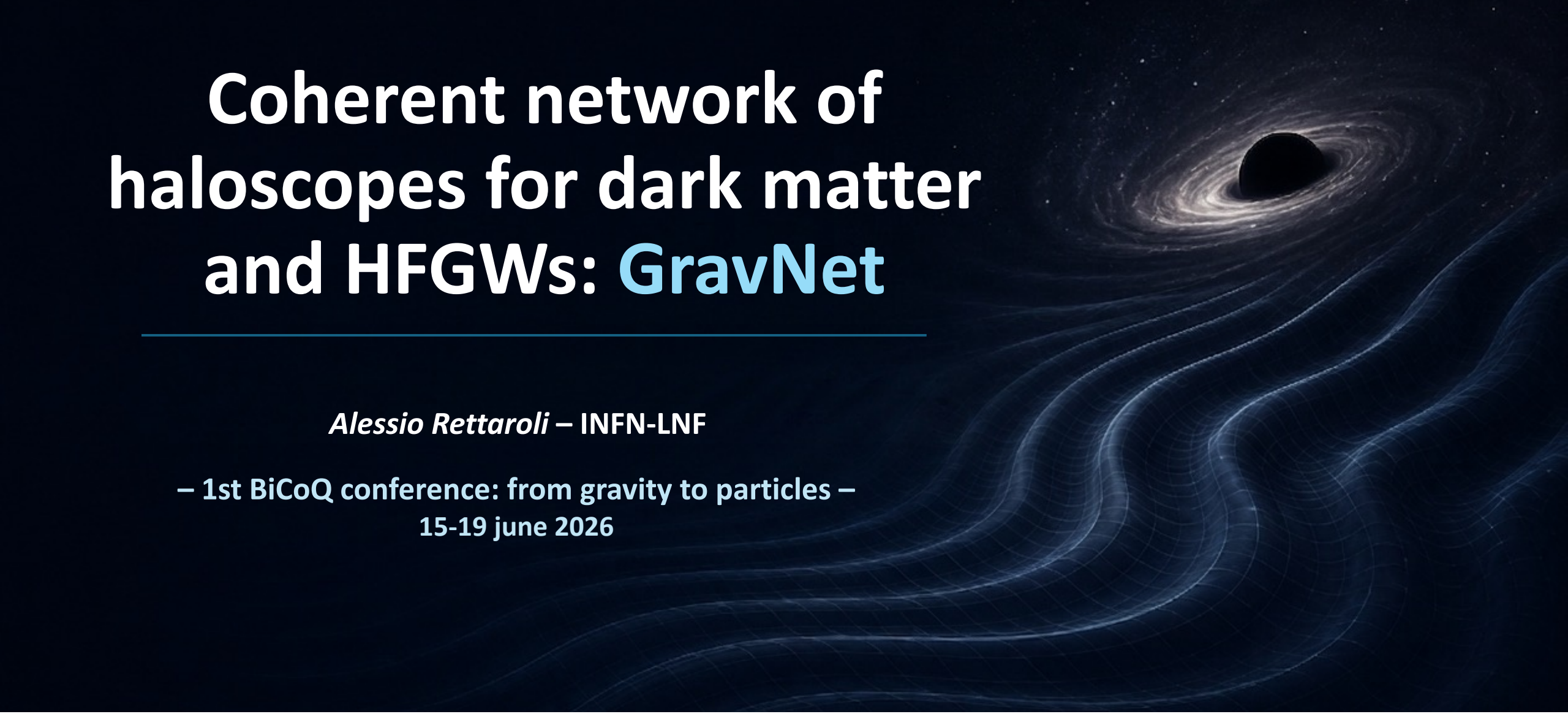
Coherent network of haloscopes for dark matter and HFGWs: GravNet

Alessio Rettaroli – INFN-LNF

– 1st BiCoQ conference: from gravity to particles –
15-19 june 2026



Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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CA21106

GravNet project

A Global Network for the Search for High-Frequency Gravitational Waves Receives ERC Synergy Grant 2024

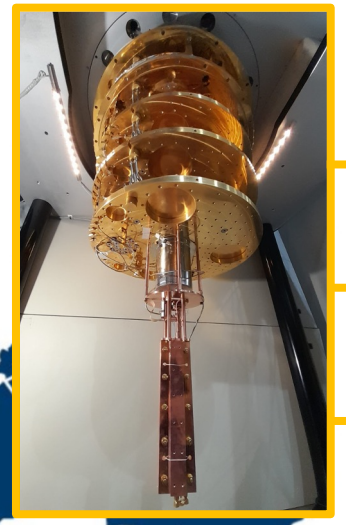
The project aims to develop the first dedicated network of detectors for high-frequency gravitational waves (MHz to GHz)

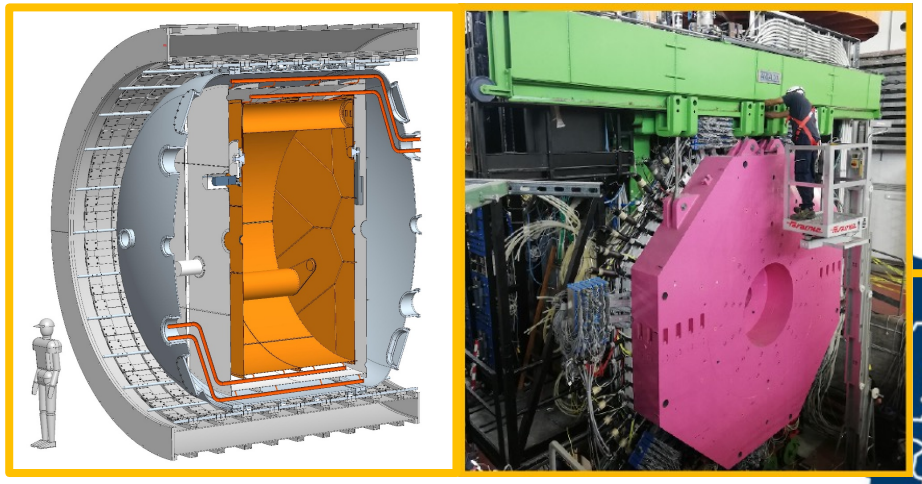
C. Gatti (LNF) D. Blas (IFAE) M. Schott (Bonn) D. Budker (Mainz)

GravNet project

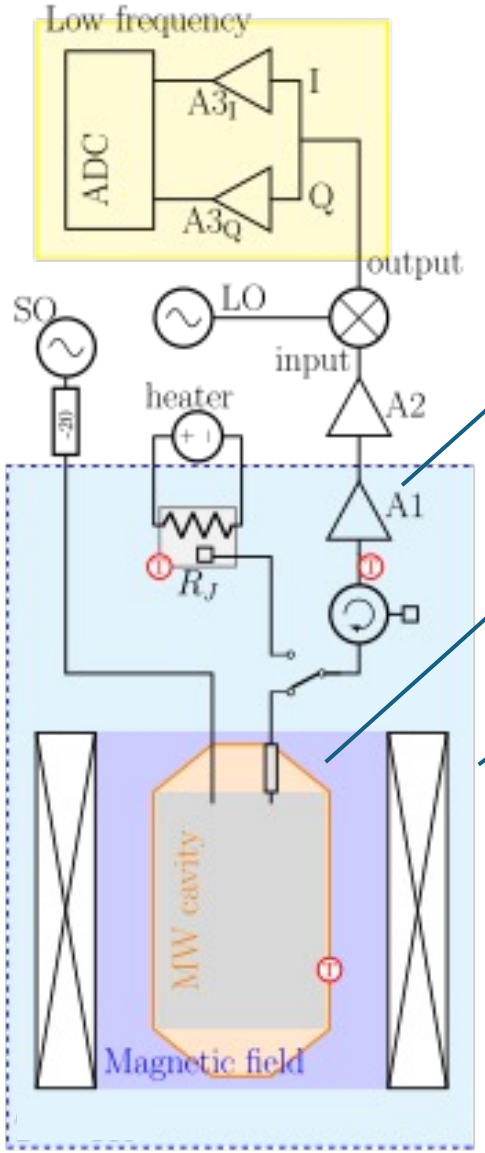
- 1 big cavity 100-300 MHz (FLASH)
- 9 small cavities (3+3+3) 6-8 GHz (incl. QUAX-LNF)
- GPS-based acquisition
- Leverage signal correlation among

