Oak Ridge National Laboratory

Realizing The Vision: Science Technologies

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U.S. DEPARTMENT OF ENERGY

Disclaimer and Acknowledgement

- This presentation is facility agnostic and is just my personal view.
- All mistakes are mine.

- A big thank you to all my colleagues for contributing slides, either directly or indirectly.

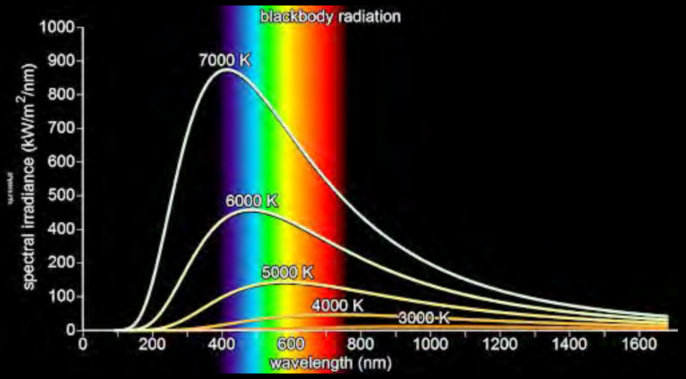
Our Vision

Deliver scientific discoveries and technical breakthroughs to answer the most fundamental questions in physics (while building a better and safer world.)

Science Technologies are foundational to ensure successful realization of the vision

Science progresses by experimentation, observation, and theory

Nobody would have predicted …

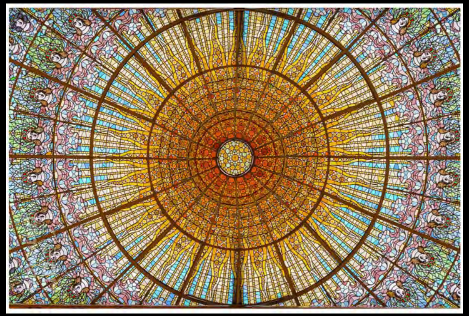


- that slight irregularities in black body radiation would have led to the entirely new concept of the quantum world;
- that pondering the constancy of the speed of light would have led to E= mc^2;

- that special relativity and quantum mechanics would have led to anti-matter;

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

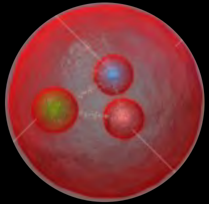
- that Noether's theorem would lead to the importance of symmetries and the corresponding conservation laws;

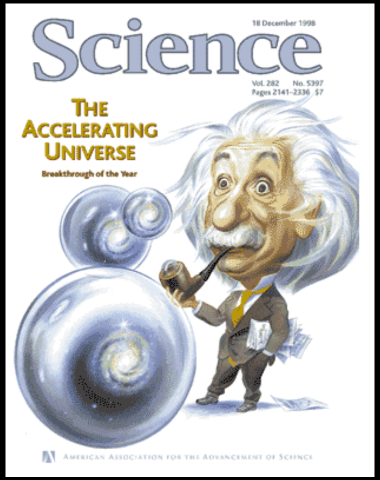

Palau De La Música, Barcelona

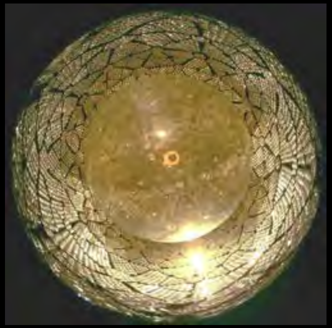
Science progresses by experimentation, observation, and theory

- that measurement of the persistent, mysterious noise in a radio receiver, not coming from the earth, sun, or our galaxy, would be a confirmation of the big bang theory (1964);
- that electron-nucleon scattering would lead to the discovery of quarks (1969);
- that non-Abelian local gauge theories would provide for the basis of the theory of fundamental interactions as we know it (1954 ff.);
- that measurements of supernovae would lead to the concept of dark energy (1998);
- that the "invisible" neutrino (1930) has mass (2002);

Bell Labs Horn antenna

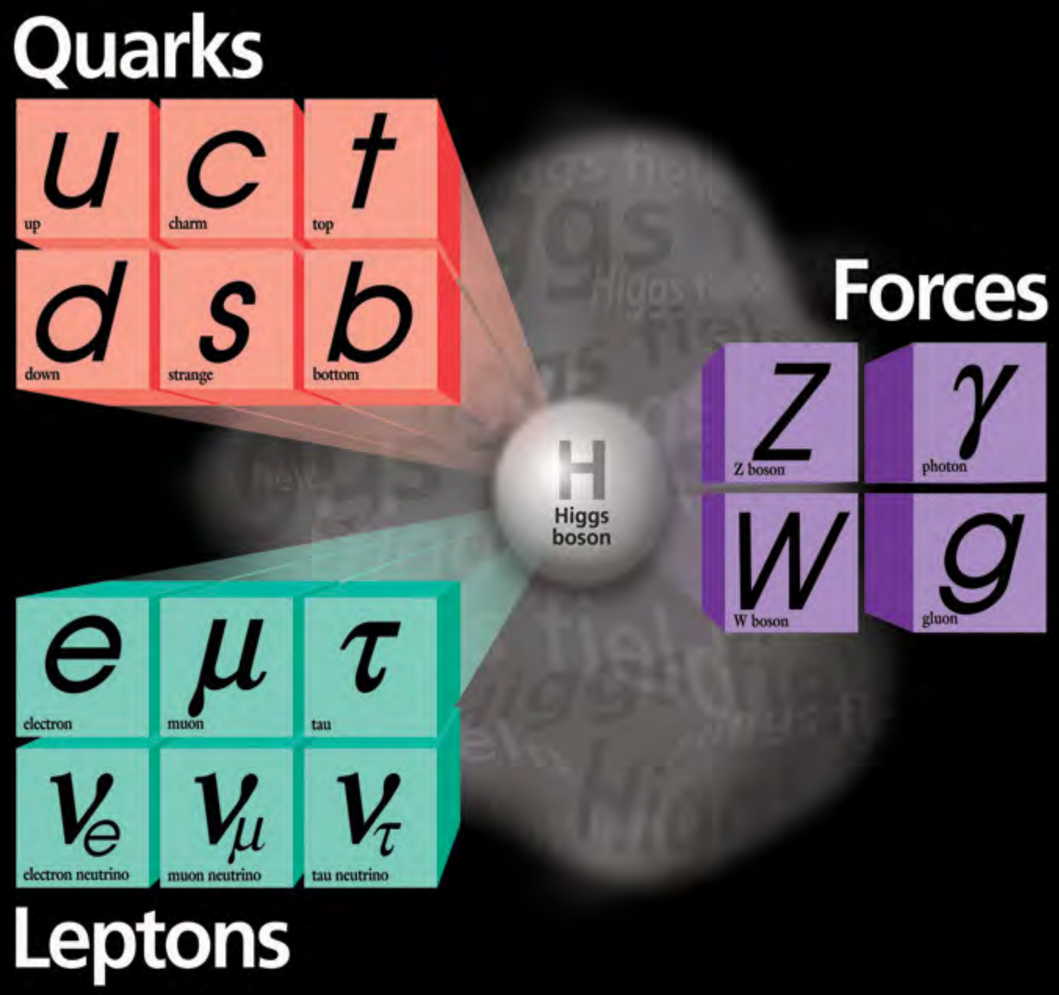






Today: The Edifice of the Standard Models

Particle Standard Model



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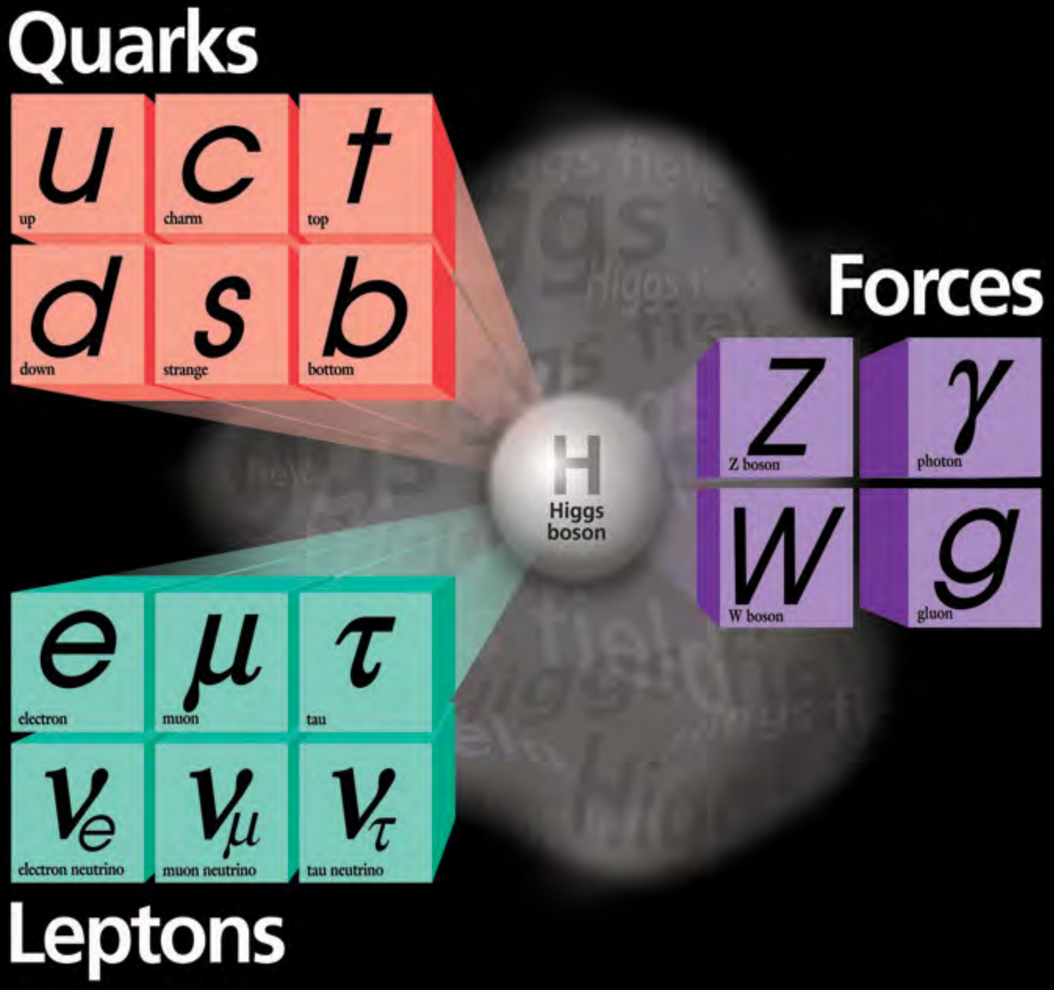
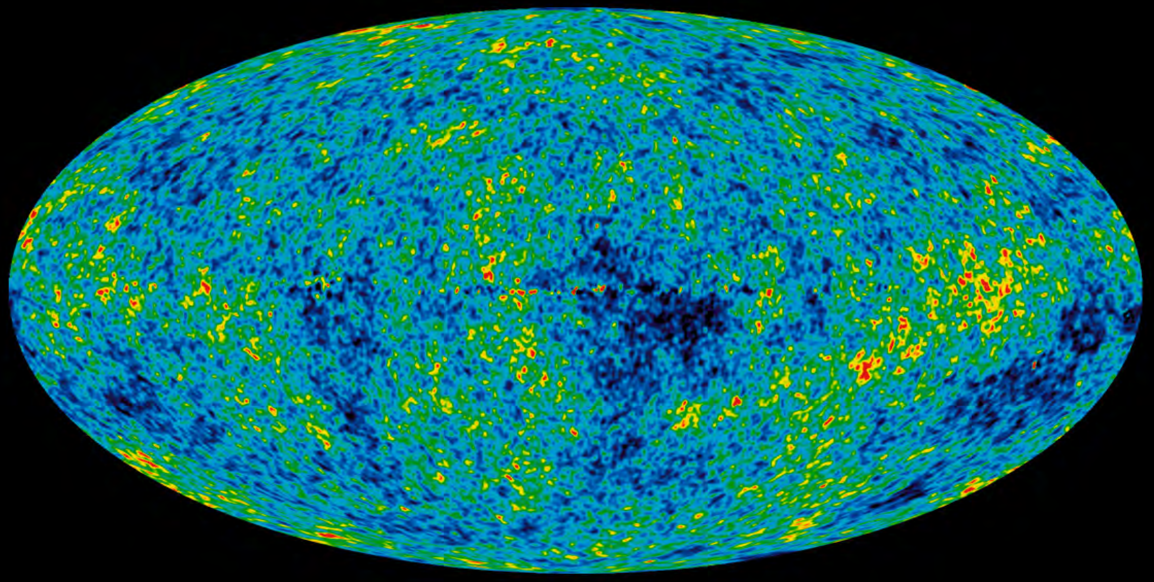


