Supax - A new axion haloscope @ Bonn

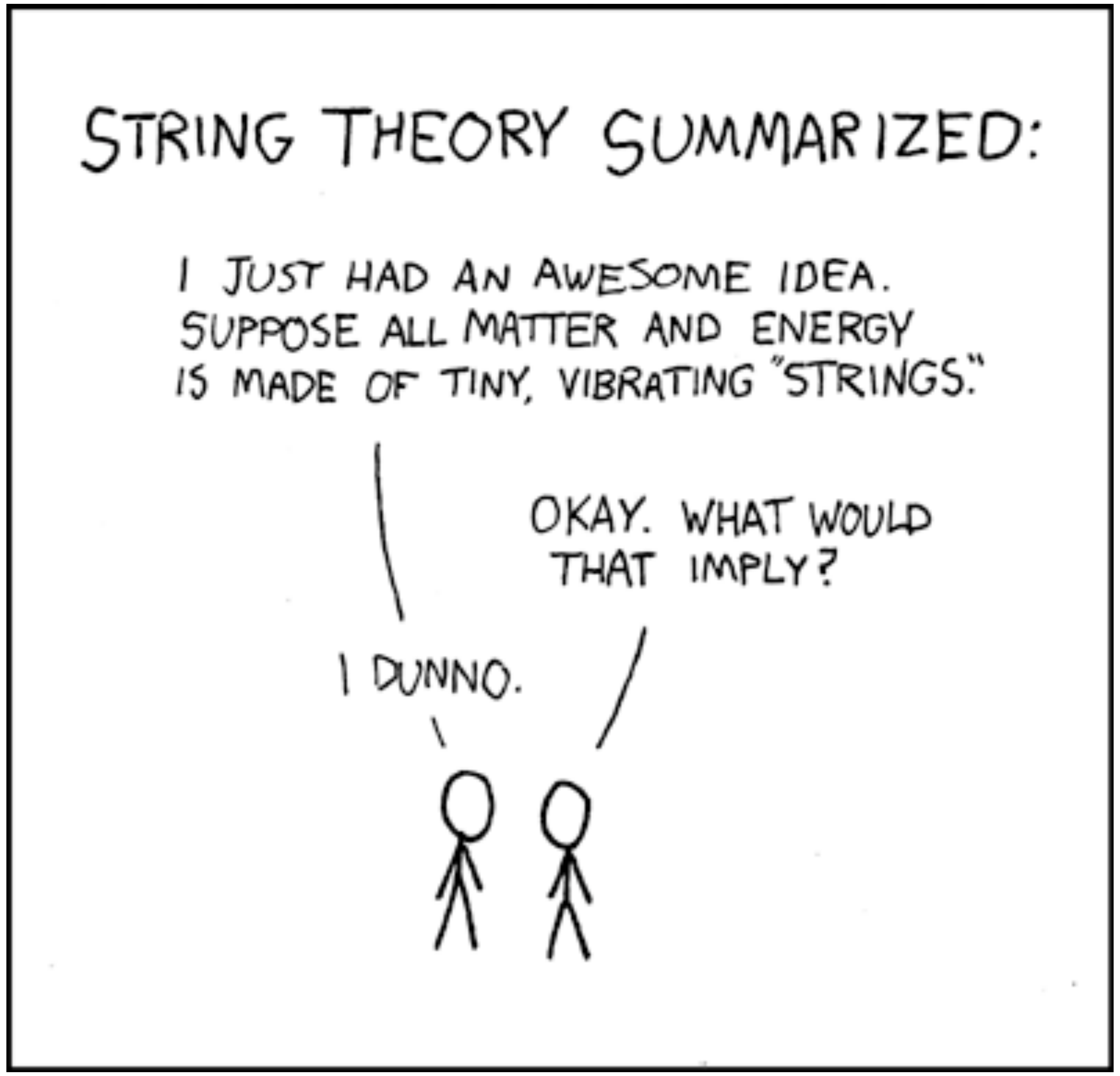
Color meets Flavor - RA4 Kickoff Meeting
02/12/2025 - Dortmund

Kristof Schmieden, Matthias Schott

5 to 6 Reasons to like Axions

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]



- "Axion-like fields emerge in string theory in 10D → 4D compactifications as Kaluza-Klein zero modes of ten-dimensional form fields" [A. Ringwald 2014 J. Phys.: Conf. Ser. 485 012013]

How to Observe Axions

Light Axions and ALPs

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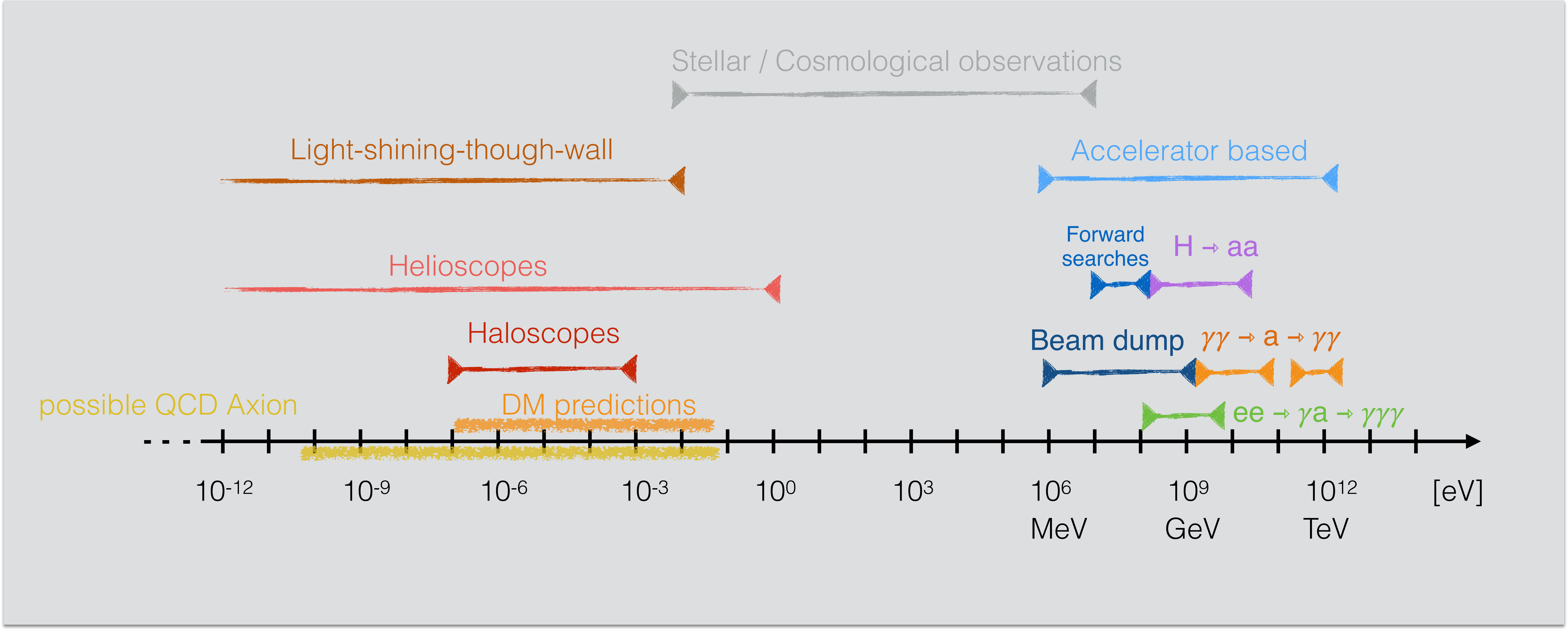

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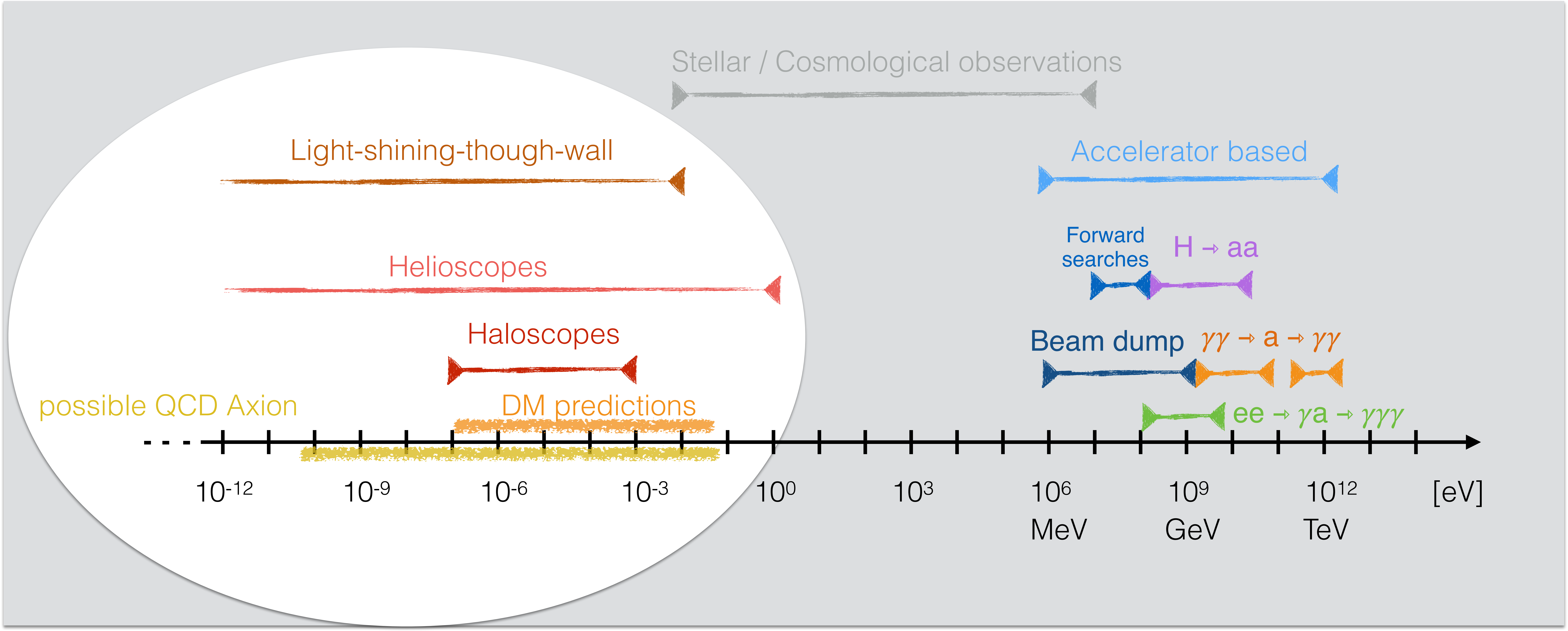

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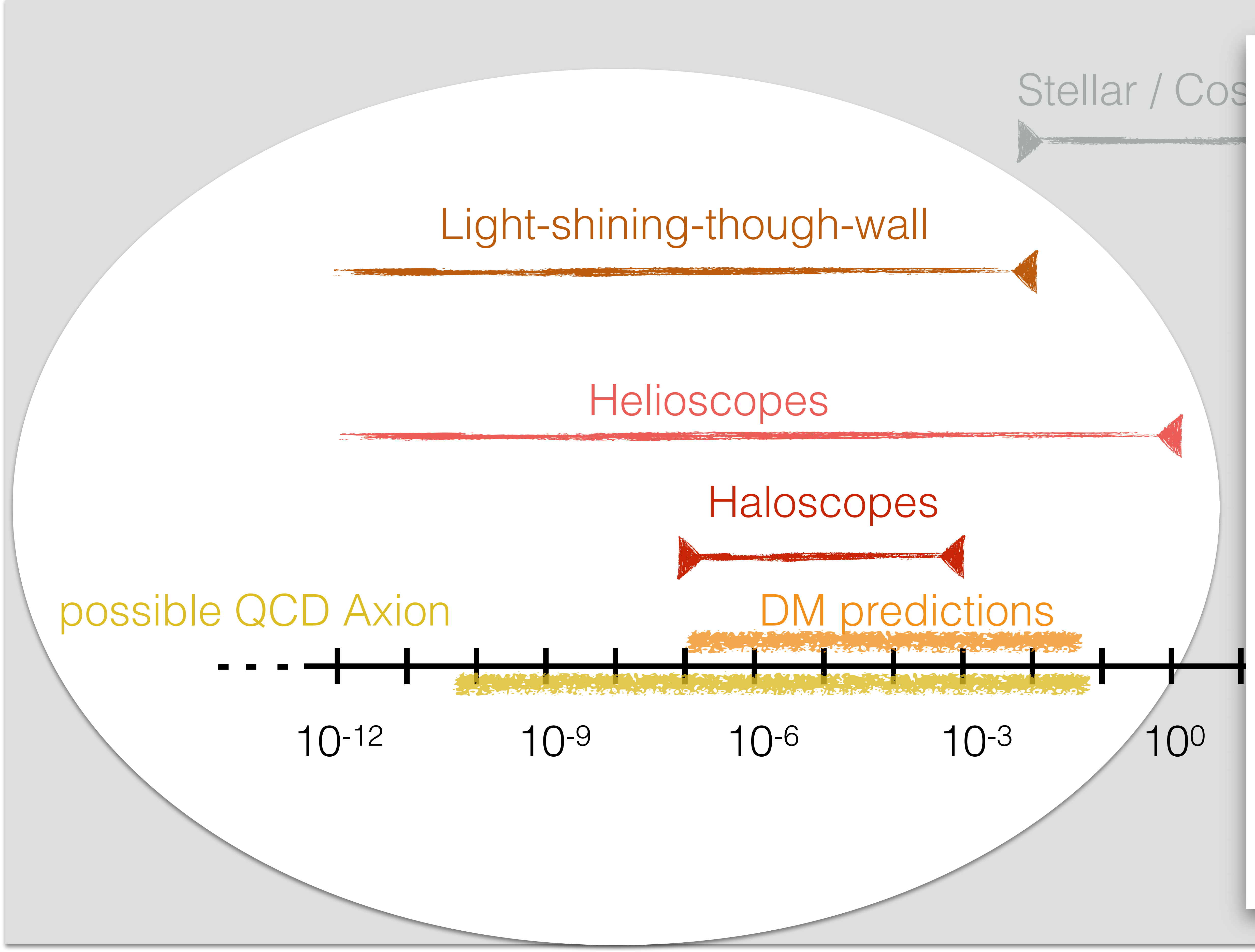
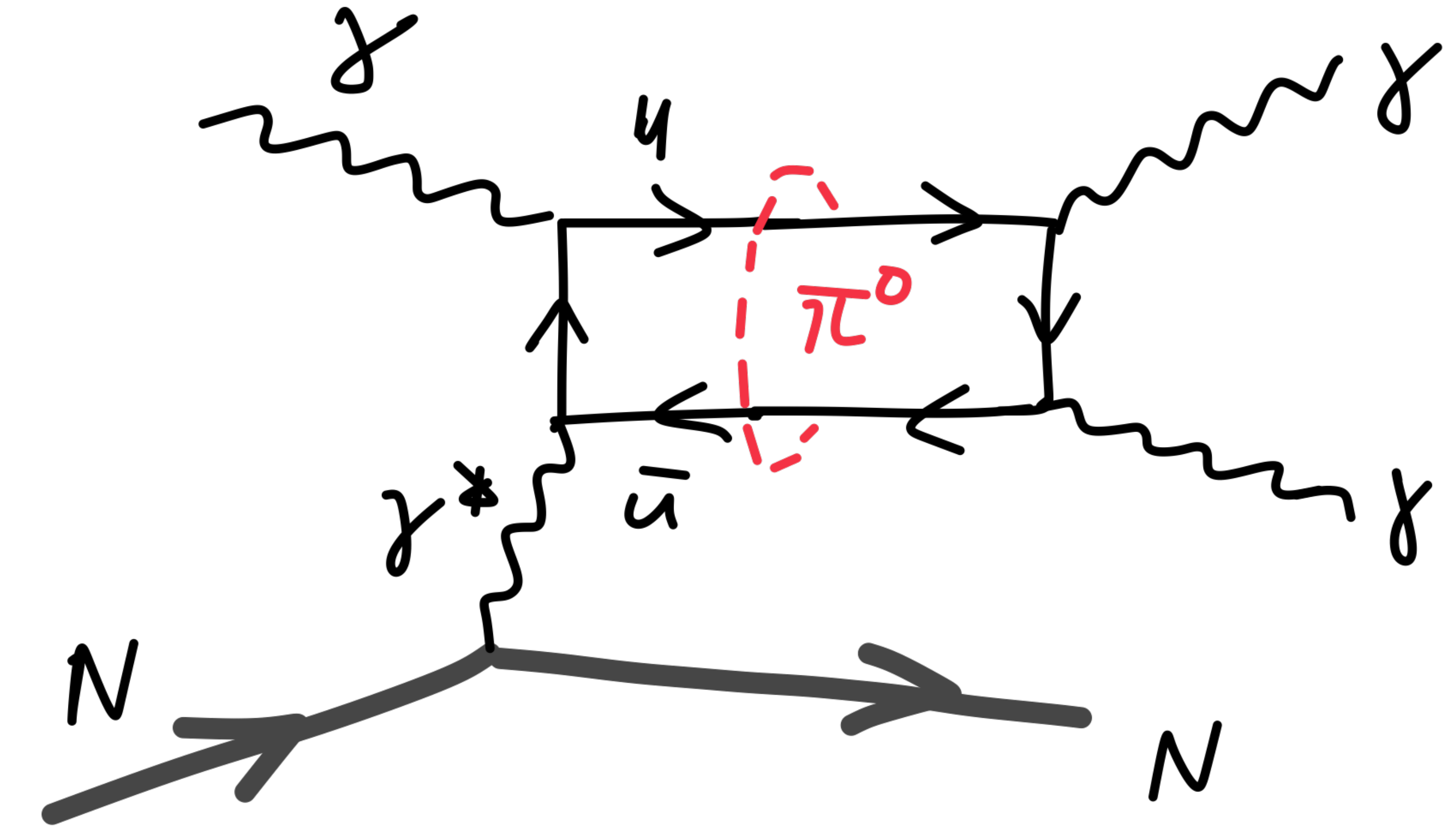
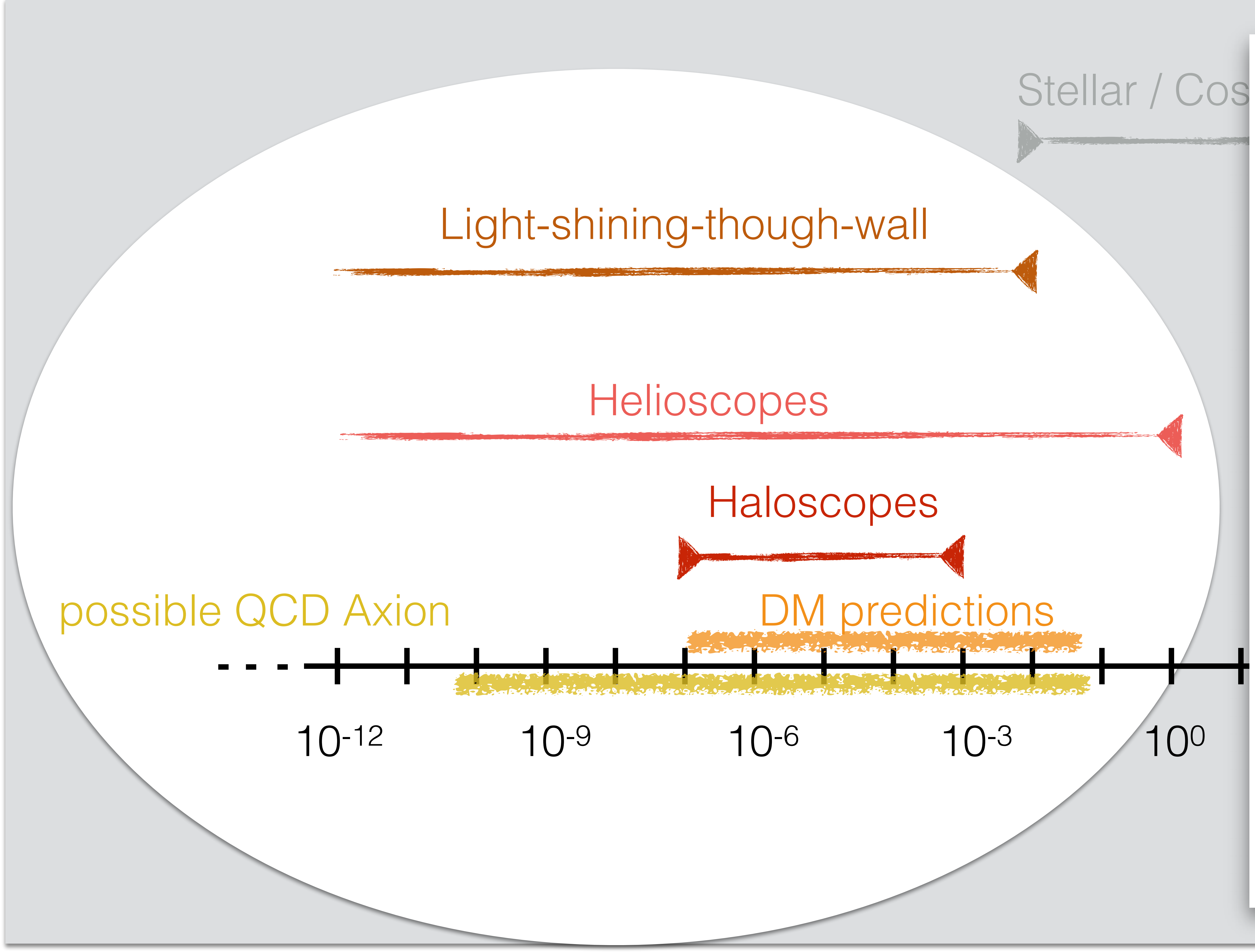
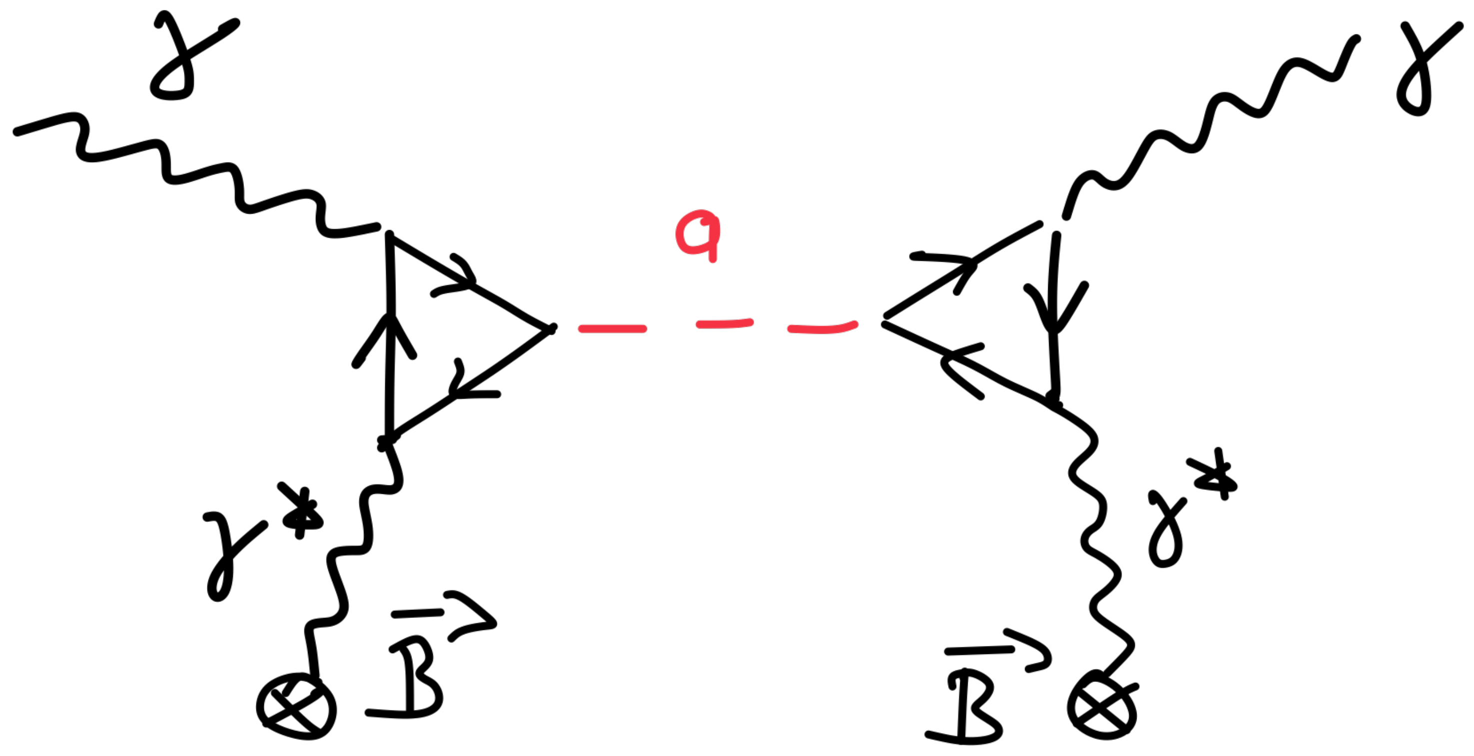




