Laser spectroscopy and magnetic resonance atomic magnetomerty in search for dark mater: New bounds on Axion like dark matter from GNOME network of OPM's

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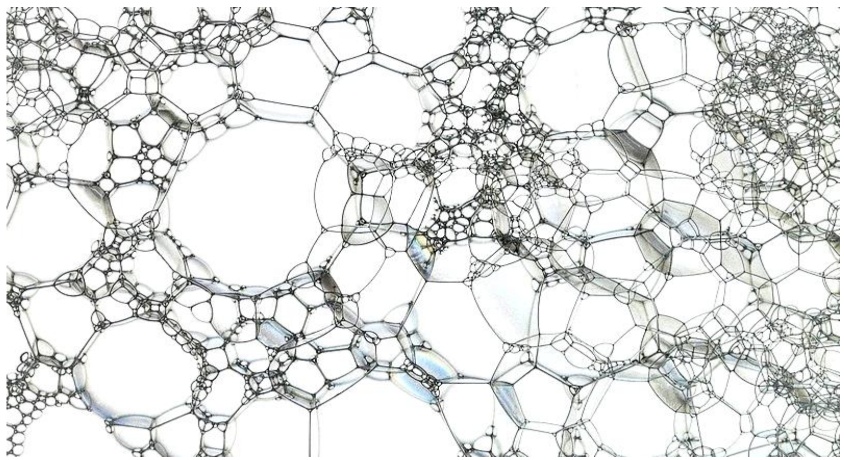
On behalf of GNOME collaboration



What this talk is all about?

GNOME: Global Network of Optical Magnetometers for Exotic physics searches

Intersection of cosmology, atomic magnetometry, distributed sensors and some smart and bold guesses.

How to use entire Earth as a kind of a telescope for exotic dark matter.

Easy accees for table-top precision physics experiments into the Big game (DM,DE, cosmology etc.).

Some newest results from latest measurement campaign.

Some sugestion on inter and trans disciplinary collaboration.

Some of unsolved problems of contemporary physics

(i) Negative results in search for WIMP-s, problems of structure formation, baritones, Dark energy vs vacuum energy, anomalous magnetic moment of muon…

(ii) Weak violation of CP symmetry => bariogenesis = matter-antimatter disbalance

(iii) MOND phenomenology on galactic scales; CDM on larger scales

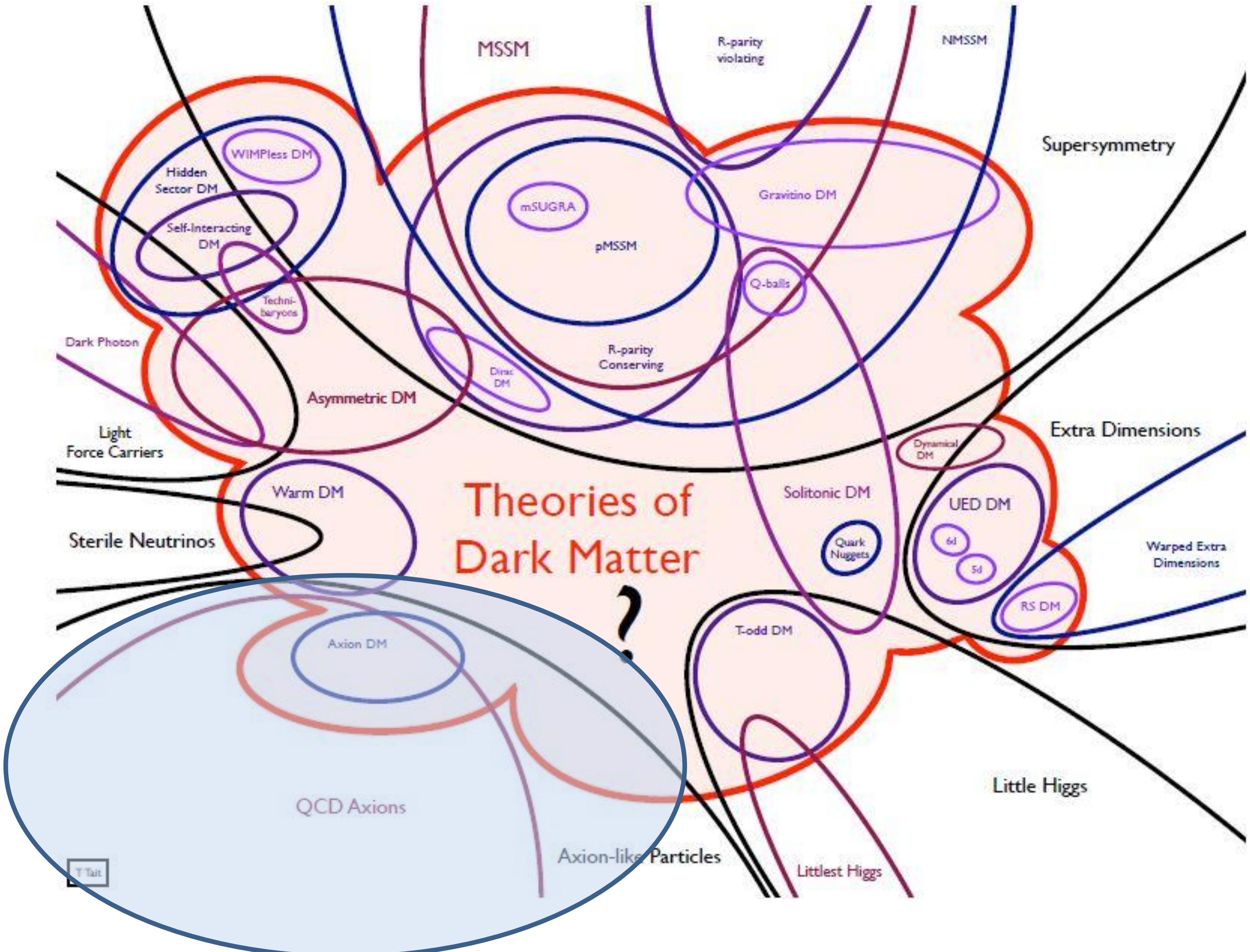
(iv) Tensions of standard Cosmological model (LambdaCDM is problematic on small scales + H0 tension)

Maybe there is one solution forr all of the above?

What do we know about DM?

- Local density of 0.4 GeV/cm^3
- Engulfs entire Universe
- Nonrelativistic (DM is dynamicaly cold)
- Boson statistics if mass of quanta is less than10 eV
- Mass of quanta is greater than 10^{-23} eV

Landscape of possible DM scenarios



Marsh, Axion cosmology, 2015

Superfluid (BEC, fuzzy, coherent, De-Broigle) dark matter!

Dark matter consists of ultra-light field whose quanta are of macroscopic De-Broigle wavelength. Quantum phase transitions become important: fluid - superfluid. Number occupancy becomes important factor for mas less than 1eV and it is crucial difference betwen boson and fermion DM.

Also It possible that ultra light scalar fields during the early evolution of universe generate is topological defects (domain walls, strings) that can under certain circumstances be long lived. It is also possible that dark ultra light DM can take the form of agglomerations such are axion stars, vortexes, stochastic backgrounds (akin to classical waves) or constant density solitons in the centre of galaxies.

What are axions?

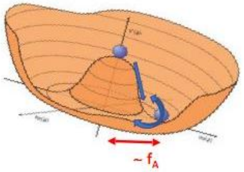
Quanta of the axionic filed which preserves U(1) symetry. More general model than QCD axion that fits in this role is ALP – axion like particle. Axions are natural consequence of QCD formalism when terms for CP violation are included.

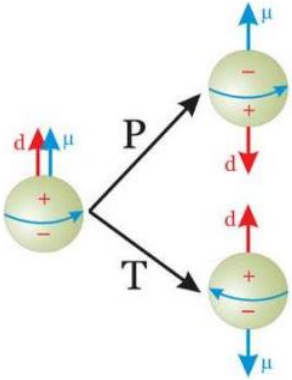
They are **pseudo-Goldstone bosons** that are created via Spontaneous Symmetry breaking.

Axions are of **small mass**, **spin 0 (hence bosons)**, of macroscopic De-Broigle wavelength and spin dependent interaction cross-section with SM fermions. Depending on details (energy of symmetry breaking scale) axions can for diluted non-relativistic gas, aglomerations, Q stars, coherent condensates and **topological defects**. .

What axion model solves:

$$m_A = 5.70(7)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$





Problem of barion asymmetry.

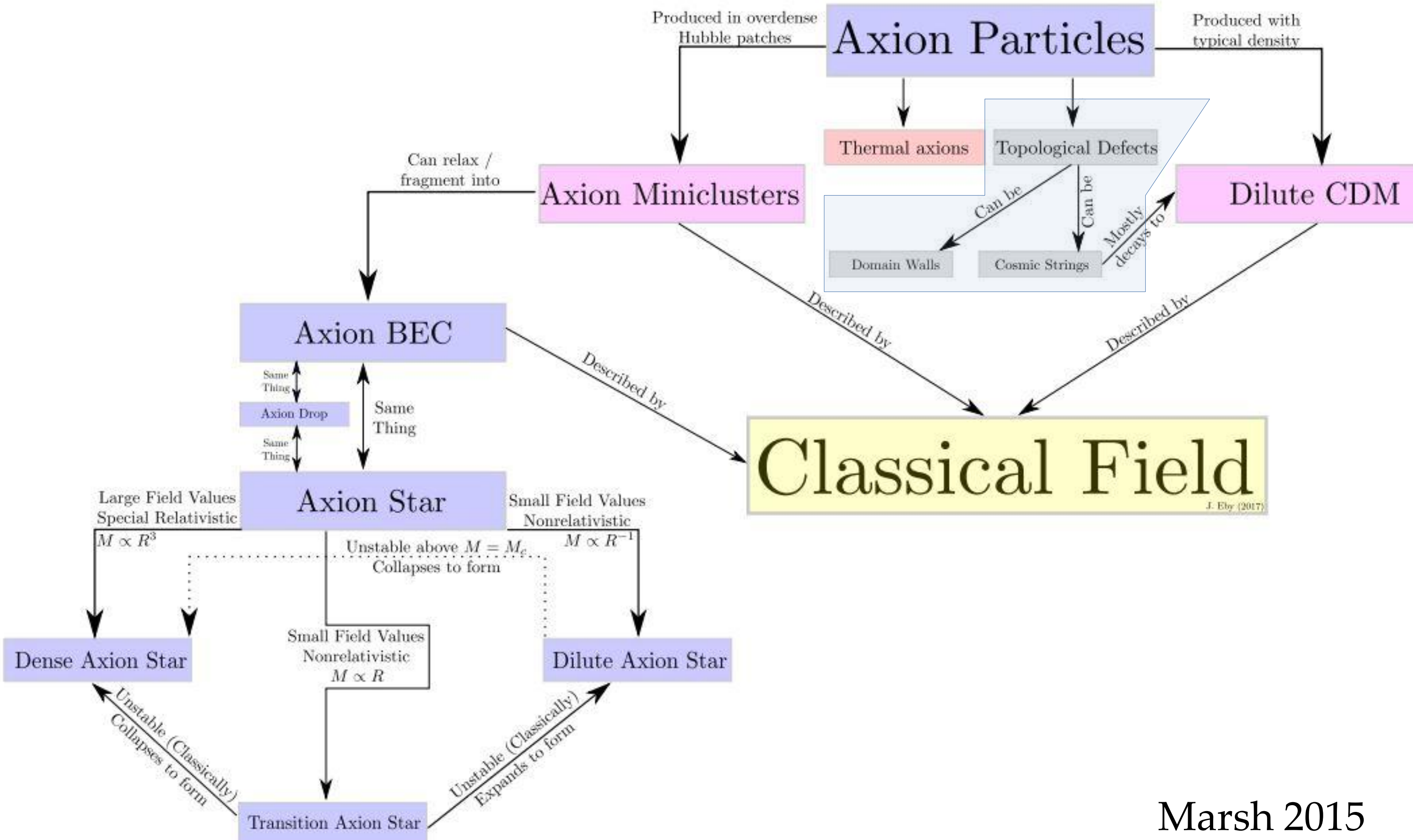
Problem of weak CP violation in QCD.

Problem of DM nature.

Weinberg, Steven (1978). *"A New Light Boson?". Physical Review Letters.* ***40*** *(4): 223–226.*

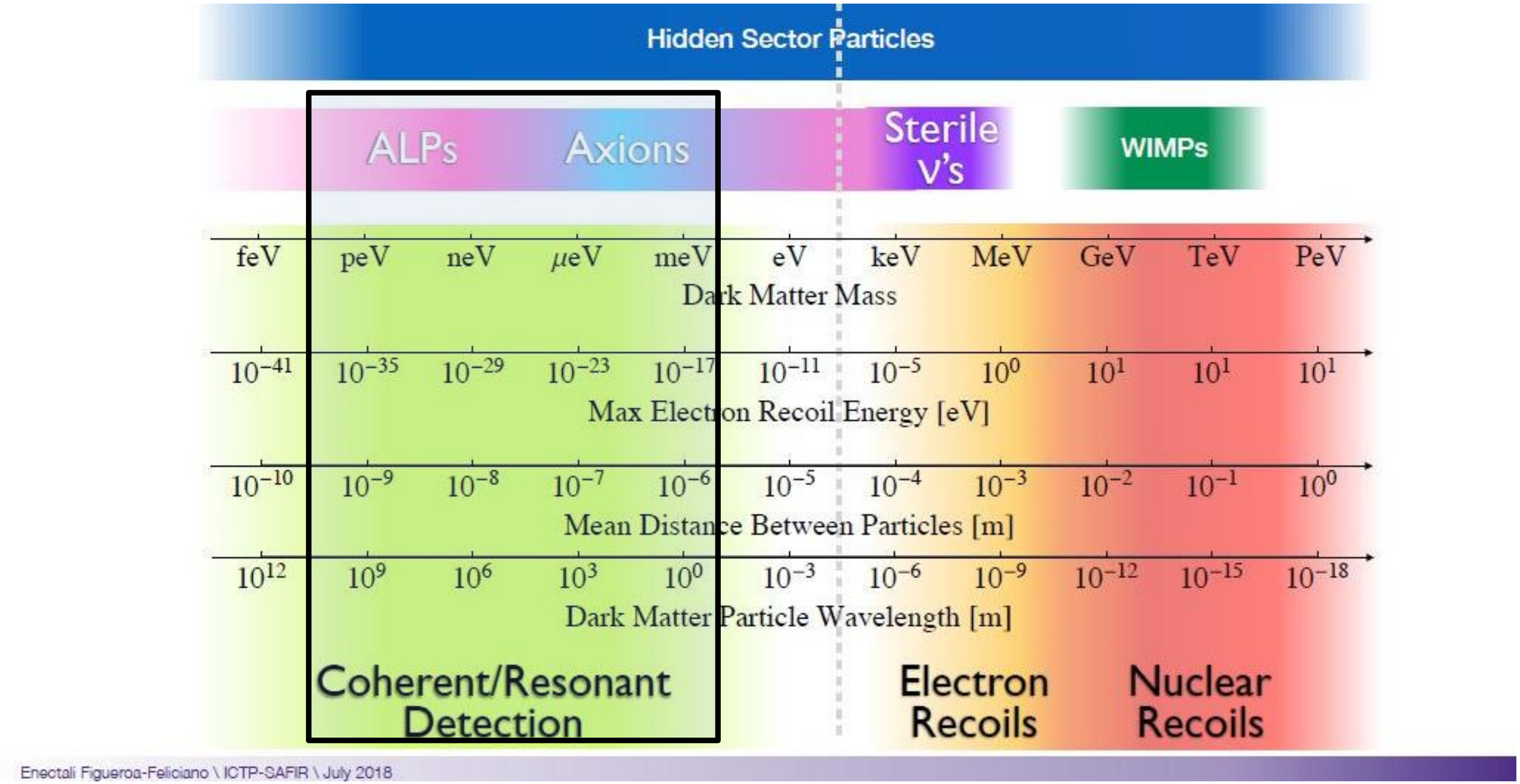
Wilczek, Frank (1978). *"Problem of Strong P and T Invariance in the Presence of Instantons". Physical Review Letters.* ***40*** *(5): 279–282*

Phenomenology of axion fields



Marsh 2015

Parametrization of DM and methods of detection

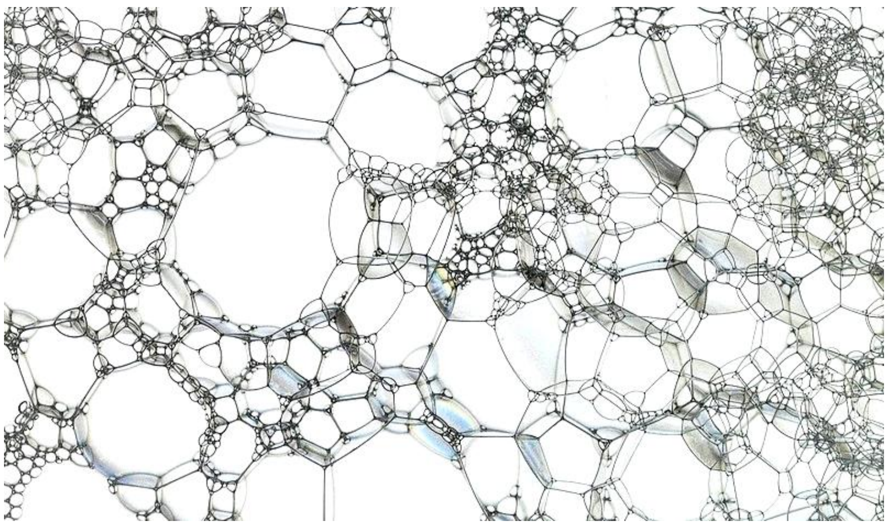


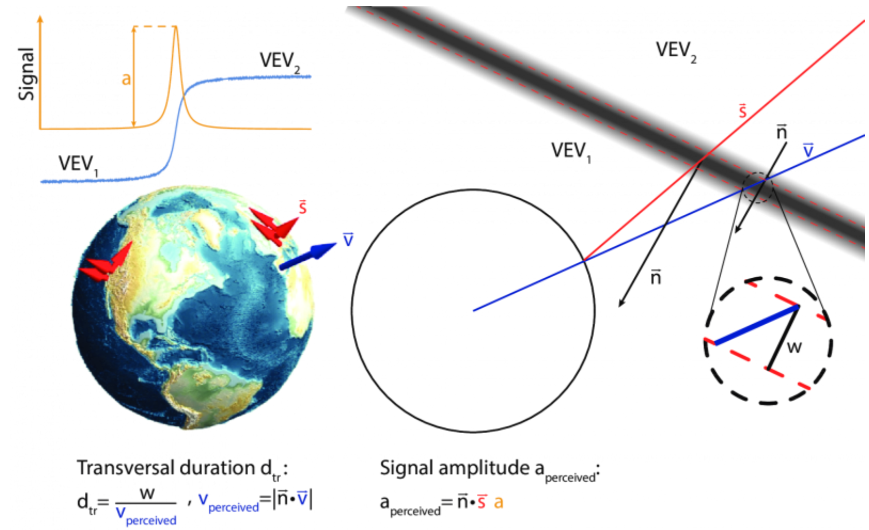
Interaction of SM fermions with axion or ALP topological defects

