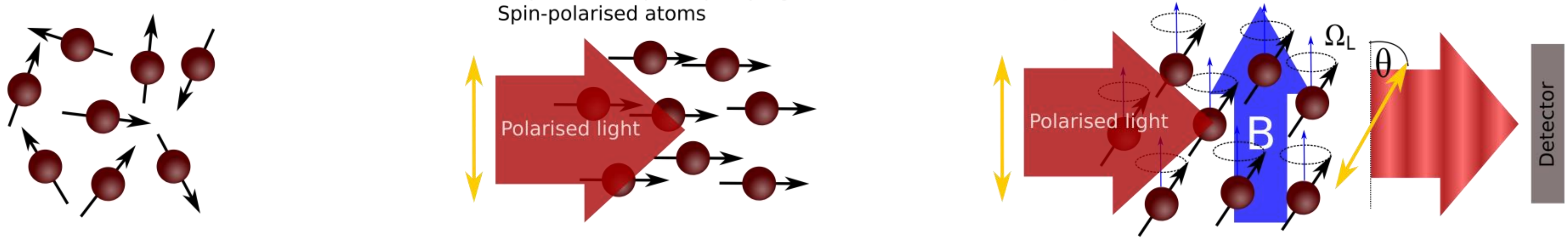
Detecting Dark Matter with Atomic Magnetometers: the GNOME network

Giovanni Barontini

Optically pumped atomic magnetometers



Step 1
Unpolarized atoms

Step 2
Preparation - optical pumping
Spin-polarised atoms

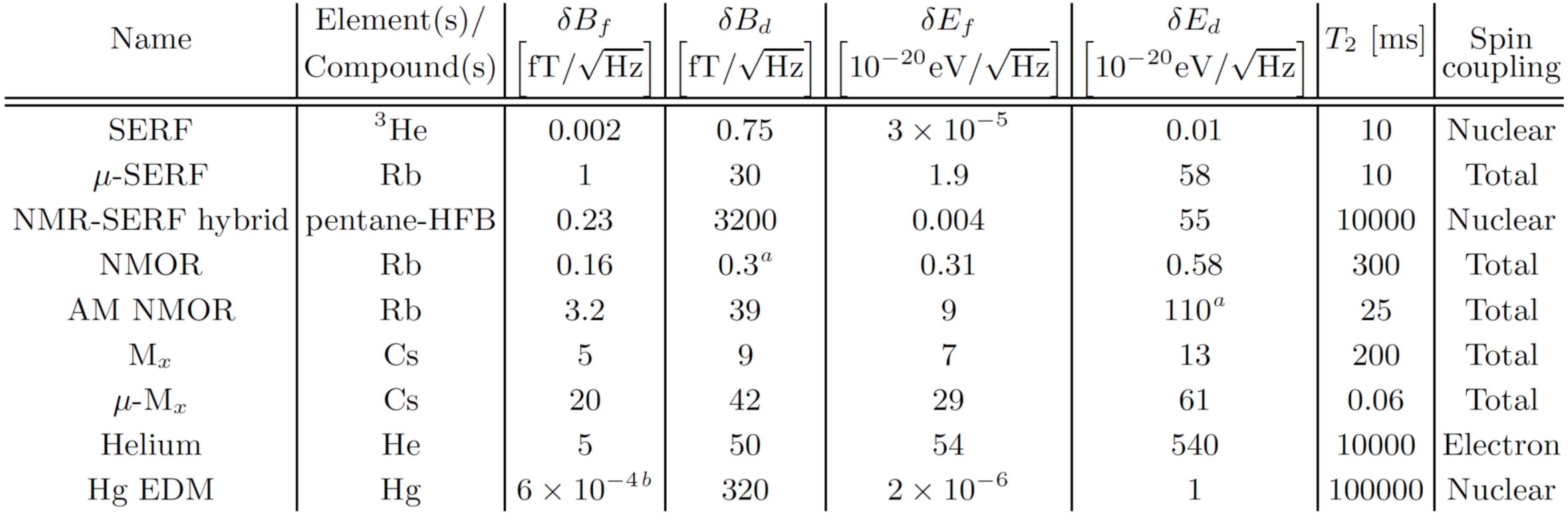
Step 3
Time evolution in the unknown
magnetic field

