PBC
Technology Working Group
Report

Guido Zavattini for the W.G.

CERN, November 2019

Core members:
Giovanni Cantatore (aKWISP), Dimitri Delikaris (CERN), Babette Döbrich (CERN), Livio Mapelli (DARKSIDE), Antonio Polosa (Nanotubes), Pierre Pugnat (LSW/OSQAR), Joern Schaffran (DESY/ALPS), Andrzej Siemko (CERN), Paolo Spagnolo (STAX), Herman ten Kate (CERN/IAXO), Guido Zavattini (PVLAS)

PBC
Technology Working group

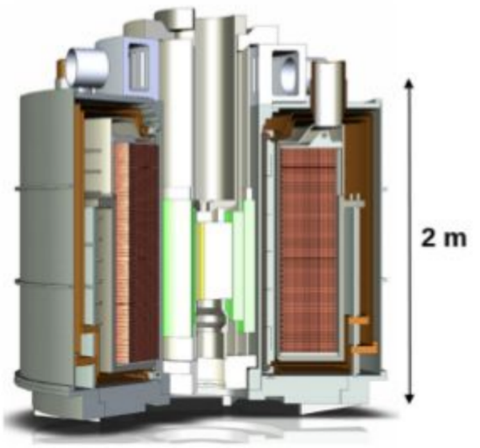
- Exploration and evaluation of possible technological contributions of CERN to non-accelerator projects
- Survey of suitable experimental initiatives and their connection to and potential benefit to and from CERN
- Description of identified initiatives and how their relation to the unique CERN expertise is facilitated

OUTLINE OF TALK

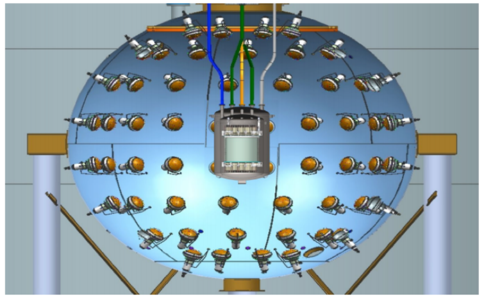
- Experiments/Initiatives within the Technology WG
- Updates on progress since January 2019:
  - GrAHal (Grenoble Axion Haloscope)
  - DarkSide
  - OSQAR – BabyJURA (Backup slides)
  - Carbon Nano Tubes
  - a-KWISP
  - STAX
- **Emphasis will be on VMB@CERN (Vacuum Magnetic Birefringence @ CERN)**

Initiatives integrated in the Technology W.G.

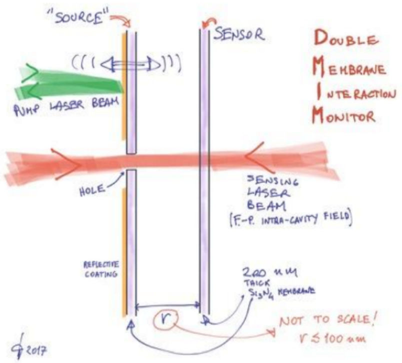
1) Haloscope LNCMI-Grenoble



2) DarkSide

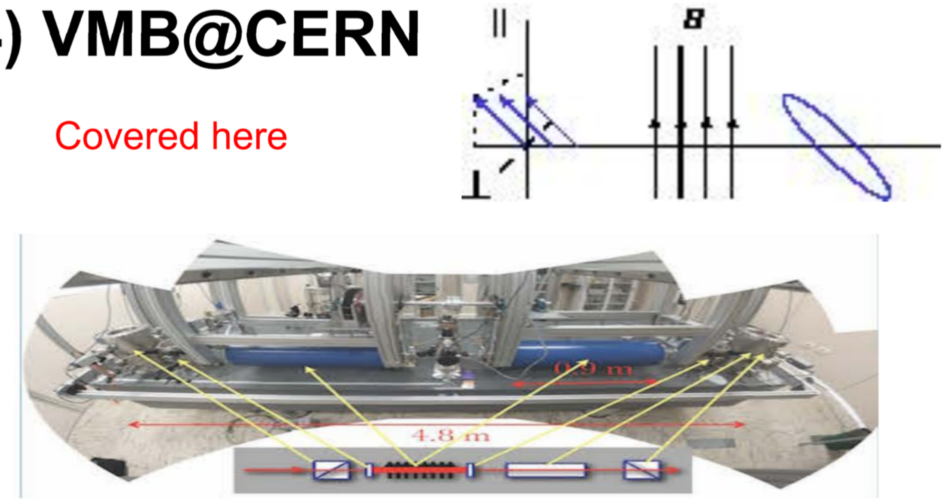


3) aKWISP



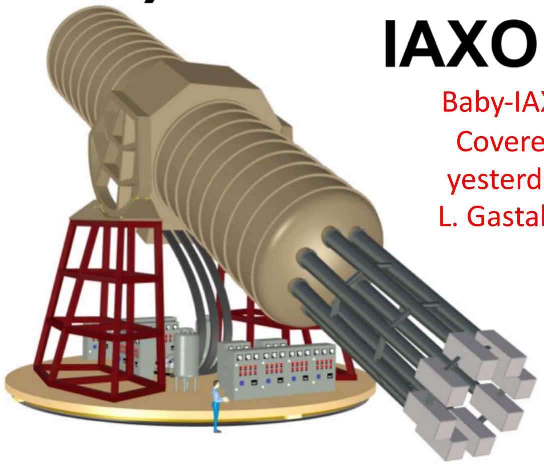
4) VMB@CERN

Covered here



5) Helioscope IAXO

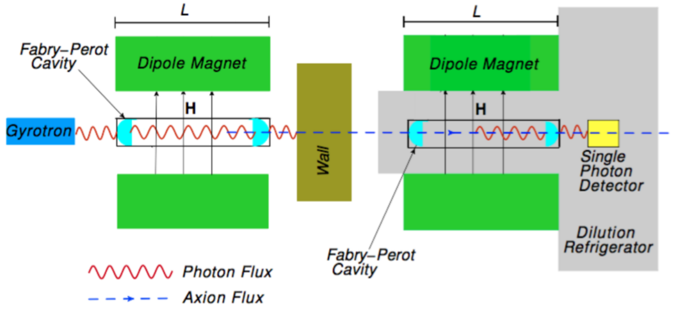
Baby-IAXO
Covered
yesterday
L. Gastaldo



6) JURA (LSW combining ALPS-III and OSQAR+)

Covered
Jan. 2019

7) LSW-STAX



Microwaves

8) CNT Based DM Detector

PTOLEMY (CNB)

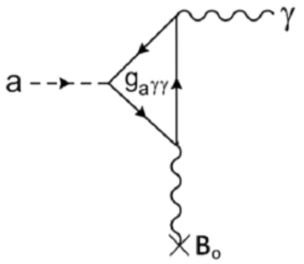
CNRS - UGA

GrAHal : Grenoble Axion Haloscope for Dark Matter search & explore the ultra-low energy frontier of cosmic particles (1-100 μeV)

R. Ballou, P. Camus, T. Grenet, S. Kramer, P. Pugnat, J. Quevillon, N. Roch, C. Smith, *CNRS-Grenoble, Univ. Grenoble-Alpes*

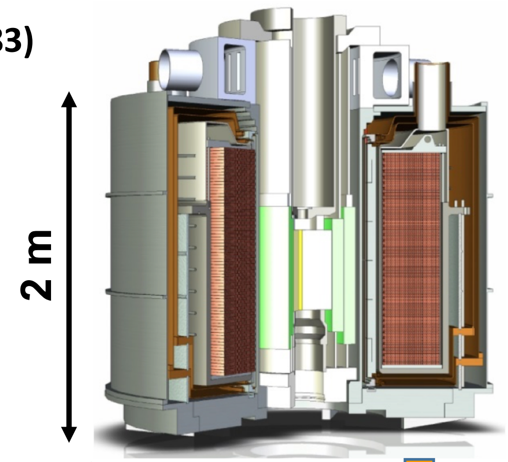
Axion & ALPs Haloscope (Sikivie 1983)