- Primakoff effect:
  Resonant photo-production of **pseudoscalar mesons**

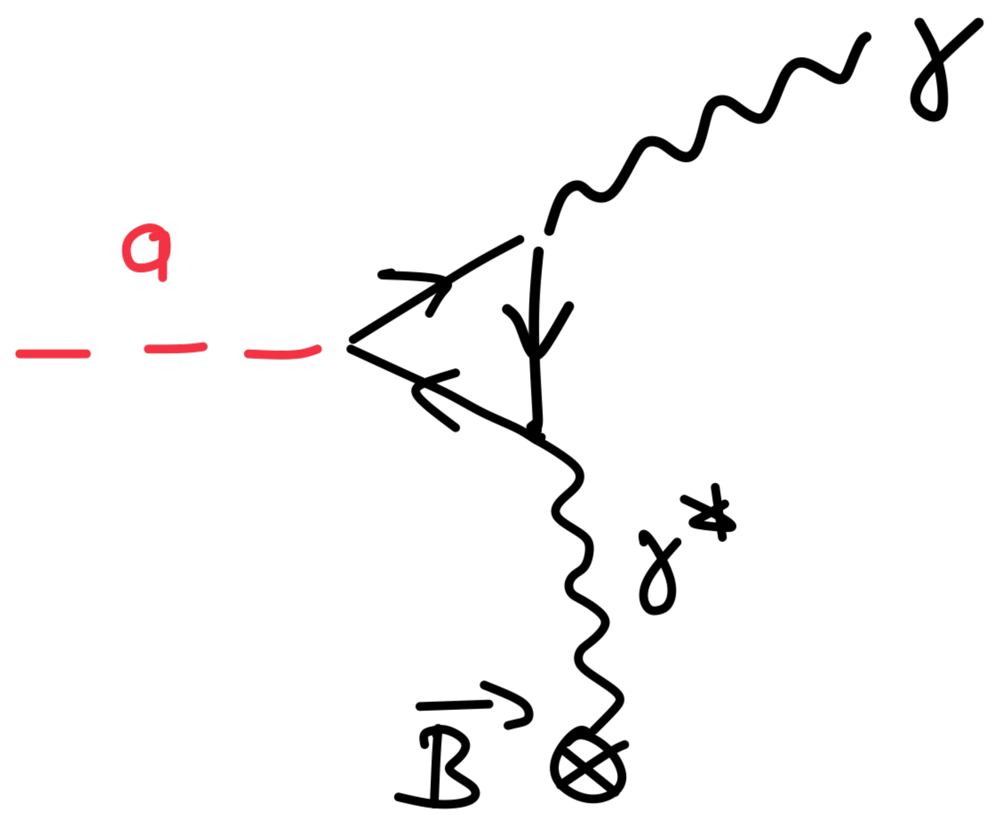
Light Axions and ALPs

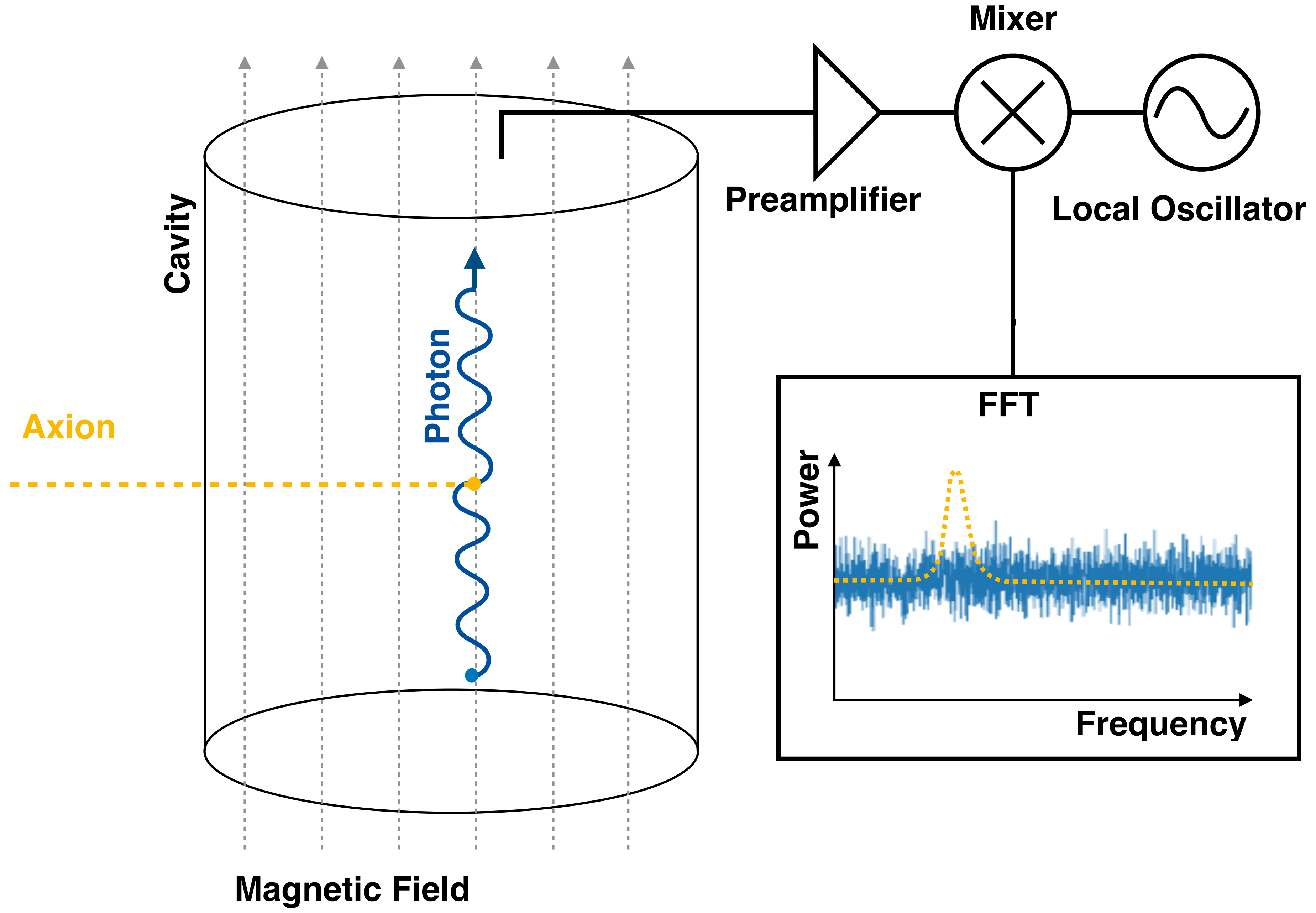




- Axion to photon conversion in magnetic field
  (inverse Primakoff effect)

Light Axions - Haloscopes - RF cavity based searches

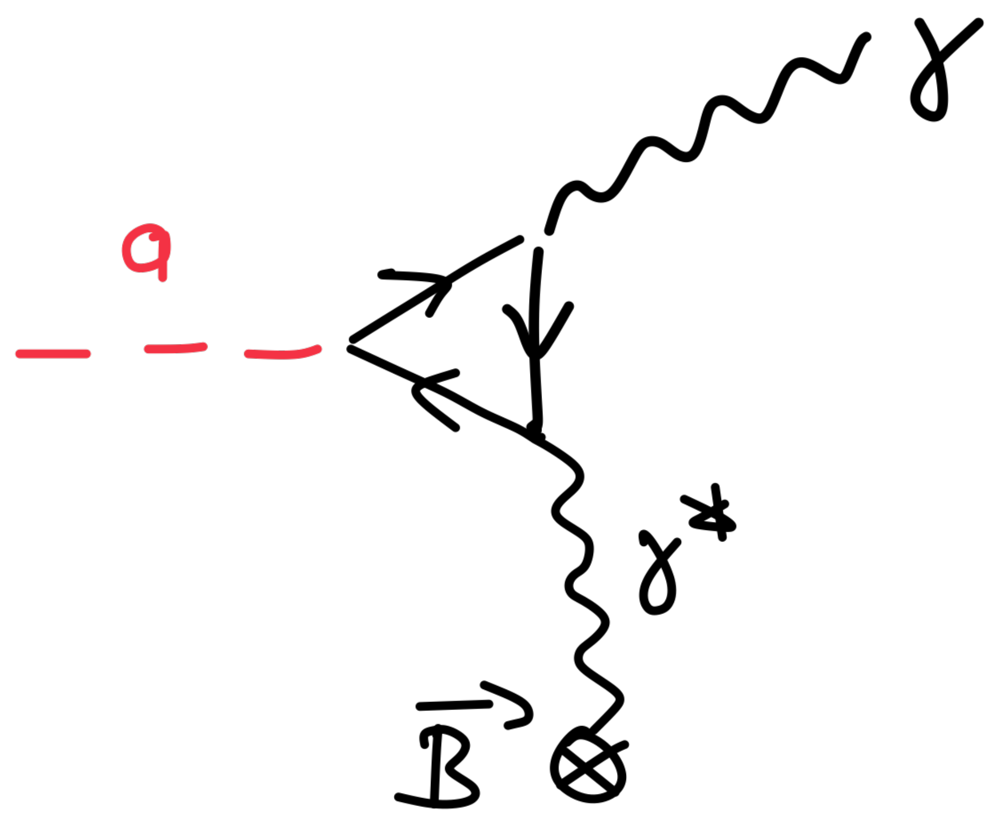


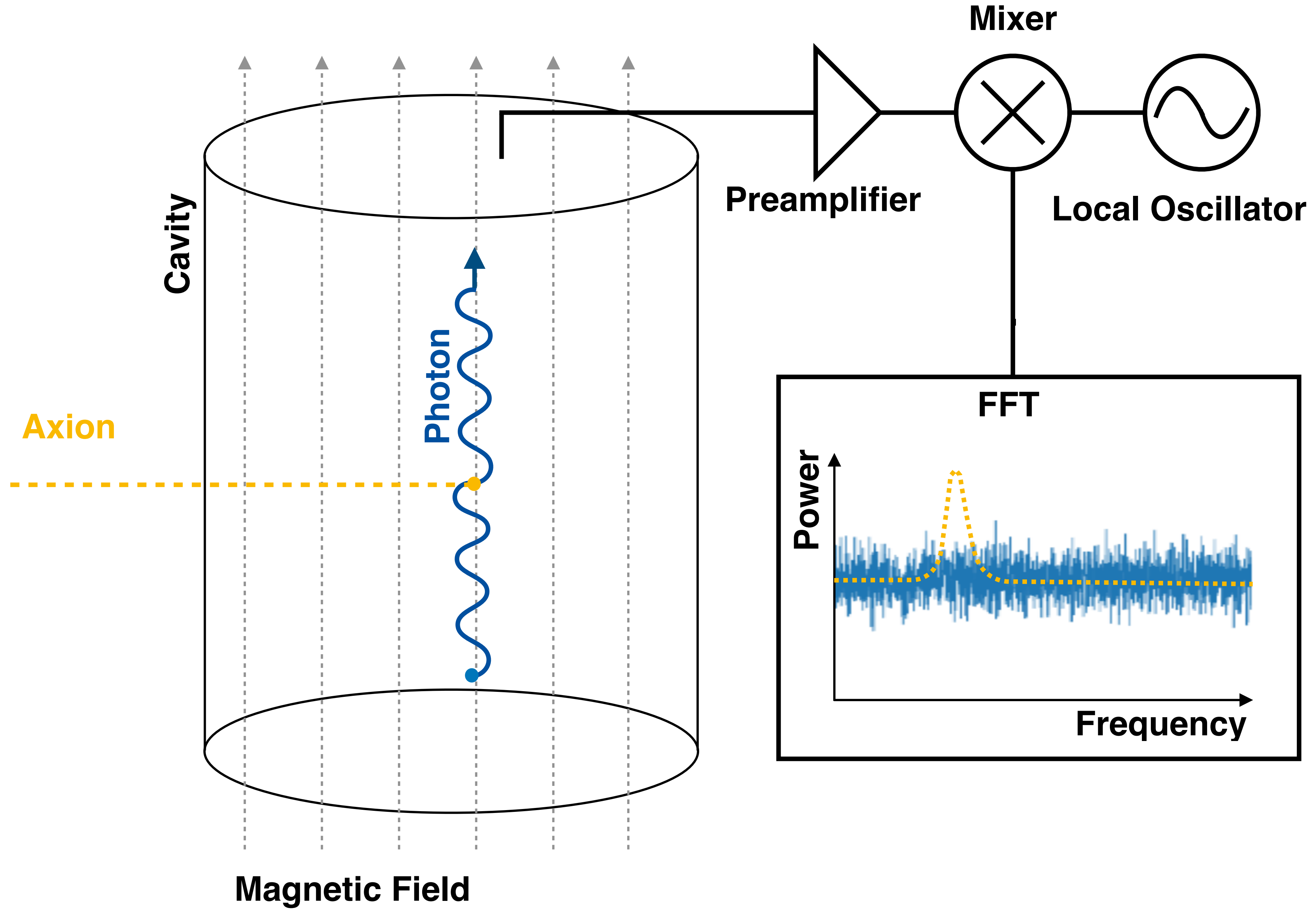


Light Axions - Haloscopes - RF cavity based searches

- Resonance frequency determined by cavity geometry
  - Limited tuning range
- Detection principle feasible in range 100MHz - 100 GHz
- 3 orders of magnitude in frequency:
  - Various designs of resonators & DAQ
  - Many experiments!

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





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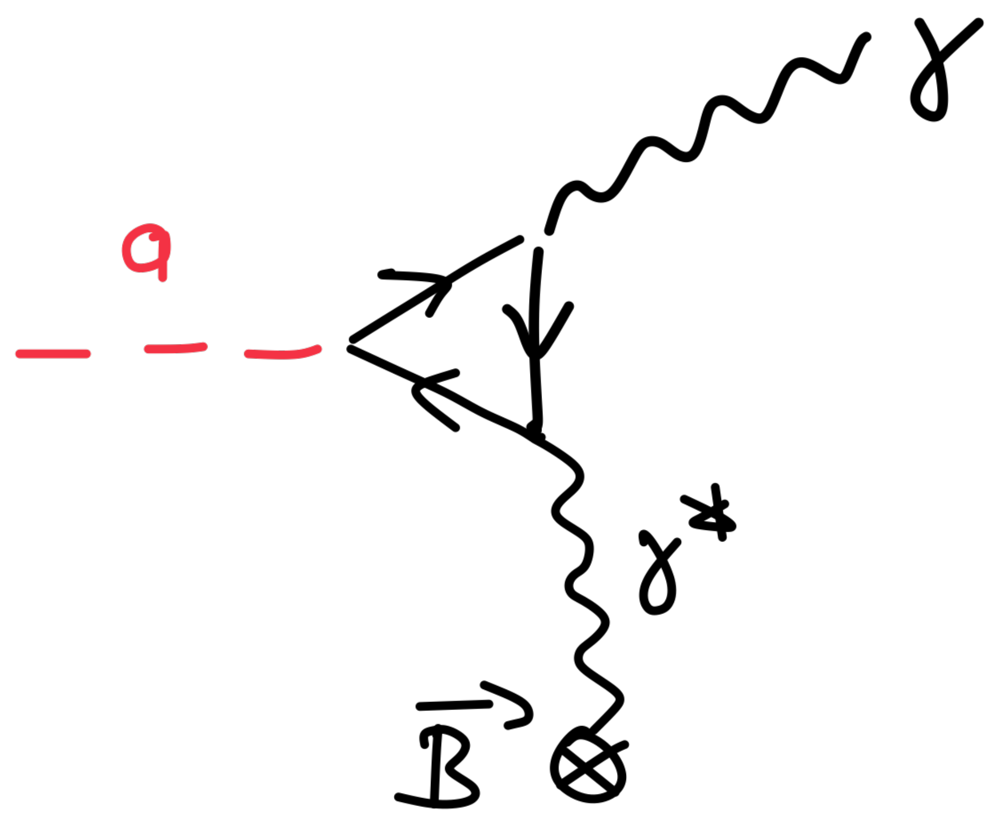
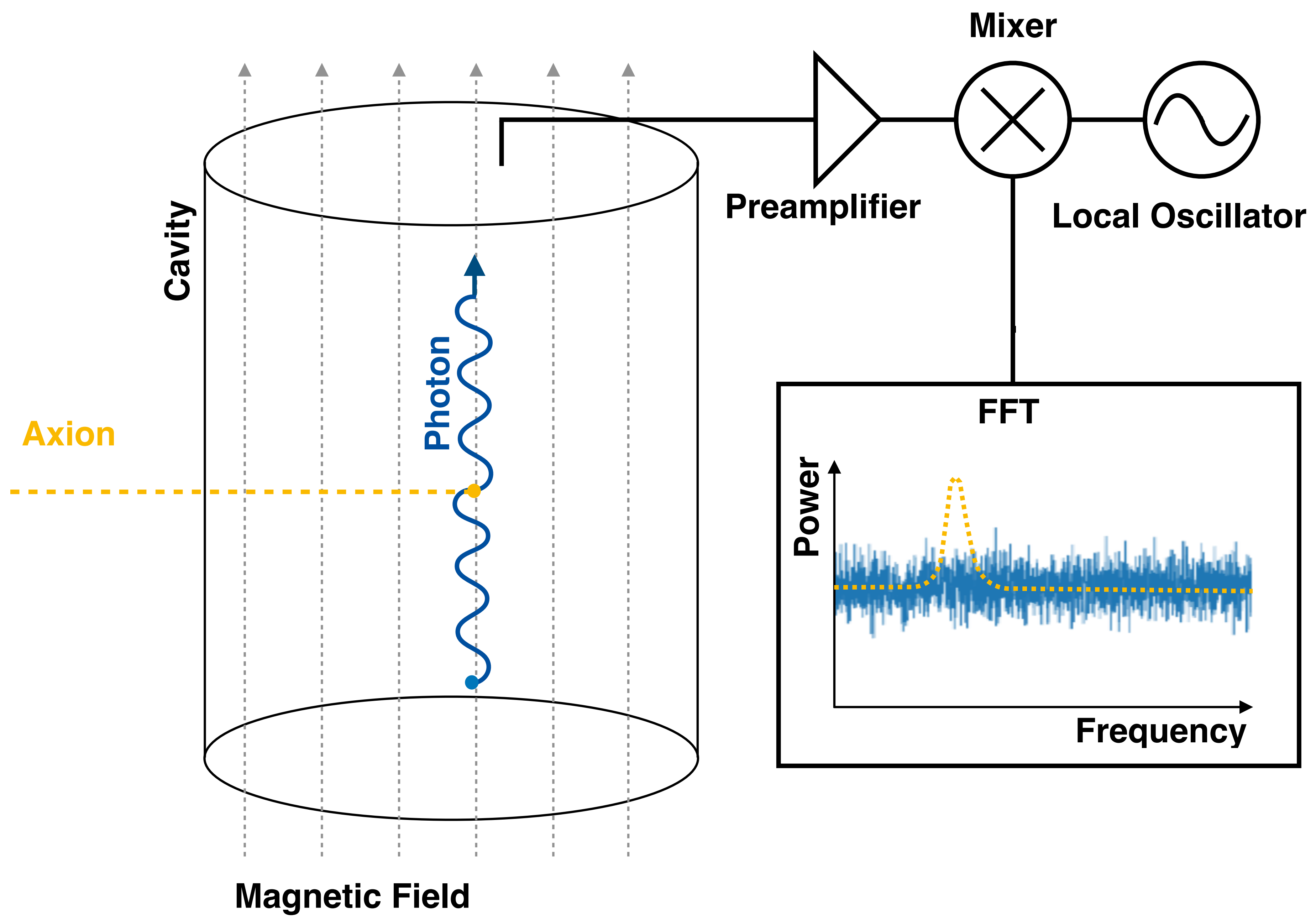
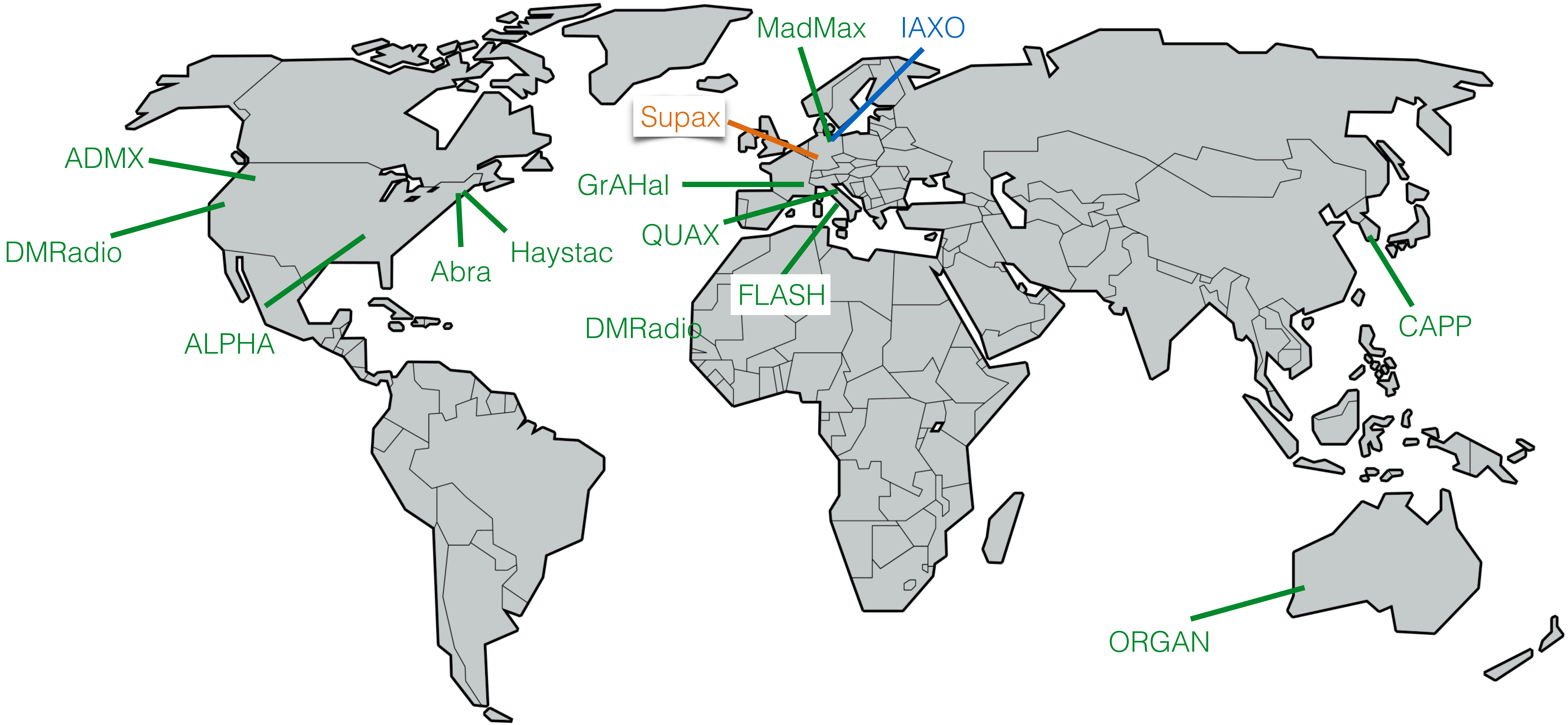