Step 4
Probing - detection of Ω_L

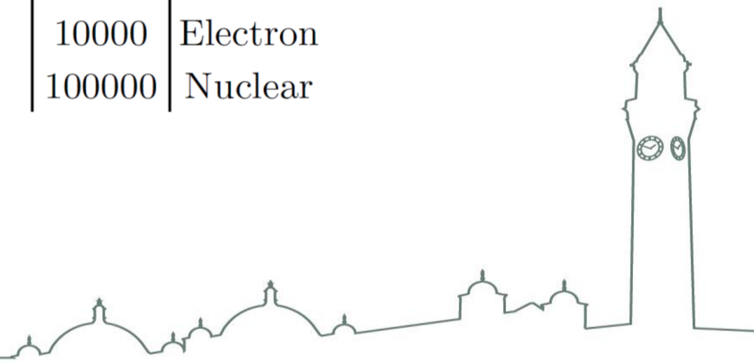
$$H_{\text{int}} = \mu \mathbf{B} \cdot \mathbf{F}/F$$

OPMs

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



Name	Element(s)/ Compound(s)	δB_f $\left[\mathrm{fT}/\sqrt{\mathrm{Hz}}\right]$	δB_d $\left[\mathrm{fT}/\sqrt{\mathrm{Hz}}\right]$	δE_f $\left[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}\right]$	δE_d $\left[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}\right]$	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	$6 \times 10^{-4\,b}$	320	2×10^{-6}	1	100000	Nuclear



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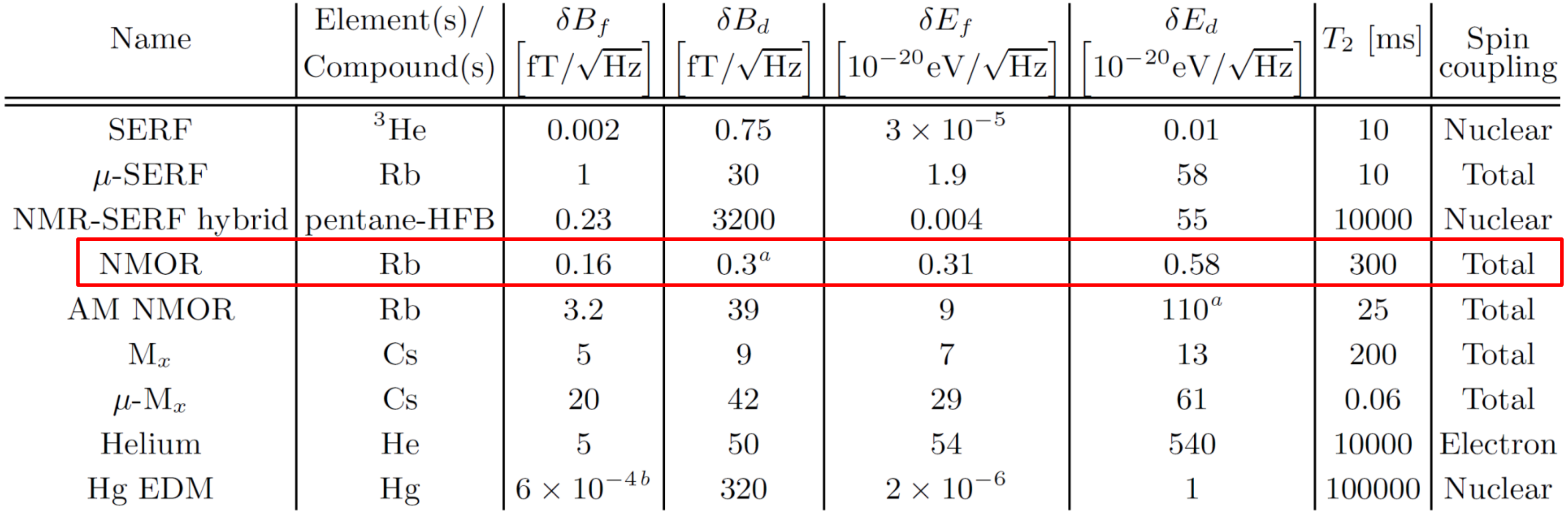