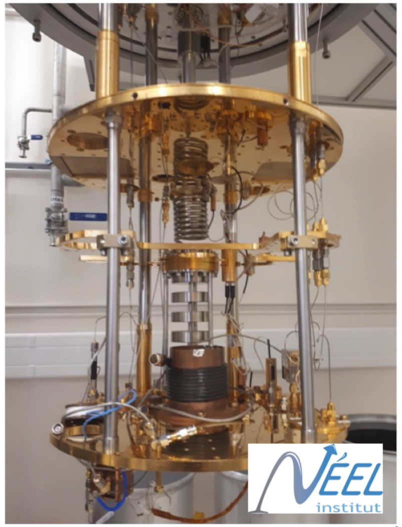
Primakoff Effect



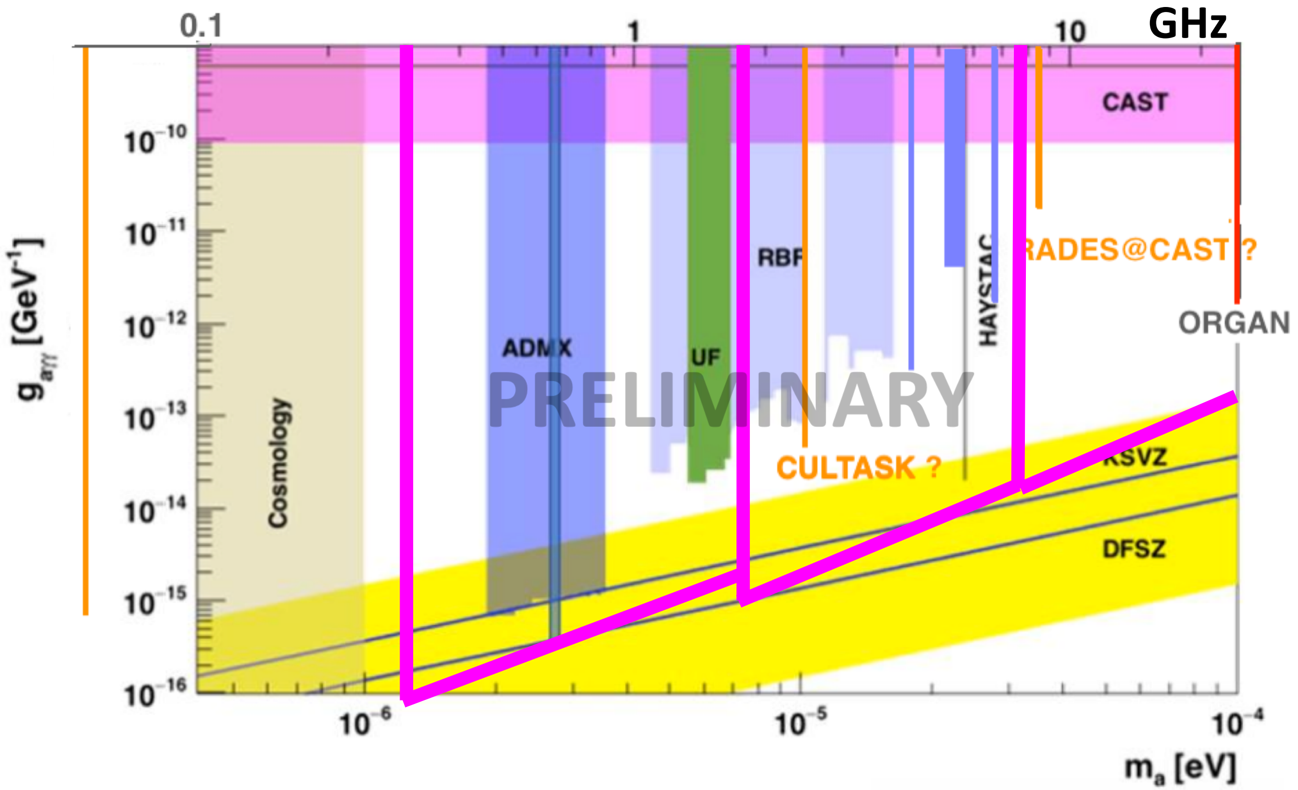
$P \;\alpha\; g_{a\gamma\gamma}^2 \; B_0^2 \, V < 10^{-21}\, W$

⇒ **RF cavities (0.3-30 GHz) at 20 mK & quantum amplifiers SQUID & JPA (IN) in strong magnetic field (LNCMI)**





Dilution fridge



- **Grenoble Hybride Magnet (Equipex LaSUP, LNCMI)**
  . 43 T/34 mm, 40 T/50 mm, 27 T/170 mm, 9 T/800 mm

https://indico.desy.de/indico/event/13889/contribution/11/material/slides/0.pdf
http://cds.cern.ch/record/2315130/files/fulltext.pdf

- **2020-2024: 1st experimental runs at 20 mK in smaller superconducting magnets (LANEF, Néel Institute)** in 16-20 T/50 mm & 14 T/70 mm

Slides: P. Pugnat

Aria Project – isotope cryogenic separation

In Sulcis - Iglesiente, Sardinia. Monte Sinni mine
Deplete underground Ar (Uar) from ^{39}Ar

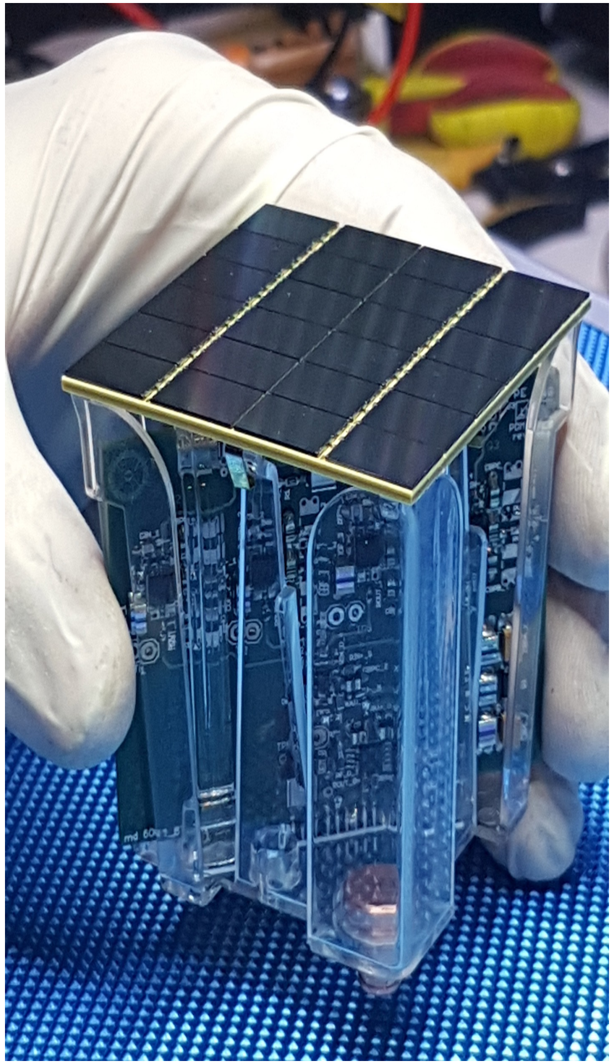
Seruci-0: pilot distilling column 27 m high

- Commissioned, June 2019
- I, II and III runs, Jul - Aug 2019
- IV runs, Oct 2019
- N_2 in column
- Next test TBD

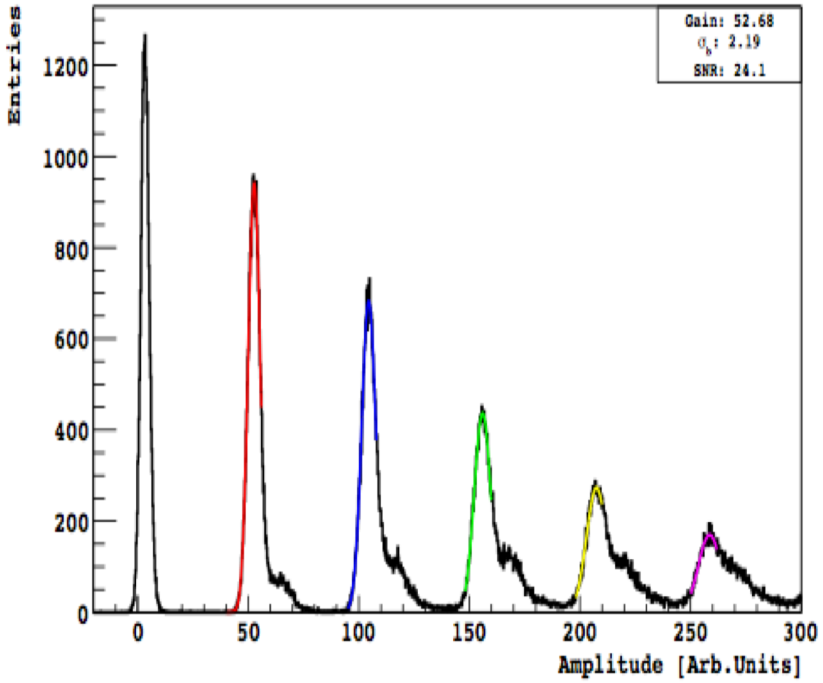
Seruci-1: 350 high distillation column

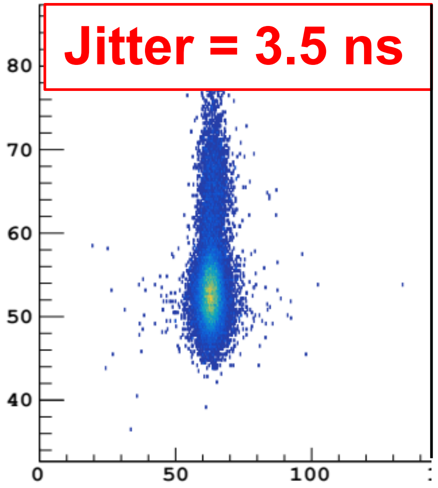
- 7 platforms installed into the Shaft
- 2 modules will be installed next months

Cryogenic photosensor



- Custom cryogenic photosensors based on Silicon Photomultipliers designed by FBK and produced by LFoundry
- True replacement of 3" cryogenic PMTs: single channels unit with 25 cm^2 active surface
- 45% Photon Detection Efficiency, 0.1 Hz/mm^2 Dark Noise Rate at 87 K
- Single photon sensitivity with very large separation of single photon peak from baseline (see next slide, SNR~14)

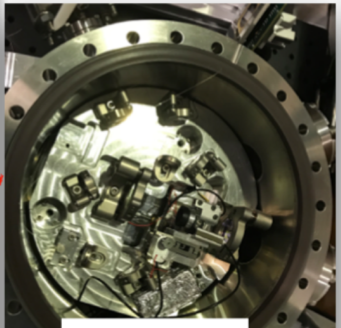


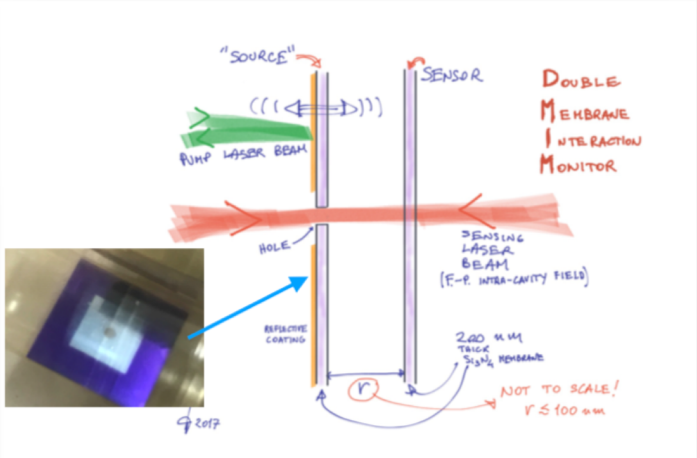


a-KWISP

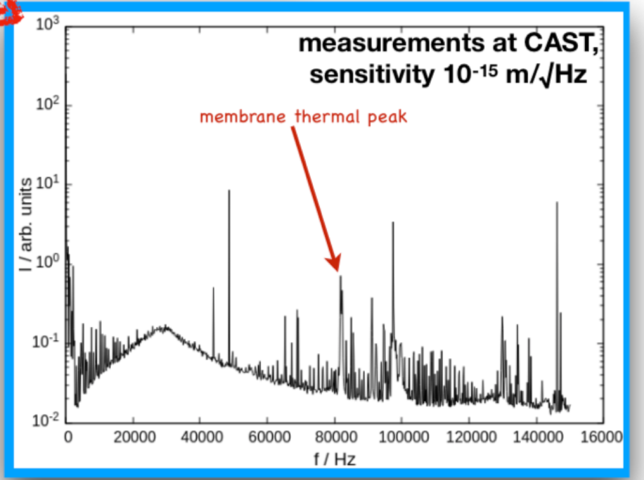
advanced-KWISP update

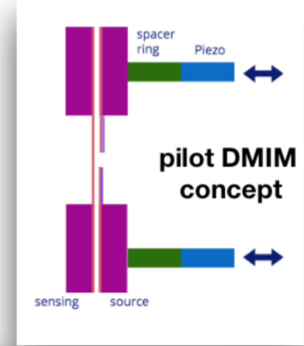
- **Recent technical advances (KWISP 3.0 at CAST)**
  - **compact, monolithic optical bench**
    - **successful vibration isolation: KWISP 3.0 is taking data at CAST in a “hostile” noise environment**
    - **ready for cooling, feasibility study programmed at CAST**
  - **custom membrane coatings**
    - **control quality factor, stiffness and electrical properties**
    - **characteristics tested in the lab with KWISP 1.5**
- **Next steps**
  - **assemble pilot DMIM**
  - **cryostat feasibility study (programmed at CAST)**