Cosmology Standard Model



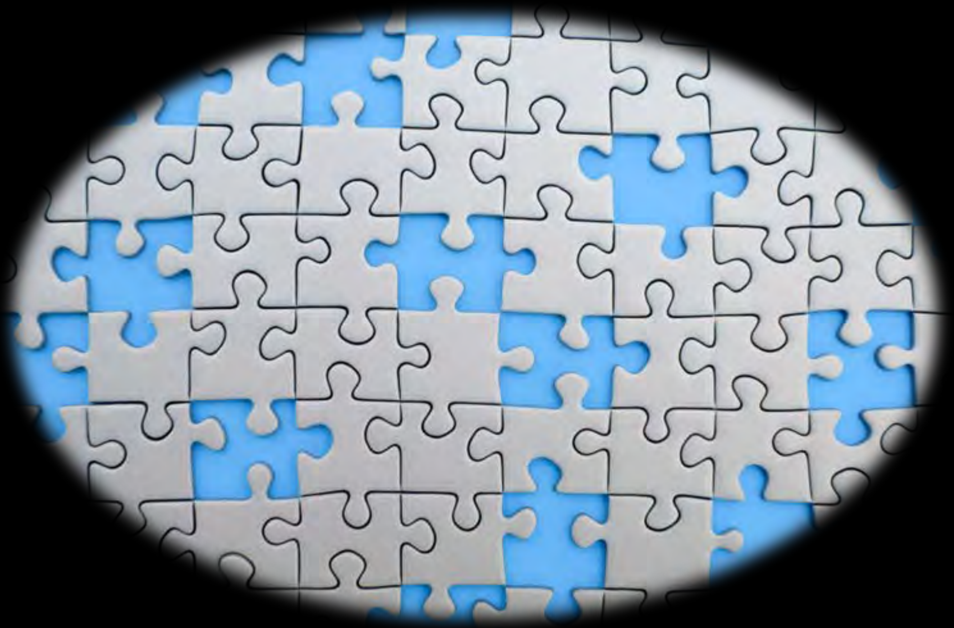
Λ_{CDM}

Our World Today

- Amazing understanding of the universe at vastly different scales
  - From Inflation to Cosmic Microwave Background radiation to creation of elements to galaxy formation
  - From the building blocks of matter and their interactions and the generation of mass
- Encapsulated in:
  - Standard Model of Particle Physics
  - Standard Model of Cosmology
- The theories are highly predictive and have been rigorously tested (in QED to 1 part in 10 billion)

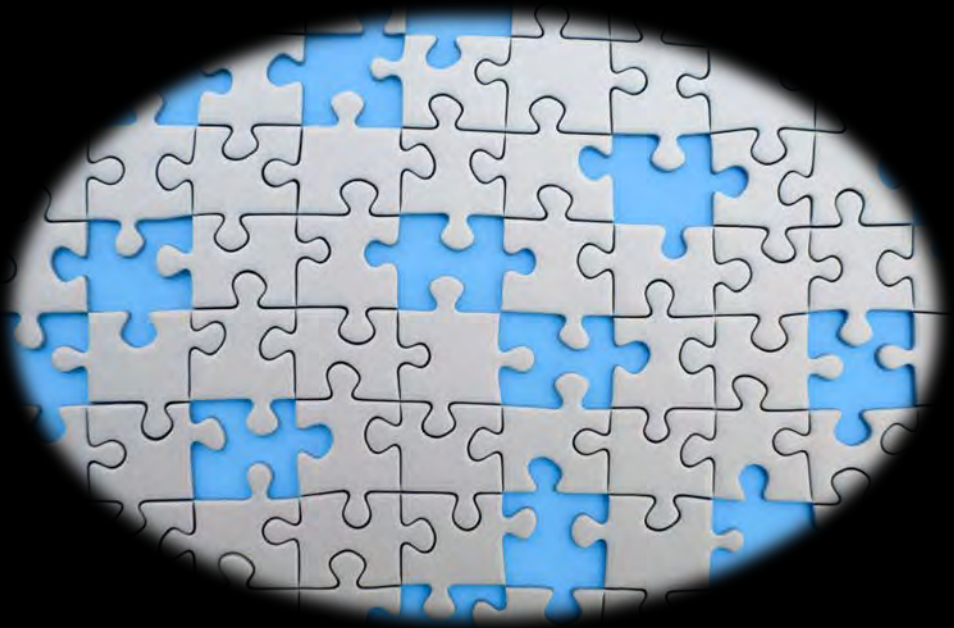
- **This has been a monumental achievement of the field!**

Incomplete



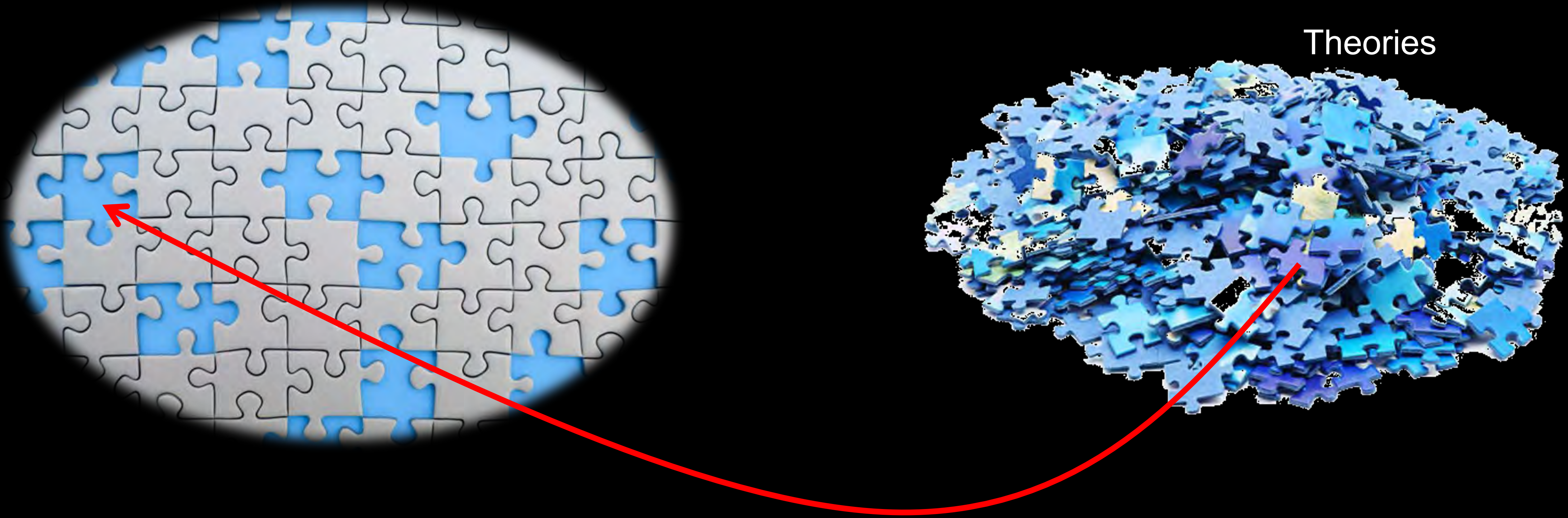
- What is the mass of the neutrino?
- What is the nature of the neutrino?
- What is the nature of Dark Matter?
- What drove inflation?
- What is Dark Energy?
- Is the Higgs fundamental?
- What is the role of scalars?

Incomplete, Resolved by Experiment



Theories

Incomplete, Resolved by Experiment

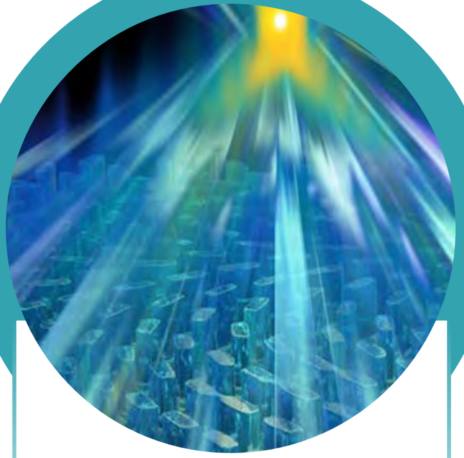


Experiment
(with highest sensitivity
and novel techniques)

Science Technologies Will Play a Pivotal Role

Directed R&D

Aimed at realizing high-priority projects

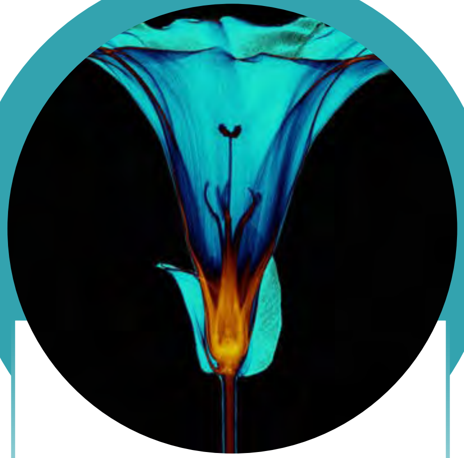


Generic R&D

Aimed at developing new methodologies and techniques, adopting emerging technologies

Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines



R&D That Inspires

Applying the techniques to other areas of science

Science Technologies Will Play a Pivotal Role

Directed R&D

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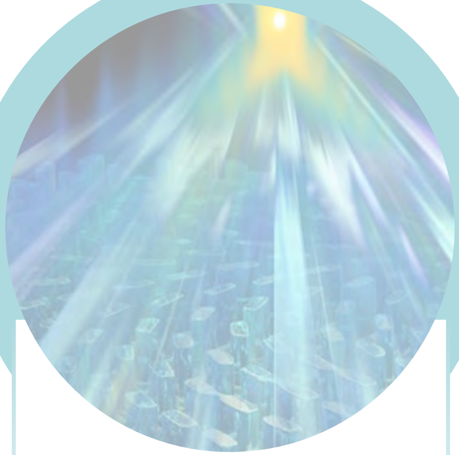

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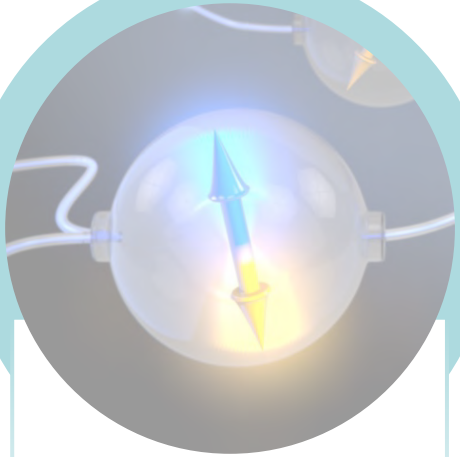

Inspired R&D

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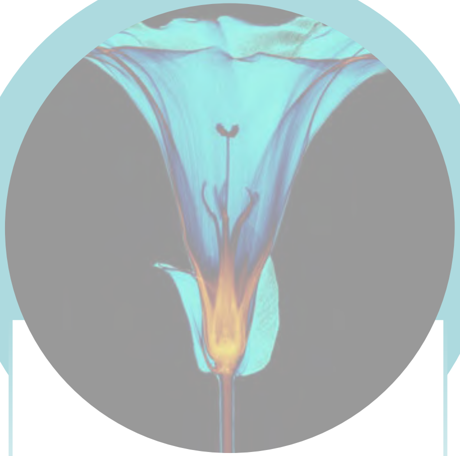

R&D That Inspires

Applying the techniques to other areas of science

Oak Ridge National Laboratory

Directed Research:
driven by the community driven strategy documents

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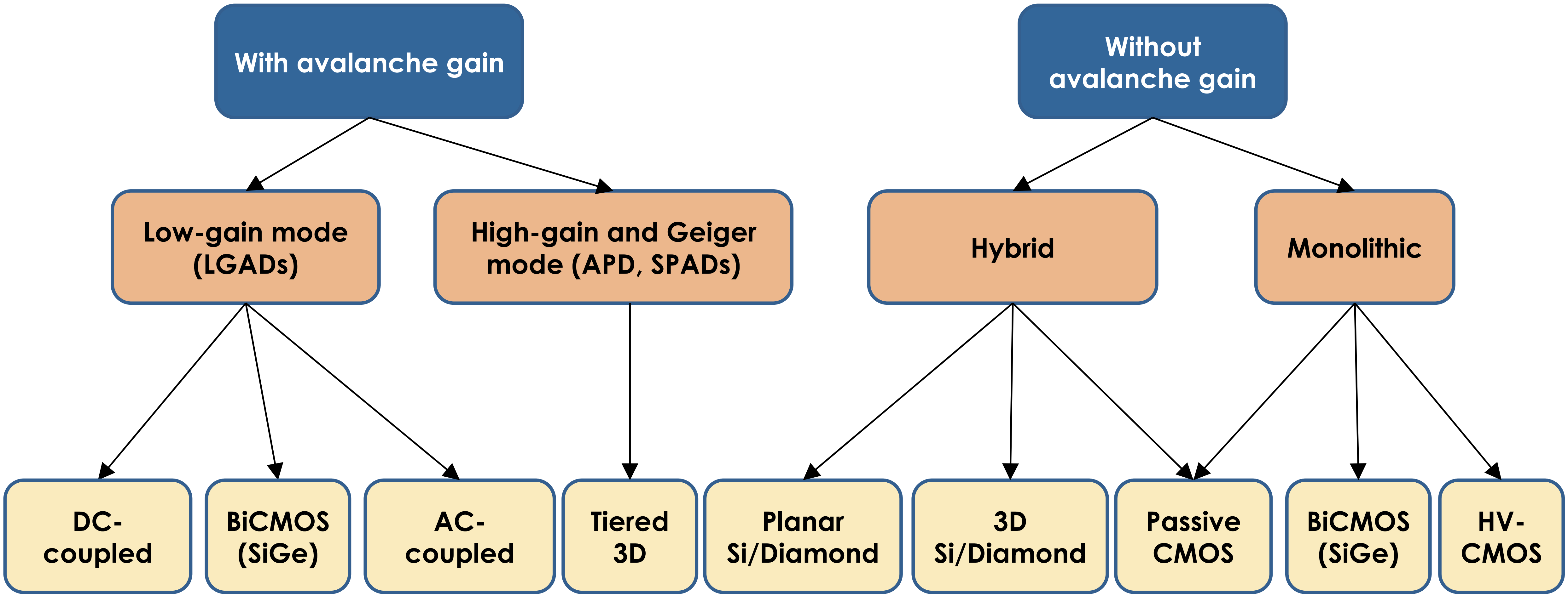
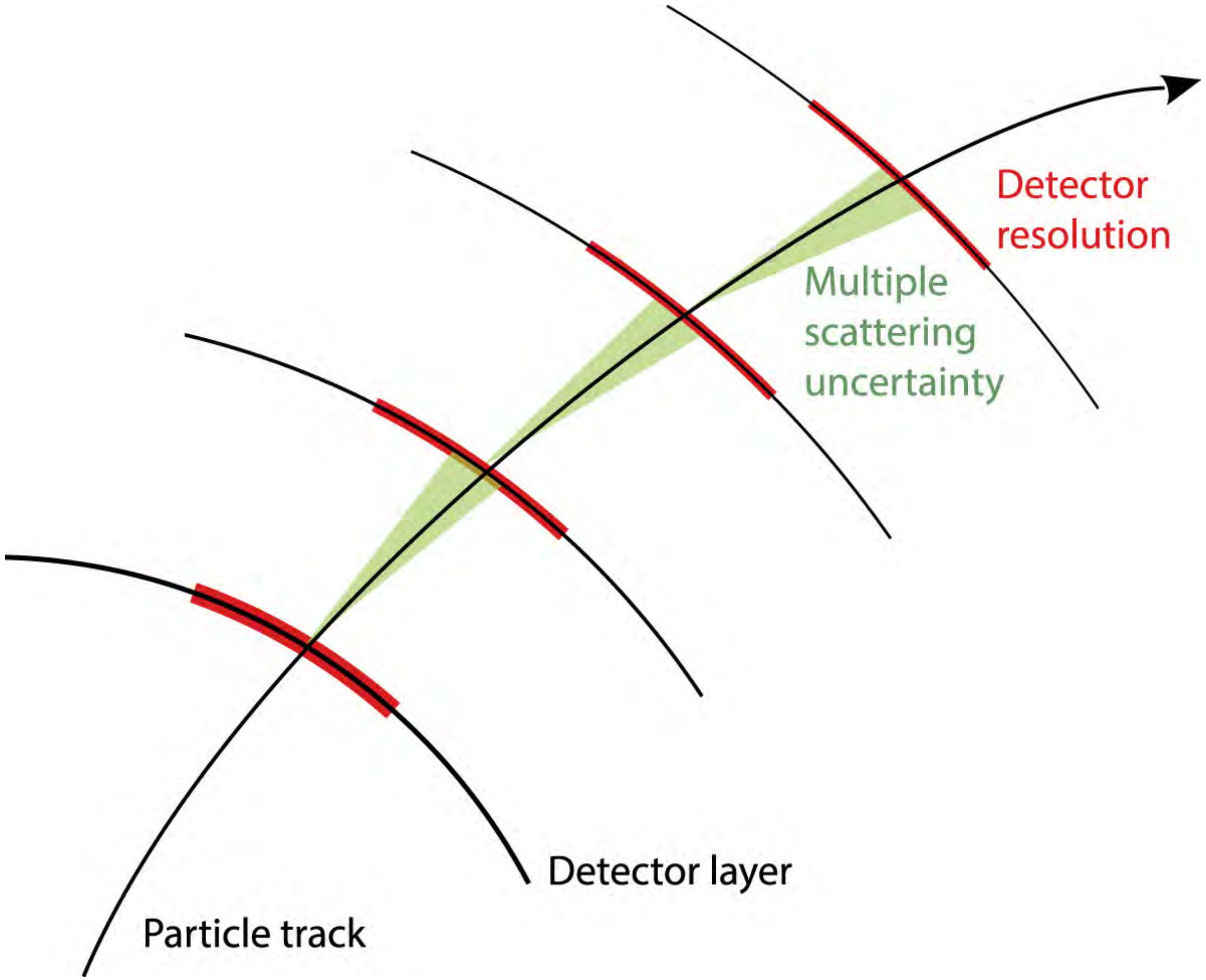
Multi-Dimensional Solid State Tracking Detectors



