A photon-magnon hybrid quantum system can be realised by coupling the electron spin resonance of a magnetic material to a microwave cavity mode. The quasiparticles associated with the system dynamics are the cavity magnon polaritons, which arise from the mixing of strongly coupled magnons and photons. We illustrate how these particles can be used to probe the magnetisation of a sample with a remarkable sensitivity, devising suitable spin-magnetometers which ultimately can be used to directly assess oscillating magnetic fields. Specifically, the capability of cavity magnon polaritons of converting magnetic excitations to electromagnetic ones, allows for translating to magnetism the quantum-limited sensitivity reached by state-of-the-art electronics. Here we employ hybrid systems composed of microwave cavities and ferrimagnetic spheres, to experimentally implement two types of novel spin-magnetometers.

Among the most studied types of hybrid quantum systems, an important role is played by photon-magnon hybrid systems (PMHS). These yielded remarkable results in the study of light-matter interaction\textsuperscript{3}, and in the last decades emerged as promising constituents for new quantum technologies as well\textsuperscript{4–6}. PMHS have different forms, as they are built with miscellaneous building blocks, but the underlying physics is similar. In a magnetic field $B_0$, an electron can change its spin quantum state from $-1/2$ to a $+1/2$ by absorbing a spin-1 boson, like a photon, and vice versa by emitting one. In this sense, a quanta of spin excitation with energy $\hbar \omega_m = \mu_B B_0$, where $\hbar$ and $\mu_B$ are the reduced Planck constant and Bohr magneton, can be effectively described as a quasiparticle, known as magnon, which can turn into a photon of the same energy $\hbar \omega$. This reciprocal conversion is quantified by the interaction strength $g_{em}$, known as vacuum Rabi splitting, which is the rate at which magnons are converted into photons and vice versa. When $g_{em}$ is much larger than the damping rates of the magnon $\gamma_m$ and of the photon $\gamma_c$, the system is in the strong coupling regime, and the quasiparticles arising from this mixing are known as cavity magnon polaritons (CMP)\textsuperscript{8,9}. PMHSs are widely investigated for advancing quantum information science. In this field their importance lies in building quantum memories\textsuperscript{10,15} in converting microwaves to optical photons\textsuperscript{17,21} or in quantum sensing, where the detection of single magnons was recently demonstrated\textsuperscript{23,24}. CMP recently found new applications in the field of non-Hermitian physics\textsuperscript{25–27} where they already yielded outstanding results\textsuperscript{28}. Exceptional points, spots of the system’s parameter space highly sensitive to external stimulations, can be probed with PMHS\textsuperscript{26,27}, and new configurations may be designed to access more exotic phenomena and study their application\textsuperscript{23,24,31,32}. The potential of hybrid systems was also shown in many other applications of quantum physics\textsuperscript{33–37}.

A distinguished physical realisation of this model can be obtained by hybridising the microwave photons of a resonant cavity with the magnons of a ferrimagnetic insulator\textsuperscript{38,42}. Such scheme was implemented with multiple purposes, for example to develop new quantum technologies with qubits\textsuperscript{10,15}, or for microwave-to-optical photon conversion\textsuperscript{20,21} making it an established platform of hybrid magnonics. In the devices described in this letter, we employ copper cavities as a photonic resonator and Yttrium Iron Garnet (YIG) spheres as magnetic material. YIG has the exceptionally high electron spin density of $2 \times 10^{28}$ spin/m$^3$ already at room temperature, and a linewidth as narrow as 1 MHz\textsuperscript{43–45}. This latter value is matched to the one of a typical copper cavity and, thanks to the chosen spherical shape, is not affected by geometrical demagnetization. Being employed in a number of microwave and rf devices, YIG is among the most well-known ferrites, and hence is readily available. The magnetic sample is placed inside the cavity, where the rf magnetic field is maximum for the selected cavity mode, and is magnetised with a static field $B_0$ perpendicular to the cavity one. In this way, the Kittel mode of magnetisation couples to the microwave cavity photons, and the system exhibits the typical anticrossing dispersion relation shown for example in Fig. 1, which also displays a schematic drawing of a PMHS. The coupling strength depends on the working frequency, on the microwave mode volume, and on the number of spins involved\textsuperscript{44}, but it is normally large enough to let the photon (magnon) oscillate into magnon ( photon) many times before being dissipated.