  N sites to enhance sensitivity



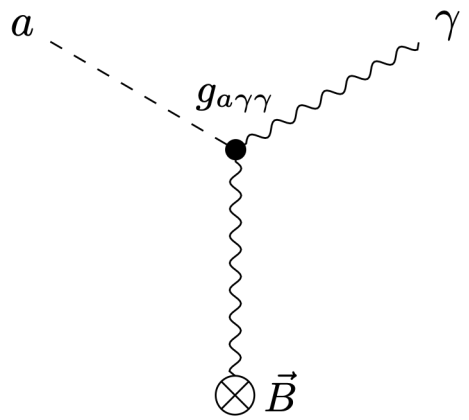


The haloscope (for axion search)



- **Dilution refrigerator**
- **Low-noise receiver**
  (quantum-lim. or beyond)
- **Resonant cavity (tunable)**
- **Strong magnet**

Primakoff effect



$$P_{a\gamma\gamma} \propto \left(\frac{g_{a\gamma\gamma}^2}{m_a^2}\rho_a \nu\right)\left(VB^2Q\right) \sim (10^{-22} - 10^{-23})\,\mathrm{W}$$

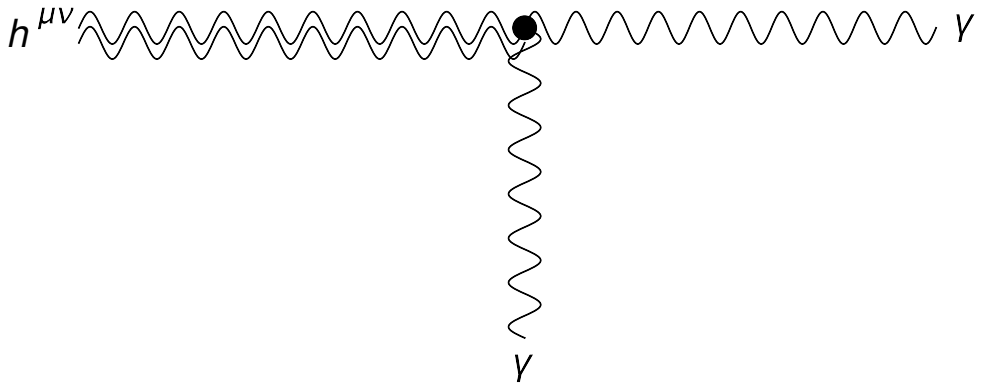
Detection principle of HFGW with cavities

Einstein-Maxwell action

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}\right)$$

Gertsenshtein effect:

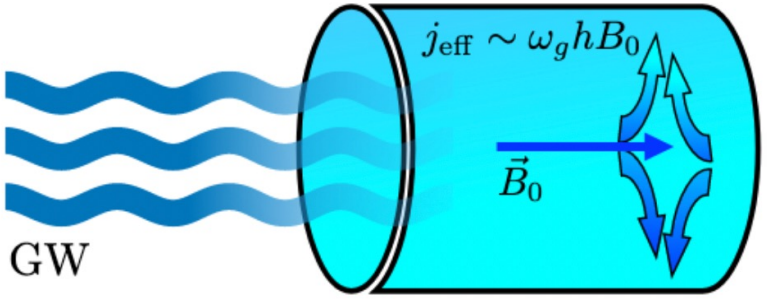
A GW propagating through a static background EM field sources a feeble EM field that oscillates at the frequency of the GW



Detection principle of HFGW with cavities

Power deposit in resonant cavity

$$P_{\mathrm{sig}} = \frac{\beta}{1+\beta}\frac{\omega_g}{2\mu_0}h^2_{\times,+}B_0^2 Q_l C^{\times,+}_{\mathrm{GW}} V$$



Coupling coefficient

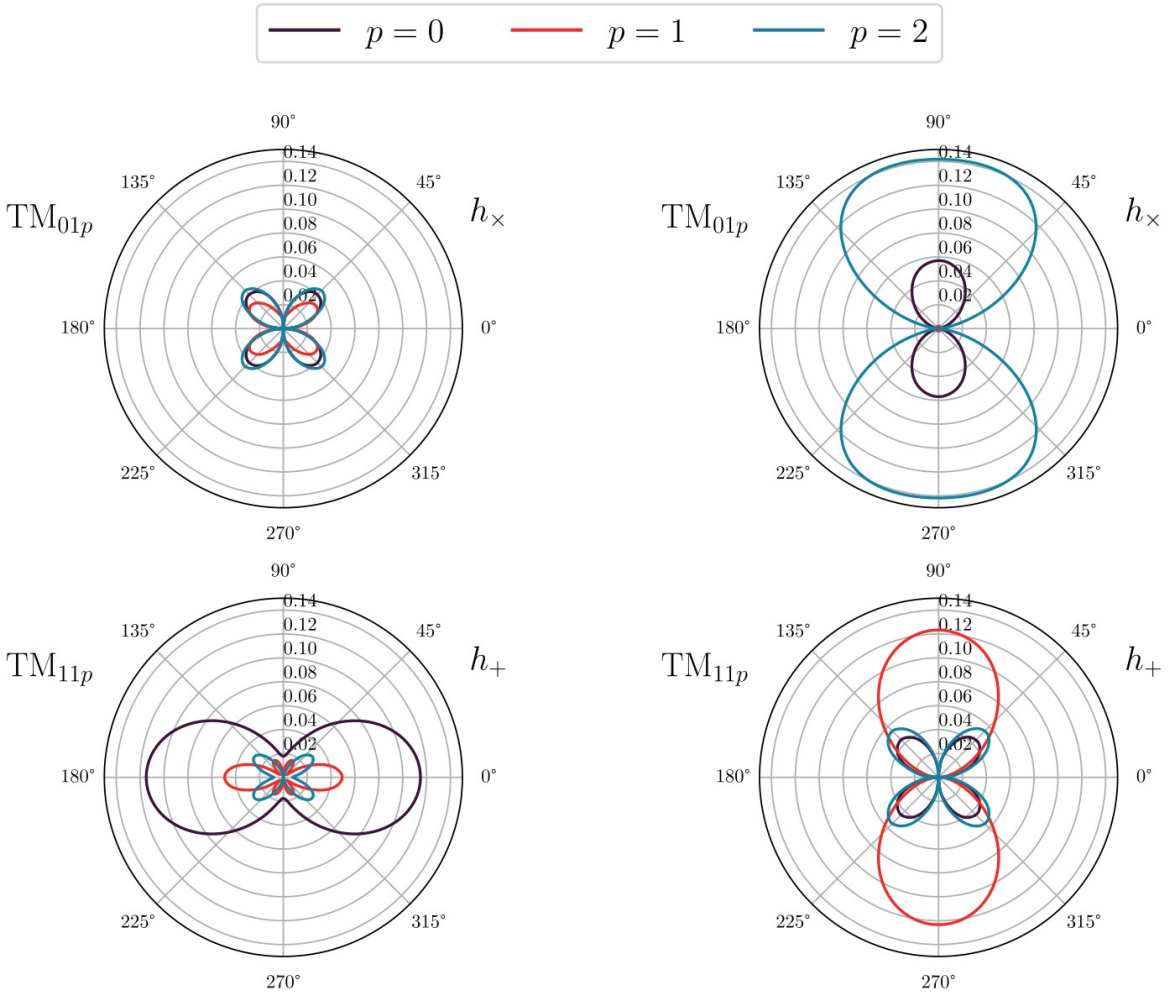
$$C^{\times,+}_{mnp}(\theta,\phi) = \frac{\left|\int d^3\mathbf{x}\, \mathbf{E}^*_n(\mathbf{x}) \cdot \hat{\mathbf{j}}_{\times,+}(\mathbf{x};\theta,\phi)\right|^2}{V\int d^3\mathbf{x}\, |\mathbf{E}_n(\mathbf{x})|^2}$$

$$\mathbf{j}_{\mathrm{eff}} = B_0\omega_n^2(h_\times \hat{\mathbf{j}}_\times + h_+ \hat{\mathbf{j}}_+)$$