Transparency in Tracking

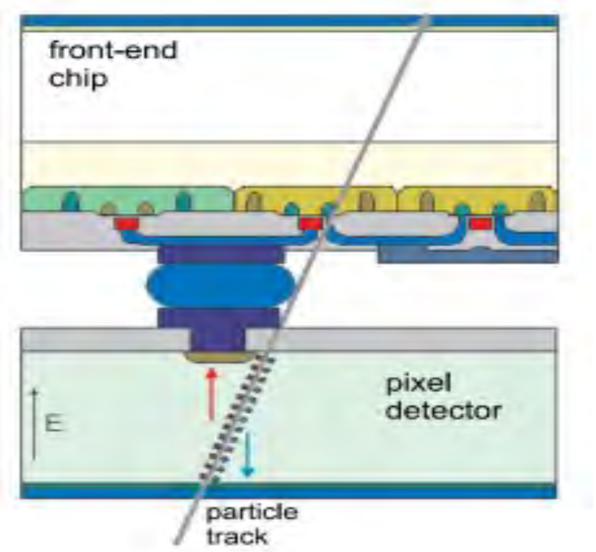
- Critical requirements:
  - High spatial resolution
  - Low mass budget
  - No active cooling
  - Low power
  - Hermetic with redundancy



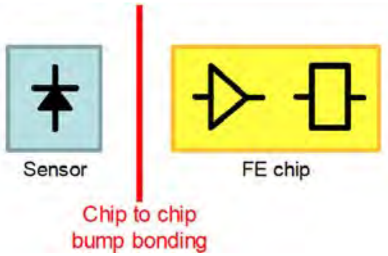
Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176
Mattiazzo, Snoeys et al., NIM A718 (2013) 288-291

Two Pixel Technologies

Hybrid Pixels

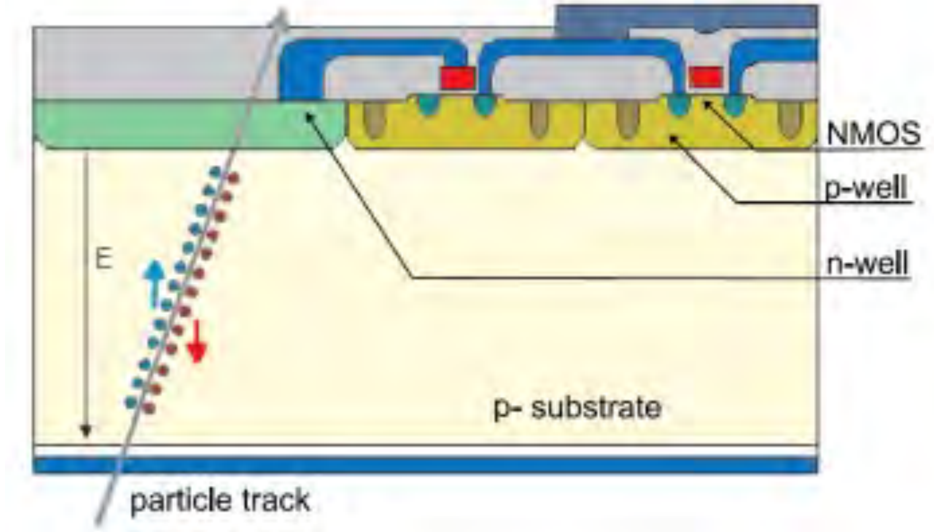


~300 μm

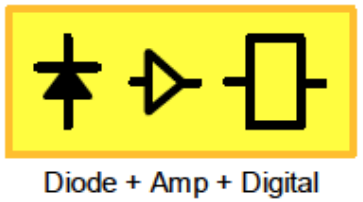


- Workhorse of the field
- Radiation hard
- Flexible (ASIC and sensor separate, 3D sensors)
- Costly

Depleted CMOS MAPS



~100 μm



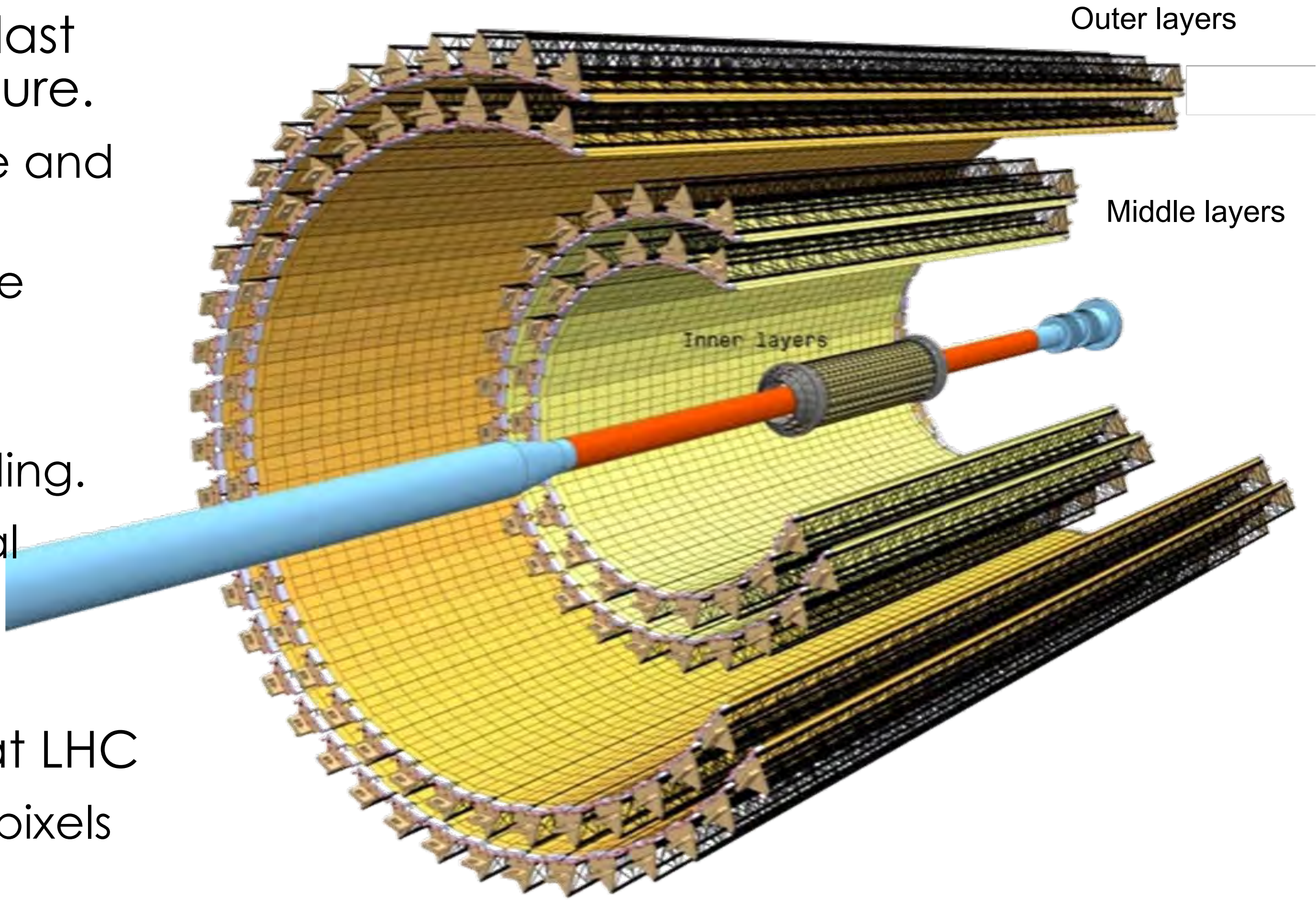
- Integration of Front-End electronics
- Not radiation hard
- Flexible integration
- Commercial process

MAPS = Monolithic Active Pixel Sensor

CMOS Trackers

- CMOS monolithic active pixel trackers have gained **enormous momentum** over the last years and hold great promise for the future.
  - Commercial processes offer high volume and large wafers (cost effective)
  - CMOS sensors can be thinned to achieve ultimate low mass trackers <1%
  - Small pixel sizes (~20 µm), low power
  - No cost (and complexity) of bump-bonding.
  - Highly integrated modules using industrial postprocessing tools.

- ALICE Inner Tracker, first CMOS tracker at LHC
  - 7 layers (R = 21-400 mm), ~ 10 m^2, 12.5 Gpixels
  - 0.35% X_0/layer (Inner)
  - Pixel size: 26.88 x 29.24 μm^2



ALICE Inner Tracker for LHC Run 3

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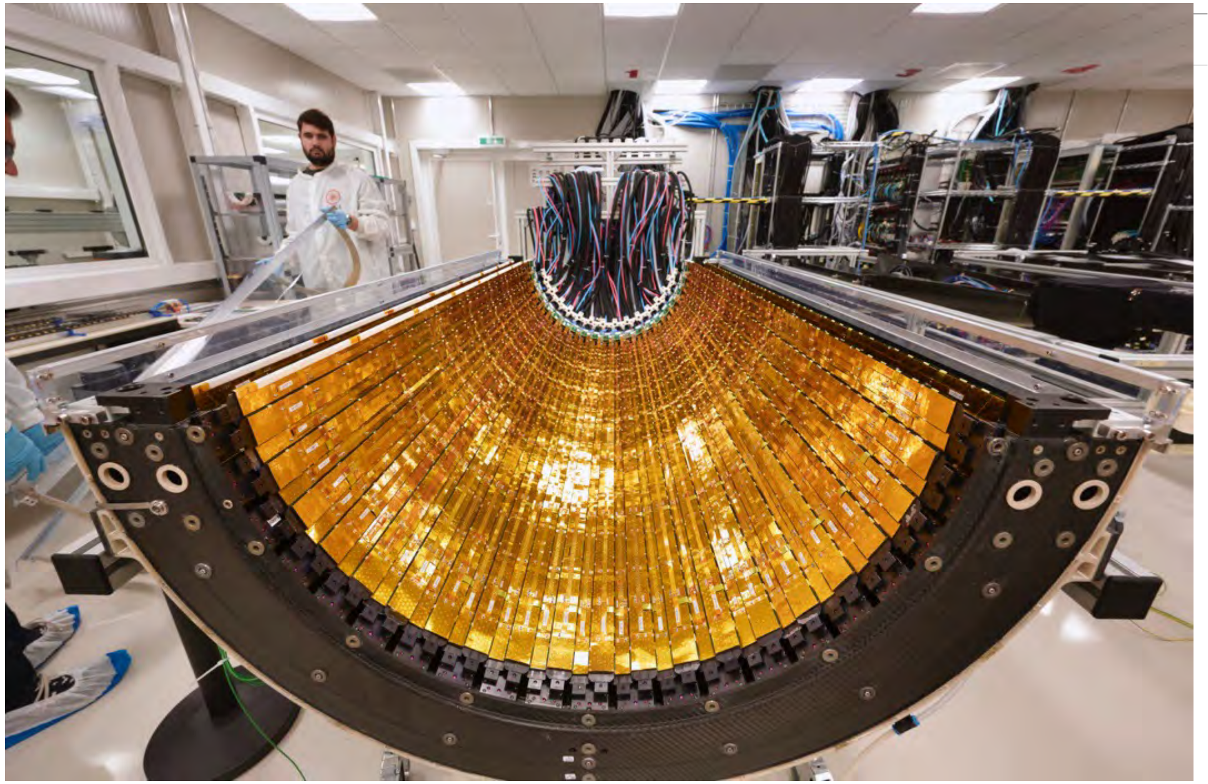
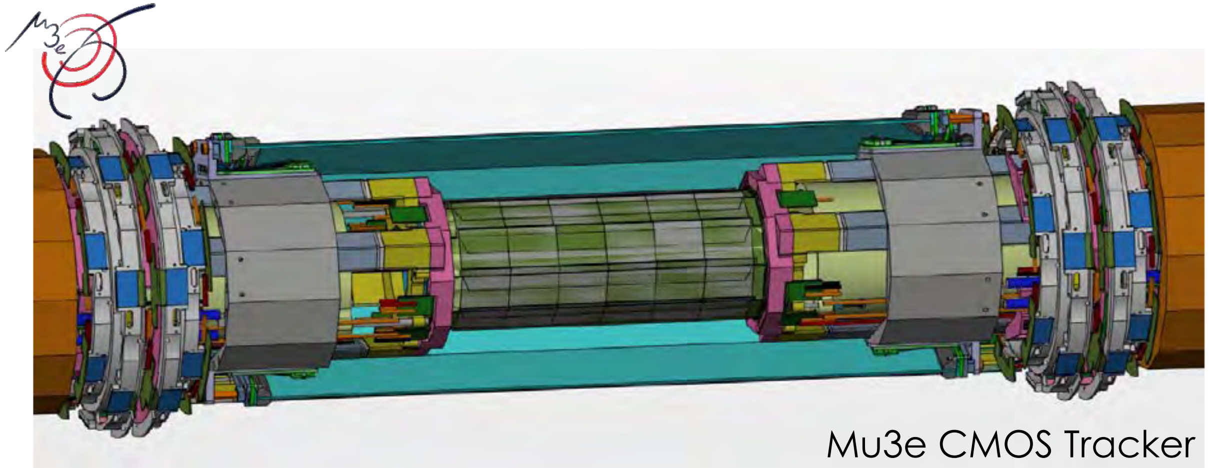
ALICE Inner Tracker System 2