This feature of CMP to be a mixed state of microwaves and spin excitations, allows one to extract information on the magnons by monitoring the photons, while maintaining an almost unitary efficiency (see Fig. 1 for a schematic diagram). Amongst other techniques to measure spin-waves\textsuperscript{30,31} the use of CMP is a particularly simple approach which exploits the sensitivity of microwave technology and transfers it to the detection of magnons. The strong coupling makes the energy stored in a cavity dependent on the one in the material, so an antenna coupled to the electromagnetic field of the cavity gives a simple access to the features of the spin system\textsuperscript{45}. Nowadays electronics is extremely developed, and the detection of electromagnetic radiation has been brought to the standard quantum limit of linear amplifiers. At microwave frequencies, Josephson Parametric Amplifiers (JPA) were demonstrated to be the best devices to measure tiniest amounts of power\textsuperscript{46}. 

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Cavity magnon polariton based precision magnetometry

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and the system evolves according to Bloch equations

\[
\frac{dM}{dt} = \gamma(M \times b_t)_\perp + \frac{M}{T_s},
\]

where \(\gamma = (2\pi)28\) GHz/T is the electron gyromagnetic ratio, and \(T_s\) is the system relaxation time. The driven magnetization resulting from Eq. (1) is

\[
M(t) = \gamma \mu_B n_s T_s \cos(\omega_b t),
\]

where \(\omega_b\) is the frequency of \(b_t\). In a steady state, the power of \(b_t\) is absorbed by the magnetization, and rapidly converted into photons thanks to the strong coupling.

The optimal experimental condition is an antenna critically coupled to the cavity, which in steady state can extract up to 1/2 of the power deposited by the external field, resulting in

\[
P_1 = \gamma \mu_B n_s \omega_b b_t^2 T_s,
\]

where \(N_s\) is the number of spins of the hybrid system. The result of Eq. (2) can be directly compared with the power sensitivity of the apparatus \(\sigma_\text{f}\), yielding the minimum detectable magnetic field

\[
b_t = \sqrt{\frac{\sigma_\text{f}}{\gamma \mu_B n_s \omega_b T_s}}.
\]

Here we can see that the spin-magnetometer sensitivity increases for larger spin-number and longer hybrid system coherence times. This suggests the use of high quality-factor cavities and samples to get a high value of \(T_s\), and of a large volume of high spin density magnetic material to increase \(N_s\). In this sense, we have found a good compromise in YIG, which we used in our spin-magnetometer prototypes. We believe that the scalability of the PMHS is of fundamental importance for obtaining a major sensitivity enhancement, and it is the most straightforward way to improve the precision of the device.

To this aim we devise spin-magnetometers based on multi-samples PMHS embedded in cylindrical cavities. We further boost the magnetic sensitivity by operating the device at milli-Kelvin temperatures, to reduce thermal noises and to consent the use of JPAs. A scheme of this device is reported in Fig. 2a. As explained previously, in these spin-magnetometers the PMHS acts as a transducer of magnetic excitation, and we devised the largest optimally-controlled system of this kind to date, comprising ten 2.1 mm YIG spheres produced in situ, coherently coupled to a single copper cavity and biased with an extremely uniform magnetic field supplied by a superconducting solenoid. The design of such a system has been done taking into account the effects of the magnetic dipole interaction between different spheres, the interference of other cavity modes, and the presence of higher order magnetostatic modes. A careful modelling is necessary in order not to reduce the sensitivity of the device. We successfully reproduce the anticrossing curve of Fig. 2d, and operate the magnetometer in the frequency band covered by the lower frequency hybrid mode (dashed line in the figure). This range must be matched with the working band of our JPA, where tuning is possible by using a small superconducting coil biased with a constant current. Fig. 2d shows the effect of the bias current on the resonance frequencies of our Josephson Parametric Converter (JPV), i.e. a JPA formed by a Josephson ring modulator shunted with four inductances. The JPC is screened from external disturbances with different layers.

Thanks to CMP, such precision can be practically shifted to a magnetization measurement, which straightforwardly becomes quantum-limited.

