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

M. Doser, CERN

EURIZON, 20.7.2023

① Some words on the landscape

Clarification of terms

Quantum sensors for low energy particle physics

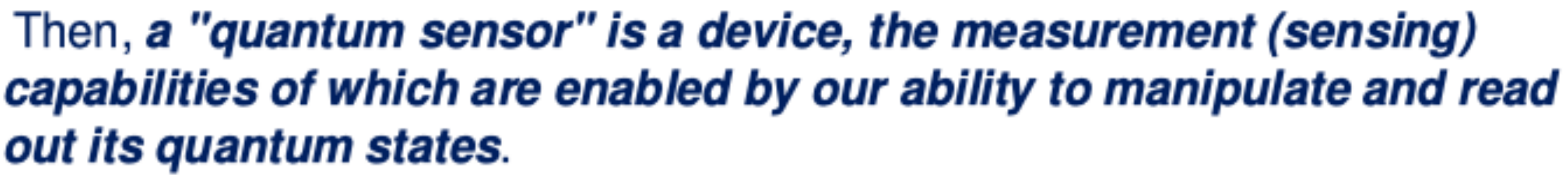
Quantum sensors for $\overbrace{\text{new}}^{\text{low energy}}$ particle physics experiments

② Quantum detectors for high energy particle physics

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 activities both in low energy and high energy particle physics

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

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

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

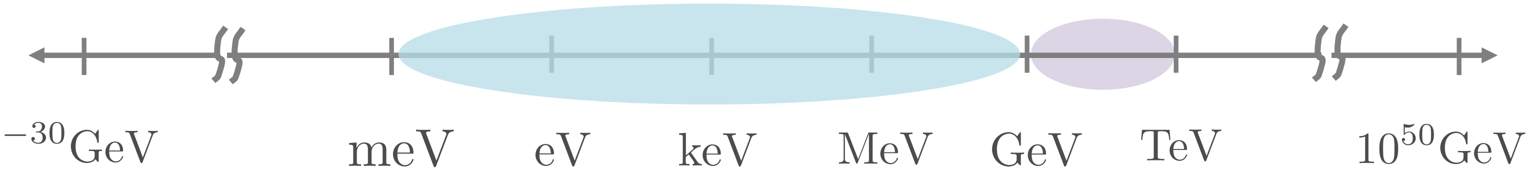
domains of physics

- 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

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

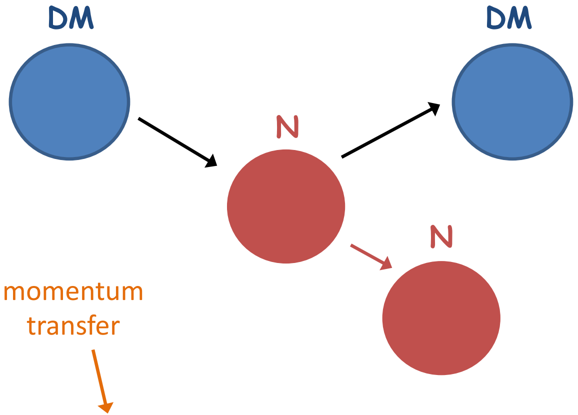
An example: searching for dark matter

from: Yonit Hochberg , Ascona / 2023
https://indico.cern.ch/event/1198655



Possible dark matter mass

Looking for nuclear recoils:
think billiard balls



$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM} v)^2}{2m_N} \gtrsim E_{\rm threshold} \sim {\rm keV}$$

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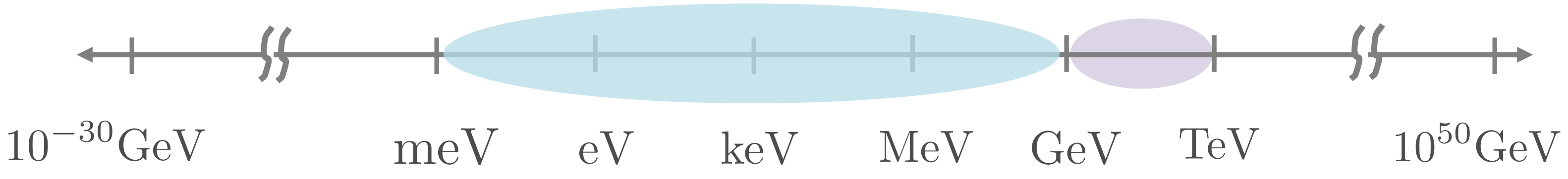

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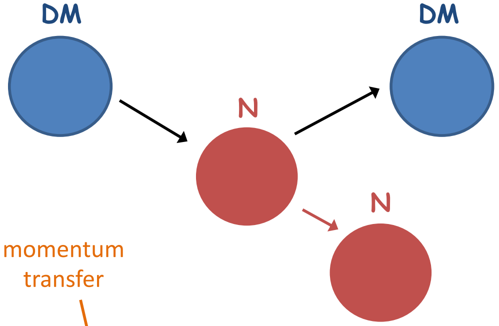

momentum transfer

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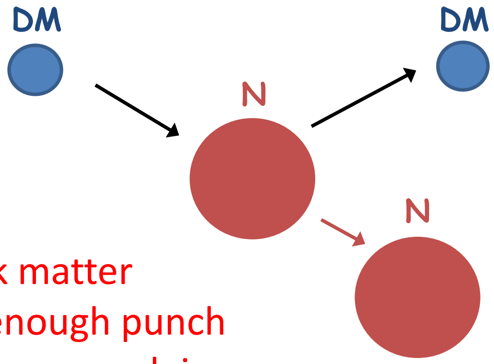

light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

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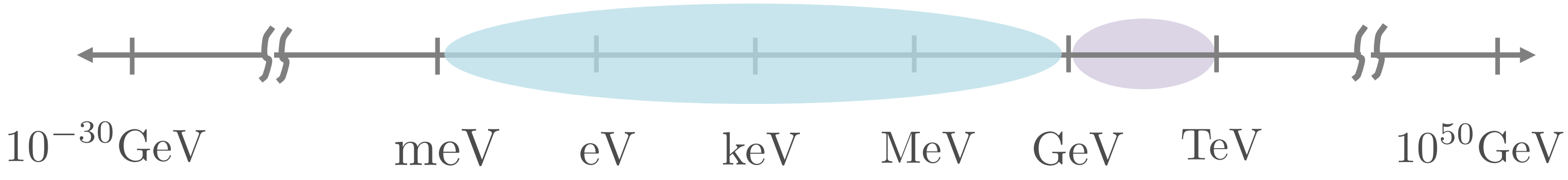
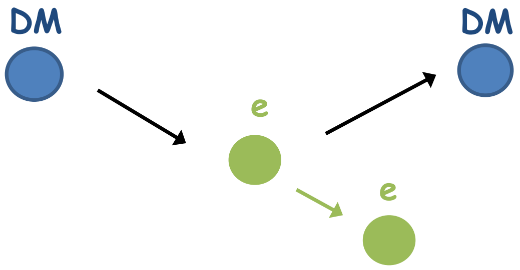
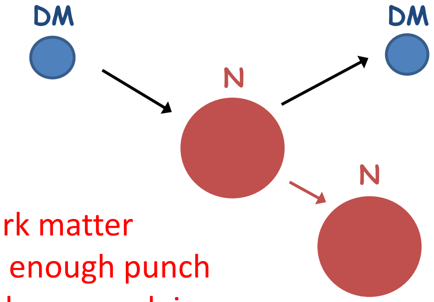


Possible dark matter mass

Light dark matter: scatter off electrons



light dark matter
can give enough punch
to kick the light electrons



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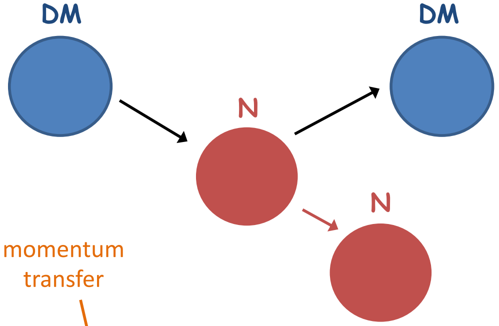

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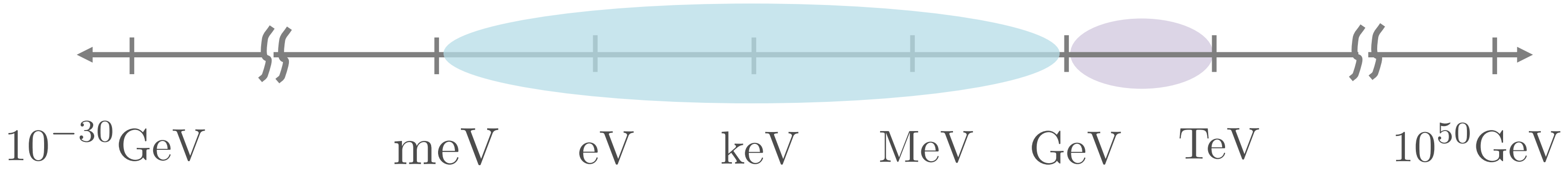

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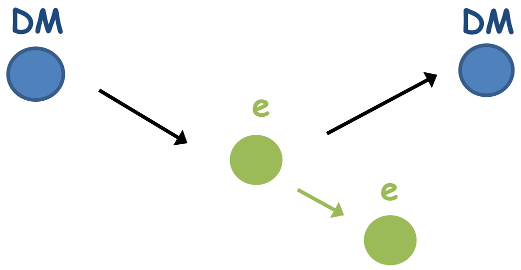

light dark matter
can give enough punch
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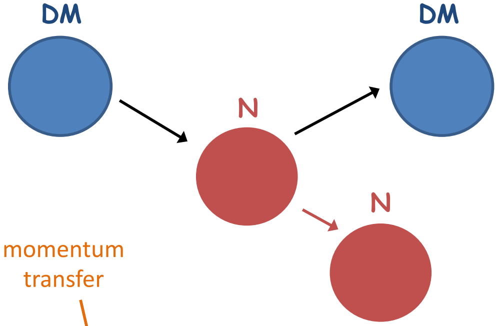

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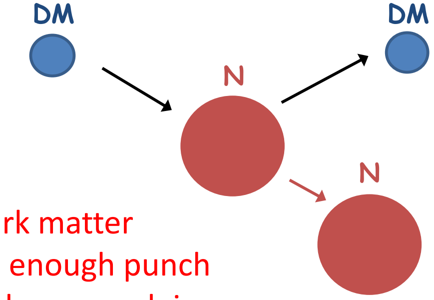

light dark matter
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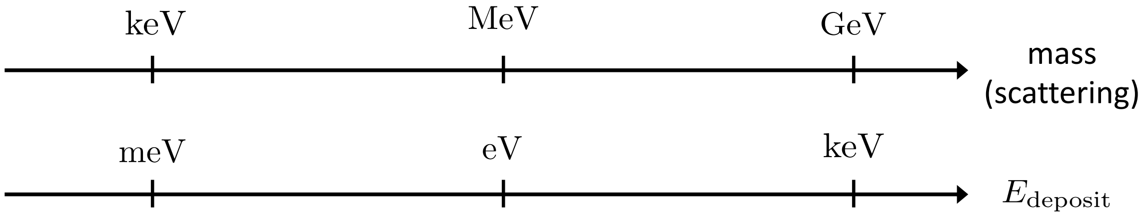
Lose sensitivity @ O(GeV) masses

Dark matter scattering: kinetic energy $m_{\rm DM}v^2 \sim 10^{-6} m_{\rm DM}$



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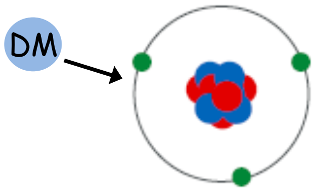
Atomic ionization

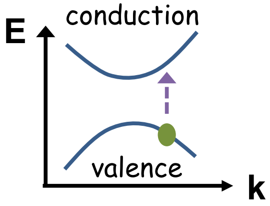


Xenon: ~12 eV

$$m_{\mathrm{DM}} \gtrsim 10\ \mathrm{MeV}$$

Essig, Mardon, Volansky, 2012

Semiconductors



Ge, Si, Diamond, SiC: ~eV

$$m_{\mathrm{DM}} \gtrsim \mathrm{MeV}$$

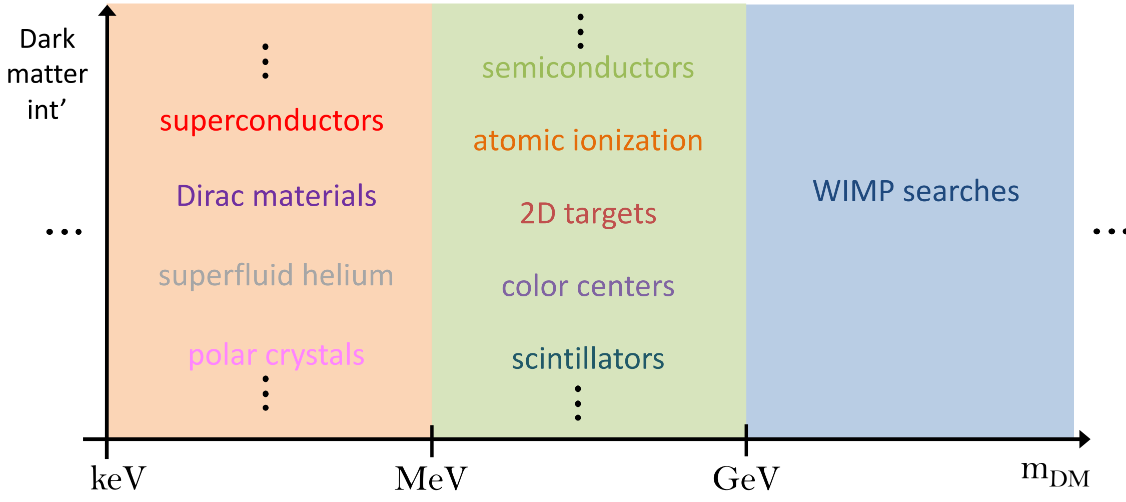
Essig , Mardon, Volansky, 2012
Graham, Kaplan, Rajendran, Walters, 2012
Kurinsky, Yu, **YH**, Blas, 2019
Griffin, **YH,** et al, 2020

Superconducting systems

- Ground state = Cooper pairs;
  Binding energy (gap) $\sim \mathrm{meV}$ ⇒ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- The idea:
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → detect

Excitations

Excitation concentration philosophy	Sensor + target philosophy
YH, Zhao, Zurek, PRL 2015 **YH**, Pyle, Zhao, Zurek, JHEP 2015	**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019



Dark matter int'

…

⋮
superconductors
Dirac materials
superfluid helium
polar crystals
⋮

⋮
semiconductors
atomic ionization
2D targets
color centers
scintillators
⋮

WIMP searches

…

keV
MeV
GeV
m_{DM}

Burgeoning field in recent years

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

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

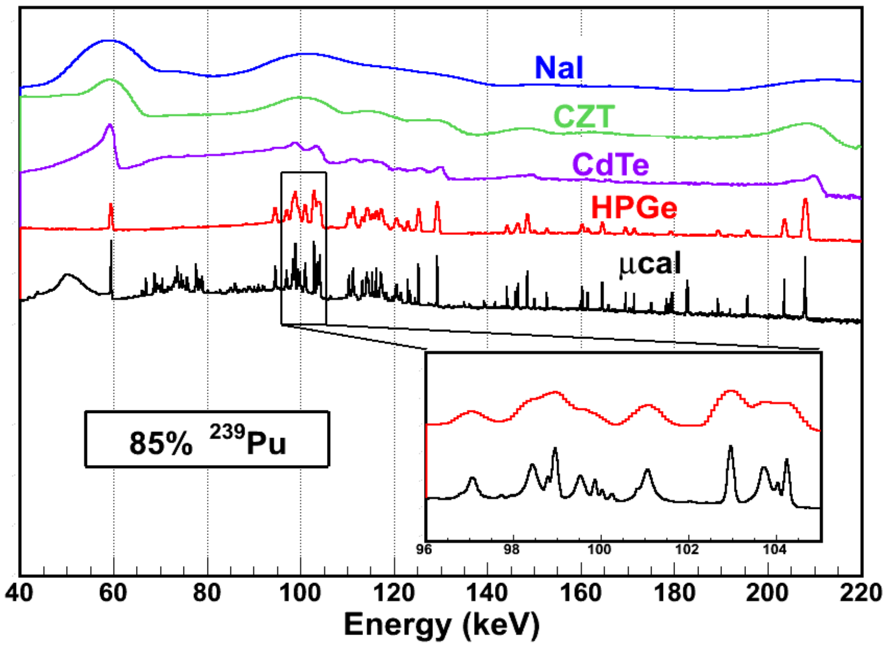
invention of kinetic inductance detectors (KID): 2000's

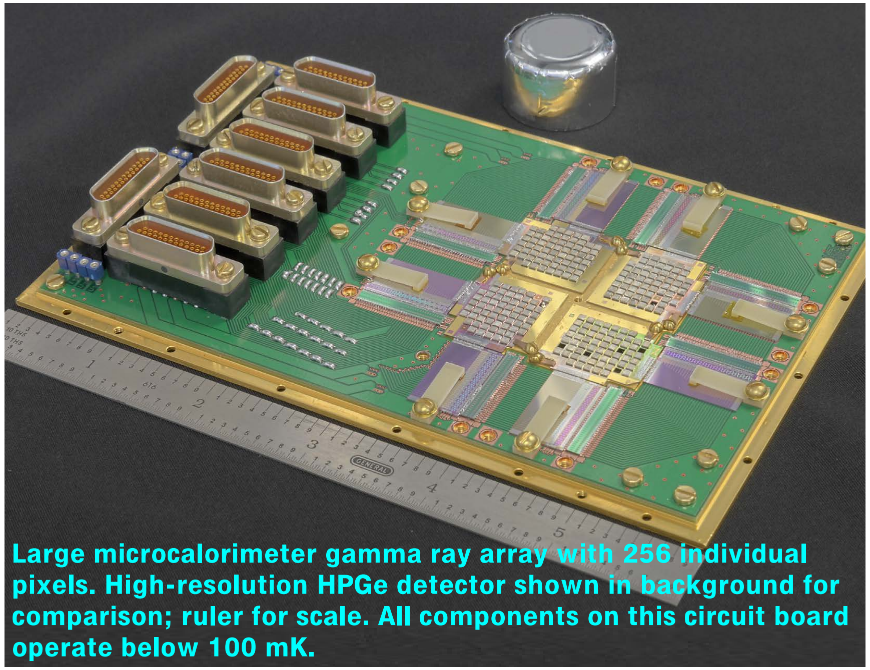
Photons incident on a strip of superconducting material break Cooper pairs and create excess quasiparticles. The kinetic inductance of the superconducting strip is inversely proportional to the density of Cooper pairs, and thus the kinetic inductance increases upon photon absorption. This inductance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

P Guss · 2015 — **Transition Edge Sensor** Using **High-Temperature**. Superconductivity

SDRD FY15 Final Review, Sept. 17, 2015

https://www.osti.gov/servlets/purl/1506422





Large microcalorimeter gamma ray array with 256 individual pixels. High-resolution HPGe detector shown in background for comparison; ruler for scale. All components on this circuit board operate below 100 mK.

①

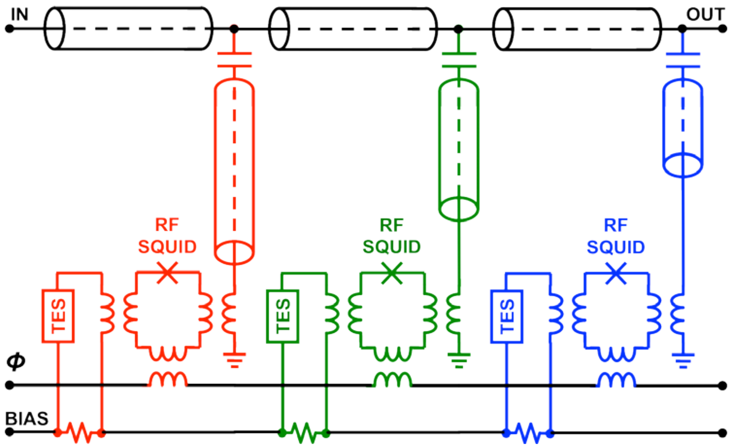
superconducting devices (TES, SNSPD, …) / cryo-electronics

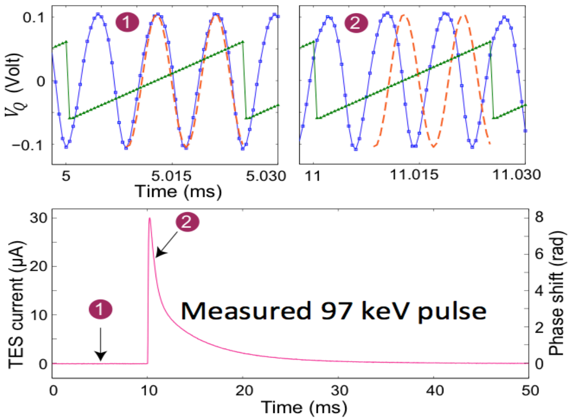
P Guss · 2015 — **Transition Edge Sensor** Using **High-Temperature**. Superconductivity

https://www.osti.gov/servlets/purl/1506422

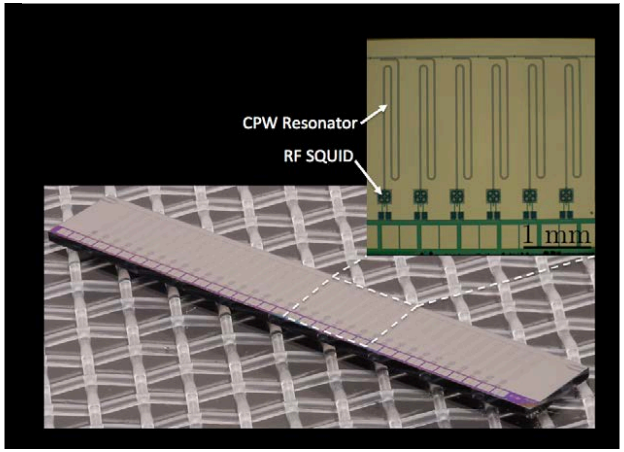
Scalable readout is the key for very large arrays

Four innovations: μCal, Microwave Multiplexing, RF-SQUIDs, Software Radio





- UCSB: 1,000 low-resolution sensors and softwaredefined radio (SDR) readout
- CU: 2 high-resolution sensors + RFSQUIDS without SDR
- CU + LANL: Demonstrated negligible readout noise from RF-SQUID
- *No one has combined all together at scale*



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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

Superconducting nanowire single photon detector

Superconducting quantum interference device

Josephson junction parametric amplifier

	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	🟢	🔴			

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

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

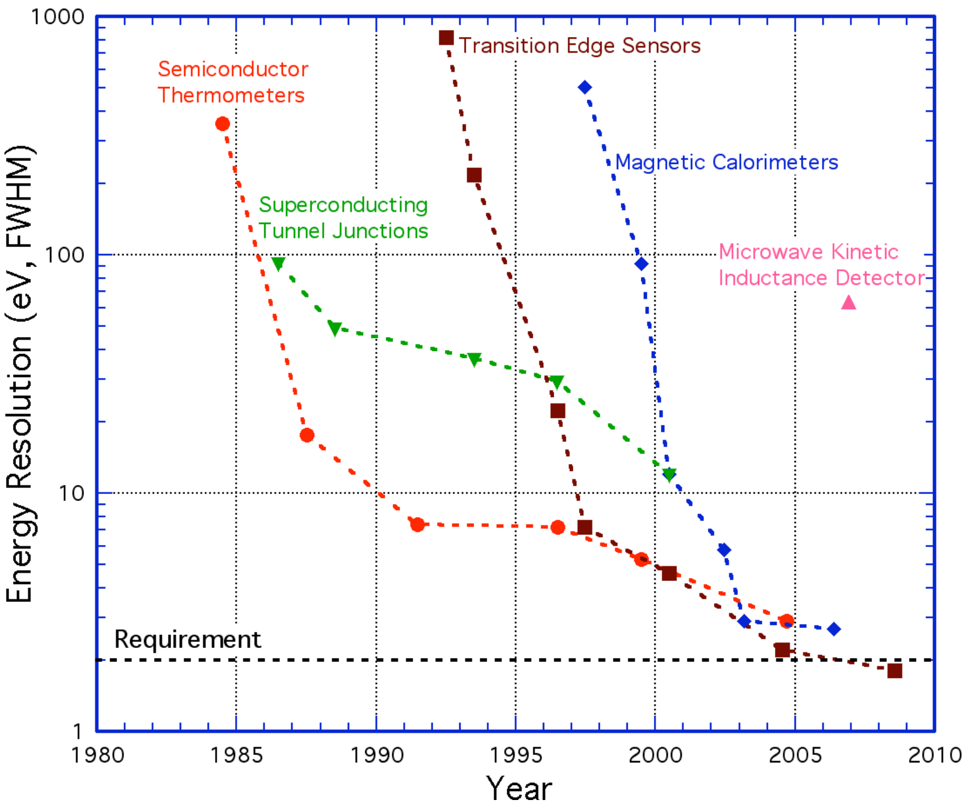
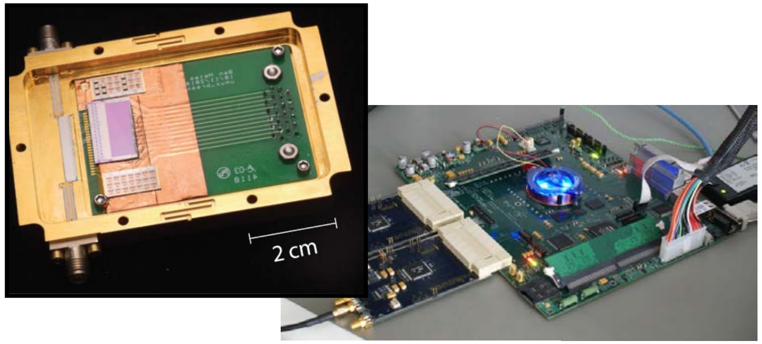
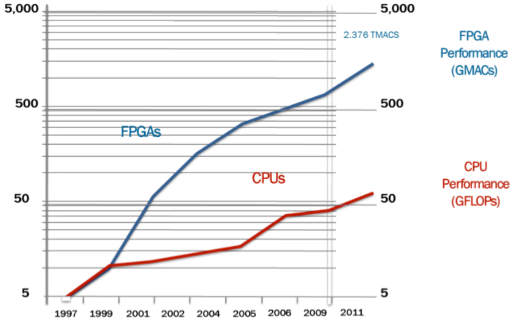


Fig. 1. Time evolution of energy resolution at 6 keV as a function of time for three microcalorimeter technologies.