monolithic optical bench

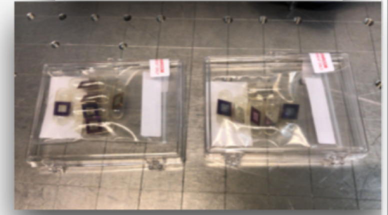


Basic *a*-KWISP concept



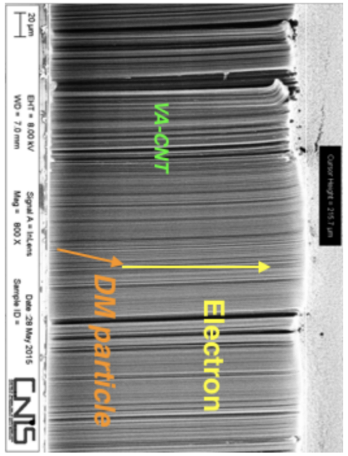


pilot DMIM concept



custom coated test membranes

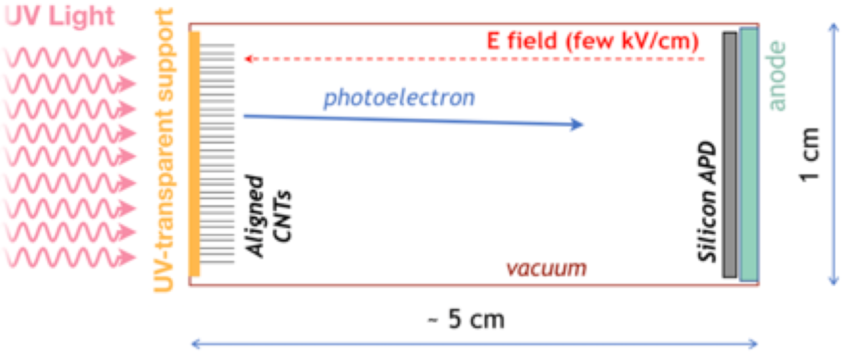
CNT detector for UV & dark PMT

arXiv:1911.01122

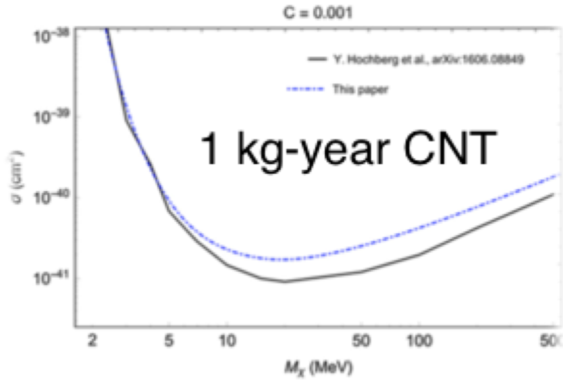


OR

- **NanoUV** - ***ATTRACT*** funded (F.Pandolfi); High QE, low noise detector for UV light

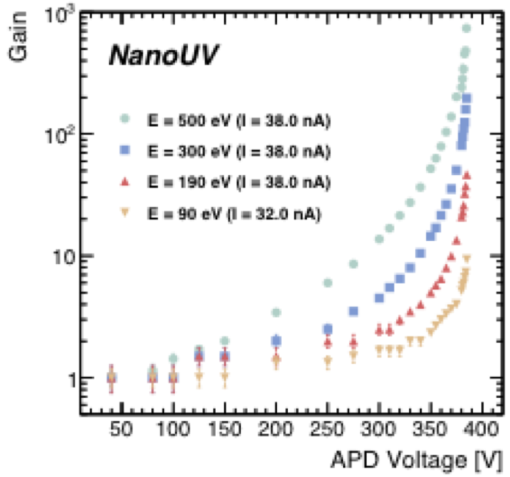


G.Cavoto, F.Luchetta, A.D.Polosa, Phys.Lett. B776 (2018) 338-344

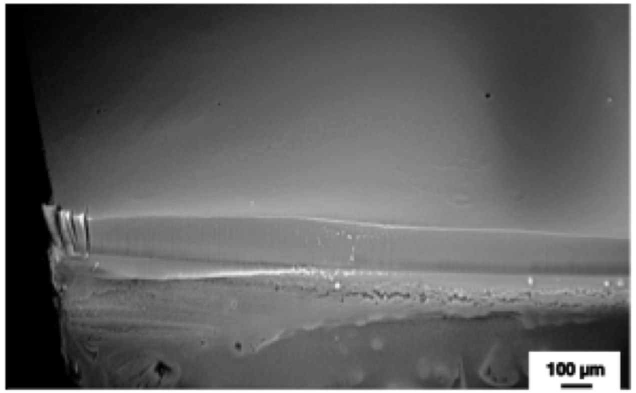


First step towards a **dark PMT**:
anisotropic photocathode filters electron scattered by DM when aligned with CNT

Si APD tested with 500 eV electrons



CNT on fused silica successfully synthesized



Slides: G. Cavoto

STAX 2019 Activities

Bilayer Cu-Al (10 nm), with tuning of Tc ~ 50 mK

Reduce T_c to improve microwave energy resolution

Submitted to Journal of Low Temperature Physics JLTP-D-19-00189

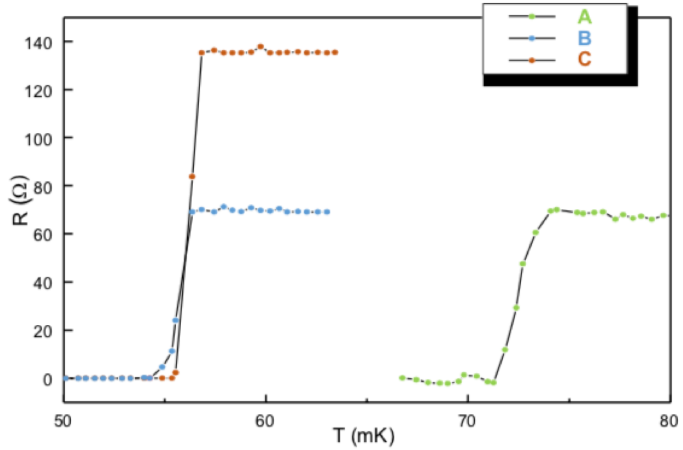
Tc suppression by vertical inverse proximity effect

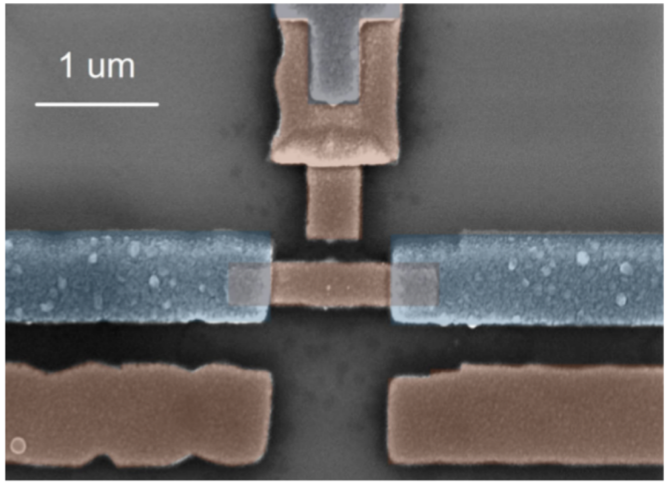
Cu/Al bilayer

Reduction of the wire section:
constant width *W*
smaller thickness *t*

t_N: thickness Cu
t_S: thickness Al

	A	B	C
W (nm)	120	120	120
Cu Thickness (nm)	14	15	15.5
Al Thickness (nm)	10	10	10





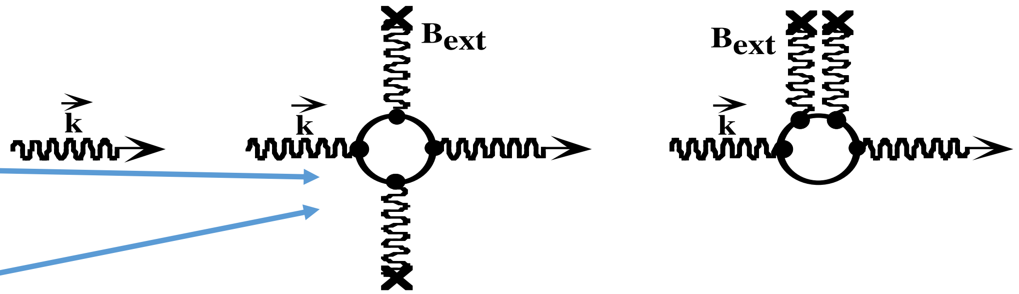
Low control on grain size for thin-film deposited at room temperature

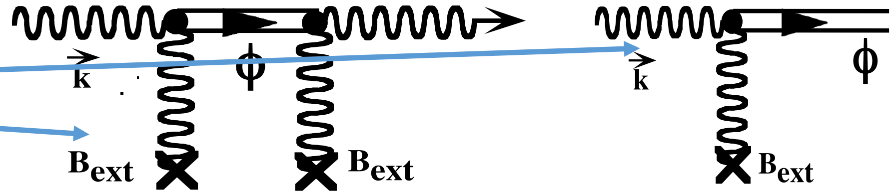
Above 15 nm the decrease in transition temperature saturates

