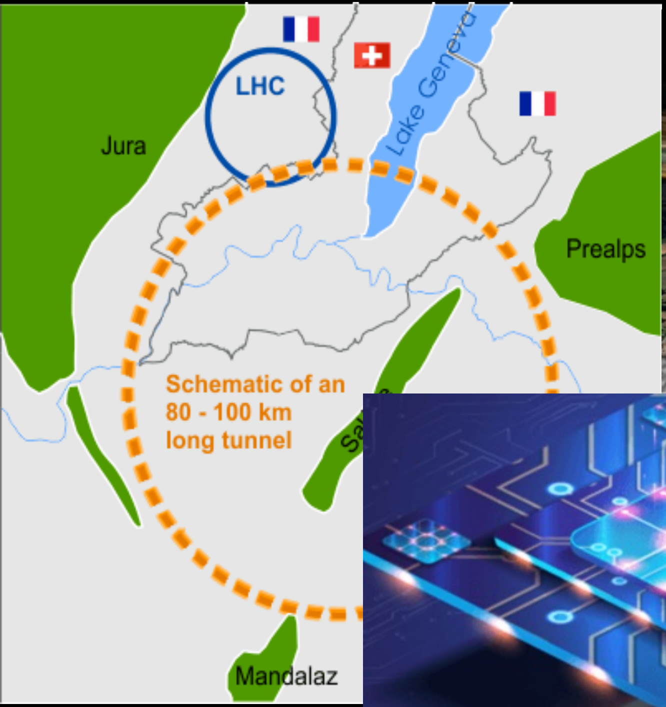
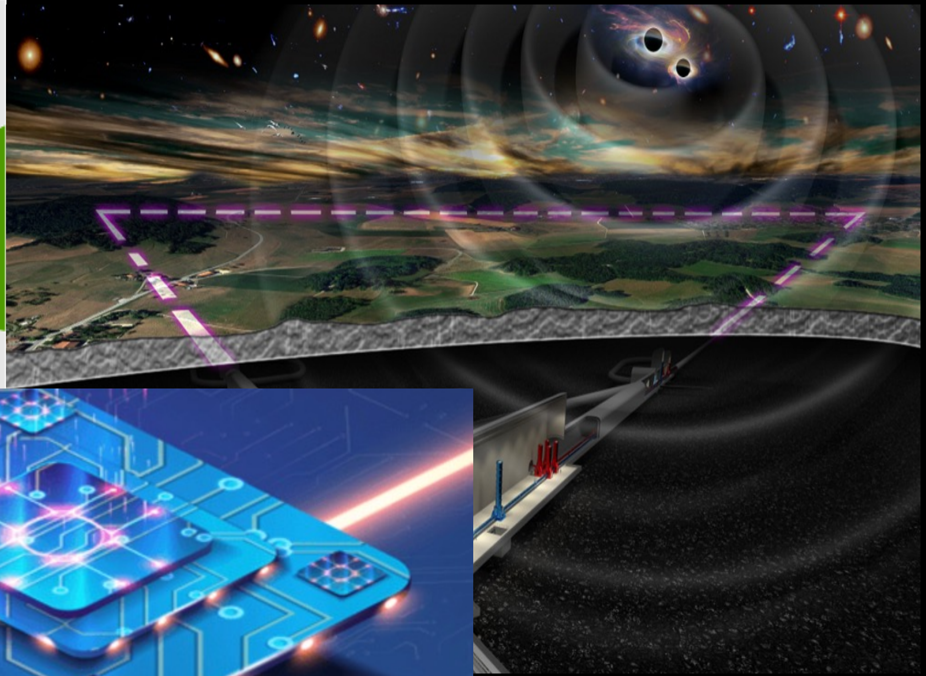
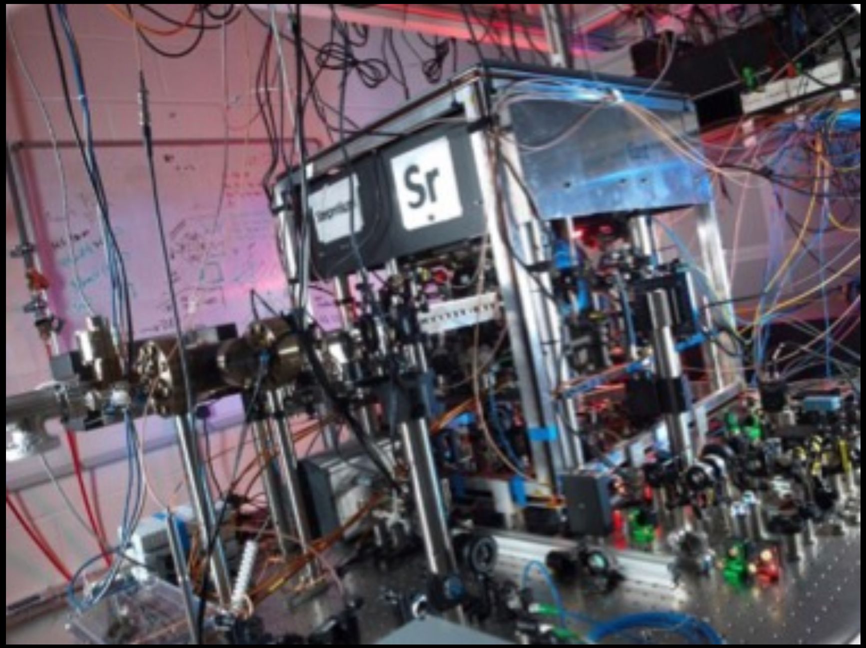
Quantum Sensors for High Energy Particle Physics







UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

International Conference on Quantum Technologies for High-Energy Physics (QT4HEP22)

Ian Shipsey,
Oxford University

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

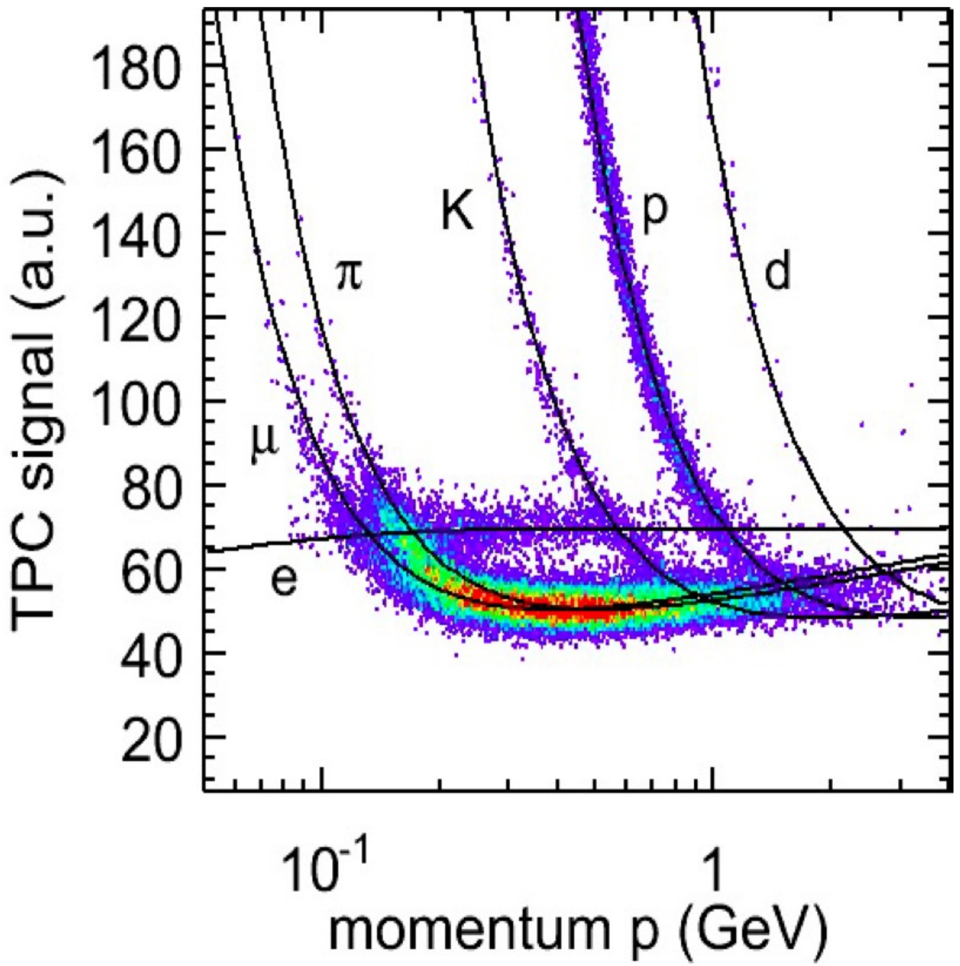
- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

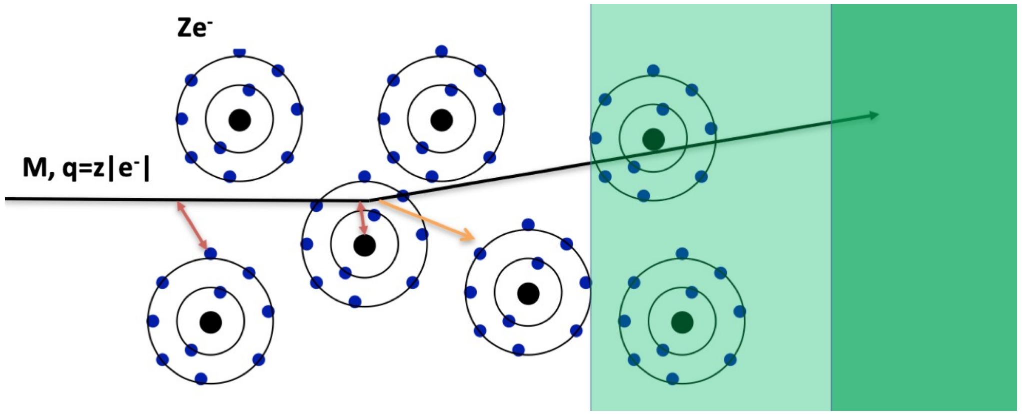
Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

10e-18 eV to meV

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

not obvious


TPC signal (a.u.)
180
160
140
120
100
80
60
40
20
e
μ
π
K
p
d
10^{-1}
1
momentum p (GeV)


Ze⁻
M, q=z|e⁻|

Quantum sensors for high energy particle physics

Reference work

frontiers | Frontiers in Physics

ORIGINAL RESEARCH
published: 24 June 2022
doi: 10.3389/fphy.2022.887738

Check for updates

Quantum Systems for Enhanced High Energy Particle Physics Detectors

M. Doser[1]*, E. Auffray[1], F.M. Brunbauer[1], I. Frank[1,2], H. Hillemanns[1], G. Orlandini[1,3] and G. Kornakov[4]

[1]CERN, Geneva, Switzerland, [2]Faculty of Physics, Ludwig Maximilian University of Munich, Munich, Germany, [3]Dept. of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany, [4]Faculty of Physics, Warsaw University of Technology, Warsaw, Poland

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

main focus on tracking / calorimetry / timing closely related: nanostructured materials Frontiers of Physics, M. Doser et al., 2022

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

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

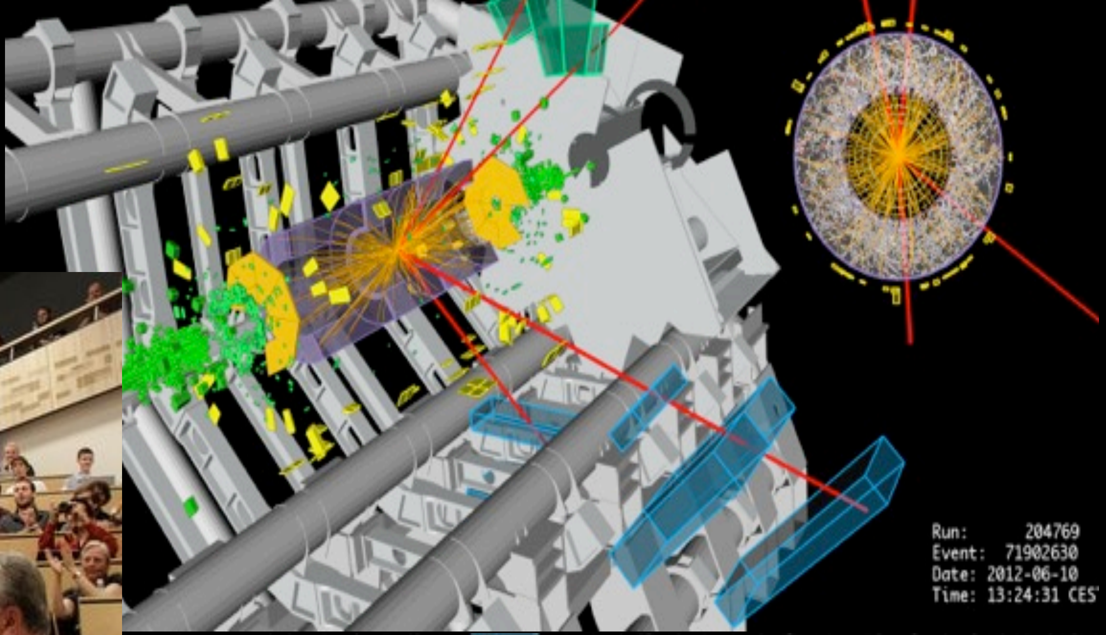
5.3.3 *

helicity detectors

ECFA Detector R&D Roadmap

2012.7.4

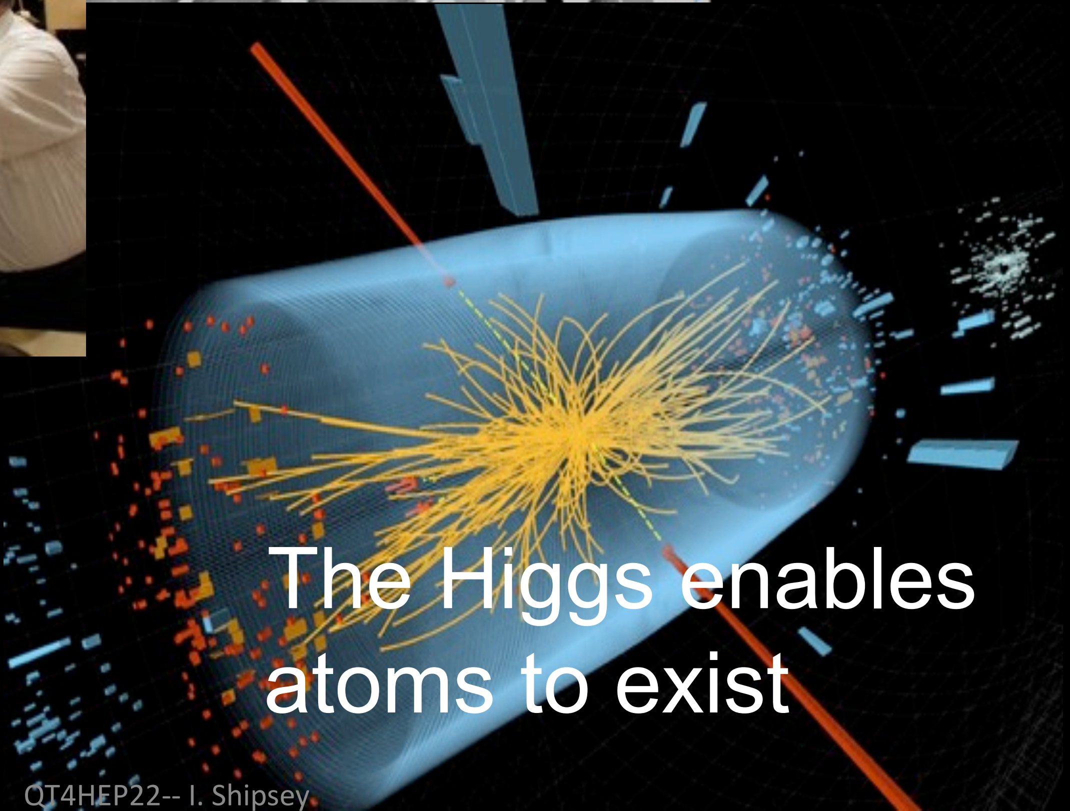
discovery of Higgs boson



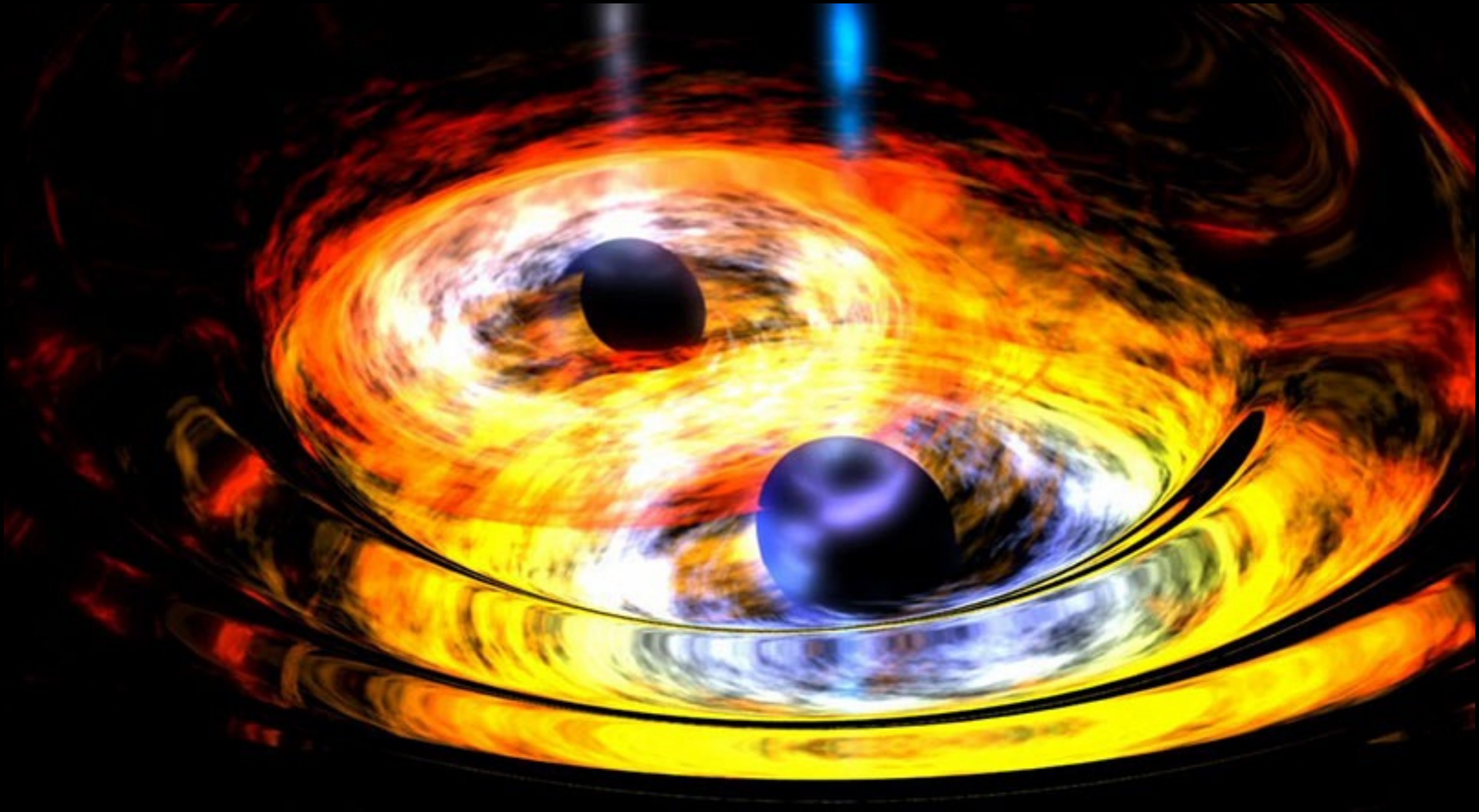
theory：1964

design：1984

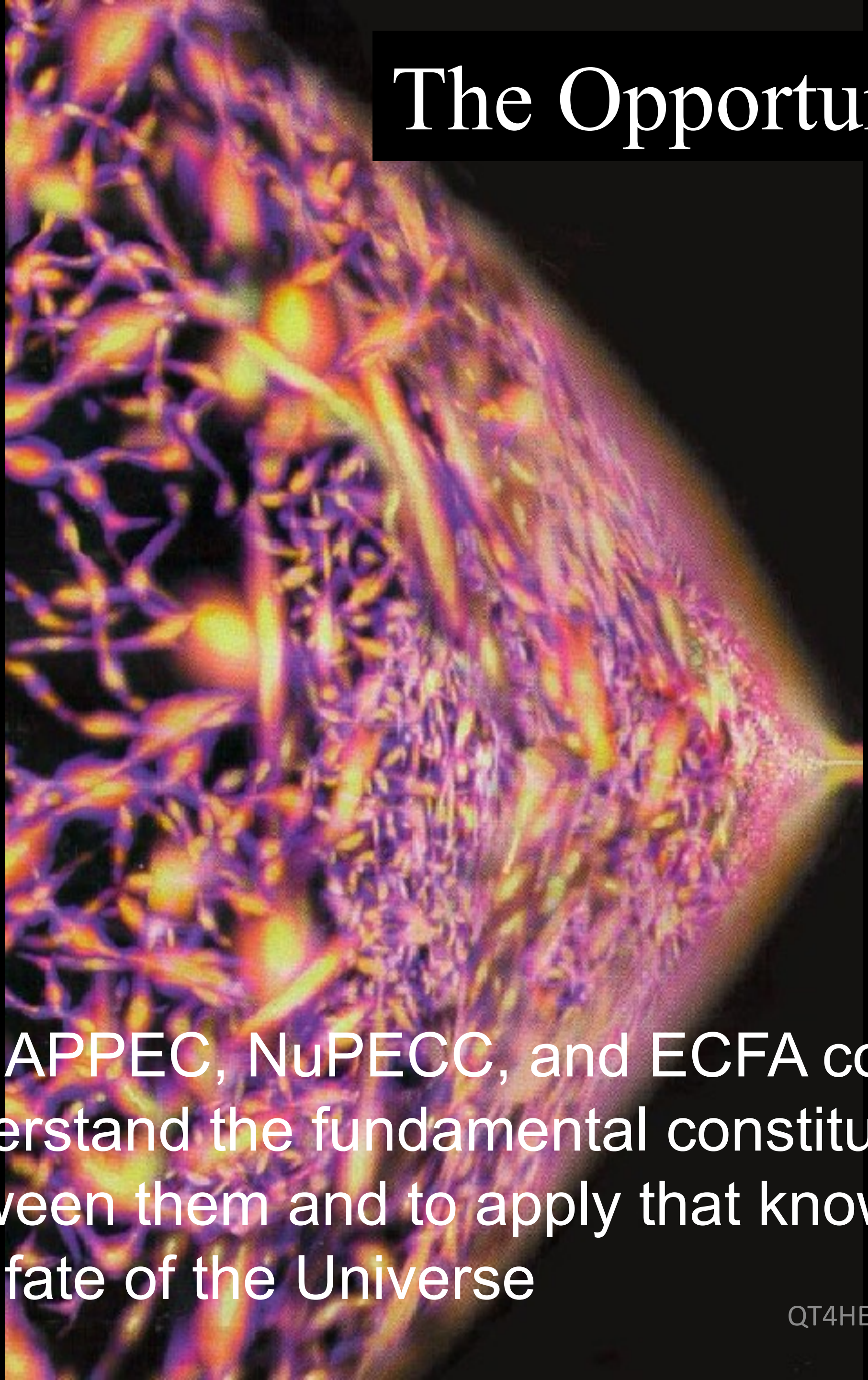
construction：1998



Detection of gravitational waves
LIGO February, 2016

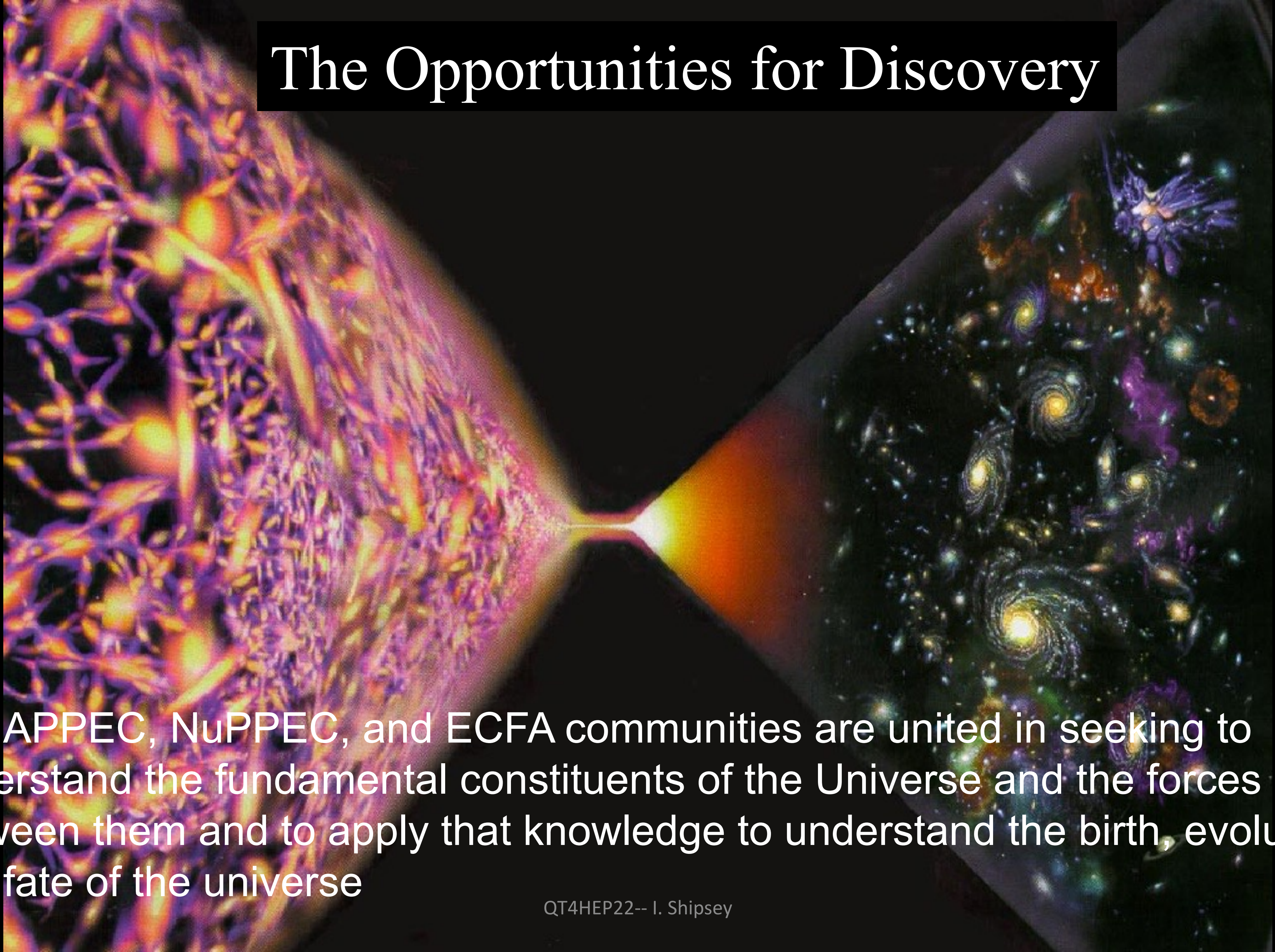


The Opportunities for Discovery



The APPEC, NuPECC, and ECFA communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

The Opportunities for Discovery



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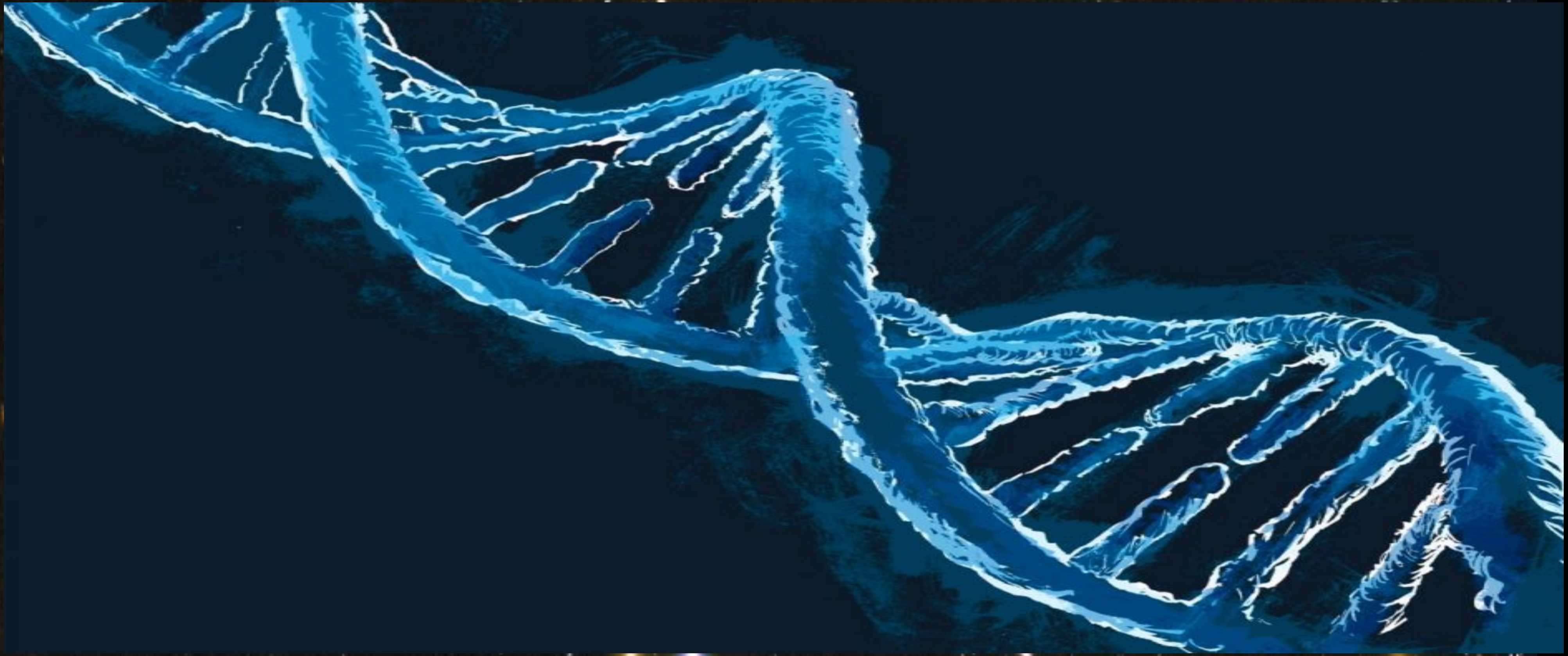
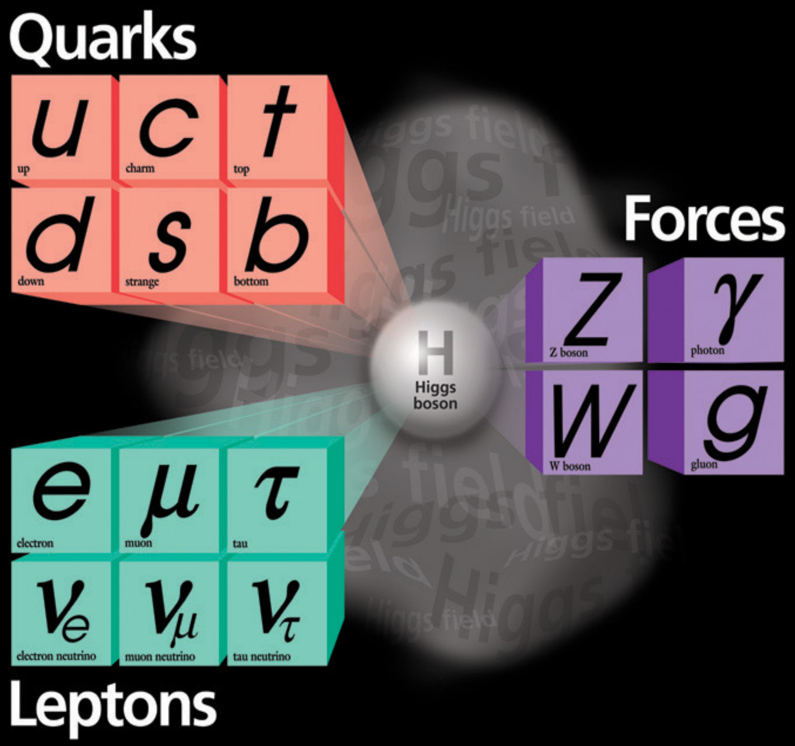
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our communities have revolutionized human understanding of the Universe – its underlying code, structure and evolution

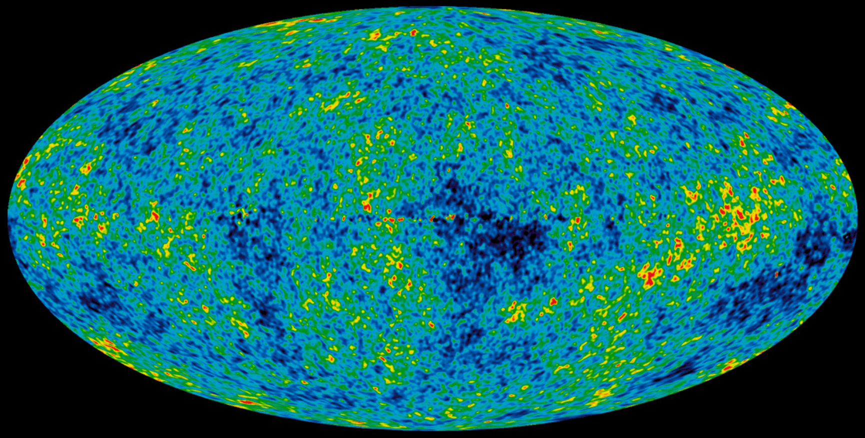


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



Cosmology Standard Model



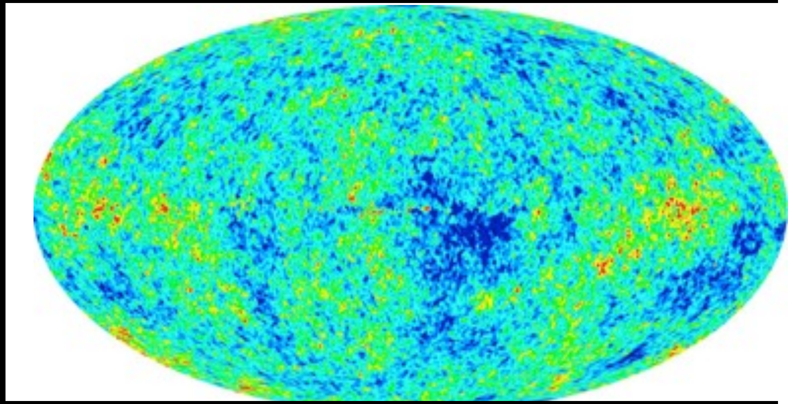
Λ_{CDM}

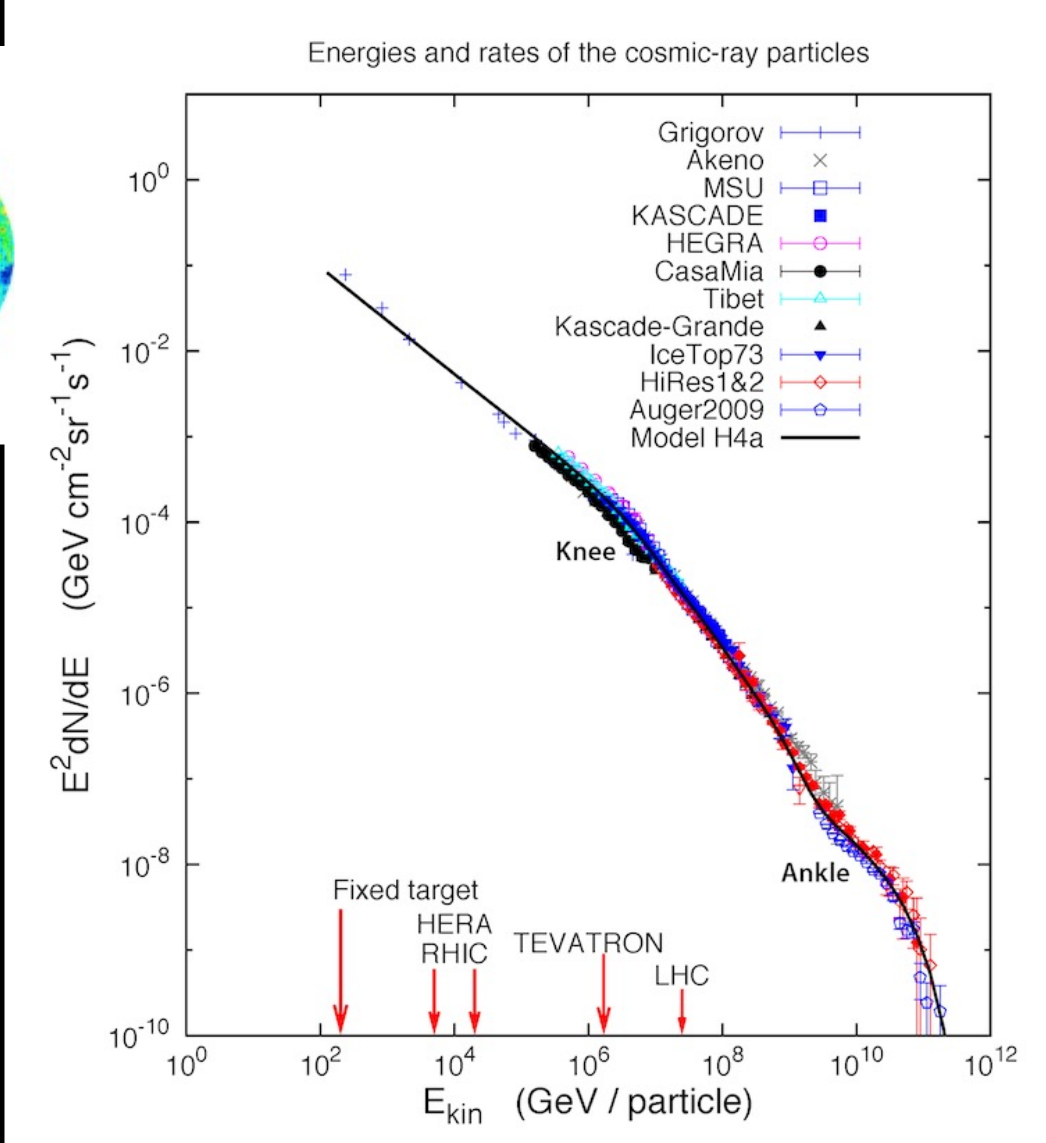
……enabled by instrumentation

APPEC
ECFA
NuPECC

Our APPEC/ECFA/NuPECC scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

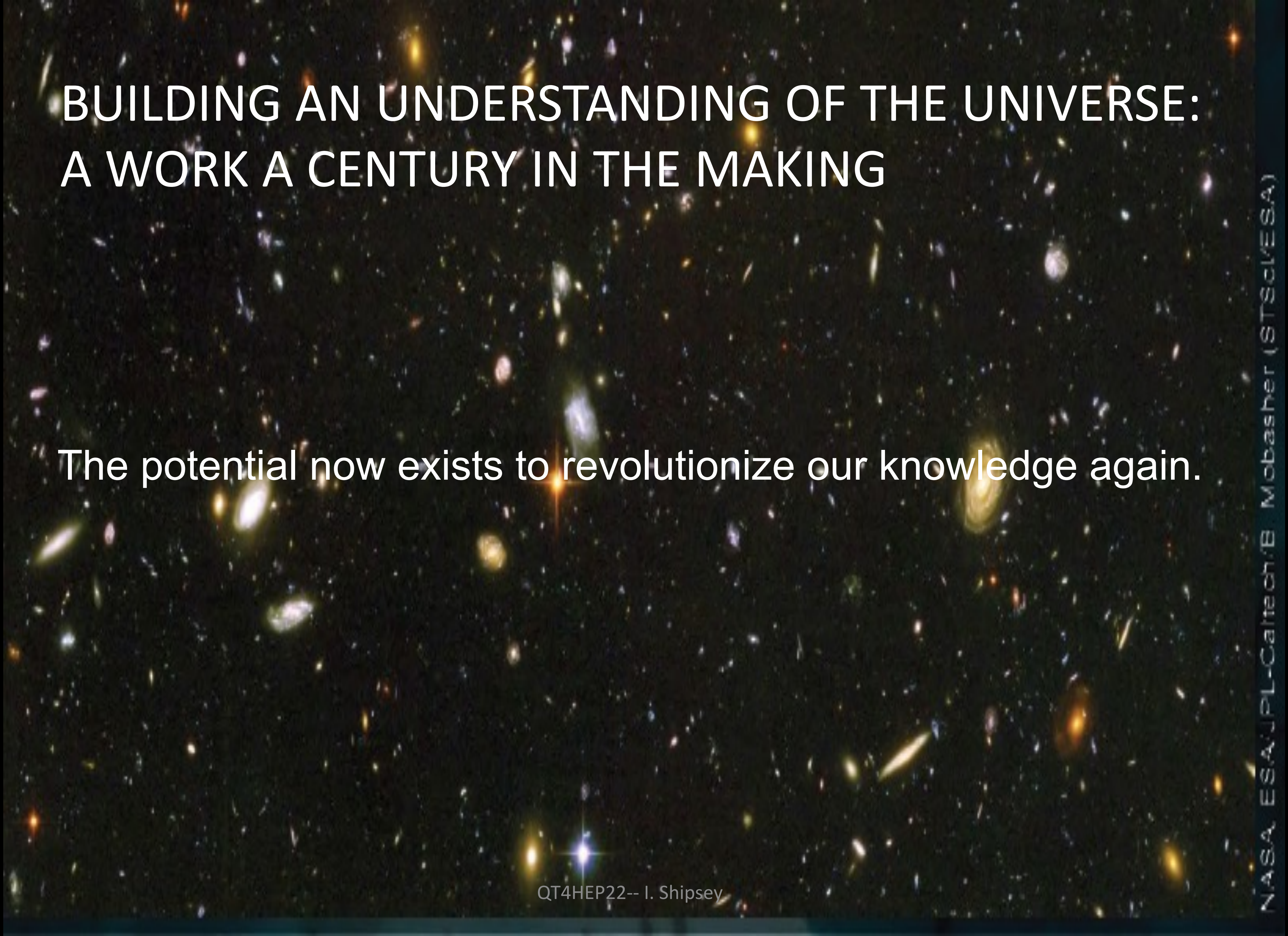
Detect & Measure over 24 orders of magnitude





A Rich Spectrum of Technologies Developed by our Community

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING



The potential now exists to revolutionize our knowledge again.

Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

They mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

The mystery of the Families of Particles

The mystery of Inflation

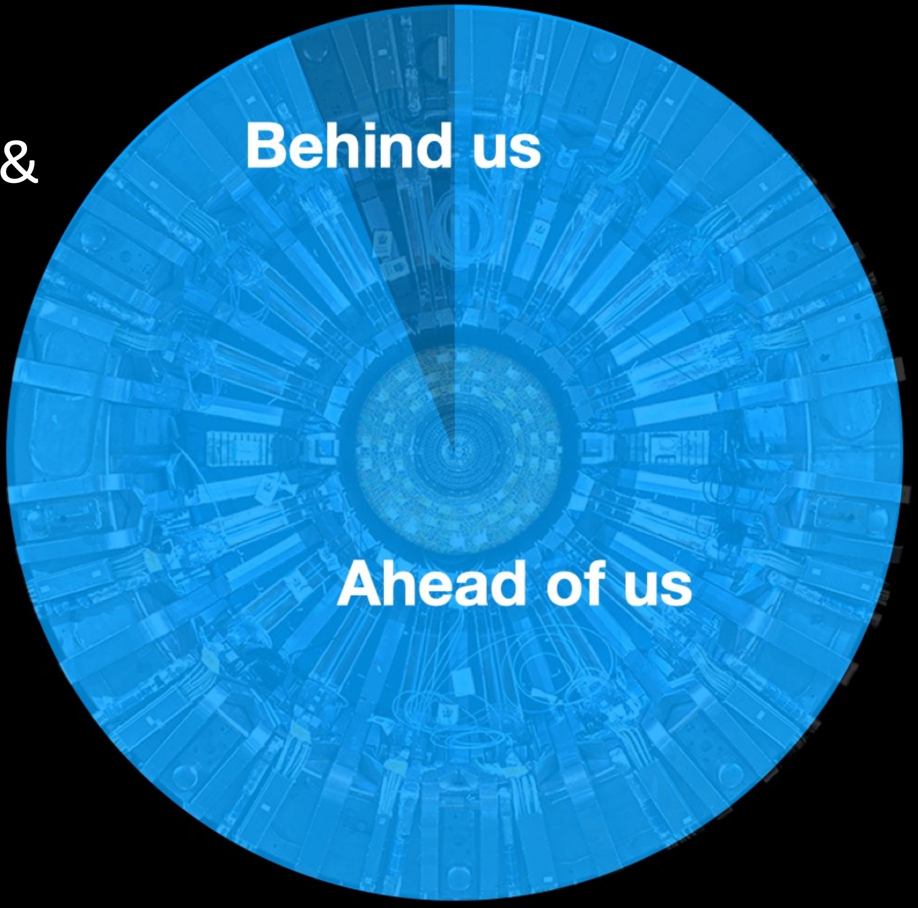
The mystery of Gravity

How do quarks and gluons give rise to the properties of nuclei
The mystery of the origin and engine of high energy cosmic particles

Multiple theoretical solutions – experiment must guide the way

We are very much in a data driven era for which we need new tools!

