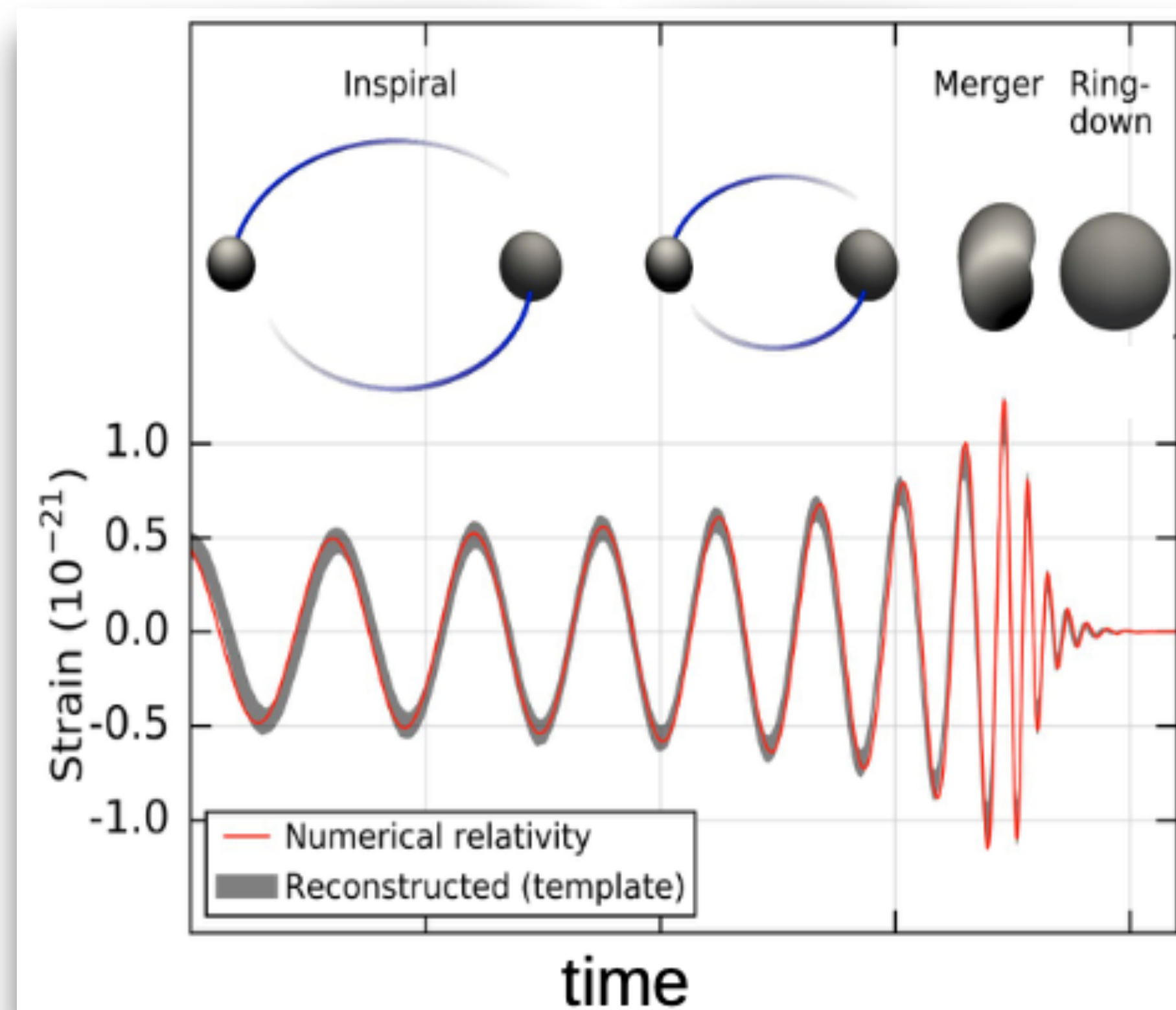
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- Merging event very short, unknown frequency

- **Focus on inspiral:**

- Sweep of huge frequency span



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

Why are PBH interesting objects?

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
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 - Fast transients ($\mu\text{s} - \text{ms}$)

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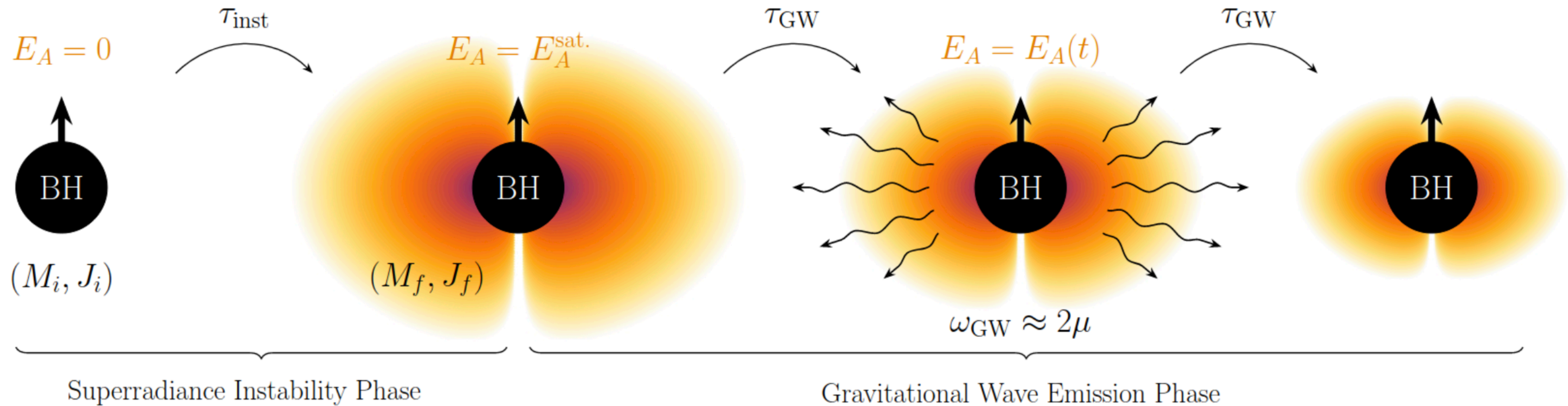
- Expected Strain: $< 10^{-24}$
 - (If all of DM is PBH, one event per year)

- 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 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**

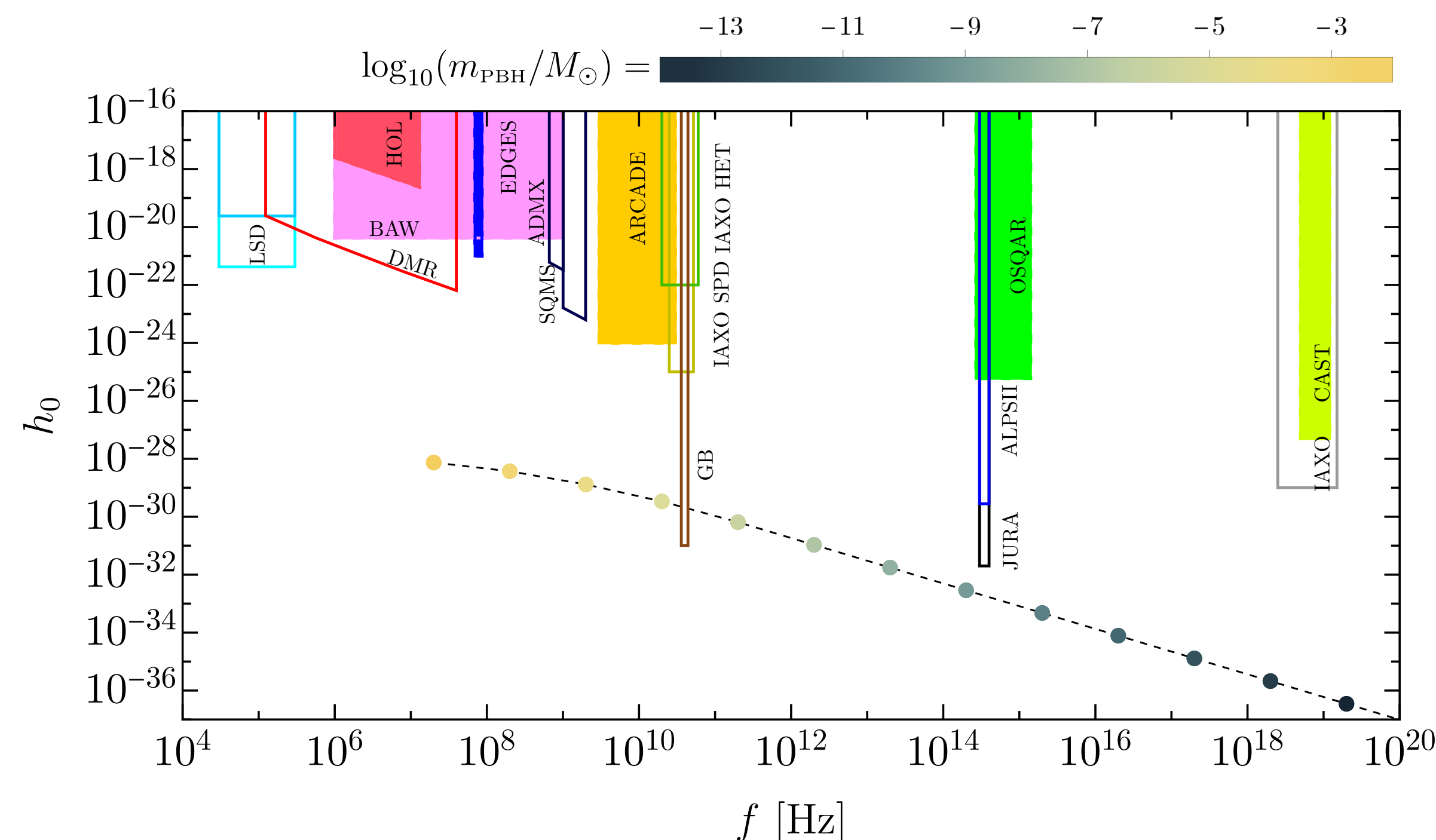
- Sources for HFGWs:

- Primordial black hole merges
- **Boson clouds (BH superradiance)**
- ...

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

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**



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

Several sources possible:

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

- Sources for HFGWs:

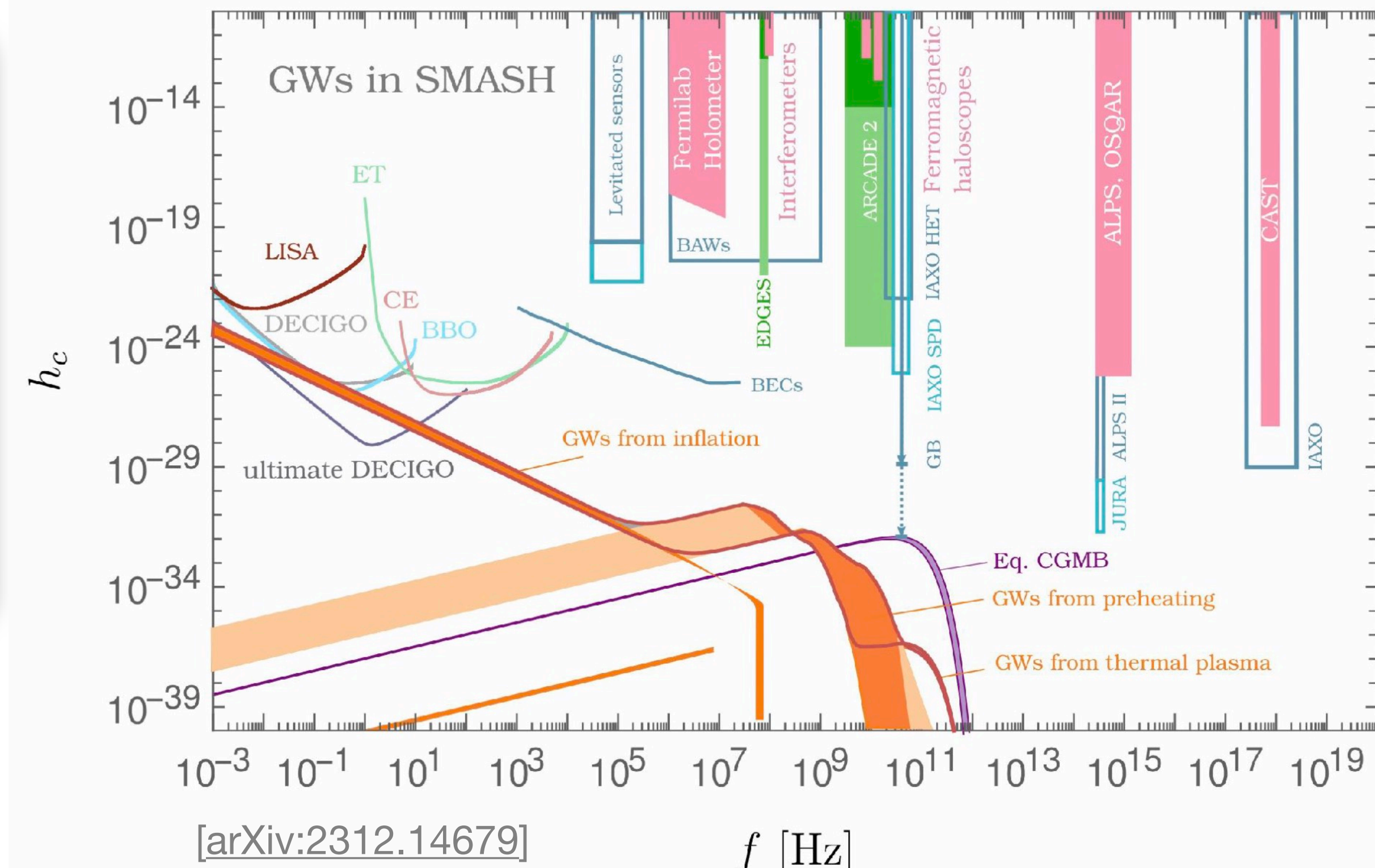
- Primordial black hole merges
- Boson clouds (BH superradiance)
- **Stochastic GW sources**

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



Expected Strain

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

- $h_0 < 10^{-24}$

- $h_0 < 10^{-29}$

- $h_0 < 10^{-32}$

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

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

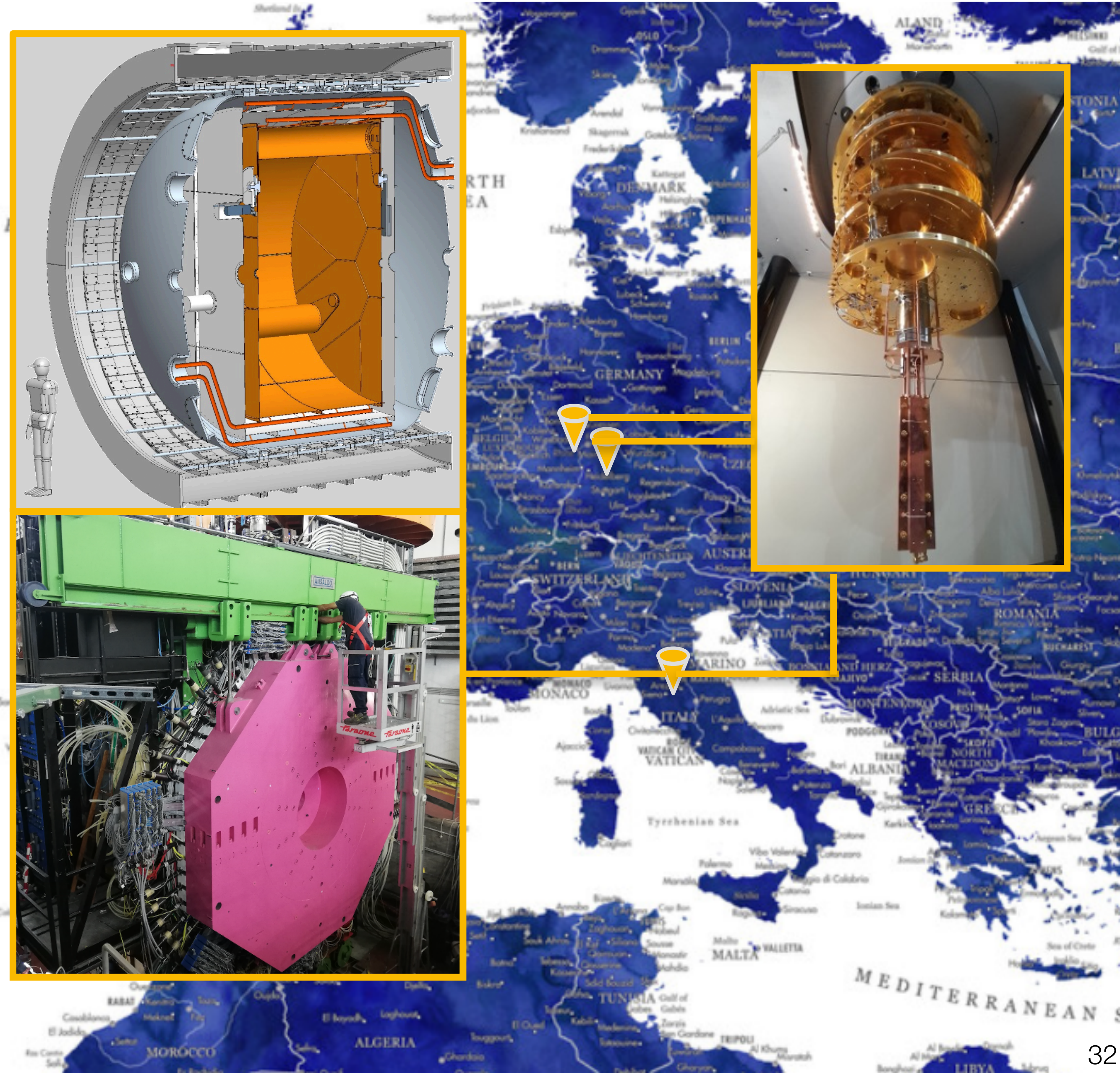
How to improve the sensitivity?

GravNet in the next years



A Global Network of HFGW Detectors

- 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)



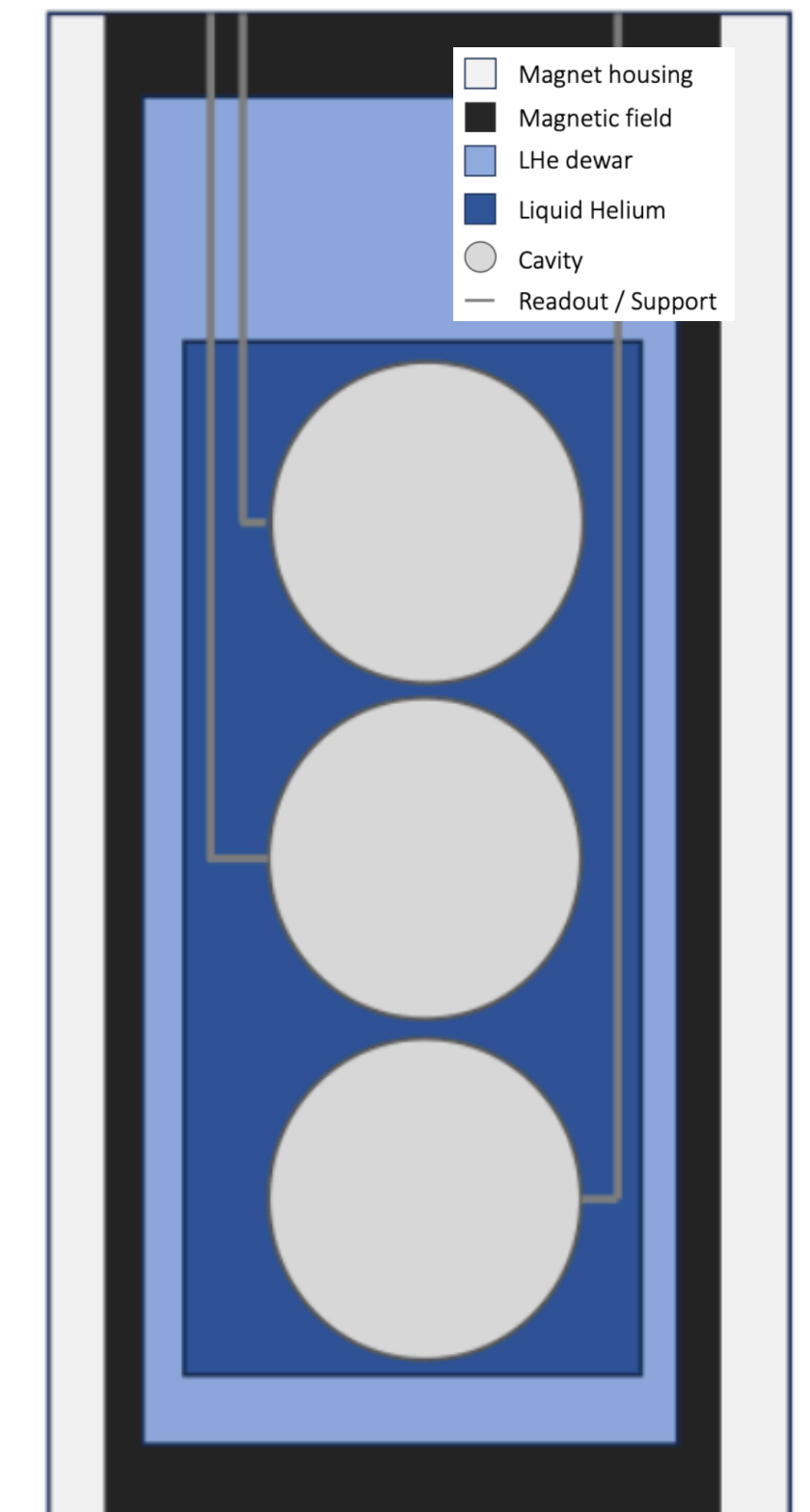
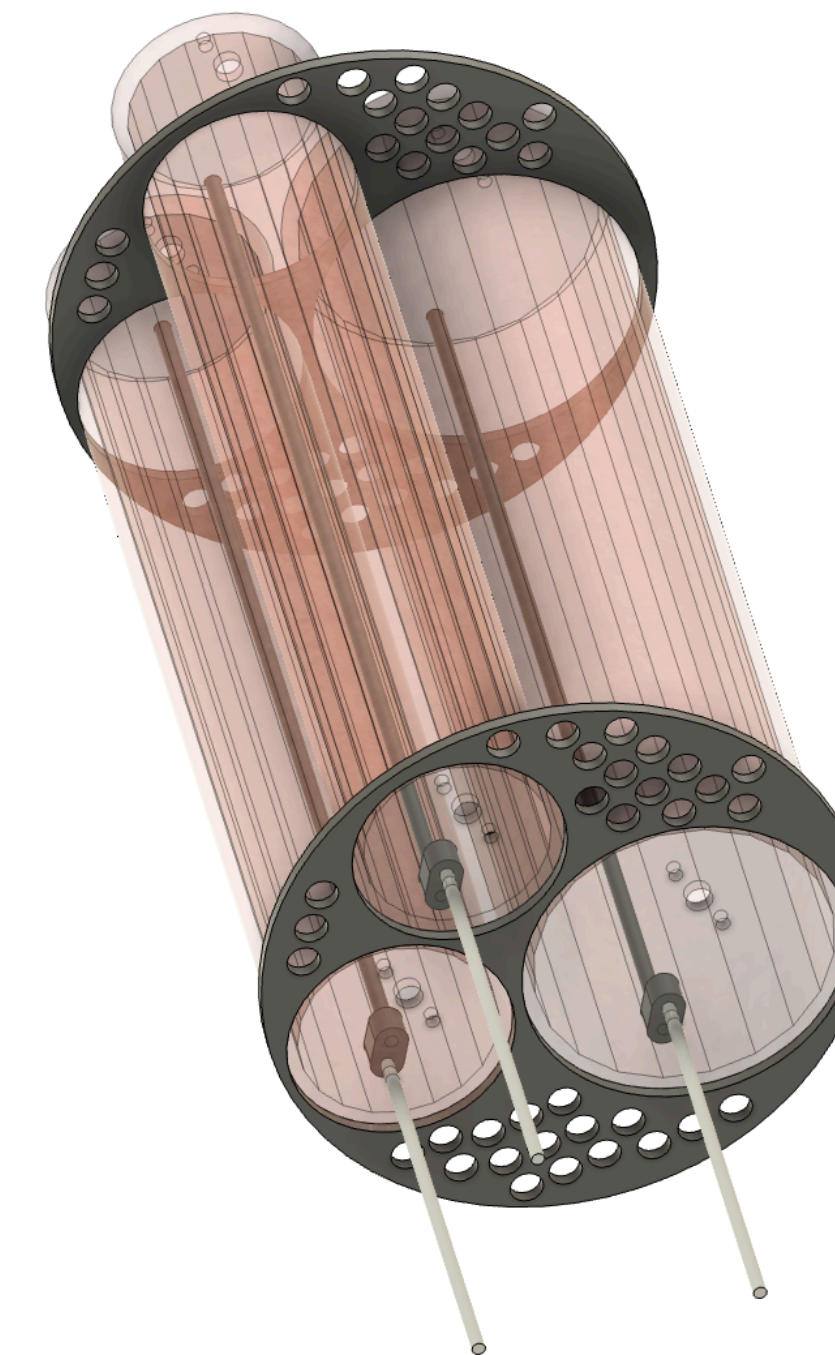
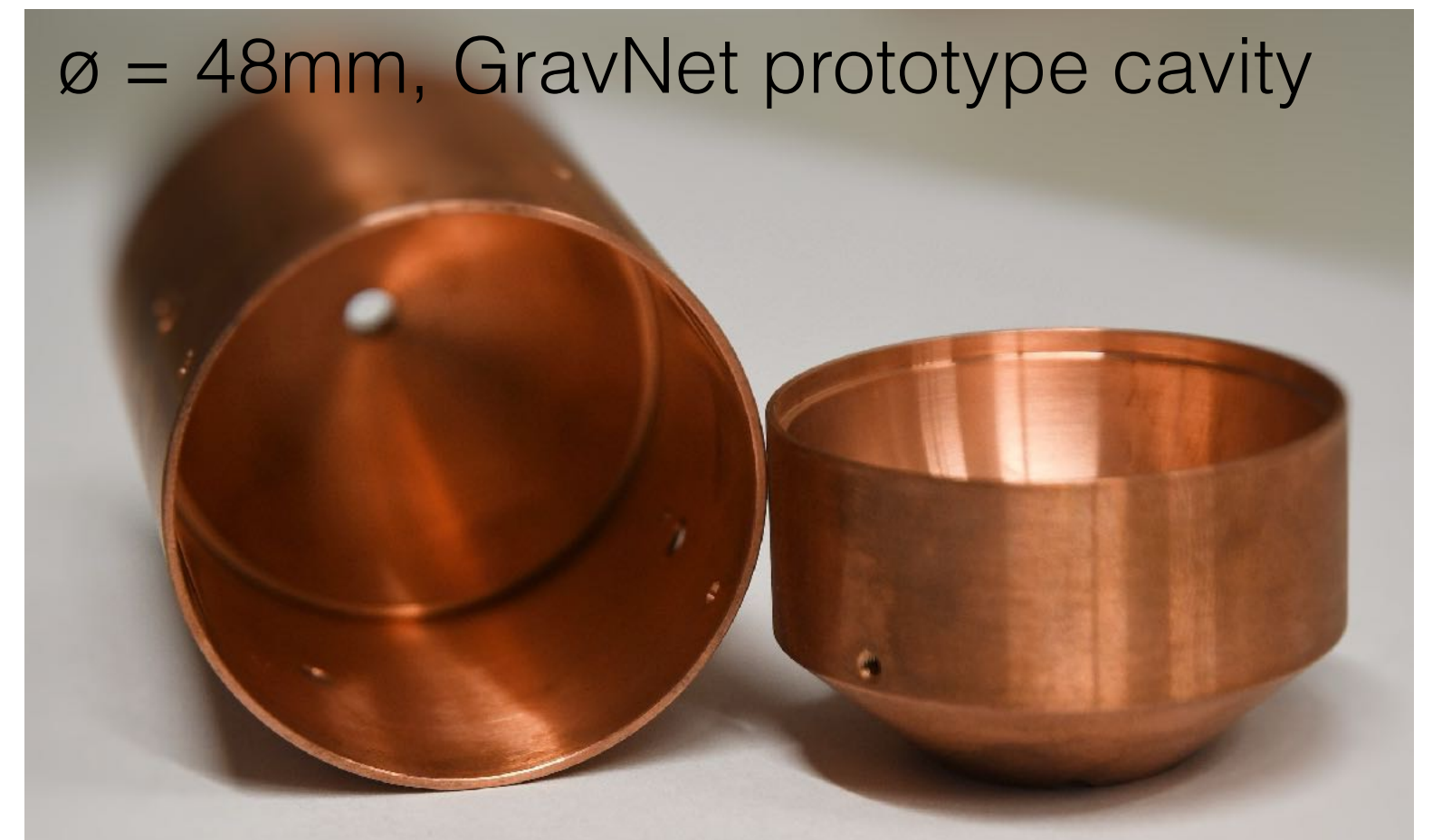
A Global Network of HFGW Detectors

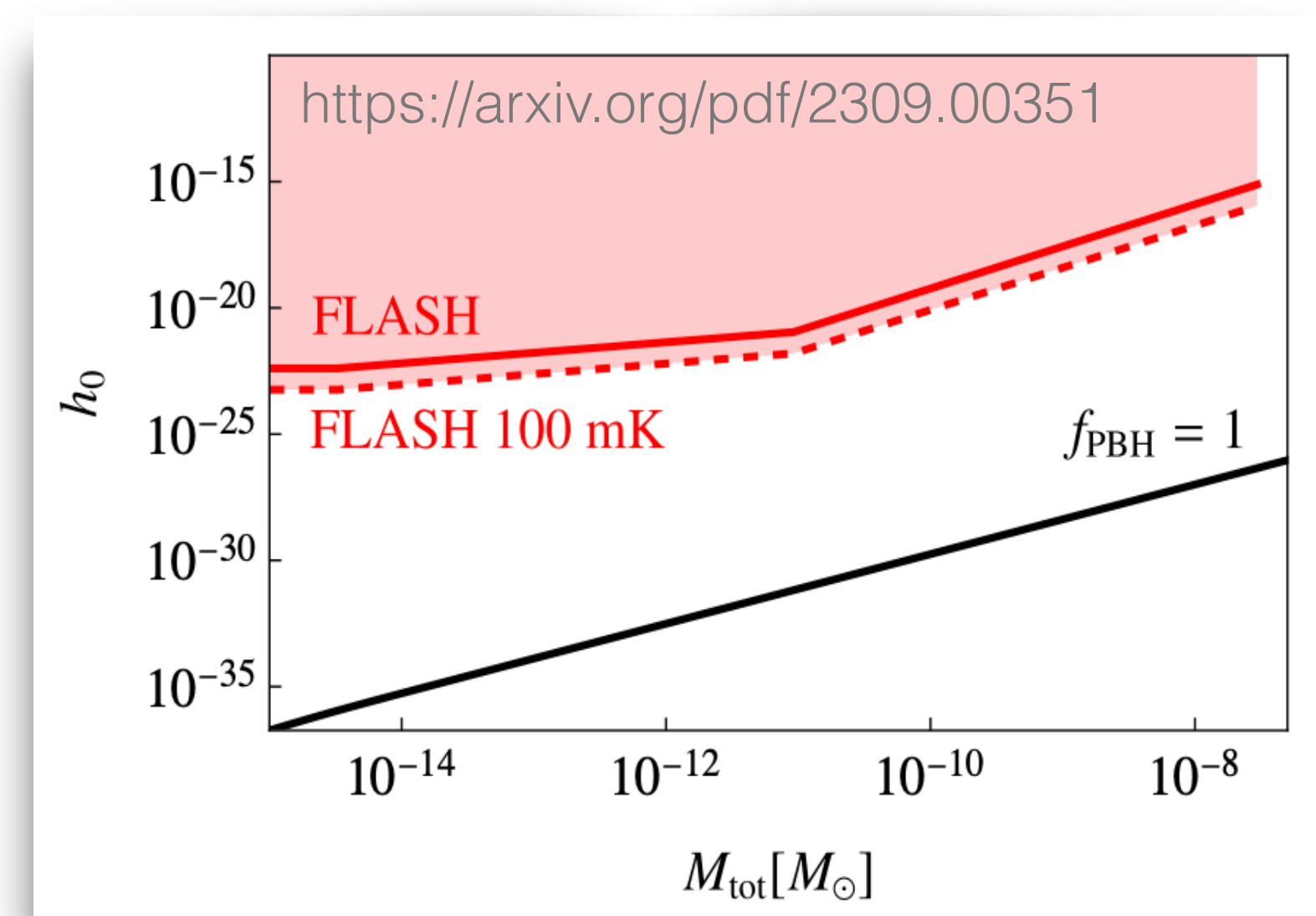
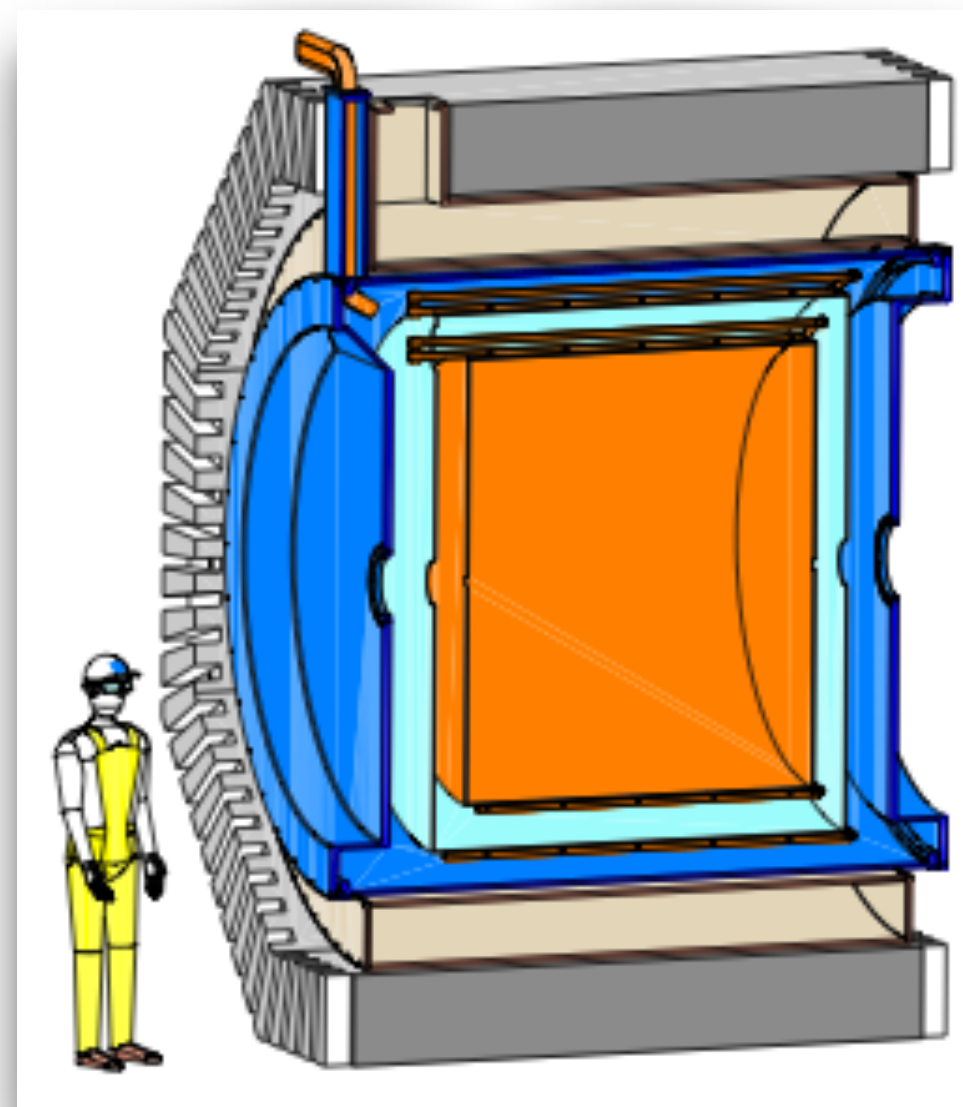
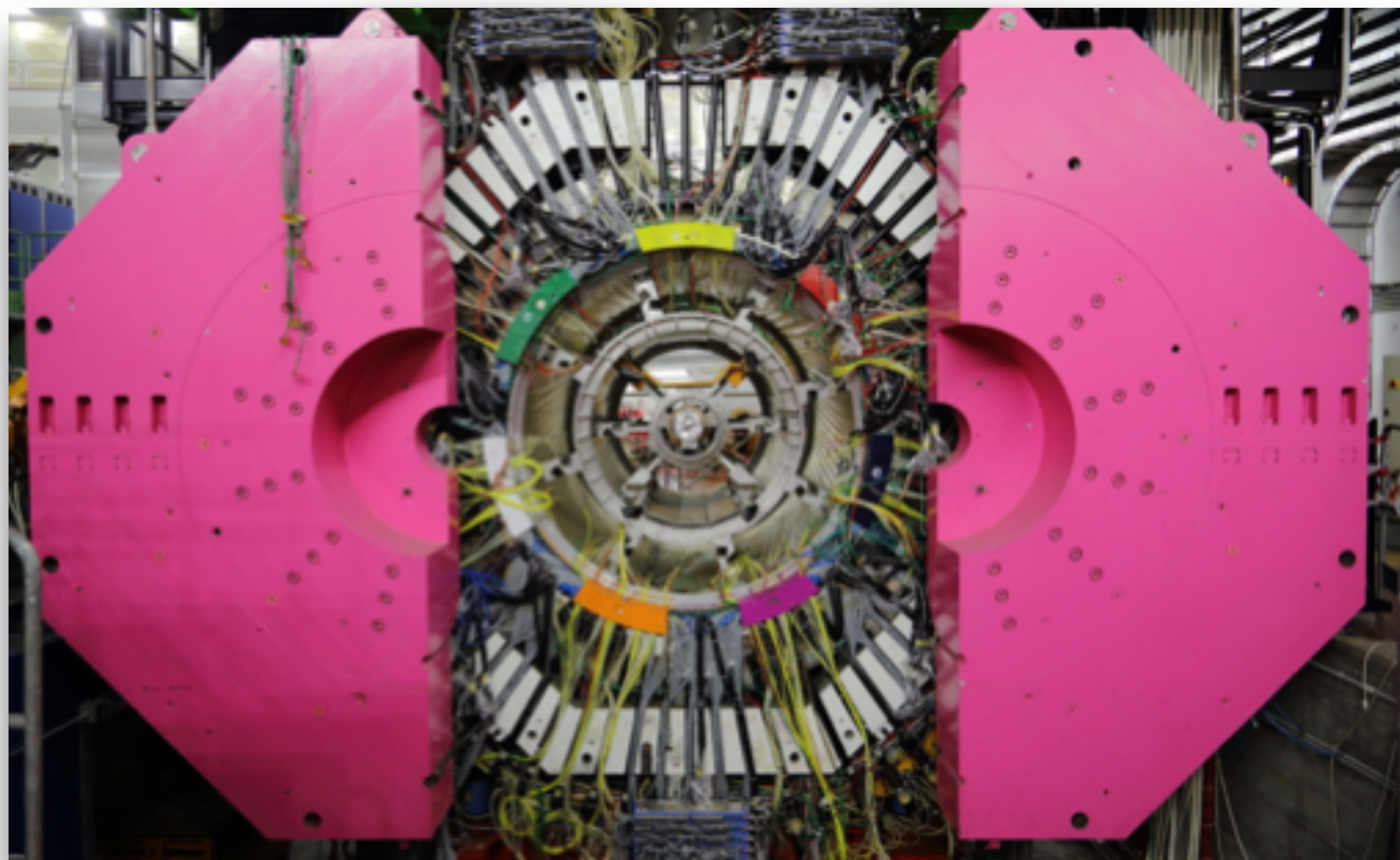
- **Example:** 8 GHz corresponds to a sphere of diameter $\approx 5\text{cm}$
 - High frequencies typically correspond to small volumes
- **Challenge:** Signal power depends nearly quadratically on volume V