VMB@CERN

Physics

- **Light-by-light interaction**
  - Velocity of light in an external field
    - First order in LbL
    - Radiative corrections
  - Existence of:
    - Millicharged particles
    - Axion-like particles
    - …





  - Light by light interaction in vacuum at low energies has been predicted but never observed yet.
  - <u>**Leads to n > 1 for the index of refraction in an external field.**</u>
  - <u>**Manifestation of quantum vacuum at a macroscopic level**</u>

Vacuum magnetic birefringence and dichroism

H. Euler and B. Kockel (1935) determined an effective Lagrangian density describing electromagnetic interactions in the presence of the virtual electron-positron sea discussed a few years before by Dirac.

$$\mathcal{L}_{\mathrm{EK}} = \frac{1}{2\mu_0}\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right)^2 + 7\left(\frac{\vec{\mathbf{E}}}{c}\cdot\vec{\mathbf{B}}\right)^2\right] + \dots$$

$$A_e = \frac{2}{45\mu_0}\frac{\hbar^3}{m_e^4 c^5}\alpha^2 = 1.32\times 10^{-24}\ \mathrm{T}^{-2}$$

H Euler and B Kochel, *Naturwissenschaften* **23**, 246 (1935)
W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)
H Euler, *Ann. Phys.* **26**, 398 (1936)
V Weisskopf, *Mat.-Fis. Med. Dan. Vidensk. Selsk.* **14**. 6 (1936)
J. Schwinger, *Phys. Rev.,* **82,** 664 (1951)

Predicts vacuum magnetic birefringence but no dichroism

$$\Rightarrow \Delta n_B = 3A_e B^2 \qquad \Delta\kappa_B \simeq 0$$

Axion-Like Particles (ALPs)

Extra terms can be added to the effective Lagrangian to include contributions from hypothetical neutral light particles weakly interacting with two photons

g_a, g_s coupling constants

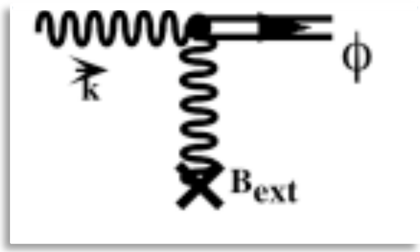
pseudoscalar

$$\mathcal{L}_a = g_a \phi_a \vec{E}_\gamma \cdot \vec{B}_{\mathrm{Ext}}$$

scalar

$$\mathcal{L}_s = g_s \phi_s \vec{B}_\gamma \cdot \vec{B}_{\mathrm{Ext}}$$

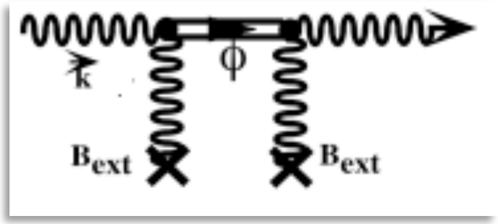
both interactions are polarisation dependent



$$x = \frac{L m_{a,s}^2}{4\omega}$$

Dichroism

$$|\Delta\kappa^{(\mathrm{ALP})}| = \kappa_{\parallel}^{a} = \kappa_{\perp}^{s} = \frac{2}{\omega L}\left(\frac{g_{a,s} B_{\mathrm{ext}} L}{4}\right)^2 \left(\frac{\sin x}{x}\right)^2$$



Birefringence

$$|\Delta n^{(\mathrm{ALP})}| = n_{\parallel}^{a} - 1 = n_{\perp}^{s} - 1 = \frac{g_{a,s}^2 B_{\mathrm{ext}}^2}{2 m_{a,s}^2}\left(1 - \frac{\sin 2x}{2x}\right)$$

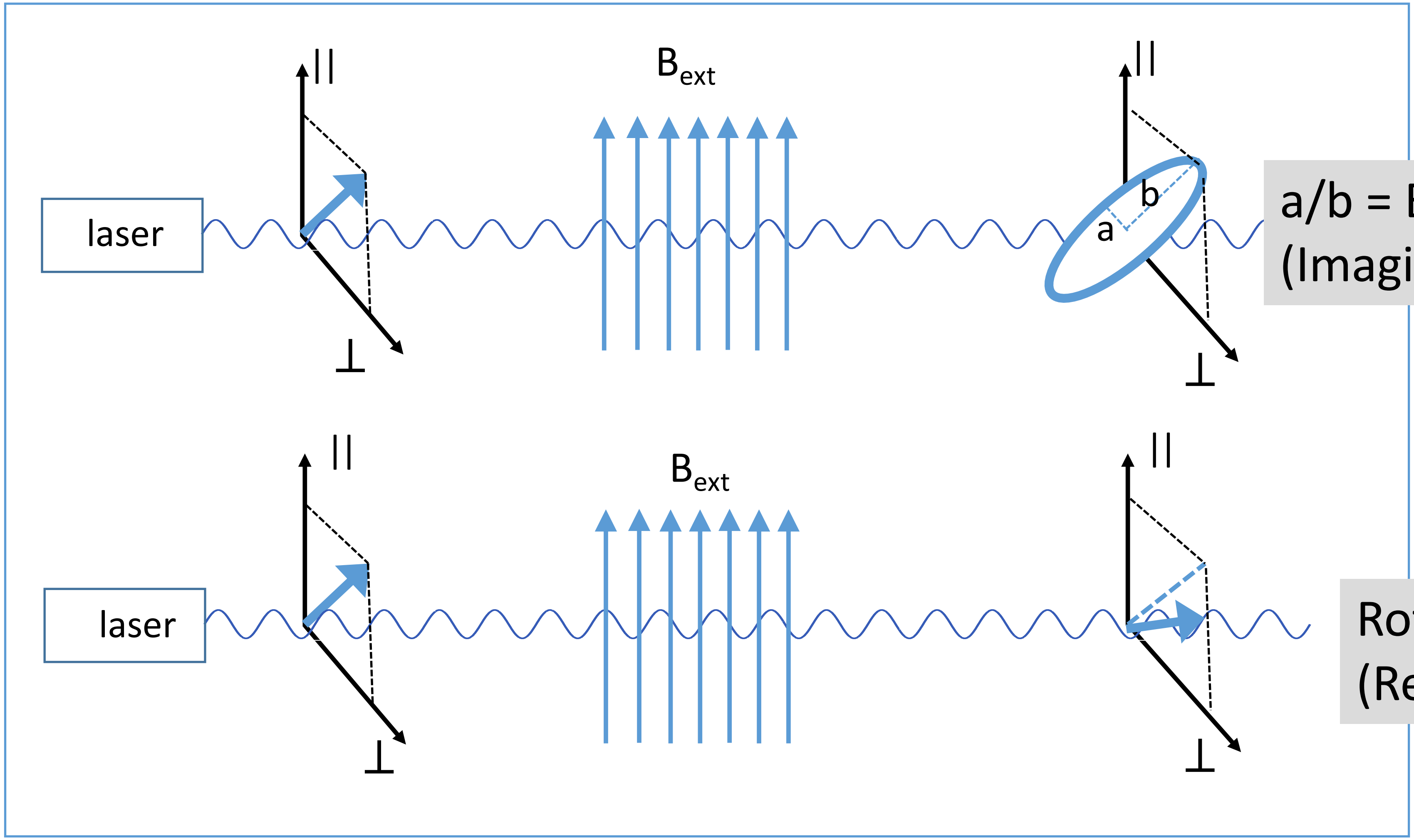
Maiani L, Petronzio R, Zavattini E, Phys. Lett B 173, 359 (1986)
Raffelt G and Stodolsky L Phys. Rev. D 37, 1237 (1988)

$$1\,\mathrm{T} = \sqrt{\frac{\hbar^3 c^3}{e^4 \mu_0}} = 195\,\mathrm{eV}^2, \quad 1\,\mathrm{m} = \frac{e}{\hbar c} = 5.06 \times 10^6\,\mathrm{eV}^{-1}$$

Measurable quantities

Birefringence Δn
- QED
- ALPs, MCPs

Dichroism $\Delta\kappa$
- ALPs, MCPs



a/b = Ellipticity (Imaginary)

Rotation (Real)

<u>Both Δn and $\Delta\kappa$ are defined with sign</u>

Key ingredients to measuring VMB

$$\Psi = \frac{\pi}{\lambda} L_{\text{eff}} \Delta n \sin 2\vartheta = N \frac{\pi}{\lambda} L_{\text{Mag}} \Delta n \sin 2\vartheta$$

Optical path multiplier (N)

Single pass ellipticity ($\frac{\pi}{\lambda} L_{\text{Mag}} \Delta n$)

- **Strong magnetic field**
  - maximize B^2L to maximize the optical path difference $\mathcal{D}_n = \Delta n\, L_{\text{Mag}}$
  - At B = 9 T => $\mathcal{D}_n = 3A_eB^2L \approx 5 \times 10^{-21}$ m
- **Long optical path** $L_{\text{eff}} = N L_{\text{Mag}}; \quad N = 2\mathcal{F}/\pi$
  - Fabry-Perot resonator
- **Modulate the induced ellipticity**
  - modulate the field or the polarization

General scheme: field modulation

ψ = single pass ellipticity
η = carrier ellipticity (either static or modulated)
N = number of equivalent passes
ϑ = angle between field and polarisation