Effective current

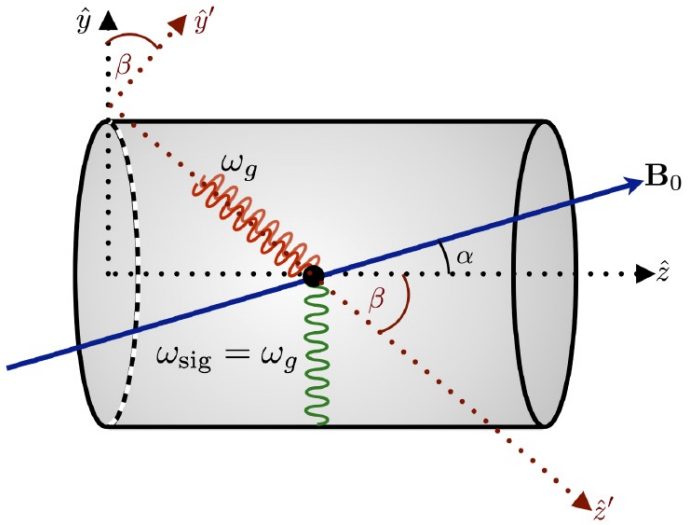
Detection principle of HFGW with cavities

Example of coupling coefficient for different TM modes



The coupling depends on:

- **Mode geometry**
- **Direction of propagation**
- **Wave polarization**

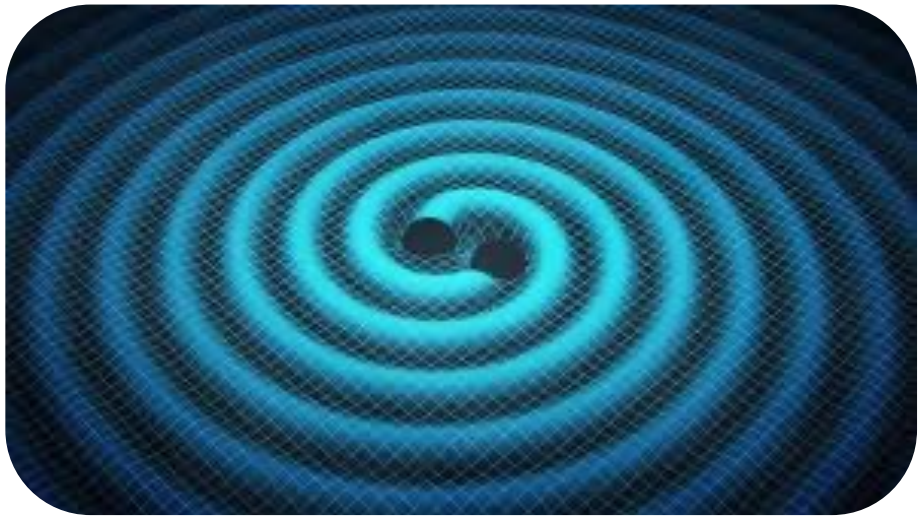


What we don't know: Sources

- **PBH binary mergers. (chirped)**
  $M_{pbh} < 10^{-12} M_{\odot}$ if number of cycles $> 10^{5}$

- **Superradiance. (monochromatic)**
  bosonic dark matter clouds (axions) around (P)BHs

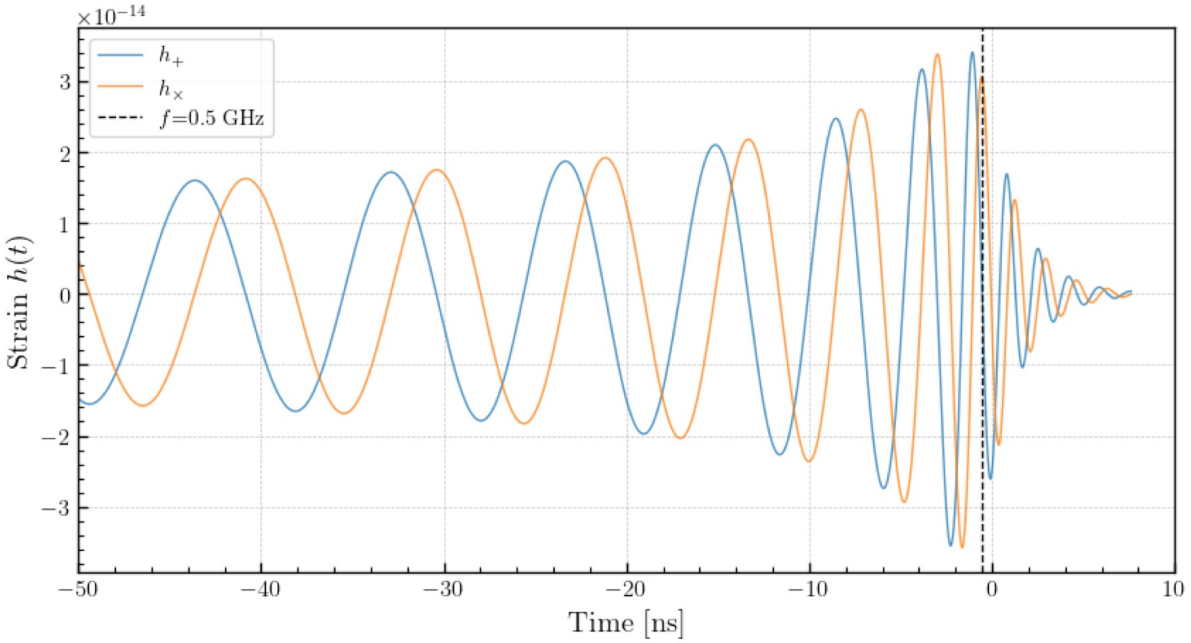
- **Processes in early universe. (stochastic)**
  inflation, phase transitions, topological defects…

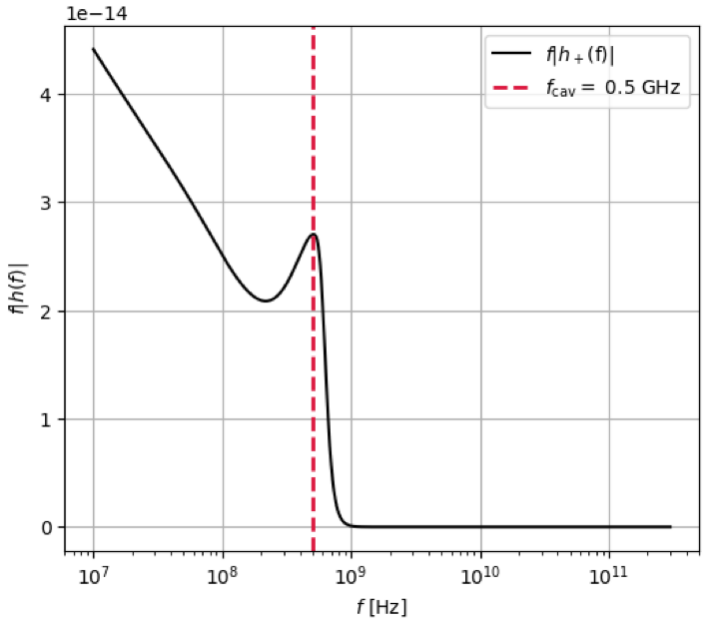


HFGWs would allow to test fundamental physics, complement astrophysics and probe the early universe phases