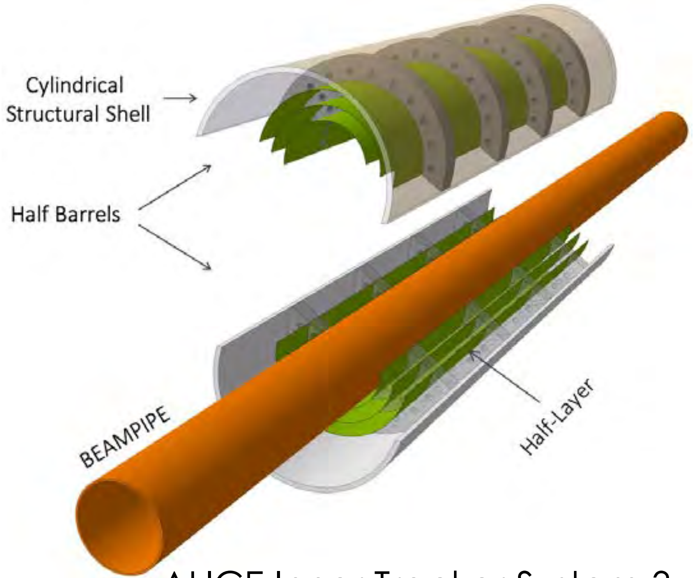
https://home.cern/news/news/experiments/alice-journey-cosmopolitan-detector

Next Generation CMOS Trackers

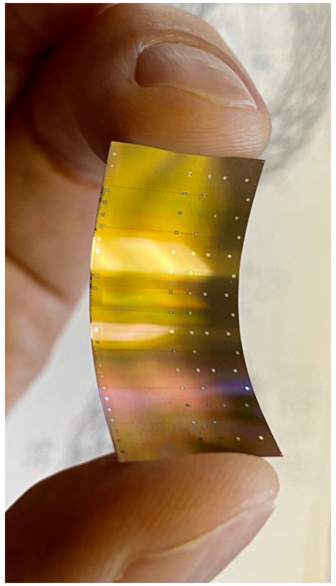


Mu3e CMOS Tracker

- Mu3e:
  - Ultra-thin, 50 μm, wafer-scale HV-CMOS Monolithic Active Pixel Sensor.
  - 180 nm technology, chip size 20.6 x 23.2 mm^2; pixel size 80x80 μm^2
  - **0.5 ‰ X_0** per layer, <30 μm resolution



ALICE Inner Tracker System 3

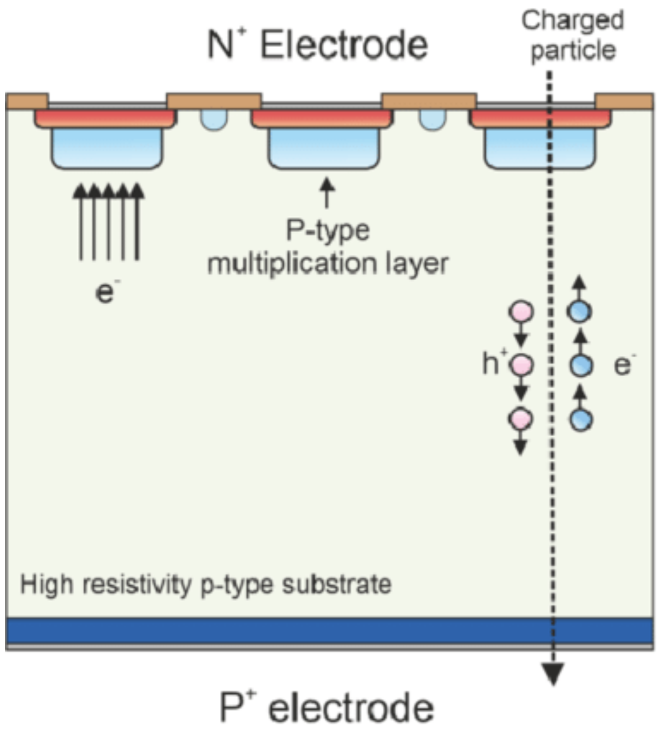


ALIPIDE thinned readout chip

- ALICE ITS-3:
  - Ultra-thin (20 μm to 40 μm), wafer-scale **HV-CMOS** Monolithic Active Pixel Sensor.
  - 65 nm technology, chip size 280 x 94 mm^2, stitched,
  - 0.5 ‰ X_0 per layer, <5 μm resolution
  - **Flexible!** Bent around beampipe.

Adding Another Dimension

- Through inclusion of internal gain, obtain hit timing information



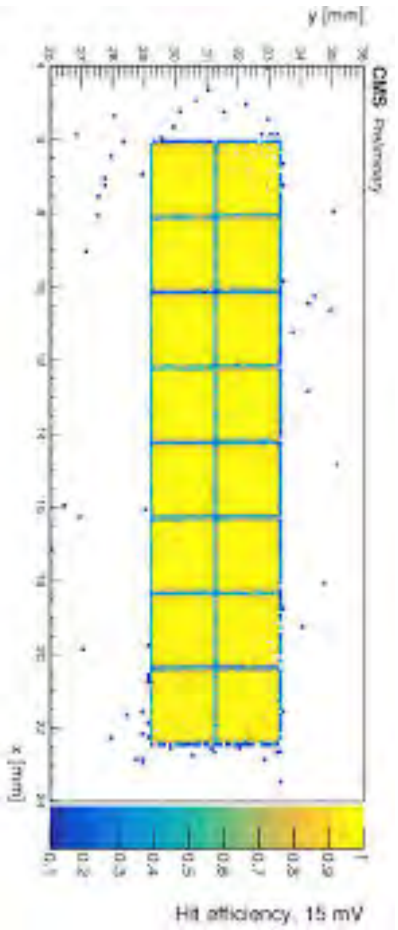
Low-Gain Avalanche Diode **(LGAD)**:

– Silicon-based, with moderately doped p-implant gain layer (~ x20)

– E ~ 10 V/μm

– To achieve spatial resolution, **segmentation** is introduced, which affects the efficiency of the detectors due to gap in the gain layers

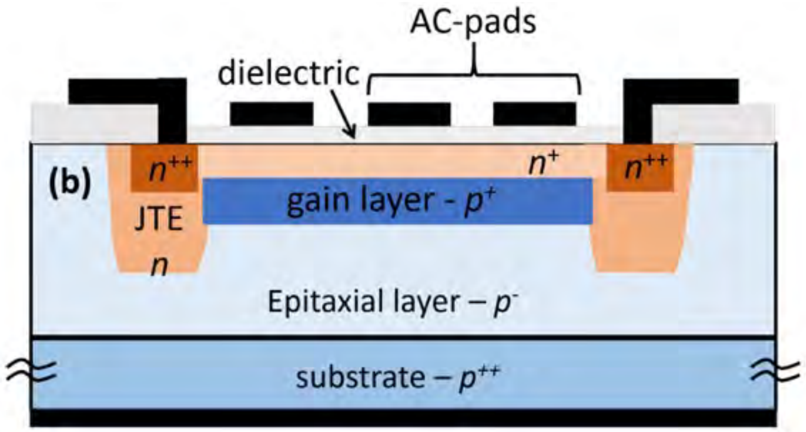
– Excellent timing resolution **σ(t) ~ 40 ps**



Implemented in the Endcap Timing Layer of CMS for the HL-LHC; 39,000 sensors, 14 m^2, 8.5 10^6 channels

Adding Another Dimension with New Ideas

- Through inclusion of internal gain, obtain hit timing information



AC-Coupled devices:

- Implement a **continuous gain** layer over a large area and use capacitive coupling to pickup the signal from the sensors
- No segmentation of the gain layer leads to better efficiency and uniformity
- Enables the fabrication of devices with **small pixels**

Bonding through Anisotropic Conductive Film:

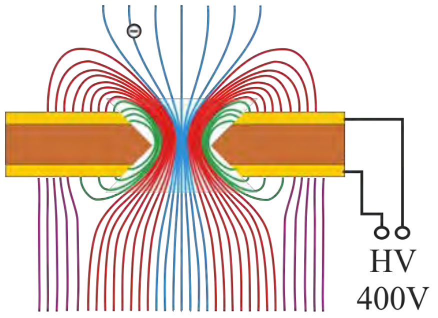
- Used in your laptop and cellphone

Being considered for the Electron Ion Collider at Brookhaven.