Small ellipticities add up algebraically

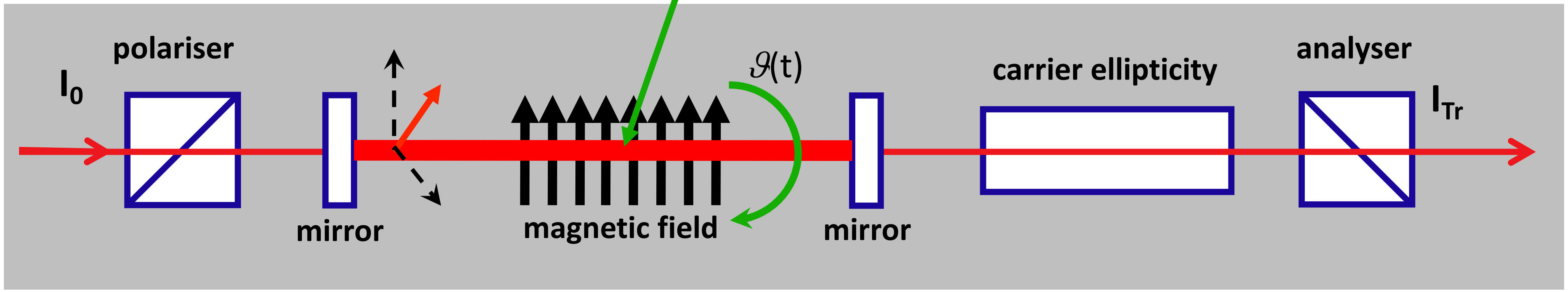
$$I_{\text{out}} \simeq I_0 \left| i\eta(t) + iN\psi \sin 2\vartheta(t) \right|^2$$

$$= I_0 \left[\eta^2(t) + 2\eta(t) N\psi \sin 2\vartheta(t) \right]$$

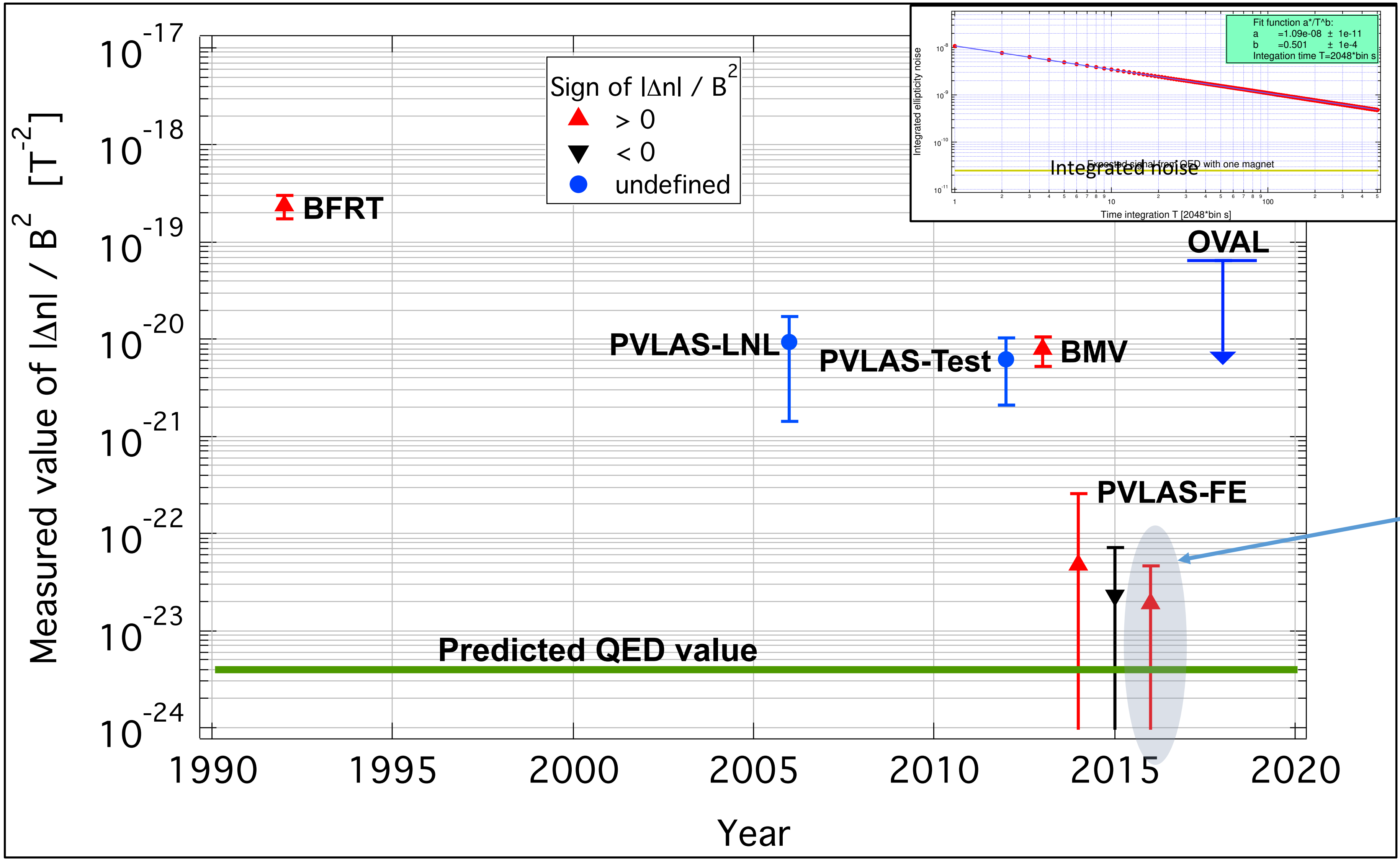
carrier ellipticity

signal

The output intensity is linear in the ellipticity ψ.



Timeline of VMB results



- 2016 PVLAS point corresponds to an integration T ≈ $5{\cdot}10^6$ s.
- Uncertainties are 1σ.
- The use of permanent magnets allowed detailed debugging.
- **Optical path difference $\Delta n\, L_{Mag}$ =(1.1 ± 1.6)·10^{-22} m**
- **PVLAS cannot overcome the gap by integrating longer.**

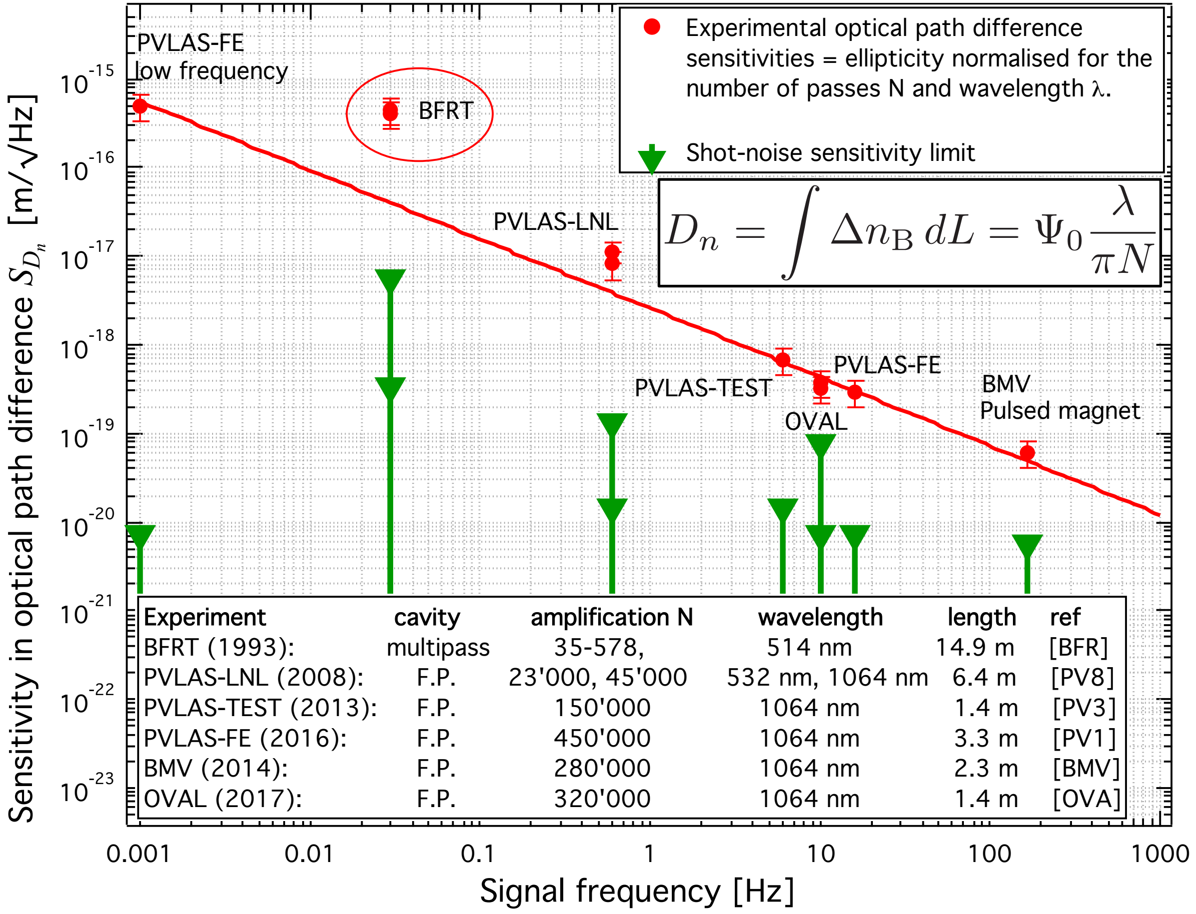
A. Ejlli, PhD Thesis, University of Ferrara, 2017, unpublished

F. Della Valle *et al.* (PVLAS collaboration), Eur. Phys. J. C 76, 24 (2016)

Limiting noise

Sensitivity in optical path difference $\mathcal{D}_n$ between two perpendicular polarizations.

All are well above their respective shot-noise.



Experiment	cavity	amplification N	wavelength	length	ref
BFRT (1993):	multipass	35-578,	514 nm	14.9 m	[BFR]
PVLAS-LNL (2008):	F.P.	23'000, 45'000	532 nm, 1064 nm	6.4 m	[PV8]
PVLAS-TEST (2013):	F.P.	150'000	1064 nm	1.4 m	[PV3]
PVLAS-FE (2016):	F.P.	450'000	1064 nm	3.3 m	[PV1]
BMV (2014):	F.P.	280'000	1064 nm	2.3 m	[BMV]
OVAL (2017):	F.P.	320'000	1064 nm	1.4 m	[OVA]

BFRT: R. Cameron et al. PRD, **47** (1993) 3707
PVLAS-LNL: M. Bregant et al. PRD, **78** (2008) 032006
PVLAS-TEST: F. Della Valle et al. NJP, **15** (2013) 053026
PVLAS-FE: F. Della Valle et al. EPJC, **76:24** (2016) 1
BMV: A. Cadène et al. EPJD, **68:16** (2014) 1

With a <u>very high finesse</u>, the sensitivity in $\mathcal{D}_n$ does not depend on the finesse.