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

- **Advantages:**

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



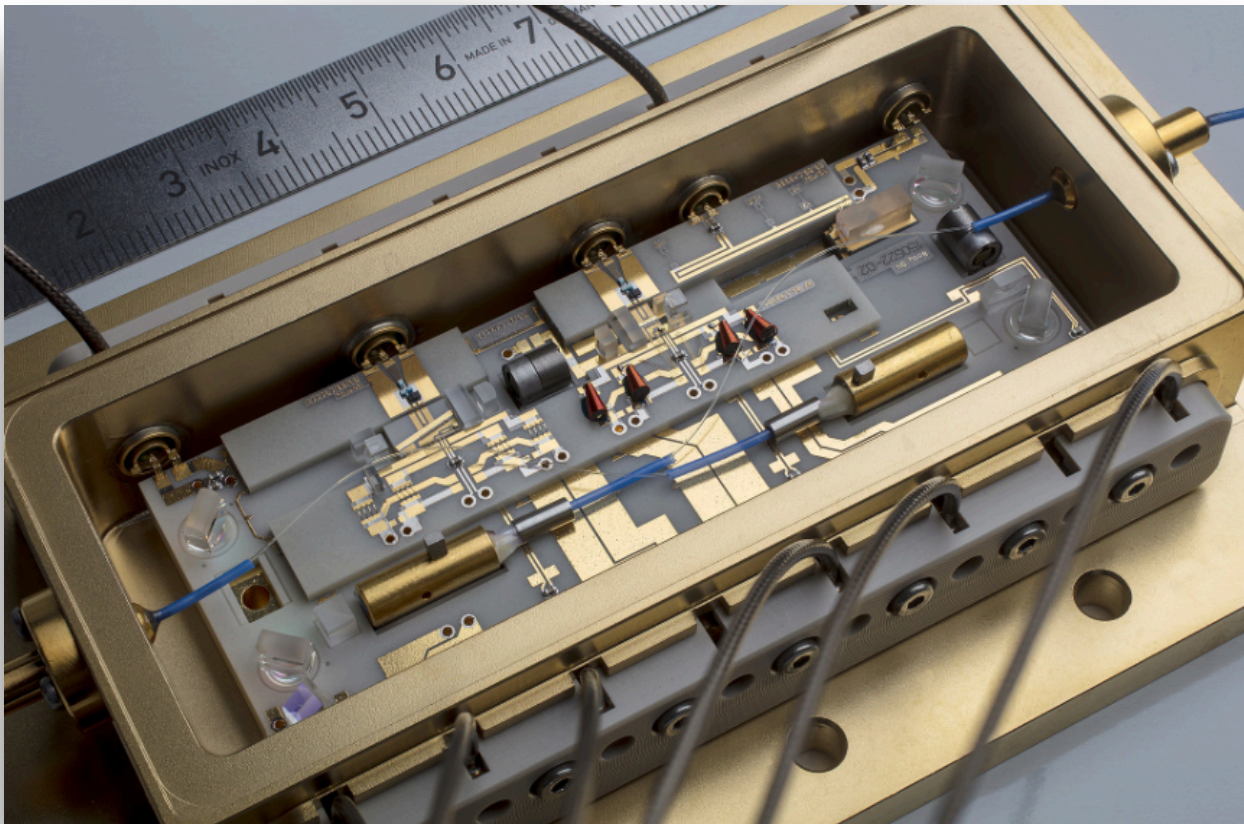


- Reuse of the FIDUNA magnet system at INFN Frascati within the FLASH Experiment:
 - Axion Search (0.49-1.49 μeV)
 - Res. Frequency: 100-300 MHz

- System properties:
 - $V = 4.15 \text{ m}^3$
 - $B = 1.1 \text{ T}$
 - $Q_L = 1.4 \times 10^5$
 - $T_{\text{sys}} = 4.9 \text{ K}$

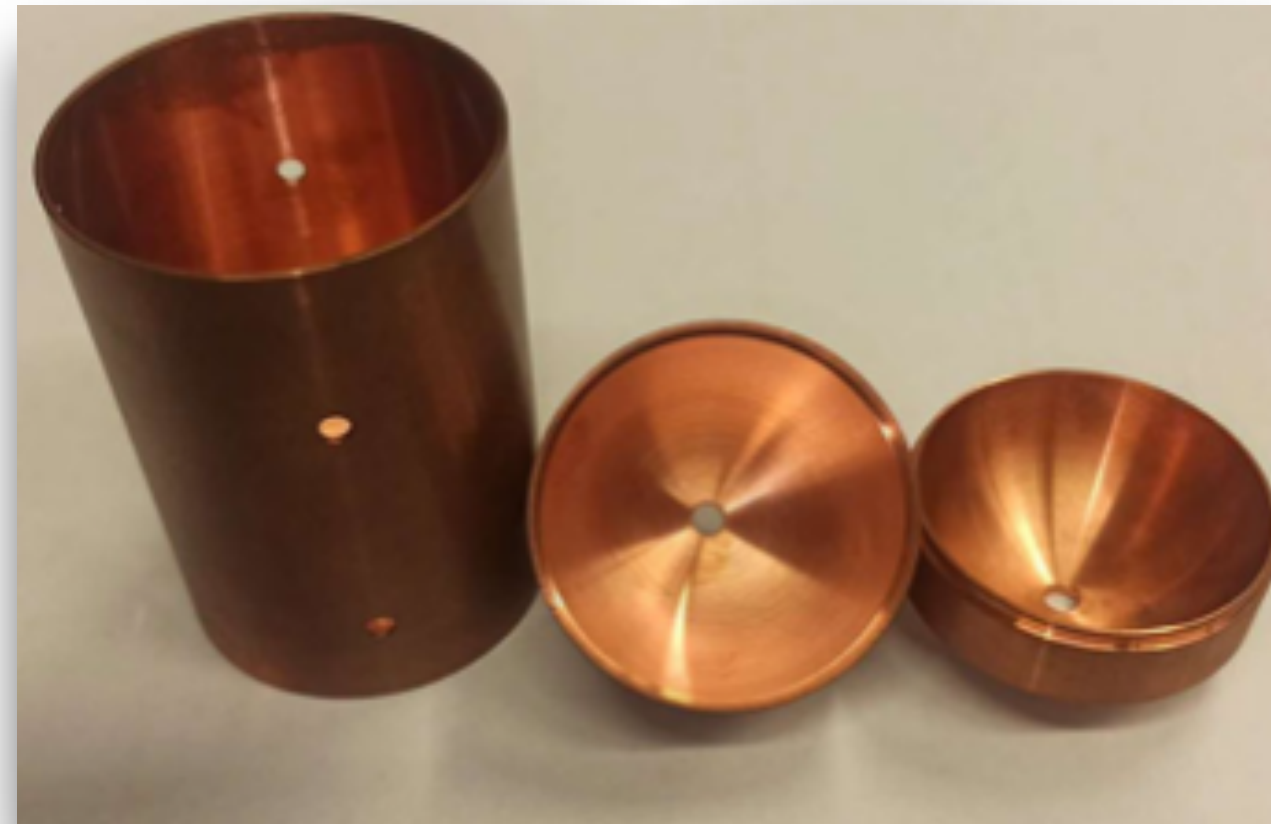
- Readout:
 - SQUID readout
 - Limited by thermal noise

Drastically reduce noise in readout



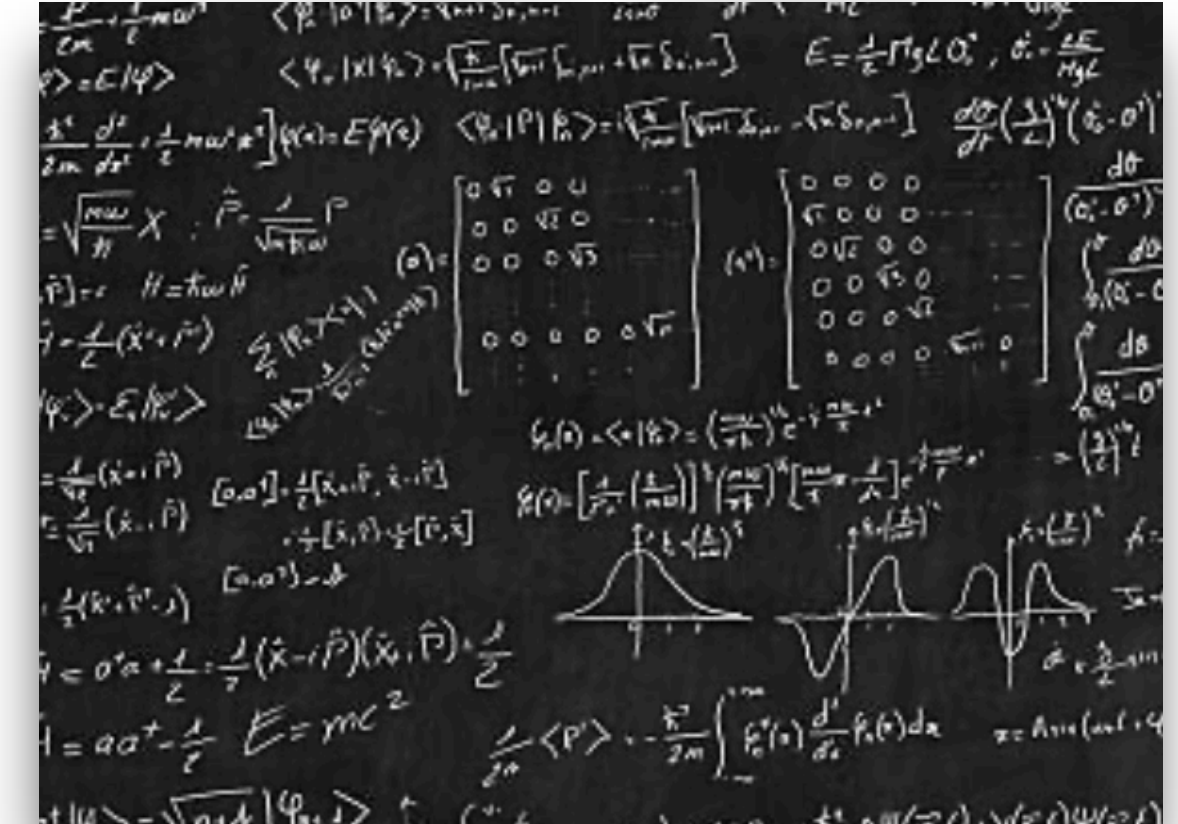
- Use of quantum sensing
- Single RD photon detection
- Quantum non-demolition measurements

Optimize Cavity

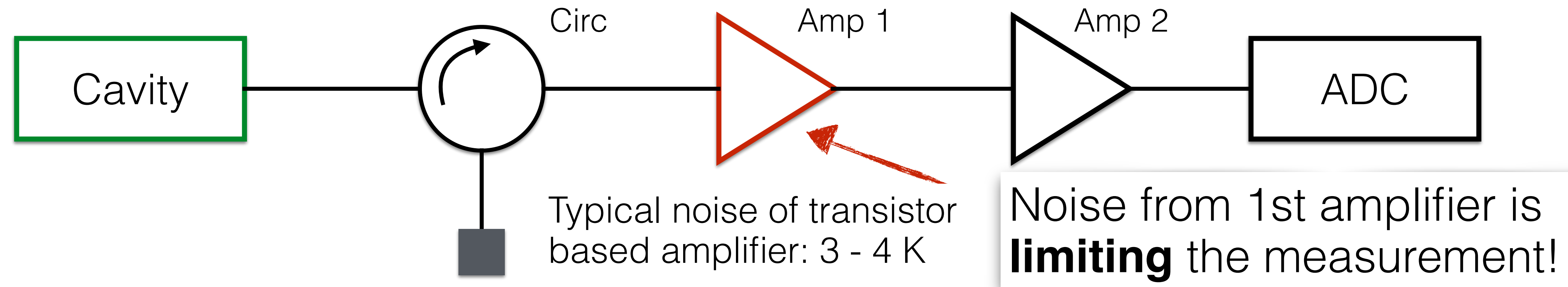


- Optimise shape to improve coupling to GW:
- Enhance quality factor using superconductors

Optimize Data Analysis

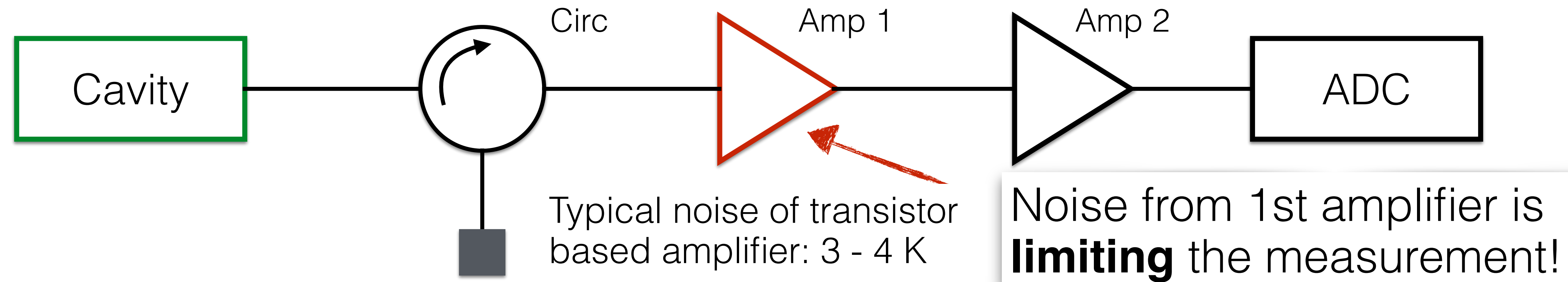


- Combination of data from distributed detectors
- Usage of advanced machine learning tool
- Signal modeling



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

- Added noise ~ 200 mK
- Below **standard quantum limit**



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

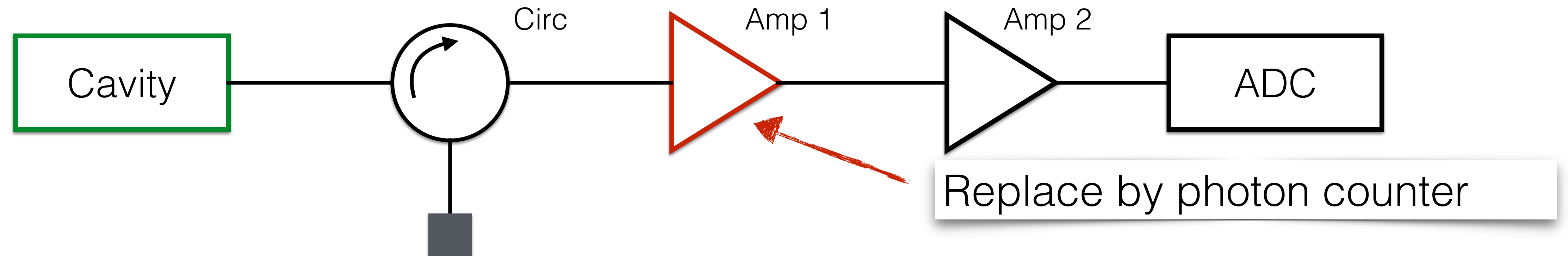
- Added noise ~ 200 mK
- Below **standard quantum limit**

System noise:

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

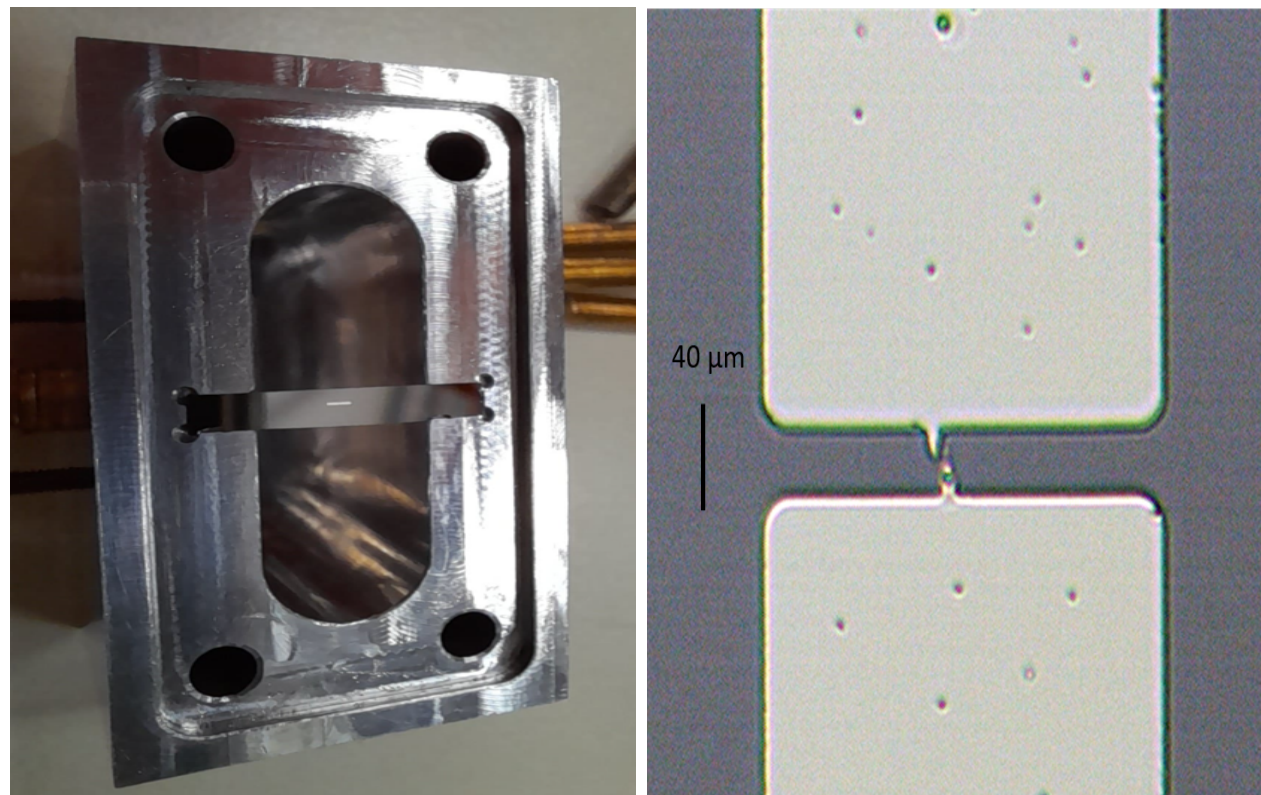
SQL: $N_A \geq 1/2 \Rightarrow N_{\text{sys}} \geq 1$

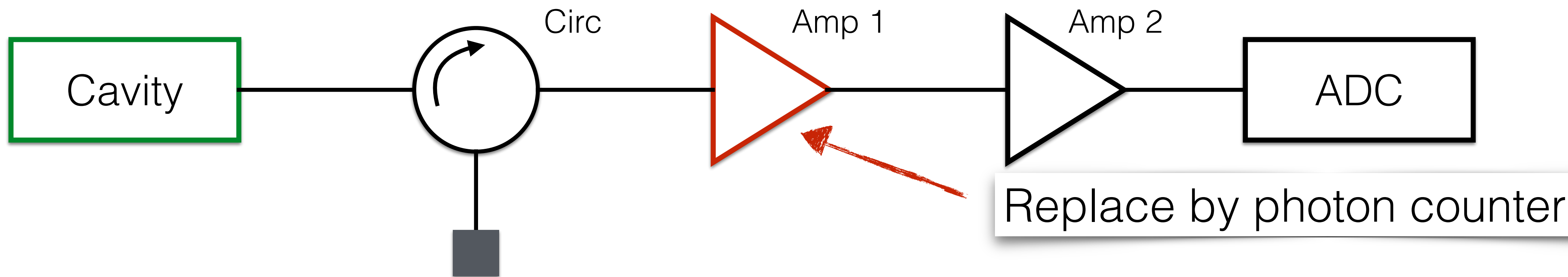
(Price for spectral resolution)



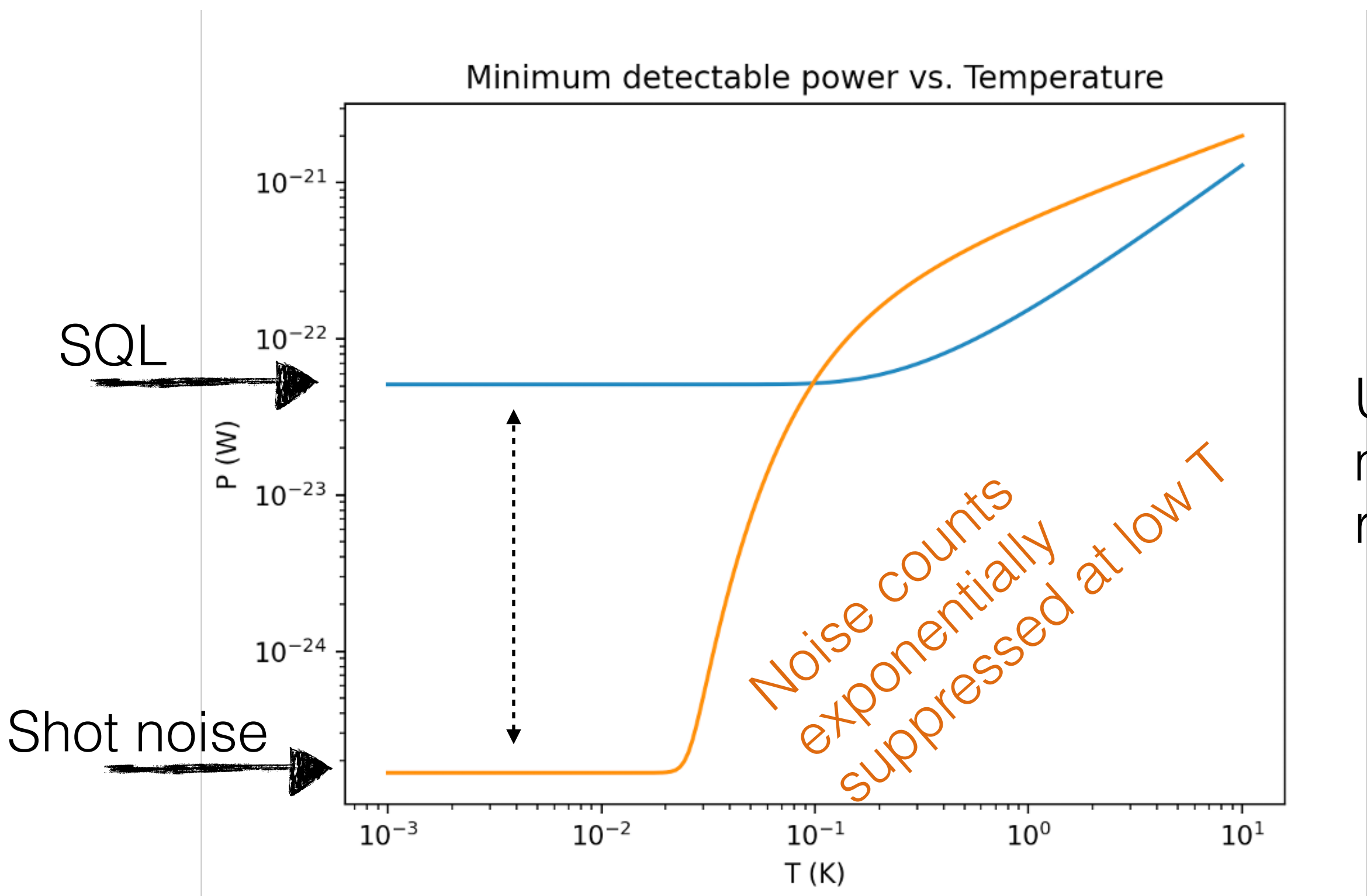
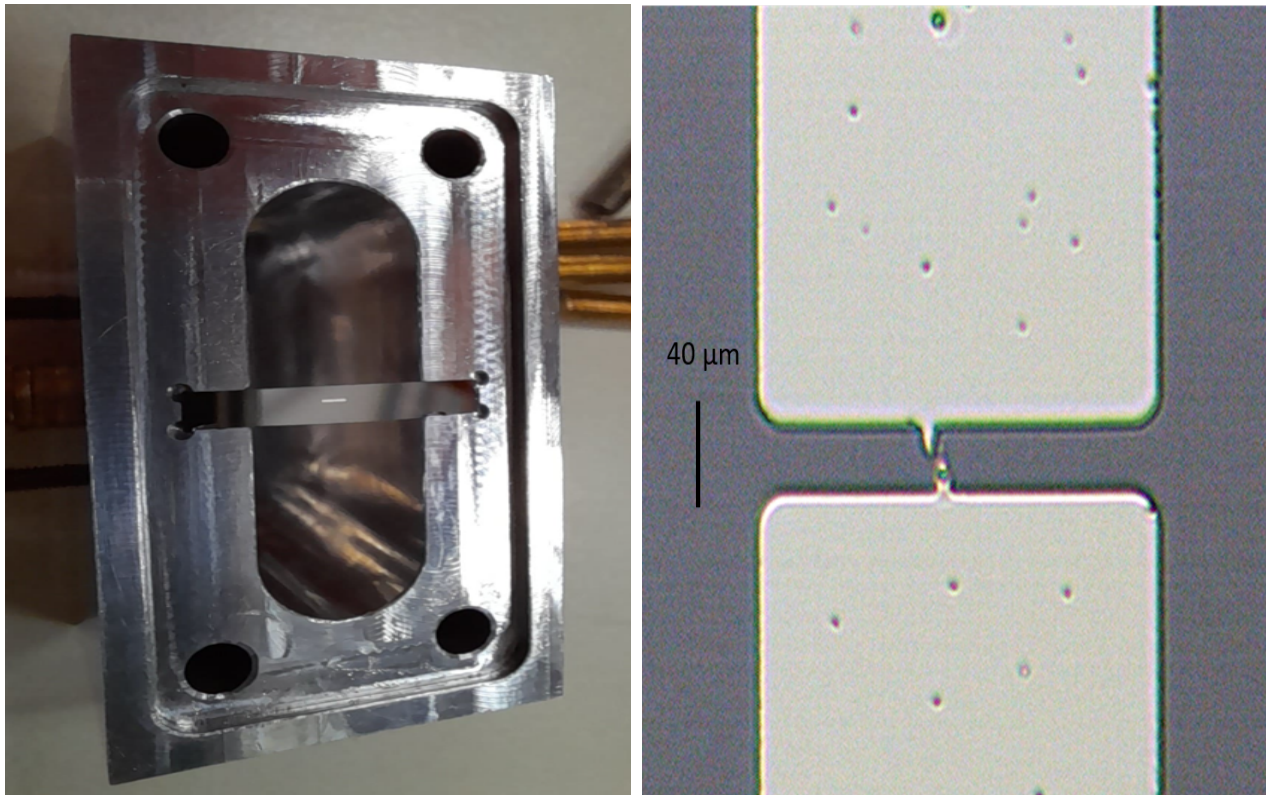
Using **photon counting**:

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

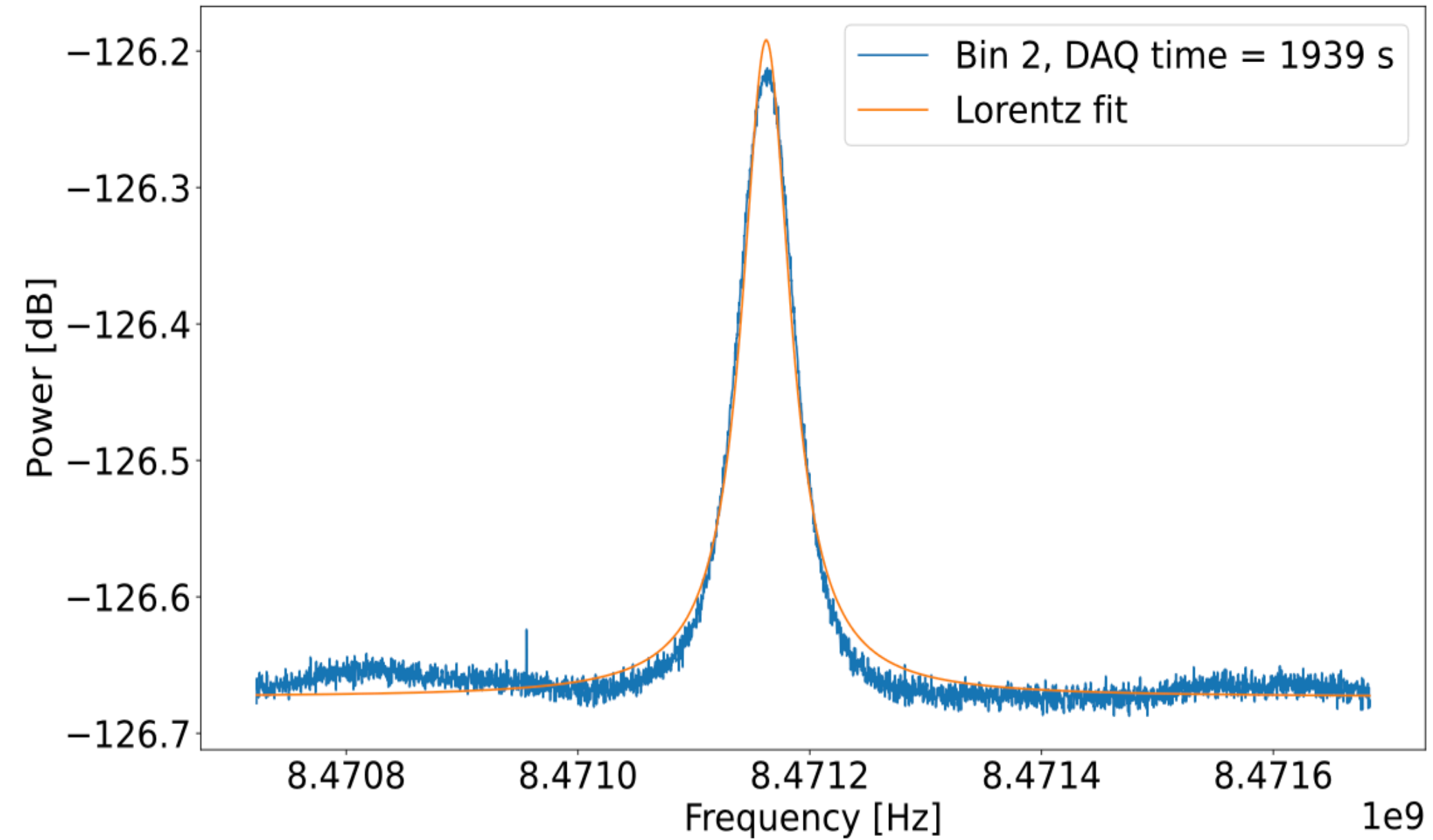




- Using **photon counting**:
- Noise below SQL possible!
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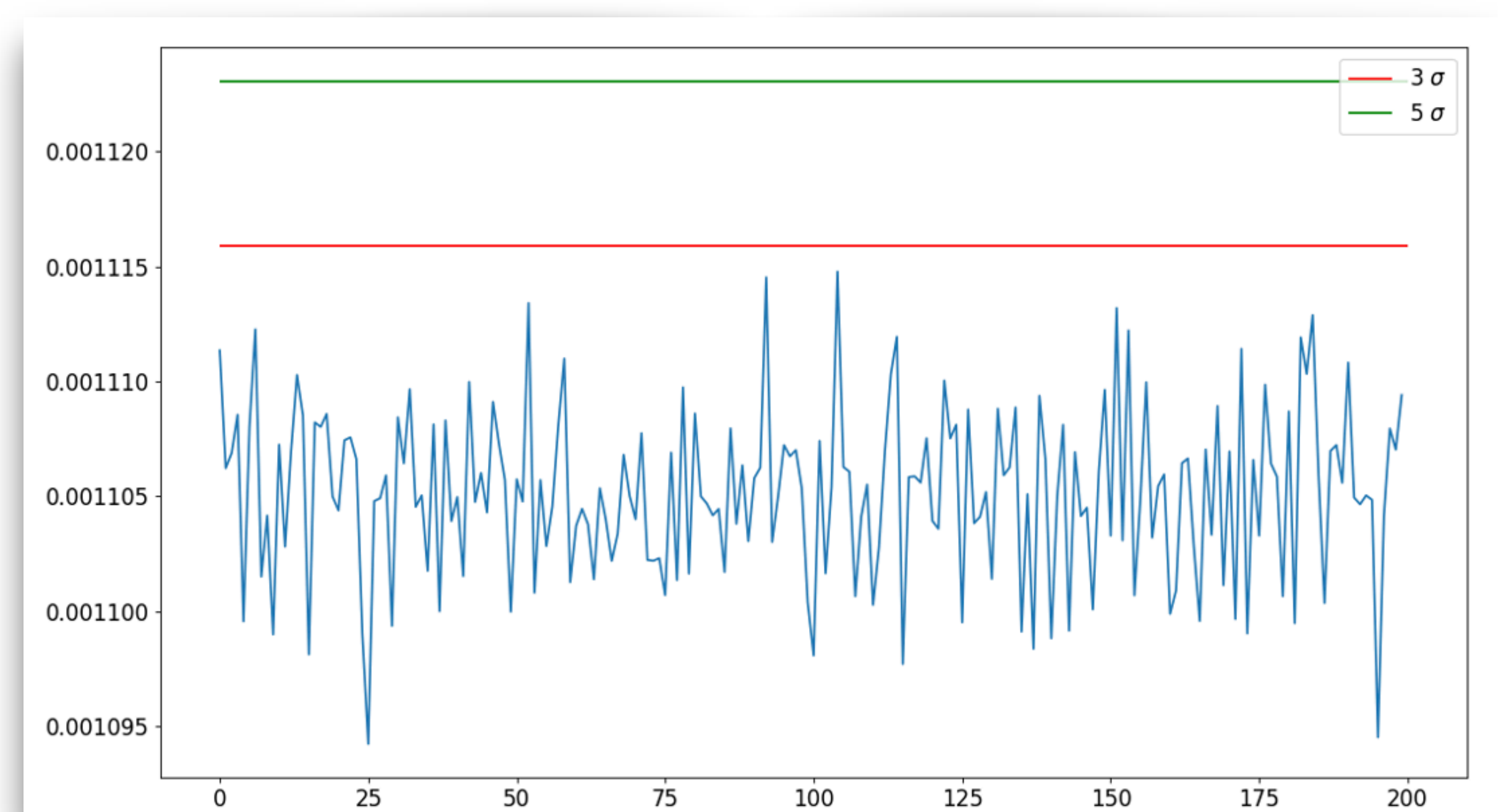
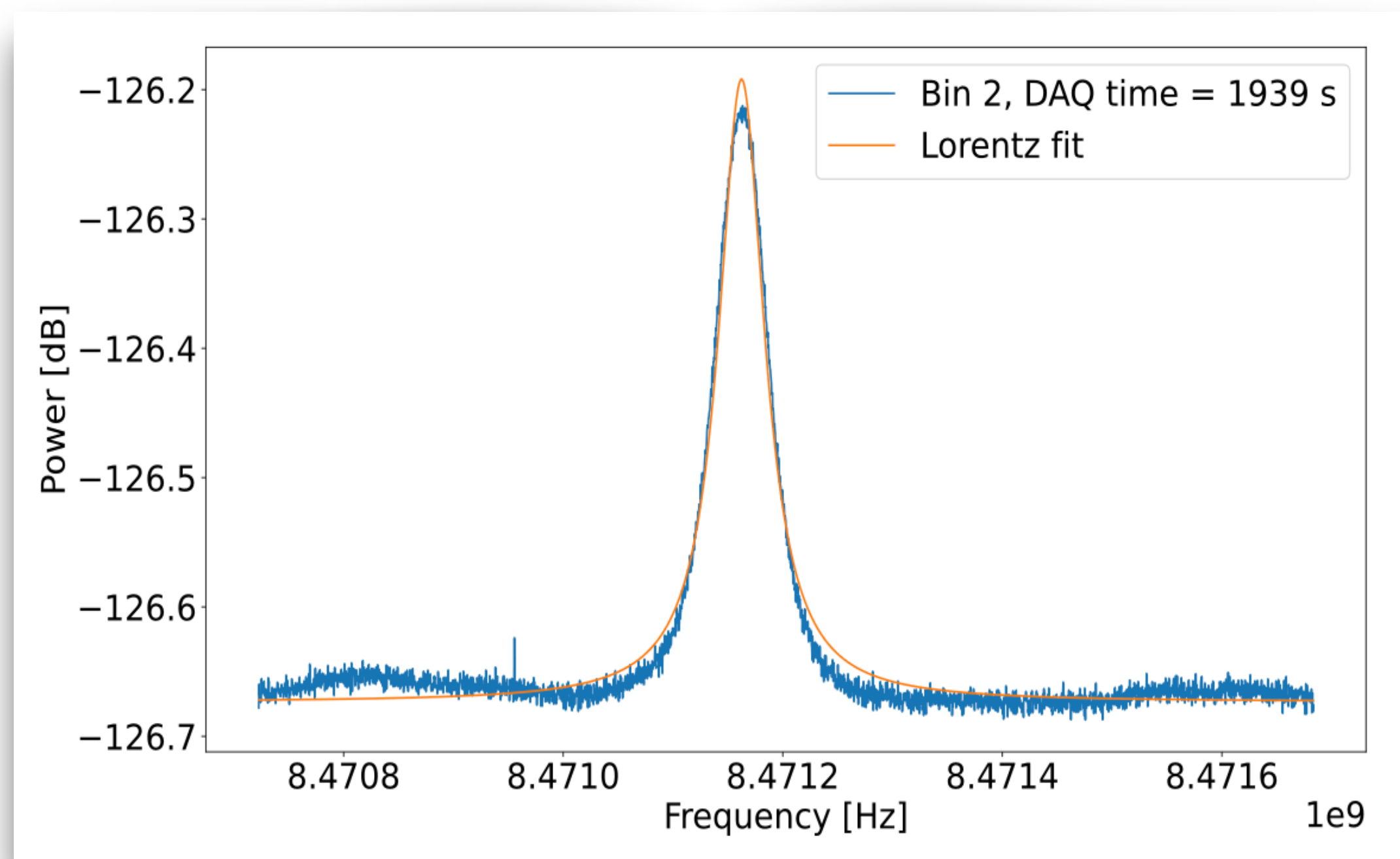


Up to 3 orders of magnitude noise reduction!