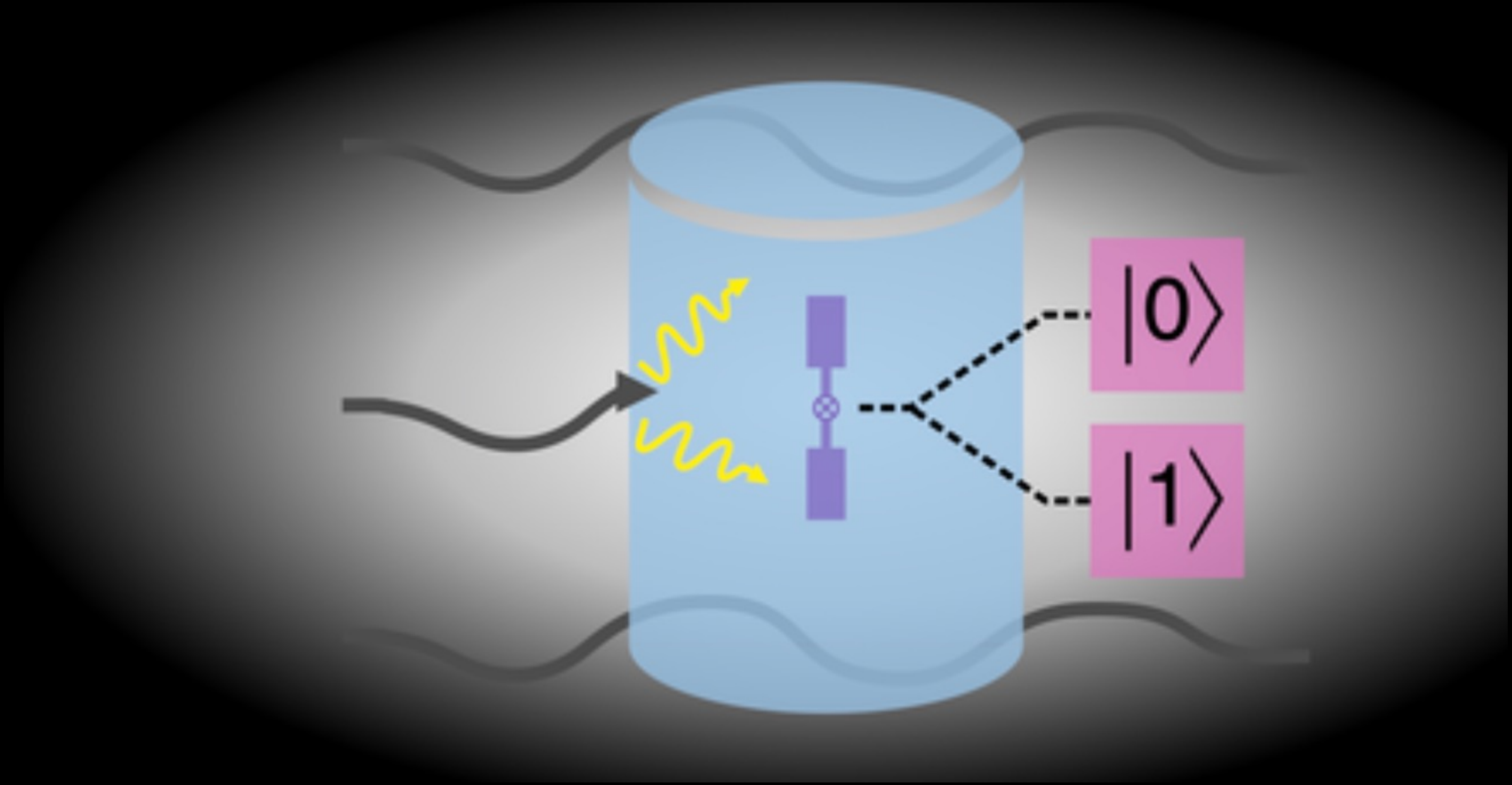
New tools:
e.g. the HL-LHC upgrades &
later FCC-ee/hh etc.



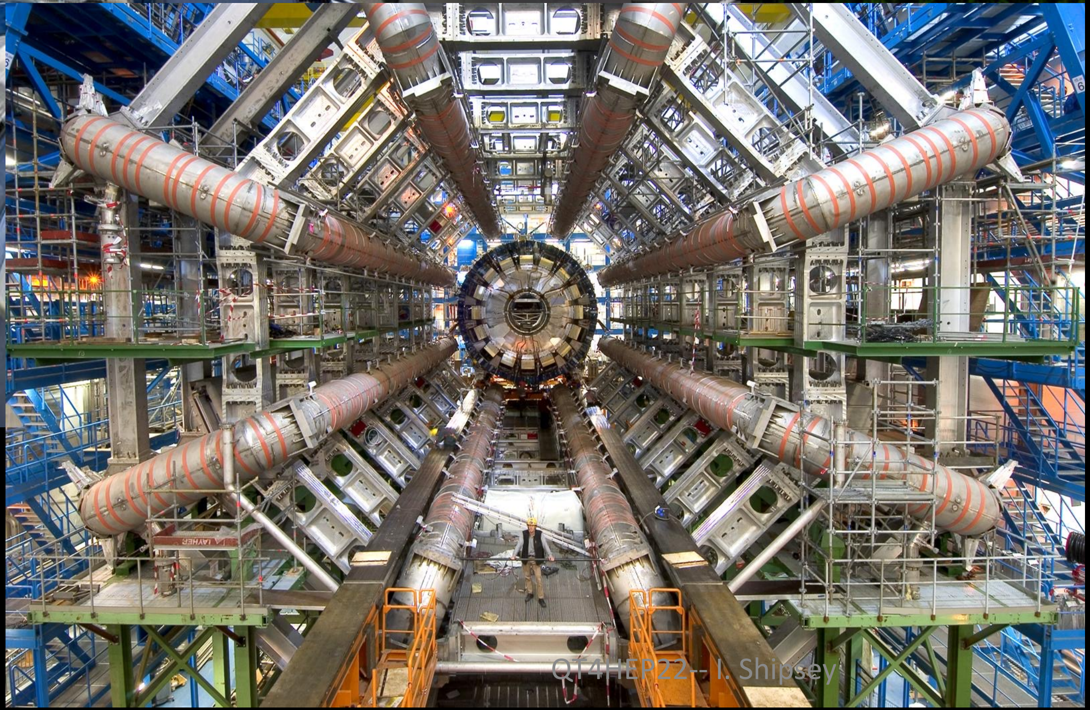
Only ~4% of the complete LHC/ HL-LHC data set has been delivered to date

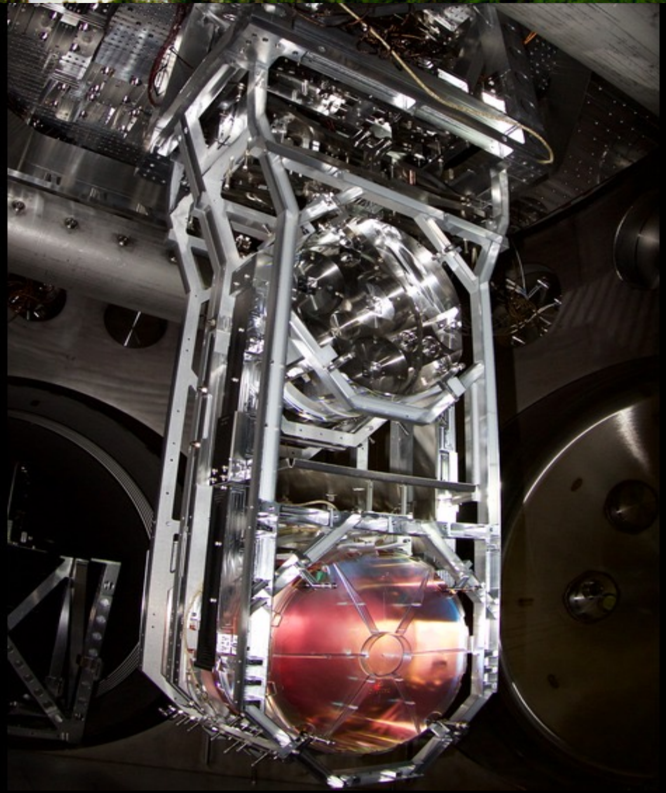
There is every reason to be optimistic that an important discovery could come at any time

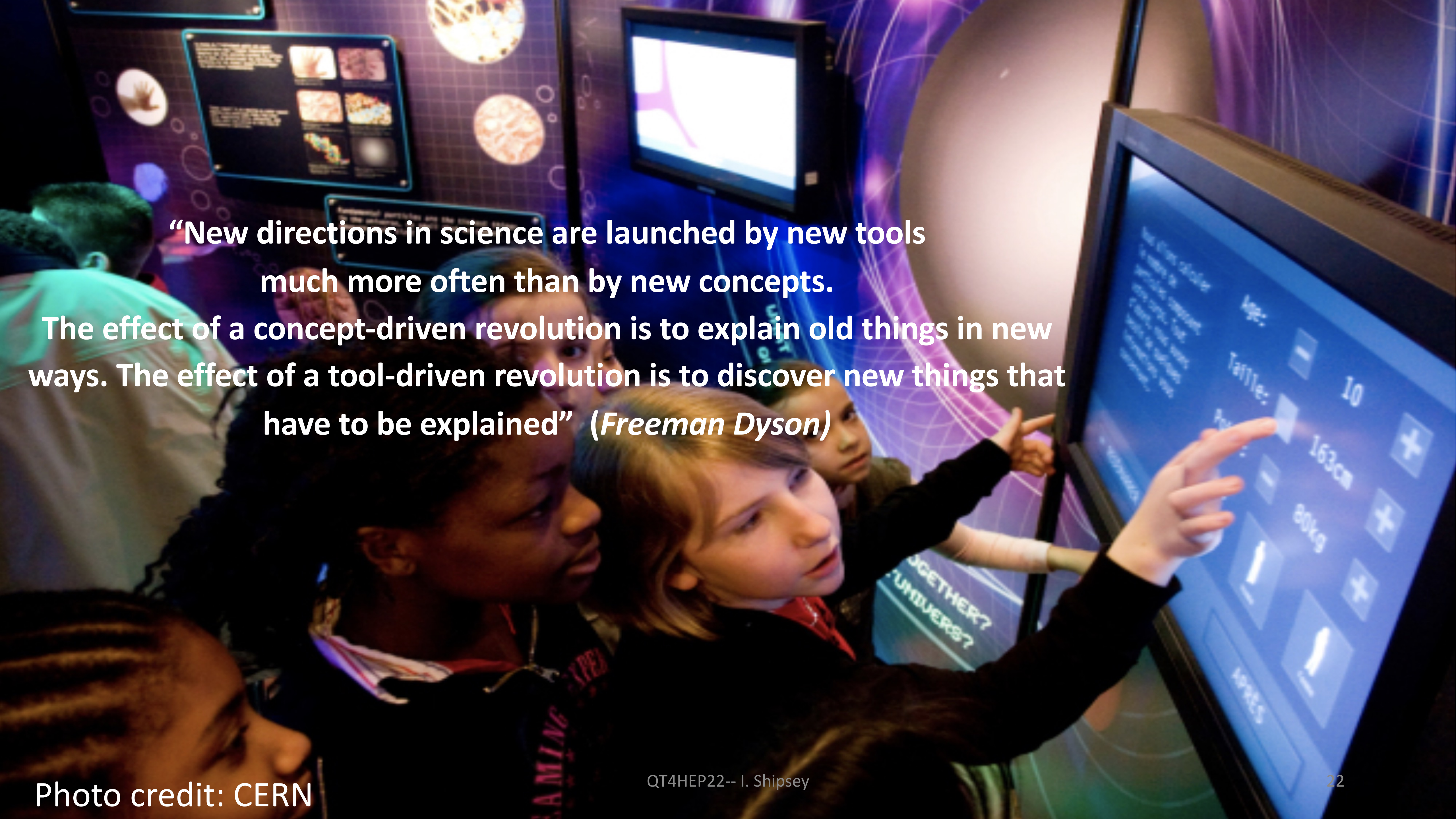
New tools e.g. Qubits as cameras



The gestation time to realize the tools and the experiments e.g. LHC & LIGO are decades long! For the most ambitious future experiments e.g FCCee/hh & Einstein Telescope to take the data and seize the opportunities for discovery, we must develop the tools (instrumentation and facilities) we need NOW.







“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained” (*Freeman Dyson)*

Photo credit: CERN

“Measure what is measurable, and make measurable what is not so” (*Galileo Galilei)*

Photo credit: CERN

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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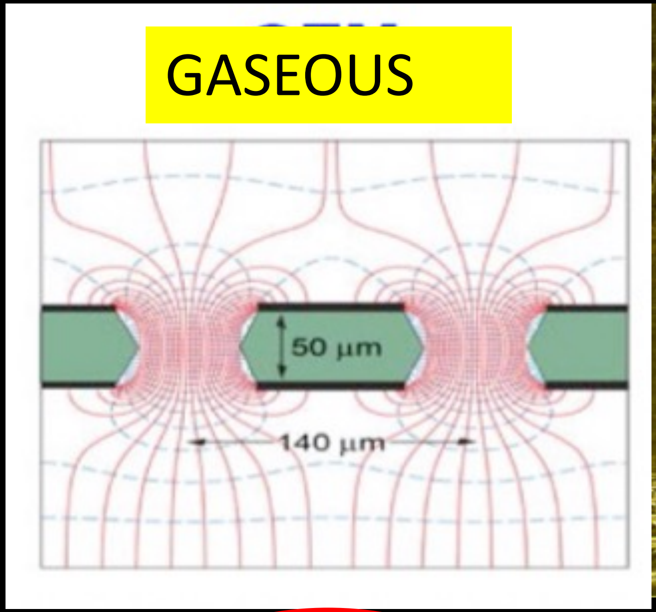
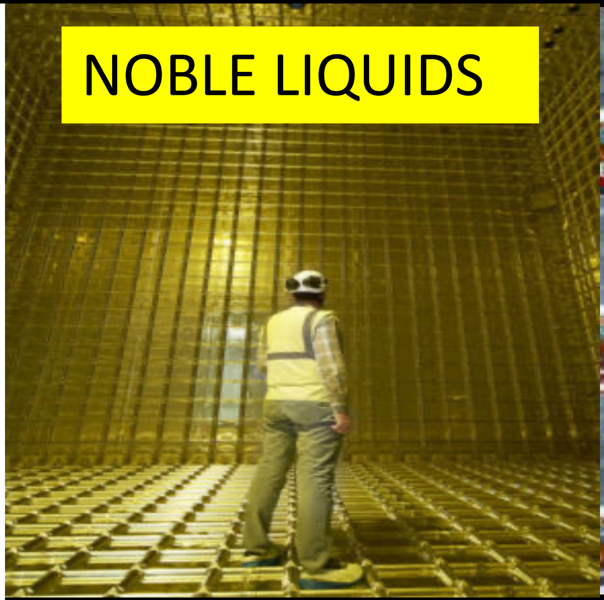
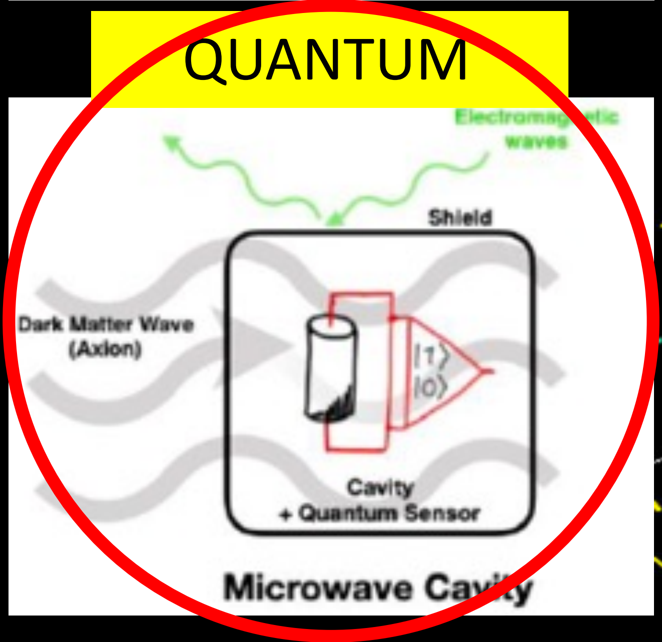
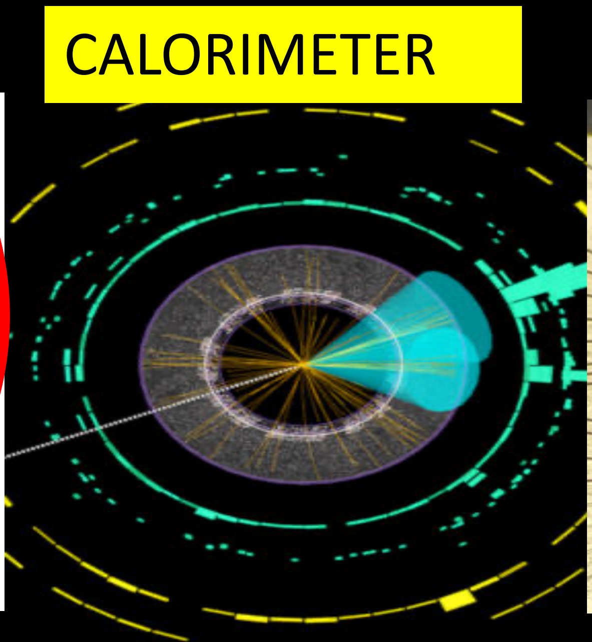
precision instruments are key to discovery when exploring new territory

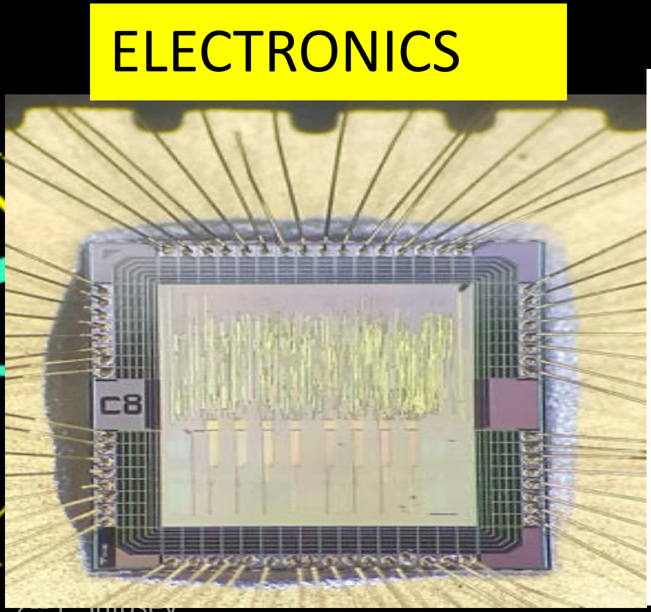
Technology Classification for the ECFA R&D Roadmap

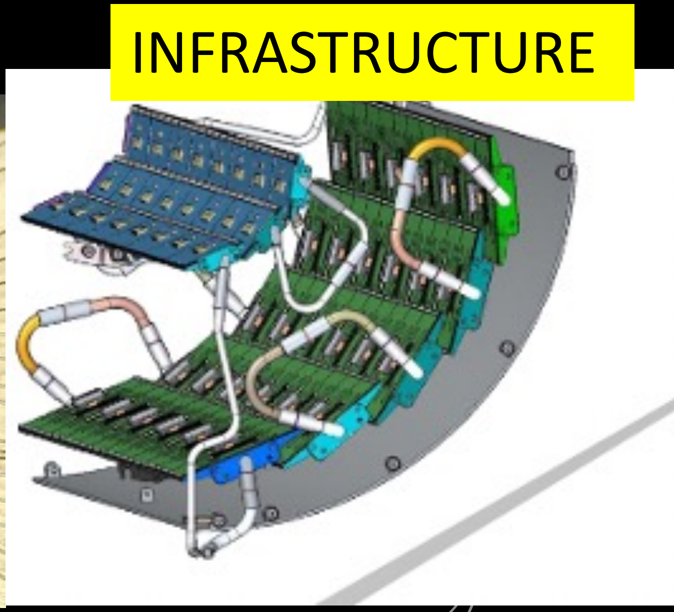












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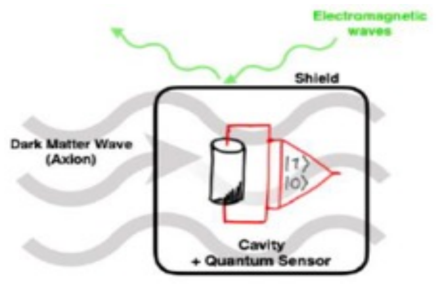
- change of resonant frequency of a system (quantized)

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;

Quantum and emerging technologies

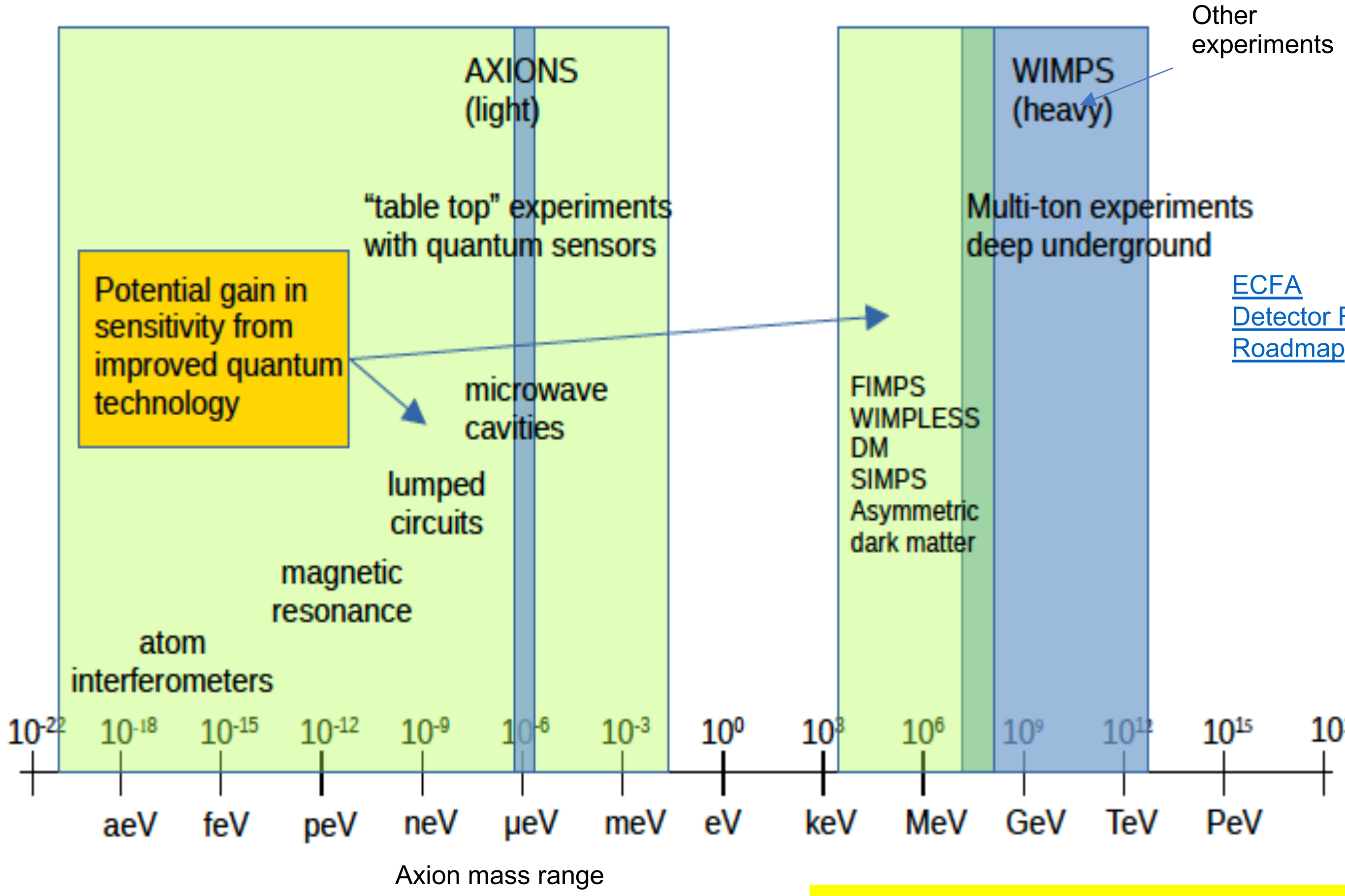
- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, …



Microwave Cavity

S. Golawa

Example: potential mass ranges that quantum sensing approaches open up for Axion searches

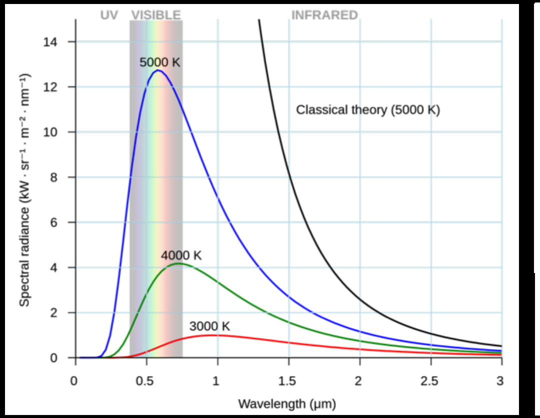


ECFA Detector R&D Roadmap

Blue: now
Light green: with quantum

While quantum sensors are not new they have increased in prominence and this is due both to technological advances & to greater appreciation in the world for quantum mechanics

Quantum 1.0



Blackbody Radiation

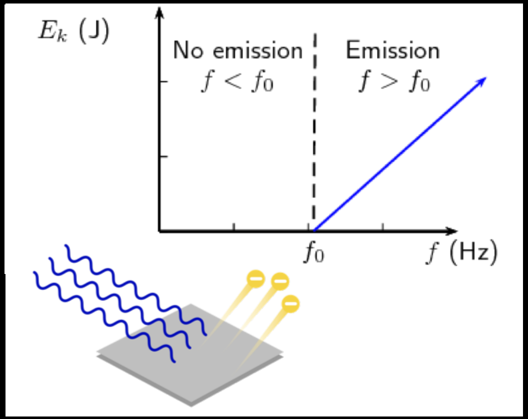
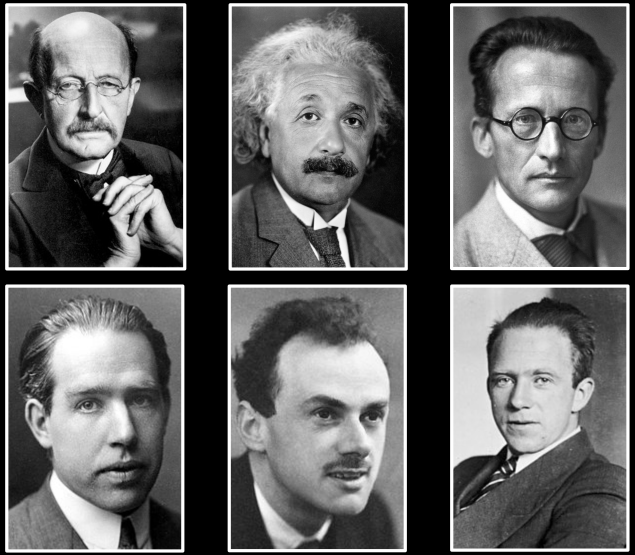
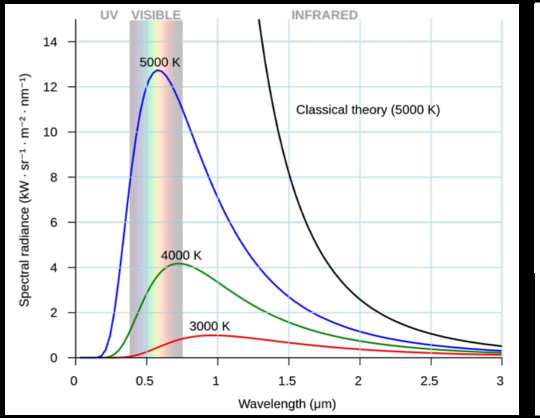


Photo-electric Effect

Quantum Mechanics



Quantum 1.0



Blackbody Radiation

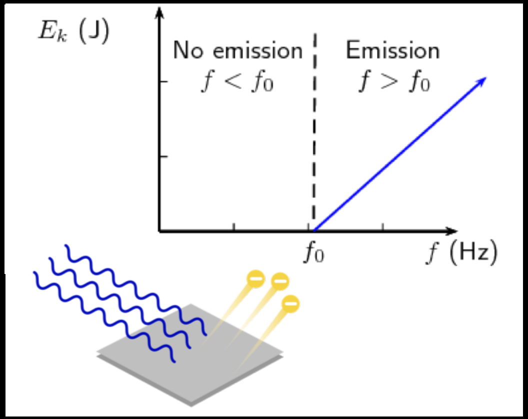
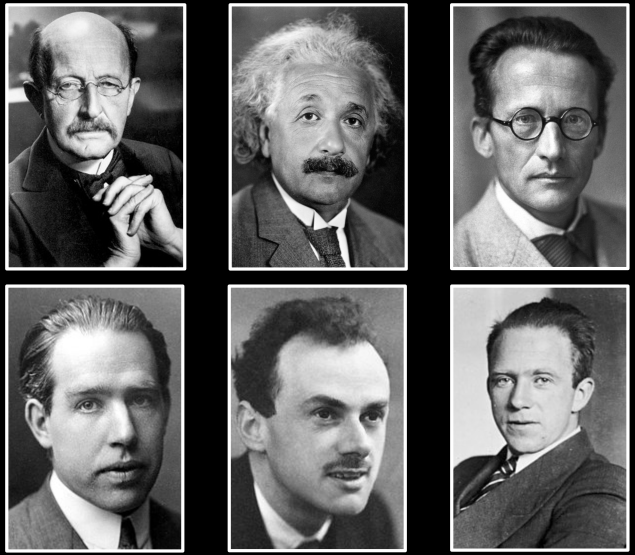


Photo-electric Effect

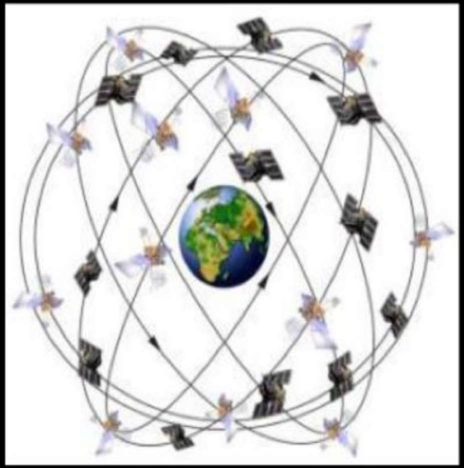
Quantum Mechanics



Exascale Computing

Laser Technology

Magnetic Resonance Imaging



Global Positioning System

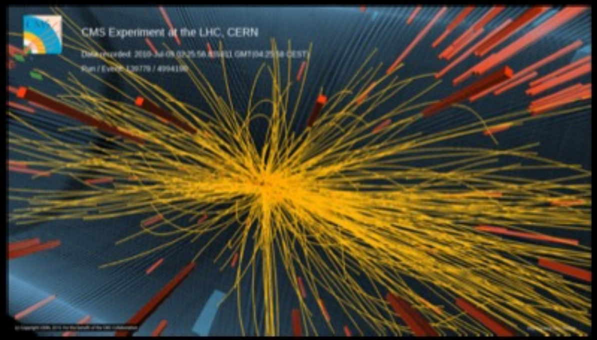
Quantum 1.0

09:41
100 %
mercredi
7
Mail
Calendrier
Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

Quantum 2.0

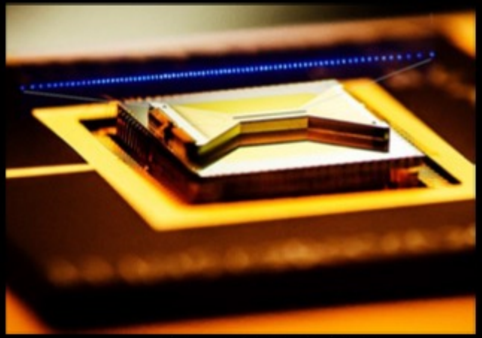
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



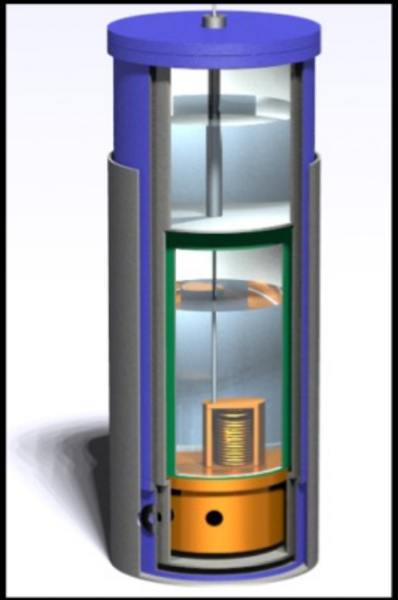
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

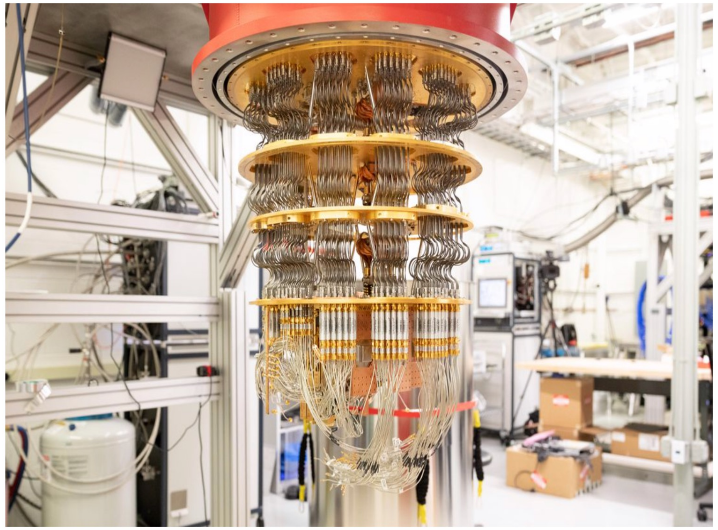
Quantum 2.0

The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

Google's quantum supremacy is only a first taste of a computing revolution

"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

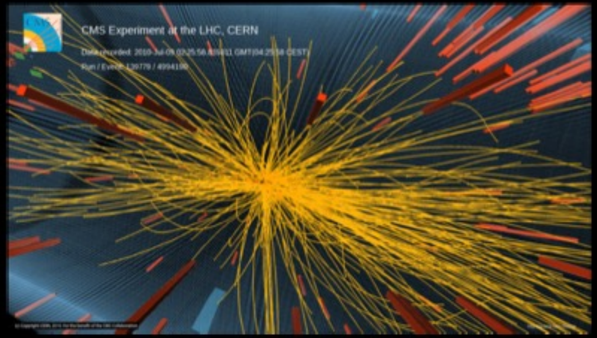
Stephen Shankland October 25, 2019 6:20 AM PDT



One of five Google quantum computers at a lab near Santa Barbara, California.

Stephen Shankland/CNET

AI, ML on Quantum annealer



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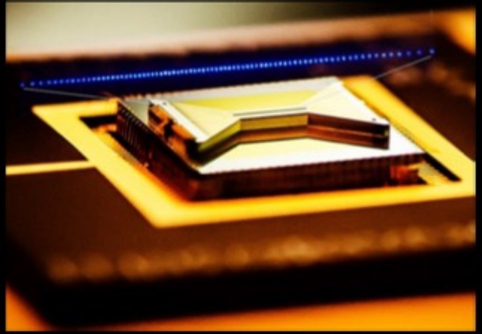

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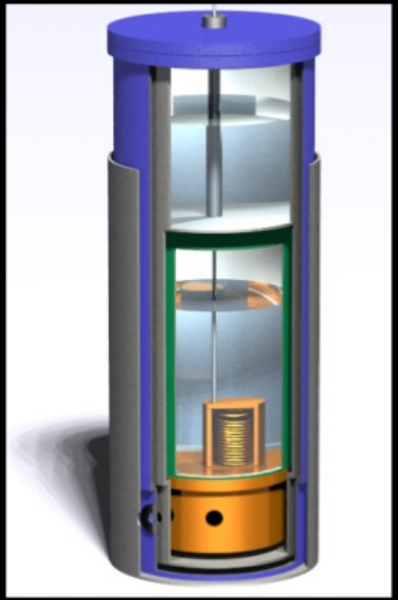

Nature (564) 87 (2018)

Quantum 2.0


09:41
100 %
mercredi
7
Mail
Calendrier
Photos
Appareil photo
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Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical," Feynmann (1981).

You can approximate nature with a simulation on a classical computer, but Feynman wanted a quantum computer that offers the real thing, a computer that "will do exactly the same as nature,"

What if?

Quantum Internet

Quantum Artificial Neural Network

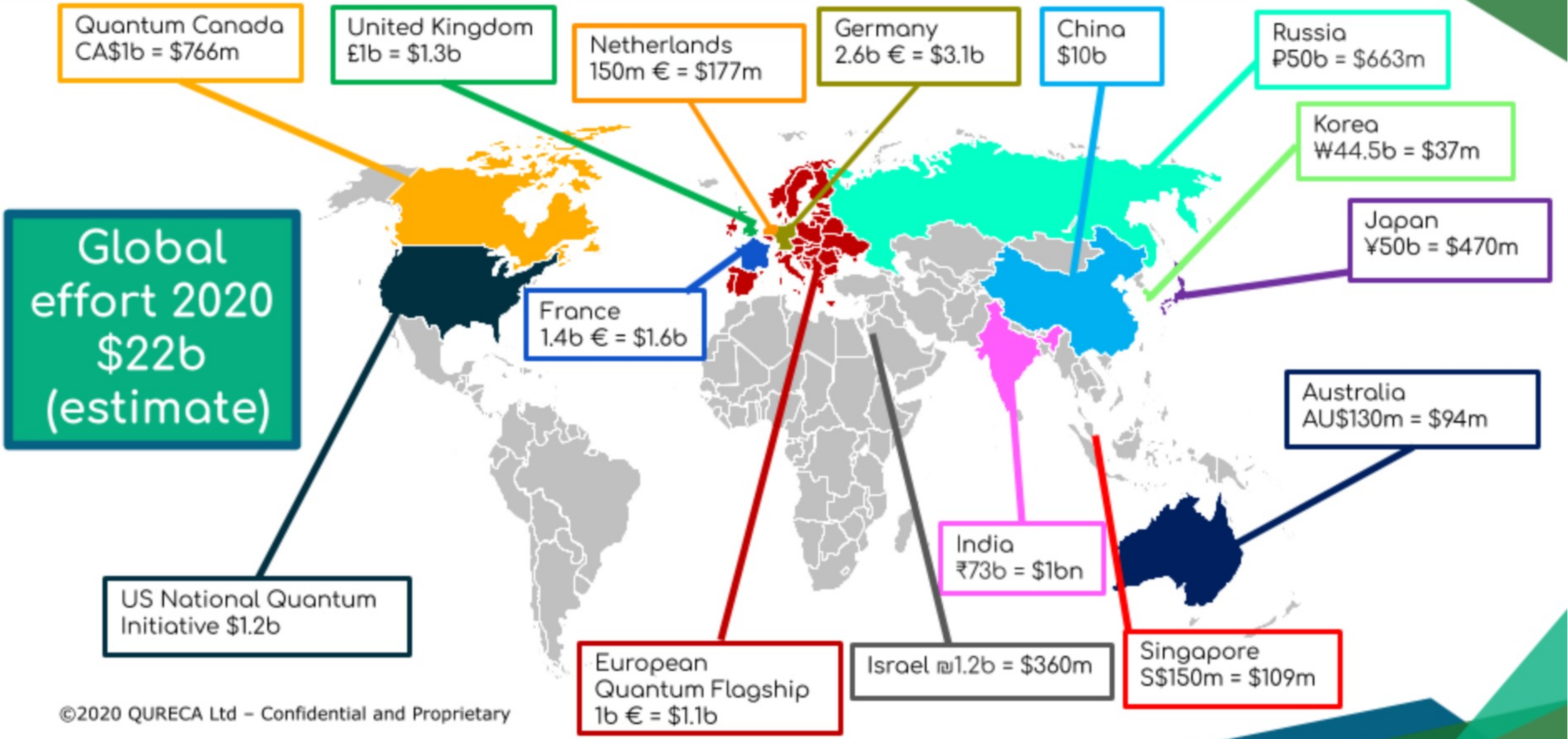
Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Quantum Technologies Public Funding Worldwide



Quantum Technologies and Particle Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
    - LIGO sources before they reach LIGO band
    - Multi-messenger astronomy: optimal band for sky localization
    - Cosmological sources

Quantum sensors for high energy particle physics

Reference work

frontiers | Frontiers in Physics

ORIGINAL RESEARCH
published: 24 June 2022
doi: 10.3389/fphy.2022.887738

Check for updates

Quantum Systems for Enhanced High Energy Particle Physics Detectors

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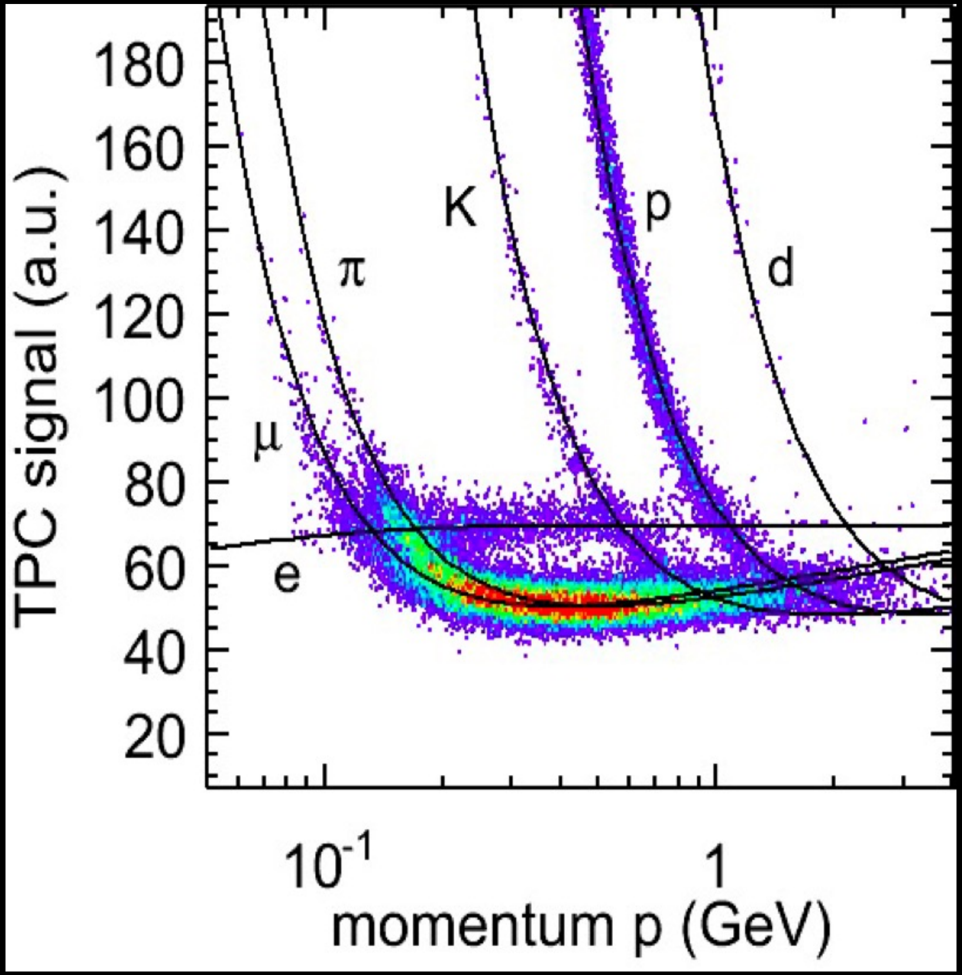
not obvious



TPC signal (a.u.)
180
160
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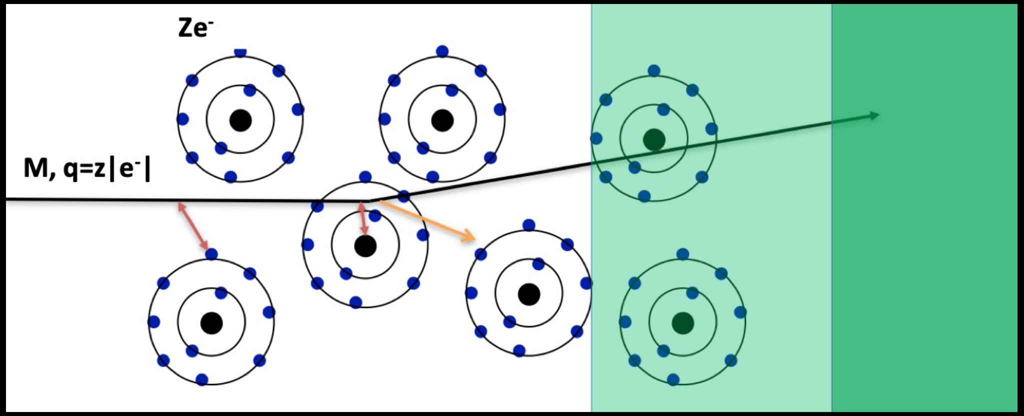
40
20
μ
π
K
p
d
e
10^{-1}
1
momentum p (GeV)



Ze^-
M, $q=z|e^-|$

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

main focus on tracking / calorimetry / timing closely related: nanostructured materials Frontiers of Physics, M. Doser et al., 2022

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

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

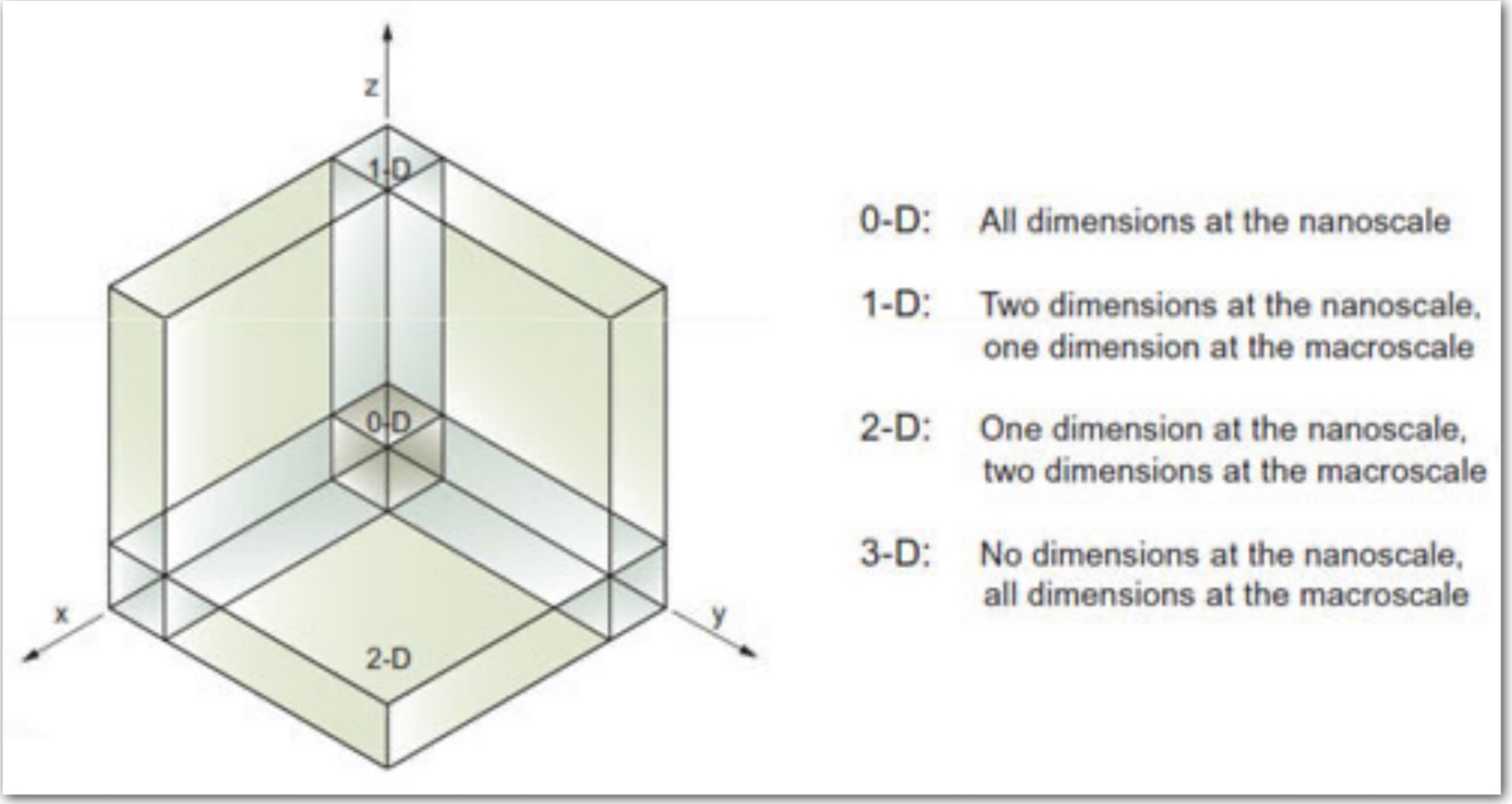
Rydberg TPC's 5.3.5 *

Spin-based sensors

helicity detectors 5.3.3 *

ECFA Detector R&D Roadmap

Low dimensional materials



Classification of nanoscale dimensions. (Source: Tallinn University of Technology)

Quantum dots
Nanocrystals

nanotubes,
nanorods,
nanowires.