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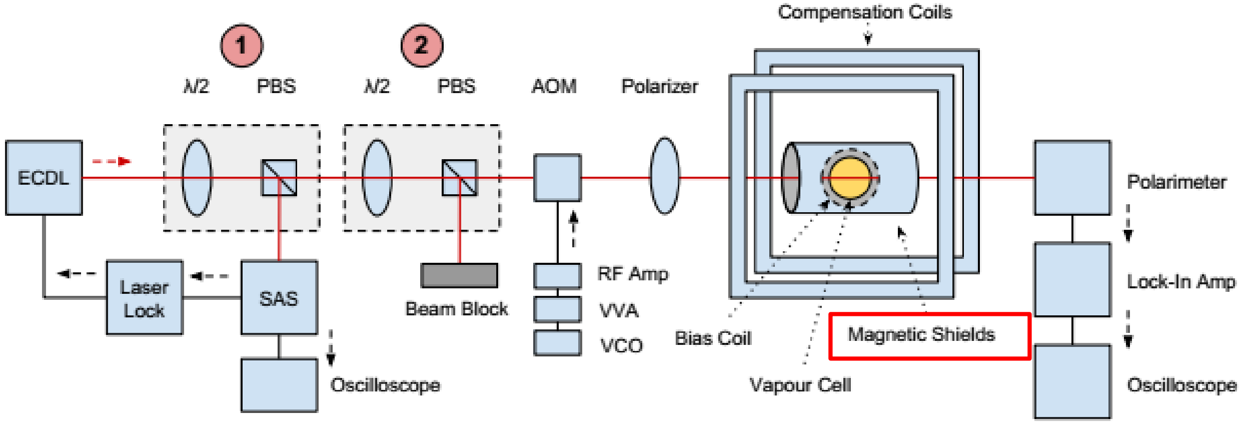
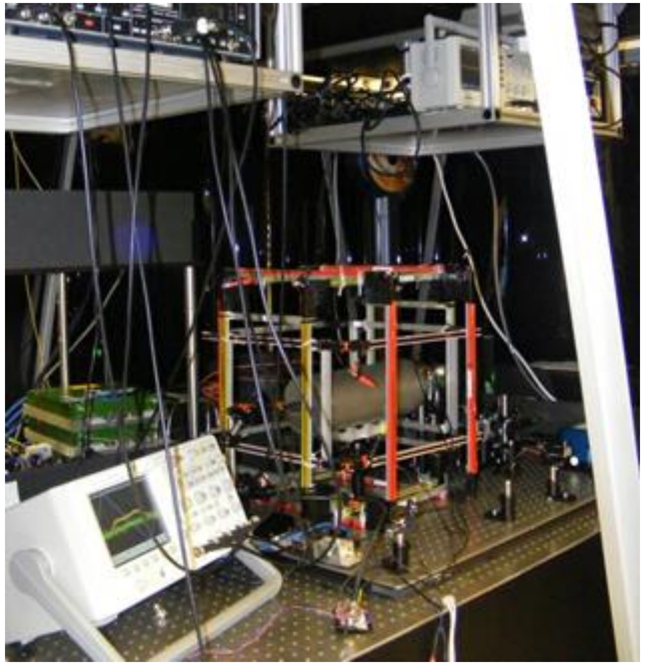
Birmingham OPM





Sensitivity ~200 pT/√Hz

Why OPMs for Dark Matter?

The high sensitivity of OPMs to spin dynamics allows to investigate other kinds of spin interactions (non-magnetic)

OPMs can be used to investigate the (feeble) coupling between the atomic spin and fields not predicted by the SM

An example are the axion-like fields that are among the DM candidates

OPMs

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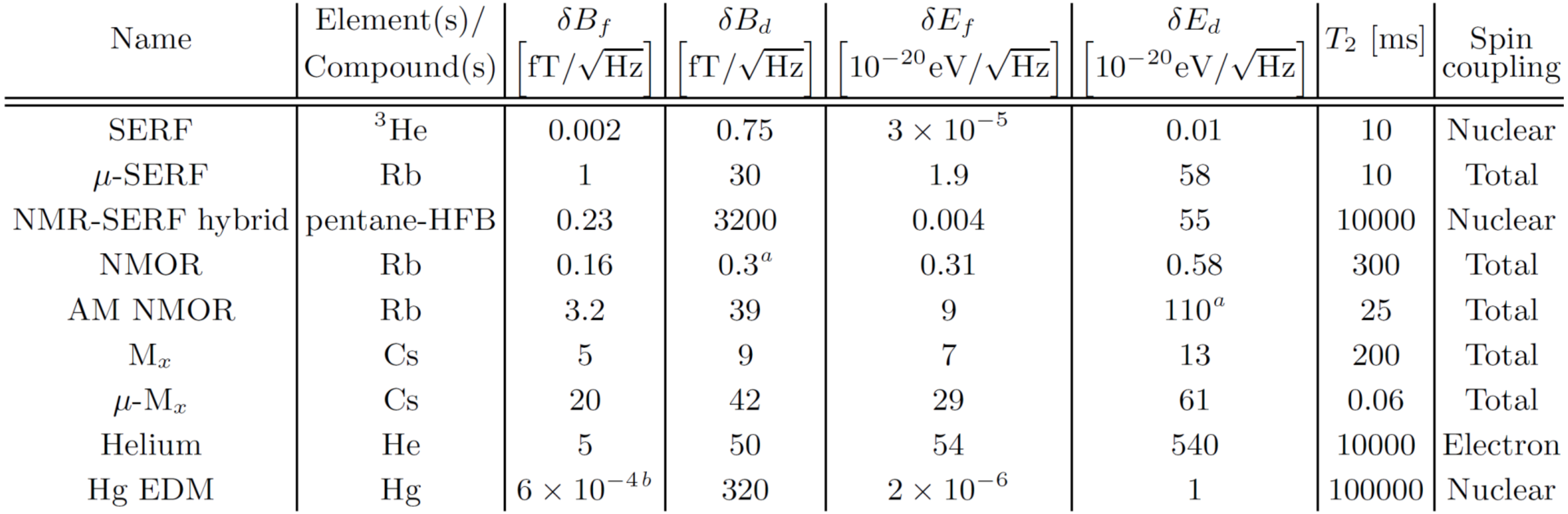