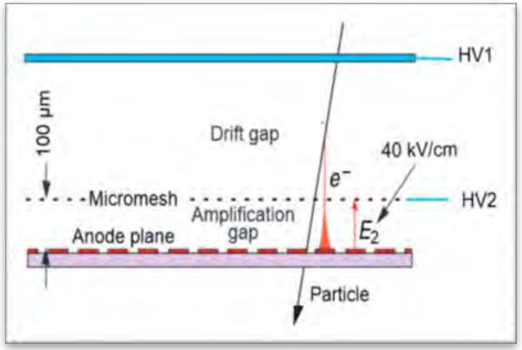
Gaseous Detectors

- Extensively used given they can be built in large areas at modest cost

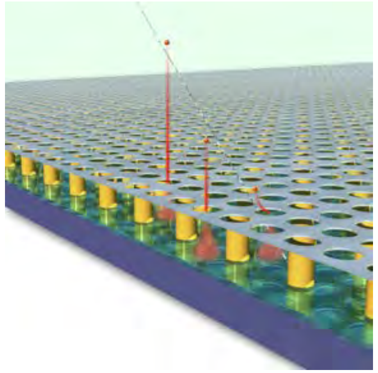
Gas Electron Multiplier



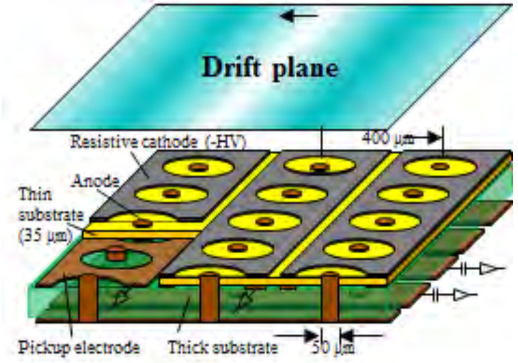
Micro Mesh Gas Chamber



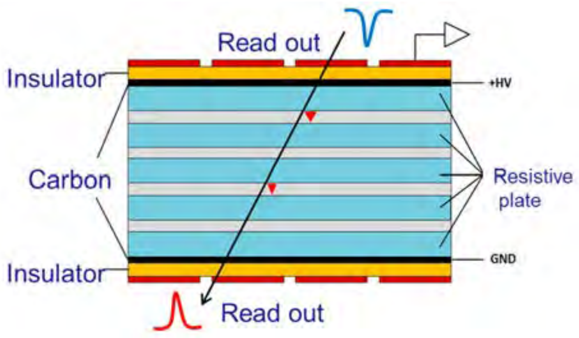
Integrated Grid



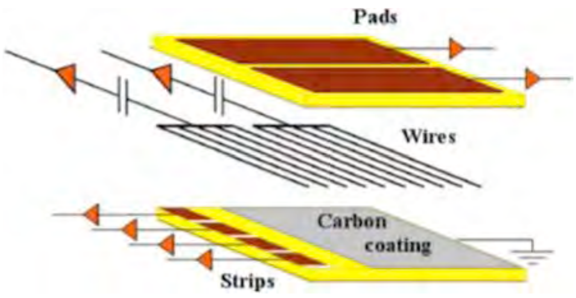
Micro R-well



Resistive Plate Chamber



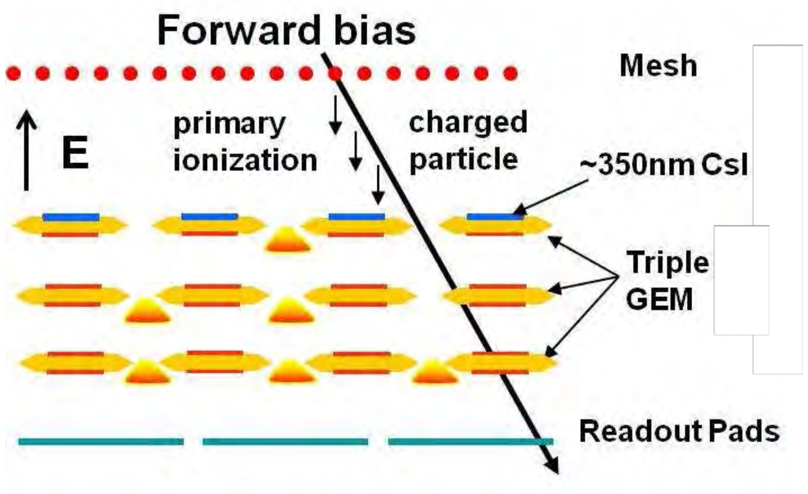
Thin Gap Chamber



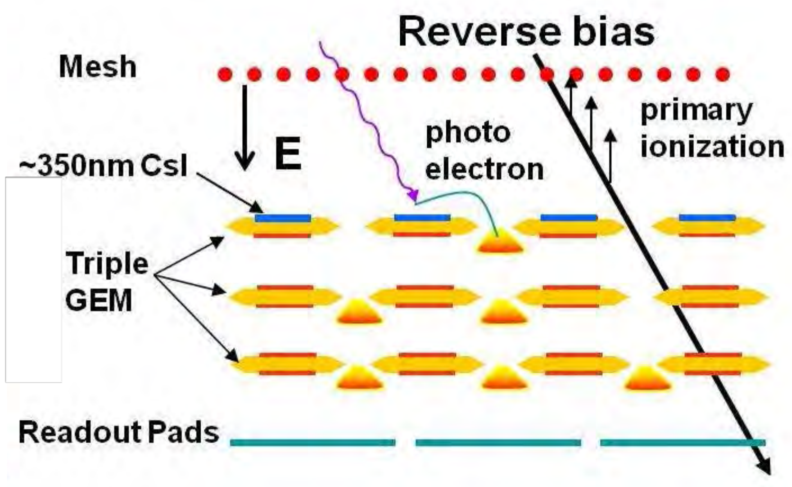
- Relatively old, but flexible technology
- Very cost effective for large areas
- Design tailored to application (rate, ion backflow, energy and spatial resolution)

https://indico.cern.ch/event/1233427/

Versatility

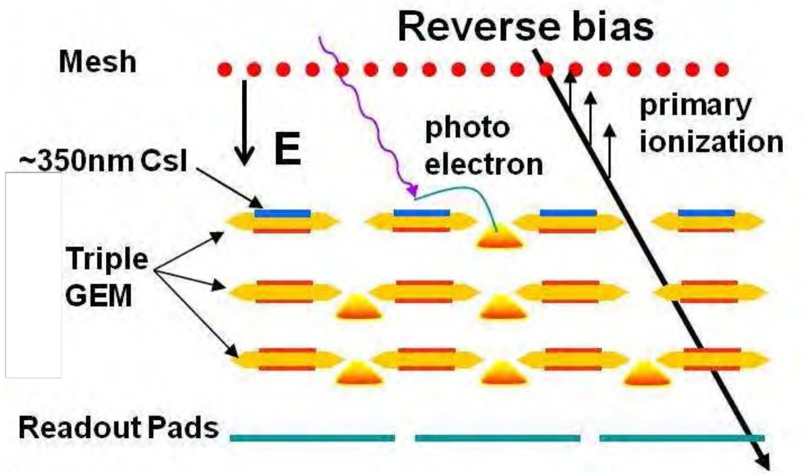


Versatility



- Hadron Blind Detector
  - Photocathode (CsI) deposited on first GEM layer
  - Operated in reverse bias
  - Detect photons from Cherenkov radiation; topological information provides more discrimination (https://www.phenix.bnl.gov/detectors/hbd.html)

Versatility



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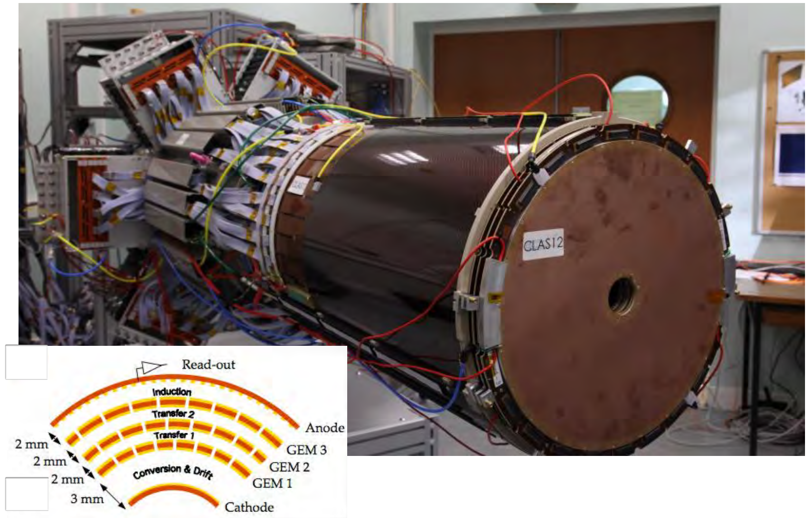
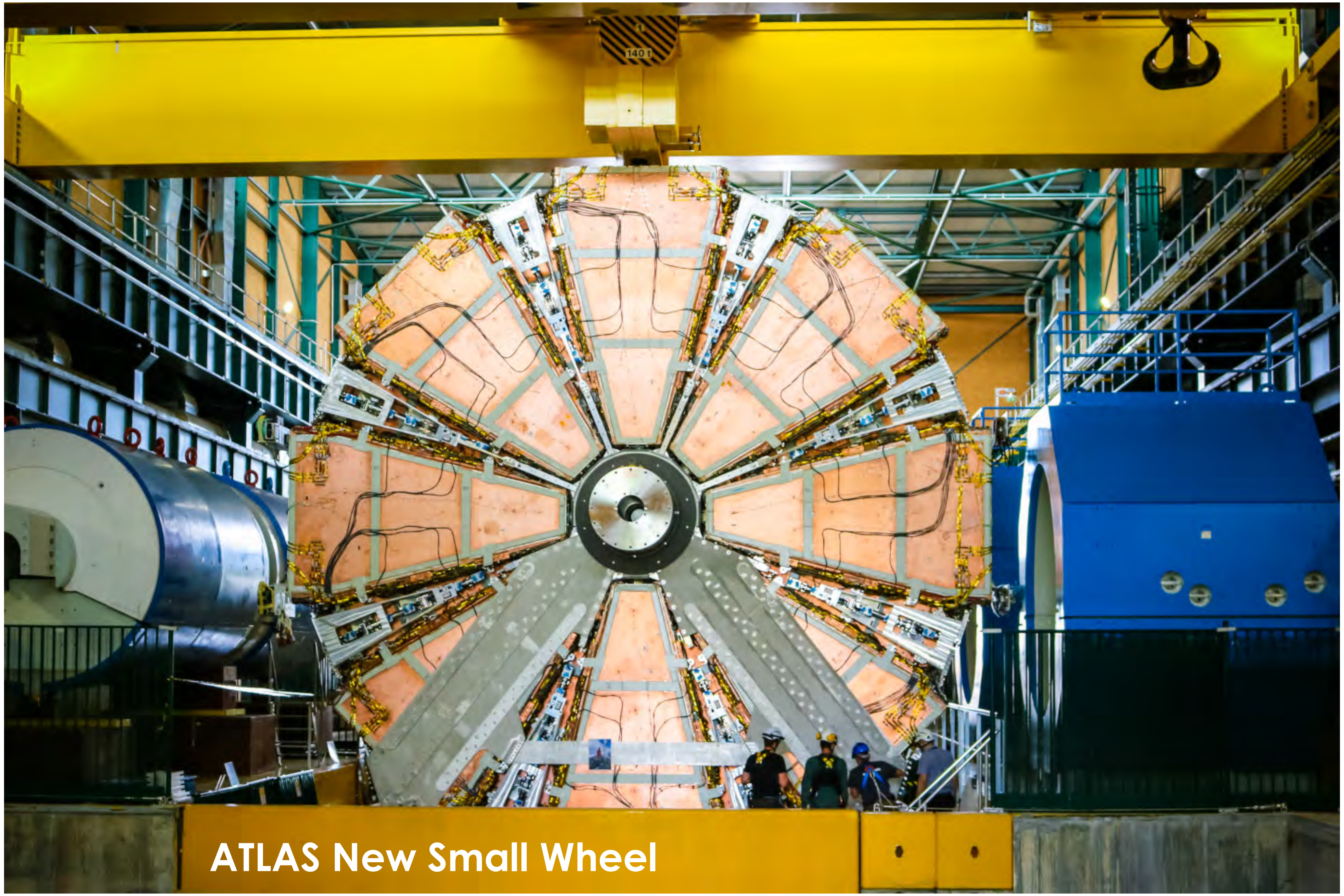


- Cylindrical Geometries: CLAS12 at JLAB
  - 1^{st} curved resistive bulk-Micromegas, 4 m^2
  - 1^{st} use in 5T field
  - High rate: ~ 30 MHz
  - 2 - 6 cylindrical layers

Versatility

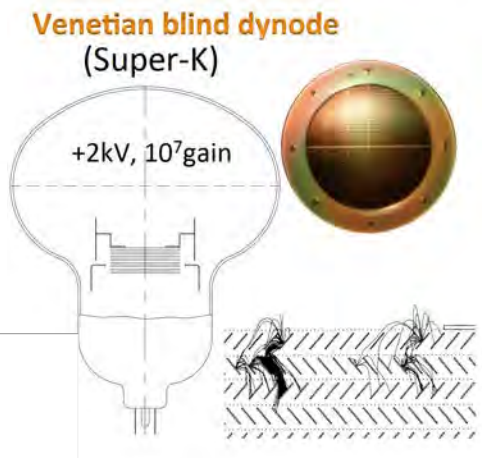


- And they scale very well!

Photodetectors

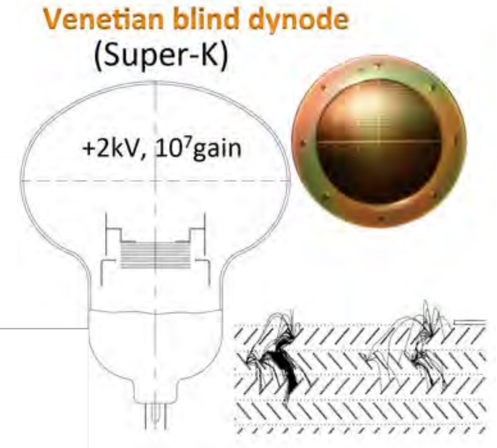
Vacuum Detector

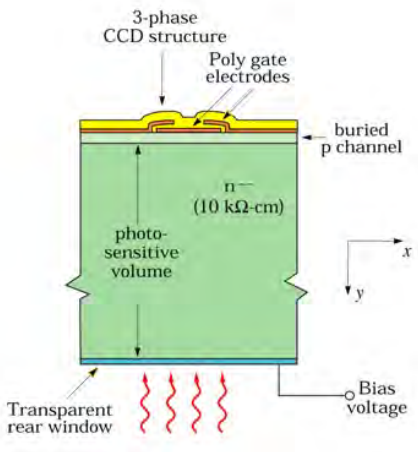
- Photo Multiplier Tube (PMT) with dynode gain structure
  - Modest resolution
- Micro-Channel Plate PMT
  - Excellent timing resolution
- Hybrid Tube
  - Application specific



Photodetectors

Vacuum Detector	Solid State
• Photo Multiplier Tube (PMT) with dynode gain structure ○ Modest resolution • Micro-Channel Plate PMT ○ Excellent timing resolution • Hybrid Tube ○ Application specific	• Silicon Photomultiplier operated slightly above breakdown in avalanche mode ○ Newest detector, quickly became the "workhorse" of the field. • Charge Coupled Devices





DES and DESI

Photodetectors

Vacuum Detector

- Photo Multiplier Tube (PMT) with dynode gain structure
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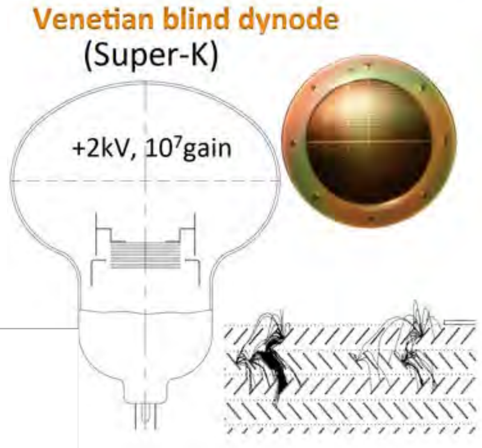
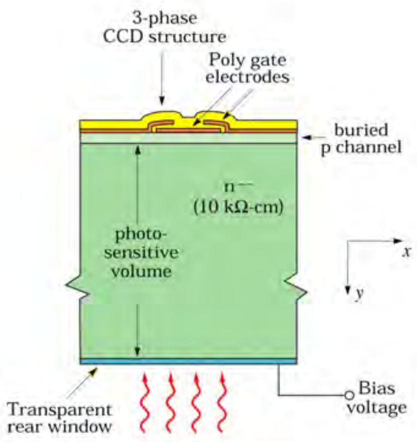


Solid State

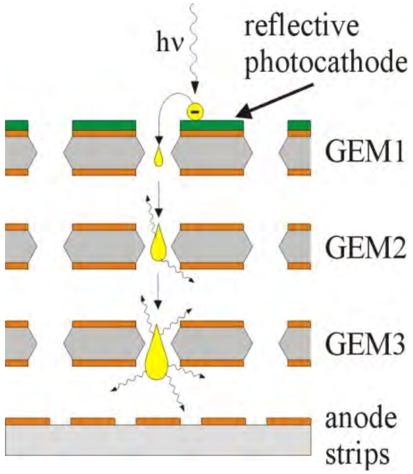
- Silicon Photomultiplier operated slightly above breakdown in avalanche mode
  - Newest detector, quickly became the "workhorse" of the field.
- Charge Coupled Devices