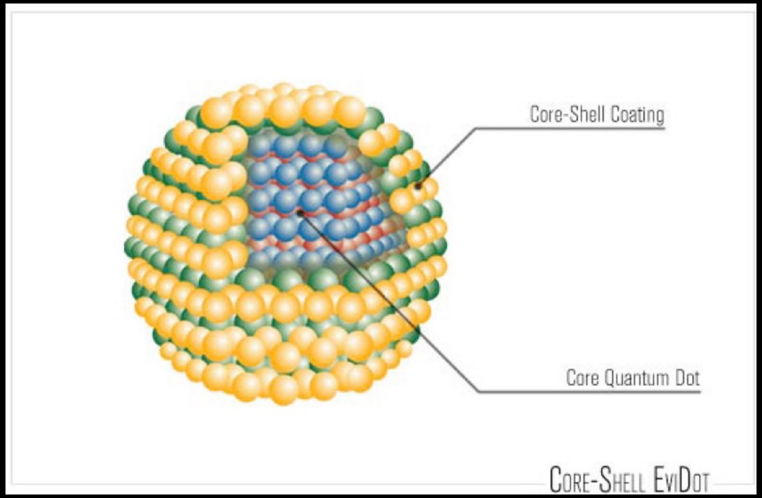
graphene, nanofilms,
nanolayers,
nanocoatings

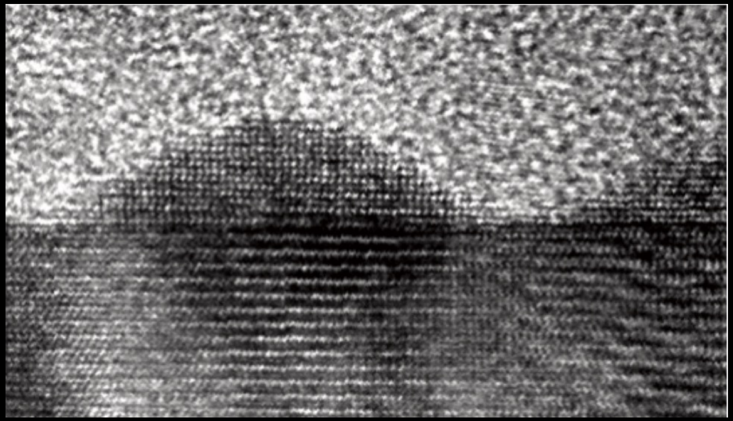
bulk powders,
dispersions of
nanoparticles,
bundles of nanowires &
nanotubes
multi-nanolayers.

Quantum Dots

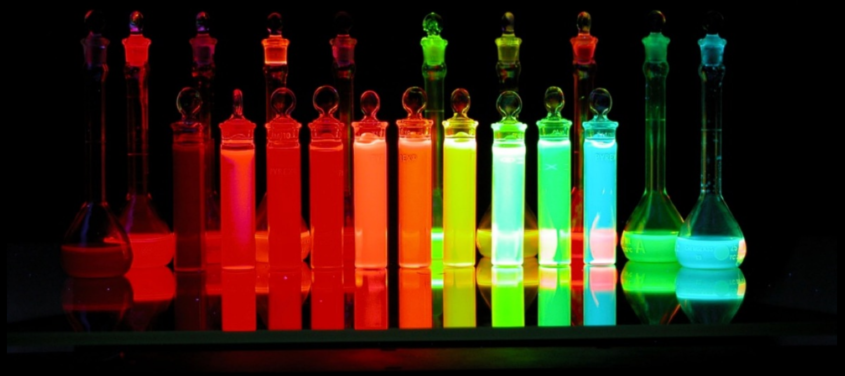

Scientific American

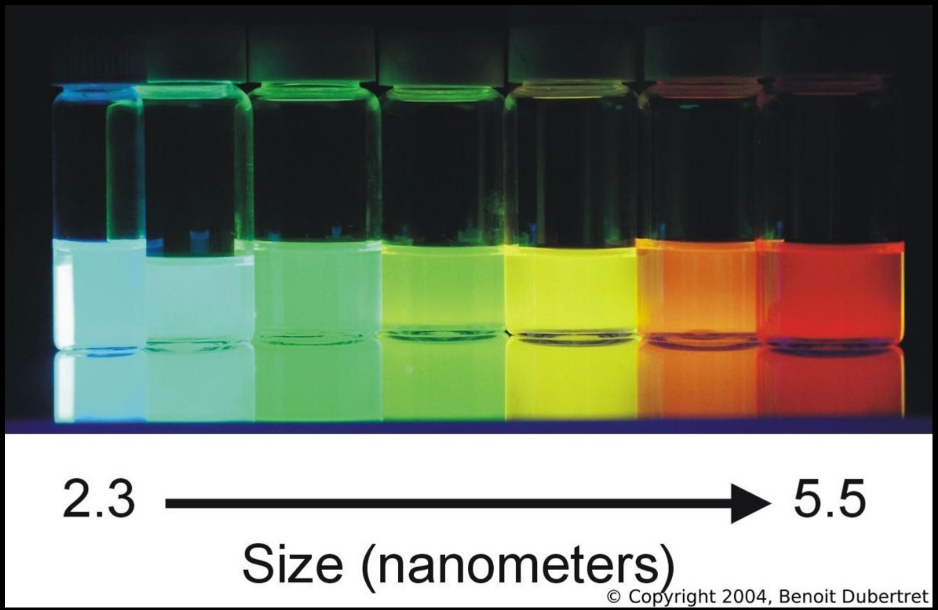
Quantum Dots





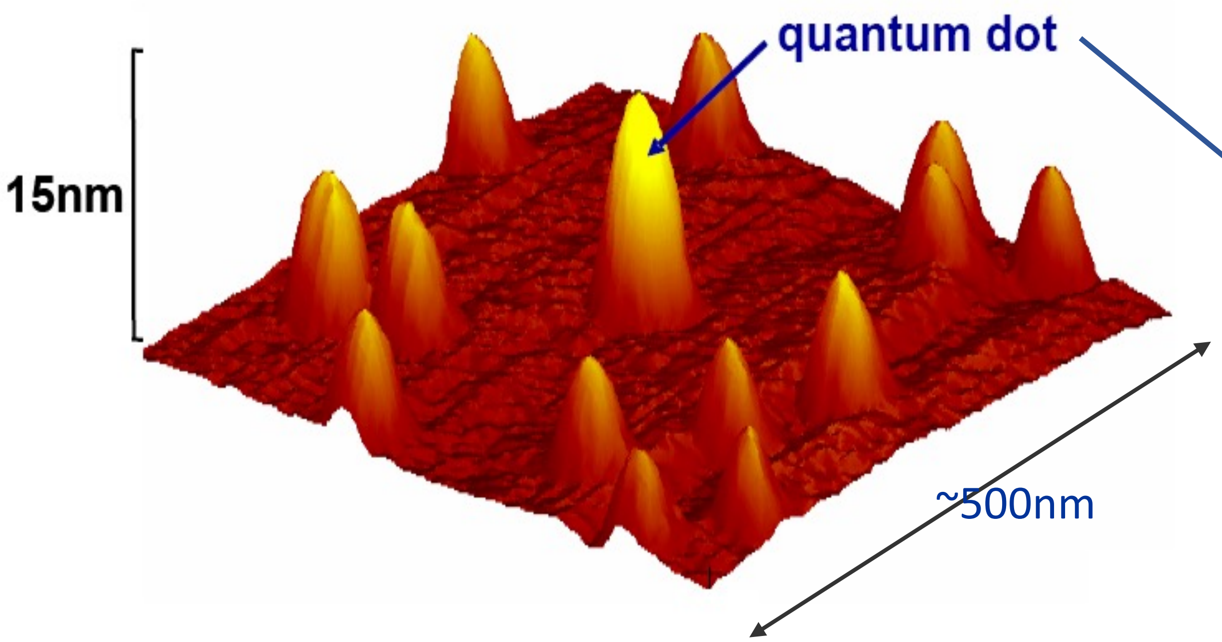
Beautiful QD emitters





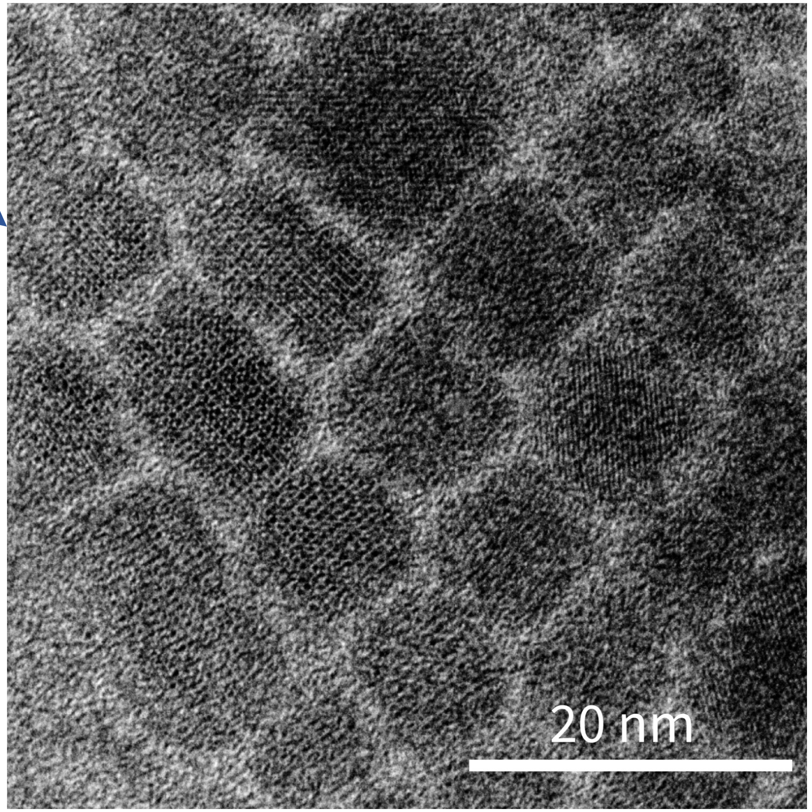
Mesolight.co

Quantum dots for quantum technologies



AFM image of a monolithic layer of InAs QDs

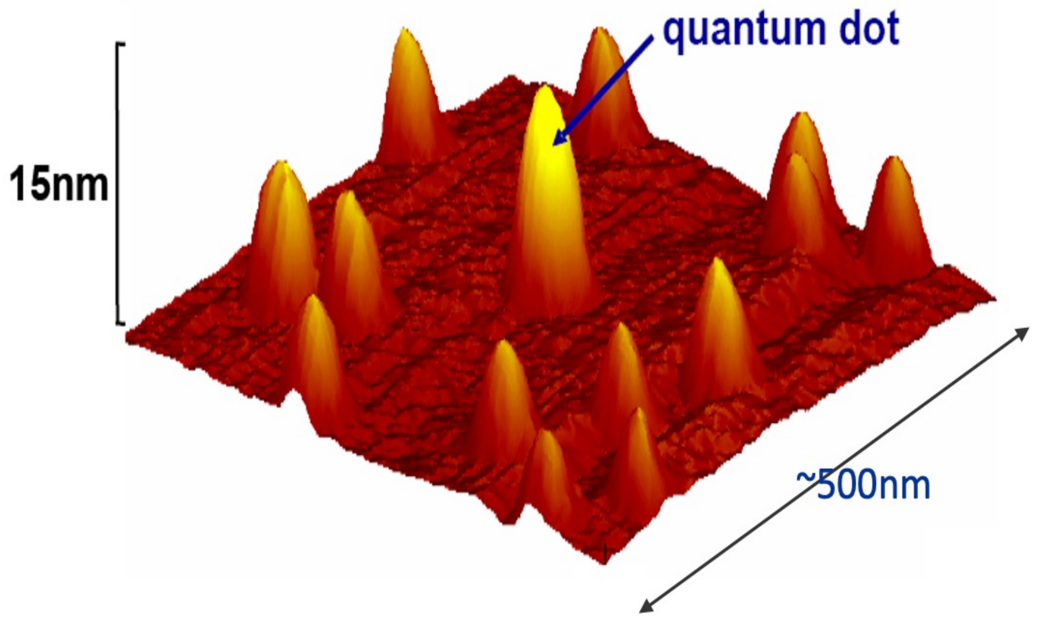
Wide pure-colour pallette



TEM image of perovskite CsPbBr3 QDs

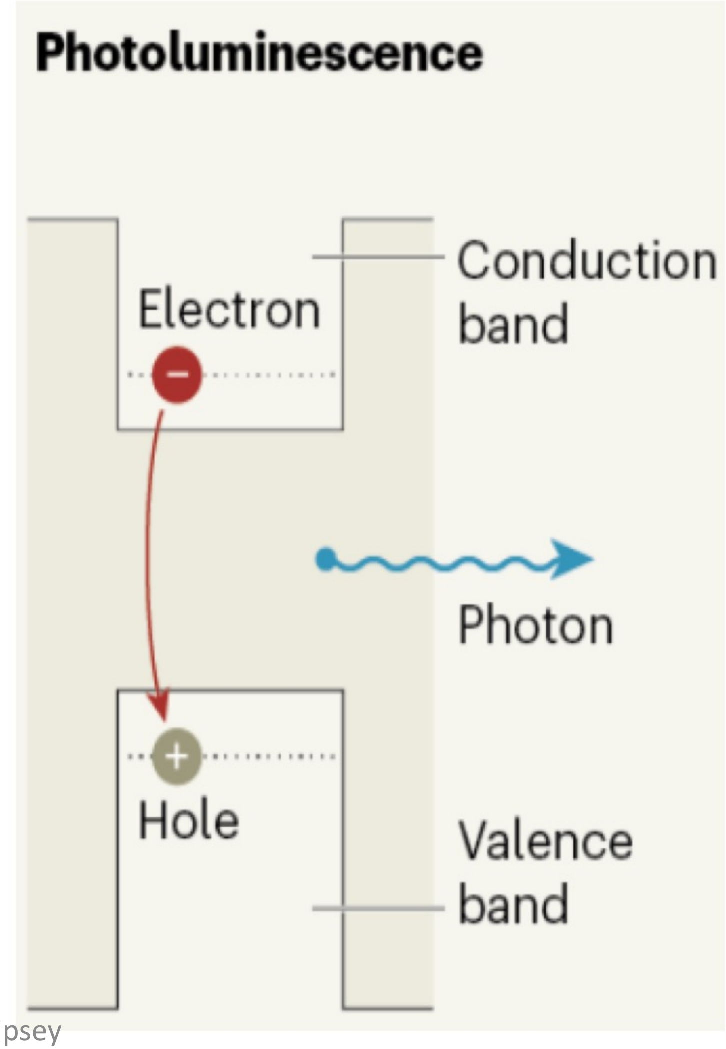
QDs produce sharp atom-like emission spectra

Generate photons by optical pumping or electrical injection of electrons into the QDs



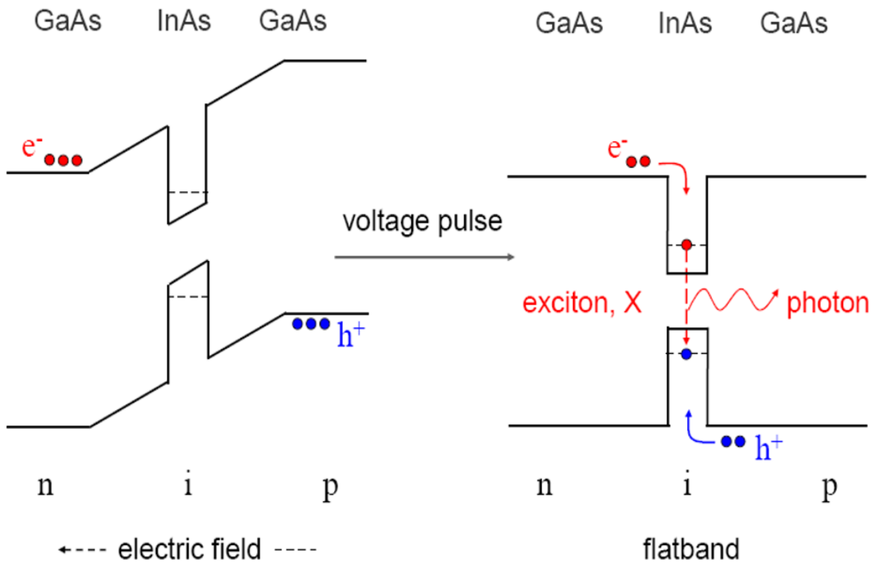
AFM image of a monolithic layer of InAs QDs

Laser pump

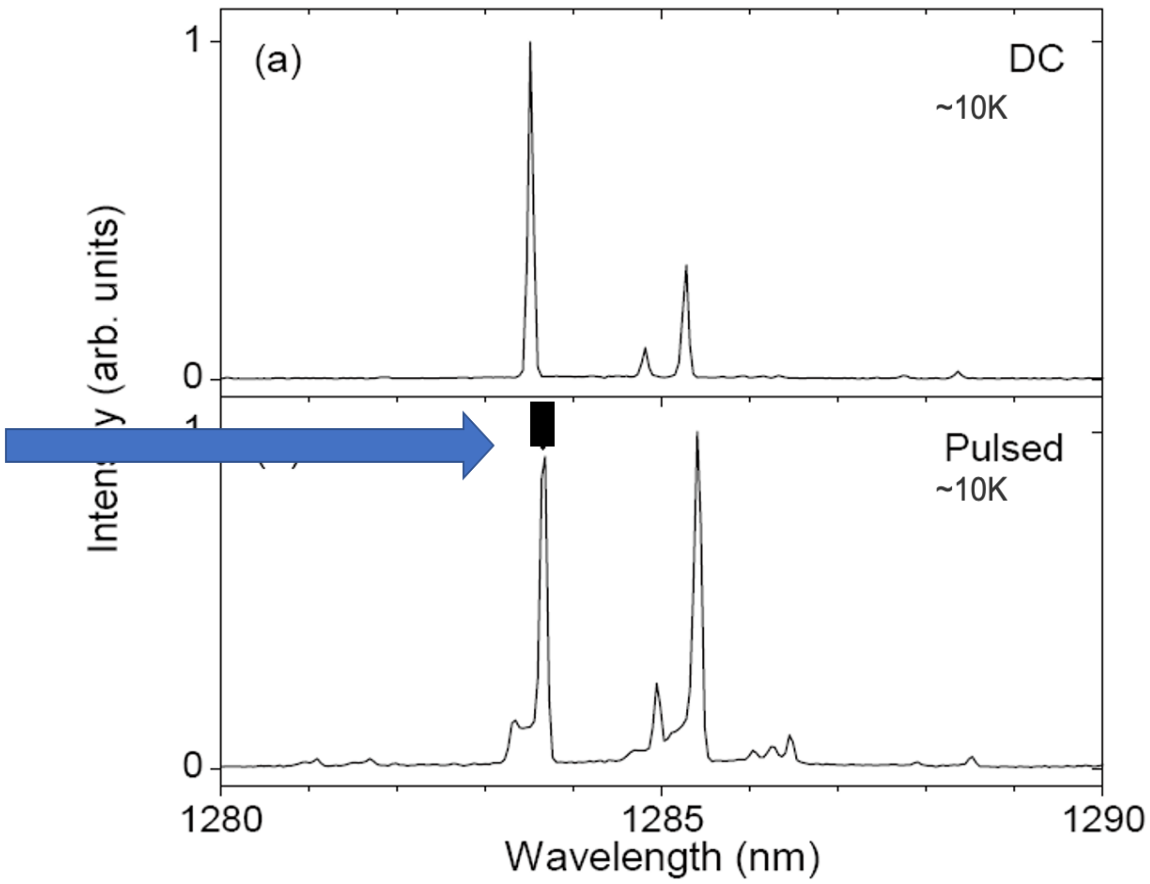


QDs produce sharp atom-like emission peaks

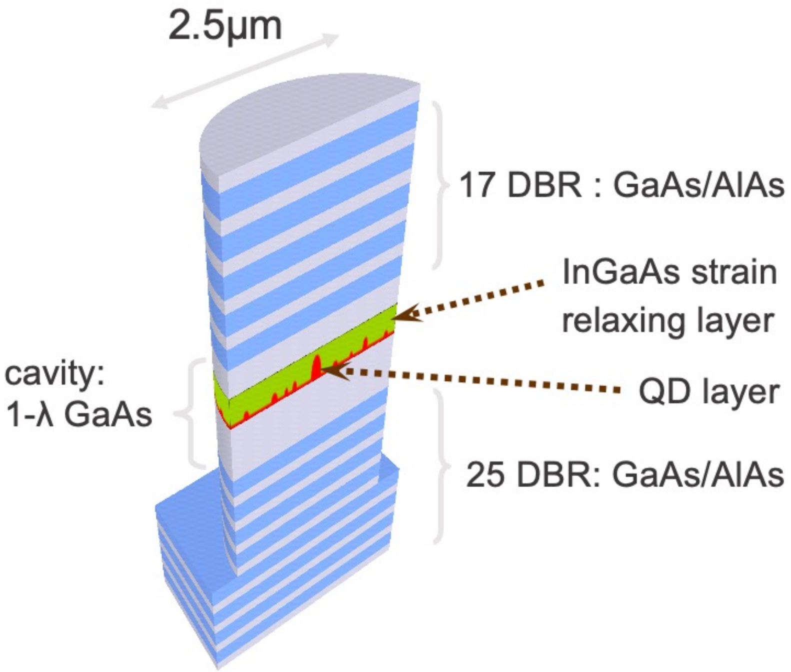
Can be generate photons by optical pumping or electrical injection of electrons into the QD



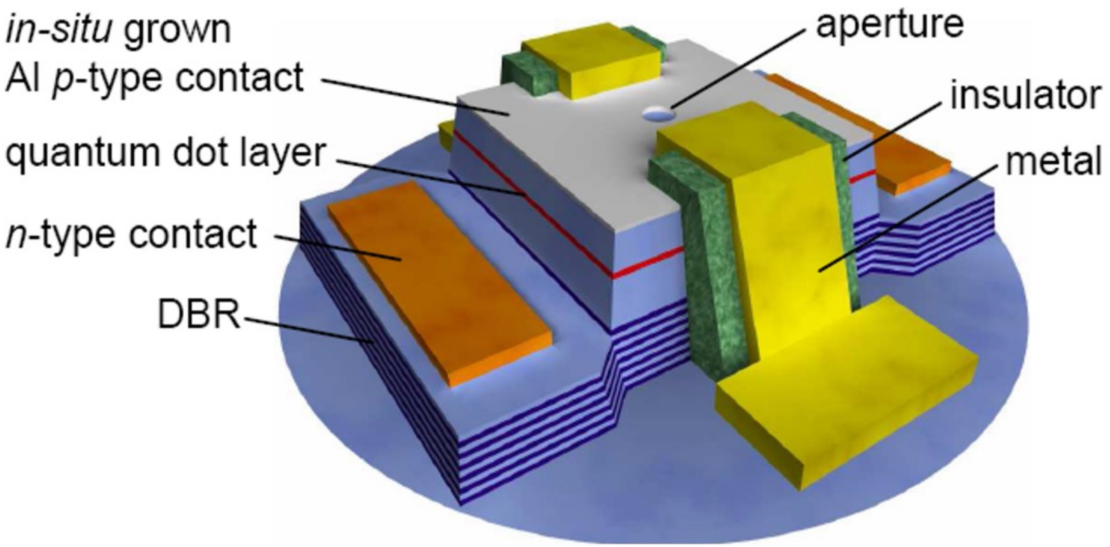
Electroluminescence (DC and pulsed)



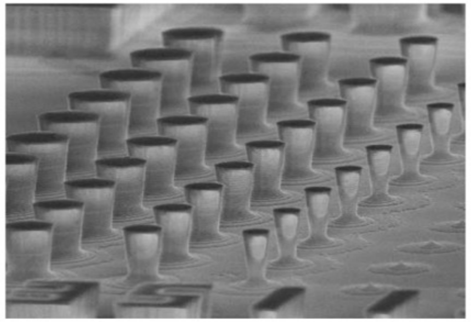
Micropillar optical cavity with QDs



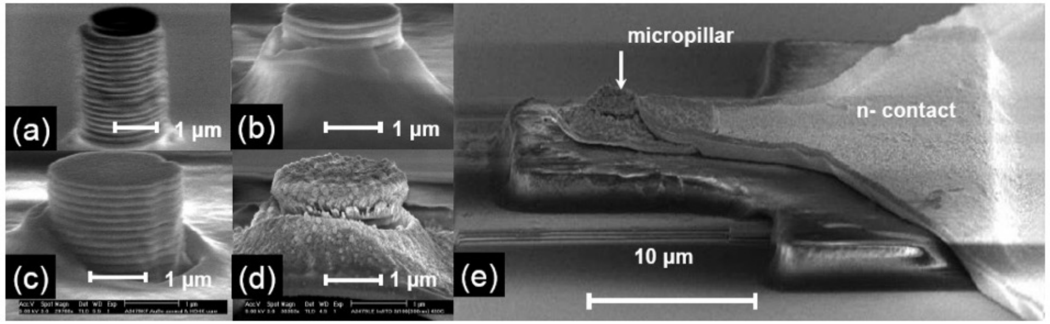
Single-photon LED



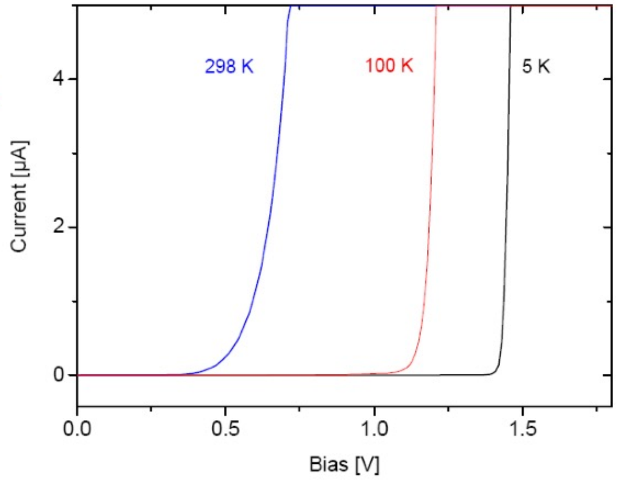
LED P-I-N junction structure has a sharp Voltage threshold turn-on



SEM of micropillar array



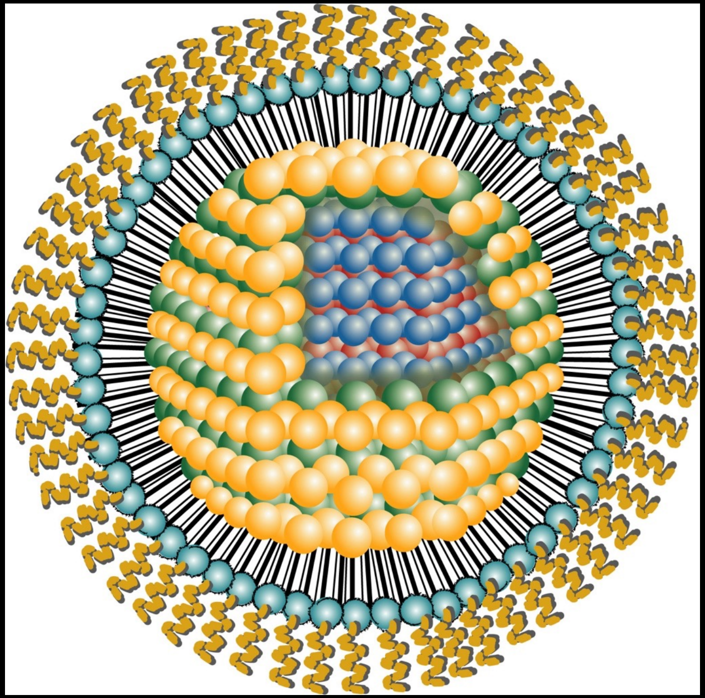
The fabrication steps of a micropillar single photon LED



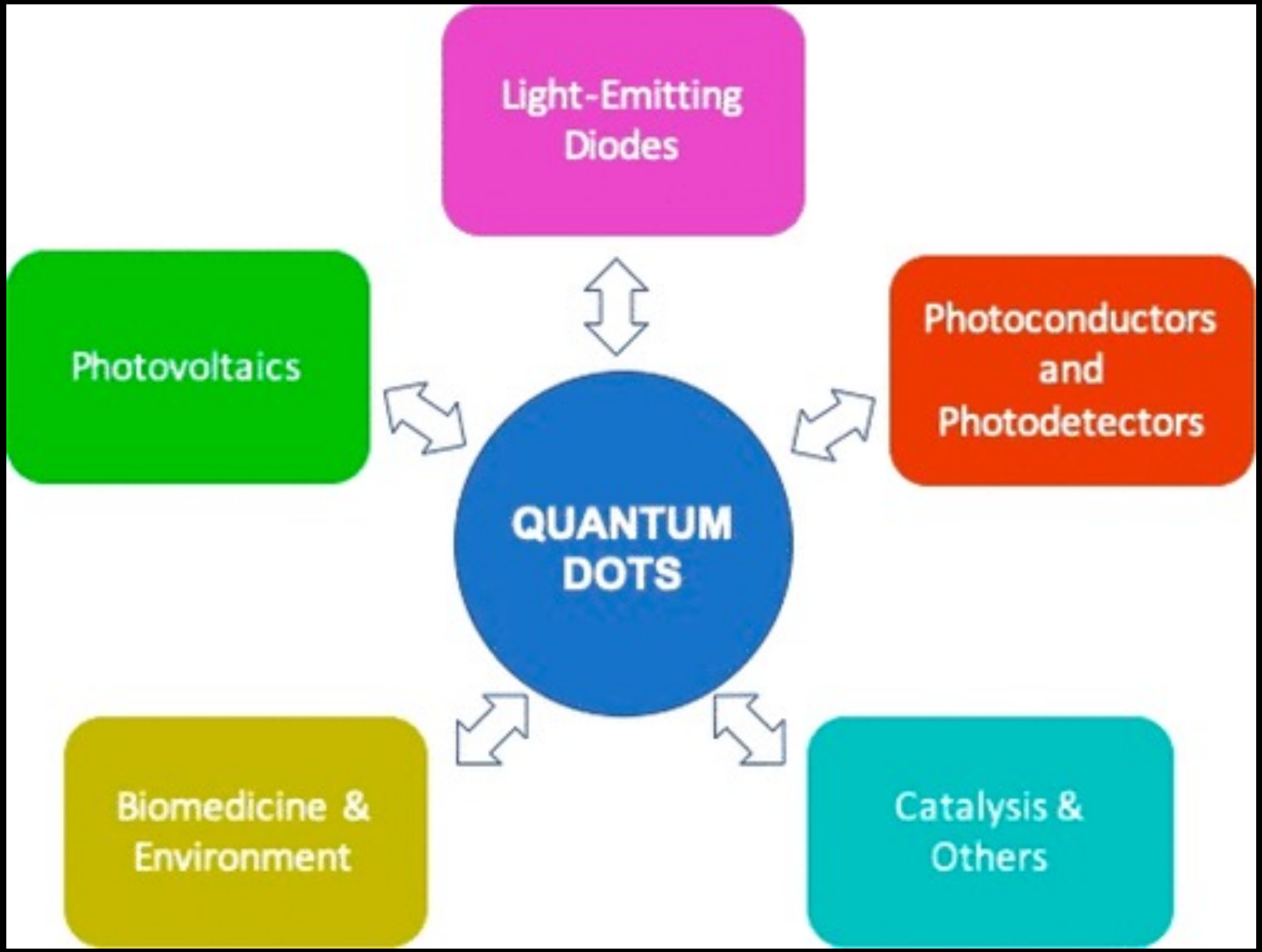
Biological applications

Clad the semiconductor dots in PEG lipids - this makes them water soluble

Can have an amine or carboxyl linker group attached so that the dots can be linked to proteins, DNA, antibodies etc.



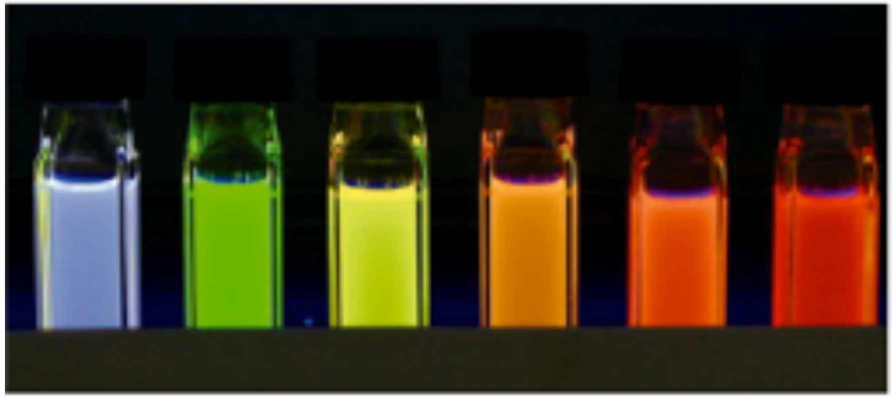
Quantum Dots and Their Applications: What Lies Ahead



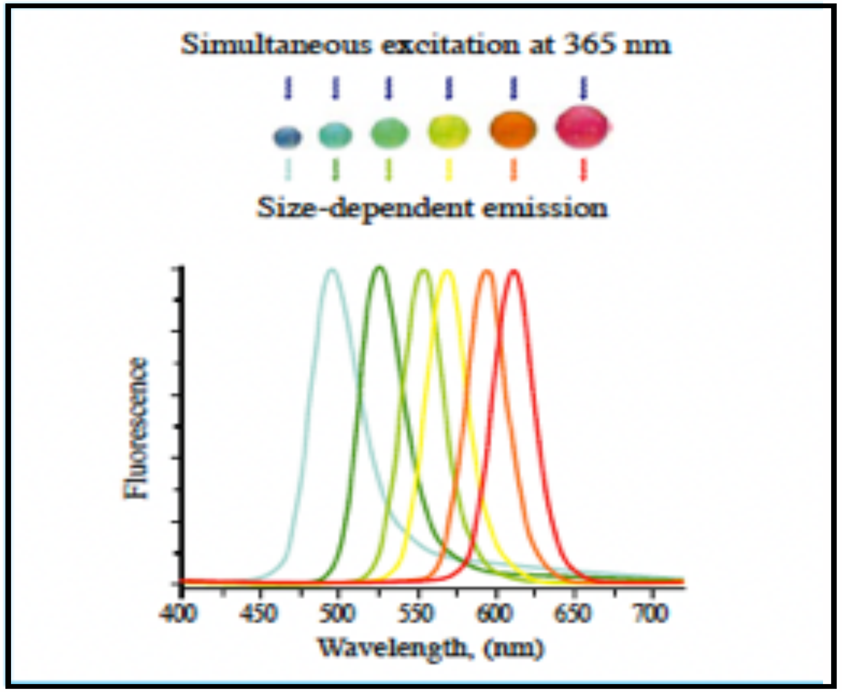
M. Cotta, ACS Appl. Nano Mater. 2020, 3, 6, 4920–4924

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



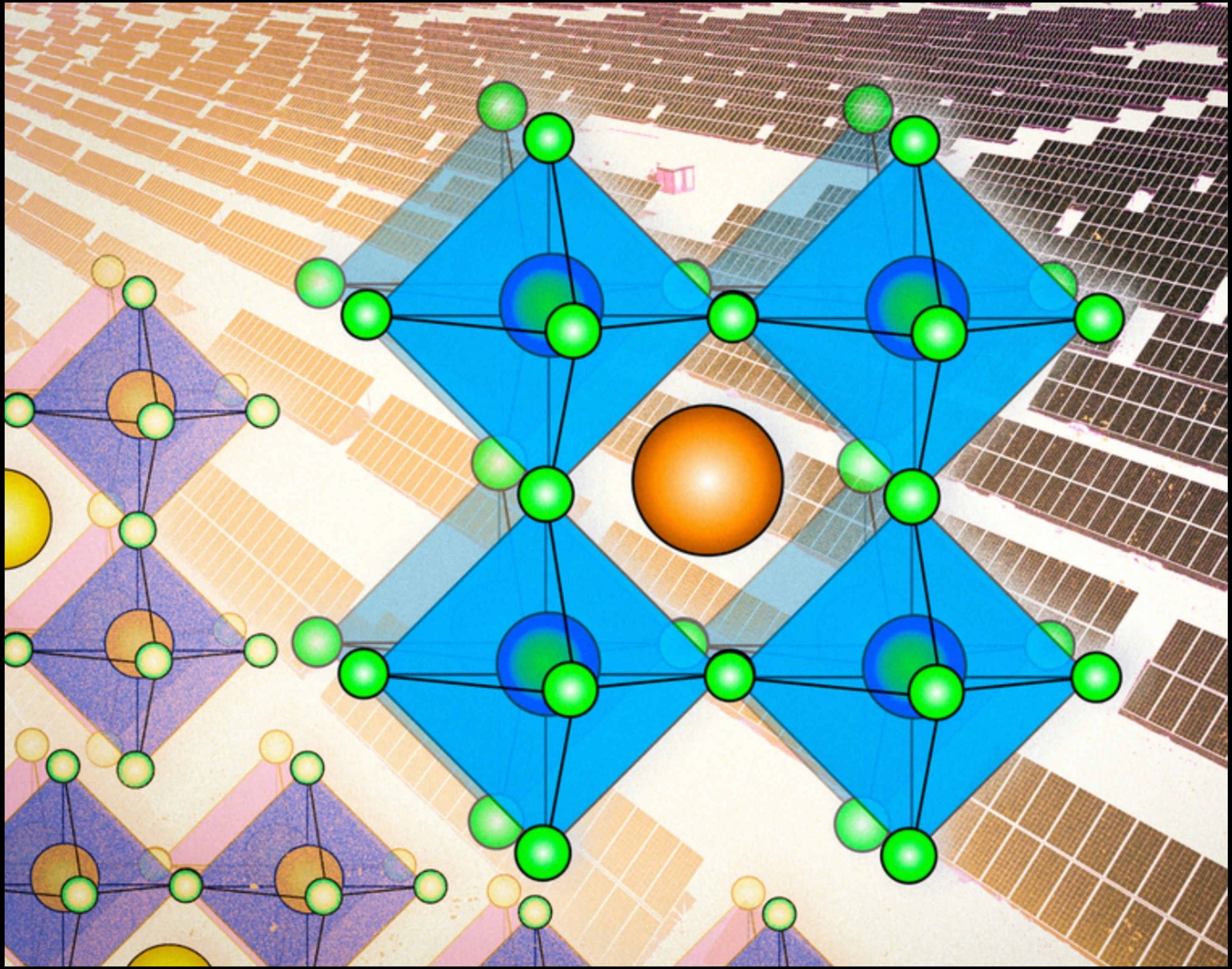
chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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

Slide credit M. Doser

Perovskytes



Paving the way for a new generation of fine-sampling calorimeters using nanocomposite scintillating materials