GW + cavity simulations

Time domain simulation of cavity response to GW chirps





$$M_{\rm tot} = 3.0 \times 10^{-5} M_\odot$$

$$q = m_1/m_2 = 1$$

$$d = 10^{-5}\,\mathrm{pc}$$

$$e = 0$$

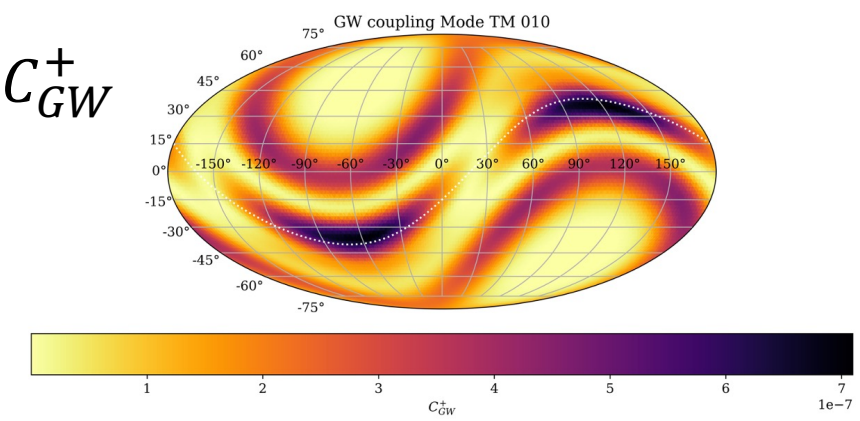
$$\chi_1 = \chi_2 = \chi_3 = 0$$

Y. Borysenkova, T. Kvietkauskas, D. Amaral, S. Kalia, D. Blas

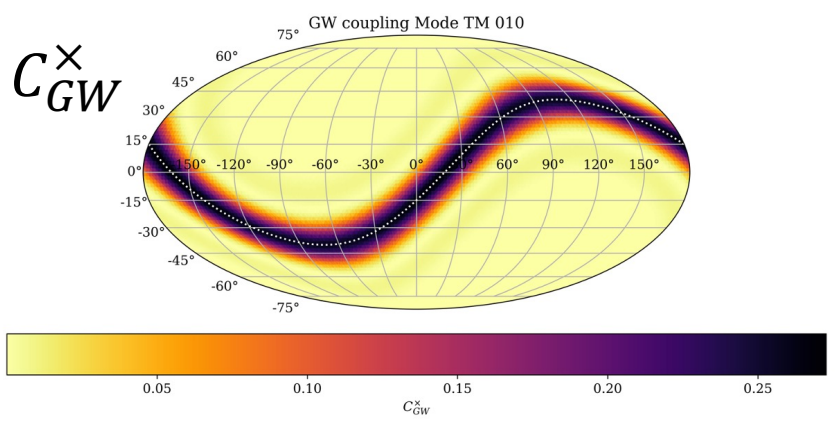
Coupling coefficients to res. modes

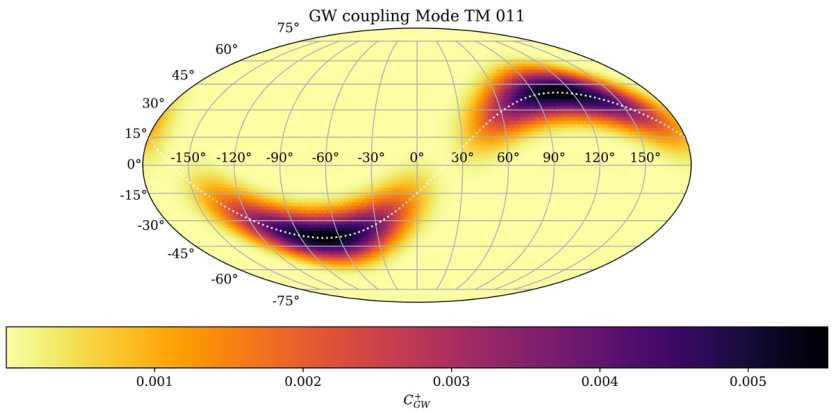
Order 0.1 couplings seem to be reachable

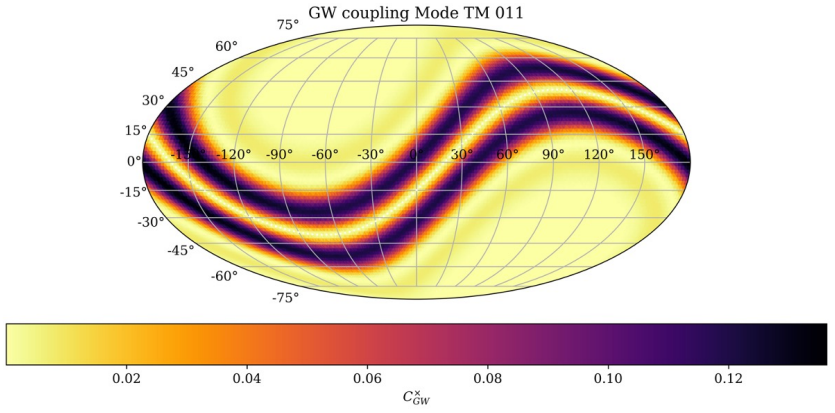
C_{GW}^{+}



$C_{GW}^{\times}$







Figures of merit to classify C_{GW}:

- $\max(C_{GW}^{+})\ Q$
- $\max(C_{GW}^{\times})\ Q$
- $\langle C_{GW}^{+} \rangle\ Q$
- $\langle C_{GW}^{\times} \rangle\ Q$

Younggeun Kim, 5 GHz cavity

Multimode DAQ demonstrator

TM010, TM011 and TM012 QUAX-LNF modes acquisition with GPS timestamp will be a demonstrator for FLASH and GravNet

Run control in MIDAS

Run Status

Run 388 Stopped Start	Start: Thu Jun 11 13:50:43 2026	Stop: Thu Jun 11 13:53:42 2026
	Alarms: On / Restart: Off	Data dir: /home/cold/data/