Naive approach:

- Bump-hunt in frequency domain
- Limited time resolution



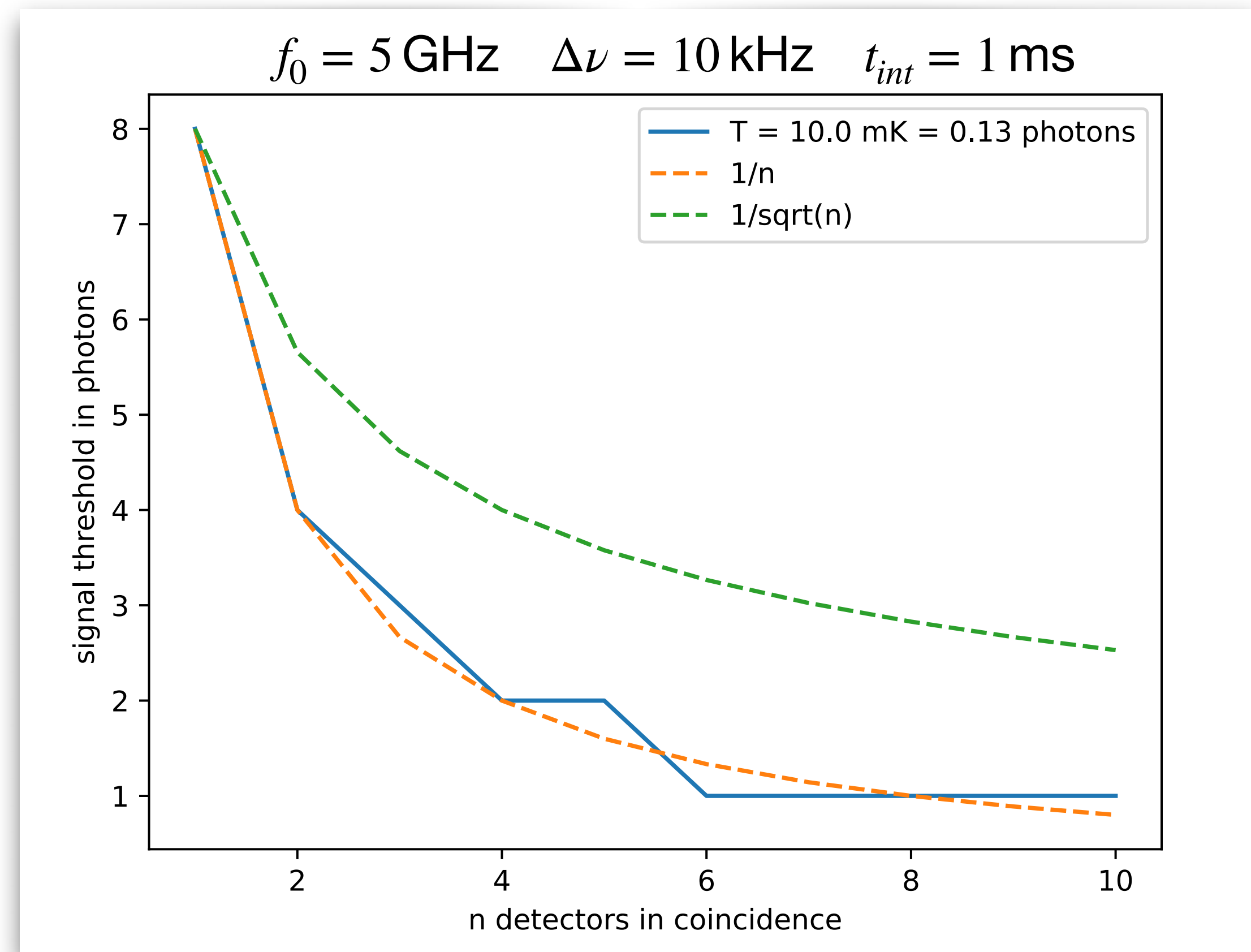
Naive approach:

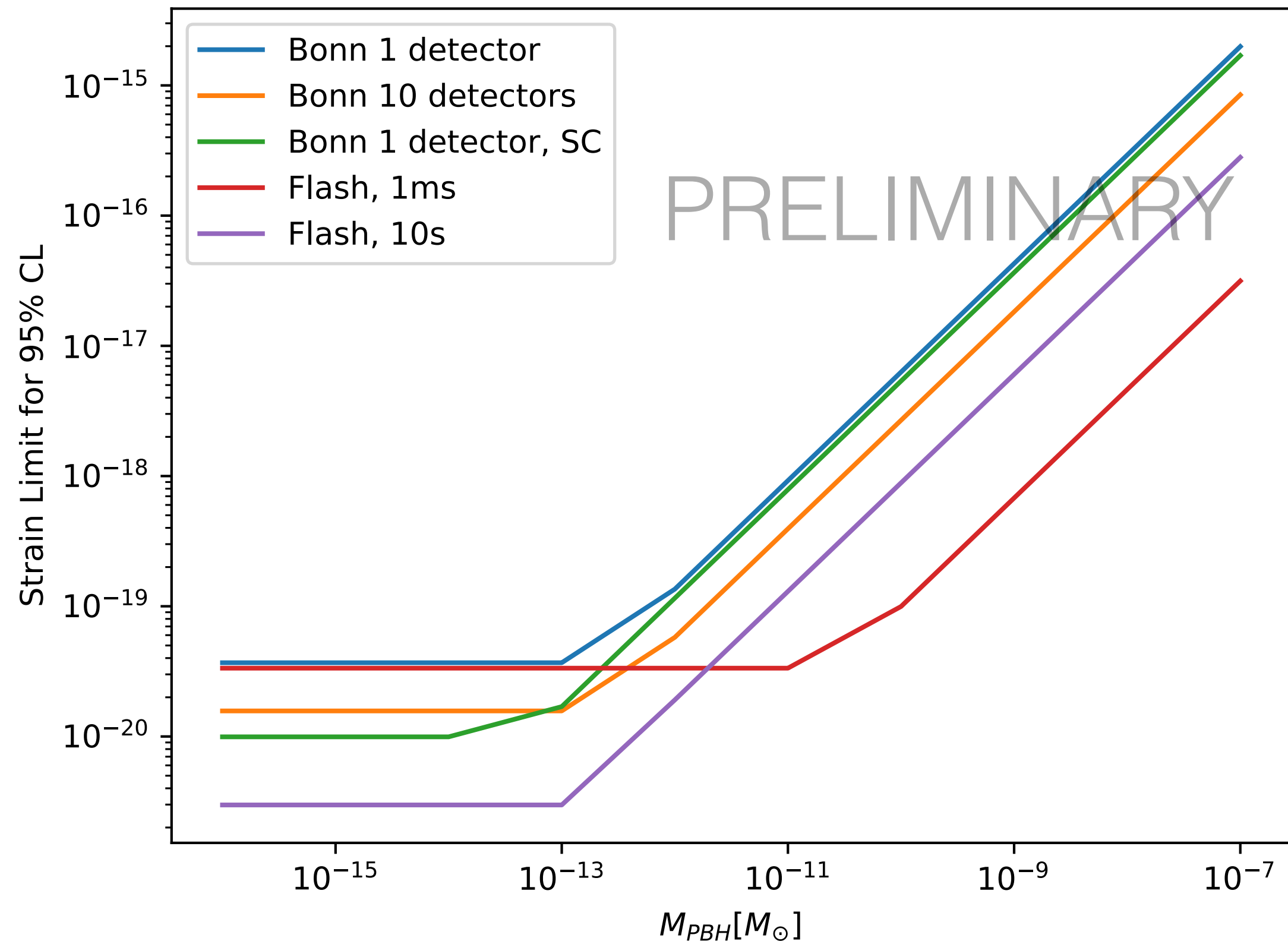
- Bump-hunt in frequency domain
- Limited time resolution

Advance approach:

- Search for signature in time series
- **Playground for modern techniques:**
 - Anomaly detection using ML
 - Noise reduction with auto-encoders
 - ML classifiers
 - ...

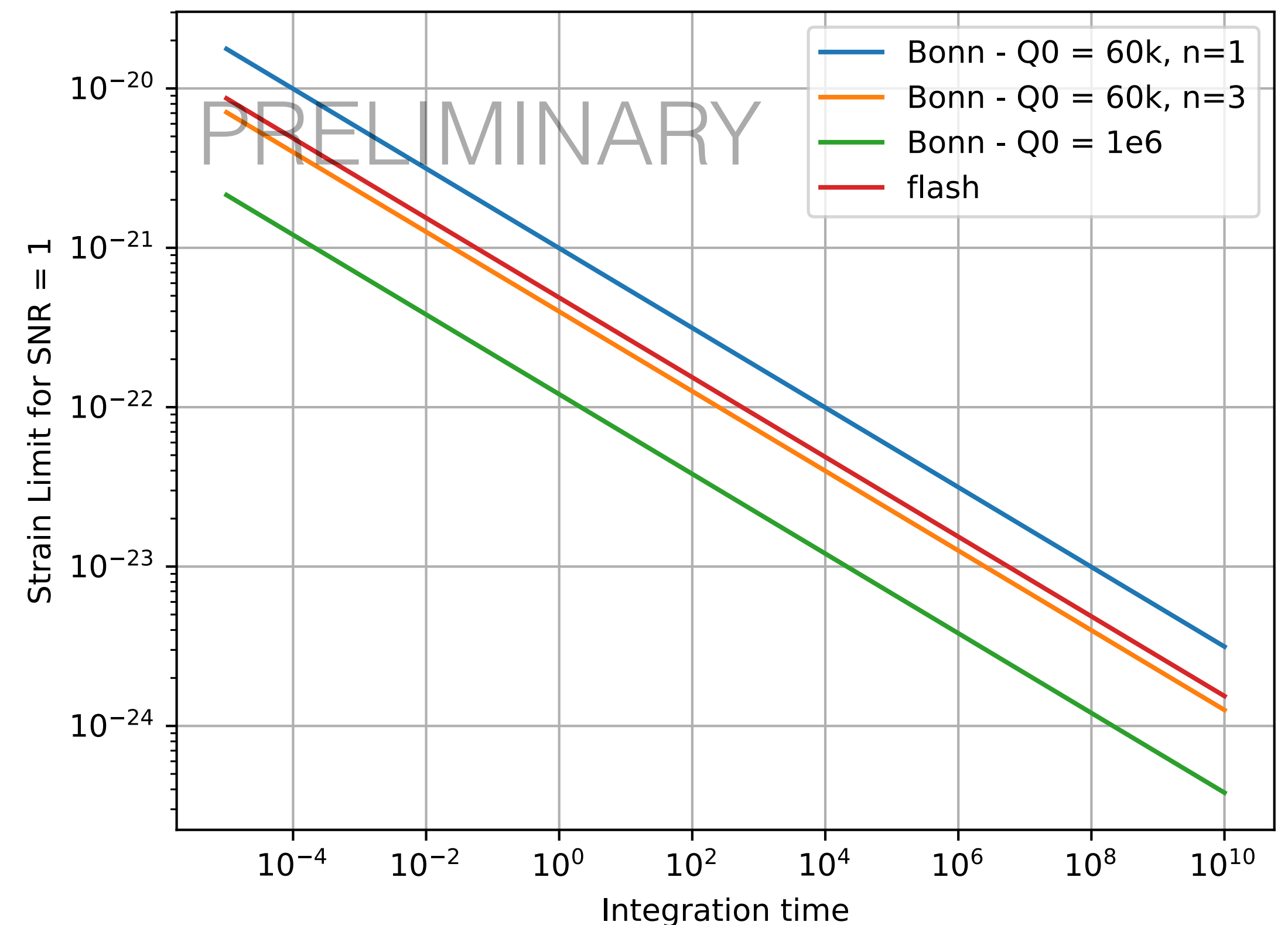
- Adding N coherent signals (in phase) yields an improvement on the SNR of $\sim N$
- Single photon readout:
 - Measurement becomes **counting experiment**
 - Thermal/quantum noise yields a certain **number of photons per time-interval**
 - Expect one signal event per year
 - Additional cavities/experimental sites suppress background (combinatorics)
- Relevant quantity: Induced power should be in the order of $O(1)$ photon

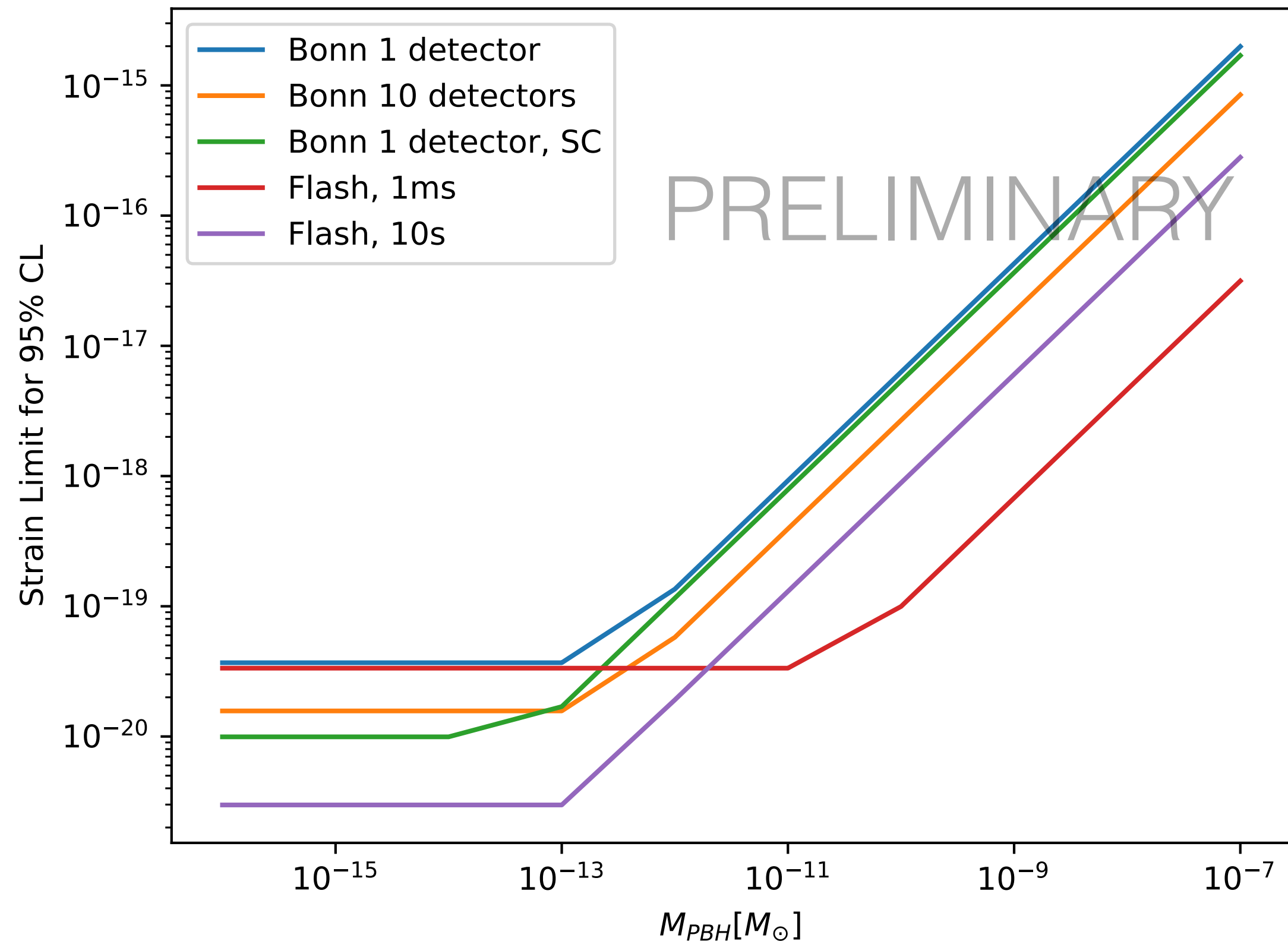




- PBH merger signals, assuming thermal background only
- Target: $h < 10^{-24}$
 - Only few orders of magnitude missing!

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



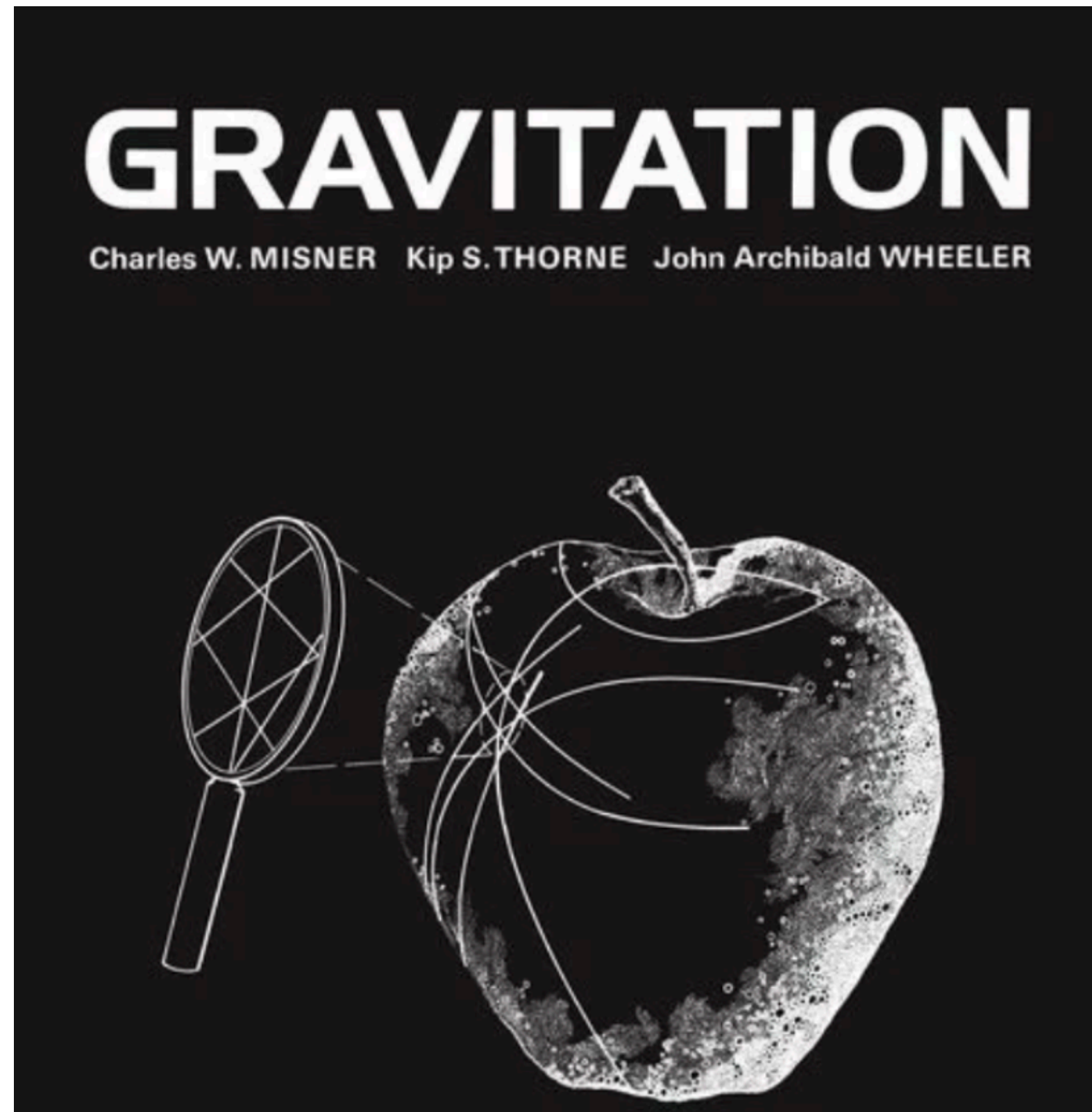


Isn't this depressing?

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

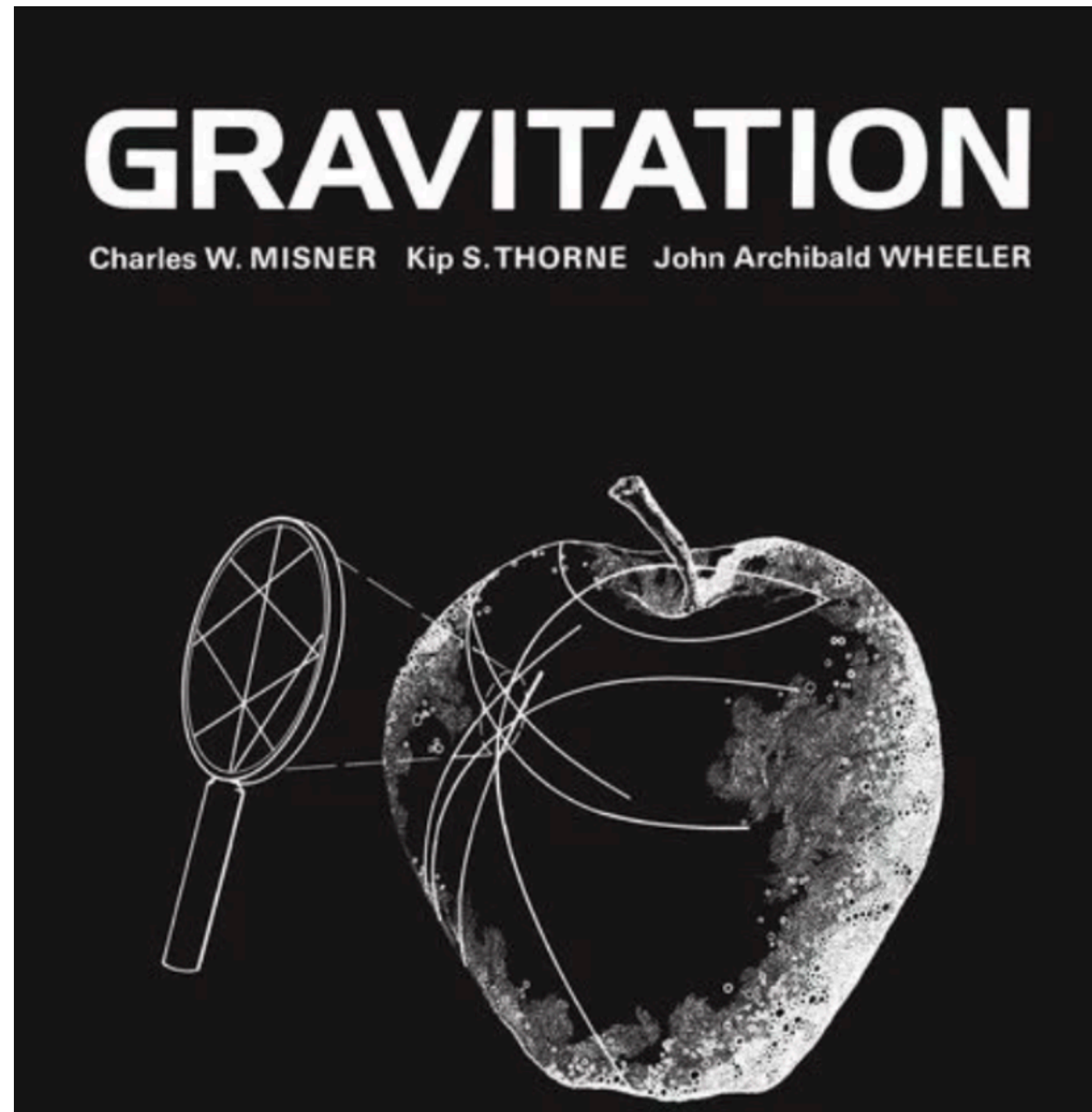
Ambitious, but rewarding goal

Misner, Thorne, Wheeler, 1973



Ambitious, but rewarding goal

Misner, Thorne, Wheeler, 1973

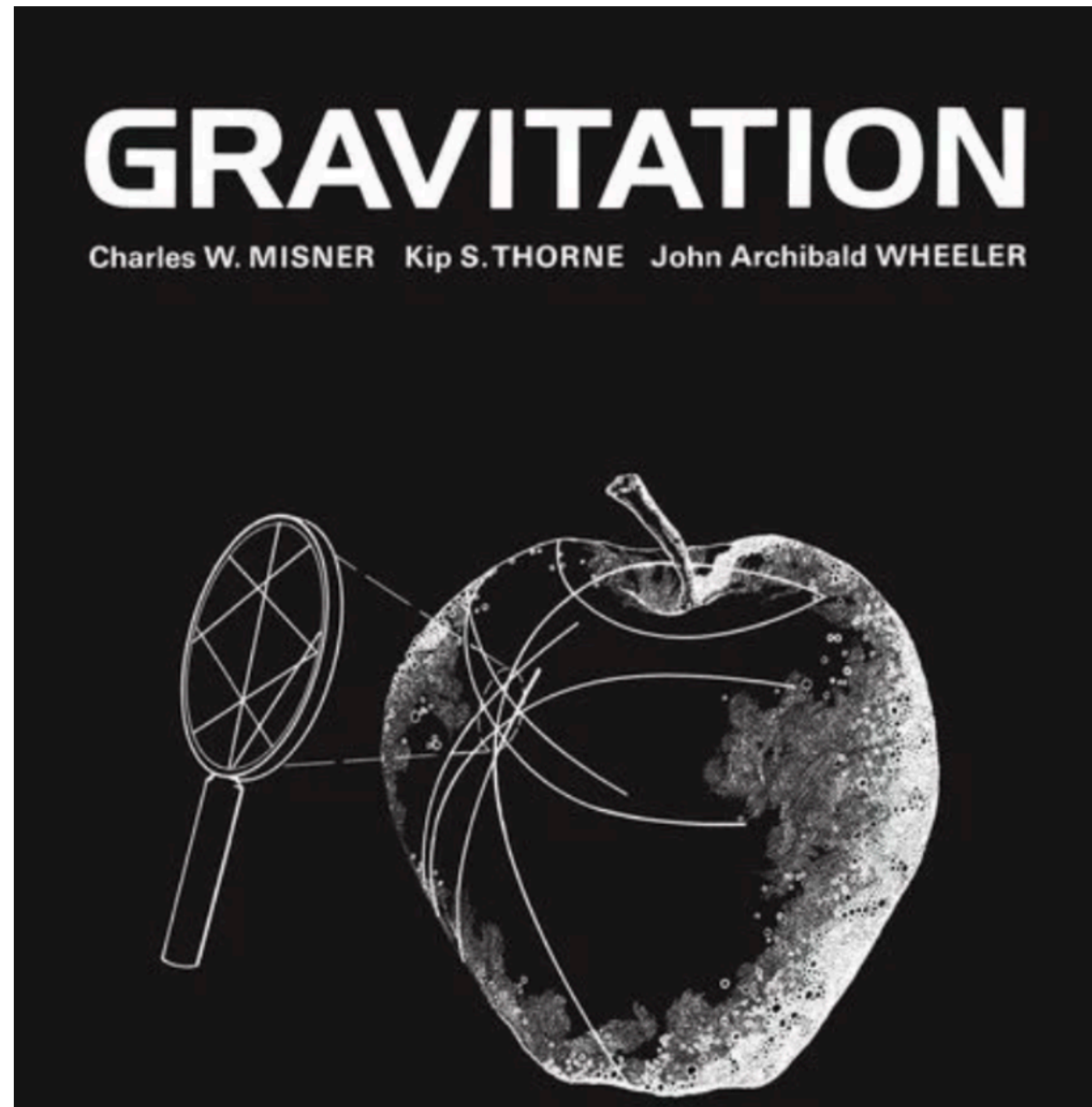


“ [interferometers] have so low sensitivity that they are of little experimental interest”

p. 1014

Ambitious, but rewarding goal

Misner, Thorne, Wheeler, 1973

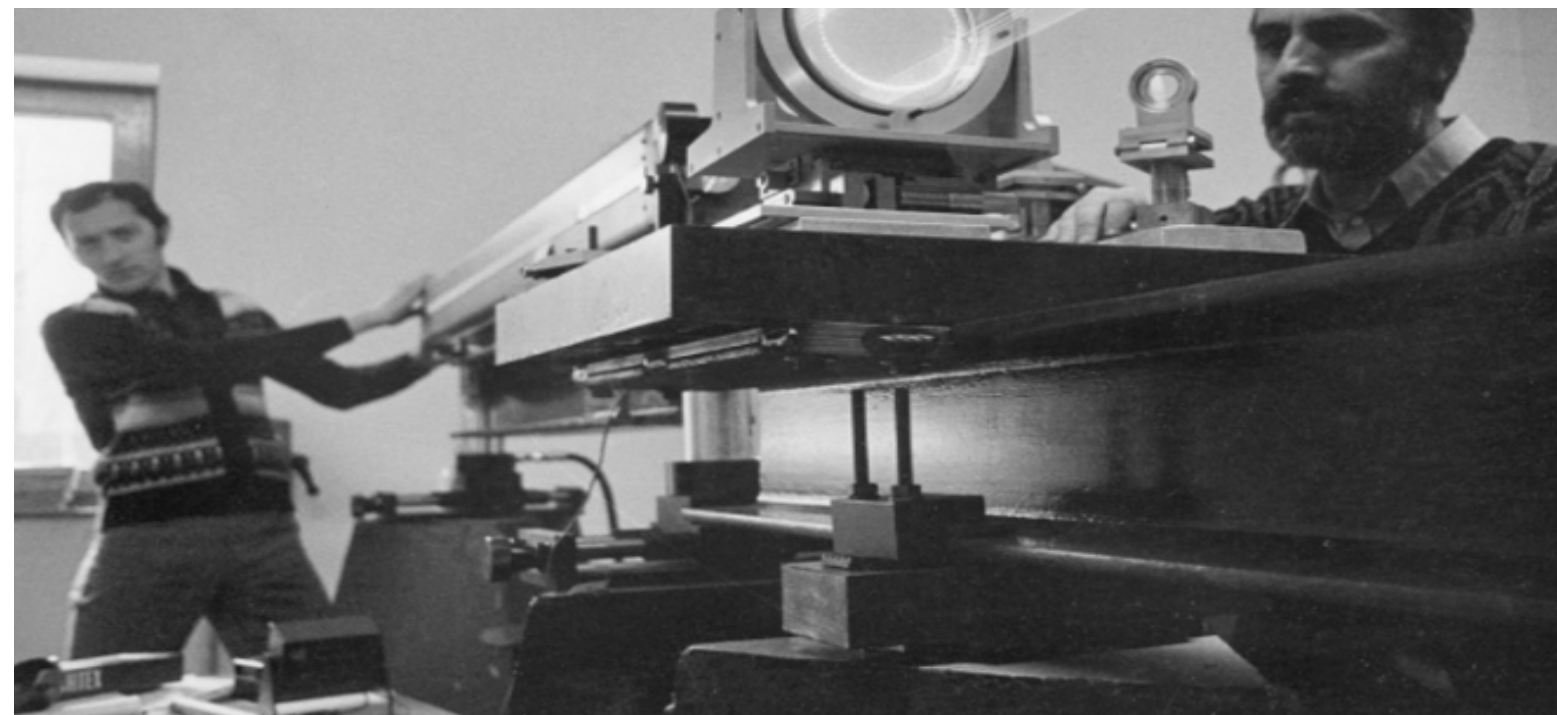


“ [interferometers] have so low sensitivity that they are of little experimental interest”

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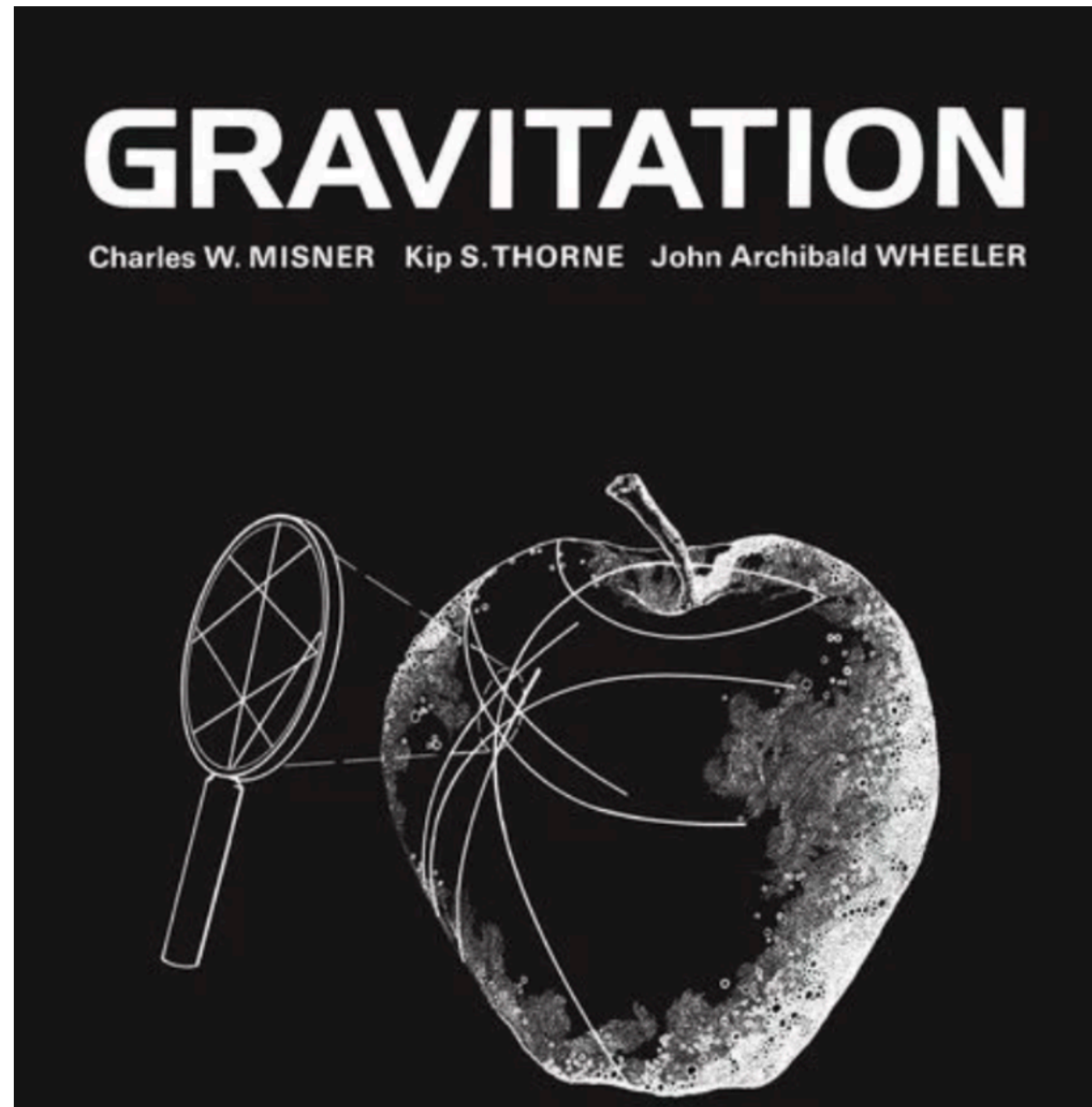


50 years of work, 23 attempts



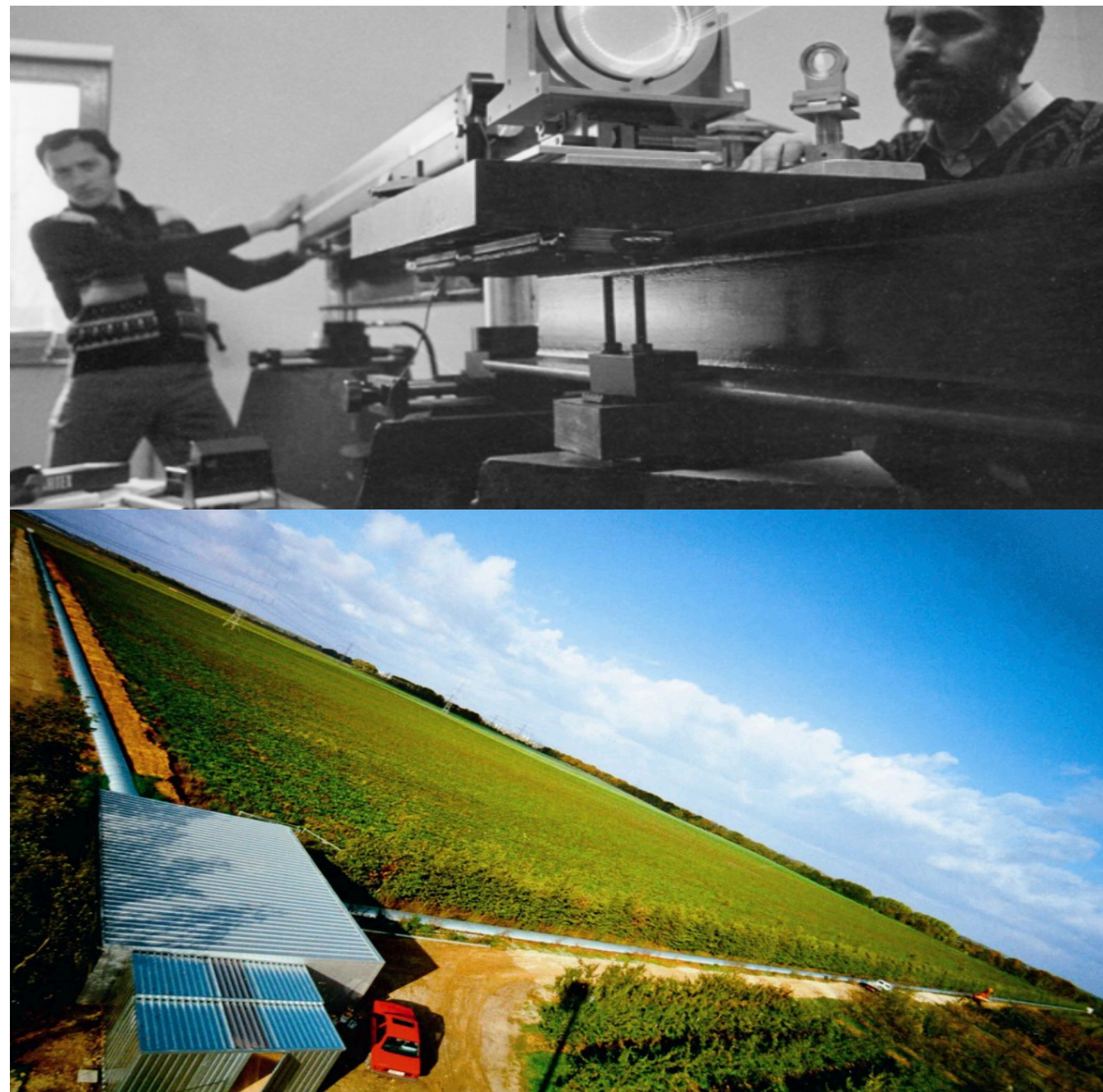
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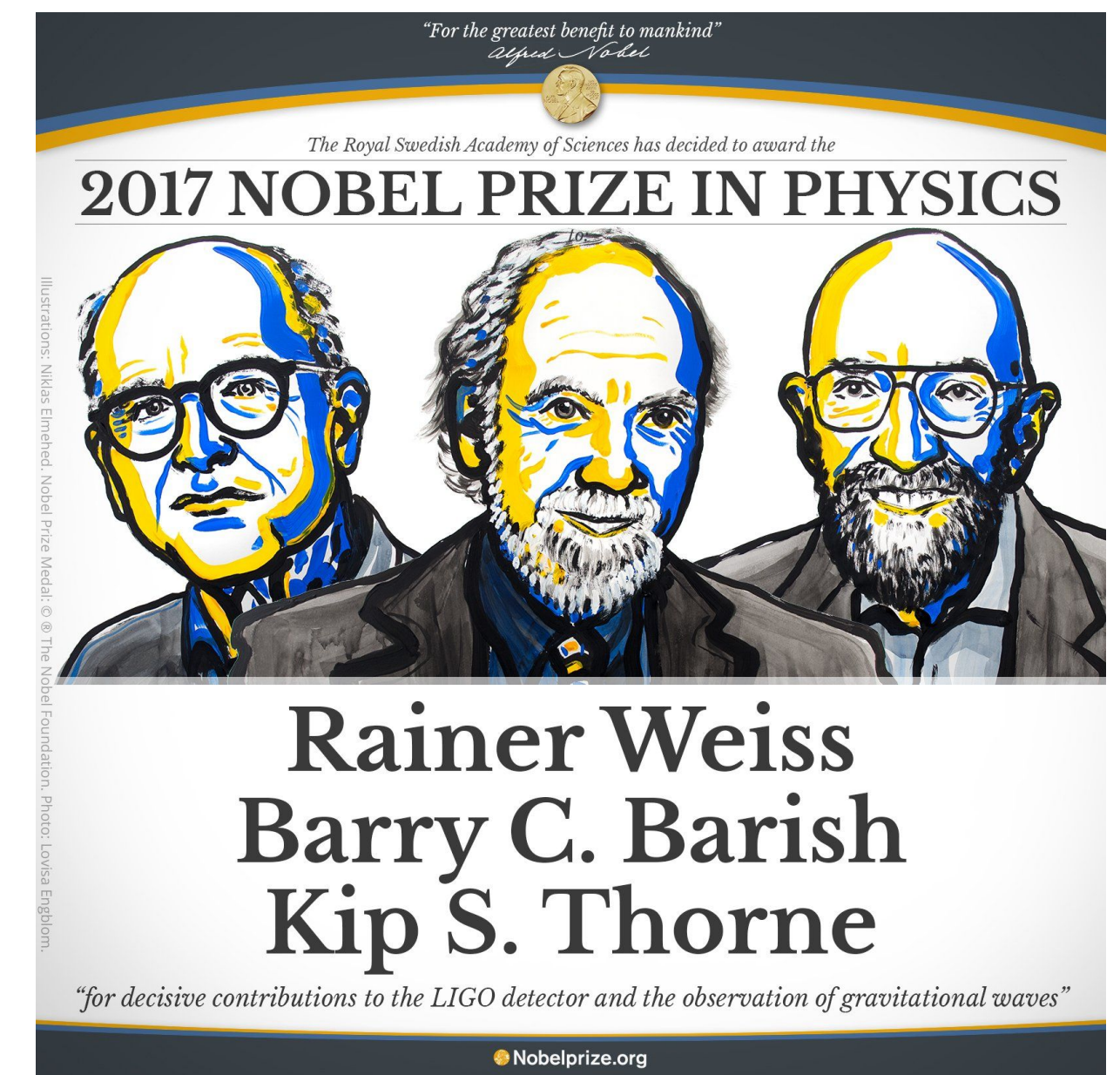