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.***

- 1,000 resonators on two coaxial cables!
- Existing commercial electronics
- Functionality shared with telecommunications industry
- Benefit from steady improvement in FPGAs, ADCs, and DACs





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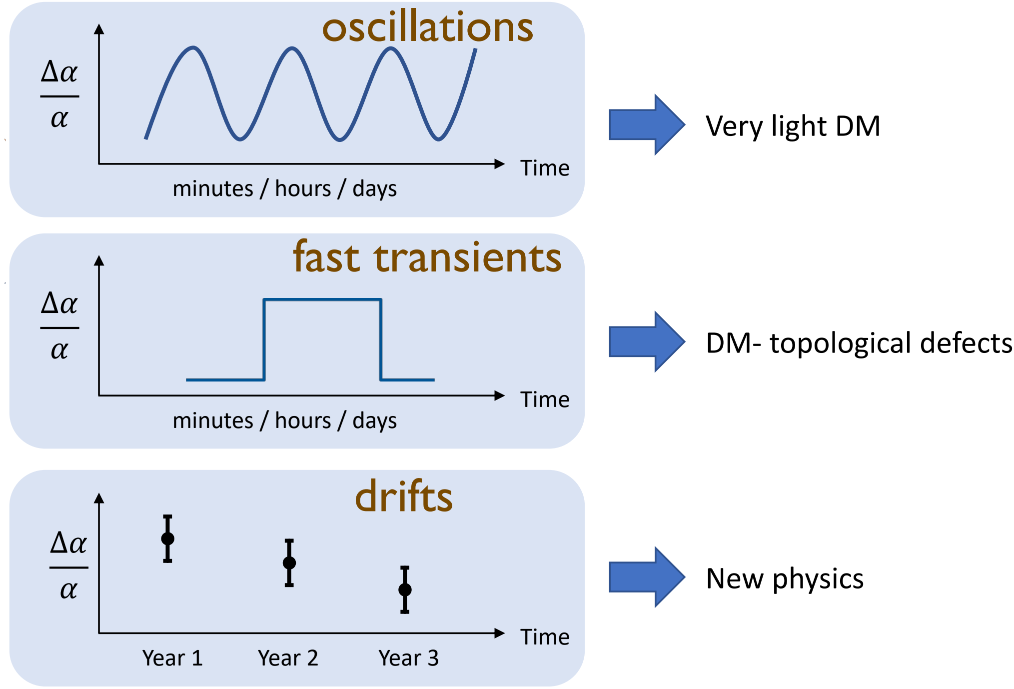
10

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

search for NP / BSM

- The only 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 ~10^{-9} eV)
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives
- Using multiple sensors increases the detection confidence and sensitivity
- Multimessenger detection, discriminating between different couplings

Signal characteristics



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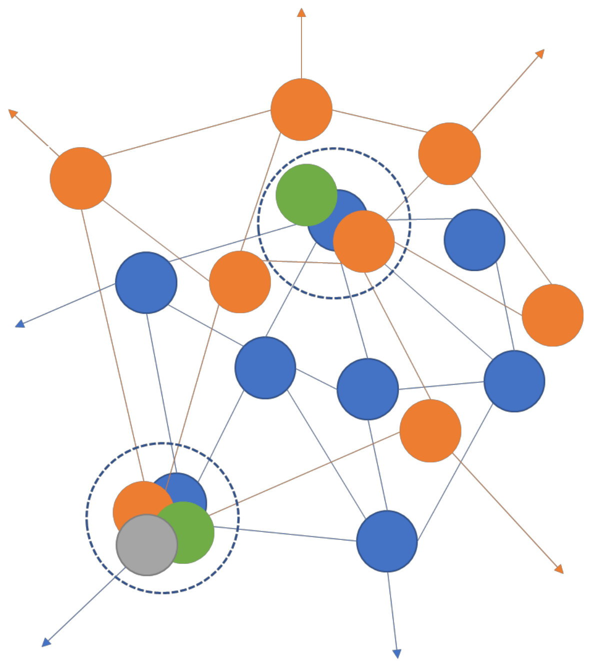
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

particle physics: what are we talking about? Networked experiments!

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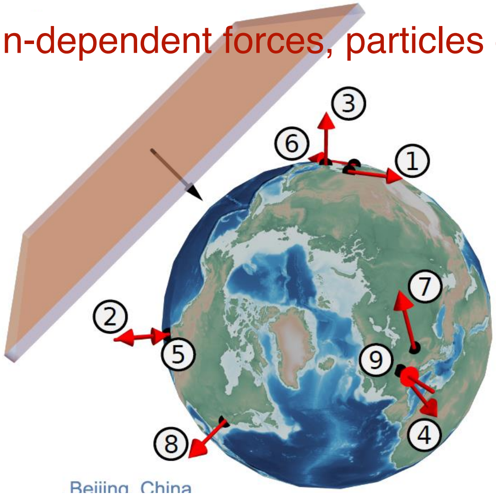
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

② spin-based, NV-diamonds, …

→ Spin-dependent forces, particles coupling to spin

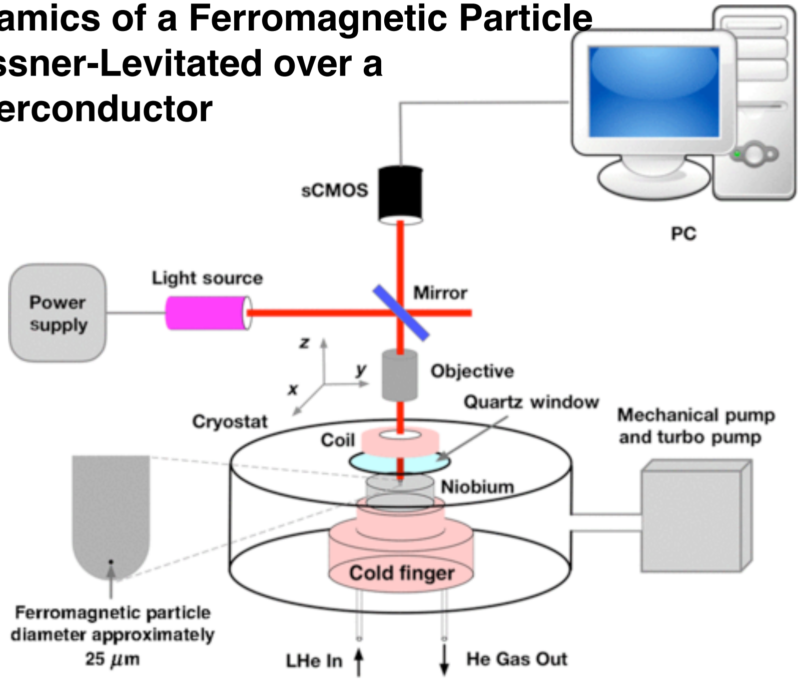
GNOME: arXiv:2102.13379 (2021)

Global Network of Optical (atomic) Magnetometers for Exotic searches



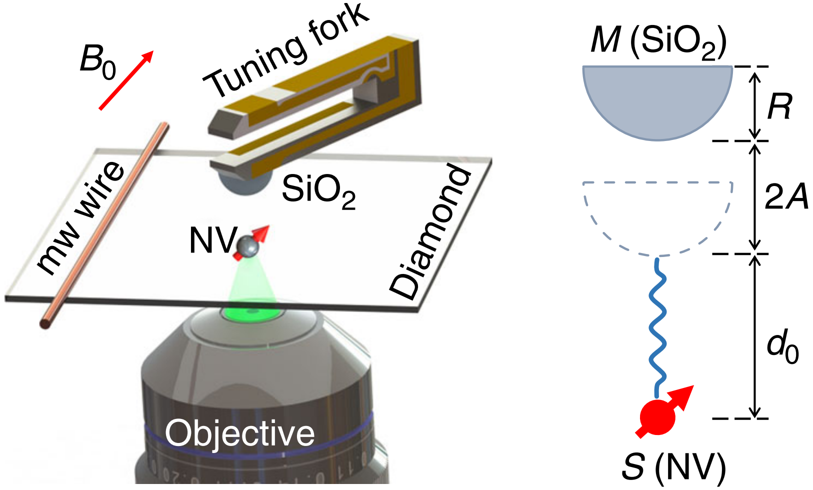
ALP's can interact with atomic spins; passage of an ALP domain wall ⟶ simultaneous / correlated signals ~ transient magnetic field pulse (down to O(pT))

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 (~ 5-10 years from now !)

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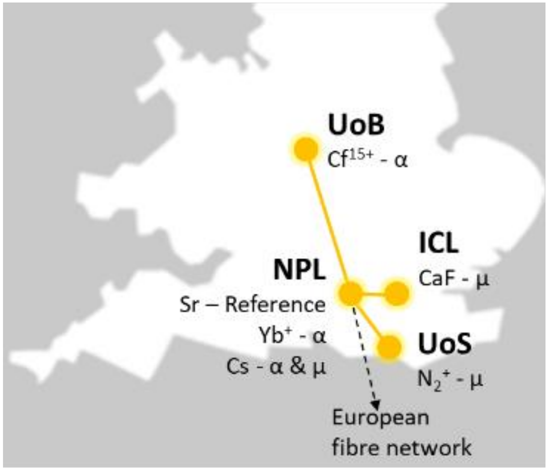
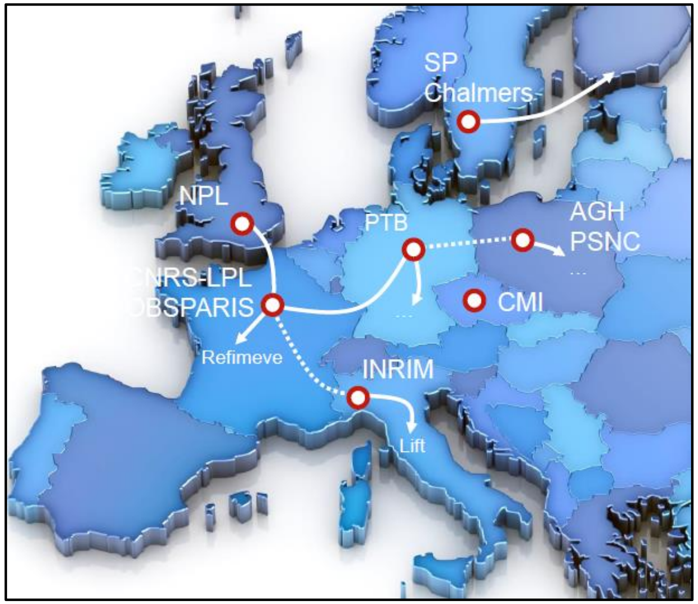
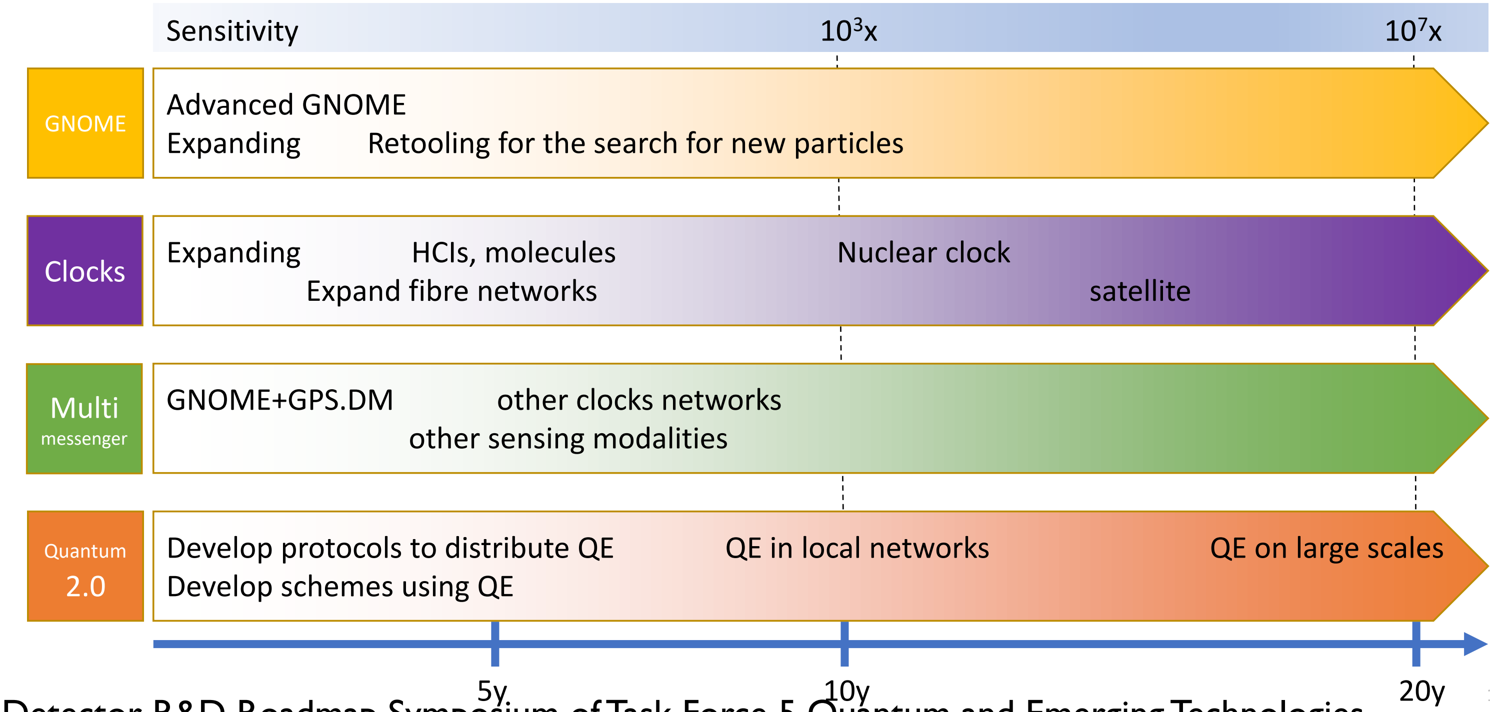
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

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

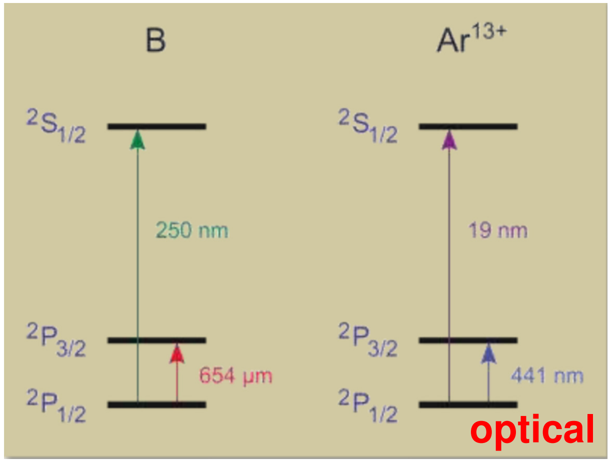
④ ionic / atomic / molecular

novel systems with greatly enhanced sensitivity wrt standard atomic systems

HCI's

e.g. $^{18}Ar \longrightarrow Ar^{13+}$
(5 e^- remain)

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

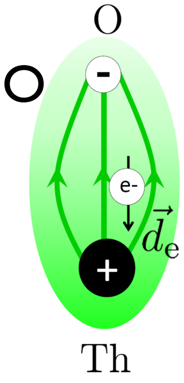


optical

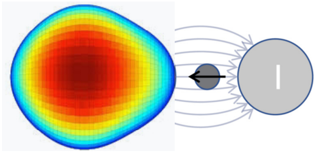
eEDM's in molecules

P and T violation

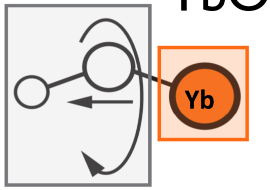
ThO



^{225}RaF



YbOH



laser-cooling
polarization

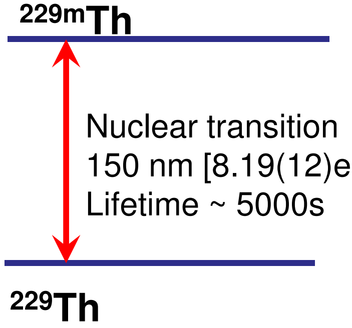
nuclear clock (^{229}Th)

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

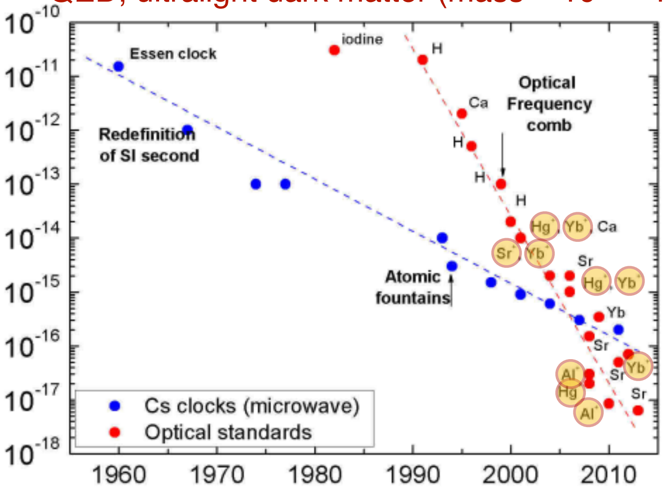


Nuclear transition
150 nm [8.19(12)eV]
Lifetime ~ 5000s

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^+

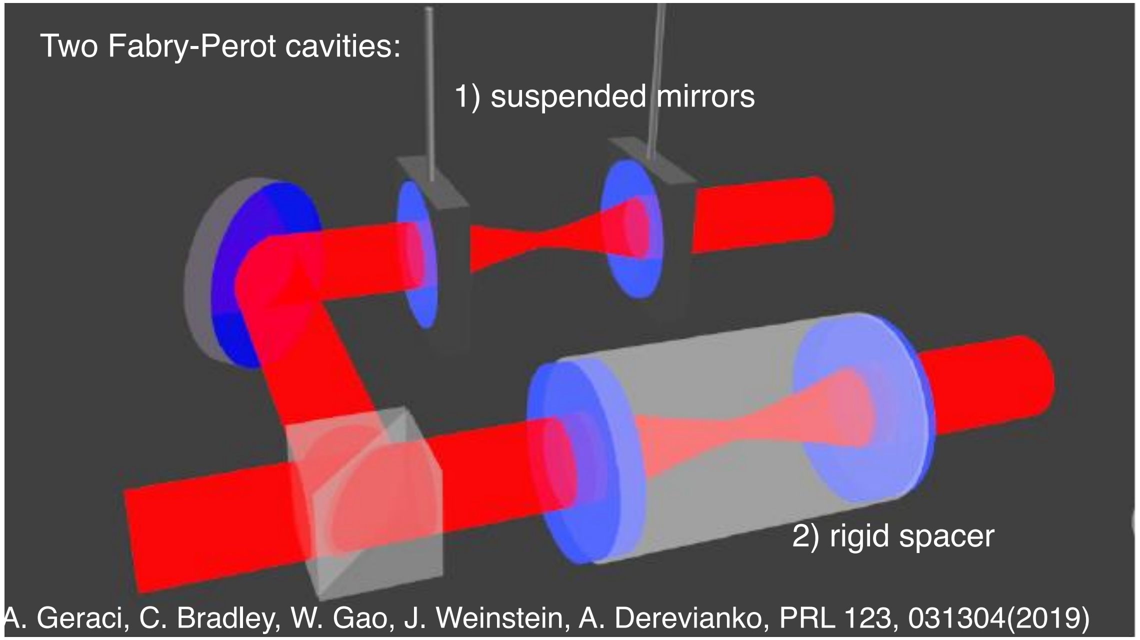
N_2^+ : 10^{-18} https://doi.org/10.1103/PhysRevA.89.032509

→ 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

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

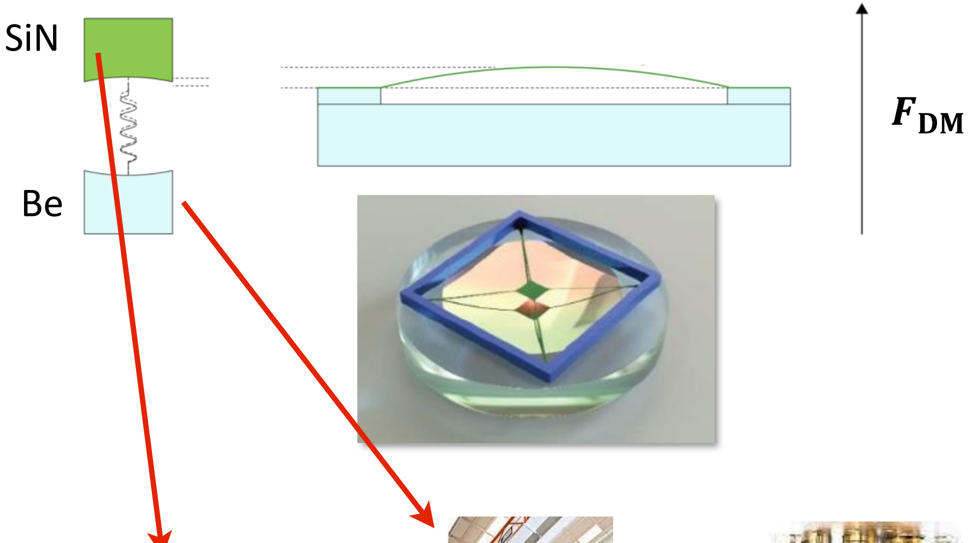
$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c E_P^{-1}}\phi(t,\mathbf{r})$$

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)



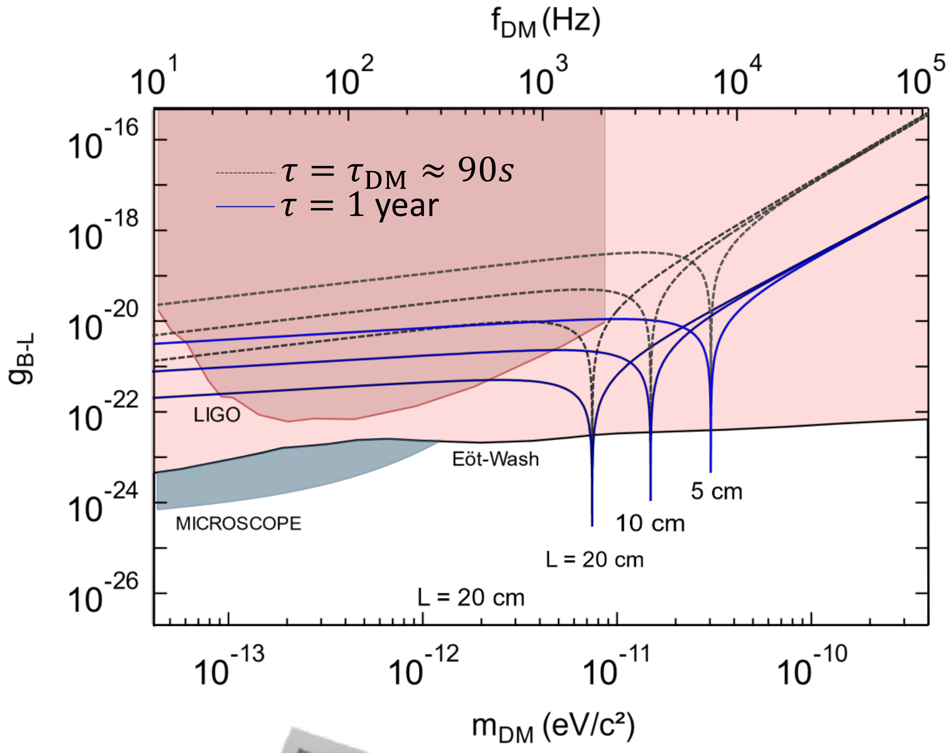
Si_3N_4 membrane
($Q\sim10^9$)

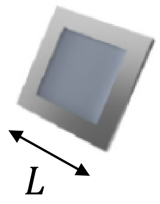
+

Be Mirror
(Webb telescope)

+

Cryogenics
(100 mK)





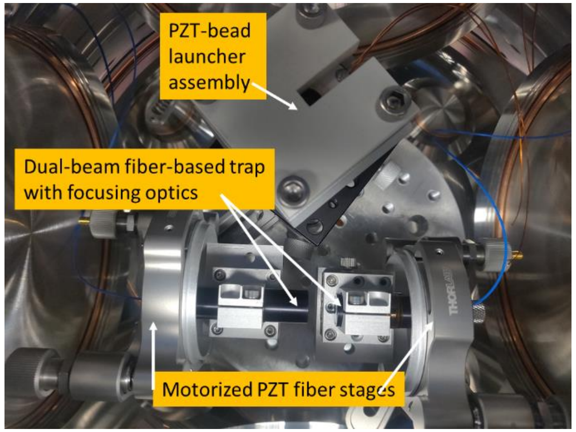
Manley et. al. PRL 126 061301 (2021)

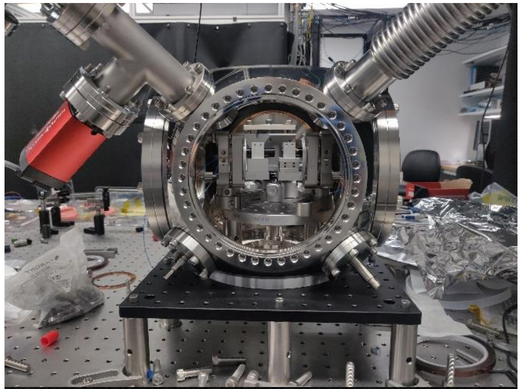
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Andrew Geraci (Northwestern)

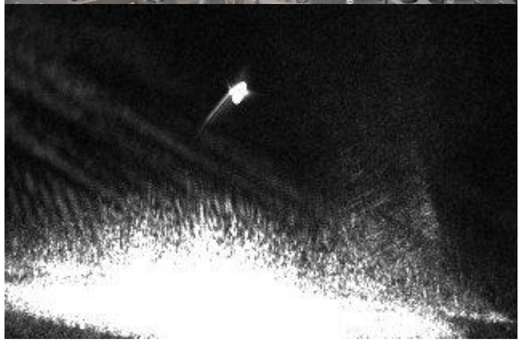
5 levitated microspheres

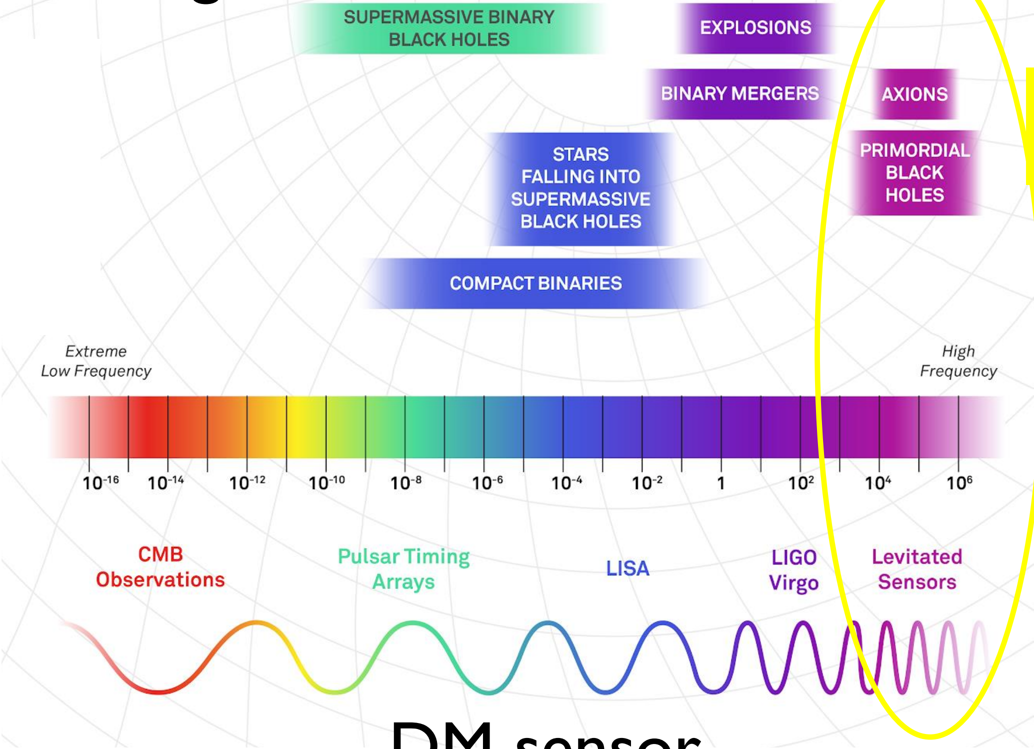
gravitational wave sensor

nanoparticle standing-wave trap (optical lattice)