Experiment Name:	QUAX
Write data:	☑
Run description:	test sequenza 15 run 850 ev

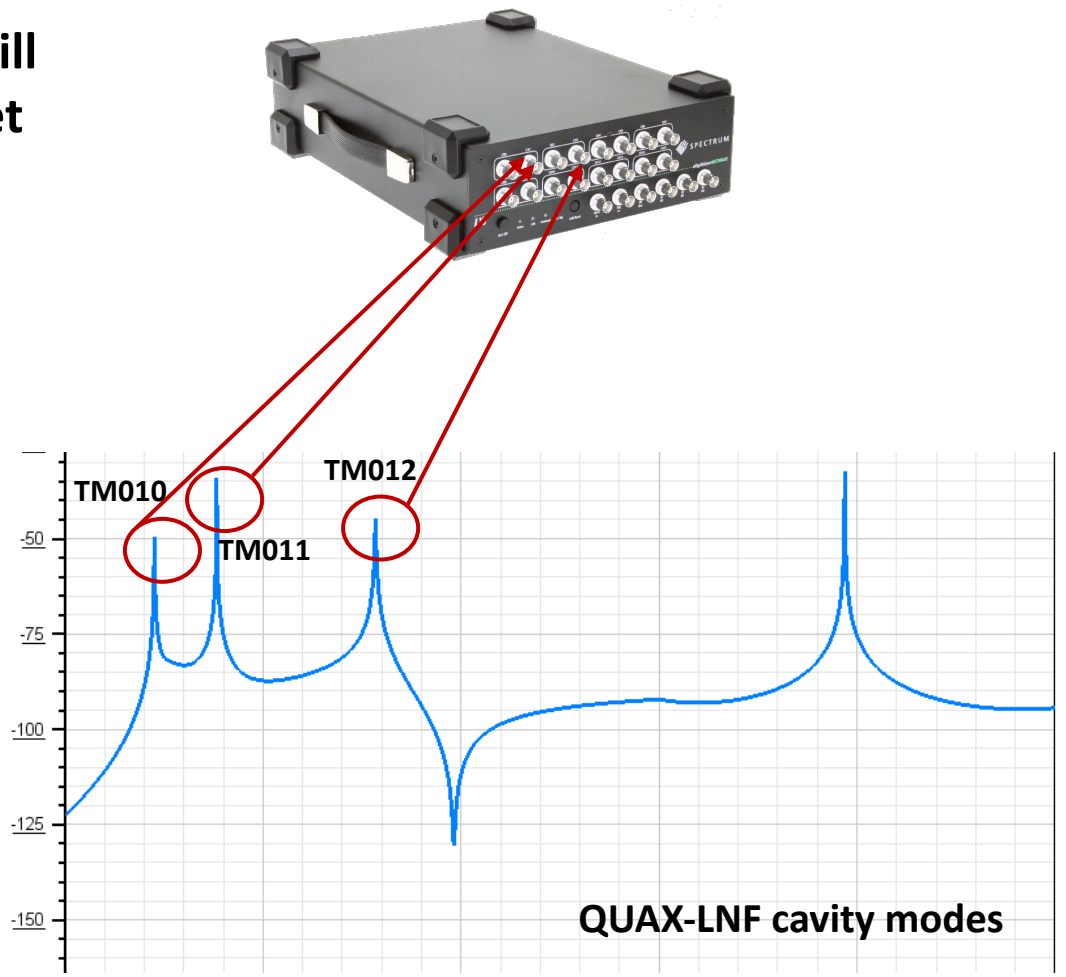
1781273211 16:06:51.240 2026/06/12 [Logger,LOG] Program Logger on host localhost started

Equipment

Equipment +	Status	Events	Events[/s]	Data[MB/s]
NetBox	cold_daq@localhost	850	0.0	0.000
timestampGPS	Running	165442	1.0	0.000
CryoSwitch	Running	0	0.0	0.000
LocalOscill	Running	1	0.0	0.000
Temp_Mercury	Ok	3535	0.3	0.000
Temp_FP	Ok	3533	0.0	0.000
Temp_AVS	Ok	3532	0.3	0.000

Logging Channels

Channel	Events	MB written	Compr.	Disk Level
#0: run00388.mid	1067	14261.990	100.0%	23.8%
Lazy Label	**Progress**	**File Name**	**# Files**	**Total**



Coherence of N detectors

Power readout

Incoherent signals

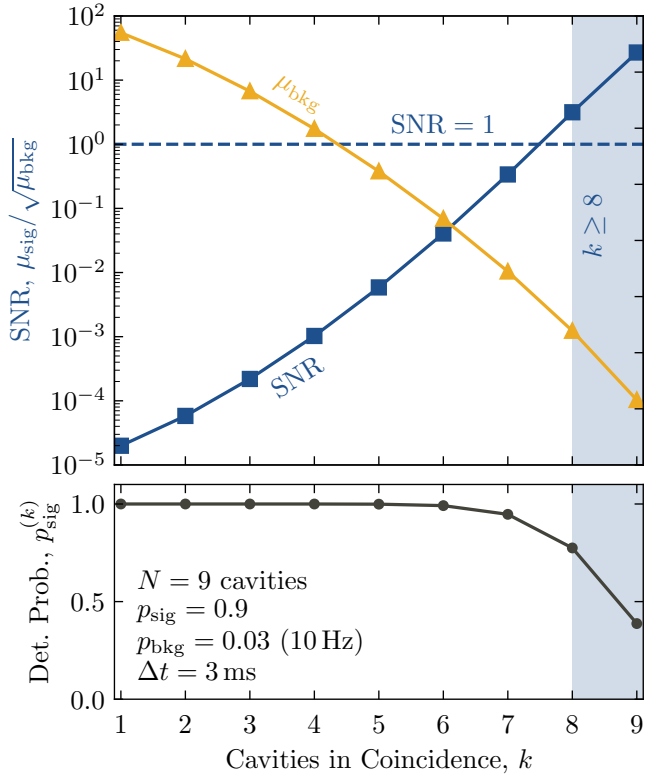
$$\mathrm{SNR}_{\mathrm{net}} = \sqrt{N_{\mathrm{cav}}} \cdot \mathrm{SNR}_{\mathrm{single}}$$

Coherent signals

$$\mathrm{SNR}_{\mathrm{net}} = N_{\mathrm{cav}} \cdot \mathrm{SNR}_{\mathrm{single}}$$

Single photon counting, with N detectors in coincidence

$$p_{\mathrm{sig}}^{(k)} = \sum_{j=k}^{N} \binom{N}{j} (p_{\mathrm{sig}})^{j} \, (1 - p_{\mathrm{sig}})^{N-j}$$



Increasing number of detectors strongly enhances SNR

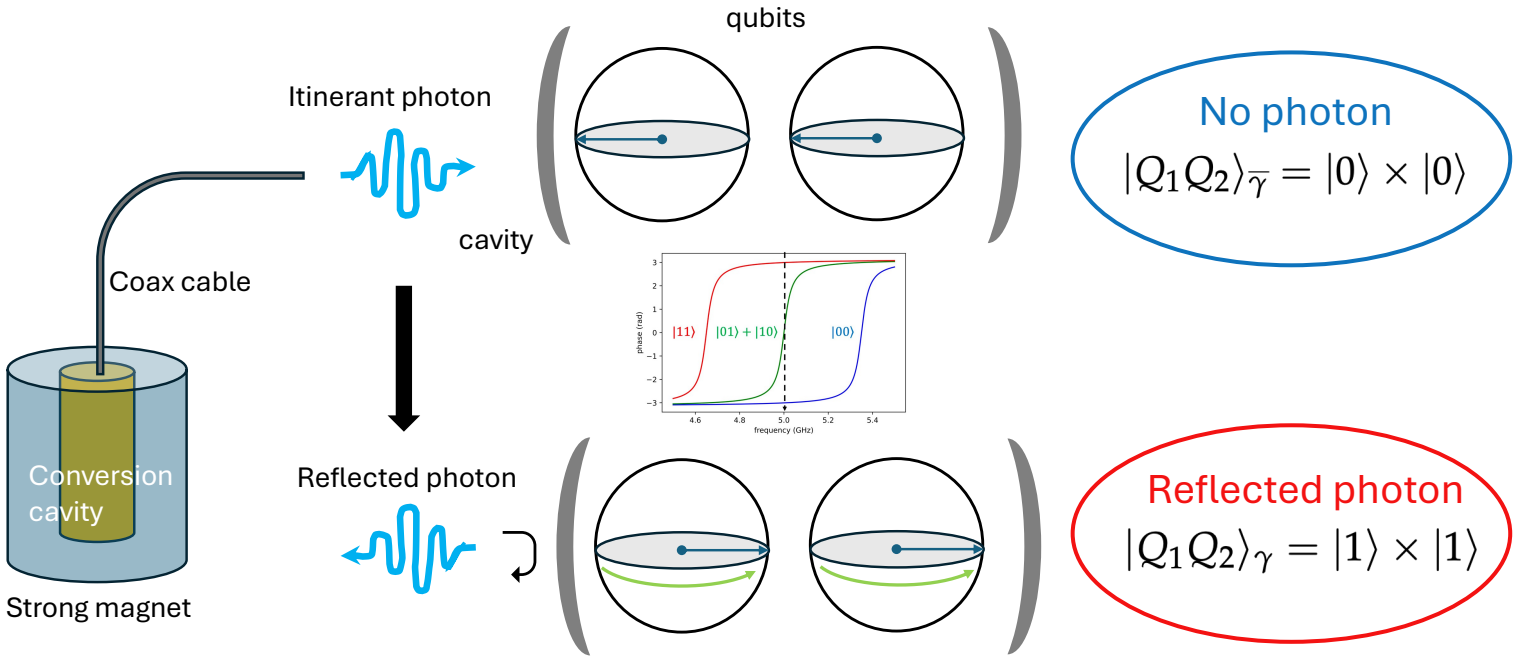
Significantly reduces accidental coincidences