“ [interferometers] have so low sensitivity that they are of little experimental interest”

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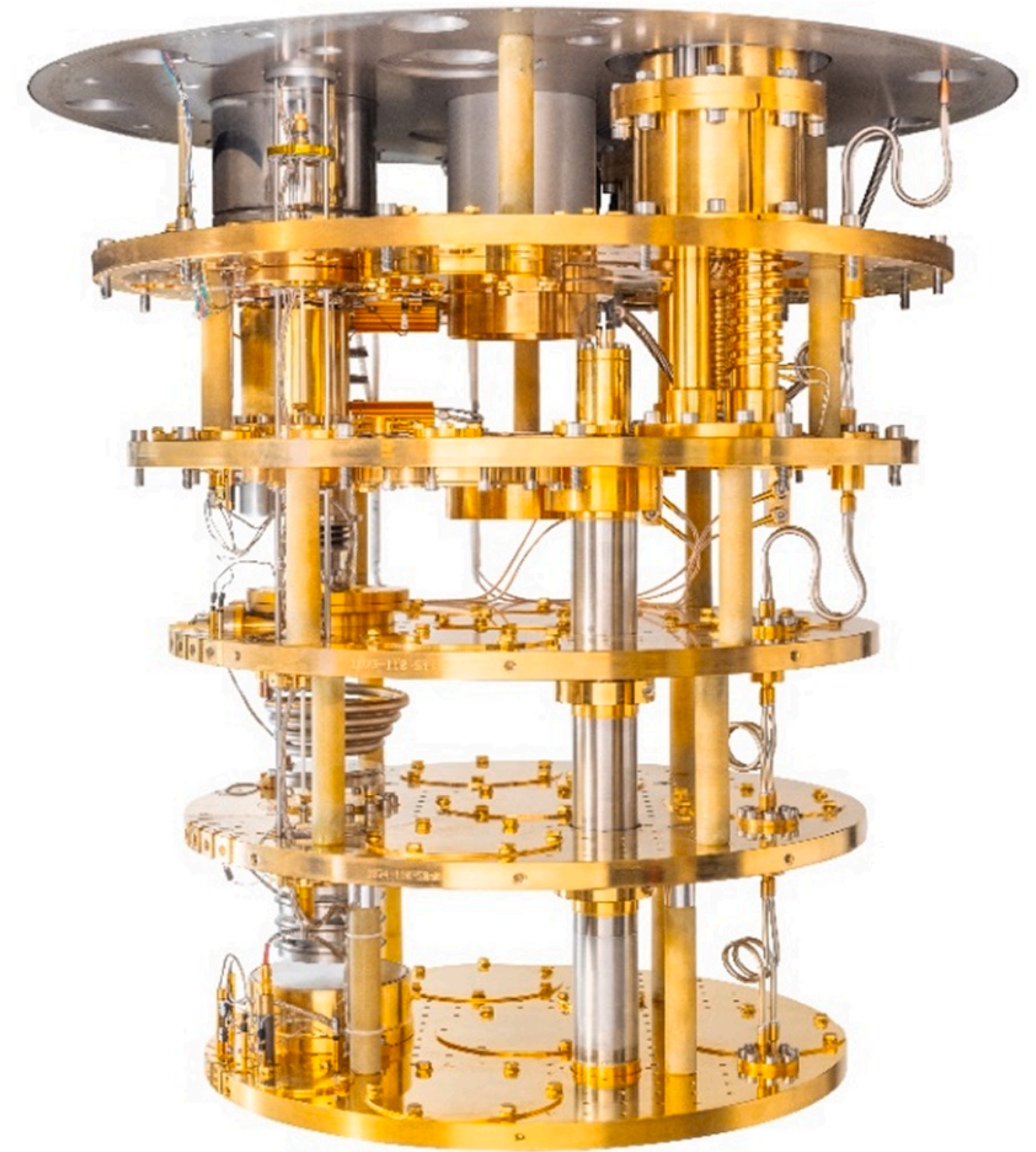


50 years of work, 23 attempts

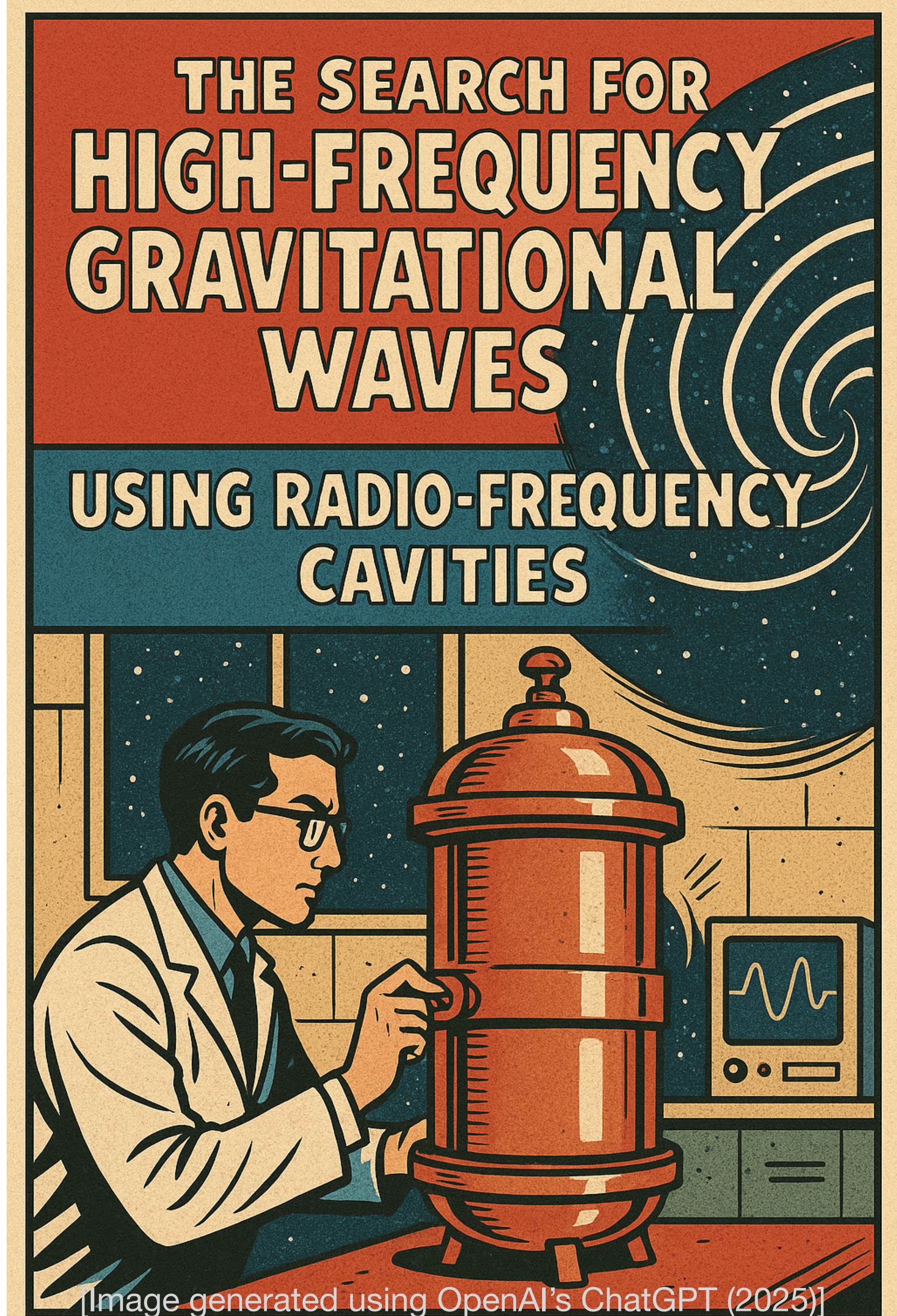


Which Technology to Choose?

- 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



- Searching for HFGW is one of the most intriguing new topics in town
 - Lots of challenges, **lots of opportunities**
- **New experiment at Bonn**
- GravNet Kick-off workshop (26/27 June)
 - <https://indico.him.uni-mainz.de/event/229>



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

BACKUP

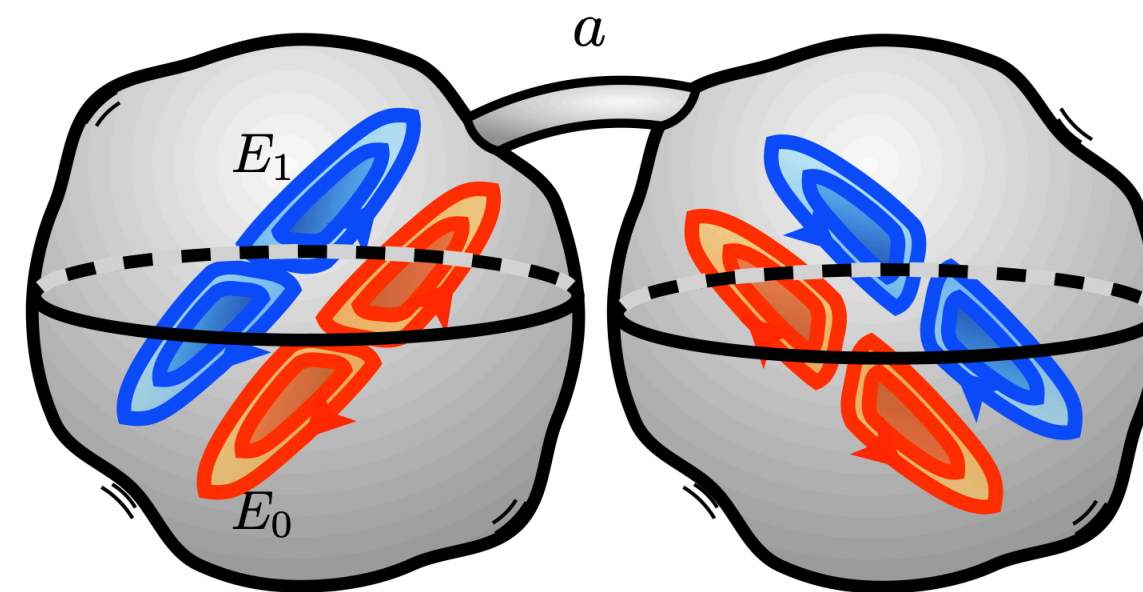
- Large range of experimental approaches tackling HFGW
- Three Categories:
 - Conversion of GWs (gravitons) into Photons
 - Something is mechanically deformed
 - Spin interaction

[arXiv:2011.12414]

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

4.2	Detection at frequencies beyond current detectors	31
4.2.1	Optically levitated sensors	31
4.2.2	Inverse Gertsenshtein effect	32
4.2.3	GW to electromagnetic wave conversion in a static electric field	33
4.2.4	Resonant polarisation rotation	33
4.2.5	Heterodyne enhancement of magnetic conversion	33
4.2.6	Bulk acoustic wave devices	33
4.2.7	Superconducting rings	34
4.2.8	GW deformation of microwave cavities	34
4.2.9	Graviton-magnon resonance	34

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



- **Pro:**
 - Amplification linear in Pump Power

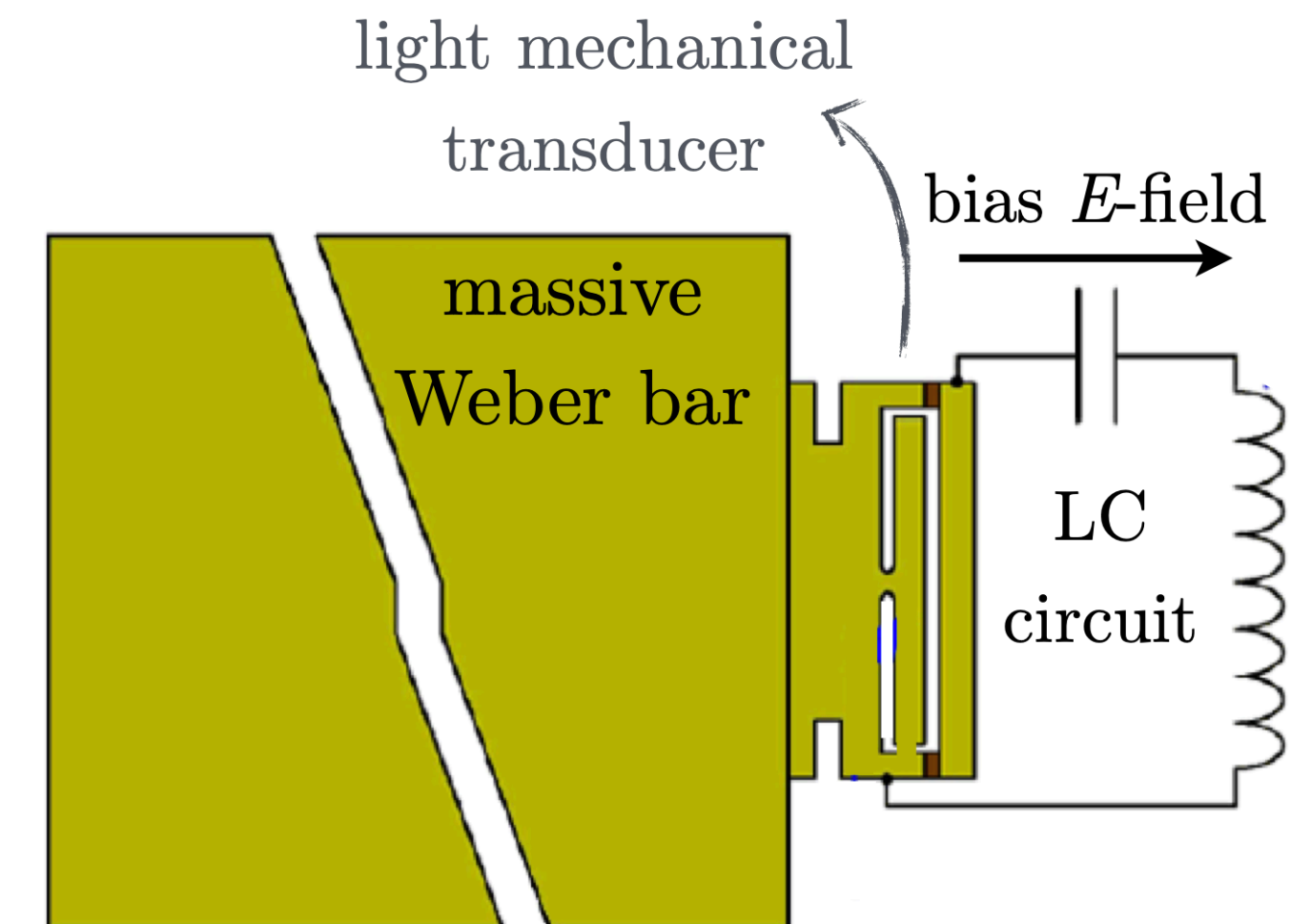
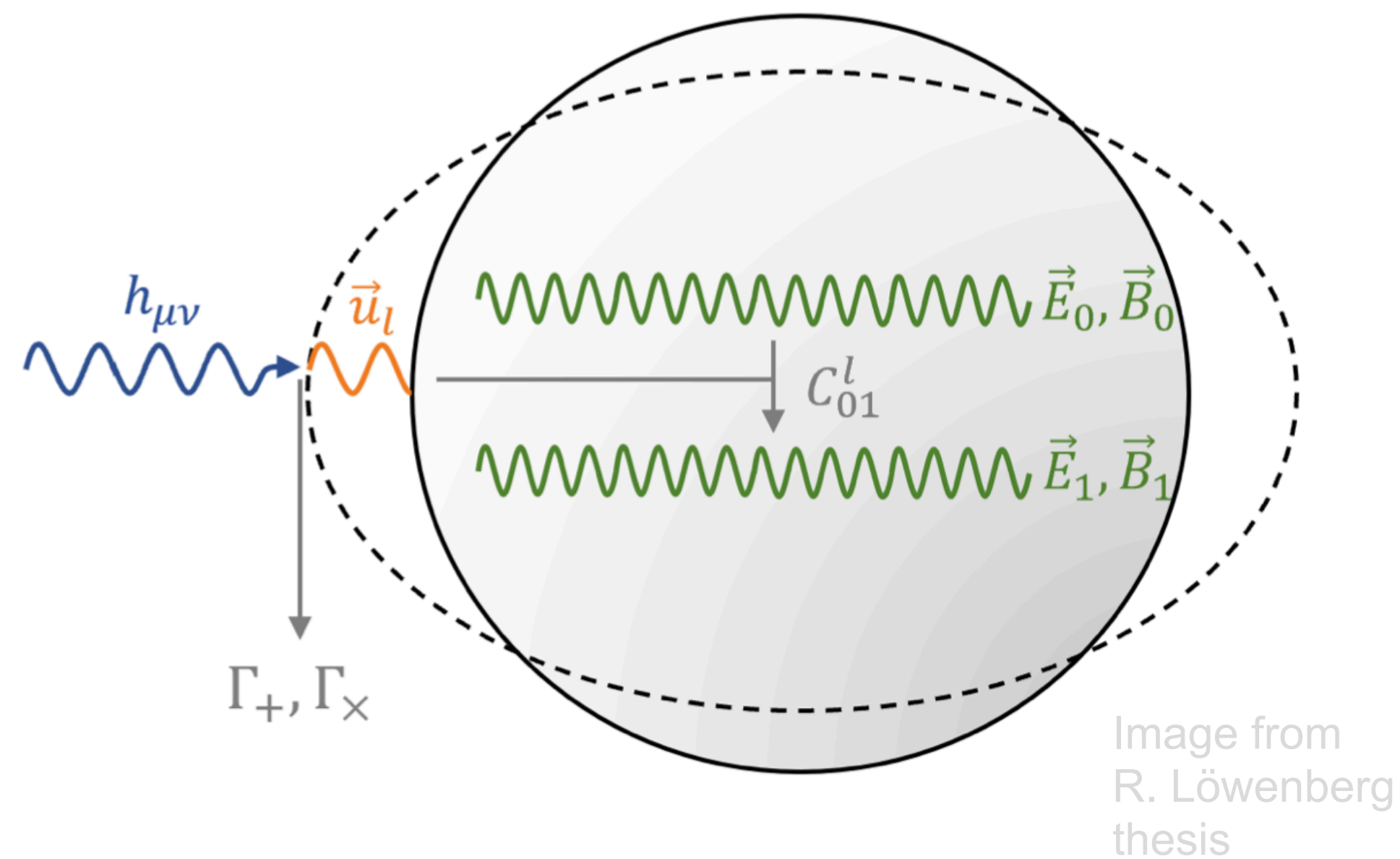
- **Con:**
 - Frequency stability of modes
 - RF leakage into signal mode

• MAGO experiment @ Desy

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

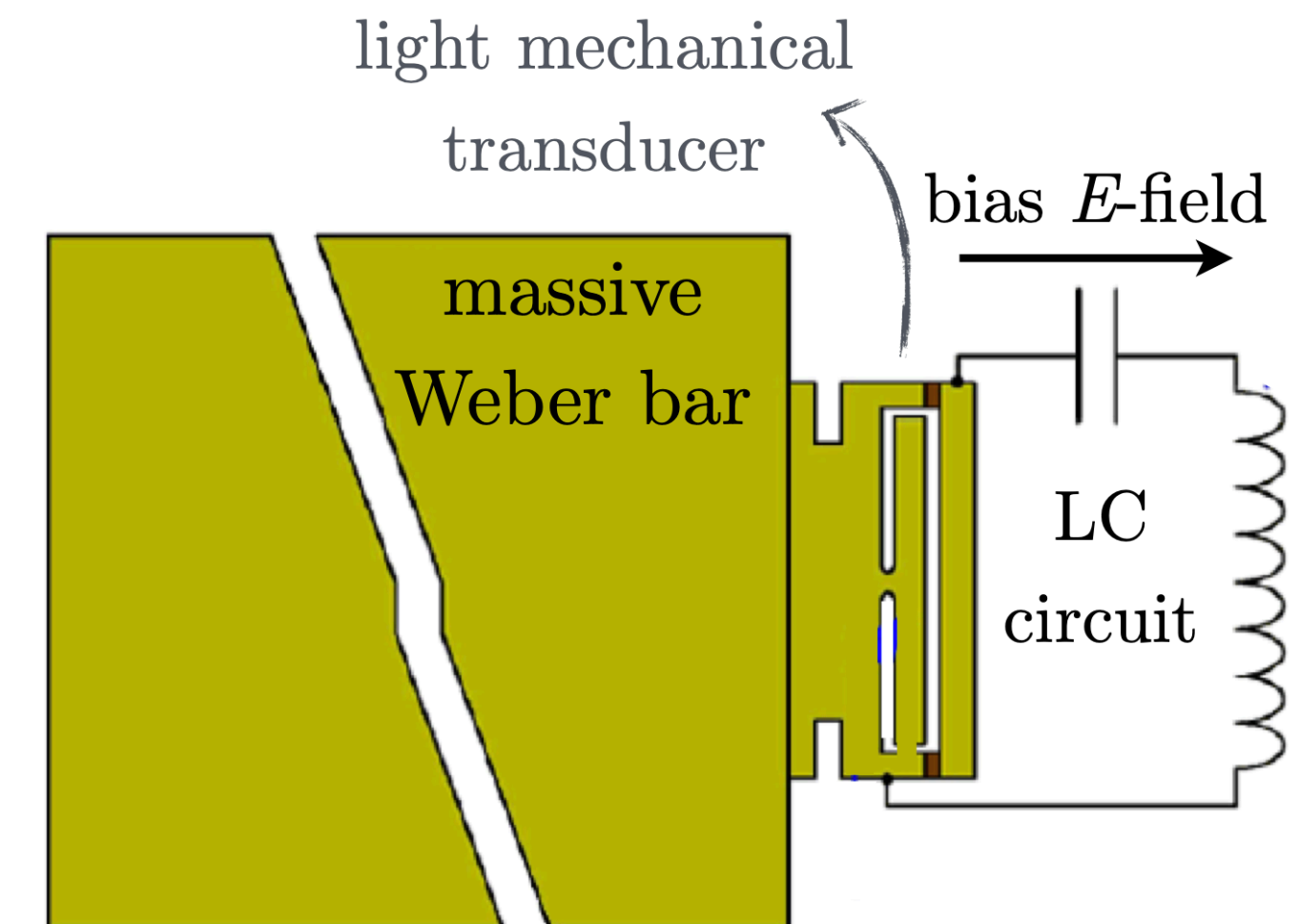
$$h_0 > 10^{-22} \quad h_0 > 10^{-21}$$

- Transfer of mechanical to EM energy
- Competing process for any cavity based detector
- Exploit mechanical resonances for enhancement
- Noise from environmental vibrations



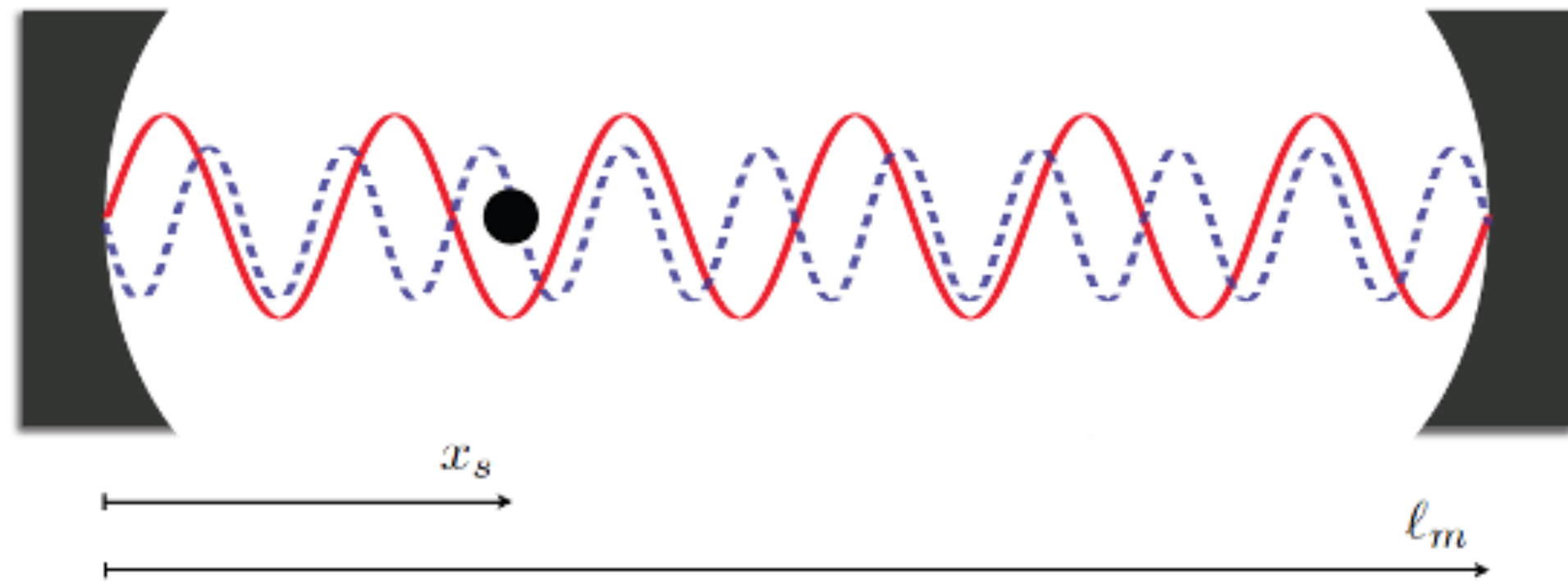
$$Q_{LC} \sim 10^6 \ll Q_{cav} \sim 10^{11}$$

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



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

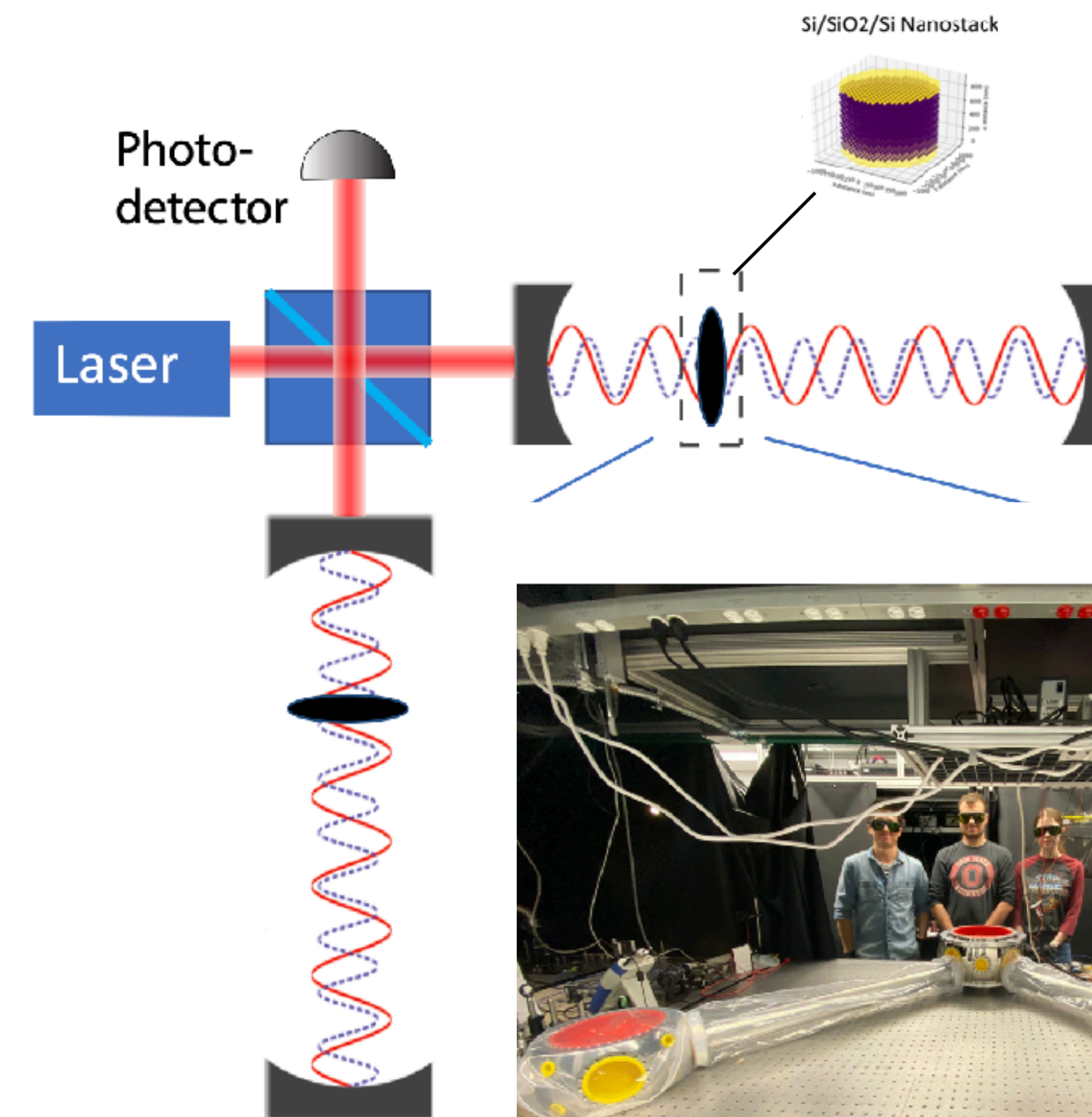
Arvanitaki, Geraci, PRL 110 (2013) 7



- Limited by thermal noise & Laser heating of levitated particle

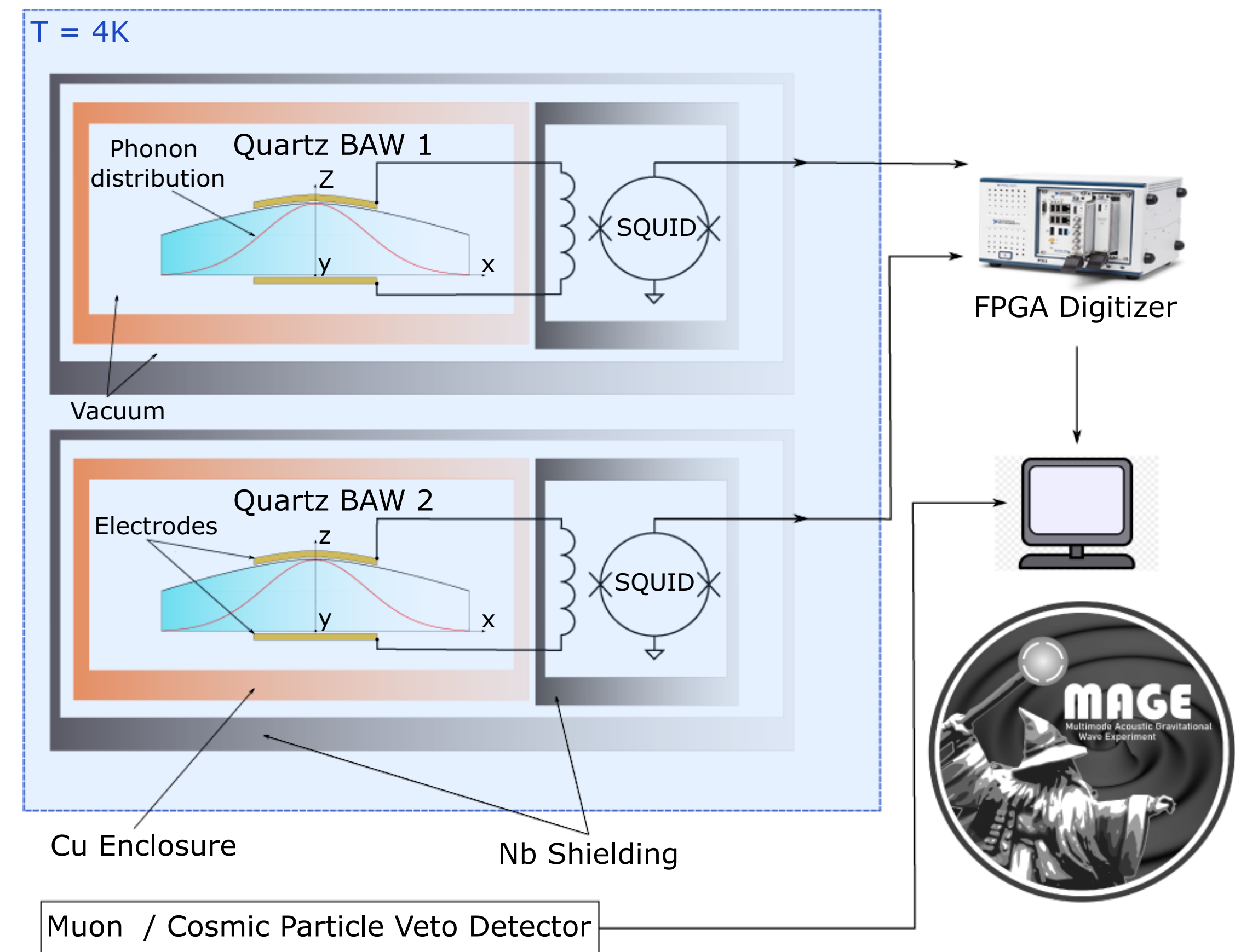
- Sensitivity from 10 kHz - 100kHz
- $h_0 > 10^{-21}$

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





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

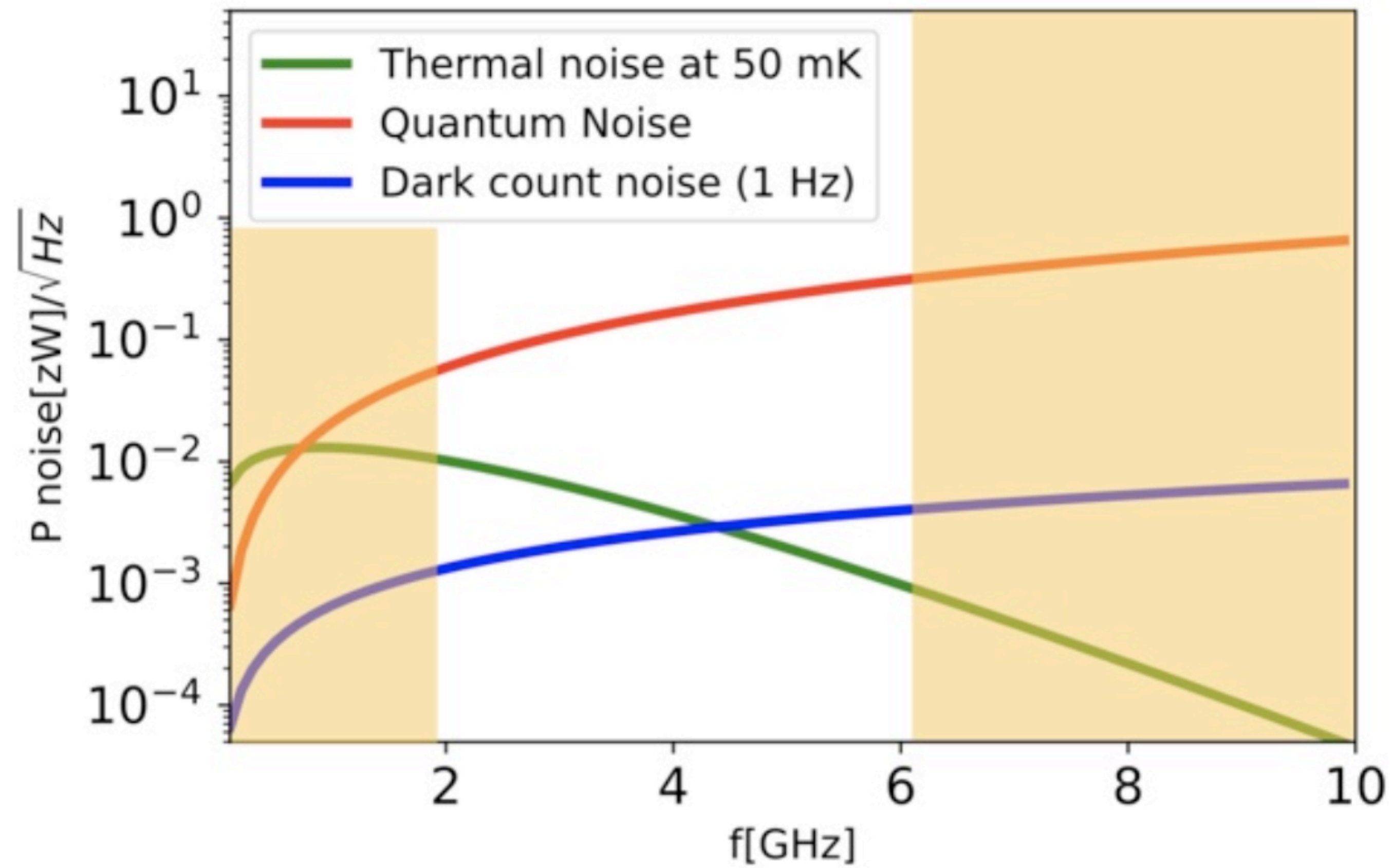


Muon / Cosmic Particle Veto Detector

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

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

Photon counting vs. Power readout



Maxwell equations in curved space time

Cosmological constant * metric tensor

$$\overset{\text{Einstein tensor}}{\underset{\uparrow}{G}}_{\mu\nu} + \overset{\downarrow}{\Lambda} g_{\mu\nu} = \kappa T_{\mu\nu} \quad \leftarrow \text{Energy-Momentum tensor}$$

