Searching for topological defects of bosonic, ultralight fields with optically detected magnetic resonance (ODMR): design, calibration and sensitivity of Belgrade GNOME station

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Motivation

We are involved in a collaborative effort to search for a proposed particle and associated quantum field that that pervades all of the Universe. The particle in question is the QCD axion or, by relaxation of certain theoretical constraints, it is called generic ALP (Axion Like Particle). Axions arise naturally in QCD formalism by introducing additional field that is postulated to solve the strong CP violation. Axions are generated by spontaneous symetry breaking mechanism and are a form of pseudo-Goldstone bosons. [3] Their characteristics are small mass, macroscopic De-Broigle wavelength and spin dependent interaction with SM fermions. Depending on the details of the model (do axions thermalise before or after inflation and what is the value of symmetry breaking scale f_sb) axions can form topological defects, dilute non-relativistic gas, macroscopic coherent CDM condensates, clumps, Q stars,[6] mini-clusters, vortexes etc.

What axions can solve? A great many things it seems!

* Baryon asymmetry problem **(where has all the anti-matter gone after the Big Bang?)** [4]

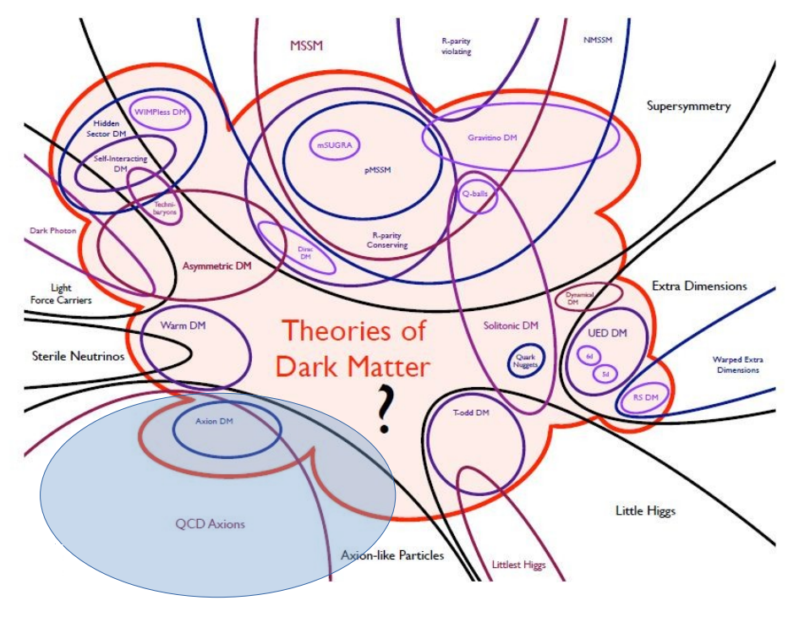
* Strong CP problem. (why is the CP violating term in QCD so small = still undetected nEDM).

* Dark matter problem? What is the exact form of supposed dark matter? Negative results of WIMP searches from the LHC, XENON, DAMA etc.and recent astronomical observations Indicate a deficiency in the current theoretical landscape and primarily in the Lambda CDM paradigm.[4]

$$L_{int} = \frac{i}{S_0 f_{int}}(\phi\partial_\mu\phi^* - \partial_\mu\phi\phi^*)\bar{\psi}\gamma^\mu\gamma^5\psi \xrightarrow{S\to S_0} \frac{\partial_\mu a}{f_{int}}\bar{\psi}\gamma^\mu\gamma^5\psi = J_a\frac{\bar{\psi}\gamma^\mu\gamma^5\psi}{f_{int}}$$

$$\Downarrow$$

$$H_{lin} = \frac{\xi}{f_{SB}}\frac{\vec{S}}{||S||}\cdot\nabla a(r,t)$$



Going through domain wall: method for detecting ALP topological defect

Domain walls are topological defects that arise in some models of cosmic evolution and structure formation. Axion and ALP domain walls have characteristic field profile, surface tension and length and via those parameters can be related to average local DM density. Some qualitative consequences of domain wall model:

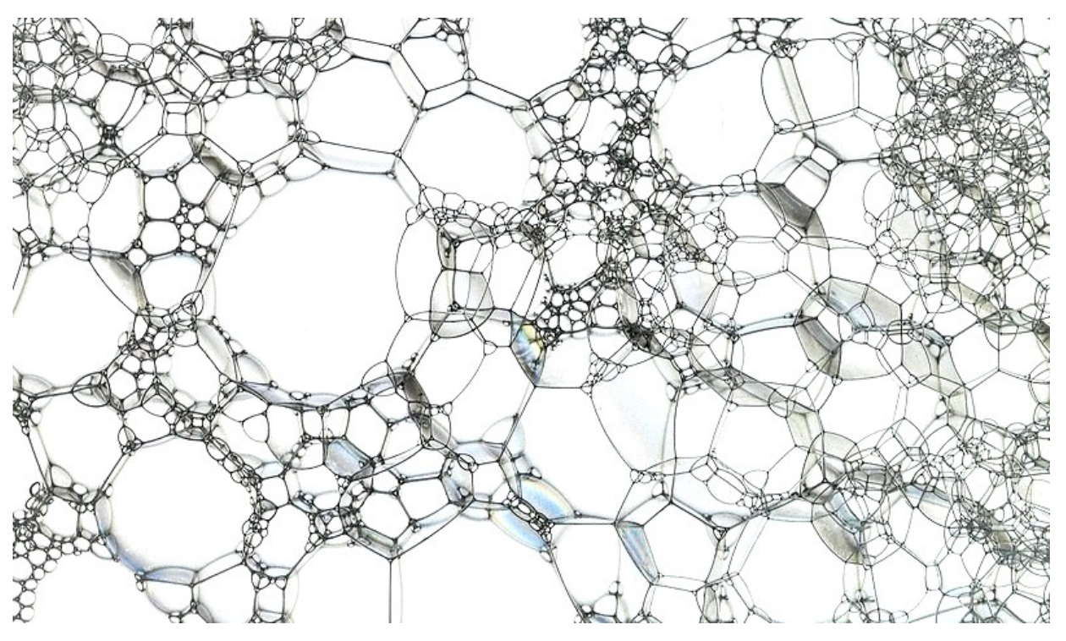
- Domain wall thickness is proportional to the axion De-Broigle wavelength. When we are considering the case of Earth-bound sensor that moves at 0.001 c at the LSR (Local Standard of Rest) it gives the order of magnitude of duration of the interaction.
- Interaction Hamiltonian is proportional to gradient of the axion field and couples to the SM fermions via axial current vector so it is spin dependent interaction. [5]
- Similarity between Zeeman and axion interaction Hamiltonian lead to the equating of those two and the result is the change in magnetic field in terms of axion filed gradient, axion mass and interaction strength – direct probe into the axion parameter space. [2]
- This change in magnetic filed can be translated to change in energy deposited to the spin polarized medium. Idea for detection: this pseudo-magnetic filed be sensed via the Larmor precession of spin polarized systems!!!!