Single-photon detector

- **Two qubits coupled to the same resonator**
- **Reduction of readout error**

$$1 \text{ qubit} \sim P(1|0)$$
$$2 \text{ qubits} \sim P(1|0)^2$$

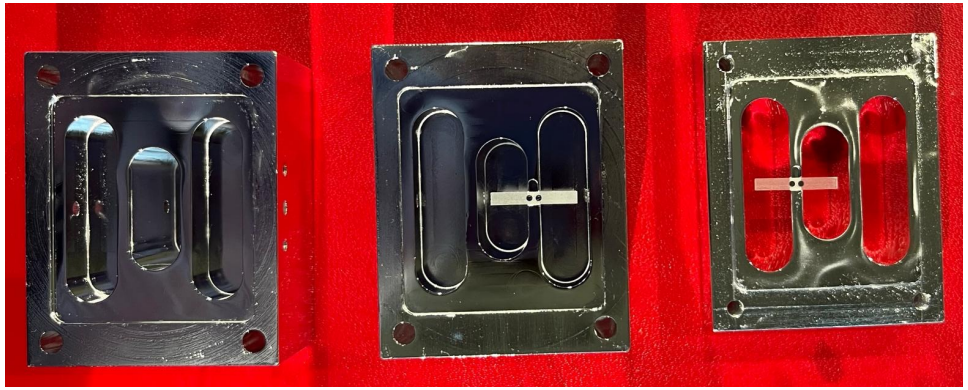
- **Dark count rate improvement**



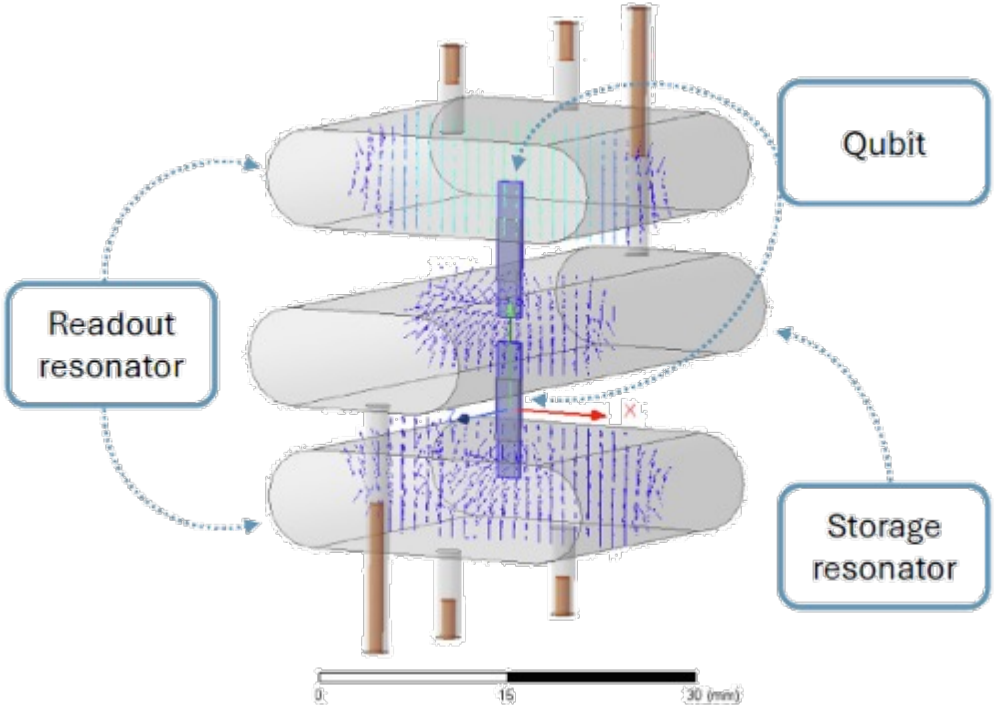
Fabrication of 3D cavities and qubits

Qubit fabrication:

- From CNR-IFN with EBL technique
- From ConScience AB (Sweden)
- Homemade NbSe2 with exfoliation techniques

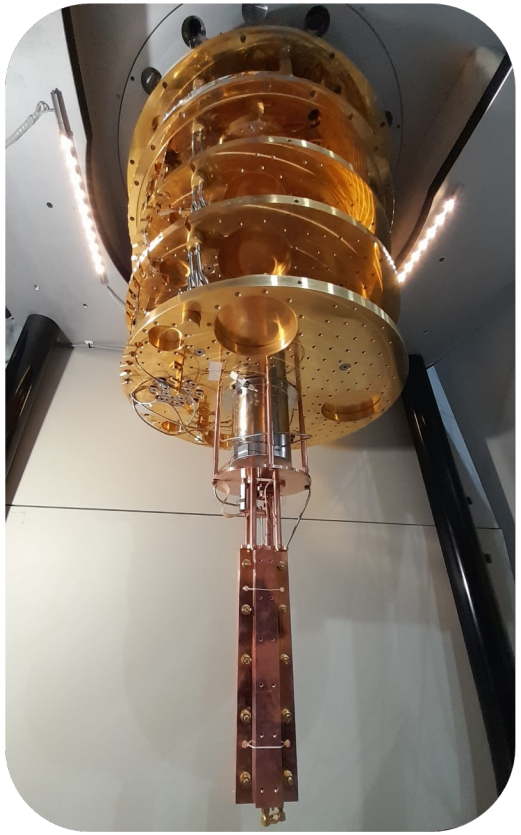


3D Al cavity designed in Frascati and fabricated in LNL

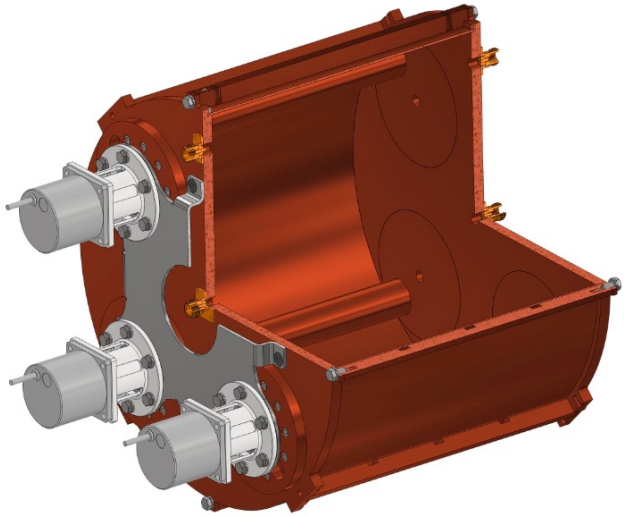


QUAX and FLASH at LNF

QUAX



- Magnet B = 8.5 T
- Volume V = 141 cm^3
- $f_{TM010} = 8.8 \div 9.1\ GHz$
- TWPA amplification
- Dilution refriger. (T = 30 mK)