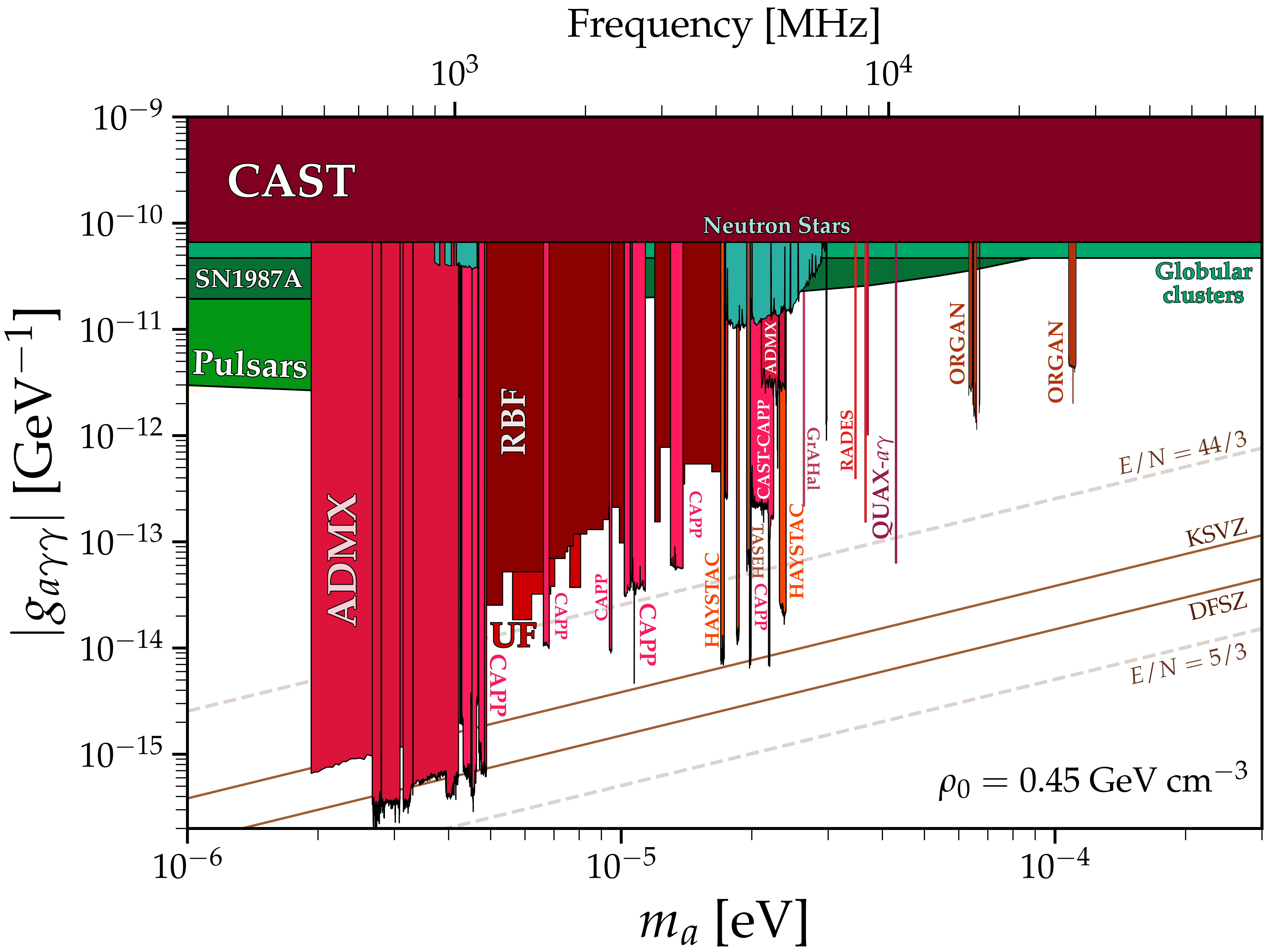
- Typ signal power: 10^{-24}W

Axion Haloscope Experiments

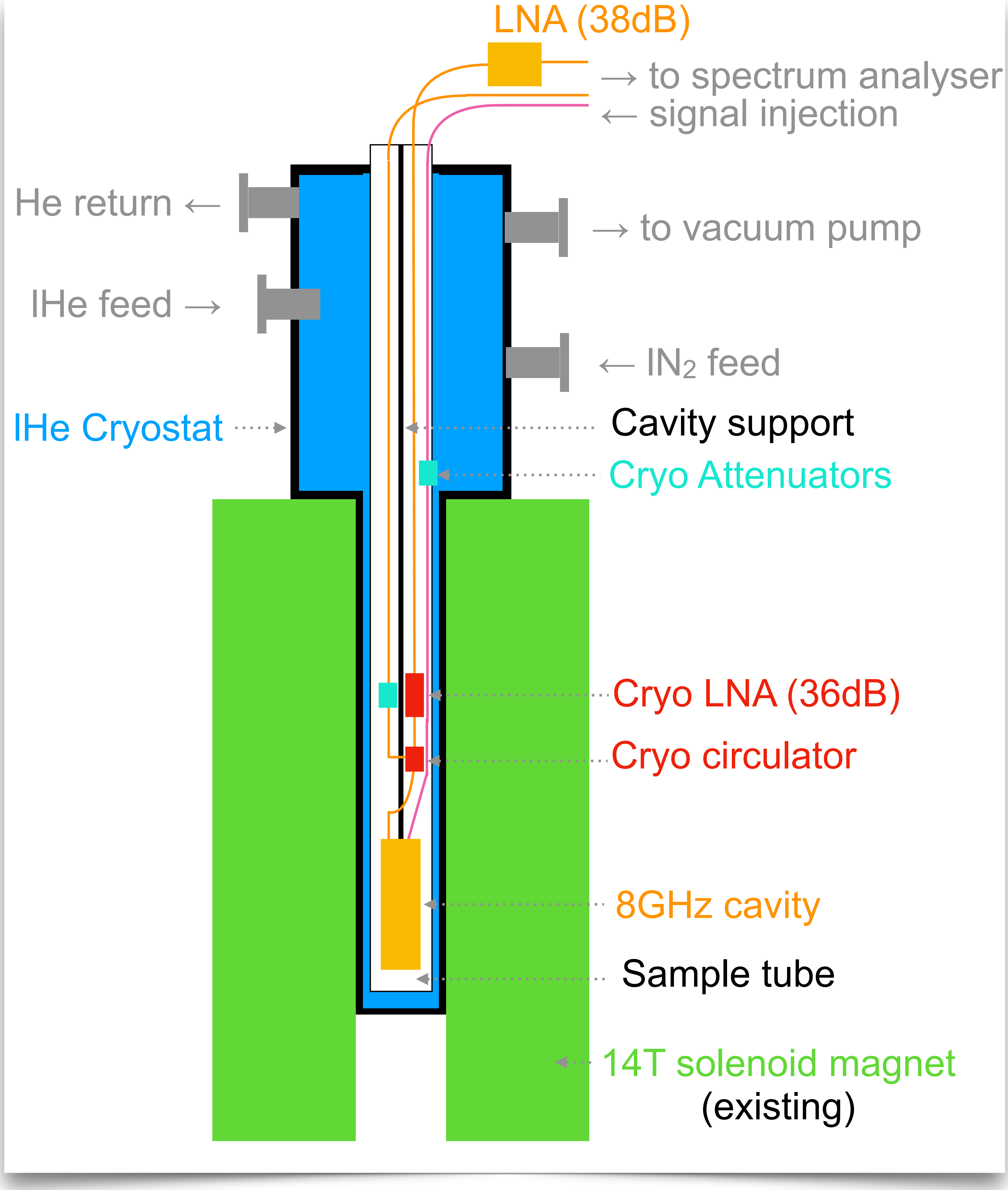


Why a new Haloscope?

- Lots of uncovered parameter space
- Mass range motivated by theory!
- Fully exploit the available infrastructure @ Bonn
    - Close gaps in interesting parameter range



Can we do it? The 4K Prototype



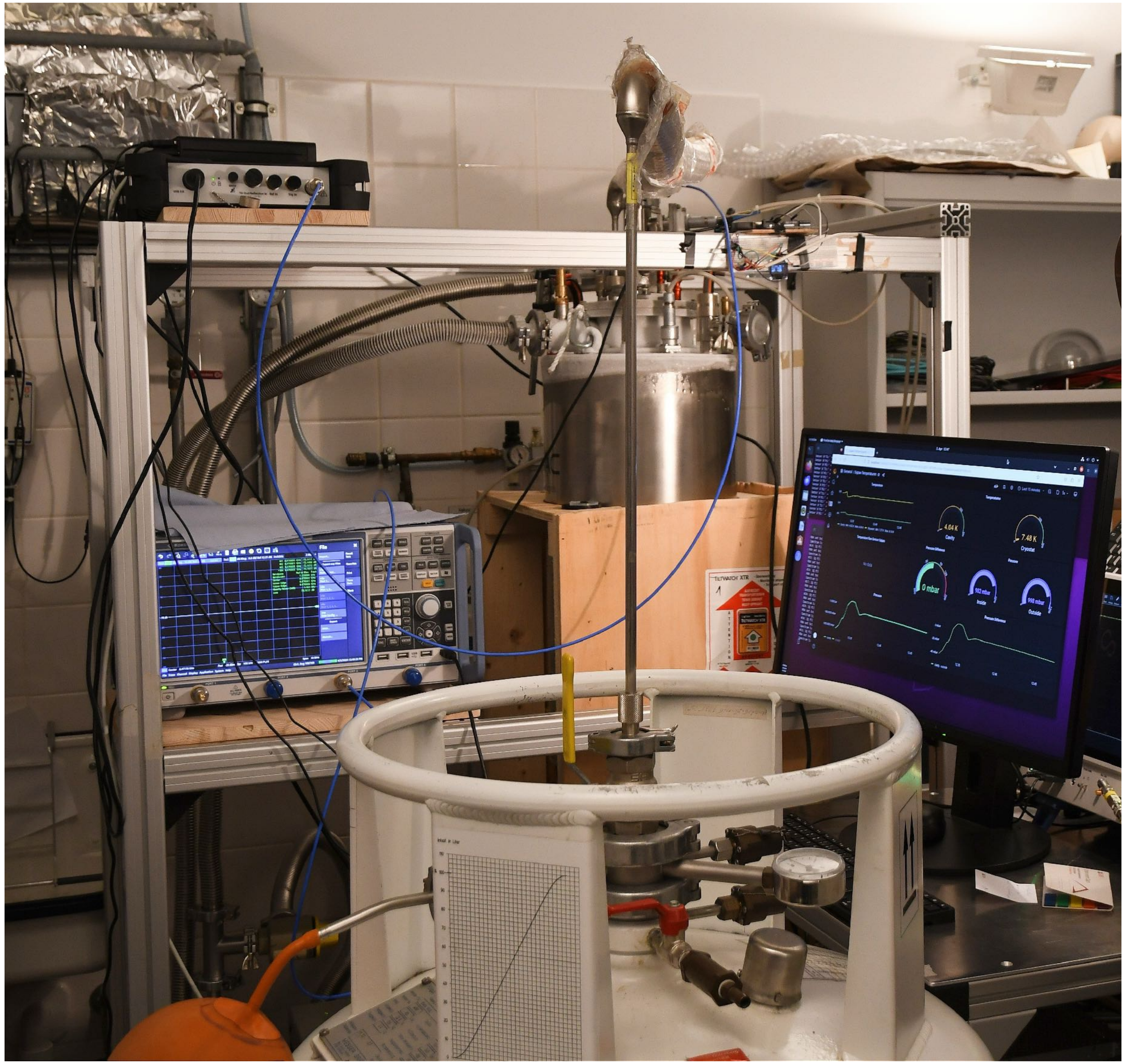
- Haloscope setup for R&D and physics @ Mainz

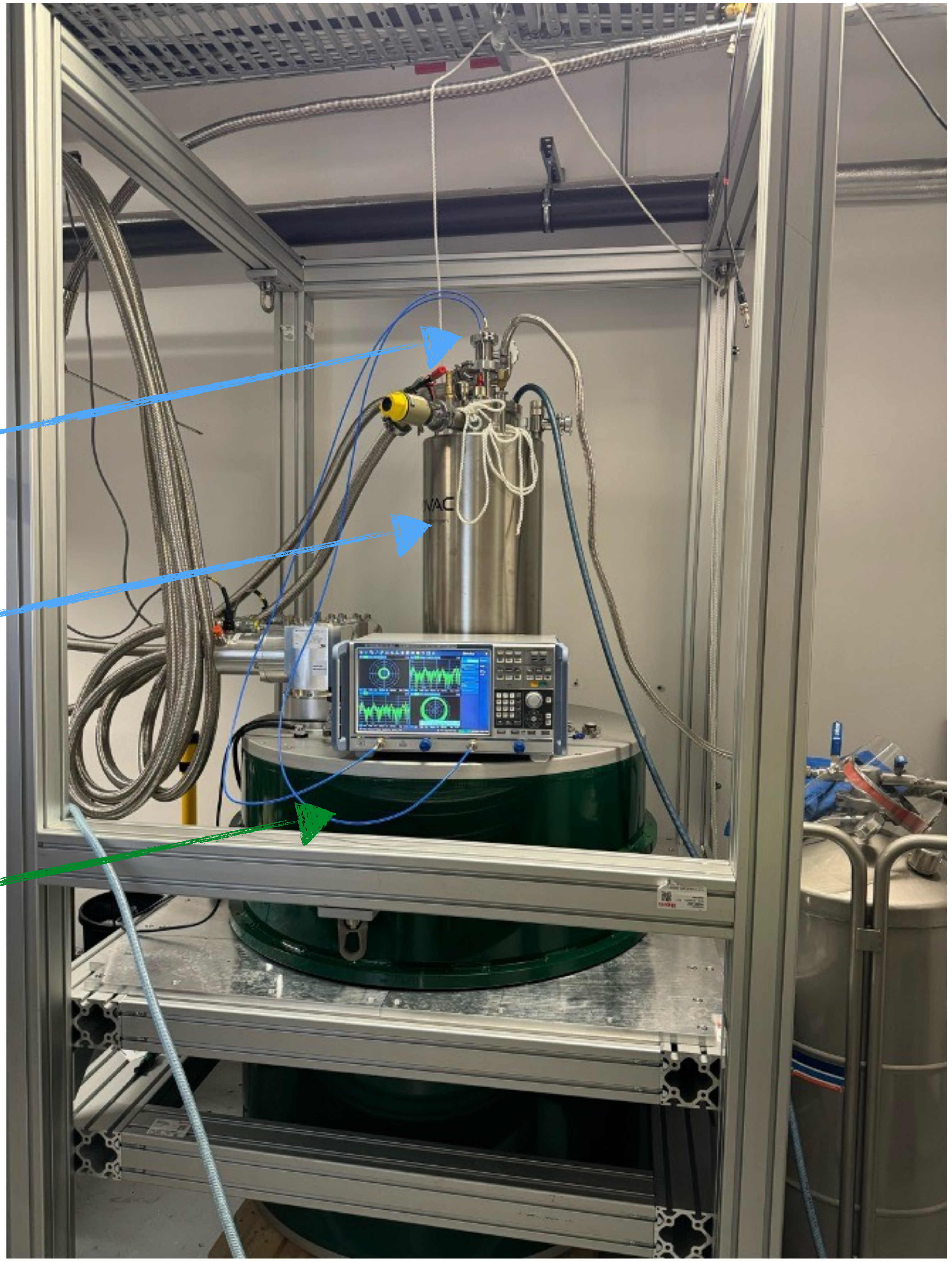
- Magnet bore: 89mm
  - Inner cryostat diameter: 50 mm

- Cryo Preamp @ 4K, 10GHz:
  - Gain: 36 dB
  - Noise: 3.8K (0.06dB)