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

$$\Downarrow$$

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

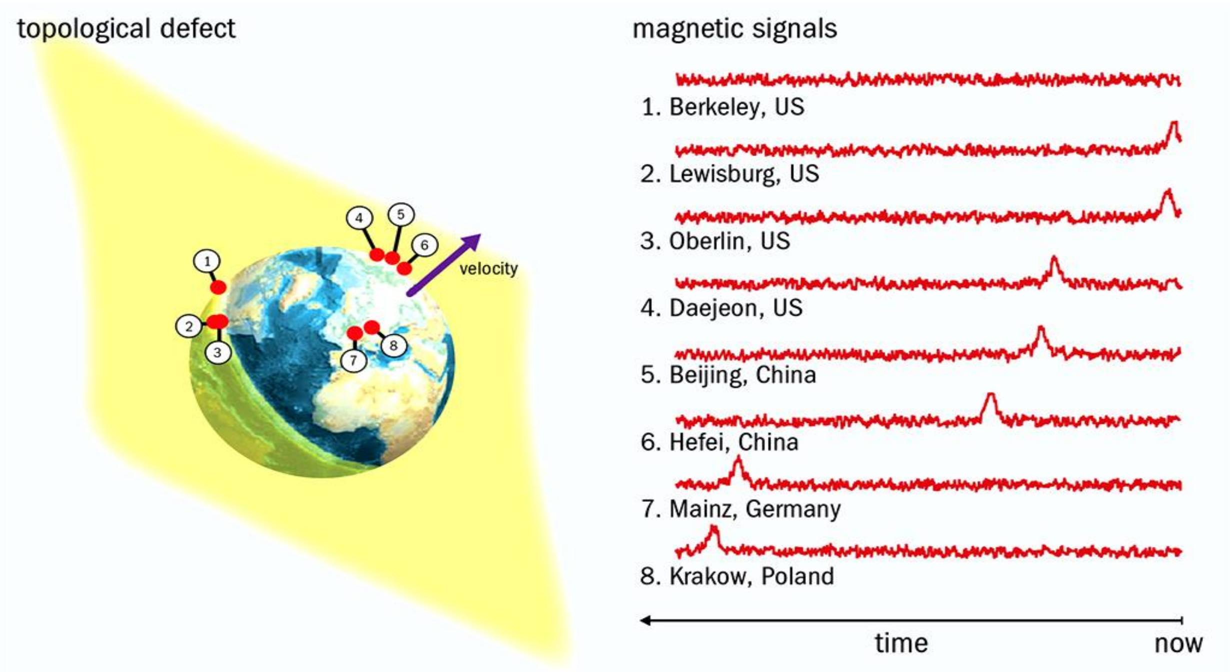




$$a(x) = 2f_{SB}\arcsin\left(\tanh\left(m_a x\right)\right)$$

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

Network of optical sensors (OPM's)



Data procesing: Matched filters (a la LIGO), excess power, machine learning etc.

https://budker.uni-mainz.de/gnome/

Pustelny, 2013

Phenomenological parameters of axion domain walls

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

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

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

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

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

$$||$$

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

$$\Downarrow$$

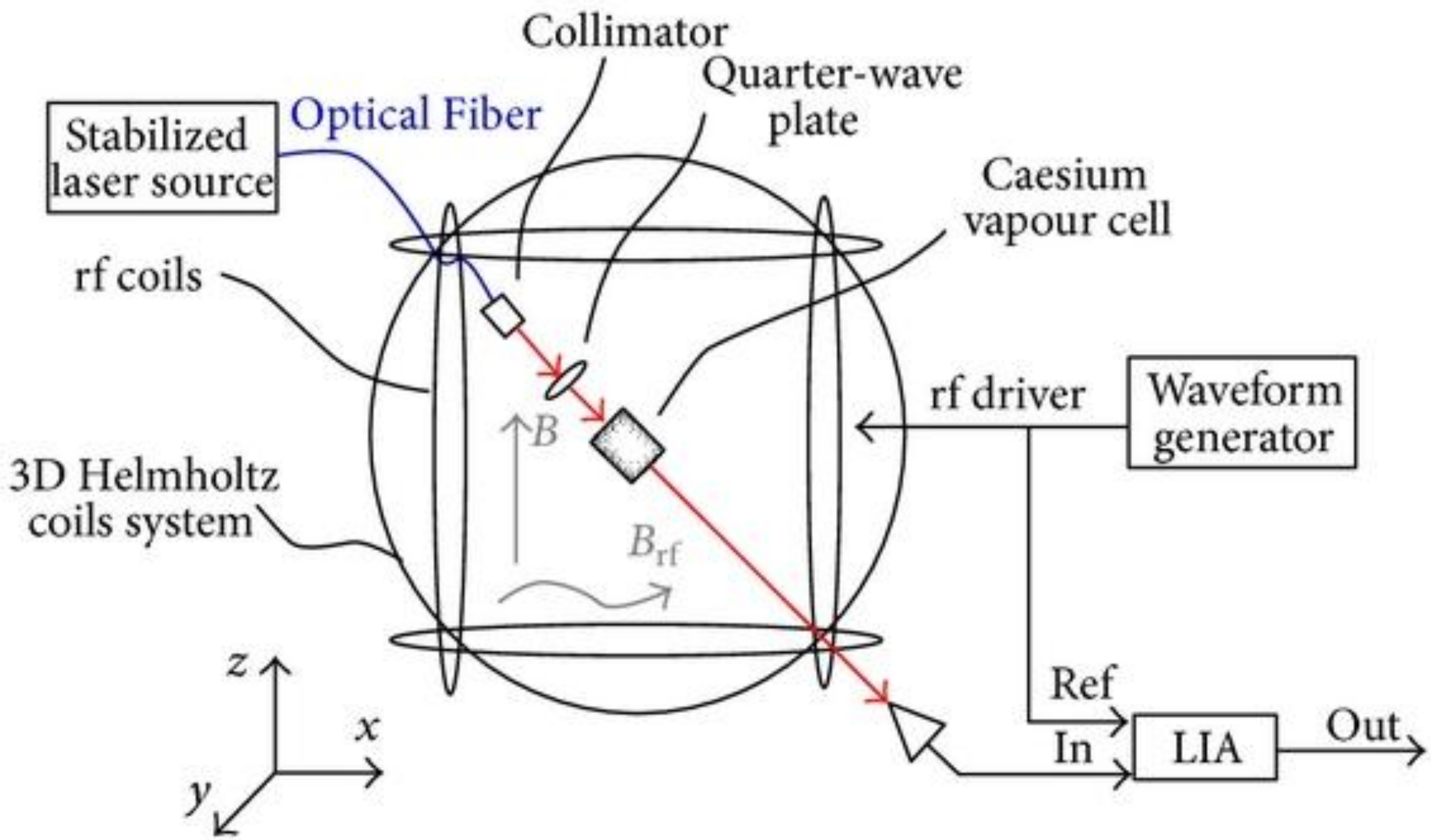
$$\vec{B} \approx 2\frac{\xi}{f_{SB}\gamma} \cdot \nabla a(r,t)$$

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

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

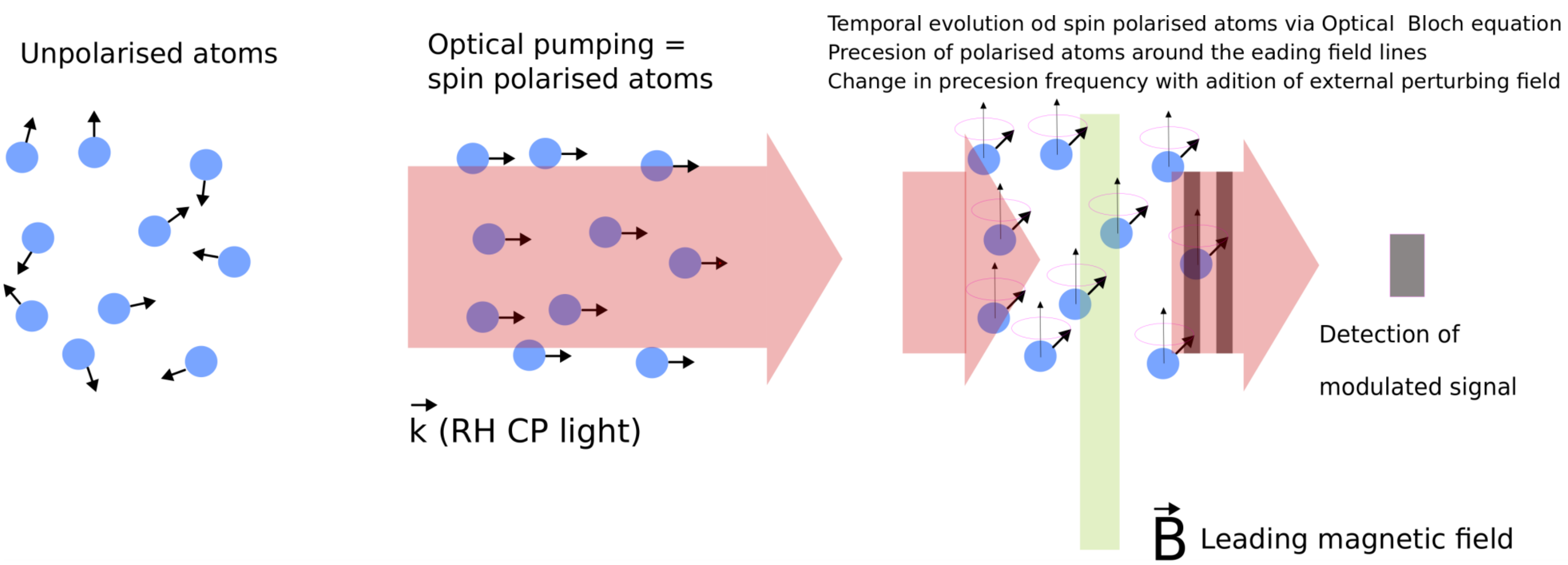
Pospelov et. al., Phys. Rev. Lett., 110, 2, 021803, 2013

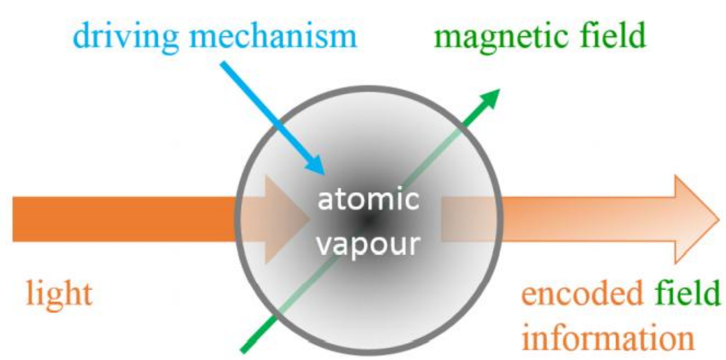
General scheme of magnetometer



Bison 2014

Detection with double resonance - optical + rf Zeeman transitiions





Optical Bloch equations with damping term

$$\frac{\partial \vec{S'}}{\partial t} = \vec{\omega}_{\mathrm{eff}} \times \vec{S'} - \Gamma(\vec{S'} - \vec{S'}_{eq});$$

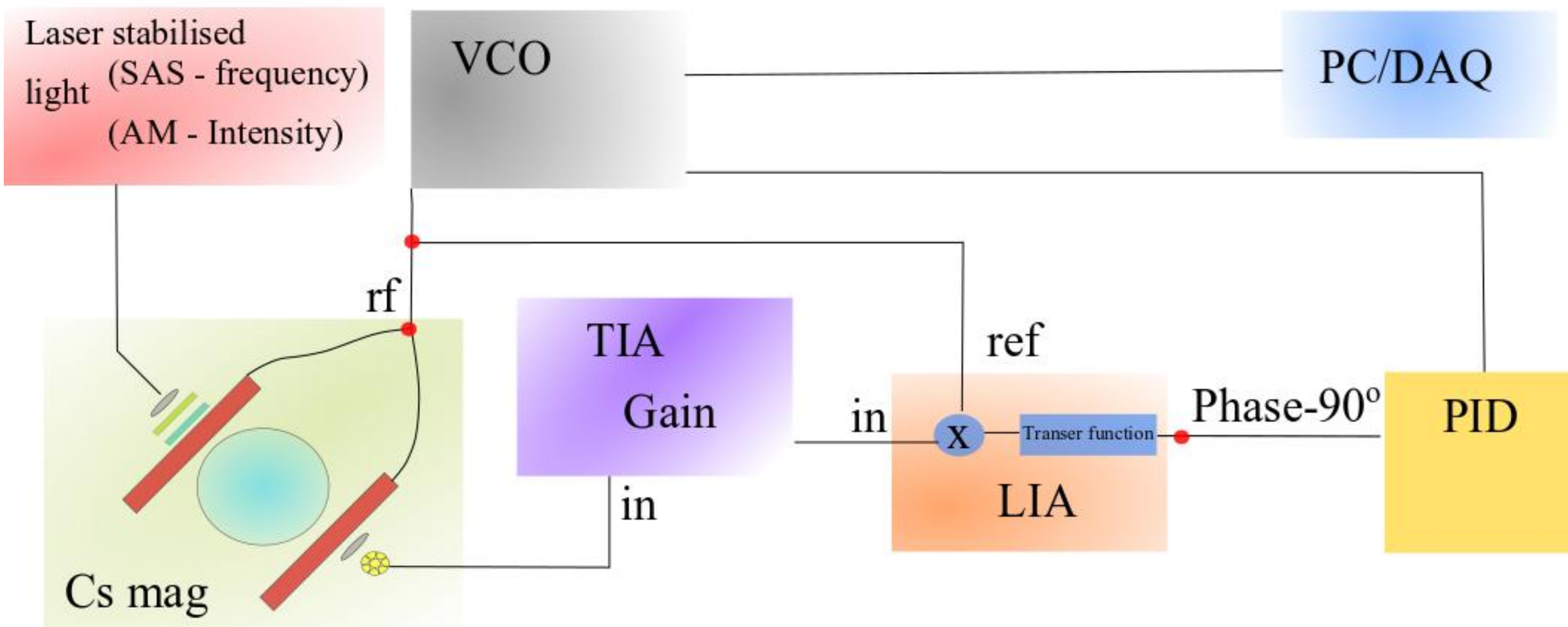
Tipes of magetometers in GNOME network

Sensitivity

$$\delta B = \frac{\hbar}{g\mu_B}\sqrt{\frac{1}{N_{at}T_2\tau}}$$

Name	Element(s)/ Compound(s)	δB_f $[\mathrm{fT}/\sqrt{\mathrm{Hz}}]$	δB_d $[\mathrm{fT}/\sqrt{\mathrm{Hz}}]$	δE_f $[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}]$	δE_d $[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}]$	T_2 [ms]	Spin coupling
SERF	^{3}He	0.002	0.75	3×10^{-5}	0.01	10	Nuclear
μ-SERF	Rb	1	30	1.9	58	10	Total
NMR-SERF hybrid	pentane-HFB	0.23	3200	0.004	55	10000	Nuclear
NMOR	Rb	0.16	0.3^a	0.31	0.58	300	Total
AM NMOR	Rb	3.2	39	9	110^a	25	Total
M_x	Cs	5	9	7	13	200	Total
μ-M_x	Cs	20	42	29	61	0.06	Total
Helium	He	5	50	54	540	10000	Electron
Hg EDM	Hg	6×10^{-4b}	320	2×10^{-6}	1	100000	Nuclear