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

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

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 + h_+ & h_\times & 0 \\ 0 & h_\times & -1 - h_+ & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

The covariant Maxwell's equations (in the source-free region) are:

$$\partial_\mu (\sqrt{-g} F^{\mu\nu}) = \partial_\mu (\sqrt{-g} g^{\mu\alpha} g^{\nu\beta} F_{\alpha\beta}) = 0 \quad (\text{A7a})$$

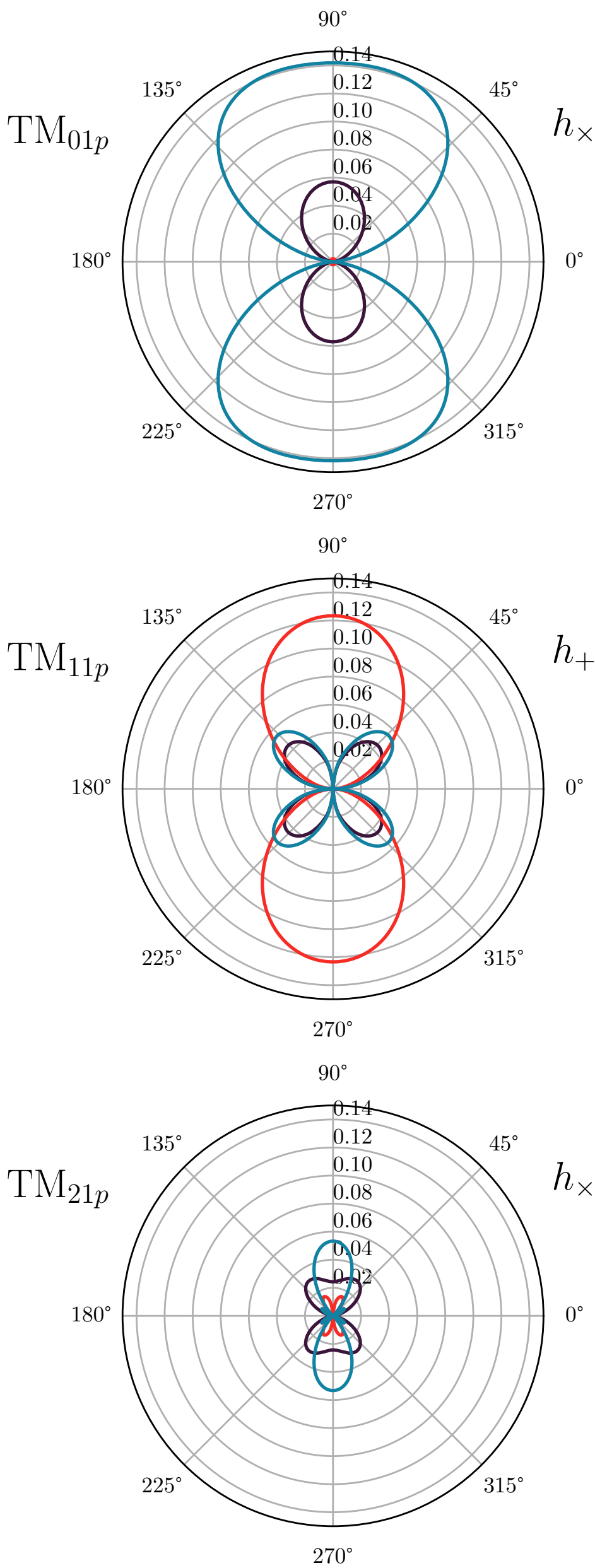
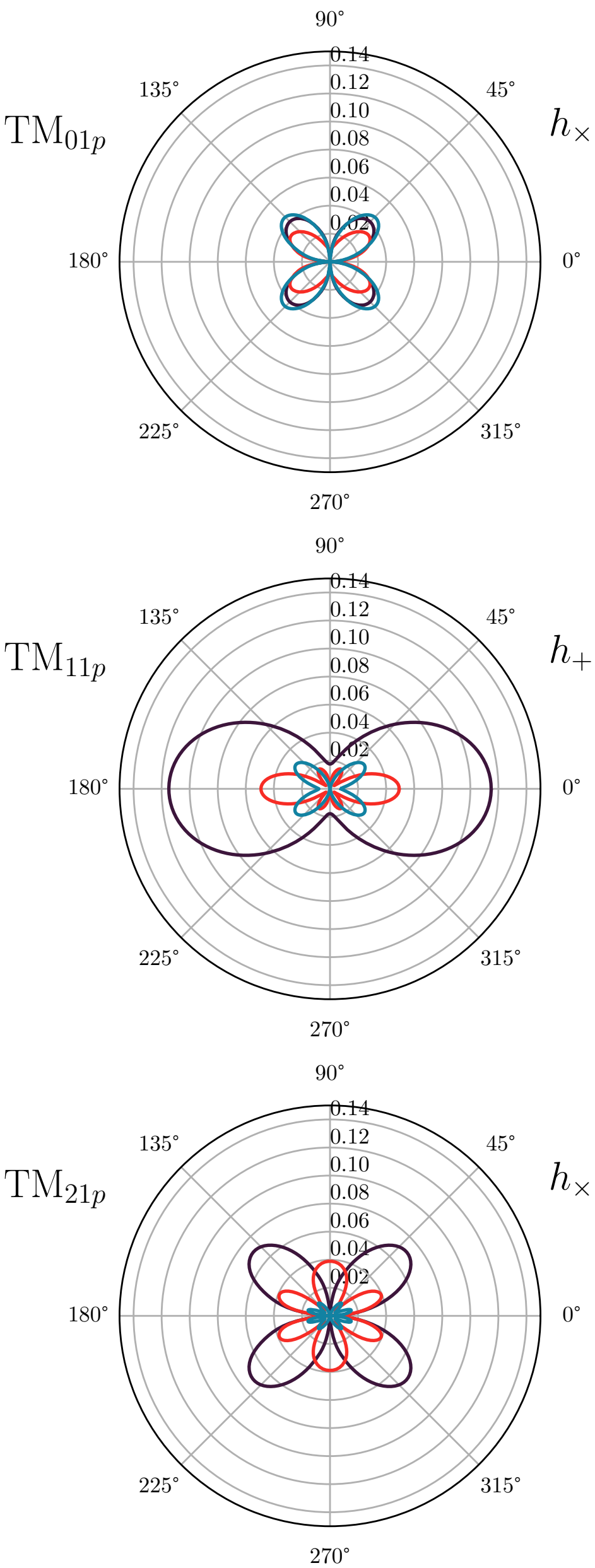
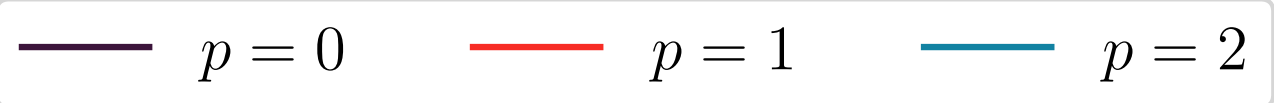
$$\partial_\mu (\sqrt{-g} \tilde{F}^{\mu\nu}) = \partial_\mu (\sqrt{-g} \eta^{\mu\nu\alpha\beta} F_{\alpha\beta}) = 0 \quad (\text{A7b})$$

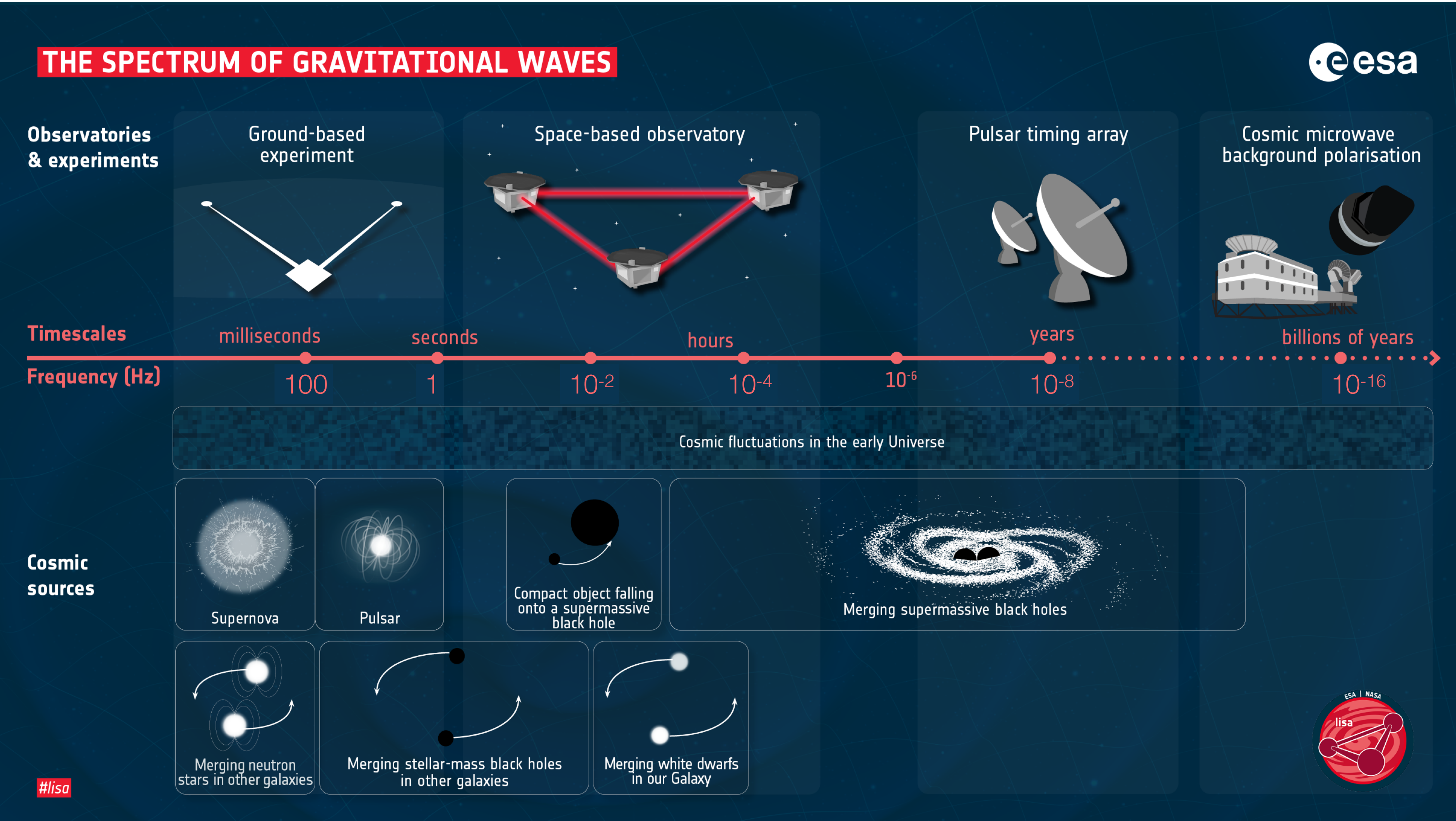
$$\eta_{\alpha\beta} = \text{diag}(1, -1, -1, -1)$$

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

$$F_{\alpha\beta} = F_{\alpha\beta}^{(0)} + F_{\alpha\beta}^{(1)} = \begin{pmatrix} 0 & \mathcal{E}_x & \tilde{E}_y & \tilde{E}_z \\ -\mathcal{E}_x & 0 & -\tilde{B}_z & \mathcal{B}_y \\ -\tilde{E}_y & \tilde{B}_z & 0 & -\tilde{B}_x \\ -\tilde{E}_z & -\mathcal{B}_y & \tilde{B}_x & 0 \end{pmatrix}$$

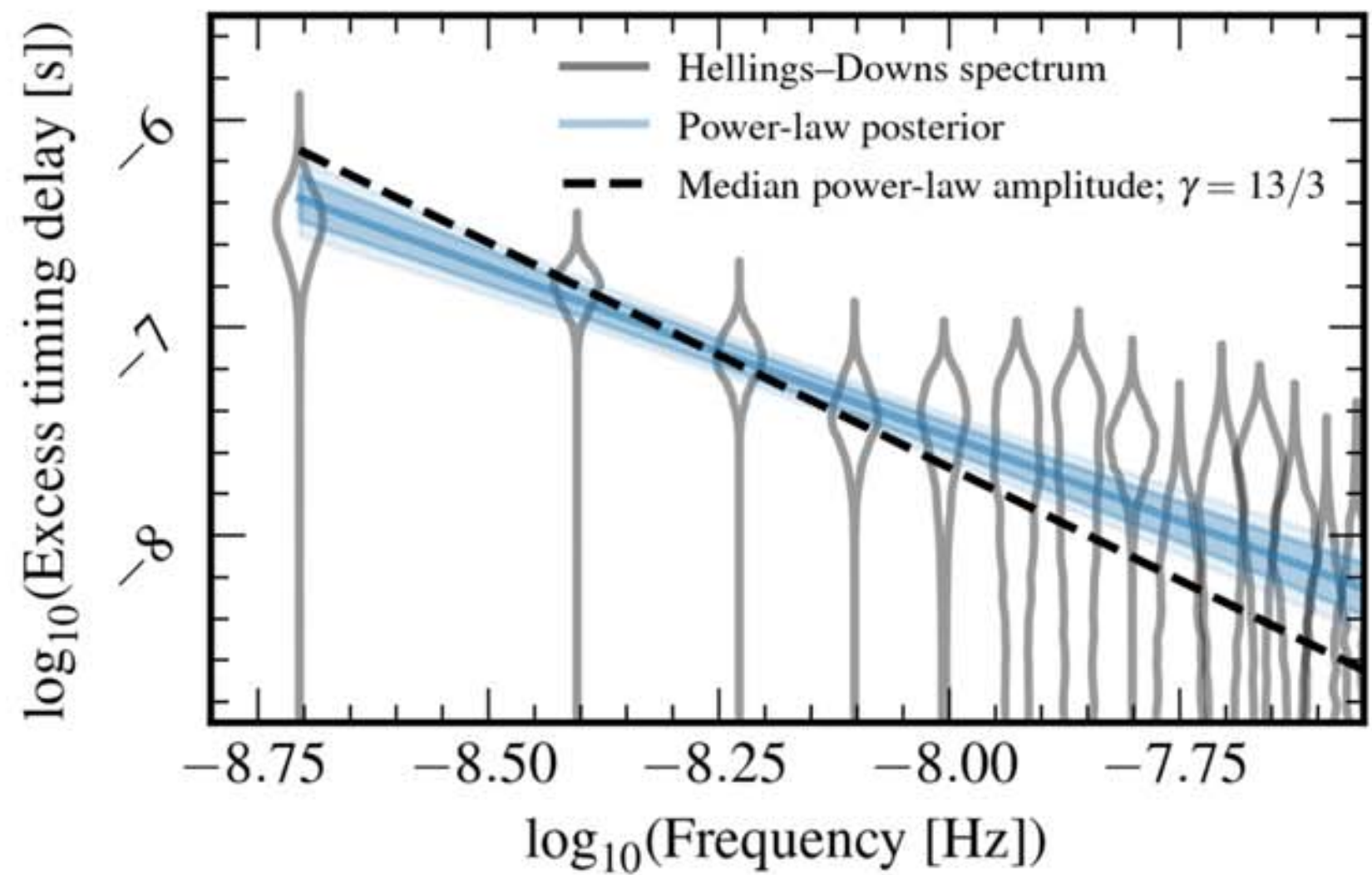
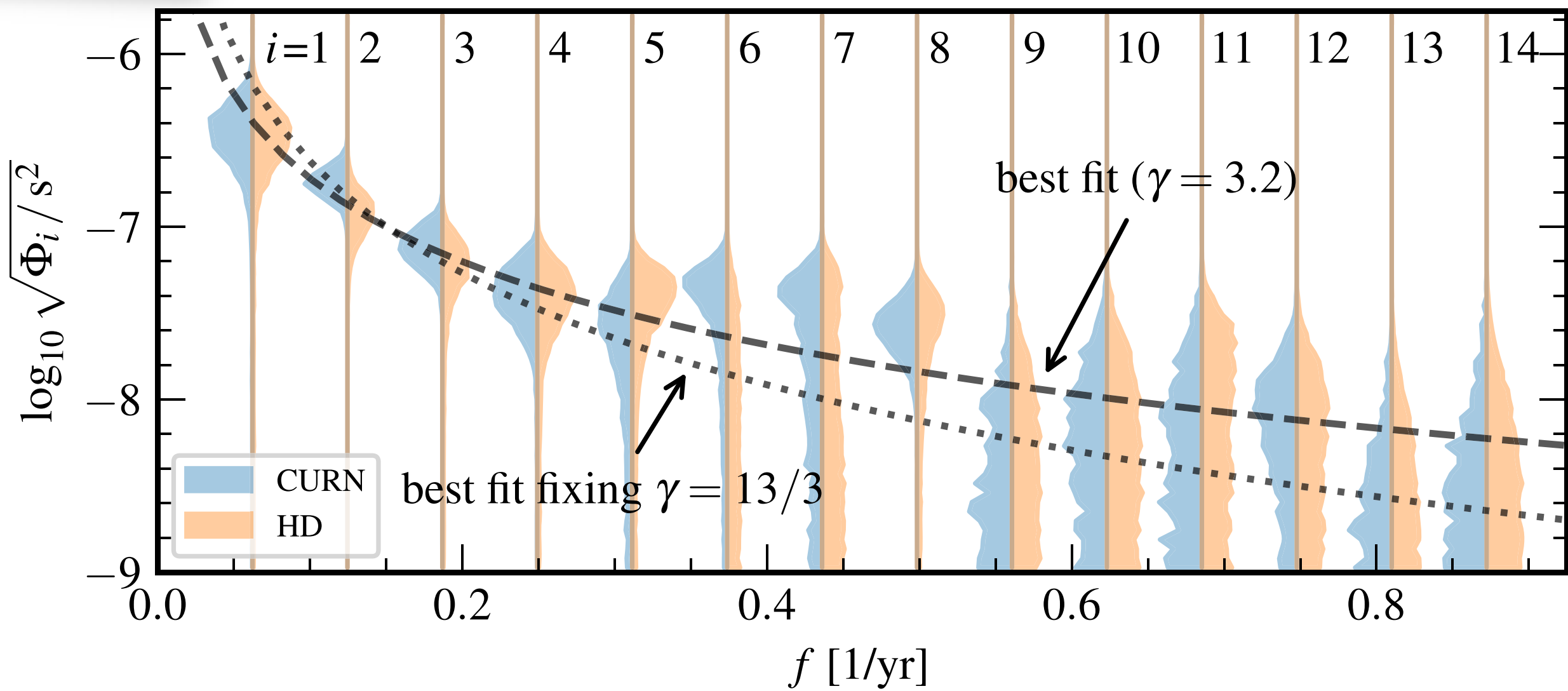
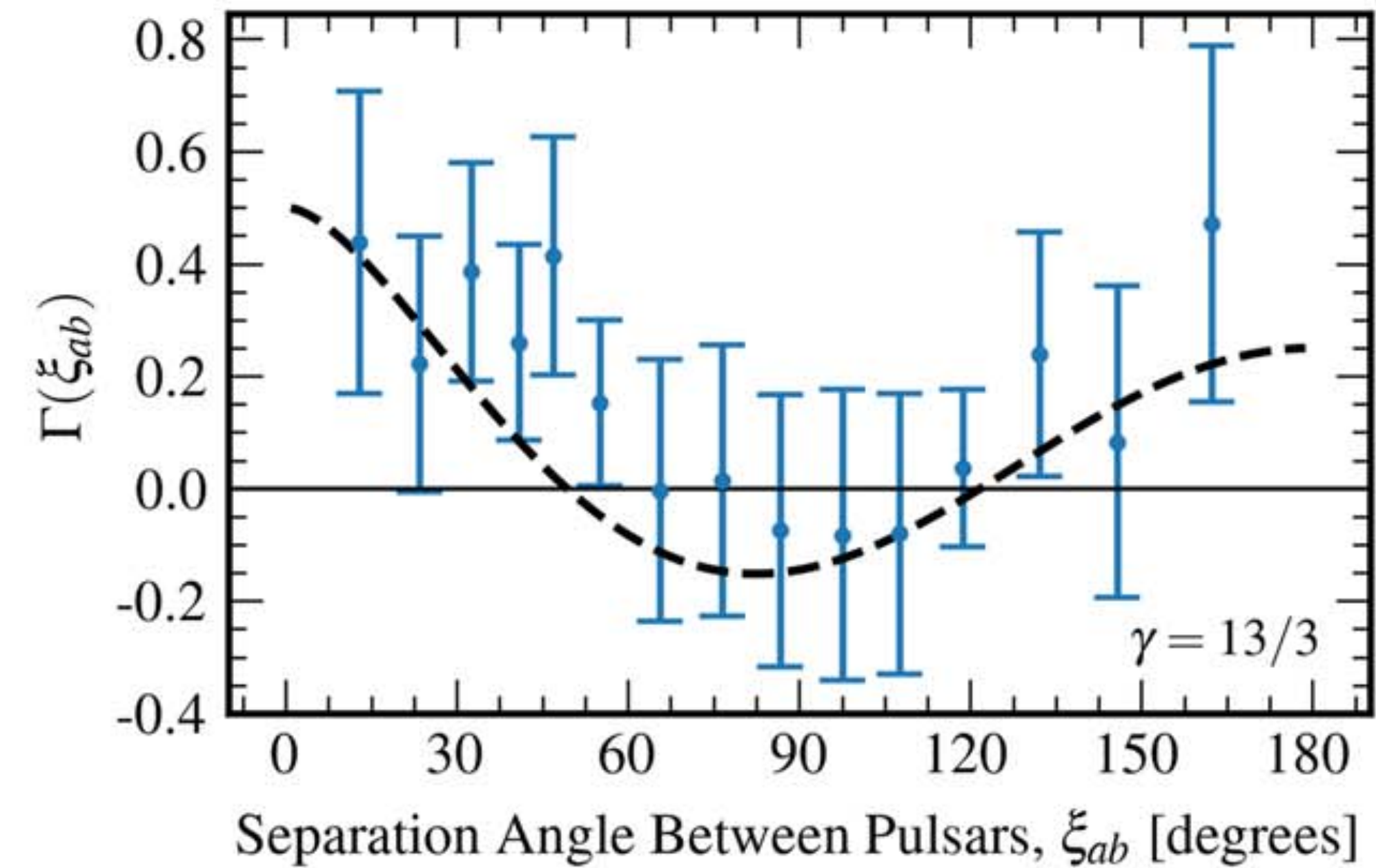
Coupling of GW - Cavity mode





- 2023: First observation of GW in Pulsar timing array data

[Gabriella Agazie et al 2023 ApJL 951 L8]

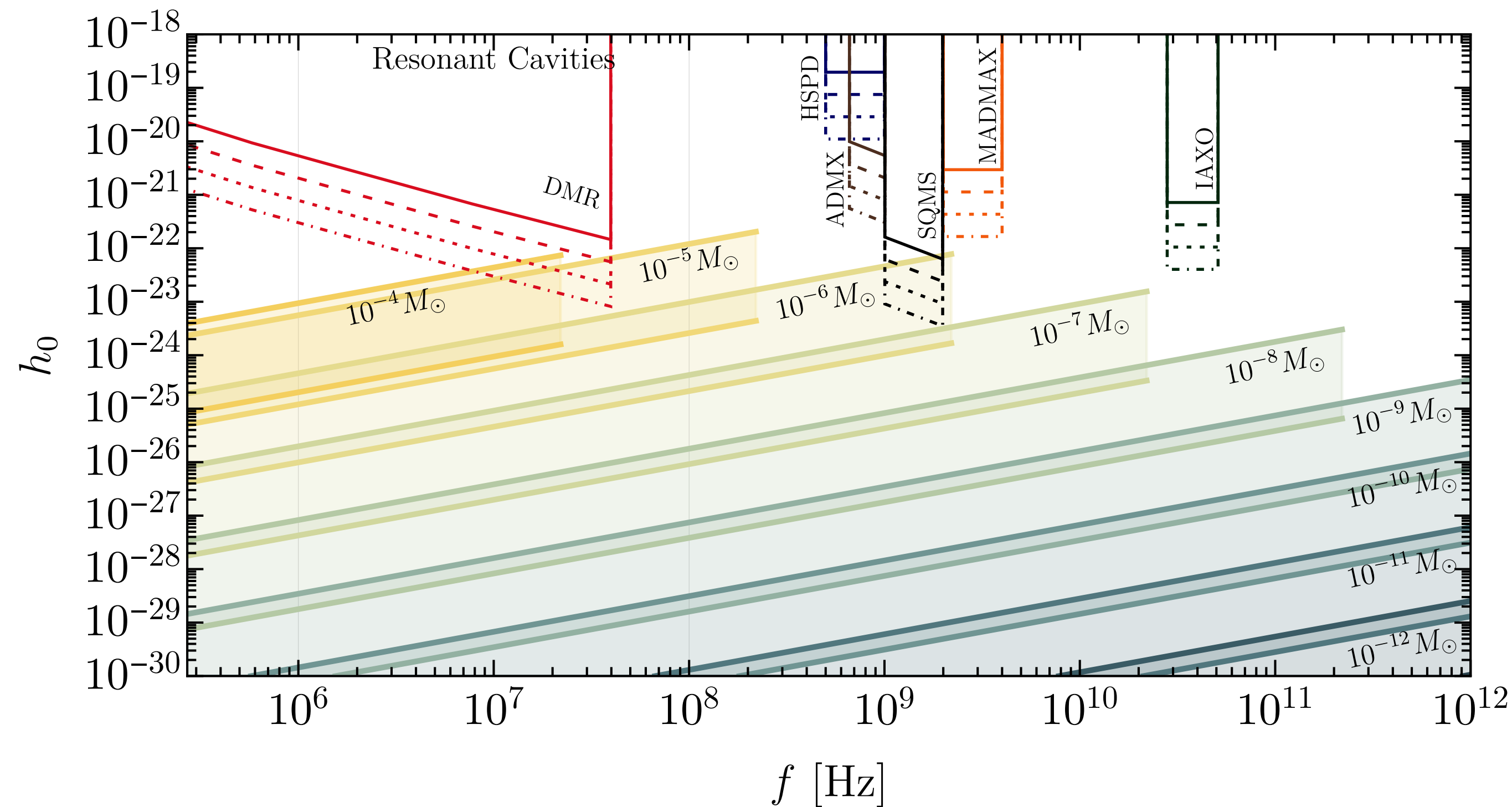


$$h_0 \simeq 9.77 \times 10^{-34} \left(\frac{f}{1 \text{ GHz}} \right)^{2/3} \left(\frac{m_{\text{PBH}}}{10^{-12} M_\odot} \right)^{5/3} \left(\frac{d_L}{1 \text{ kpc}} \right)^{-1}$$

- Assuming $f_{\text{PBH}} = \Omega_{\text{PBH}}/\Omega_{\text{DM}} = 1$

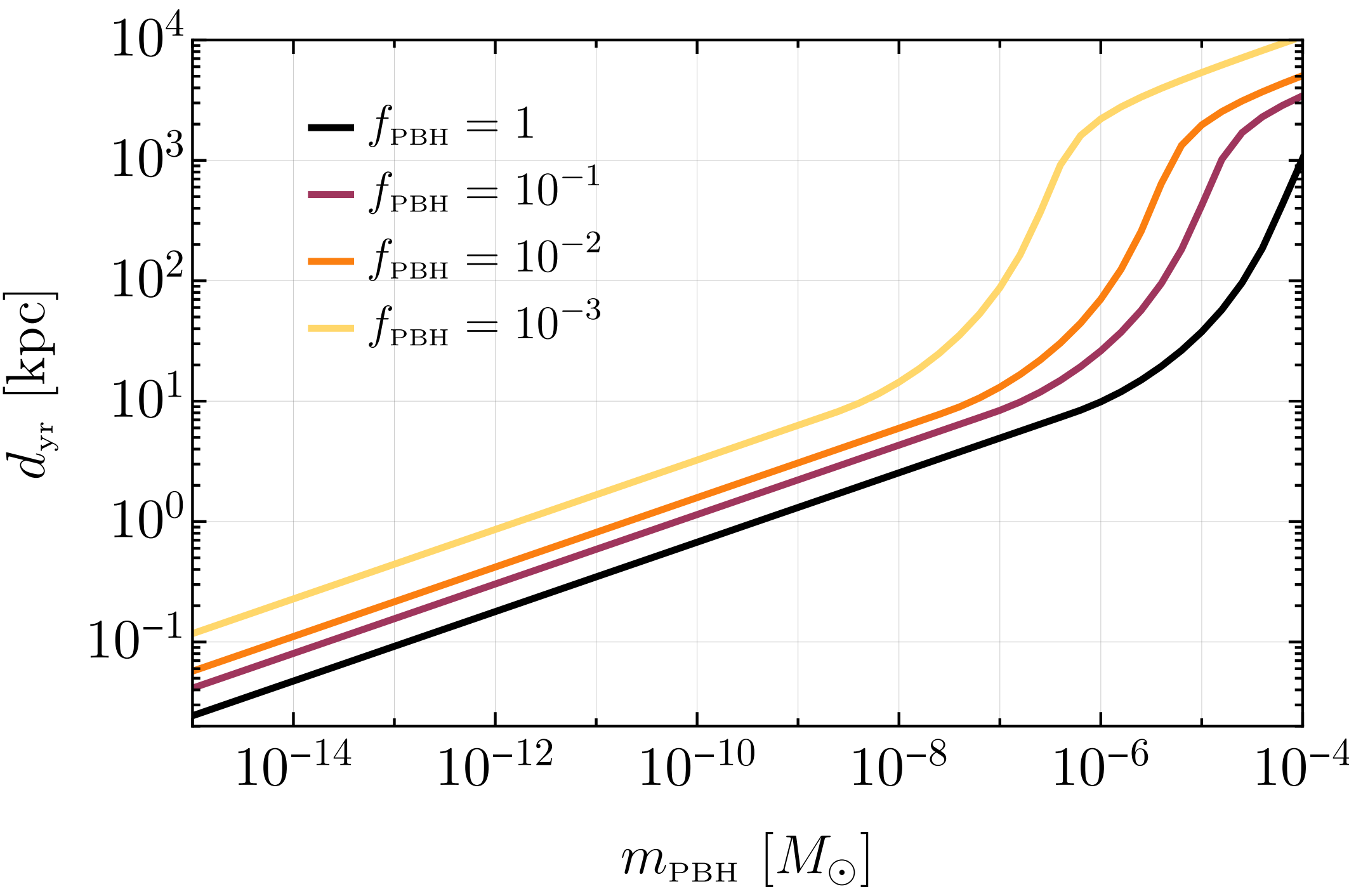
- Allowed for: $m_{\text{PBH}} \subset (10^{-16} \div 10^{-10}) M_\odot$

[arXiv:1906.05950]



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

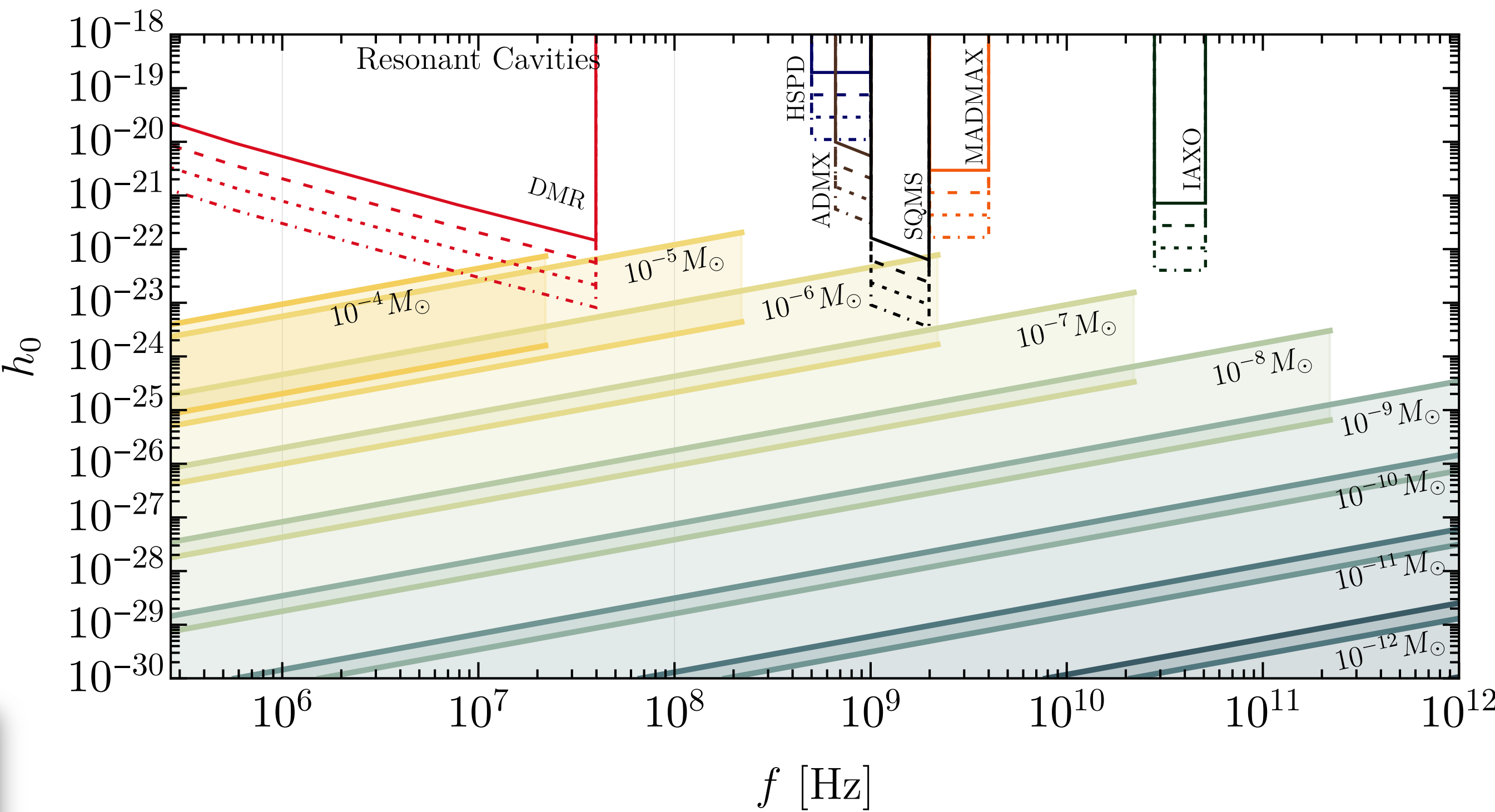
$$h_0 \simeq 9.77 \times 10^{-34} \left(\frac{f}{1 \text{ GHz}} \right)^{2/3} \left(\frac{m_{\text{PBH}}}{10^{-12} M_\odot} \right)^{5/3} \left(\frac{d_L}{1 \text{ kpc}} \right)^{-1}$$



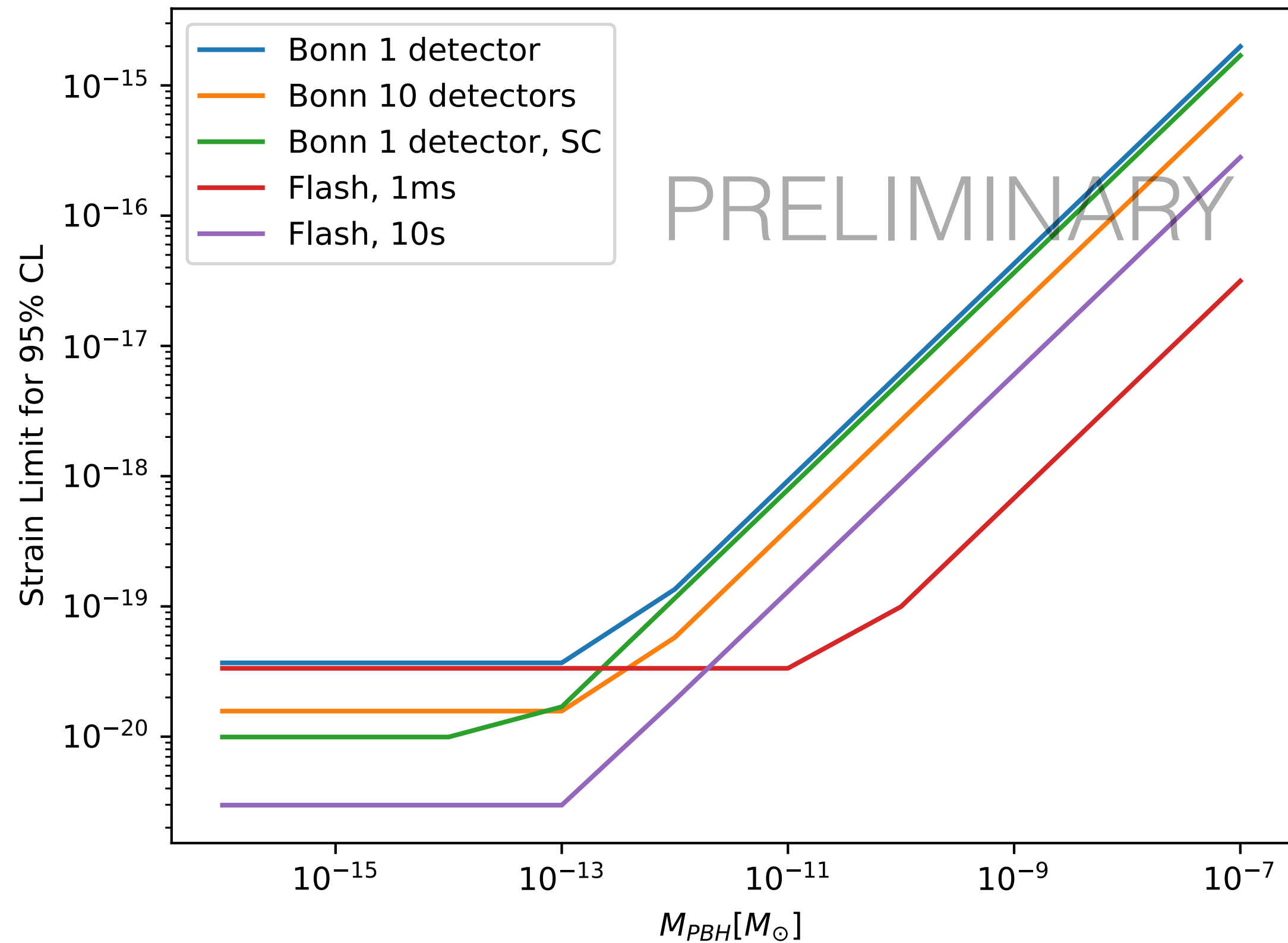
- Distance = d_{yr} = radius of sphere with ≥ 1 PBH merger / year
- Slope change: impact of local DM over density