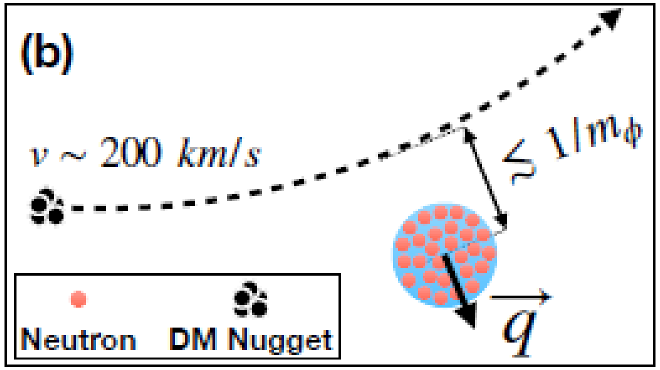








DM sensor



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

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

= zeptonewton sensing

→ 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

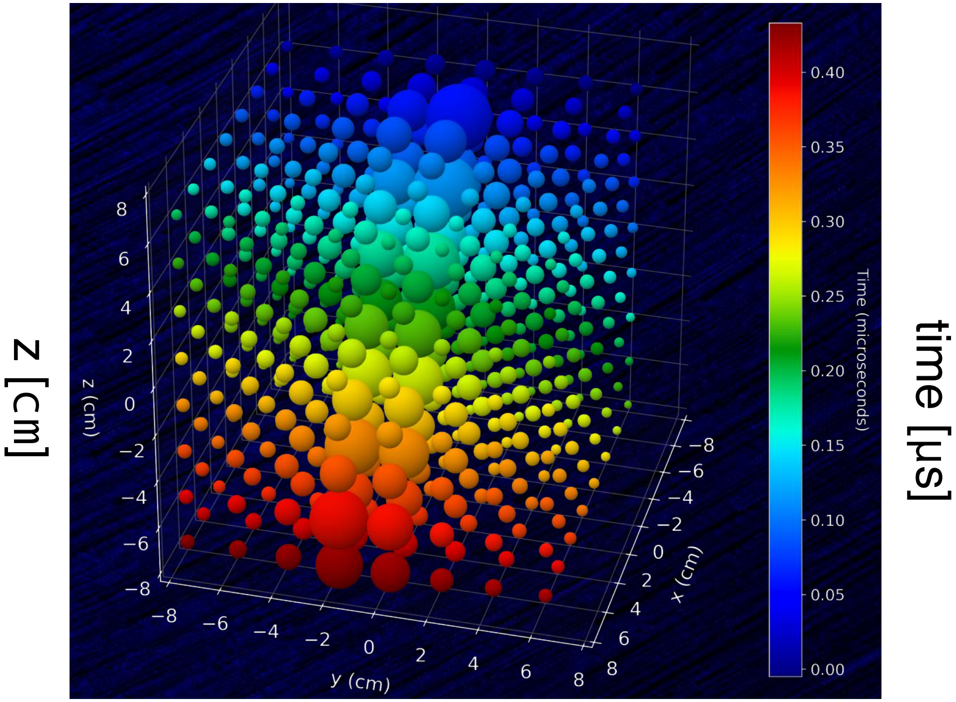
vision: “Our proposed strategy is to build a three-dimensional array of force sensors. A heavy DM particle passing through the array will exert a small but correlated force on the sensors nearest its trajectory. Much like tracking a particle in a bubble chamber, we can then pick out this correlated force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

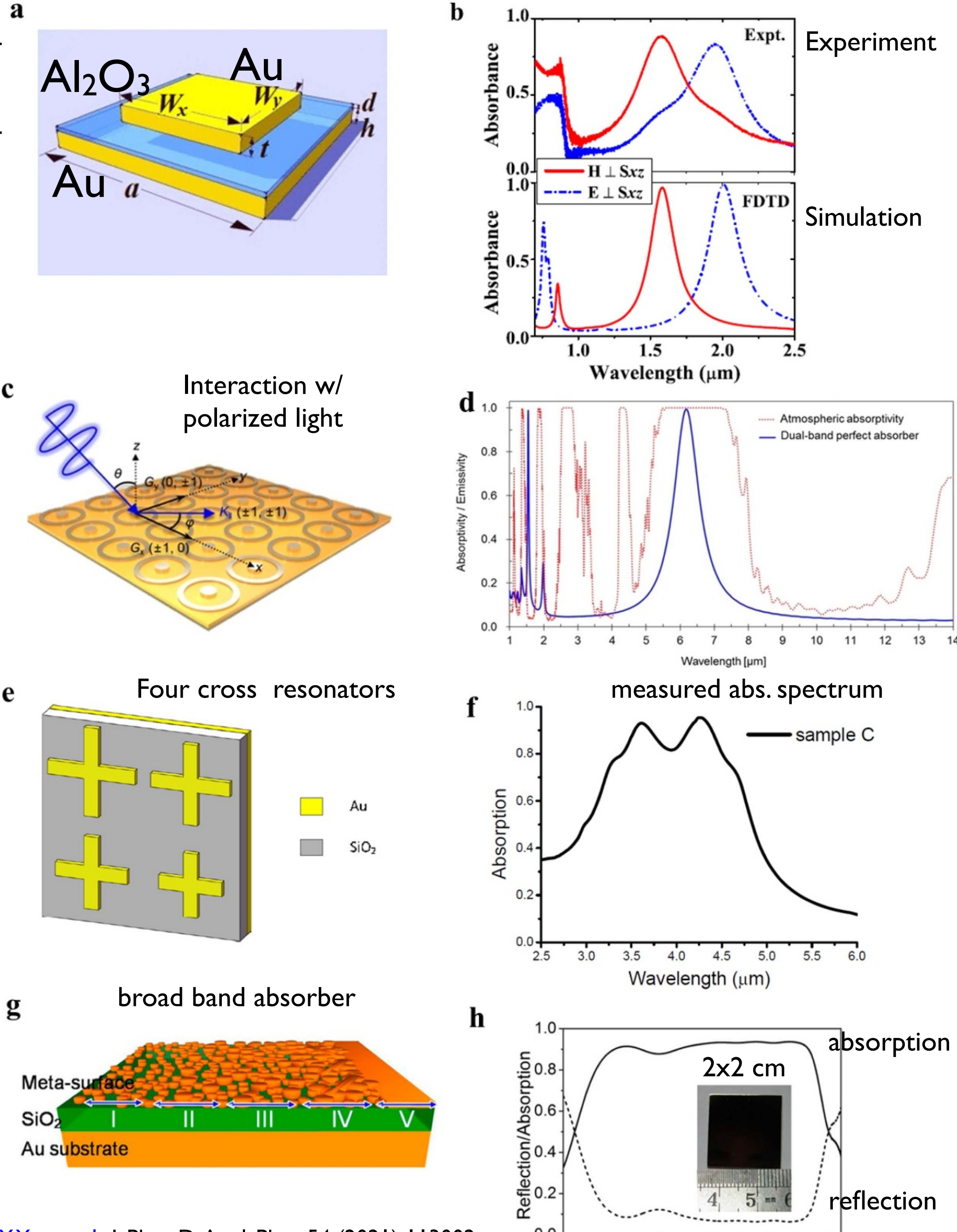
<u>metamaterial</u> : materials that obtain their properties from their *structure* rather than the material of which they are *composed*

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:

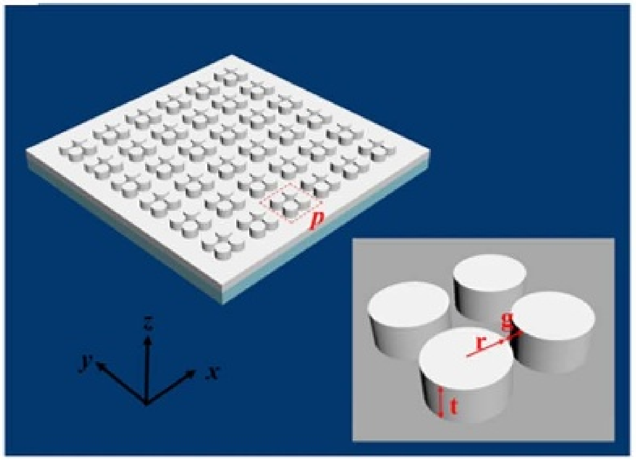
Importantly: the properties can be designed!



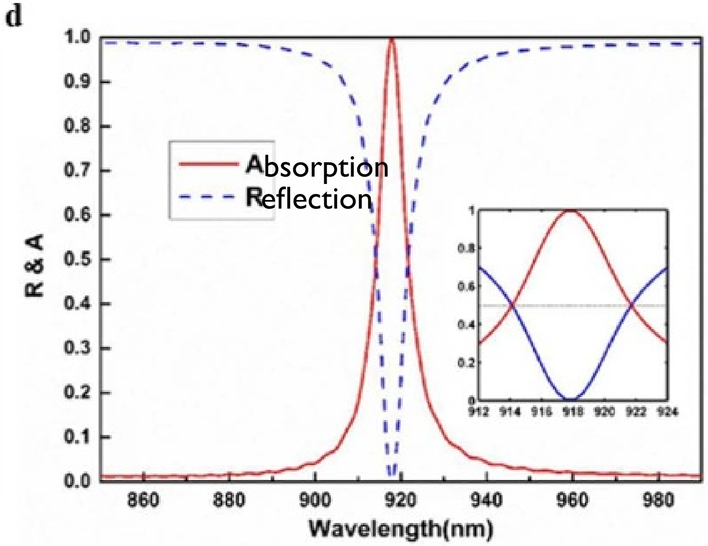
Y. Yao et al., J. Phys. D: Appl. Phys. 54 (2021) 113002
https://doi.org/10.1088/1361-6463/abccf0

⑥ metamaterials, 0/1/2-D materials

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



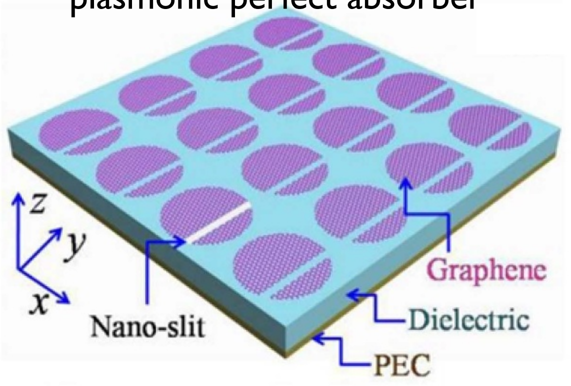
(relatively) *narrowband* absorption:



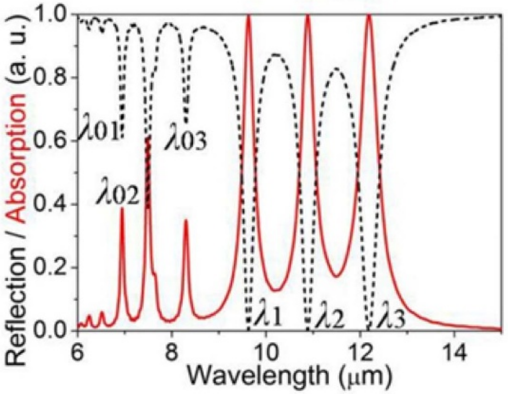
Y. Yao et al., J. Phys. D: Appl. Phys. 54 (2021) 113002 https://doi.org/10.1088/1361-6463/abccf0

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

Schematic of the graphene plasmonic perfect absorber



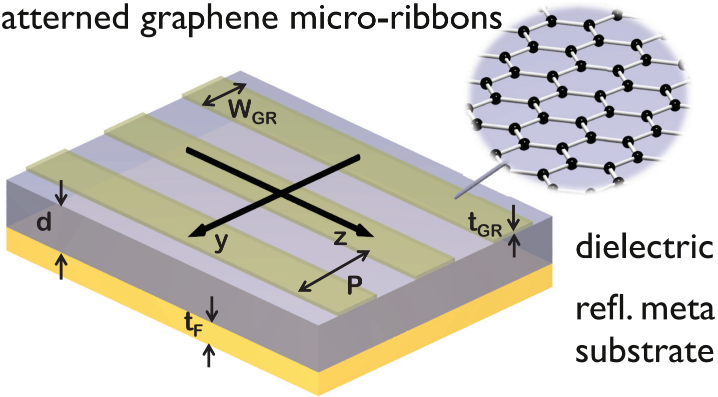
Absorption and reflection of the absorber.



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

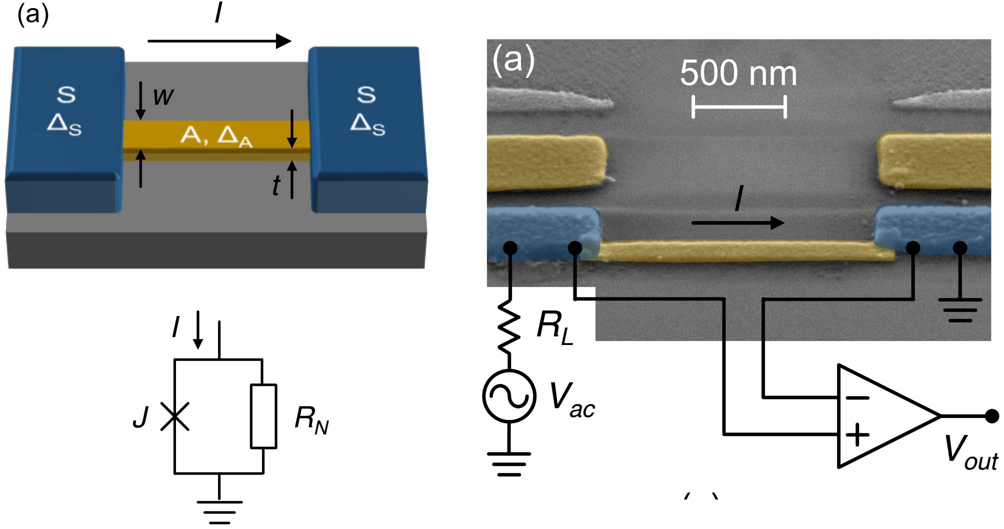
R. Alaee et al., Opt. Express. 20 (2012) 28017 https://doi.org/10.1364/OE.20.028017

6 metamaterials, 0/1/2-D materials

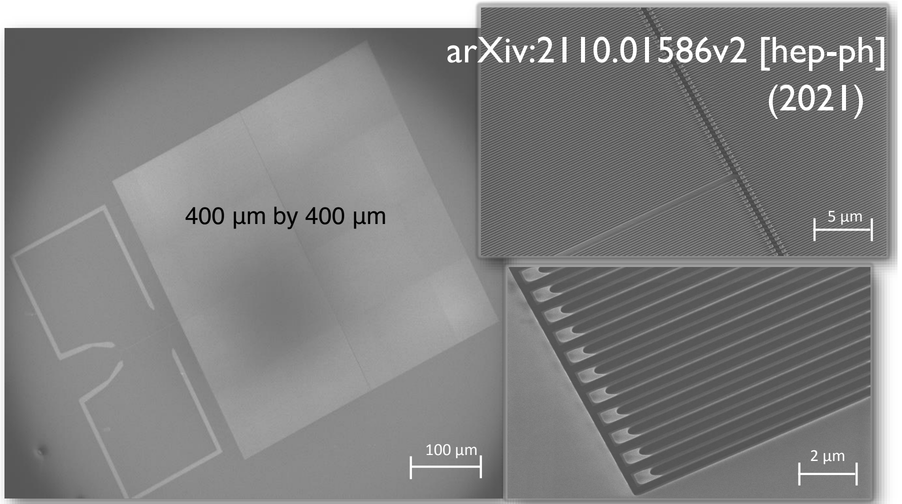
1-D junction: JES: Josephson escape sensor, nanoscale transition edge sensor (nano-TES)

well suited to detecting dark matter / axion interactions with electrons

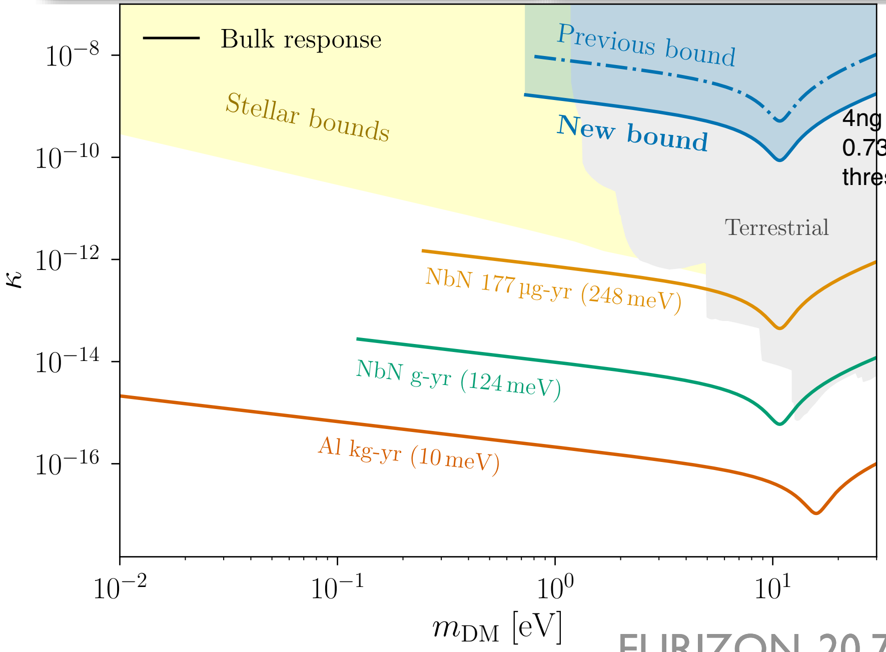
superconducting single-photon detection arXiv:2101.08558v2



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

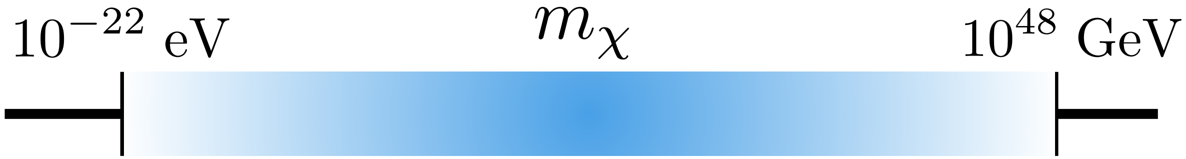
dark matter scattering produces initial excitations with an anisotropic distribution which is preserved during de-excitation

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

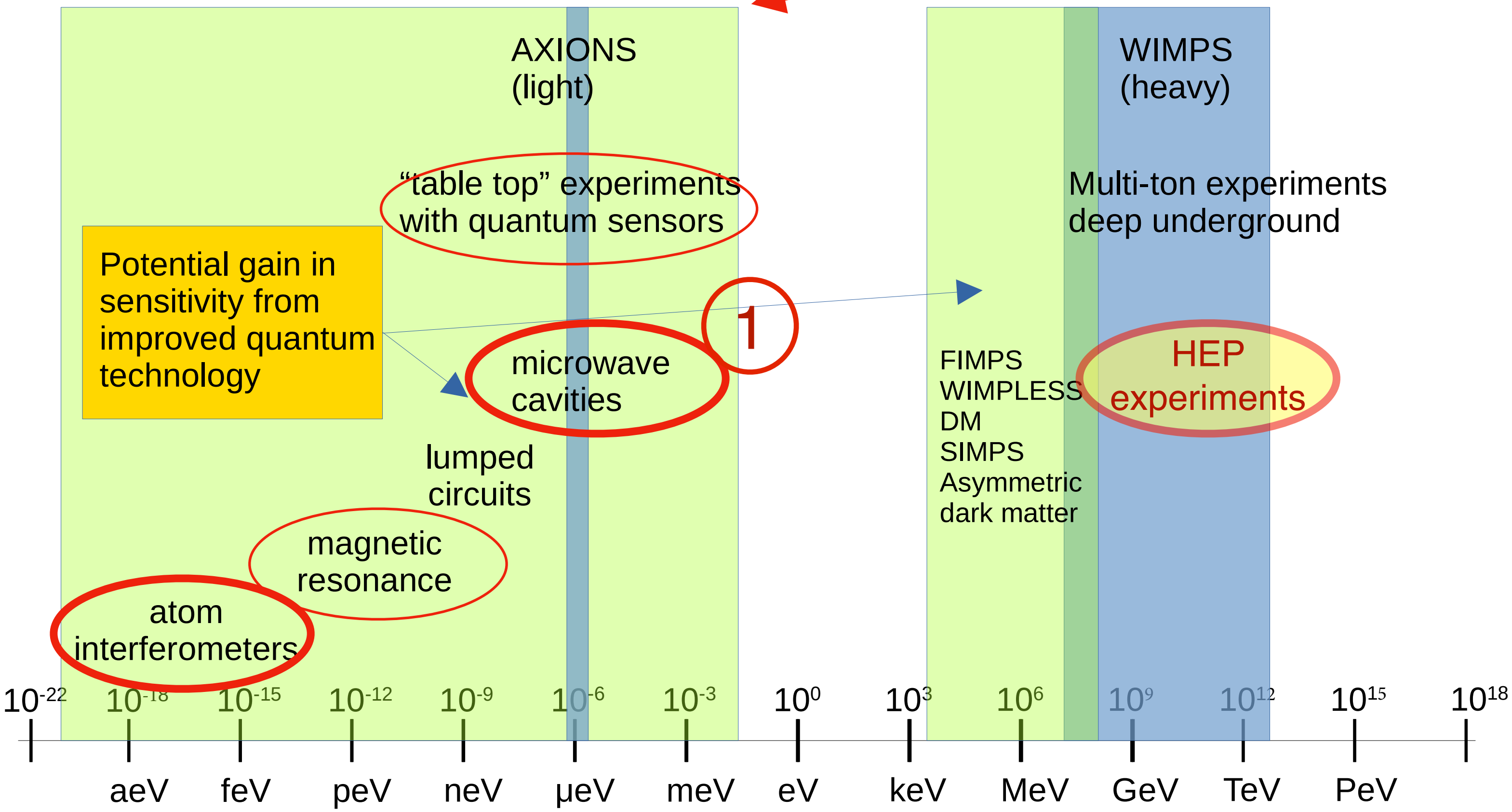


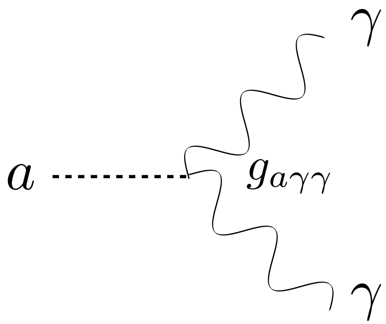
cavity size = axion size

axion mass = unknown

$$F \sim g^2_{a\gamma} m^2_A B^4 V^2 T^{-2}_{sys} G^4 Q,$$

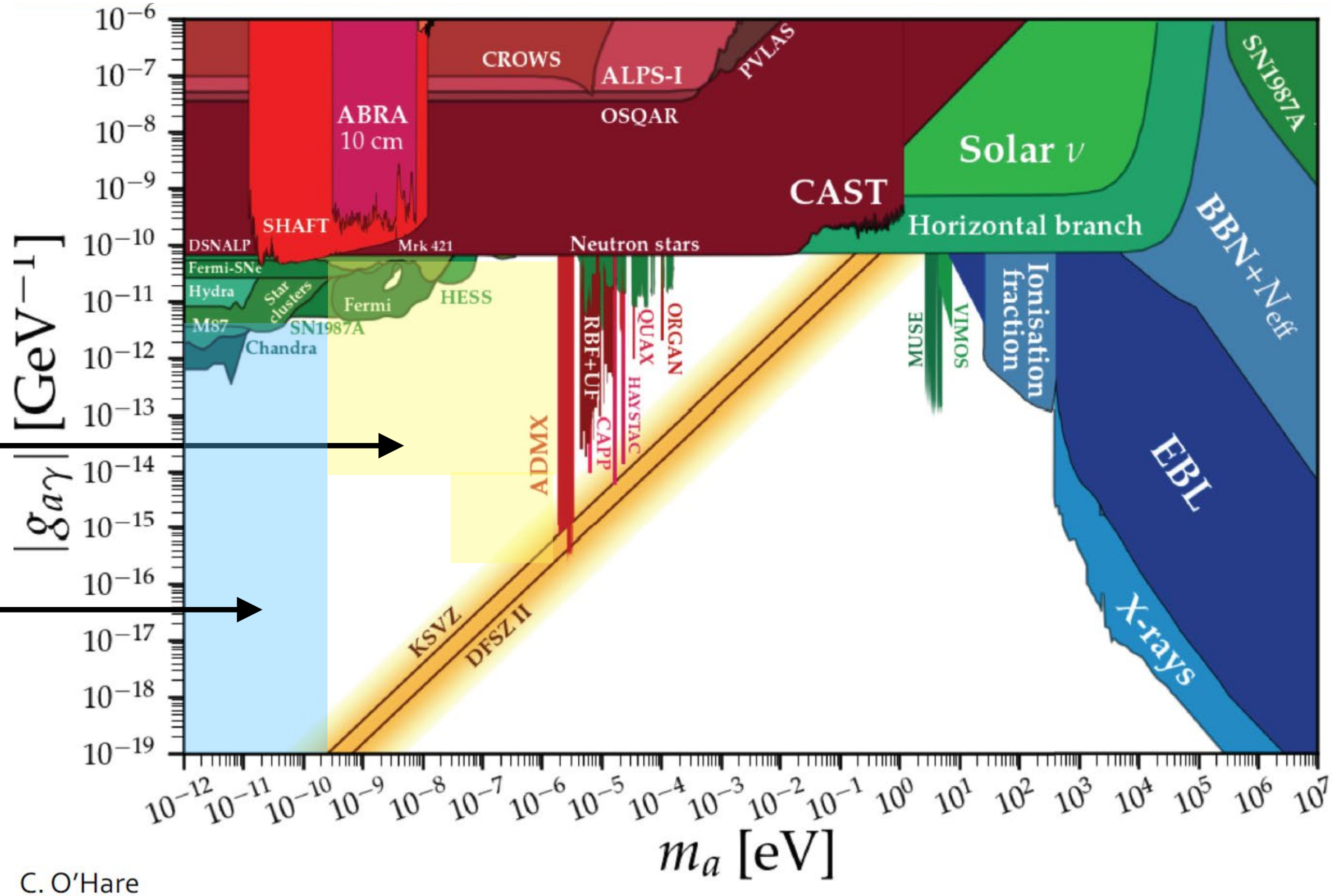
system noise temperature
cryo-amplifiers JJPA





(but not only…)

particle physics: what are we talking about?