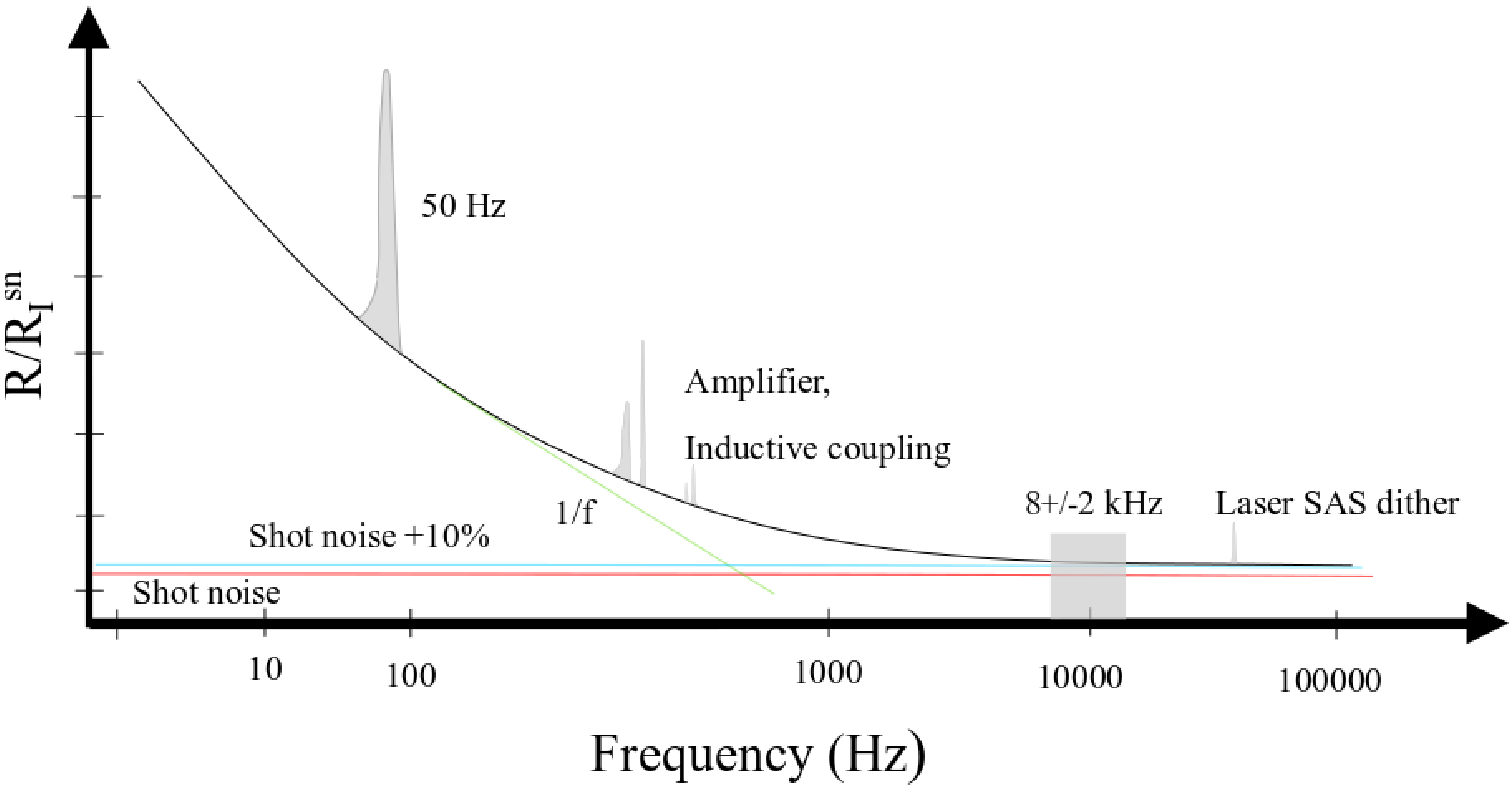
OPM in PLL



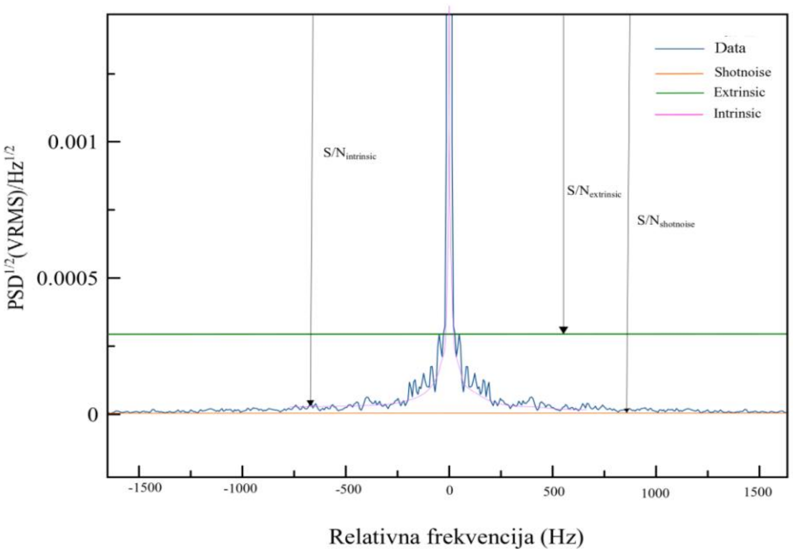
Laser stabilised
light
(SAS - frequency)
(AM - Intensity)
VCO
PC/DAQ
rf
TIA
Gain
in
ref
in
x
Transer function
Phase-90^o
PID
LIA
Cs mag

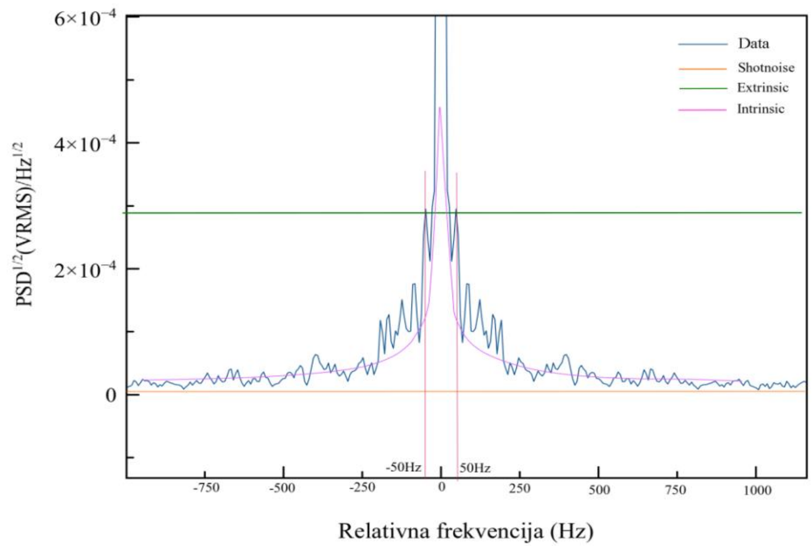
Noises in OPM

Noises: Internal, external, fundamental



SNR and noise decomposition





$$\Delta B = \sqrt{\Delta B_{int}^2 + \Delta B_{ext}^2} = \sqrt{\Delta B_{sn}^2 + \Delta B_{technical}^2 + \Delta B_{ext}^2}$$

$$\Delta B_{int} = \frac{1}{\gamma} \frac{\Delta \nu}{A/\rho}$$

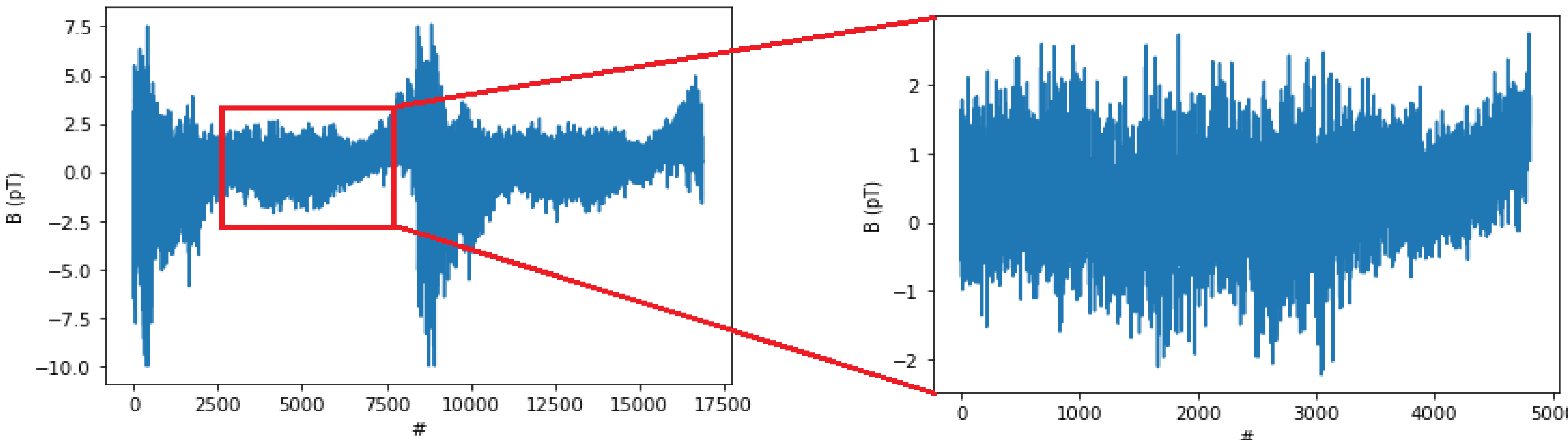
$$\Delta B = \frac{1}{\gamma} \frac{\Delta \nu}{A/\sqrt{\rho_{int}^2 + \rho_{ext}^2}} = \frac{1}{\gamma} \frac{\Delta \nu}{A/\sqrt{\rho_{sn}^2 + \rho_{technical}^2 + \rho_{ext}^2}}$$

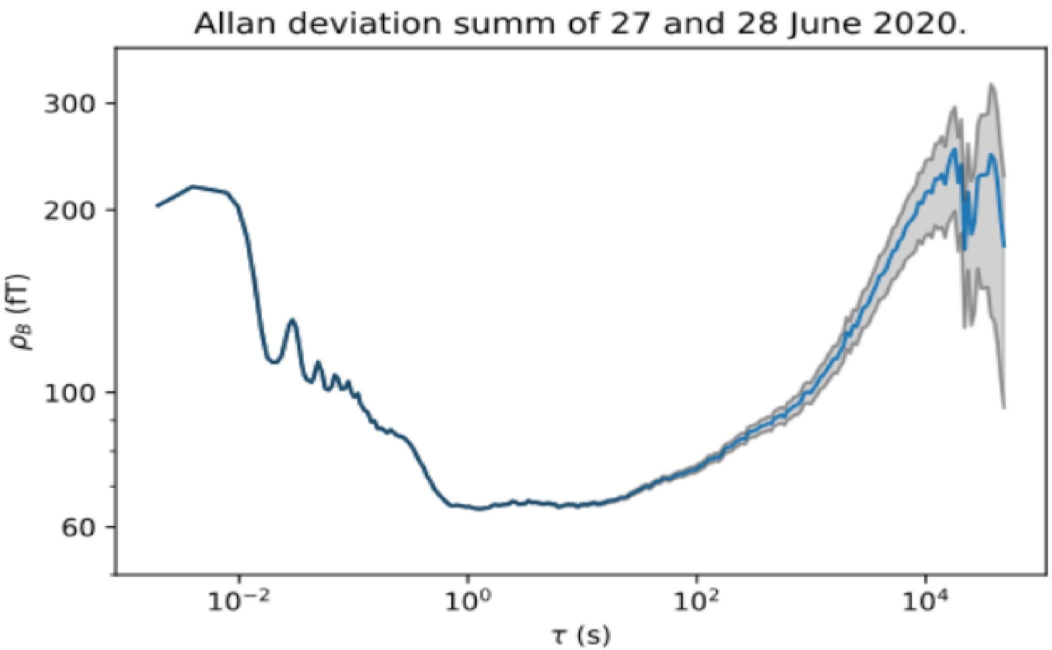
$$\Delta B_{SN} = \frac{2\nu}{\epsilon\gamma}\sqrt{\frac{q}{I_0}}$$

Anthropogenic, Schuman resonances, 50 Hz AC, CME and GeoMagTransients, Variations in pressure temp and humididy

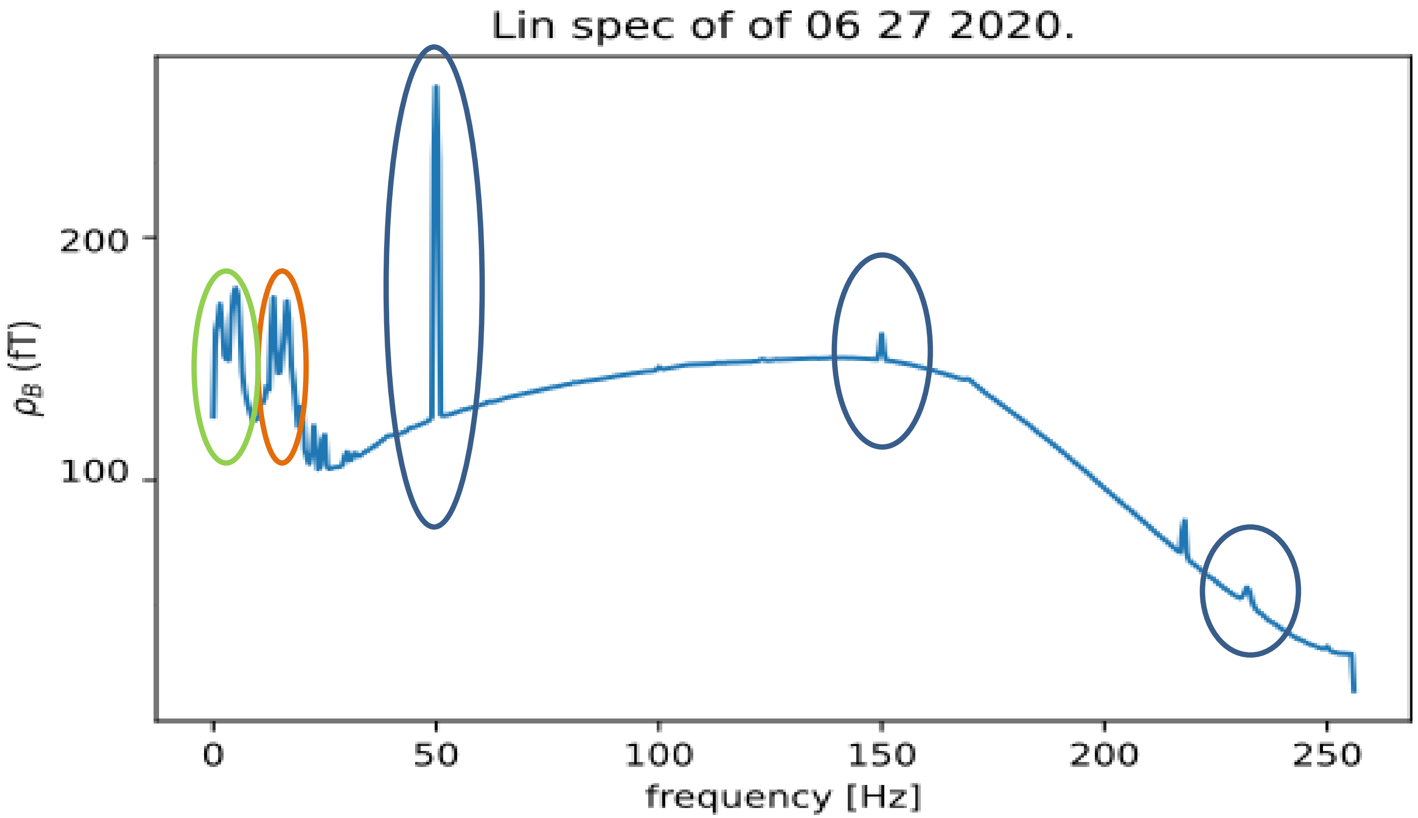
$$\rho_{Int}^2 = \rho_{SP}^2 + \rho_{SN}^2 + \rho_{Darkcurrent}^2 + \rho_{Johnson}^2 + \rho_{B,CSN}^2 + \rho_{\phi PLL}^2$$

Timeseries and Allan standard deviation



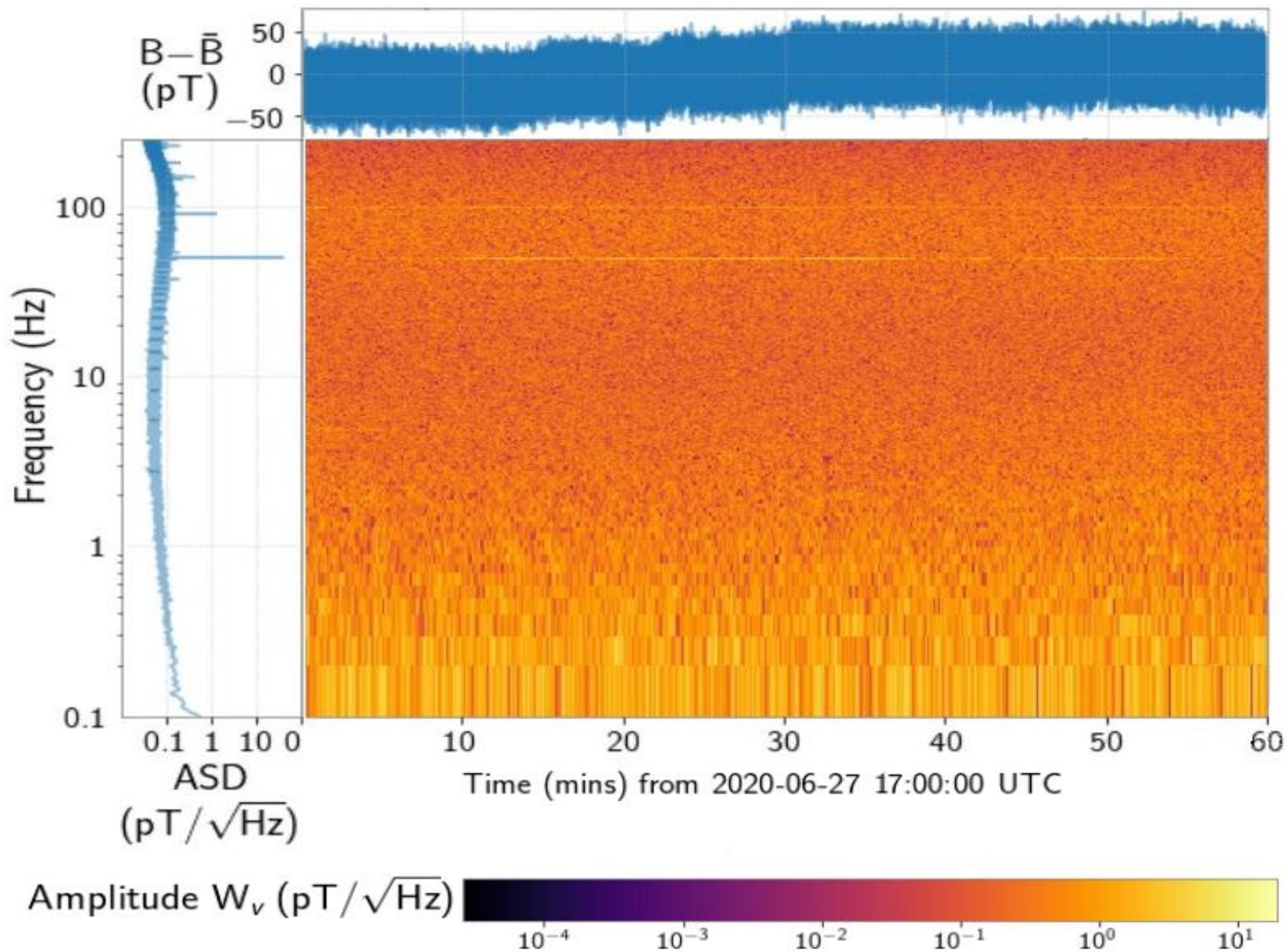


PSD



Lin spec of of 06 27 2020.
200
100
ρ_B (fT)
0
50
100
150
200
250
frequency [Hz]