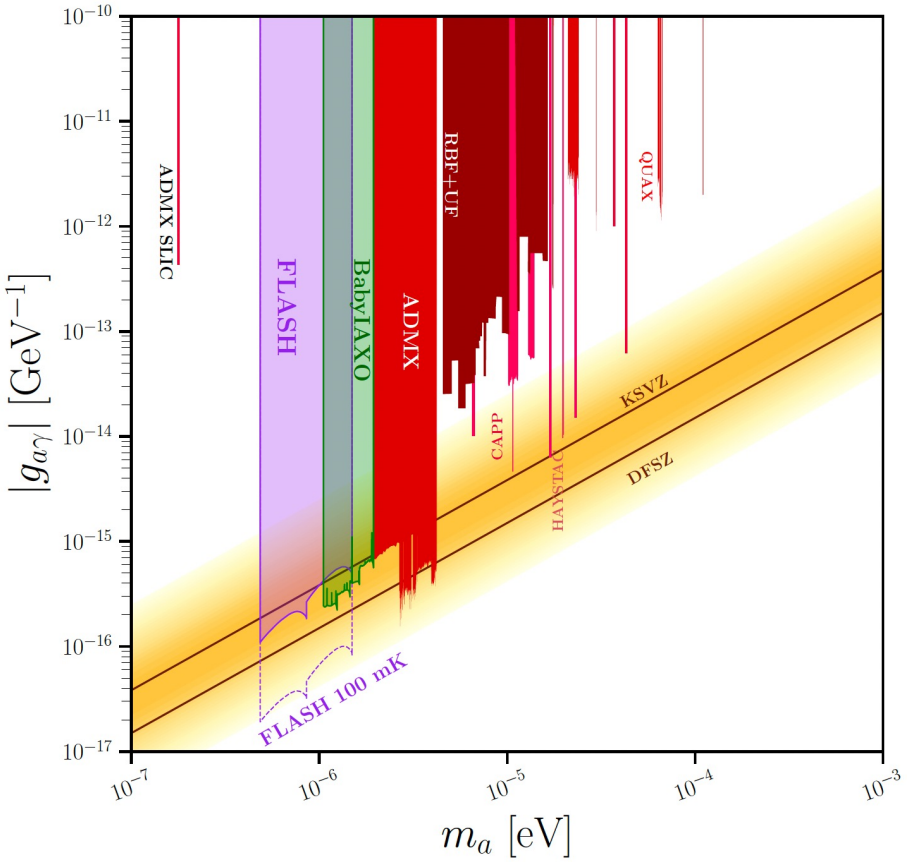
FLASH

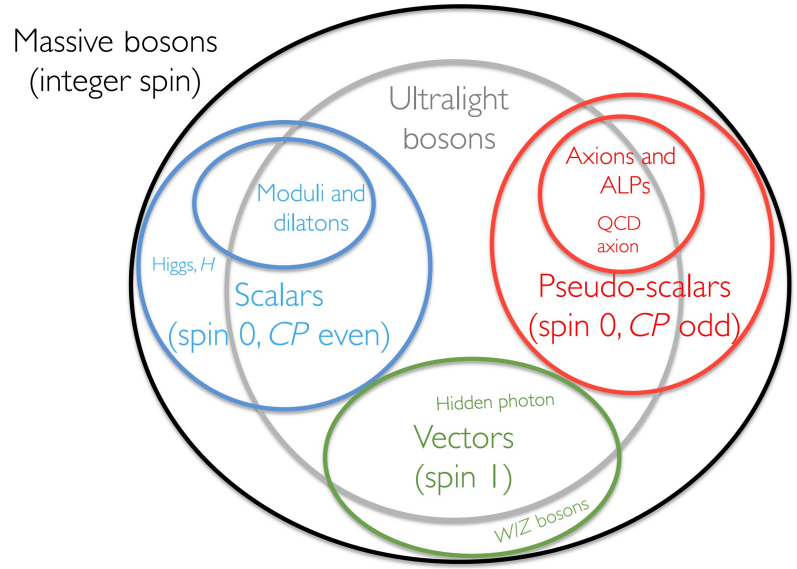
- ex-FINUDA magnet (B = 1.1 T)
- Large volume V = 4.25 m^3
- $f_{TM010} = 120 \div 350\ MHz$
- MSA SQUID amplification
- ex-Daphne cryogenics (T = 1.9 K)