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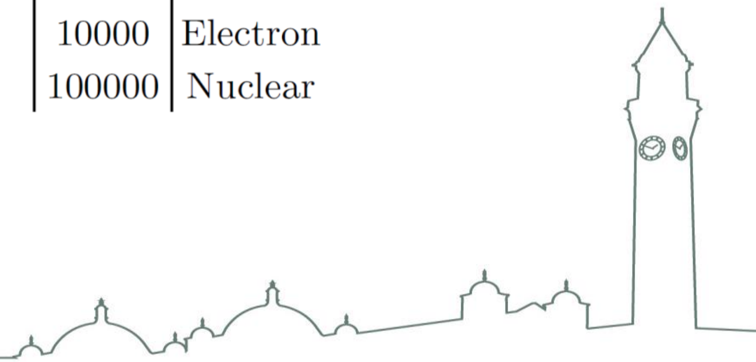


Axion-like fields and OPMs

- Uniformly distributed axion-like particles would not produce effects detectable with OPMs

- Some models predict a stable domain structure and **domain walls** for (light) axion-like fields [PRL 110, 040402 and references therein]

- Such topological defects are formed as the Universe expands and cools (KZ mechanism)

Axion-like fields and OPMs

We consider an axion like pseudoscalar field a(**r**)

We consider that between different domains the field takes the form

$$a(z) = 4a_0 \arctan[\exp(m_a z c/\hbar)]$$

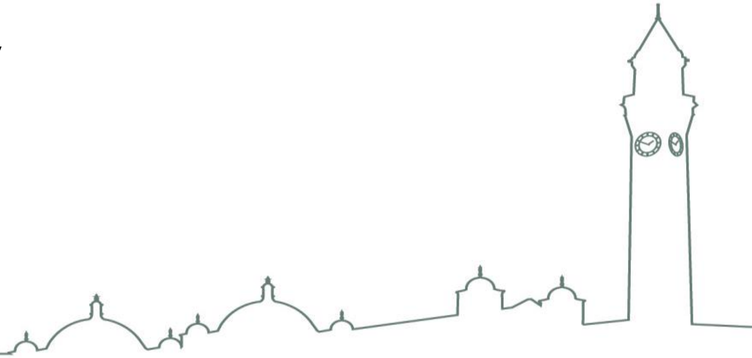
That implies a domain wall at z=0

The coupling with the spin arises during the DW crossing as

$$H_{\mathrm{DW}} = \hbar c \frac{\mathbf{F} \cdot \boldsymbol{\nabla} a}{F f_{\mathrm{eff}}}$$

Where f_{eff} is the Peccei-Quinn scale that is related to the axion mass by

$$m_a = 0.60\ \mathrm{eV} \frac{10^7\ \mathrm{GeV}}{f_a}$$



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$$H_{\mathrm{DW}} = \hbar c \frac{\mathbf{F} \cdot \boldsymbol{\nabla} a}{F f_{\mathrm{eff}}} \Rightarrow H_{\mathrm{int}} = \mu \mathbf{B} \cdot \mathbf{F}/F \Rightarrow \mu \mathbf{B}_{\mathrm{eff}} \cdot \hat{\mathbf{F}}/F = \nabla a \cdot \mathbf{F}/(F f_{\mathrm{eff}})$$