- Cavity resonance frequency:
  - 8.4 GHz

Supax - Measurements





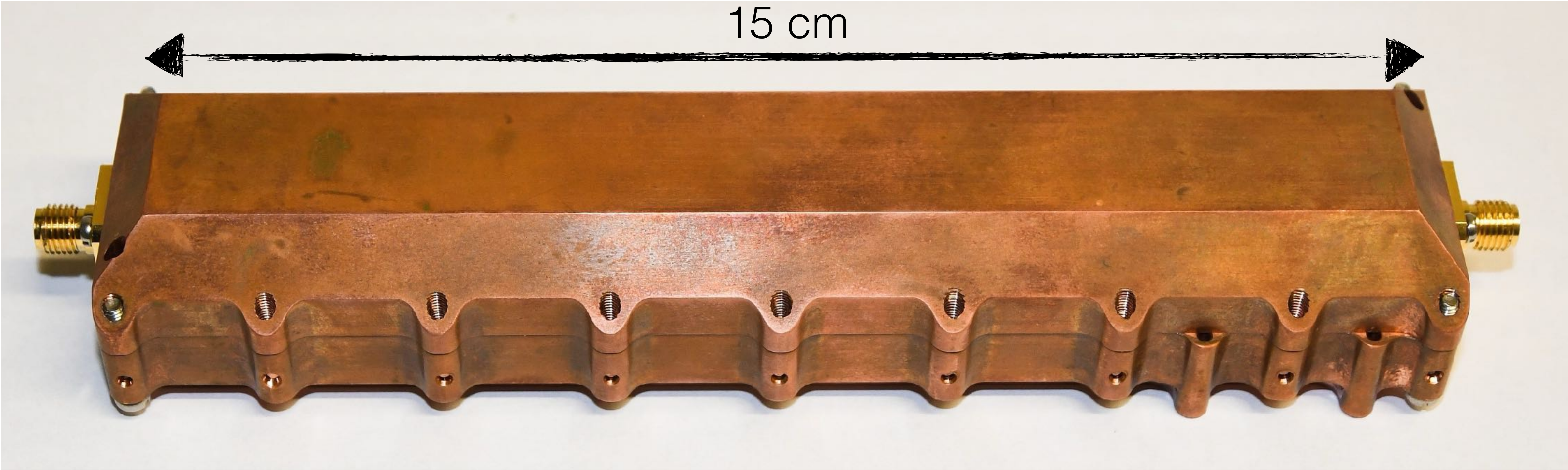
Inset Top

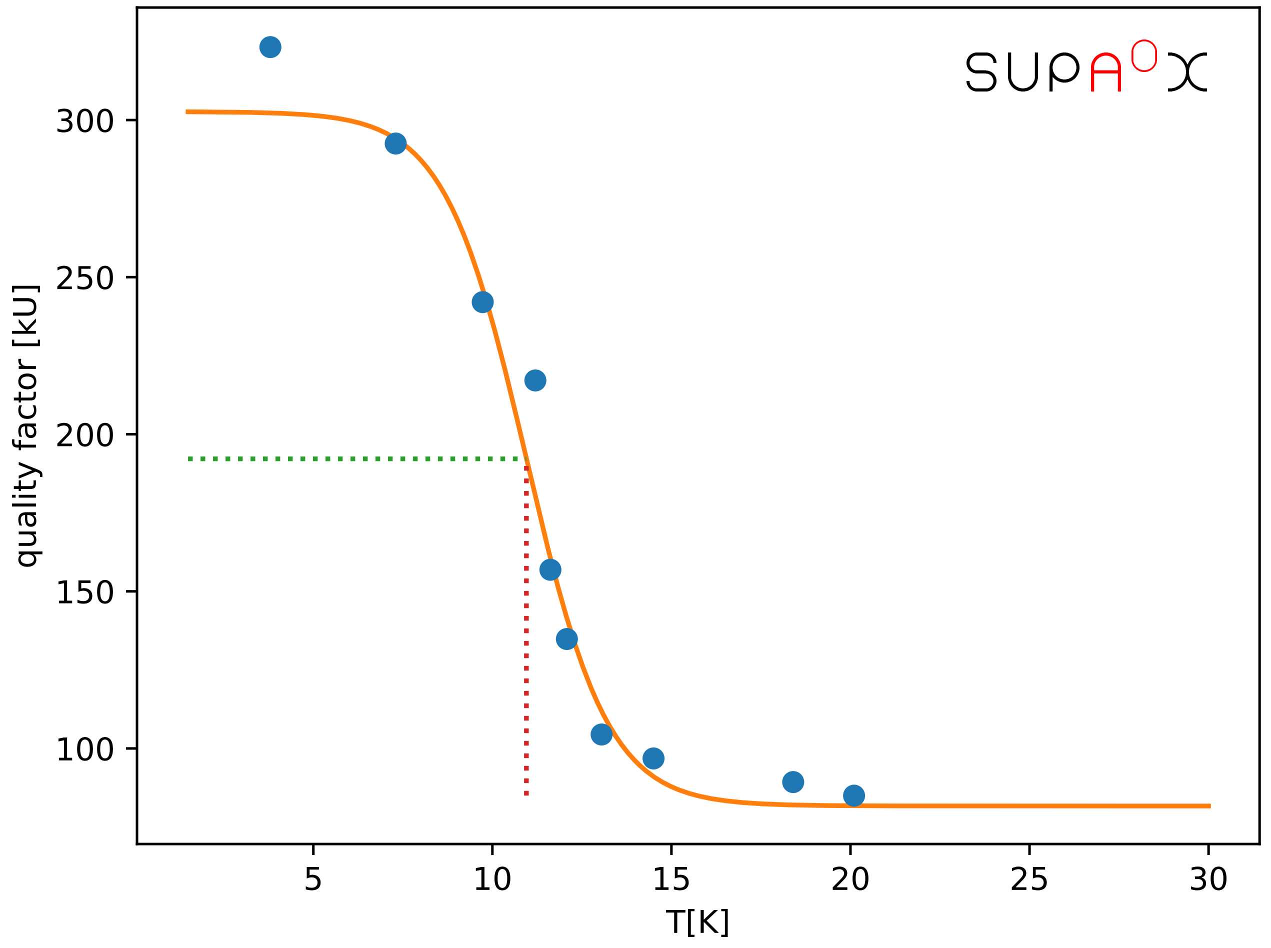
Cryostat

Magnet
(warm bore)

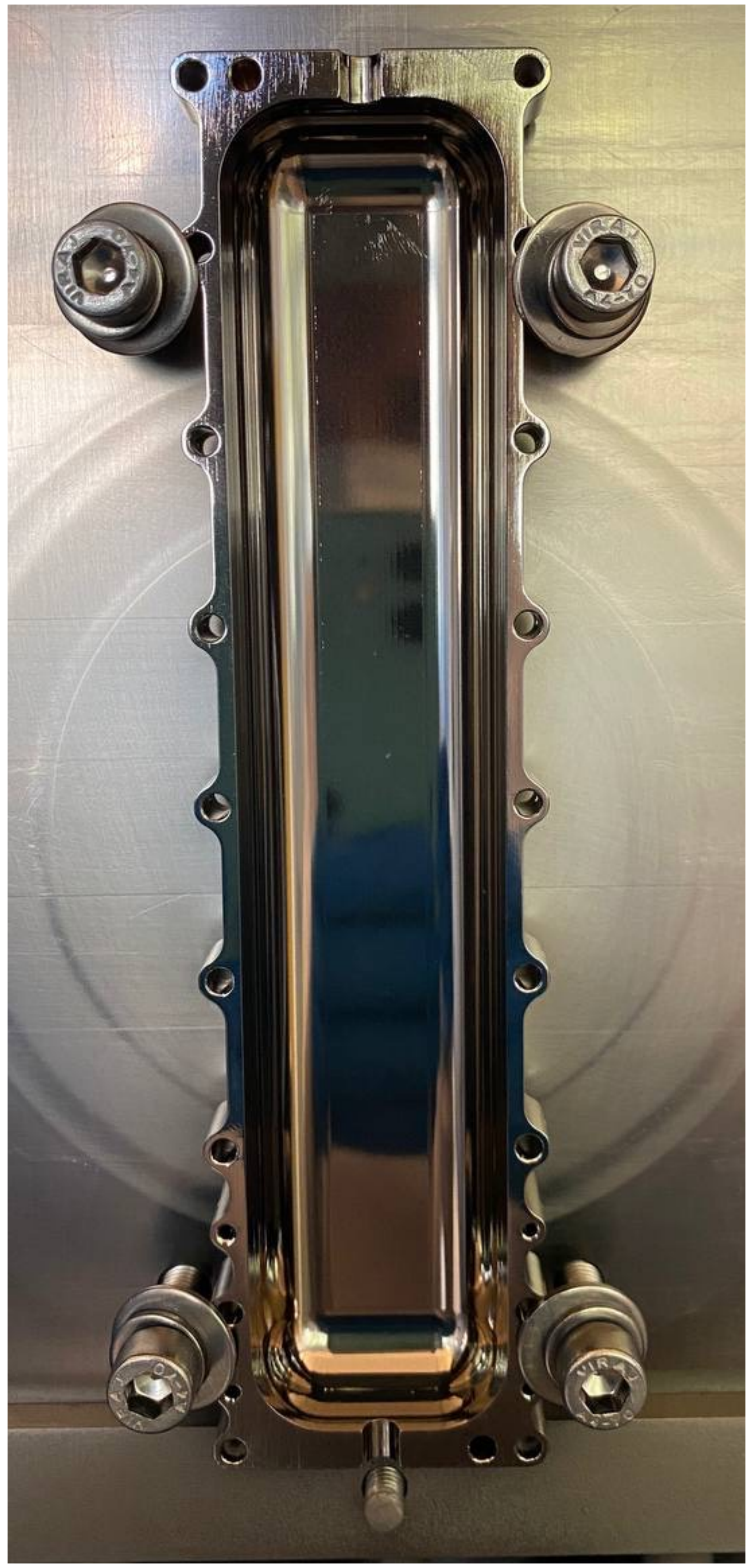
Supax - Cavities

- Test of various cavity geometries and coatings



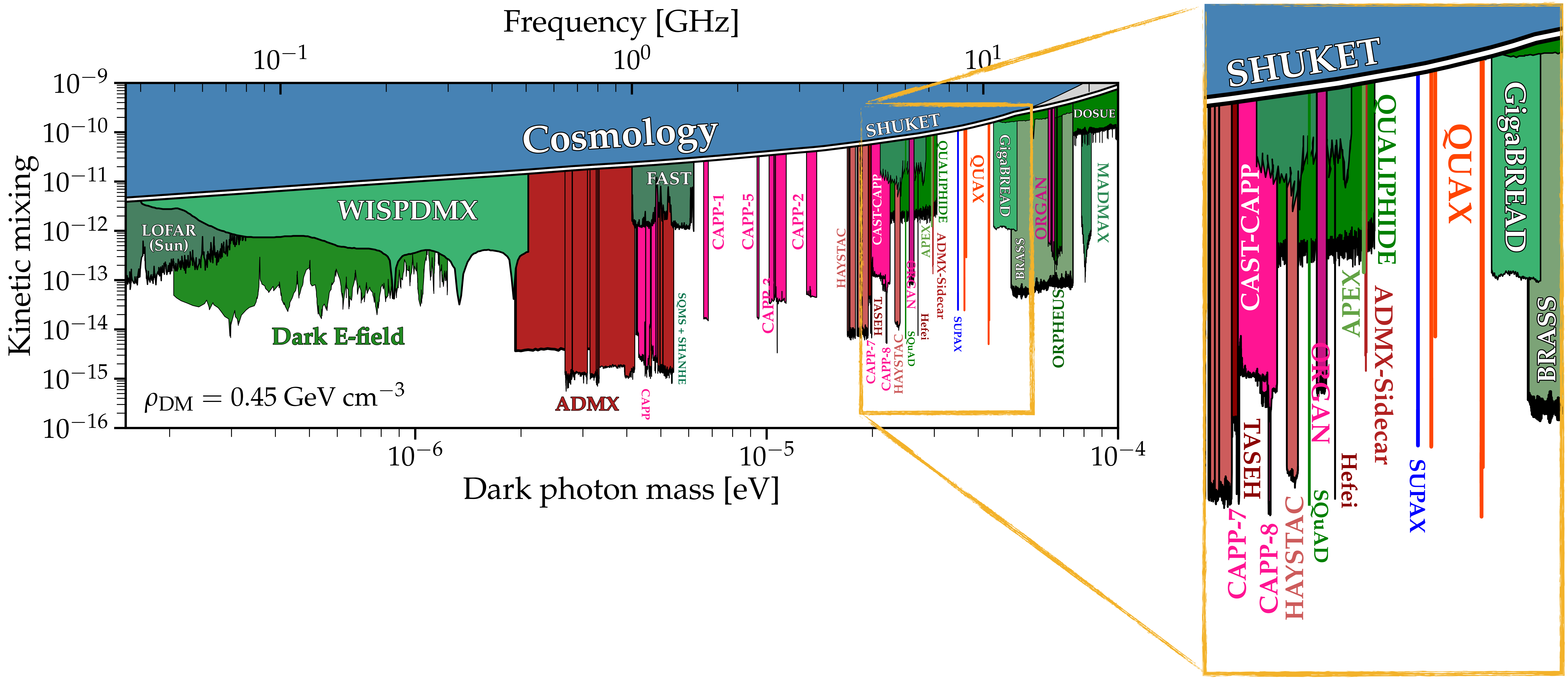


Cu coated with NbN
Coating by Zubtsovskii @ Uni Siegen



Results of Supax - Prototype

Dark Photon results (< 4h of data):



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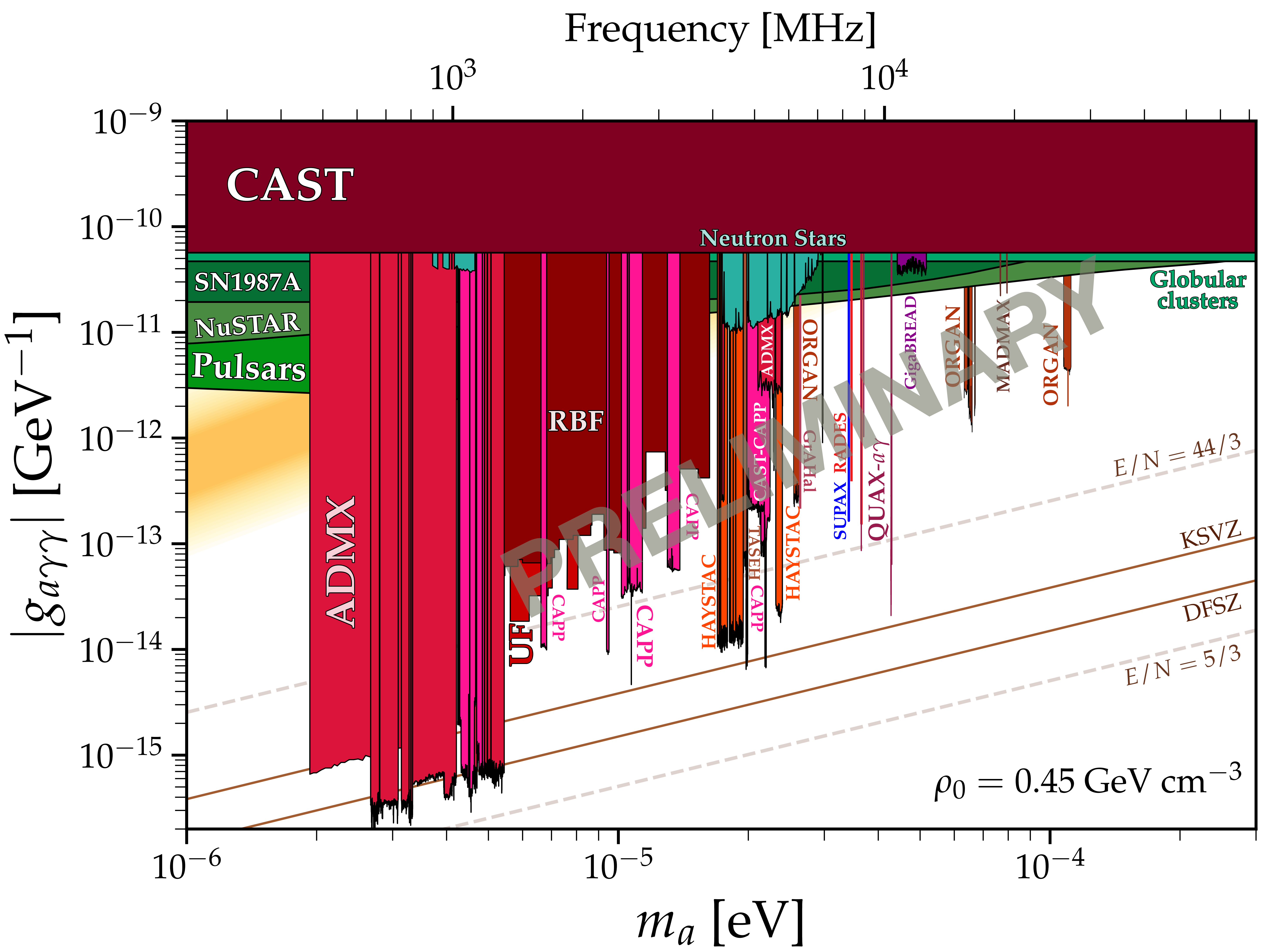

The NEW Supax Experiment @ Bonn

The NEW Supax Experiment

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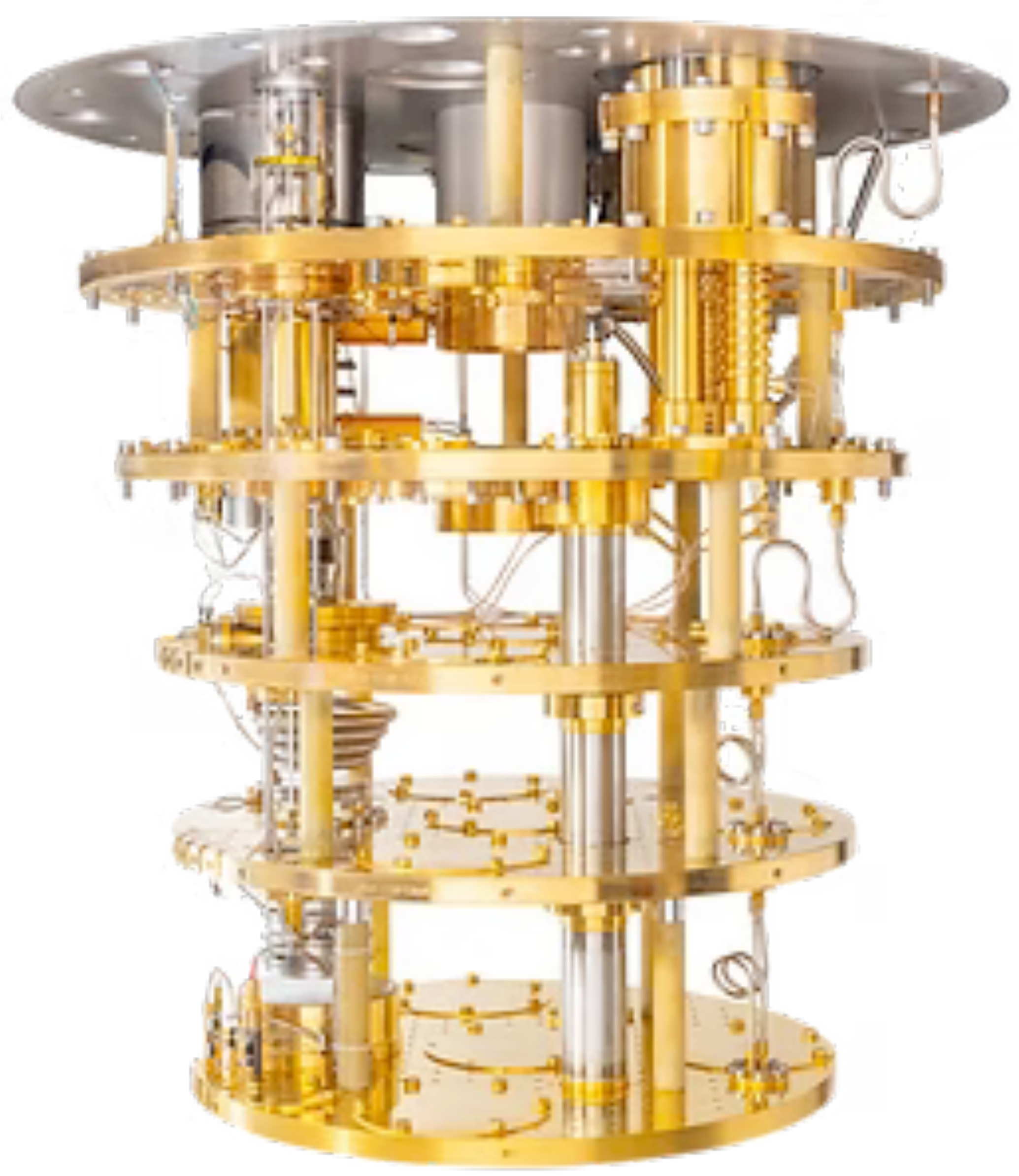
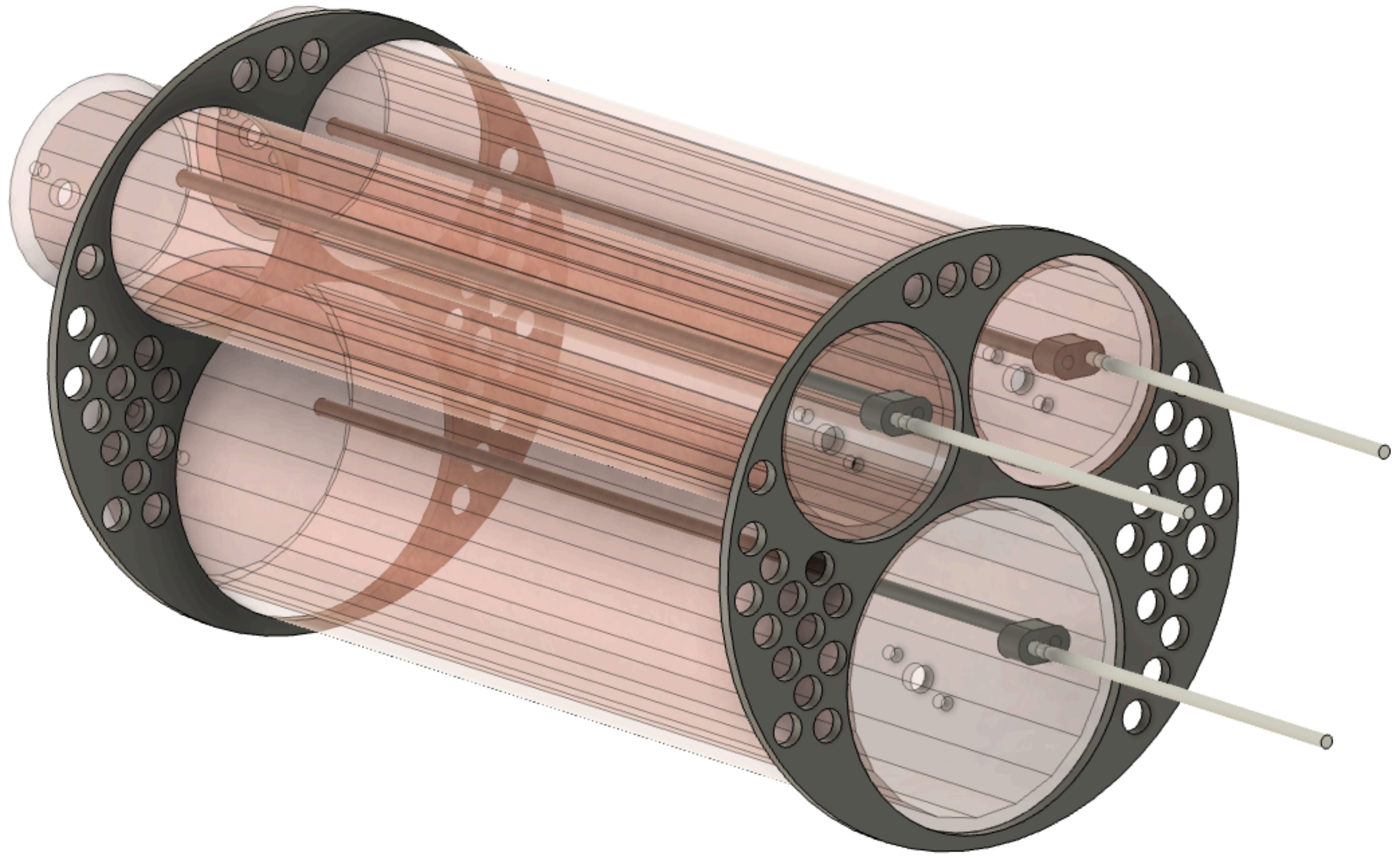
- Dual use: **Axions** & **GWs**