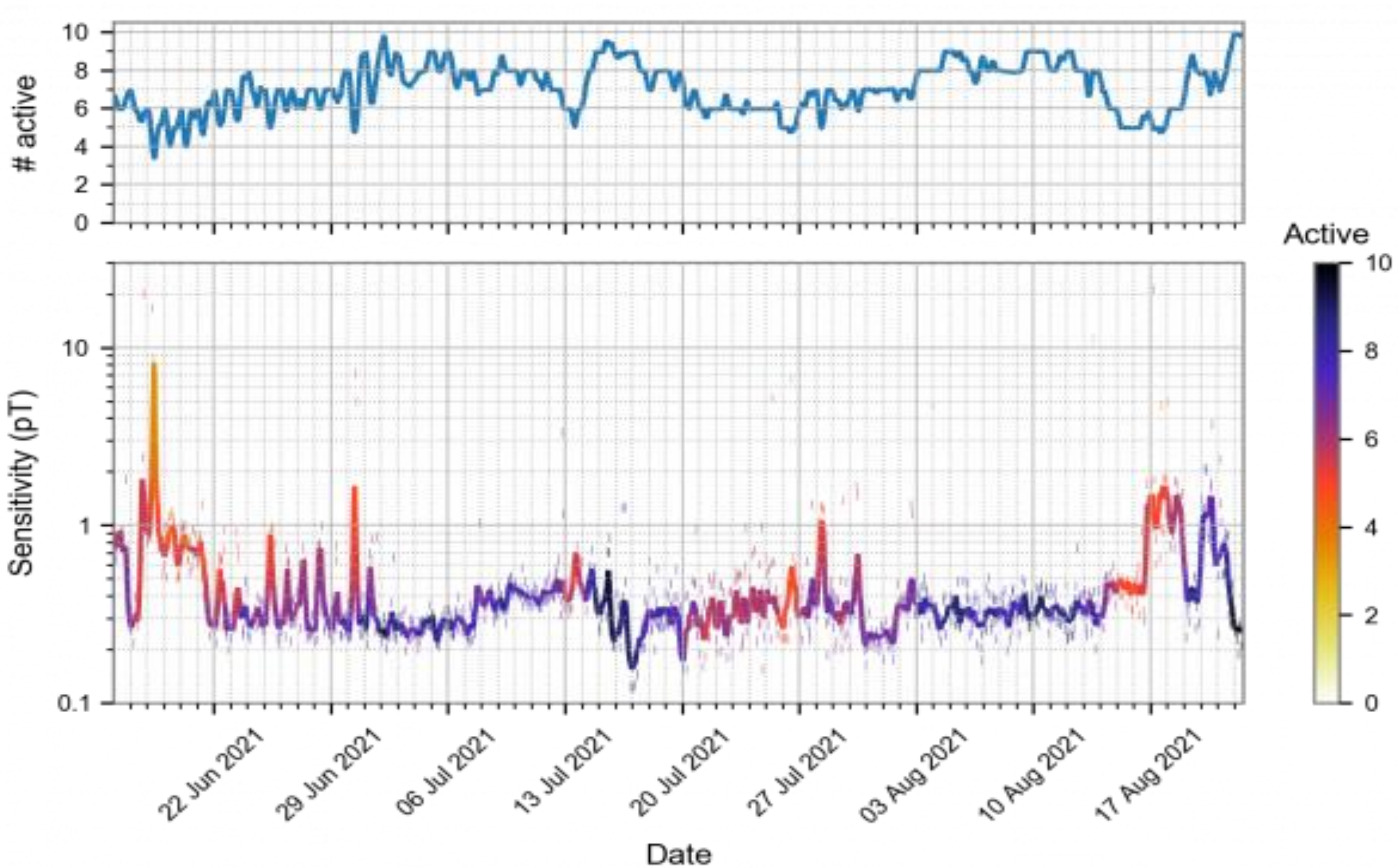
Typical timeseries and evolution of its PSD



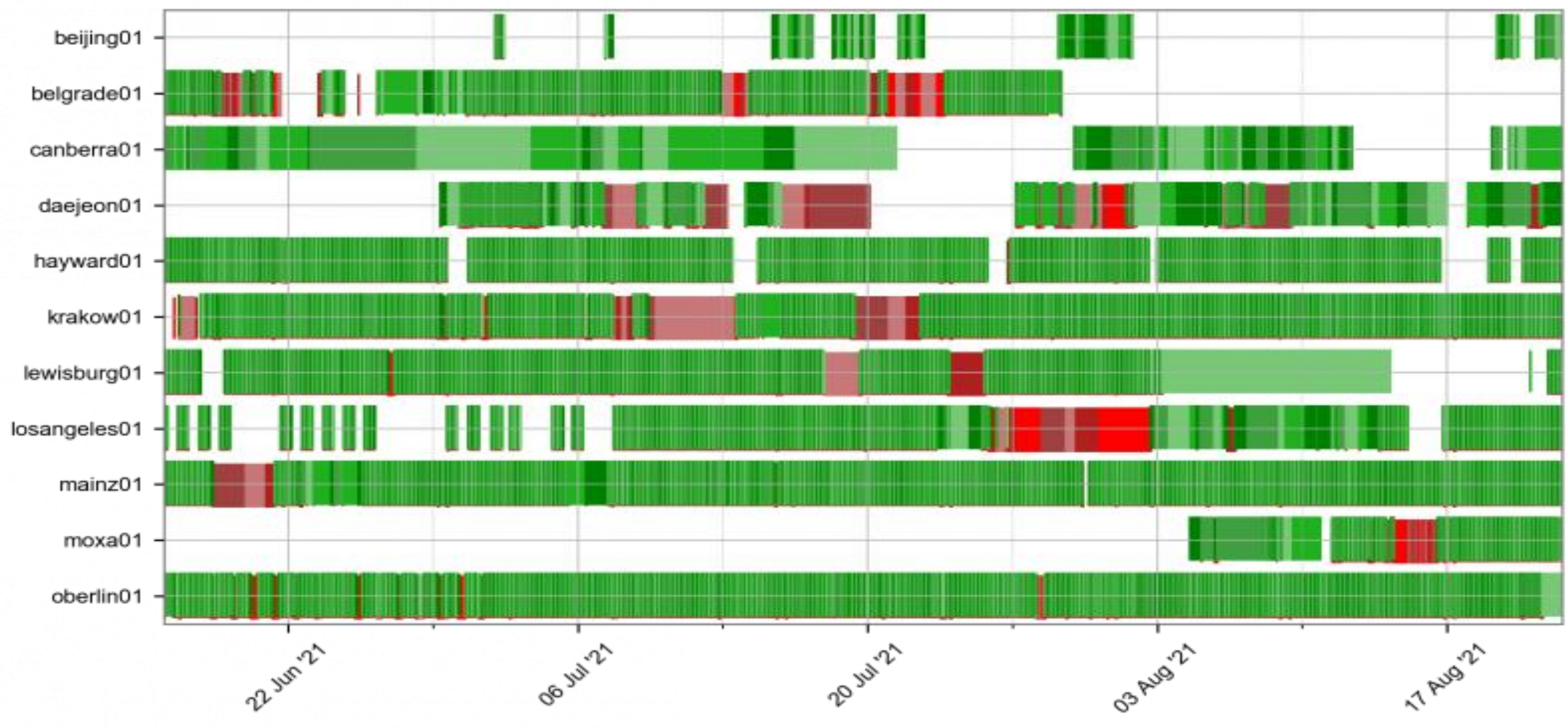
Stations active during sci Run 5

Station	Longitude	Latitude	Elevation	Az	Alt	Sensor Type	Probed system	Probed transition
Beijing	116.1868° E	40.2457° N	107.46 m	251°	0°	NMOR	^{133}Cs	D2 F=4
Berkeley 2	122.2570° W	37.8723° N	99.31 m		90°	SERF (Quspin)	^{87}Rb	D1 F=2
Canberra	149.1185° E	35.2745° S	593.42 m		90°	SERF	^{87}Rb	D1
Daejeon	127.3987° E	36.3909° N	71.14 m		90°	NMOR	^{133}Cs	D2 F=4
Hayward	122.0539° W	37.6564° N	155.20 m		+90°	SERF (Quspin)	^{87}Rb	D1
Krakow	19.9048° E	50.0289° N	263.55 m		90°	SERF (Quspin)	^{87}Rb	D1 F=2
Lewisburg	76.8825° W	40.9557° N	126.94 m		90°	SERF	^{87}Rb	D2
Los Angeles	118.4407° W	34.0705° N	149.68 m	270°	0°	rf-driven	^{85}Rb	D2 F=2
Mainz	8.2354° E	49.9915° N	193.02 m		-90°	SERF (Quspin)	^{87}Rb	D1 F=2
Moxa	11.6147° E	50.6450° N	528.62 m	270°	0°	rf-driven	^{133}Cs	D1 F=4
Oberlin	82.2204° W	41.2950° N	216.63 m	300°	0°	SERF	K/Rb	D1
Belgrade01	20.3928° W	44.8546° N	120.00 m	300°	0°	rf-driven	^{133}Cs	D1 F=4

Pre run preparation – # of stations and sensitivity of GNOME network in function of # of sensors and time

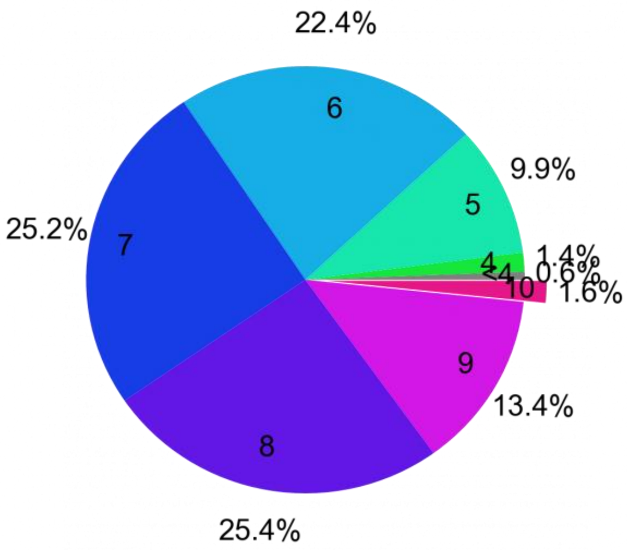


Pre run preparation – list of stations and status of delivered signals of GNOME network in function of time. Sane, flagged signals and calibration sequences



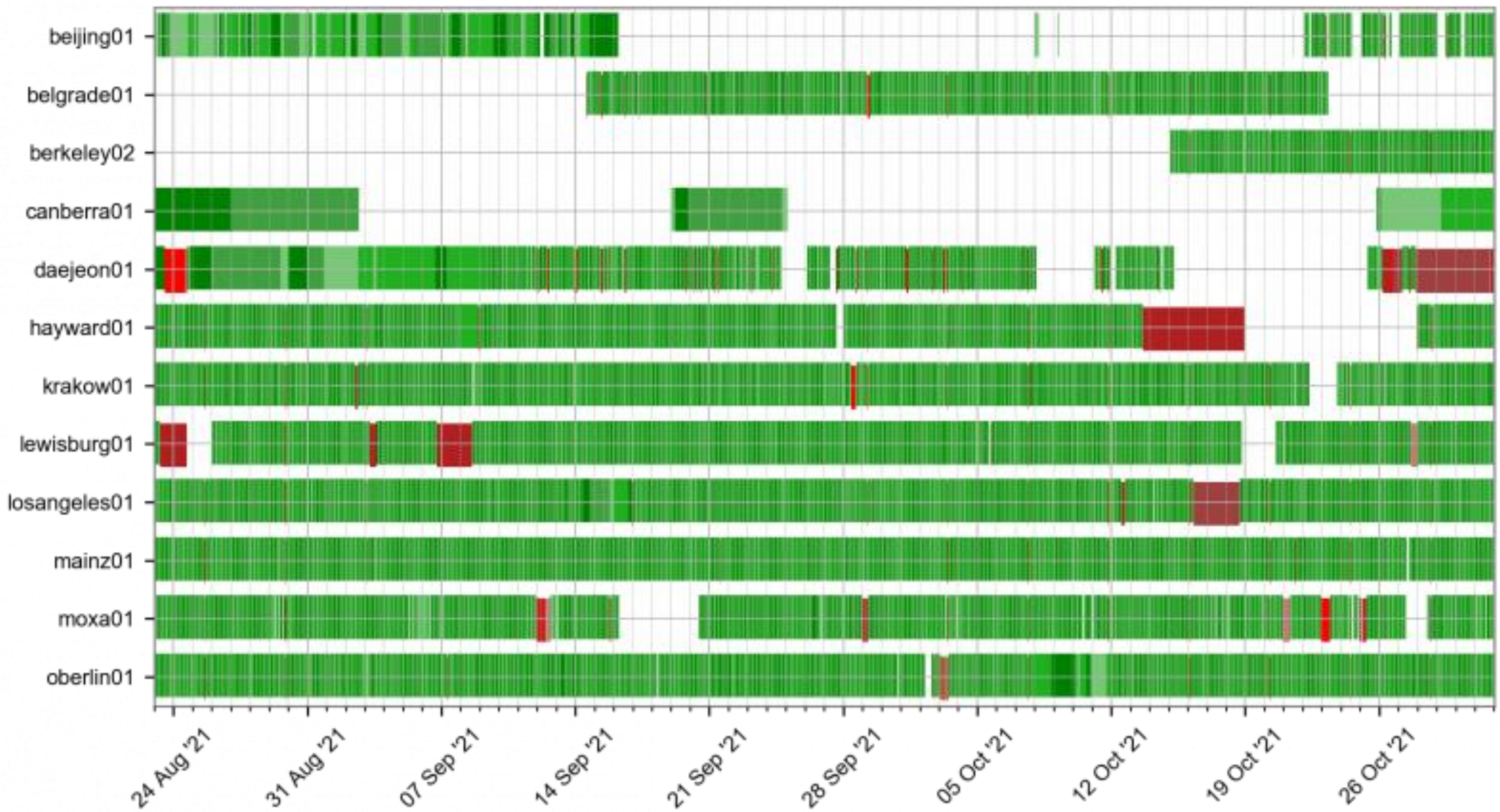
Calibration sequence and pie chart for pre run test

Frequency (Hz)	Duration (s)
1	4
10	2
35	1
55	0.6
70	0.4
80	0.2
90	0.2
110	0.2
130	0.2
160	0.1
190	0.1

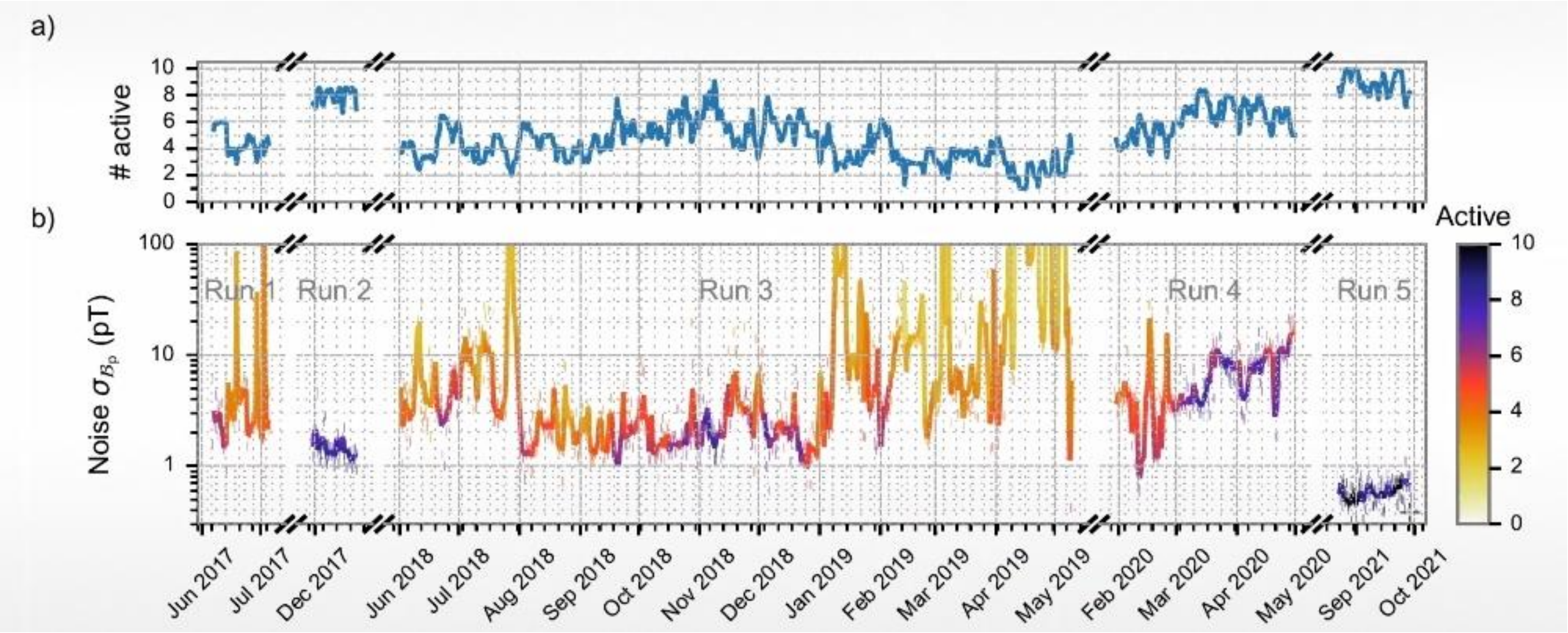


- During the pulse period, the data is flagged insane by the Sanity Box.
- Each test pulse is both preceded and followed by a 4s Ardunio signal that flags the data insane for additional 8s.
- This 17s data marked as insane can easily be eliminated from the exotic physics searches.

