Quantum sensor applications to (low and high)-energy physics

M. Doser, CERN

“Sala TV” but no popcorn…

Otranto, 5.6.2022

What are the challenges?

① Some words on the landscape

Clarification of terms

Quantum sensors for low energy particle physics

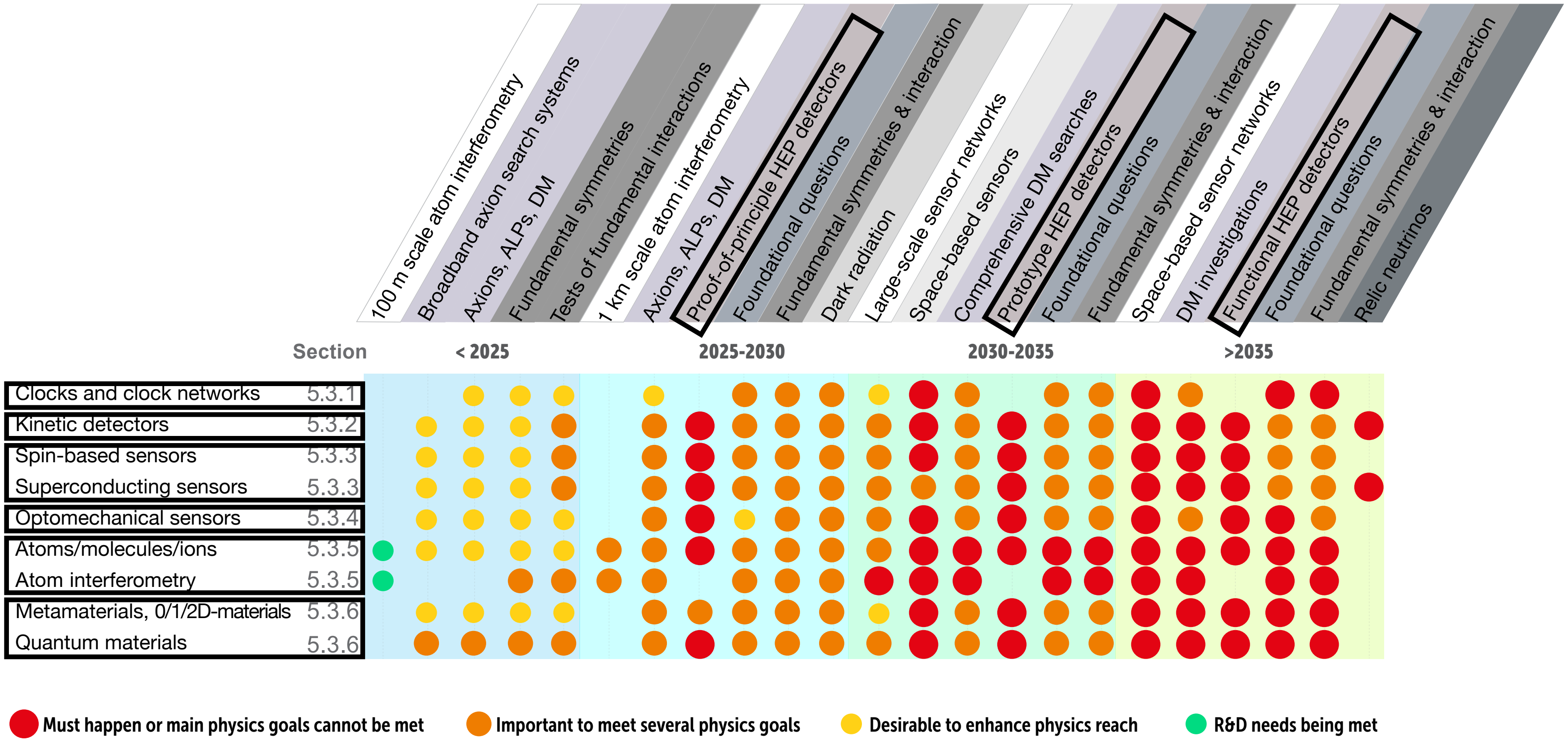
② Quantum sensors for new particle physics experiments

③ Quantum detectors for high energy particle physics

RECFA Detector R&D roadmap 2021

https://cds.cern.ch/record/2784893

Chapter 5: Quantum and Emerging Technologies Detectors



	Section	< 2025					2025-2030						2030-2035						>2035					
		100 m scale atom interferometry	Broadband axion search systems	Axions, ALPs, DM	Fundamental symmetries	Tests of fundamental interactions	1 km scale atom interferometry	Axions, ALPs, DM	Proof-of-principle HEP detectors	Foundational questions	Fundamental symmetries & interaction	Dark radiation	Large-scale sensor networks	Space-based sensors	Comprehensive DM searches	Prototype HEP detectors	Foundational questions	Fundamental symmetries & interaction	Space-based sensor networks	DM investigations	Functional HEP detectors	Foundational questions	Fundamental symmetries & interaction	Relic neutrinos
Clocks and clock networks	5.3.1			🟡	🟡	🟡		🟡		🟠	🟠	🟠	🟡	🔴	🟠		🟠	🟠	🔴	🟠		🔴	🔴	
Kinetic detectors	5.3.2		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Spin-based sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	
Superconducting sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🟠	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Optomechanical sensors	5.3.4		🟡	🟡	🟡	🟡		🟠	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🟠	🔴	🔴	🟠	
Atoms/molecules/ions	5.3.5	🟢	🟡	🟡	🟡	🟡	🟠	🟠	🔴	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Atom interferometry	5.3.5	🟢			🟠	🟠	🟠	🟠		🟠	🟠	🟠	🔴	🔴	🔴		🔴	🔴	🔴	🔴		🔴	🔴	
Metamaterials, 0/1/2D-materials	5.3.6		🟡	🟡	🟡	🟡		🟠	🟠	🟠	🟠	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	
Quantum materials	5.3.6		🟠	🟠	🟠	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	

🔴 Must happen or main physics goals cannot be met

🟠 Important to meet several physics goals

🟡 Desirable to enhance physics reach

🟢 R&D needs being met

Chapter 4: Particle Identification and Photon Detectors

It is recommended that several “blue-sky” R&D activities be pursued. The development of solid state photon detectors from novel materials is an important future line of research, as is the development of cryogenic superconducting photosensors for accelerator- based experiments. Regarding advances in PID techniques, gaseous photon detectors for visible light should be advanced. Meta-materials such as photonic crystals should be developed, giving tune-able refractive indices for PID at high momentum. Finally, for TRD imaging detectors, the detection of transition radiation with silicon sensors is an important line of future research.

Anna Grassellino, Marcel Demarteau, Michael Doser, Caterina Braggio, Stafford Withington, Peter Graham, John March-Russel, Andrew Geraci

ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

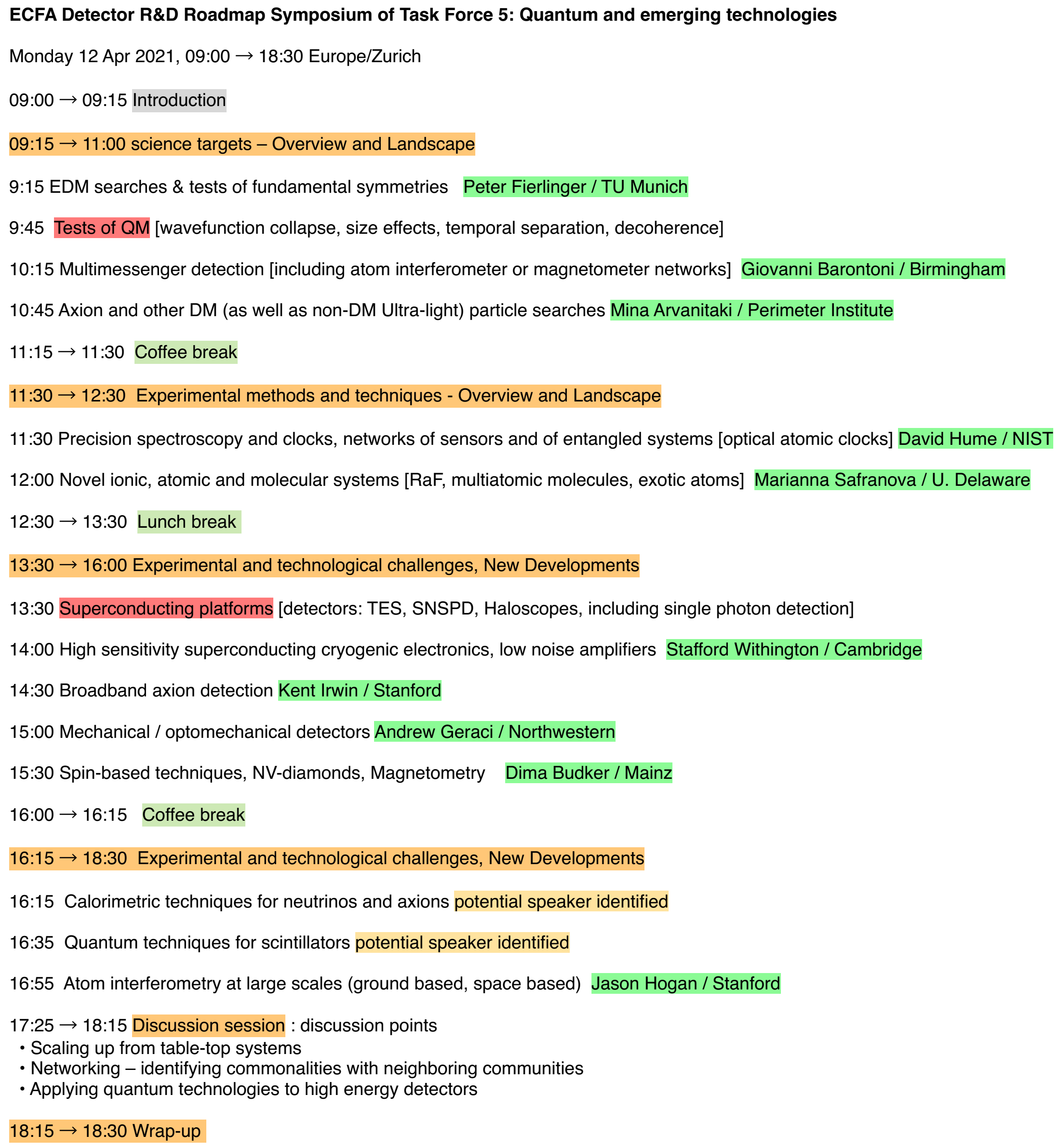
Symposium: April 12, 2022 https://indico.cern.ch/event/999818/

14 presentations

first block covering physics landscape

following blocks focusing on technologies

discussion of three important points



ECFA Detector R&D Roadmap Symposium of Task Force 5: Quantum and emerging technologies

Monday 12 Apr 2021, 09:00 → 18:30 Europe/Zurich

09:00 → 09:15 Introduction

09:15 → 11:00 science targets – Overview and Landscape

9:15 EDM searches & tests of fundamental symmetries Peter Fierlinger / TU Munich

9:45 Tests of QM [wavefunction collapse, size effects, temporal separation, decoherence]

10:15 Multimessenger detection [including atom interferometer or magnetometer networks] Giovanni Barontoni / Birmingham

10:45 Axion and other DM (as well as non-DM Ultra-light) particle searches Mina Arvanitaki / Perimeter Institute

11:15 → 11:30 Coffee break

11:30 → 12:30 Experimental methods and techniques - Overview and Landscape

11:30 Precision spectroscopy and clocks, networks of sensors and of entangled systems [optical atomic clocks] David Hume / NIST

12:00 Novel ionic, atomic and molecular systems [RaF, multiatomic molecules, exotic atoms] Marianna Safranova / U. Delaware

12:30 → 13:30 Lunch break

13:30 → 16:00 Experimental and technological challenges, New Developments

13:30 Superconducting platforms [detectors: TES, SNSPD, Haloscopes, including single photon detection]

14:00 High sensitivity superconducting cryogenic electronics, low noise amplifiers Stafford Withington / Cambridge

14:30 Broadband axion detection Kent Irwin / Stanford

15:00 Mechanical / optomechanical detectors Andrew Geraci / Northwestern

15:30 Spin-based techniques, NV-diamonds, Magnetometry Dima Budker / Mainz

16:00 → 16:15 Coffee break

16:15 → 18:30 Experimental and technological challenges, New Developments

16:15 Calorimetric techniques for neutrinos and axions potential speaker identified

16:35 Quantum techniques for scintillators potential speaker identified

16:55 Atom interferometry at large scales (ground based, space based) Jason Hogan / Stanford

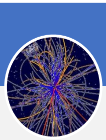
17:25 → 18:15 Discussion session : discussion points
- Scaling up from table-top systems
- Networking – identifying commonalities with neighboring communities
- Applying quantum technologies to high energy detectors

18:15 → 18:30 Wrap-up

CERN quantum initiative

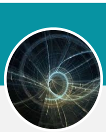
https://quantum.web.cern.ch/

CERN | QUANTUM TECHNOLOGY INITIATIVE



- Assess the **areas of potential quantum advantage** in HEP applications (QML, classification, anomaly detection, tracking)
- Develop **common libraries of algorithms, methods, tools**; benchmark as technology evolves
- Collaborate to the development of shared, **hybrid classic-quantum infrastructures**

Computing & Algorithms



- Identify and develop techniques for **quantum simulation** in collider physics, QCD, cosmology within and beyond the SM
- Co-develop quantum computing and sensing approaches by providing **theoretical foundations** to the identifications of the areas of interest

Simulation & Theory

- Develop and promote **expertise in quantum sensing** in low- and high-energy physics applications
- Develop quantum sensing approaches with emphasis on **low-energy particle physics measurements**
- Assess **novel technologies and materials** for HEP applications

Sensing, Metrology & Materials

currently: 2.5 PhD’s

- **Co-develop CERN technologies relevant to quantum infrastructures** (time synch, frequency distribution, lasers)
- Contribute to the **deployment and validation of quantum infrastructures**
- Assess requirements and **impact of quantum communication on computing applications** (security, privacy)

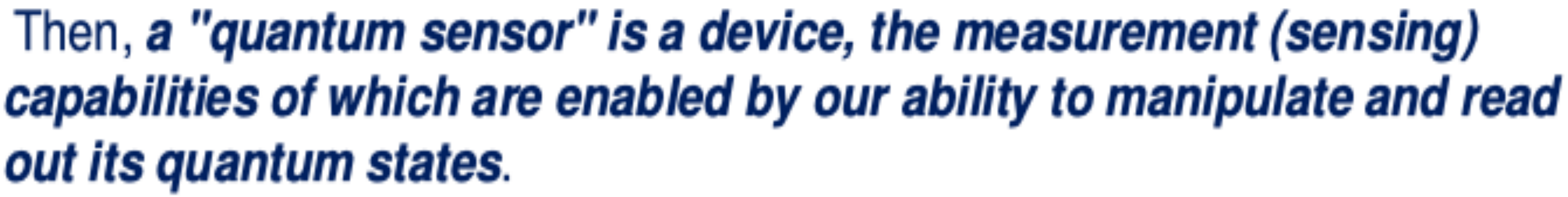
Communications & Networks

https://quantum.web.cern.ch/

Clarification of terms

quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)



Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states.***

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

→focus on CERN activities both in low energy and high energy particle physics

(I will not however be talking about entanglement and its potential applications)

particle physics: what are we talking about?

Background

- Light DM candidate have large mode volume occupation number -> can be treated as classical fields

- QCD Axions and ALPs $\mathcal{L}_{axion} \supset \sum_f \frac{c_f}{\Lambda} \partial_\mu a \, \bar{f}\gamma^\mu\gamma^5 f \rightarrow \mathrm{H} \propto \sum_f \boldsymbol{\nabla} a \cdot \boldsymbol{S}_f$
  - $\boldsymbol{\nabla} a$ acts as a pseudo magnetic field ➔ can be detected by atomic magnetometers

- Scalar fields $\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon}F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$
  - Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as variations of fundamental constants

- symmetry violations probed via precision measurements ($\not{C}$P, C$\not{P}$T, Lo$\not{r}$enz, W$\not{E}$P, …) ➔ SME

D. Colladay, V.A. Kostelecký, "CPT violation and the standard model". Physical Review D. 55 (11) (1997) 6760–6774. arXiv:hep-ph/9703464

quantum sensors & particle physics: what are we talking about?

domains of physics

- search for NP / BSM
- Axions, ALP's, DM & non-DM UL-particle searches
- tests of QM — wavefunction collapse, decoherence
- EDM searches & tests of fundamental symmetries

quantum technologies

① superconducting devices (TES, SNSPD, …) / cryo-electronics

② spin-based, NV-diamonds

③ optical clocks

④ ionic / atomic / molecular

⑤ optomechanical sensors

⑥ metamaterials, 0/1/2-D materials

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/

① superconducting devices (TES, SNSPD, …) / cryo-electronics

superconducting bolometers in the form of a transition edge sensor (TES) : 1990

invention of kinetic inductance detectors (KID): 2000's

Photons incident on a strip of superconducting material break Cooper pairs and create excess quasiparticles. The kinetic inductance of the superconducting strip is inversely proportional to the density of Cooper pairs, and thus the kinetic inductance increases upon photon absorption. This inductance is combined with a capacitor to form a microwave resonator whose resonant frequency changes with the absorption of photons

introduction of the travelling wave parametric amplifier (TWPA) for quantum noise limited coherent amplification of large bandwidth: 2010

Superconducting qubits for quantum computing, superconductor/spin-system quantum memory elements: 2020

Superconducting device physics is a whole technology, based on thin film deposition techniques and lithographic patterning and allowing large scale integration with high degree of functionality

	Microwave	Submillimetre	Far infrared	Optical	High energy
	10 – 100 GHz 3 cm- 3 mm	100 GHz – 1 THz 3 mm – 300 µm	1 – 10 THz 300 – 30 µm	2 µm – 300 nm	UV, Yray and Xray
SIS mixers		🟢			
HEB			🟢		
CEB		🟢			
TES	🔴	🟢	🟢	🟢	🟢
KID	🔴	🟢	🟢	🟢	
SNSPD			🔴	🟢	
SQUID	🟢				
JJPA	🟢				
TWPA	🟢	🔴			

Superconducting nanowire single photon detector

Superconducting quantum interference device

Josephson junction parametric amplifier

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https://indico.cern.ch/event/999818/ Stafford Withington (Cambridge)

① superconducting devices (TES, SNSPD, …) / cryo-electronics

superconducting bolometers in the form of a transition edge sensor (TES) : x-ray imaging

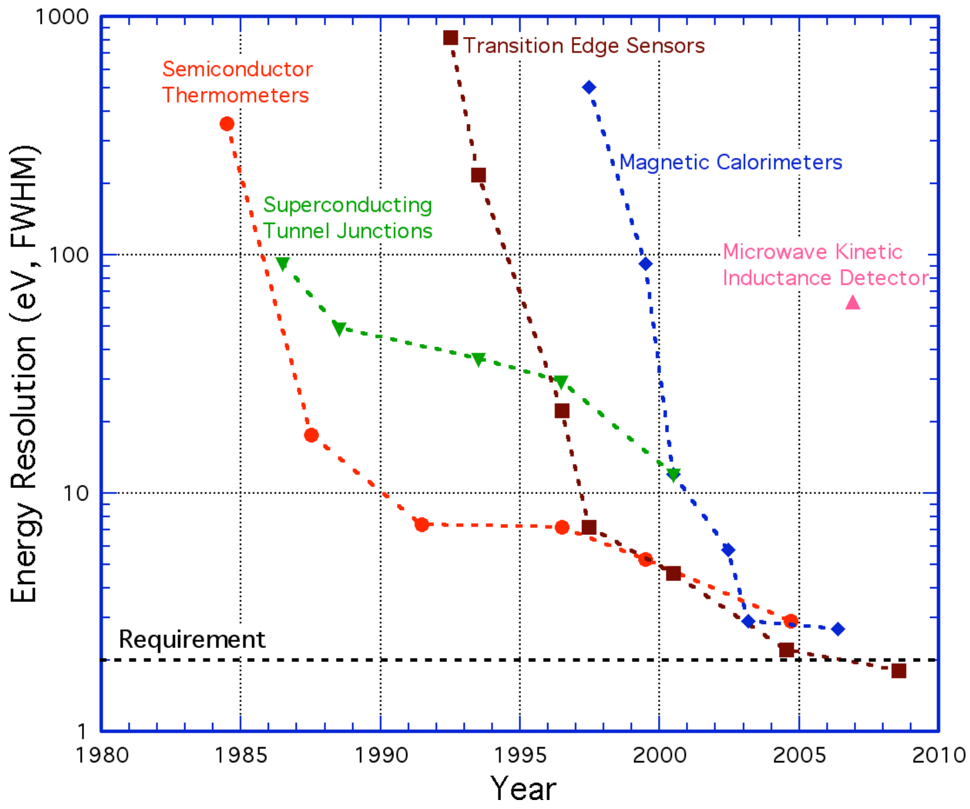
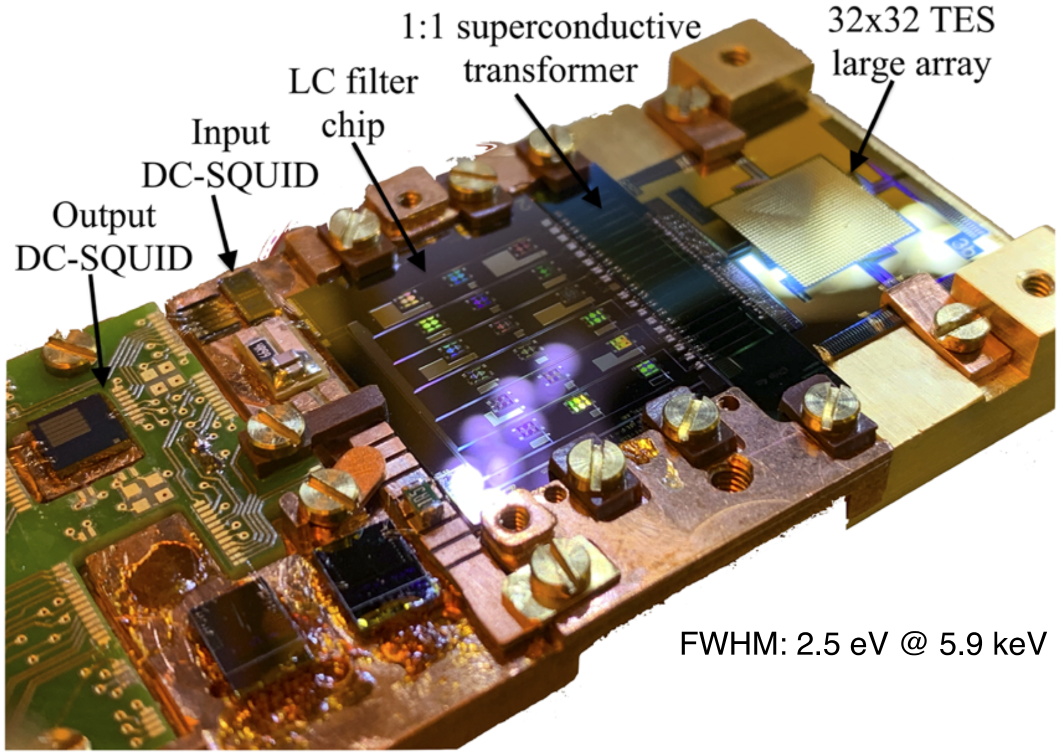


Fig. 1. Time evolution of energy resolution at 6 keV as a function of time for three microcalorimeter technologies.

Development of Low-Temperature Detectors For Generation-X and Other Missions Requiring High-Resolution, Large-Format, X-ray Detector Arrays A White Paper submitted to ***Electromagnetic Observations from Space (EOS)*** Discipline Program, Simon Bandler ***et al.***



FWHM: 2.5 eV @ 5.9 keV

Picture of the setup used to characterize the kilo-pixels array hung on the mixing chamber of a dilution refrigerator and held at a base temperature of 50 mK. Main parts are highlighted by arrows.