Extensive physics reach

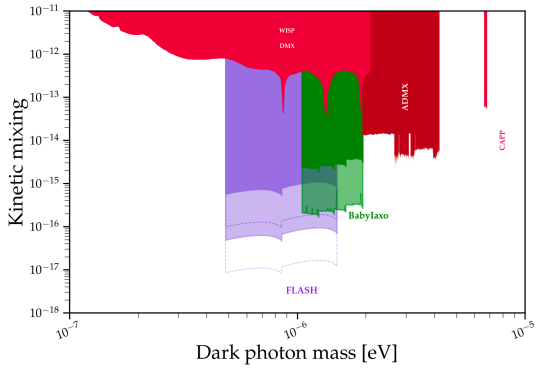
Forecasts for FLASH

Axions

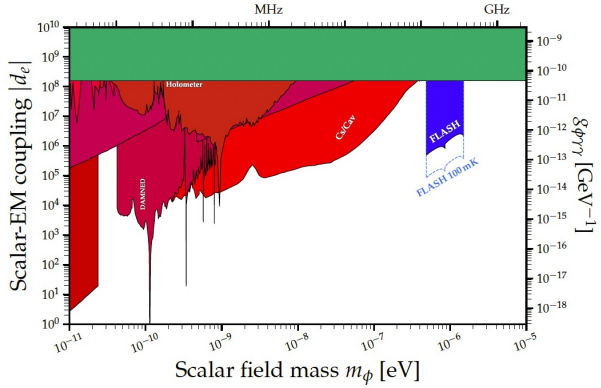




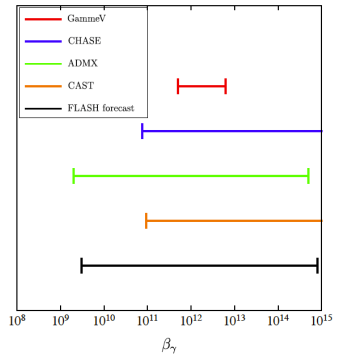
Vector Dark Matter



Scalar Dark Matter



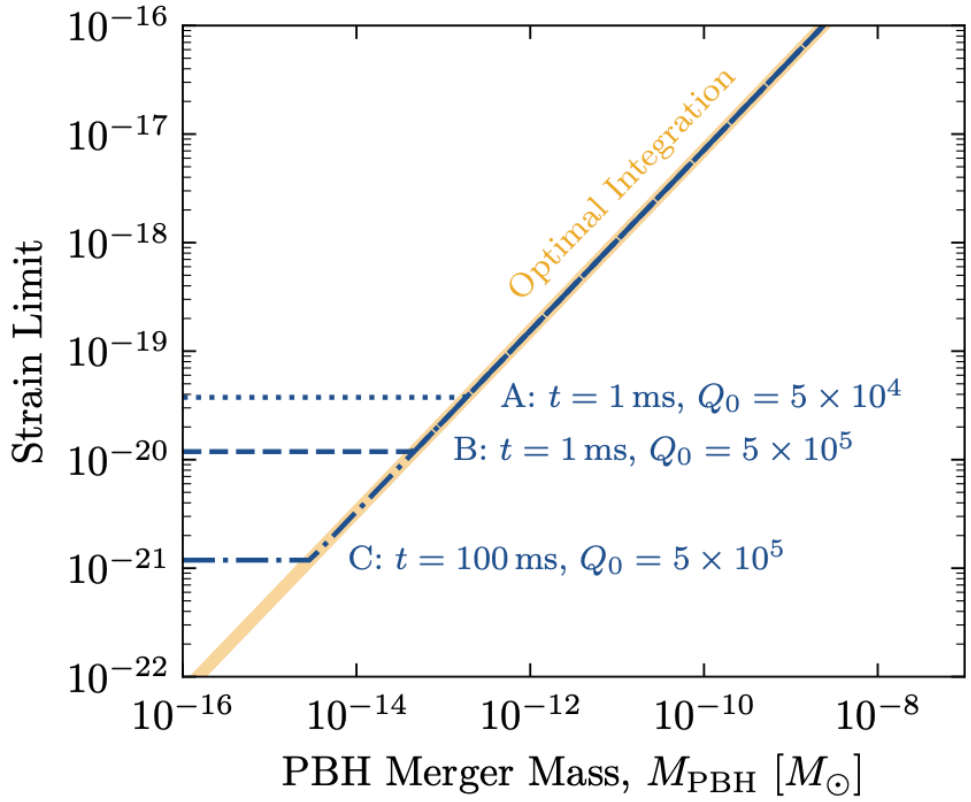
Theories of Dark Energy

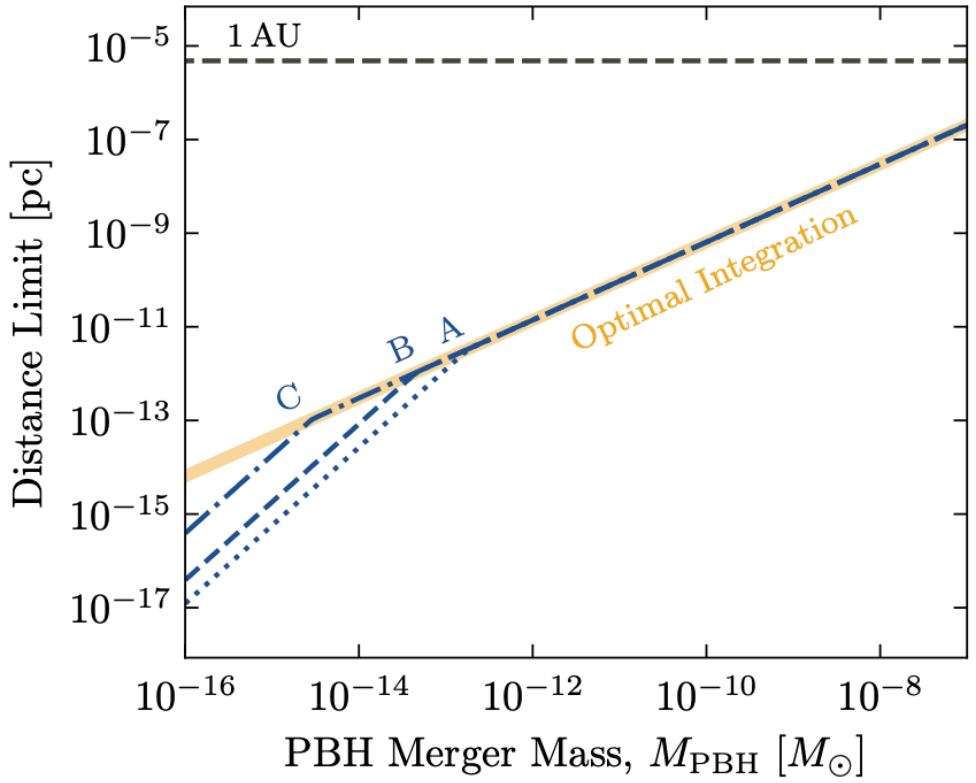


PBH mergers strain sensitivity

> 4 detectors in coincidence; required dark count of 10 Hz.

The transient is supposed to be shorter of the cavity readout time.





Conclusions

- GravNet is an ambitious project to build a network of detectors for HFGWs to operate in coincidence
- Working groups are at work to finalize designs, simulations, analysis strategies and readout
- QUAX is a running experiment. FLASH is refining its cavity design and already has a cryogenic plant ready
- The other sites are under development (retrieval of dilution units, cavities, rf instruments etc)

Thanks for your attention!

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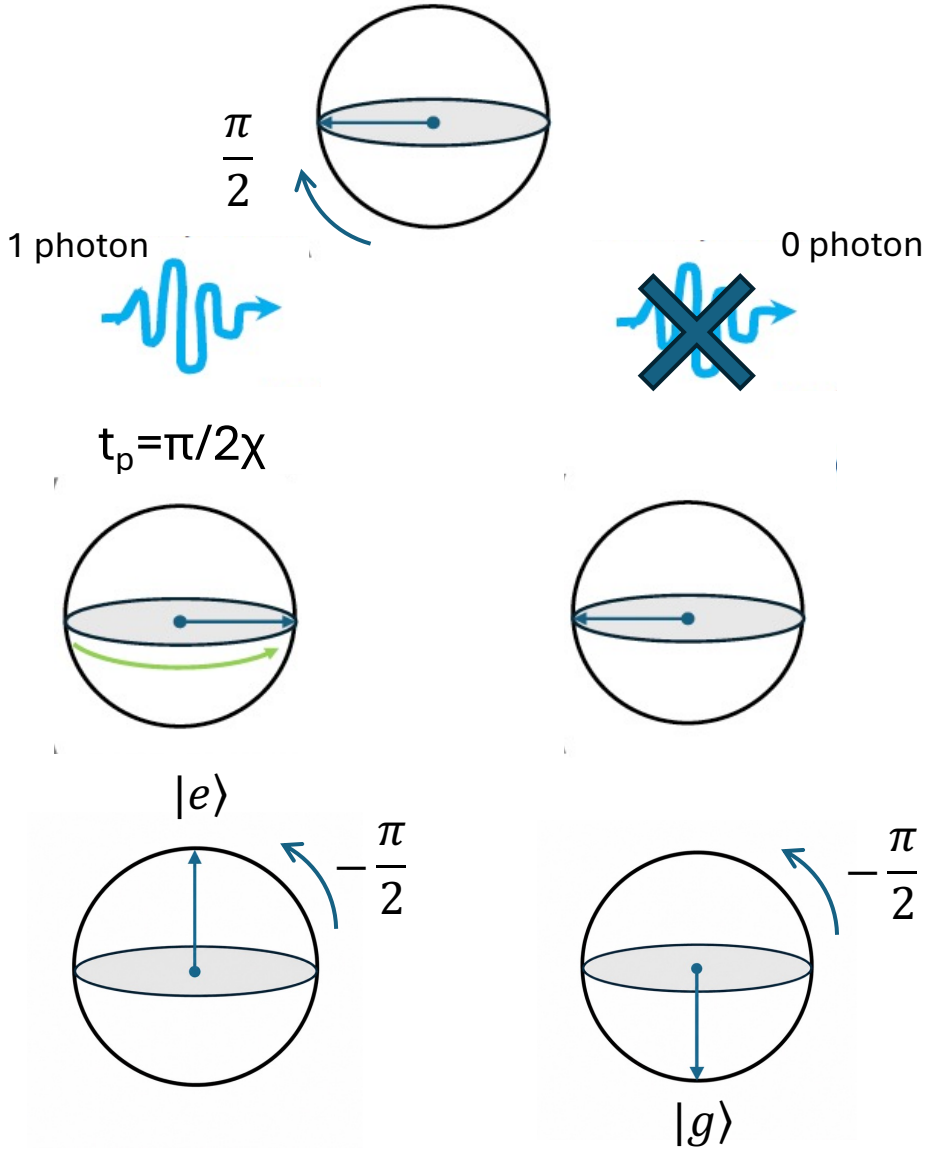
Detection of itinerant microwave photons



- Ramsey-like protocol => Qubit state depends on photon number
- After an interaction time t_p the qubit acquires a phase of π
- Closing the cycle with a – π/2 pulse the qubit state is |e> only in presence of a photon