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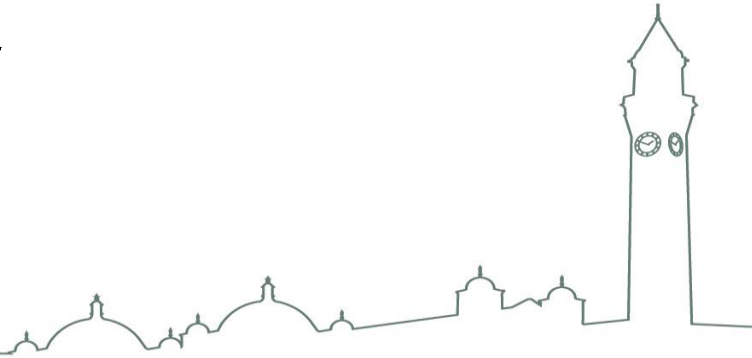
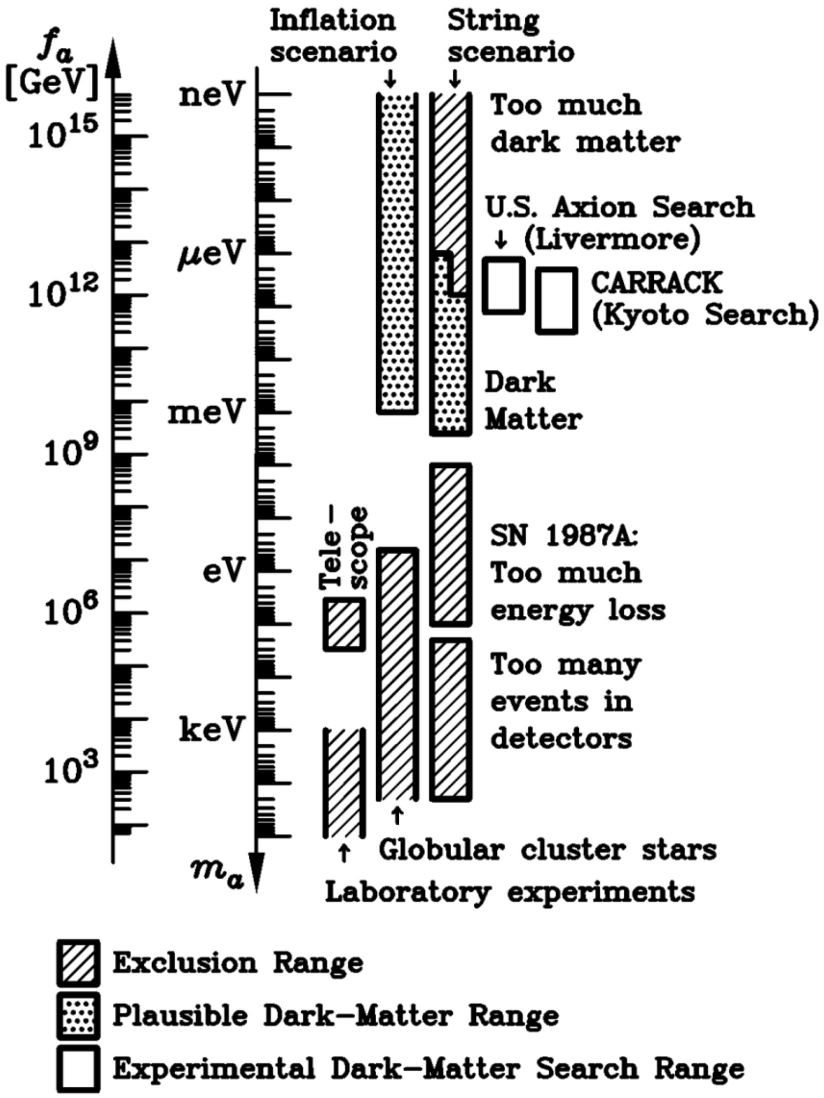