$$\Delta x \approx 2\sqrt{2\lambda_a} = 2\sqrt{2}\frac{\hbar}{m_a c}$$

$$\Delta t = \Delta x/v \approx m_a^{-1}$$

$$\rho_{DW} = 1/2(\frac{m_a c}{\hbar})^2 a_0^2 \approx 1/2\frac{a_0^2}{\Delta x^2}$$

$$\rho_{DW} \approx \frac{L}{\Delta x}\rho_{dm}$$



$$H_{int} = \frac{\nabla a(r,t)}{f_{int}}\cdot\frac{\vec{S}}{||S||}$$

$$||$$

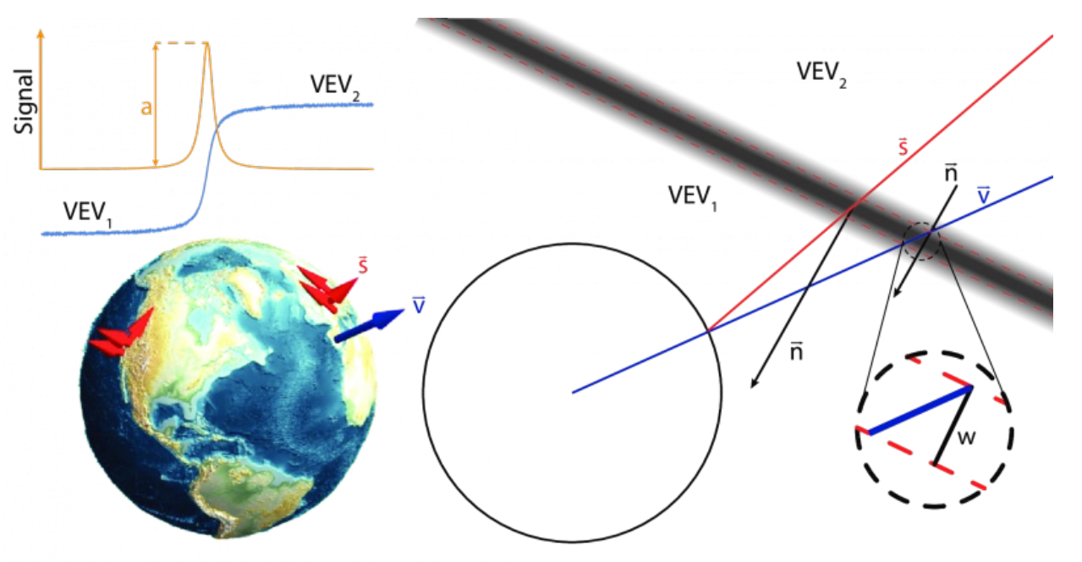
$$H_{Zeeman} = \gamma\vec{S}\cdot\vec{B}$$

$$\Downarrow$$

$$\vec{B} \approx 2\frac{\xi}{f_{SB}\gamma}\cdot\nabla a(r,t)$$

$$\Delta E = \mu_B B = \frac{\nabla a(r,t)}{f_{int}} \approx \frac{a_o}{\Delta x f_{int}}$$

$$\omega_L = \gamma_F\left|\vec{B}\right|$$



Transversal duration d_{tr}: $d_{tr} = \frac{w}{v_{perceived}}$, $v_{perceived} = |\vec{n}\cdot\vec{v}|$

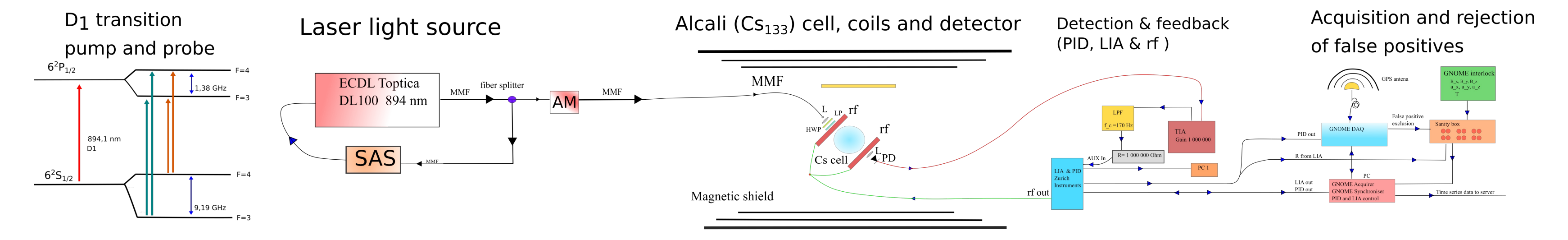
Signal amplitude $a_{perceived}$: $a_{perceived} = \vec{n}\cdot\vec{s}\ a$