C. O'Hare

DMRadio →

CASPEr electric NMR →

spin-based, NMR ②

microwave cavities ①

electromagn. resonators

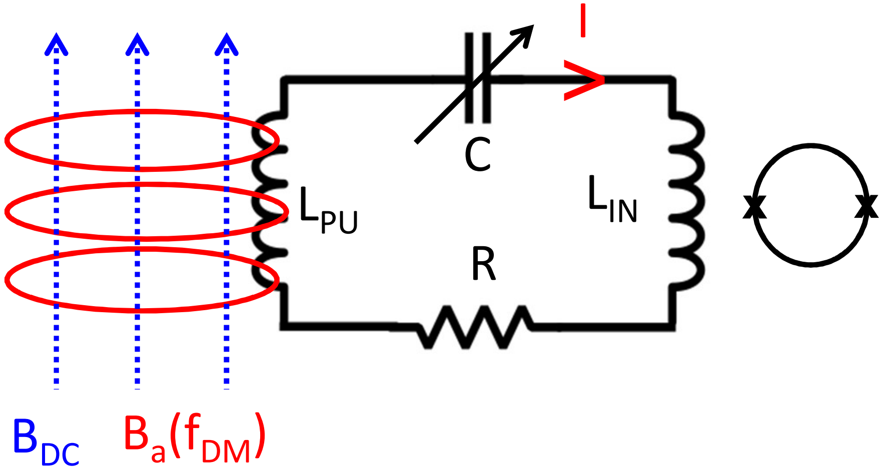
bolometers, TES ①

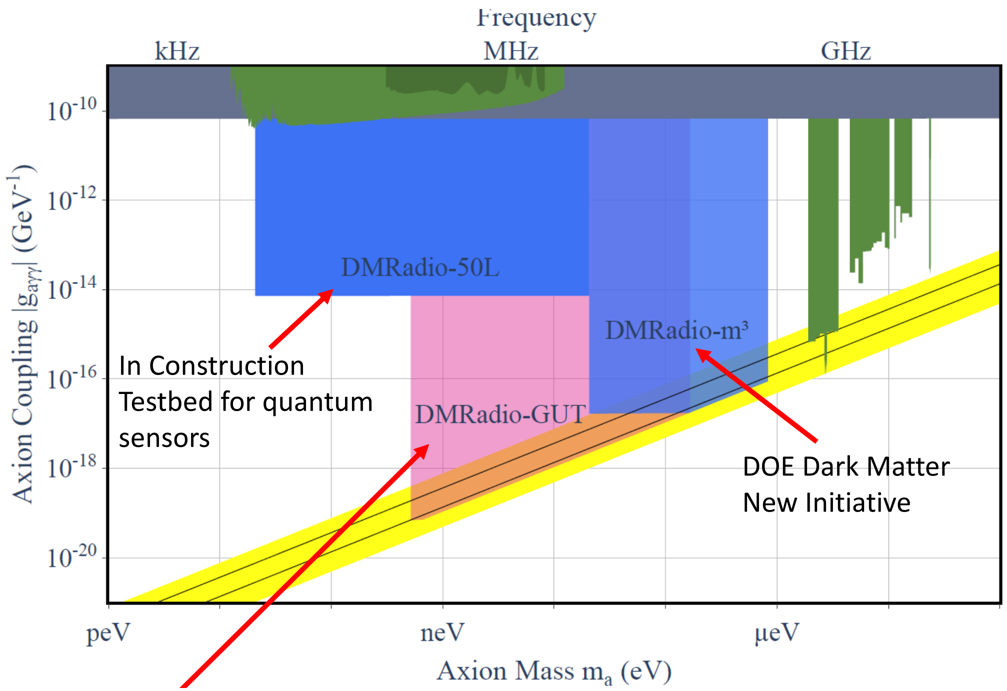
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Kent Irwin (Stanford University)

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





In Construction
Testbed for quantum sensors

DOE Dark Matter
New Initiative

- 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)

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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 g_d or via the gradient coupling g_{aNN}.

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

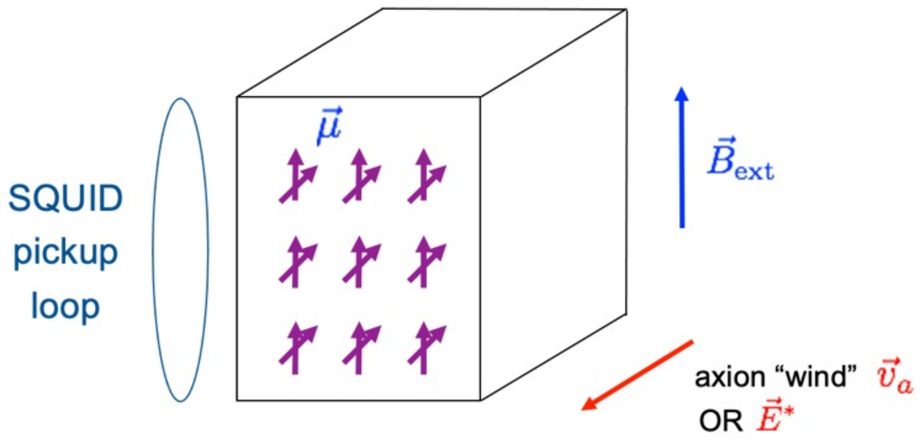
$$\boxed{H_e \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^*}$$

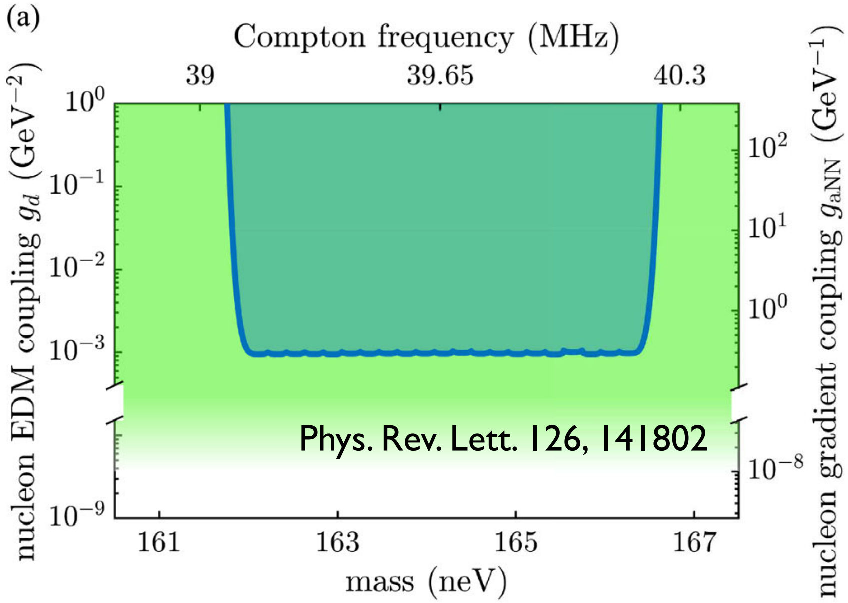
CASPEr-electric

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

$$\boxed{H_g \propto \boldsymbol{\sigma}\cdot\nabla a}$$

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)

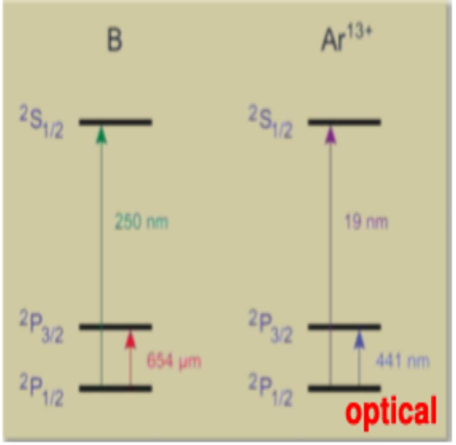
particle physics @ CERN : what are we talking about?

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

HCI's in Penning traps

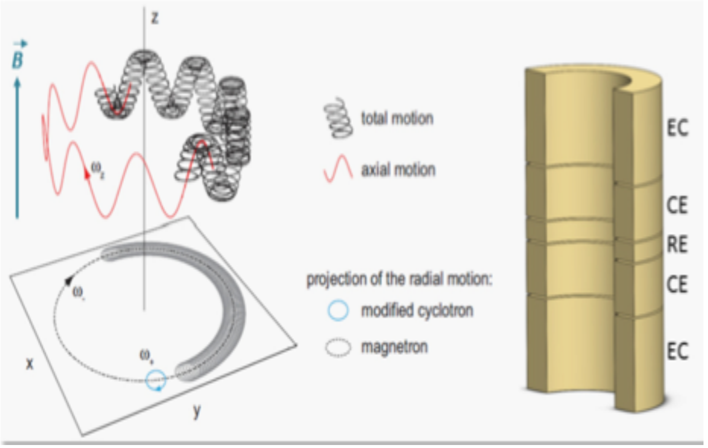
Scaling with a nuclear charge Z

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



@ CERN:

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



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

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)

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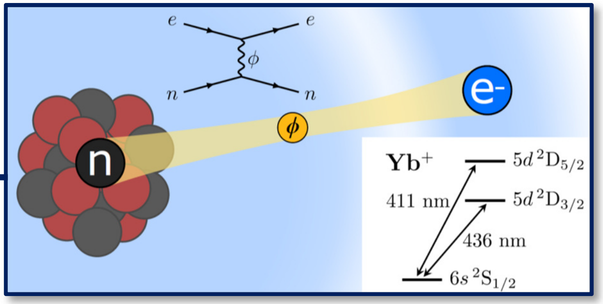
https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

Quantum sensors for new particle physics experiments: Penning traps

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

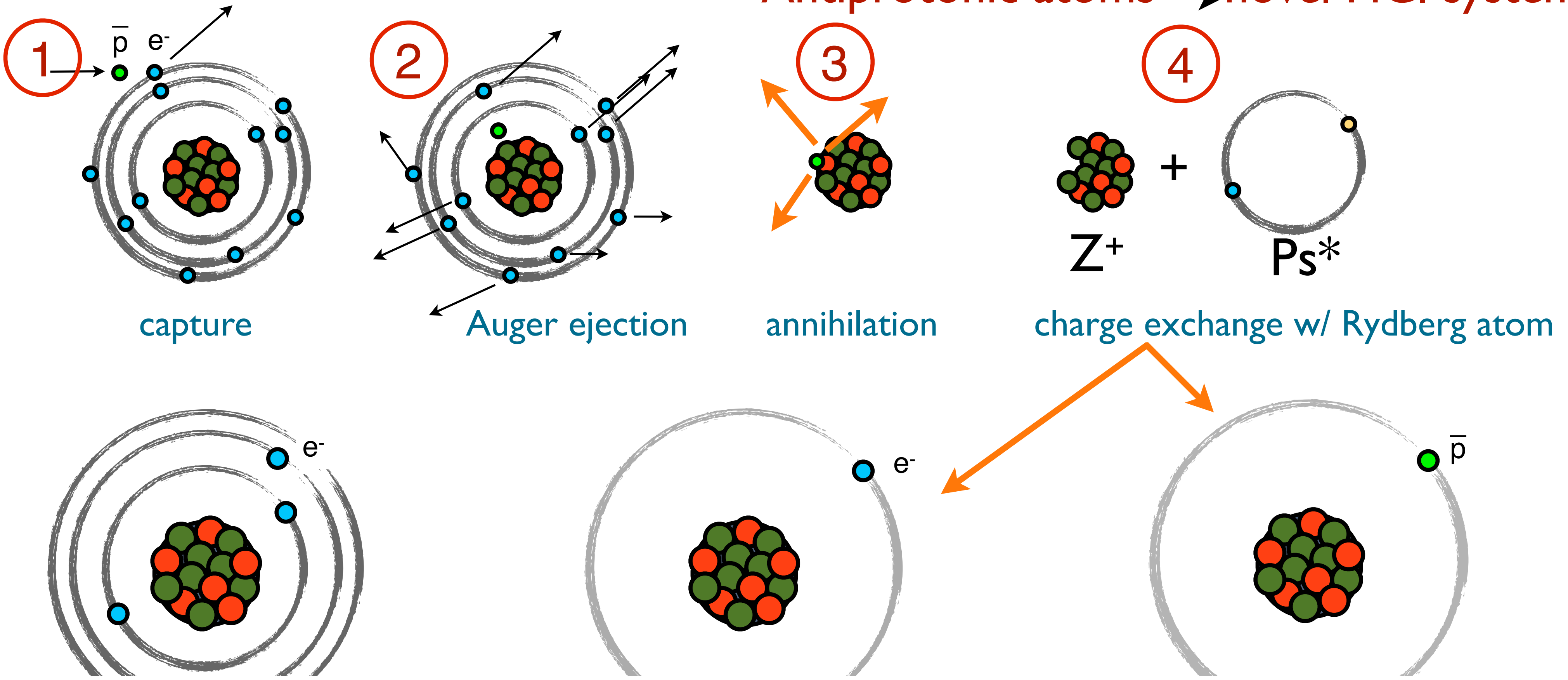
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot

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



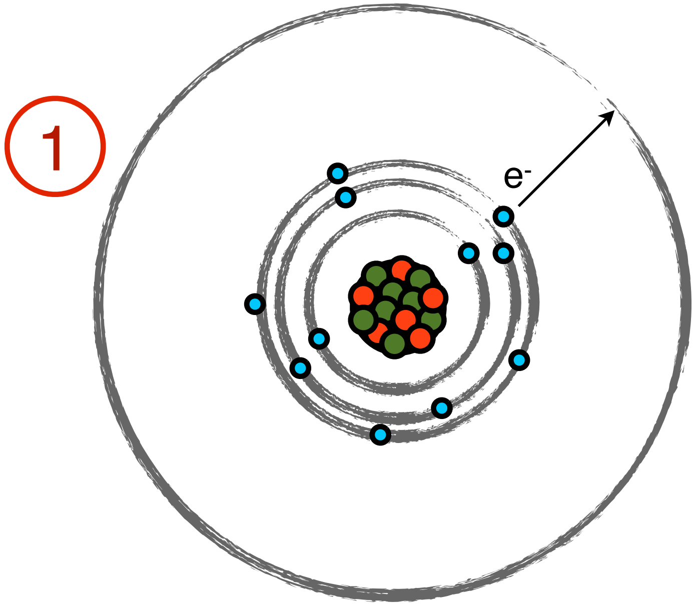
HCI (stable), (Z-n)+

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

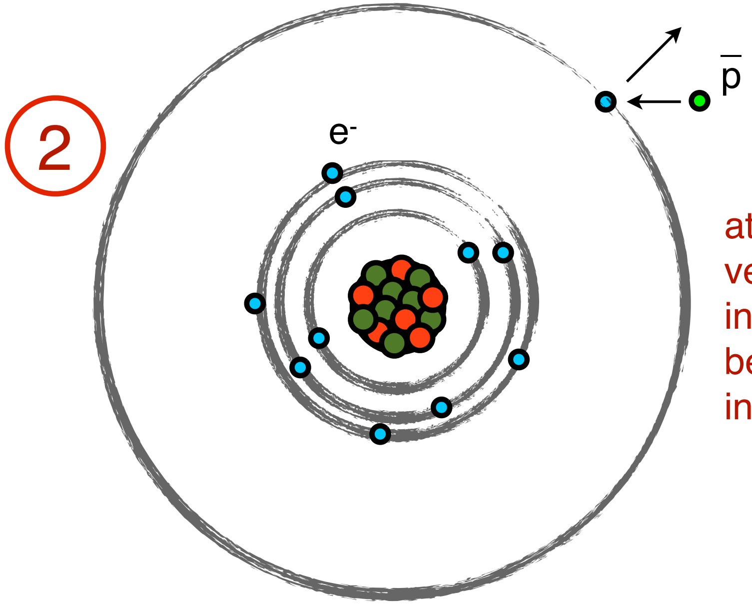
HCI*(stable or unstable), (Z-1)+

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



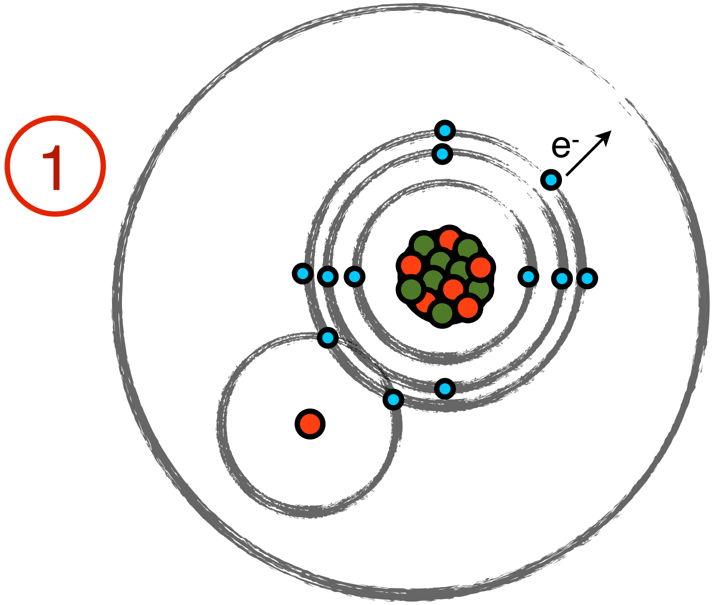
Rydberg excitation



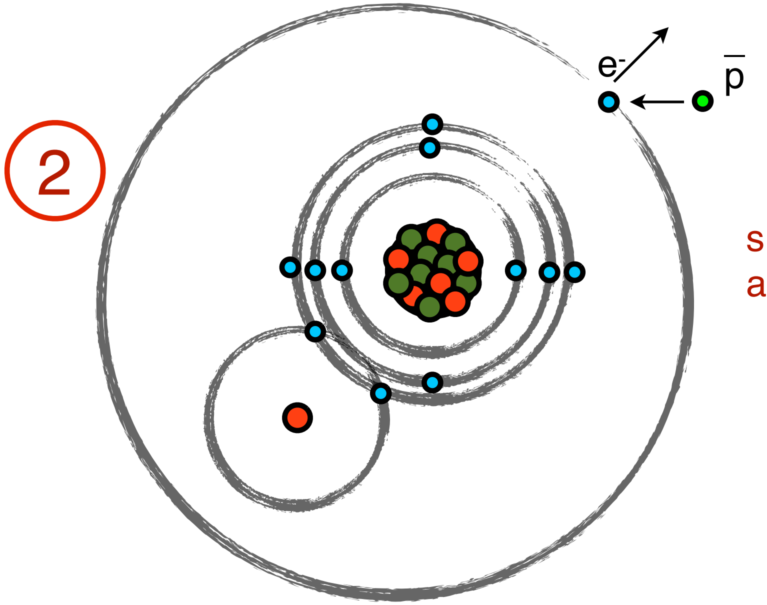
at end of cascade, p is very close to nucleus… investigate long-range behavior of strong interaction?

charge exchange

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



Rydberg excitation



similar approach as eEDM in molecules

charge exchange

end of part 1...

Some words on signal read out ...

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

spin-based, NV-diamonds

optical clocks

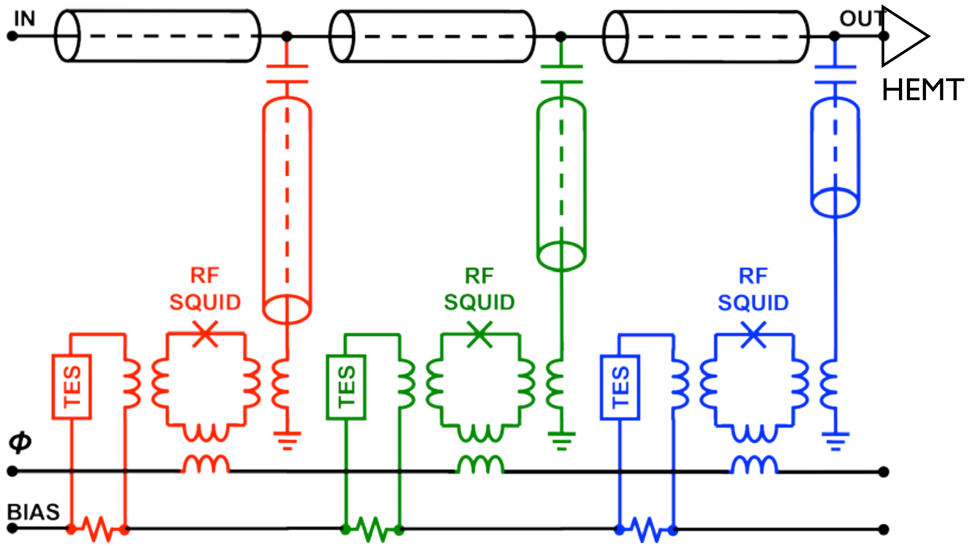
ionic / atomic / molecular

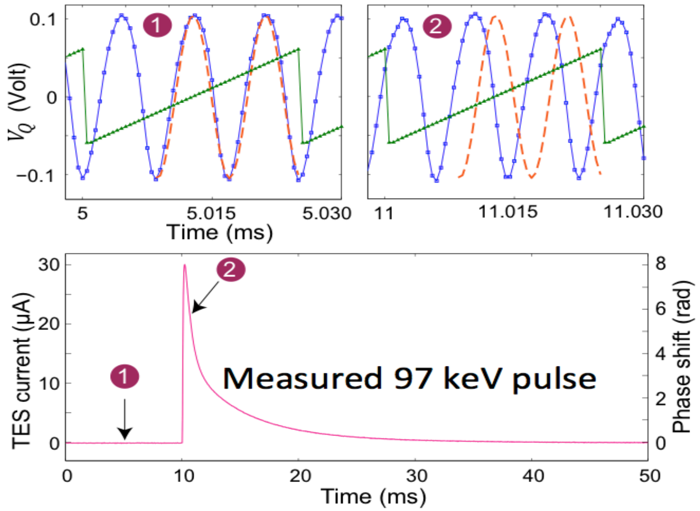
Some words on signal read out ...

https://arxiv.org/abs/2209.05621

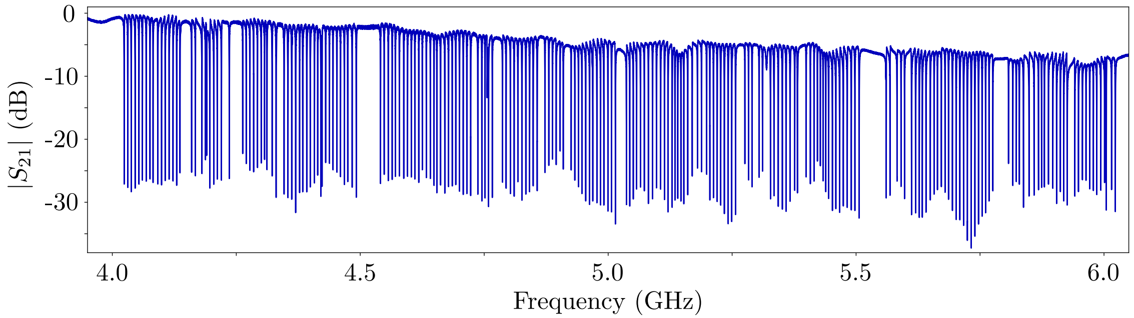
superconducting devices (TES, SNSPD, …) / cryo-electronics

Microwave SQUID multiplexing (μmux) is a form of frequency- domain multiplexing that allocates this bandwidth between input channels by the use of distinct, high-Q microwave resonances, each coupled to its own rf-SQUID and reading out the current signal from its own detector. As a superposition of microwave tones passes through the circuit, each tone is modulated by its own SQUID/resonator circuit before being amplified by the HEMT and brought to room temperature on a single coaxial cable.



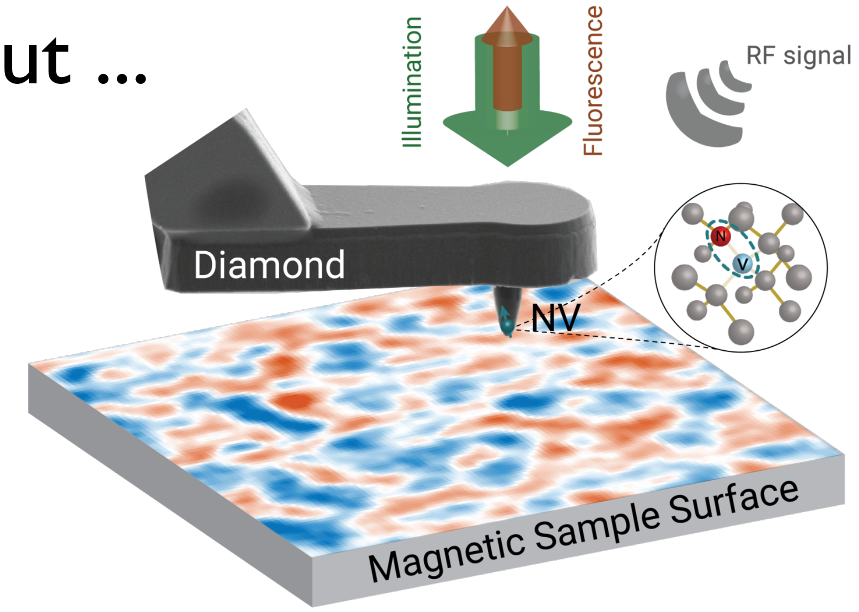


Critical current brings TES close to critical transition: Detection-induced transition leads to change in resonant frequency of circuit; slightly different resonant frequencies for each SQUID circuit (through voltage biasing): unique identification of each pixel. Injected microwave signal is then shifted in phase and amplitude

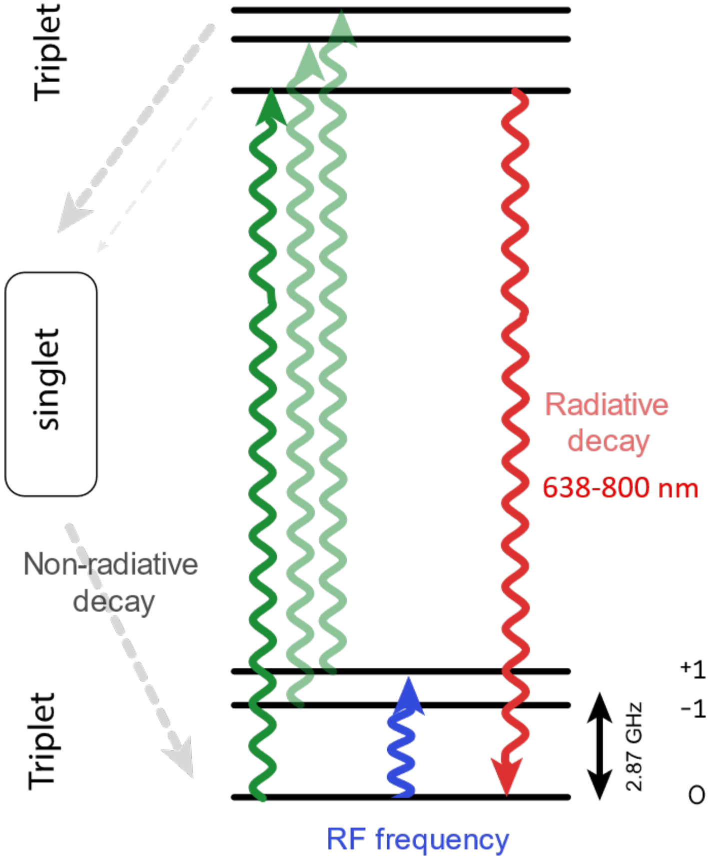


microwave transmission |S21| through a microwave-SQUID multiplexer operating in the 4 GHz to 6 GHz band, with 256 channels distributed across 4 discrete μmux chips.