Exclusion regions



Axion-like fields and OPMs

Since the thickness of a DM depends on the mass as

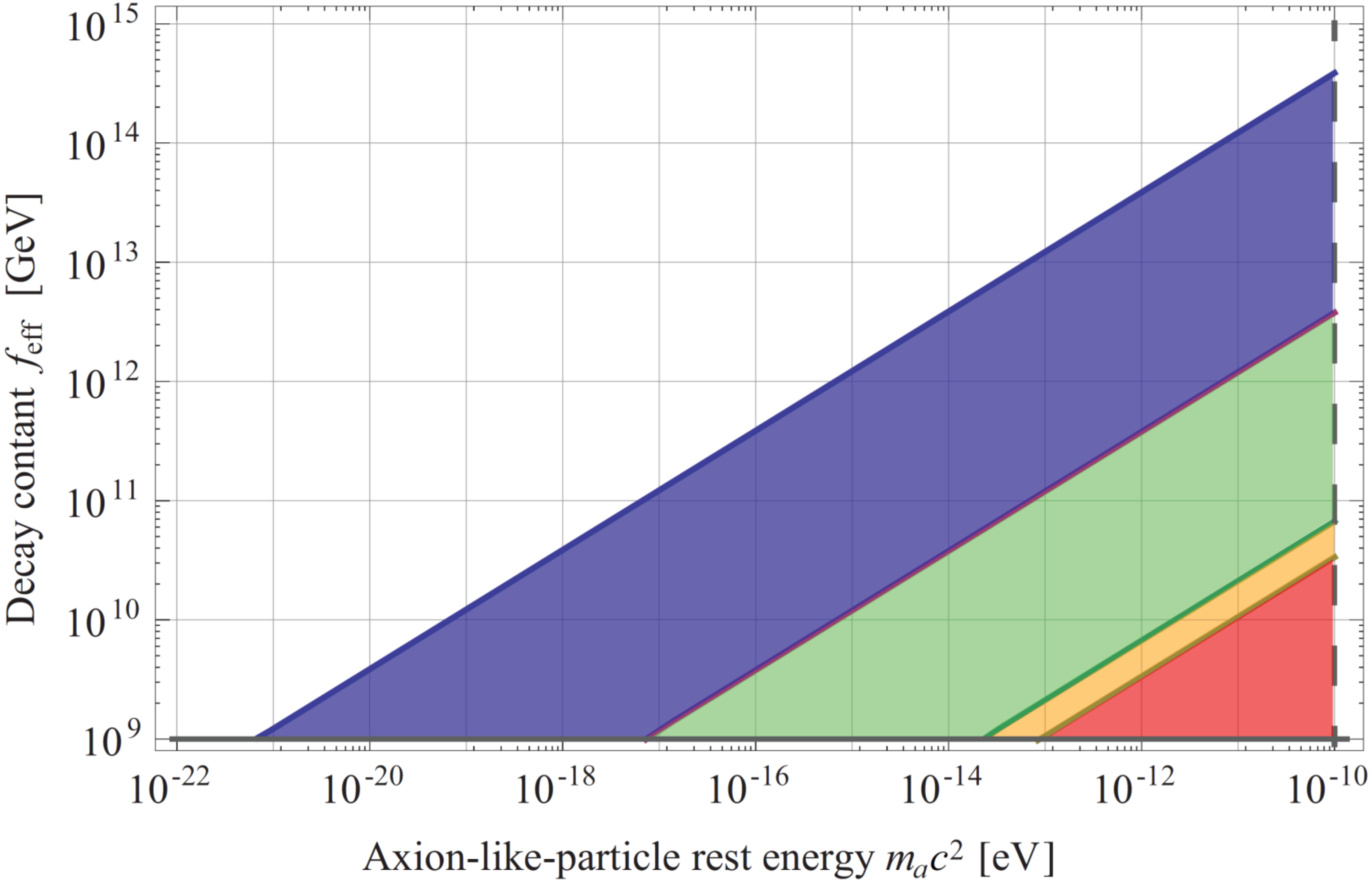
$$d = \frac{2\hbar}{m_a c}$$

We obtain the experimental limit for f

$$f_{\text{exp}} = \hbar c^2 \frac{\sqrt{\rho_{\text{DW}} L m_a}}{\delta E_d} \cos\varphi$$

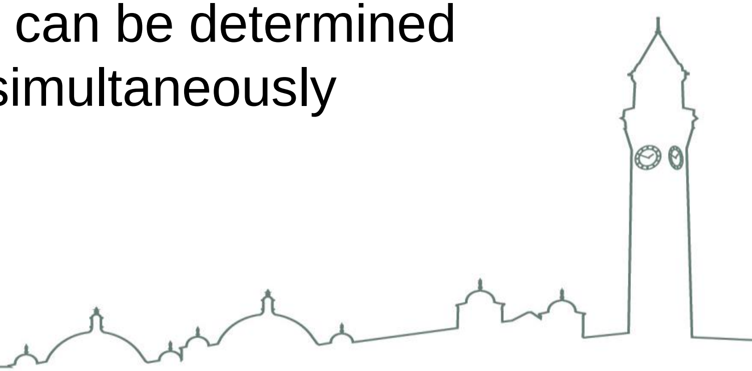
Taking into account the speed of the solar system relative to the Galactic frame ($v \approx 10^{-3}c$), a DW crossing event will likely occur within a time-span of 10 years if the domain size is less than 10^{-2} ly