- Assuming $f_{\text{PBH}} = \Omega_{\text{PBH}}/\Omega_{\text{DM}} = 1$
- Allowed for: $m_{\text{PBH}} \subset (10^{-16} \div 10^{-10}) M_\odot$

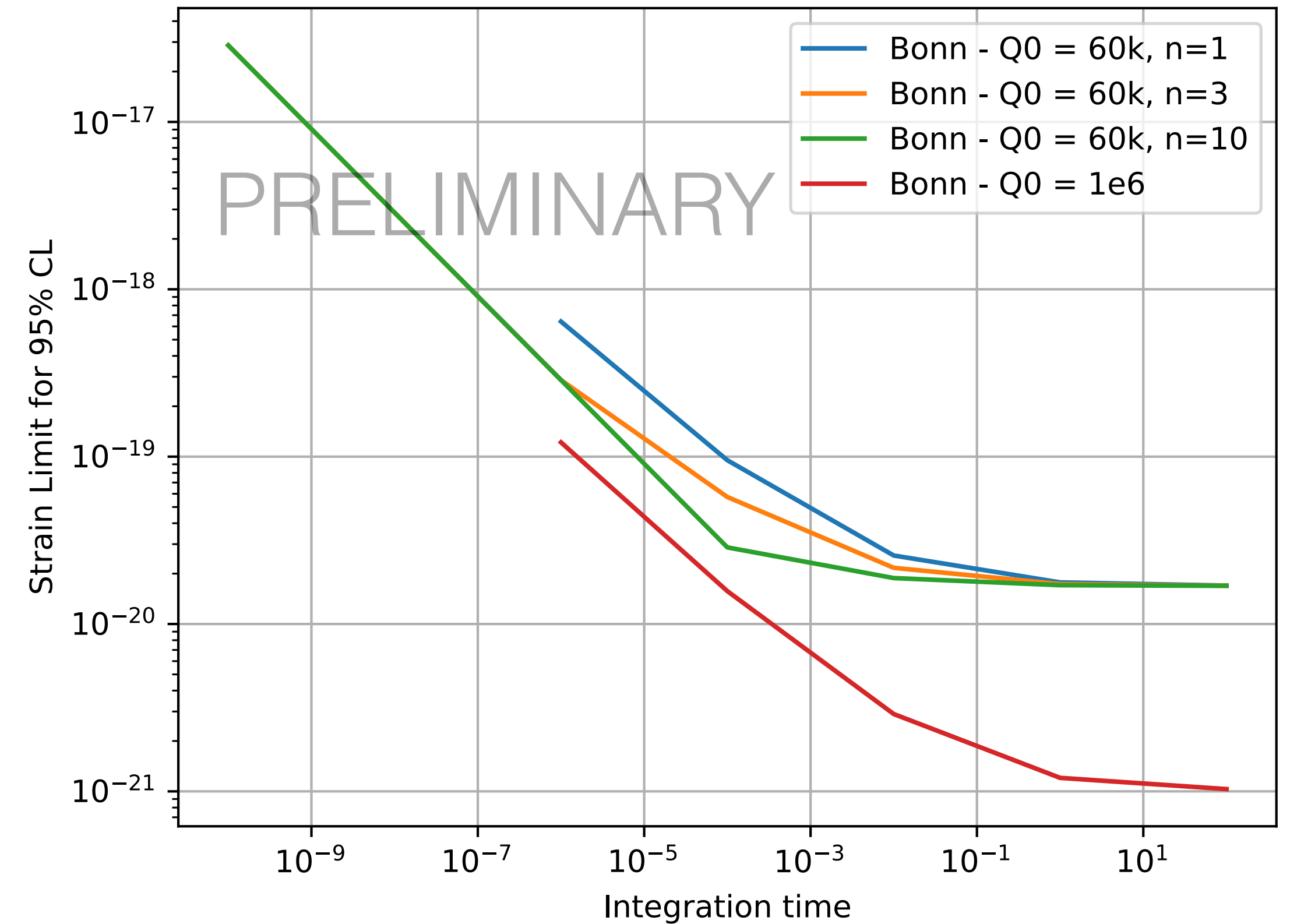
[arXiv:1906.05950]



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



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



- Most interesting UHFGW source: **Primordial black hole merges**
 - **Fast transient** signal!
 - Typically **< ns - ms** in GHz range
 - Novel **analysis strategies needed**
 - **Frequency domain** analysis with **short integration intervals**
 - **Time-domain** analysis
 - **Full correlation of time-series**
 - Define **'Trigger'** and combined time window around
 - **Single photon detection**: coincidence experiment

$$\dot{f} = 4.62 \cdot 10^{11} \text{Hz}^2 \left(\frac{m_{PBH}}{10^{-9} M_{\odot}} \right)^{5/3} \left(\frac{f}{\text{GHz}} \right)^{11/3}$$

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- **To resonantly excite a cavity:**
 - GW frequency must stay within resonator bandwidth
 - $\omega/Q \approx 10^9 Hz / 10^5 = 10 kHz$
 - Broadband setup might be superior to high Q-factor cavities

$$\dot{f} = 4.62 \cdot 10^{11} Hz^2 \left(\frac{m_{PBH}}{10^{-9} M_{\odot}} \right)^{5/3} \left(\frac{f}{GHz} \right)^{11/3}$$

$m_{PBH} [M_{\odot}]$	$f_{ISCO} [GHz]$	$f_{cavity} [GHz]$	$\dot{f} [Hz/s]$	$\Delta t [s]$
1E-13	4E+07	1.0	9.95E+04	1.00E+00
1E-13	4E+07	5.0	3.64E+07	2.75E-03
1E-13	4E+07	10.0	4.62E+08	2.16E-04
1E-11	4E+05	1.0	2.14E+08	4.66E-04
1E-11	4E+05	5.0	7.84E+10	1.28E-06
1E-11	4E+05	10.0	9.95E+11	1.00E-07
1E-09	4E+03	1.0	4.62E+11	2.16E-07
1E-09	4E+03	5.0	1.69E+14	5.92E-10
1E-09	4E+03	10.0	2.14E+15	4.66E-11
1E-07	4E+01	1.0	9.95E+14	1.00E-10
1E-07	4E+01	5.0	3.64E+17	2.75E-13
1E-07	4E+01	10.0	4.62E+18	2.16E-14

Table 1. For all resonance frequency a quality factor of $Q = 50k$ is assumed.

- Readout Noise
 - Linear amplifiers:
 - Standard Quantum Limit
- Overcome by:
 - **Parametric** amplifiers (today's standard)
 - Single RF **Photon counting**
 - Tomorrow's Standard
 - Allows coincidence experiments

- Readout Noise

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- Recent progress in R&D for single RF photon counters
- Several technologies under study
 - Current Biased Josephson Junctions
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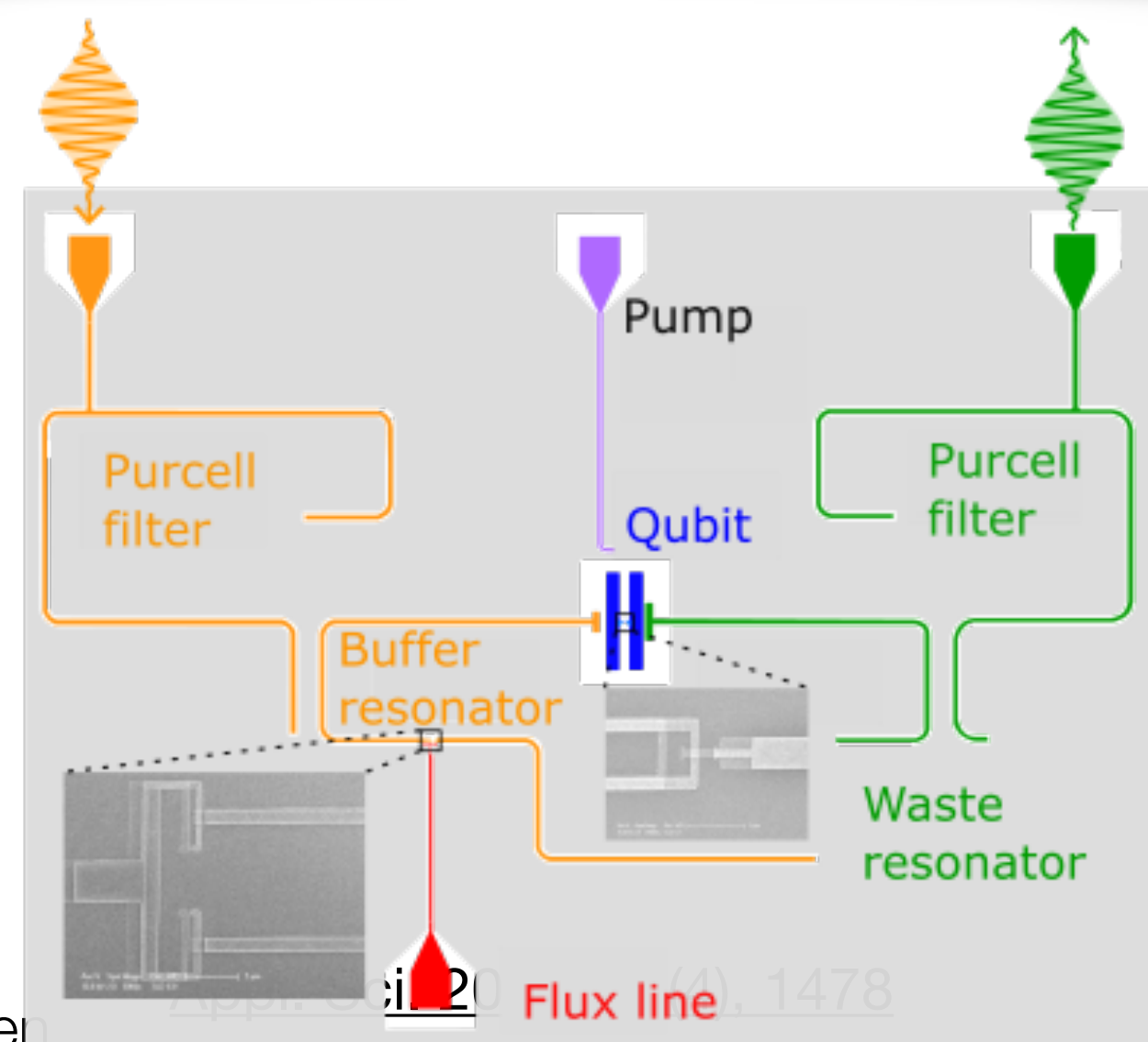
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[arXiv:2307.03614]

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

GravNet - Current Efforts

- **Mainz** (Schmieden, Schott, Schneemann, Schwaller, Schenk):
 - Preparatory studies within PRISMA+
 - Haloscope setup and first data, cavity design, analysis strategies,
 - D. Budker will join next year with ERC synergy grant with Schott, Gatti, Blas



- **Bonn** (M. Schott):
 - Currently working on analysis strategies
 - New Setup expected late 2025 (10 mK, 12 T, 5 GHz)



- **INFN** Frascati (C. Gatti):
 - Leading FLASH experiment (150MHz, m3 Cavity)
 - Work on TDR for FLASH started
 - GW runs foreseen from design on



Ultra-high frequency gravitational waves: where to next ?

Dec 4, 2023, 9:00 AM → Dec 8, 2023, 7:00 PM Europe/Zurich

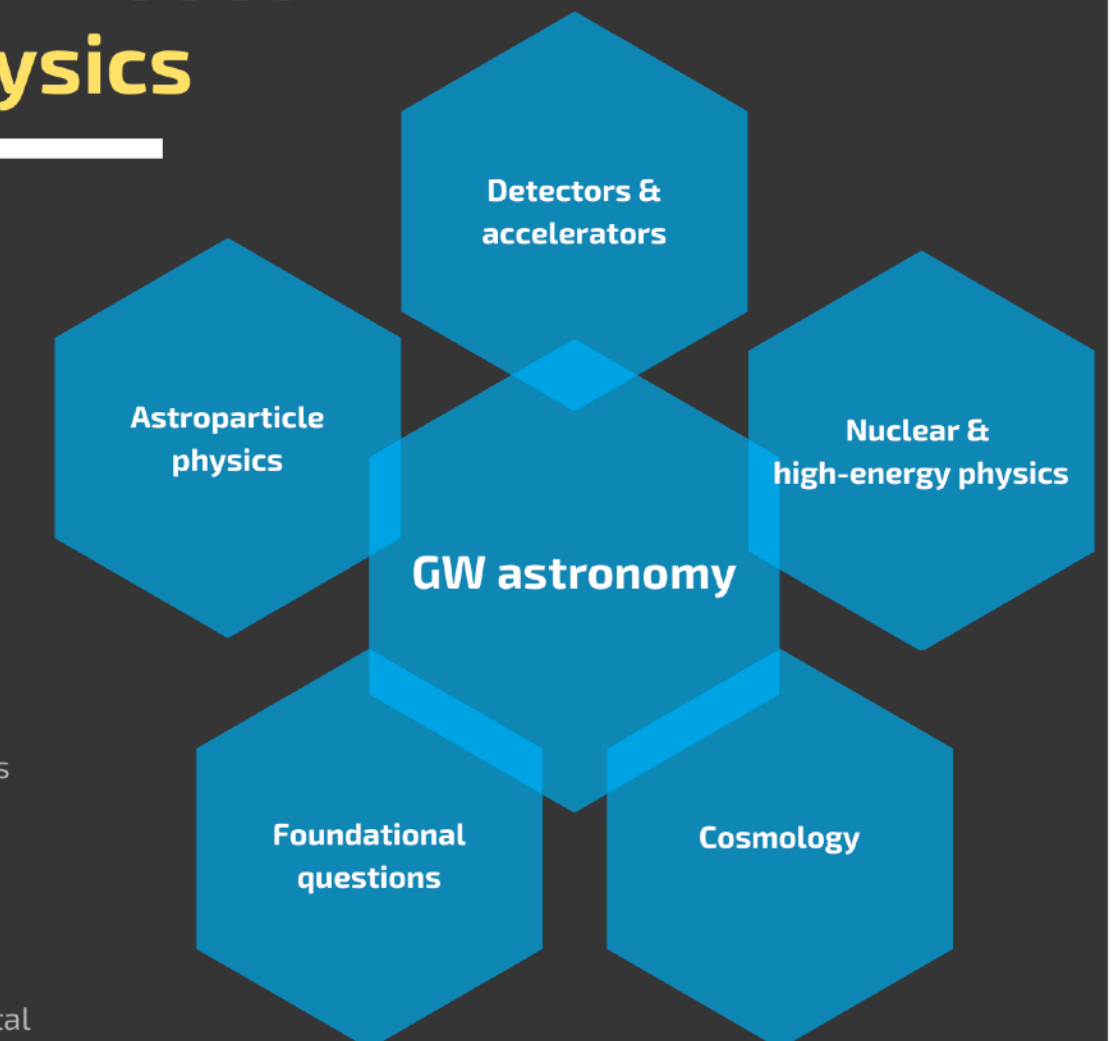
4/3-006 - TH Conference Room (CERN)



Gravitational Wave Probes of Fundamental Physics

A cross-cutting initiative for a common platform to:

- Foster synergies among astroparticle, atomic, nuclear, high-energy, and gravitational physics, cosmology, and GW and multi-messenger astronomy
- Strengthen the connection between the theoretical and experimental/observational communities
- Share expertise, tools, cutting edge technologies to attack multidisciplinary problems
- Train a new generation of researchers with diverse expertise and background
- Share and disseminate knowledge in fundamental physics



Endorse this initiative @ <https://agenda.infn.it/e/GWFundPhys>

- Target sensitivity: $h_0 < 10^{-24}$ with **ms** - **μ s** time resolution

Network of distributed GW detectors

- Various possibilities
 - **Time evolution of ms spectra**
 - Easy, very noisy
 - **Simultaneous fit of time series data**
 - Computationally challenging
 - **Coincident experiment**
 - Requires **single RF photon detection**
 - Technique developed here at KIT

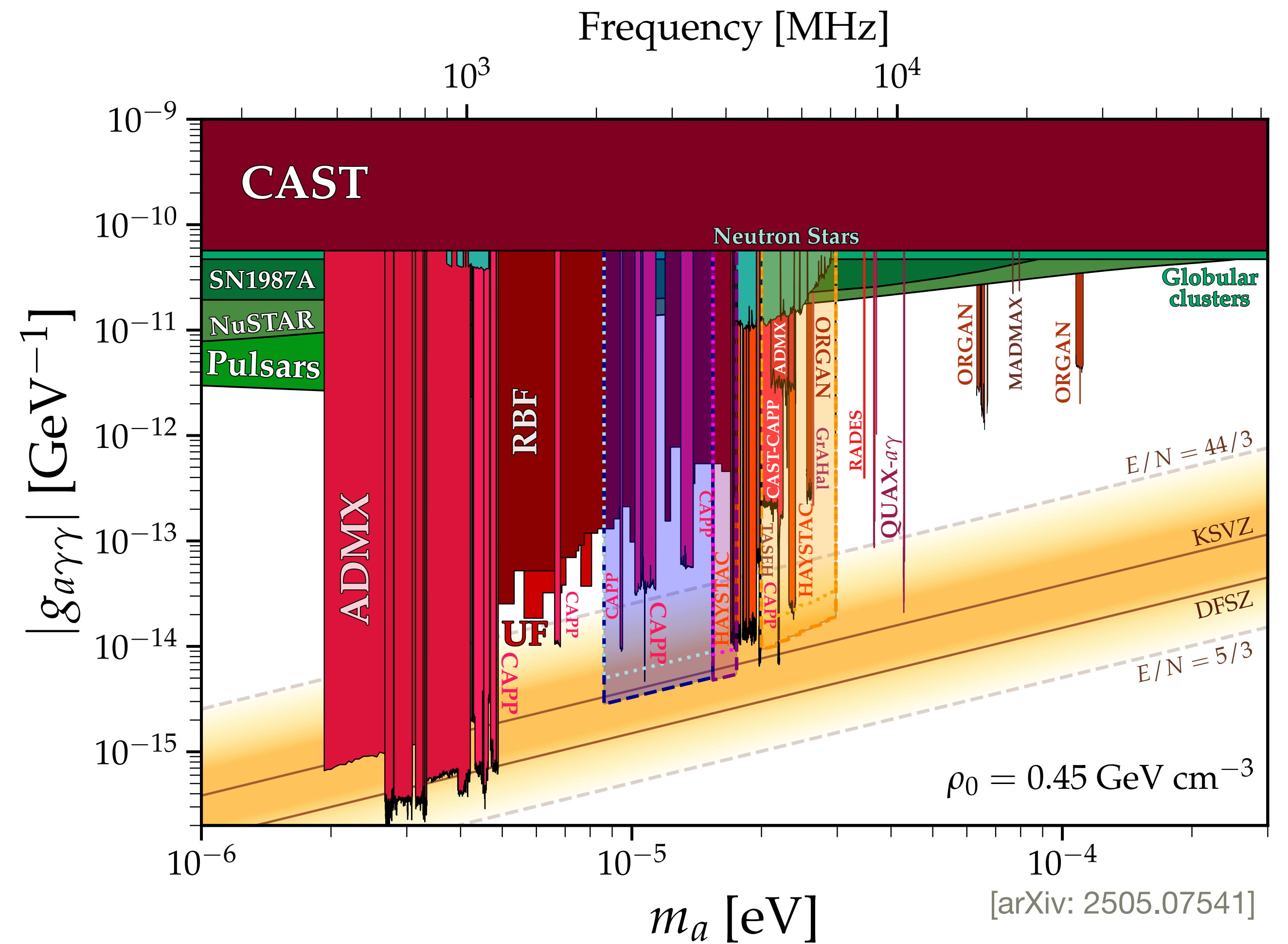
Combining information of distributed detectors at various frequencies!

GravNet Idea

[\[arXiv:2308.11497\]](https://arxiv.org/abs/2308.11497)

Interlude: Axioms

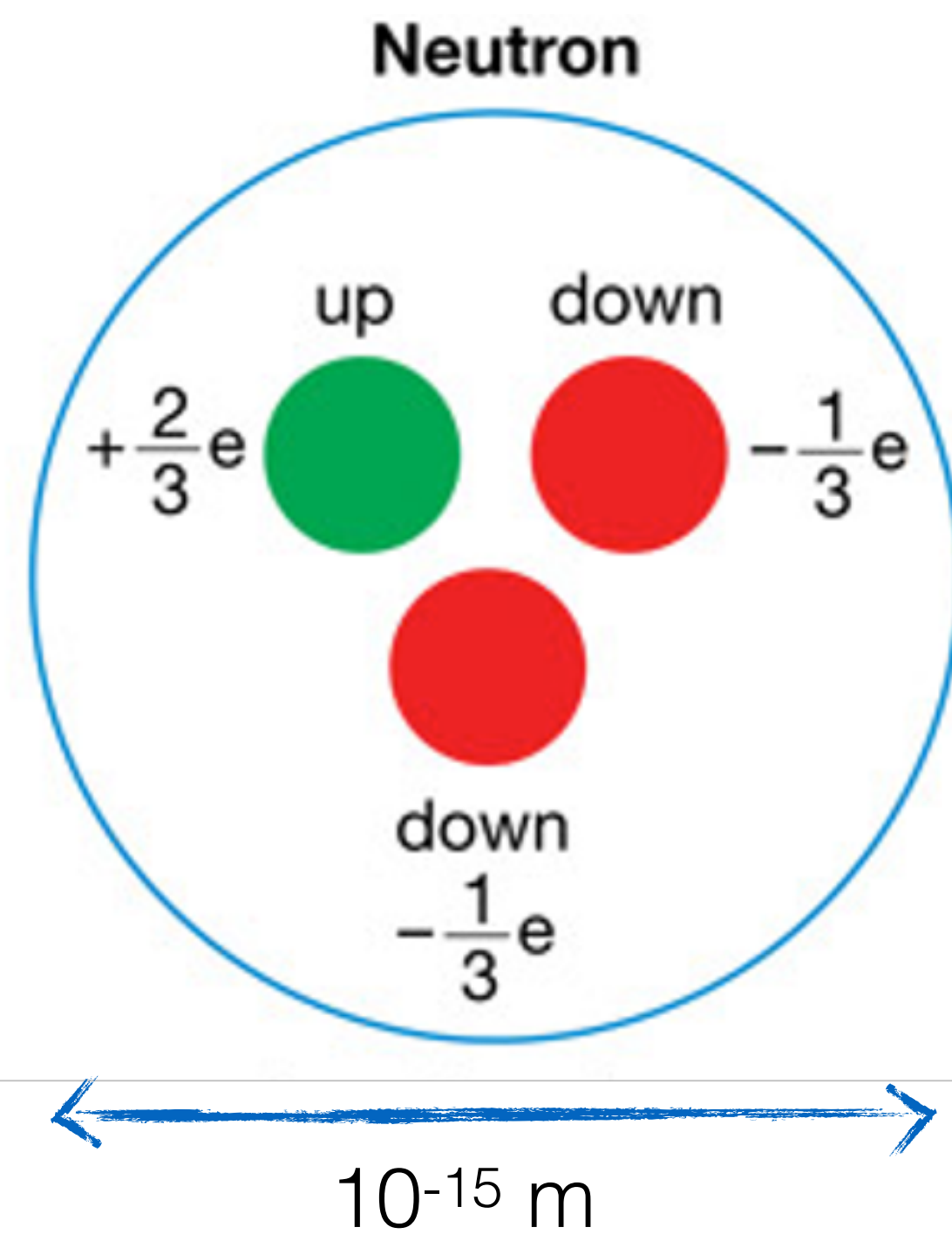
UNIVERSITÄT **BONN**



Naive estimate gives:

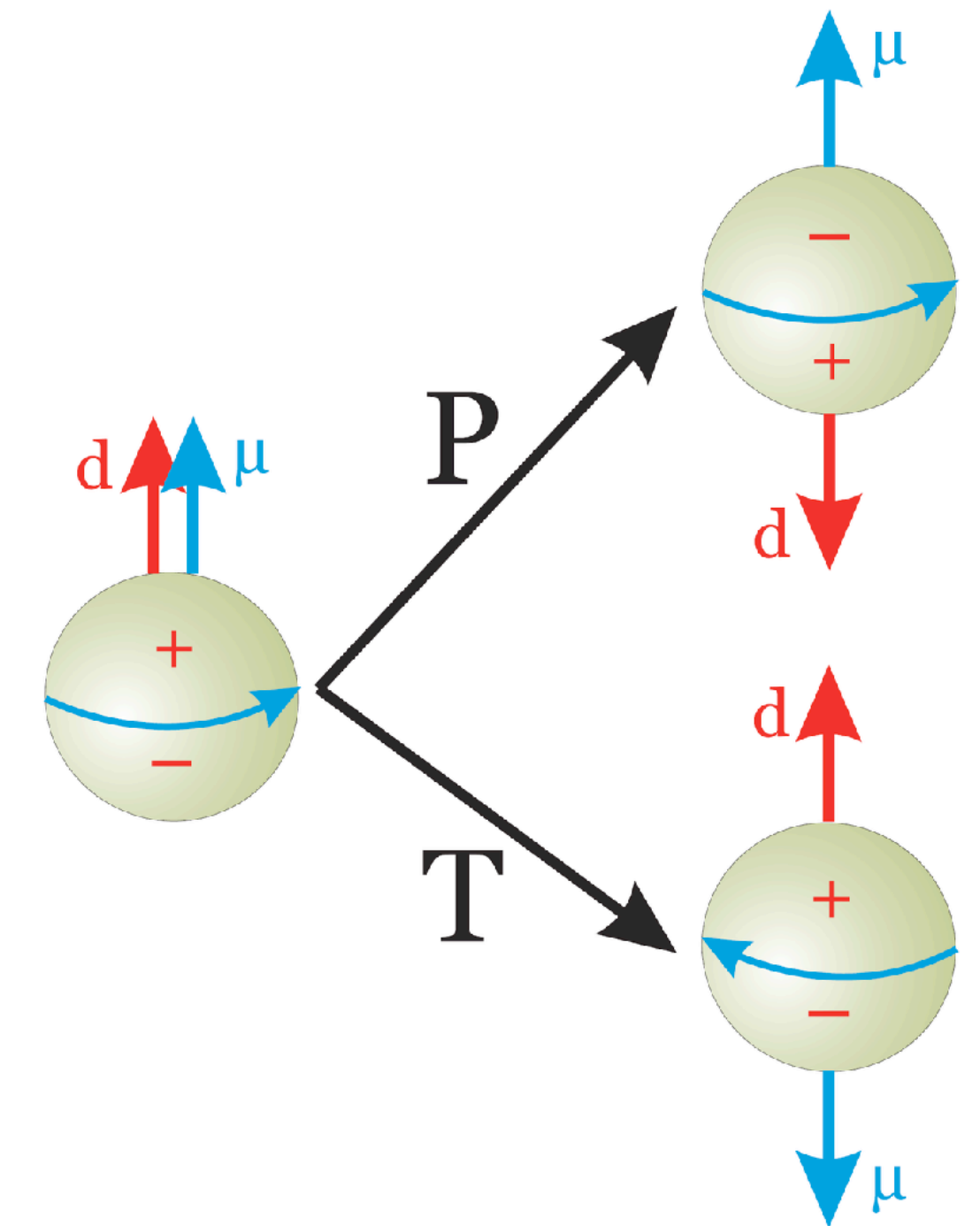
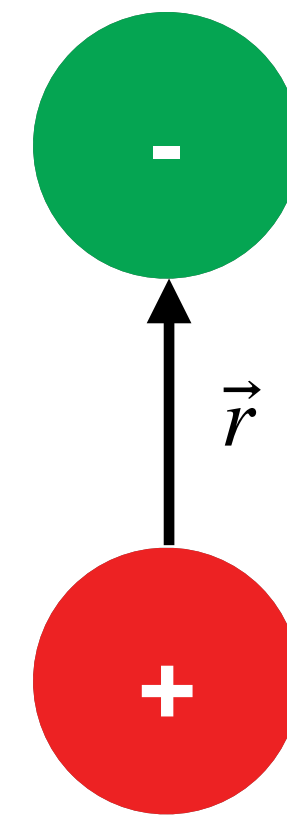
$$\text{EDM}_n \approx 10^{-16} \text{ e cm}$$

[<https://cds.cern.ch/record/198102/>]



Dipole moment

$$\vec{d} = q \cdot \vec{r}$$

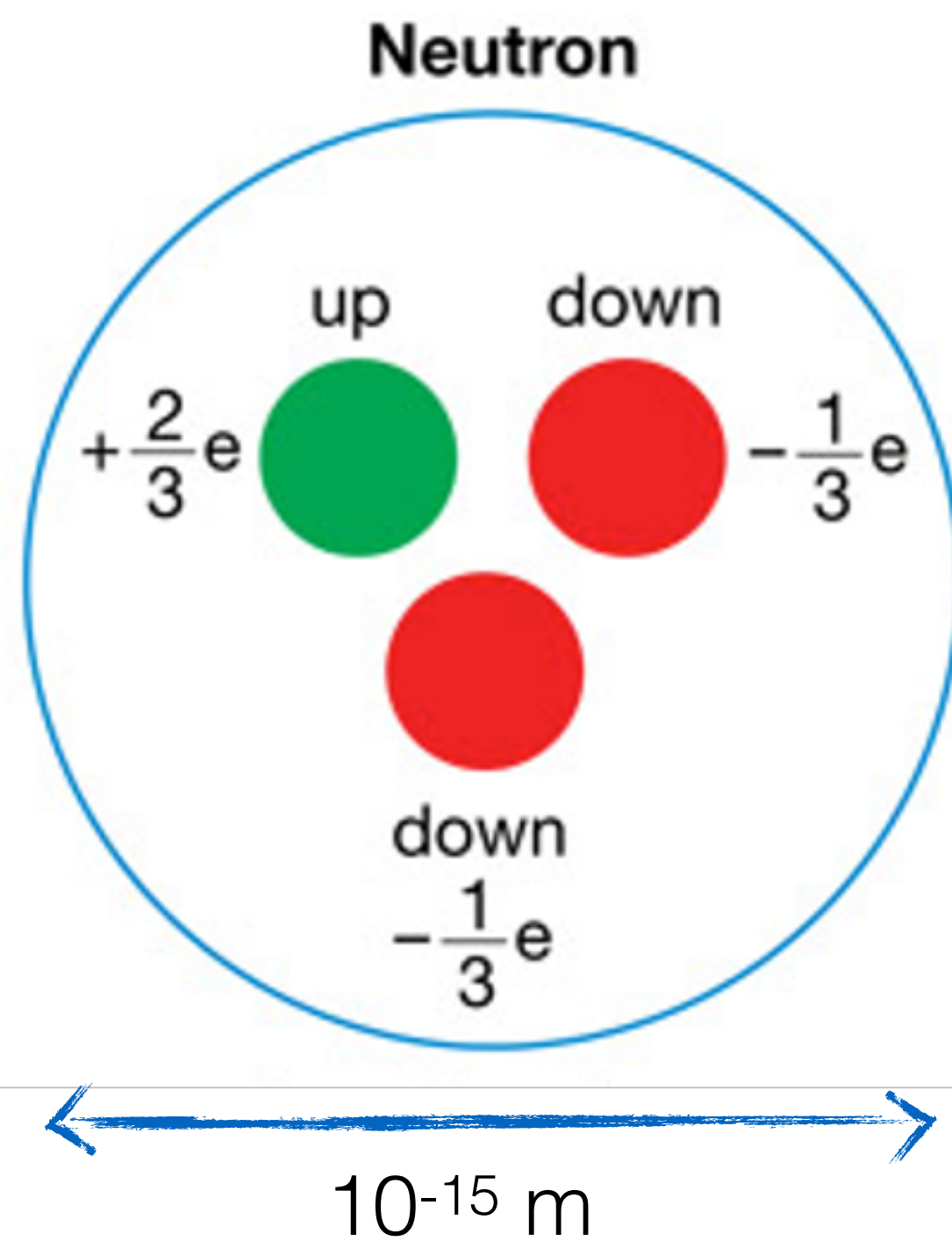


$$CPT|n\rangle = |n\rangle$$

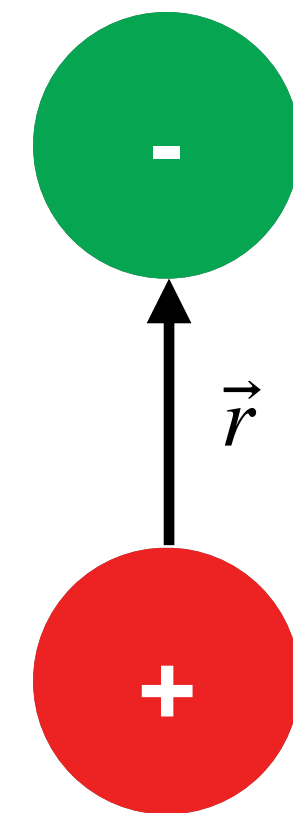
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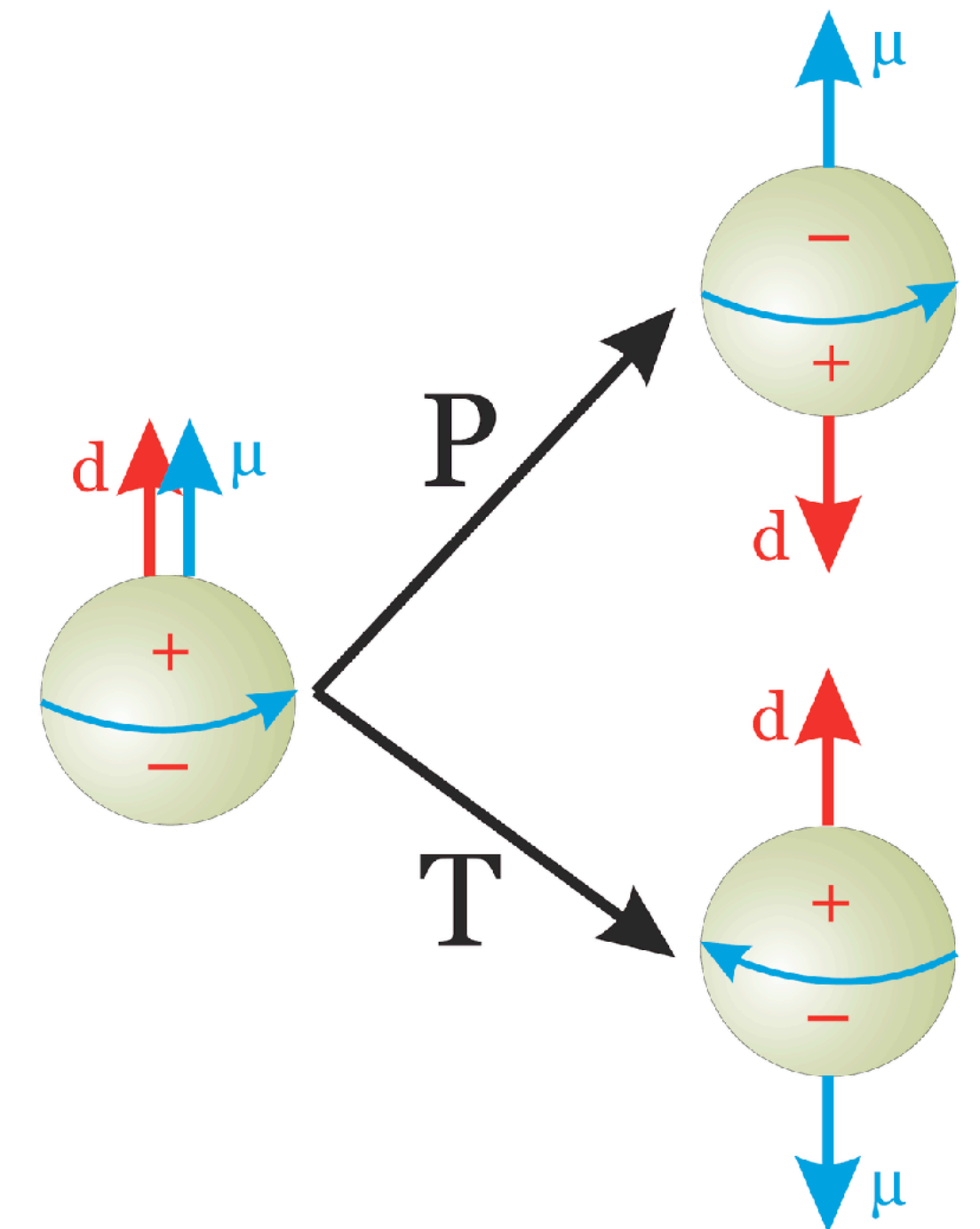
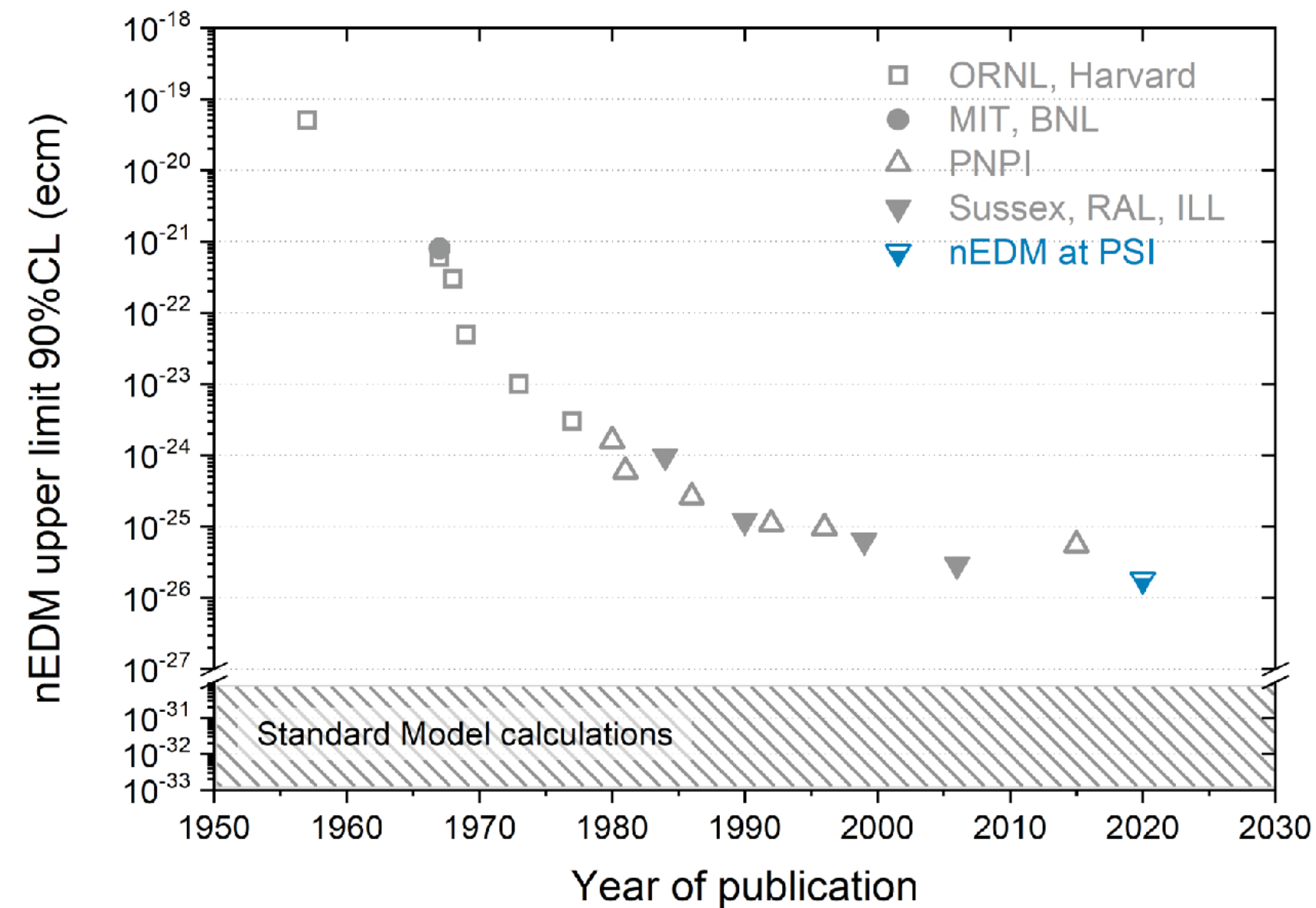