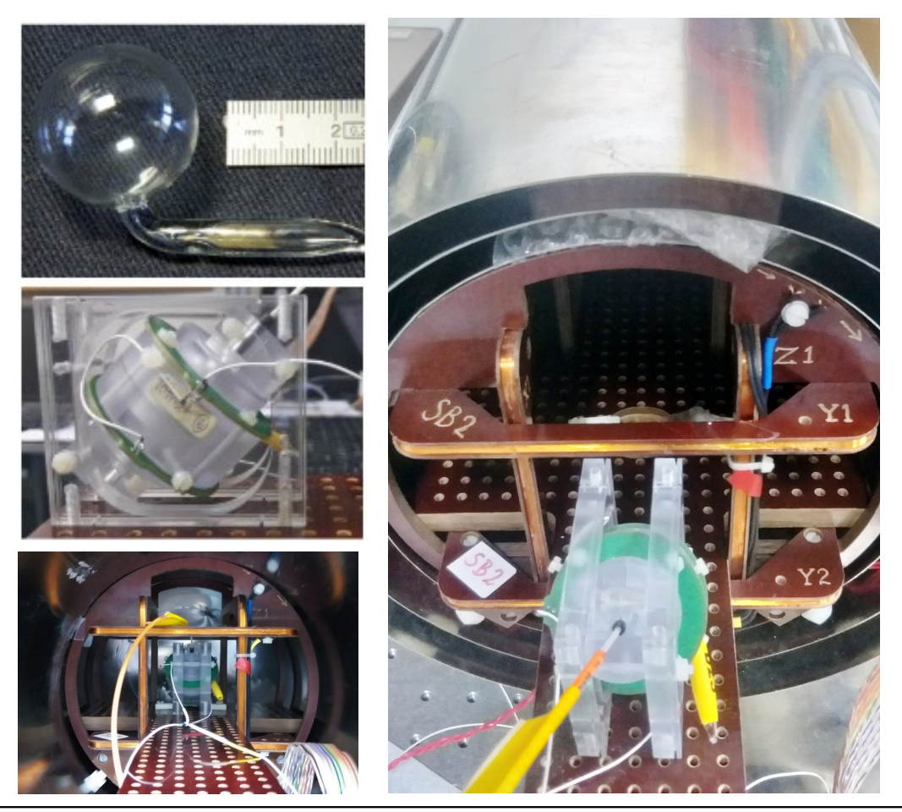
$$a(x) = 2f_{SB}\arcsin\left(\tanh\left(m_a x\right)\right)$$

$$\sigma_{DW} \approx \rho_{dm}L \approx \rho_{dm}vT$$

Experimental setup: Belgrade magnetometer for GNOME

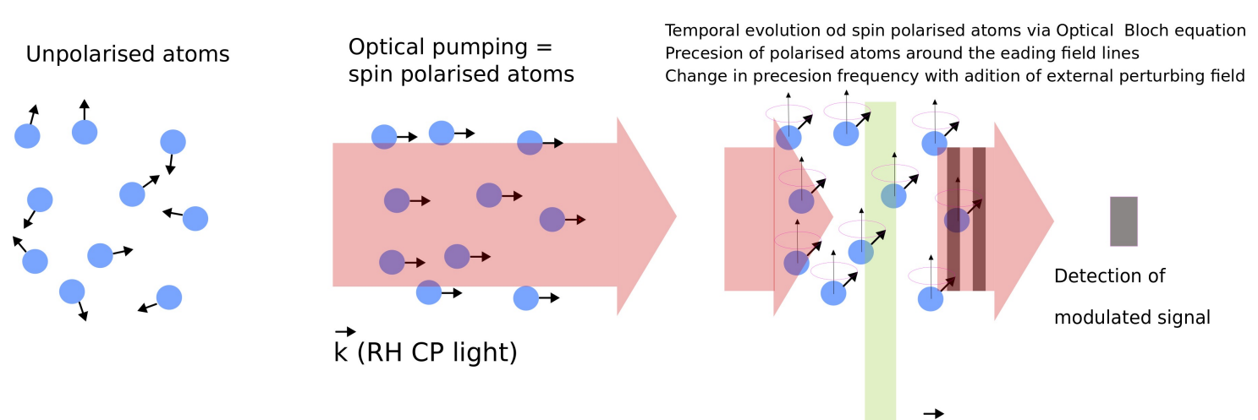
Our magnetometer is a **sensitive magnetometer: it** can detect a small field change - Shot noise limit of **27 fT**, but it's absolute field reading can be wrong by **3 orders of magnitude which is not of importance to GNOME network because of cross correlation of all the stations**!





In our setup spin-orientation is produced and detected by a single beam of circularly polarized resonant and SAS stabilized laser light (so called *sigma+* light or RHCP – right handed circulary polarized light) that is traversing room-temperature Cesium 133 vapor contained inside a paraffin-coated 30 mm glass cell that is subjected to DC transverse leading magnetic field. Cell, optics and coil system are enclosed in 3 layer magnetic shield. Laser frequency is actively locked via SAS scheme to the transition of the Cs D1 hyper-fine transition. An electro-optic modulator (EOM) is used to control the light intensity that goes into experiment. Pair of rf coils are used to supply the resonant field that cycles populations from dark to bright states and vice versa in order to create the MR signal. Modulated signal is detected by photo-diode. Photo-current passes through the Trans-impedance amplifier and is demodulated at the LIA which determines the phase and deviation from the lock-point. PID controller actively stabilizes signal and the error signal from the PID is brought out t the acquisition system and is the recorded as magnetic field value. Acquisition system has many component which serve to exclude false positives, record and log the magnetometric signals, timestamp the data which is sent out to central server at Johanes Gutenberg University, Mainz (Germany). [5]