Axion-like fields and OPMs

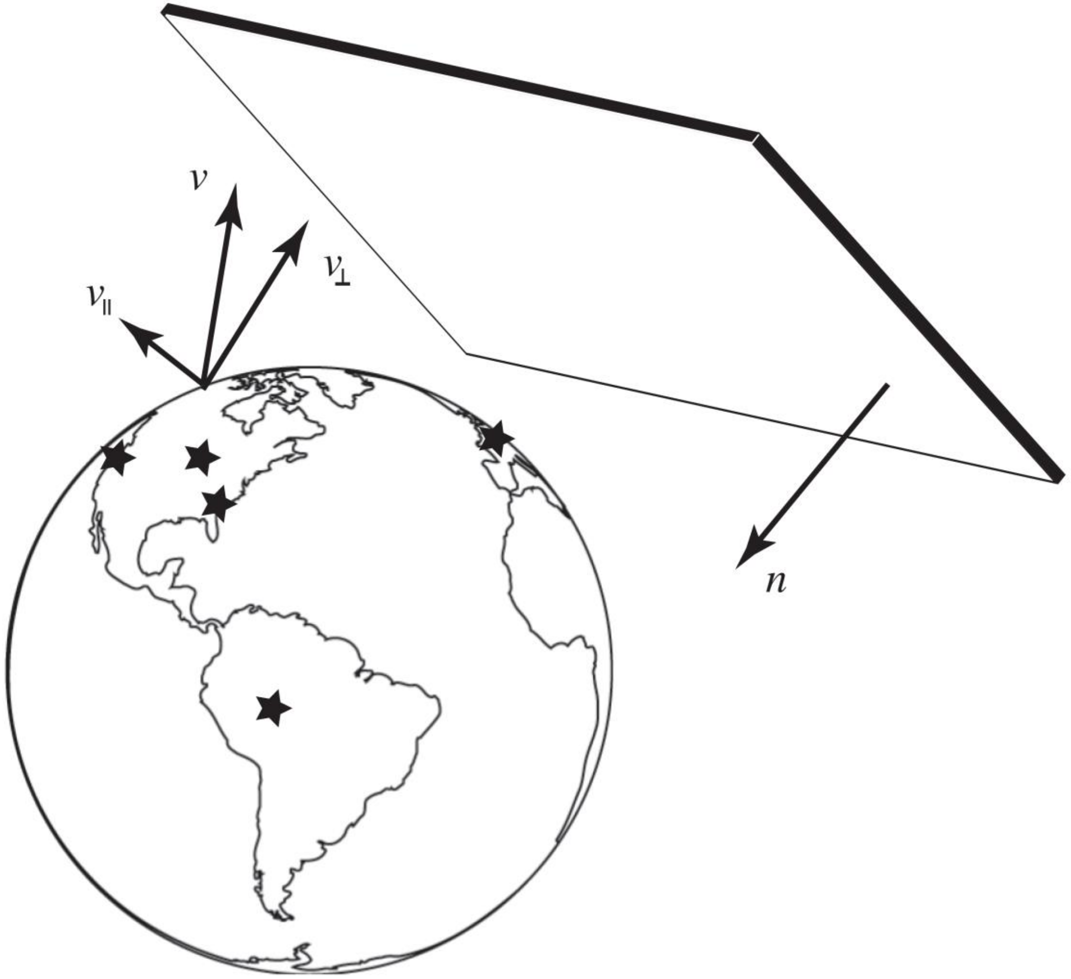


Axion-like fields and OPMs

- The detection of the DW crossing of the axion-like field requires to record a short transient event (>~ 10 ms) within a 10-year time span!
- With a single OPM brief spikes in the OPM signal related to technical noise or abrupt magnetic field changes are frequent, and rejection of false positives is difficult.
- Coincident measurements between two or more instruments are helpful in rejecting false positives
- Additional information about an event such as its impinging direction can be determined by triangulation if several instruments (at least four) are taking data simultaneously



The GNOME network



The GNOME network

The outputs of the magnetometers are acquired using custom-made devices based on Trimble Resolution-T GPS time receivers .

The data acquisition devices provides time markers separated by one second with a precision of about 80 ns synchronized with a quartz clock built into the devices.

The acquisition devices can record simultaneously signals in four channels at a rate of 1000 samples/s.

Each record is stored on a memory card with a header containing information on time, measurement condition, GPS-device warnings…

The records are into groups of 10-1000 (typically 2-minute long bins are generated).