Above the radiofrequency band, measuring a sample’s magnetization becomes increasingly difficult because of technological limitations and fundamental problems, like for example radiation damping. In free space and at GHz frequencies, radiation damping consists in the magnetic dipole emission of a magnetized sample which drastically decreases its coherence time, limiting the experimental sensitivity. This effect is avoided in PMHS, as the sample is housed in a resonant cavity which removes the damping by inhibiting the phase space of the emission.

For all their characteristics, PMHSs emerge as an outstanding platform for precision magnetic measurements, which are of interest for a broad range of applications as well as for approaching fundamental physics issues. Hereafter, we describe two types of spin-magnetometers which can be designed with hybrid systems, detail their design and report on their operation. These devices are originally meant to measure tiniest magnetization changes, radiation damping consists in the magnetic dipole emission of a sample’s magnetization, related for example to a Dark Matter Axion field, but can be used to assess many other physical phenomena.

**Transverse spin-magnetometer (TSM).** - If an oscillating electromagnetic, or pseudo-electromagnetic, field \(b_t\) is oriented perpendicularly to the static field, its quanta can be absorbed by the hybrid magnetic mode. As the magnetization vector \(M\) precesses around \(b_t\), an excitation lying on the plane transverse to the static field can resonantly interact with \(M\), and the system evolves according to Bloch equations

\[
\frac{dM}{dr} = \gamma(M \times b_t) \perp + \frac{M}{T_s},
\]
of superconducting and \( \mu \)-metal shields, and we verified that the solenoid providing the static field is not affecting the resonance frequencies of the amplifier. The two dashed lines in Fig. 2a and c share a large frequency interval, which practically is the working band of the spin magnetometer. The spin number and relaxation time are obtained through the transmission measurements of Fig. 2b, while the noise and gain of the amplification chain are calibrated with the injection of rf signals of known amplitudes. The quantum-noise of the JPC can be quantified as an effective temperature \( T_\text{q} = h \omega_b / k_B \approx 0.5 (\omega_b / 10 \text{GHz}) \), our measurement shows that the whole system noise is around two quanta, \( T_n \approx 1 \text{K} = \sigma_P / k_B \). With this setup we obtain the record magnetic sensitivity per unit bandwidth of

\[
\bar{b}_1 = 0.9 \times 10^{-18} \left[ \frac{1 \text{K}}{T_n} \right] \left( \frac{N_s}{10^{17}} \right) \left( \frac{\omega_1 / 2 \pi}{10.4 \text{GHz}} \right) \left( \frac{\omega_s}{168 \text{ns}} \right)^{1/2} \text{ T} \text{ Hz}^{1/2},
\]

which we used with a fixed bandwidth of 5 kHz to search for Dark Matter axions, obtaining a limit on their effective field of \( 5.5 \times 10^{-19} \text{ T} \) after several hours of integration.

We stress that the sensitivity given by Eq. (4) holds if the field to be detected has two characteristics: a coherence time longer than \( T_\text{c} \) (the shorter time is the critical value), and a coherence length large enough to compose all the \( N_s \) spins. In particular, this is the case of the field induced by Dark Matter axions, which at GHz frequencies satisfies both conditions. A TSM has the advantage of being sensitive to a (pseudo)magnetic field acting on a sample which is within the volume of a resonant cavity. In such a controlled environment, external electromagnetic disturbances are unlikely to be present, making it an interesting testbed for fundamental physics, which are usually not subjected to such screening. However, from the point of view of the possible TSM technological employment, this feature is a limitation. In fact, the screening due to the cavity makes it difficult to expose the material to a field which is uniform and coherent over the magnetic material volume. Hence, the application of this device is limited, and its preferred usage is in the search of new physics.

Longitudinal spin-magnetometer (LSM). - In another possible measurement scheme a persistent oscillating B-field is parallel to the static one. In this configuration, the sample’s magnetization precesses about a field \( B_0 + b \sin(\omega_2 t) \), where \( \omega_2 \) and \( b \) are the oscillating field frequency and amplitude, and \( t \) is time. We first consider a simplified scheme and ignore the presence of the cavity to only include the material. The experimental scheme is shown in Fig. 3a, where a sphere is surrounded by two crossed loops. Loop number 1 is used to excite the material, while loop number 2 senses the transmitted rf signal, and \( S_{21} \) plots are measured. The electron spin resonance (ESR) frequency \( \omega_m \) of the magnetized sample is modulated at \( \omega_m \approx \omega_2 \) by the varying \( b \)-field, which consequently shifts its phase. If a monochromatic tone is applied on resonance with \( \omega_m \), the effect of \( b \) is then to transfer some of the pump power, the carrier, to sidebands at frequencies \( \omega_m \pm n \omega_2 \), as schematically shown in Fig. 4 for \( n = 1 \). In the