Dipole moment
 $\vec{d} = q \cdot \vec{r}$



Phys. Rev. Lett. 124 (8) 081803:

$$\text{EDM}_n = 0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}} \times 10^{-26} \text{ e cm}$$

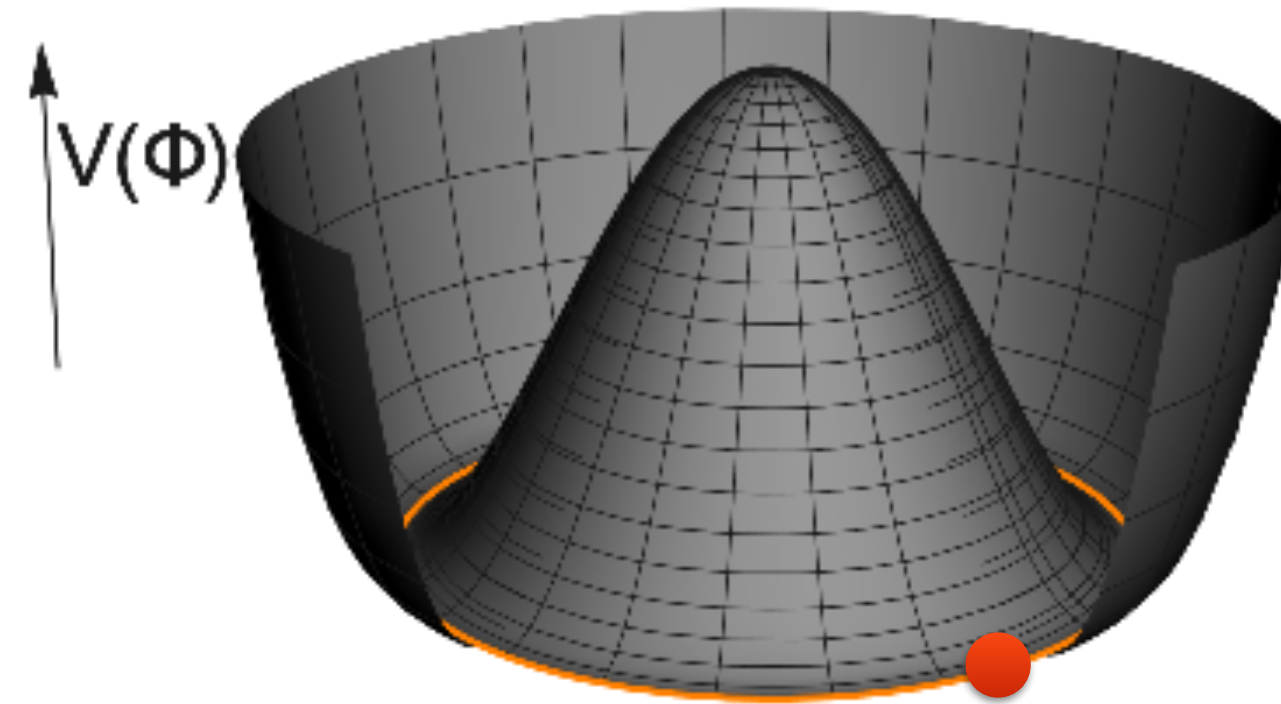


Why is EDM so small ?

$$CPT |n\rangle = |n\rangle$$

Possible Solution to strong CP problem

- 1977 by Peccei and Quinn:
 - Postulated **new** U(1) **symmetry**
 - Generic coupling to quarks
- Symmetry **spontaneously broken** at scale f_a
- New massive Goldstone boson: **Axion**
- Exact way of symmetry breaking (structure of QCD vacuum)
 - **CP violating term nulled dynamically**



Robert Peccei



Helen Quinn



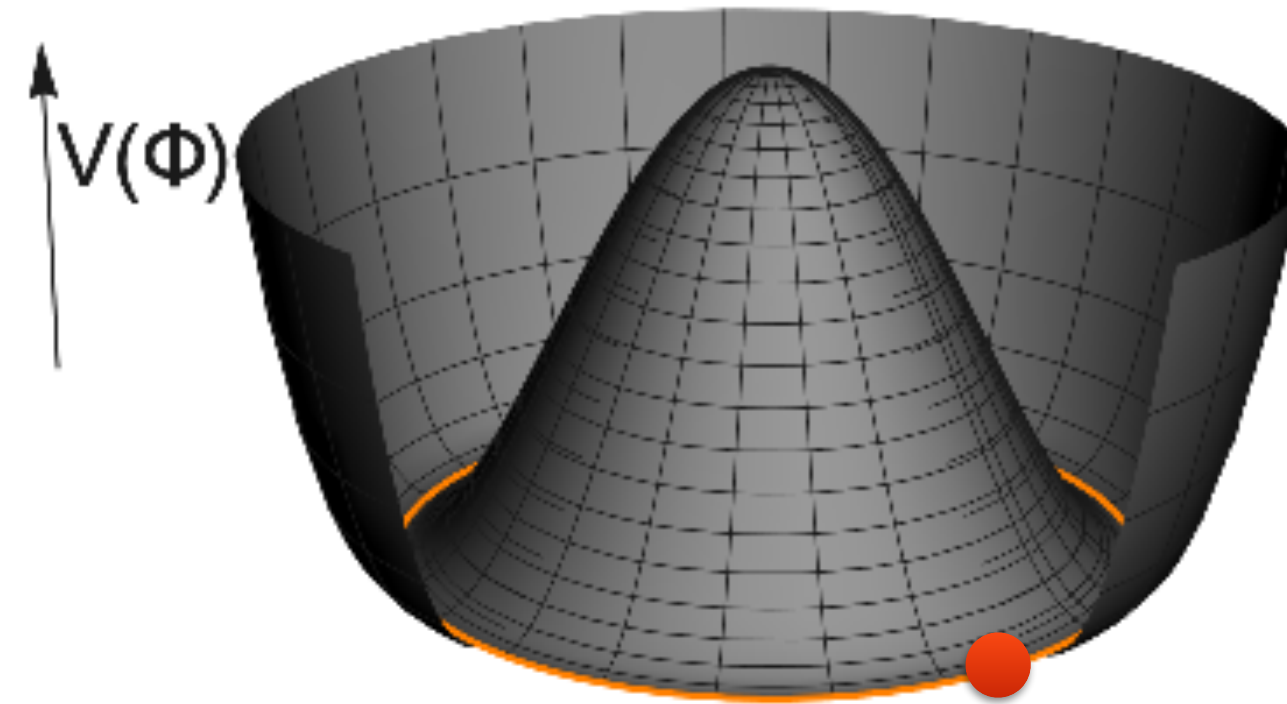
Steven Weinberg



Frank Wilczek

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Axion:

'Washes away all problems'

Here:

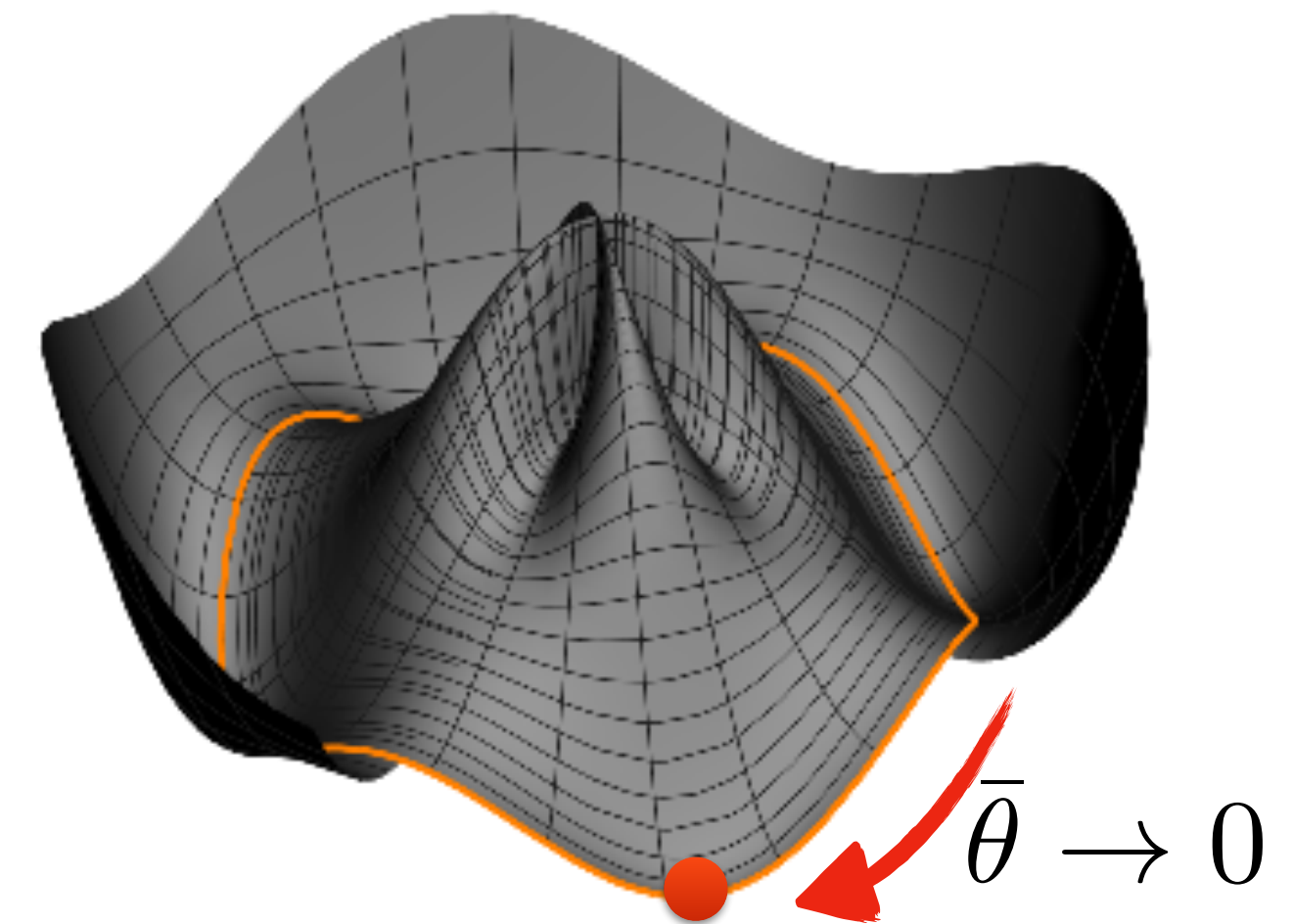
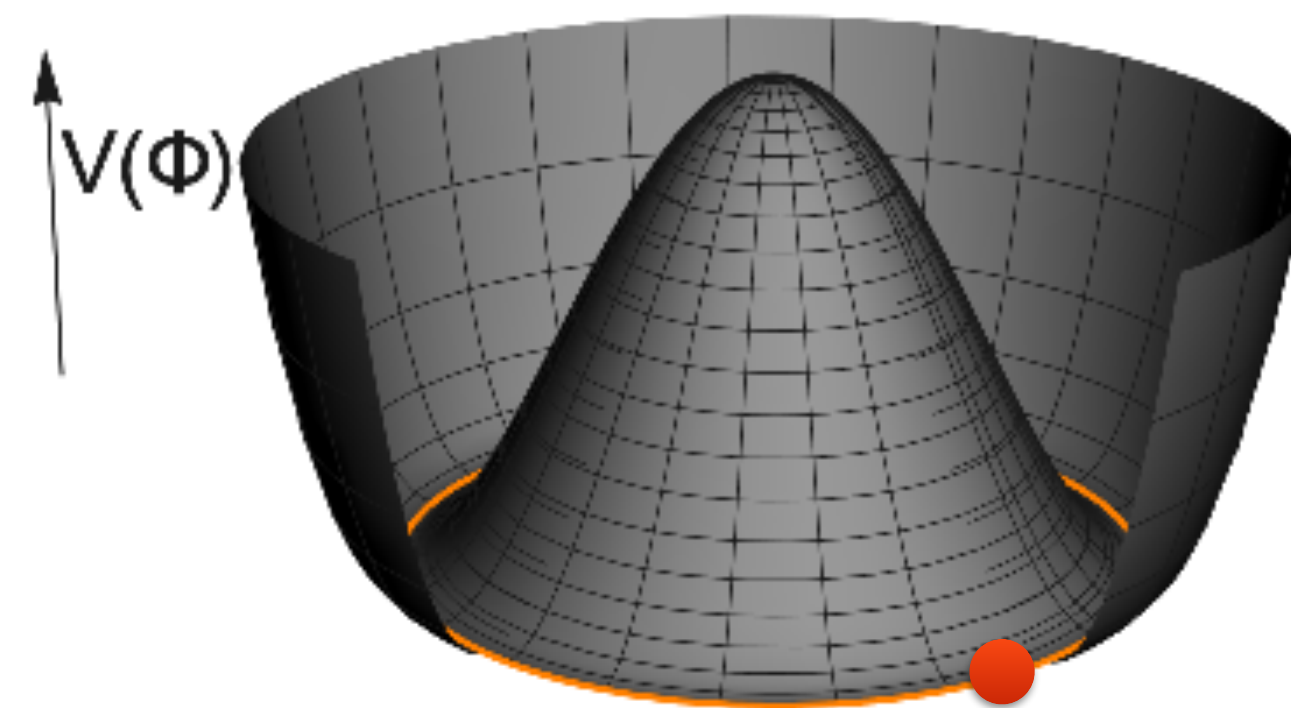
Massive, pseudo-scalar particle

Possible Solution to strong CP problem

- a : Axion field
- f_a : “Peccei-Quinn scale”

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{SM,axion}} + \underbrace{\bar{\theta} \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{\alpha\beta}^a}_{\text{QCD term}} + \underbrace{\xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{\alpha\beta}^b}_{\text{Axion term}}$$

- $E \sim f_a$ (large)
 - Spontaneously broken symmetry
 - Axion = Nambu-Goldstone boson (**massless**)



Possible Solution to strong CP problem

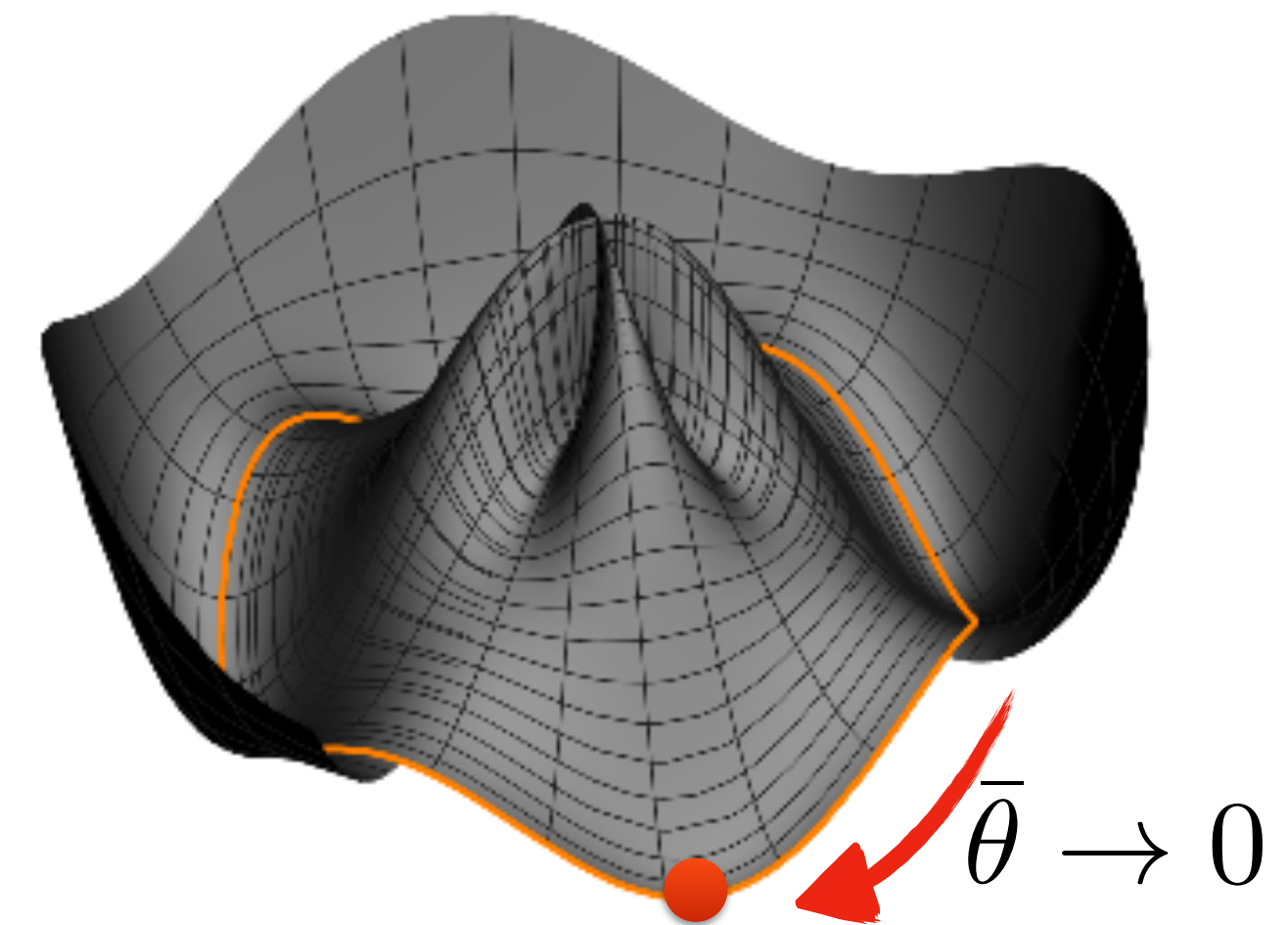
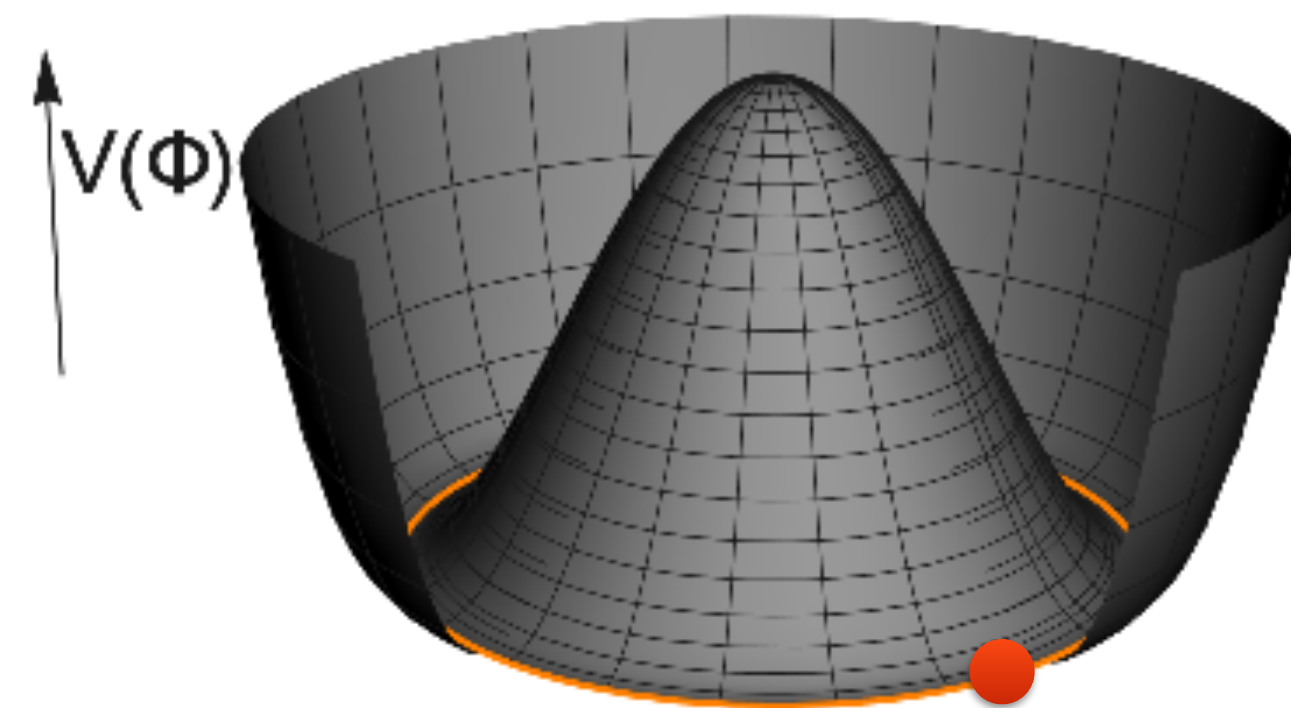
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QCD term

Axion term

- $E \sim \Lambda_{QCD}$
- **QCD instanton** effects break U(1) explicitly
 - “tilted mexican hat”
- Axion becomes **massive**
- Drives potential to $\theta = 0$
 - CP symmetry restored



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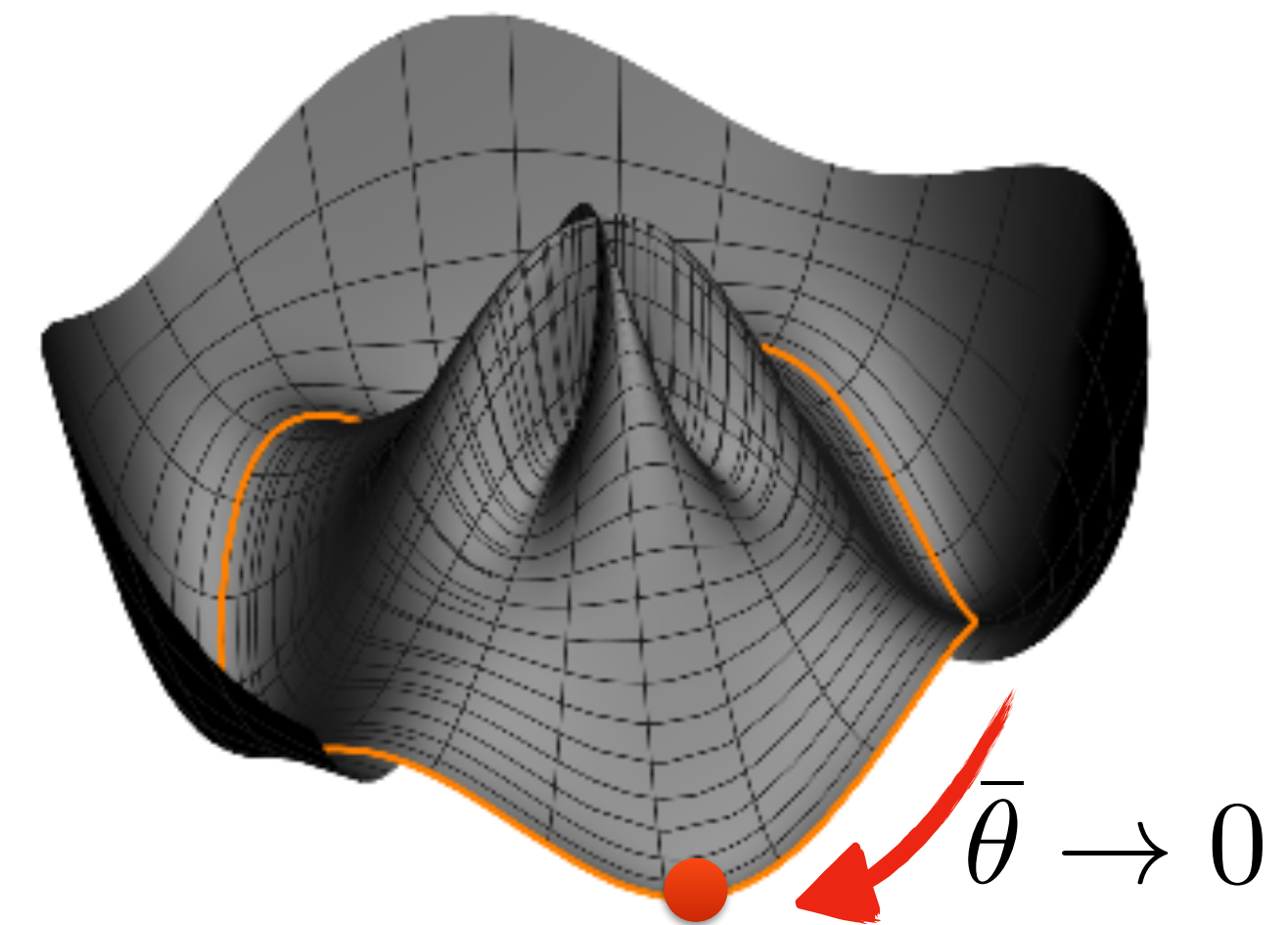
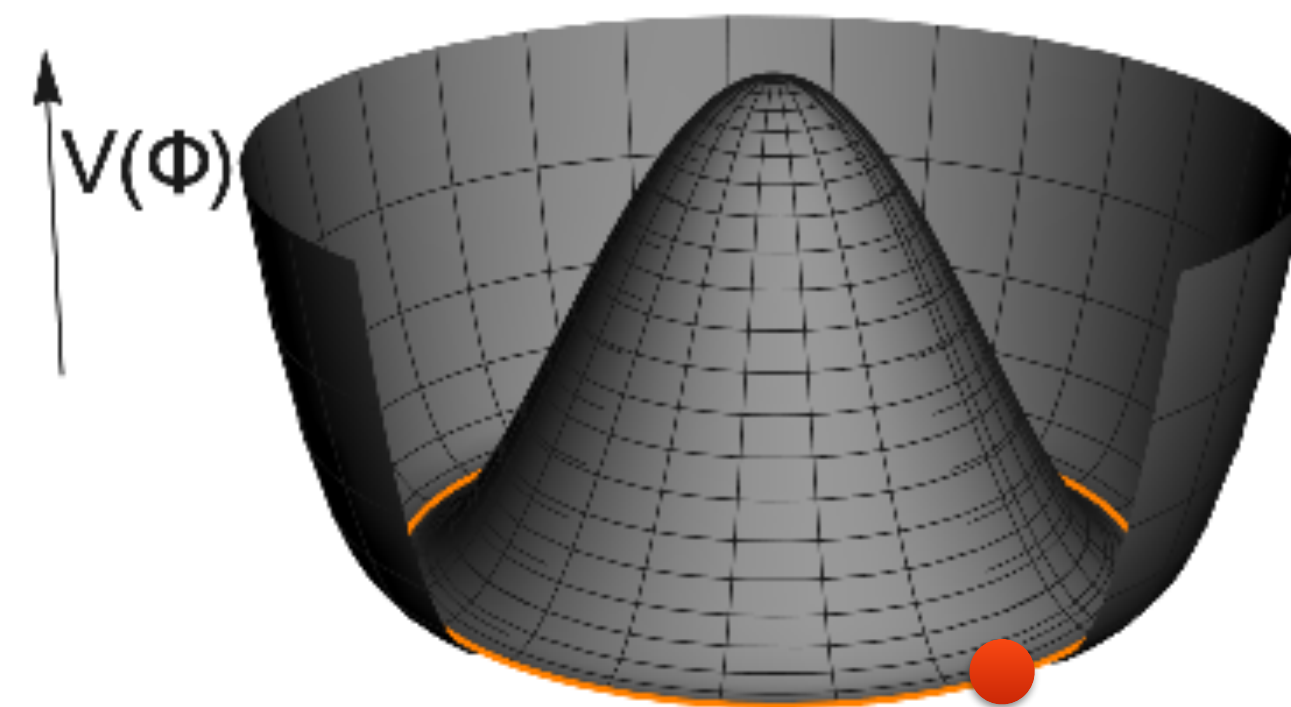
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- Only free parameter:
 - Scale of symmetry breaking

Coupling: $g_i \propto \frac{1}{f_a} \quad g_i \propto m_a$

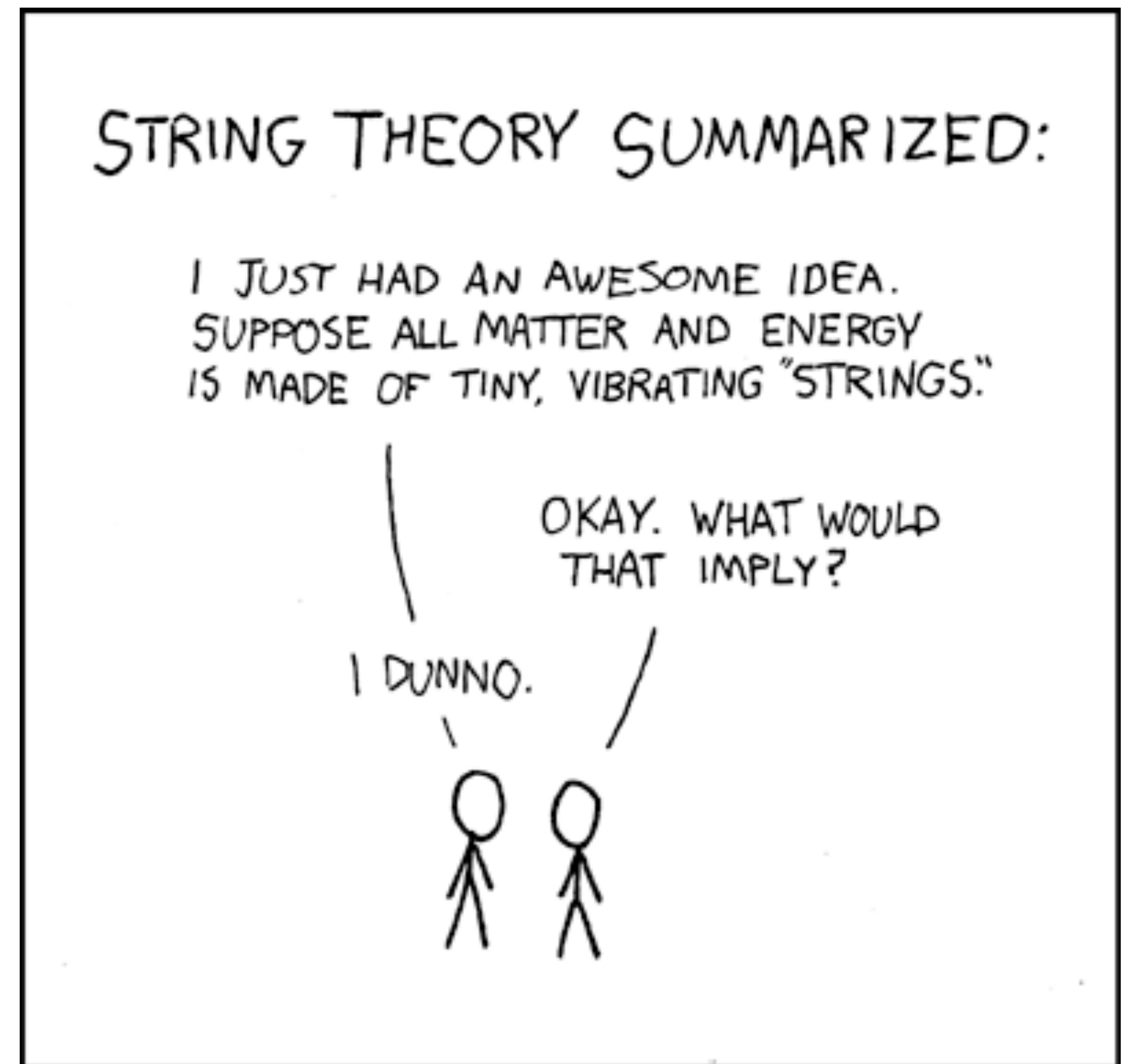


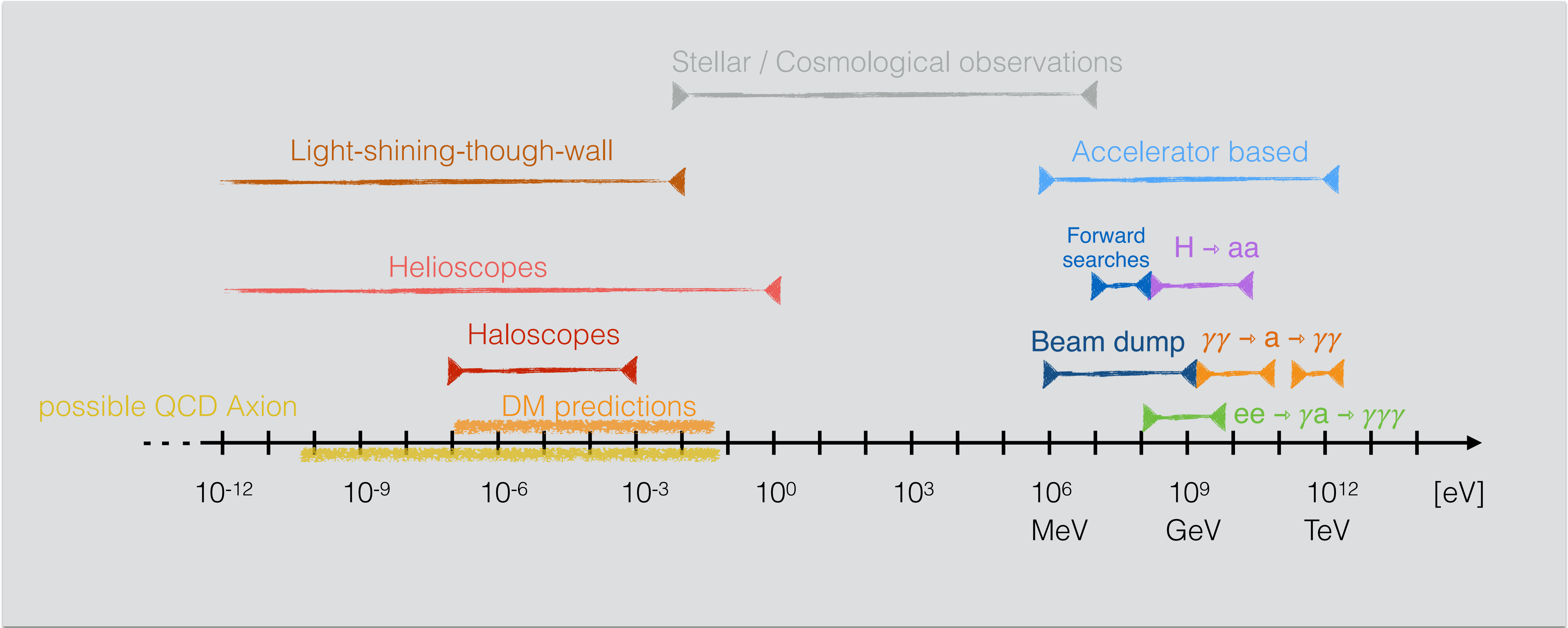
1. ... may solve the strong CP problem
2. ... may be Dark Matter
3. ... may explain anomalous star cooling
4. ... may explain TeV transparency of intergalactic space
5. ... may contribute to $(g-2)_\mu$
6. ... are **well motivated** by string theory