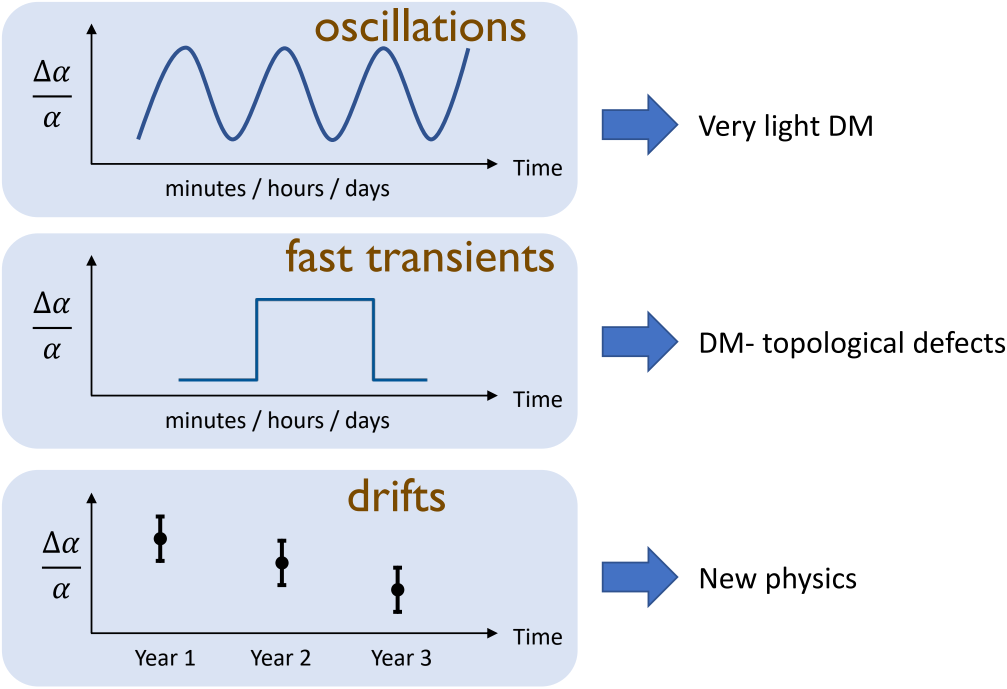
Performance and uniformity of a kilo- pixel array of Ti/Au transition-edge sensor microcalorimeters
E. Taralli, M. D'Andrea, L. Gottardi, et al., Rev. Sci. Instrum. 92, 023101 (2021);
https://doi.org/10.1063/5.0027750

② spin-based, NV-diamonds, … ③ optical clocks

search for NP / BSM

Signal characteristics

- The <u>only</u> possibility of detecting transient events such as topological defects, solitons, Q balls and dark stars
- Oscillations of dark matter fields at different locations as long as the distance is below the coherence length (100 km: mass $\sim 10^{-9}$ eV)
- Sensors with similar sensitivities and different systematics are <u>necessary</u> to confirm any measurements and reject false positives
- Using multiple sensors increases the detection confidence and sensitivity
- Multimessenger detection, discriminating between different couplings



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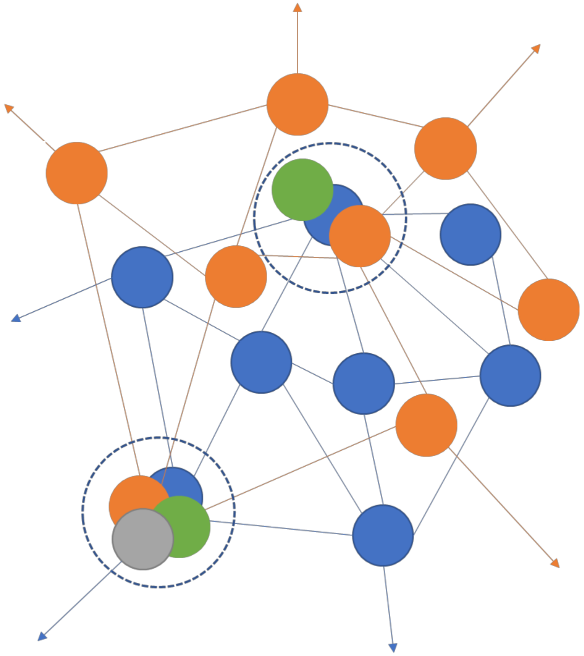
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

particle physics: what are we talking about?

search for NP / BSM

networks of sensors



magnetometers ②

Afach et al, arXiv:2102.13379v2

atomic clocks nuclear, HCI, molecules ③

Wcislo et al, Sci. Adv. 4, 4869 (2018)

optical fiber networks ③

Roberts et al, New J. Phys. 22, 093010 (2020)

Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

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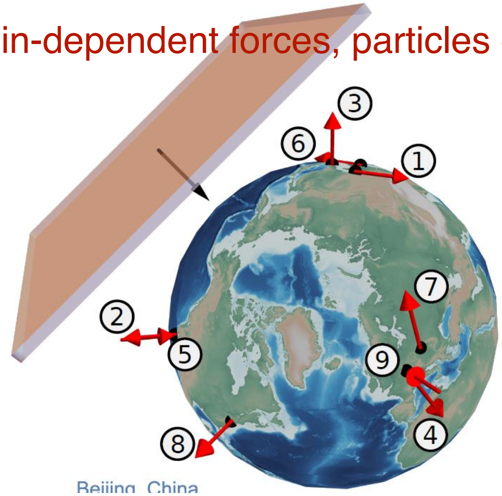
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

② spin-based, NV-diamonds, …

→ Spin-dependent forces, particles coupling to spin

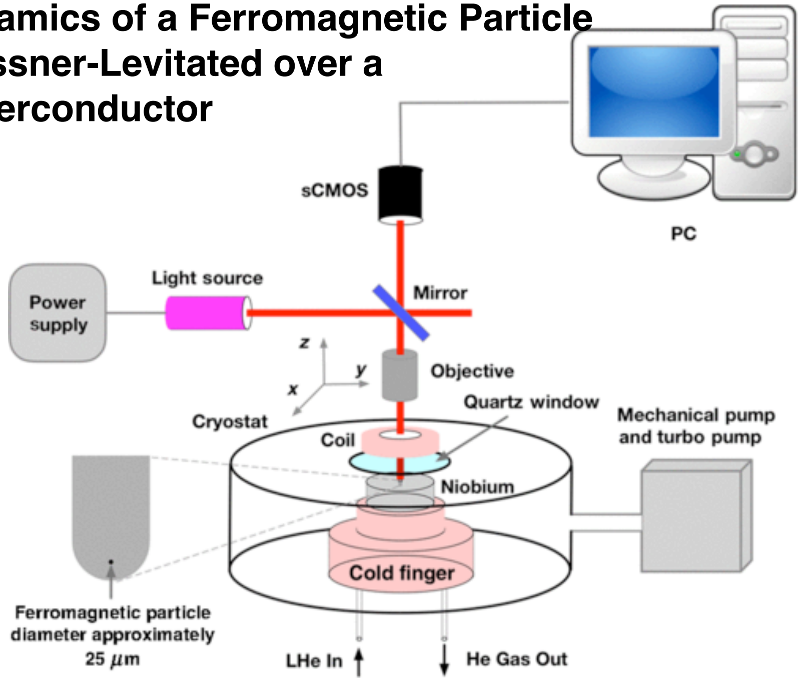


GNOME: arXiv:2102.13379 (2021)

Global Network of Optical (atomic) Magnetometers for Exotic searches

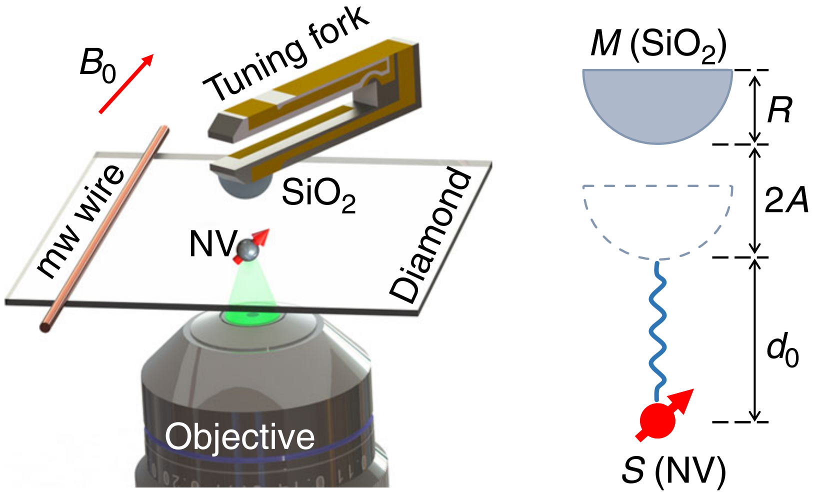
ALP's can interact with atomic spins; passage of an ALP domain wall ⟶ simultaneous / correlated signals ~ transient magnetic field pulse (down to O(pT))

Dynamics of a Ferromagnetic Particle Meissner-Levitated over a Superconductor



https://doi.org/10.1103/PhysRevApplied.11.044041

Searching for an exotic spin-dependent interaction with a single electron-spin quantum sensor



Rong, X., Wang, M., Geng, J. *et al.*, *Nat Commun* **9,** 739 (2018).
https://doi.org/10.1038/s41467-018-03152-9

③ optical clocks

- Atomic clocks measure with extreme precision atomic and molecular spectra
- Spectroscopy lends itself to measure variations of:

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

- Different clocks have different sensitivities to variations of α and μ

$$\frac{\delta\omega}{\omega} = K_\alpha\frac{\delta\alpha}{\alpha} + K_\mu\frac{\delta\mu}{\mu}$$

- Clocks are “naturally” networked, need to compare at least 2

A common, stable, and insensitive frequency reference (a Sr clock), against which all the clocks of the network can measure variations

Clock		Kα	Kμ
Higly-charged ion clock	Cf^{15+} (775 nm)	59	0
Atomic clock	Yb^{+} (467 nm)	-5.95	0
Molecular ion clock	N_2^{+} (2.31 µm)	0	0.5
Molecular clock	CaF (17 µm)	0	0.5
Atomic clock	Sr (698 nm)	0.06	0
	Cs (32.6 mm)	2.83	1

Quantum 2.0

- Entanglement between sensors can give an advantage when measuring multiple non-commuting parameters of dealing with “nuisance” parameters [PRA 95, 012326 (2017)]
- Creating a super-stable global network of clocks synchronized with entanglement [Nat. Phys. 10, 582 (2014)]
- Need more measurement schemes

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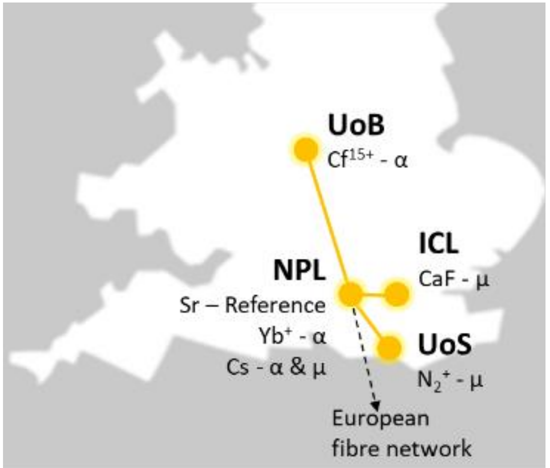
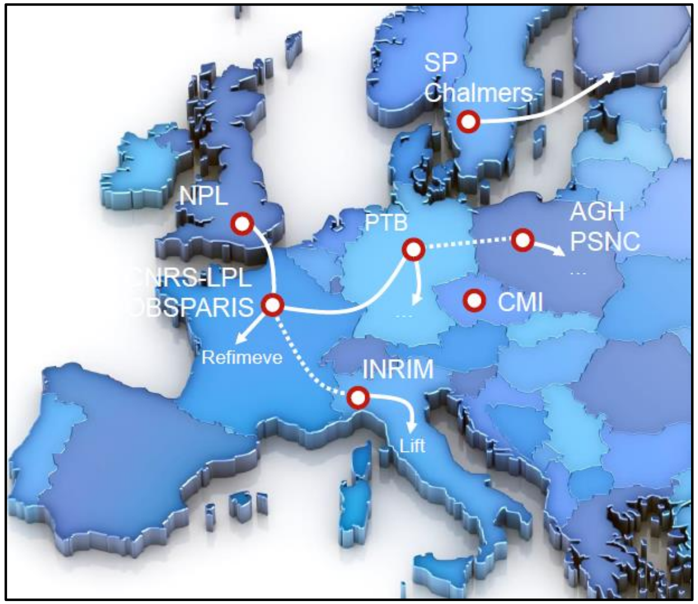
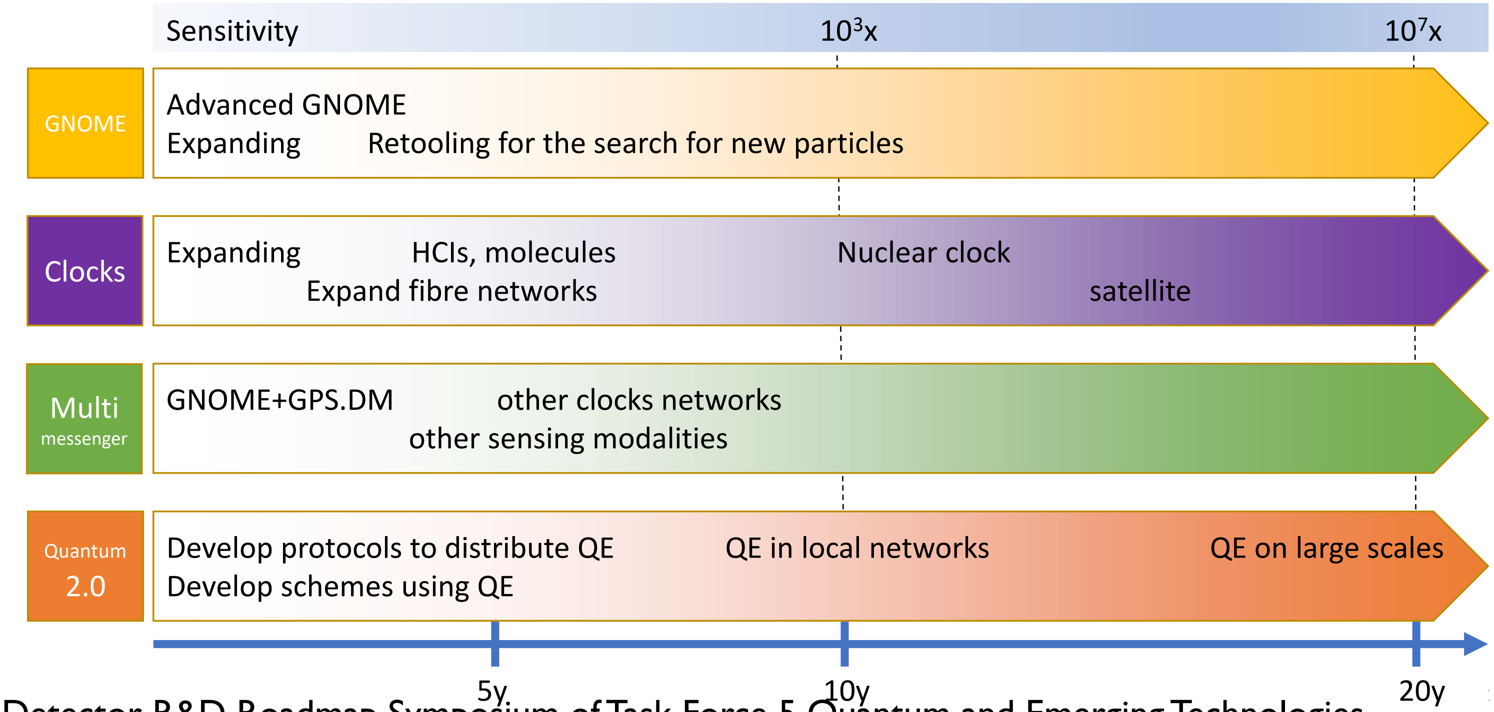
③ optical fiber networks



QSNET





GNOME
Advanced GNOME
Expanding
Retooling for the search for new particles

Clocks
Expanding
HCIs, molecules
Expand fibre networks
Nuclear clock
satellite

Multi messenger
GNOME+GPS.DM
other clocks networks
other sensing modalities

Quantum 2.0
Develop protocols to distribute QE
Develop schemes using QE
QE in local networks
QE on large scales

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https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

Quantum Sensors for New-Physics Discoveries
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

Search for new physics with atoms and molecules
Rev. Mod. Phys. 90, 025008 (2018)

Barontini et al. EPJ Quantum Technology (2022) 9:12
https://doi.org/10.1140/epjqt/s40507-022-00130-5

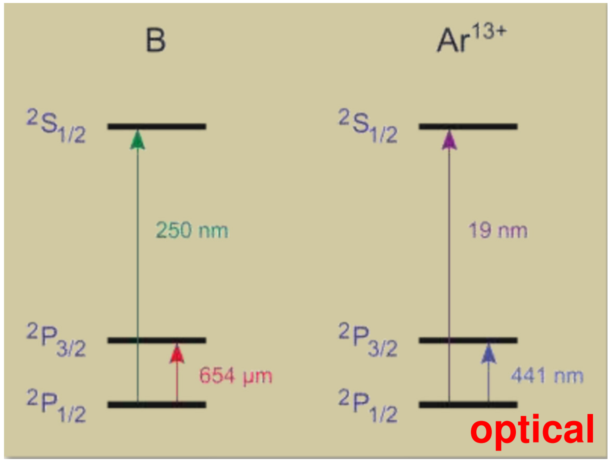
④ ionic / atomic / molecular

novel systems with greatly enhanced
sensitivity wrt standard atomic systems

HCI's

e.g. ^{18}Ar ⟶ Ar^{13+}
(5 e^- remain)

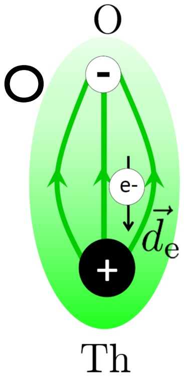
Lorentz violation searches
variation of fund. constants
DM searches
tests of QED
5th force searches



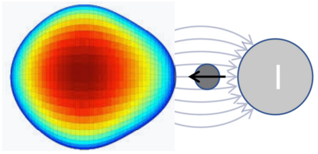
eEDM's in molecules

P and T violation

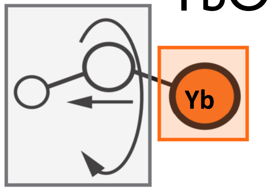
ThO



^{225}RaF



YbOH



laser-cooling
polarization

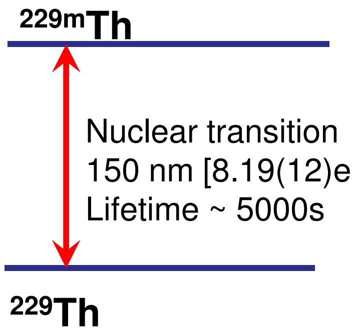
nuclear clock (^{229}Th)

typical nuclear energy levels are in MeV. Six orders of magnitude from ~few eV we can access by lasers!

only ONE exception:

sensitivity to dark matter, variation of α

~ 8.19 eV / MeV ~ 10^5 wrt current clocks

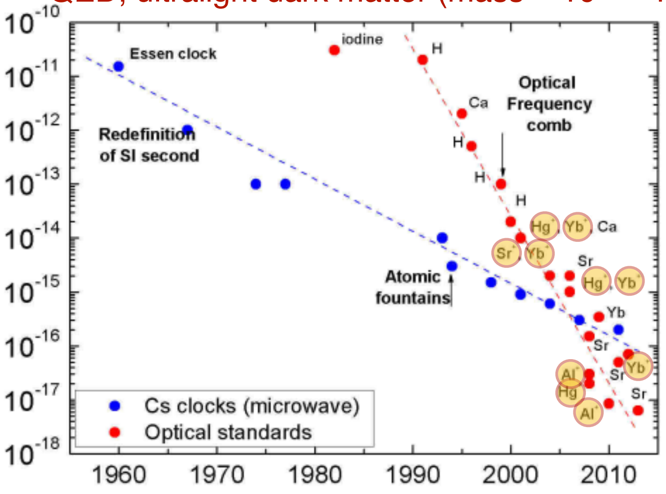


Nuclear transition
150 nm [8.19(12)eV]
Lifetime ~ 5000s

Review: E. Peik, et al., arXiv:2012.09304, in press, Quantum Science and Technology (2021)

molecular / ion clocks

QED, ultralight dark matter (mass ~ 10^{-22} – 10^{-15} eV)



Hg^+
Al^+
Yb^+

CaF
N_2^+

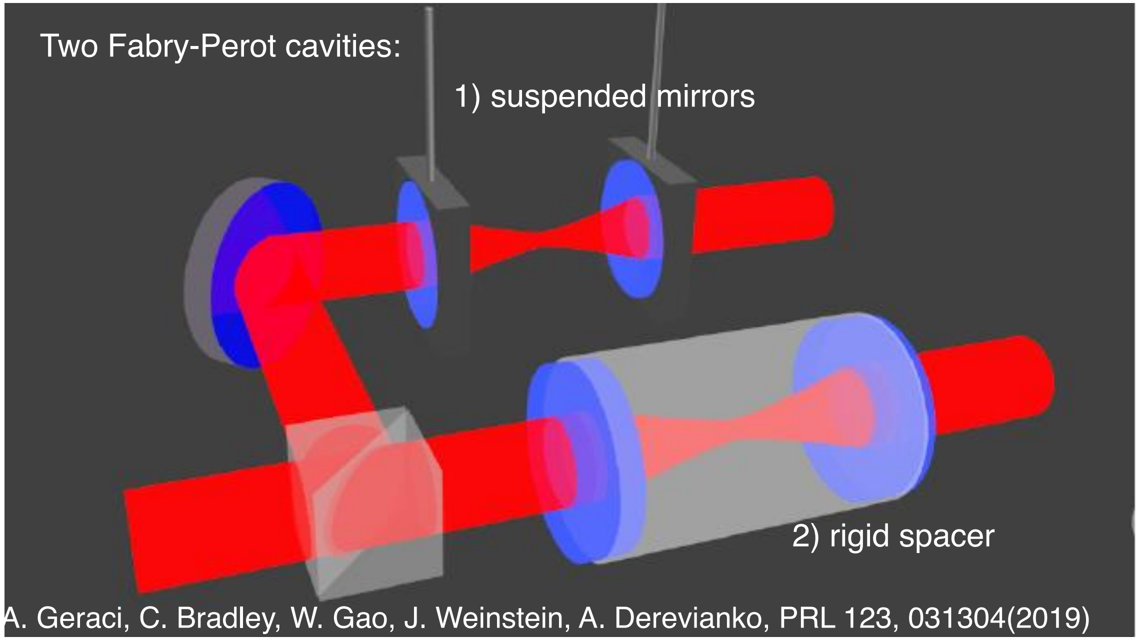
N_2^+ : 10^{-18} https://doi.org/10.1103/PhysRevA.89.032509

⟶ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware) David Hume (NIST)

⑤ optomechanical sensors

- Wavelike DM
  - -Scalar-like: Optical-cavity-based detectors
  - -Vector-like: Accelerometer detectors
- Particle/extended-object DM
  - -Gravitational Wave detectors for DM (also Axions)
  - -Levitated microspheres
  - -Windchime experiment

Isotropic strain in material objects due to variation of atomic size from interaction with ultra-light DM Manley et al. PRL **124**, 151301 (2020)



A. Geraci, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL 123, 031304(2019)

$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\mathrm{DM}}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi \cdot \mathbf{r} + \ldots\right]$$

$k_\phi = m_\phi v/\hbar$

m_ϕ is the mass of the DM field,
v is the relative speed of the DM

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

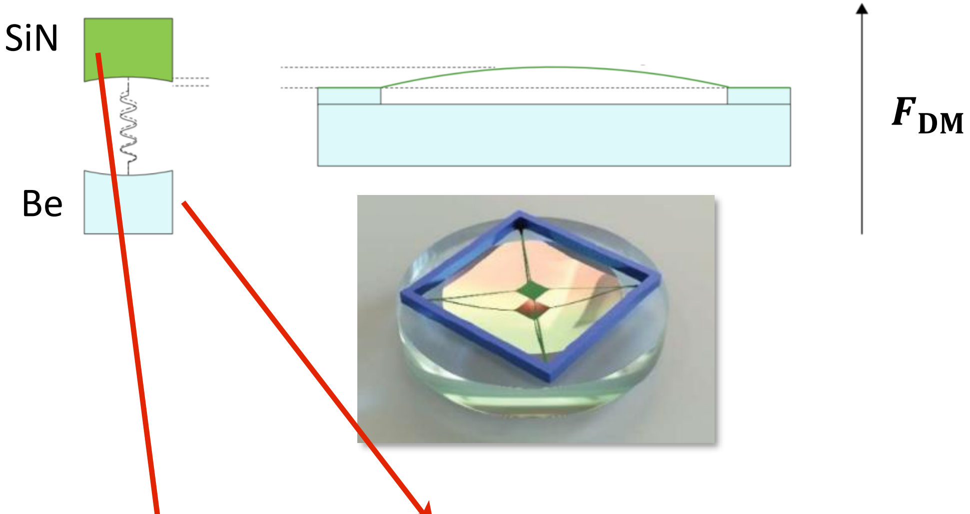
$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

strain : $h = -\frac{\delta\alpha}{\alpha_0} - \frac{\delta m_e}{m_{e,0}},$

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Andrew Geraci (Northwestern)

⑤ accelerometers

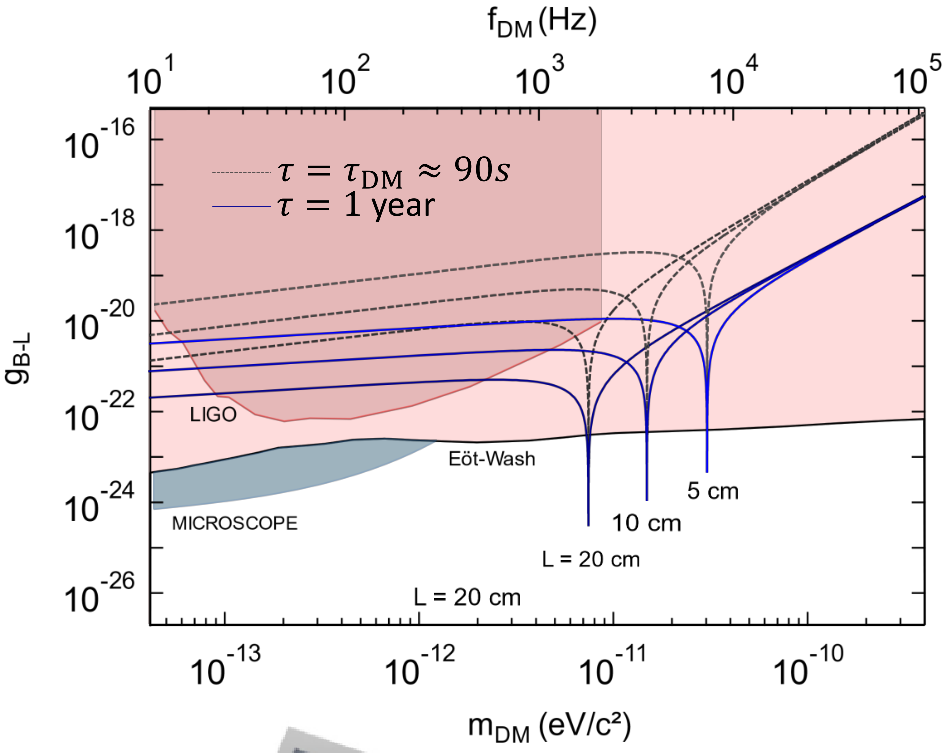
differential acceleration between materials of different composition (probe of B-L couplings)

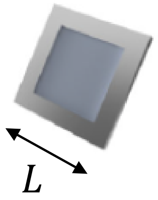


Si_3N_4 membrane
$(Q \sim 10^9)$

Be Mirror
(Webb telescope)

Cryogenics
(100 mK)



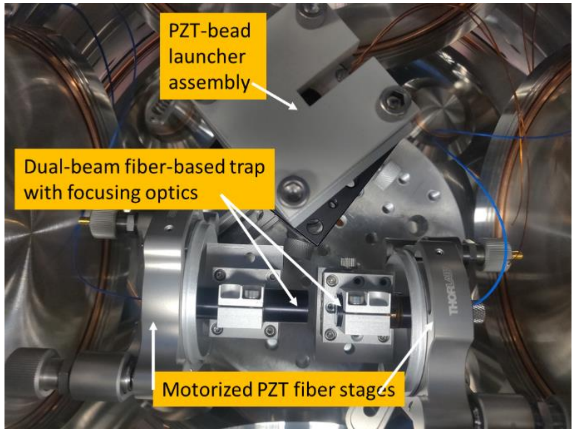


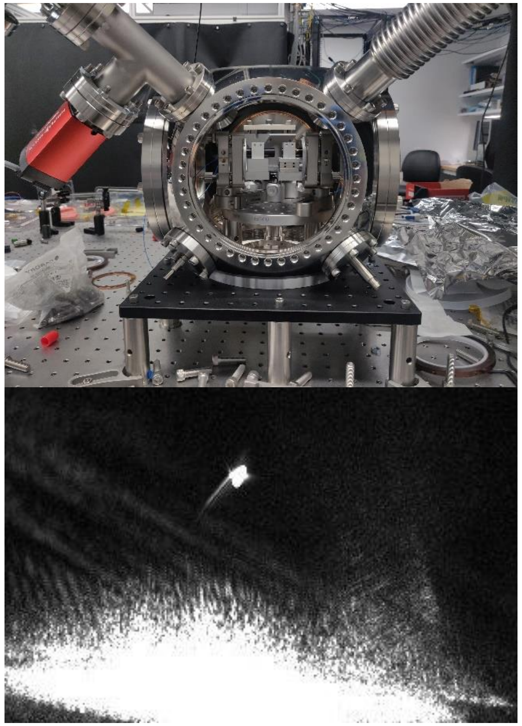
Manley et. al. PRL 126 061301 (2021)

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Andrew Geraci (Northwestern)

⑤ levitated microspheres

nanoparticle standing-wave trap (optical lattice)