DES and DESI

Gaseous

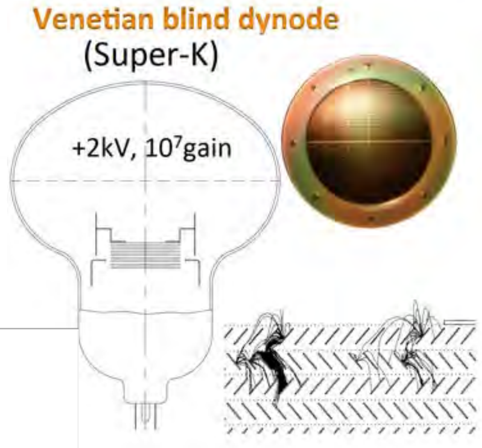
- Based on Micro-Pattern gas detector technology
  - Manufacturing process of combined photocathode and readout is complicated

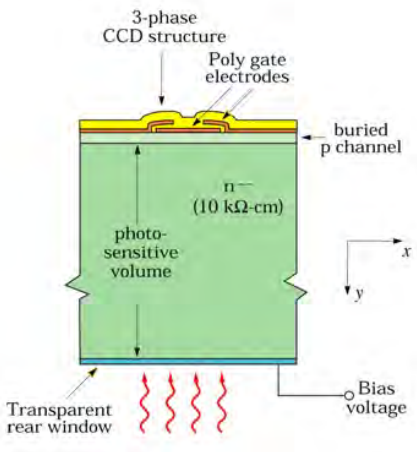


Photodetectors

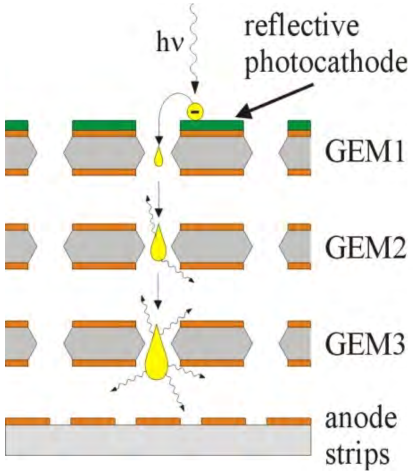
Vacuum Detector	Solid State	Gaseous	Superconducting

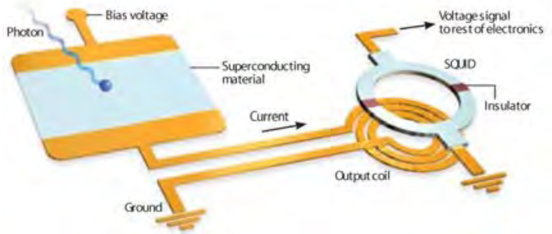
• Photo Multiplier Tube (PMT) with dynode gain structure
  ○ Modest resolution
• Micro-Channel Plate PMT
  ○ Excellent timing resolution
• Hybrid Tube
  ○ Application specific
	• Silicon Photomultiplier operated slightly above breakdown in avalanche mode
	  ○ Newest detector, quickly became the "workhorse" of the field.
	• Charge Coupled Devices
		• Based on Micro-Pattern gas detector technology
		  ○ Manufacturing process of combined photocathode and readout is complicated
			• Transition Edge Sensors, mainly used for $0\nu\beta\beta$-decay and CMB
			• Kinetic Inductance Detectors
			• Superconducting Single photon Nanowire Detectors





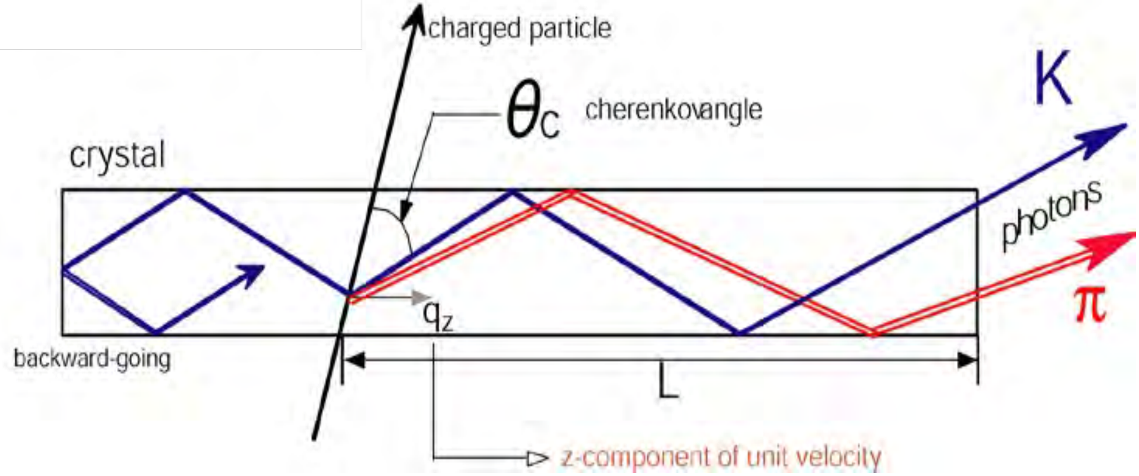
DES and DESI

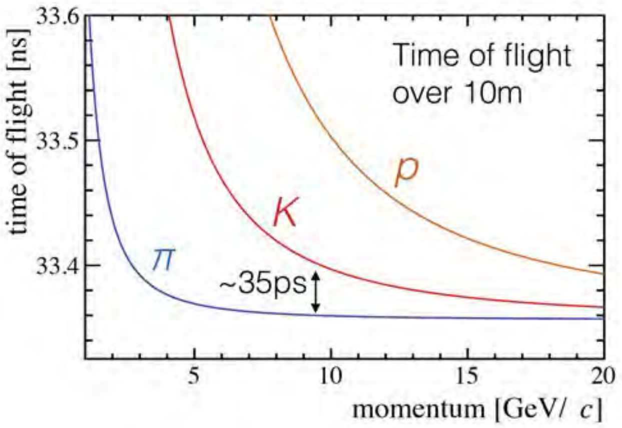


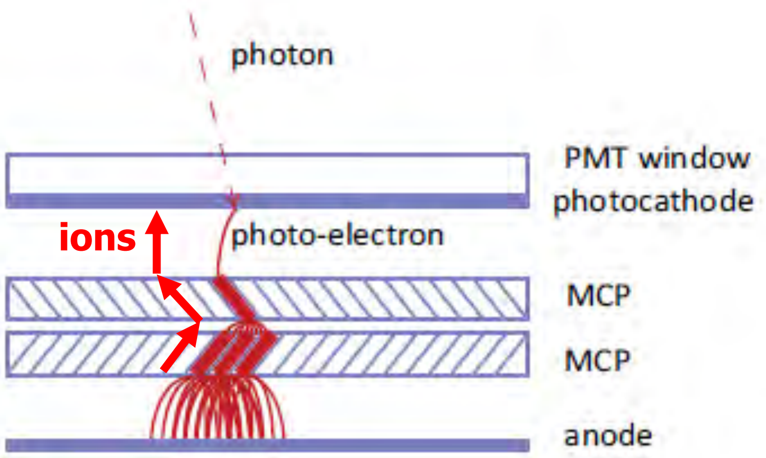


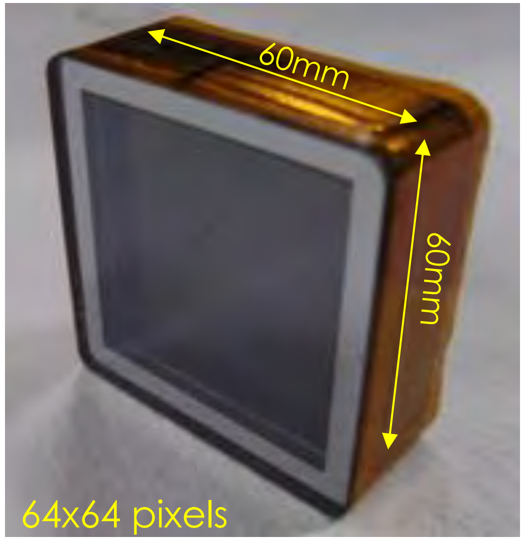
Particle Identification

- Exclusive measurements with full particle identification provides more complete picture of the process under study
  - Detection of Internally Reflected Cherenkov (DIRC) light
  - Time Of internally Reflected CHerenkov (TORCH) light
  - Different opening angle for the same momentum gives different propagation length, thus time.
- Requires excellent timing resolution: ~45ps
- MCP-based detectors
  - Magnetic field a major issue to maintair



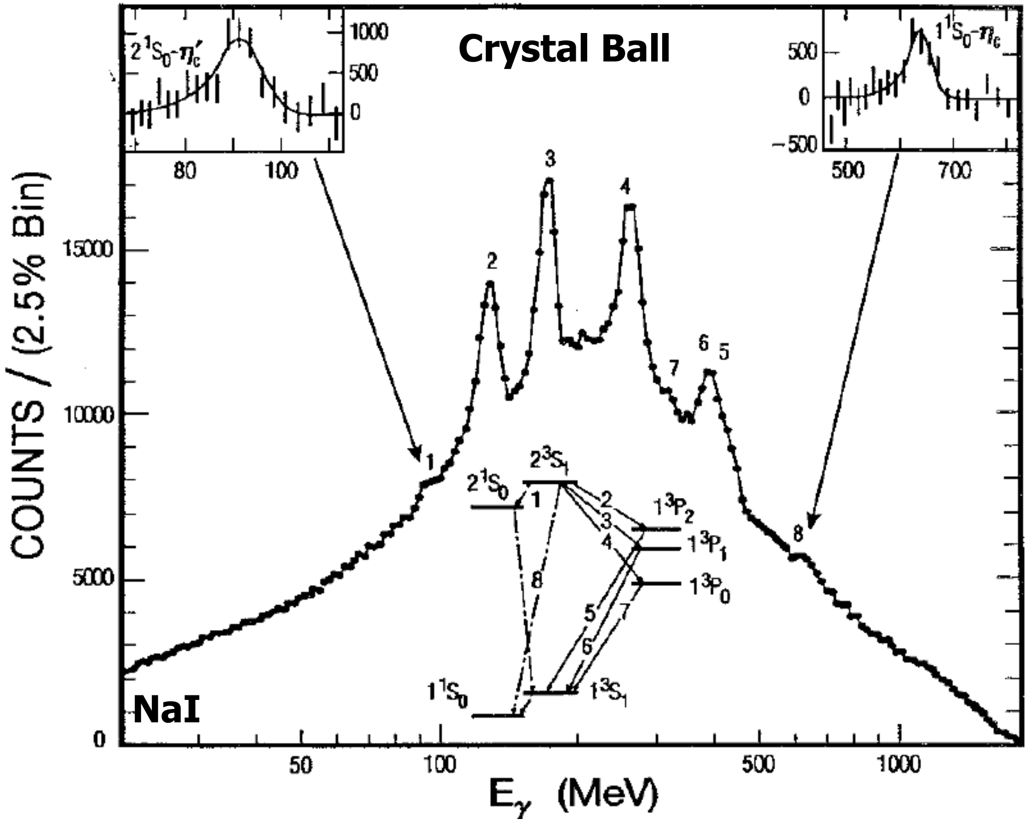






Energy Measurement

Ann. Rev. Nucl. Part. Sci. 1983. 33: 143-97



Crystal Ball Experiment (SLAC)

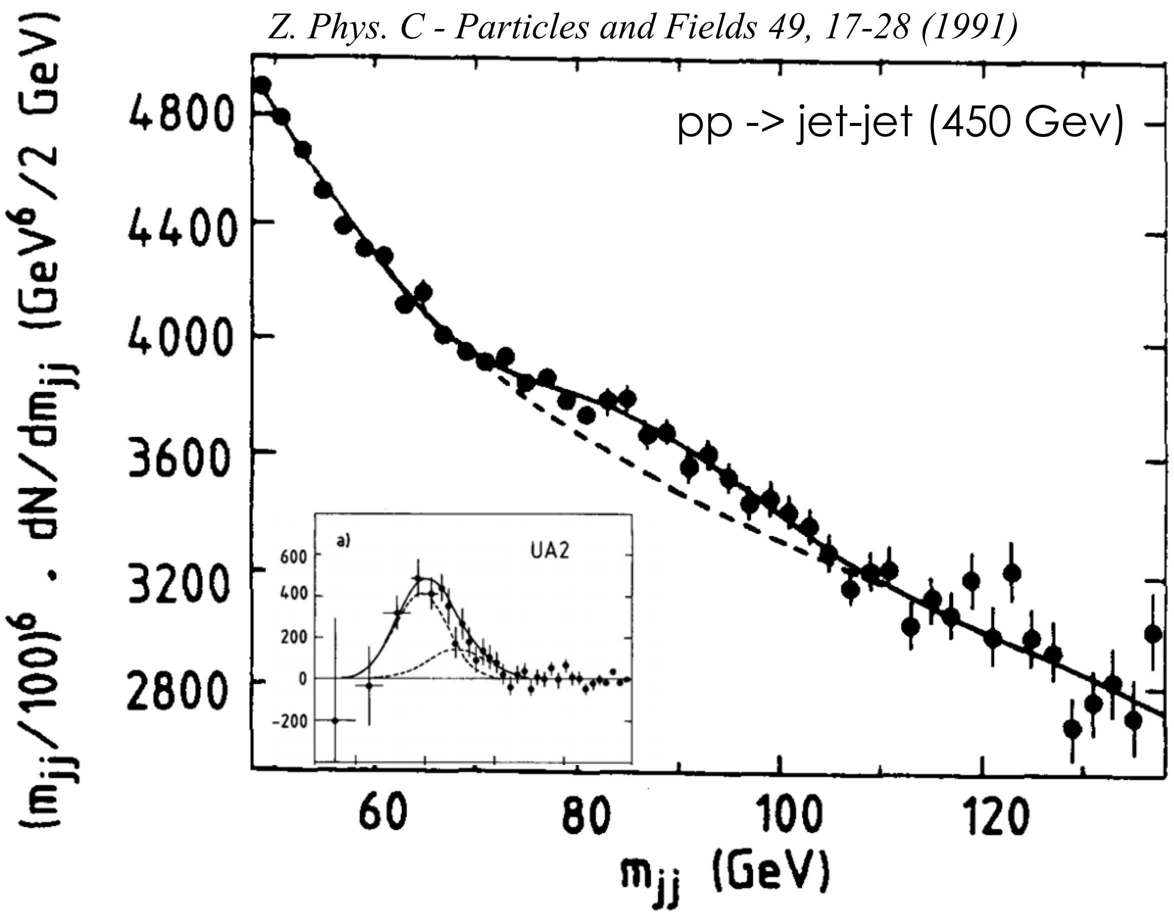
- Charmonium spectroscopy with crystal calorimeter for electromagnetic showers.
- Superior energy resolution.
- Total absorption crystal calorimetry provides best energy resolution; expensive and only used for EM calorimeters.