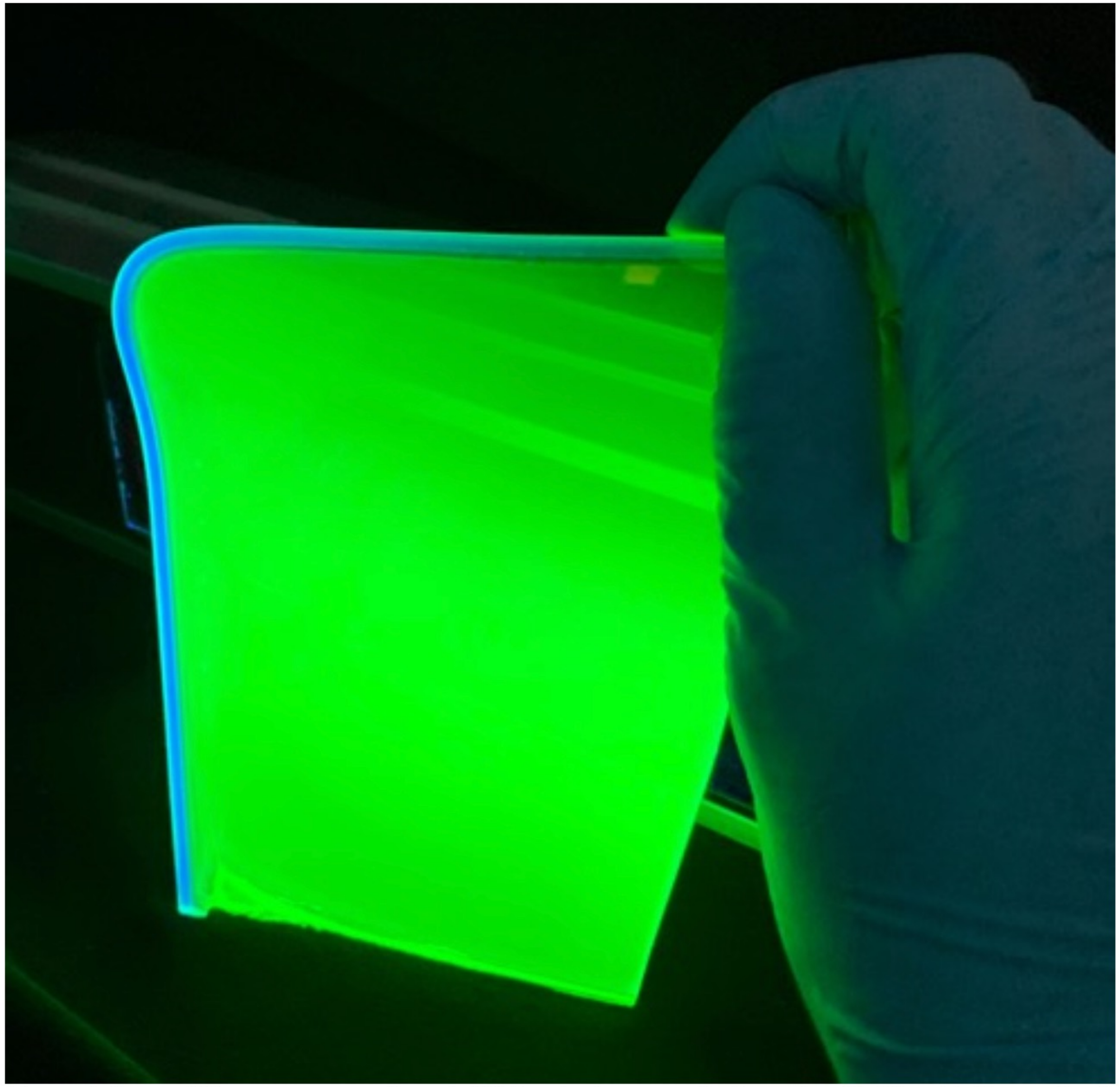
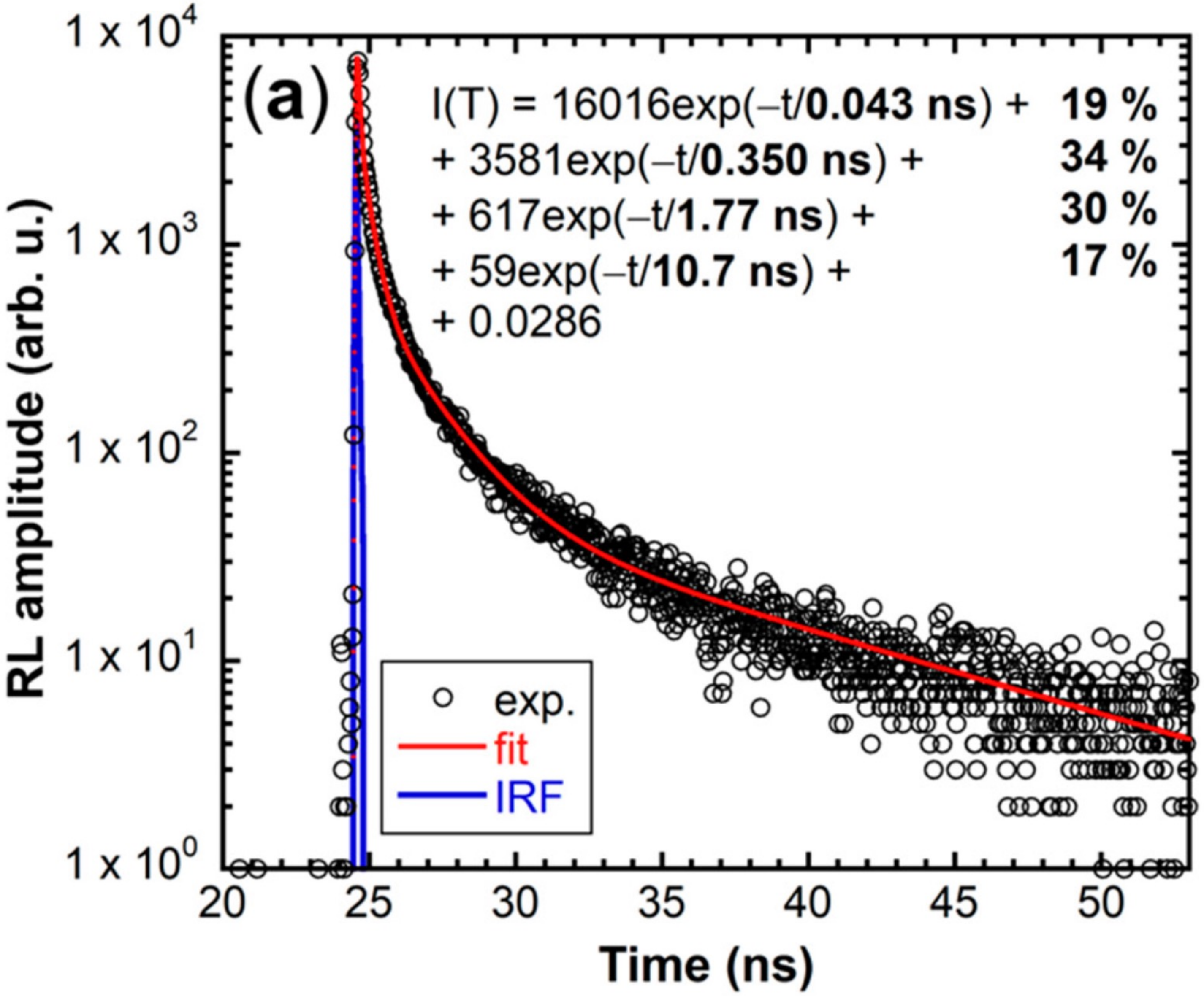


Figure 1: Perovskite nanocomposite scintillator during manufacture. Credit: Glass To Power S.p.A.

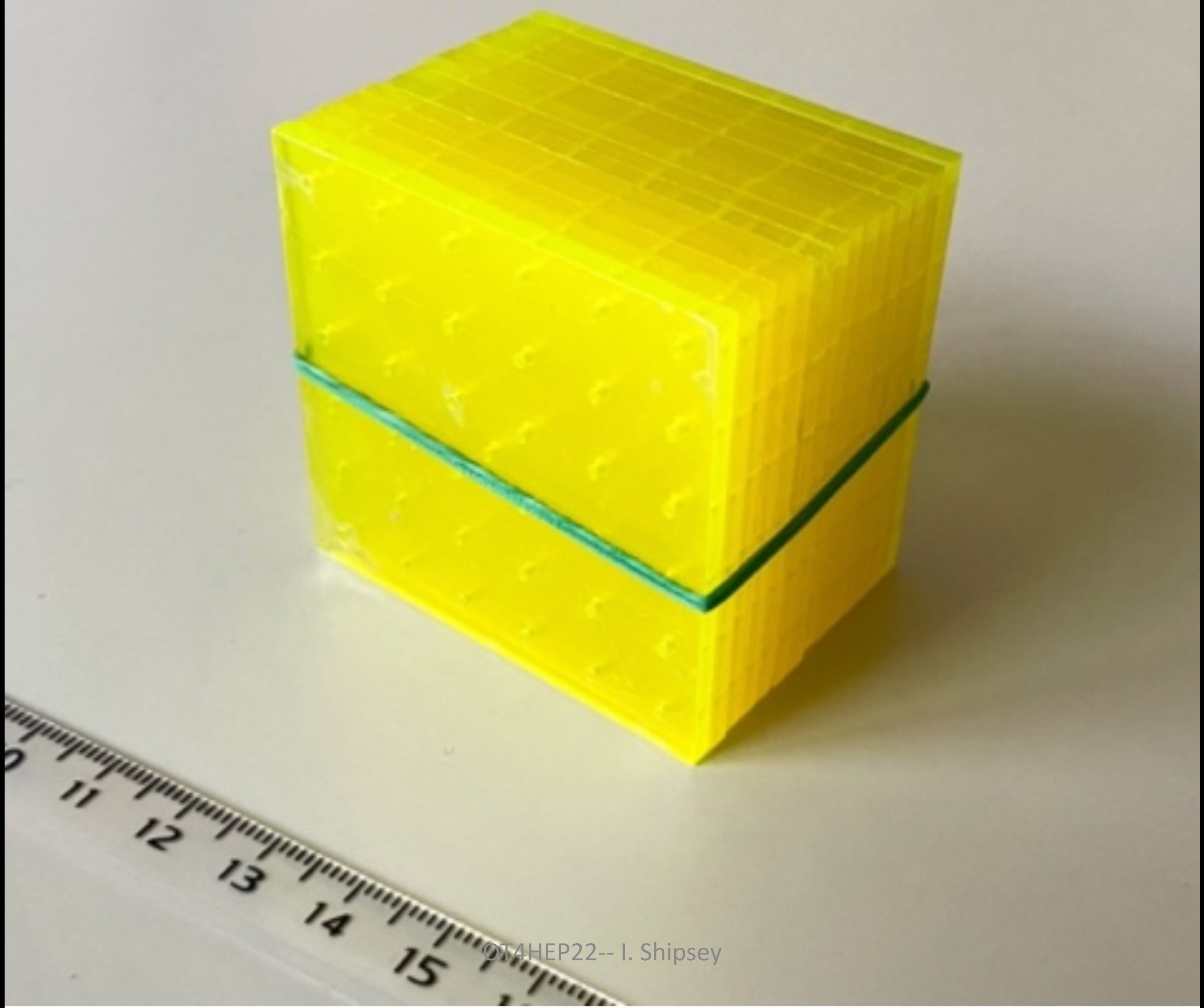
https://aidainnova.web.cern.ch/paving-way-new-generation-fine-sampling-calorimeters-using-nanocomposite-scintillating-materials

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

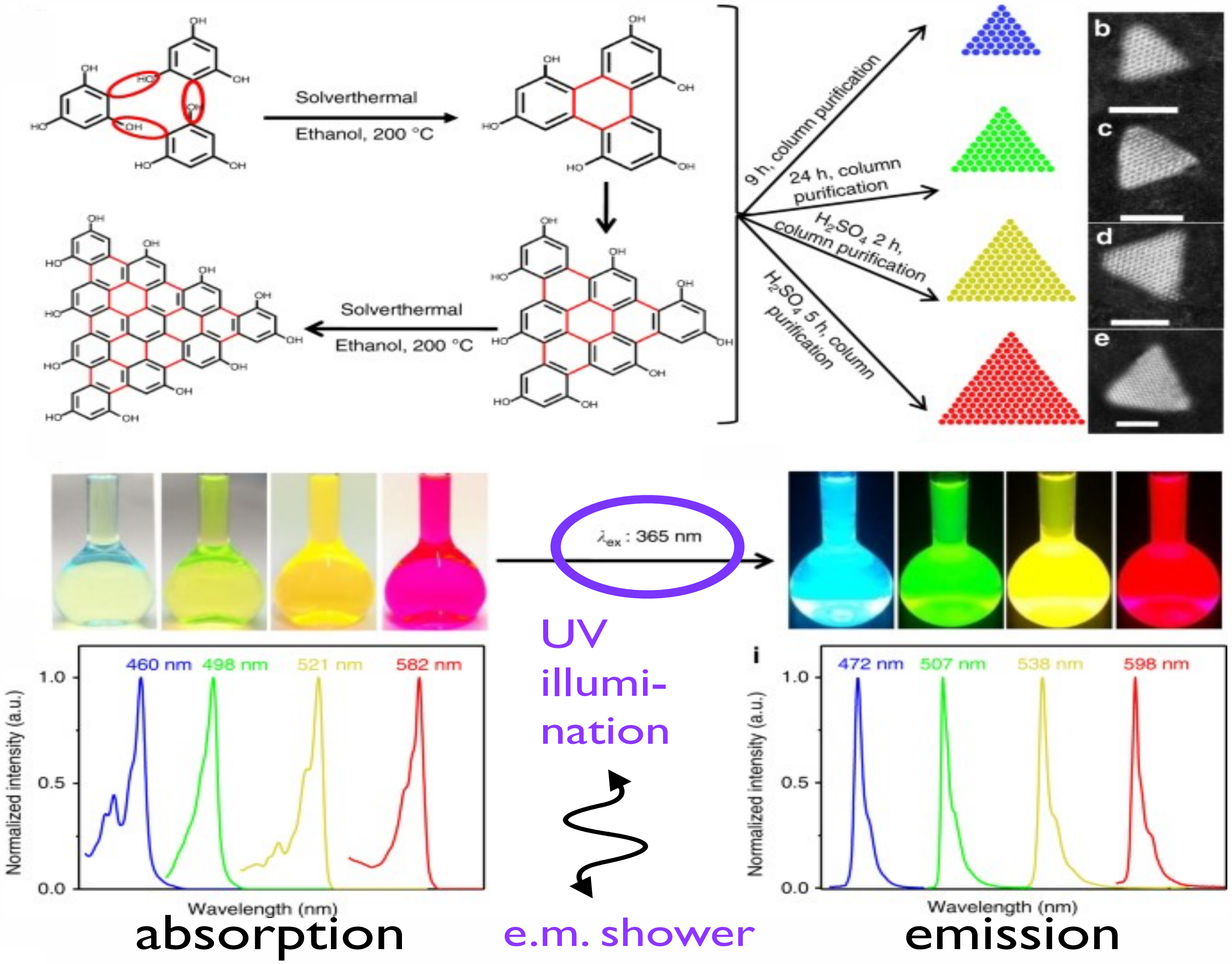


K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. Nanomaterials 2022, 12, 14. https://doi.org/ 10.3390/nano12010014

First prototypes of shashlyk calorimeter tiles made with perovskite nanocrystals. Produced at Glass To Power S.p.A. Credit: Matthew Moulson.



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

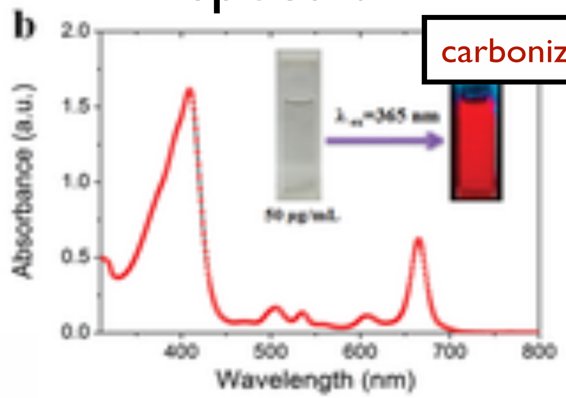
e.g. triangular carbon nanodots

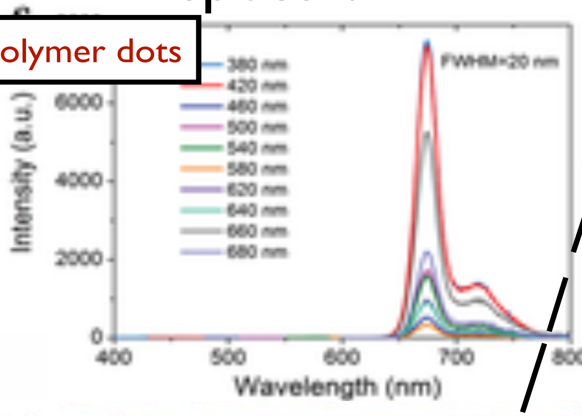
Slide credit M. Doser

absorption spectrum

emission spectrum

carbonized polymer dots





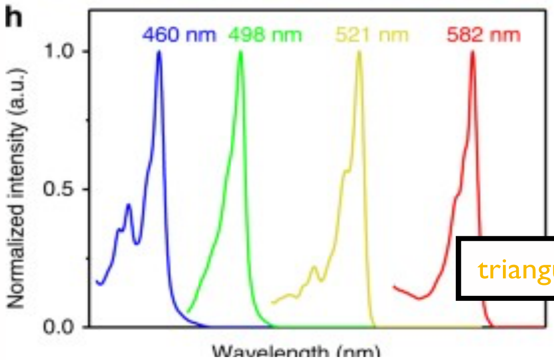
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

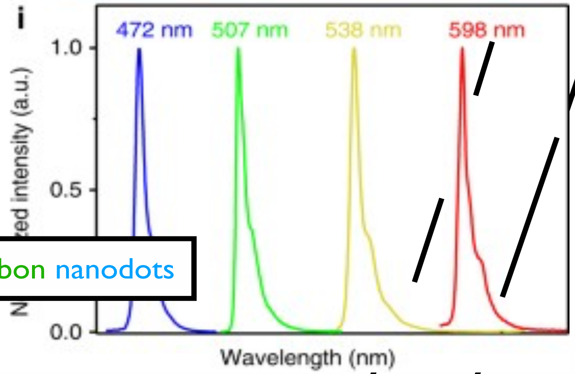
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

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

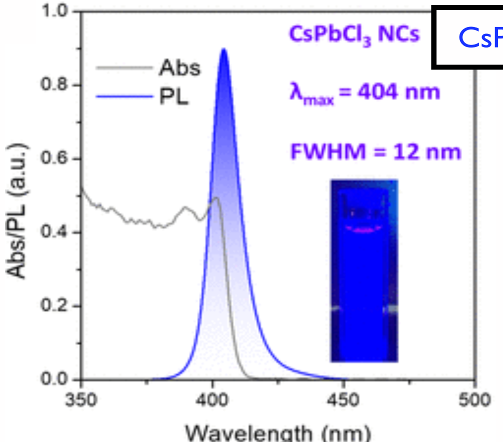
triangular carbon nanodots

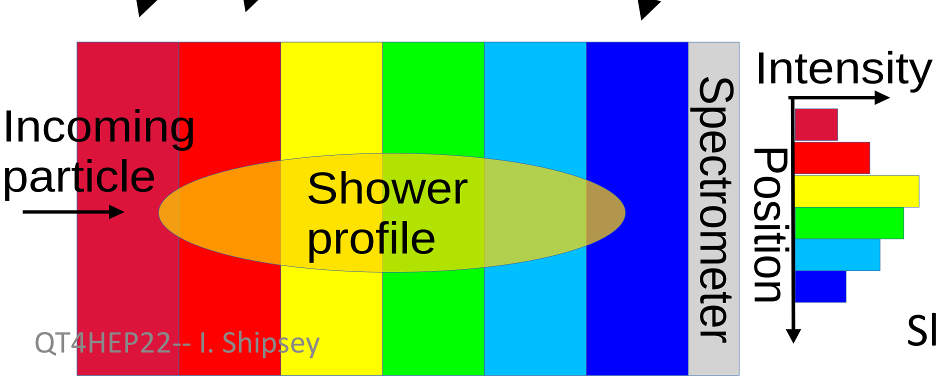




if high-Z substrate transparent in 400-700 nm, then no re-absorption of emitted light

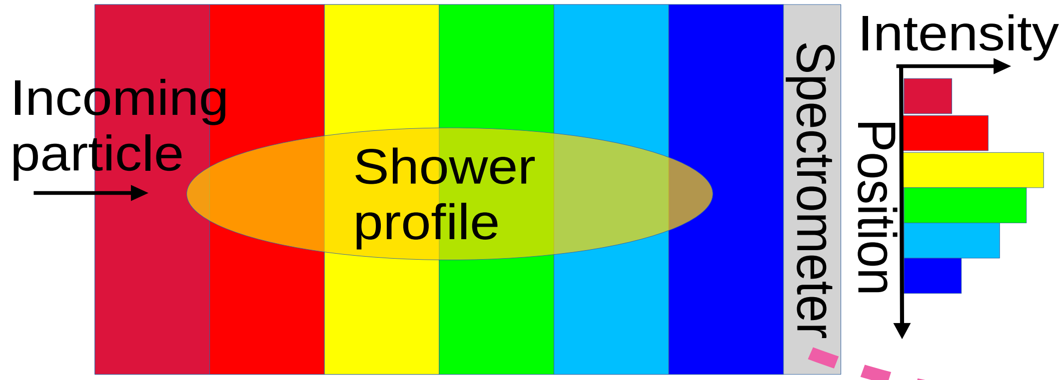
$CsPbCl_3$ nanocrystals





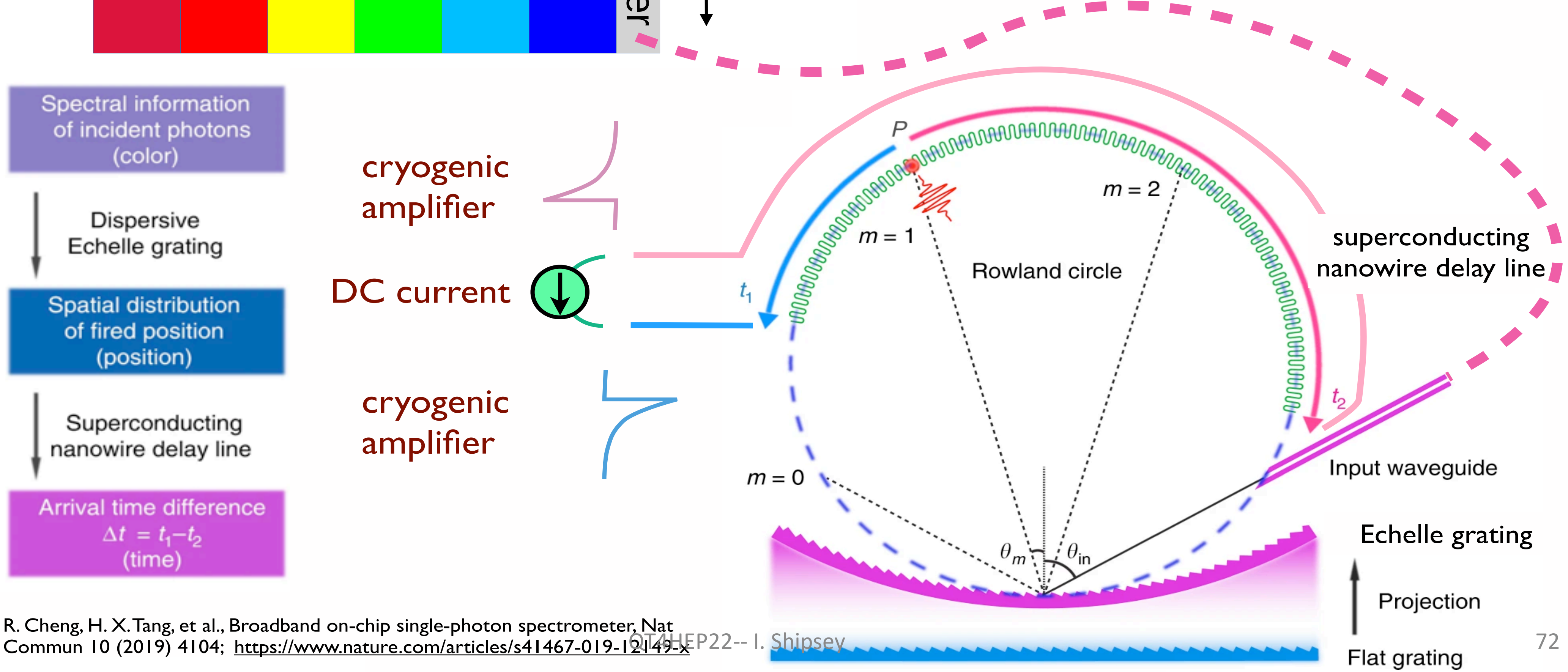
Slide credit M. Doser

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



different options for spectrometry:

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



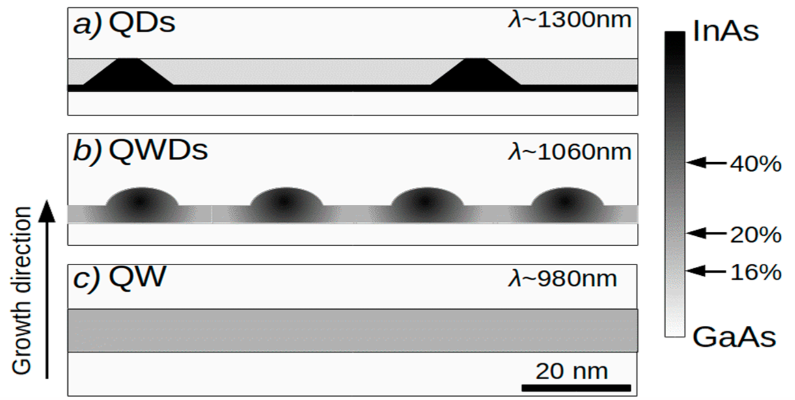
R. Cheng, H. X. Tang, et al., Broadband on-chip single-photon spectrometer, Nat Commun 10 (2019) 4104; https://www.nature.com/articles/s41467-019-12149-x

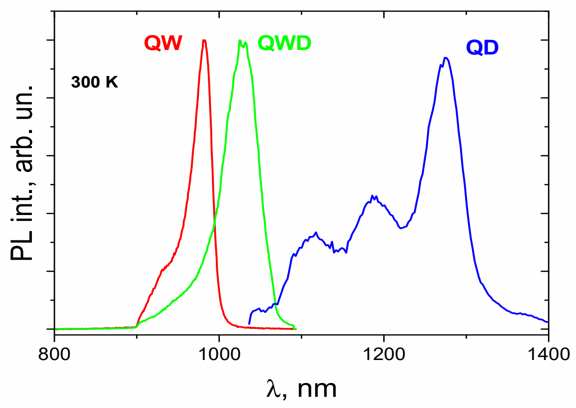
Active scintillators (QWs, QDs, QWDs, QCLs)

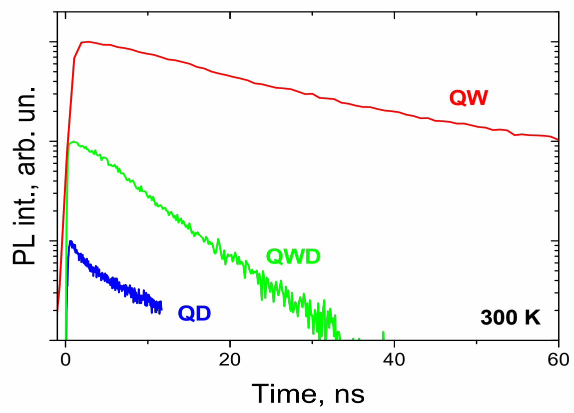
standard scintillating materials are passive
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

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

Applications to tracking:

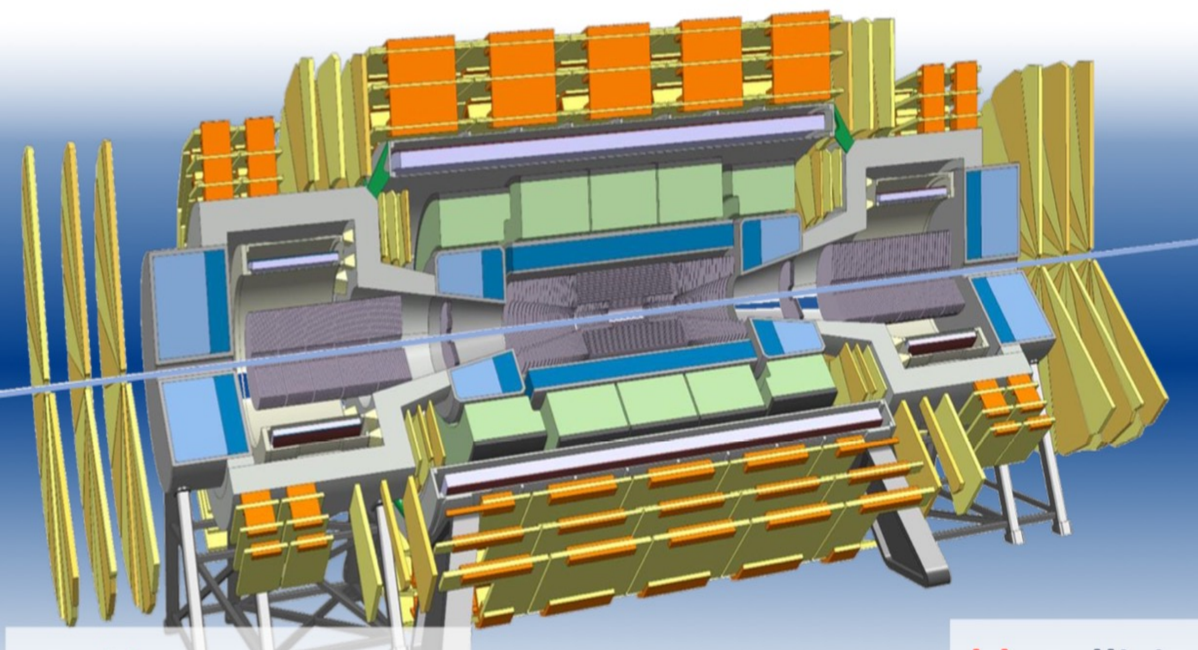
Chromatic tracking

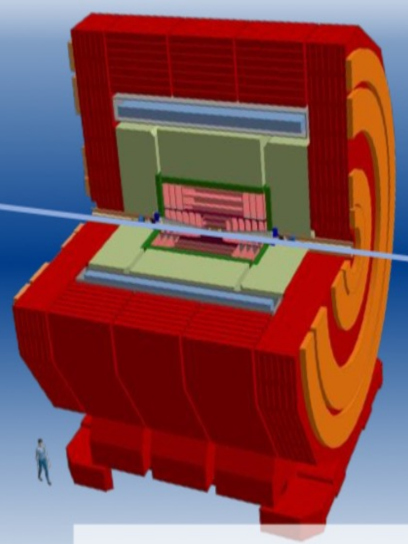
Emission in IR! Silicon is transparent at these wavelengths…
Can this IR light be transported *through* a tracker to outside PDs?

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.

Slide credit M. Doser





FCChh, *HE-LHC, …*

hh collisions

e^+e^- collisions

CLIC, FCCee, ILC, CEPC,…

- **Large dimensions (50m)**
- **High radiation Level (up to 2.8 x10^{17}neq/cm2; 90MGy @10 year)**
- Central solenoid (10m) 4T, Forward solenoids 4T
- Silicon tracker **Tracker Radius 1.6m, Length 32m**

radiation damage is a concern

One of the many challenges: radiation hardness. Radiation levels go well beyond what any currently available microelectronics can survive (≲ MGy) and few sensor technologies can cope beyond ~10^{16} n_{eq}/cm^2

- Standard dimensions
- Low radiation Level, Radiation level NIEL (<4×10^{10} neq cm^{-2}/yr); TID (<200Gy/yr)
- Magnet 4T, 2T
- Silicon tracker
  - **unprecedented spatial resolution (1-5 µm point resolution)**
  - **very low material budget (0.1X%)** Dissipated power (vertex) (<50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

➔ Detector R&D essential

➔ Detector R&D essential

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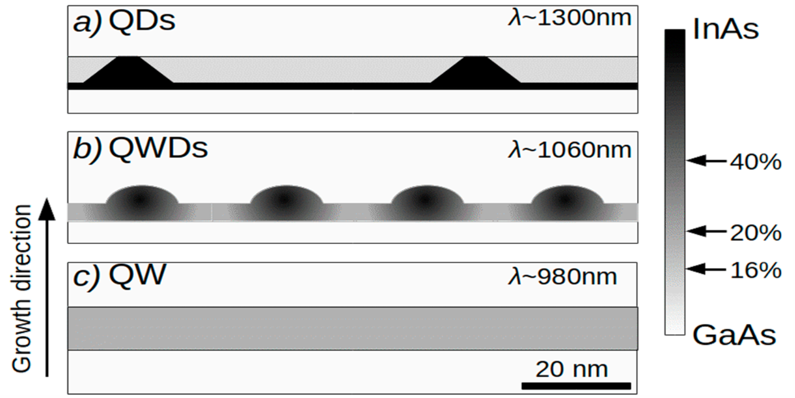

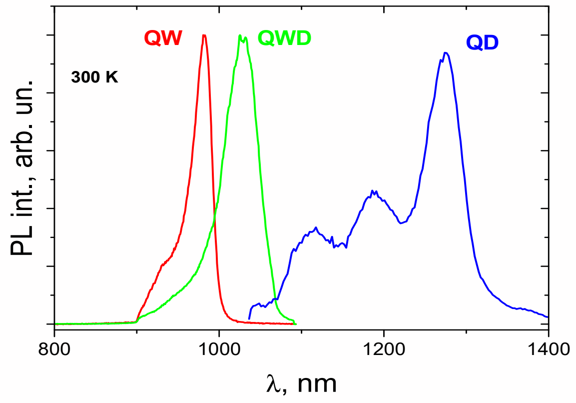

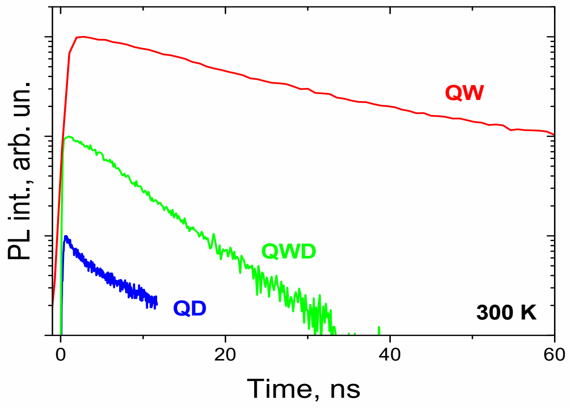

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Slide credit M. Doser

Quantum Well

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

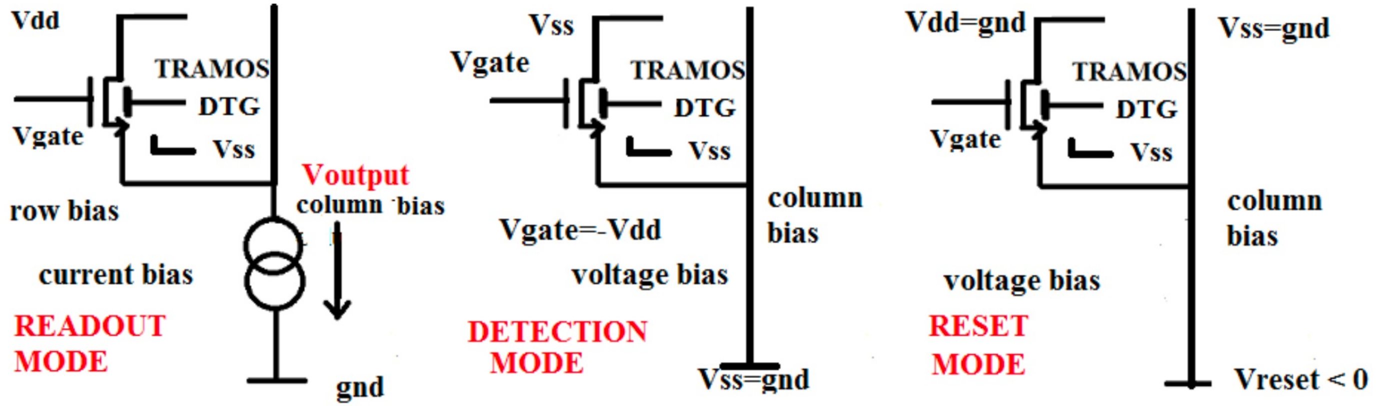


Figure 1: single DoTPiX pixel and connections, with the electric operation mode [24]

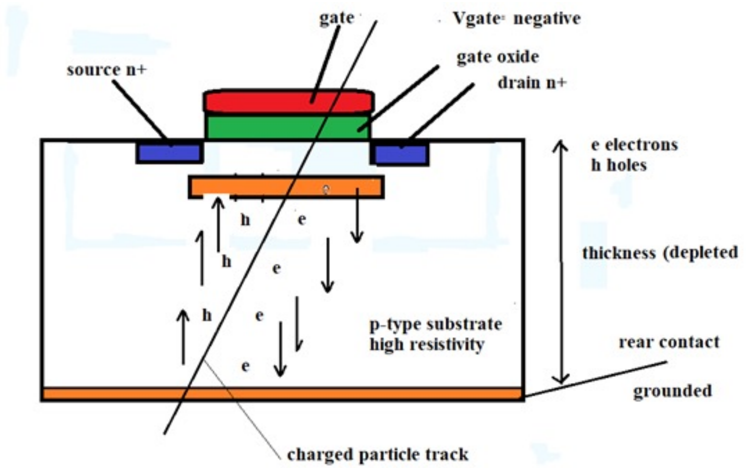
Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021

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

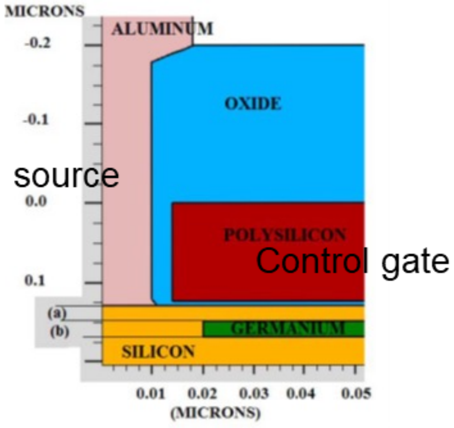
DotPIX a new pixel detector concept for particle physics

- Device simulations , general simulations



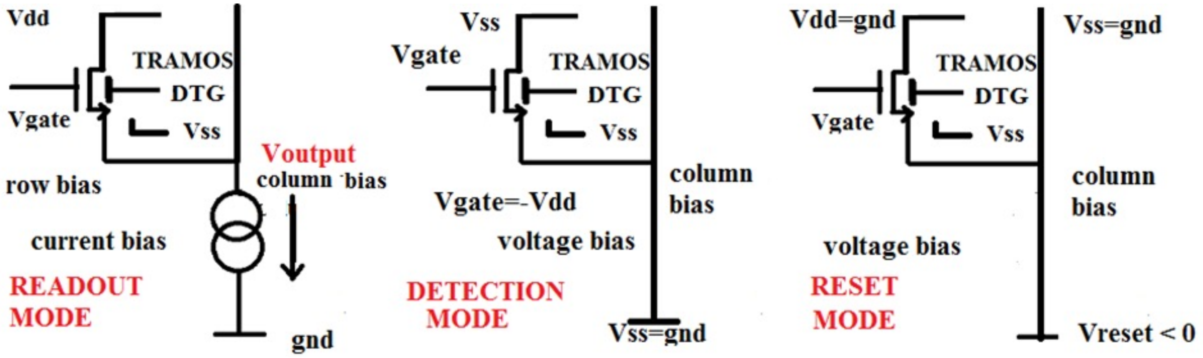
The device is based on :

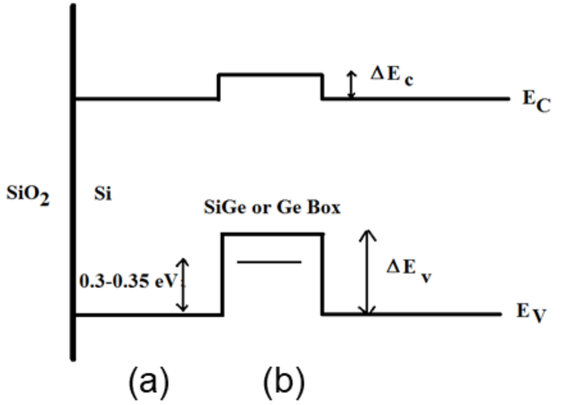
1. **A n-channel MOS structure**
2. **With drain source and an uppercontrol gate**
3. **A buried sensing gate that can trap and localise holes and modulate the source to drain current**



Bulk thickness ~ 2 µm for simulations

- The buried Ge gate is 20 nm thick for a 1 micrometer width

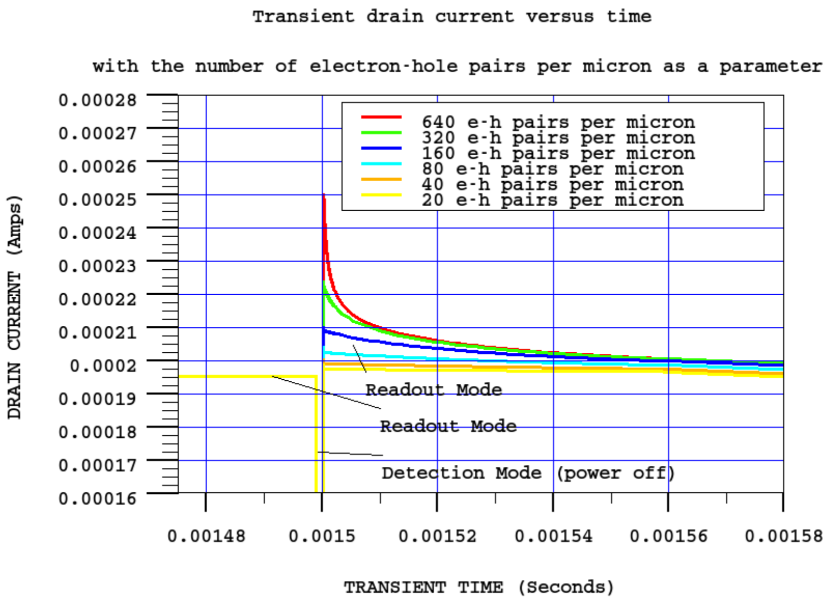


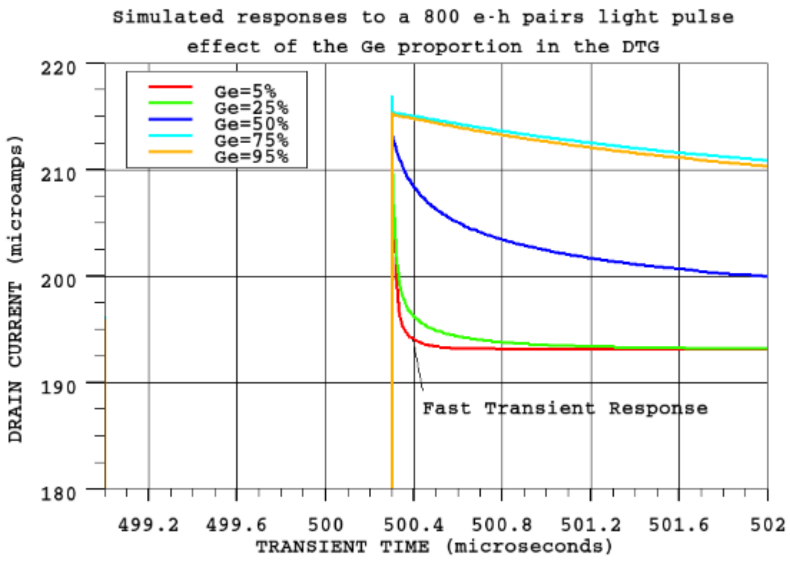


DotPIX a new pixel detector concept for particle physics

Description of the DoTPiX

- Proposed in 2017, derived from another structure (TRAMOS 2010) : goal ultimate point to point spatial resolution (~ 1µm) , See : N. T. Fourches, "Ultimate Pixel Based on a Single Transistor With Deep Trapping Gate", IEEE Trans. on Electron Devices 64, pp. 1619-1623 (2017). https://doi.org-98/10.1109/TED.2017.2670681
- We have a 100 nm x 20 nm x 1000 nm volume quantum box (Carrier lifetime < 1ns , high readout drain current)
- Simulation: device operates adequately with device simulation software used when ionizing tracks are introduced. The quantum effect are introduce simply with density gradient model.