Optical pumping and ODMR

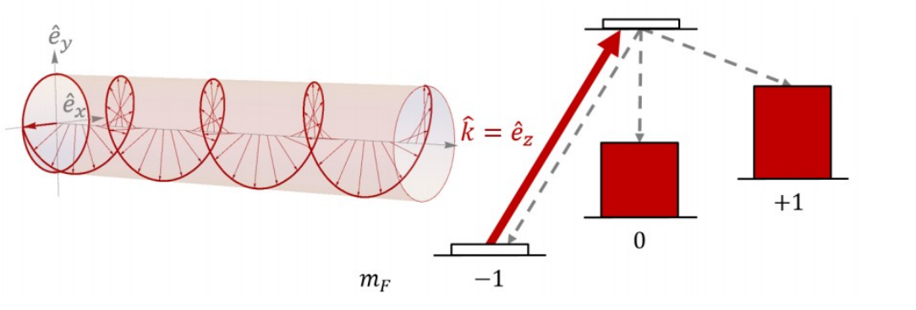


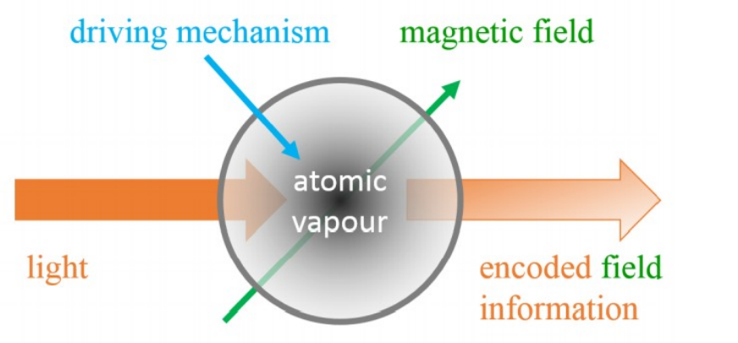
$$\kappa(t) = \kappa_0(1 - |\vec{S}|\cos(\omega_L t))$$

$$\vec{S} = \frac{\left\langle\vec{F}\right\rangle}{\hbar F} = \langle\vec{\nu}\rangle\frac{1}{\mu_B g_F F}$$

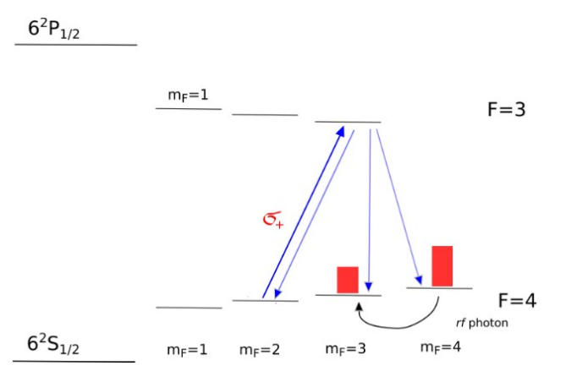
$$\omega_L = \gamma_F\left|\vec{B}\right|$$

Atoms of spin polarized medium, that is subjected to DC leading magnetic field , precess around the lines of the field at the Larmor frequency [1]. This precession is detected on the photo-diode as modulation of opacity coefficient kappa. However, for determination of perturbing magnetic field it is necessary to employ some resonant driving mechanism that can be contained in the vectorial variable S at to create the MR signal. One method is driving with the resonant rf magnetic field.





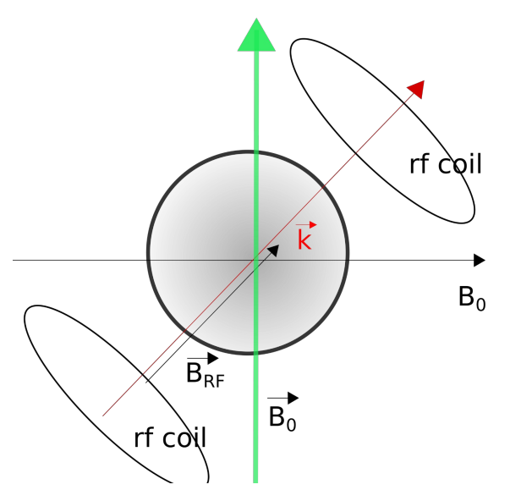
The ODMR magnetometer, in the form of orientation magnetometer relies on generation of spin polarized medium (most suited for this purpose are alkali vapors). Spin polarization is created and sustained by action of actively stabilized resonant laser light that is tuned to some hyper-fine transition. Different polarization states can created different resultant magnetic level populations and de-excitations according to selection rules. It this case sigma+ light was used to polarize the medium (Top left). In this scheme we use the approximation of the *two level atom* and the so called *rotating wave approximation*. According to this pump beam of resonant laser light couples and excites the alkali atoms via the *dipole operator* so that spin polarized atoms undergo internal oscillations between ground and exited state at the so called *Rabi frequency (*bottom right*)*. In order to generate Magnetic resonance signal it is necessary to couple the Zeeman sub-levels to each other. By using resonant field it is possible to bunch the populations at the m_f=3 and m_f=4 that can be cycled so as to create so called *dark* and *bright* states (bottom left). Detuning of this resonant frequency from the frequency of precession in the leading field is the proxy for perturbing magnetic field measurement. [1]