Energy Measurement

UA2 (CERN)

- Identification of hadronic decay of W- and Z-bosons into jets.
- Jet energy resolution limited for multiple reasons.
- Total absorption crystal calorimetry – no sampling – with multi-dimensional shower identification could provide much better energy resolution; characterize every particle.

Z. Phys. C - Particles and Fields 49, 17-28 (1991)



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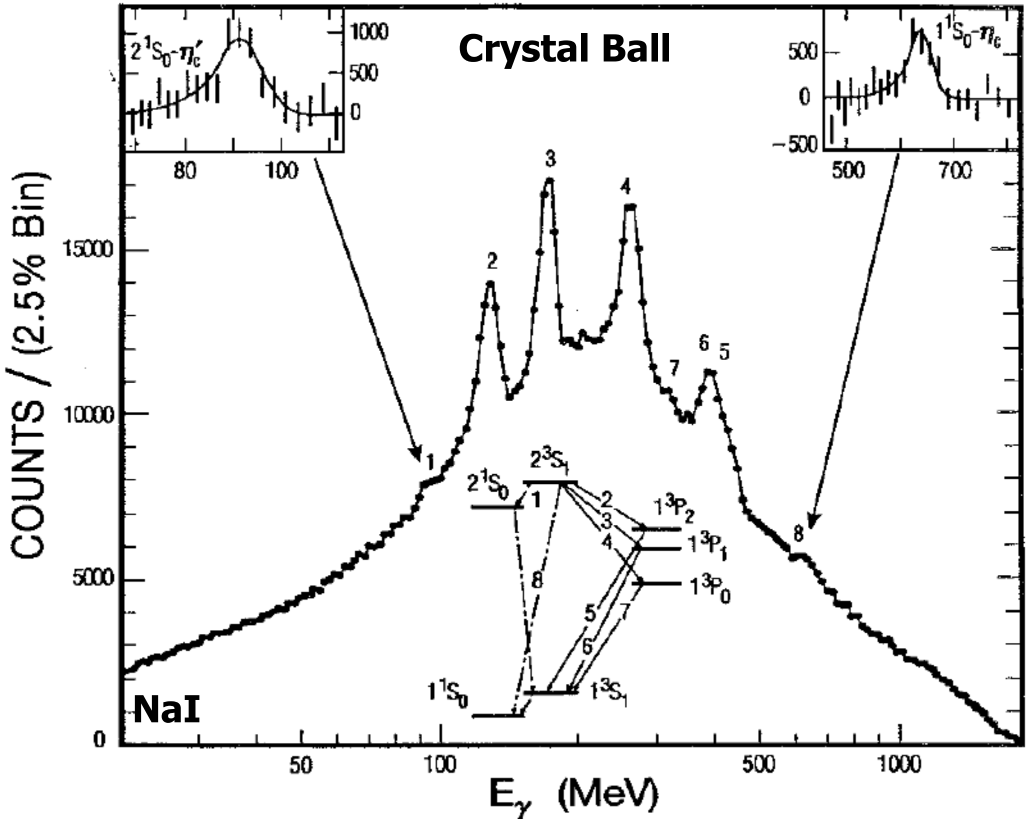

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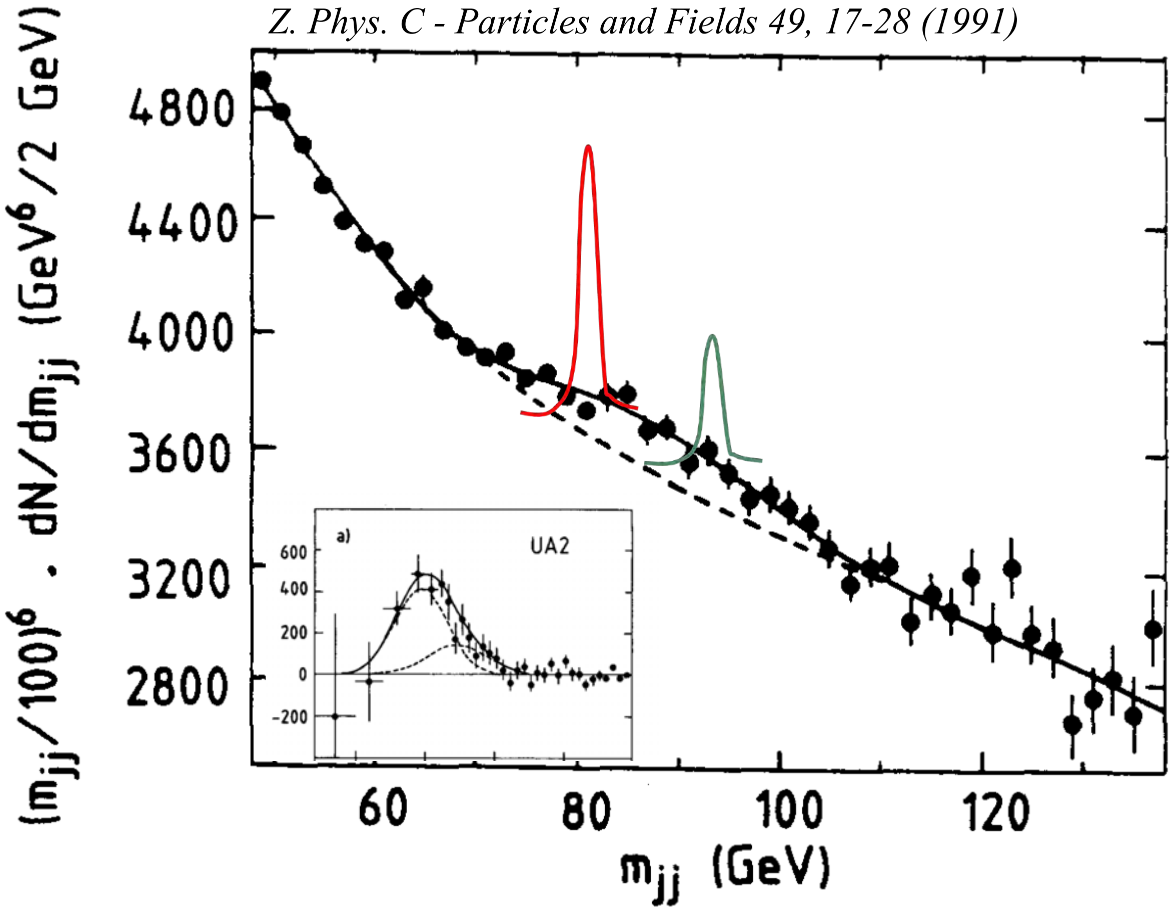
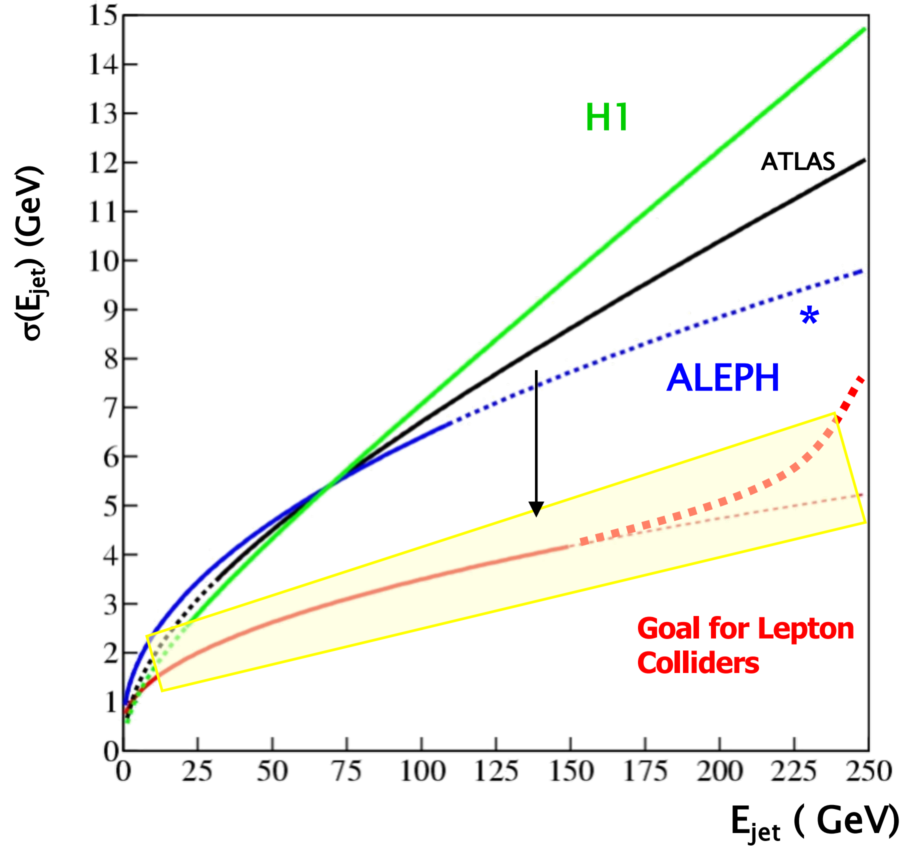


- Quest for superior hadronic energy resolution

Multi-Dimensional Calorimetry

- Ultimate goal is to use all the information from a showering particle in an engineered medium to extract the most information in combination with other detectors.
- **Imaging calorimetry (Particle Flow)**
  - Charged particles measured in tracker
  - γ: by EM Calorimeter
  - Neutral hadron: by EM and Hadron Calorimeter



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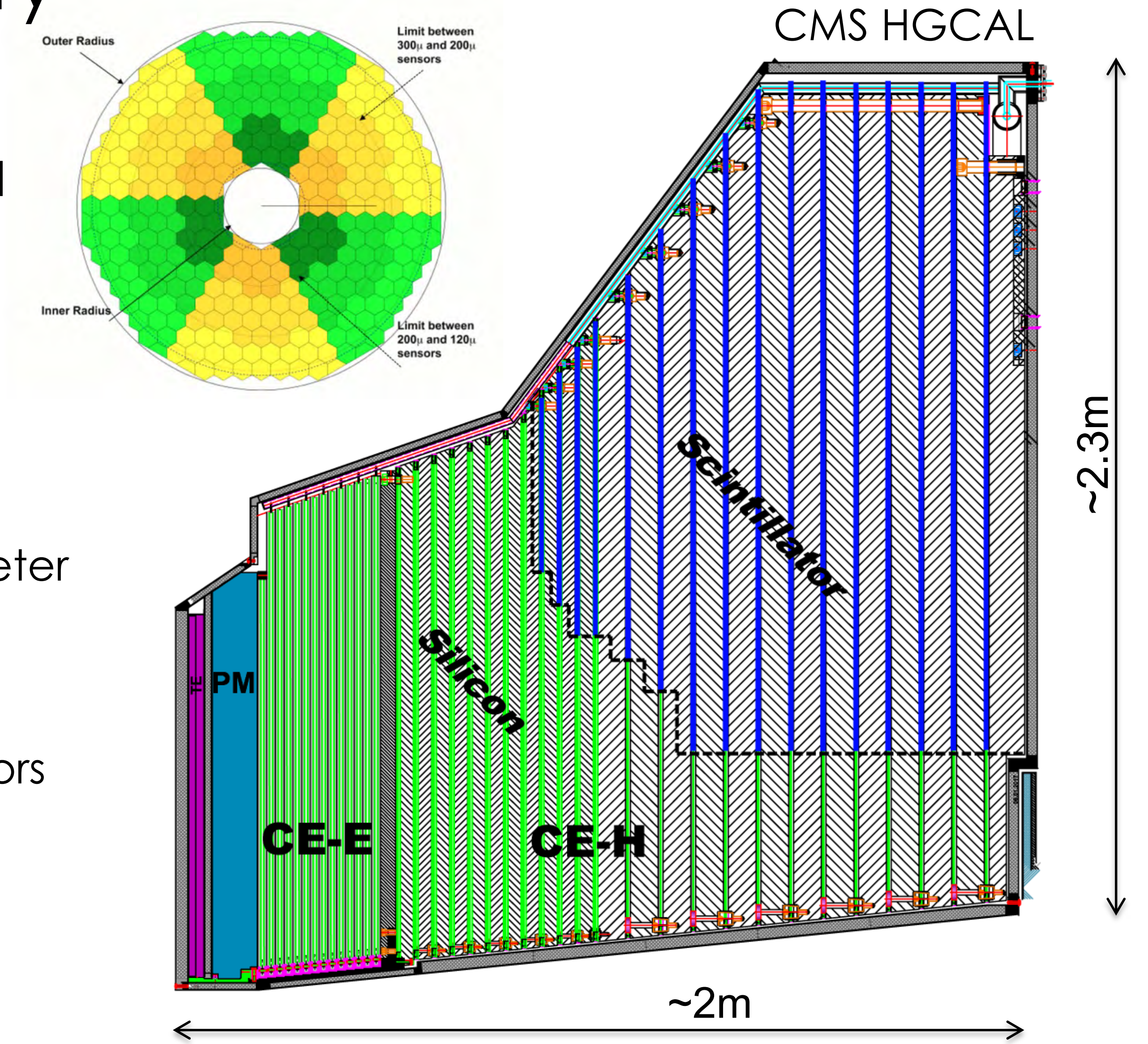
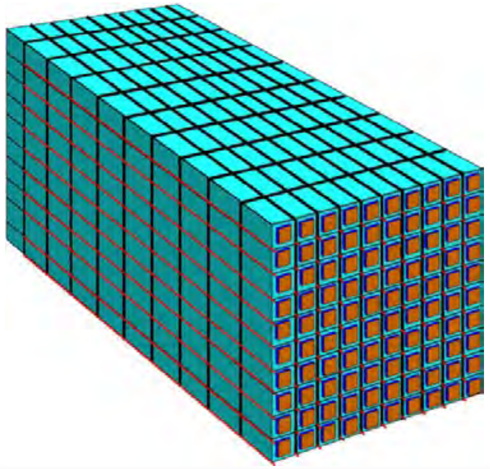
- **Imaging calorimetry (Particle Flow)**
  - Charged particles measured in tracker
  - γ: by EM Calorimeter
  - Neutral hadron: by EM and Hadron Calorimeter
- **5D calorimetry (x,y,z,E,t):** CMS High-Granularity Calorimeter
  - ~640m^2 of silicon sensors, ~370m^2 of scintillators
  - 6.1M Si channels, 0.5 or 1.1 cm^2 cell size
  - 240k scintillator tile channels
  - Data readout from all layers
  - ~31,000 Si modules (incl. spares)