Some words on signal read out ...



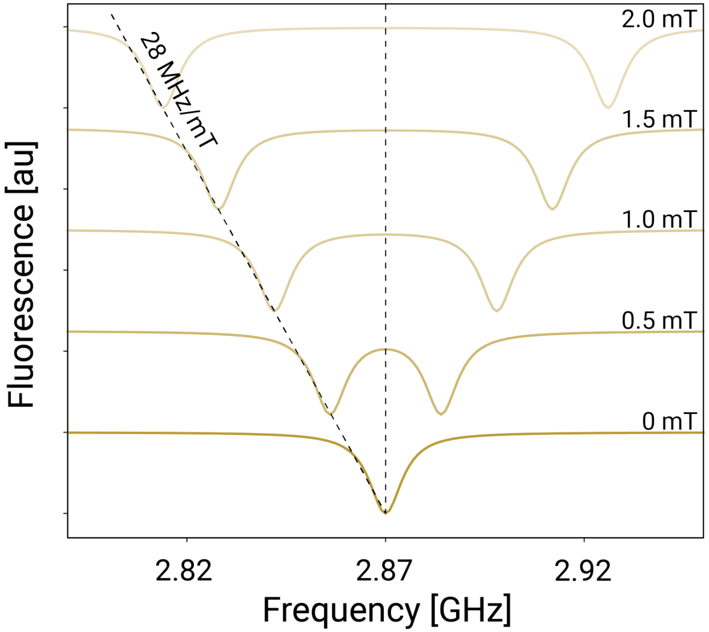
spin-based, NV-diamonds



two level system, with an energy spacing in the microwave range

State readout is based on the fact that the excited state couples to a "dark state", reducing the fluorescence rate compared to the ground state

Probe ground state population by detecting red fluorescence light



Magnetic field sensitivity: Zeeman shift: microwave resonance frequence changes

Some words on signal read out ...

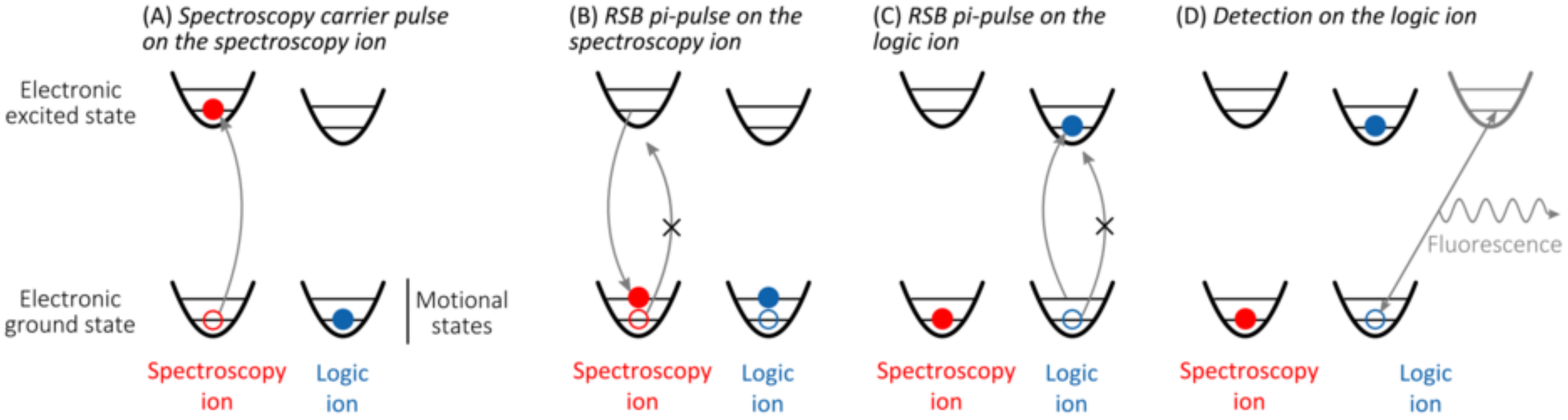
ionic / atomic / molecular

optical clocks

Various schemes: e.g. antiprotonic atoms (very low statistics): resonant transitions result in annihilation

Generally: fluorescence from resonant state back to ground state

Quantum logic spectroscopy: via co-trapped ions of another species (e.g. for Al^+)



https://www.quantummetrology.de/eqm/research/iqloc/quantum-logic-spectroscopy/

(Quantum non-demolition measurement)

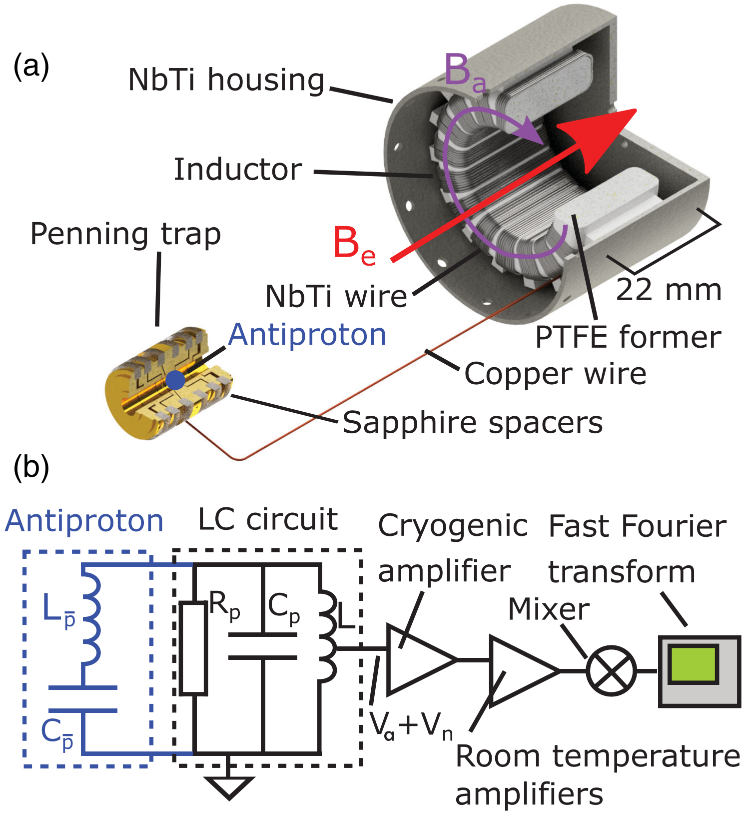
Quantum sensors for new particle physics experiments: Penning traps

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

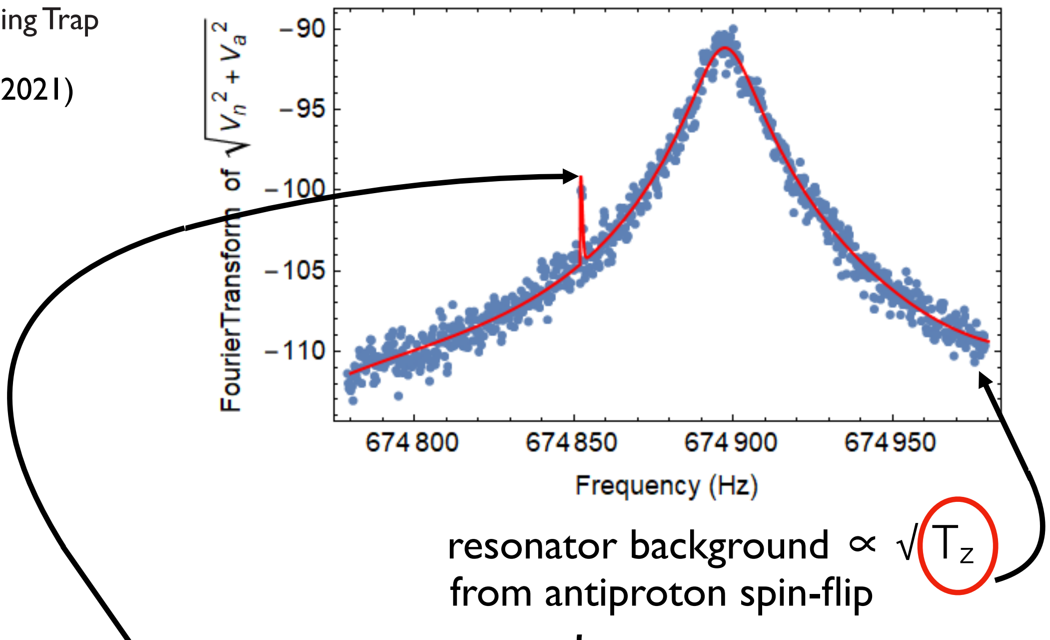
Constraints on the Coupling between Axion-like Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

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

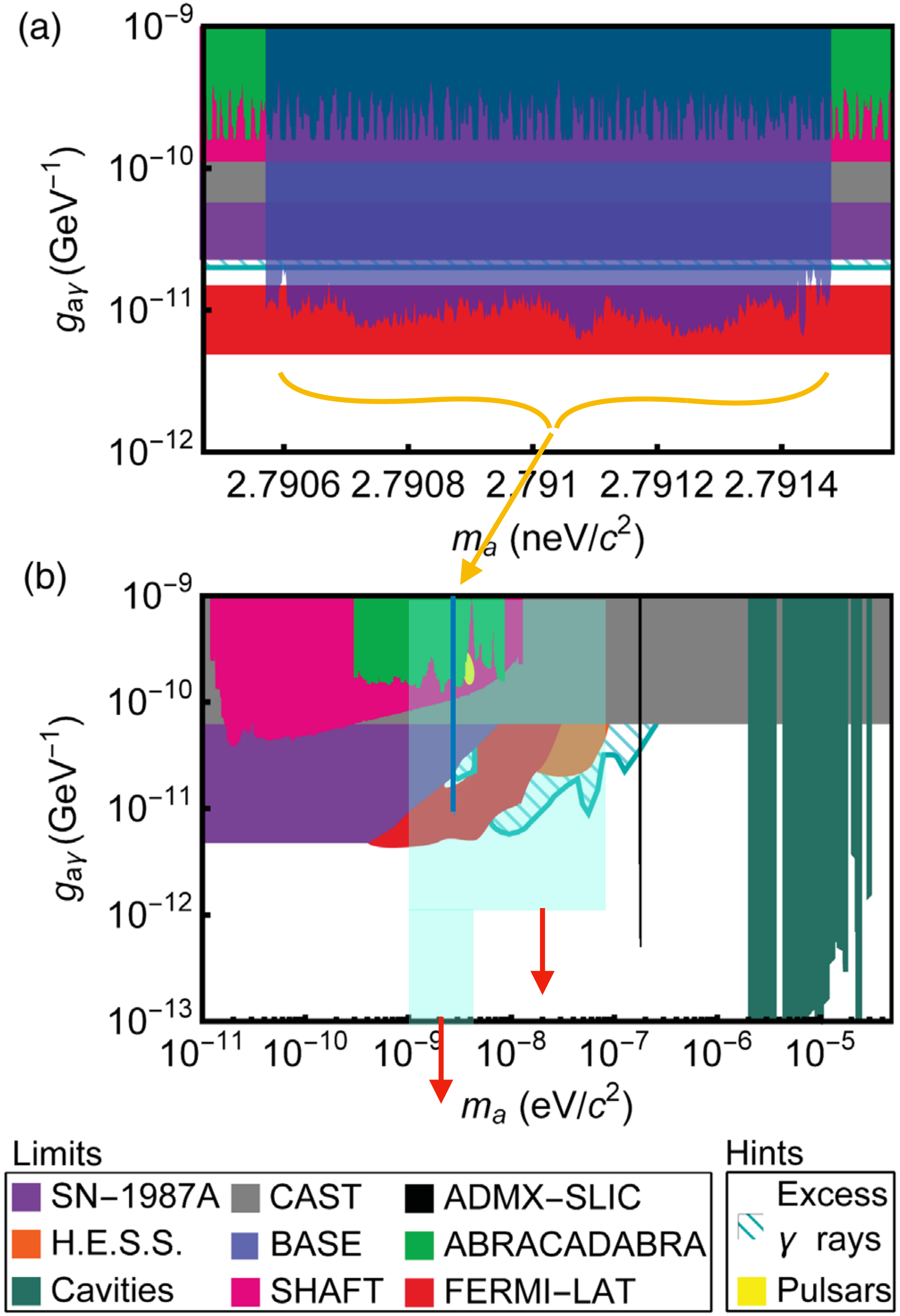
$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})}\, \kappa \nu_a l N_\mathrm{T} (r_2^2 - r_1^2) g_{a\gamma} |\mathbf{B}_e| \sqrt{\rho_a \hbar c}\,.$$

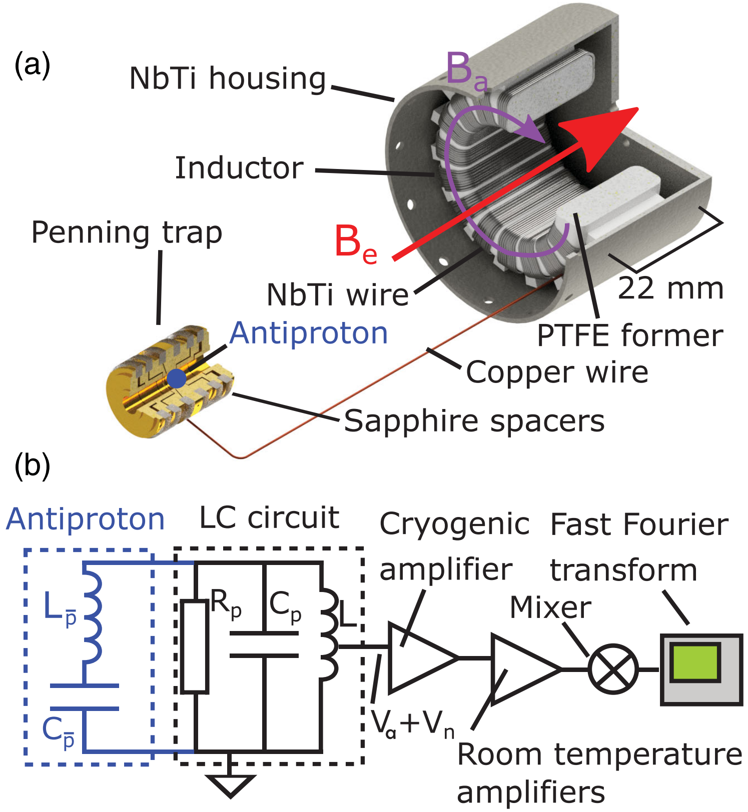
$f(\nu,Q,\mathbf{q})$ is a lorentzian line-shape function proportional to Re{Z}
e_n is the equivalent input noise of the amplifier
κ is the coupling constant
Q is the resonator Q-factor
N_T is the number of turns
l is the length of the toroid along the magnet B field

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!

Quantum sensors for new particle physics experiments: Penning traps

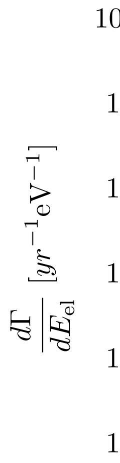




currently developing superconducting tunable capacitors & laser-cooled resonators

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

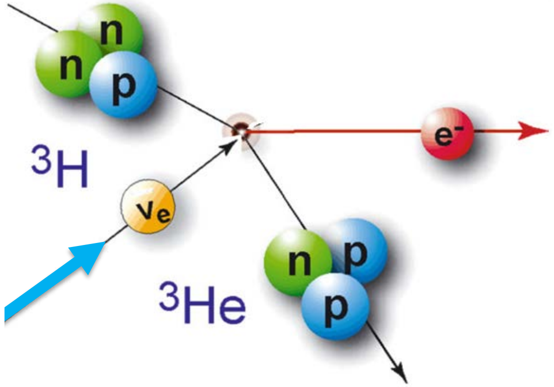
Challenge: Detection of primordial neutrino flux: $E_\nu \sim \mu eV$



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!

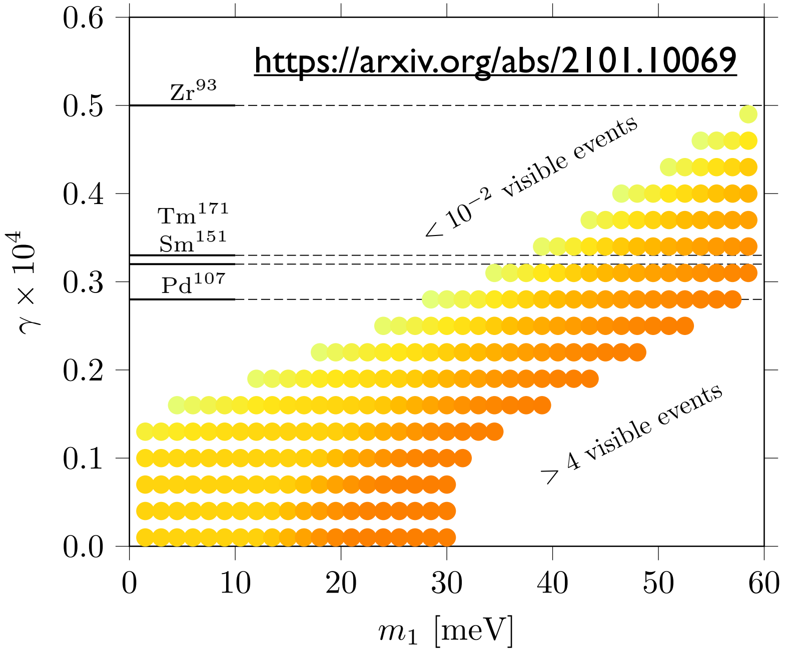


PTOLEMY experimental quest

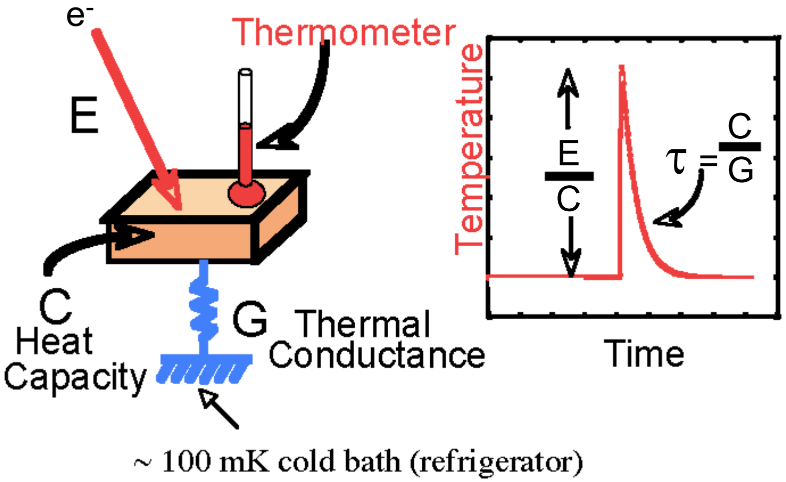
relic neutrino capture
RF tracker (EM radiation in B field)
microcalorimeter (TES: sub-eV for ~eV)

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

<u>what are the challenges?</u>

- 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)
- sensitivity!

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

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs)

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's

Spin-based sensors

helicity detectors

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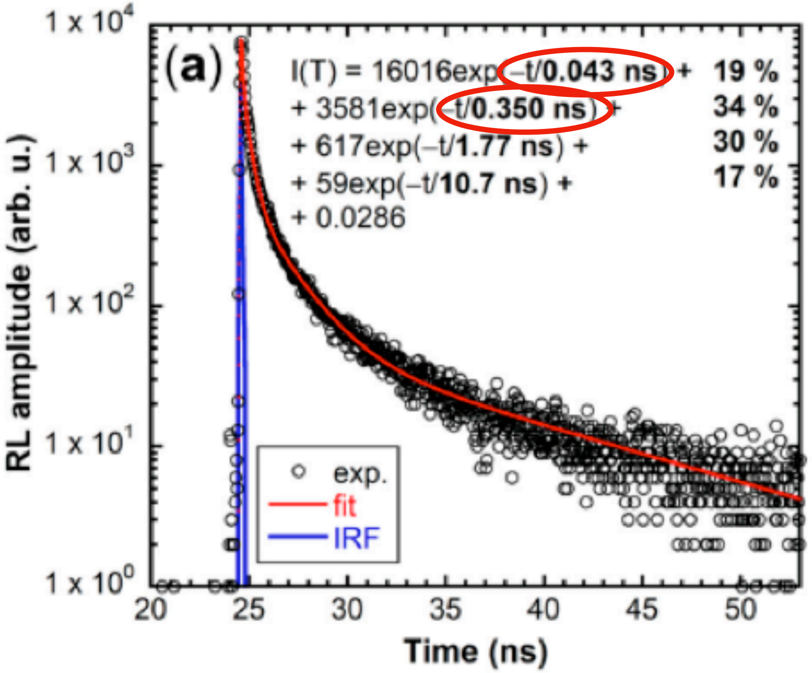
helicity detectors

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN

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



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

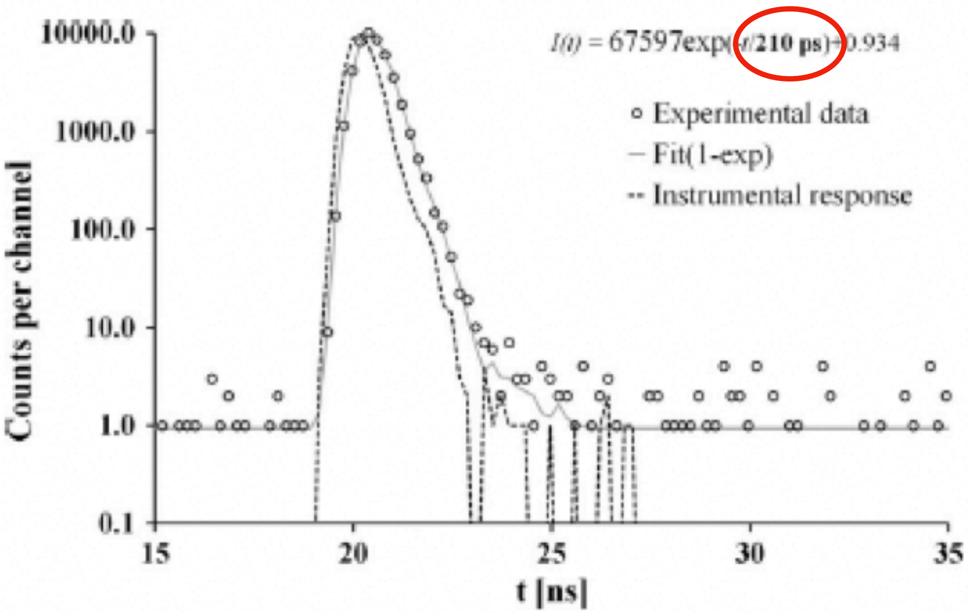


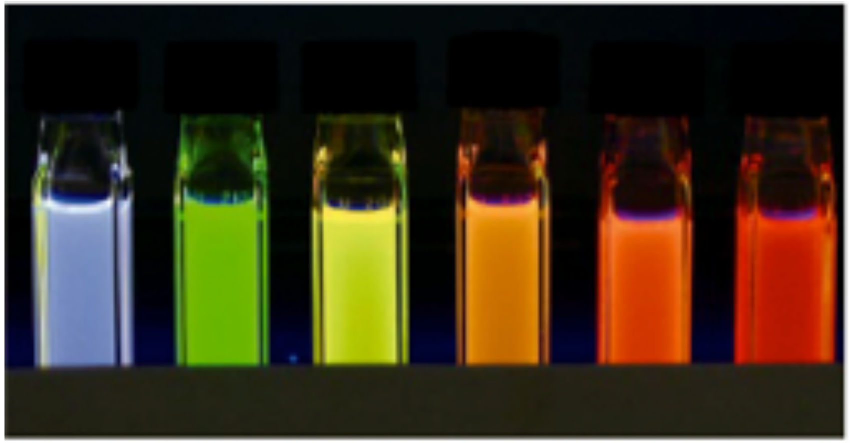
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function *I*(*t*) provided in the figure.