<u>The noise originates from mirrors. It is amplified by *N* just like a signal</u>

Starting point for VMB@CERN

1) Highest possible B^2L with field always ON

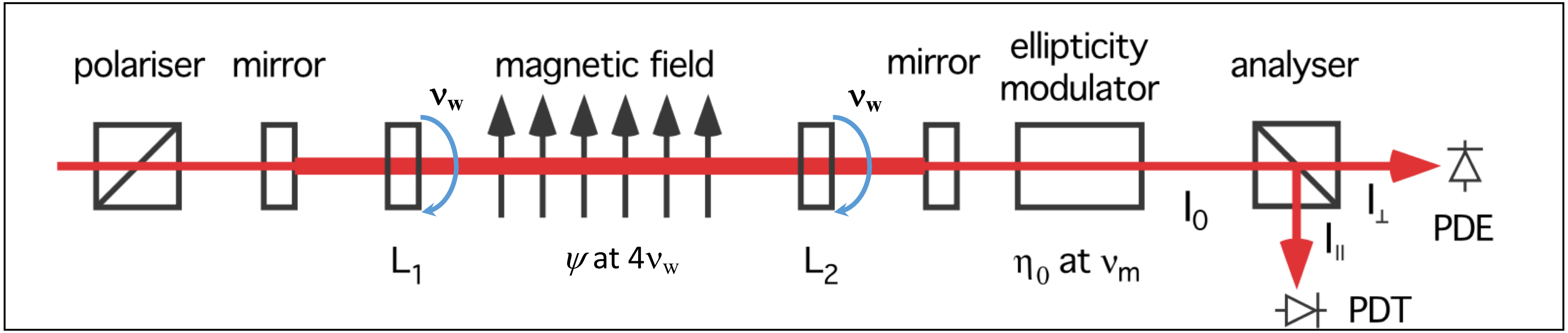
2) Separate modulation of effect from magnetic field

3) Assume the intrinsic noise curve in $\mathcal{D}_n$

- Increase B^2L: Static superconductor field
  - 1 LHC magnet has $B^2L \approx 1200$ T^2m.
  - 1 HERA magnet has $B^2L \approx 250$ T^2m
- Modulation of effect
  - Cannot be done with superconductor magnets above ≈ 0.1 Hz. Intrinsic noise dominates.
  - **Rotate the polarisation inside the magnetic field**
  - **… But must be kept fixed on the mirrors.**

Polarization modulation scheme

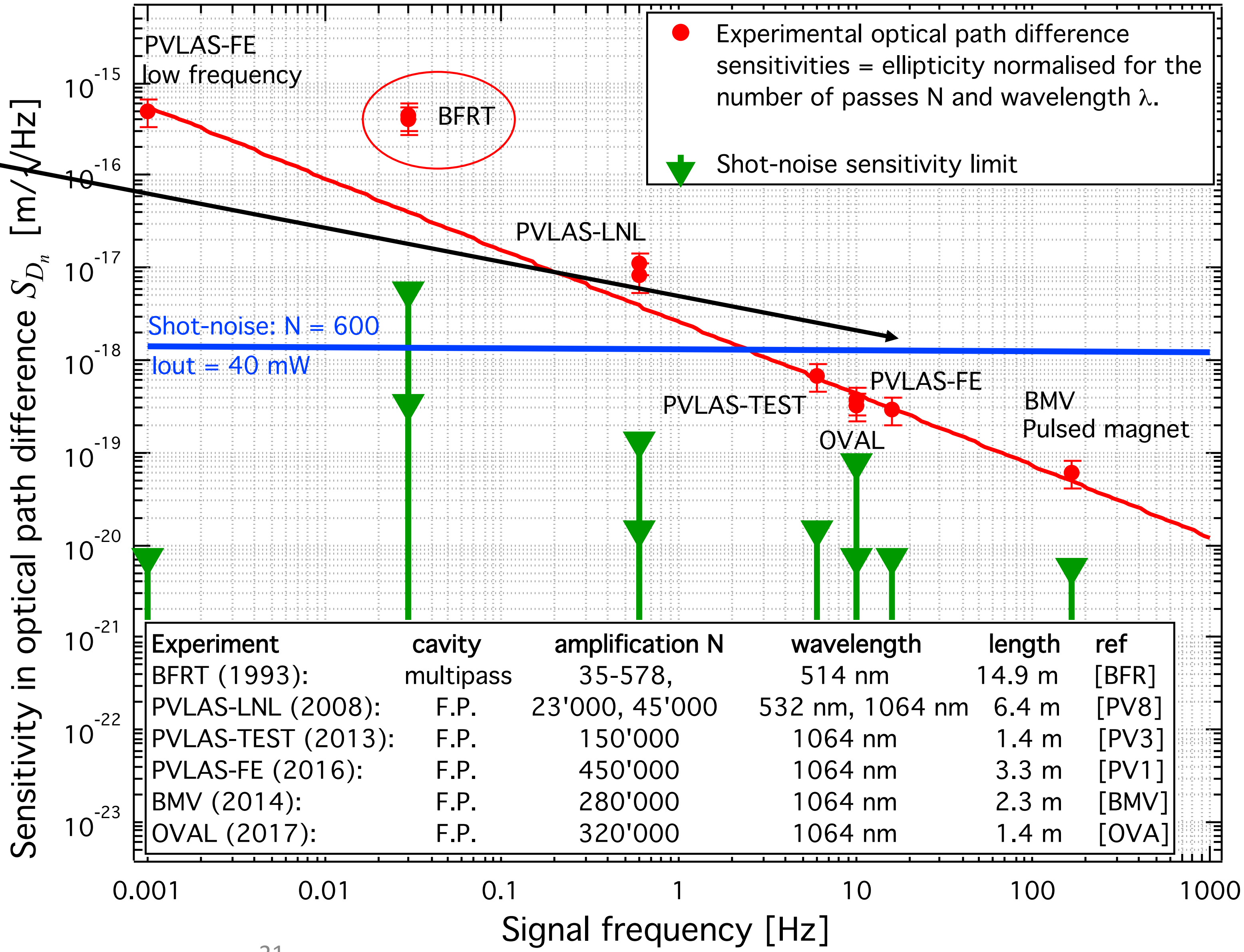
- Rotate polarization inside the magnet
- Fix polarization on mirrors to avoid mirror birefringence signal
- Insert two co-rotating half wave plates with a fixed relative angle $\Delta\phi$
  - Total losses ≤ 0.4% (commercial). Maybe 10 times lower is possible.
  - Maximum N ≈ 600 (with ≤ 0.4% losses). Maybe X 10 ?
  - N = 600 ⇔ $\mathcal{F}$ = 1000



• Systematic effects must be studied during the first 2 years of the project (in local labs)

Optical path difference sensitivity

- VMB can be reached at SNR = 1 in ≈12 hrs with sensitivity 10^{-18} m/√Hz
- Not limited by cavity noise above ≈ 3 Hz
- Possible parameters: N = 600, I_{out} = 40mW at shot noise
- Parameter space (N, I_{out}, freq) needs to be explored
- sensitivity needs demonstration



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VMB@CERN Letter of Intent

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

2018-xxx
December 3, 2018

Letter of Intent to measure Vacuum Magnetic Birefringence: the VMB@CERN experiment

R. Ballou[1], F. Della Valle[2], A. Ejlli[3], U. Gastaldi[4], H. Grote[3], Š. Kunc[5], K. Meissner[6], E. Milotti[7], W.-T. Ni[8], S.-s. Pan[9], R. Pengo[10], P. Pugnat[11], G. Ruoso[10], A. Siemko[12], M. Šulc[5] and G. Zavattini[13]*

[1]Institut Néel, CNRS and Université Grenoble Alpes, Grenoble, France
[2]INFN, Sez. di Pisa, and Dip. di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (SI), Italy
[3]School of Physics and Astronomy, Cardiff University, Cardiff, UK
[4]INFN, Sez. di Ferrara, Ferrara (FE), Italy
[5]Technical University of Liberec, Czech Republic
[6]Institute of Theoretical Physics, University of Warsaw, Poland
[7]Dip. di Fisica, Università di Trieste and INFN, Sez. di Trieste, Trieste (TS), Italy
[8]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, ROC
[9]Center of Measurement Standards, Industrial Technological Research Institute, Hsinchu, Taiwan, ROC
[10]INFN, Lab. Naz. di Legnaro, Legnaro (PD), Italy
[11]LNCMI, EMFL, CNRS and Université Grenoble Alpes, Grenoble, France
[12]CERN, Genève, Switzerland
[13]Dip. di Fisica e Scienze della Terra, Università di Ferrara and INFN, Sez. di Ferrara, Ferrara (FE), Italy

- Polarisation scheme was presented at the PBC open meeting in November 2017
- VMB@CERN coagulated within the PBC from PVLAS, OSQAR and independently from Q&A
- Why at CERN? With the LHC magnets, CERN has the highest B^2L
- December 2018: presented LoI to SPSC
- January 2019: assigned referees from SPSC
- April 2019: first meeting with SPSC referees
- September 2019: funded testing phase by INFN for 2020. Approved also for 2021 depending on CERN iter.
- October 2019: presented to the SPSC with a positive feedback