- Temperature: **10 mK**
- B-field: 12 T
- Usable volume: ø = 9 cm x 20 cm
- Freq. range: 2 GHz - 7GHz
- Up to 3 cavities in parallel

Sensitivity to Axions: [arXiv:2505.07541]





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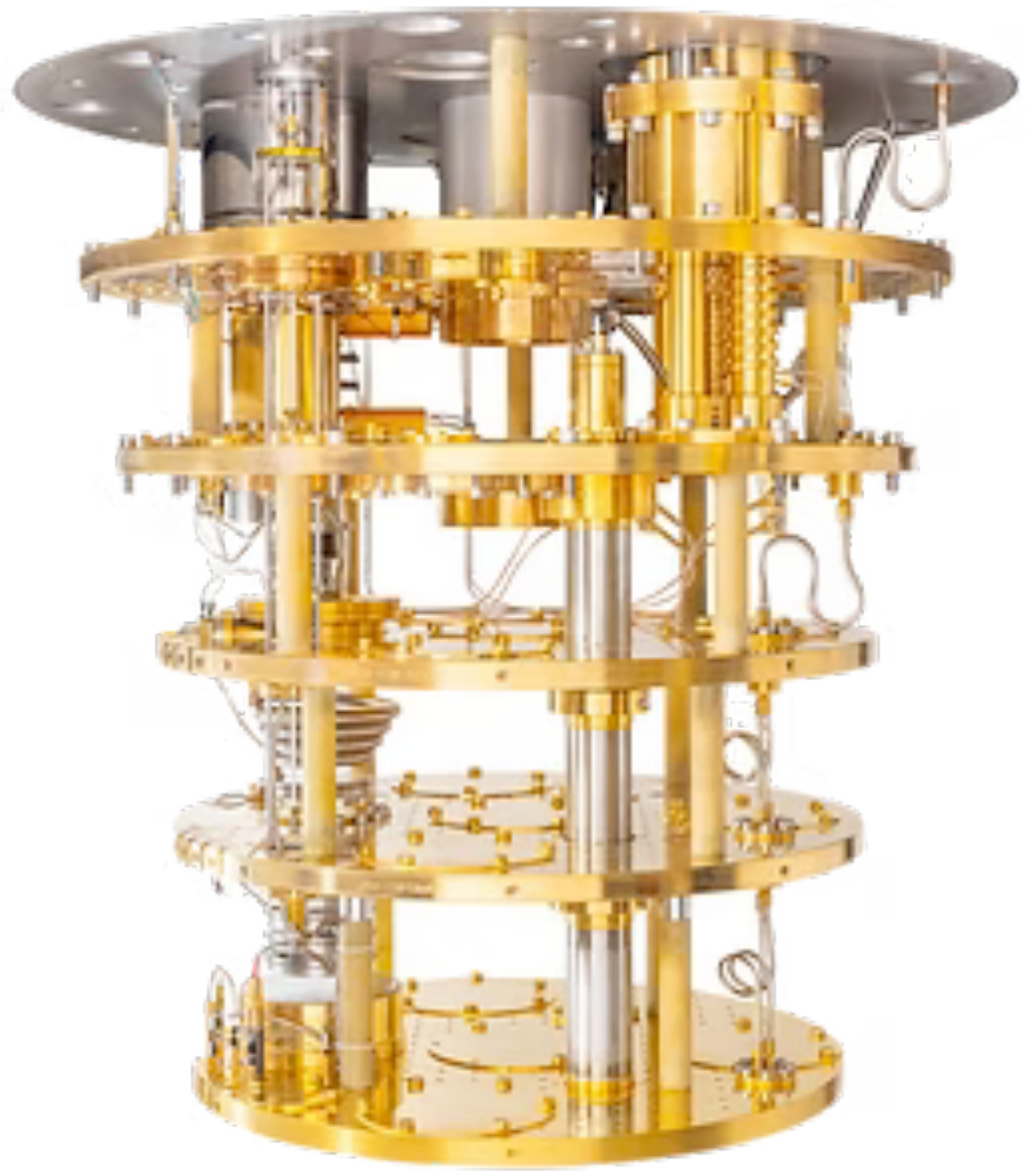
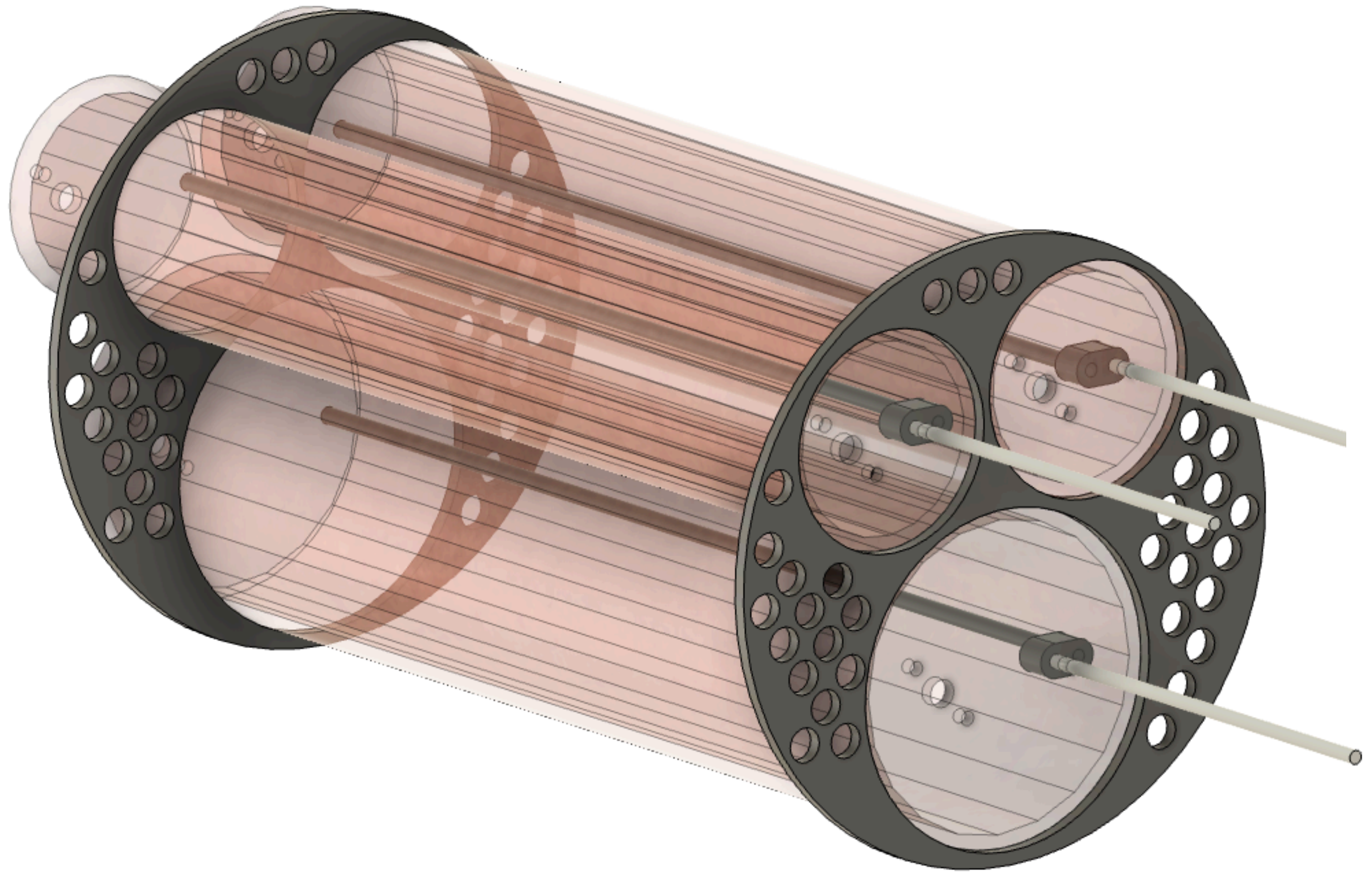
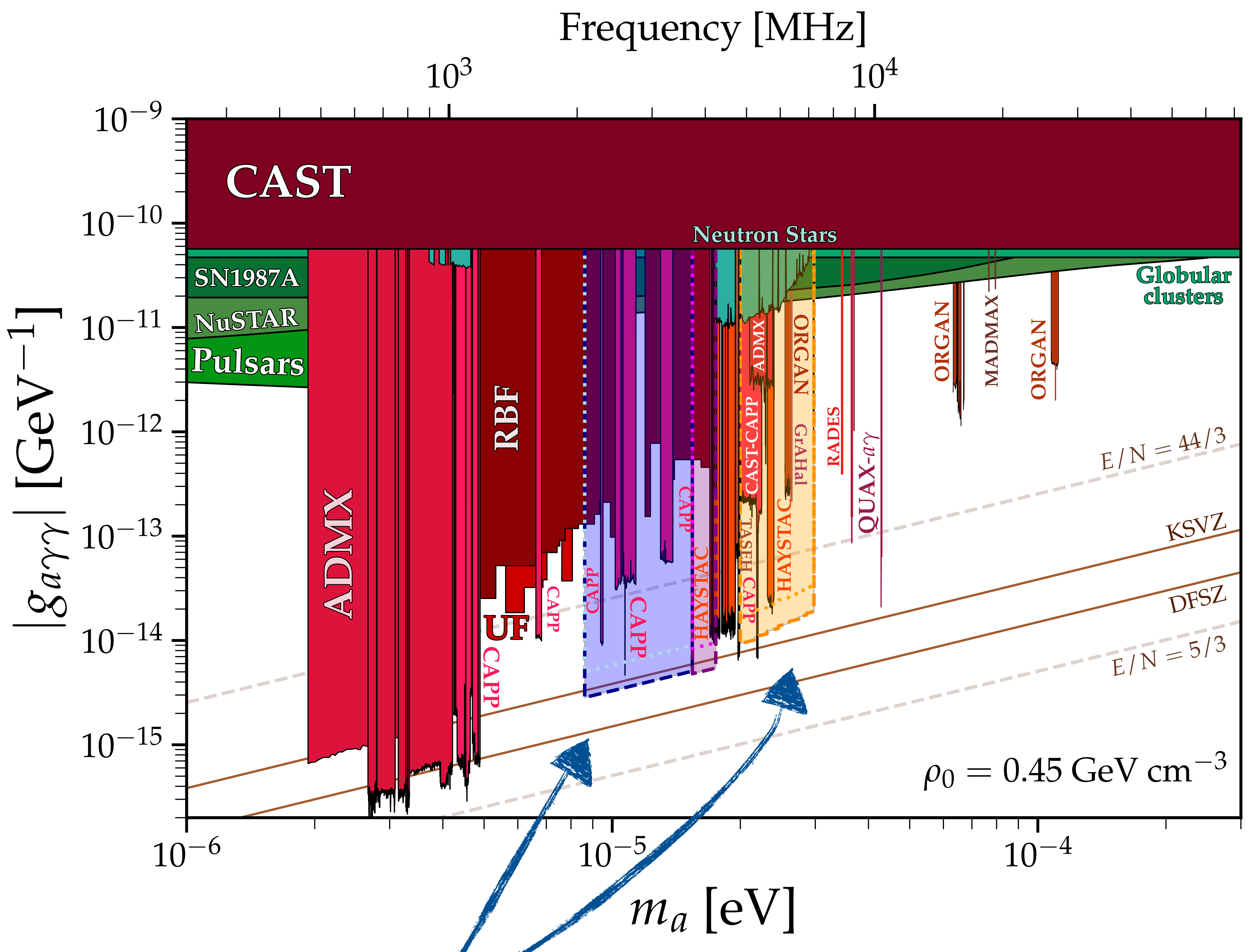
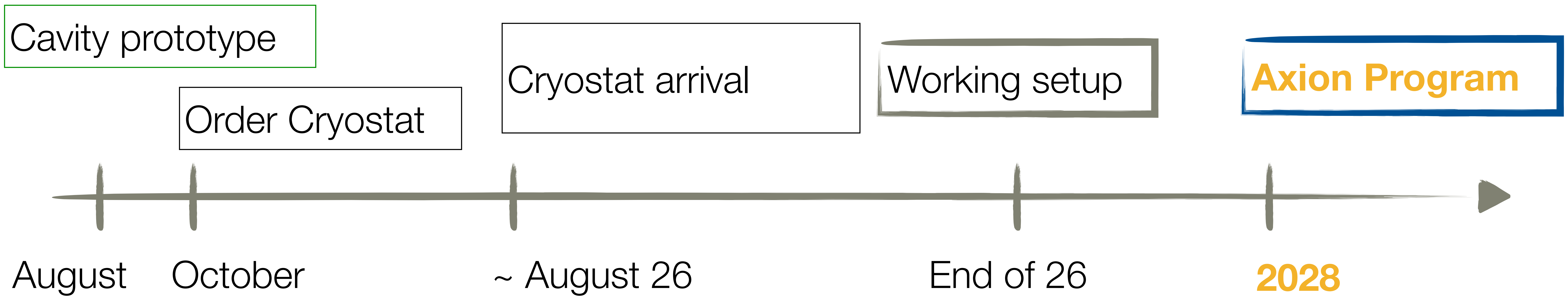






Sensitivity to axions in
40 weeks measurement time / block

The NEW Supax Experiment



Commissioning with

- One cavity
- 'Classic' readout: TWPA - HEMPT - RF digitisation
  10 mK 2 K Room temp
- 2027: Initial physics measurements: GW / Axions

The NEW Supax Experiment

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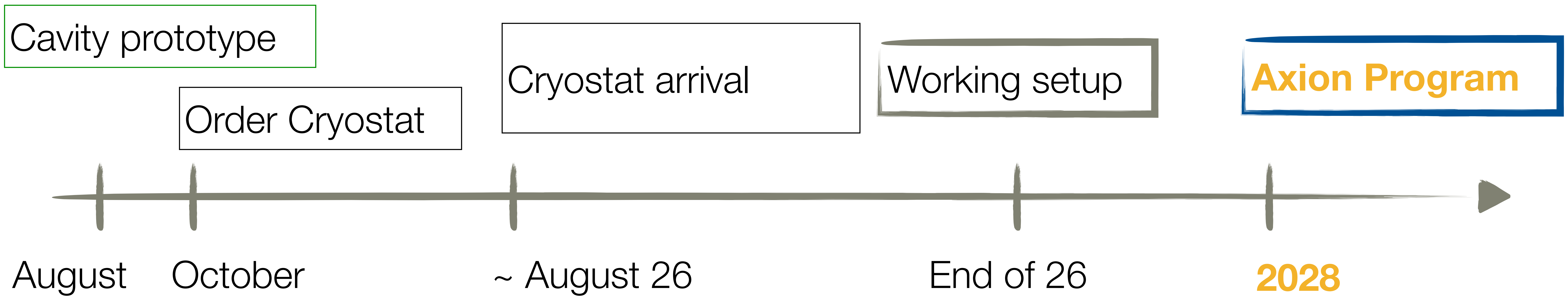

Axion Program: 2028 - …

- Three cavities - additional DAQ channels
- Quantum sensing: single photon detectors
  - Developed e.g. for RADES within dark Quantum

- **1 Phd student from CmF** to setup quantum readout and harvest axion results

Take Away Messages

- New haloscope will be built at Bonn
  - **Dedicated Axion campaign!**
    - **Axions are very likeable after all ;)**
- Expect to significantly contribute to the global search for the QCD Axions
- Collaboration with RADES
  - Profit from Quantum sensing developed within Dark Quantum

Who does the work?

To fully exploit the setups potential:

dedicated **phd student** required

BACKUP SLIDES

6 reasons to like axions - details

Axions as Dark Matter - I

- Axions follow Bose-Einstein statistics
- Ensemble of light axions:
  macroscopic, wave-like behaviour
  - **Acts as cold dark matter**
- **Mass Limits:**
  - $m_a > 10^{-22}$ eV, otherwise no structure formation possible
  - QCD axions: $m_a < 2 \cdot 10^{-2}$ eV from neutrino flux of SN1987A
  - No upper bound on mass of ALPs

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- Assuming all of DM is QCD Axions: Predict it's mass
  - Depends on production mechanism
  - Computationally difficult:
    - no ab initio calculation possible
      ➡ **model dependent results**

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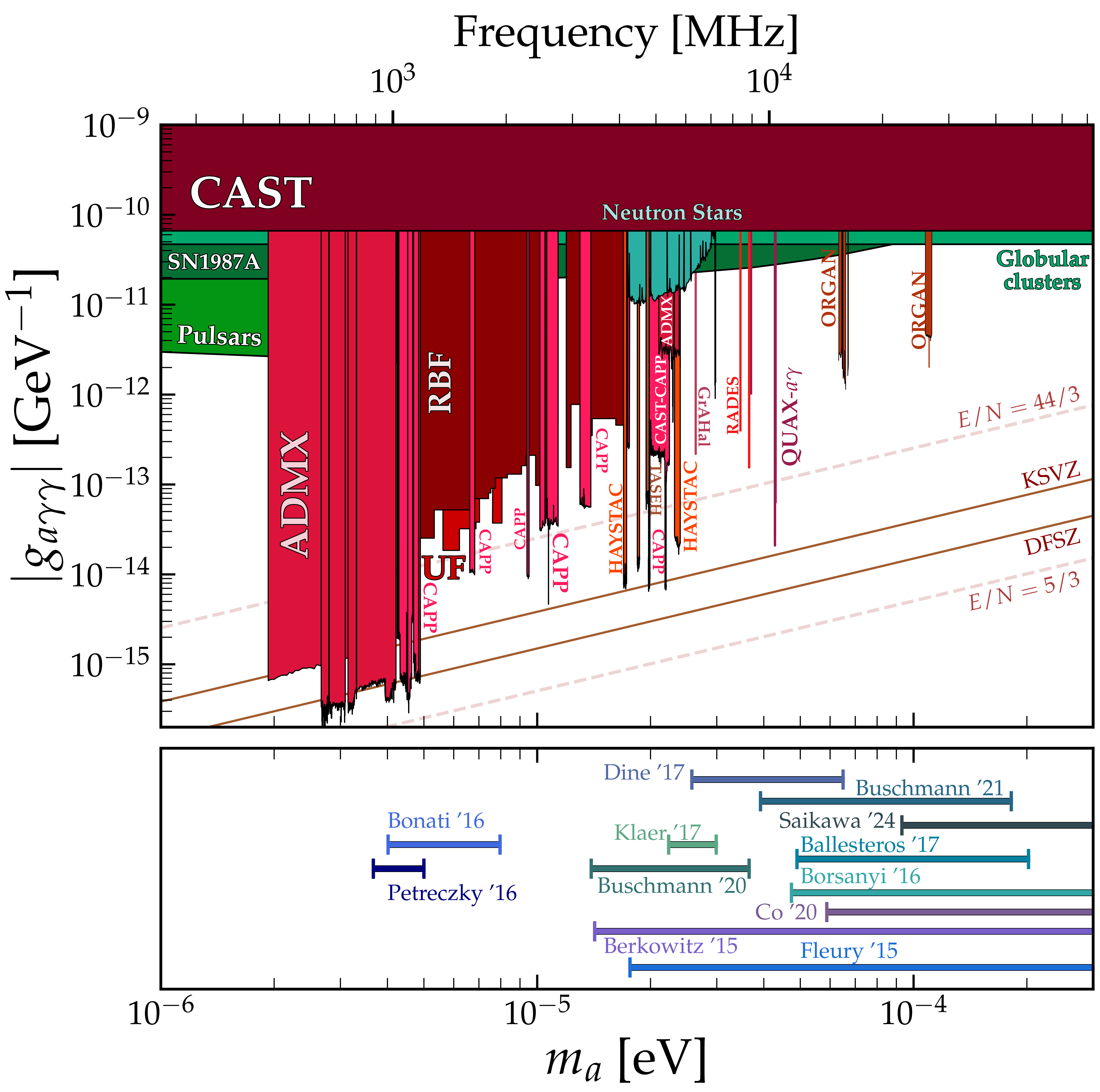


[source: https://github.com/cajohare/AxionLimits]

Possible Solution to strong CP problem - II

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

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

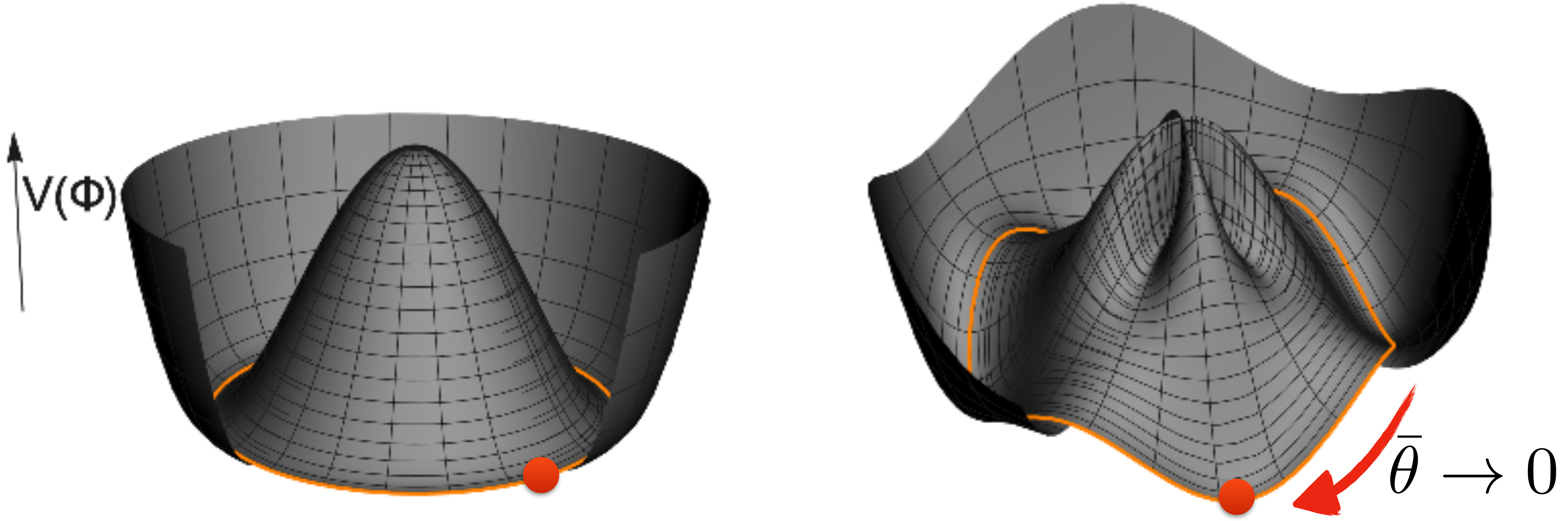
QCD term — Axion term

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

- E ~ f_a (large)
  - Spontaneously broken symmetry
  - Axion = Nambu-Goldstone boson (massless)