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

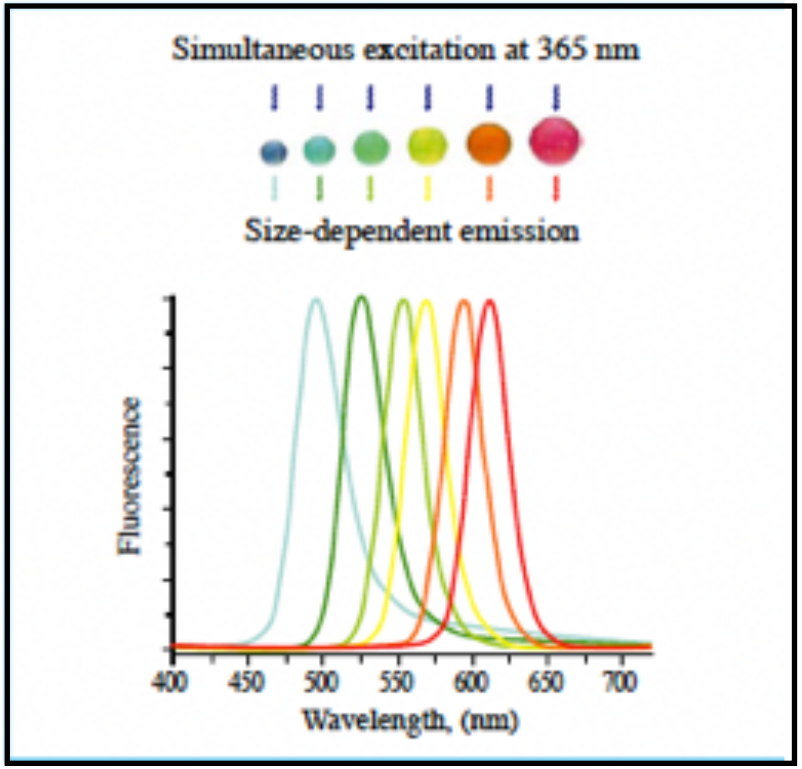
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

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

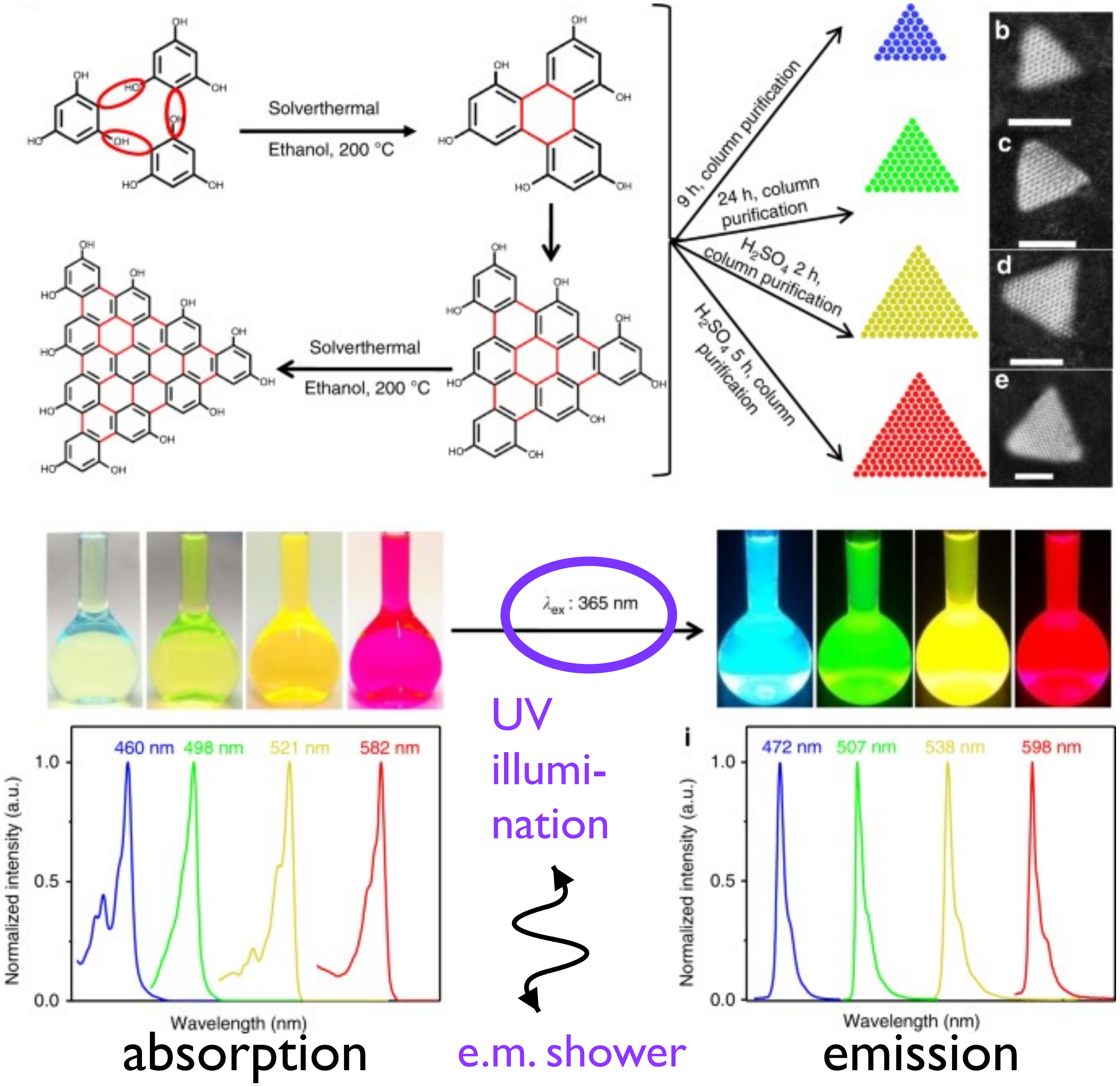


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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



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

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

requires:

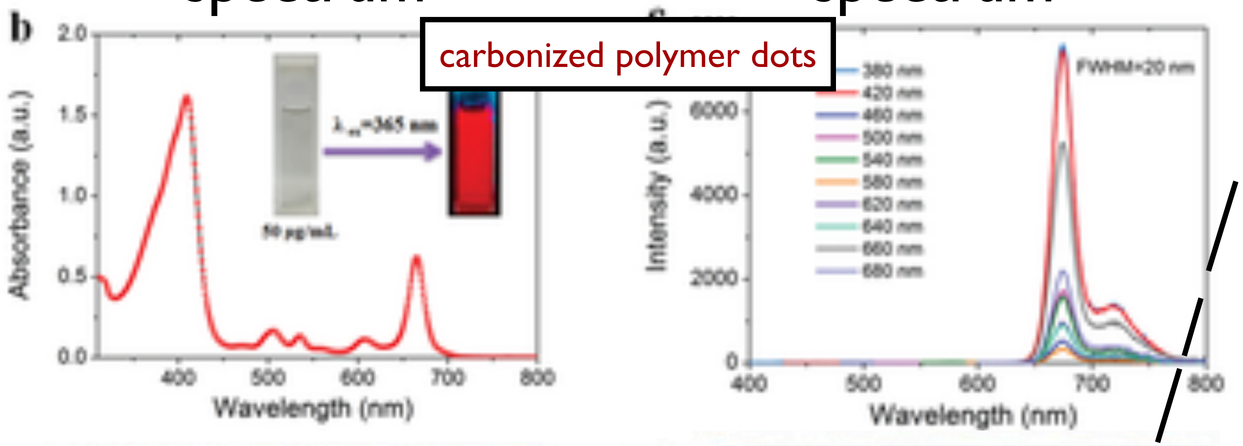
- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise / decay times

select appropriate nanodots

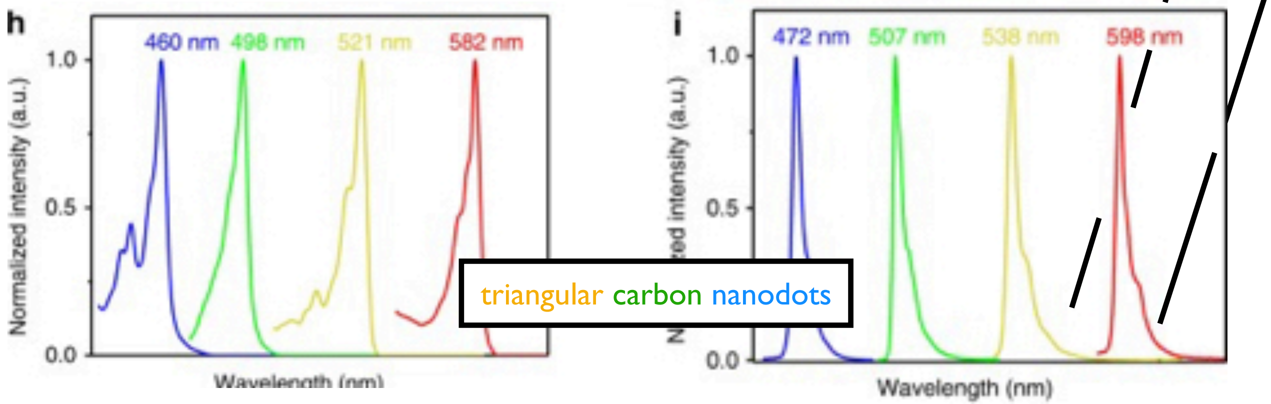
e.g. triangular carbon nanodots

absorption spectrum

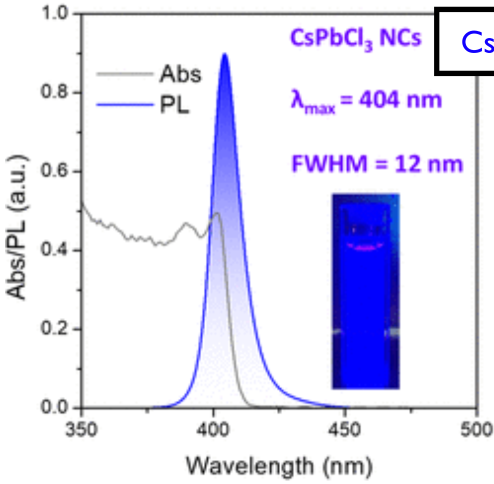
emission spectrum



carbonized polymer dots



triangular carbon nanodots



CsPbCl$_3$ nanocrystals

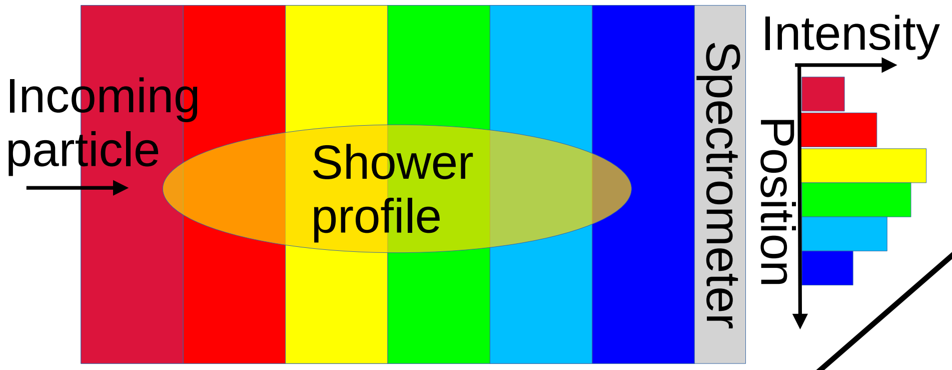
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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

…

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

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

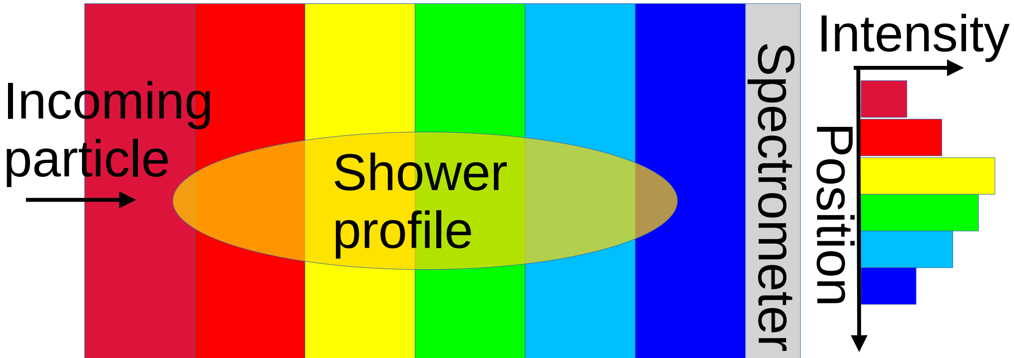


(shower profile via ***spectrometry***)

Metalenses?

M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

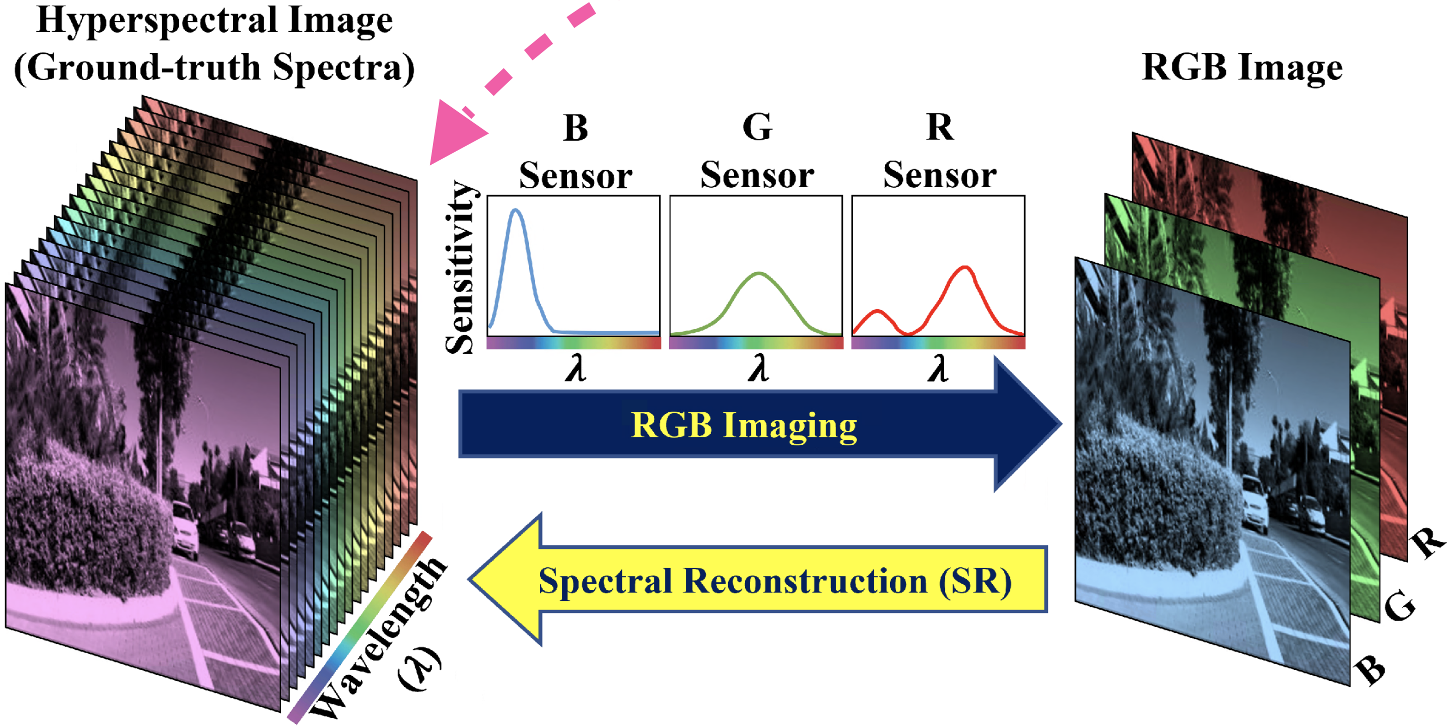
Quantum dots: chromatic calorimetry (shower profile via ***spectrometry***)



different options for spectrometry:

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

A Rehabilitation of Pixel-Based Spectral Reconstruction from RGB Images
Yi-Tun Lin and Graham D. Finlayson
Sensors **2023**, *23*(8), 4155; https://doi.org/10.3390/s23084155

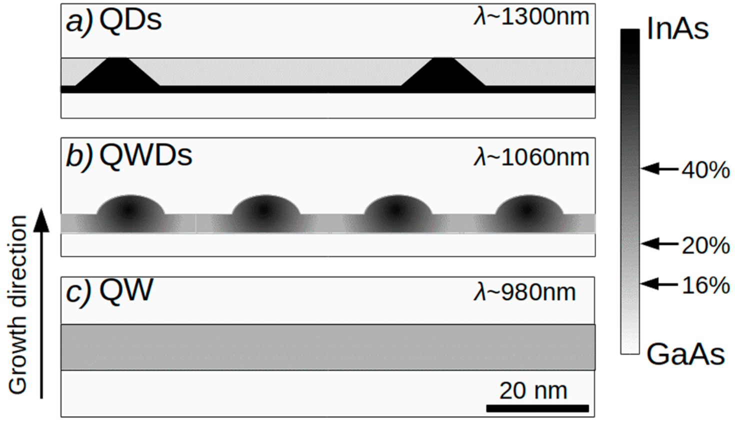


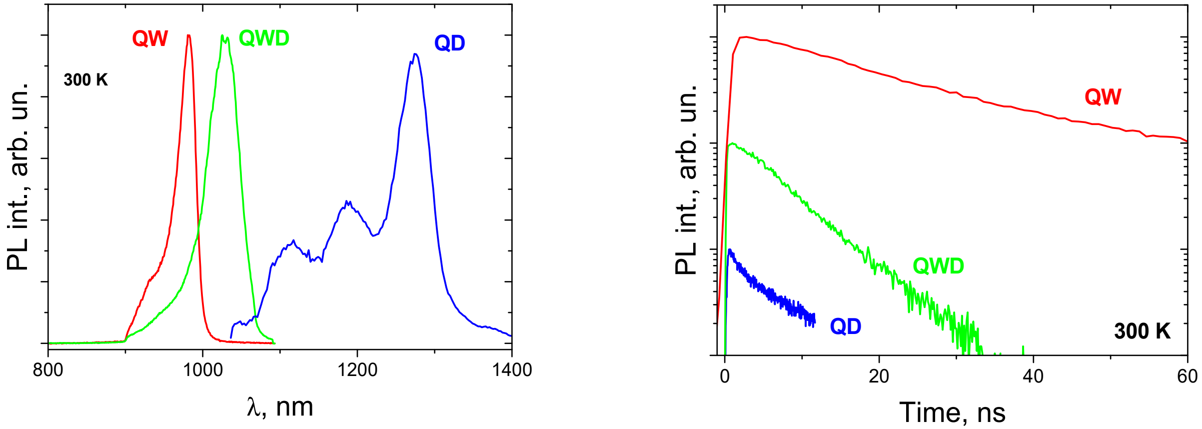
Active scintillators (QWs, QDs, QWDs, QCLs)

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?

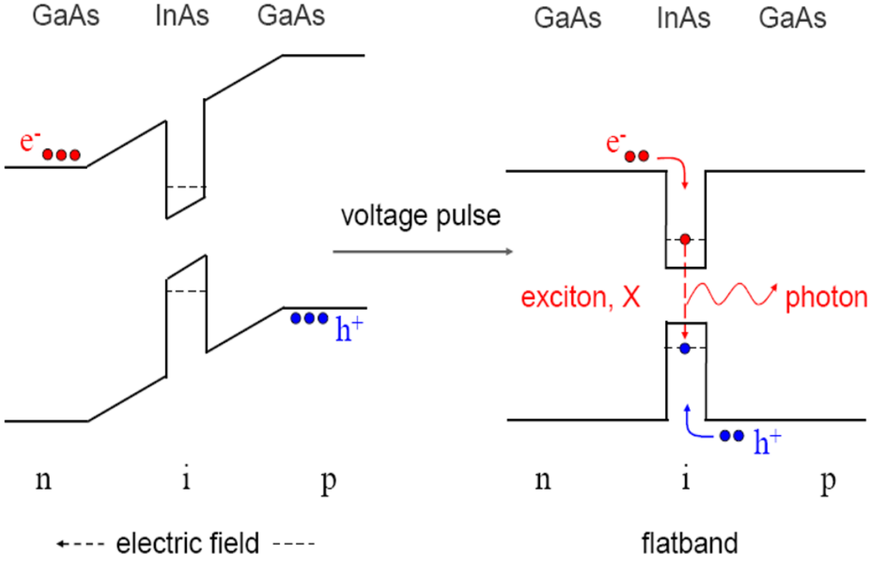
QD's are radiation resistant

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.

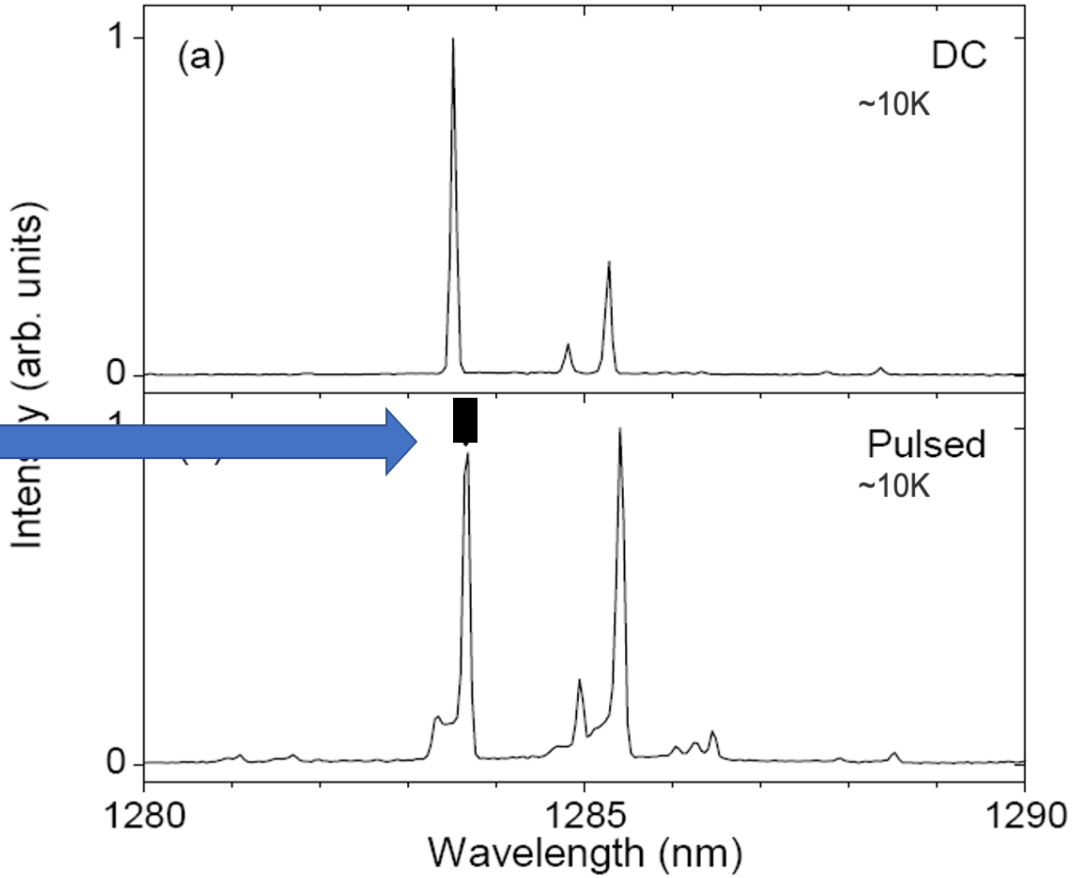
Active scintillators (QWs, QDs, QWDs, QCLs)

QD's produce sharp atom-like emission peaks

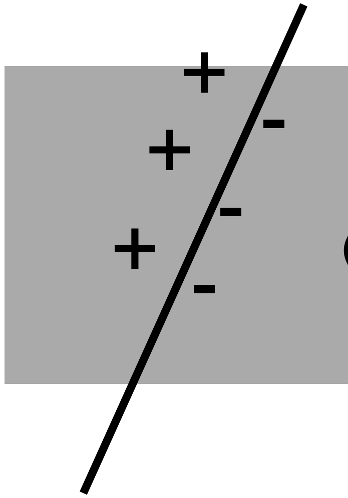
generate photons by optical pumping or electrical injection of electrons into the QD



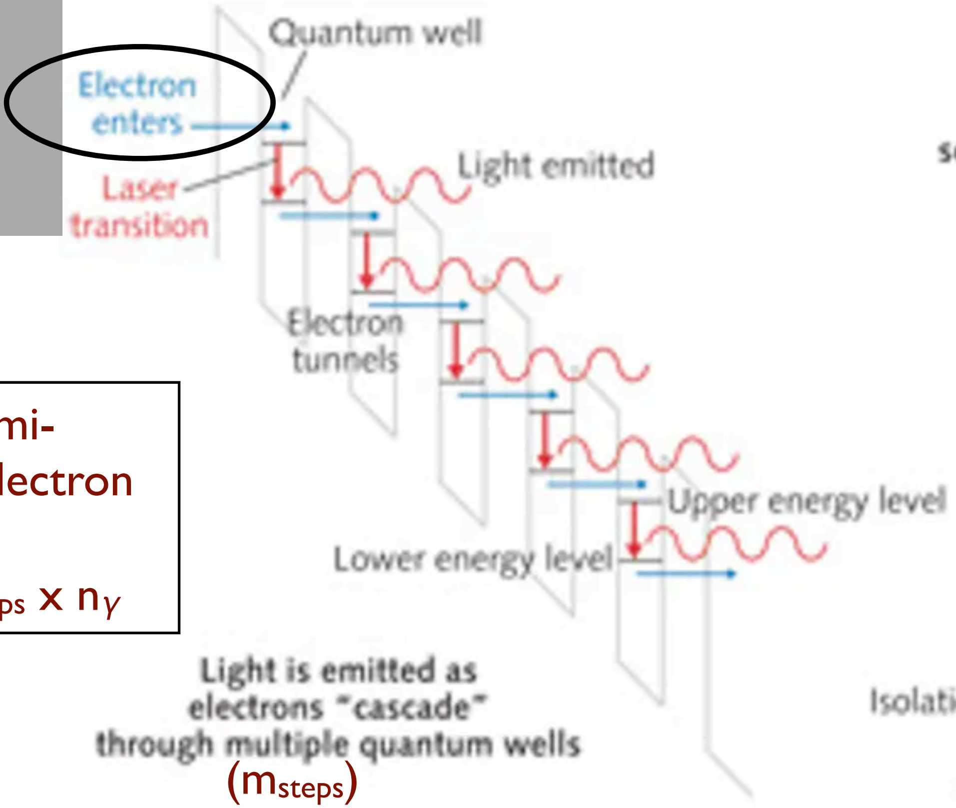
Electroluminescence (DC and pulsed)

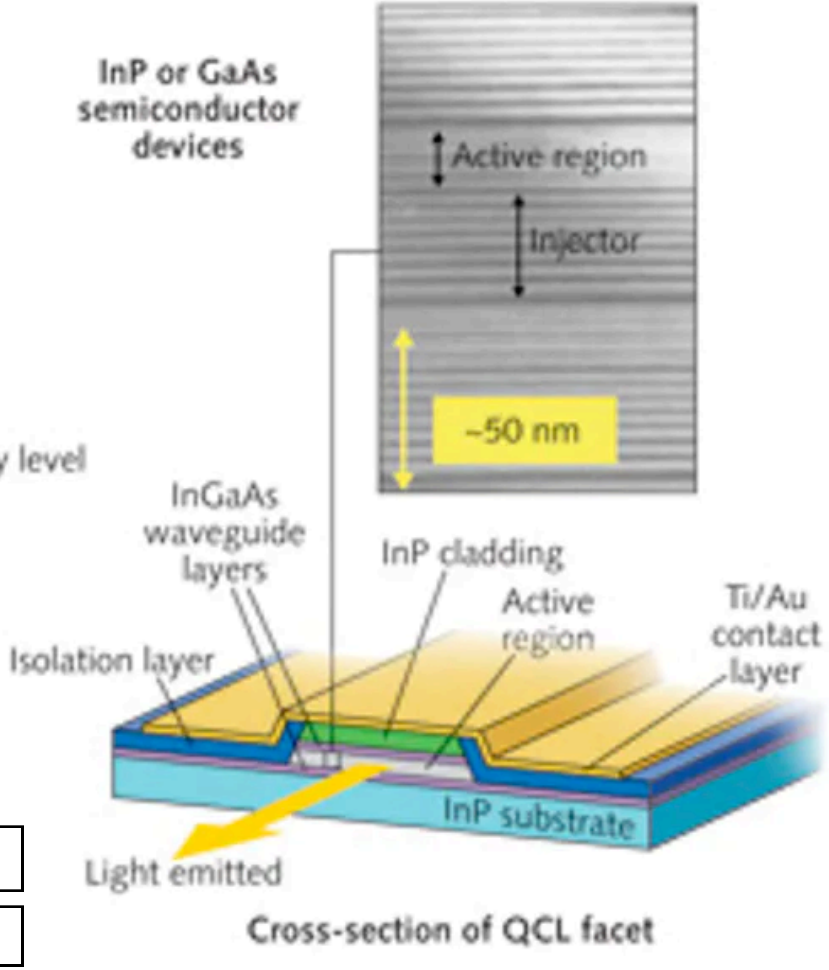


Active scintillators (QCLs, QWs, QDs, QWDs)



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:

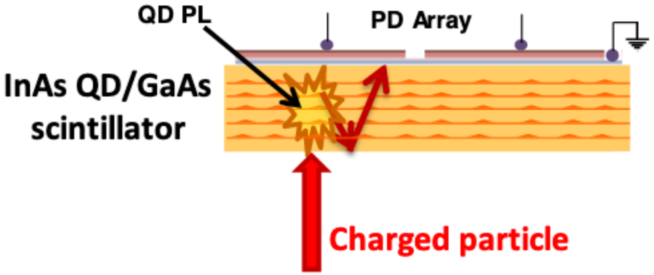
- as a hole-collecting electrode and
- as a channel current modulation gate