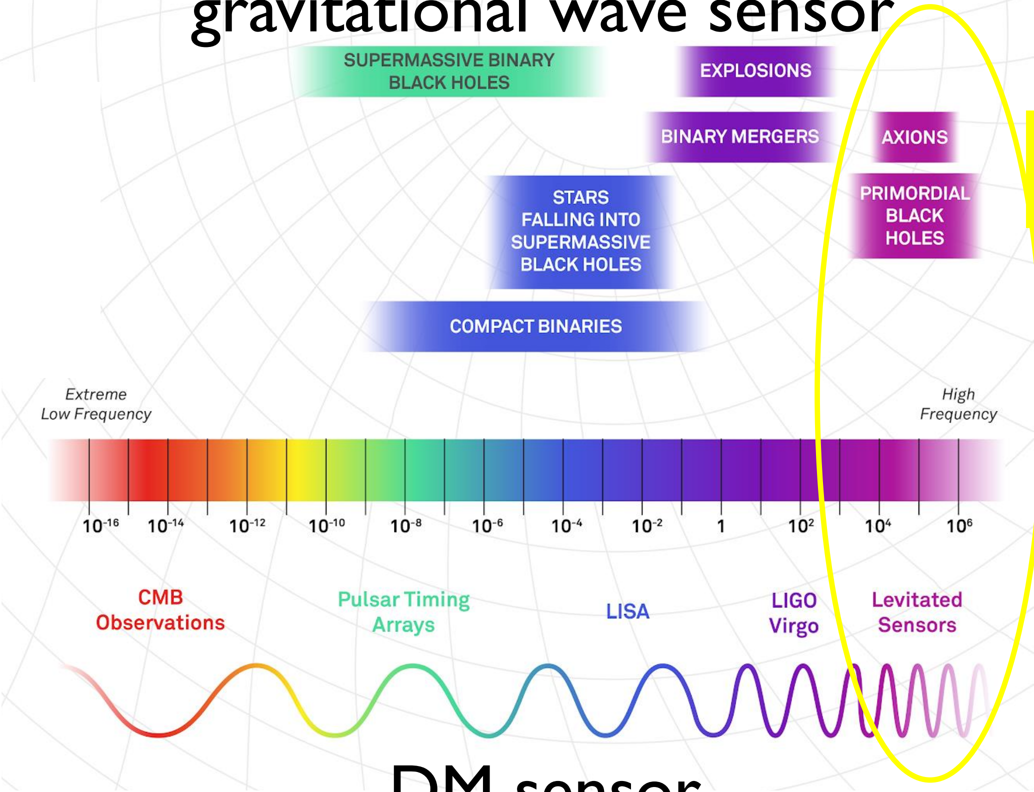




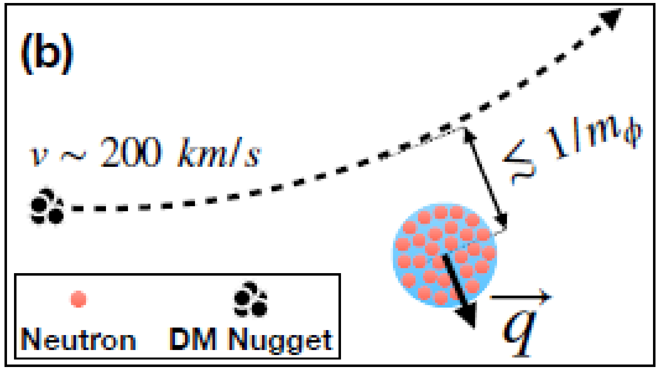
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016)
C. Montoya et. al. arXiv:2103.03420 (2021)

= zeptonewton sensing

gravitational wave sensor



DM sensor



Search for Composite Dark Matter with Optically Levitated Sensors

Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore
Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Andrew Geraci (Northwestern)

5 "Wind chime"

Planck-scale DM: measure the gravitational effect of flying-by DM on an array of accelerometers

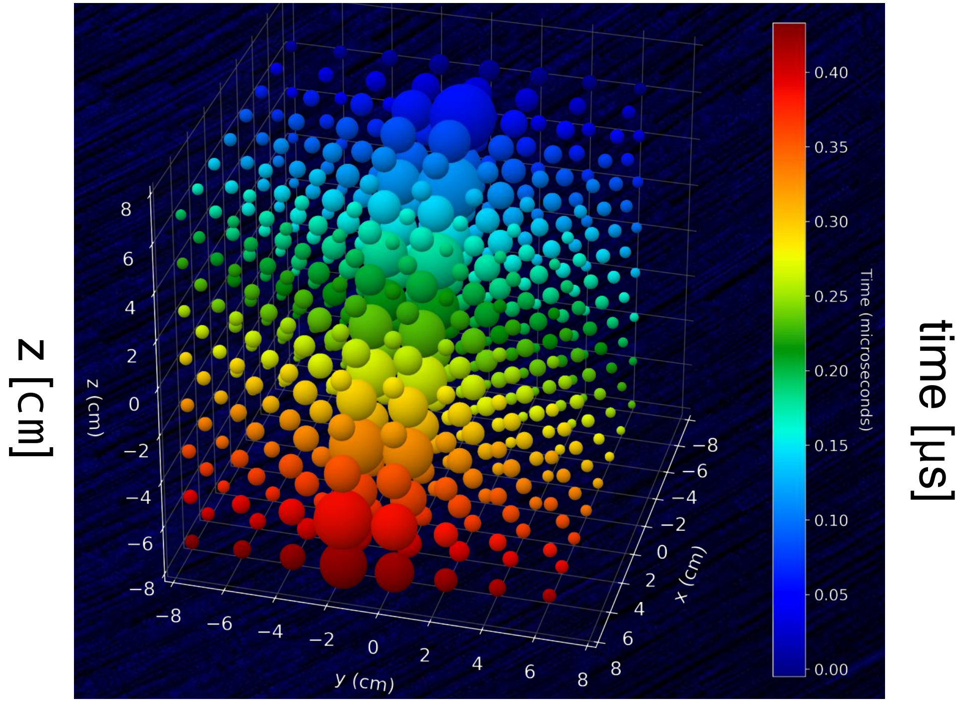
vision: "Our proposed strategy is to build a three-dimensional array of force sensors. A heavy DM particle passing through the array will exert a small but correlated force on the sensors nearest its trajectory. Much like tracking a particle in a bubble chamber, we can then pick out this correlated force signal along the DM "track" through the array."

https://arxiv.org/abs/1903.00492

flux: 1/m^2/year

"With a billion detectors at the gram scale, Planck-scale gravitational DM detection is achievable."

sensors: "cryogenic opto-mechanical devices", e.g.: atoms in a lattice that are continuously optically probed



→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Andrew Geraci (Northwestern)

⑥ metamaterials, 0/1/2-D materia

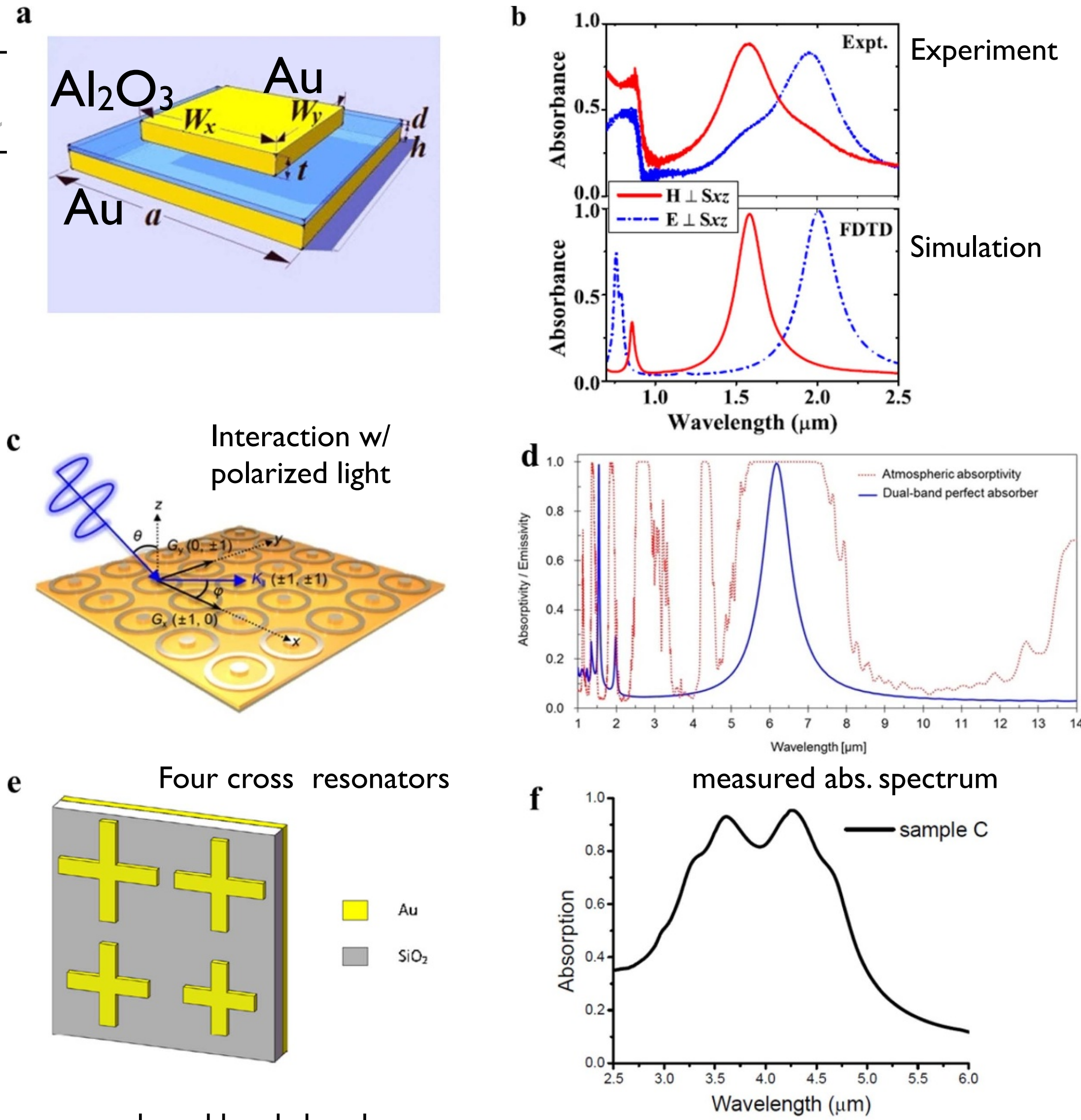
metamaterial : materials that obtain their properties from their *structure* rather than the material of which they are *composed*

These are *engineered composite materials* mainly consisting of artificially designed periodic sub-wavelength structures.

One particular application revolves around the absorption / reflectance characteristics in the IR in very compact devices.

(relatively) *broadband* absorption:

Importantly: the properties can be designed!



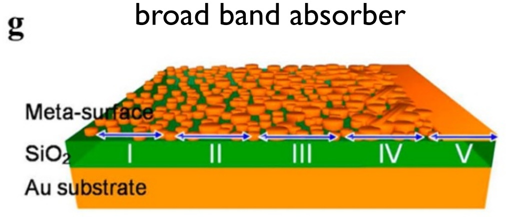
Experiment

Simulation

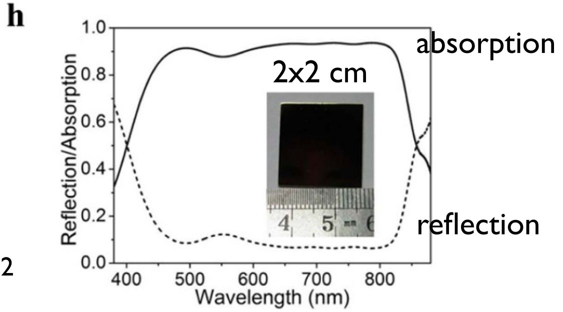
Interaction w/ polarized light

Four cross resonators

measured abs. spectrum



broad band absorber



absorption

2x2 cm

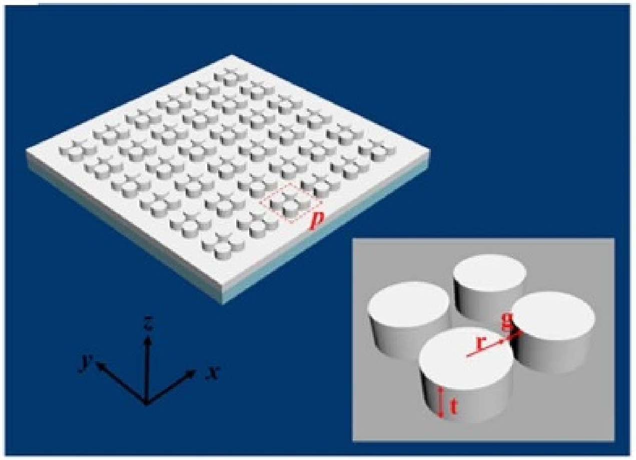
reflection

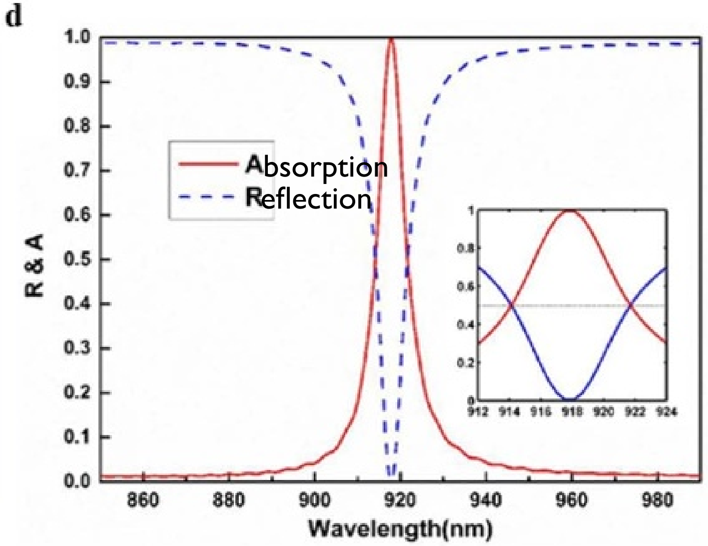
Y. Yao et al., J. Phys. D: Appl. Phys. 54 (2021) 113002
https://doi.org/10.1088/1361-6463/abccf0

⑥ metamaterials, 0/1/2-D materials

Schematic of the MMA
r = 80nm
t = 100 nm
g = 20 nm

(relatively) *narrowband* absorption:

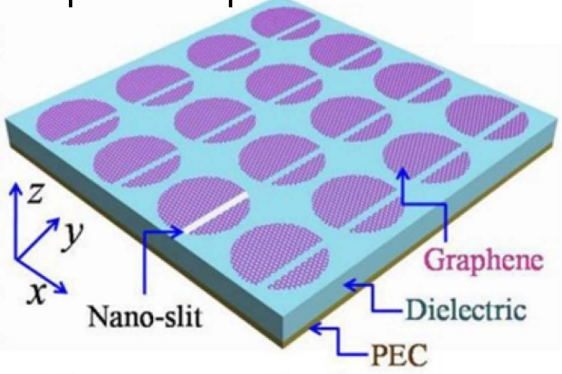




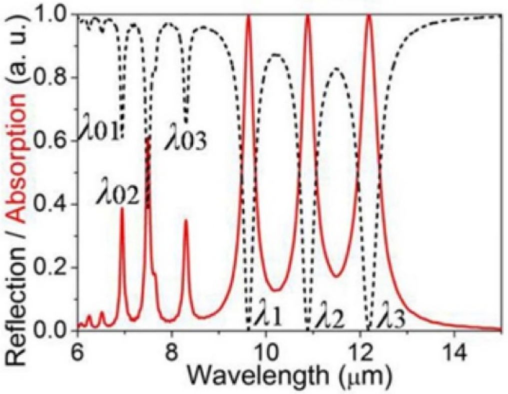
Y. Yao et al., J. Phys. D: Appl. Phys. 54 (2021) 113002 https://doi.org/10.1088/1361-6463/abccf0

2D materials based MMAs: strong tunability by tuning gate voltage

Schematic of the graphene plasmonic perfect absorber



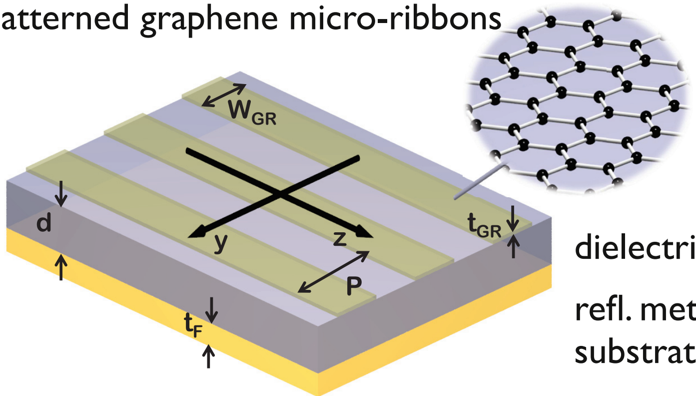
Absorption and reflection of the absorber.



Y. Yao et al., J. Phys. D: Appl. Phys. 54 (2021) 113002 https://doi.org/10.1088/1361-6463/abccf0

plasmonic metamaterials: perfect absorption of light

patterned graphene micro-ribbons



dielectric

refl. metal substrate

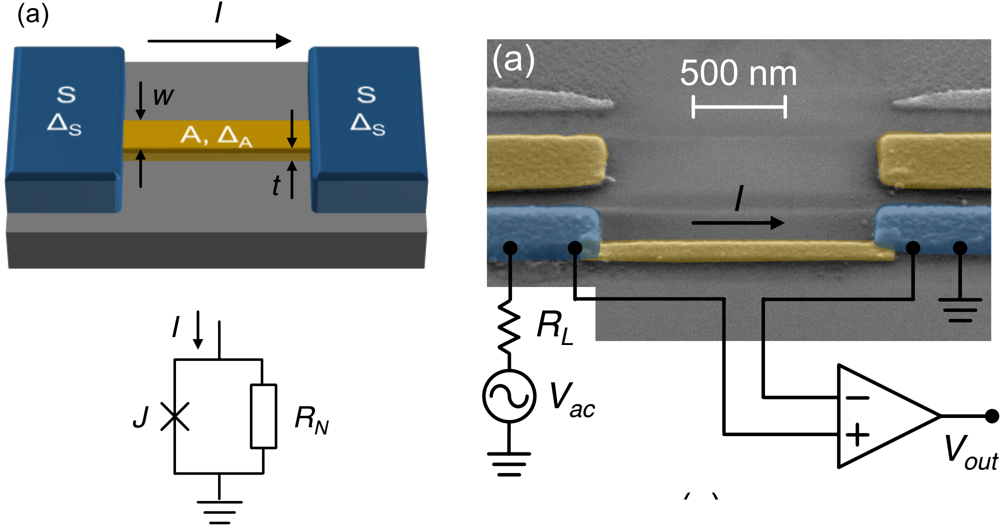
R. Alaee et al., Opt. Express. 20 (2012) 28017 https://doi.org/10.1364/OE.20.028017

6 metamaterials, 0/1/2-D materials

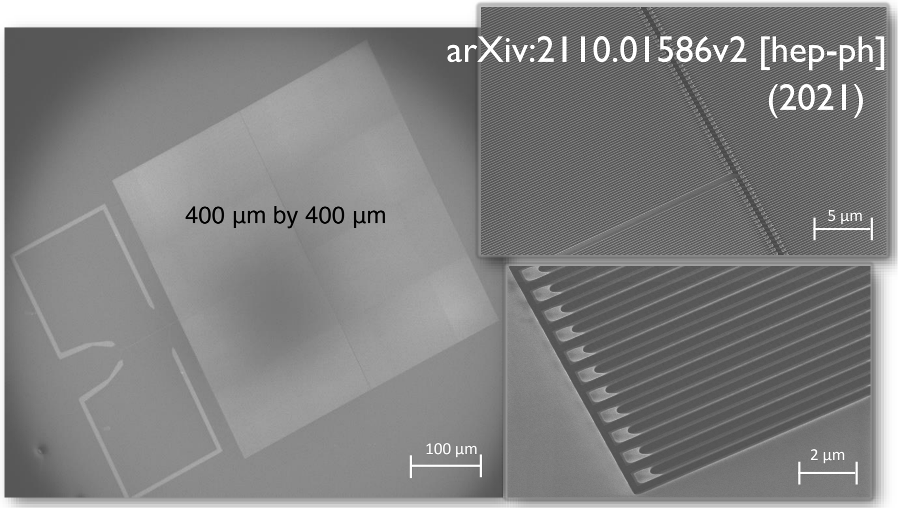
1-D junction: JES: Josephson escape sensor, nanoscale transition edge sensor (nano-TES)

well suited to detecting dark matter / axion interactions with electrons

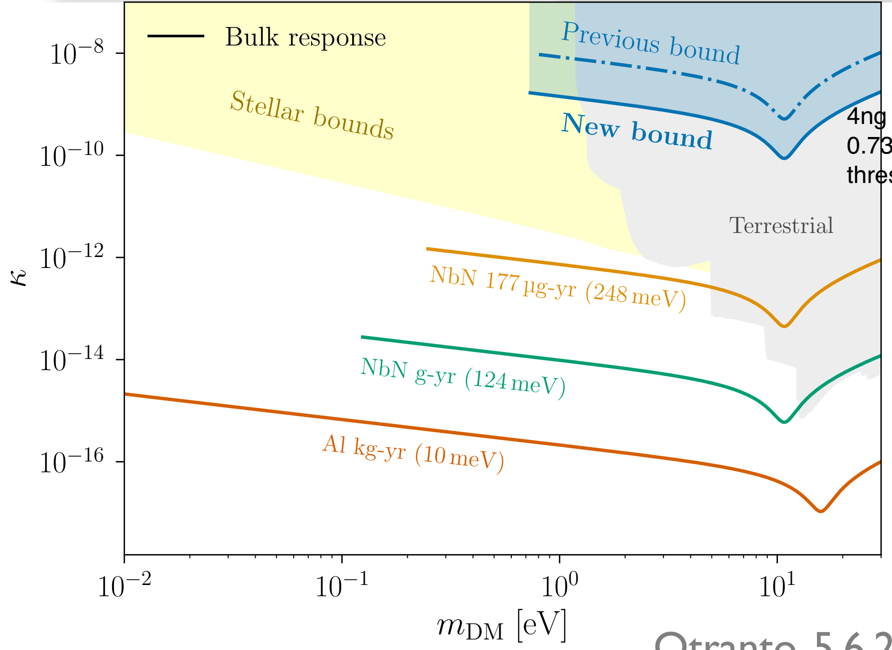
superconducting single-photon detection arXiv:2101.08558v2



Superconducting nanowire single-photon detectors (SNSPDs): sub-eV energy deposition thresholds



arXiv:2110.01586v2 [hep-ph] (2021)



4ng x 180 h
0.73 eV
threshold

directional detection of light dark matter

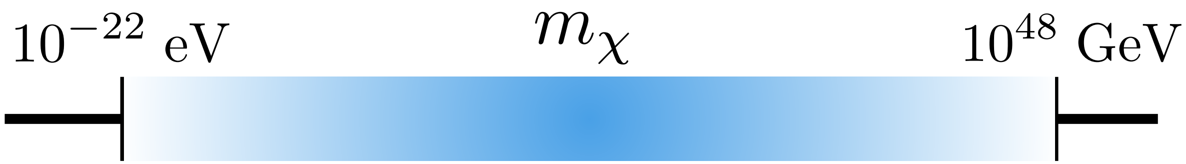
dark matter scattering produces initial excitations with an anisotropic distribution which is preserved during de-excitation

https://arxiv.org/abs/2109.04473

Quantum sensors for new particle physics experiments

quantum sensors & particle physics: what are we talking about?

Axions, ALP's, DM & non-DM UL-particle searches

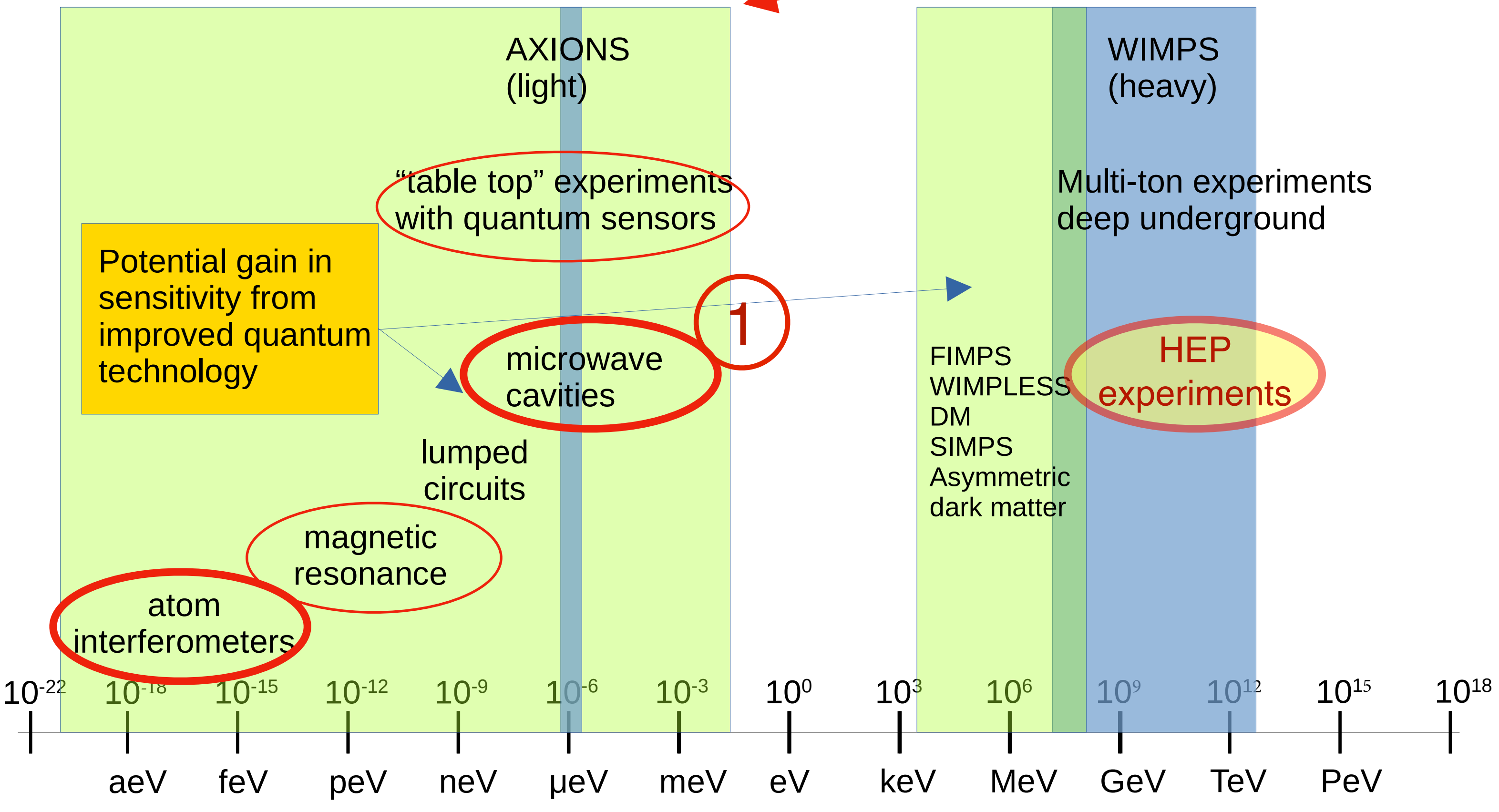


cavity size = axion size

axion mass = unknown

$$F \sim g_{a\gamma}^2 m_A^2 B^4 V^2 T_{sys}^{-2} G^4 Q,$$

system noise temperature
cryo-amplifiers JJPA


AXIONS
(light)