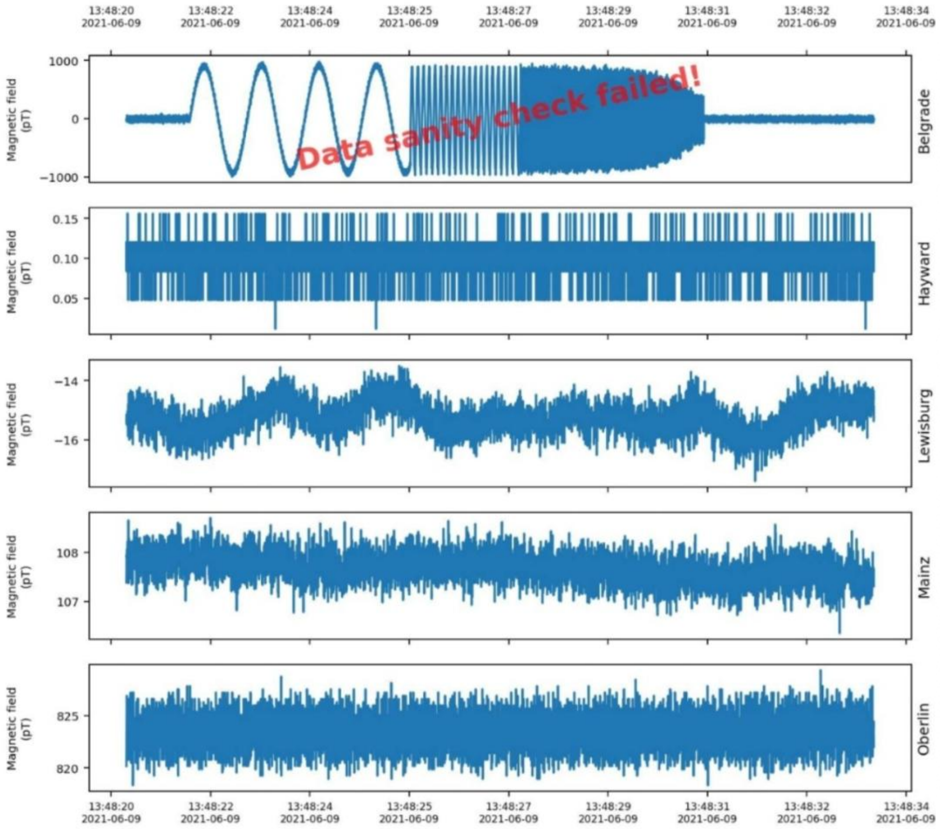
Status of data during sci Run 5

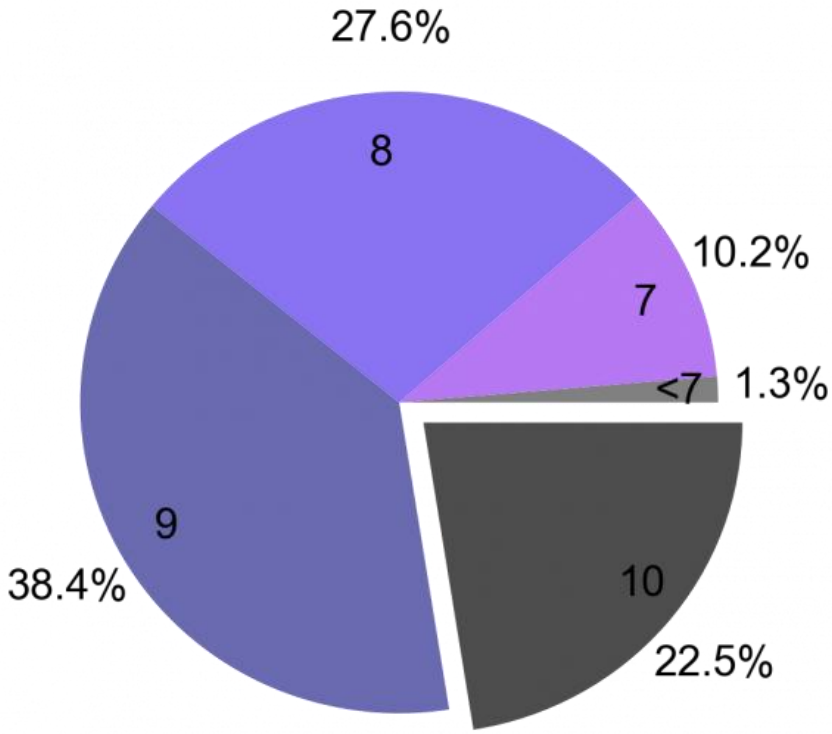


of active station and sensitivity in mag field accros all the sci Runs

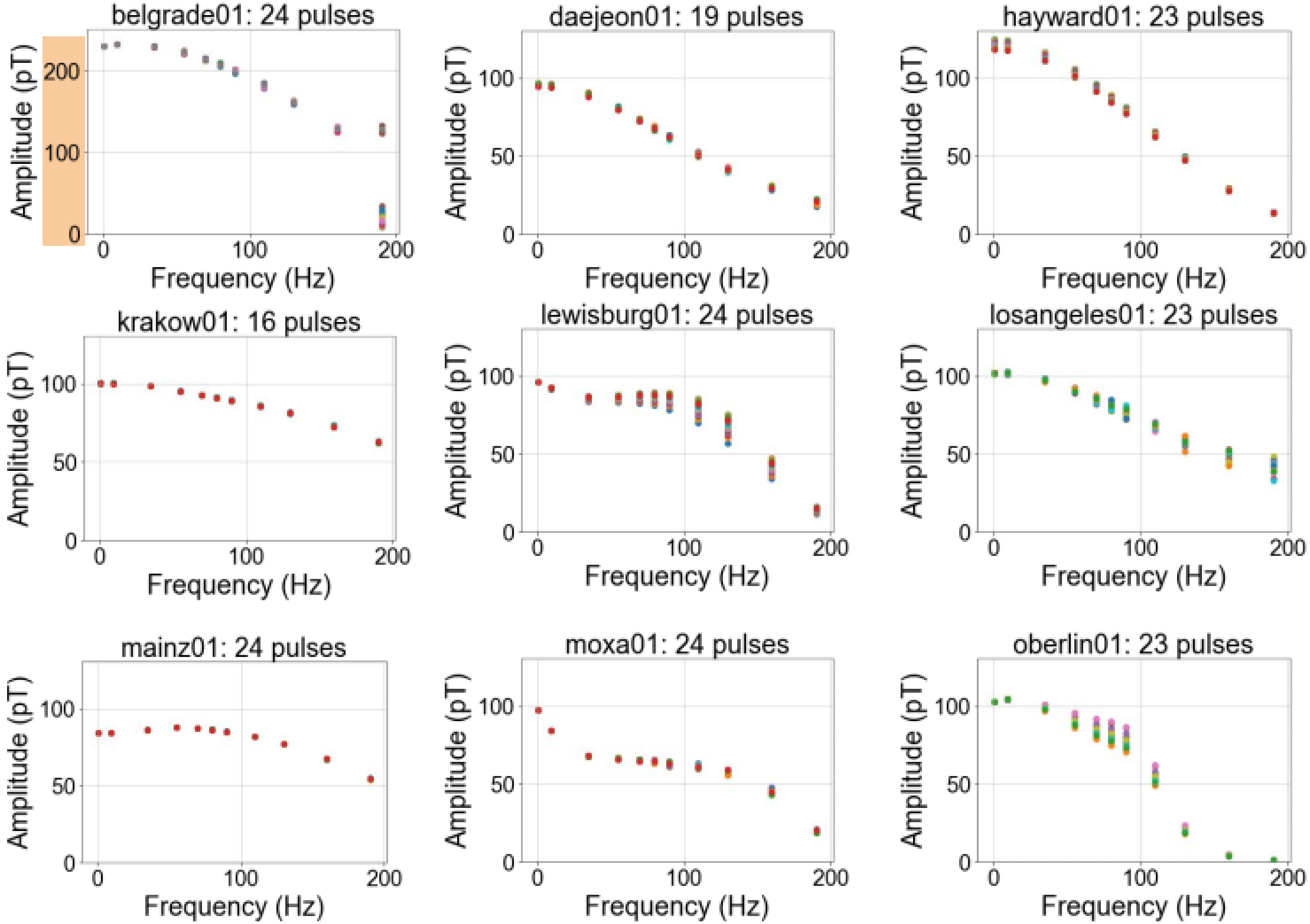


Calibration sequence and pie chart for sci Run 5



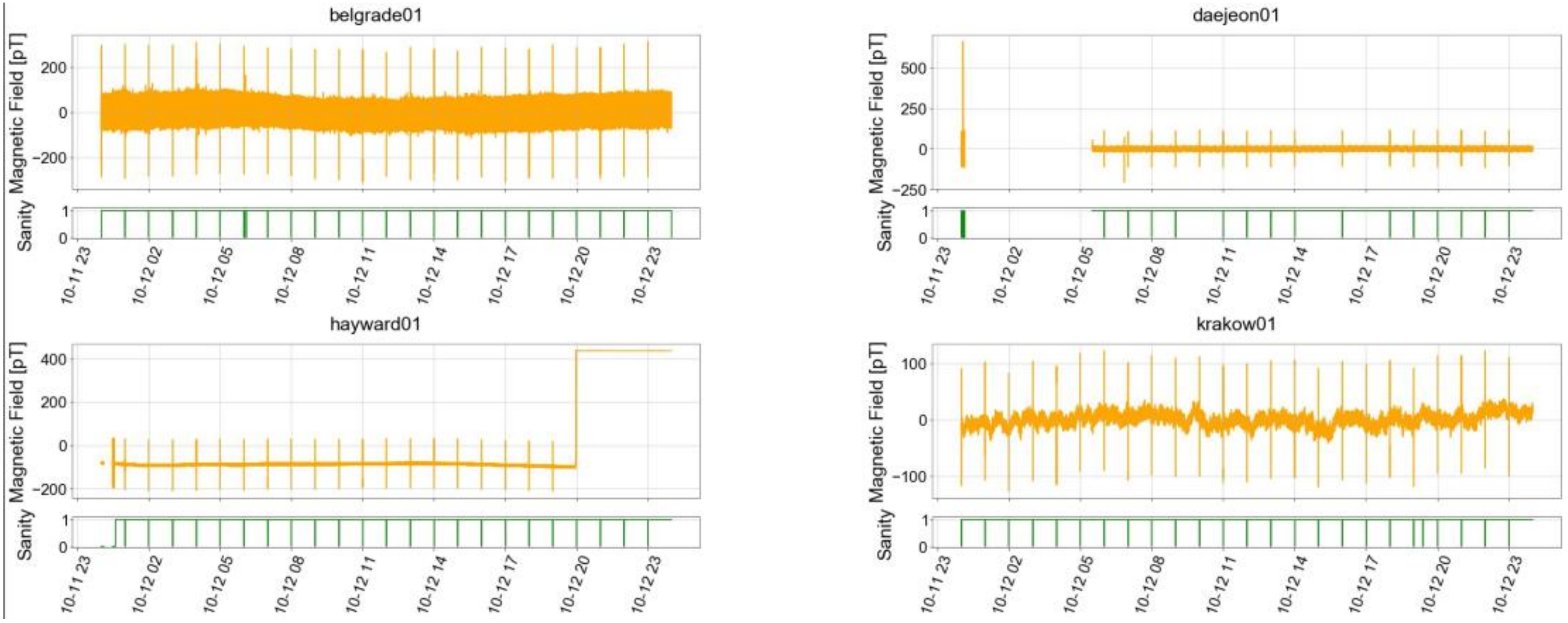


Bandwidth



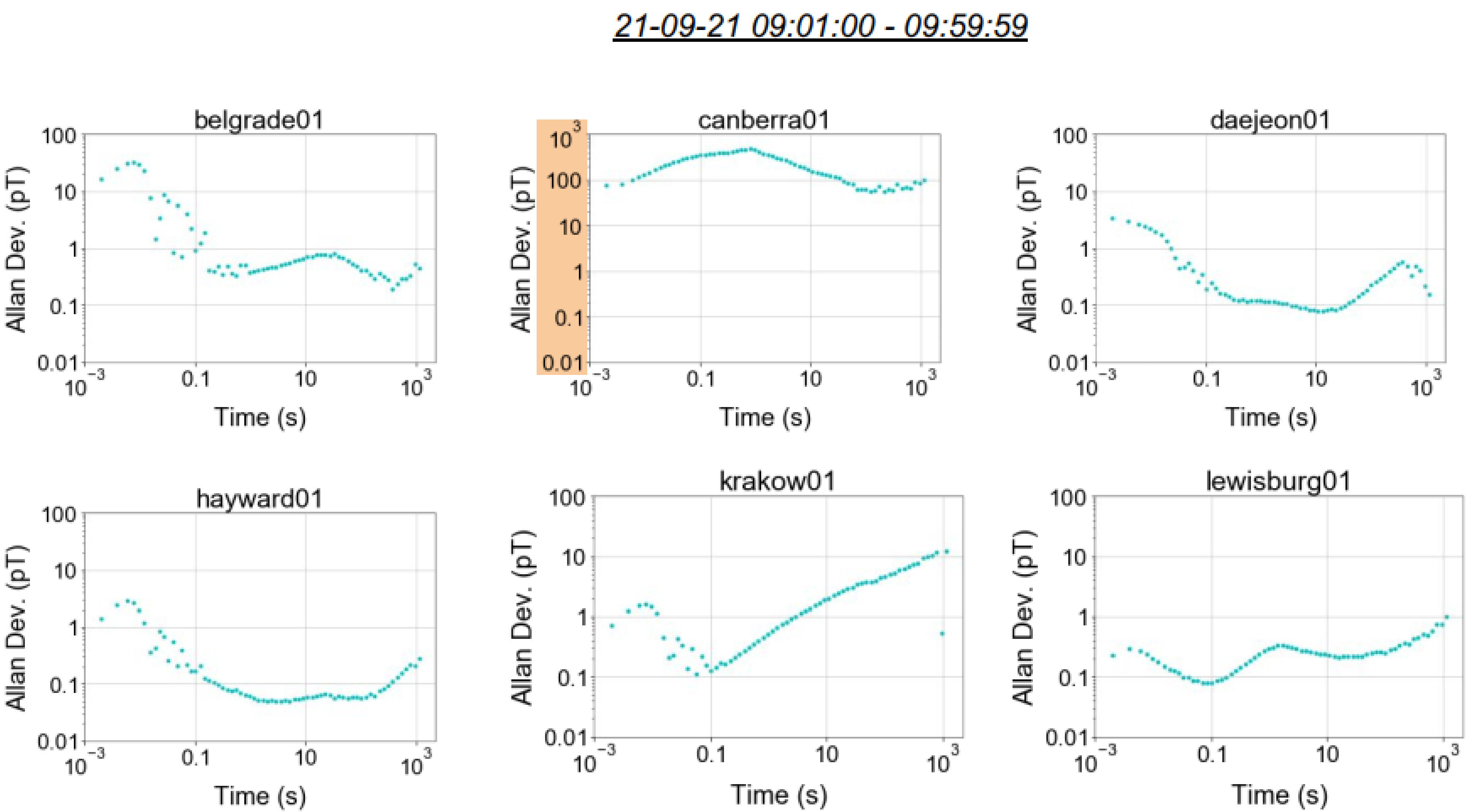
Date: 2021-09-28

Timeseries



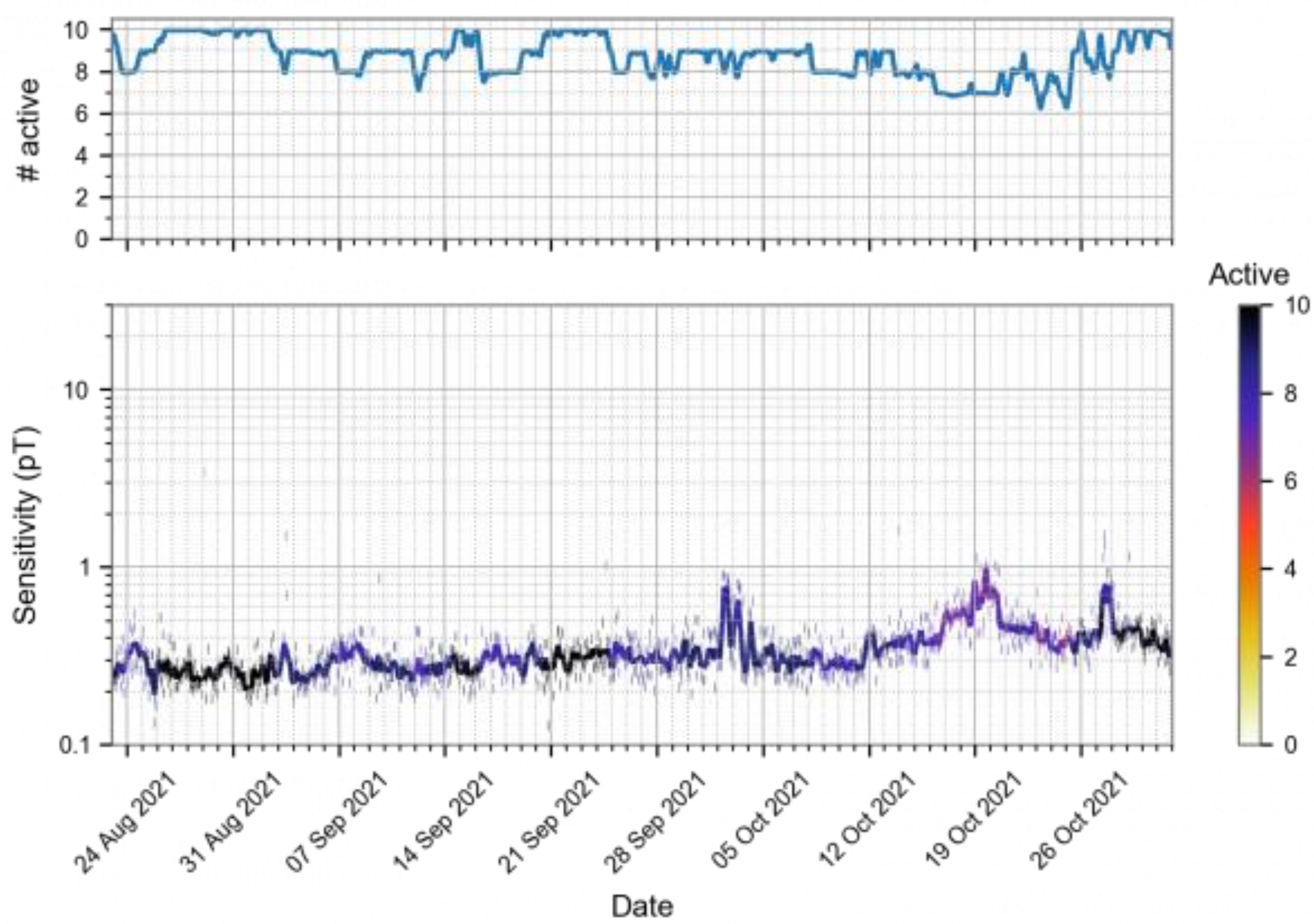
belgrade01