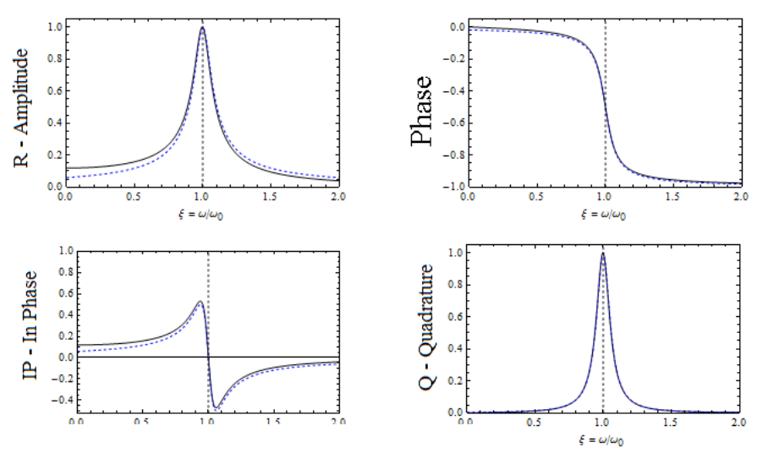


$$\Omega = -\frac{2(\langle g|\epsilon\cdot\vec{d}|e\rangle E_0^{(+)}}{\hbar} = -\frac{(\langle g|\epsilon\cdot\vec{d}|e\rangle E_0}{\hbar}$$

$$H_{atom-field} = \frac{\hbar\Omega}{2}(\sigma e^{(iwt)} + \sigma^\times e^{(-iwt)}))$$

Principle of Mx magnetometers in PLL: lineshapes and optimisation

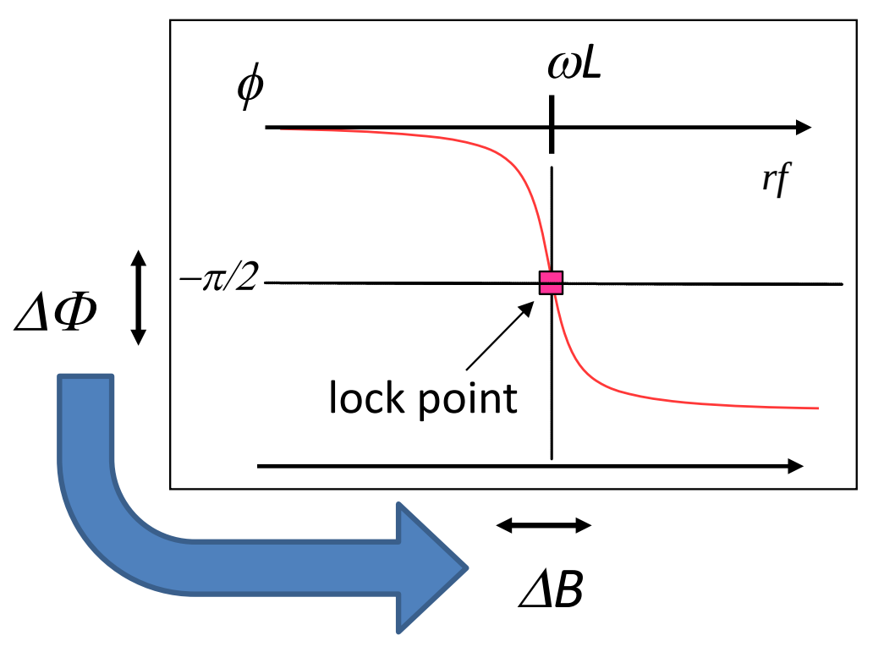


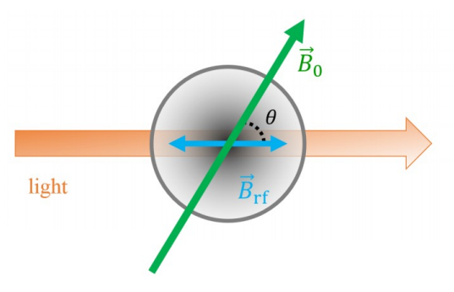


$$P_R = \frac{\tilde{P}}{2}\frac{\sqrt{\delta\omega^2+\Gamma^2}\tilde{\Omega}}{\delta\omega^2+\Gamma^2+\tilde{\Omega}^2}$$

$$\tilde{\phi} = \phi_0 - \arctan\left(\delta\omega/\Gamma\right)$$

$$\Delta\phi = \Delta B\frac{d\phi}{dB} = \Delta B\frac{\gamma_F}{\Gamma}$$





$$I_R = \tilde{I}\frac{\Gamma\tilde{\Omega}}{\Gamma^2+\tilde{\Omega}^2}$$

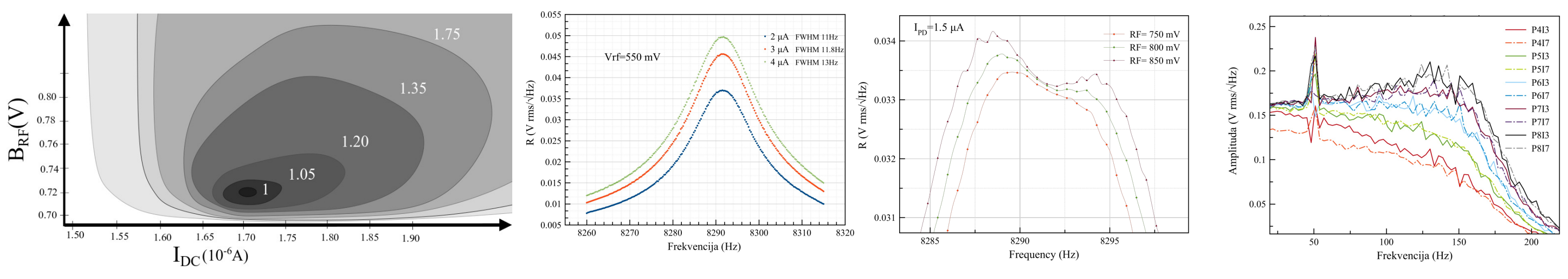
Photo-current on resonance

$$\rho_B = \sqrt{2}\frac{\rho_I\Gamma}{I_R\gamma_F} = \sqrt{2}\rho_I\frac{\Gamma^2+\tilde{\Omega}^2}{\tilde{I}\gamma_F\tilde{\Omega}}$$