- Only free parameter:
  - Scale of symmetry breaking

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



More Reasons to like Axions - III

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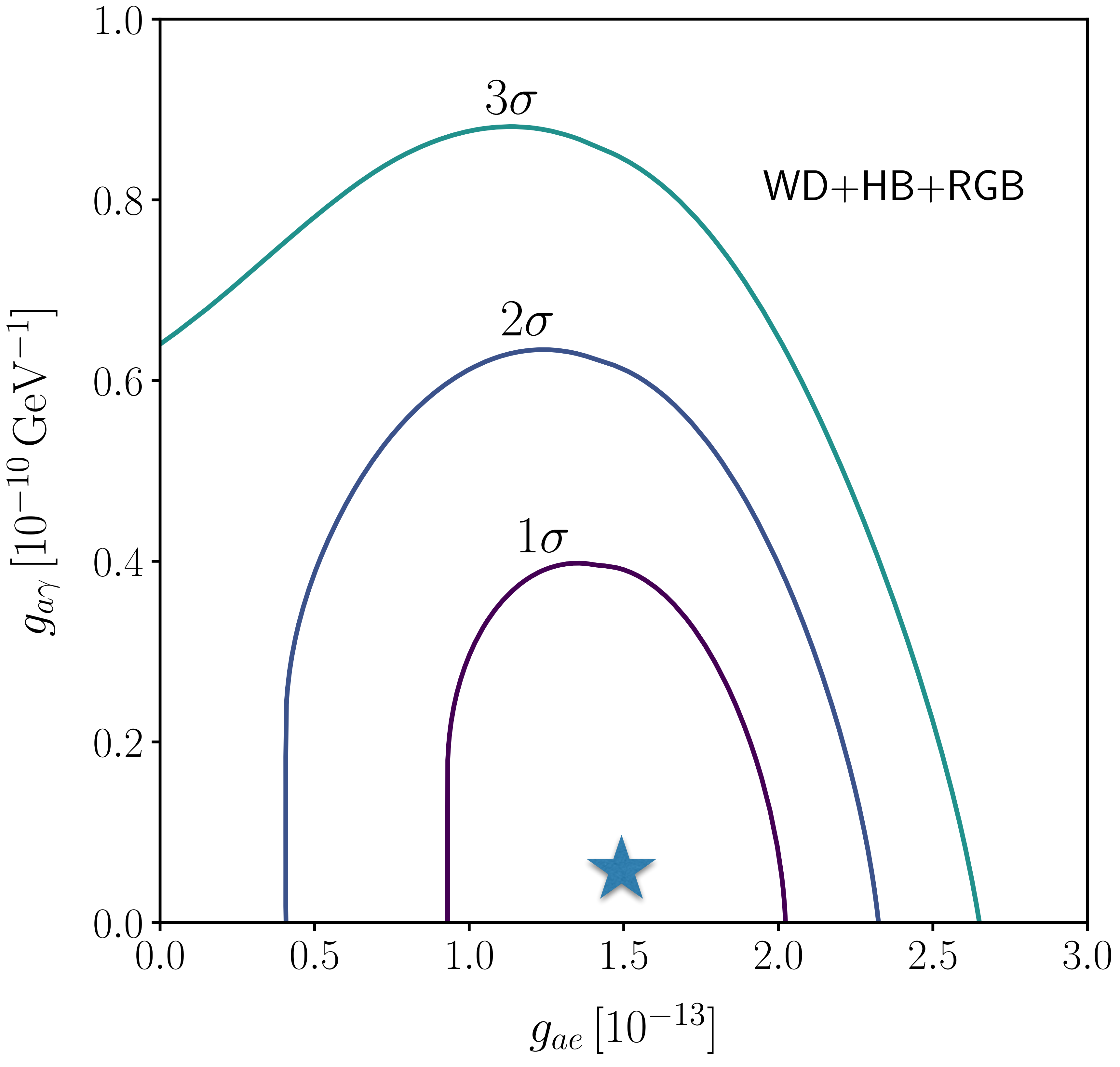
- Emission of Axions strongly constrained from too fast cool down of stars

<u>Bounds:</u>

Stellar system	Bound
RGB stars	$g_{ae} \leq 4.3 \times 10^{-13}$
WDs	$g_{ae} \leq (3-4) \times 10^{-13}$
HB stars	$g_{a\gamma} \leq 0.65 \times 10^{-10}\ \mathrm{GeV}^{-1}$
SN 1987A	$g_{ap} \leq 6 \times 10^{-10}$
NS	Similar to SN 1987A

More Reasons to like Axions - III

- Some stars appear to cool down faster than expected
- (Weak) evidence seen in white dwarfs, horizontal branch and red giant branch stars



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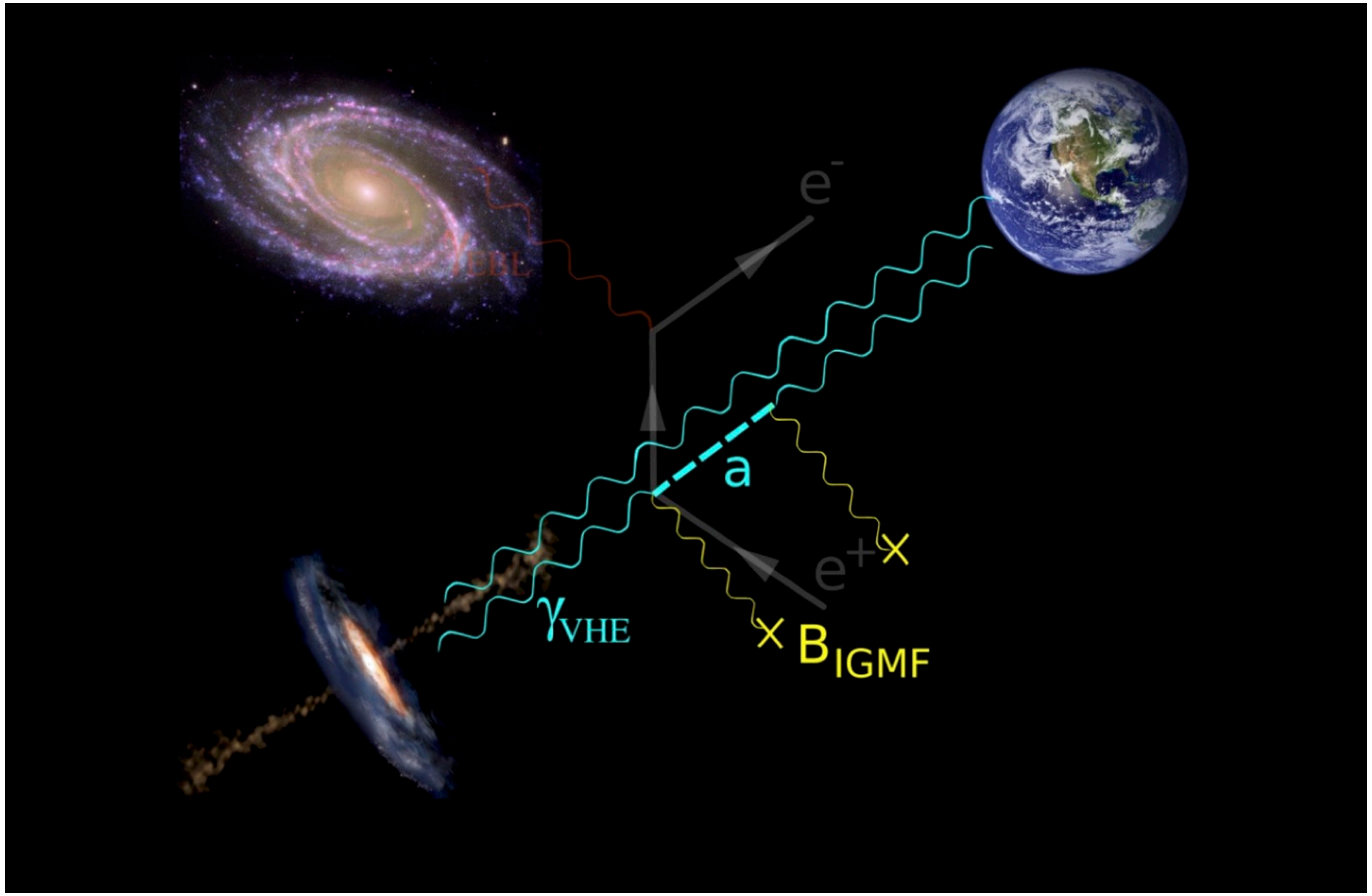
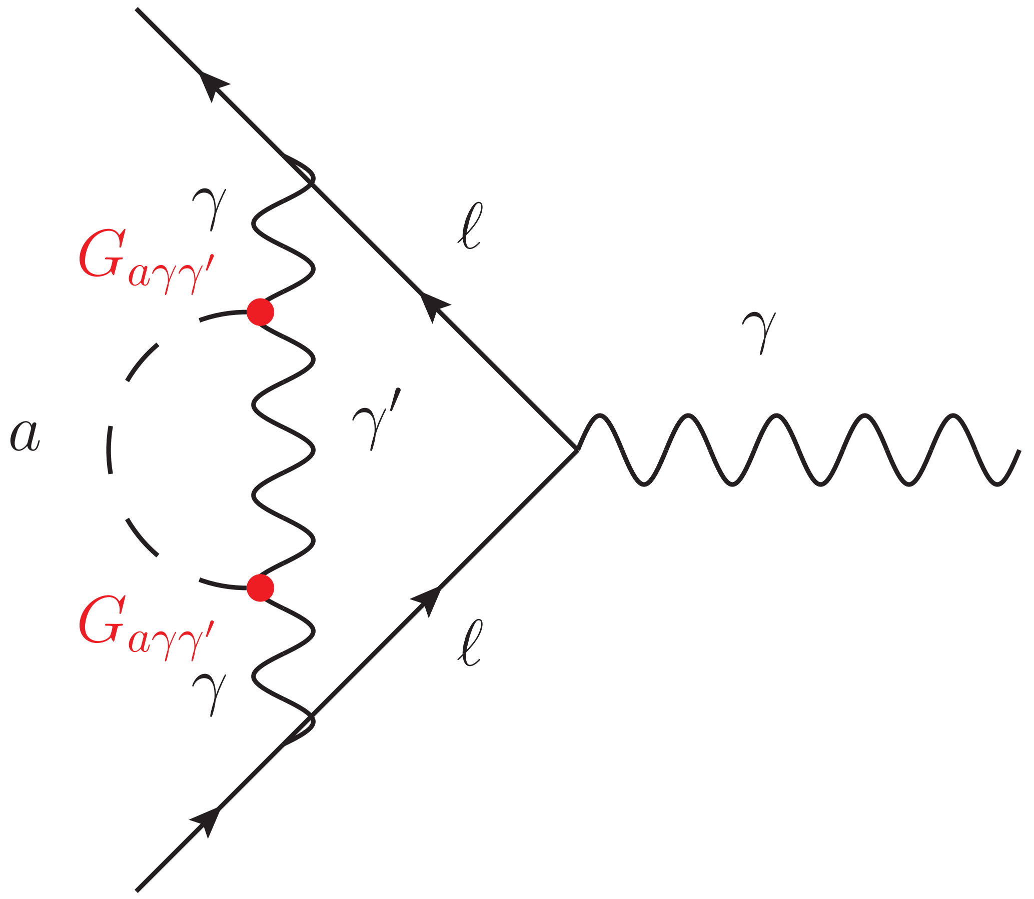
More Reasons to like Axions - IV

[arXiv:2004.08321, arXiv:1602.07499]

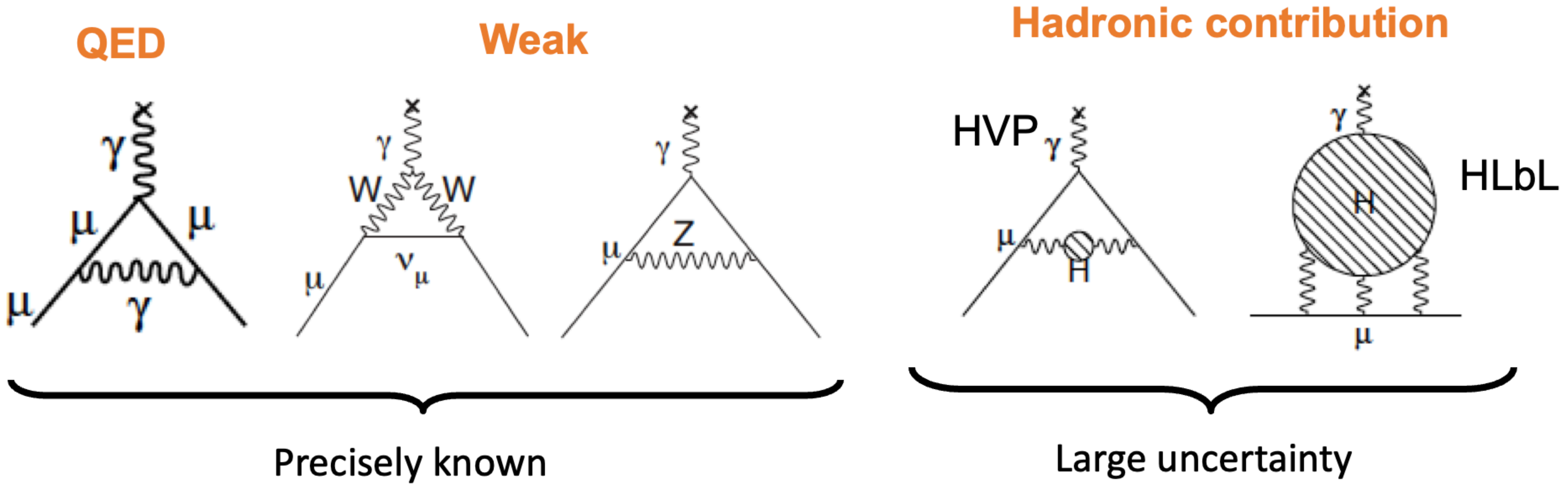


More Reasons to like Axions - V

- Contribute to $(g\text{-}2)_\mu$
  - Debated in literature if it helps to solve the remaining $(g\text{-}2)_\mu$ discrepancy

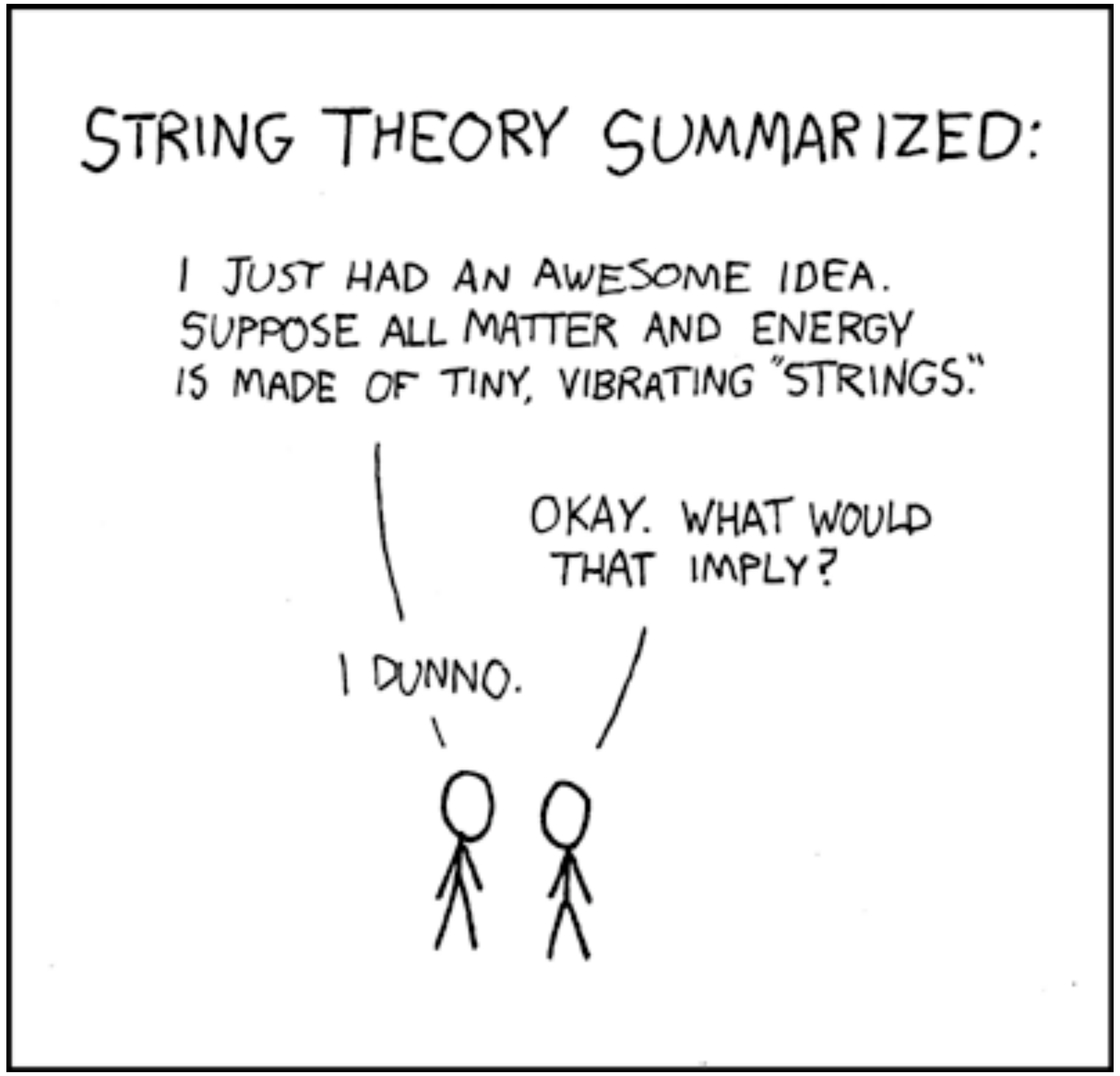


Probably solved



More Reasons to like Axions - VI

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 $(g\text{-}2)_\mu$
6. … are **well motivated** by string theory



[arXiv:0605206]

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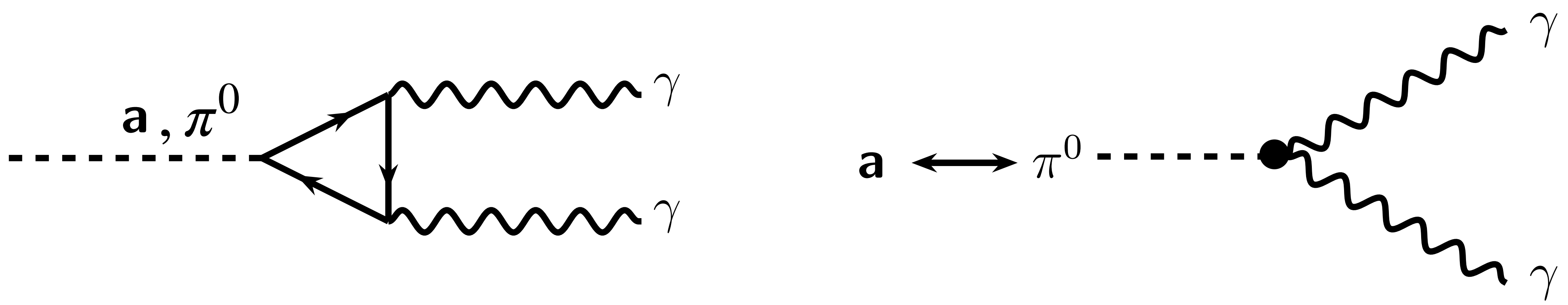
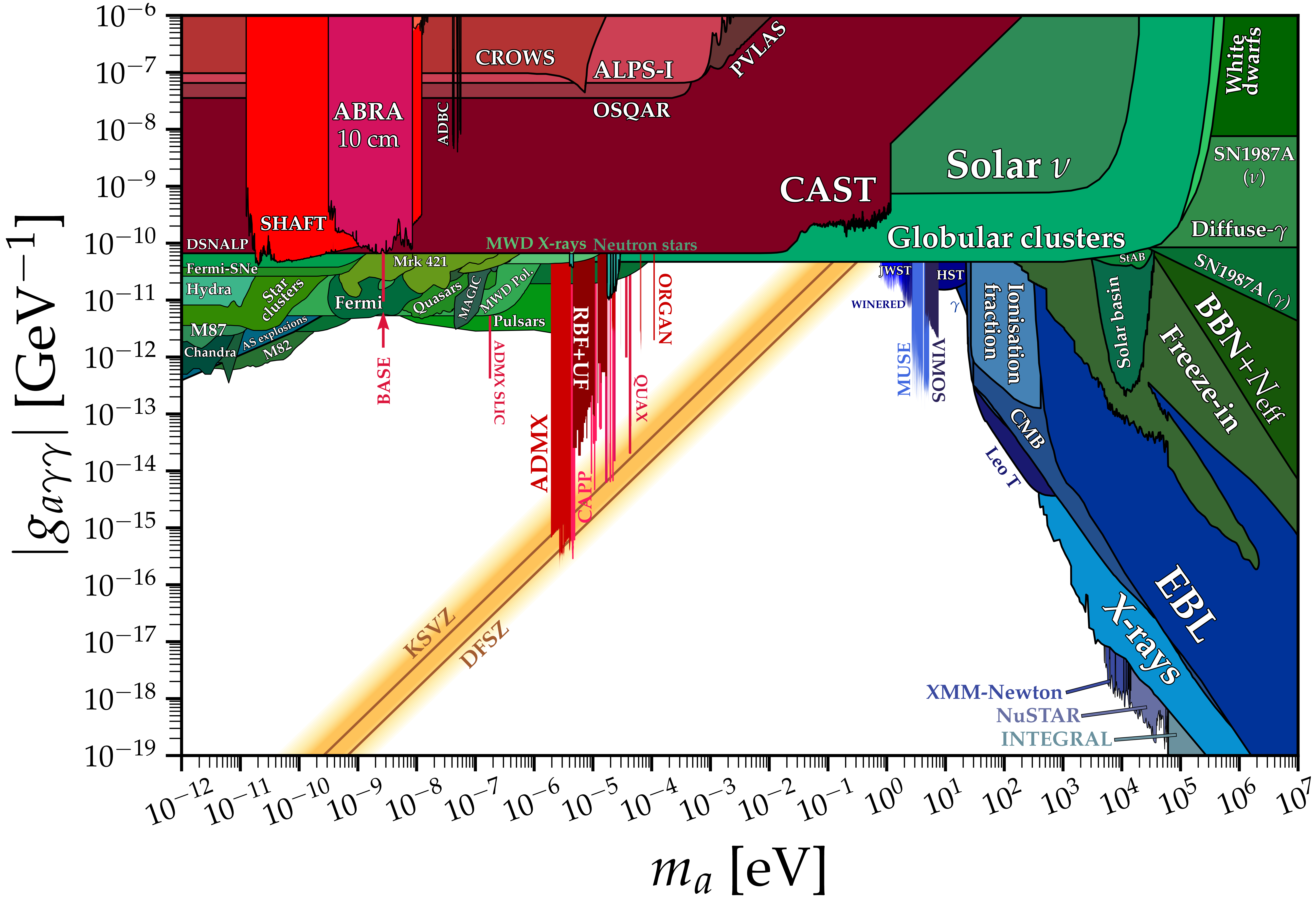
Couplings of the QCD Axion