"table top" experiments
with quantum sensors

Potential gain in sensitivity from improved quantum technology

microwave
cavities

1

lumped
circuits

magnetic
resonance

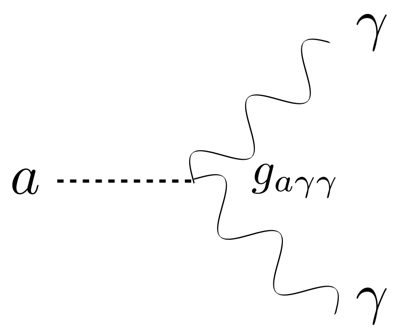
atom
interferometers

WIMPS
(heavy)

Multi-ton experiments
deep underground

FIMPS
WIMPLESS
DM
SIMPS
Asymmetric
dark matter

HEP
experiments

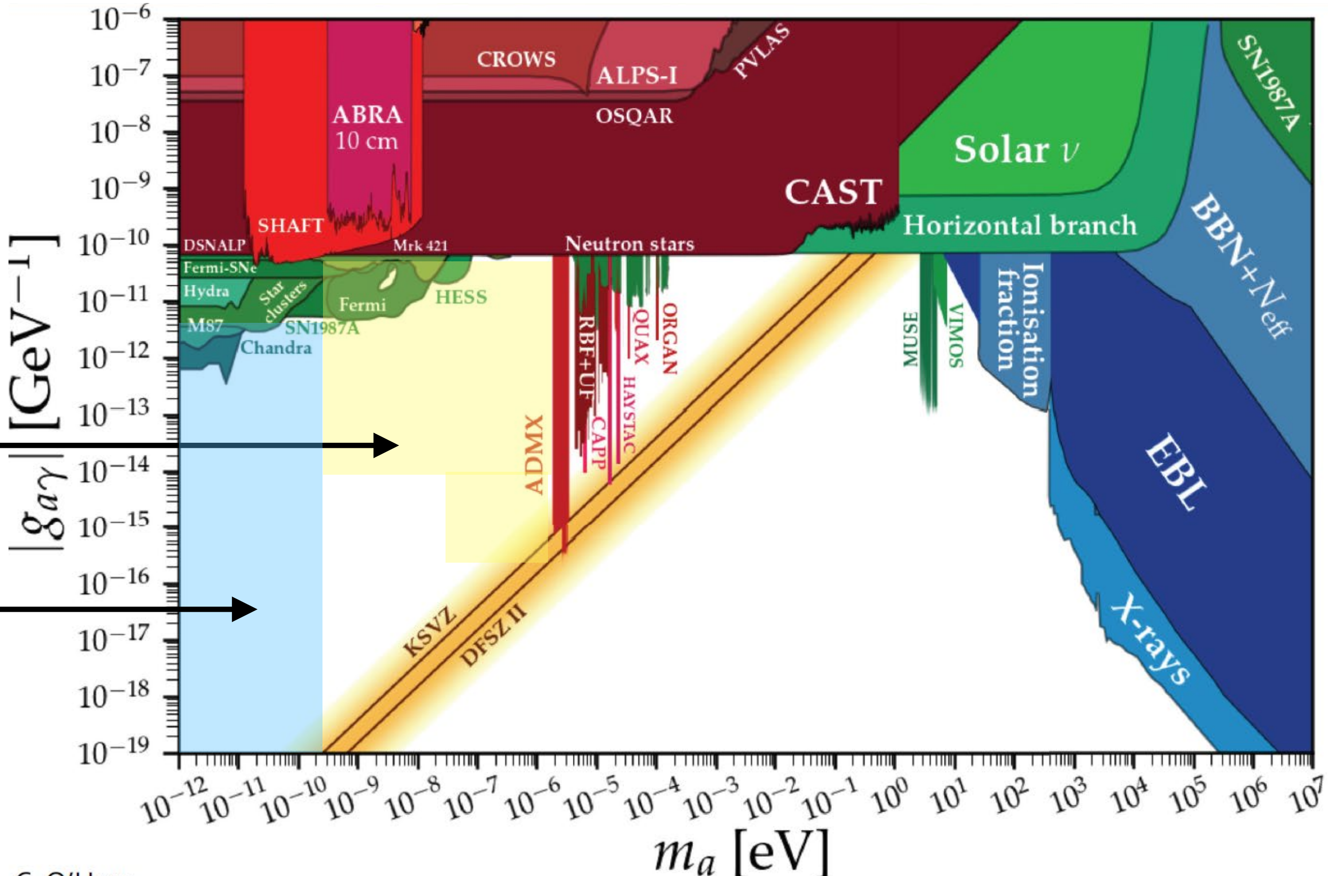


(but not only…)

particle physics: what are we talking about?

DMRadio

CASPEr
electric
NMR



C. O'Hare

spin-based, NMR ②

microwave cavities ①

electromagn. resonators

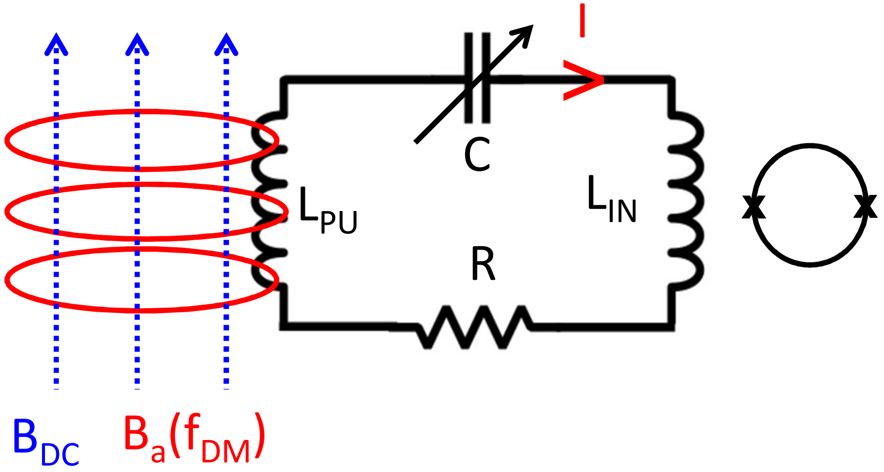
bolometers, TES ①

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Kent Irwin (Stanford University)

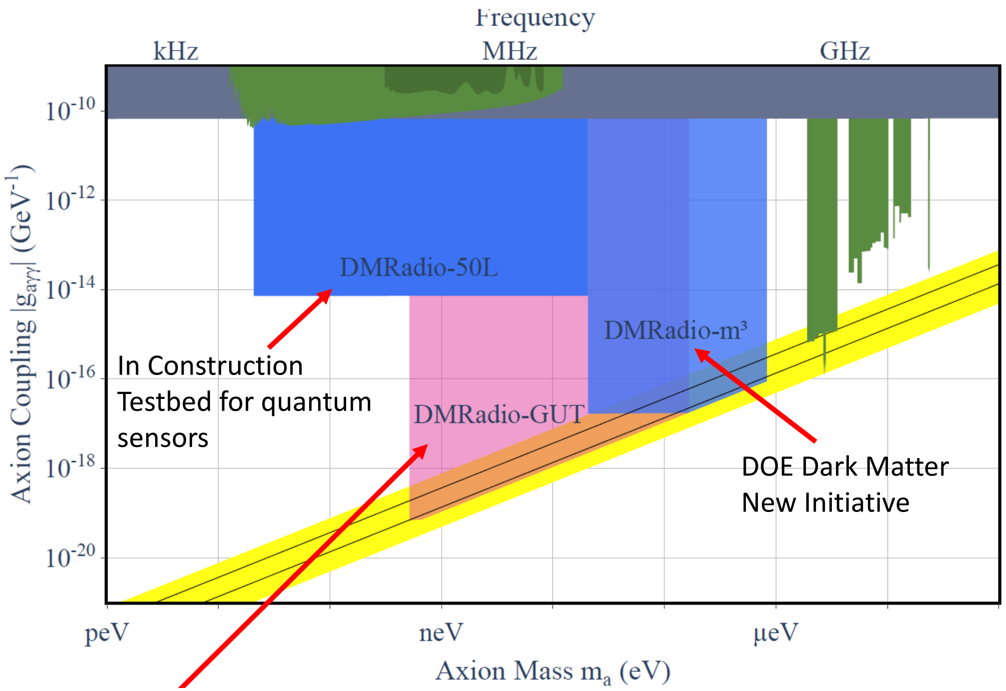
DMRadio

Focus on electromagnetic interaction: axions and photons mix in the presence of a strong magnetic field

Focus on detecting not a particle (a photon), but a field



- Axion field converts to oscillating EM signal in background DC magnetic field
- Detect using tunable resonator
- Signal enhancement when resonance frequency matches rest-mass frequency $\nu_{DM}=mc^2/h$
- SQUID's, RF Quantum upconverters, cryoamplifiers (e.g. JJPA)



In Construction

Testbed for quantum sensors

DOE Dark Matter New Initiative

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

https://indico.cern.ch/event/999818/ Kent Irwin (Stanford University)

CASPEr electric NMR

Focus on different interactions: the electric dipole moment (EDM) interaction and the gradient interaction with nuclear spin I. The EDM interaction arises from the coupling of the axion to the gluon field.

Cosmic Axion Spin Precession Experiment is based on a precision measurement of ^{207}Pb solid-state nuclear magnetic resonance in a polarized ferroelectric crystal. Axion-like dark matter can exert an oscillating torque on ^{207}Pb nuclear spins via the electric dipole moment coupling gd or via the gradient coupling gaNN.

→ spin $\boldsymbol{\sigma}$ to axion coupling:

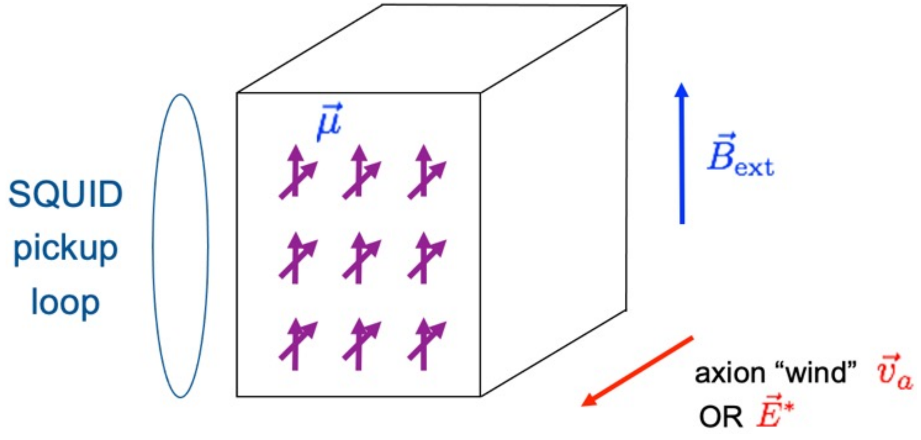
$$\boxed{H_{\mathrm{e}} \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^{*}}$$

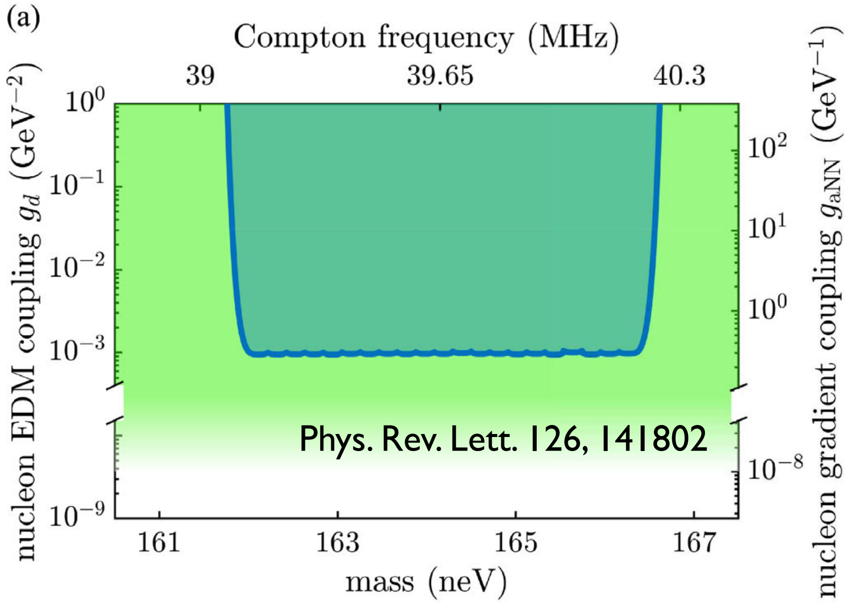
CASPEr-electric

→ spin $\boldsymbol{\sigma}$ to axion gradient coupling:

$$\boxed{H_{\mathrm{g}} \propto \boldsymbol{\sigma}\cdot\boldsymbol{\nabla} a}$$

CASPEr-gradient





Phys. Rev. Lett. 126, 141802

numerous improvements possible ➔ many orders of magnitude in mass and sensitivity range

⟶ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Dima Budker (Mainz University)

Initial experiments with quantum sensors world-wide
→ rapid investigation of new phase space

→ scaling up to larger systems, improved devices
→ expanding explored phase space

→ particles, atoms, ions, nuclei:	tests of QED, symmetries
→ atomic interferometers:	DM searches
→ RF cavities:	axion searches

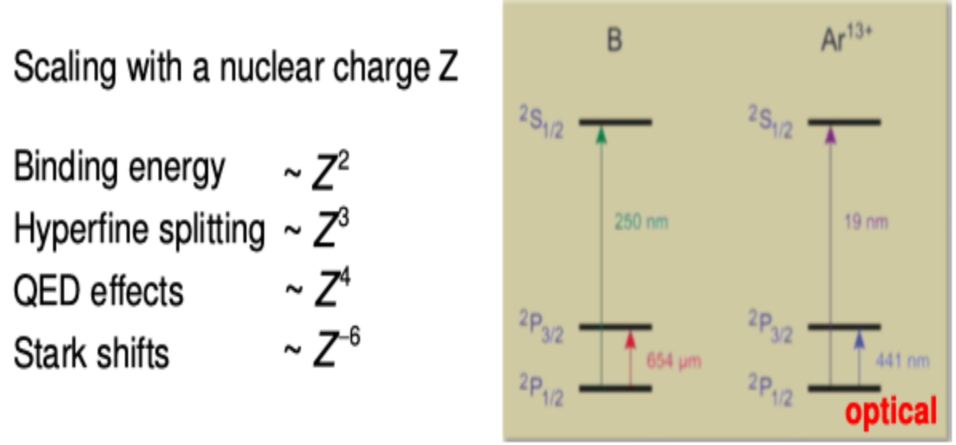
@ CERN: PBC, large low energy physics community…

https://indico.cern.ch/event/1002356/	PBC technology annual workshop 2021 (focus on quantum sensing)
https://indico.cern.ch/event/1057715/	PBC technology mini workshop: superconducting RF (Sep. 2021)

particle physics @ CERN : what are we talking about?

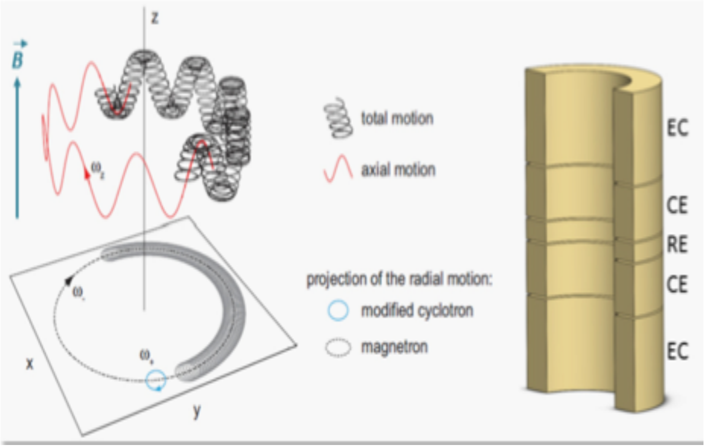
tests of QED, T-violation, P, Lorentz-violation, DM searches

HCI's in Penning traps



Scaling with a nuclear charge Z

Binding energy	~ Z^2
Hyperfine splitting	~ Z^3
QED effects	~ Z^4
Stark shifts	~ Z^{-6}



K. Blaum et al., Quantum Sci. Technol. 6 014002 (2021)

@ CERN:

- eEDM's in molecules
- nuclear clock (^{229}Th)
- molecular / ion clocks

Quantum Sensors for New-Physics Discoveries

https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

Present status: 5×10^{-12} relative mass precision

R. X. Schüssler et al., Nature 581, 42 (2020)

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

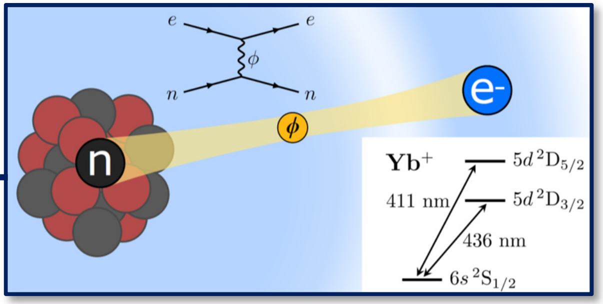
https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

Quantum sensors for new particle physics experiments: Penning traps

HCIs: **much larger** sensitivity to variation of α and dark matter searches than current clocks

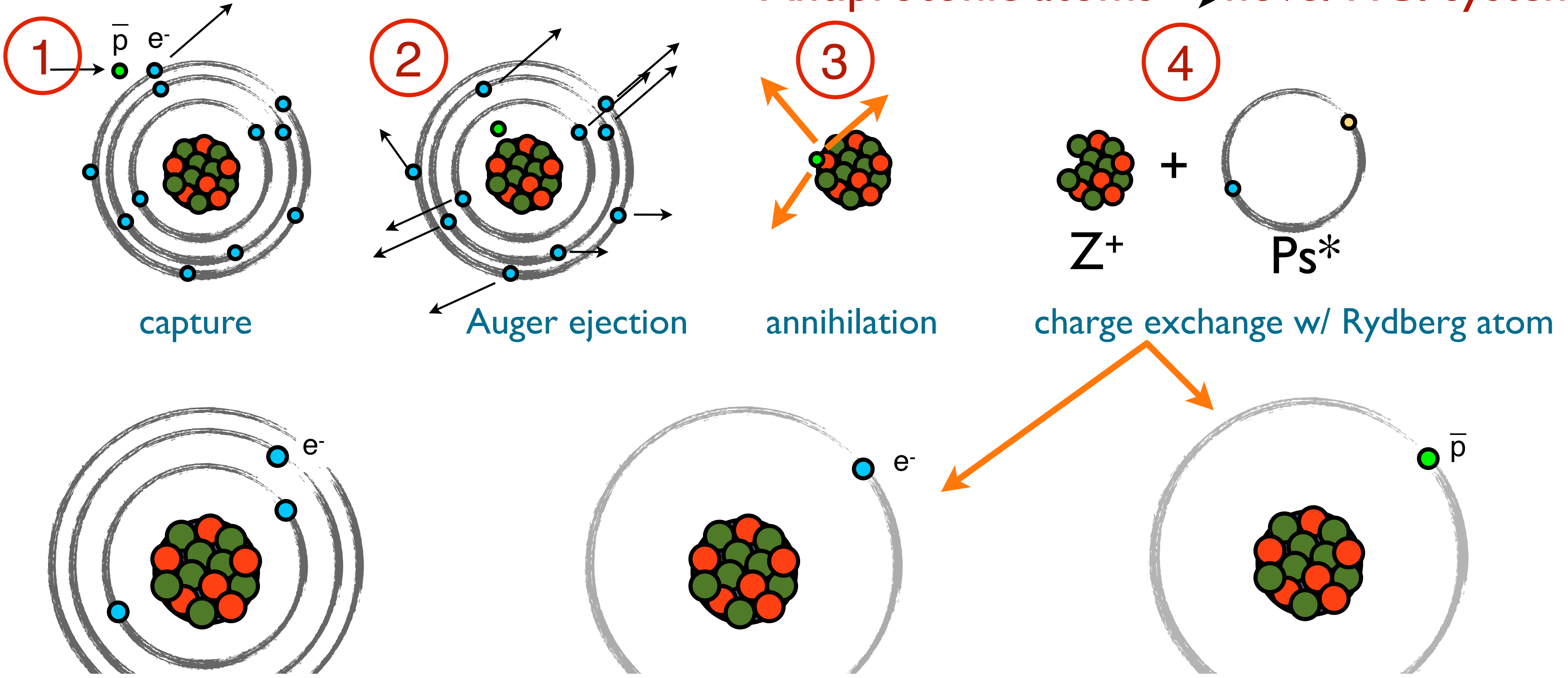
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot

linear relation in isotope shifts between two transitions caused by e.g. new force mediated by weakly interacting boson
Mikami, K. Et al.. Probing new intra-atomic force with isotope shifts. The European Physical Journal C. 77. 10.1140/epjc/s10052-017-5467-4.



Review on HCIs for optical clocks: Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)

Antiprotonic atoms → novel HCI systems



capture

Auger ejection

annihilation

charge exchange w/ Rydberg atom

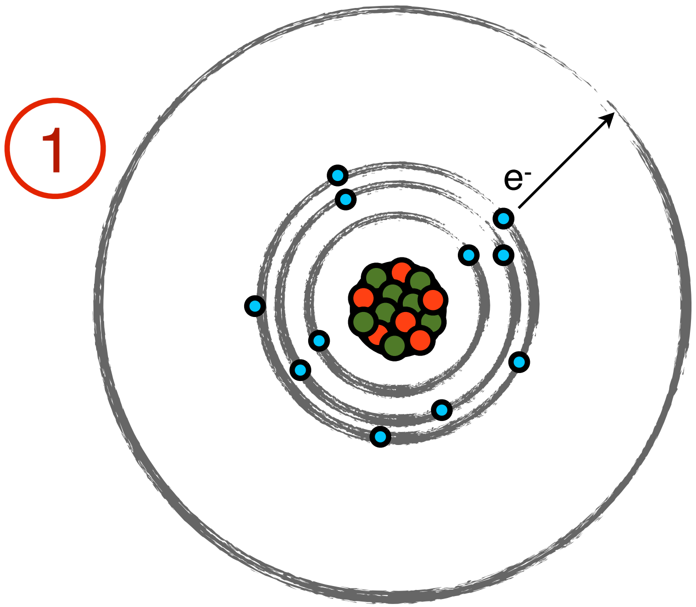
HCI (stable), (Z-n)+

HCI*(stable or unstable), (Z-1)+

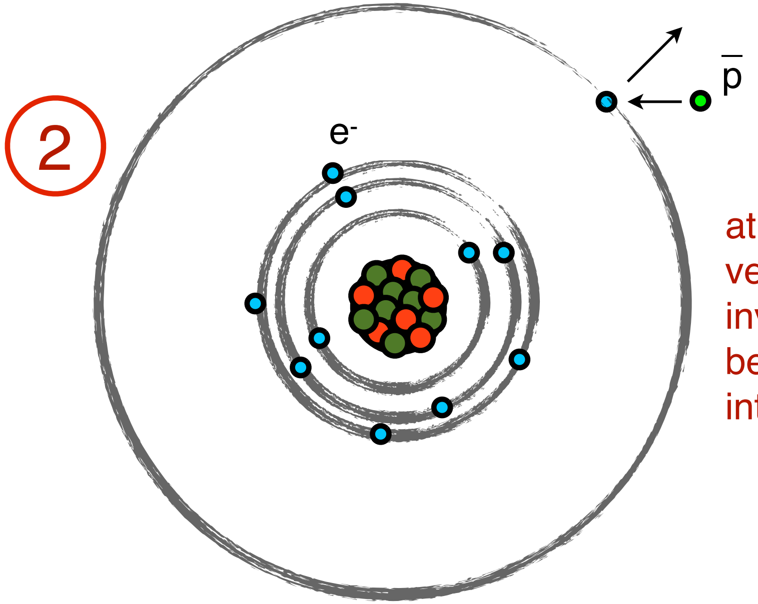
HCI*(stable or unstable), (Z-1)+

M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964

Antiprotonic Rydberg atom: exotic couplings, similar approach as spectroscopy of muonic atoms, CPT tests



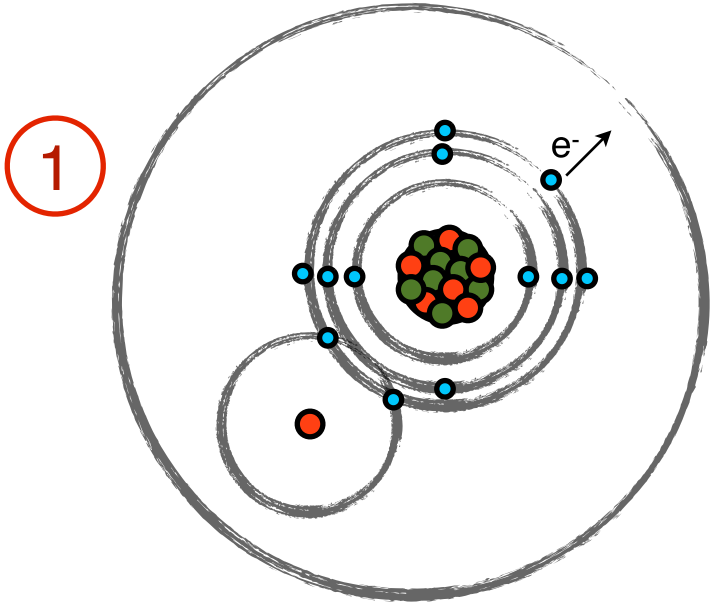
Rydberg excitation



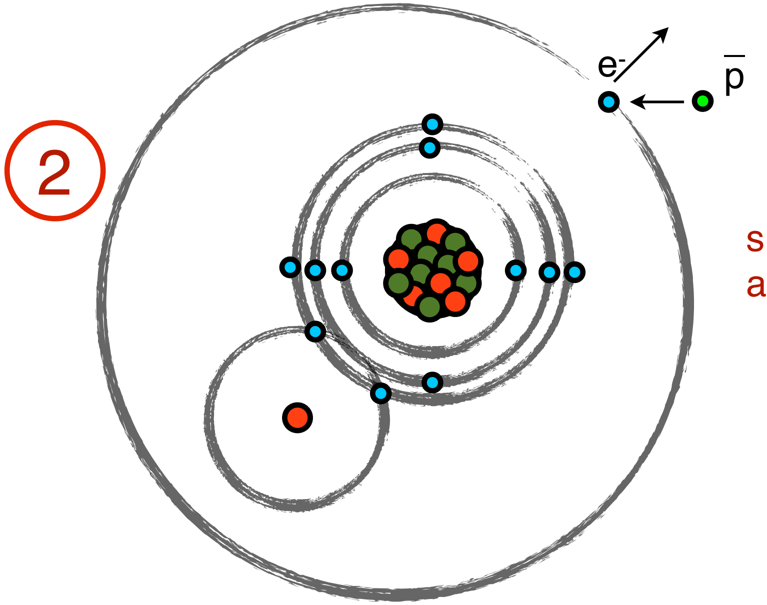
charge exchange

at end of cascade, p is very close to nucleus… investigate long-range behavior of strong interaction?

Antiprotonic Rydberg molecule: $\bar{p}$EDM?