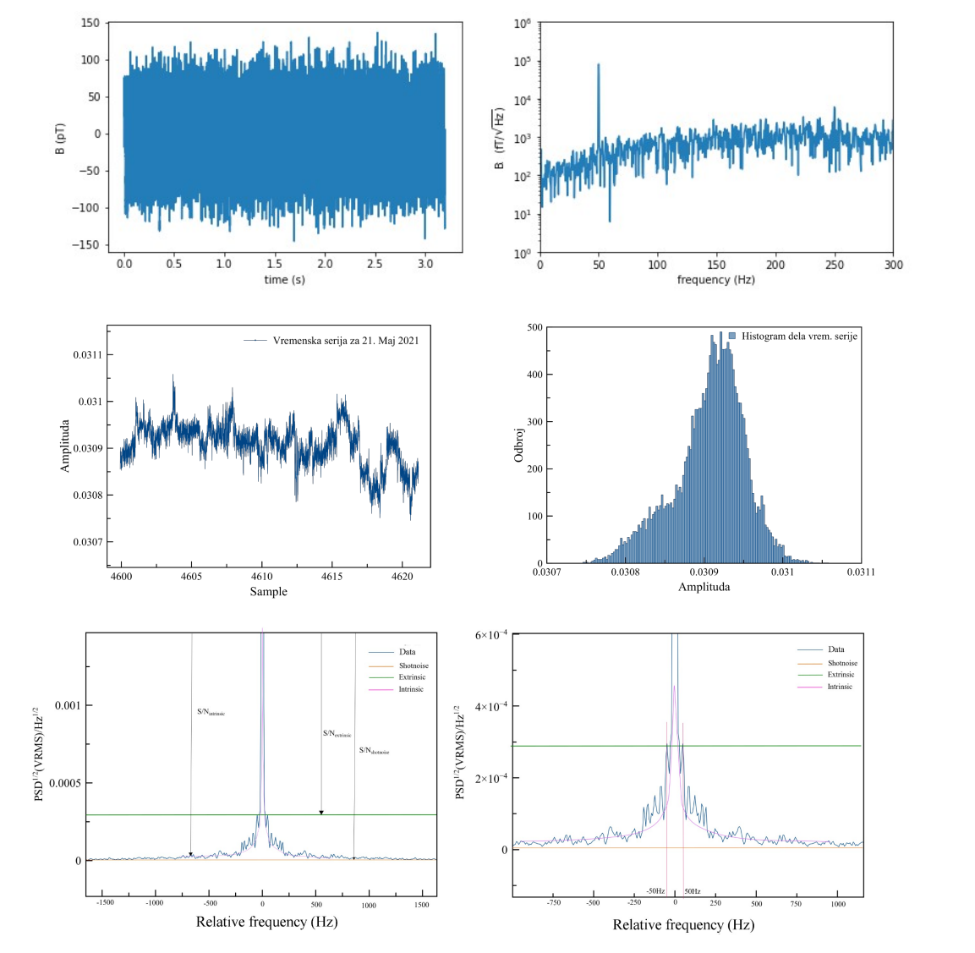
$$\rho_B \approx \rho_I\frac{\Gamma}{\tilde{I}} \approx \sqrt{P_0}\frac{(1+P_0/P_{sat})^2}{P_0^2/P_{sat}} \approx \frac{1+G_{op}}{G_{op}^{3/2}}$$

Another topic is optimising the parameters of magnetometer: power of the pump beam, strength of the rf field and parameters of PID controller. Two dimensional interpolation plot (Bottom leftmost) determines combination of photo-current (proxy for pump beam power) and voltage on rf coils for which magnetometer is the most sensitive (given by expressions on the left). Too intense pump beam leads to resonance broadening (Bottom second from left), which if too great reduces sensitivity. Too great rf field leads to Zeeman splitting of the resonance (Bottom third from left) which is detrimental to SNR. Also it is necessary to tune the PID controller for the flat response (Bottom right).

Magnetometer is designed as a Mx magnetometer where the probe beam is parallel to the leading magetic filed and both are positioned at 45 deg in regard to the resonant driving rf field. Any phase error yields a lockpoint error, i.e., an error in the value of magnetometer oscillation frequency and hence of the field reading which is translated to measured magnetic field. It san bee seen how this relation, in vicinity of lock point is linear.