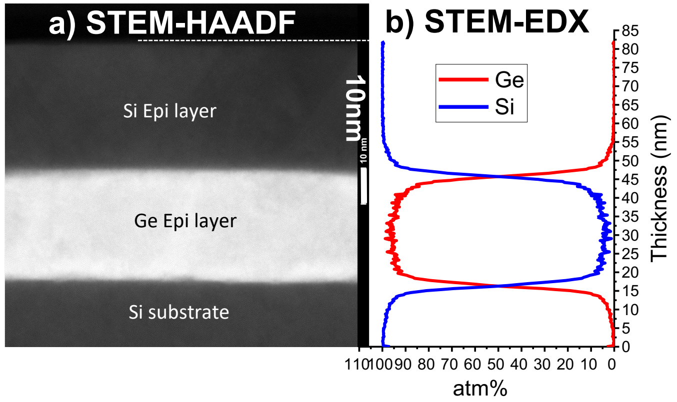
Proof of the principle is validated as far as we can trust simulation…

DotPIX a new pixel detector concept for particle physics

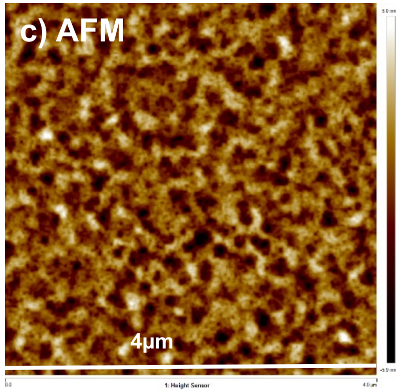
Successful growths epitaxial of the Si (25nm)/Ge(30nm) layers on silicon substrate by UHV-CVD

a) High Angle Annular Dark Field Imaging shows the epitaxial Ge layer (bright contrast) and the epitaxial Si layer (dark contrast)

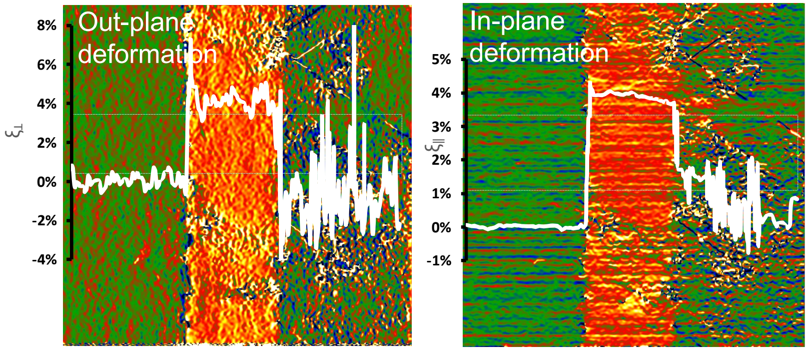
b) STEM-EDX profil shows a very high Ge concentration with abrupt interfaces



c) AFM image estimates the roughness at Rq=1,56nm

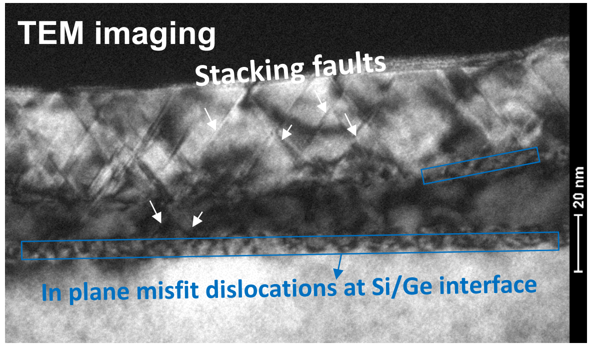


Geometrical Phase Analysis (GPA) shows :
-The Ge layer is fully relaxed out-of-plane and in-plane with about +4% (red area) deformation respect to silicon.
- The Si layer is slightly deformed out-of-plane in tension about -1% and decrease his in-plane compression deformation about +1%

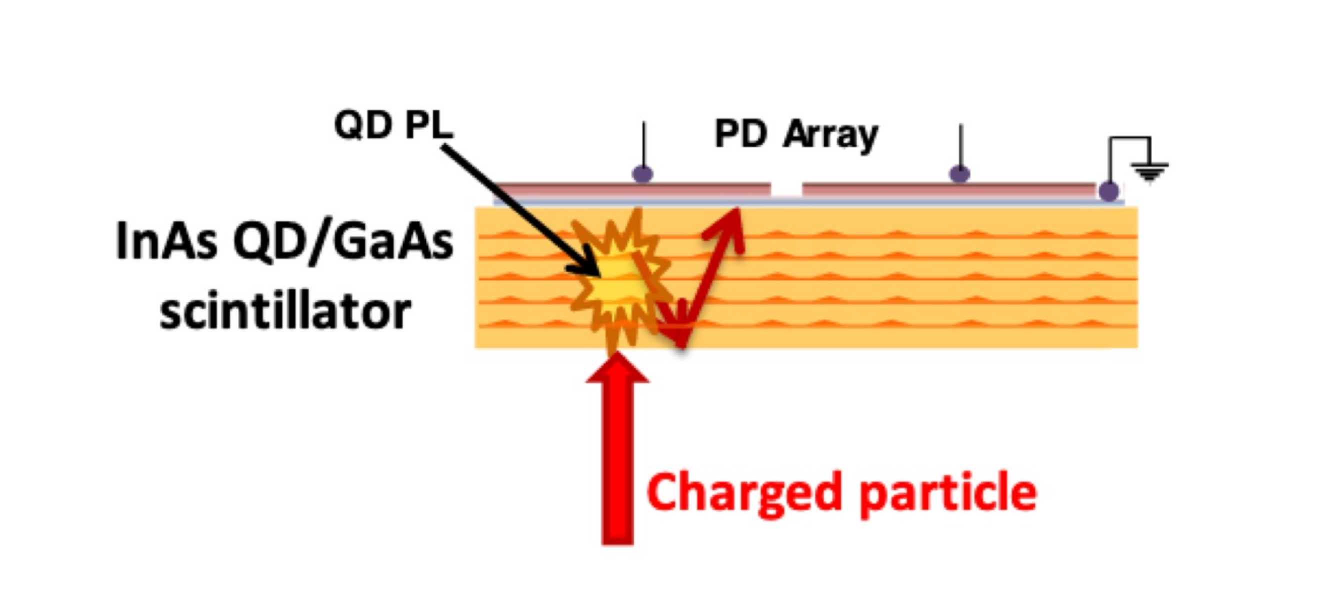


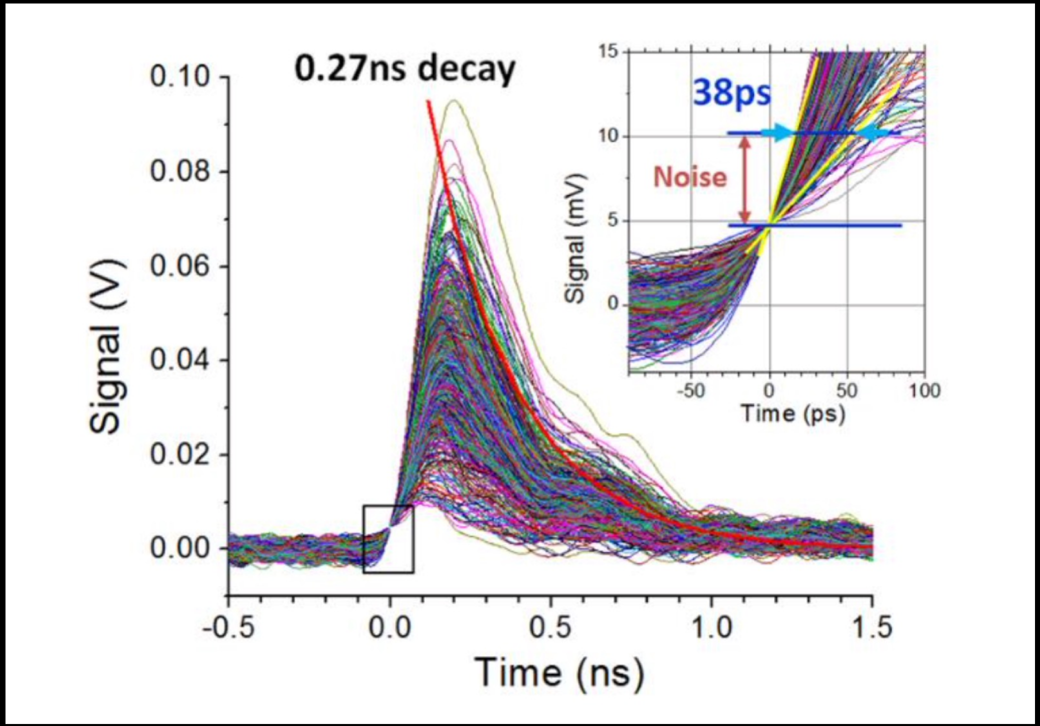
Issues

- We have to reduce the stacking faults (mainly in Si layer) due to out-plane dislocations in the Ge/Si interface (partial-not total crystal lattice relaxation)
- We have to estimate the effects of the thermal treatments post epitaxy → evaluate the intermixing

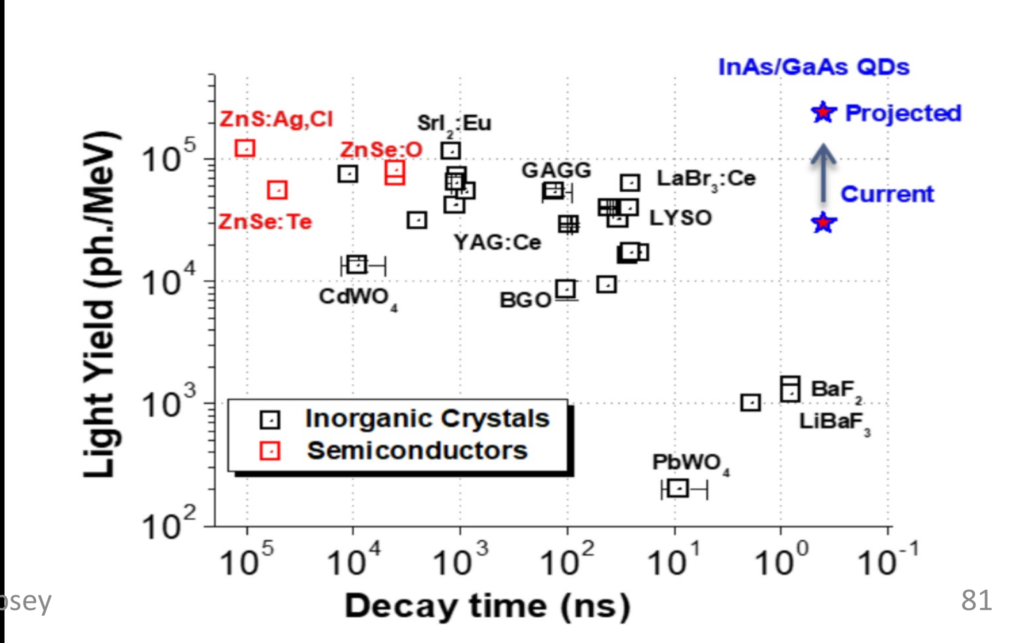


scintillating (chromatic) QD scintillating tracker





IR emission from InaAs QD
Integrated PD 1-2 micron thick

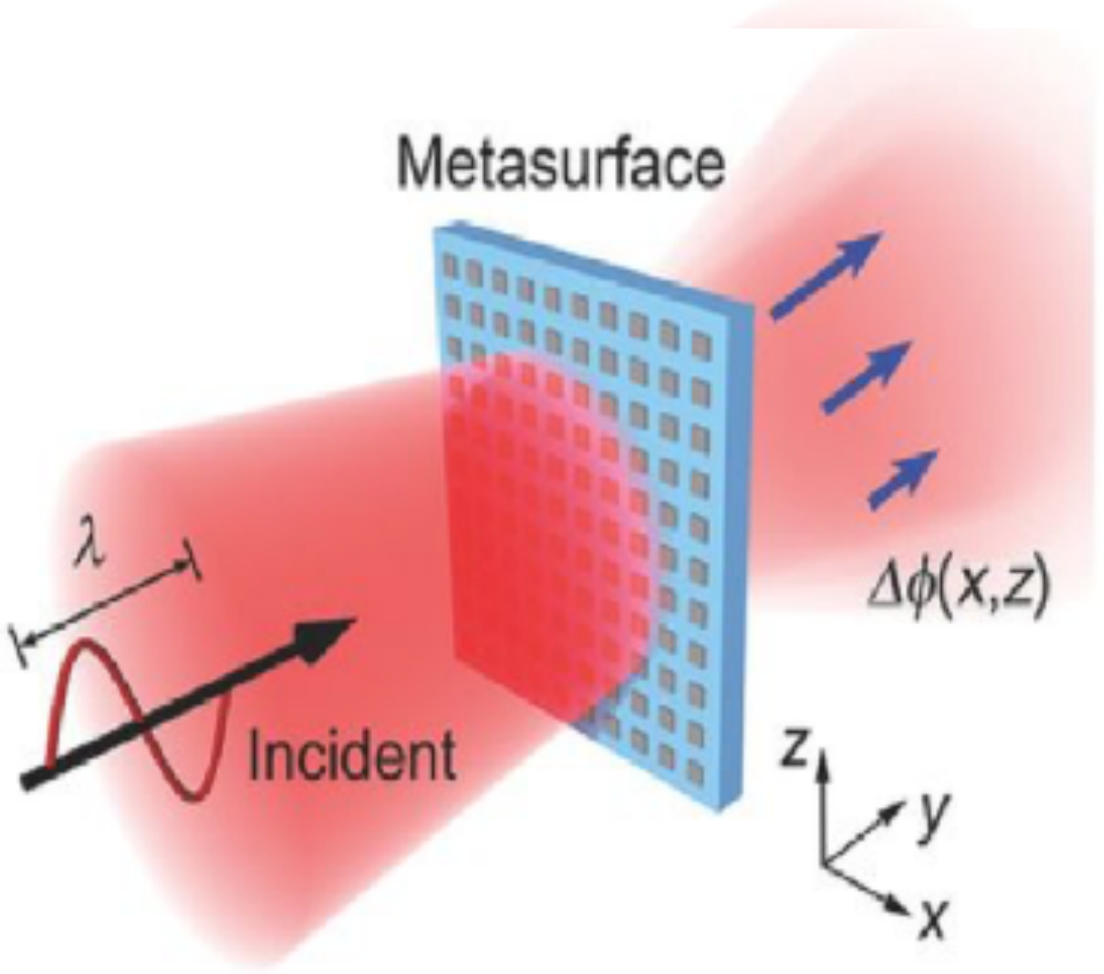


Metasurfaces and metalenses for HEP

Slide credit Roxanne Guenette

Metasurfaces (nanophotonics)

- Arrays of sub-wavelength spaced nanostructure that can manipulate light wavefronts
- Can control phase, amplitude and polarization state of transmitted light
- Optically **thin and light**
- **Low cost**, mass production (e-beam lithography or nano-imprints)
- Extremely versatile (which requires **dedicated design** for different applications)



Kim, K.-H., Jung, G.-H., Lee, S.-J., Park, H.-G. and Park, Q.-H. (2016), Ultrathin Capacitive Metasurfaces for Strong Electric Response. Advanced Optical Materials, 4: 1501-1506. https://doi.org/10.1002/adom.201600146

Slide credit Roxanne Guenette

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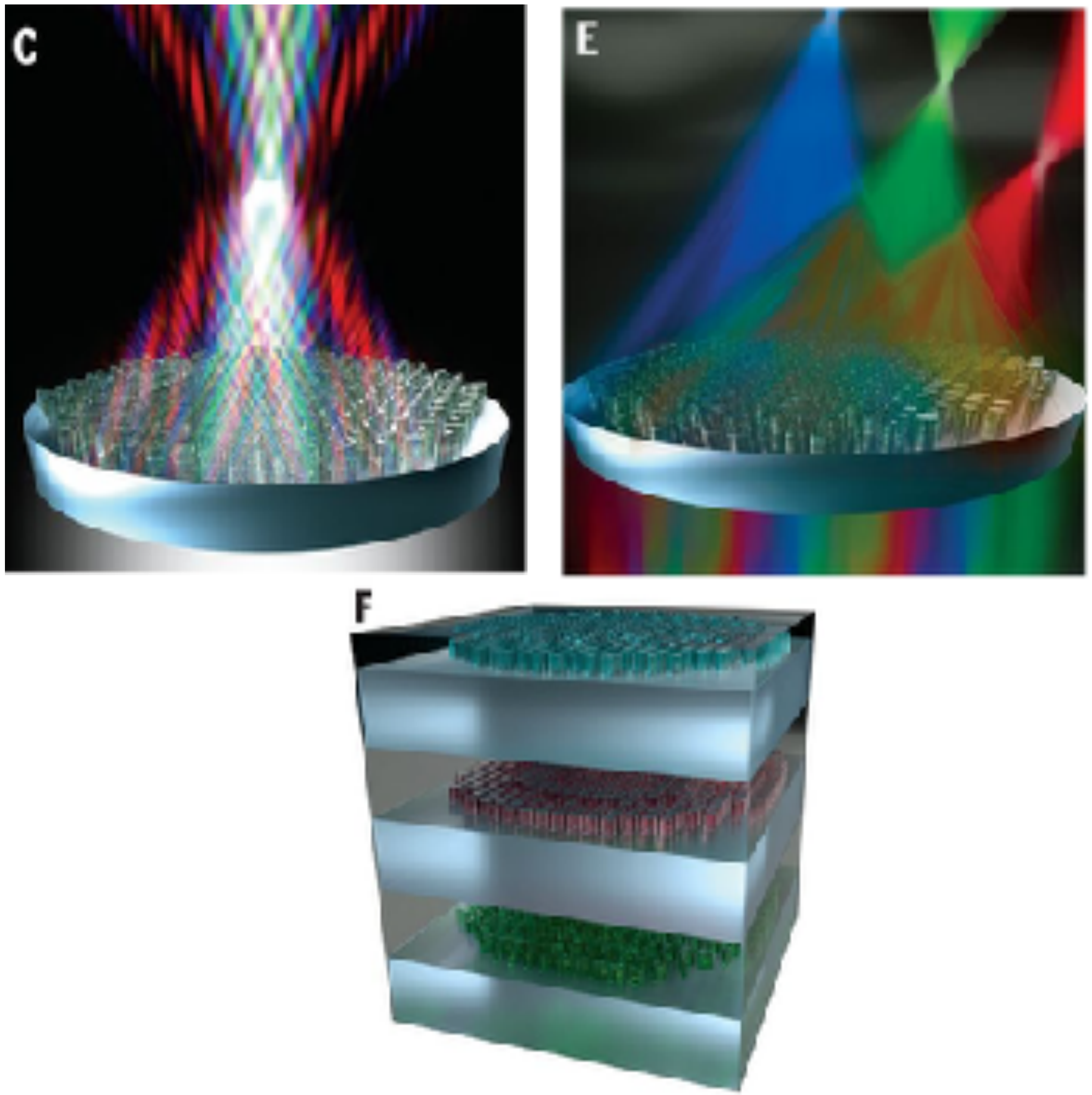
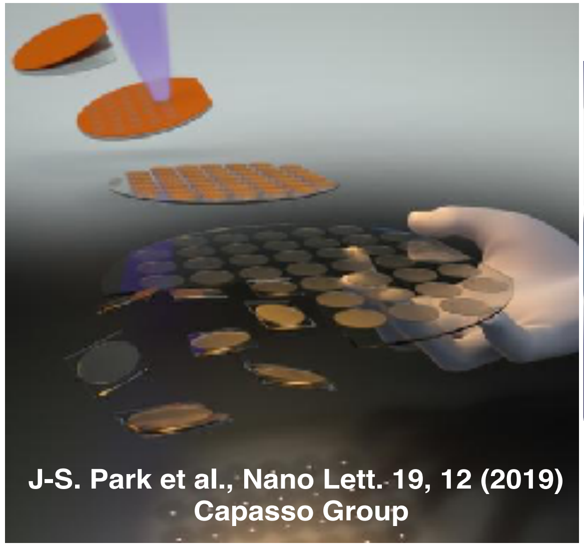


M. Khorasanineiad & F. Capasso. Science 358. 6367 (2017)

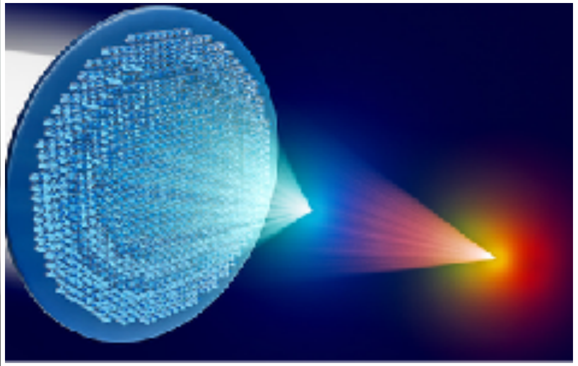
Slide credit Roxanne Guenette

Huge range of applications

- Light focusing (metalenses)
  - ✳Very large area metalenses (up to ~10cm)
  - ✳Wavelength separation
  - ✳Diffraction-limited images
  - ✳Correction for chromatic aberrations
  - ✳….



J-S. Park et al., Nano Lett. 19, 12 (2019)
Capasso Group

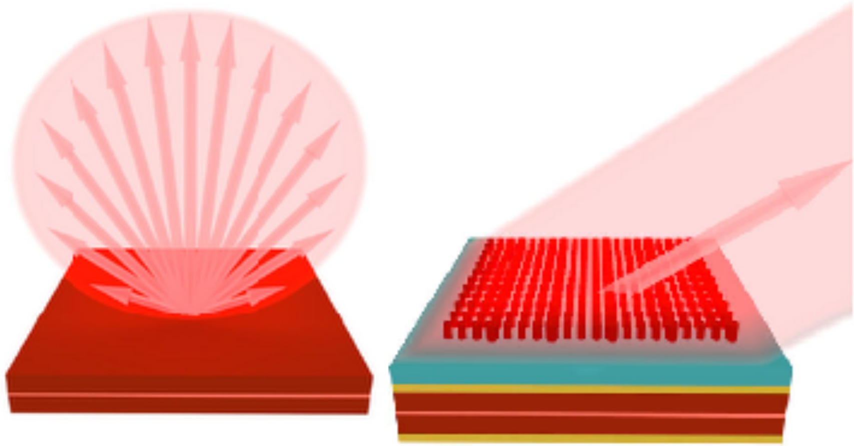


J. Sisler, APL Photonics (2020)
Capasso Group

- Shaping light re-emission profiles

- Light emission enhancements or resonators (Purcell effect)

Phys. Rev. B 92, 195127 (2015)

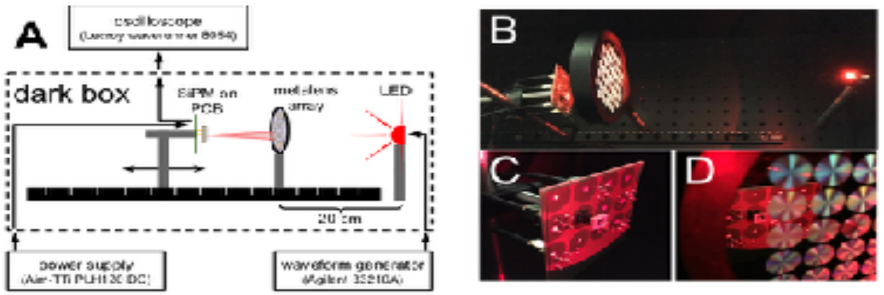


E. Khaidarov et al., Laser Photonics Rev., 1900235 (2019)

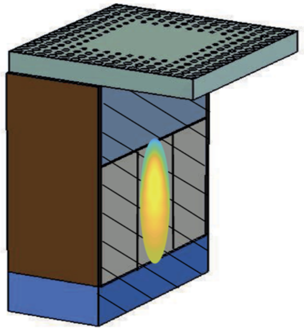
- And more!

Applications to HEP detectors

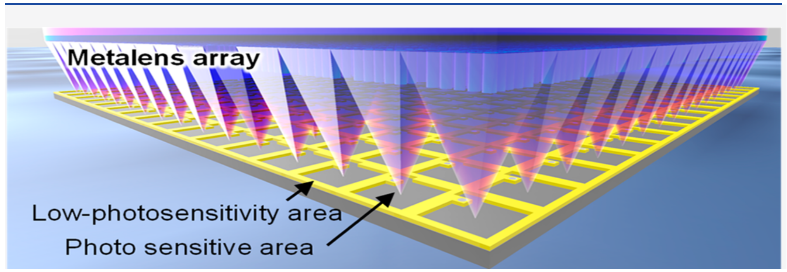
- Combining metalenses to SiPMs (to increase light collection with small SiPMs and/or to correct for dead-space)



A.A. Loya Villalpando et al., (2020), JINST 15, P11021.



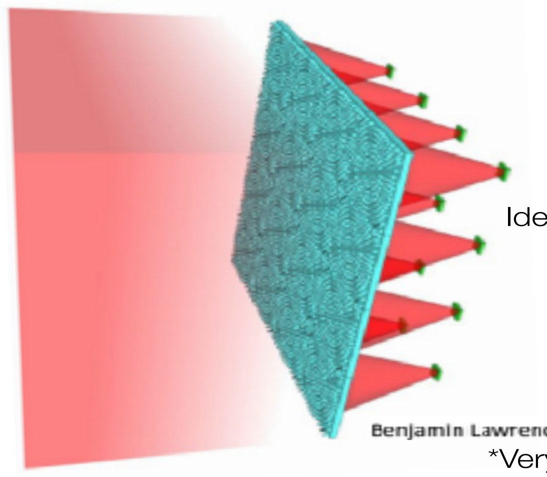
E. Mikheva et al., APL Photonics 5, 116105 (2020)
FBK+CERN



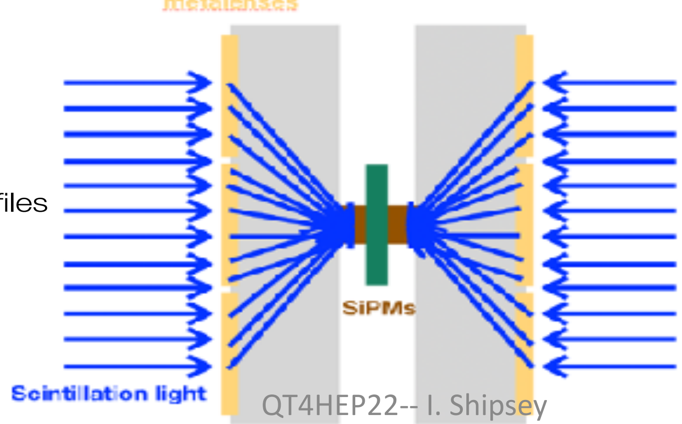
S. Uenoyama et al., ACS Photonics 8 (2021)
Hamamatsu

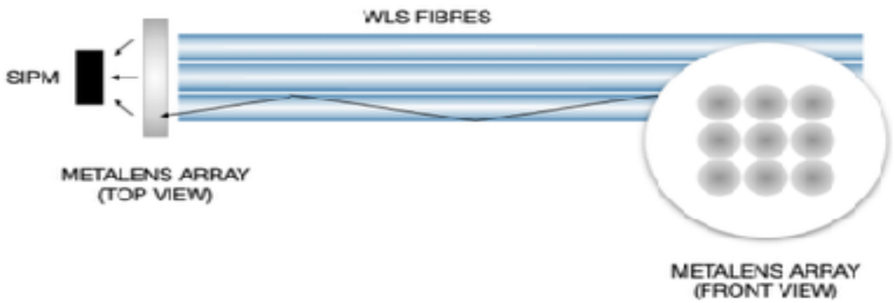
- Different detector concepts under study:

one-to-one



many-to-one



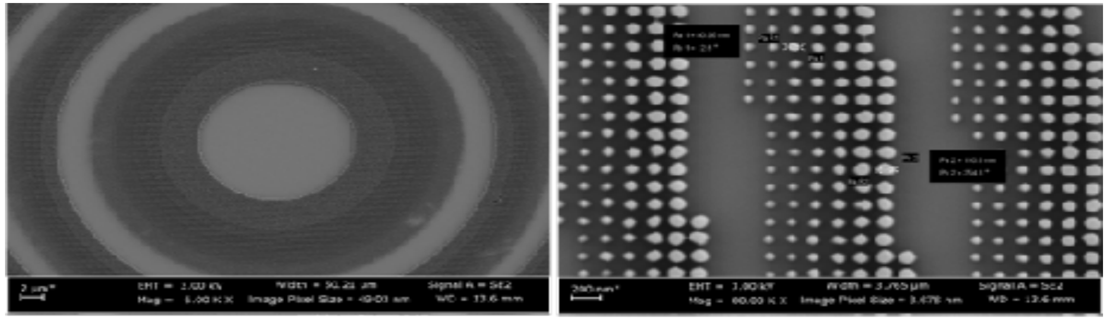


*Very sensitive to arrival angles of photons

Slide credit Roxanne Guenette

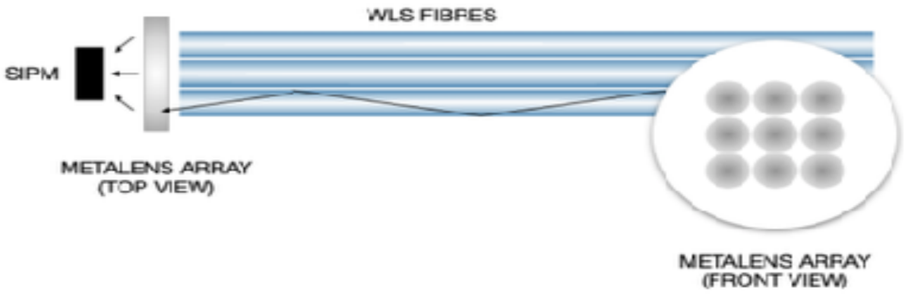
Recent developments

- Fabrication of a 175nm metalense (shortest wavelength to date)

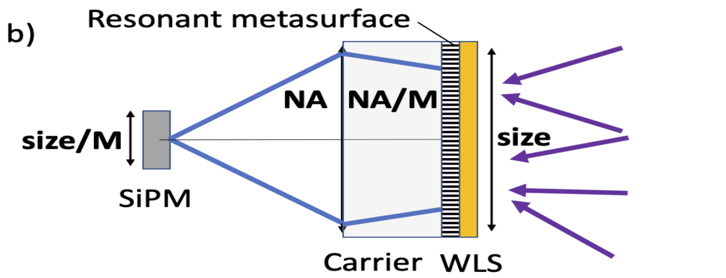


A.Martins (Guenette & Capasso groups)

- Fabrication of metalense array to combine to optic fibers



- Design of resonating cavity metasurface to enhance wavelength shifting efficiency (TPB and other novel materials that can wavelength shift as metasurface)



Guenette (Manchester) & Krauss (York) groups

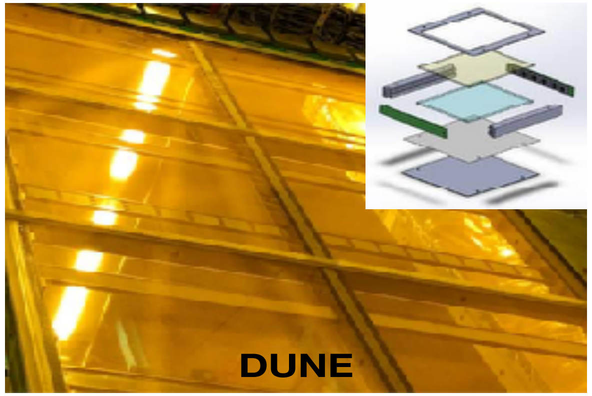
Slide credit Roxanne Guenette

Future of metasurfaces in HEP

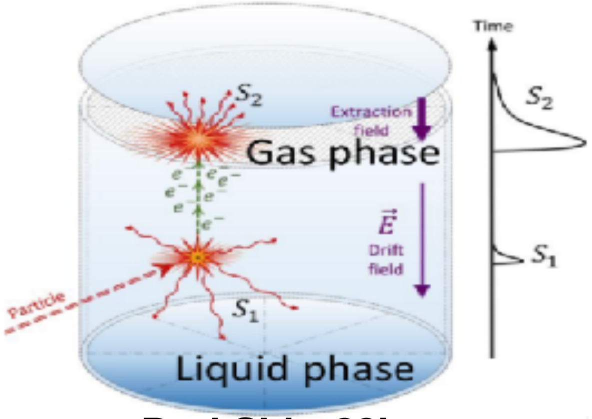
- The huge range of applications and capabilities of metasurfaces (and the low cost / mass production potential) make them very attractive for large scale detectors

- R&D for applications to HEP has just started and several avenues are being pursued. The challenges are to tailor the metasurface design to the exact detector concept

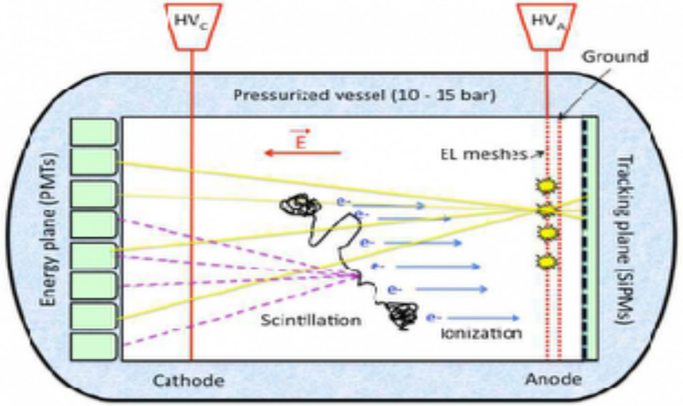
- Each detector has its own light profile, light collection area needs, detection wavelengths…



DUNE



DarkSide-20k

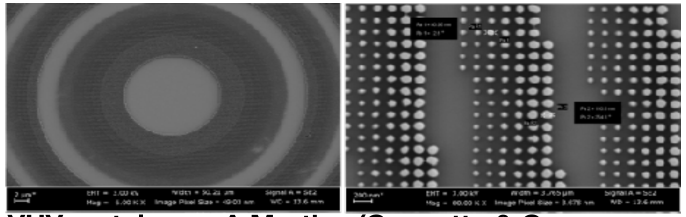


NEXT

Slide credit Roxanne Guenette

Future of metasurfaces in HEP

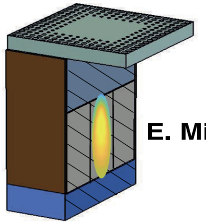
- Metasurfaces could be game changing for many detector applications and directly address many of the future needs identifies by community reports (DOE BRN, ECFA R&D Roadmap, SNOWMASS)



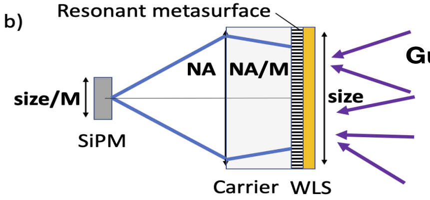
First VUV metalense: A.Martins (Guenette & Capasso groups)

✓Noble Element detectors

✓SiPMs efficiency

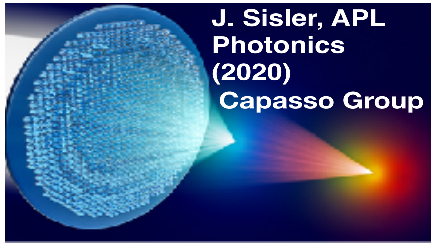


E. Mikheva et al., APL Photonics 5, 116105 (2020)
FBK+CERN



Guenette (Manchester) & Krauss (York) groups

✓Wavelength shifting efficiency

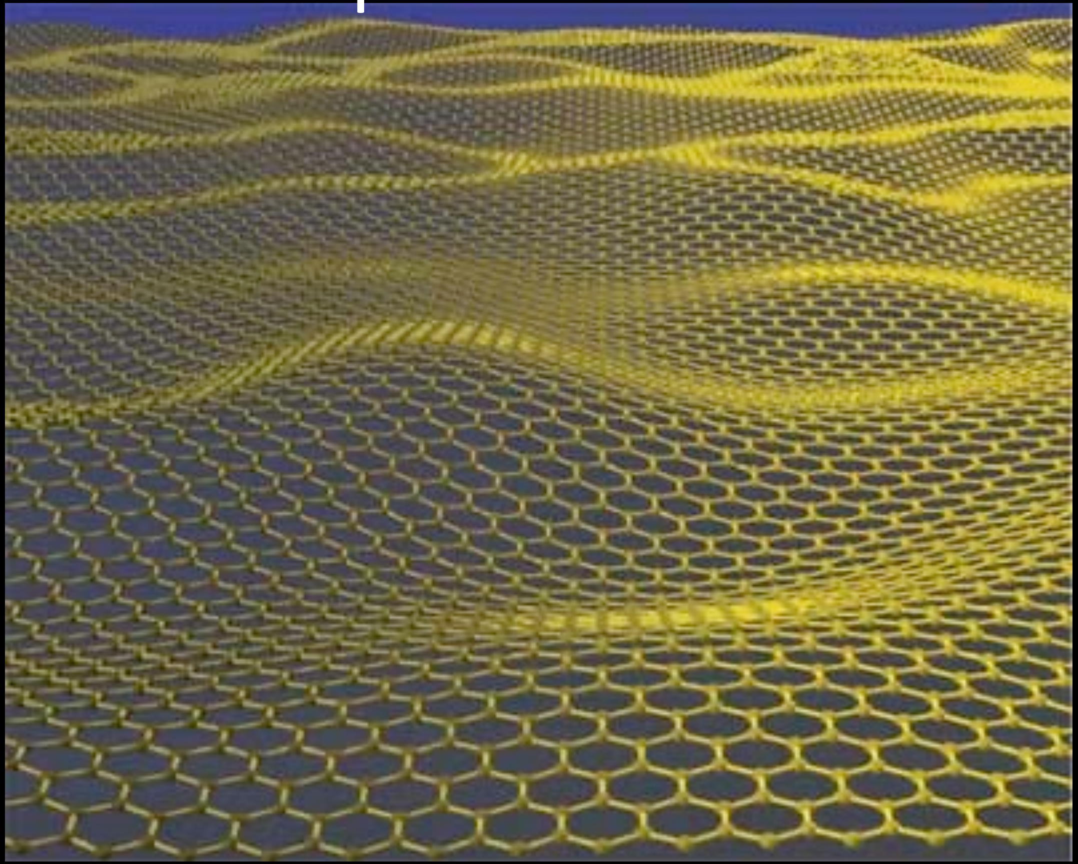


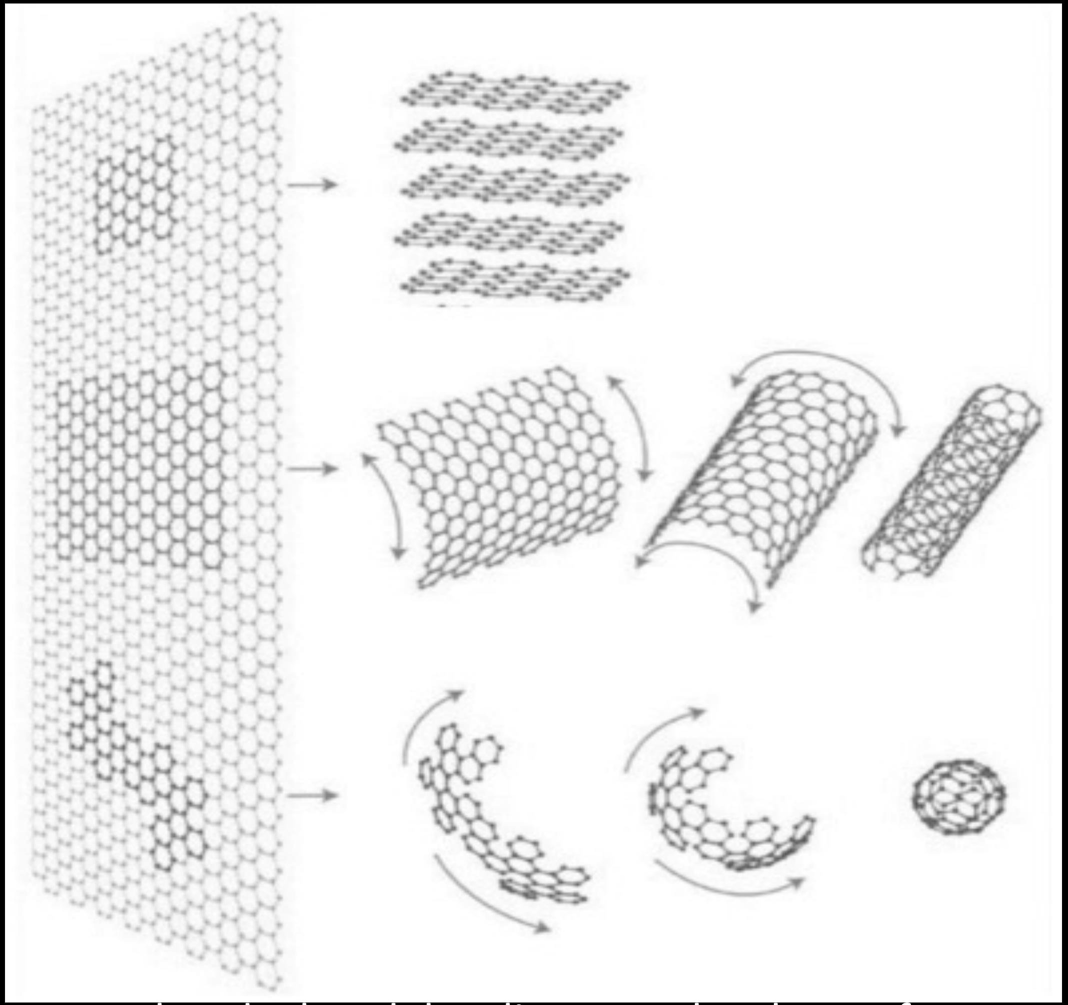
✓Wavelength separation (Scintillation and Cherenkov)

- Dedicated R&D needed **in collaboration with nanophotonics experts** to identify solutions

Slide credit Roxanne Guenette

Graphene





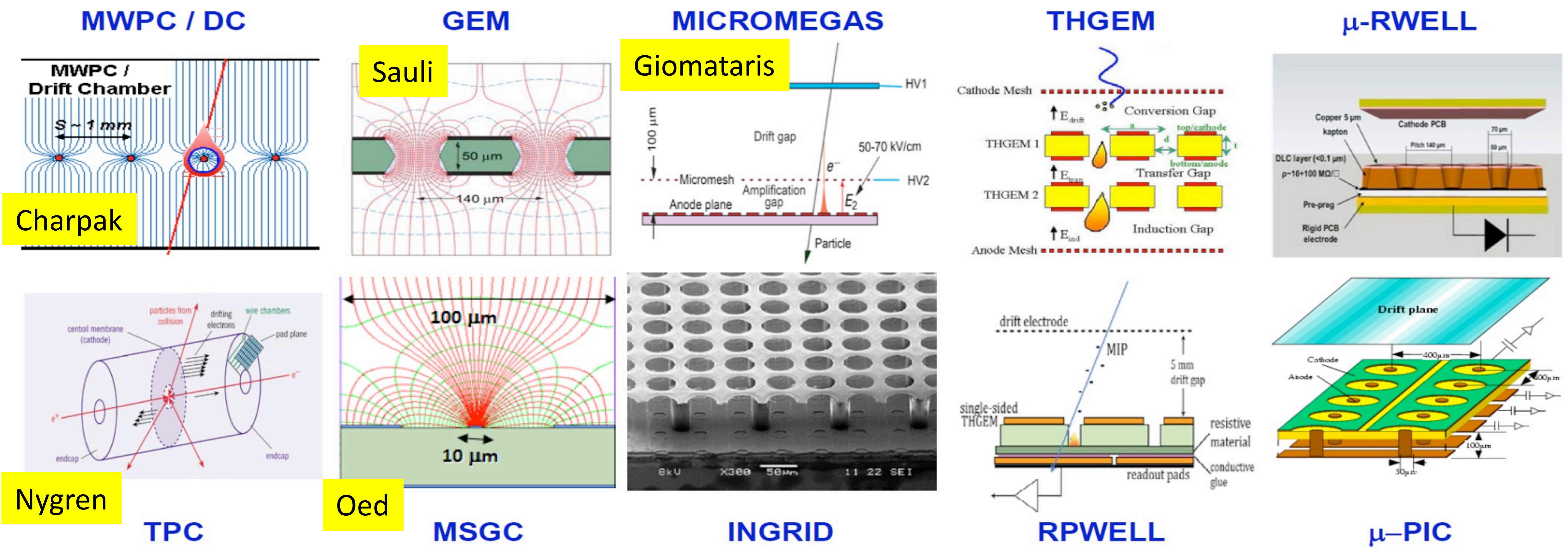
graphene properties originate from the 2p orbitals, which form the π state bands that delocalize over the sheet of carbons that constitute graphene.

Electron mobility X100 Si; heat conduction x2 Diamond, electron conductivity x 13 Cu,   it absorbs only 2.3% of reflected light; impermeable to He; strongest material known: harder than diamond more elastic than rubber, high surface area of 2,630 m2/g.