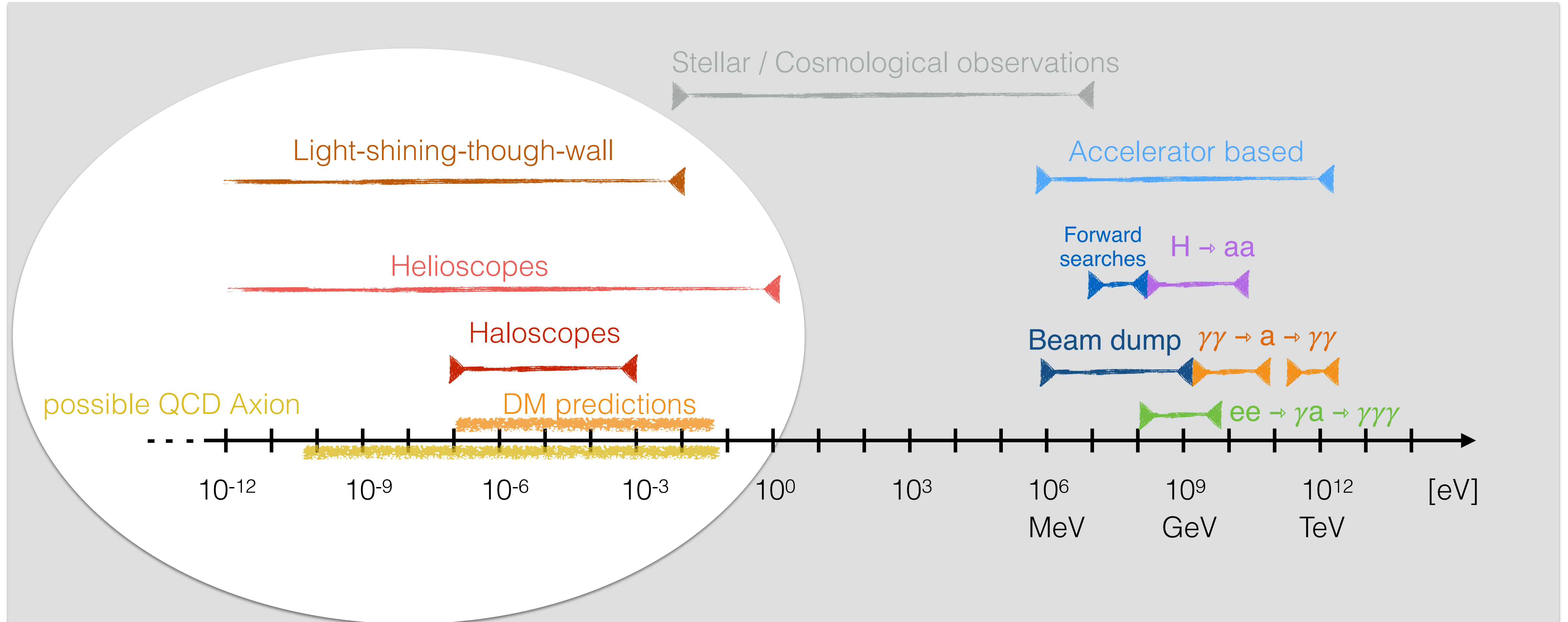
[[arXiv:0605206](https://arxiv.org/abs/0605206)]

- Axion-like fields emerge in string theory in 10D $\rightarrow$ 4D compactifications as Kaluza-Klein zero modes of ten-dimensional form fields

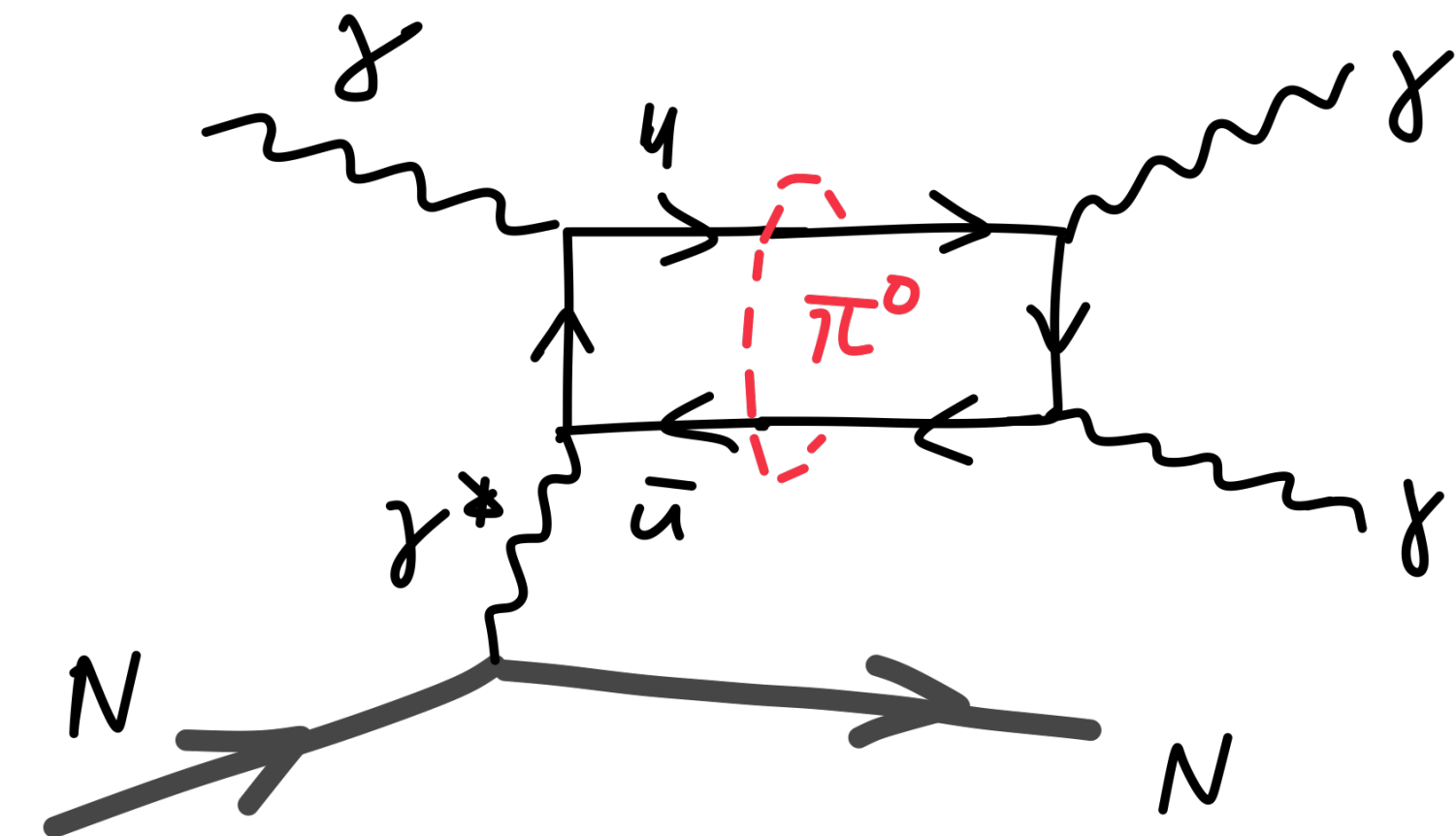
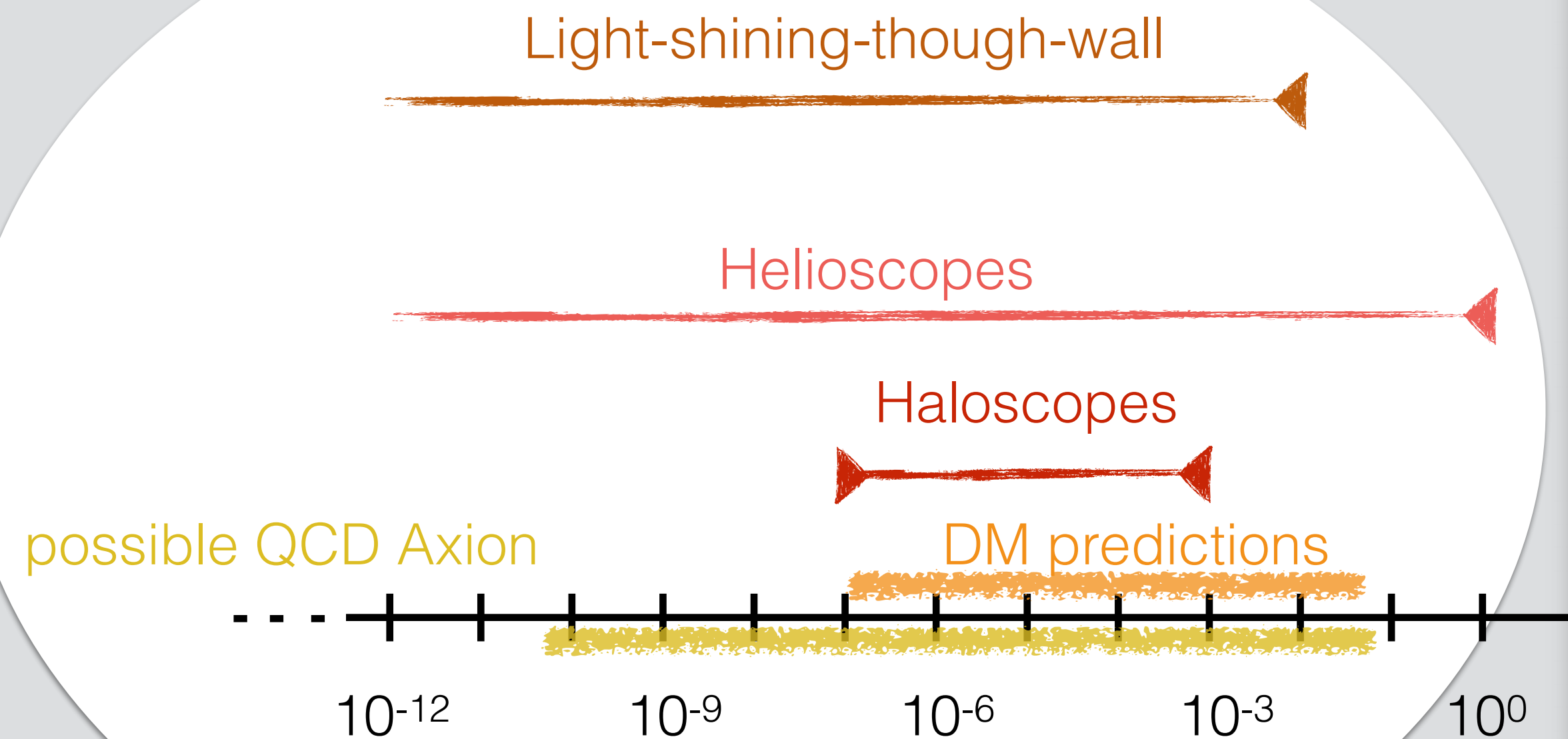
[[A. Ringwald 2014 J. Phys.: Conf. Ser. 485 012013](#)]





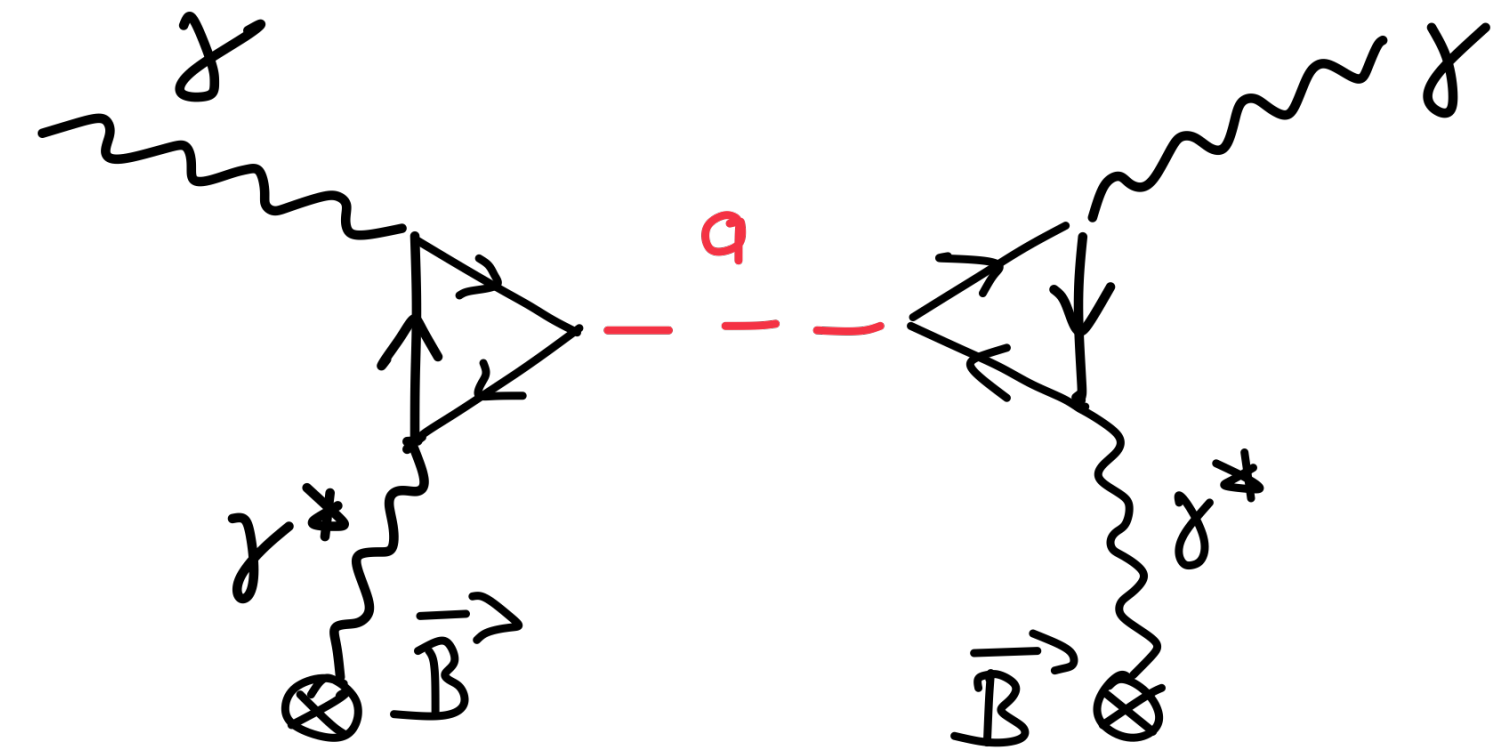
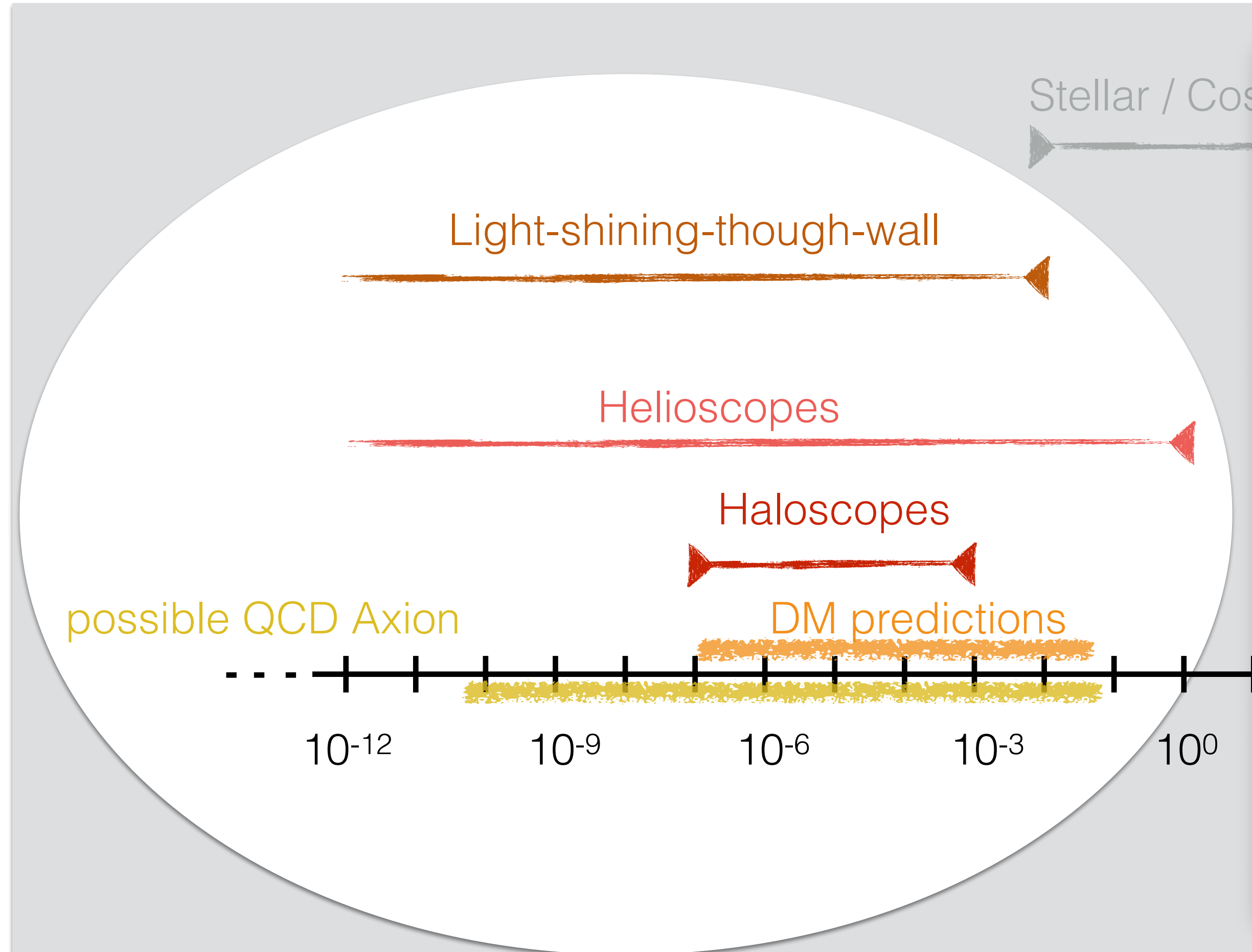


Stellar / Cos



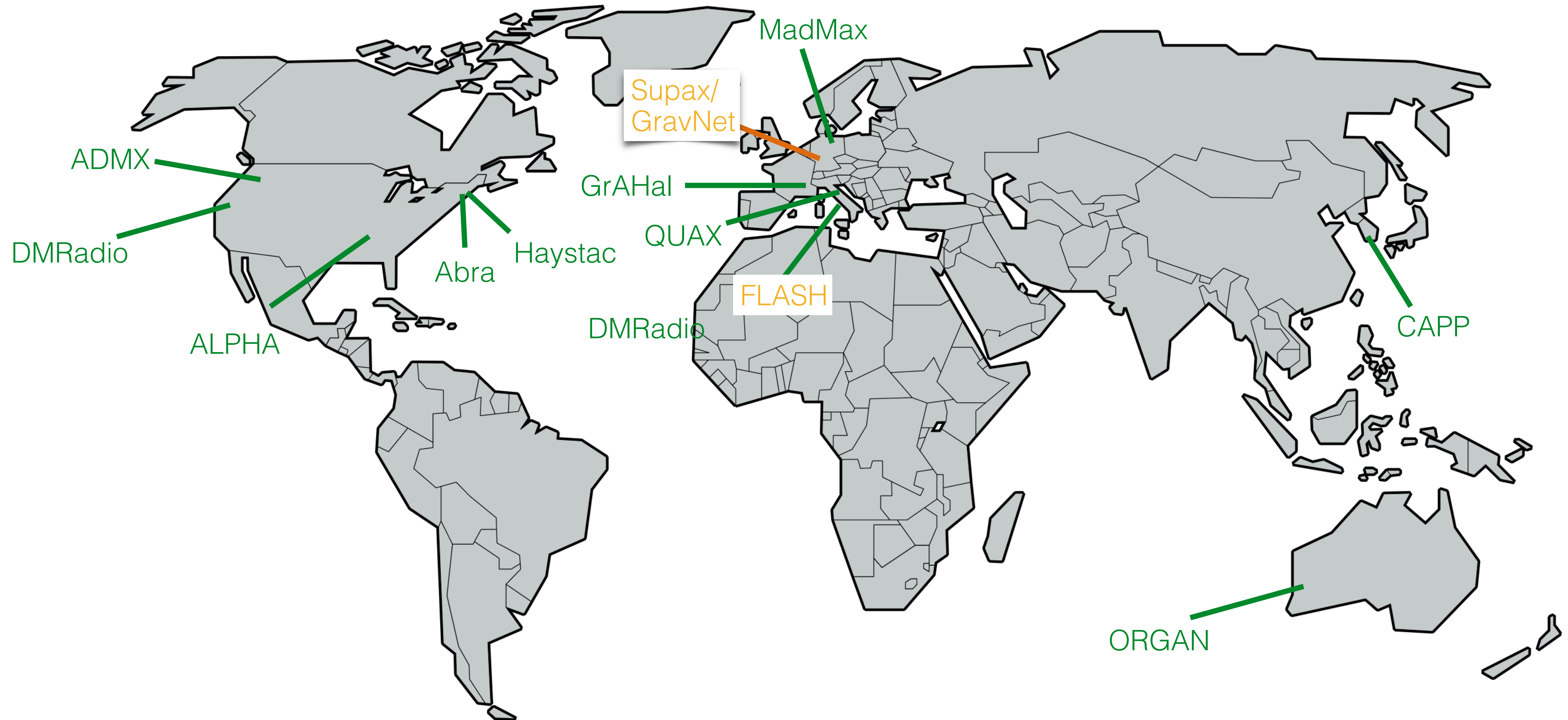
- Primakoff effect:
Resonant photo-production of
pseudoscalar mesons

Stellar / Cos



- Axion to photon conversion in magnetic field (inverse Primakoff effect)

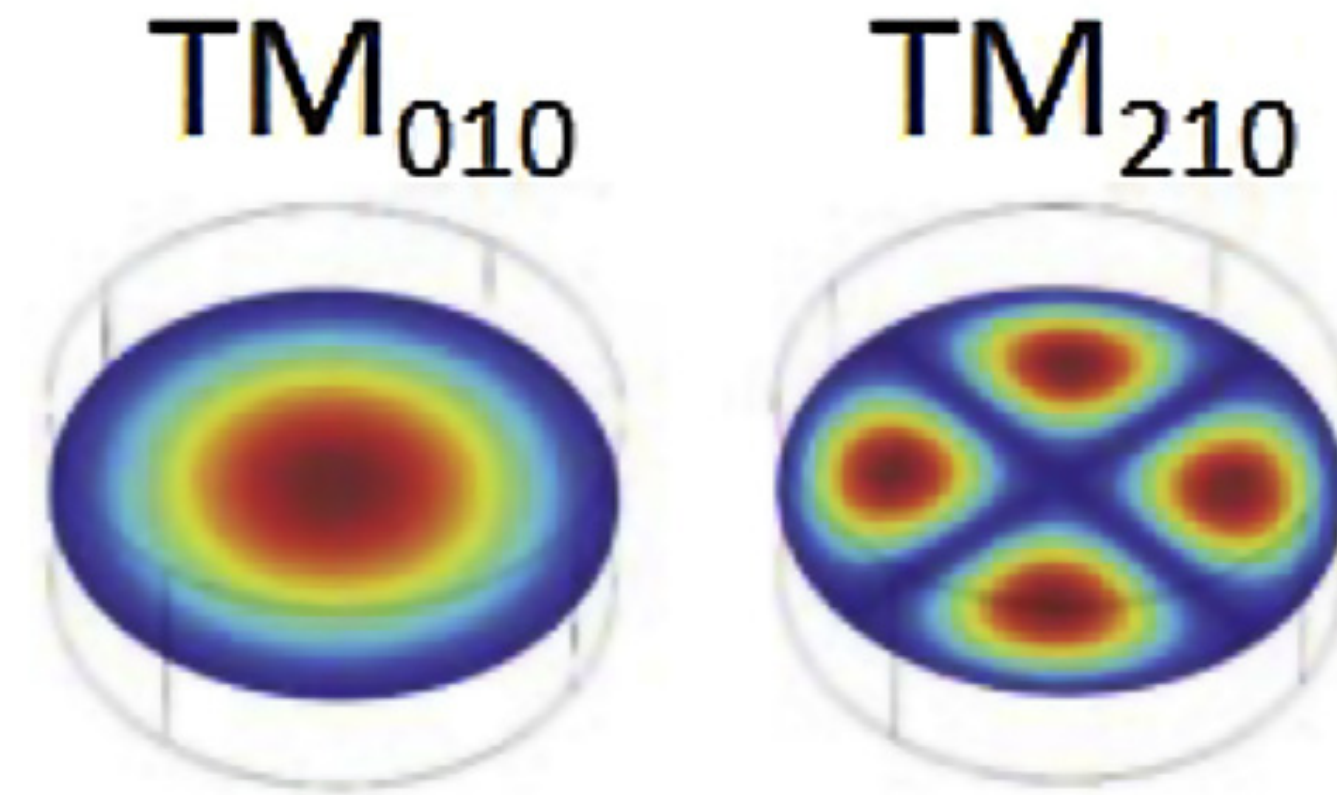
Axion Haloscope Experiments



GW waves exited higher order mode(s) in cavity

- Fundamental differences to Axions:
 - **Quadrupole** vs. **Dipole** structure
 - GWs are **transient signals!**
 - Long integration times not useful

E - field distribution

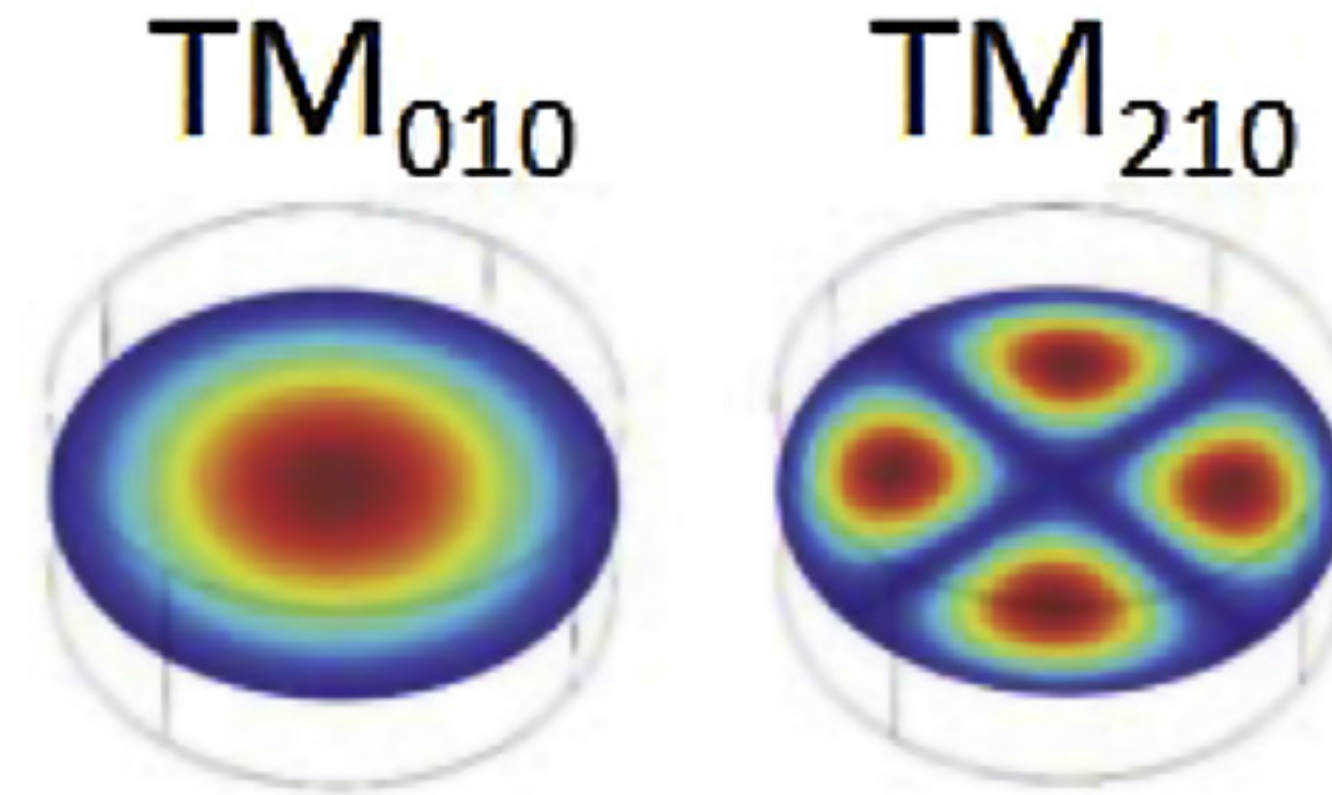


- Dedicated cavities needed for GW detection
 - Optimal geometry?

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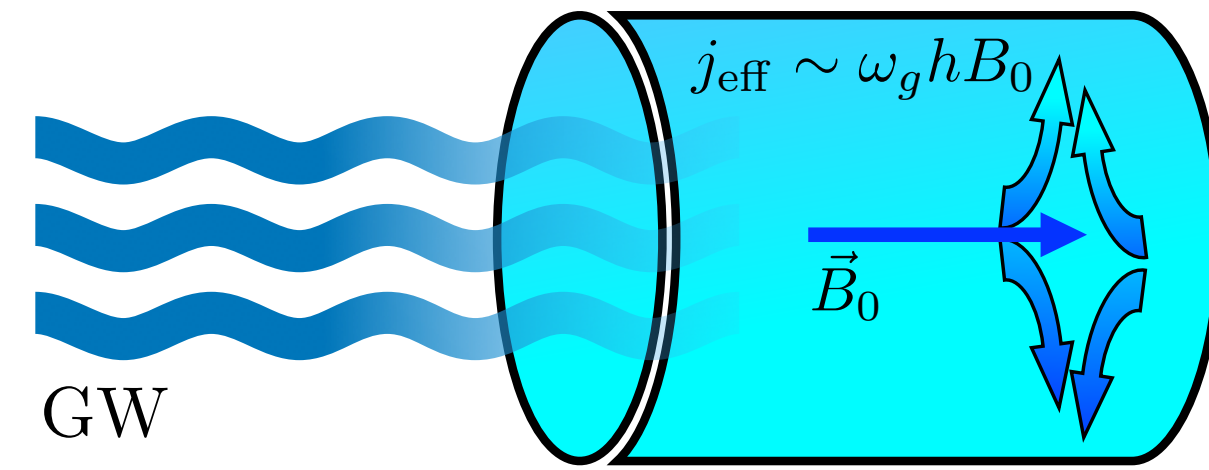
- Optimal geometry?

- Collaboration with our theory colleagues at Mainz:

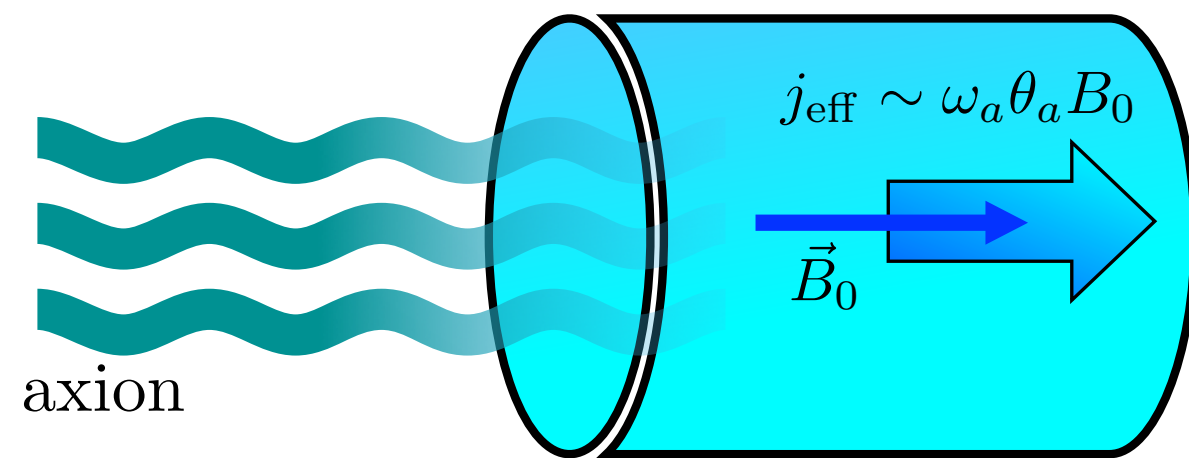
[P. Schwaller et. al. arXiv:2404.08572](#)

ø = 48mm, GravNet prototype cavity





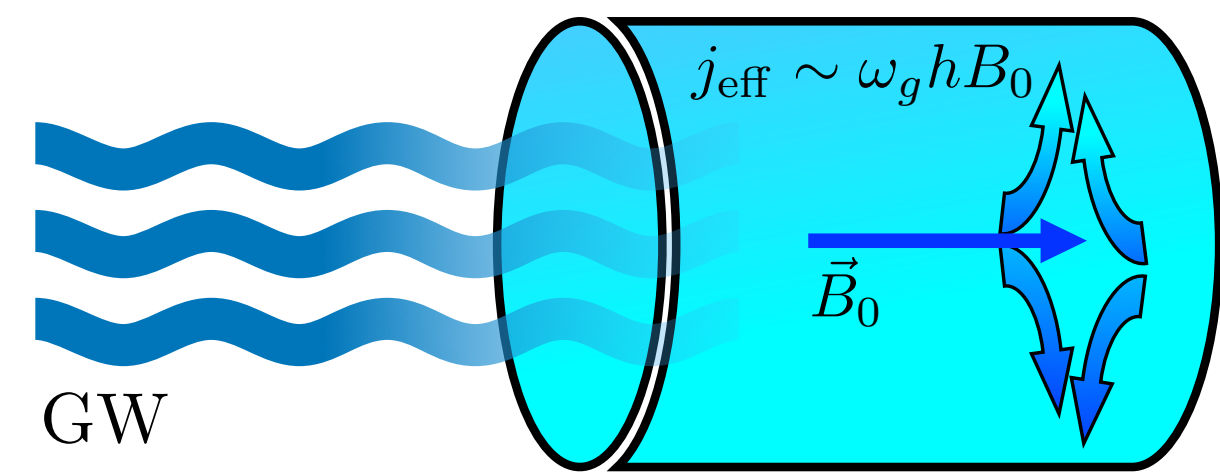
- **GW:**
 - Typical quadruple structure
 - Preferred mode: **TM 020**
 - Current direction dependent on GW



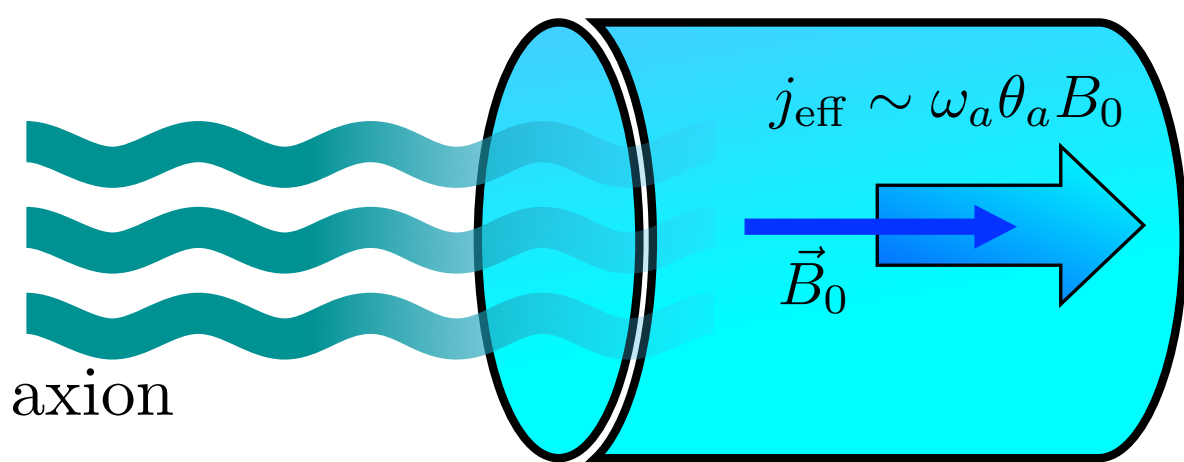
- **Axions:**
 - Preferred mode: **TM 010**
 - Current dependent on B-field direction
 - Little overlap with GW mode

[arXiv:2112.11465]

- **Ideal setup:**
 - Axion setup has NO overlap with GW mode!
- **Signal lifetime:**
 - Axions: infinite => Integration time O(100s)
 - GW merging events: $\mu\text{s} - \text{ms}$ => Need new analysis techniques



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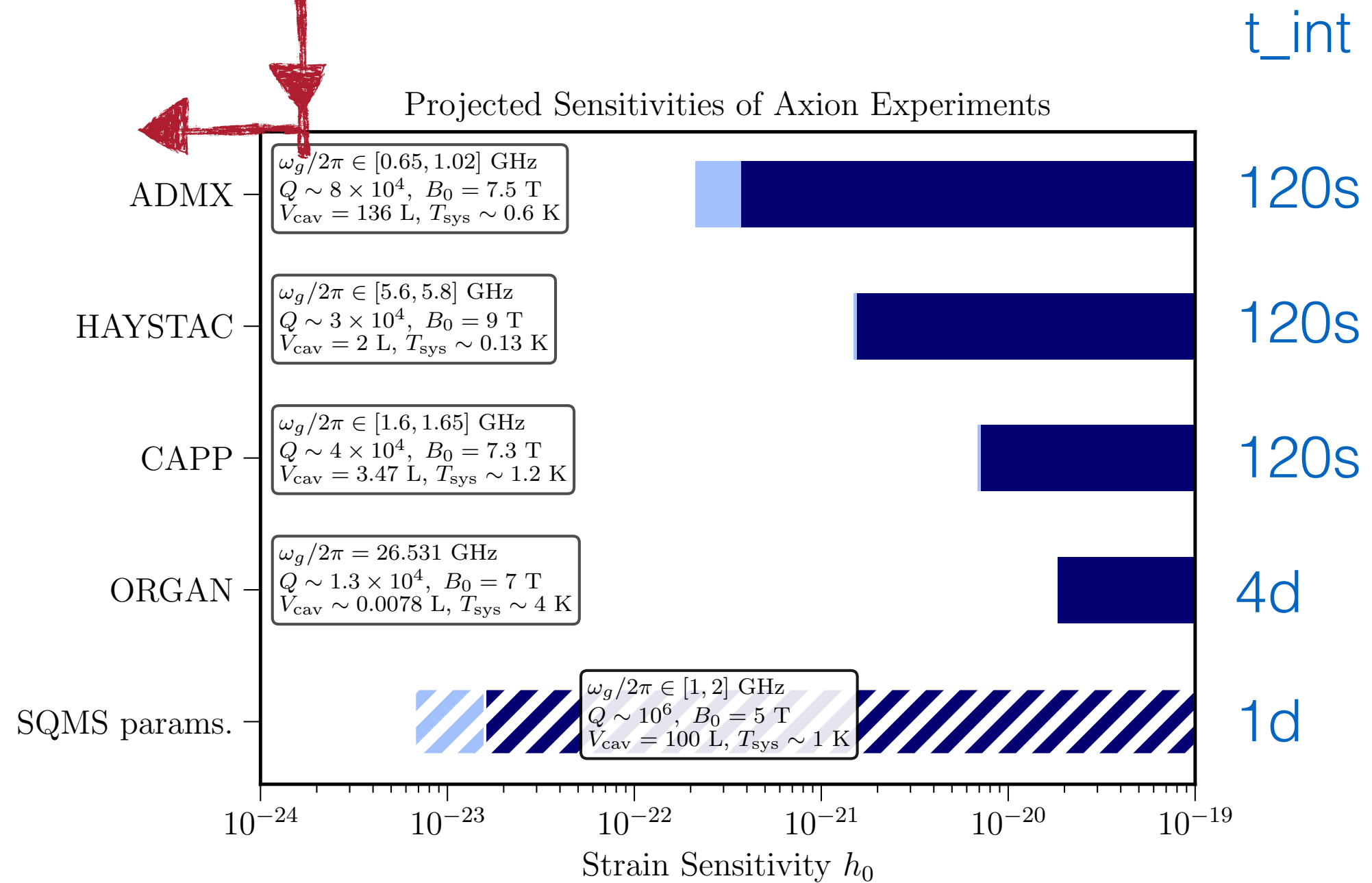


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Interesting sensitivity range for PBH



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