Time series and signal characteristics

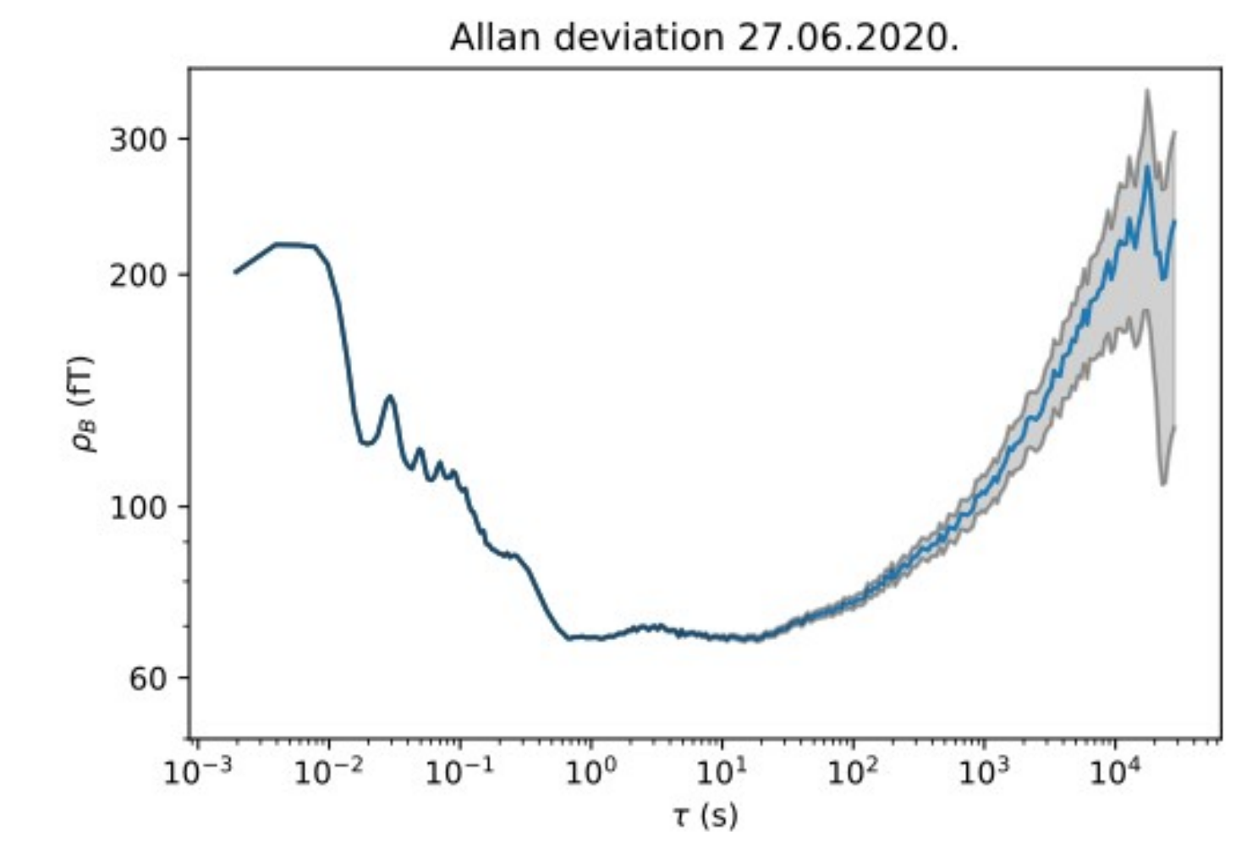


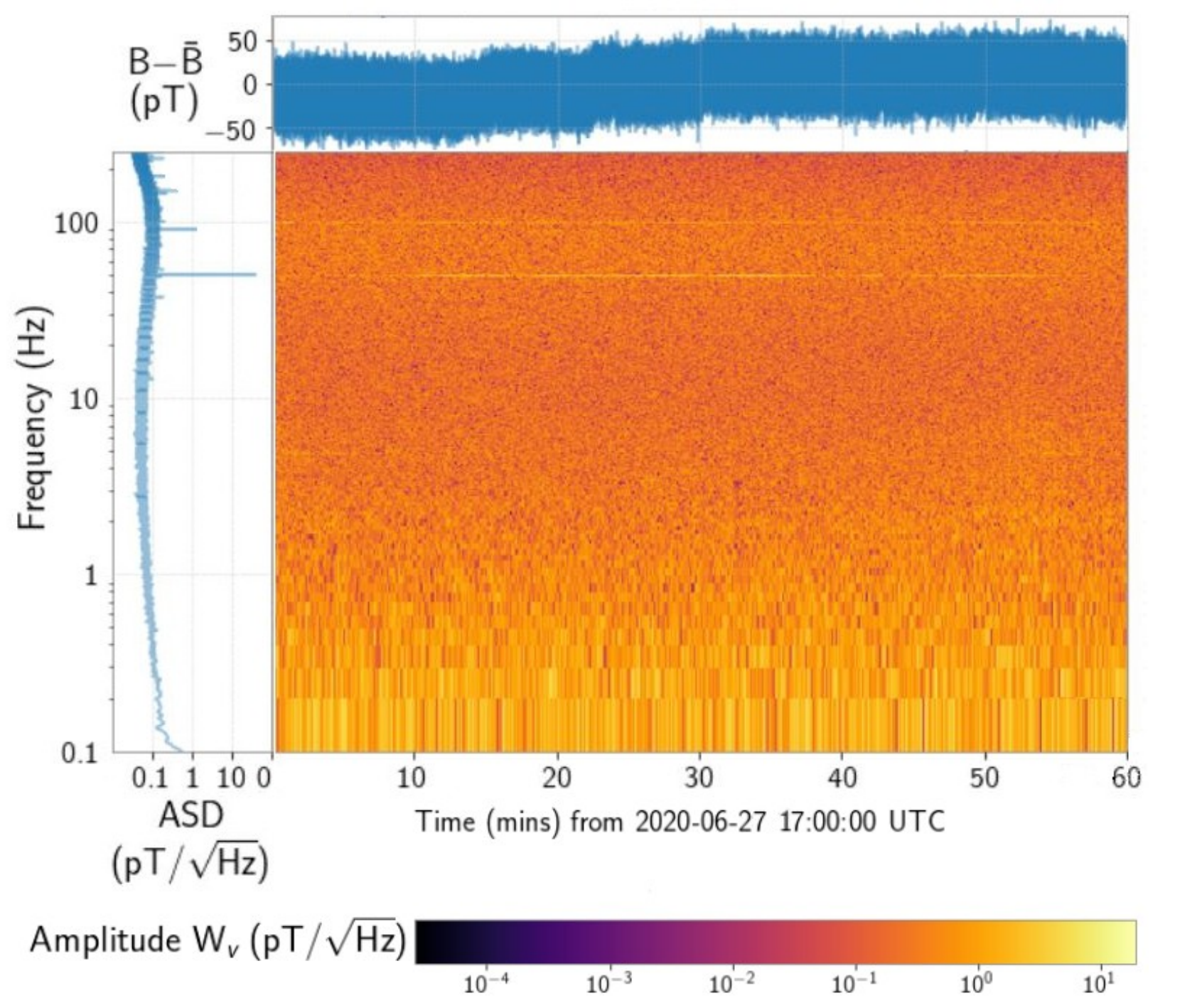
Probe beam signal contains oscillatory components at the frequency of the resonant driving field. After passing through the LIA those rf components are filtered out and what is seen at the exit of the LIA is the signal that measures the magnetic filed that is contaminated by several components. First is prominent 50 Hz AC peaks that make considerable side-bands around the signal. Others are fluctuations in the light field, loss of the off resonant drive, laser 1/f noise, shot noise of the leading coil system, contribution from the external field fluctuations (AC, machinery, rail lines, ionospheric interference etc.). Last contribution is the shot noise that is inherent in the photo-detection process and is referred to as the *fundamental quantum limit* (that can be surpassed if one employs so called squeezed states of light.). Ultimate shot noise limited sensitivity is 27 fT/√Hz and the total sum of all internal noise sources is around 50 pT/√Hz. Additional extrinsic contributions add up 50 to 100 pT/√Hz more on top of this intrinsic noise. The output frequency spectrum is considerably flat, which is desirable but the long-term histogram display non-gausianities that need to bee accounted for.