daejeon01
hayward01
krakow01
Magnetic Field [pT]
Sanity
10-11 23
10-12 02
10-12 05
10-12 08
10-12 11
10-12 14
10-12 17
10-12 20
10-12 23

Allen plots

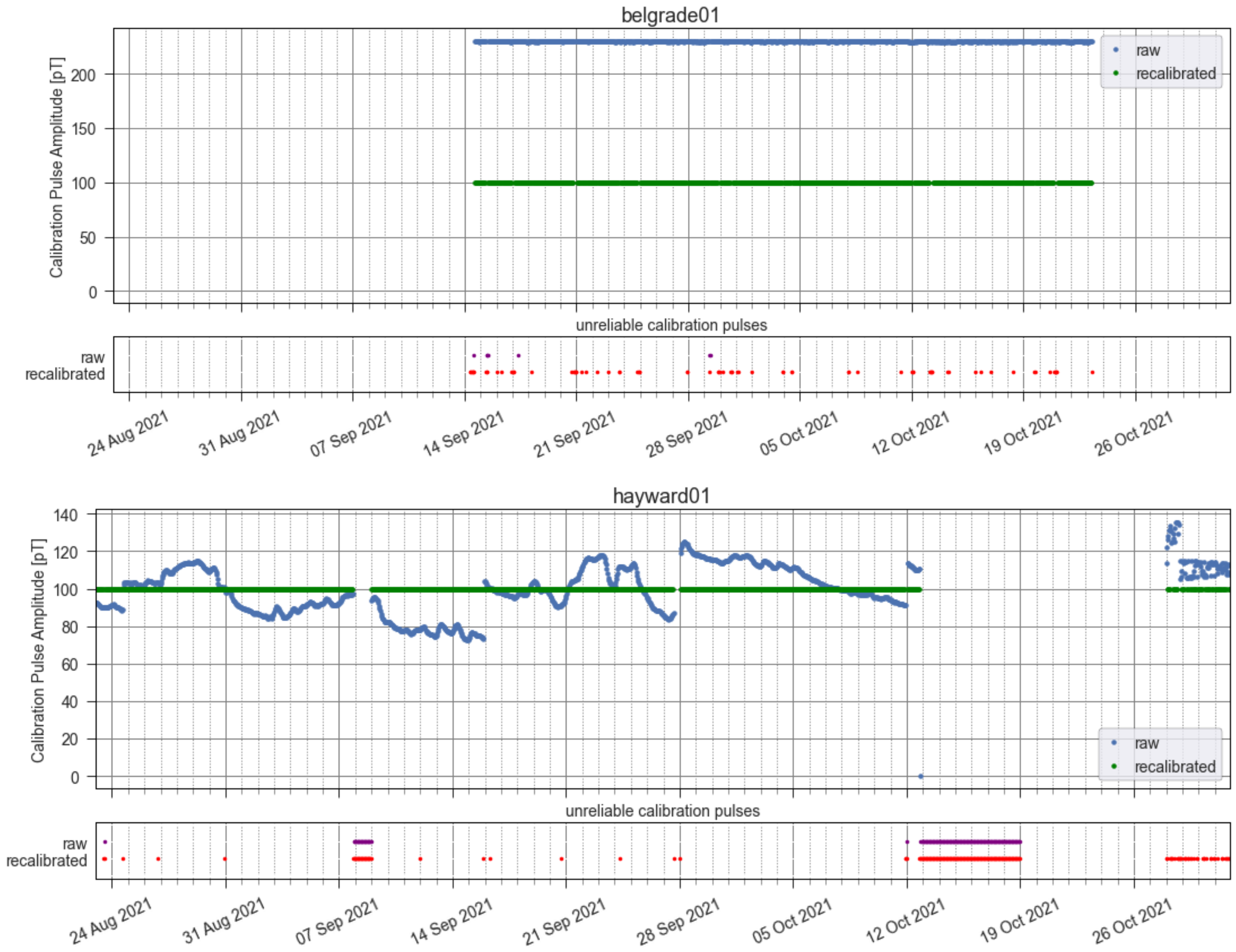


ASSPECTRO 2022 A&M, 2022 Fruška Gora

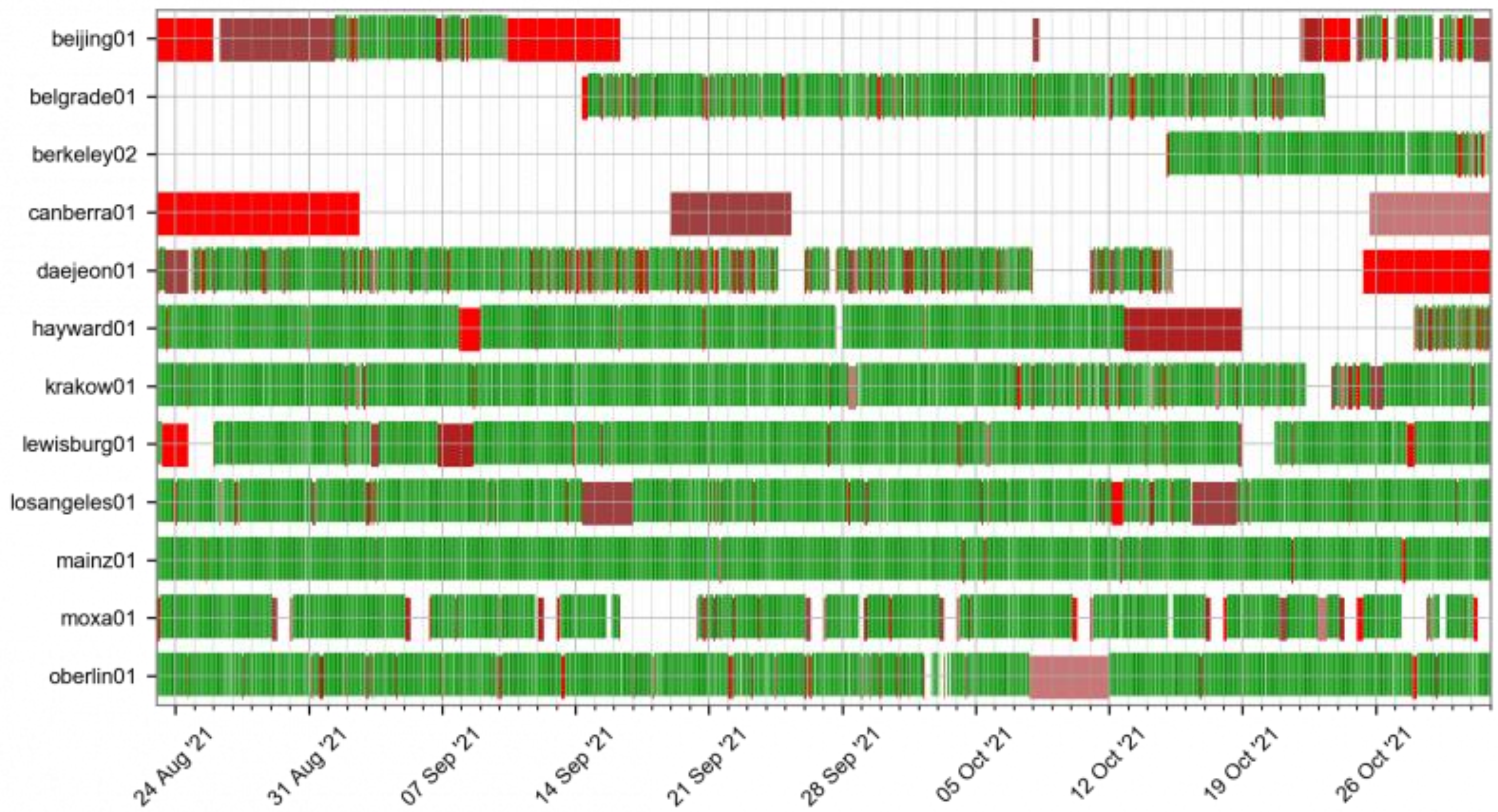
Naive homogeneious coupling sensitivity



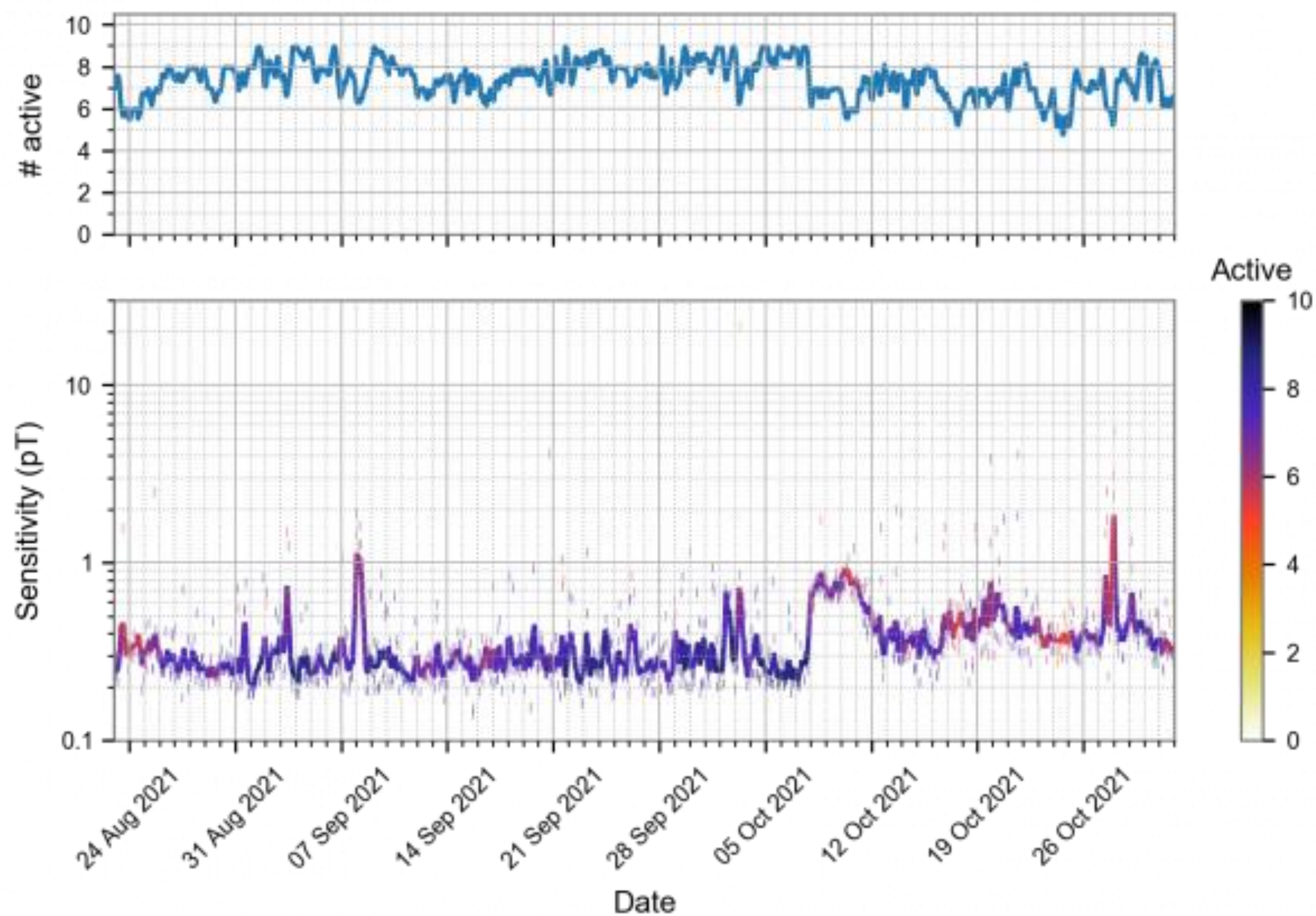
The need for rescaling



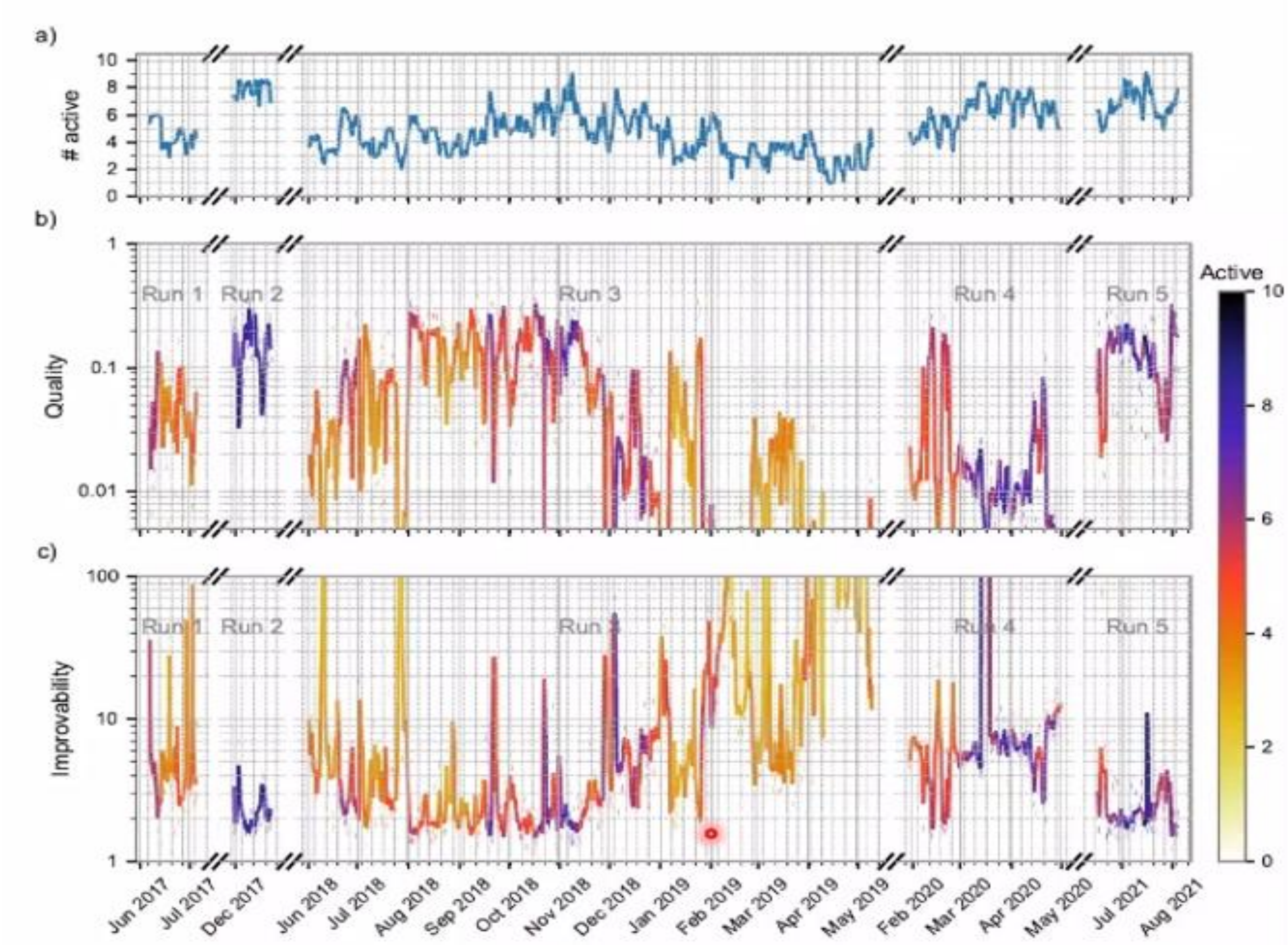
Rescaled and cleaned data from sci Run 5