- **Gaseous detectors:** from Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

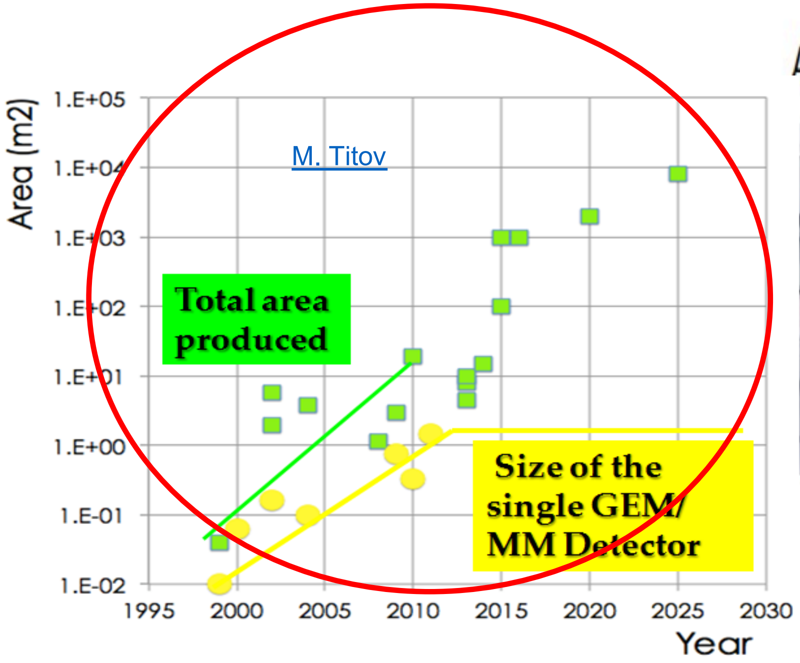
Evolution over 50 years

- Primary choice for large-area coverage with low material budget

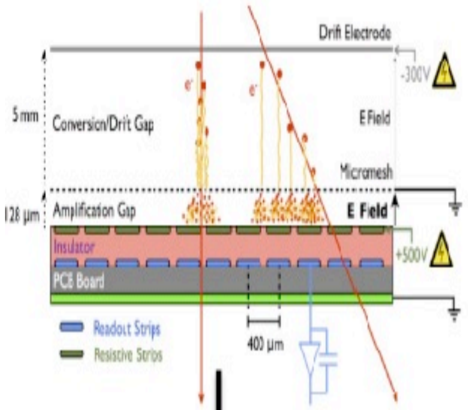


Gaseous detectors: MPGD area increasing dramatically

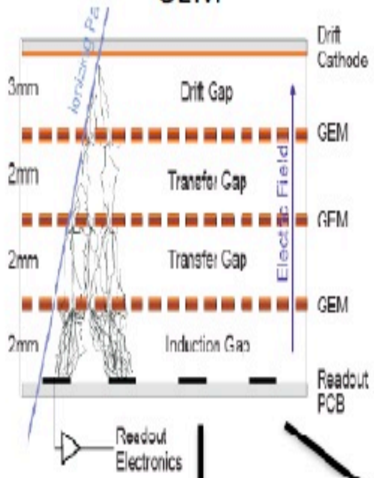
- **Upgrades to a number of systems used at the LHC** for tracking, muon spectroscopy and triggering have **taken advantage of the renaissance in gaseous detectors** (*esp* MPGDs)
- **New generation of TPCs use MPGD-based readout**: e.g. ALICE Upgrade, T2K, ILC, CepC



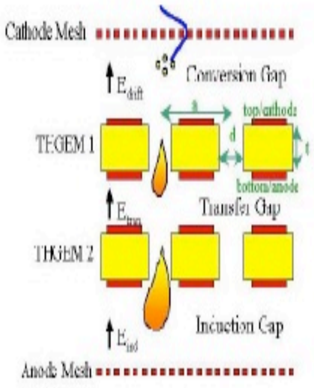
MicroMegas (MM)



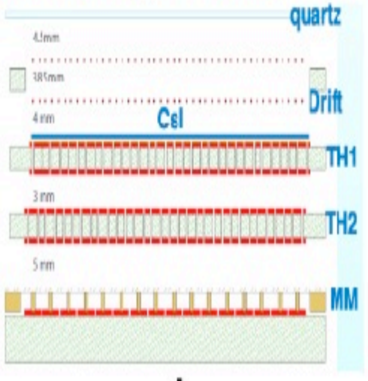
GEM



THGEM



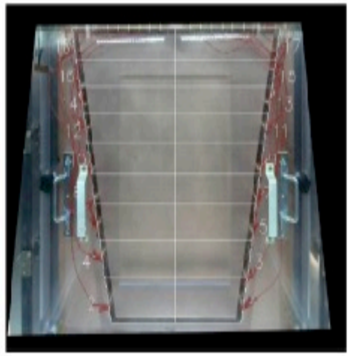
Hybrid design THGEM + MM



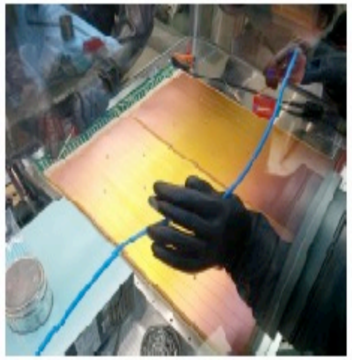
ATLAS new small wheels

CMS GEM

ALICE TPC upgrade



COMPASS RICH



From widely used MWPC to widely used MPGD has taken 50 years

Gaseous detectors: timing

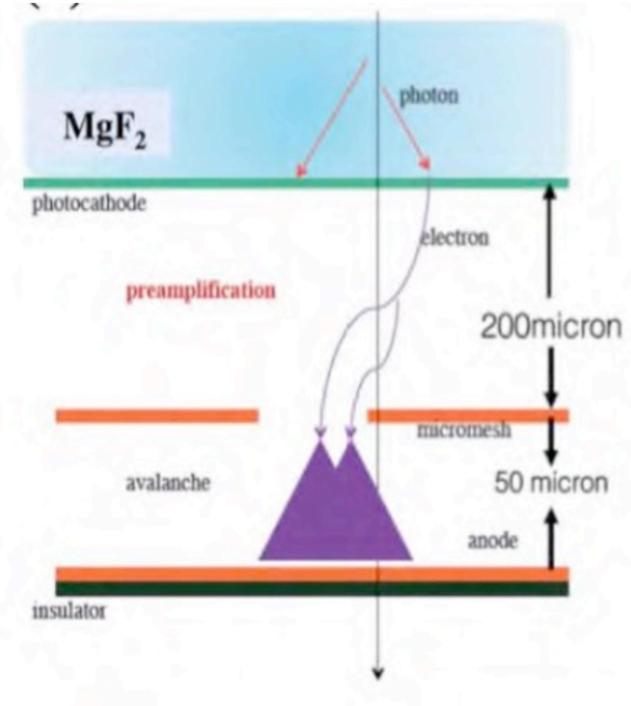
- **Gaseous detectors offer very competitive timing** through e.g.
  - **Multi-gap Resistive Plate Chambers** (down to 60 ps time resolution) (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)

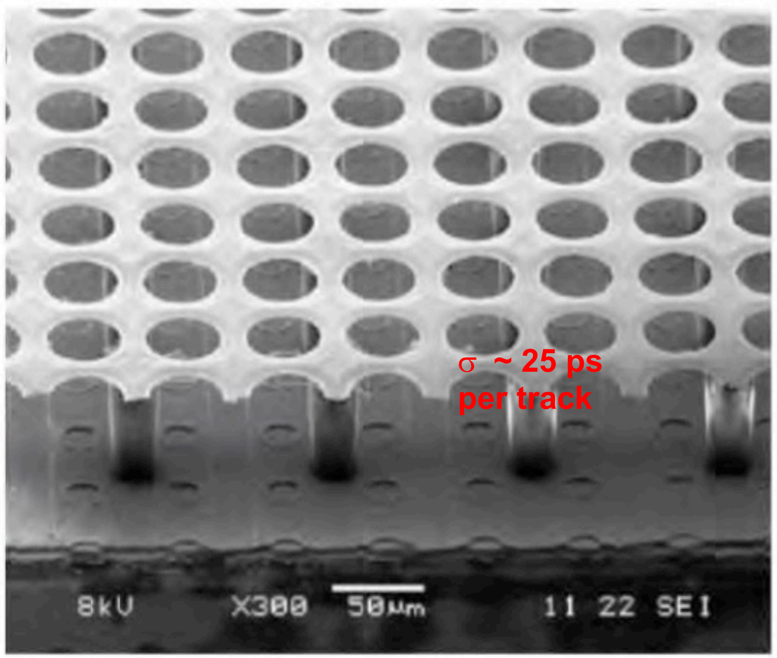
- An enabling emerging R&D: **Micromegas with timing** (PICOSEC concept)

→ Many developments emerged from the R&D studies within the RD51 Collaboration

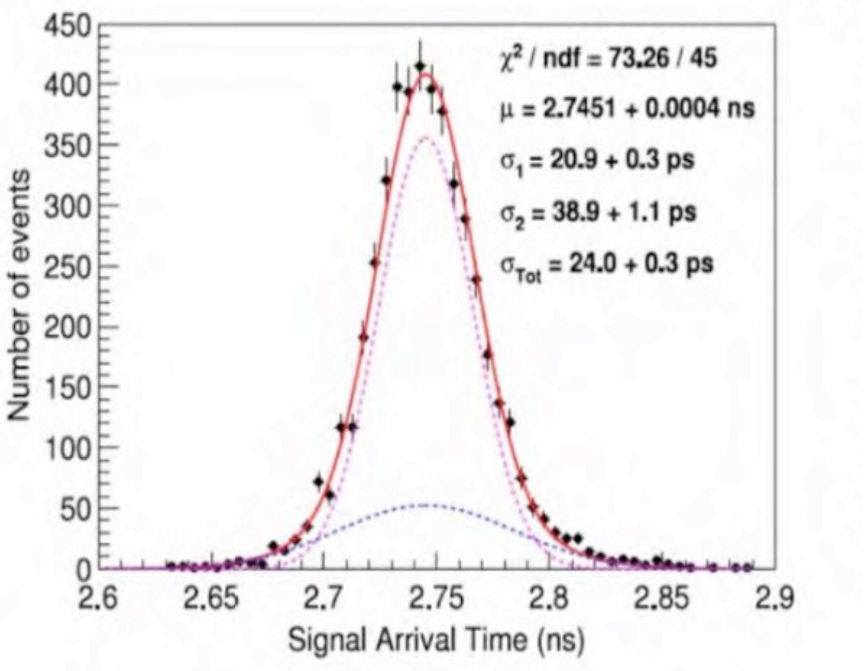
Cherenkov radiator + Photocathode + MM

J. Bortfeldt, NIM A903 (2018) 317





Timing (MIP test-beam):



Enhancement of Charge Conversion in Low Dimensional Materials

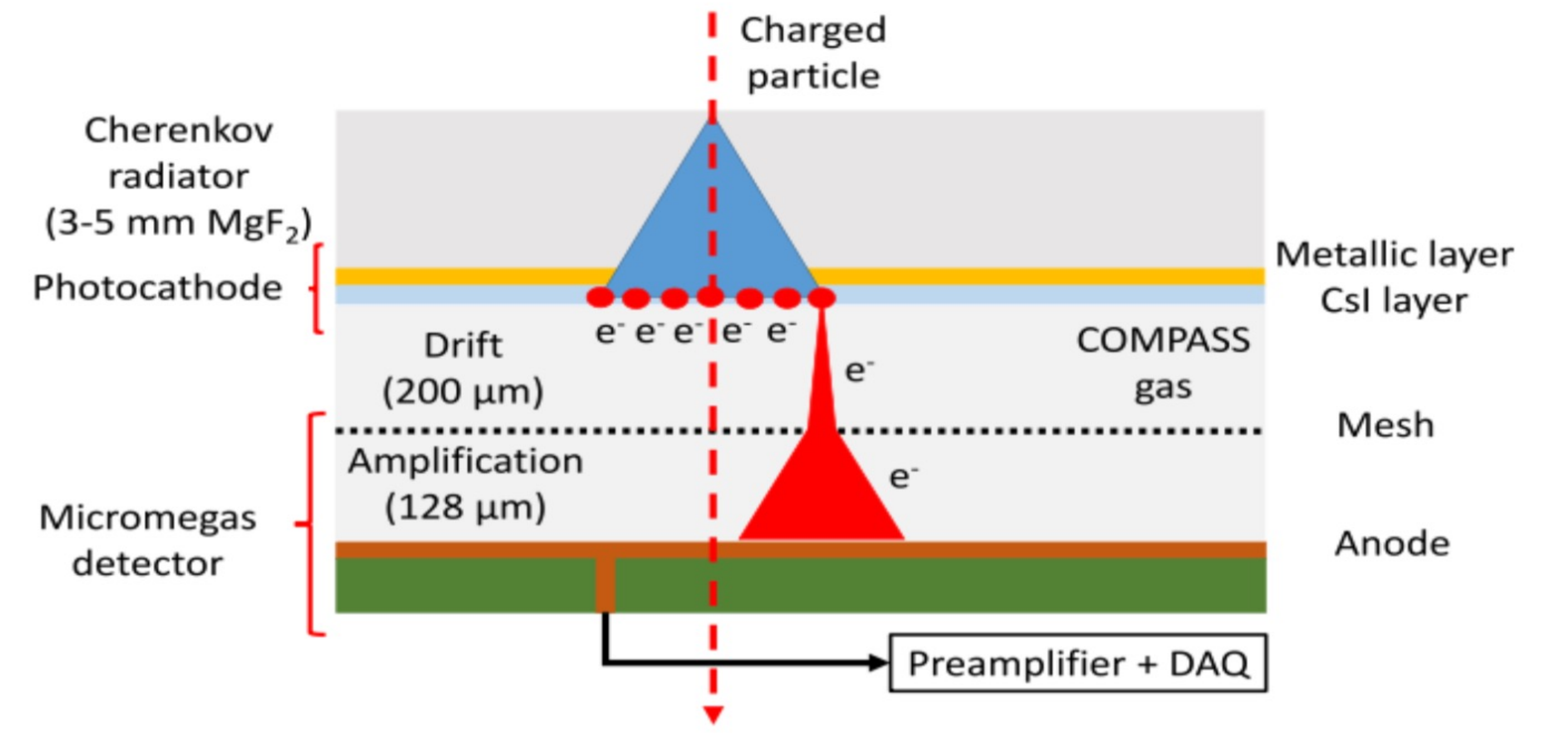


Fig. 1. Schema of the first PICOSEC prototype. In beam tests, a charged particle produces UV photons when passing through the Cherenkov radiator. These photons are then absorbed at the photocathode and partially converted to photoelectrons. In laser tests, the laser impacts on the photocathode and produces single photoelectrons. In both cases, photoelectrons are amplified in the two stages of the Micromegas detector (drift and amplification gaps), and the secondary electrons induce a fast signal in the anode. The Micromegas detector is filled with COMPASS gas at 1 bar absolute pressure.

Micropattern
Gas Detector
PICOSEC
achieves <25ps
time time resolution

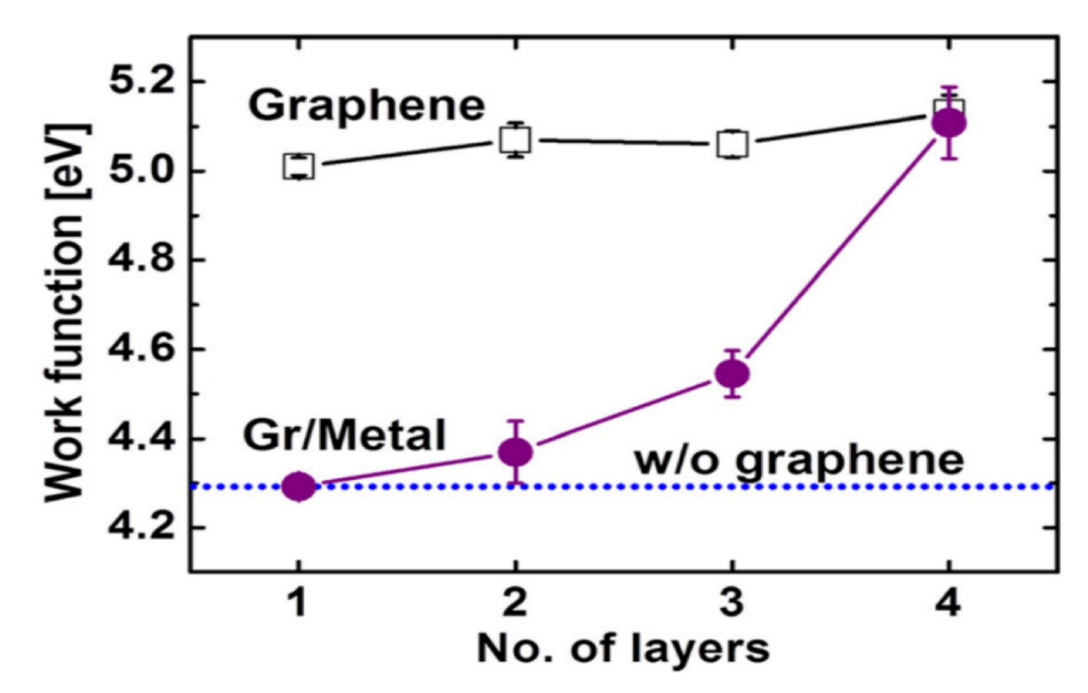
The efficiency of the photocathode directly
Translates to achievable timing resolution

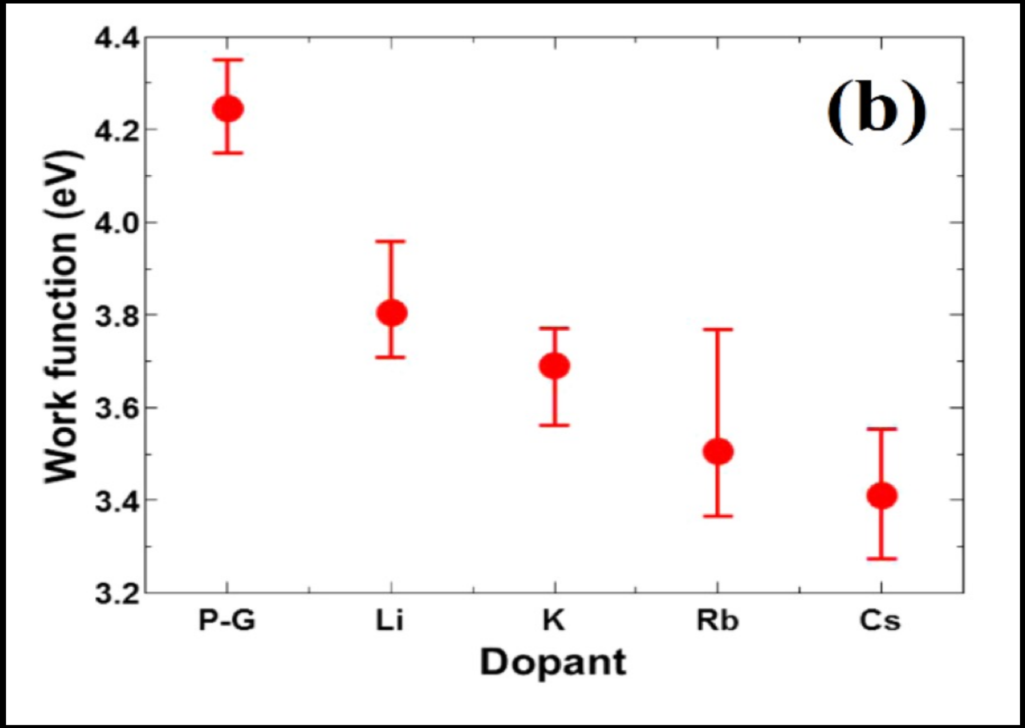
An enhancement of photocathode QE
by resonant processes in low dimensional structures has shown promising results

MPGDs use of 2-D materials to improve.

- tailor the primary charge production process,
- protect sensitive photocathodes in harsh environments

#1 Tune the workfunction





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

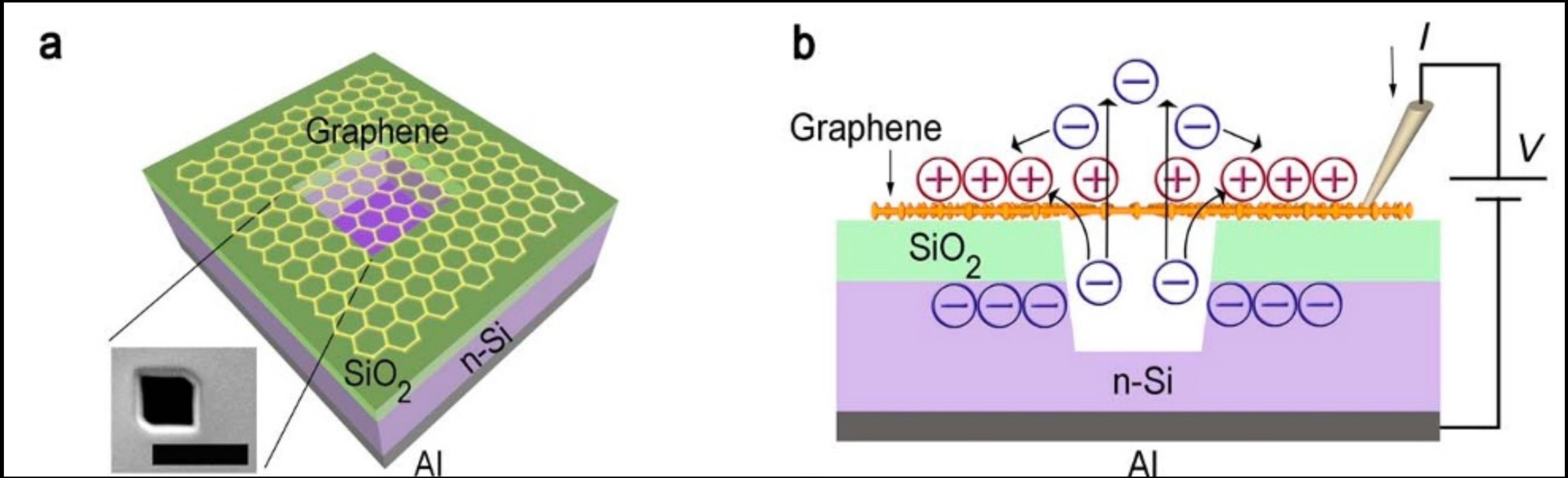
(additionally, encapsulation of semiconductive as well as metallic (i.e. Cu) photocathodes increases operational lifetime)

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

MPGDs use of 2-D materials to improve.

- improve the performance of the amplification stage

#2 Amplification

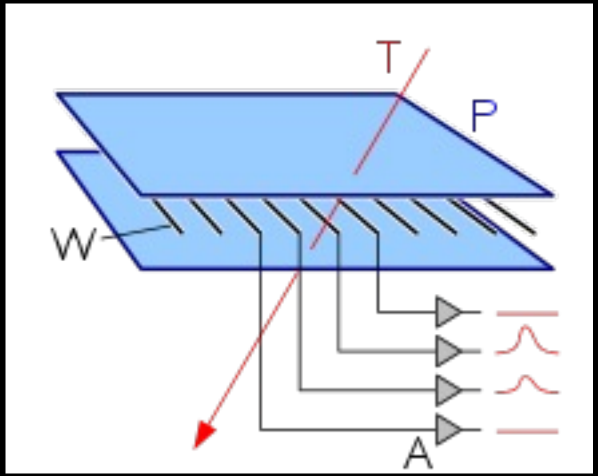


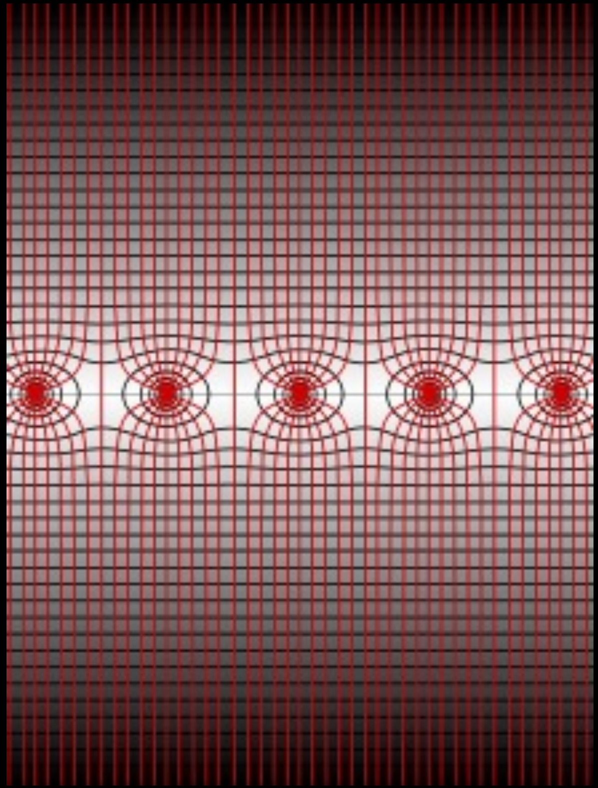
back flow of positive ions created during charge amplification to the drift region can lead to significant distortions of electric fields

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

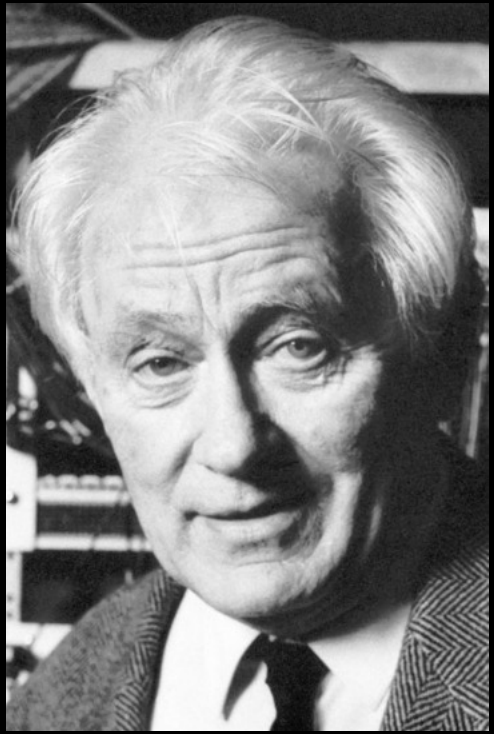
Space charge neutralization by electron-transparent suspended graphene, Siwapon Srisonphan, Myungji Kim & Hong Koo Kim, Scientific Reports 4, 3764 (2014)

Gaseous Detectors
Multiwire Proportional Chamber
1960’s



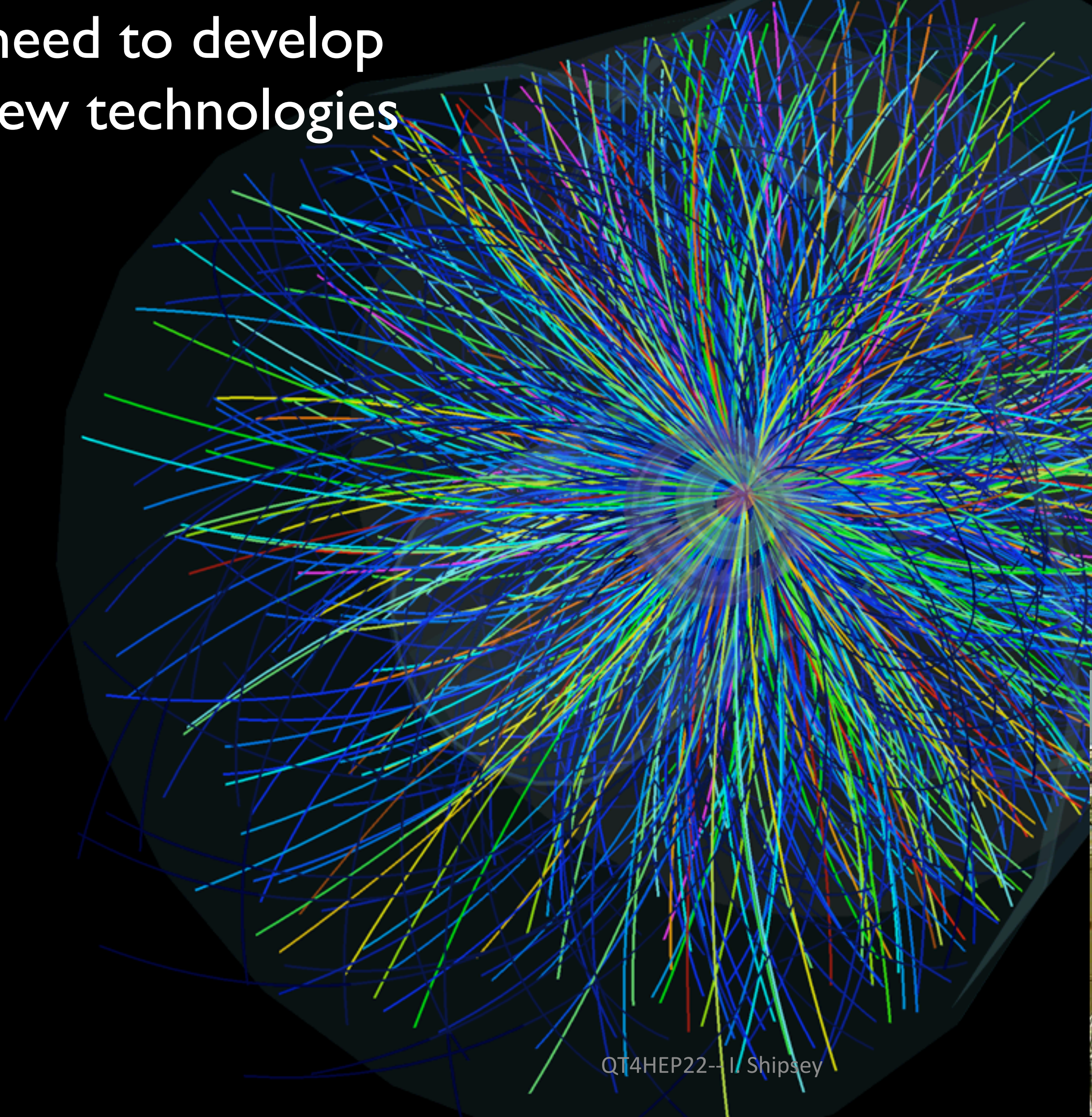


The Nobel Prize in Physics 1992 was awarded to Georges Charpak "for his invention and development of particle detectors, in particular the multiwire proportional chamber."



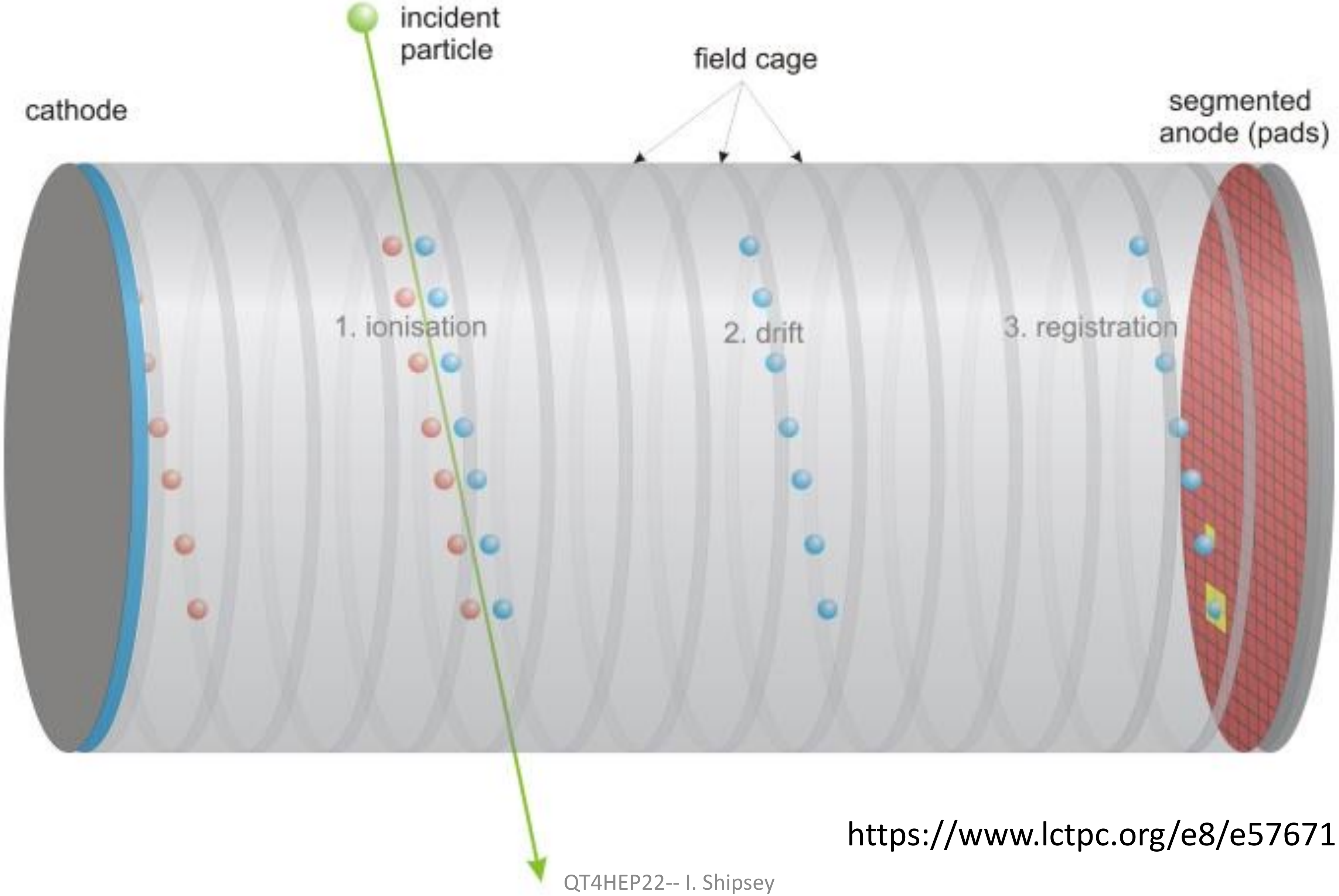
need to develop
new technologies

TPC
1970s



TPC

TPC

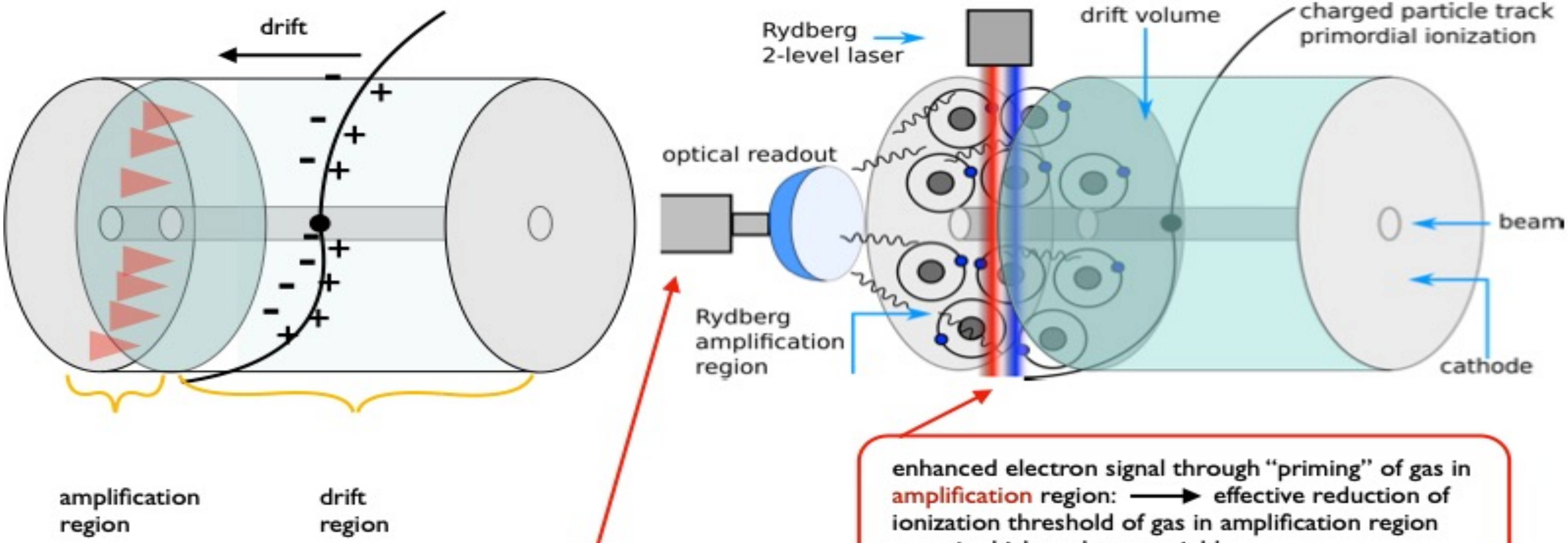


https://www.lctpc.org/e8/e57671

Rydberg atom TPC’s

Georgy Kornakov / WUT

Act on the amplification region



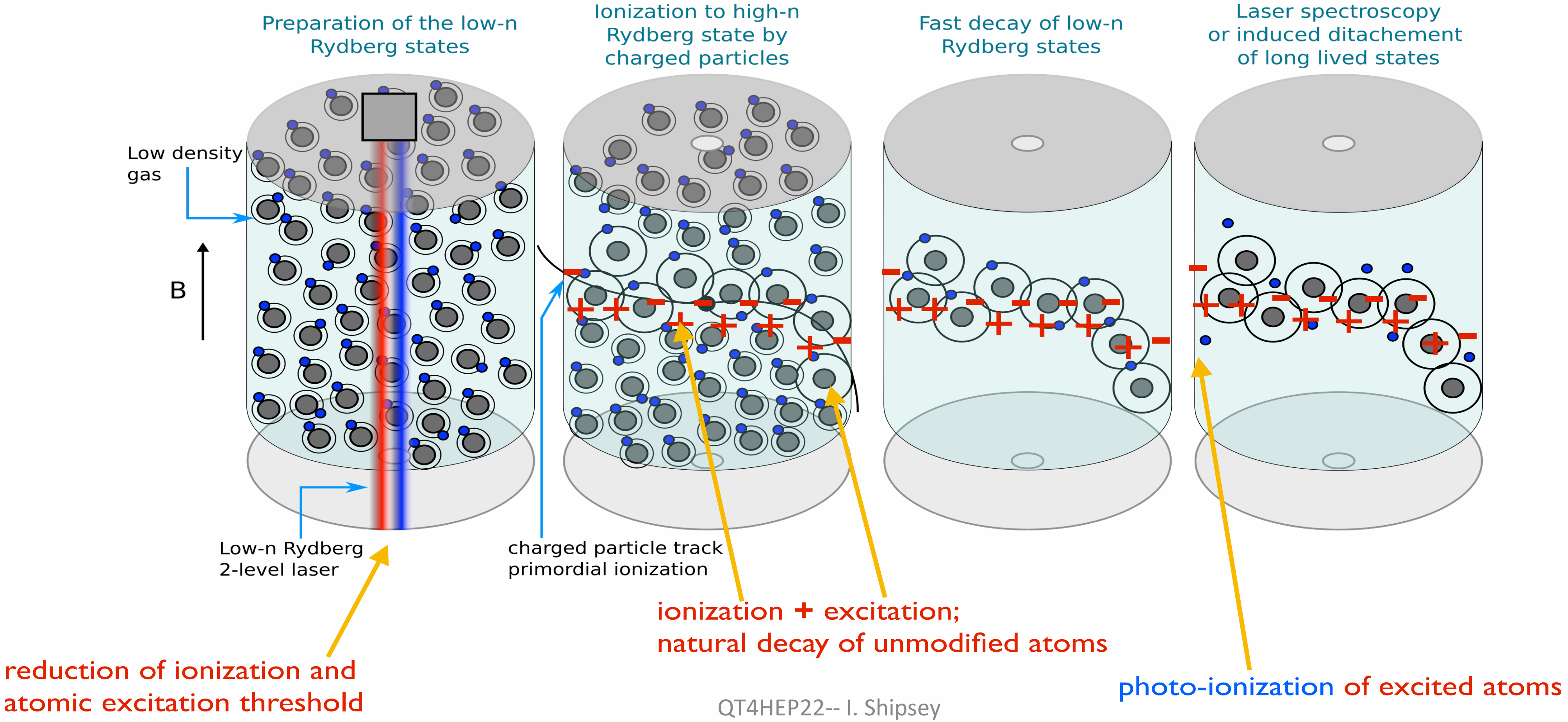
enhanced electron signal through “priming” of gas in amplification region: ⟶ effective reduction of ionization threshold of gas in amplification region ⟶ higher electron yield

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

Rydberg Tracking Chamber

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 amplification region
increased dE/dx through standard primary ionization + photo-ionization of atoms excited by mip's

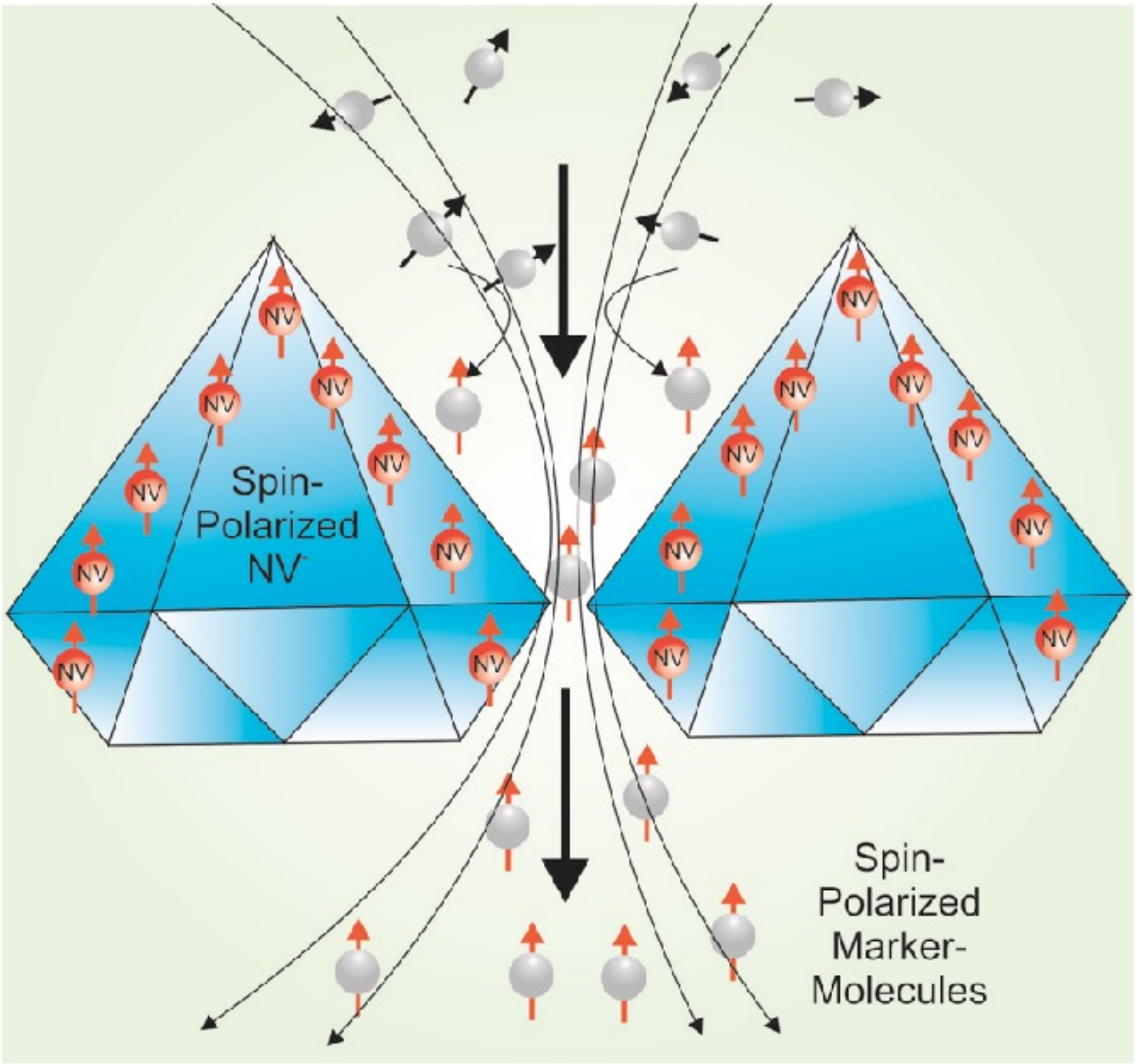


Diagnosing cardiovascular diseases through the use of diamond. The technique, called hyperpolarisation, utilises defects in diamond's quantum properties to transfer *spin* to molecules that are used to improve MRI images in patients