Rydberg excitation



charge exchange

similar approach as eEDM in molecules

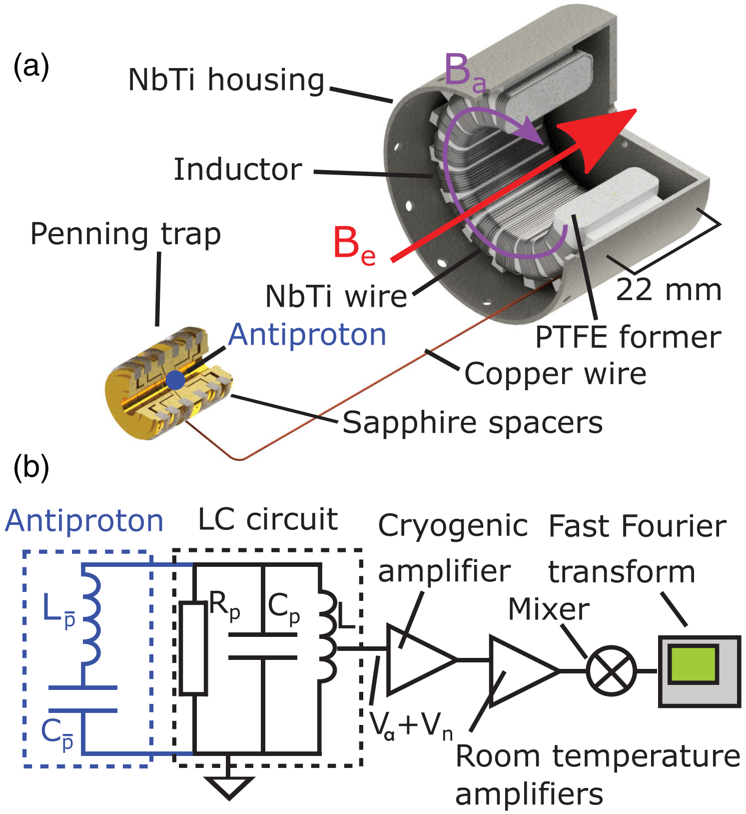
Quantum sensors for new particle physics experiments: Penning traps

search the noise spectrum of fixed-frequency resonant circuit for peaks caused by dark matter ALPs converting into photons in the strong magnetic field of the Penning-trap magnet

Resolving single antiproton spin flips requires the highest Q and lowest temperature LC resonant detectors ever built: BASE-CERN is the state of the art

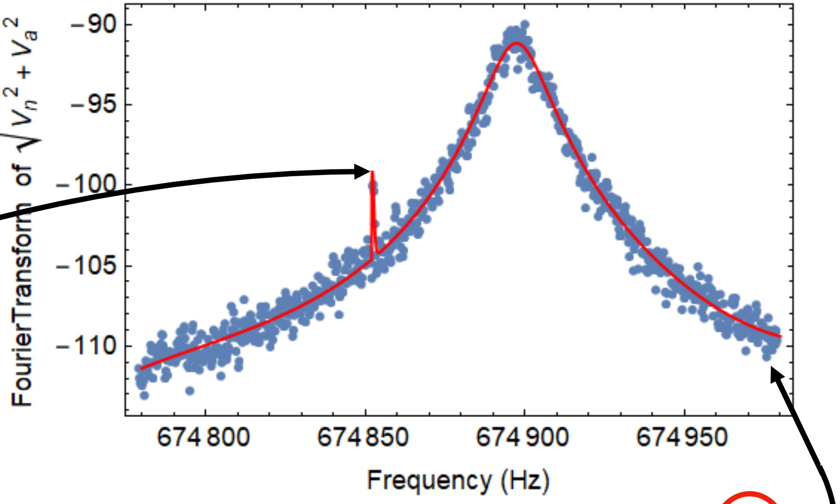
Constraints on the Coupling between Axion-like Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

J. Devlin *et al.*, BASE collaboration, Physical Review Letters 126, 041301 (2021)



H. Nagahama et al., Rev. Sci. Instrum. 87, 113305 (2016)

https://indico.cern.ch/event/1002356/



resonator background ∝ $\sqrt{T_z}$ from antiproton spin-flip

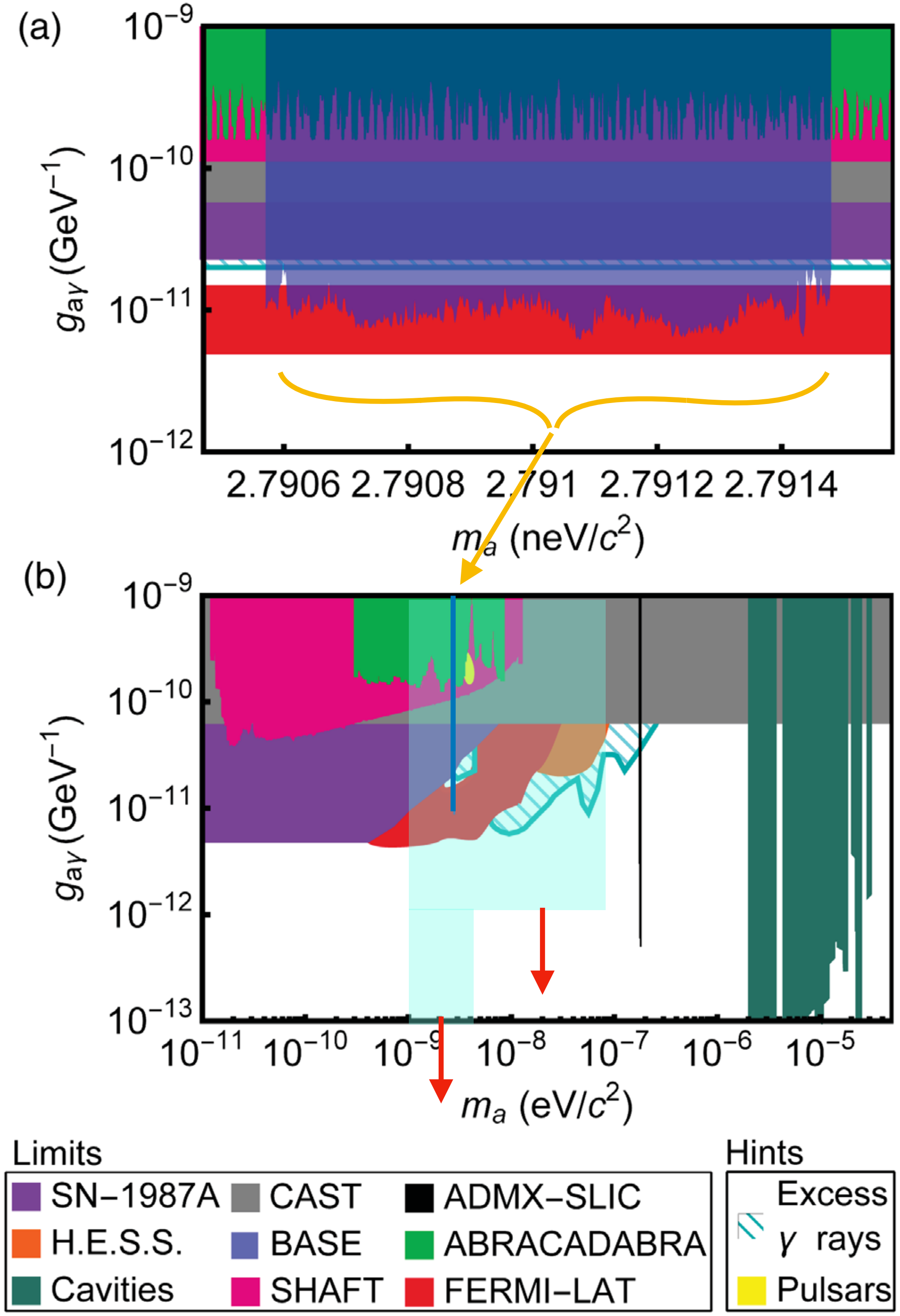
The axion signal

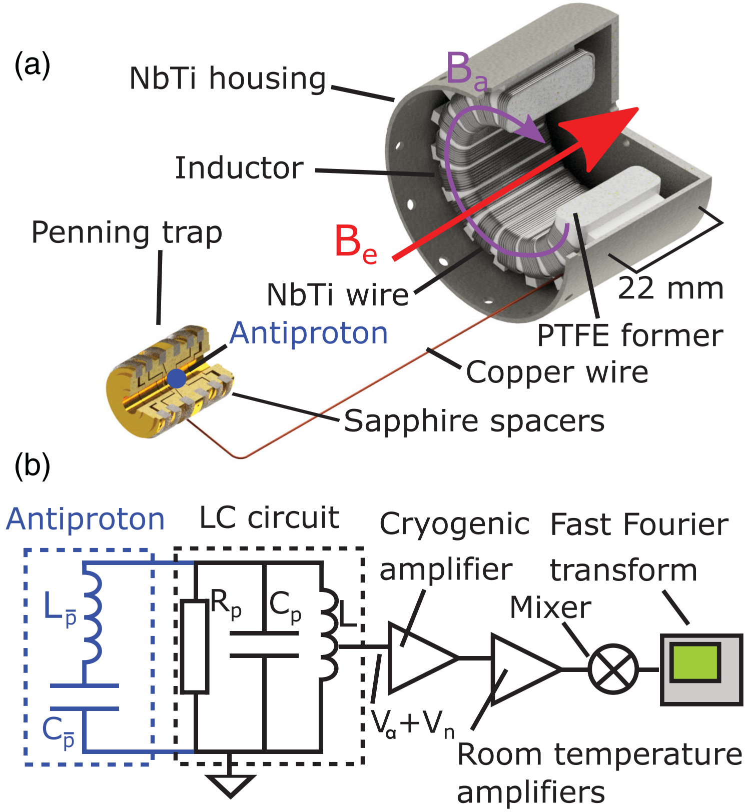
$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})} \kappa \nu_a l N_{\mathrm{T}} (r_2^2 - r_1^2) g_{a\gamma} |\mathbf{B}_e| \sqrt{\rho_a \hbar c}\,.$$

$f(\nu,Q,\mathbf{q})$ is a lorentzian line-shape function proportional to Re{Z}
e_n is the equivalent input noise of the amplifier
κ is the coupling constant
Q is the resonator Q-factor
N_T is the number of turns
l is the length of the toroid along the magnet B field

r_1 is the inner radius of the toroid
r_2 is the outer radius
$g_{a\gamma}$ is the coupling constant
B is the static magnetic field
ρ_a is the dark matter density

Tunability!





currently developing superconducting tunable capacitors & laser-cooled resonators

7 T magnet + broader FFT span: one month →
2 and 5 neV to an upper limit of 1.5×10^{-11} GeV^{-1}

Axion heterodyne detection

problem: cavity resonance generally fixed

Conceptual Theory Level Proposal:

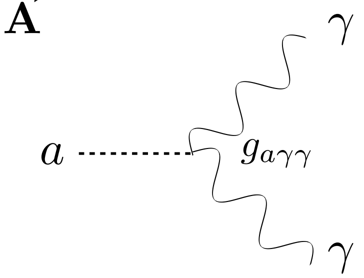
A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, K. Zhou, arXiv:2007.15656

vector potential

Axion DM coupling to electromagnetism through

$$-\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} \supset \frac{1}{2} \mathbf{J}_{\text{eff}} \cdot \mathbf{A}$$



In the presence of **B**, axion → effective current density

$$\mathbf{J}_{\text{eff}} \simeq g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B}\,.$$

Static **B** → $\mathbf{J}_{\text{eff}}$ oscillates with the same frequency as the axion field

Resonant cavities possible down to μeV; below that, need huge volume

→ frequency conversion: driving "pump mode" at ω_0 ~ GHz allows axion to resonantly drive power into "signal mode" at $\omega_1 \sim \omega_0 \pm m_a$

→ scan over axion masses m_a = slight perturbation of cavity geometry, which modulates the frequency splitting $\omega_0 - \omega_1$

→ superconducting RF cavities

Tunability!

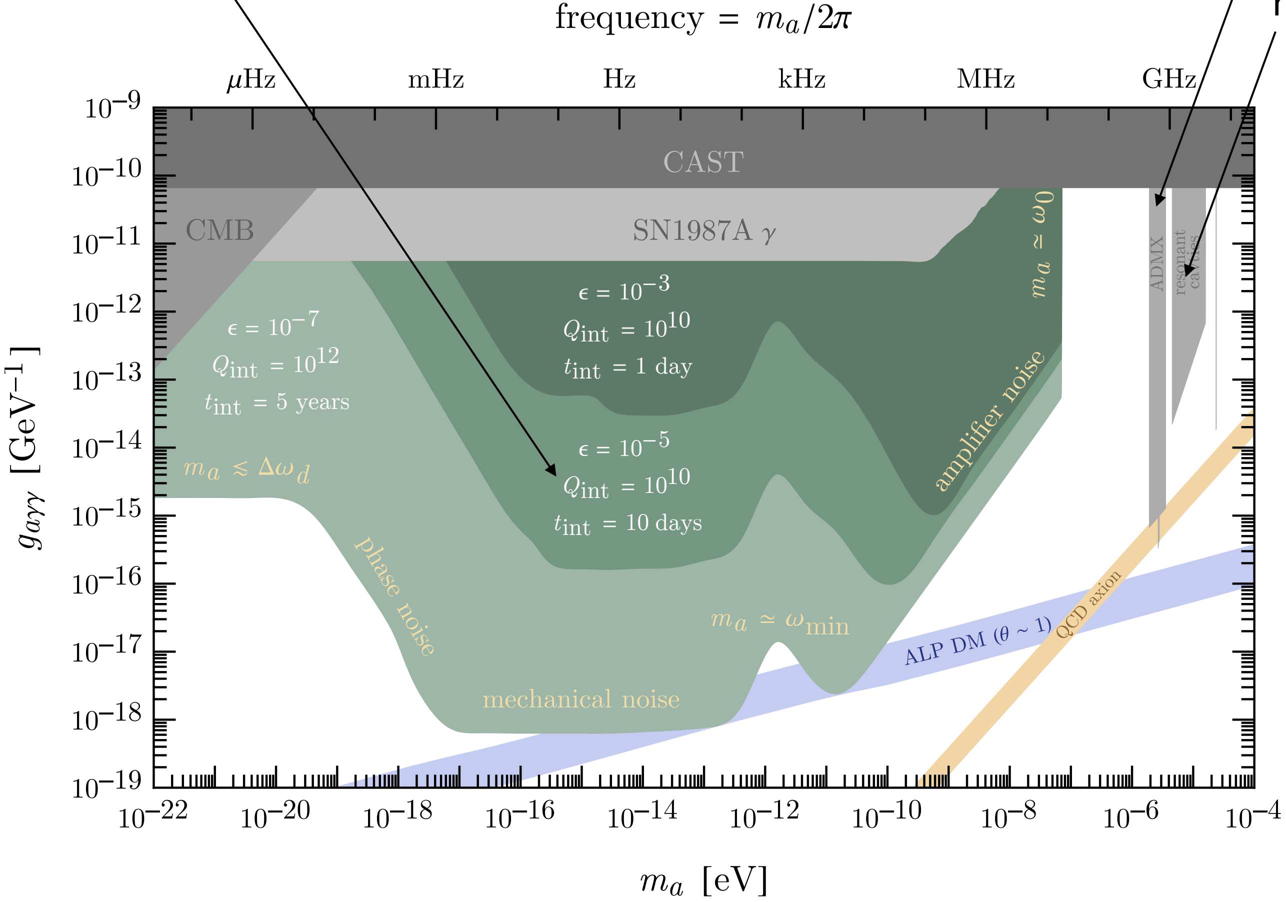
Quantum sensors for new particle physics experiments: tunable RF cavities

$Q_{int} \gtrsim 10^{10}$ achieved by DarkSRF collaboration (sub-nm cavity wall displacements)

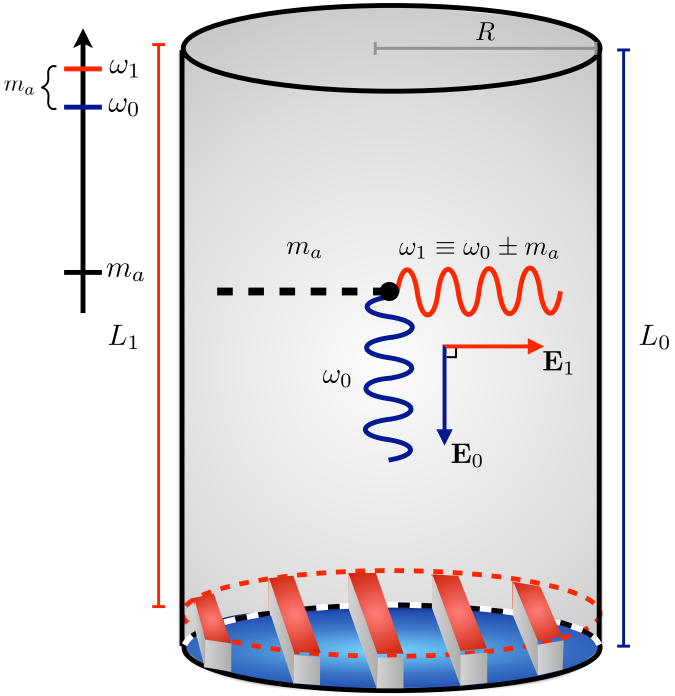
A. Grassellino, “SRF-based dark matter search: Experiment,” 2019. https://indico.fnal.gov/event/19433/session/2/ contribution/2/material/slides/0.pdf

ADMX experiment

resonant cavities



A. Berlin, Raffaele Tito D’Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088



(a) Cartoon of cavity setup.

Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, https://arxiv.org/abs/1912.11048

”The cavity is designed to have two nearly degenerate resonant modes at ω_0 and $\omega_1 = \omega_0 + m_a$. One possibility is to split the frequencies of the two polarizations of a hybrid HE_{11p} mode in a corrugated cylindrical cavity. These two polarizations effectively see distinct cavity lengths, L_0 and L_1, allowing ω_0 and ω_1 to be tuned independently.”

High Q in high B!

Axion searches with resonant haloscopes: resonant cavity immersed in a high and static magnetic field

Relic Axion Detector Exploratory Setup (RADES) searches for axion dark matter with $m_a > 30$ µeV

$$F \sim g_{a\gamma}^2 m_A^2 B^4 V^2 T_{sys}^{-2} G^4 Q,$$

figure of merit ↗ magnetic field ↗ quality factor ↗

Cavity coatings: type II superconductor with a critical magnetic field B_c well above 11 T at 4.2 K

Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter

S. Golm, …, Sergio Calatroni, … *et al.* https://ieeexplore.ieee.org/document/9699394 DOI: 10.1109/TASC.2022.3147741

→ developments of HTS for coatings is essential in improving the sensitivity of resonant haloscopes

Multiple cavities: optimal coupling with external B field, very selective (high Q), centered on resonant ν

Universe **2022**, *8*(1), 5; https://doi.org/10.3390/universe8010005

other frequencies: e.g. solenoidal magnet in dilution cryostat at 10 mK (Canfranc Underground Lab.)

→ to exploit the ultra-low temperatures and go beyond the standard quantum limit:
Josephson parametric amplifiers (JPA), superconducting qubit-based single photon counters,
(or for higher frequencies, kinetic inductor devices (KID))

Universe **2022**, *8*(1), 5; https://doi.org/10.3390/universe8010005

AION: atom interferometer (start small, ultimately → space)

L. Badurina et al., AION: An Atom Interferometer Observatory and Network, JCAP 05 (2020) 011, [arXiv:1911.11755].

Topological Dark Matter (TDM)

TDM can be expressed as a scalar field that couples to fundamental constants, thus producing variations in the transition frequencies of atomic clocks at its passage.

Ultralight Dark Matter

spatial variation of the fundamental constants associated with a change in the gravitational potential

Local Lorentz Invariance (LLI)

independence of any local test experiment from the velocity of the freely-falling apparatus.

searching for daily variations of the relative frequency difference of e.g. Sr optical lattice clocks or Yb$^+$ clocks confined in two traps with quantization axis aligned along non-parallel directions

Local Position Invariance (LPI)

independence of any local test experiment from when and where it is performed in the Universe

comparing atomic clocks based on different transitions can be used to constrain the time variation of fundamental constants and their couplings, comparison of two ^{171}Yb$^+$ clocks and two Cs clocks -> limits on the time variation of the fine structure constant and of the electron-to-proton mass ratio

Gravitational wave detector

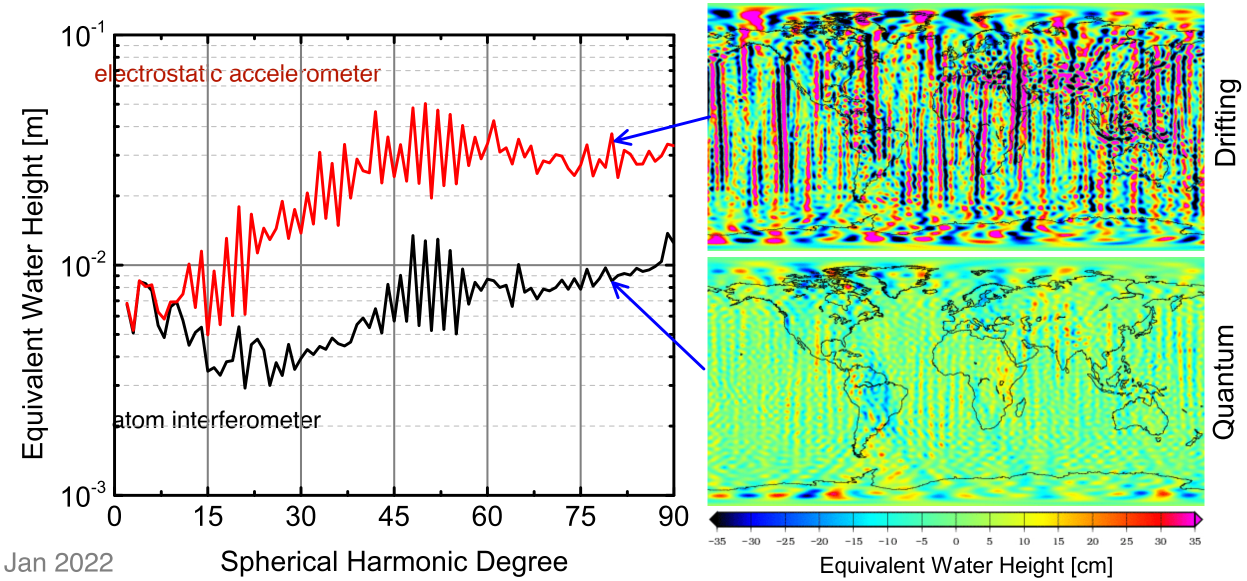
clocks act as narrowband detectors of the Doppler shift on the laser frequency due to the relative velocity between the satellites induced by the incoming gravitational wave

R & D needed:

Optical lattice clocks at up to 1×10^{-18} relative accuracy

& expanded optical fibre network (operated between a number of European metrology institutes)

& develop cold atom technology for robust, long-term operation



Ultralight Dark Matter

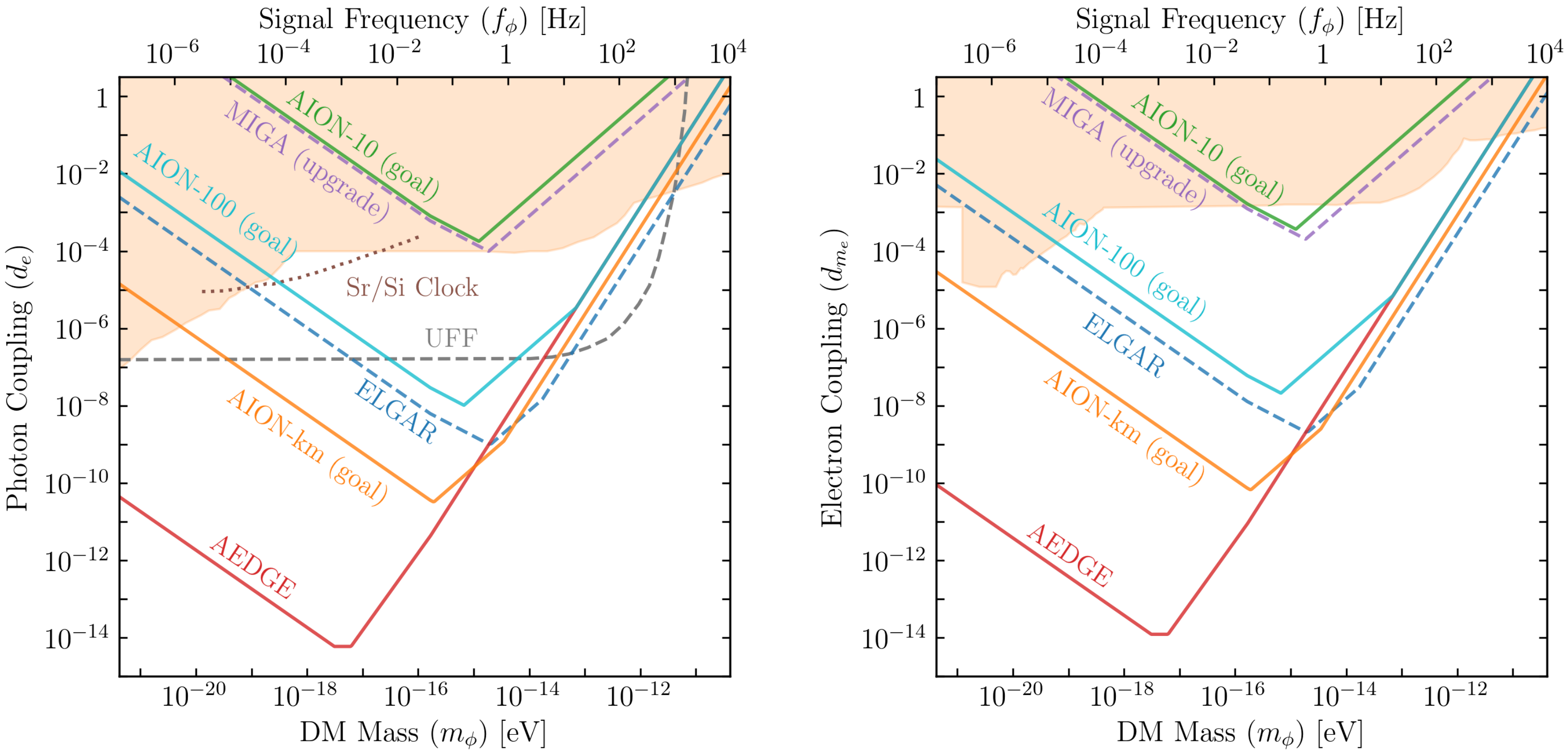


Figure 10. *Sensitivities to the possible couplings of scalar ULDM to photons (left panel) and to electrons (right panel) of the terrestrial AION [181], MIGA [182] and ELGAR [180] experiments, and of the AEDGE space-borne concept [5]. Also shown is a combination of the current constraints from MICROSCOPE [189] and terrestrial torsion balance and atomic clock experiments and (in the left panel) the sensitivity of a prospective measurement of the universality of free fall (UFF) with a precision of* 10^{-17} *[6].*

arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

Where does this fit in? Go after 10^{-20} eV < m_a < 10^{-12} eV

atom interferometry at macroscopic scales: arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

MIGA France

AION UK

ZAIGA China

CERN? shafts (100~500 m ideal testing ground), cryogenics, vacuum, complexity…

MAGIS Fermilab

M. Abe, P. Adamson, M. Borcean, D. Bortoletto, K. Bridges, S. P. Carman et al., Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100), arXiv:2104.02835v1.