Adjusted sensitivity



Quality of data

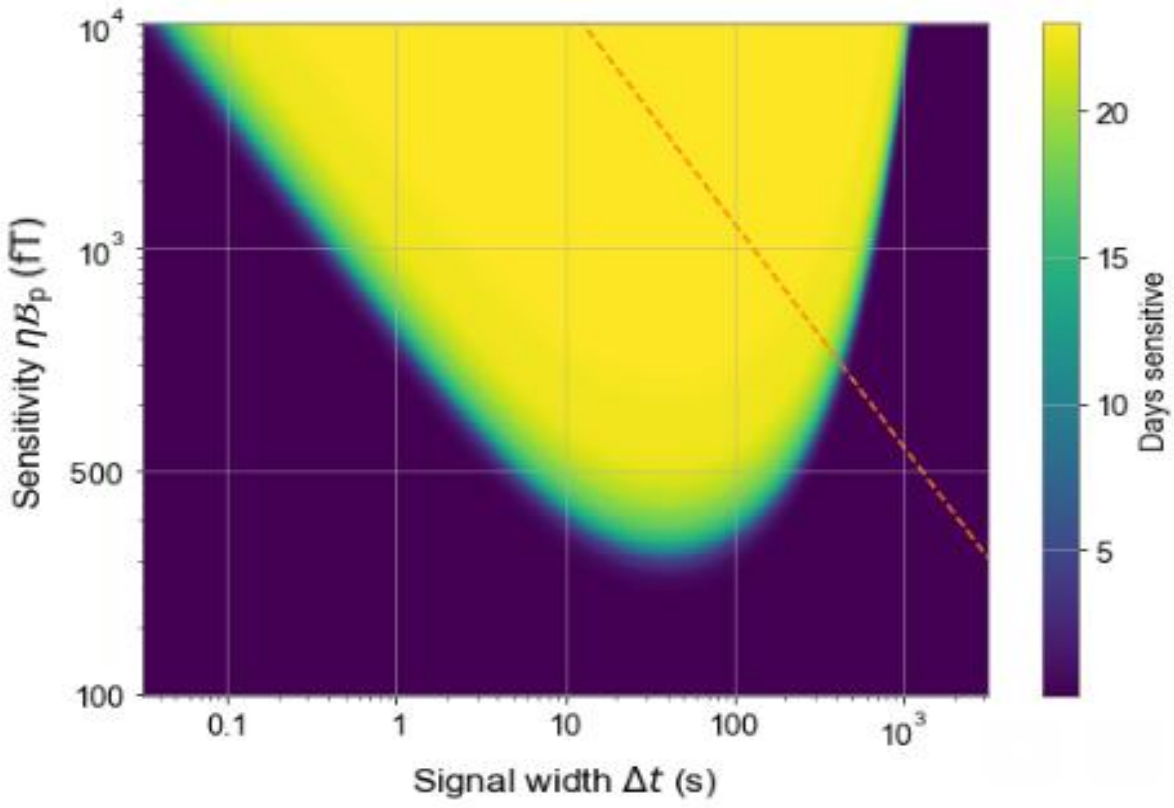


Smiga, Joseph. Assessing the quality of a network of vector-field sensors. *Eur. Phys. J. D* **76,** 4 (2022)

Phenomenological parameters

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

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



$$r = v\frac{\rho_{DW}}{\sigma_{DW}} = v\frac{\rho_{DW}}{8m_a f_{SB}^2}.$$

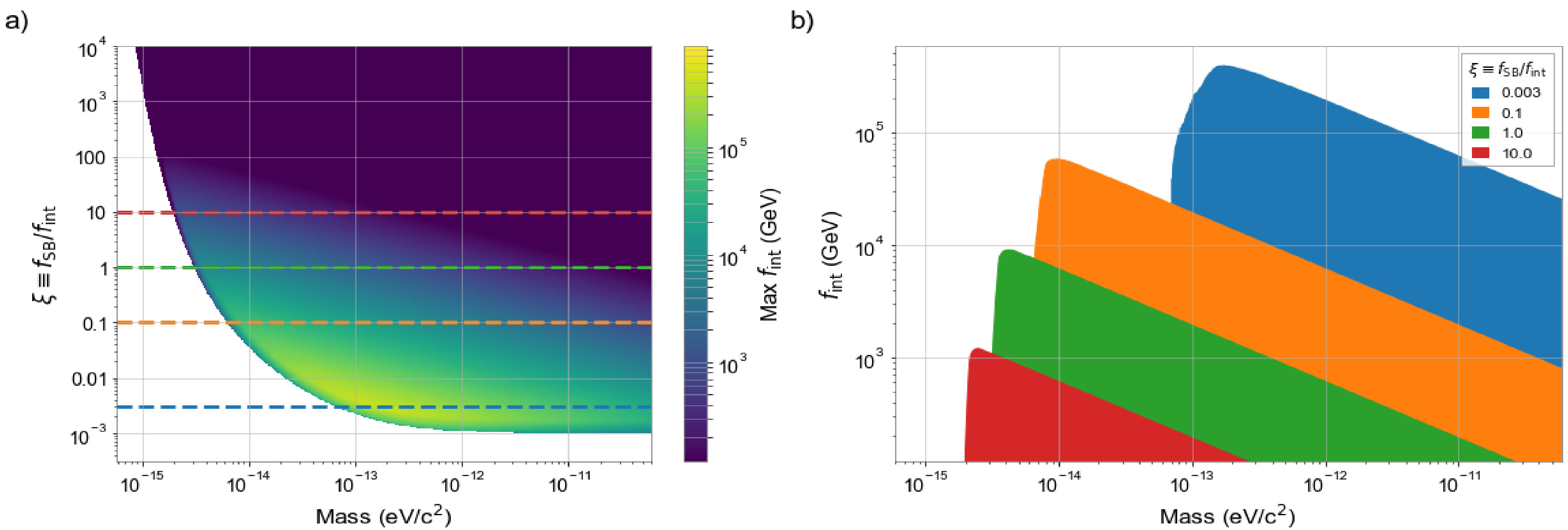
$$P(k;n) = \frac{n^k}{k!}e^{-n}.$$

$$\sum \frac{rT^k}{k!}e^{-rT}(1-\epsilon)^k = e^{-\epsilon rT}.$$

Bounds on axion mass and coupling strength to SM fermions extrapolated from sci Run 2 and sci Run 2 4 results

$$f_{int} \leq f_{exp} = \frac{\sqrt{\rho_{DW} L m_a}}{\Delta B_p}, \qquad f_{exp} \approx \frac{1}{B_p}\sqrt{\frac{2\rho_{dm}T}{\Delta t}} \approx \frac{1}{B_p}\sqrt{\rho_{DW} L m_a}.$$

$$f_{int} \leq \frac{1}{\eta}\sqrt{\frac{-v\rho_{DW}\epsilon}{8m_a(1-C)}T(\Delta t, B_p)}, \qquad C \leq 1 - e^{-R_C T},$$



GNOME in pre Covid era

Post Covid: Belgrade station (Serbia, PI: Zoran Grujić, Saša Topić) assembled in 2020
GNOME Rio (Brasil, PI: Theo Scholtes), TBD

Next GNOME meeting: 13 and 14 August at Mainz

That’s not all folks: Some ideas and Posibilities for collaboration

Schuman resonances on local and global scale – geophysics, solar wind and space weather comunitiy.

Magnetic field transients such as sudden perturbations of Earth magnetic field made by **CME**, anthropogenic source, meteorite or other source

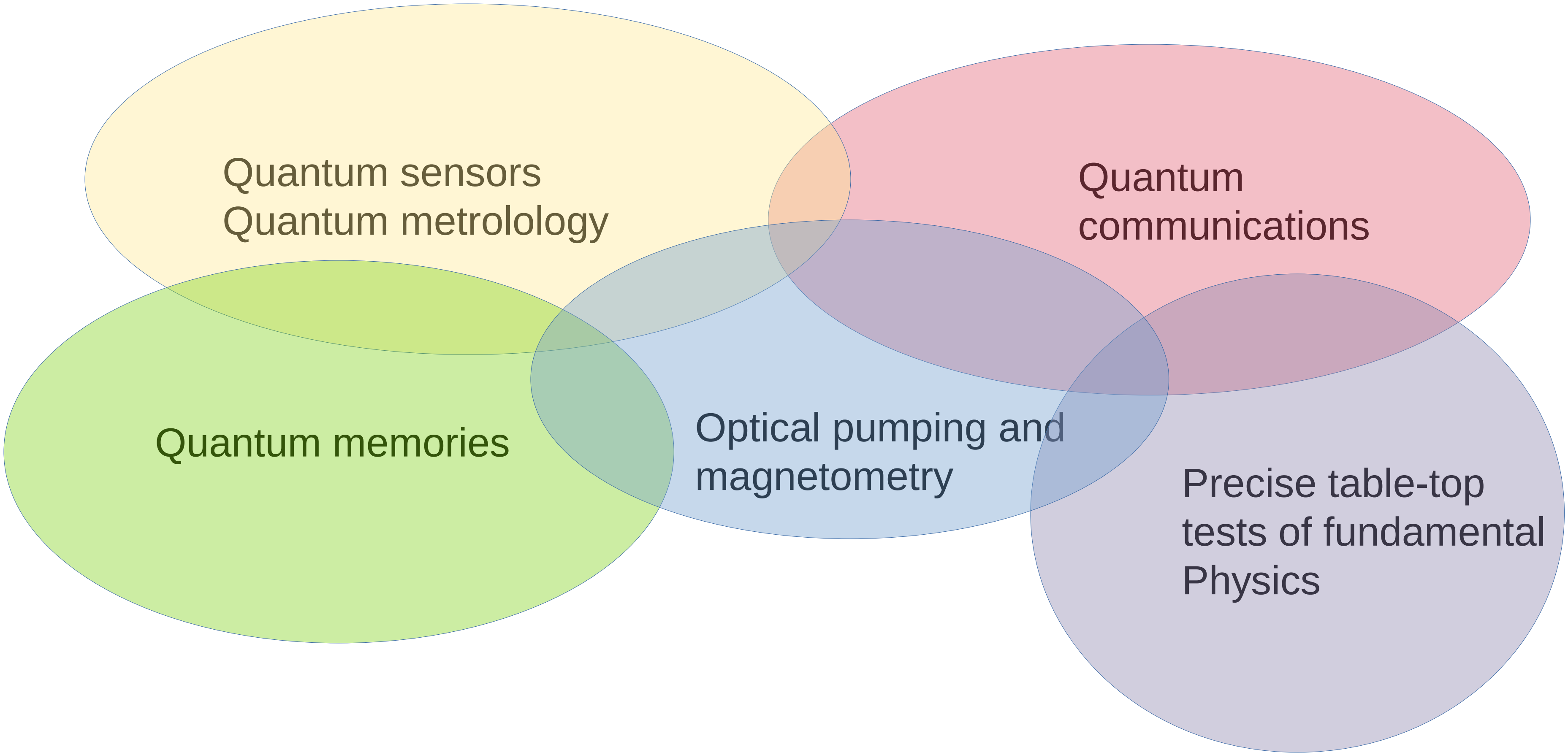
Correlation of terestrial muon flux – and by extension progenitor cosmic rays (that is connected to stage of Solar activity)**with the different indicies of magnetic field activity** and perturbtion that is available in the wealth of archieved GNOME data

Collaboration with theoreticians (both quatum fueld thepreticians from the IPB) and cosmologists/structure formation group from the AOB in relation to the axion problematics

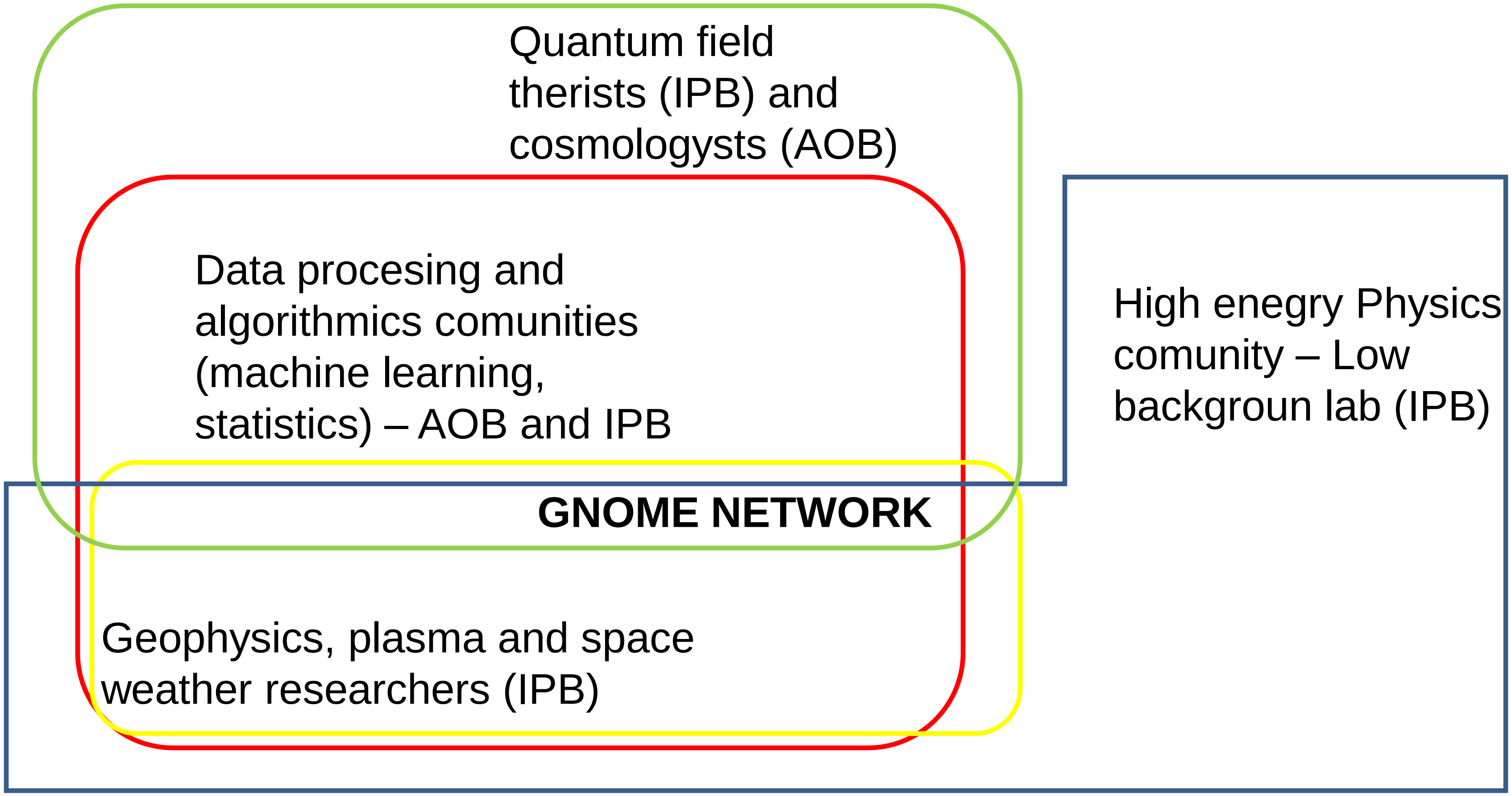
VERY IMPORTANT: **We are looking for** EM isolated, quiet and sparsely visited measuring **space for future comisioning of our Belgrade station**. Main requirements are low EM contamination (50 Hz free), with fairly constant and inert temperature and humidity, preferably underground!

The GNOME collaboration is a machine for churning out papers: last year there is a paper published in *Nature Physics*!

Inter-Trans disciplinarity?



Opportunities from unification of diversitiy



Thank You for attention!

Questions…Comments...