Top: Raw signal from magnetometer output (without the LPF) and its Fourier transform.
Middle: time series for of 5 minutes and its histogram. Non-Gausian distribution is attributed to imperfect magnetic shielding.
Bottom: magnetic resonance signal with labeled noise contributions.

Preliminary results

$$\sigma(\tau) = \sqrt{\frac{1}{2(N-1)}\sum_{i=1}^{N}[B_{i+1}(\tau) - B_i(\tau)]^2}$$



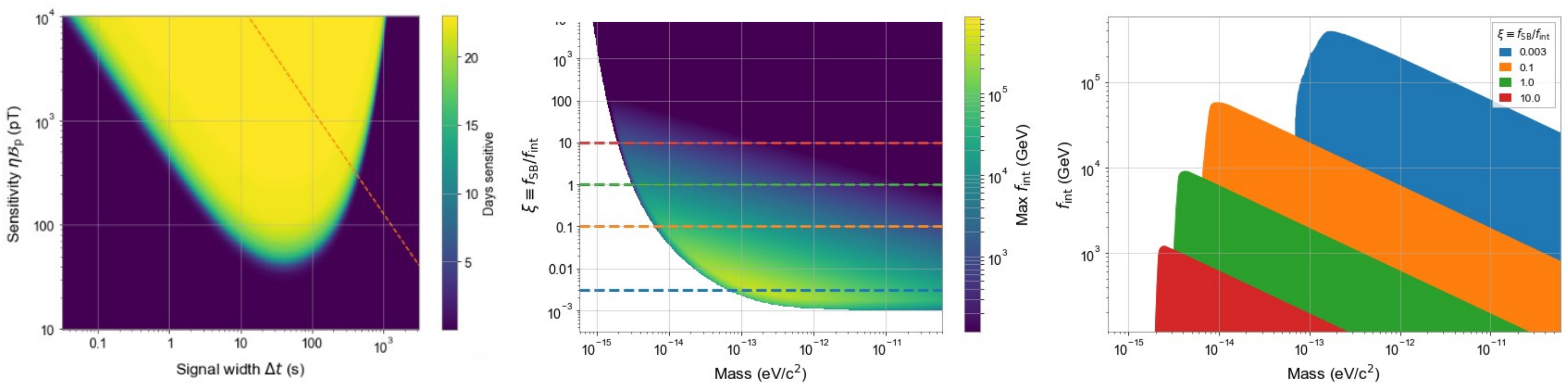


The most basic metric that can quantify the stability of the system is Allen standard deviation. It quantifies the stability of the measuring apparatus at various temporal baselines. From the graph (Top left) it can bee seen that our magnetometer has outstanding stability. It has characteristic V shape with a deep plateau which indicates that measurements on the baseline of 0.1 to 1000 second are of great confidence. Allen deviation can discriminate between different noise contributions and it is clear that for high frequencies 1/f noise dominates while for low the most dominant is drift (that can be attributed to external influences). Allen plot is made with data for full 24 hours of measurement

Second important characteristic is the PSD and its variation through time. From the PSD evolution (Top right) it can be seen that mean PSD is around 100 pT/√Hz and is stable in the time of an hour. Prominent peaks are visible at 50 Hz and it's multiples which are main contributors to noise.

Most important data product of the GNOME collaboration are the exclusion plots. GNOME collaboration processes the data by various means (excess power detection, matched filter techniques, machine learning etc. [6]) while searching for characteristic signals that could be signature of domain wall crossing. If no events are found, and considering Poasonian statistics of detection exclusion plots in terms of observable quantities (magnetic field sensitivity and signal duration) can be made (Bottom left) or in terms of axion field parameters (interaction strength, symmetry breaking scale and axion mas) can be made (Bottom middle and right). These exclusion plots are still above those determined by astronomical observations ones but is expected that in science run 5 (starting 23. August 2021) they are to be surpassed.

$$f_{int} \leq f_{exp} = \frac{\sqrt{\rho_{DW}Lm_a}}{\Delta B_p} \approx \frac{1}{B_p}\sqrt{\frac{2\rho_{dm}T}{\Delta t}}$$



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Conclusion

We have present the design and calibration of optically pumped magnetometer (OPM), based on a paraffin coated cesium cell, and estimate its ultimate reach in terms of mass and interaction strength of a hypothetical axionic or axion-like dark matter fields in form of a topological defects i.e. domain wals. The GNOME experiment is designed as a GPS referenced worldwide distributed network of quantum cross-correlated sensors that increases its sensitivity, discovery reach and excludes false positives by methodology similar to LIGO network that cross-corelates signals from various stations in order to triangulate source and to exclude false positives. Belgrade GNOME station is built around a double resonant magneto-optical cesium magnetometer in Mx configuration and is functioning as a scalar magnetometer in Phase Locked Loop with a sensitivity less than 100 fT/√Hz. We have here presented fundamentals of supposed interactions of axion and ALP topological defects with Standard Model fermions, give an overview of atomic magnetometry and basic theory of ODMR measurement and have quantified various noise contributions. Special attention is given to PSD, time series characteristics, stability and sensitivities and reaches of ALP search via the GNOME network.

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