The GNOME network

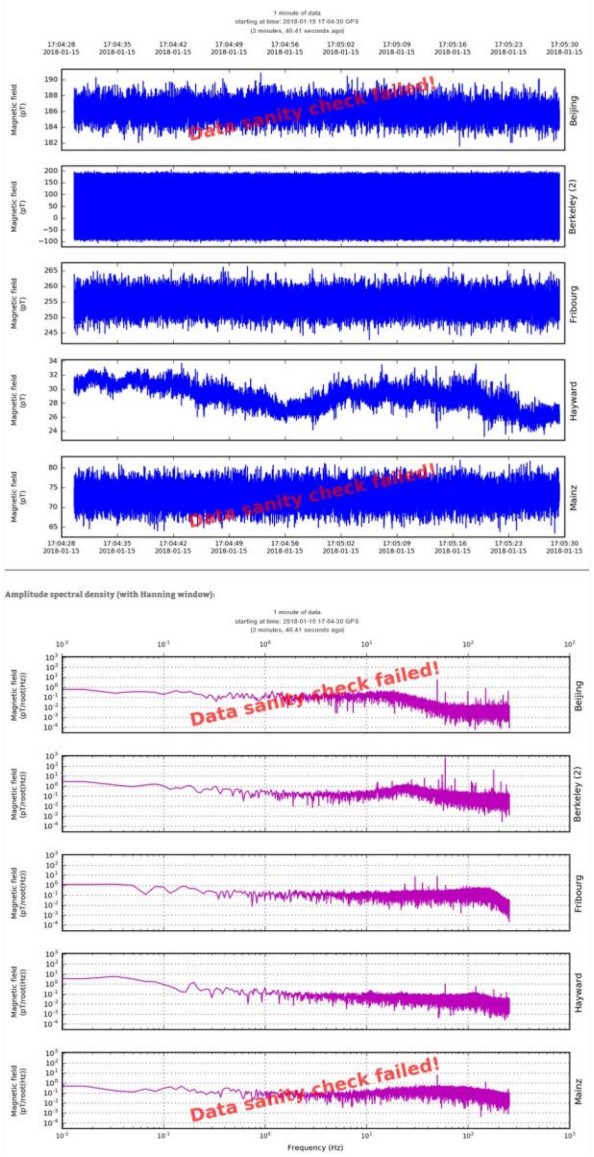
Current date: 2018/01/15 17:05:33 GPS

View data of: 2018/01/15 17:05:33 with length 60 seconds

or

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

The GNOME network



1 minute of data
starting at time: 2018-01-15 17:04:30 GPS
(3 minutes, 40.41 seconds ago)

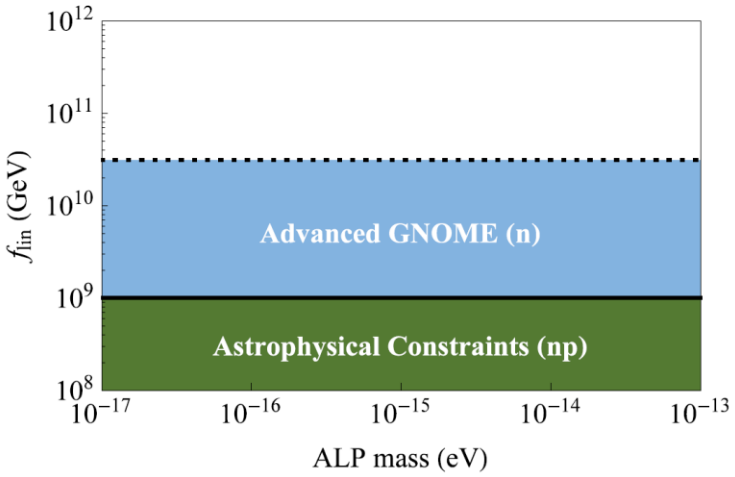
Amplitude spectral density (with Hanning window):

1 minute of data
starting at time: 2018-01-15 17:04:30 GPS
(3 minutes, 40.41 seconds ago)

Axion stars

Initial inhomogeneities in the galactic dark matter distribution may enable gravity or self-interactions to generate bound clumps or **stars** composed of Axion-like particles.

The tidal effects of such a soliton-star encounter on gravitational-wave observatories such as LIGO are orders of magnitude below LIGO's strain sensitivity



Conclusions

Small table-top experiments can be used to probe **unexplored regions of the DM parameter space**

Such regions are currently not probed by other experiments

An international network already exists and is taking data

The UK already has the necessary tools and expertise to join the network

It would be important to be part of the network before the starting of Phase II

Thanks