Suplemental slides

Details of detection of pasage through domain wall

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

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

$$\sigma_{DW} \approx \rho_{dm} L \approx \rho_{dm} v T.$$

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

$$f_{int} \approx \frac{(\hbar c)^{3/2}}{\mu_B B_p}\sqrt{\frac{2\rho_{dm}T}{\Delta t}}.$$

$$r = v\frac{\rho_{DW}}{\sigma_{DW}} = v\frac{\rho_{DW}}{8 m_a f_{SB}^2}.$$

$$f_{int} \approx \frac{1}{B_p}\sqrt{\frac{2\rho_{dm}T}{\Delta t}} \approx \frac{1}{B_p}\sqrt{\rho_{DW} L m_a}.$$

$$P(k;n) = \frac{n^k}{k!}e^{-n}.$$

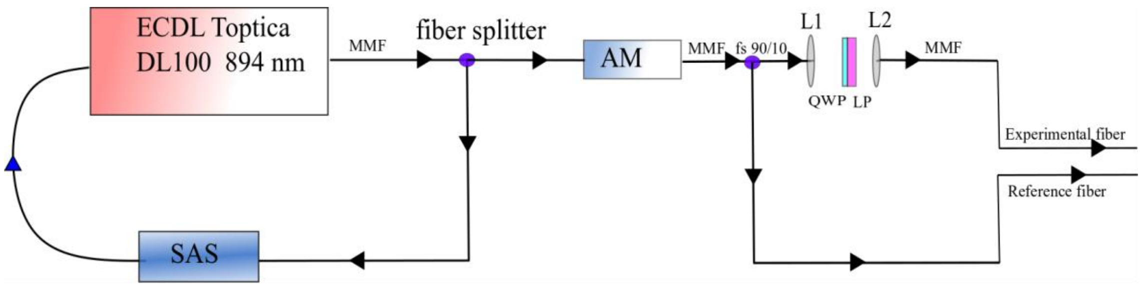
$$\sum \frac{rT^k}{k!}e^{-rT}(1-\epsilon)^k = e^{-\epsilon r T}.$$

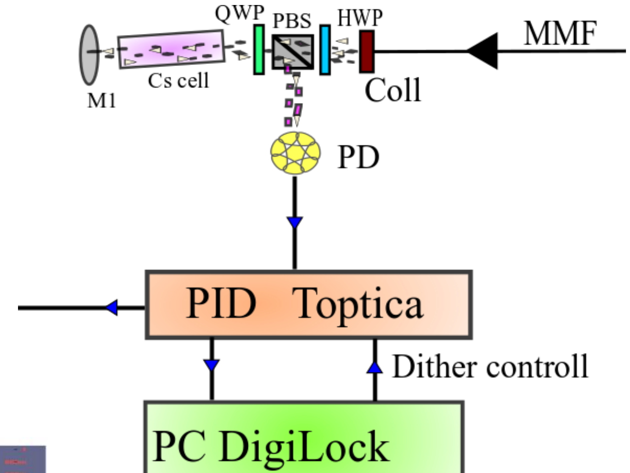
$$f_{int} \leq f_{exp} = \frac{\sqrt{\rho_{DW} L m_a}}{\Delta B_p},$$

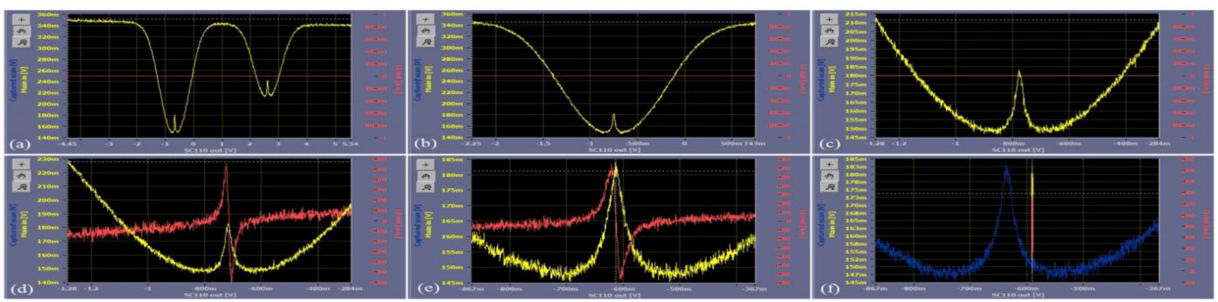
$$C \leq 1 - e^{-R_C T},$$

$$f_{int} \leq \frac{1}{\eta}\sqrt{\frac{-v\rho_{DW}\epsilon}{8m_a(1-C)}T(\Delta t, B_p)},$$

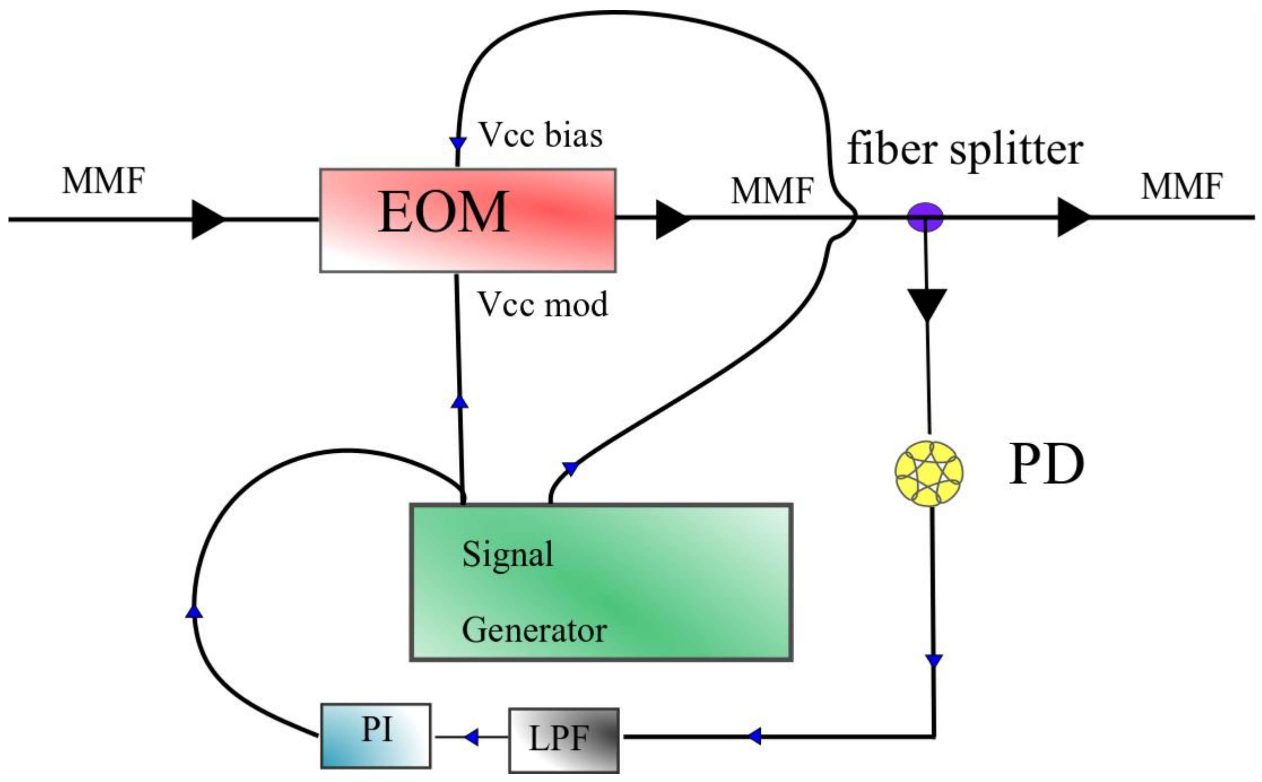
SAS – Saturated Absorption Spectroscopy – scheme for frequency stabilisation of laser light

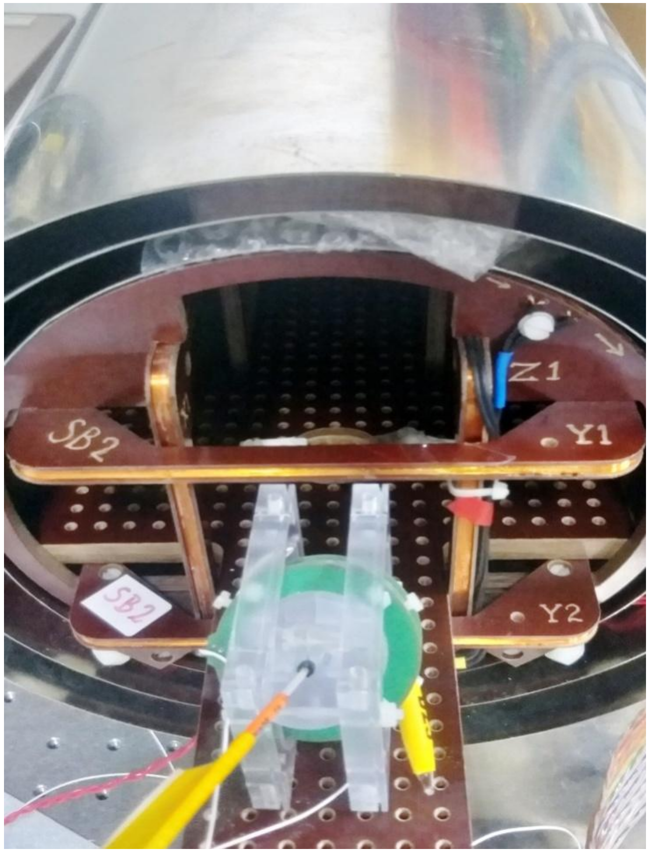


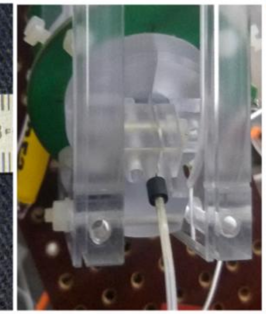


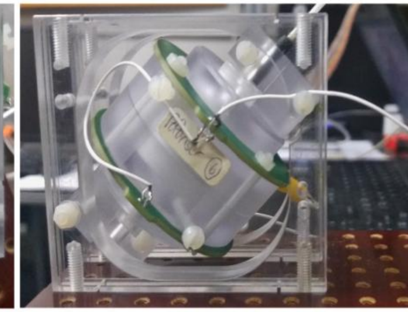


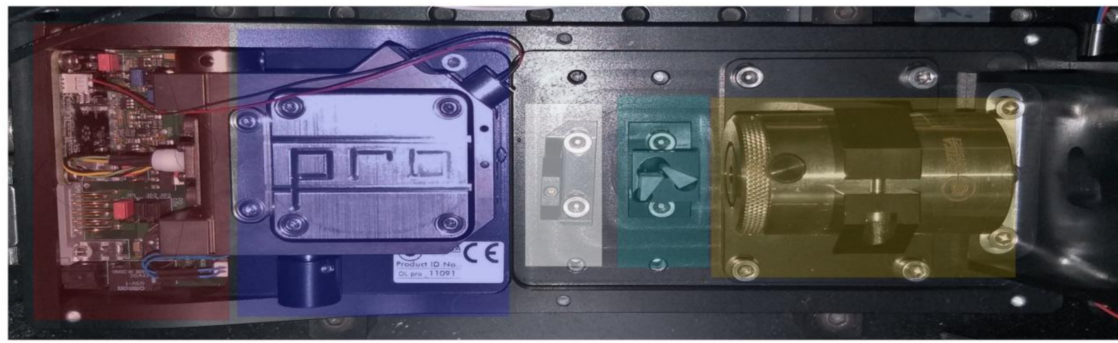
System for amplitude stabilisation




Z1
SB2
Y1
SB2
Y2



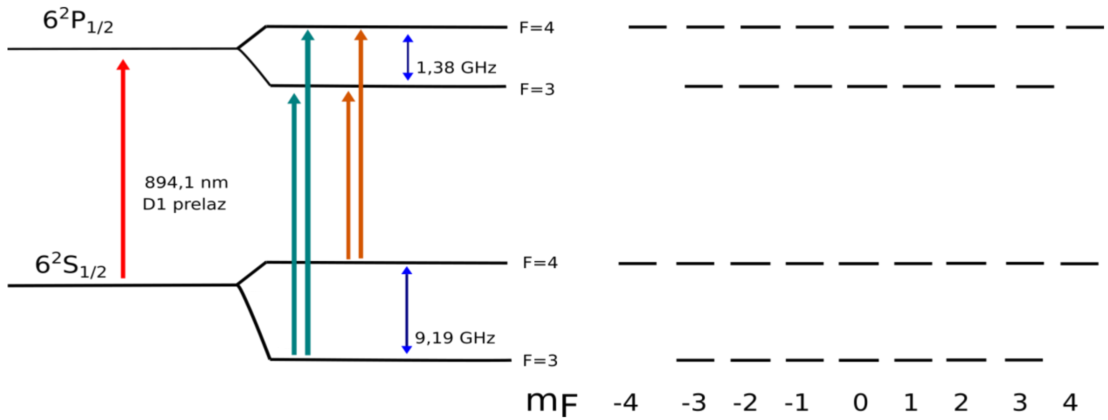


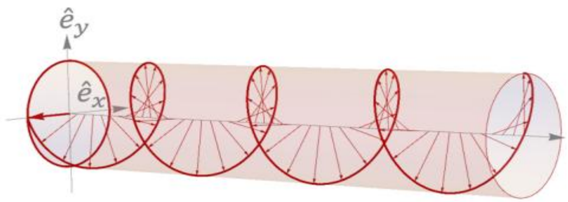


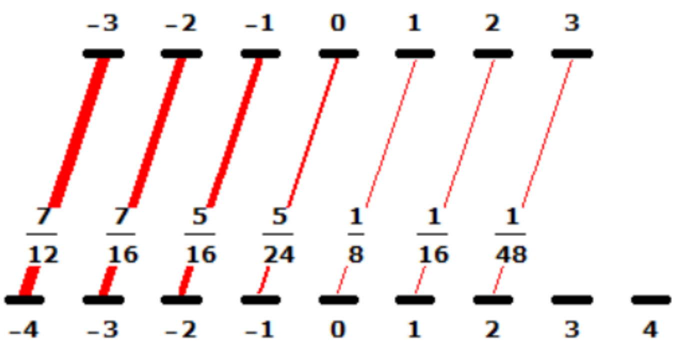

D3 D1 A9 A7 A5 A3 A1
D2 D0 A8 A6 A4 A2 A0
Sanity out
D-Sub to Sanity-Box


Manual switch
Sanity: OK
Failed


D-Sub to Breakout-Box
USB to PC





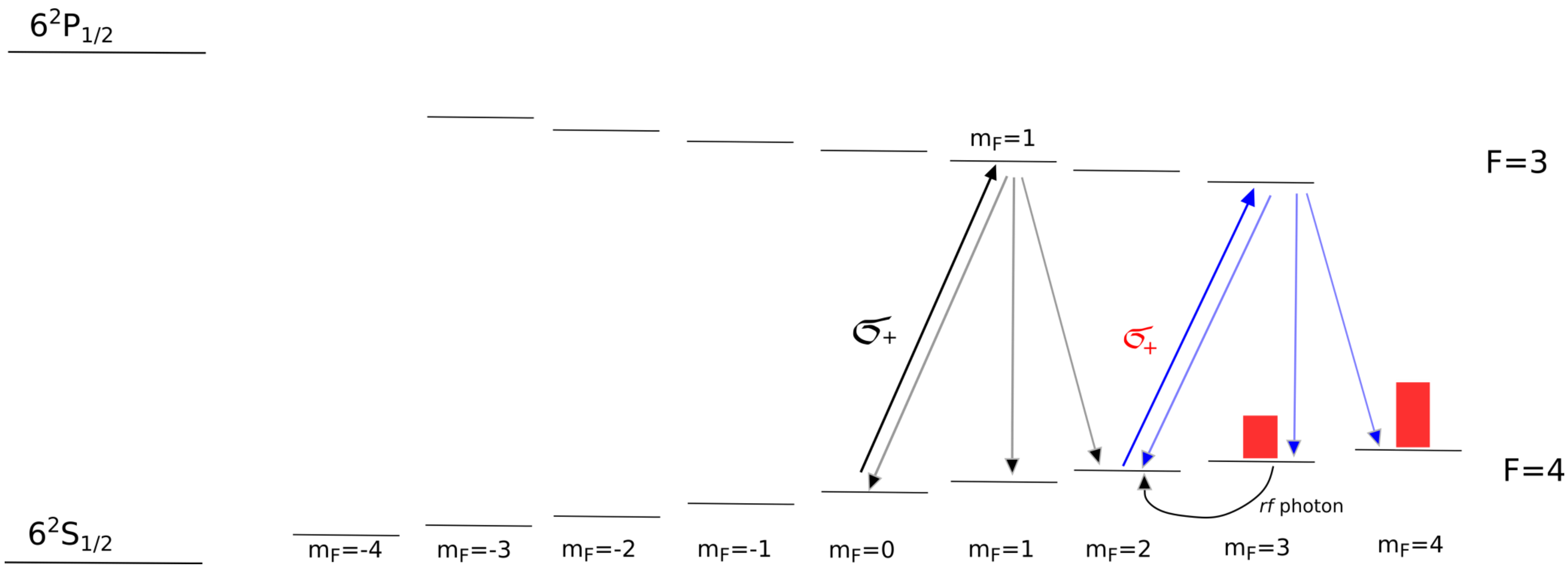


$$\Omega = -\frac{2(\langle g|\epsilon\cdot\vec{d}|e\rangle\, E_0^{(+)}}{\hbar} = -\frac{(\langle g|\epsilon\cdot\vec{d}|e\rangle\, E_0}{\hbar}$$

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

	$m_{F=-4}$	$m_{F=-3}$	$m_{F=-2}$	$m_{F=-1}$	$m_{F=0}$	$m_{F=1}$	$m_{F=2}$	$m_{F=3}$	$m_{F=4}$
$F'=4$	$\sqrt{\frac{1}{12}}$	$\sqrt{\frac{7}{48}}$	$\sqrt{\frac{3}{16}}$	$\sqrt{\frac{5}{24}}$	$\sqrt{\frac{5}{24}}$	$\sqrt{\frac{3}{16}}$	$\sqrt{\frac{7}{48}}$	$\sqrt{\frac{1}{12}}$	
$F'=3$	$\sqrt{\frac{7}{12}}$	$\sqrt{\frac{7}{16}}$	$\sqrt{\frac{5}{16}}$	$\sqrt{\frac{5}{24}}$	$\sqrt{\frac{1}{8}}$	$\sqrt{\frac{1}{16}}$	$\sqrt{\frac{1}{48}}$		

Introduction of external B field lifts Zeeman degenracy + resonant field



$$\frac{\vec{\nu}}{\mu_B} = -g_F \frac{\vec{F}}{\hbar}$$

$$S_z = \frac{\langle F_z \rangle}{\hbar F} = \frac{1}{F} \sum m_f p_{mf}$$

$$\omega_L = \frac{g_F \mu_B}{\hbar} B_0$$

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

$$H = H_{hf} - \vec{\mu} * \vec{B} = A\vec{J} * \vec{I} - \frac{g_f \mu_B}{\hbar} \vec{F} * \vec{B}$$

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

$$H = AJ_z I_z - \frac{g_f \mu_B}{\hbar} F_z B = AJ_z I_z - g_f \omega_L F_z$$