MAGIS collaboration, Graham PW, Hogan JM, Kasevich MA, Rajendran S, Romani RW. Mid-band gravitational wave detection with precision atomic sensors. arXiv:1711.02225

satellite missions:

ACES (Atomic Clock Ensemble in Space): 2024-2025

ESA mission for ISS

two on-board clocks rely on atomic transitions in the microwave domain

probe time variations of fundamental constants, and to perform tests of the Lorentz-Violating Standard Model Extension (SME). Possibly topological dark matter

pathfinder / technology development missions:

I-SOC: key optical clock technology (laser cooling, trapping, optical resonators) for space; Sr optical lattice clock / Sr ion clock; microwave and optical link technology;

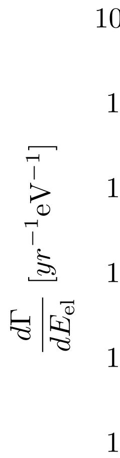
FOCOS (Fundamental physics with an Optical Clock Orbiting in Space): Yb optical lattice clock with 1×10^{-18} stability

~2030

AEDGE: ~2045

satellite mission

El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7,** 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

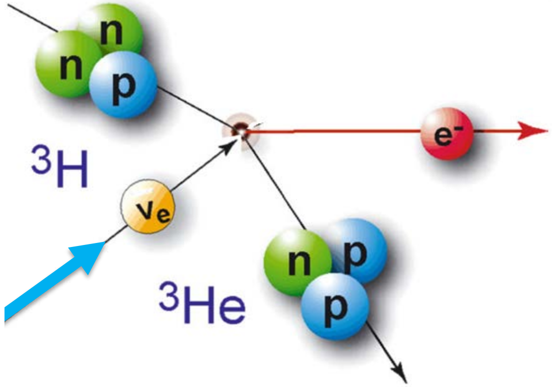


Challenge: Detection of primordial neutrino flux: E_{ν} ~ μeV

neutrino capture on β-decay nuclei as a detection method for the Cosmic Neutrino Background (CNB) was laid out in the original paper by Steven Weinberg in 1962

S. Weinberg, Universal Neutrino Degeneracy, Phys. Rev. 128, 1457 (1962)

detection!
directionality!
energy!

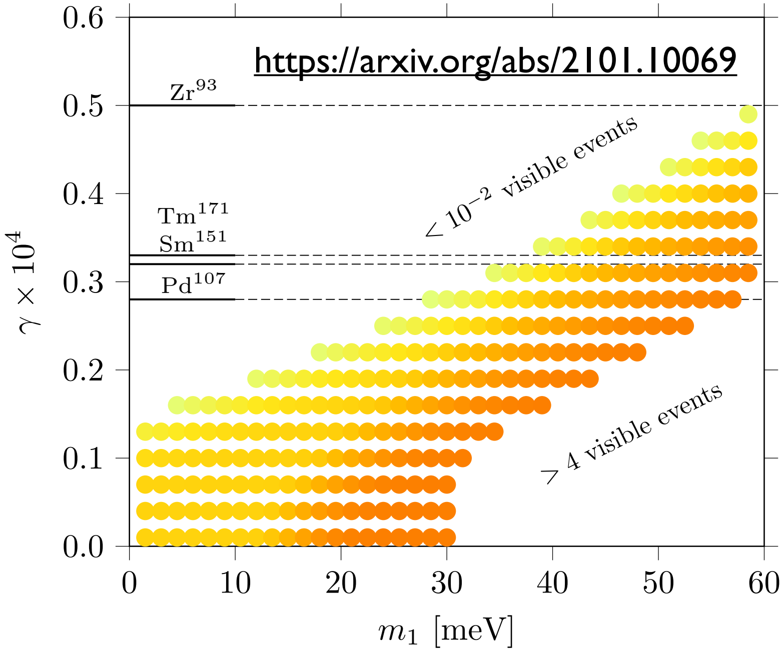


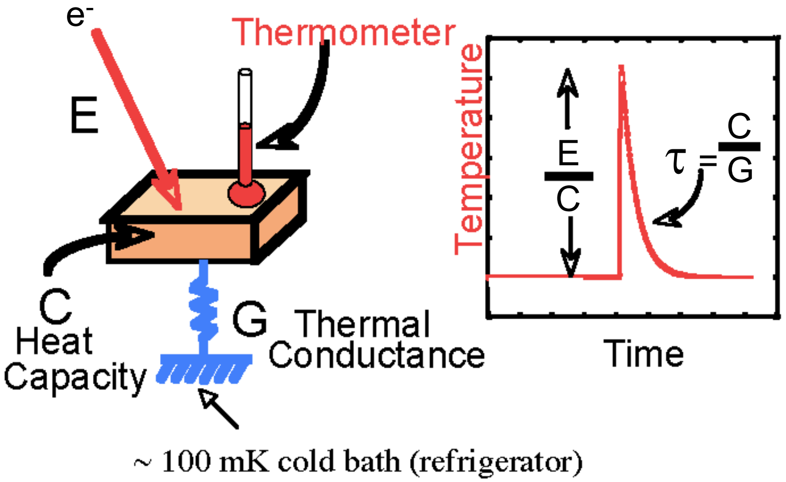
PTOLEMY experimental quest

relic neutrino capture
RF tracker (EM radiation in B field)
microcalorimeter (TES: sub-eV for ~eV)

https://indico.cern.ch/event/1090250/

event rate low!
Better use heavier isotopes than tritium as targets!


https://arxiv.org/abs/2101.10069



MUCH R&D needed!

Quantum detectors for high energy particle physics

typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Cerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them, but do not necessarily use them as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

these are not developed concepts, but rather the kind of approaches one might contemplate working towards

very speculative!

main focus on tracking / calorimetry / timing

closely related: nanostructured materials
→ Frontiers of Physics, M. Doser et al., 2022

what are the challenges?

- tracking: hit positions, material budget, vertexing
- timing: TOF ~ sub-ns (ideally ps) for PID
- calorimetry: shower shape, timing, granularity, particle flow
- redundancy / independent modes of measurement
- novel observables: helicity / polarization
- power budget, event rate, PU (timing)

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6 *

GEMs (graphene)

Atoms, molecules, ions

5.3.5 *

Rydberg TPC's

Spin-based sensors

5.3.3 *

helicity detectors

* https://cds.cern.ch/record/2784893

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6

GEMs (graphene)

Atoms, molecules, ions

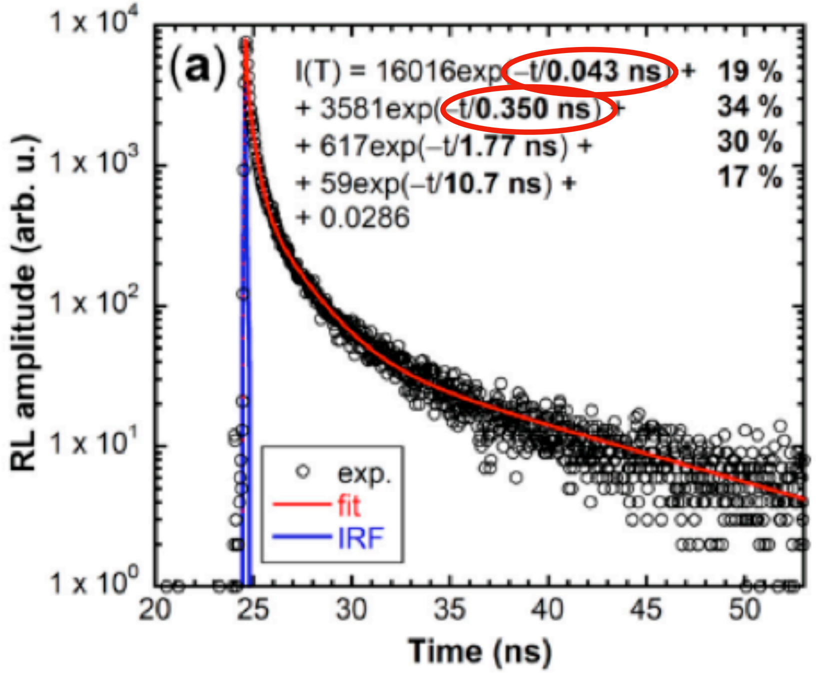
Rydberg TPC's 5.3.5

Spin-based sensors

helicity detectors 5.3.3

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. Nanomaterials 2022, 12, 14. https://doi.org/ 10.3390/nano12010014

Scintillation decay time spectra from $CsPbBr_3$ nanocrystal deposited on glass

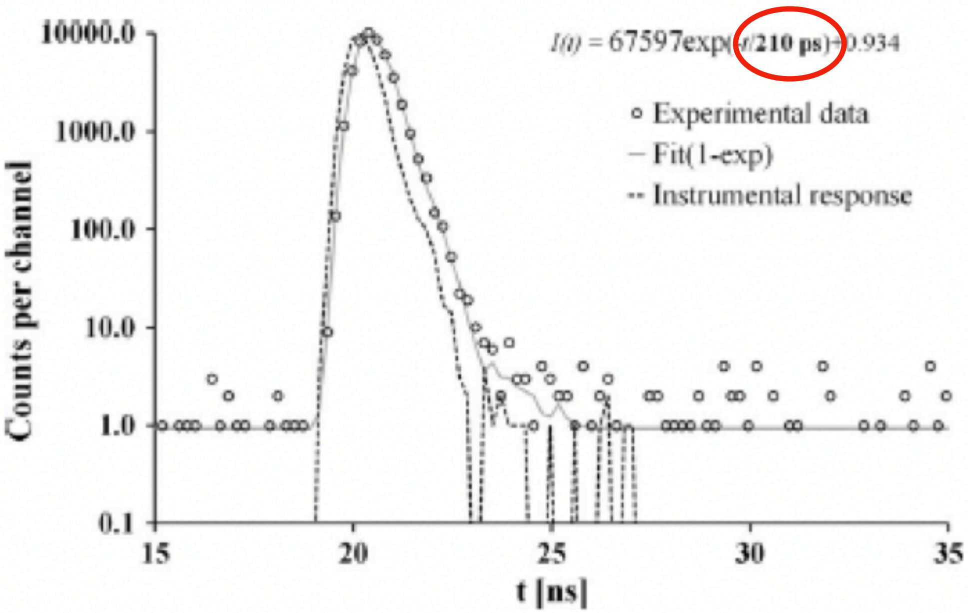


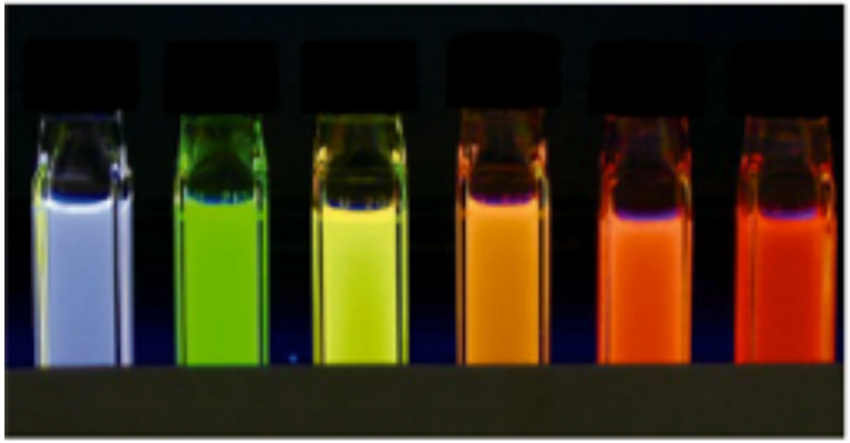
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function *I*(*t*) provided in the figure.

Lenka Prochazkova et al., Optical Materials 47 (2015) 67–71

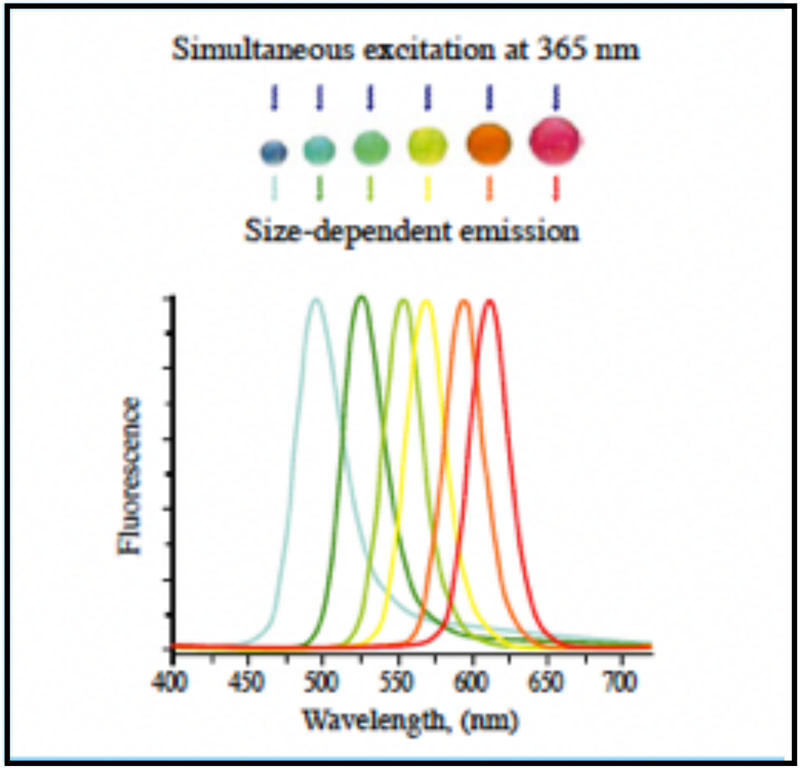
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN



Hideki Ooba, "Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements," AIST TODAY Vol.6 , No.6 (2006) p.26- 27

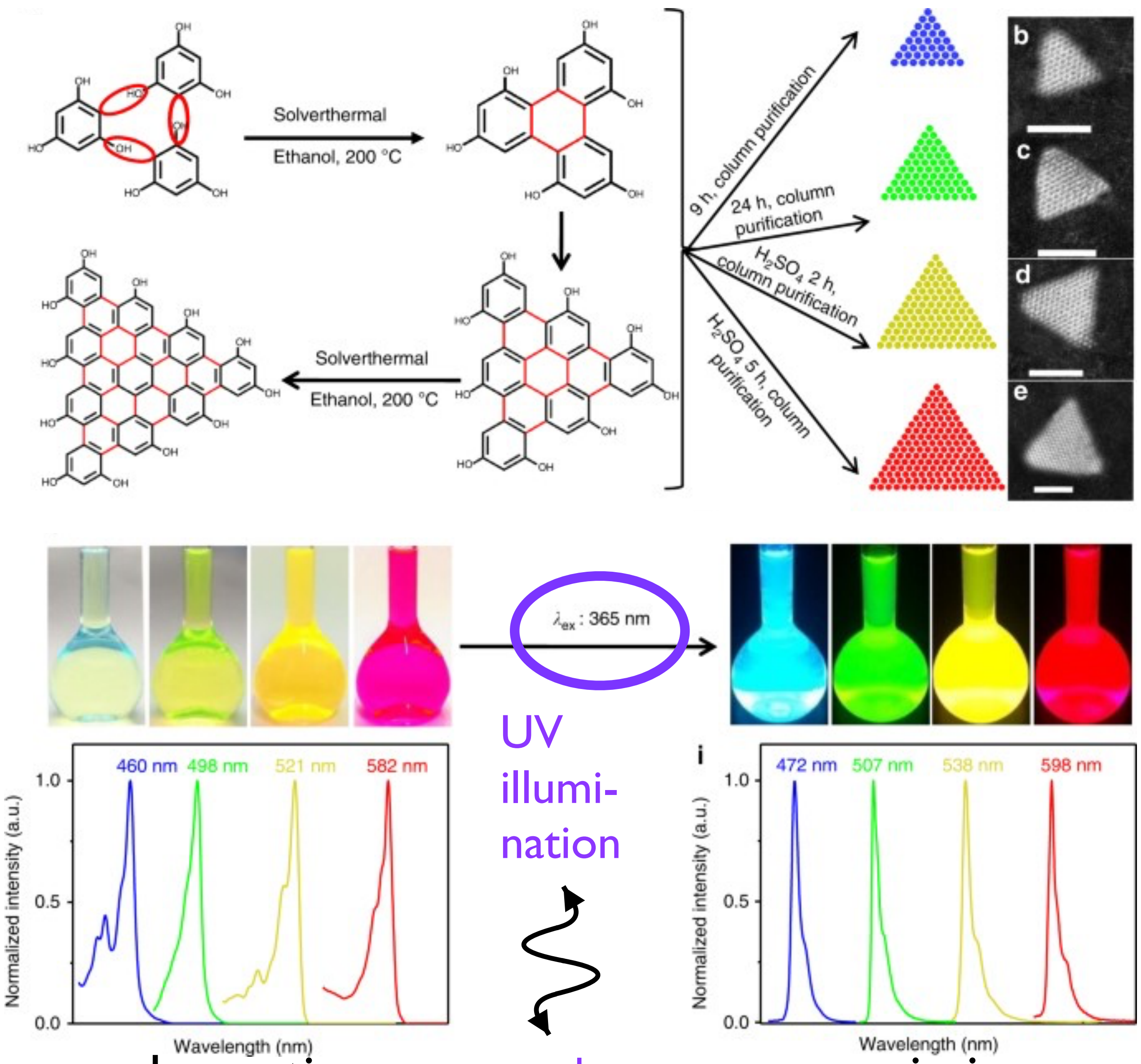


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

deposit on surface of high-Z material → thin layers of UV → VIS WLS

embed in high-Z material ? two-species (nanodots + microcrystals) embedded in polymer matrix?
→ quasi continuous VIS-light emitter (but what about re-absorbtion?)

Quantum dots: chromatic calorimetry



UV illumination

absorption

e.m. shower

emission

F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

<u>idea</u>: seed different parts of a "crystal" with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is <u>uniquely</u> assignable to a specific nanodot position

requires:
- <u>narrowband</u> emission (~20nm)
- only absorption at longer wavelengths
- <u>short rise / decay times</u>

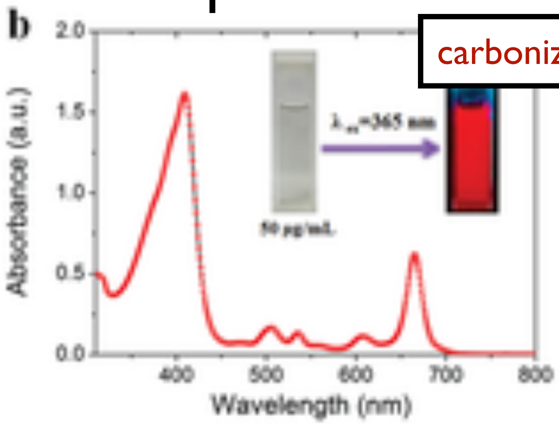
select appropriate nanodots

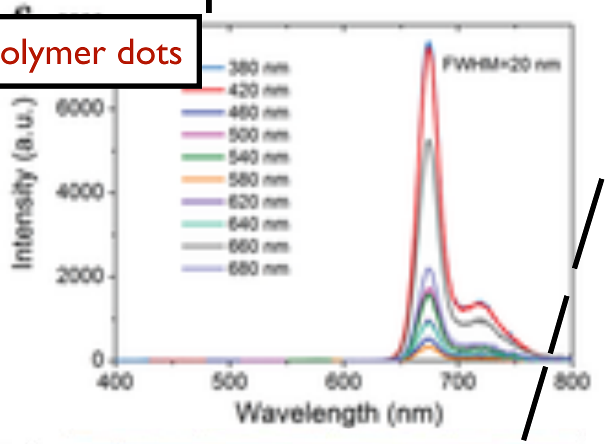
e.g. triangular carbon nanodots

absorption spectrum

emission spectrum

carbonized polymer dots





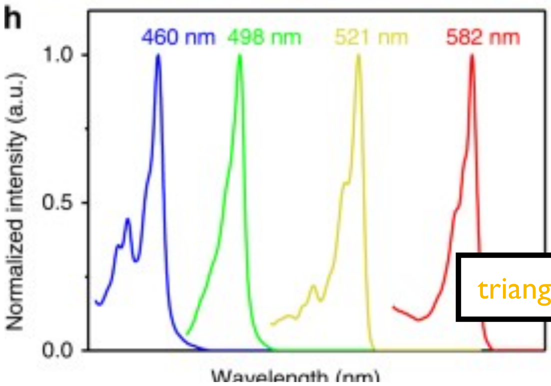
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

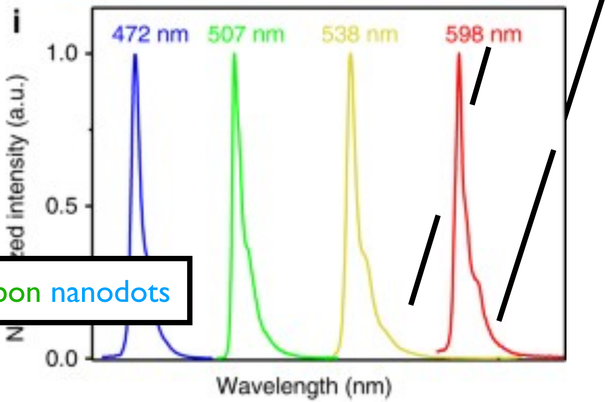
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

rightmost nanodots:
absorb wavelengths < 410 nm
emit at > 420 nm

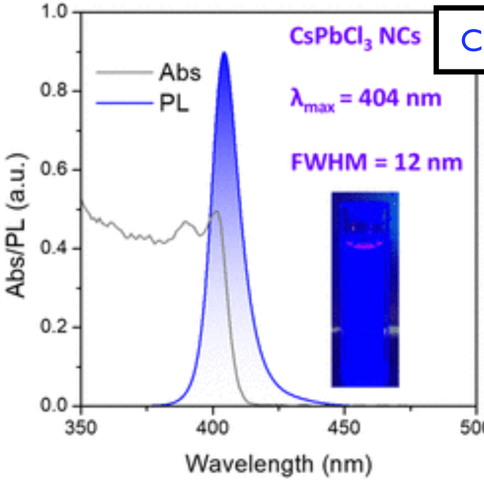
triangular carbon nanodots

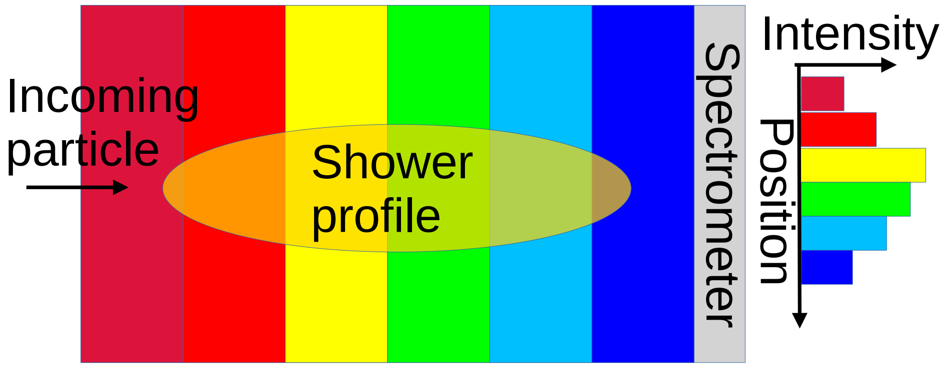




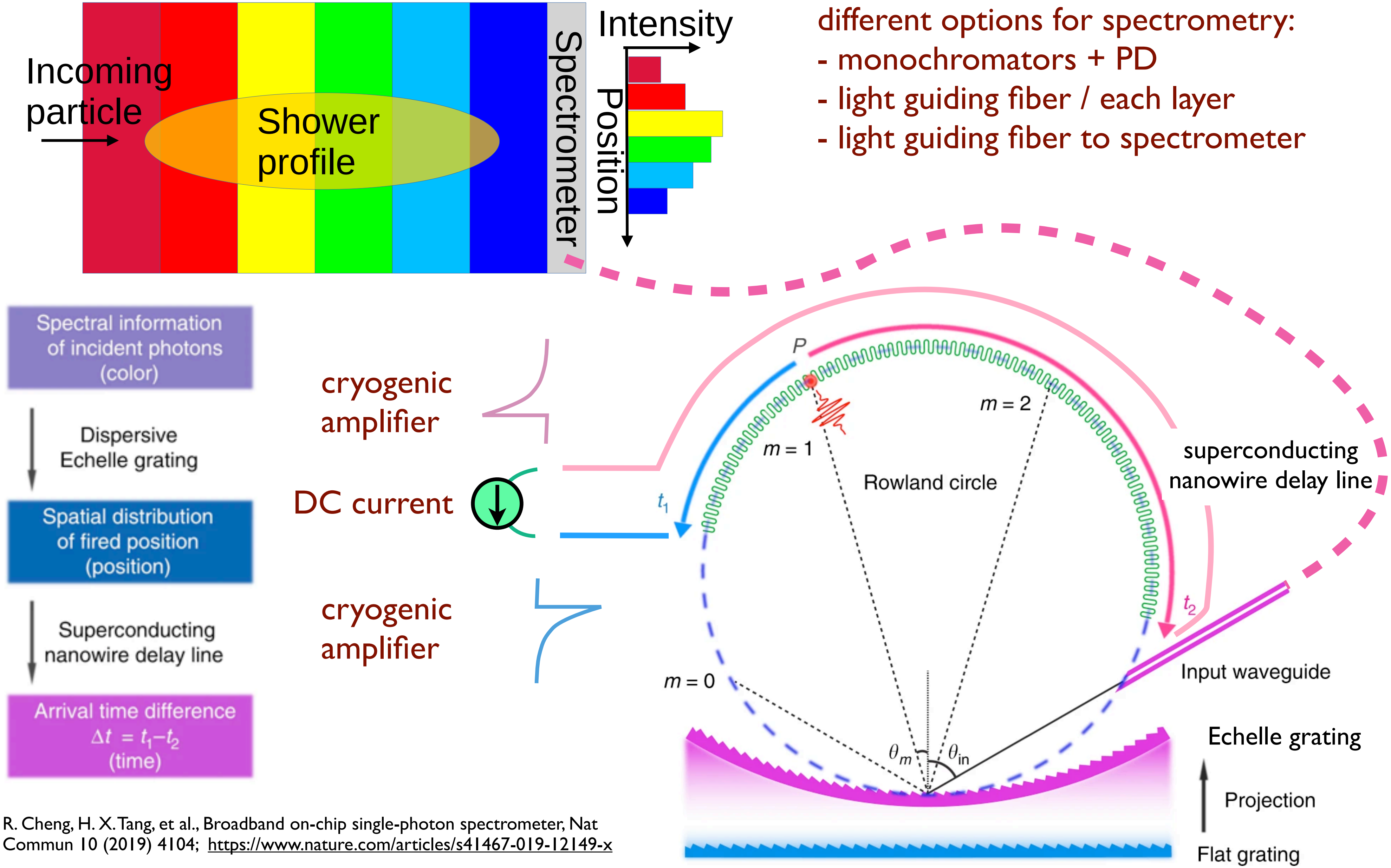
if high-Z substrate transparent in 400-700 nm, then no re-absorption of emitted light

CsPbCl₃ nanocrystals





Quantum dots: chromatic calorimetry (shower profile via ***spectrometry***)



different options for spectrometry:

- monochromators + PD
- light guiding fiber / each layer
- light guiding fiber to spectrometer

R. Cheng, H. X. Tang, et al., Broadband on-chip single-photon spectrometer, Nat Commun 10 (2019) 4104; https://www.nature.com/articles/s41467-019-12149-x

Active scintillators (QWs, QDs, QWDs, QCLs)

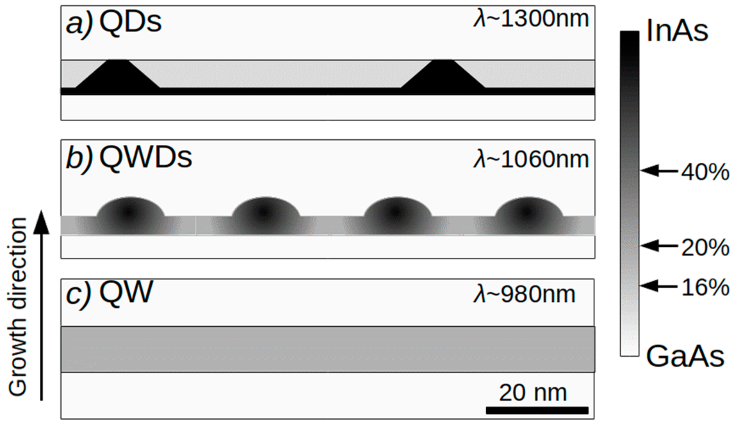
standard scintillating materials are passive

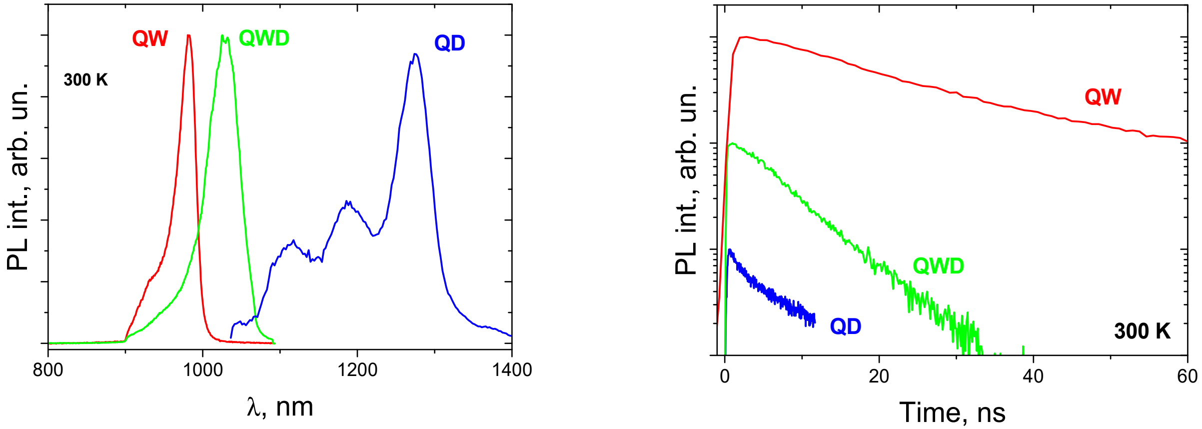
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

is it possible to produce active scintillating materials?