Present VMB@CERN collaboration

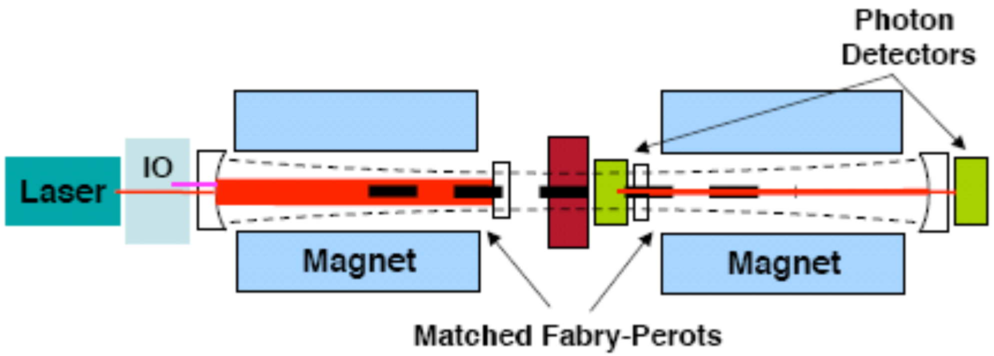
Š. Kunc, M. Šulc
Technical University of Liberec, Czech Republic
R. Balou
Institut Néel, CNRS and Université Grenoble Alpes, Grenoble, France
P. Pugnat
LNCMI, EMFL, CNRS and Université Grenoble Alpes, Grenoble, France
M. Andreotti, P. Cardarelli, U. Gastaldi
I.N.F.N., Sezione di Ferrara, Via Saragat 1, Blocco C, 44100 Ferrara, Italy
G. Di Domenico, G. Zavattini
I.N.F.N., Sezione di Ferrara and Dipartmento di Fisica, Università di Ferrara, Via Saragat 1, Blocco C, 44100 Ferrara, Italy
F. Della Valle, C. Marinelli, E. Mariotti
INFN, Sez. di Pisa, gruppo collegato di Siena and Dip. di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (SI), Italy
V. Biancalana
INFN, Sez. di Pisa, gruppo collegato di Siena and Dip. di Ingegneria, Università di Siena, Siena (SI), Italy
R. Pengo, G. Ruoso
I.N.F.N., Laboratori Nazionali di Legnaro, viale dell'Università 2, 35020 Legnaro, Italy
Y-R Liang
Wuhan Institute of Physics and Mathematics, Chinese Academy of Science, Wuhan, People's Republic of China
K. Meissner
Institute of Theoretical Physics, University of Warsaw, Poland
A. Siemko
CERN, CH-1211 Geneva-23, Switzerland
W-T. Ni
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, ROC
S-s Pan
Center of Measurement Standards, Industrial Technological Research Institute, Hsinchu, Taiwan, ROC
A. Ejlli, H. Grote
University of Cardiff, Wales, UK

Lots of progress on initiatives

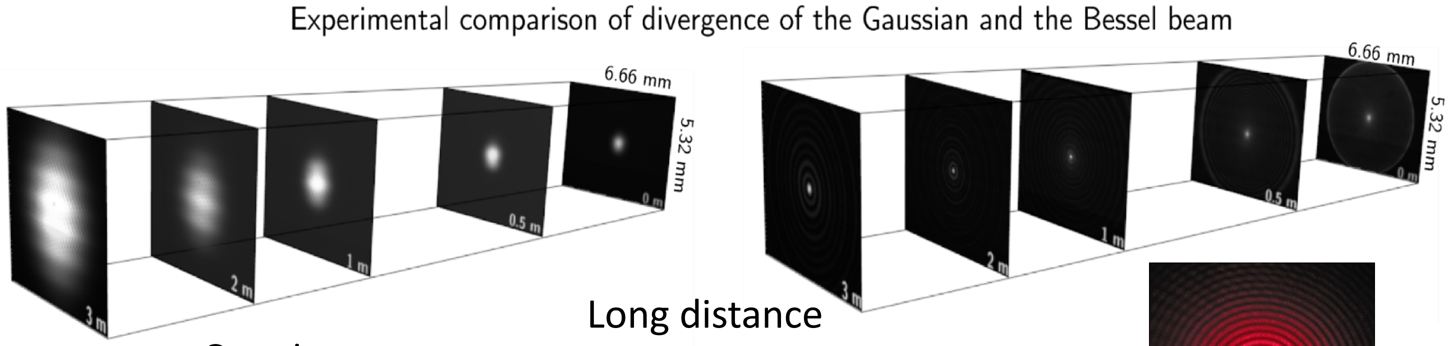
Backups

From OSQAR & ALPS toward Baby-JURA & JURA

- Exploiting the unique opportunity offered by LHC/FCC sc. dipole magnets
  - Use **up to** 15+15 LHC dipoles, 9 T, 14.3 m, 50 mm dia.
  - Use 16 T FCC sc. dipoles to be built
- Synergy with VMB@CERN & ALPS-II for the development of long fabry-Perot cavities and optical schemes
- Synergy with OSQAR for the development of low divergent optical beam

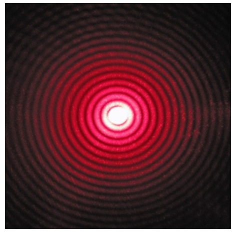


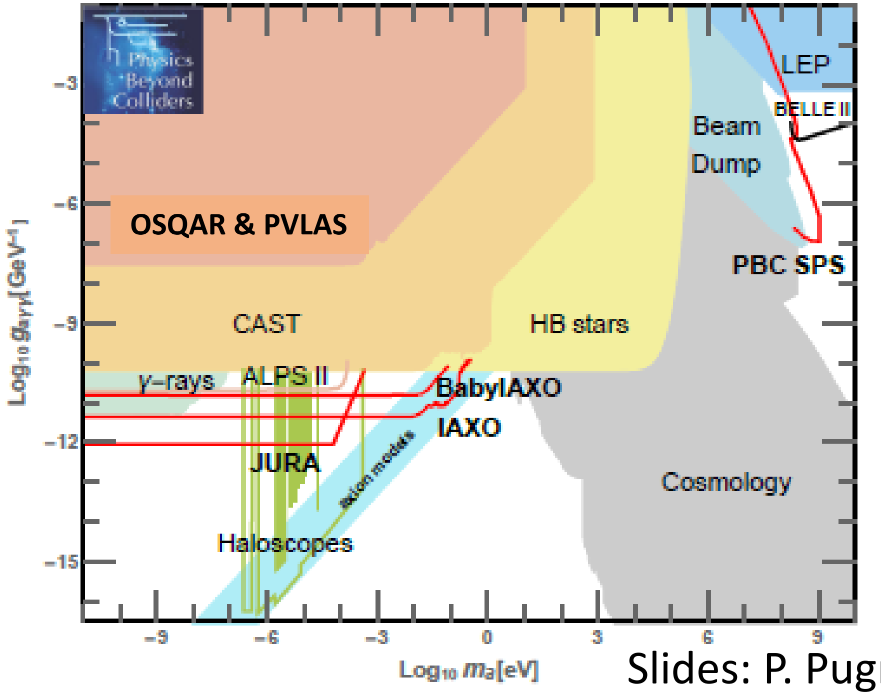
P. Sikivie at al, Phys. Rev. Lett. **98**, 172002 (2007)



Gaussian

Long distance
Structured Beam – Bessel



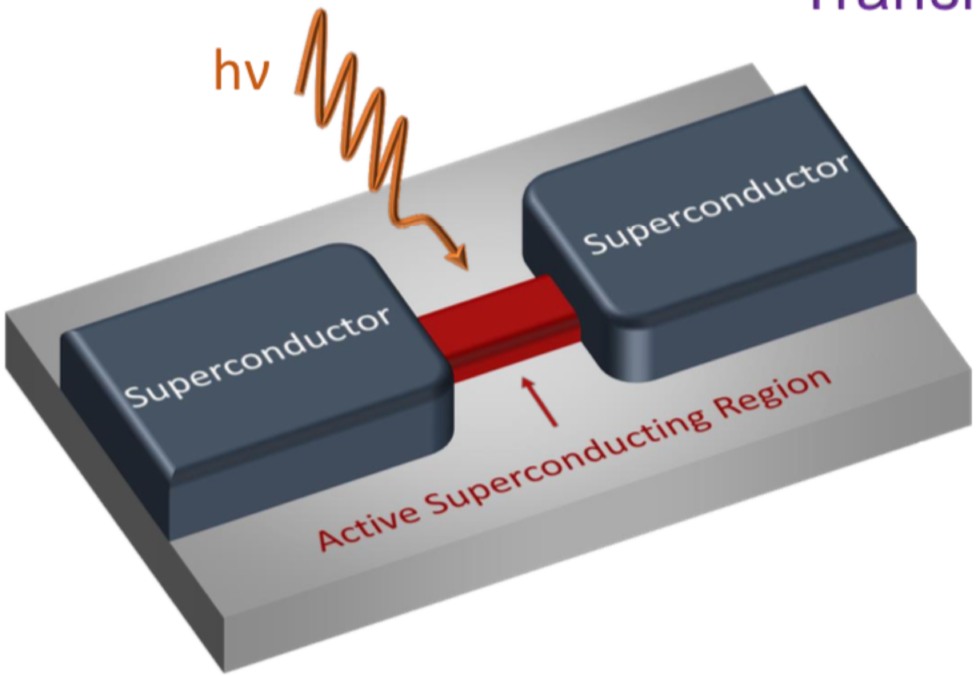


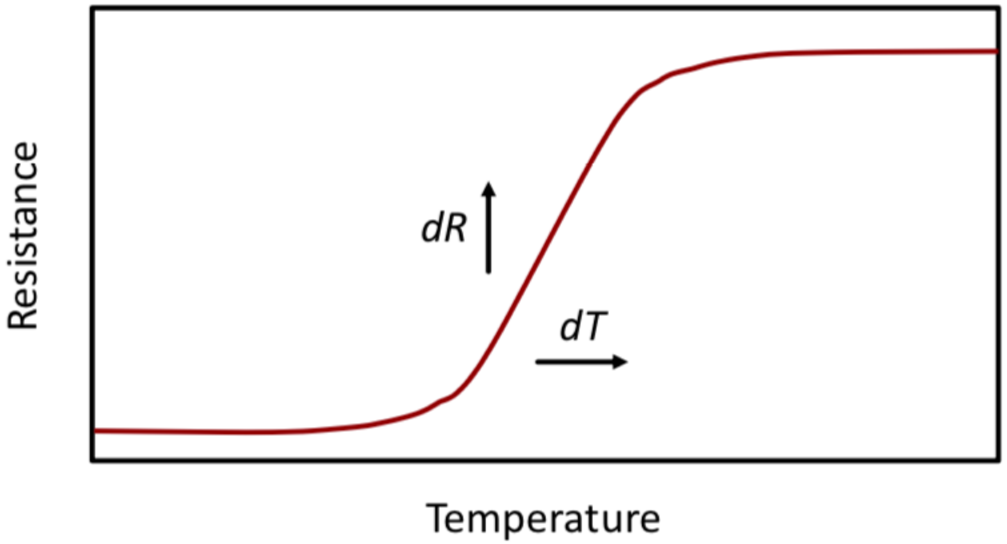
Beam diameter	3 m distance	100 m distance
Gaussian	0.8 mm	240 mm
SB	0.01 mm	1.4 mm