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

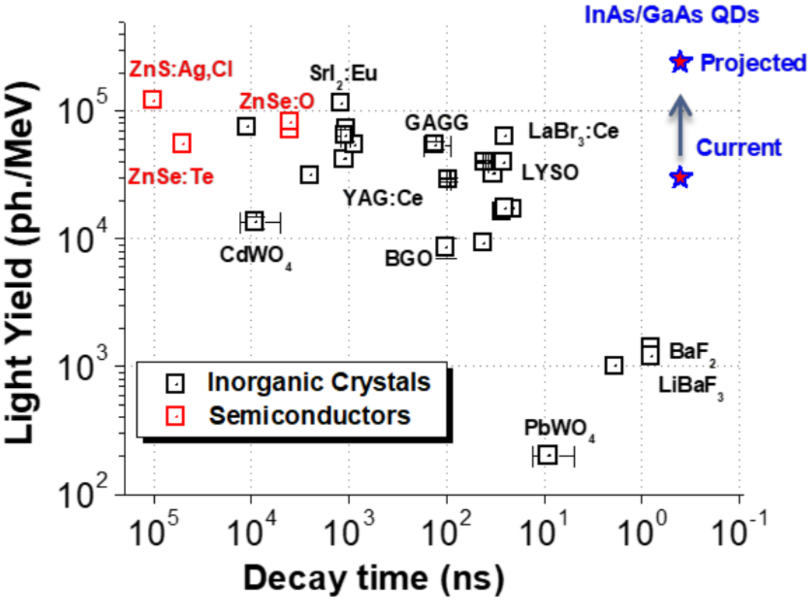
M.R. Hoeferkamp, S. Seidel, S. Kim, J. Metcalfe, A. Sumant, H. Kagan, W. Trischuk, M. Boscardin, G.-F. Dalla Betta, D.M.S. Sultan, N.T. Fourches, C. Renard, A. Barbier, T. Mahajan, A. Minns, V. Tokranov, M. Yakimov, S. Oktyabrsky, C. Gingu, P. Murat, M.T. Hedges

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

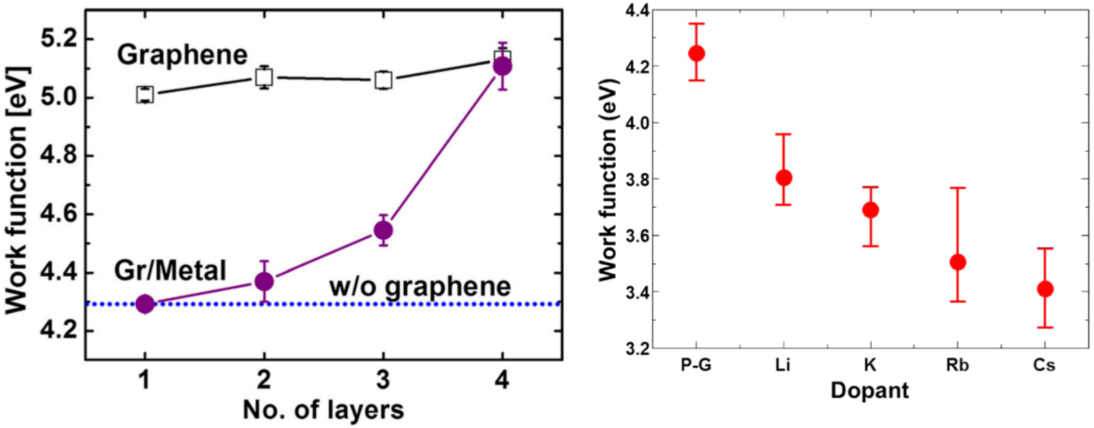
efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

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

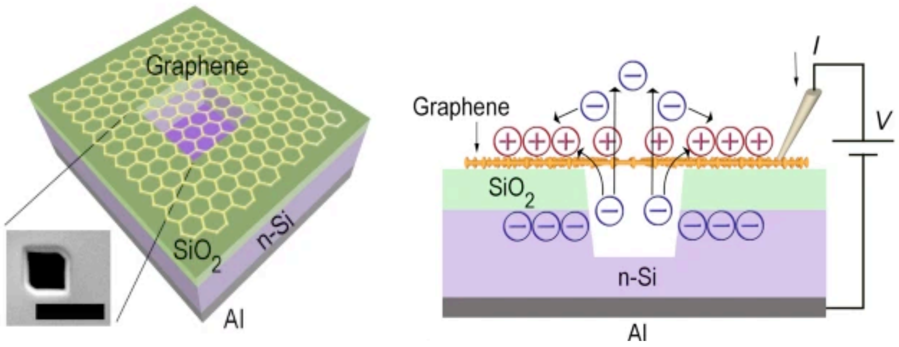
amplification

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)

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's

Spin-based sensors

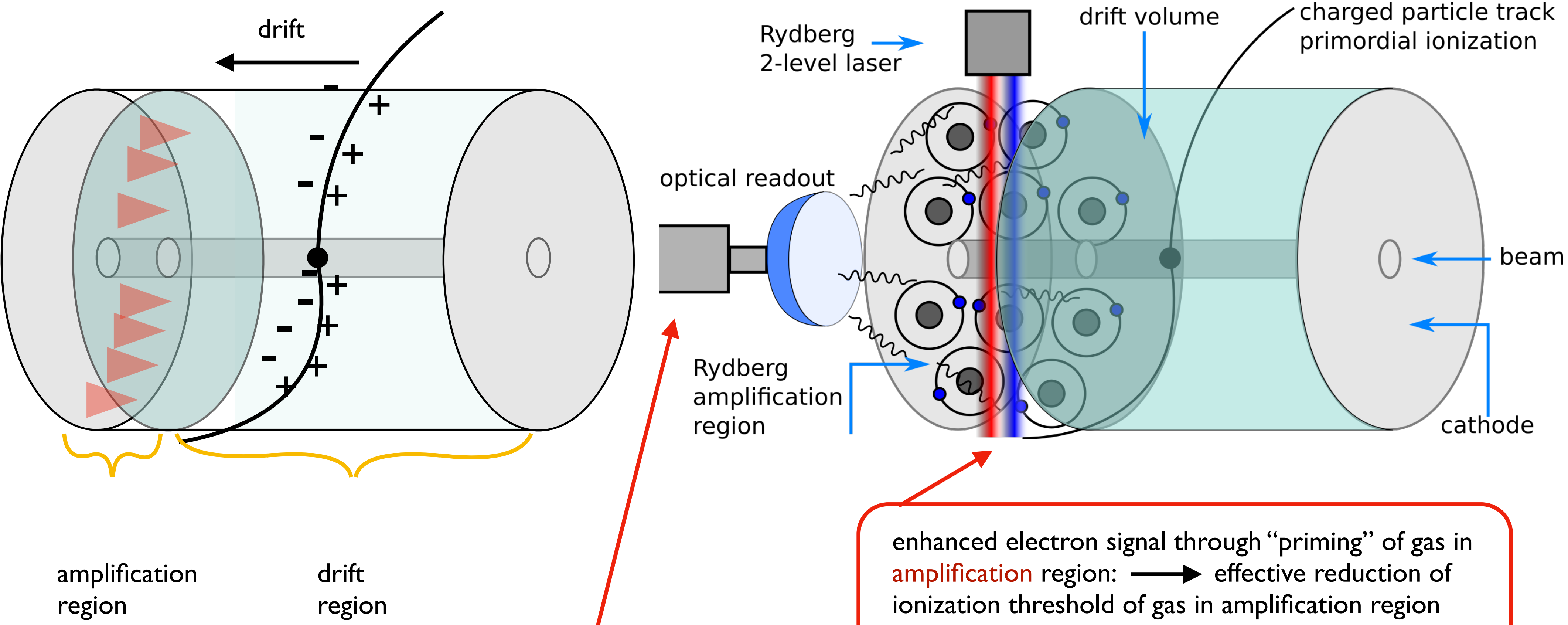
helicity detectors

Superconducting sensors

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

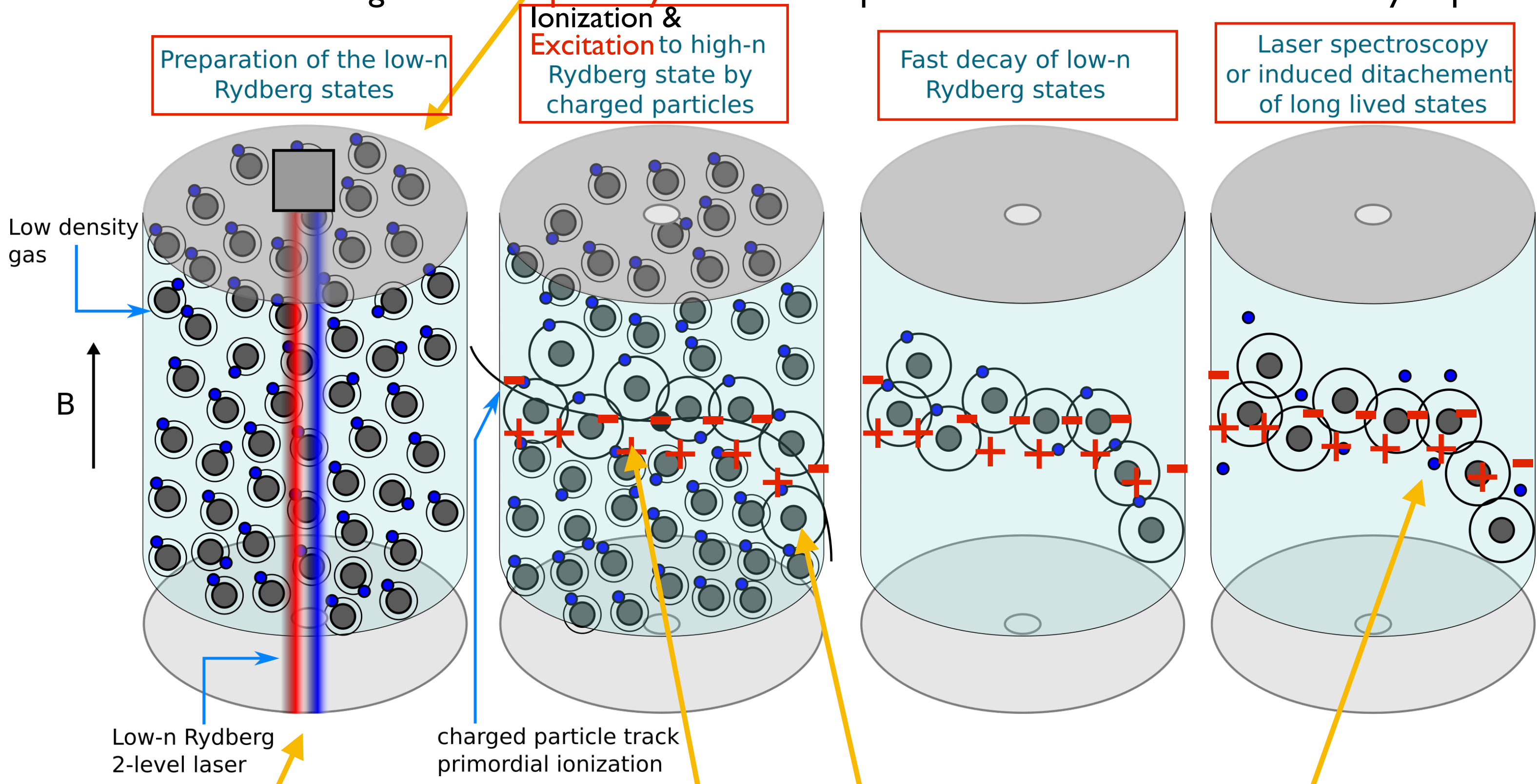
Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

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



reduction of ionization and atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

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Spin-based sensors

- helicity detectors

Superconducting sensors

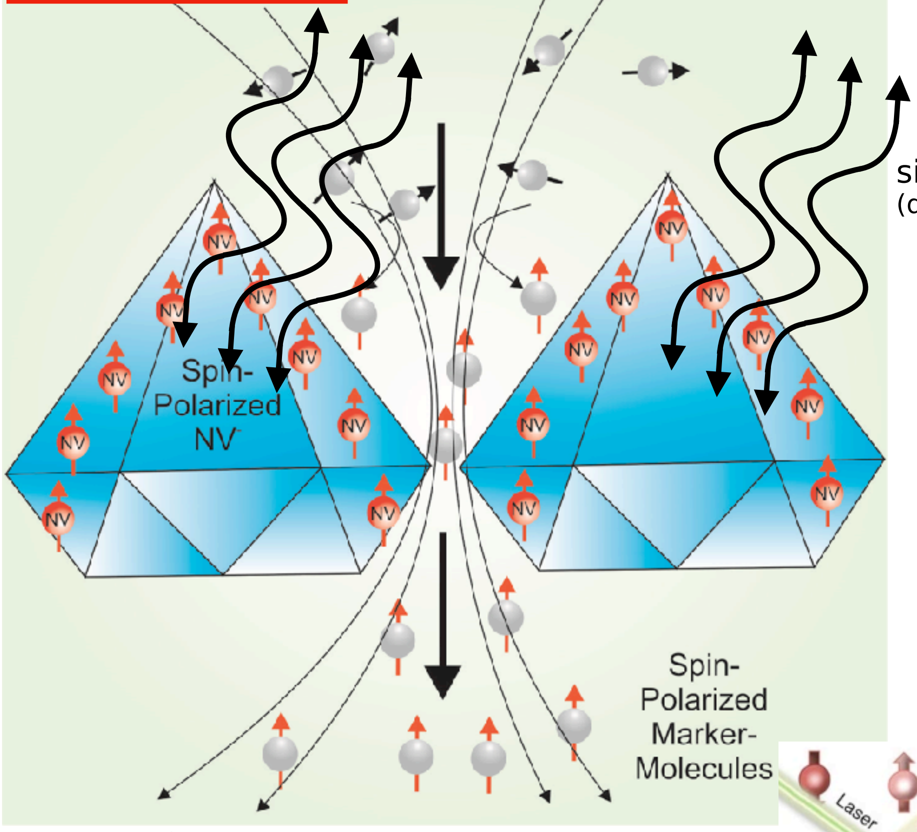
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

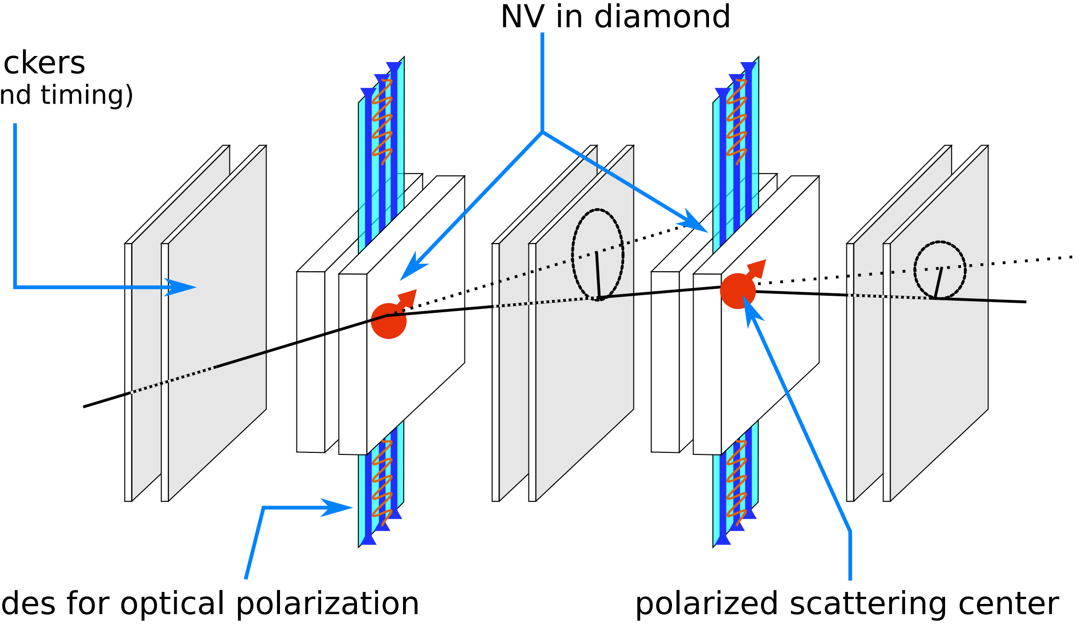


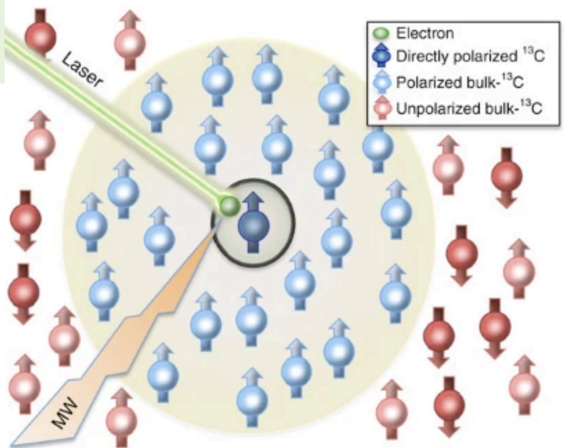
© Dr. Christoph Nebel, Fraunhofer IAF

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)





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

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Atoms, molecules, ions

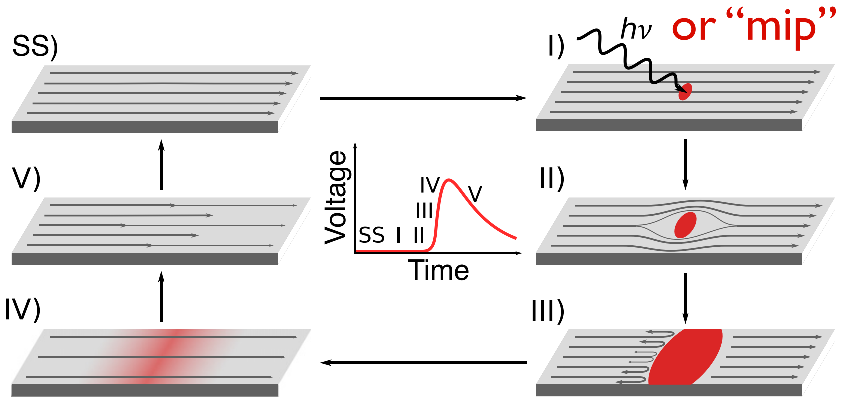
- Rydberg TPC’s

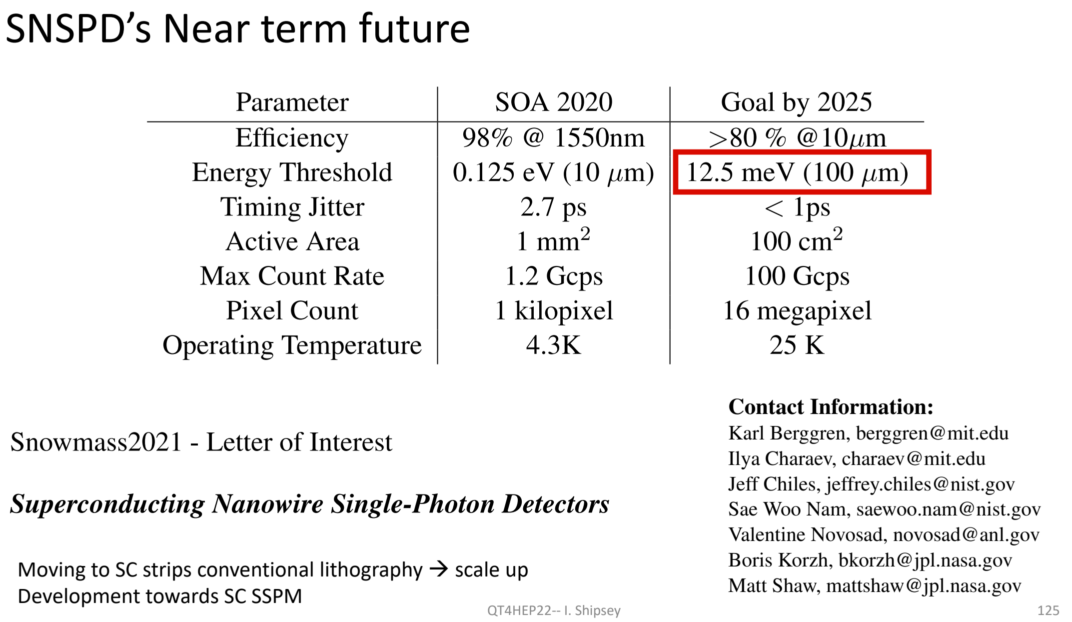
Spin-based sensors

- helicity detectors

Superconducting sensors

Extremely low energy threshold detectors: SNSPD





SNSPD's Near term future

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10μm
Energy Threshold	0.125 eV (10 μm)	12.5 meV (100 μm)
Timing Jitter	2.7 ps	< 1ps
Active Area	1 mm^2	100 cm^2
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

Snowmass2021 - Letter of Interest

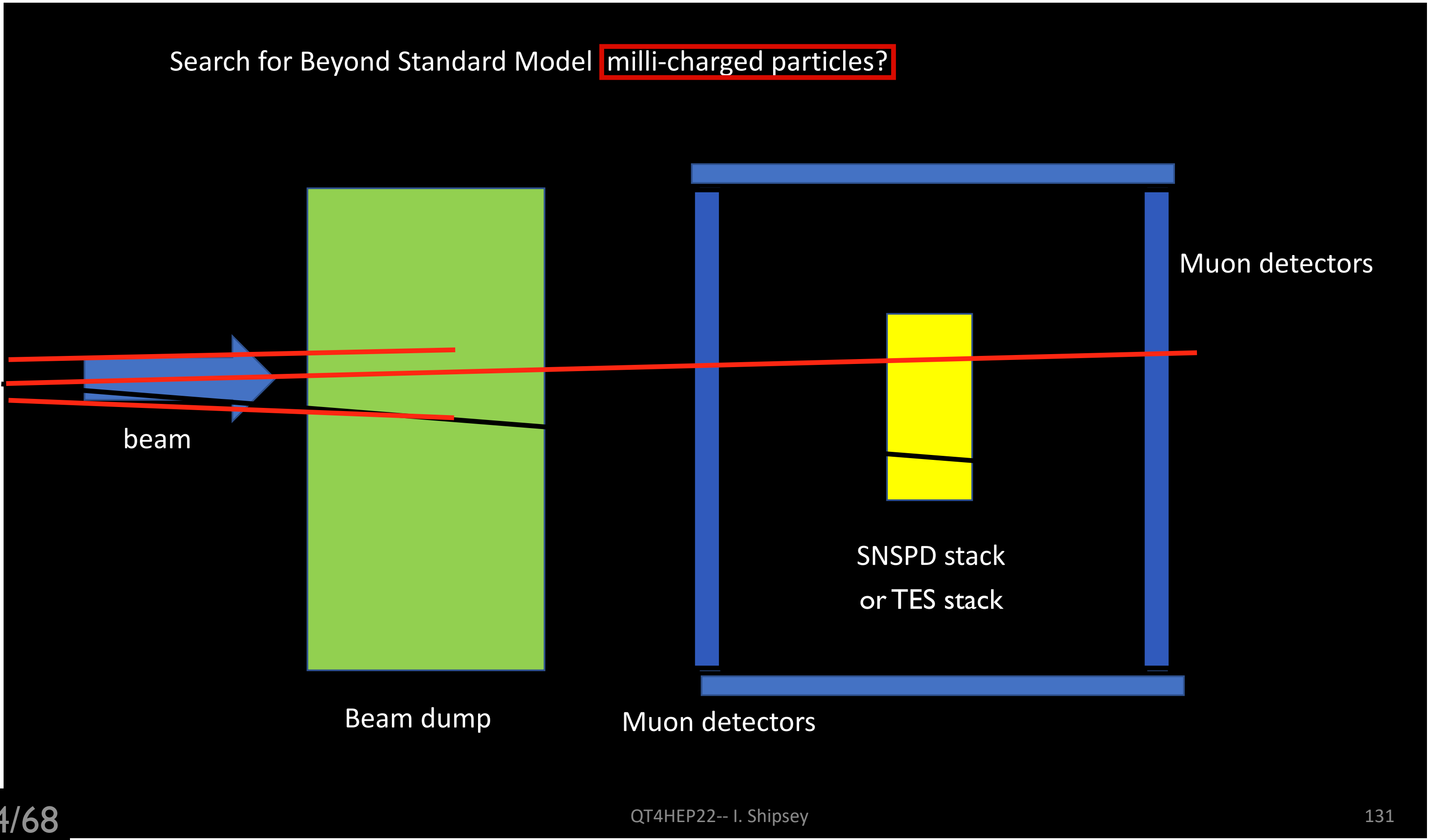
Superconducting Nanowire Single-Photon Detectors

Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
Matt Shaw, mattshaw@jpl.nasa.gov

Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

QT4HEP22-- I. Shipsey

125



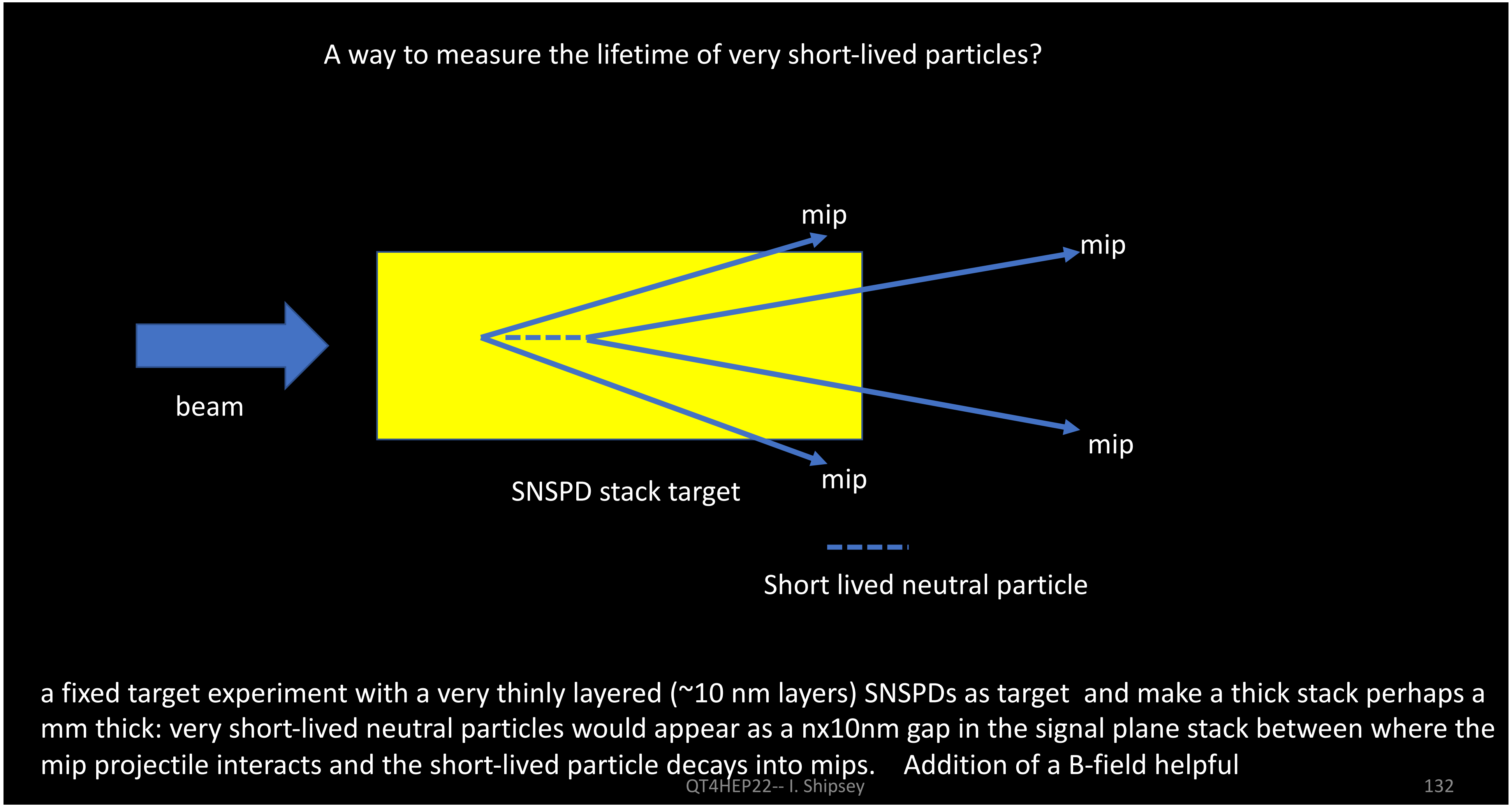
Search for Beyond Standard Model milli-charged particles?