- Axions couple to quarks by definition
- Axions also couple to **photons**
  - Can mix with pi^0
- May couple to other SM particle
- Two benchmark models:
  - **KSVZ**:
    New heavy, electrically neutral quarks carrying PQ charge
  - **DFSZ**:
    SM Quarks carry PQ charge, additional Higgs doublet needed



[DOI:10.5281/zenodo.3932430 https://cajohare.github.io/AxionLimits/]



From Axions to Axion Like Particles

AXION energy

AXION
RISK MANAGEMENT STRATEGIES

Axion $m_a \sim 1/f_a$

ALPS m_a and f_a independent

ALPS may arise “generically” from “any” broken U(1) symmetry…

There may be more than one ALP

From Axions to Axion Like Particles

- Dropping requirement to solve strong CP problem:
  - No strict mass - coupling strength relation
  - Vast parameter space opens up
- Any new pseudo-scalar particle:
  - Qualitatively similar properties to QCD Axion
    ➡ Axion Like Particle (ALP)
    ➡ Connection to collider physics
- ALPs appear in many extension to the SM
  - Any new symmetry breaking 'Higgs'-like field requires additional (pseudo)-scalar particles
  - e.g. **SUSY, GUT**
  - **String theories**:
    - Any theory using extra dimensions leads to the existence of ALPs

Axions and Axion Like Particles

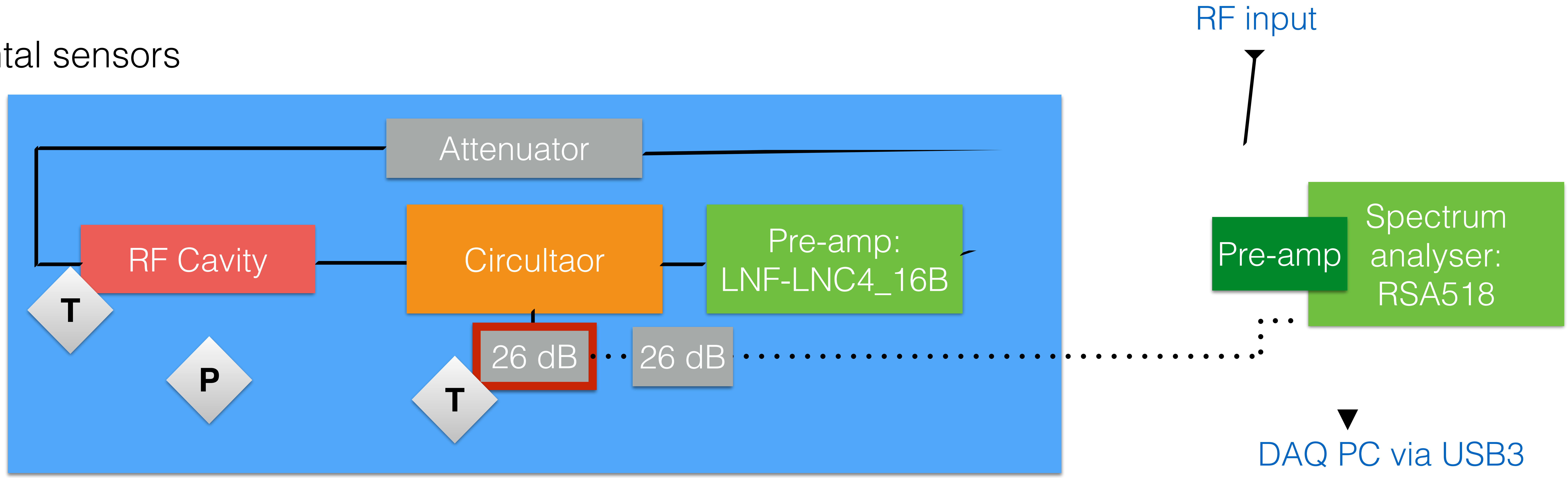
- Axions and ALPs are fascinating!

- May explain **several mysteries** of particle physics
- Strict mass - coupling relation for Peccei-Quinn (QCD) axion
- Will couple to photons
- Huge parameter space in coupling and mass for ALPs

DAQ

Typical Readout

T : Environmental sensors



- **Slowcontrol**
  - Temperature and pressure sensors
  - Monitoring with Influx + Grafana
  - T: PID control
  - P: Actuator in development

- **Readout**
  - Linear HEMPT amplifier
  - 40 MHz realtime IQ data: 200MB/s
  - Realtime FFT, averaging and DQ

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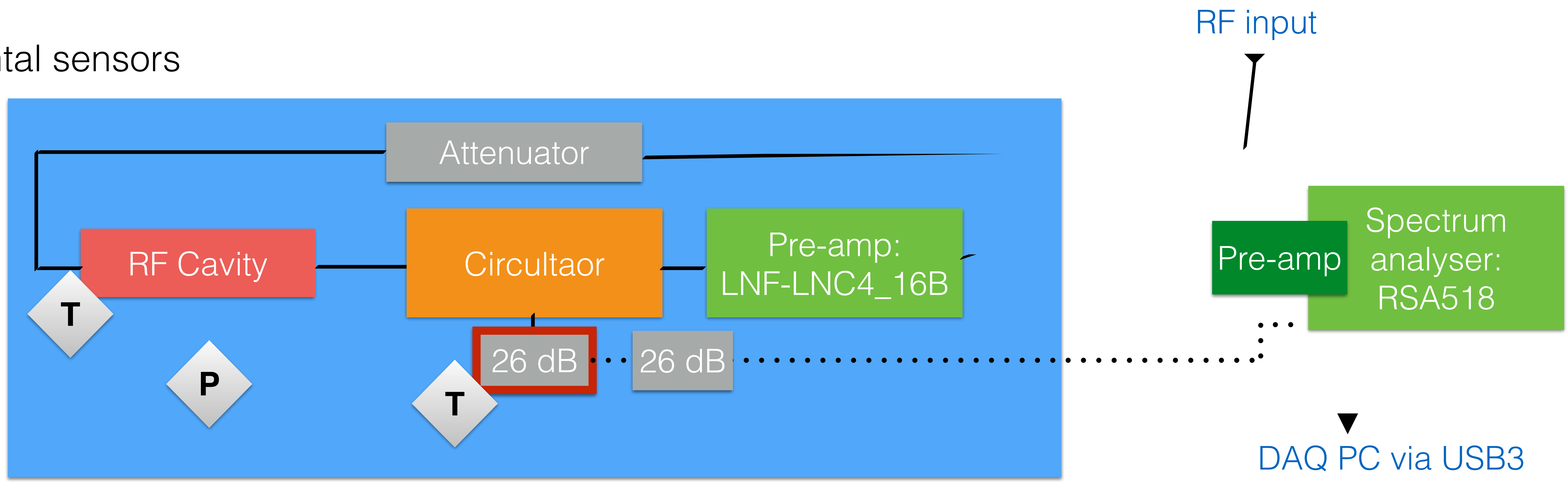

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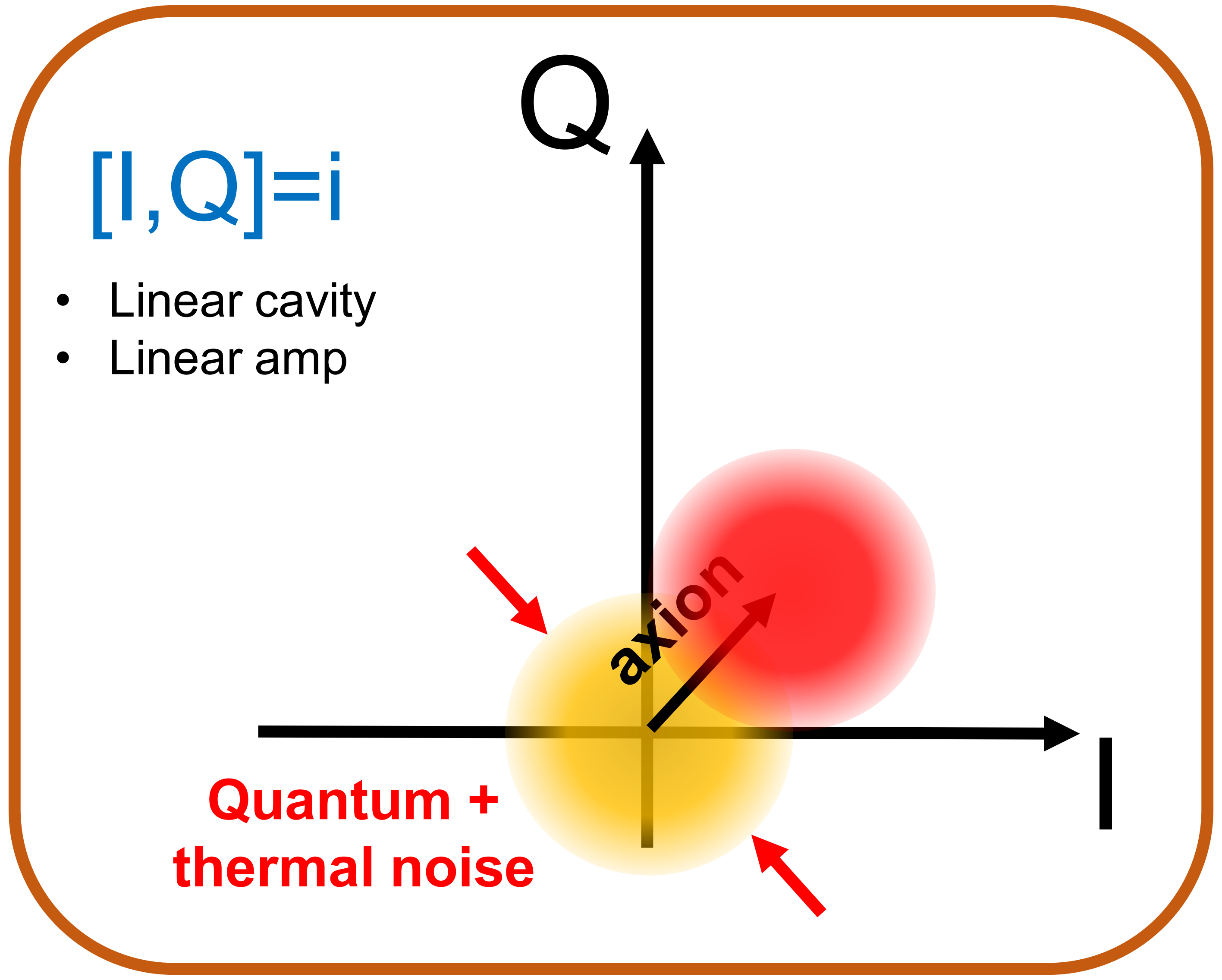
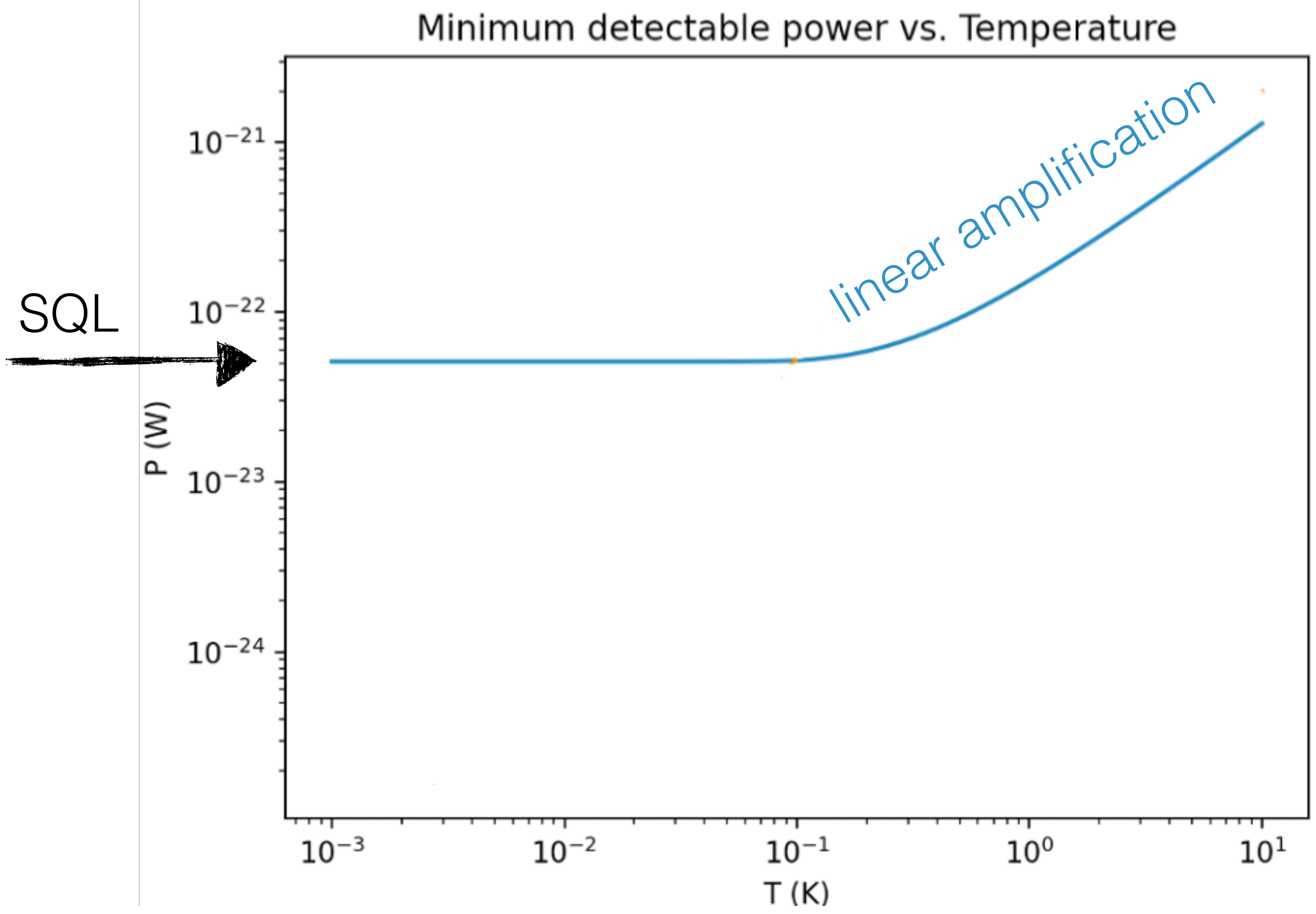
- **Readout**
  - Linear HEMPT amplifier
  - 40 MHz realtime IQ data: 200MB/s
  - Realtime FFT, averaging and DQ

- **Readout - Future**
  - JPA based readout
  - Eventually: **Quantum detectors** for single photons

Standard Quantum Limit

- Measurement of amplitude and phase of EM wave:
  - Minimum noise corresponding to one quantum (c.f. zero point energy)