\[
S_{21}(\omega) = \frac{A_p Q b_2}{2B_0},
\]

where \( A_p \) is the carrier amplitude and \( Q \) the quality factor of the ESR. In a standard ESR technique an externally applied \( b \) is used to detect the derivative of the ESR curve with a lock-in amplifier. Here we invert such scheme, and search for oscillating \( b \)-fields by sensing the presence of sidebands above the detection noise \( A_n \). The amplitude \( \xi_s \) given by Eq. (5) is actually valid only within the linewidth of the ESR, while its value drastically reduces for higher \( \omega_2 \). Moreover, extra noise induced by the pump residual amplitude and phase noise is also present. As a consequence, in this configuration the sensitivity for measuring a \( b \)-field is poor and needs some improvements.
that can be engineered using PMHSs.

By including the cavity one may consider a hybrid mode instead of a bare ESR. CMPs frequencies are also modulated by the oscillating field, thus we can use their feature to improve the detection sensitivity. The rf electromagnetic field of the PMHS, pumped with a tone on-resonance with one of the hybrid modes, is phase-modulated by the variation of the ESR Larmor frequency, and therefore produces sidebands too. Their amplitude drastically decreases when they depart from the resonance frequency by several linewidths, but in a PMHS, at the frequency of the second hybrid mode, one sideband does not vanish and hence can be detected (see Fig. 3b). This device is thus sensitive to fields which are at frequencies \( \omega_2 \simeq 2g_{cm} \), the splitting of the two hybrid modes. The possibility of detecting the sideband at a frequency much different from the pumping one allows us to drastically reduce the noise by heavily filtering the pump. For example, a waveguide is a high pass filter which can reduce low frequency power by tens of dB, and that we can employ to remove the noise of the pump. By assuming that the carrier noise can be made lower than thermal fluctuations, the latter becomes the fundamental limitation to the sensitivity of the apparatus. The magnetic sensitivity per unit of bandwidth can be calculated by recasting Eq. (6) as

\[
\bar{b}_2 = \frac{2B_0}{\pi Q} \sqrt{\frac{A_n^2}{A_p^2}},
\]

where, in this case, \( Q \) is the quality factor of the hybrid mode. From Eq. (7), one can see that the carrier power \( A_n^2 \) can be arbitrarily increased to improve the LSM magnetic sensitivity, assuming that its noise can be reduced consequently. With realistic parameters of our PMHS, one can estimate the sensitivity of a room-temperature LSM

\[
\bar{b}_2 = 5.2 \left( \frac{B_0}{0.4\,\text{T}} \right) \left( \frac{Q}{10^4} \right) \sqrt{\frac{A_n^2/k_B}{300\,\text{K}}} \left( \frac{100\,\text{mW}}{A_p^2} \right) \frac{T}{\sqrt{\text{Hz}}},
\]

which is already competitive with state-of-the-art magnetometers like superconducting quantum interference devices (SQUIDs)\(^{37,61}\) or spin-exchange relaxation-free (SERFs)\(^{57–61}\).

Interestingly, \( \bar{b}_2 \) does not depend on any extensive parameter, in contrast with \( \bar{b}_1 \) which relies on the total number of spins, meaning that the device can in principle be miniaturized without compromising its sensitivity, and removing the need of detecting a uniform field over a large volume.