QT4HEP22-- I. Shipsey

131

mip: ~20 keV/100 μm

Extremely low energy threshold detectors: SNSPD



A way to measure the lifetime of very short-lived particles?

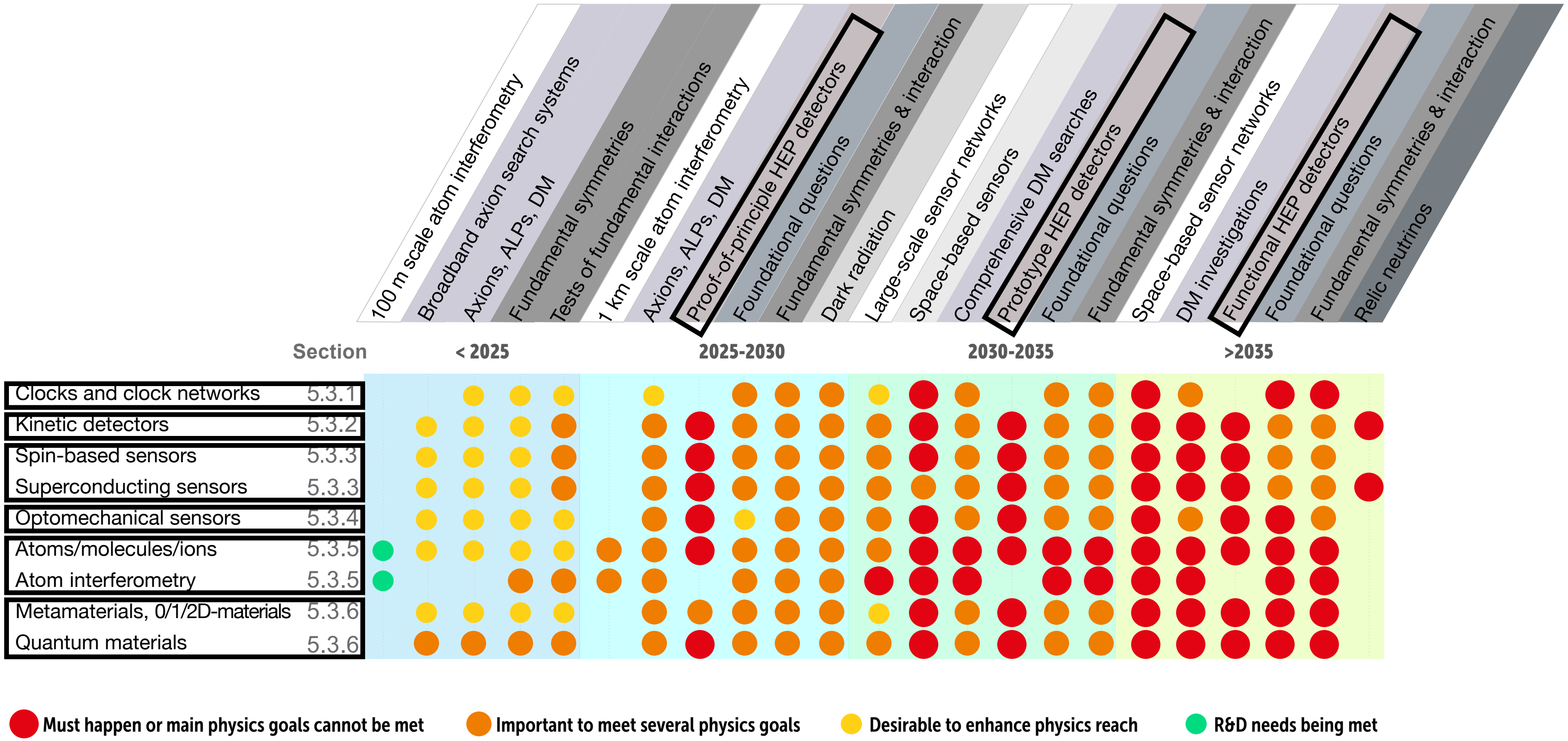
a fixed target experiment with a very thinly layered (~10 nm layers) SNSPDs as target and make a thick stack perhaps a mm thick: very short-lived neutral particles would appear as a nx10nm gap in the signal plane stack between where the mip projectile interacts and the short-lived particle decays into mips. Addition of a B-field helpful

QT4HEP22-- I. Shipsey 132

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

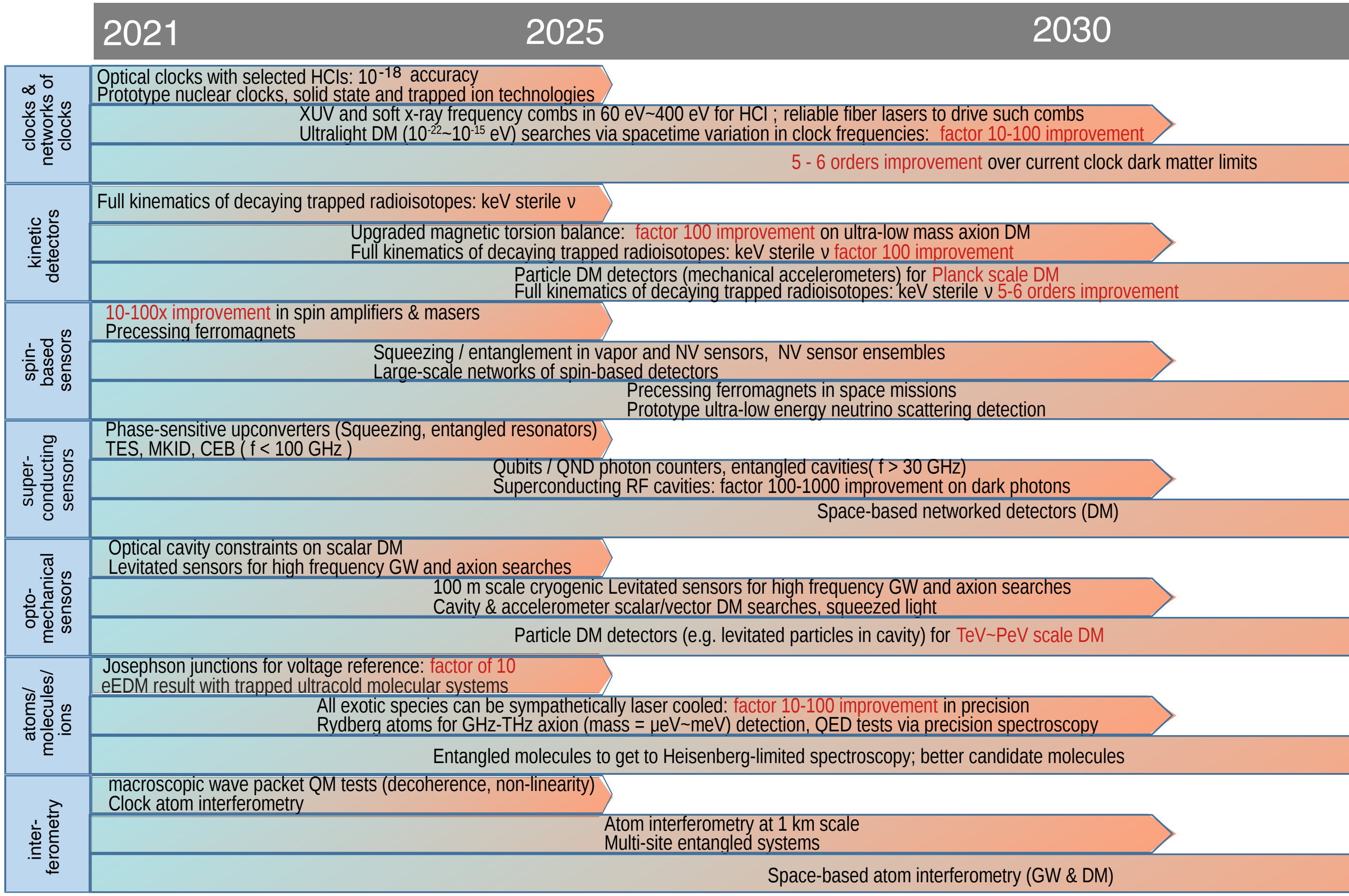
It is recommended that several "blue-sky" R&D activities be pursued. The development of solid state photon detectors from novel materials is an important future line of research, as is the development of cryogenic superconducting photosensors for accelerator- based experiments. Regarding advances in 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.

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



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!

thank you!

quantum sensors (an electromagnetic perspective)

	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, ϒray and Xray
SIS mixers		🟢			
HEB			🟢		
CEB		🟢			
TES	🔴	🟢	🟢	🟢	🟢
KID	🔴	🟢	🟢	🟢	
SNSPD			🔴	🟢	
SQUID	🟢				
JJPA	🟢				
TWPA	🟢	🔴			

Stafford Withington (Cambridge)

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

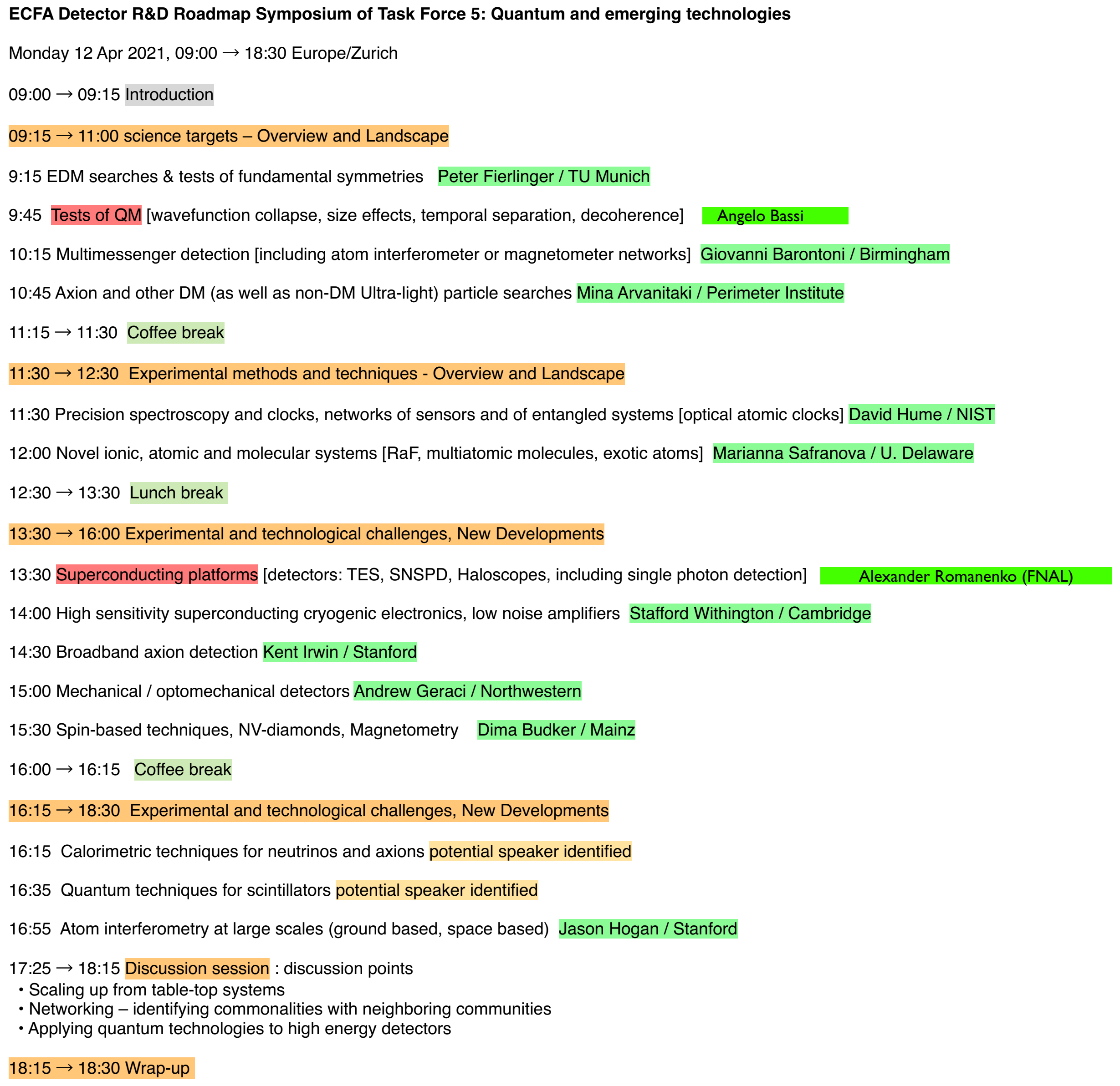
Symposium: April 12, 2022 https://indico.cern.ch/event/999818/

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] Angelo Bassi

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] Alexander Romanenko (FNAL)

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

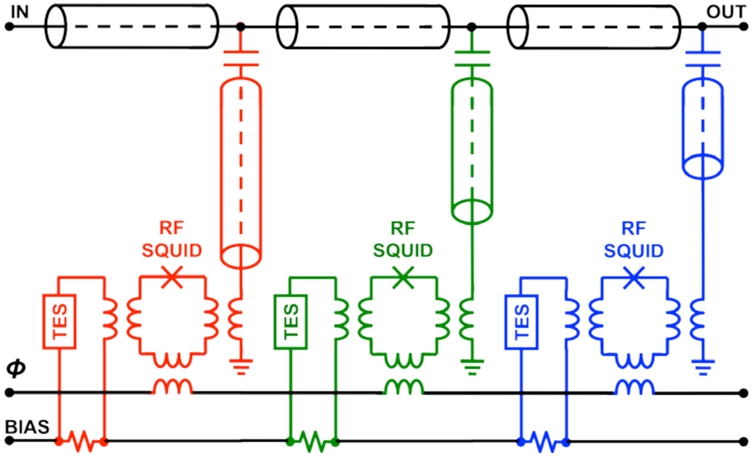
16:55 Atom interferometry at large scales (ground based, space based) Jason Hogan / Stanford

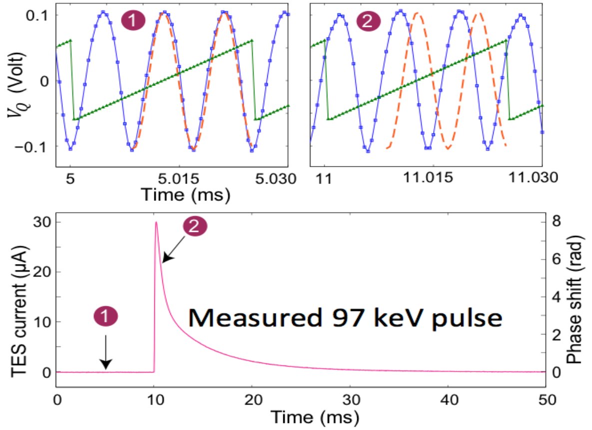
17:25 → 18:15 Discussion session : discussion points
- Scaling up from table-top systems
- Networking – identifying commonalities with neighboring communities
- Applying quantum technologies to high energy detectors

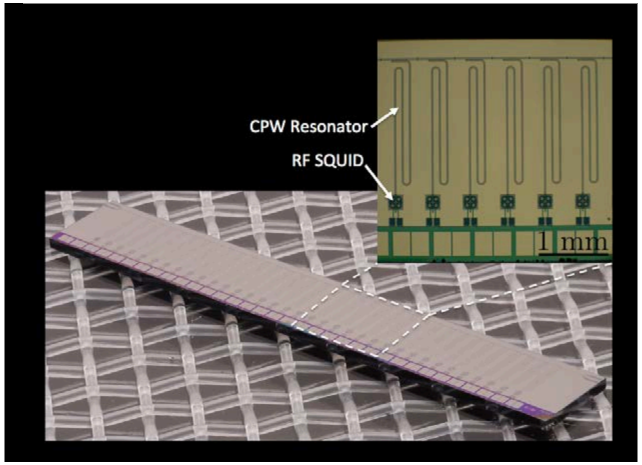
18:15 → 18:30 Wrap-up

Scalable readout is the key for very large arrays

Four innovations: μCal, Microwave Multiplexing, RF-SQUIDs, Software Radio



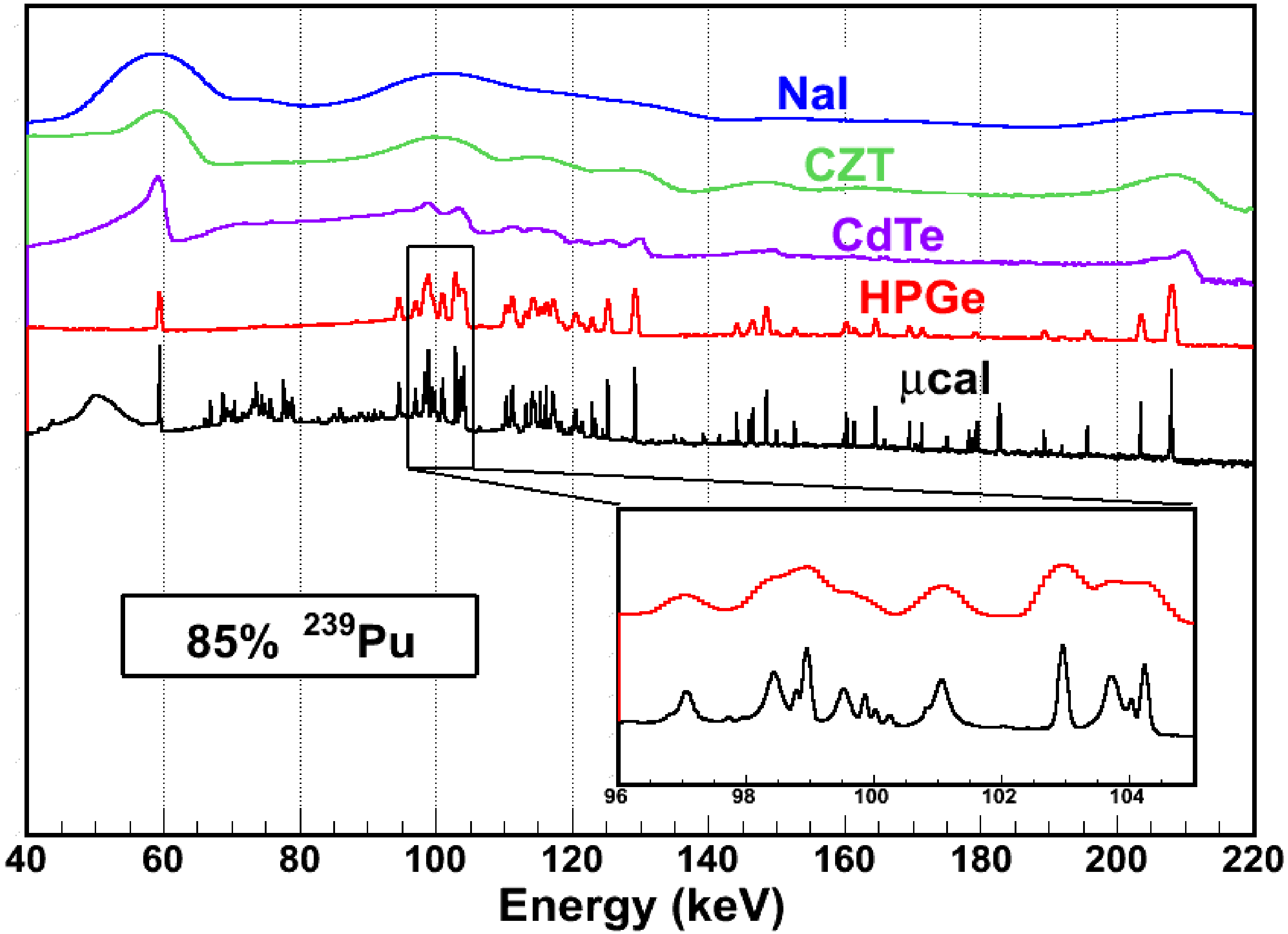


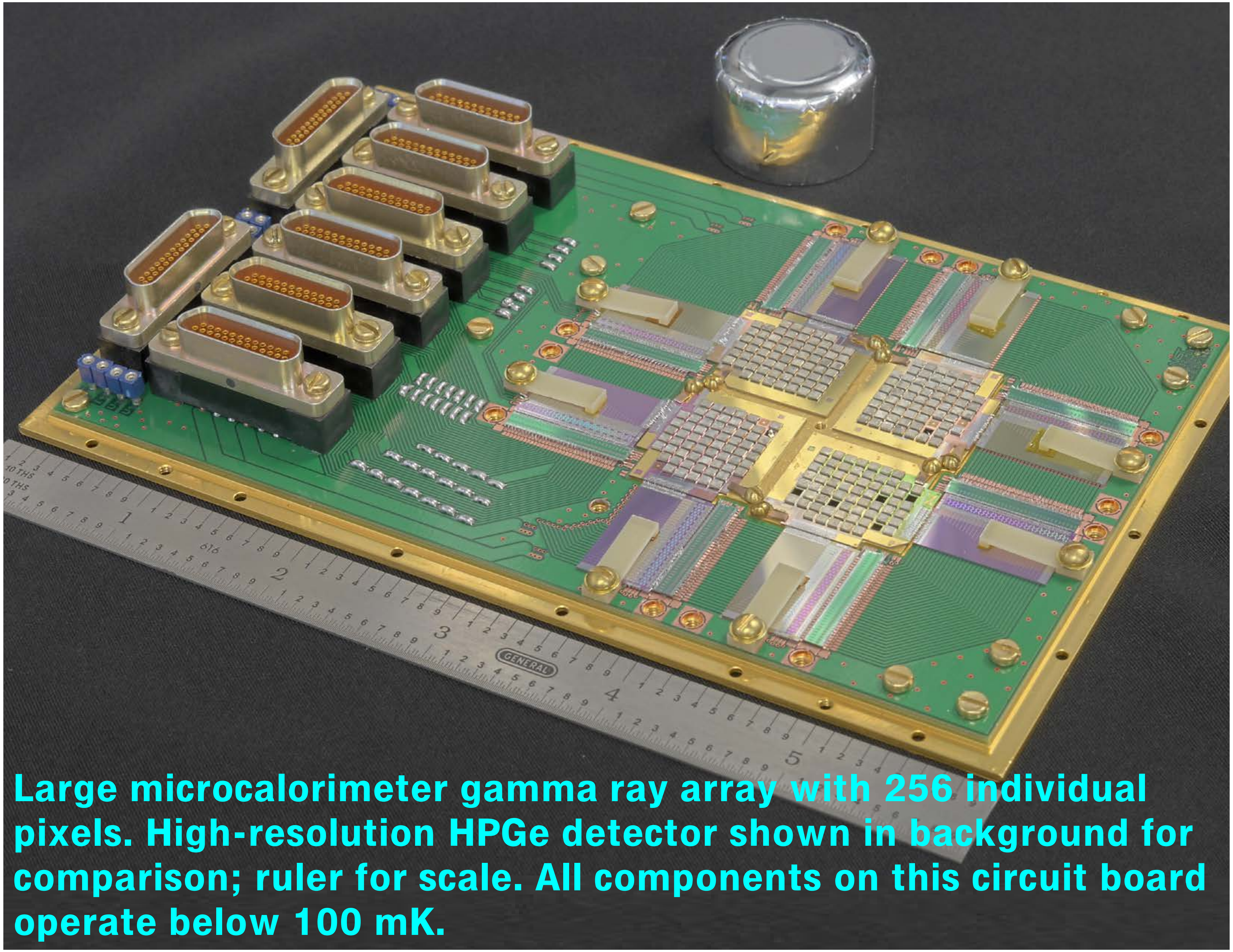


- UCSB: 1,000 low-resolution sensors and softwaredefined radio (SDR) readout
- CU: 2 high-resolution sensors + RFSQUIDS without SDR
- CU + LANL: Demonstrated negligible readout noise from RF-SQUID
- *No one has combined all together at scale*

https://www.osti.gov/servlets/purl/1506422

What is your technical approach? Describe background and your techniques.





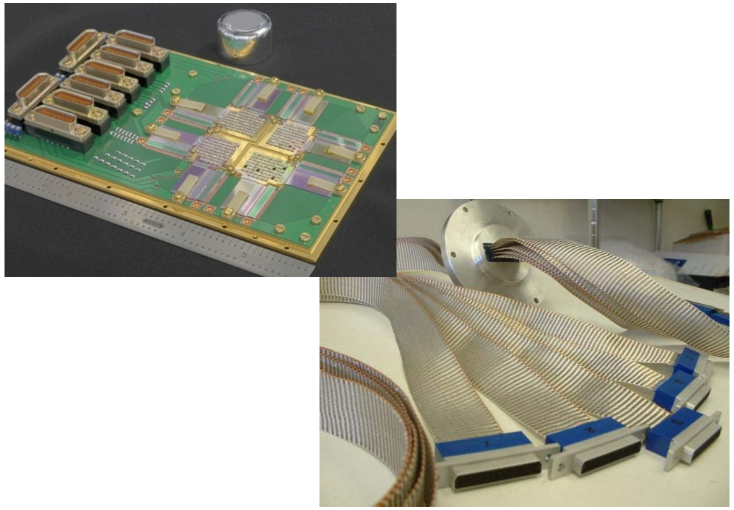
Large microcalorimeter gamma ray array with 256 individual pixels. High-resolution HPGe detector shown in background for comparison; ruler for scale. All components on this circuit board operate below 100 mK.

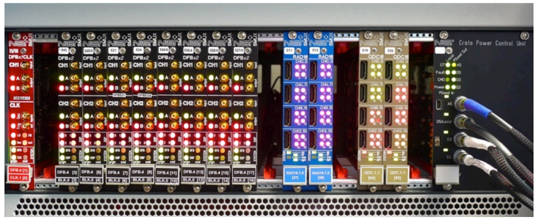
What have we learned so far? Results to date

Microwave readout reduces complexity and cost

Present Techniques

- 500 wires per 1,000 sensors
- Elaborate wiring harnesses and connectors
- Unique control electronics





Microwave Techniques

- 1,000 resonators on two coaxial cables!
- Existing commercial electronics
- Functionality shared with telecommunications industry
- Benefit from steady improvement in FPGAs, ADCs, and DACs