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

optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

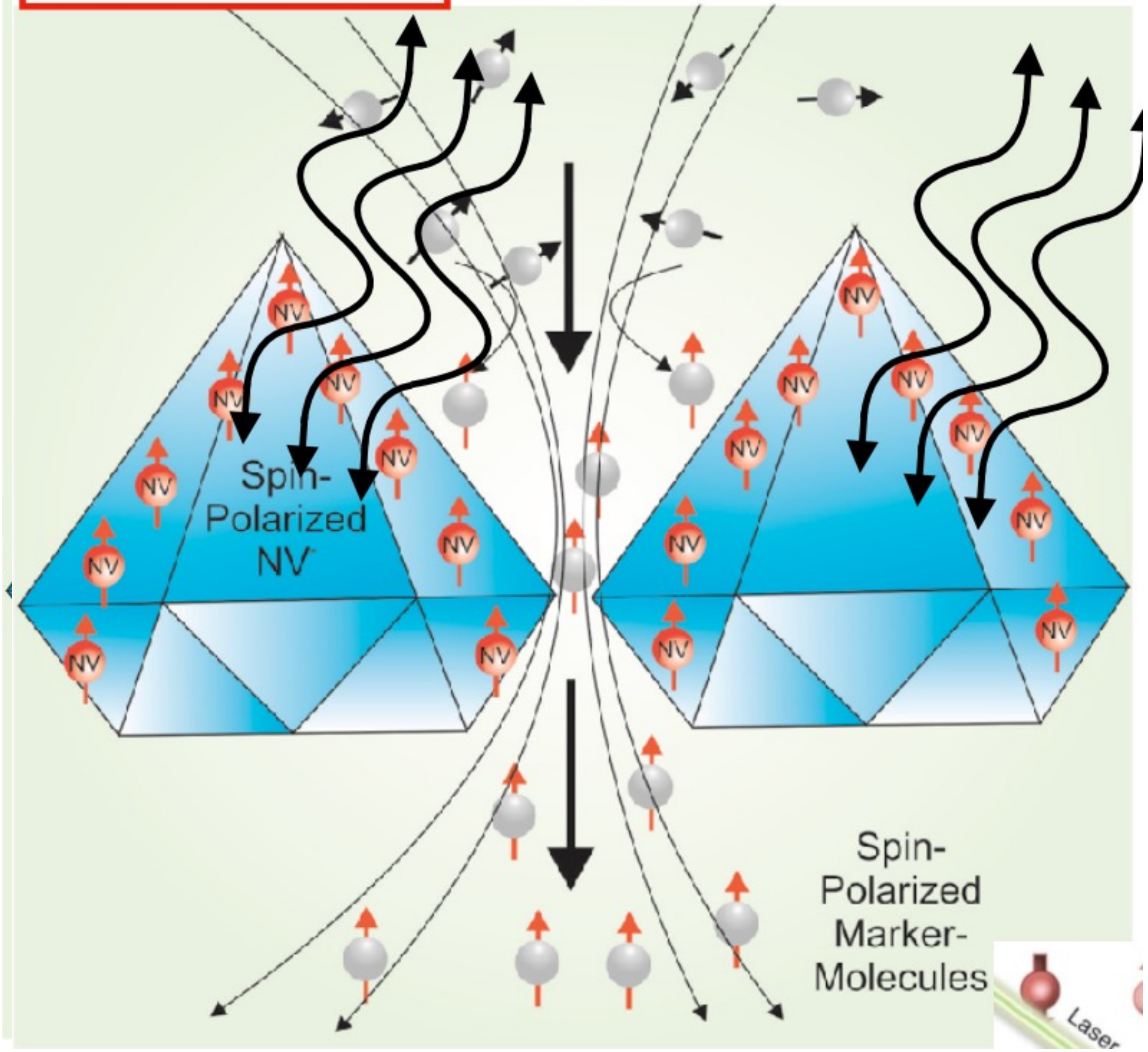


https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

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



optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

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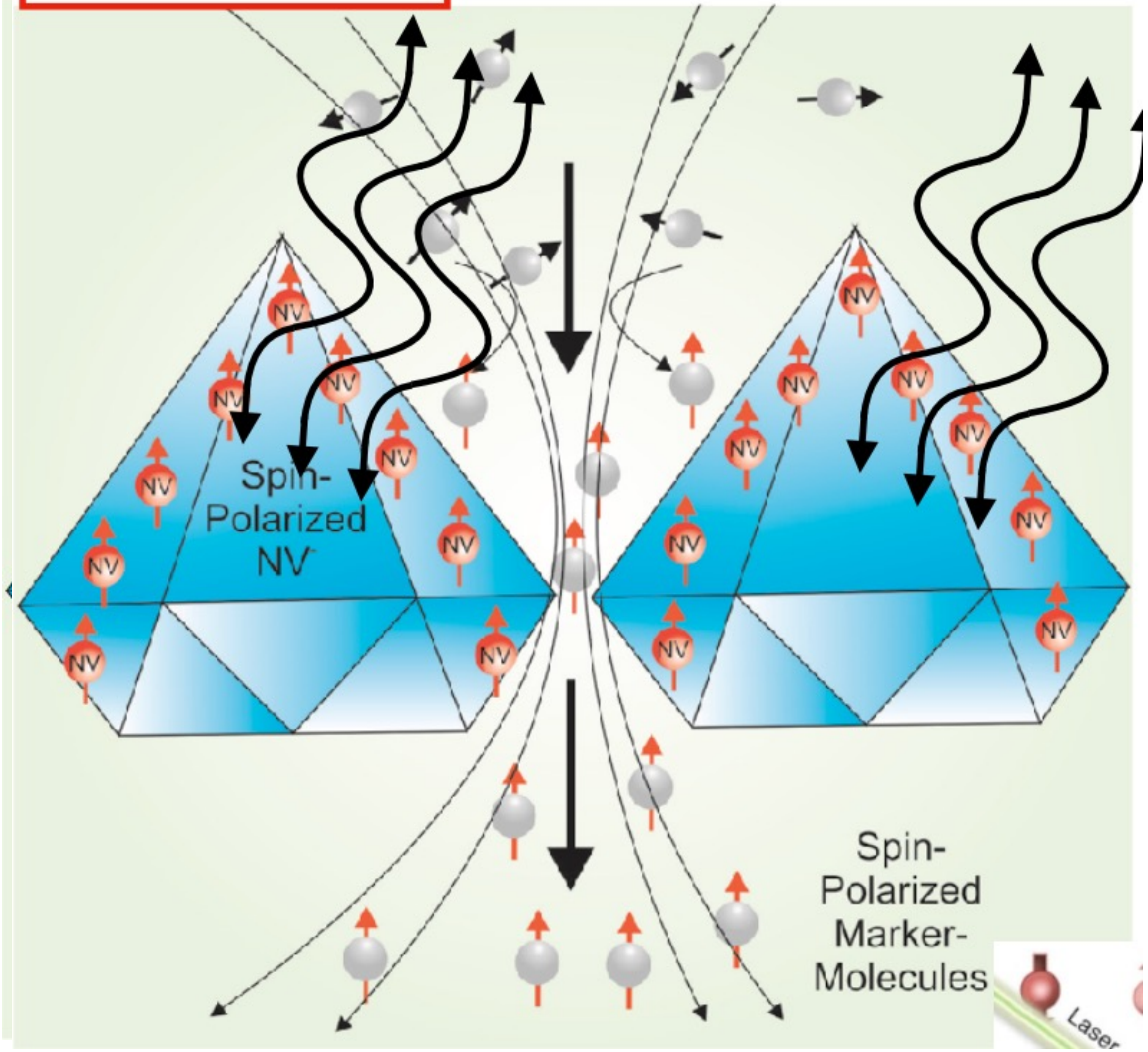
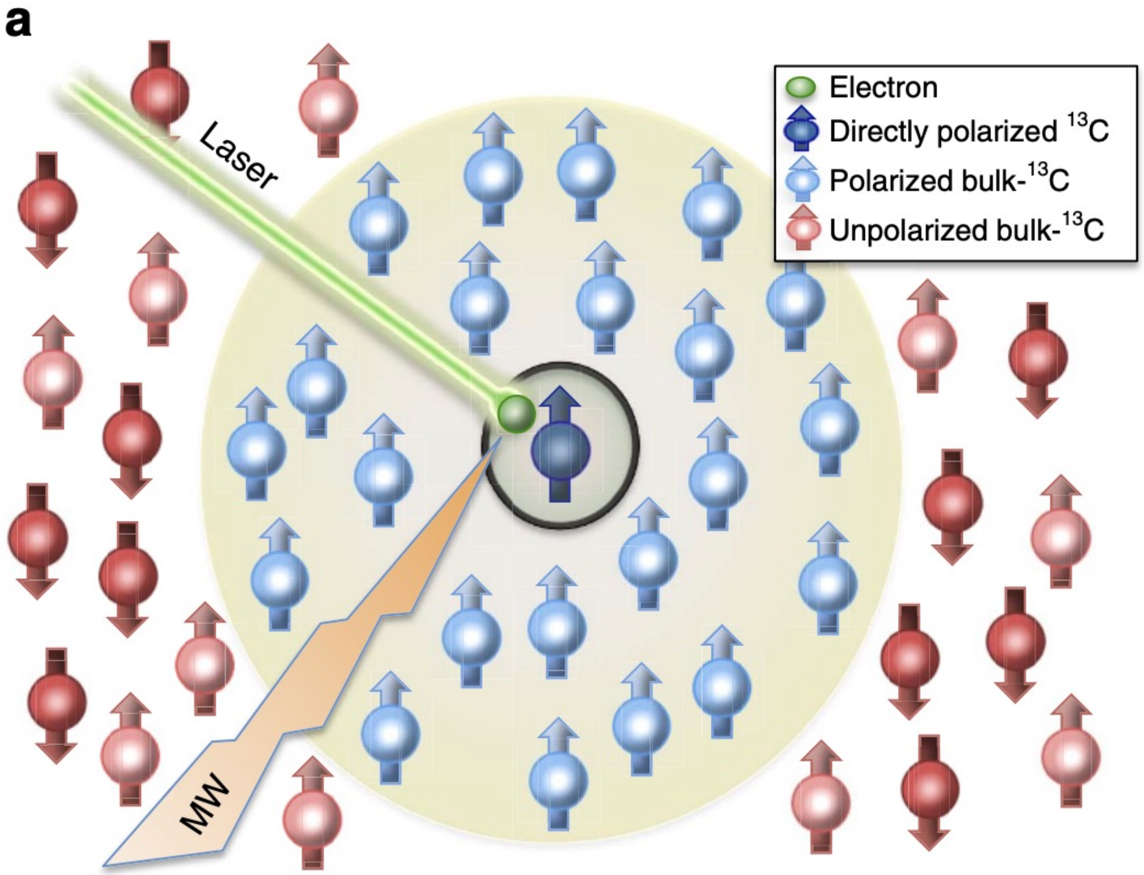




x 10^2

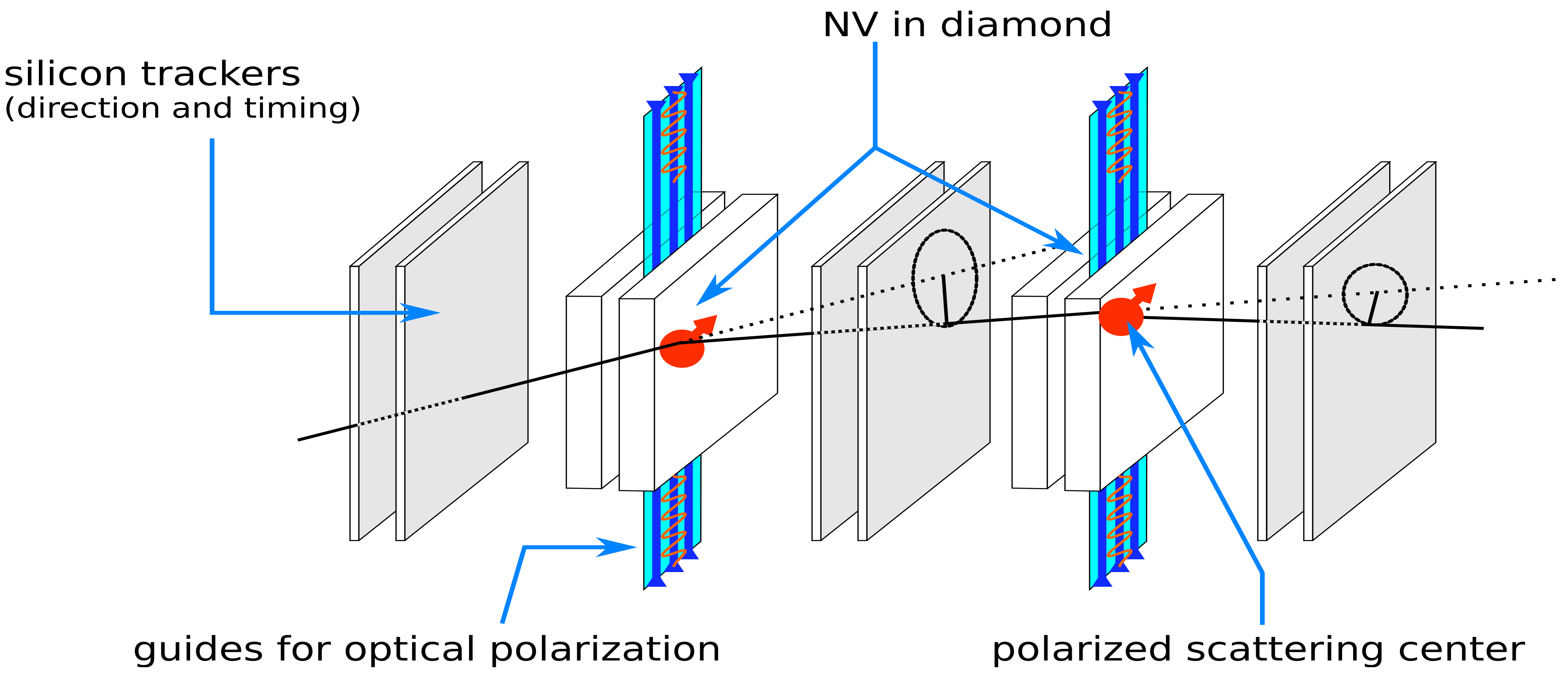
Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)
https://www.nature.com/articles/ncomms9456

optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

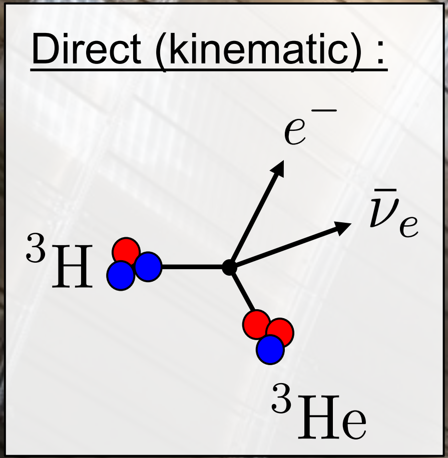
Georgy Kornakov / WUT

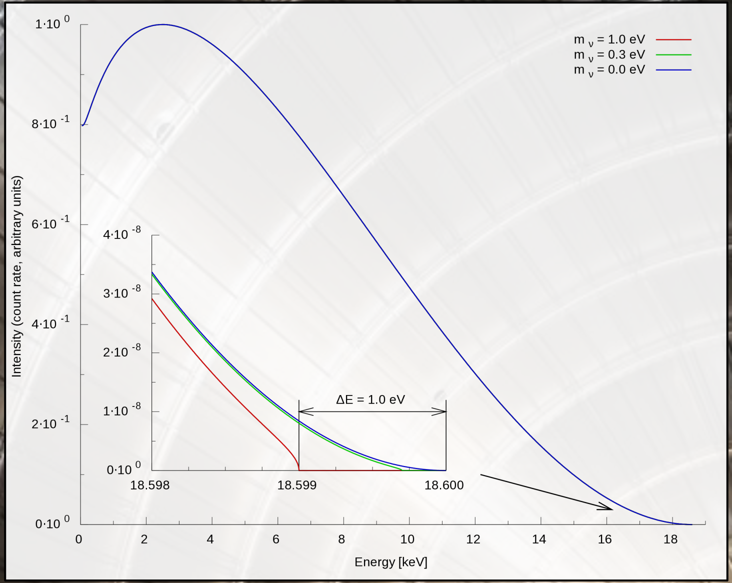
spin-spin scattering for helicity determination: usually with polarized beams and/or polarized targets or self-analysing decays like the /\.

introduce polarized scattering planes to extract track-by-track particle helicity to learn a great deal about standard model particles that have not previously been studied in this way



Direct Neutrino Mass Measurement

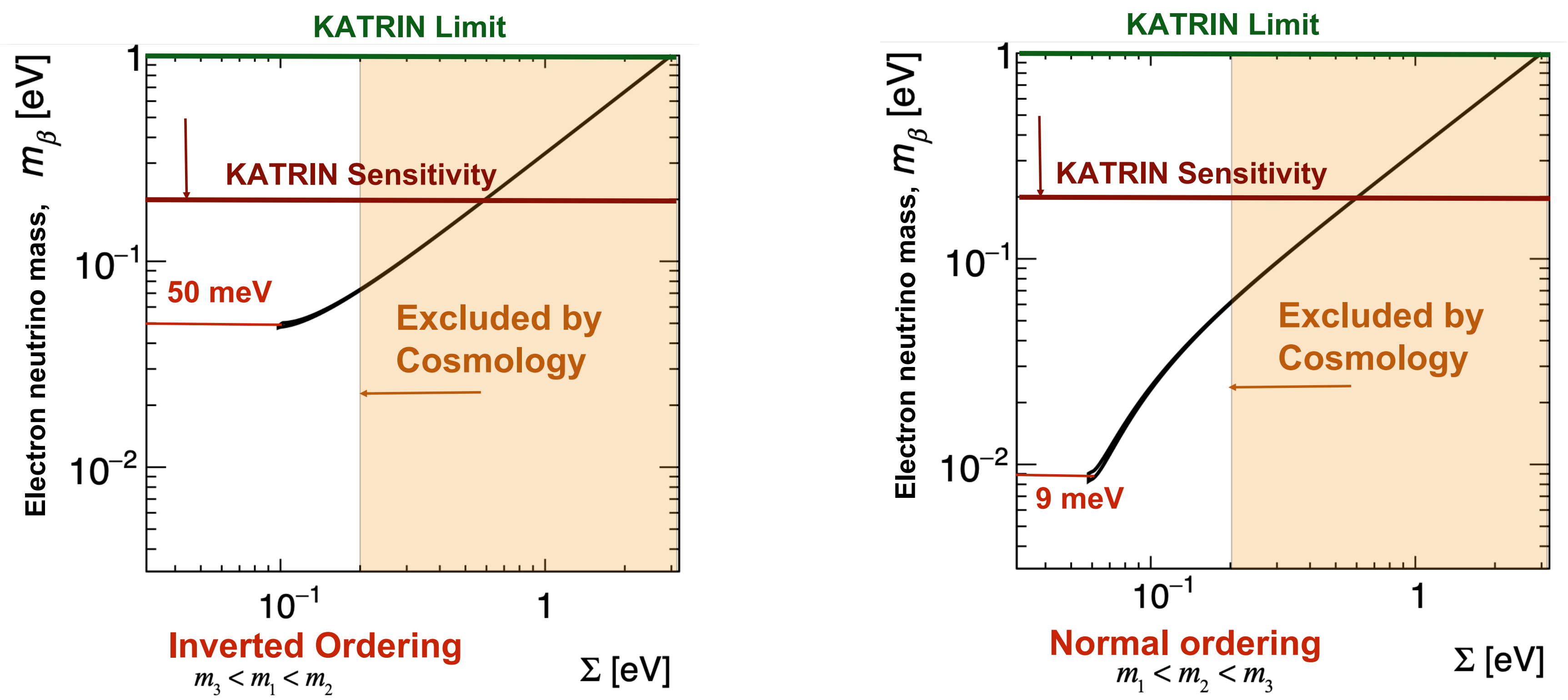




KATRIN (2022)

$$m_\nu < 0.8 \text{ eV} \ (90\% \text{ C.L.})$$

Direct Neutrino Mass Measurement

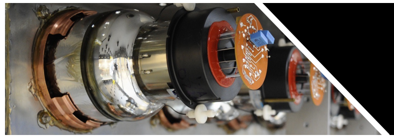


Adapted from M. Agostini et al, Phys. Rev., D96(5):053001, 2017

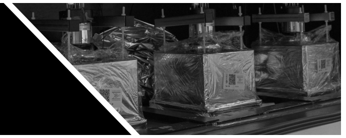
- Powerful constraints from cosmology but cannot replace **lab measurements.**
- Kinematic" measurement of β-decay spectrum is the **only model independent method.**
- Two clear sensitivity goals: **50 meV** for **I.O.** and **9 meV** for **N.O.**

Goal of next generation experiments.

"Guaranteed" observation if reached.



CRES



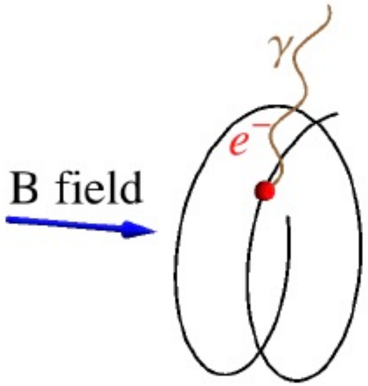
A. Schawlow: “Never measure anything but frequency!”

Cyclotron **R**adiation **E**mission **S**pectroscopy

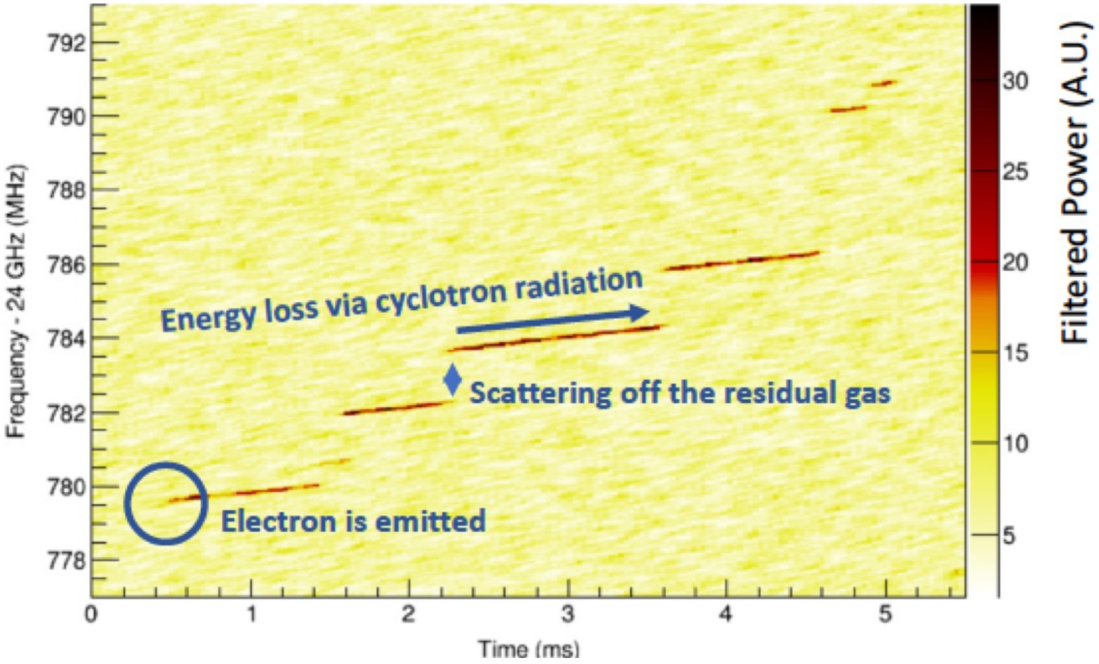
(Monreal and Formaggio, Phys. Rev. D 80 2009)

$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$

≈ 27 GHz for 18.6 keV and 1 Tesla.



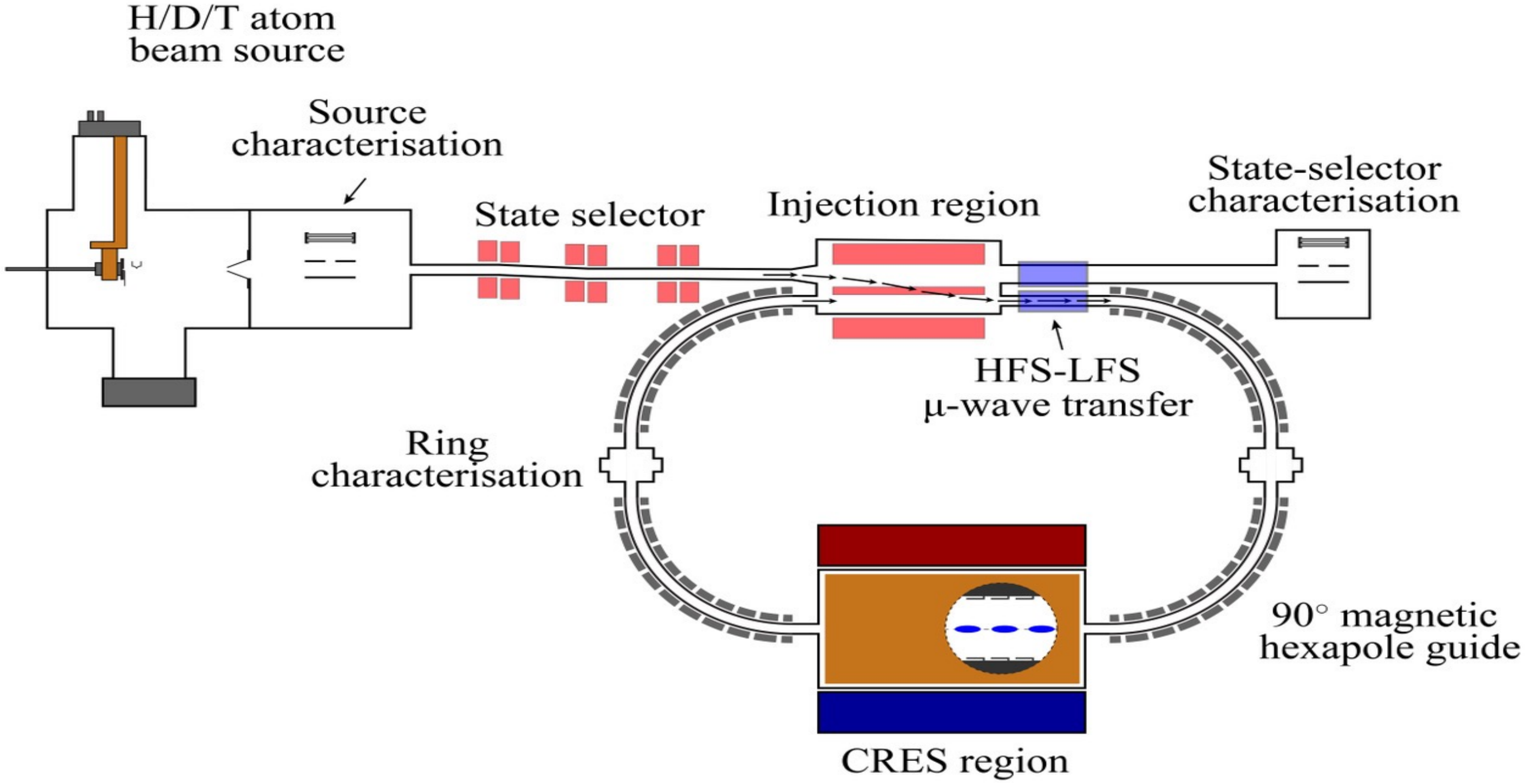
Project-8 (2015)



QTNM-CRESDA

QTNM
Part of UK's
QTFP
Programme
Similar to
Project-8
with which
there is a close
collaboartion

- Novel atomic source and delivery system together with characterisation.
- Quantum-limited microwave detection system in CRES region.
- High-precision B-field mapping.
- Software, simulations & sensitivity studies.



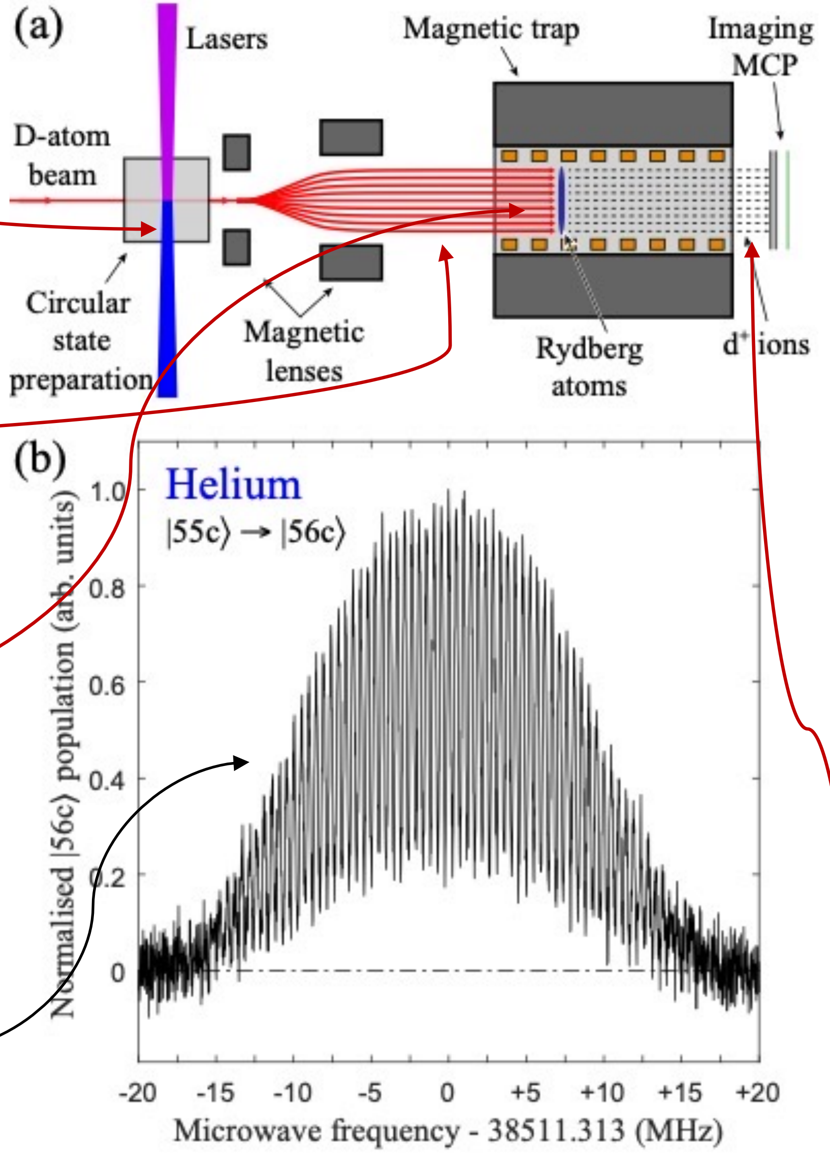
Precise B-field mapping using D/T atoms as *quantum sensors* in the QTNM experiment

D/T atoms are prepared in circular Rydberg states (quantum state superposition)

Beam is expanded to fill the CRES* region

At selected time pulses of MW-radiation applied within CRES volume drive Rydberg-Rydberg transition (wave-function collapse). These transitions are sensitive to B-field variations at ***1 part in 10^7 for B=1T (<0.1ppm)***

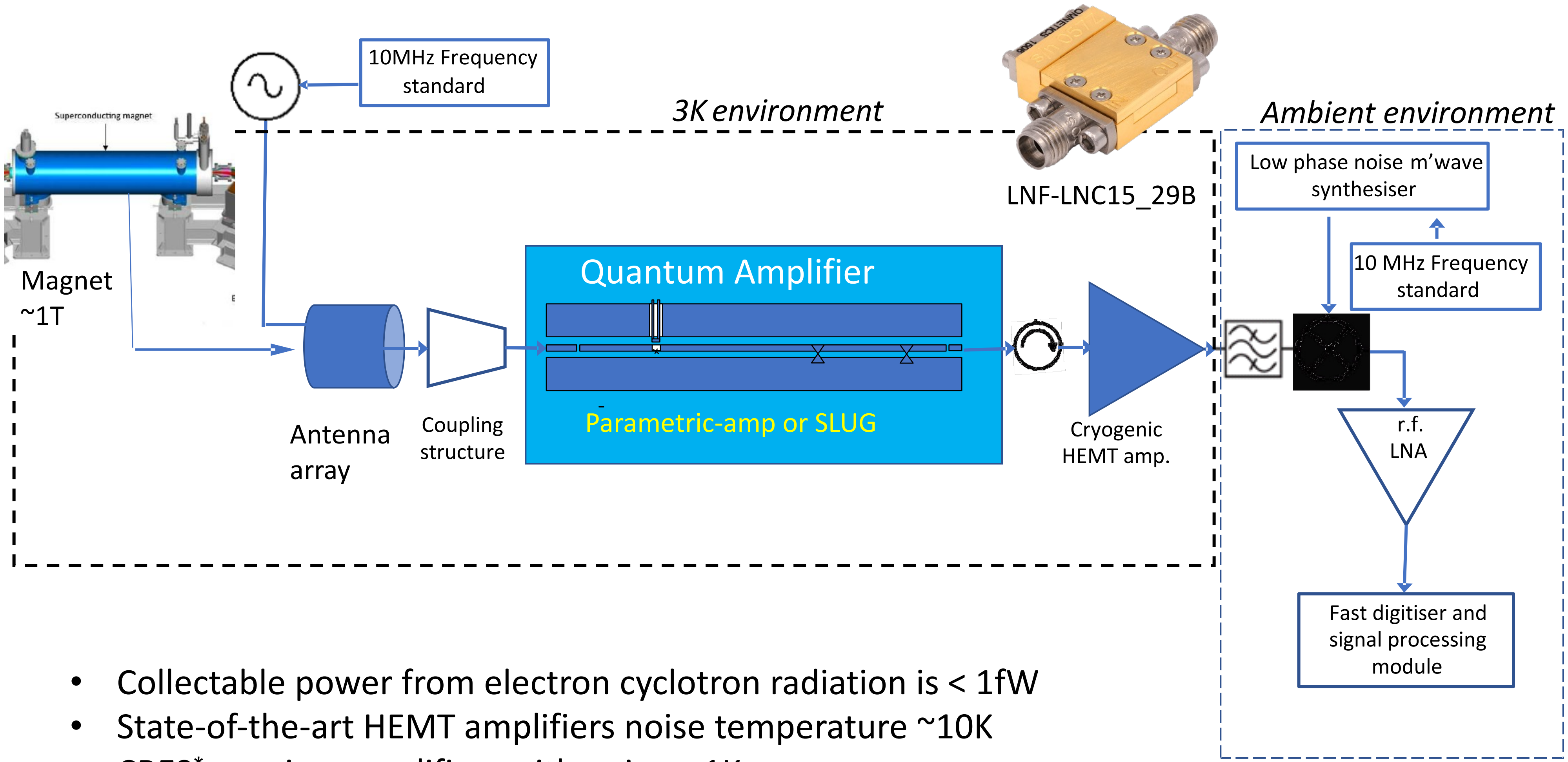
Transitions are detected by state-selective ionisation



Ramsey spectrum of MW-transition between circular Rydberg states (Helium example)

* Cyclotron Radiation Emission Spectroscopy

Cyclotron Radiation Readout in QTNM



- Collectable power from electron cyclotron radiation is < 1fW
- State-of-the-art HEMT amplifiers noise temperature ~10K
- CRES* requires amplifiers with noise ≤ 1K

Quantum Amplifiers!

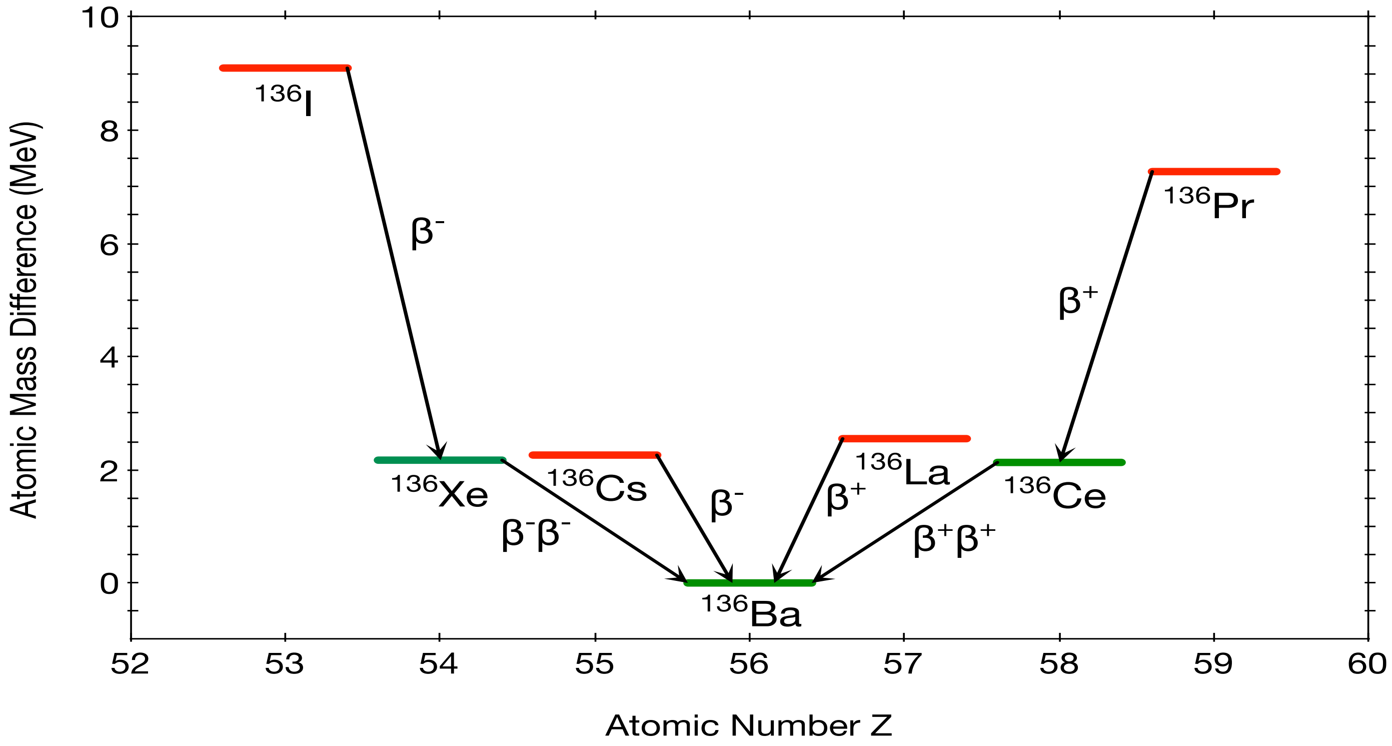
* Cyclotron Radiation Emission Spectroscopy

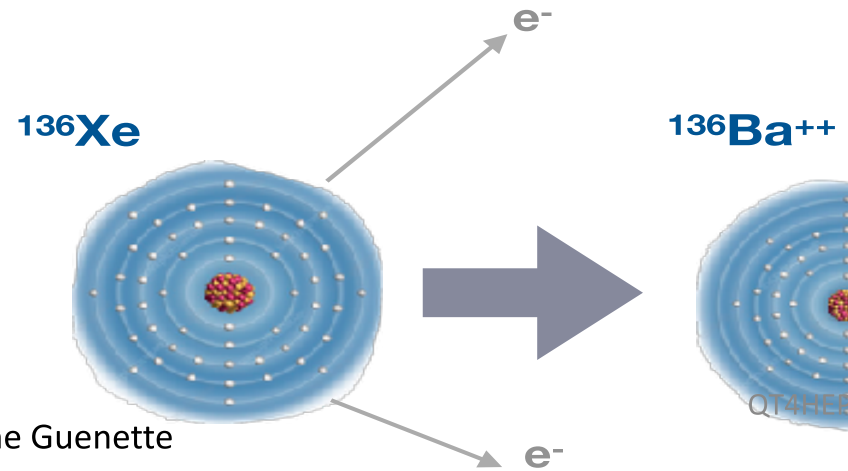
Barium Tagging in Xe neutrinoless double beta decay experiments

1

Slide credit Roxanne Guenette

Xe -> Ba





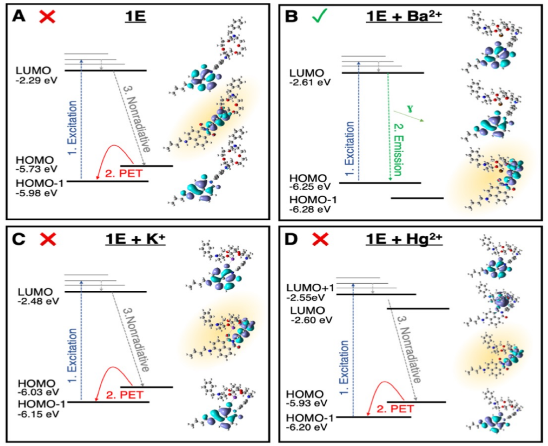
Slide credit Roxanne Guenette

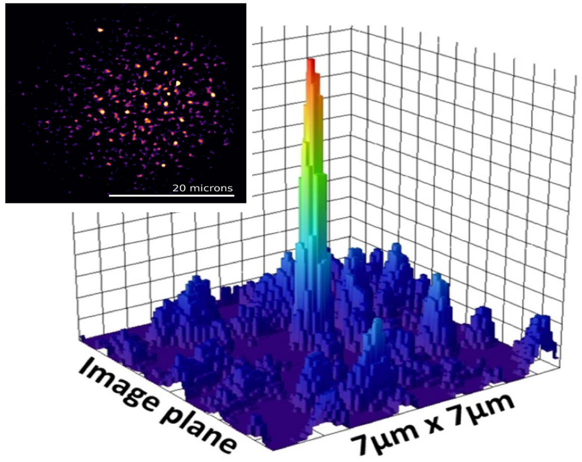
Detecting a single Ba ion

- Original idea to use Single Molecule Fluorescent Imaging

D.R. Nygren, J.Phys.Conf.Ser. 650 (2015) no.1, 012002

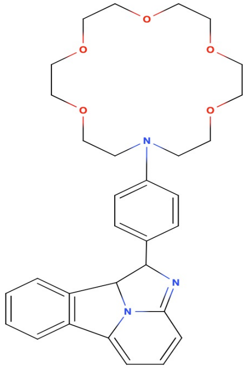
- On-Off chemosensors developed

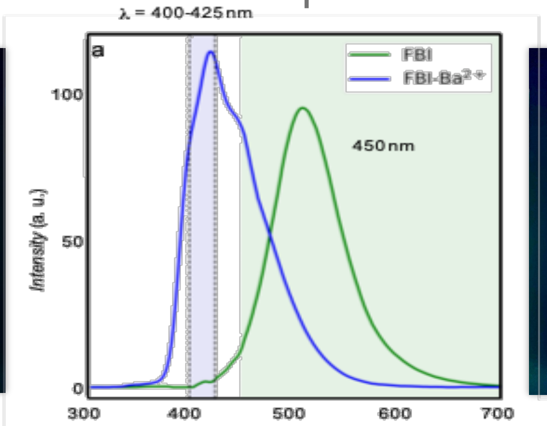


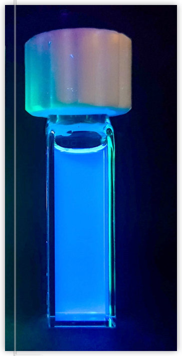


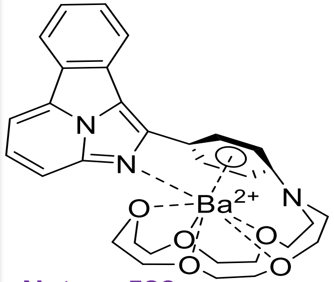
ACS Sensors 6, 1, 192–202 (2021)

- Bi-Color chemosensors developed







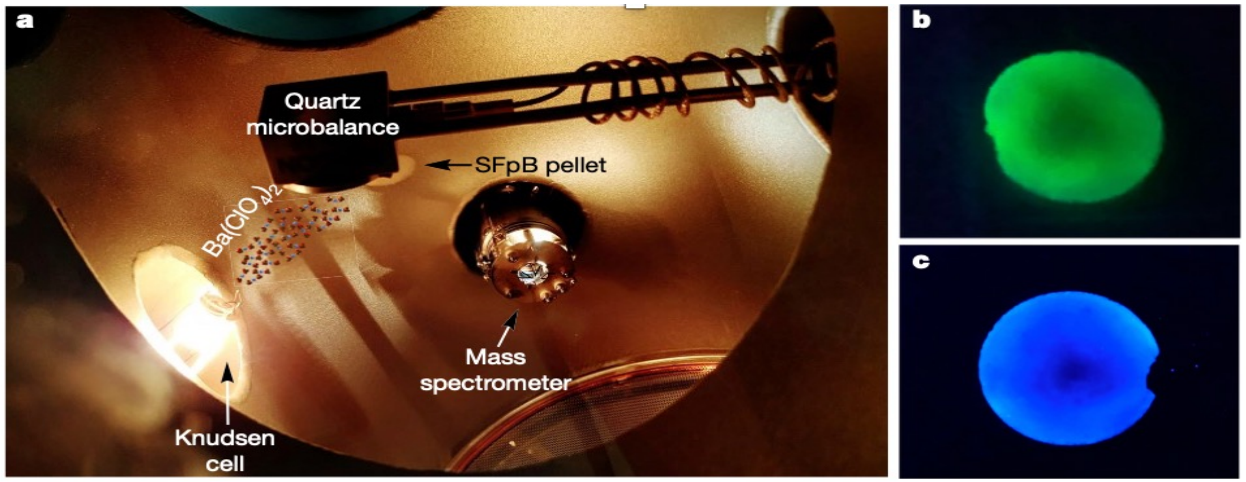


Nature 583, 48–54 (2020)