https://home.cern/fr/news/news/knowledge-sharing/long-sighted-laser-beam

Slides: P. Pugnat

Transition Edge Sensors





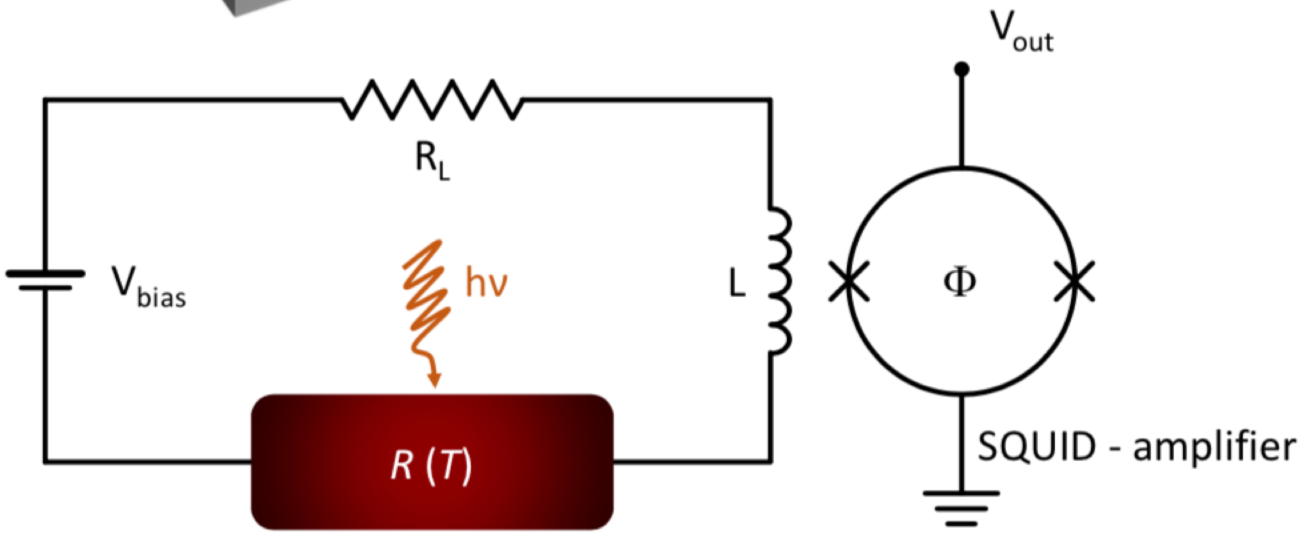


Figure of merit: $\alpha = \frac{T}{R}\frac{dR}{dT}$

R - resistance of active region

T - temperature of active region

Energy resolution: $\Delta E \cong 2.35\sqrt{2k_B T^2 \frac{C}{\alpha}}$

k_B - Boltzmann constant

Heat capacity: $C = \gamma V_{Active} T$

γ - Sommerfeld coefficient

V_{Active} - active region volume

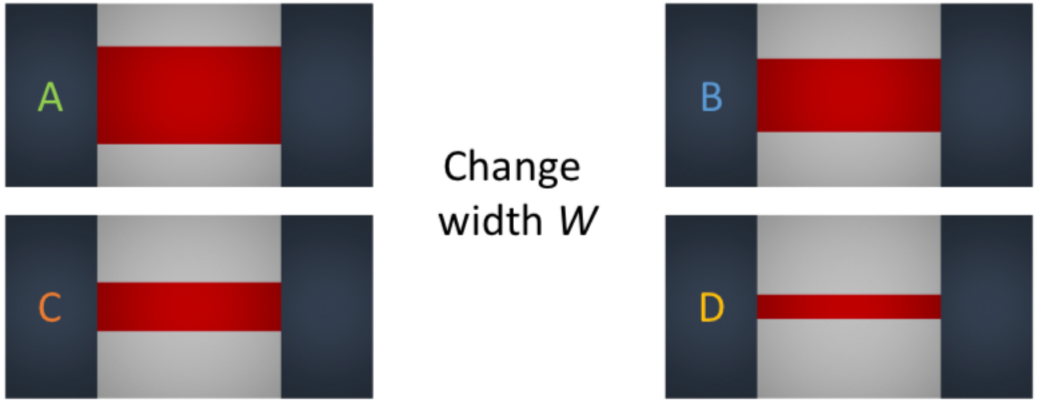
Transition Edge Sensors: Critical Temperature

For axions detection: $T_{C,Active}$~20mK

Phys. Dark Universe **12**, 37 (2016)

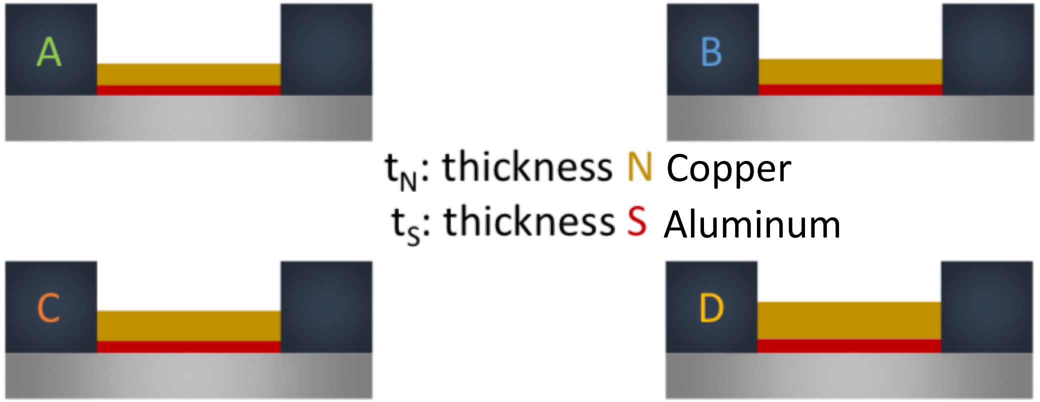
T_C suppression by spatial confinement

Phys. Rev. B **85**, 094508 (2012)C

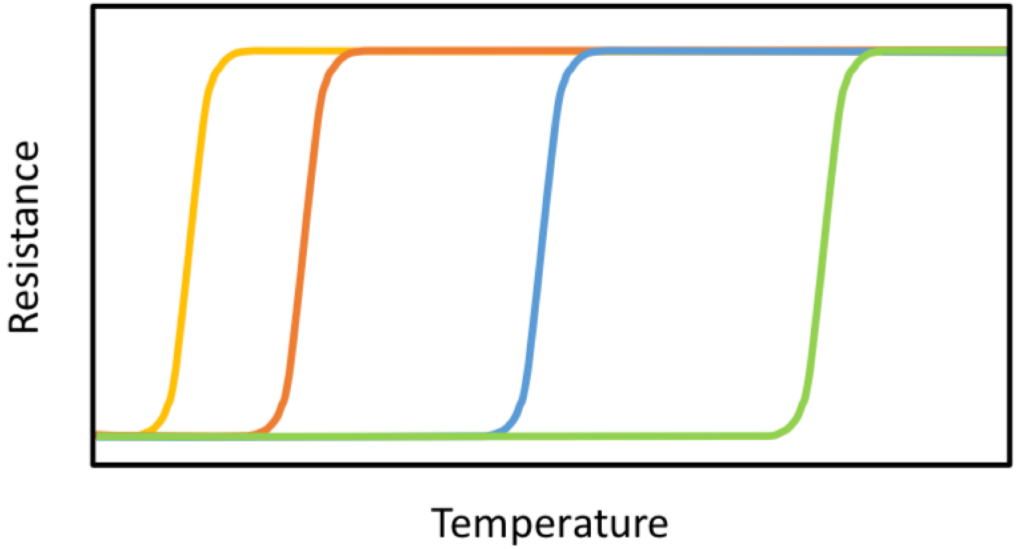


T_C suppression by vertical inverse proximity effect

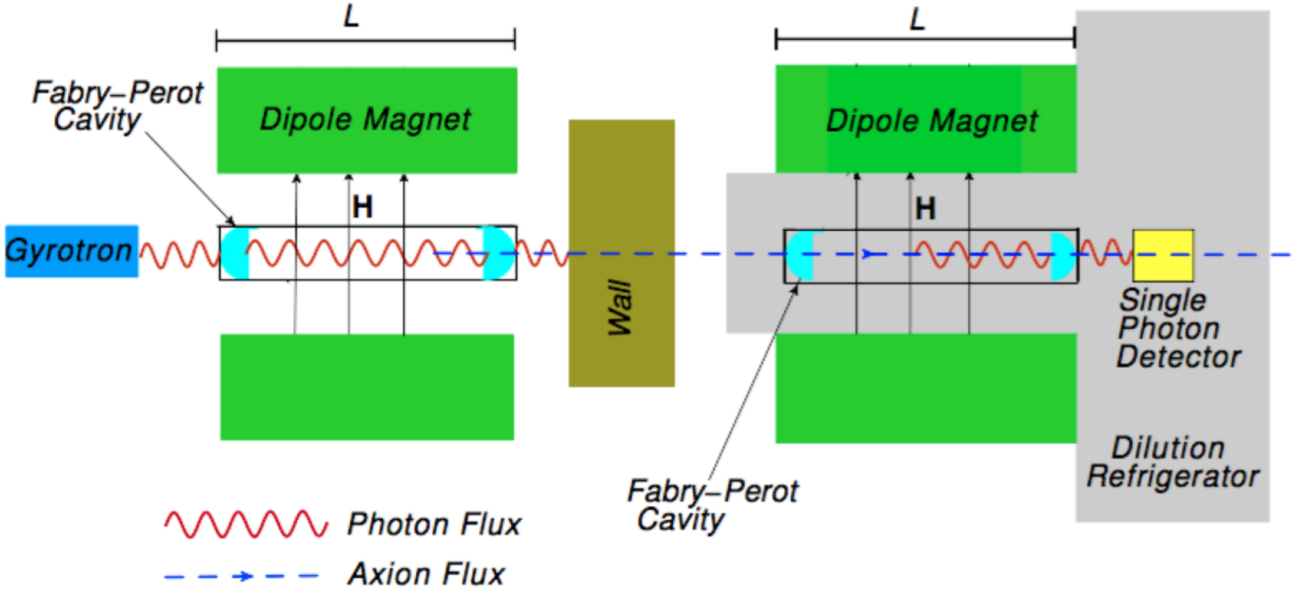
Superconductivity Of Metals And Alloys, Advanced Books Classics (Westview Press, 1999)



Reduction of the wire section:
constant thickness *t*
smaller width *W*



Bilayer:
Normal metal
Superconductor



STAX

Development of a microwave TES single photon detector

LSW - experiment with microwaves

Slides: P. Spagnolo