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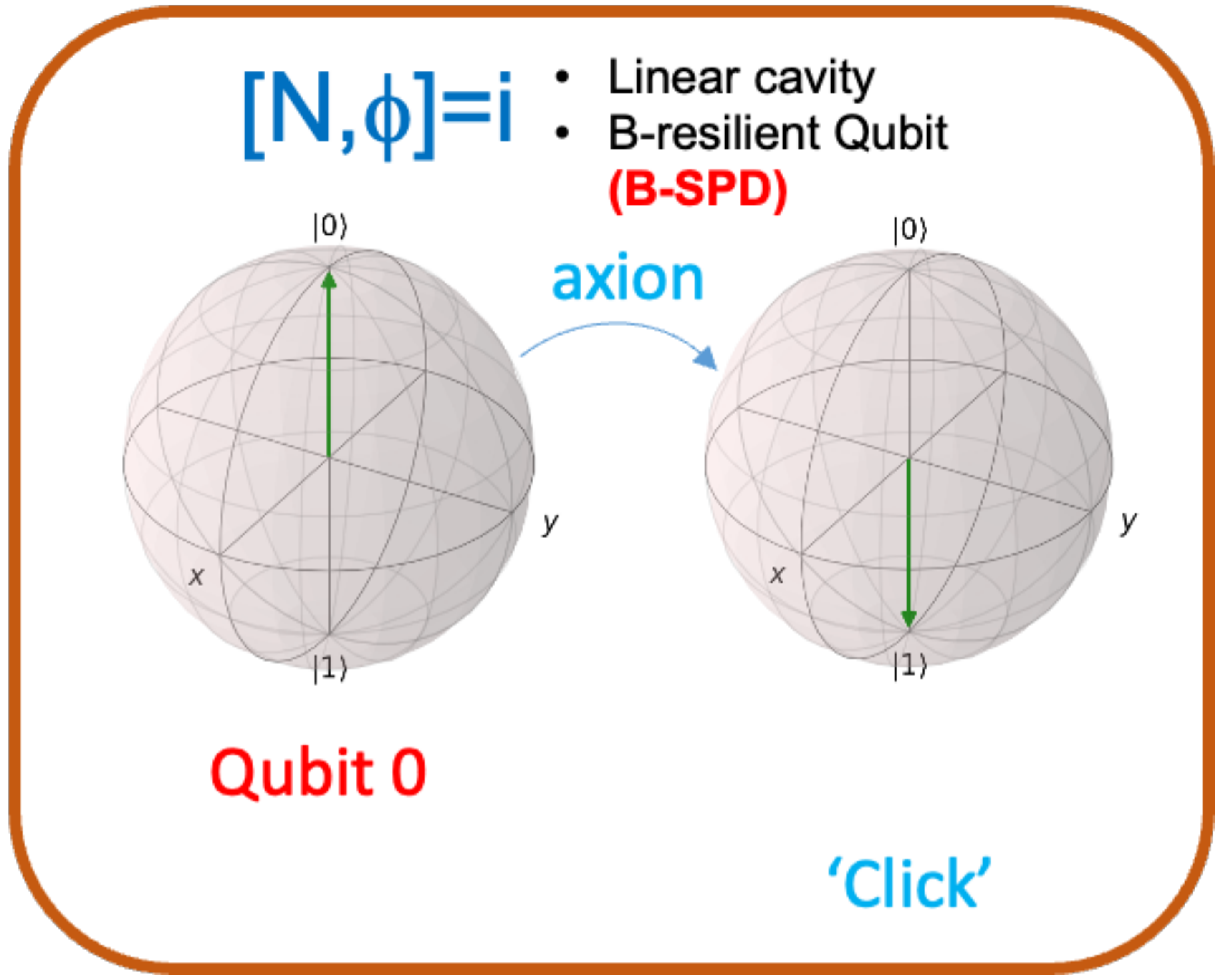
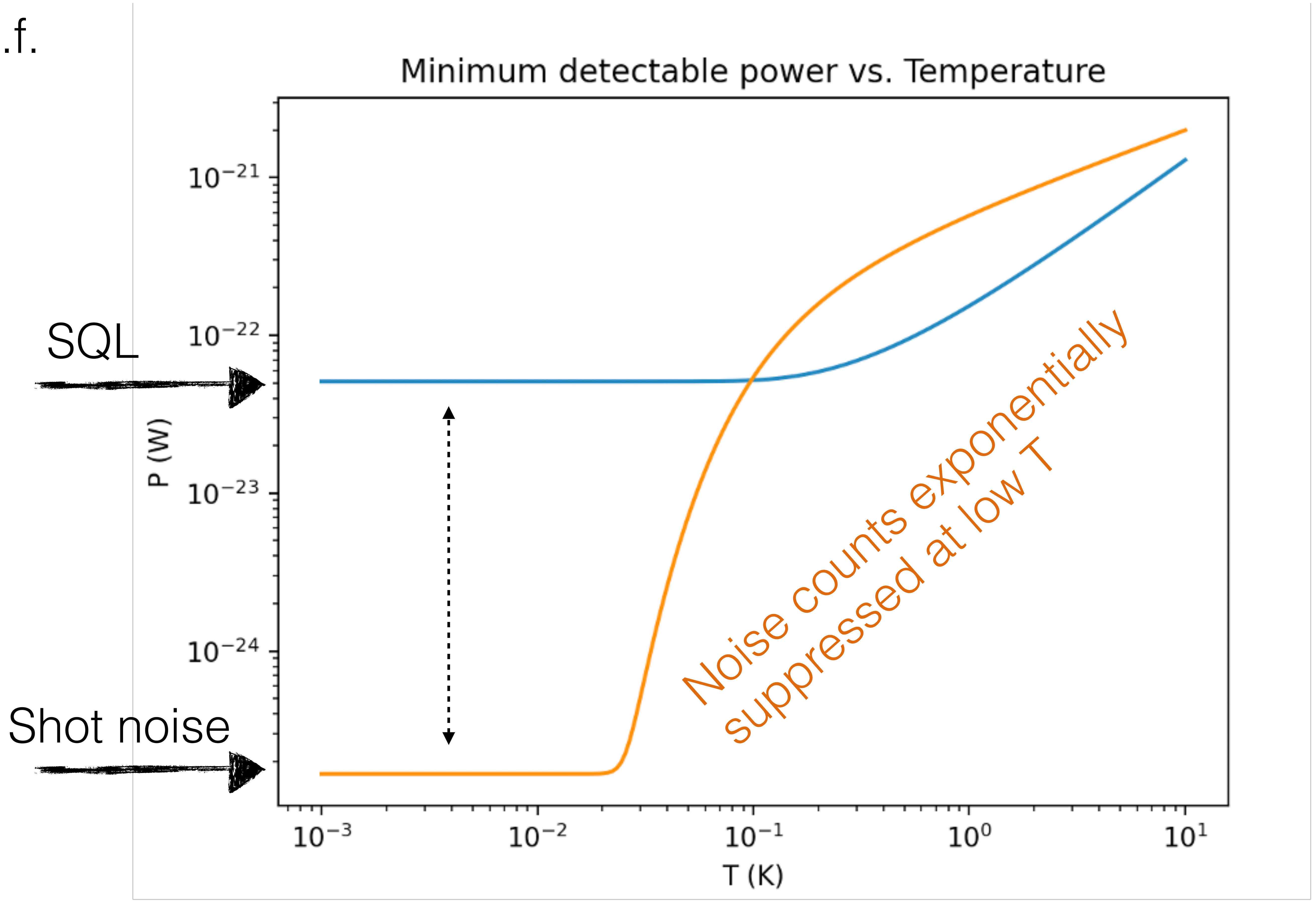
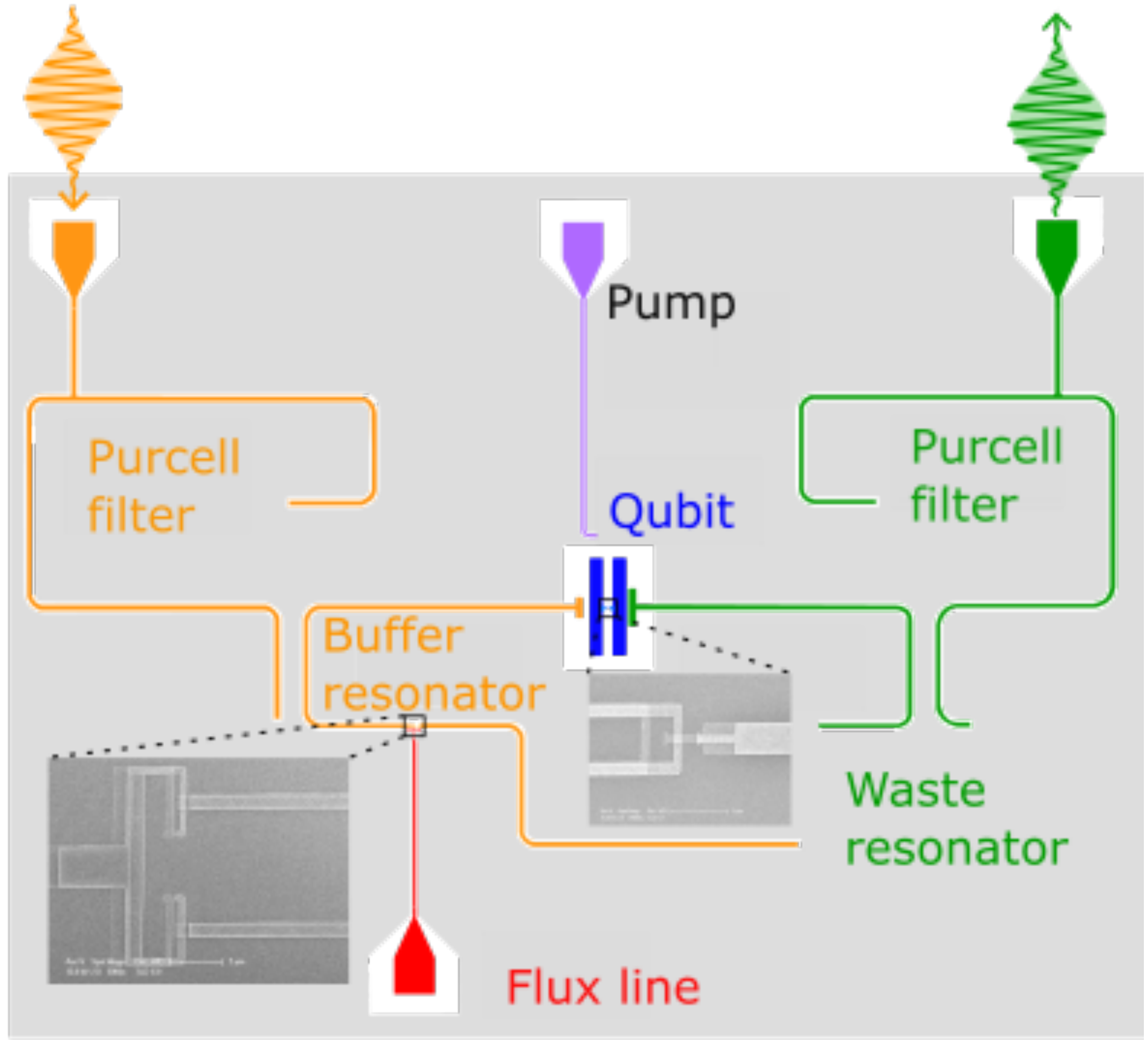




- Change of paradigm
  - Number-Phase conjugates **evade the SQL**

Single RF Photon Detection

[arXiv:2302.07556]
[arXiv:2308.07084]
[arXiv:2307.03614]



[arXiv:2307.03614]

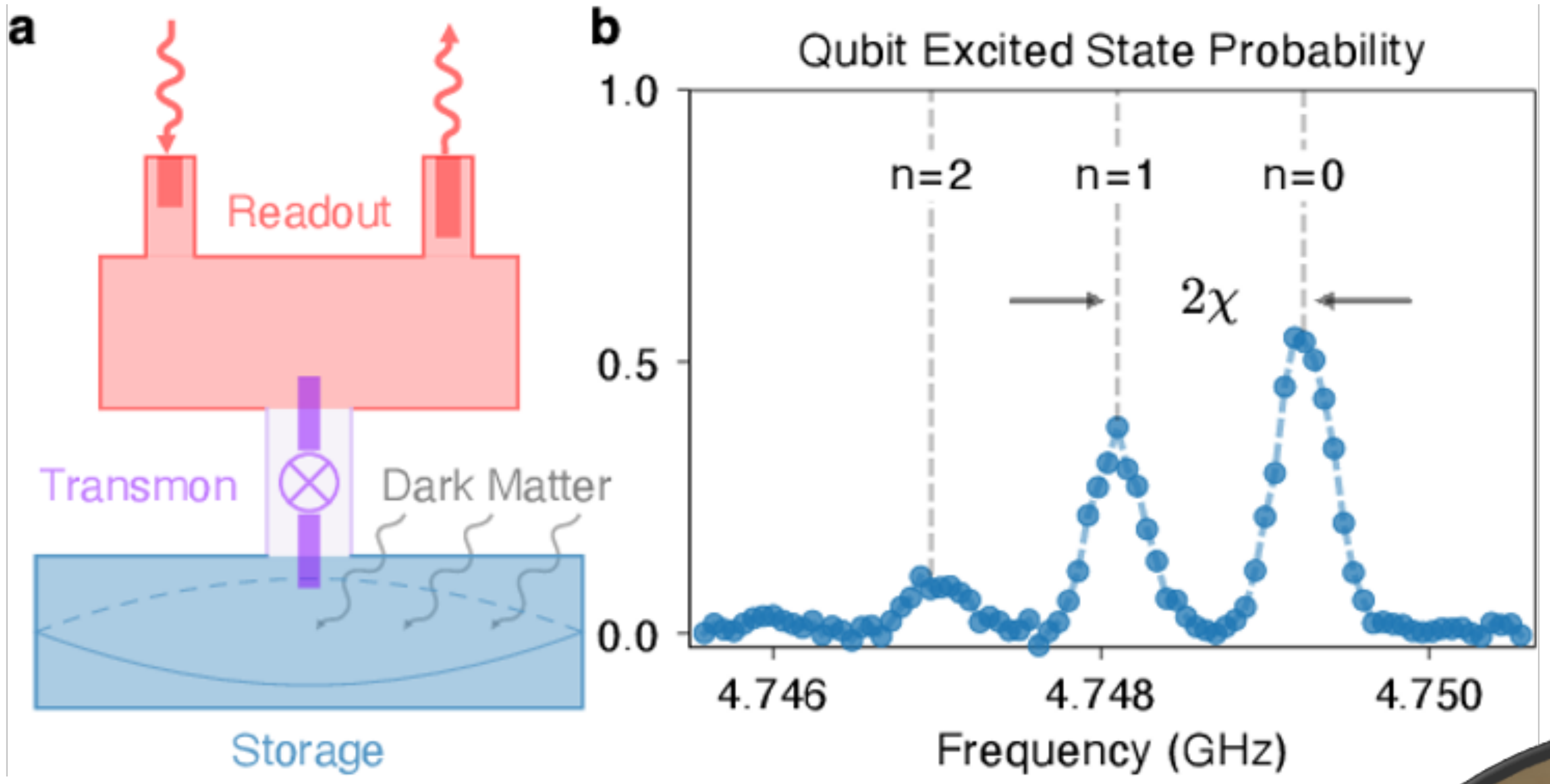
- Shown single photon efficiency: 43% @ 90 Hz dark count rate
  - Big R&D effort ongoing [ERC syn.: "Dark Quantum"]

- Using **Q-bits** for single **RF photon sensing**

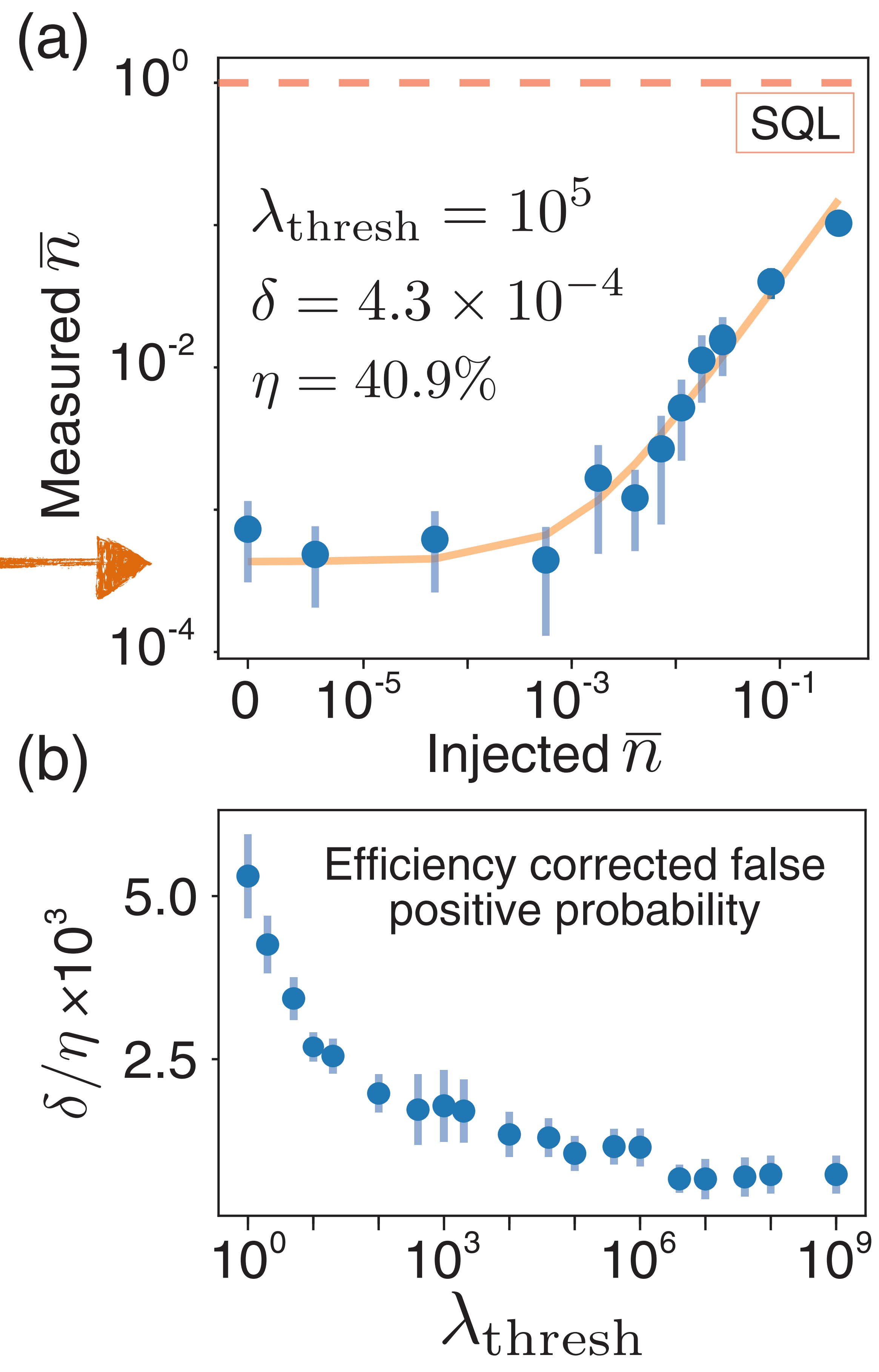
https://doi.org/10.1103/PhysRevLett.126.141302

Transmon Q-Bit

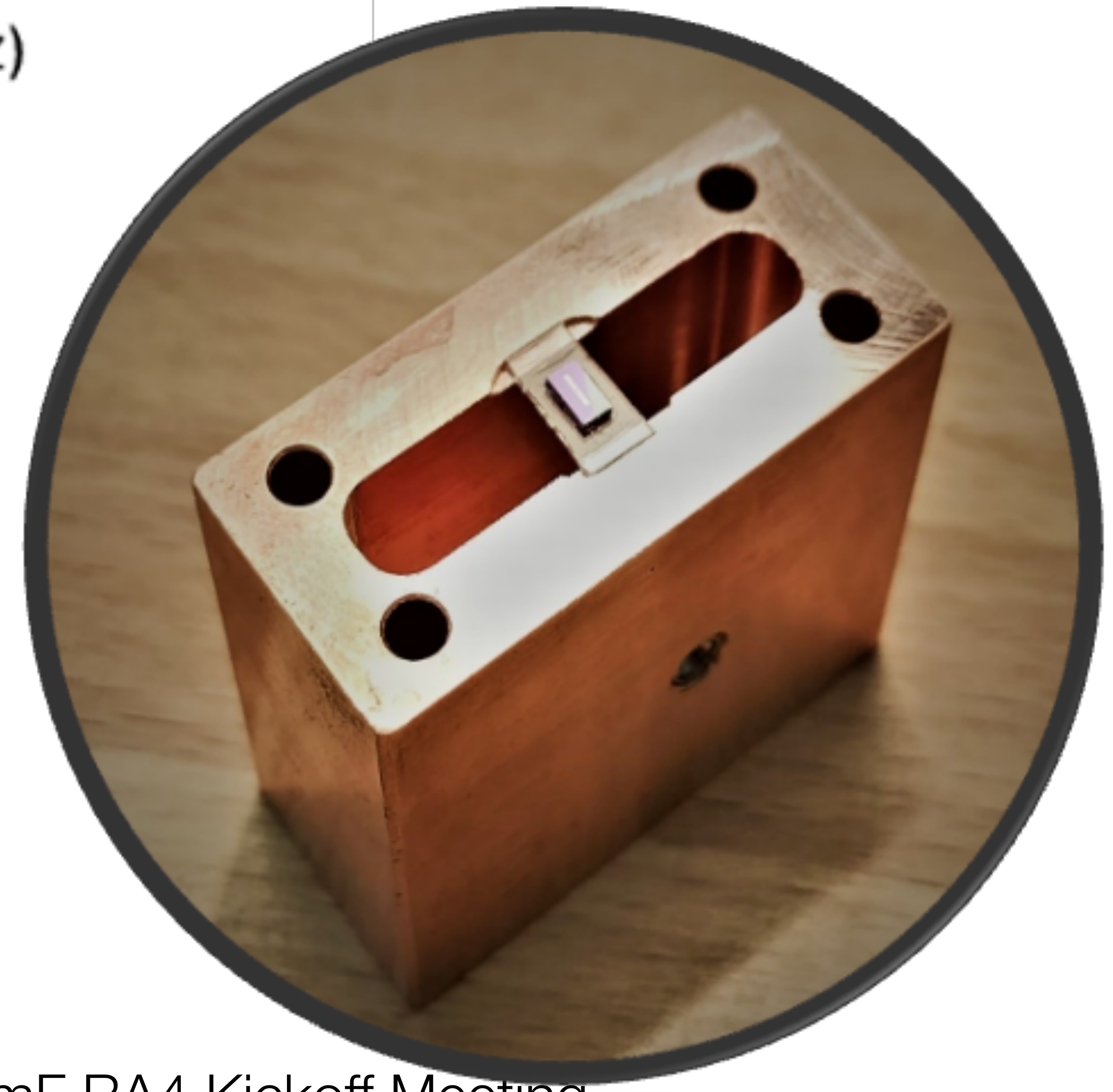
https://doi.org/10.1103/PhysRevLett.126.141302



Effective noise
$T_{noise} = 40\,mK$



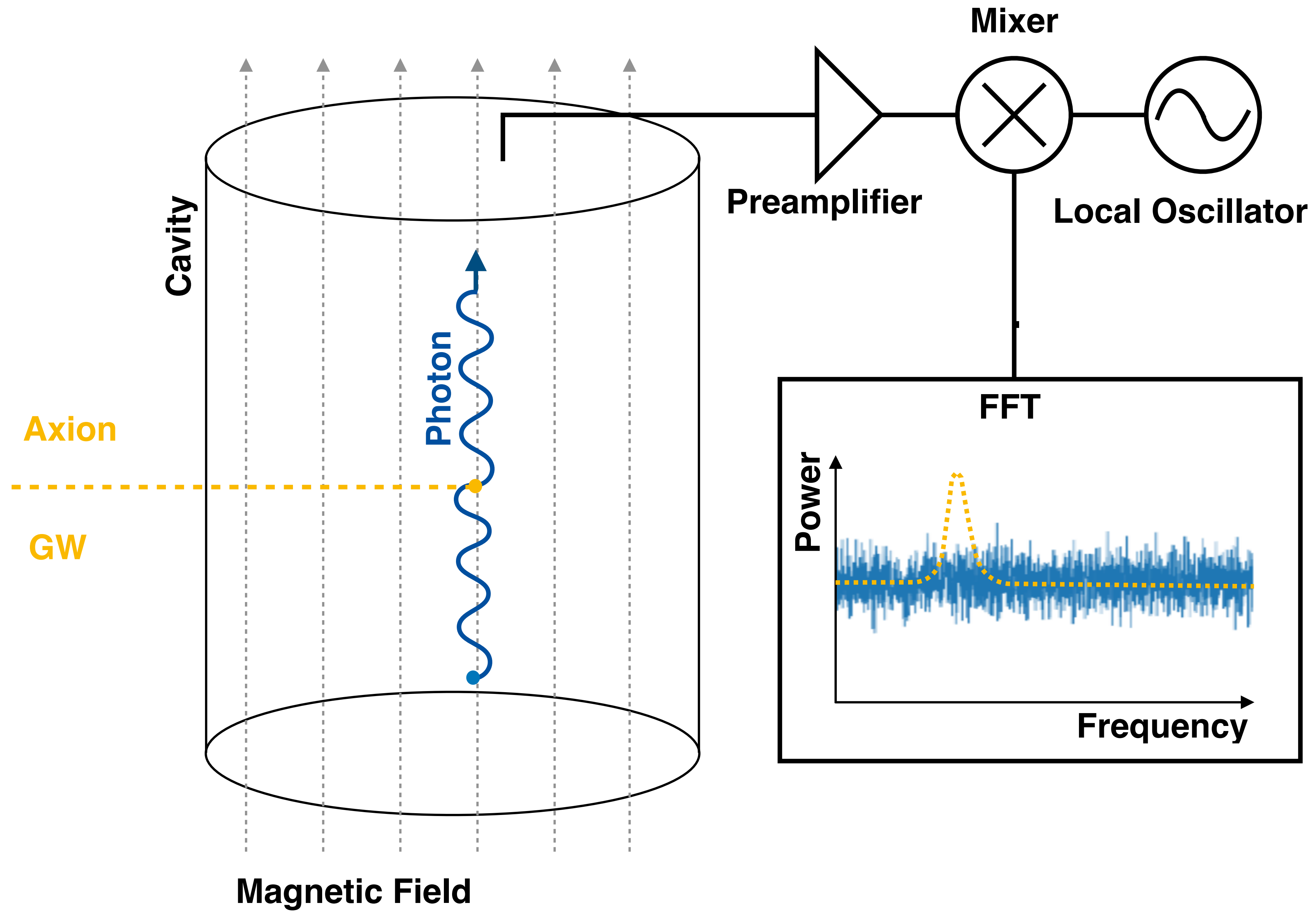
Detection efficiency: $\epsilon = 0.41$
False positive probability: $\delta = 4.3 \cdot 10^{-4}$



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



- Identical setup to **axion haloscopes**