Slide credit Roxanne Guenette

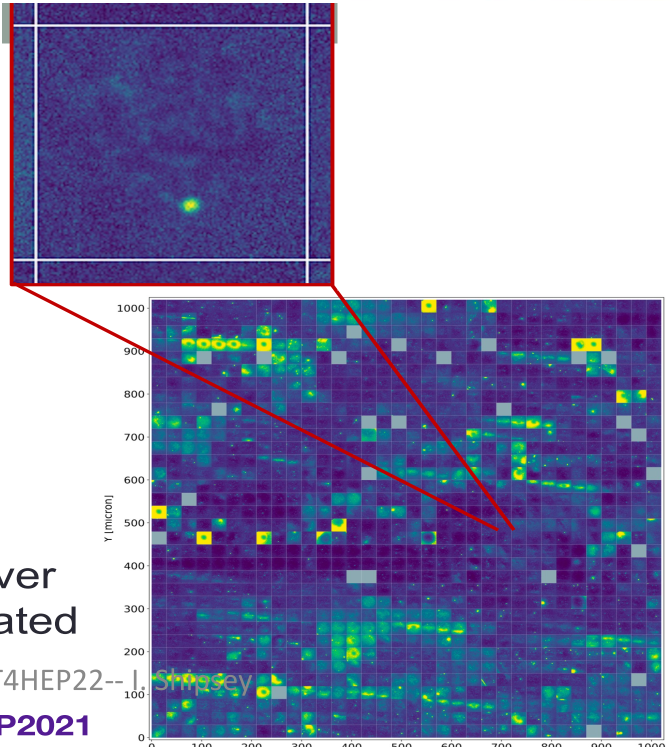
Further technological advances

- Bi-color molecule activation



Nature 583, 48–54 (2020)

- High pressure microscopy



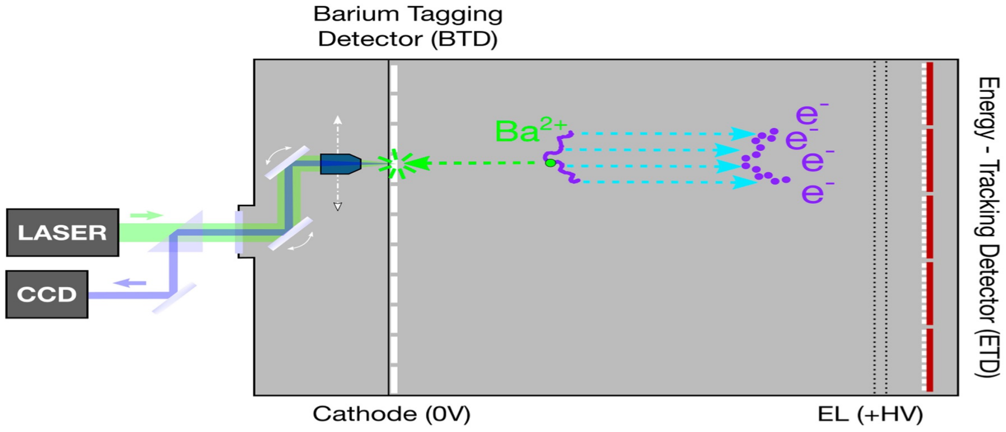
Single barium ion imaging over mm^2 surface area demonstrated in 10 bar xenon gas

B.Jones, TAUP2021

Slide credit Roxanne Guenette

Demonstrators

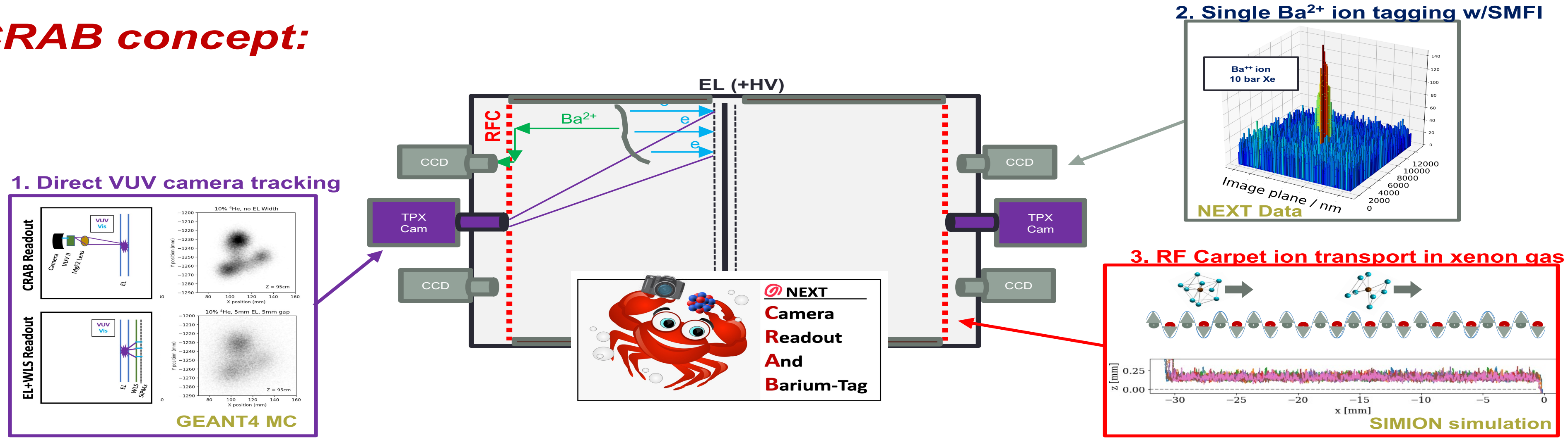
NEXT-BTX concept:



Demonstrators

- Single ion sensor development is now fairly advanced
- Important R&D remains for ion concentration and collection:
  - *Sensor-to-ion (BTX concept)*
  - *Ion-to-sensor (CRAB concept)*

NEXT-CRAB concept:

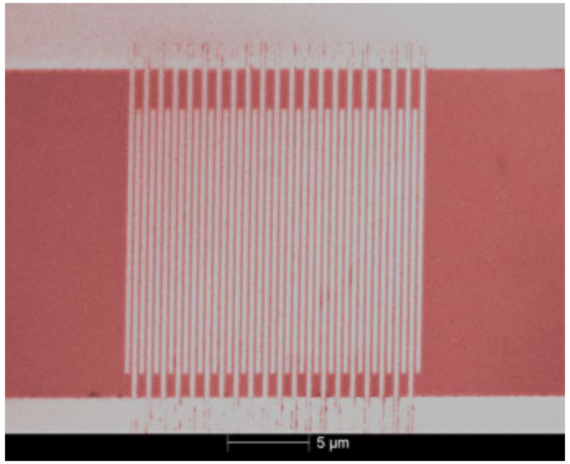


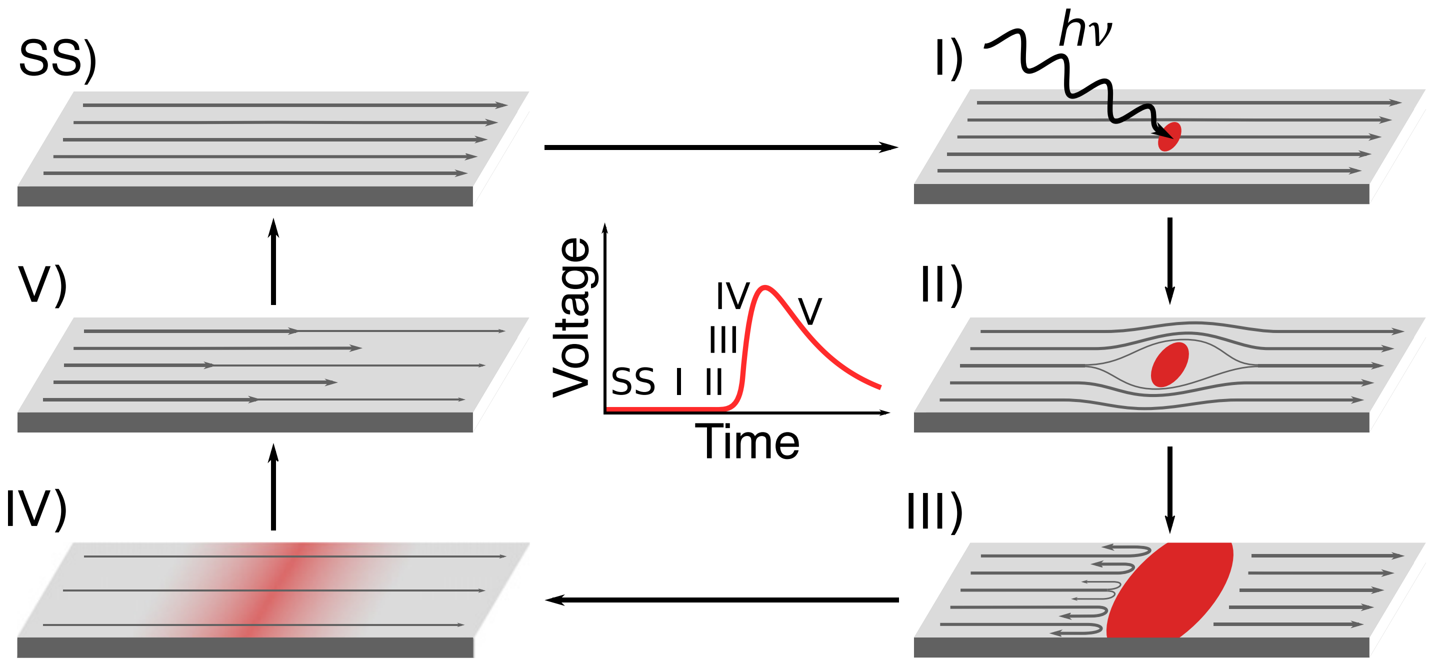
→ **Demonstrator phases under intensive development on 2-3 year timescale**

Slide credit Roxanne Guenette

Superconducting Nanowire Single Photon Detectors (SNSPDs)

- Threshold detector for single photons
  - Very narrow (~100 nm) superconducting meander biased close to transition
  - Absorption of photon drives normal
- ps timing resolution
- Provides high-efficiency, high-fidelity photon counter for QIS applications
- WSi demonstrated with 100 meV threshold
- Very low dark count rate demonstrated, applicable for DM searches
  - But very small volume





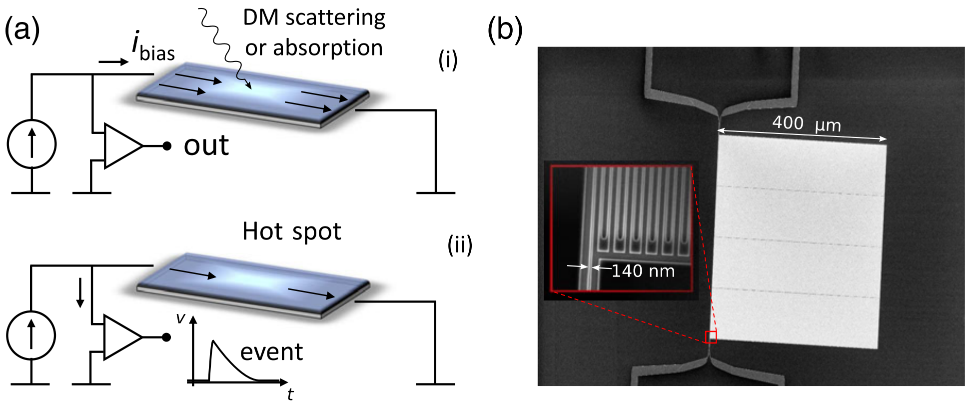
SNSPDs

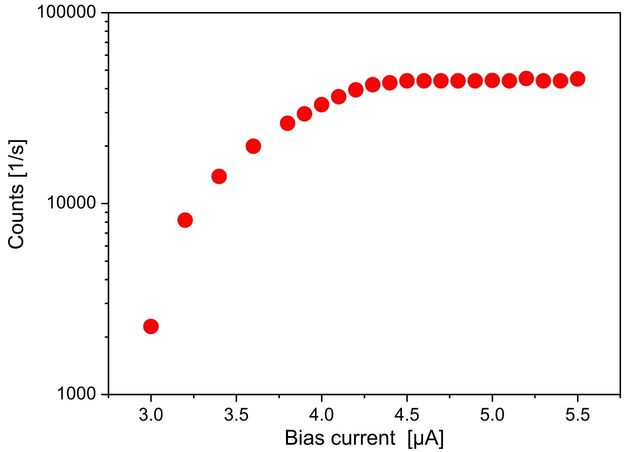
Strengths:

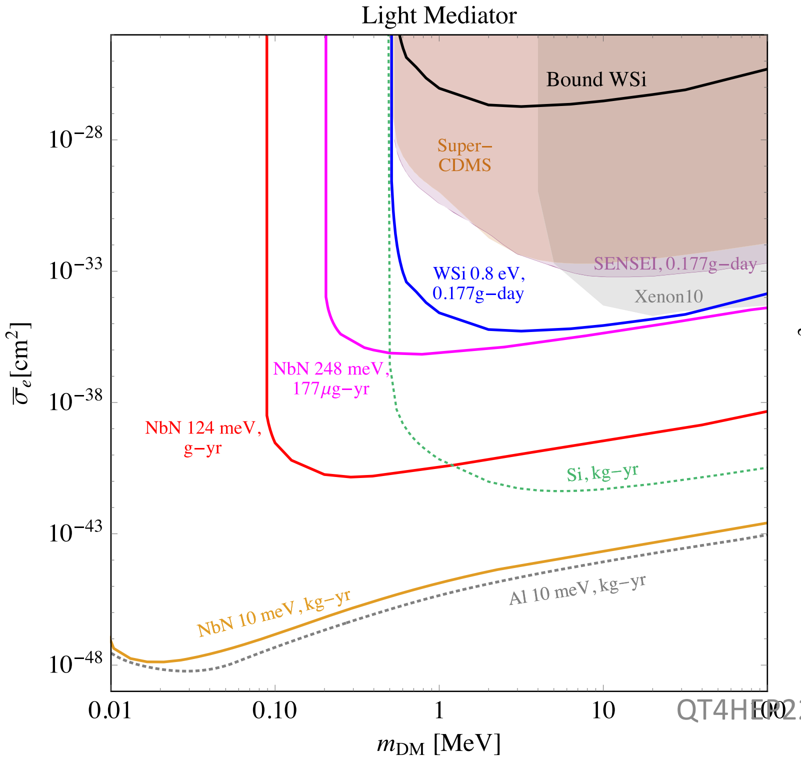
1) detecting photons by absorption with <10 ps timing resolution and nearly unity quantum efficiency. This is why they are used as photon counters in QIS applications and also why they are being developed for deep space optical communication.

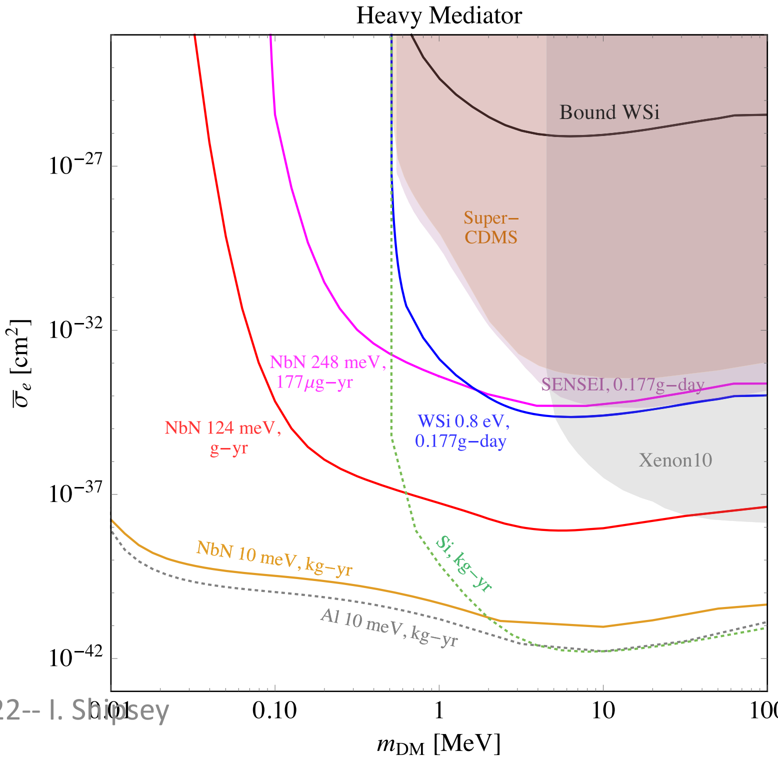
2) detecting sub-eV energy depositions — this is why they get used for dark matter, as dark photon detection with semiconductors otherwise limits one to energies of roughly 1 eV and above. SNSPDs have demonstrated roughly 100 meV energy threshold.

Detecting Sub-GeV Dark Matter with Superconducting Nanowires









DOI: 10.1103/PhysRevLett.123.151802

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

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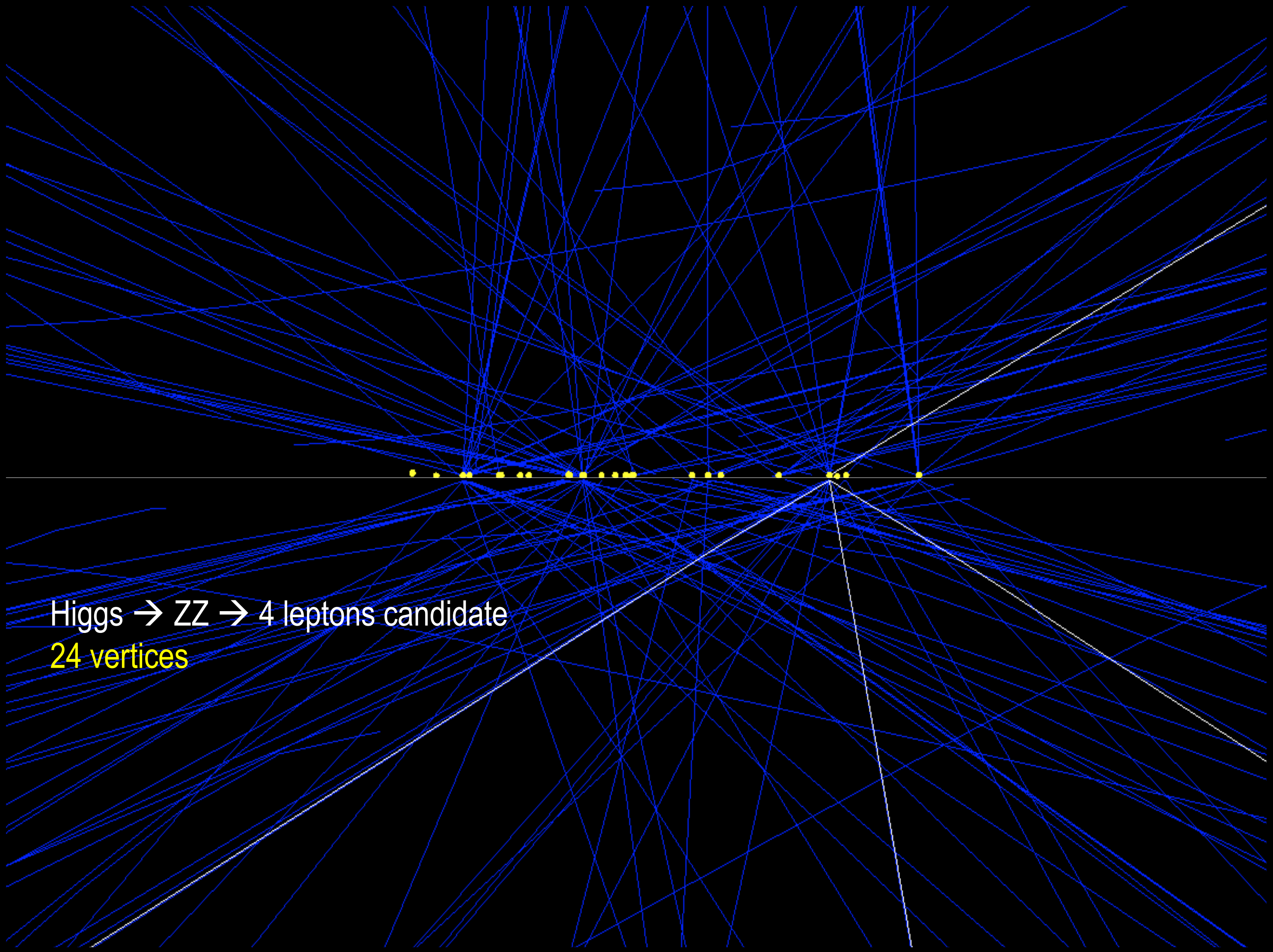
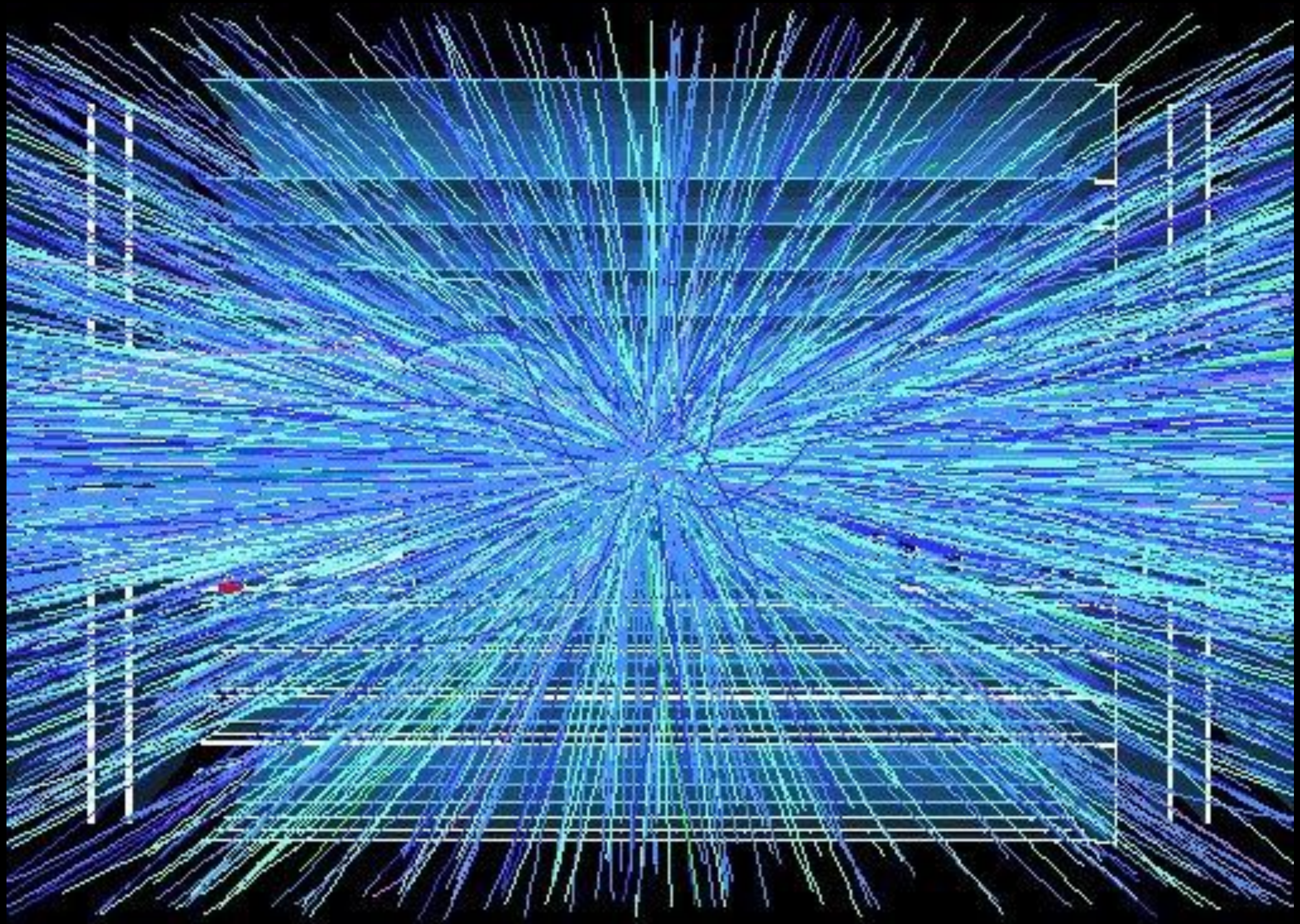
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

Collisions at the LHC



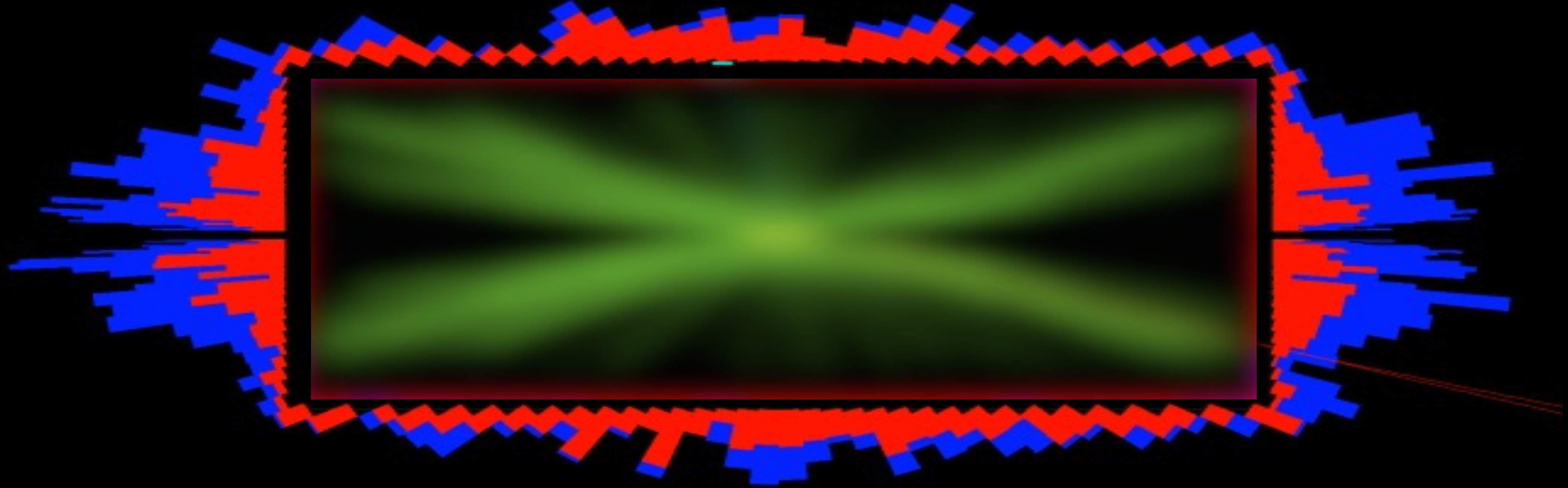
Collisions at the HL-LHC (~2029)



Event reconstruction challenges at HL-LHC

- High Luminosity → large data set, large pileup, high radiation dose

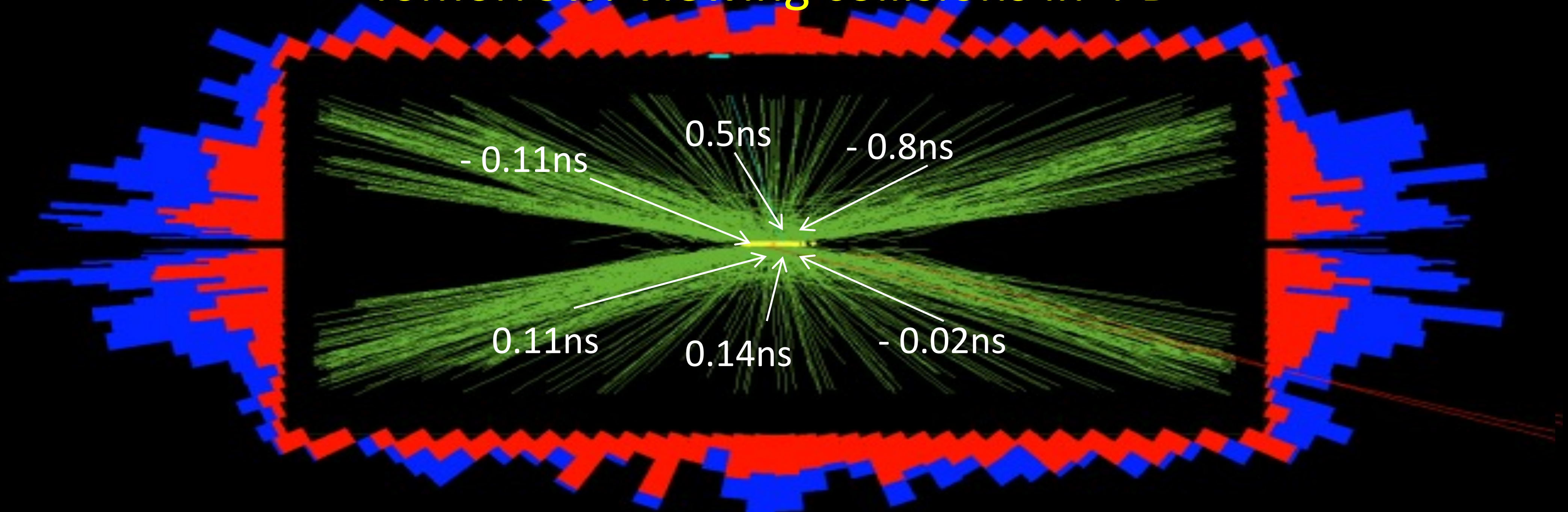
Today: Viewing collisions in 3 D



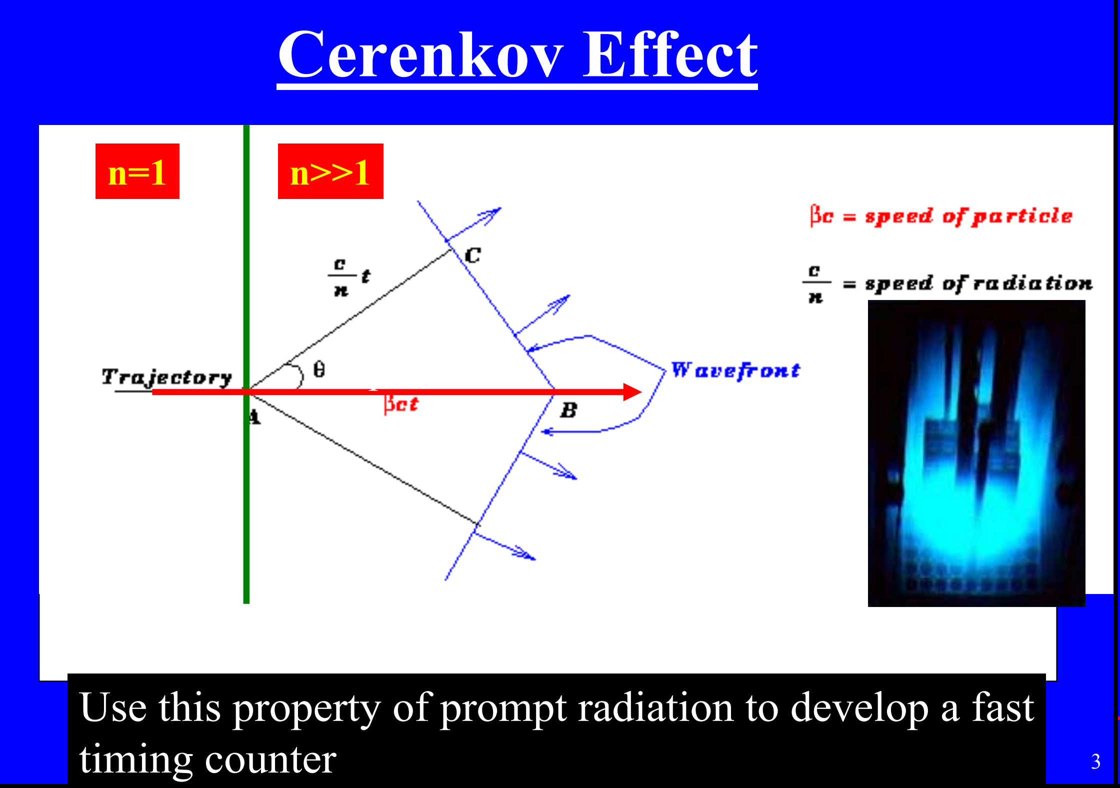
Event reconstruction challenges at HL-LHC

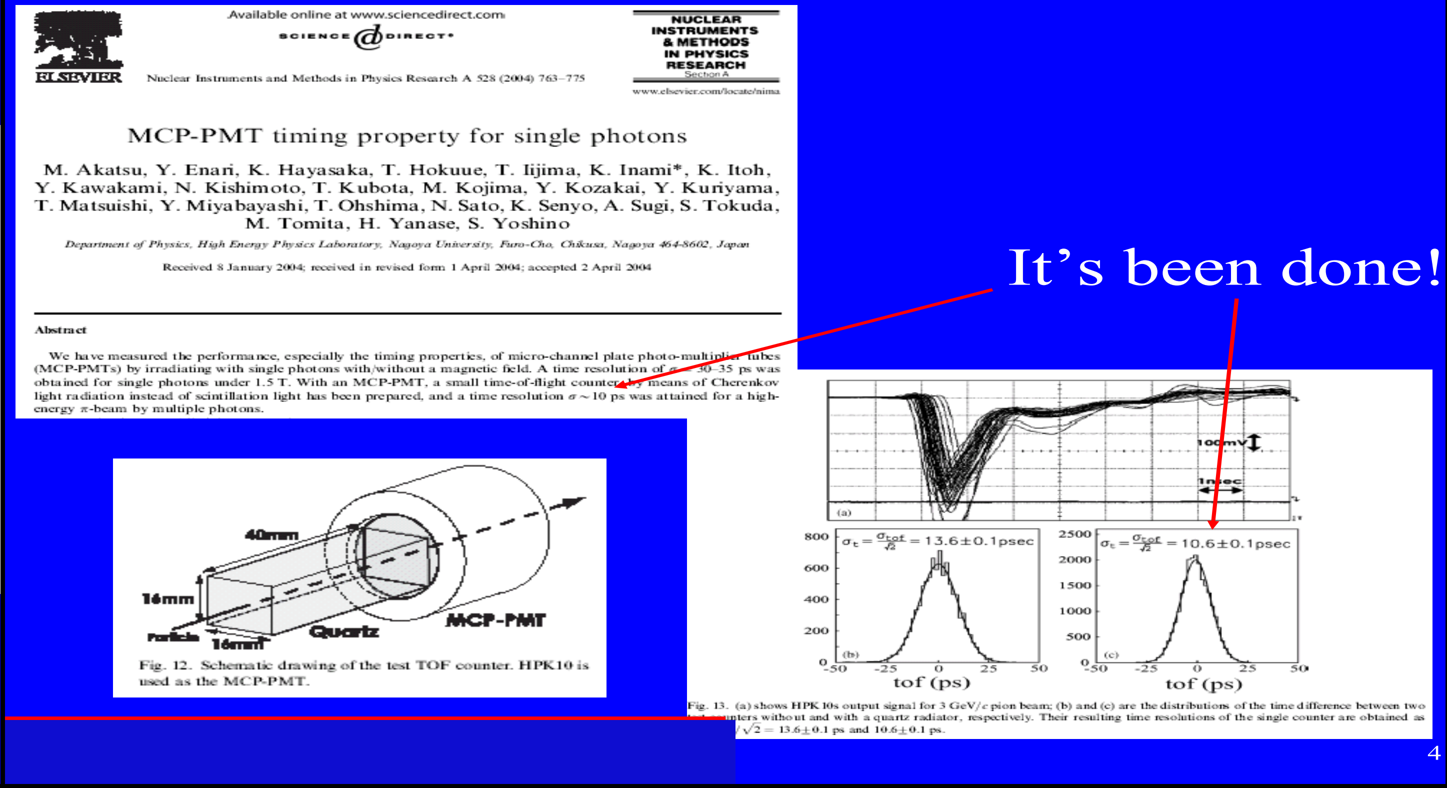
- High Luminosity → large data set, large pileup, high radiation dose

Tomorrow: Viewing collisions in 4 D



- For HL-LHC, this is enabled by new precision timing detectors → LGADs and SiPMTs
- Experience gained will be crucial for future high energy hadron colliders





How can we exploit the spectacular timing of SNSPDs for a future collider experiment?

TOF detector, maybe coupling scintillators made by metamaterials to SNSPDs?

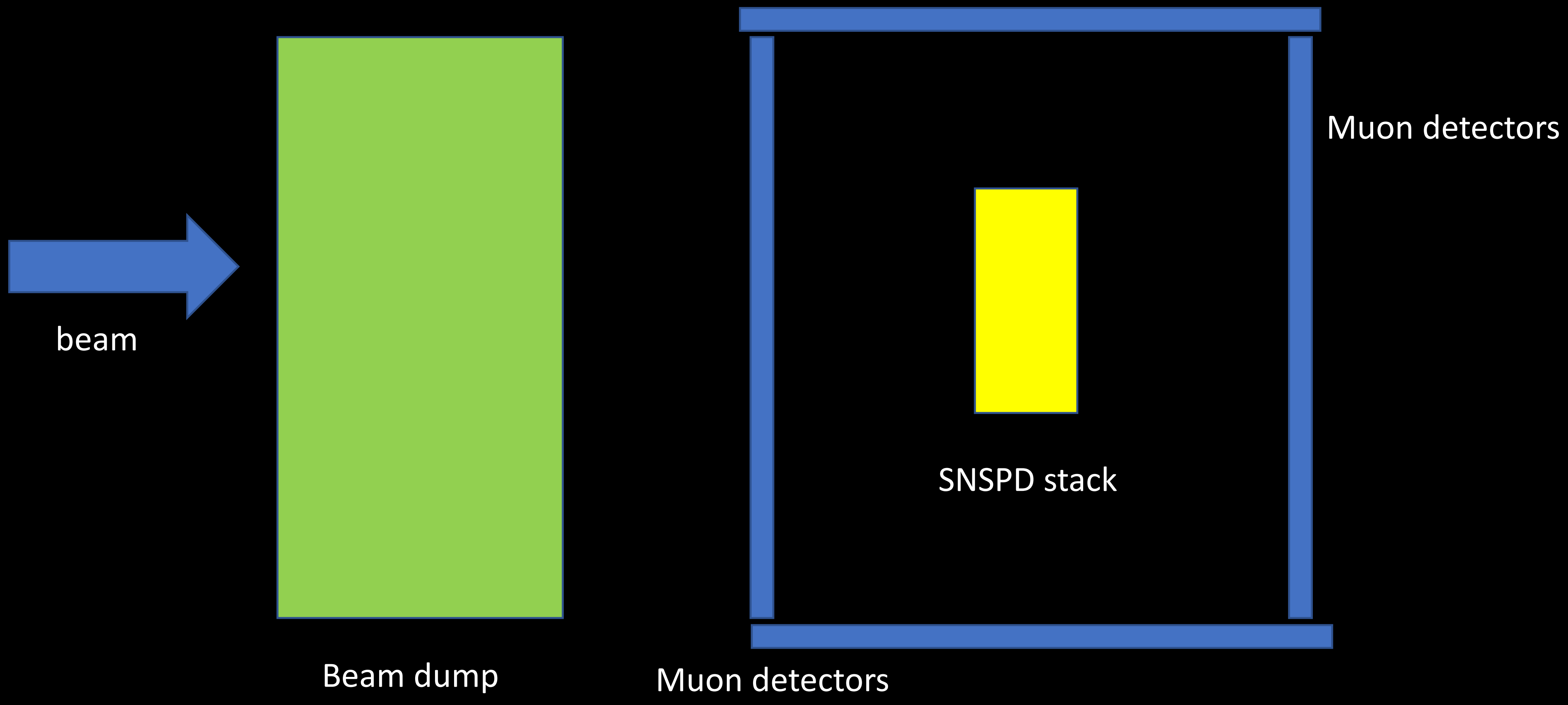
TOF detector reading out the Cherenkov photons emitted by fused silica radiators with SNSPD's instead of MCP-PMT (the QUARTIC project for CMS)?

In front of ECAL?

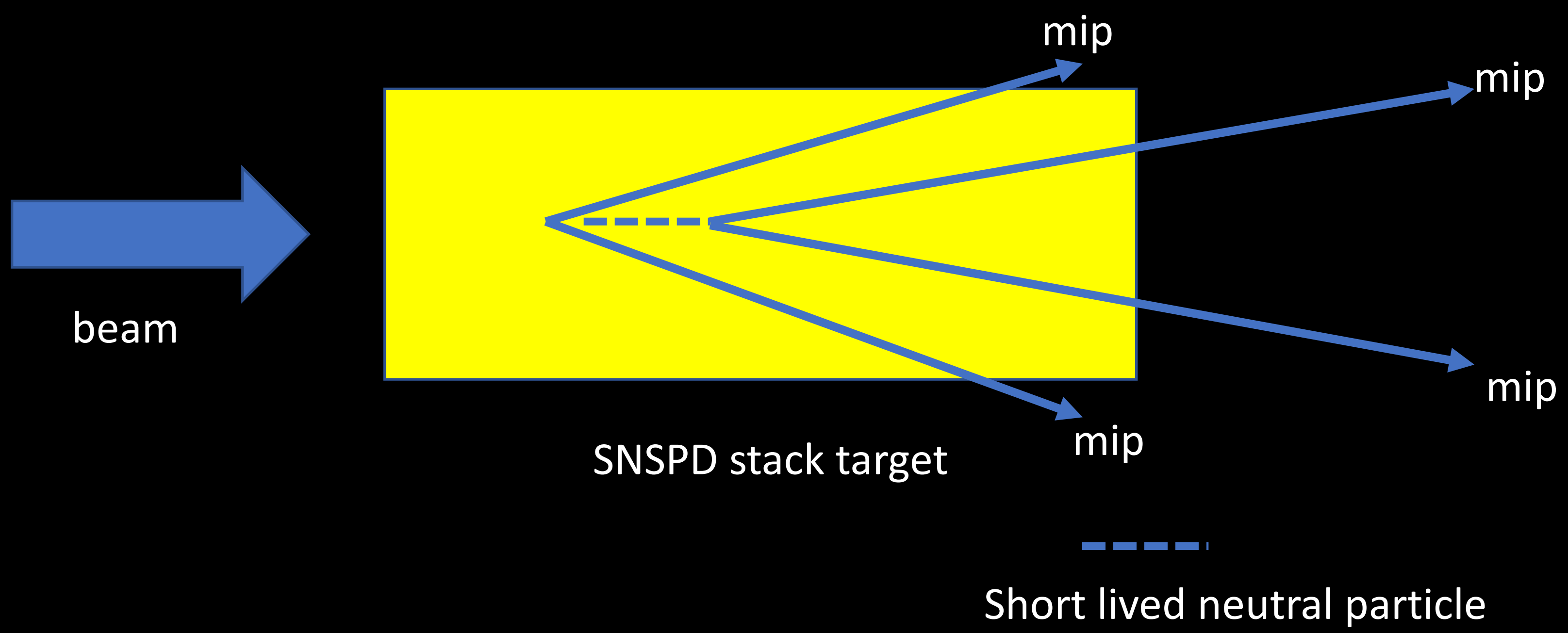
Or at very small radius?

Major, major challenges to overcome – SC so passive material from cryostat must give better performance than current solutions LGADS and SiPMs. Application only in far future – but there is time

Search for Beyond Standard Model milli-charged particles?



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

The field of quantum sensors is very broad-ranging, employing a wide range of techniques from condensed matter physics, atomic/molecular/ optical physics, and quantum information science

The interaction between particle physicists and these other fields has been intellectual exciting and very fruitful

Quantum Sensors are opening up significant new parameter space for precision measurement searches for new (low energy) particle physics, resulting in the initiation of a wide range of new experiments

Remarkably, 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 appear very promising and a programme to thoroughly explore them with high priority is well-motivated

Acknowledgements

Many thanks to Michael Doser, Marcel Demarteau, Fabrice Retiere, Sunil Golwala, Eugenio Nappi, Ruben Saakyan, Stafford Withington, Roxanne Guenette, Seamus Davies, Robert Taylor, Tristan Farrow

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Mina Arvanitaki, Themis Bowcock, Chip Brock, Oliver Buchmueller, Nathaniel Craig, Marcel Demarteau, Savas Dimopoulos, Michael Doser, Gerry Gabrielse, Andrew Geraci, Peter Graham, Joanne Hewett, Rafael Lang, David Hume, Jason Hogan, John March-Russell, Hitoshi Murayama, Marianna Safronova, Alex Sushkov, Chris Tully, Stafford Withington & the UK Quantum Technologies for Fundamental Physics Program