A room-temperature prototype was realized to test the actual functioning of this device, and a scheme of the setup is reported in Fig. 3b. The number of spins in the sphere, together with the shape of the rf-magnetic field of the cavity mode, set the magnetometer working frequency \( \omega_2 \simeq (2\pi)200\,\text{MHz} \). The linewidths of the cavity and Larmor resonances set the overall quality factor of the mode, which results roughly the average of the two. An antenna with variable coupling is coupled to the cavity to inject and extract power in the hybrid system through a circulator. The input power is a pump on resonance with the high-frequency hybrid mode, which is filtered with a waveguide before entering the hybrid system. The

signal to be detected is the sideband at the lower-frequency mode, where thanks to the filter the noise is mainly thermal, and results \( A_n^2 \simeq 4 \times 10^{-21}\,\text{W/Hz} \). The extracted signal is amplified with a low noise high electron mobility transistor am-

FIG. 3. Schematic explanation of the LSM working principles. (a) Usual design used for the detection of an ESR in a magnetic material (light grey sphere). The rf is fed into the system by loop antenna 1 and the output is read with the perpendicular loop 2. A pump, shown as a blue line in the spectra, is applied on-resonance with the ESR curve (green areas in the \( S_{11} \) spectra). In absence of other fields the result is a single peak (left plot), while with a superimposed oscillating field the phase of the carrier is modulated by the shifting of the ESR induced by \( b_2 \sin(\omega_2 t) \). Two sidebands, reported in dark red in the right plot, appear at \( \omega_{cm} \pm \omega_2 \). (b) In the LSM a microwave tone is applied at the frequency of an hybrid mode, while the detection of a sideband, on-resonance with the second mode, probes the presence of \( b_2 \)-like fields. The picture shows our room-temperature pilot setup, comprising a YIG sphere and a cavity. Numbers 1 and 2 are two antennas coupled to the cavity, and the side of the cavity colored in light orange represent a hole housing a loop used for calibration. See text for further details.
plifier before being acquired with a spectrum analyser. To calibrate the device we inject pico-Tesla fields at 200 MHz using a single loop on one side of the cavity, which creates a known field parallel to $B_0$ on the YIG sphere (see Fig. 3b). The quality factor of the hybrid resonance is $Q = 2750$, the static field is $B_0 = 0.4$ T, and the pump power is $A_f^2 = 0.2$ mW. The setup was not optimized, but the expected losses due to imperfect matchings can be measured and accounted for by a factor 0.2, lowering the LSM sensitivity. With these quantities, from Eq. 7, the $b_2$ of the apparatus results 2.4 pT/√Hz. The prototype was calibrated with fields ranging from 2 to 14 pT and shows a sensitivity of $2.9 ± 0.5$ pT/√Hz, compatible with the estimated value. In this setup the loop on the side of the cavity was used for calibration, but in principle, it can be an input coil which transduces a field to the sensitive element of the magnetometer (the magnetic sphere). This signal transduction is similar to what is usually done with SQUIDs, where an input coil is coupled to the junctions loop.

This magnetometer has a lot of possible PMHS configurations, which can boost its sensitivity and make it adaptable to multiple applications. In general, open resonators, like coplanar waveguides, are more suitable to couple with a transducer, but more difficult to keep stable when using strong carrier power. The use of LSM at cryogenic temperatures is useful to reduce the noise and increase the $Q$ factor. Imperfect matchings can be measured and accounted for by a factor 0.2, lowering the LSM sensitivity. With these quantities, from Eq. 7, the $b_2$ of the apparatus results 2.4 pT/√Hz. The prototype was calibrated with fields ranging from 2 to 14 pT and shows a sensitivity of $2.9 ± 0.5$ pT/√Hz, compatible with the estimated value. In this setup the loop on the side of the cavity was used for calibration, but in principle, it can be an input coil which transduces a field to the sensitive element of the magnetometer (the magnetic sphere). This signal transduction is similar to what is usually done with SQUIDs, where an input coil is coupled to the junctions loop.

Both the spin-magnetometers benefit from the extremely low noise of quantum-limited amplifiers, and would have a further sensitivity boost thanks to the use of quantum counters. We foresee the use of broadband Travelling Wave JPA further sensitivity boost thanks to the use of quantum counters. We also thank Enrico Bert, Andrea Benato, Fulvio Calano, and Mario Tessaro for the help in the building of the experimental setups, and in particular for the aid with the mechanics, cryogenics, and electronics of the apparatuses. We acknowledge the support of INFN-Laboratori Nazionali di Legnano, for hosting all the experimental setups described in this work, and for the availability of large quantities of liquid helium.

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**DATA AVAILABILITY**

The data supporting the findings of this work are available from the corresponding author upon reasonable request.

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