- electronically amplified / modulable
- pulsed / primed
- gain adapted in situ

existing QD's, QWD's are elements of optoelectronic devices, typically running at 10 GHz, quite insensitive to temperature





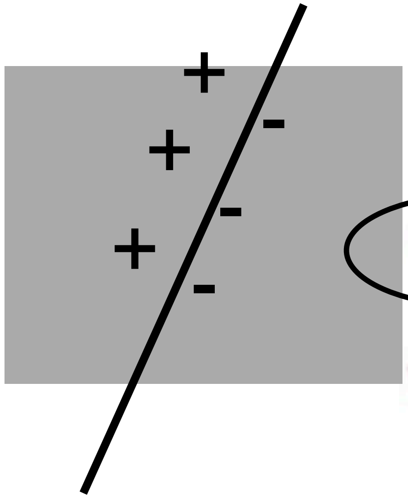
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

Emission in IR! Silicon is transparent at these wavelengths…
Can this IR light be transported *through* a tracker to outside PDs?

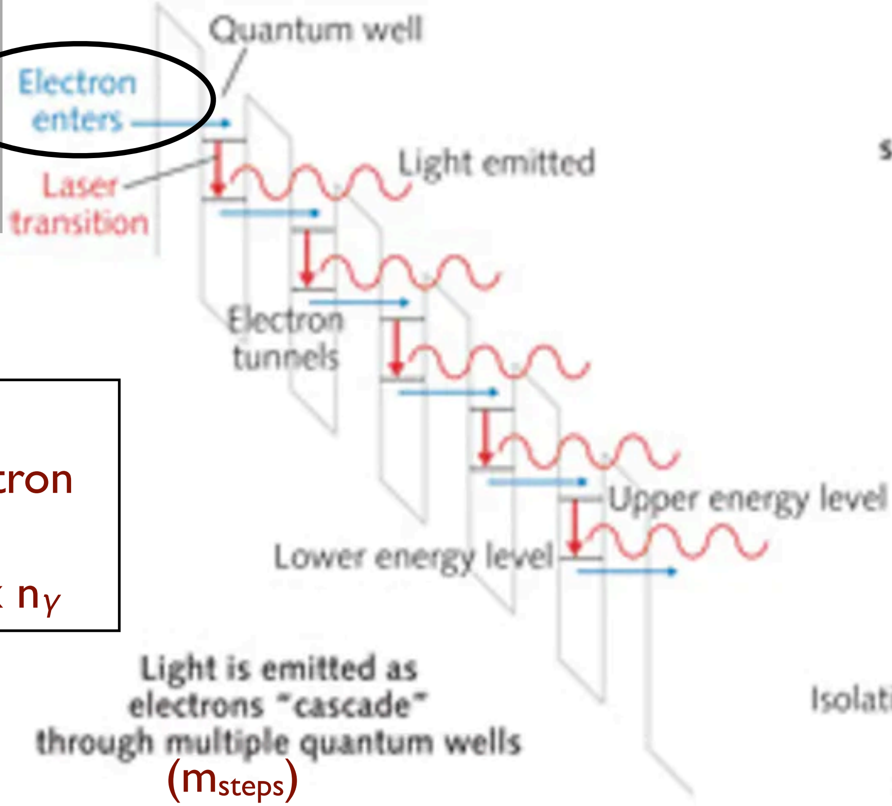
QD's are radiation resistant

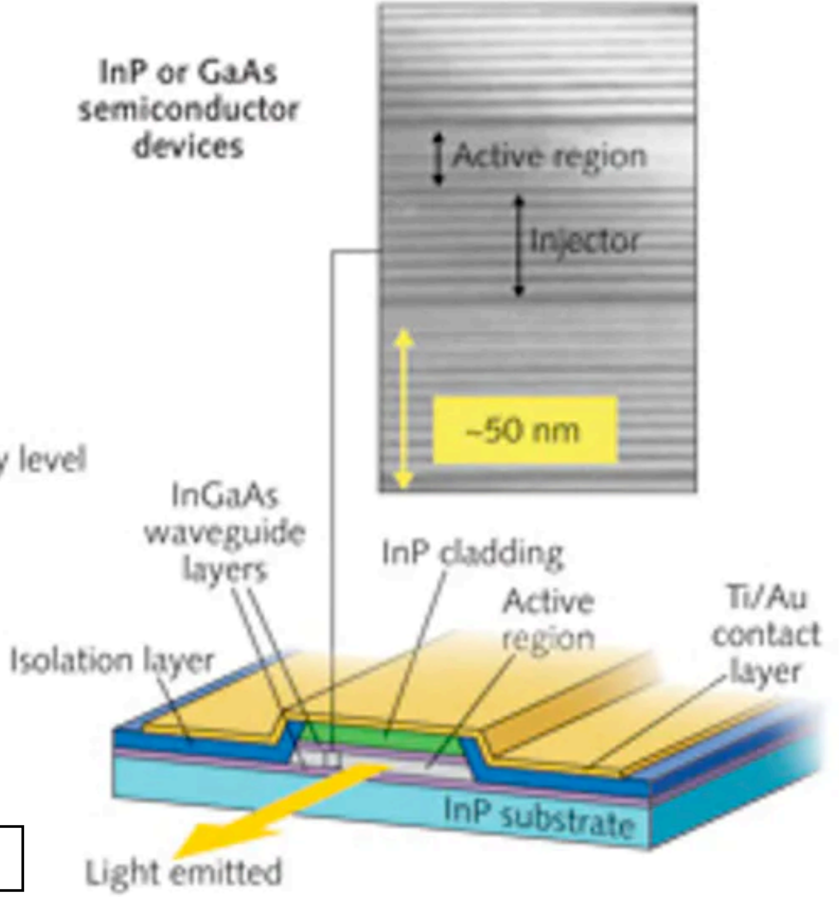
R. Leon et al., "Effects of proton irradiation on luminescence emission and carrier dynamics of self-assembled III-V quantum dots," in IEEE Transactions on Nuclear Science, 49, 6, 2844-2851 (2002), doi: 10.1109/TNS.2002.806018.

Active scintillators (QCLs, QWs, QDs, QWDs)



https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy





Cross-section of QCL facet

Couple bulk semi-conductor to electron injection layer:

$n_e \longrightarrow m_{steps} \times n_\gamma$

Emitted light is IR~THz, normally mono-chromatic but tunable from 3 μm ~ 12 μm

Radiation resistant (Radiation Physics and Chemistry 174, 2020, 108983)

Quantum dots and wells: https://arxiv.org/abs/2202.11828

submicron pixels

DoTPiX

= single n-channel MOS transistor, in which a buried quantum well gate performs two functions:

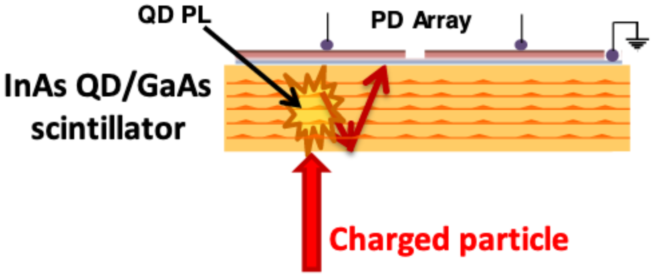
- as a hole-collecting electrode and
- as a channel current modulation gate

Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021

M.R. Hoeferkamp, S. Seidel, S. Kim, J. Metcalfe, A. Sumant, H. Kagan, W. Trischuk, M. Boscardin, G.-F. Dalla Betta, D.M.S. Sultan, N.T. Fourches, C. Renard, A. Barbier, T. Mahajan, A. Minns, V. Tokranov, M. Yakimov, S. Oktyabrsky, C. Gingu, P. Murat, M.T. Hedges

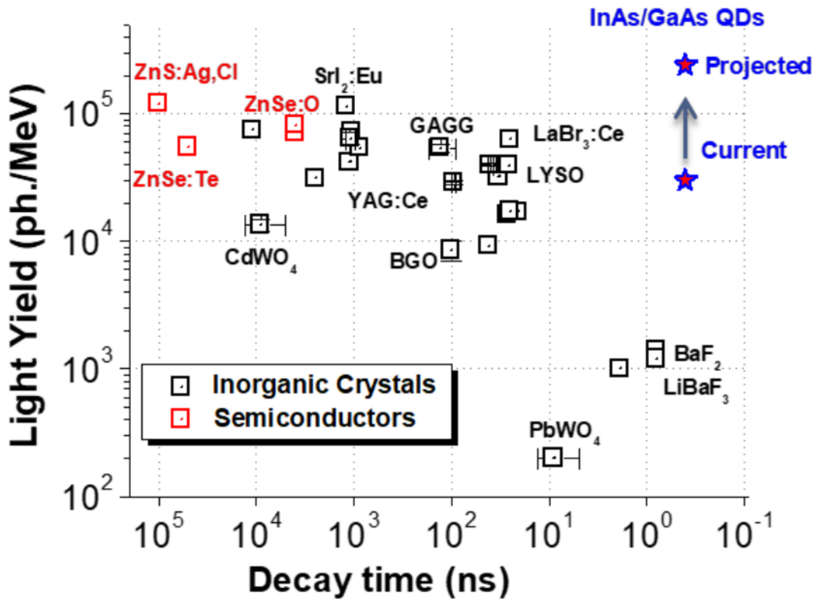
https://arxiv.org/abs/2202.11828

scintillating (chromatic) tracker



IR emission from InAs QD's

integrated PD's (1-2 μm thick)



2-D materials for MPGDs

Florian Brunbauer / CERN

State-of-the-art MPGDs:
- high spatial resolution
- good energy resolution
- timing resolution <25ps (PICOSEC Micromegas)

use of 2-D materials to improve:
- tailor the primary charge production process,
- protect sensitive photocathodes in harsh environments
- improve the performance of the amplification stage

tunable work function

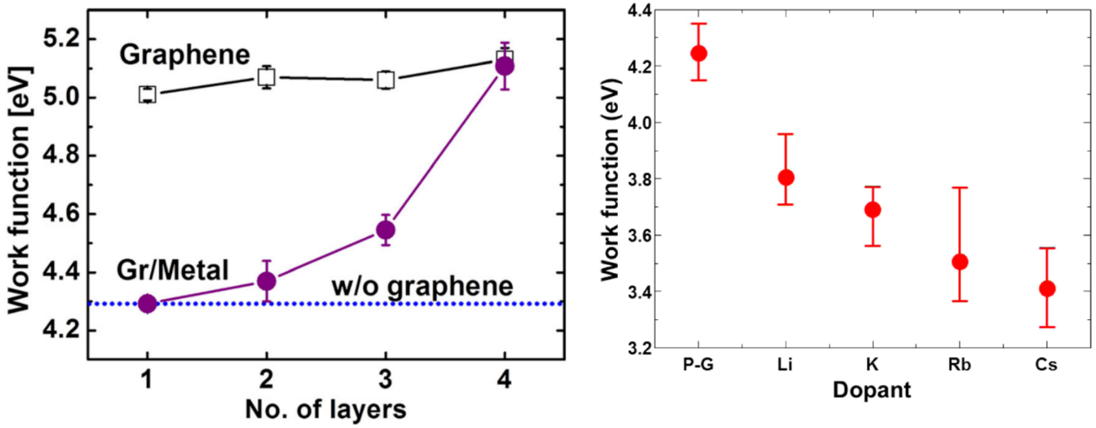
efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

(additionally, encapsulation of semiconductive as well as metallic (i.e. Cu) photocathodes increases operational lifetime)

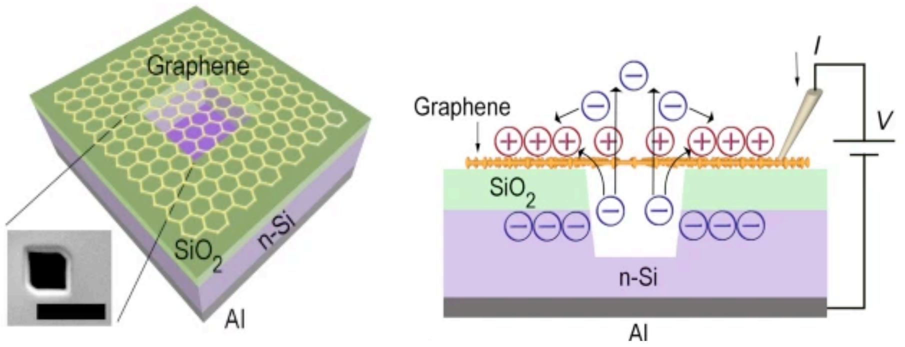
amplification

back flow of positive ions created during charge amplification to the drift region can lead to significant distortions of electric fields

Graphene has been proposed as selective filter to suppress ion back flow while permitting electrons to pass:
Good transparency (up to ~99.9%) to very low energy (<3 eV) electrons (?)



Tuning the work function of graphene toward application as anode and cathode, Samira Naghdi, Gonzalo Sanchez-Arriaga, Kyong Yop Rhee, https://arxiv.org/abs/1905.06594



Space charge neutralization by electron-transparent suspended graphene, Siwapon Srisonphan, Myungji Kim & Hong Koo Kim, Scientific Reports 4, 3764 (2014)

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's 5.3.5

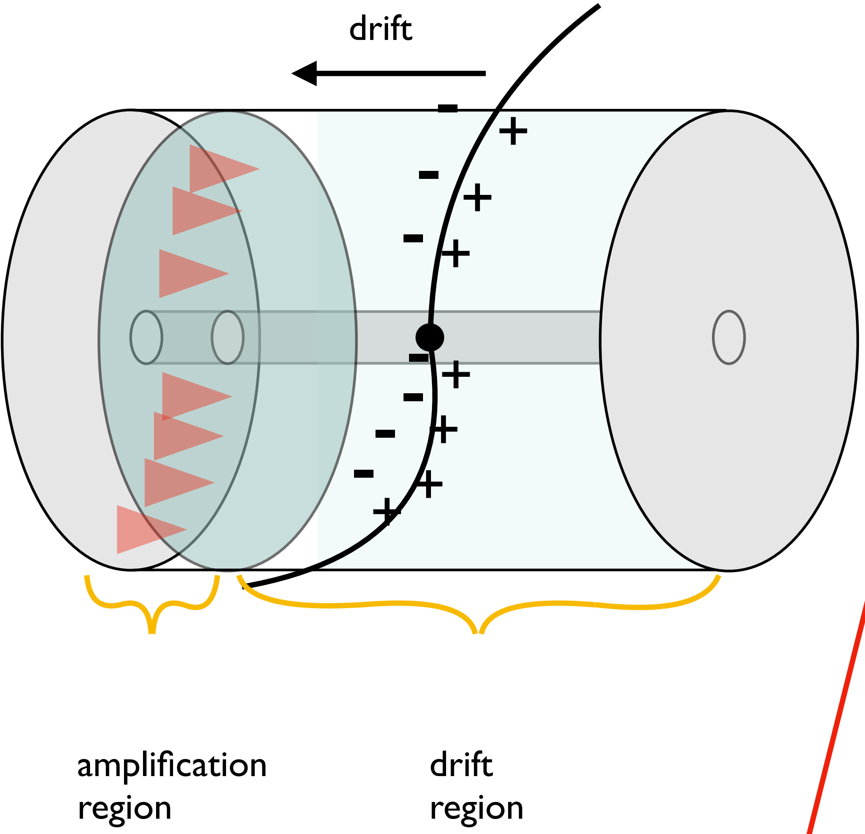
Spin-based sensors

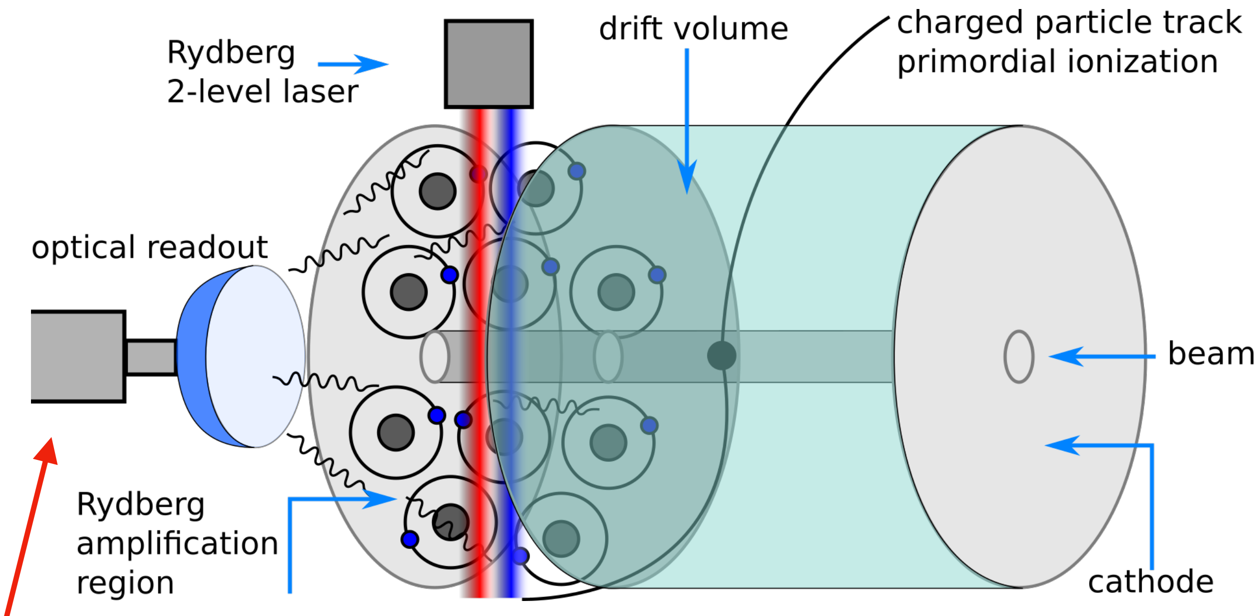
helicity detectors 5.3.3

Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the amplification region





enhanced electron signal through "priming" of gas in amplification region: ⟶ effective reduction of ionization threshold of gas in amplification region ⟶ higher electron yield

Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the drift region

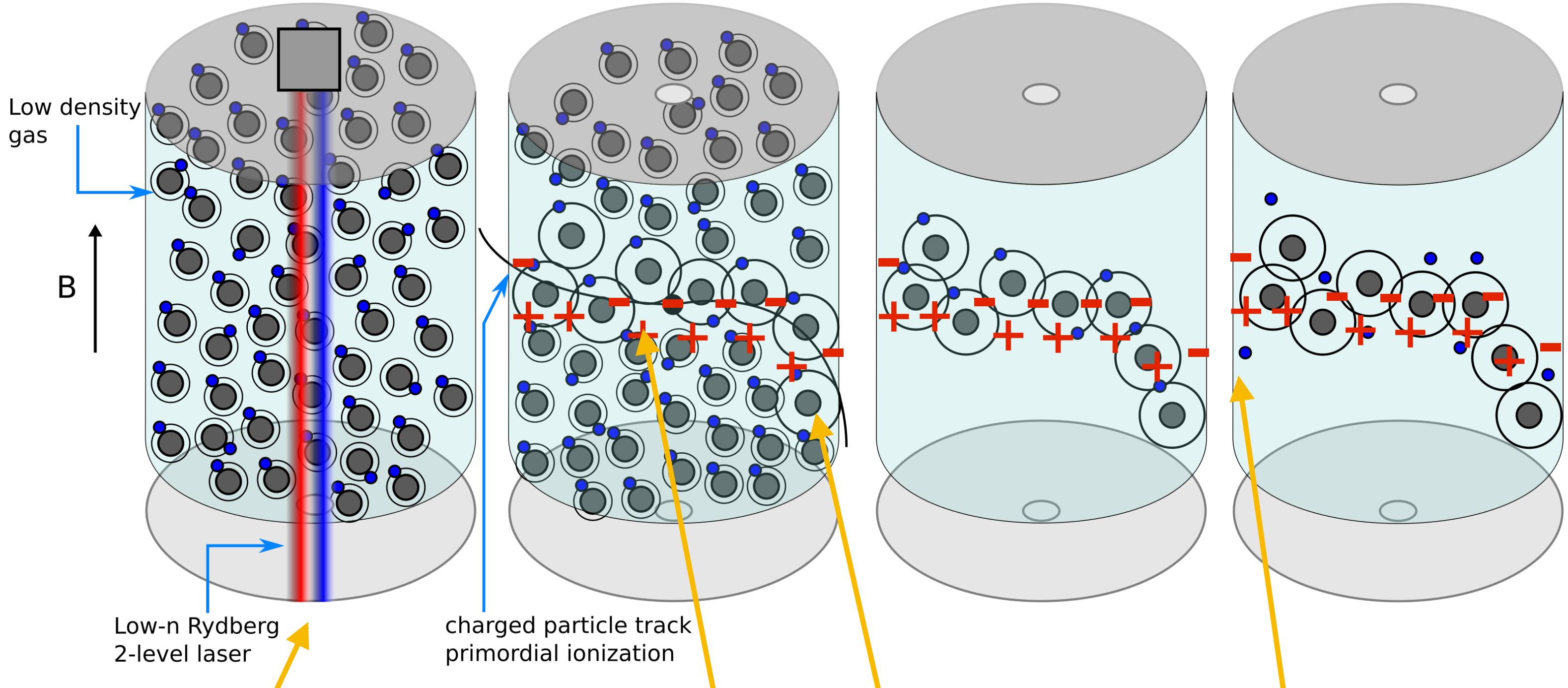
principle carries over to drift region:
enhanced electron signal through "priming" of gas in drift region:
effective reduction of ionization threshold of gas in drift region
increased dE/dx through standard primary ionization + photo-ionization of atoms excited by mip's

Preparation of the low-n Rydberg states

Ionization to high-n Rydberg state by charged particles

Fast decay of low-n Rydberg states

Laser spectroscopy or induced ditachement of long lived states



ionization + excitation;
natural decay of unmodified atoms

reduction of ionization and
atomic excitation threshold

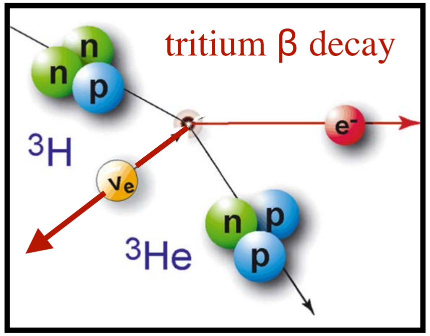
photo-ionization of excited atoms

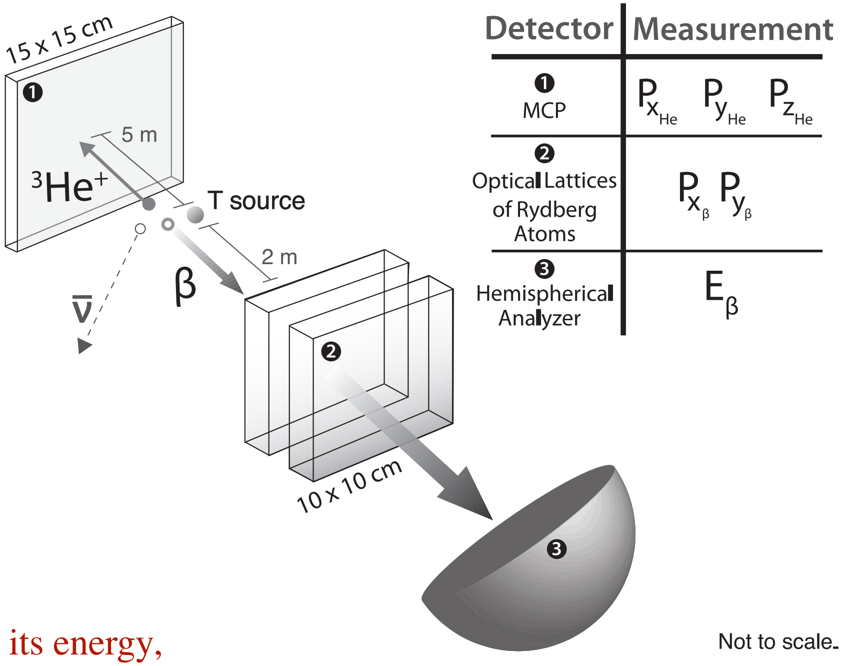
Rydberg atom TPC's

Using cold atoms to measure neutrino mass

M Jerkins, J R Klein, J H Majors, F Robicheaux and M G Raizen
2010, *New J. Phys.* **12** 043022

https://iopscience.iop.org/article/10.1088/1367-2630/12/4/043022/meta





Detector	Measurement
❶ MCP	$P_{x_{He}}$ $P_{y_{He}}$ $P_{z_{He}}$
❷ Optical Lattices of Rydberg Atoms	P_{x_β} P_{y_β}
❸ Hemispherical Analyzer	E_β

Not to scale.

"In order to measure the momentum of the β without significantly altering its energy, we propose exploiting the effect of a passing electron on Rydberg atoms [22, 23]. In the β's flight path before it reaches the spectrometer, we create an optical lattice filled with rubidium atoms in the ground state [24, 25]. Using laser excitation, we can excite the atoms to a high Rydberg state [26, 27], such as 53s. When the β passes one of these atoms, it can excite the atom from a 53s state to a 53p state, and the atom will remain trapped in its optical lattice position. We propose slowing the electrons with a controlled voltage soon after they leave the source so that by the time they reach the optical lattice, they have a maximum energy of 900 eV, which increases their cross section for exciting a Rydberg atom to 0.36 × 10−9 cm2.5 When a β signal is detected downstream in the spectrometer, the 53 s atoms are optically de-excited using stimulated Raman adiabatic passage (STIRAP) [27], and an electric field of 100 V cm−1 is ramped within ~130 ns to ionize any Rydberg atoms in a 53p state. Once the atoms are ionized, they will be detected by a multi-hit position-sensitive MCP. Based on realistic density limits, the β will excite several Rydberg atoms as it passes through the optical lattice, so we will be able to obtain the projection of a track from the passing β."

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's 5.3.5

Spin-based sensors

helicity detectors 5.3.3

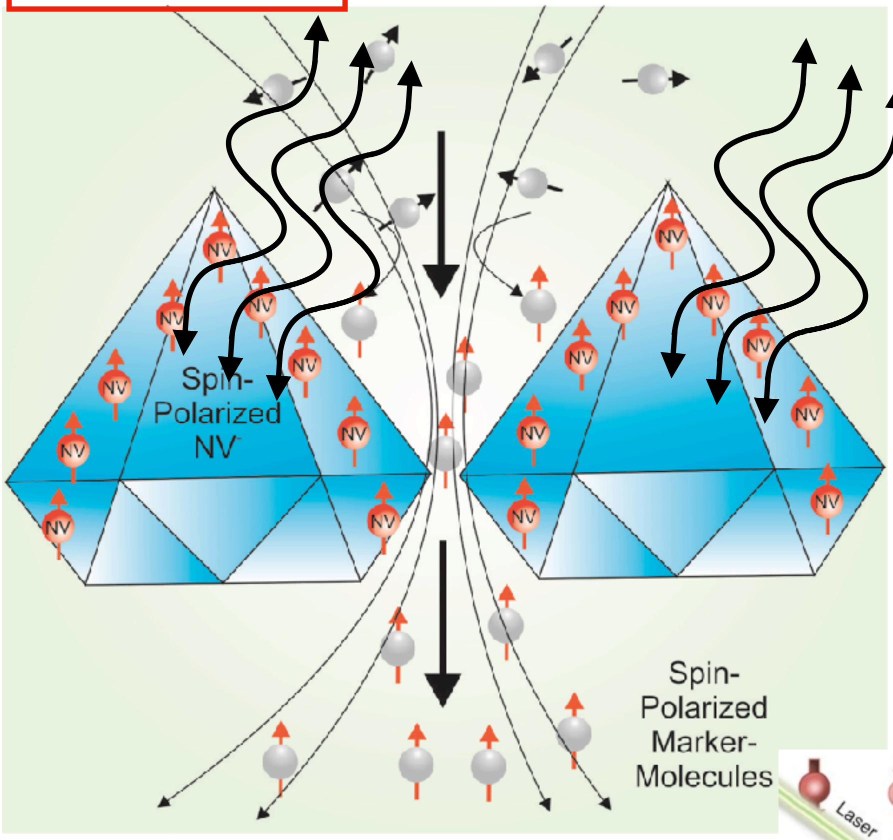
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

spin-spin scattering for helicity determination: usually with polarized beams and/or polarized targets

introduce polarized scattering planes to extract track-by-track particle helicity

$10^{16} \sim 10^{18}$ / cm^3



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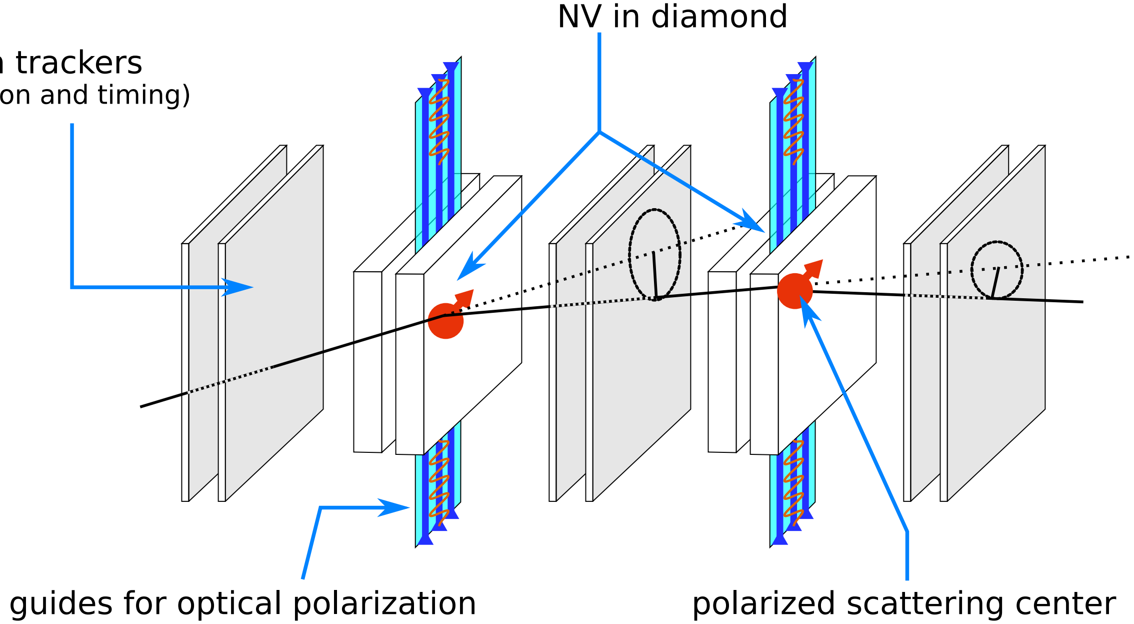
https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

Diamond plates of up to 8 × 8 mm^2 in size, fabricated by Element Six

use NV-diamonds to *scatter* mips (spin-dependent scattering)

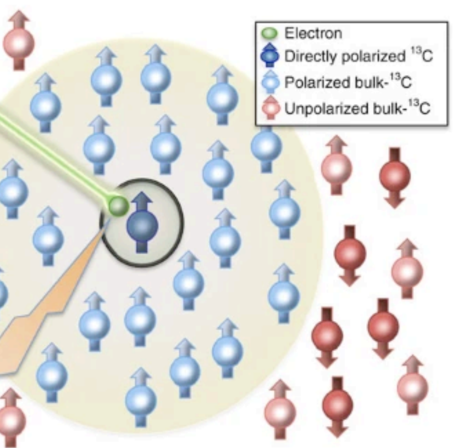


NV in diamond

silicon trackers
(direction and timing)

guides for optical polarization

polarized scattering center



Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

https://www.nature.com/articles/ncomms9456

x 10^2

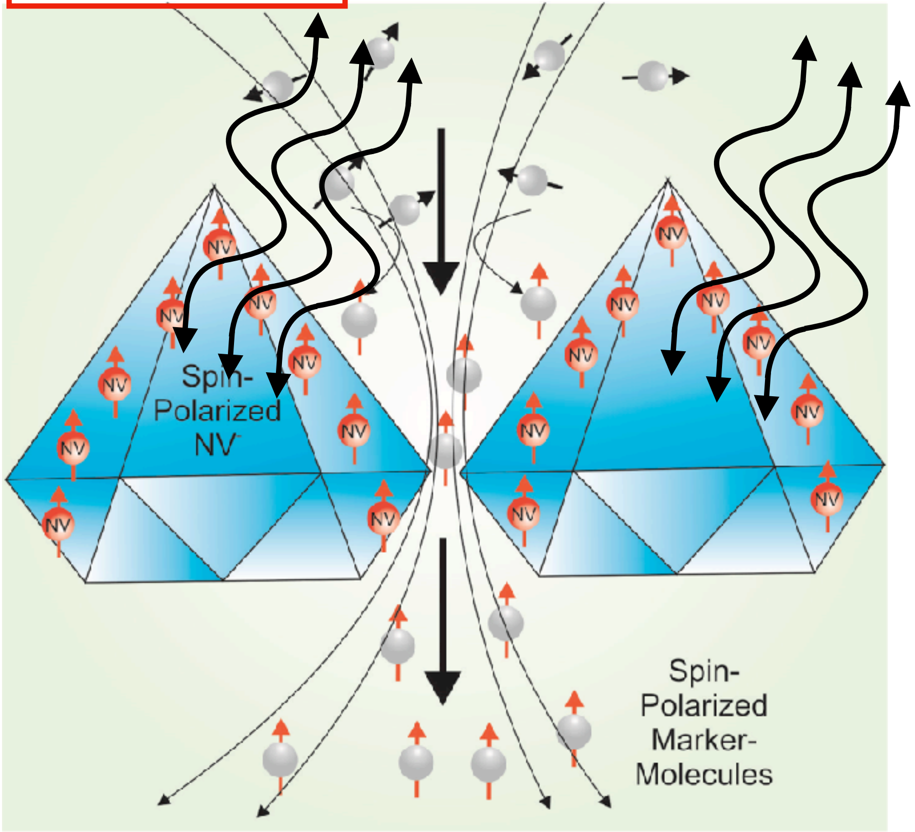
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

spin-spin scattering for helicity determination: usually with polarized beams and/or polarized targets

polarimetry of target fragments (active target)

$10^{16} \sim 10^{18}$ / cm^3



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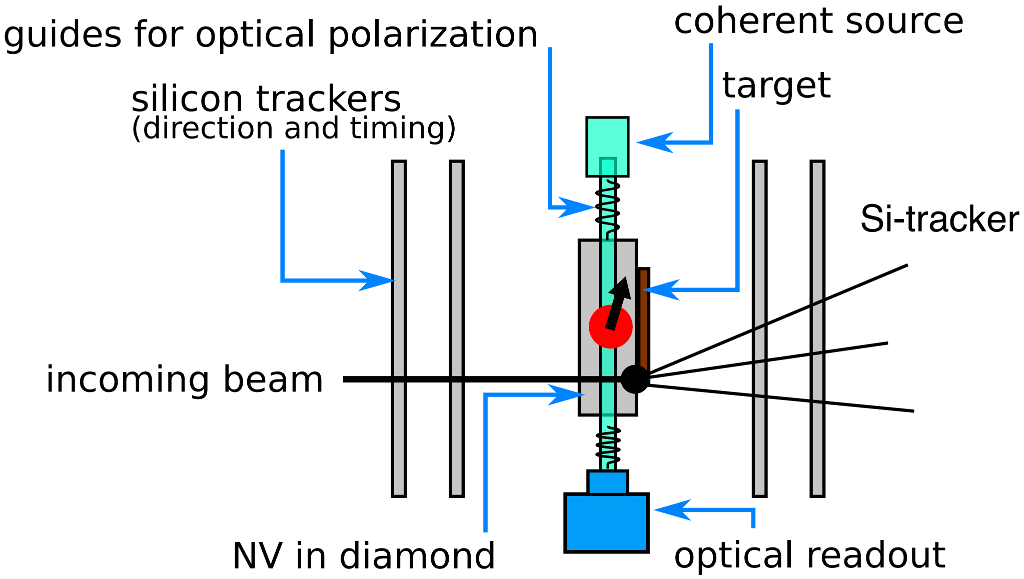
https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

Diamond plates of up to 8 × 8 mm² in size, fabricated by Element Six

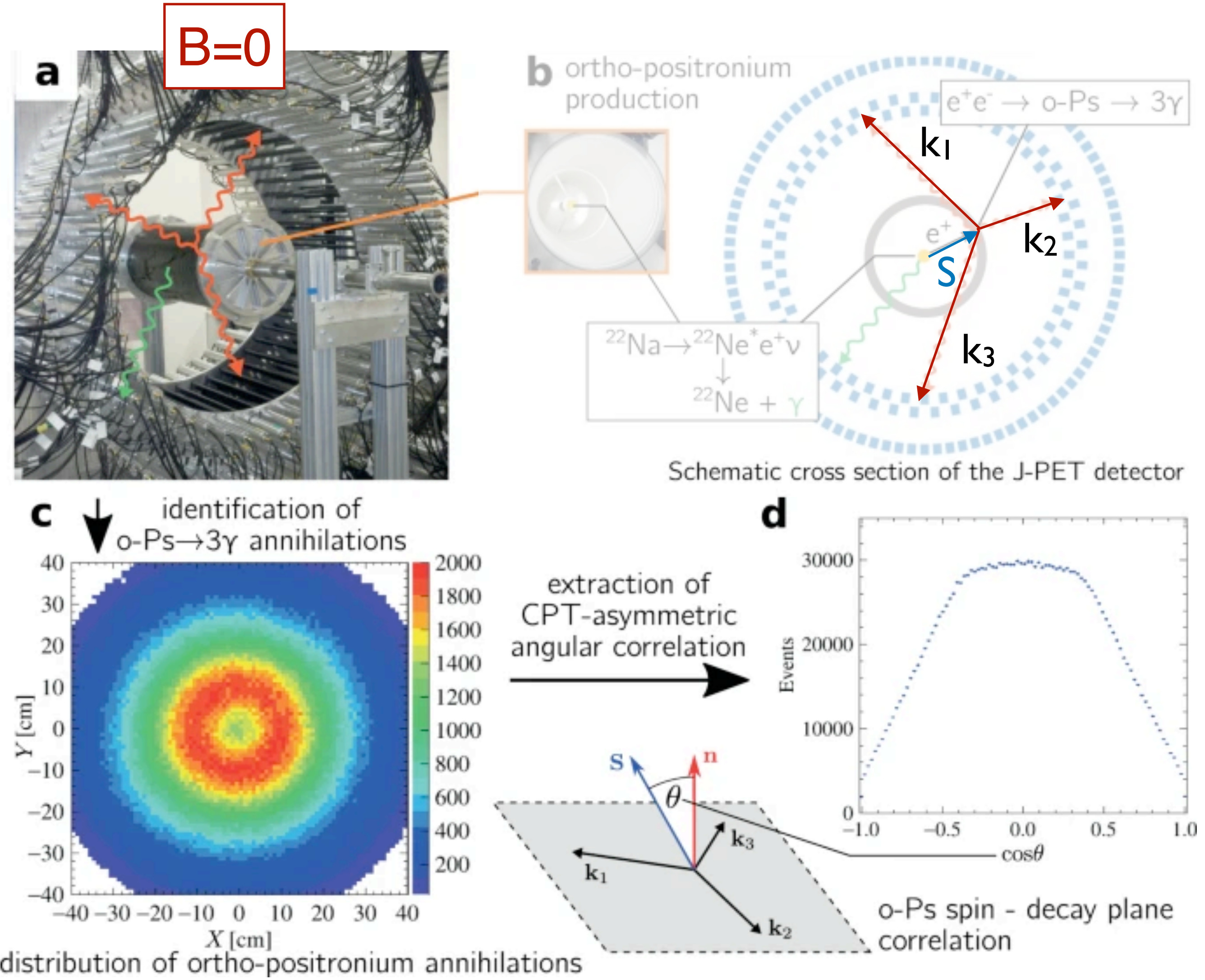
use NV-diamonds to *sense* spin of heavy nuclear spectator fragment



measurement of photon polarizations

Pawel Moskal / Krakow

J-PET: 3-photon correlations / entanglement



Hyperfine Interact (2018) 239: 56 https://doi.org/10.1007/s10751-018-1527-x

discrete symmetry operators

Operator	C	P	T	CP	CPT
$S \cdot k_1$	+	−	+	−	−
$S \cdot (k_1 \times k_2)$	+	+	−	+	−
$(S \cdot k_1) \cdot (S \cdot (k_1 \times k_2))$	+	−	−	−	+

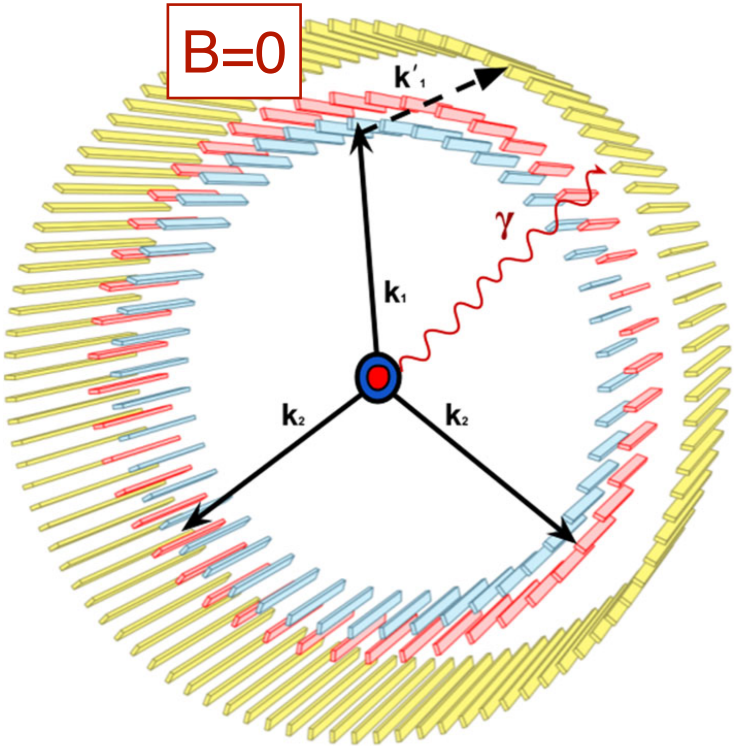
Operator	C	P	T	CP	CPT
$\epsilon_1 \cdot k_2$	+	−	−	−	+
$S \cdot \epsilon_1$	+	+	−	+	−
$S \cdot (k_2 \times \epsilon_2)$	+	−	+	−	−

limit on CPT violation in purely leptonic system

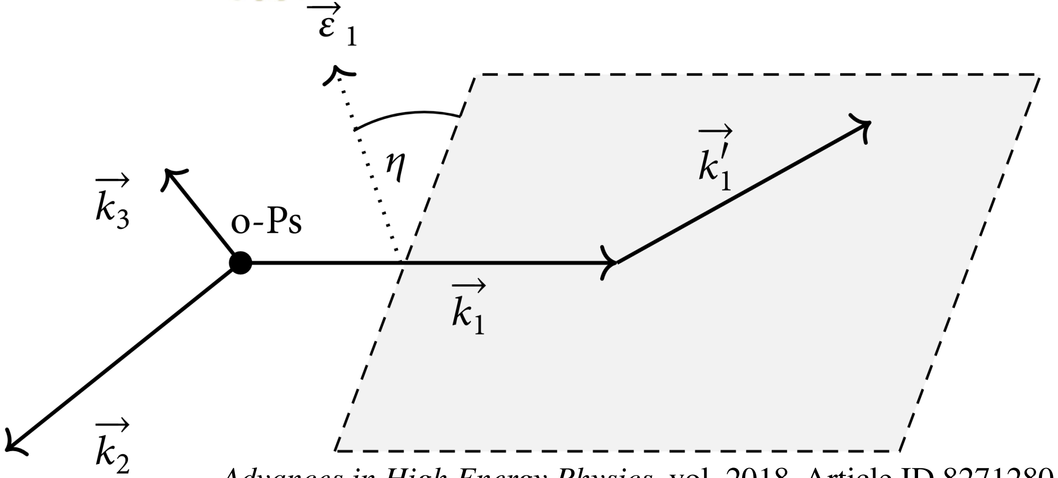
measurement of photon polarizations

Pawel Moskal / Krakow

Compton scattering → polarization



$\varepsilon_1 \sim k_1 \; x \; k'_1$



Advances in High Energy Physics, vol. 2018, Article ID 8271280
https://doi.org/10.1155/2018/8271280

discrete symmetry operators

Operator	C	P	T	CP	CPT
$S \cdot k_1$	+	−	+	−	−
$S \cdot (k_1 \times k_2)$	+	+	−	+	−
$(S \cdot k_1) \cdot (S \cdot (k_1 \times k_2))$	+	−	−	−	+

Operator	C	P	T	CP	CPT
$\epsilon_1 \cdot k_2$	+	−	−	−	+
$S \cdot \epsilon_1$	+	+	−	+	−
$S \cdot (k_2 \times \epsilon_2)$	+	−	+	−	−

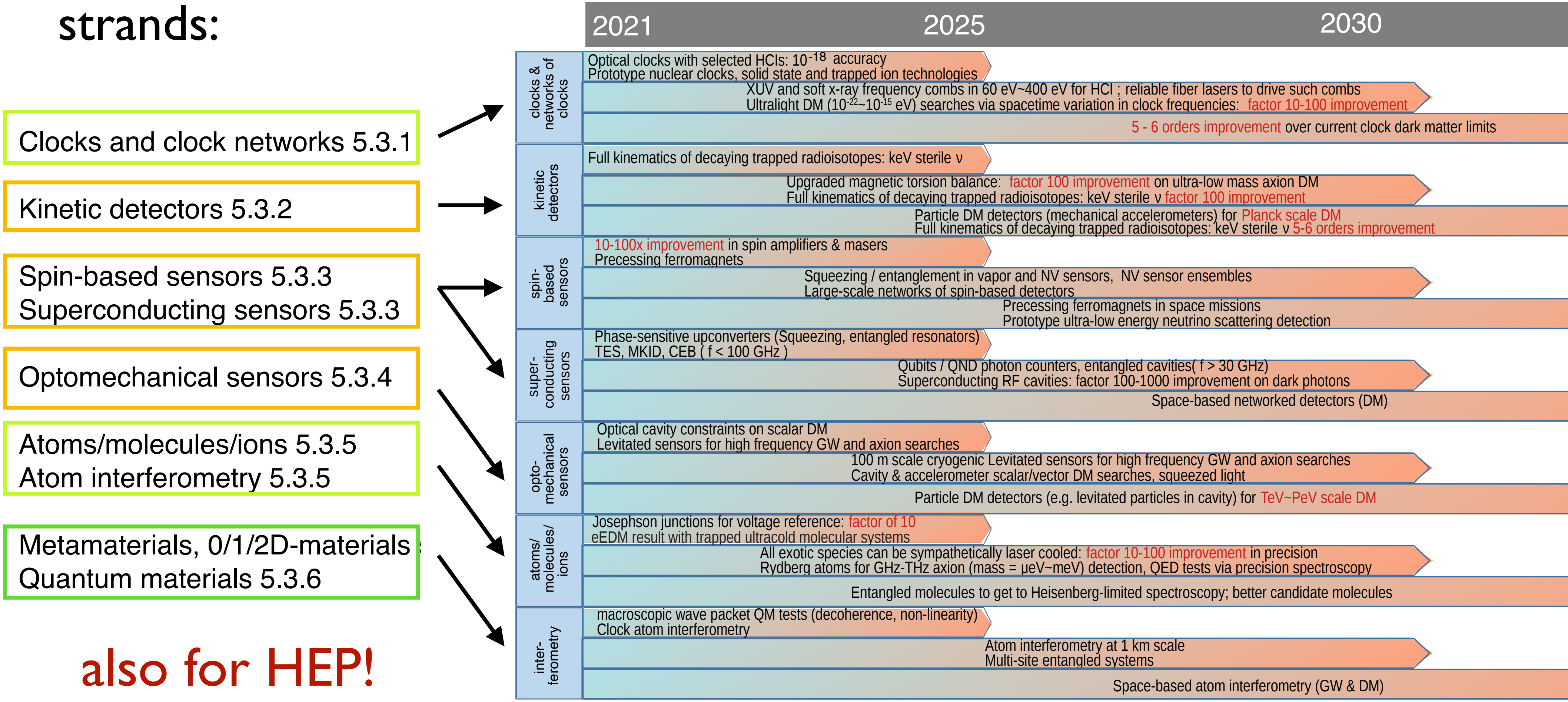
novel symmetry operators

→ challenge: is it possible to identify Compton scattered HE γ's?

What’s next?

These potential applications of quantum sensors also in HEP require dedicated R&D to evaluate their potential and feasibility.

In line with the RECFA R&D roadmap, it makes sense to consider a quantum-sensing R&D program that brings together the following strands:



Clocks and clock networks 5.3.1

Kinetic detectors 5.3.2

Spin-based sensors 5.3.3
Superconducting sensors 5.3.3

Optomechanical sensors 5.3.4

Atoms/molecules/ions 5.3.5
Atom interferometry 5.3.5

Metamaterials, 0/1/2D-materials
Quantum materials 5.3.6

2021 2025 2030

clocks & networks of clocks
- Optical clocks with selected HCIs: 10^{-18} accuracy
  Prototype nuclear clocks, solid state and trapped ion technologies
- XUV and soft x-ray frequency combs in 60 eV~400 eV for HCI ; reliable fiber lasers to drive such combs
  Ultralight DM (10^{-22}~10^{-15} eV) searches via spacetime variation in clock frequencies: factor 10-100 improvement
- 5 - 6 orders improvement over current clock dark matter limits

kinetic detectors
- Full kinematics of decaying trapped radioisotopes: keV sterile ν
- Upgraded magnetic torsion balance: factor 100 improvement on ultra-low mass axion DM
  Full kinematics of decaying trapped radioisotopes: keV sterile ν factor 100 improvement
- Particle DM detectors (mechanical accelerometers) for Planck scale DM
  Full kinematics of decaying trapped radioisotopes: keV sterile ν 5-6 orders improvement

spin-based sensors
- 10-100x improvement in spin amplifiers & masers
  Precessing ferromagnets
- Squeezing / entanglement in vapor and NV sensors, NV sensor ensembles
  Large-scale networks of spin-based detectors
- Precessing ferromagnets in space missions
  Prototype ultra-low energy neutrino scattering detection

super-conducting sensors
- Phase-sensitive upconverters (Squeezing, entangled resonators)
  TES, MKID, CEB (f < 100 GHz)
- Qubits / QND photon counters, entangled cavities(f > 30 GHz)
  Superconducting RF cavities: factor 100-1000 improvement on dark photons
- Space-based networked detectors (DM)

opto-mechanical sensors
- Optical cavity constraints on scalar DM
  Levitated sensors for high frequency GW and axion searches
- 100 m scale cryogenic Levitated sensors for high frequency GW and axion searches
  Cavity & accelerometer scalar/vector DM searches, squeezed light
- Particle DM detectors (e.g. levitated particles in cavity) for TeV~PeV scale DM

atoms/ molecules/ ions
- Josephson junctions for voltage reference: factor of 10
  eEDM result with trapped ultracold molecular systems
- All exotic species can be sympathetically laser cooled: factor 10-100 improvement in precision
  Rydberg atoms for GHz-THz axion (mass = μeV~meV) detection, QED tests via precision spectroscopy
- Entangled molecules to get to Heisenberg-limited spectroscopy; better candidate molecules

inter-ferometry
- macroscopic wave packet QM tests (decoherence, non-linearity)
  Clock atom interferometry
- Atom interferometry at 1 km scale
  Multi-site entangled systems
- Space-based atom interferometry (GW & DM)

also for HEP!

Status of TF5

Anna Grassellino, Marcel Demarteau,
Michael Doser, Caterina Braggio,
Stafford Withington, Peter Graham,
John March-Russel, Andrew Geraci

“Recommendations”

- many fascinating opportunities in nascent fields
- encourage exploratory approaches
- adapt funding profiles to both exploratory as well as consolidation approaches:
    - exploratory: funding cycle of 3 years, lightweight grant application, “fail early / fail often / proof-of-principle” mindset
    - consolidation: funding cycle of 10 years, after initial proof of principle, proposal
- importance of interdisciplinarity
    - training not only of early stage researchers but also of established researchers
    - opportunistic (awareness of developments elsewhere - physics or industry)

thank you!