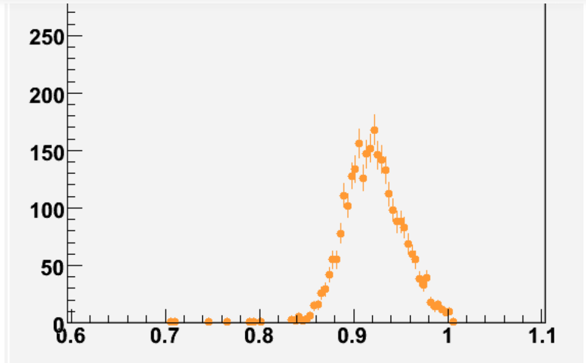
OAK RIDGE National Laboratory

Multi-Dimensional Calorimetry



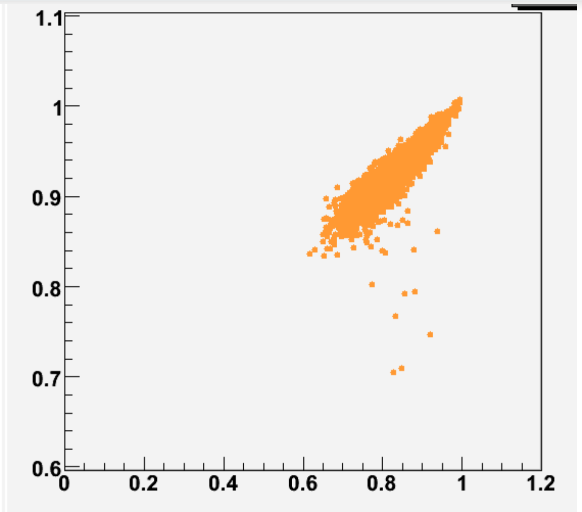
- **Total absorption calorimetry (homogenous)**
  - Fully contained shower in scintillating medium;
  - No sampling fluctuations.
- **6D calorimetry (x,y,z,λ,Q,t):**

Scintillation Only



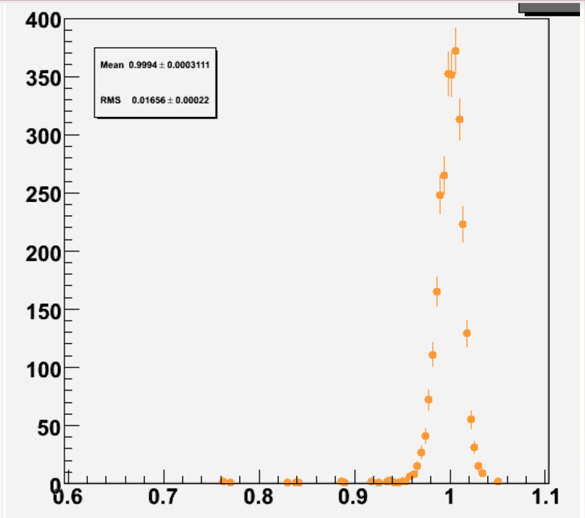
ΔE/E ~ 3.3% @ 100 GeV
Significant non-linearity: mean = 92 GeV

S – C Correlation



Use correlation to limit resulting resolution to local width of scatter plot

Corrected Response



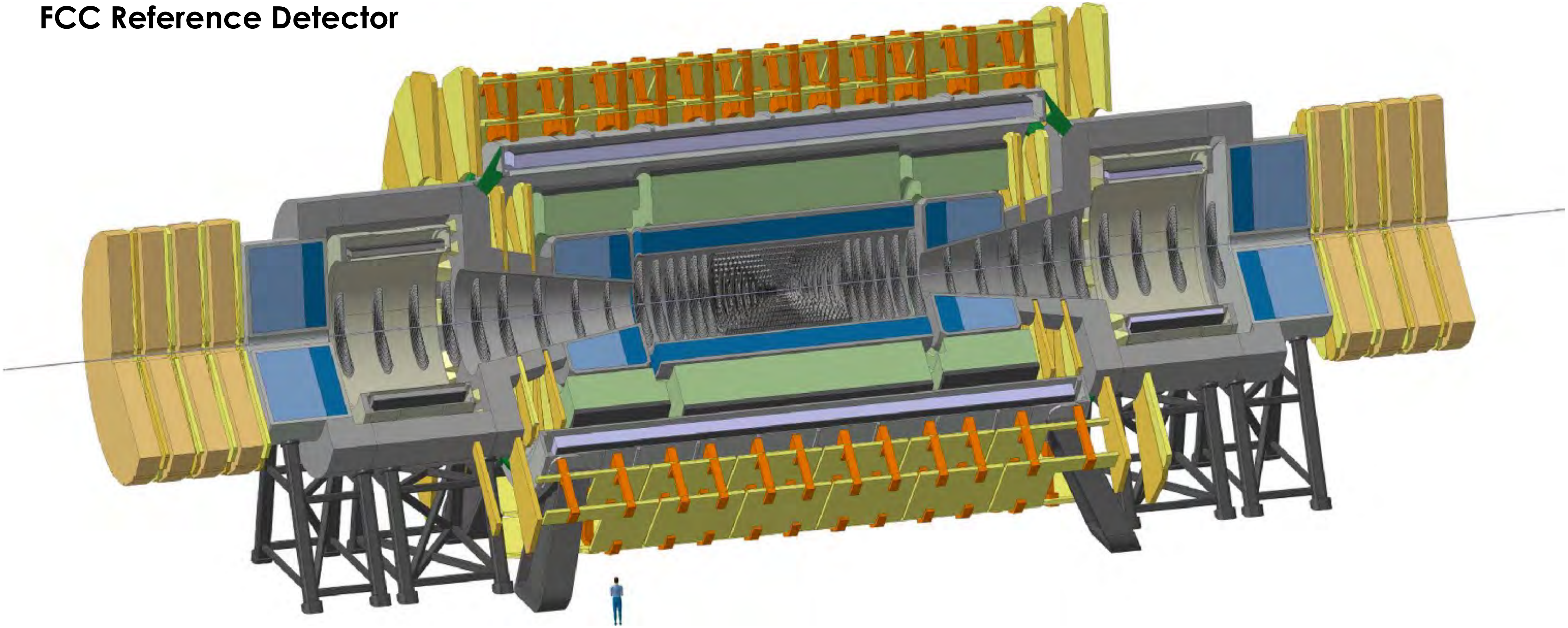
ΔE/E = ~1.2-1.5% @ 100 GeV, Linear response

OAK RIDGE National Laboratory

A. Benaglia et al., IEEE TNS 63(2016) 574-579

A Sense of Scale: 100 TeV

FCC Reference Detector



Eur. Phys. J. Special Topics 228, 755{1107 (2019)

A Sense of Scale: 100 TeV

	CMS	ATLAS	CMS HGCal		FCC/SPPC
Diameter (m)	15	25			~27m
Length (m)	28.7	46			~70m
B-Field (T)	3.8	2/4			6
EM Cal channels	~80,000	~110,000	6.1M		70M (2x2cm^2)
Had Cal channels	~7,000	~10,000	0.3M		80M (5x5cm^2)

- Challenges
  - Embedded readout electronics at 1mW/channel = 1.5MW of power
  - Timing on a system scale of millions of channels at the level of 50ps
  - Pile-up reaching 1000 events
- Simply scaling CMS High-Grained calorimeter would require >5,000 m^2 of silicon

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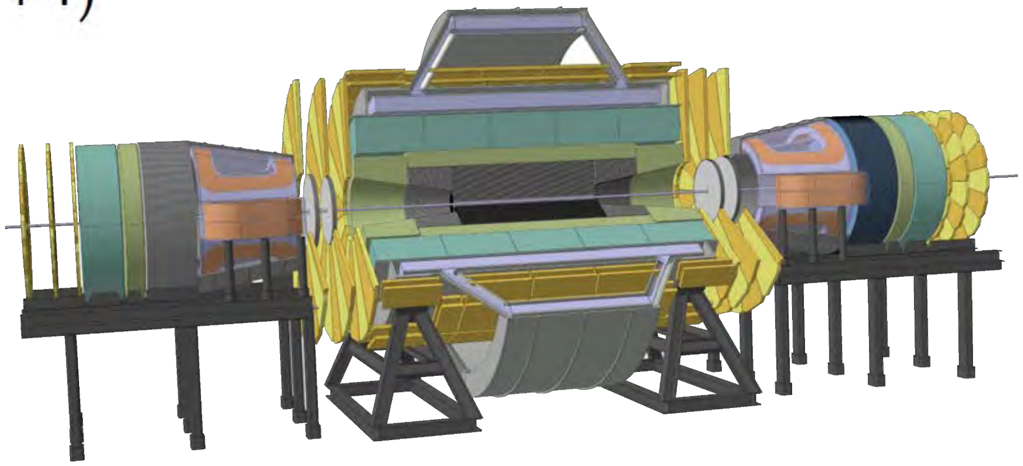
Eur. Phys. J. Special Topics 228, 755{1107 (2019)

Tracking And B-Field

- Momentum Resolution: $$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$
- Challenge:
  - A factor 7 in energy from 14 TeV → 100 TeV, requires a gain of a factor 7 in σ/BL^2 to retain LHC p_T resolution, down to $|\eta|<6$!
    - B=4T → B=6T
      σ=20μm → 5μm
    - L=1.1m → 2.4m



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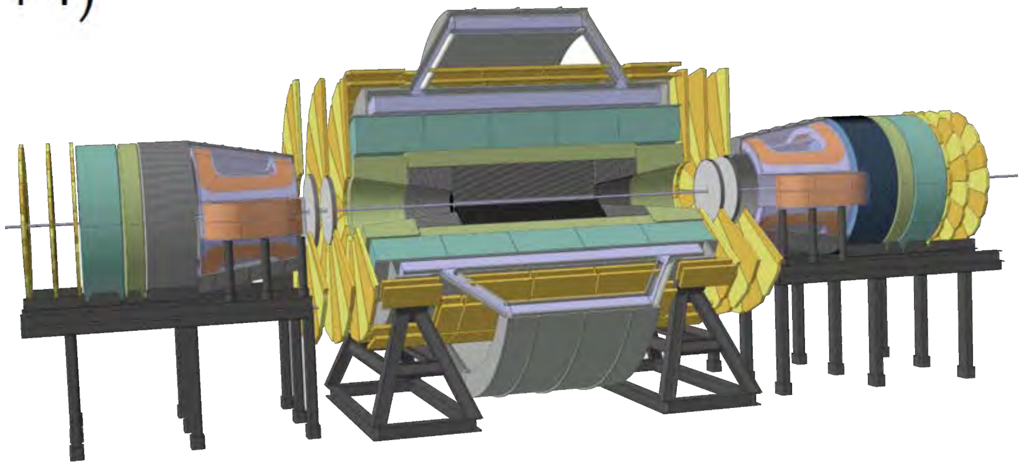
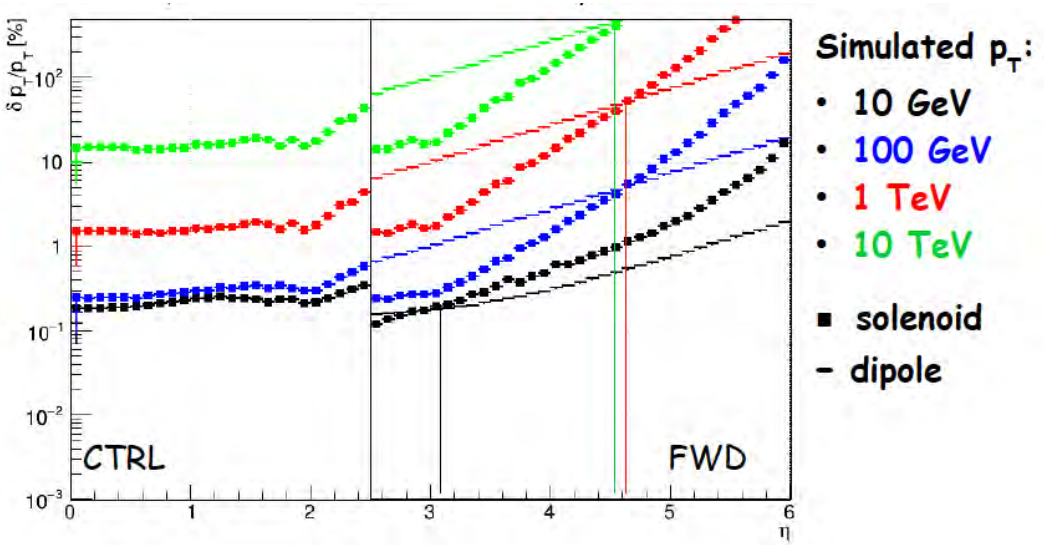


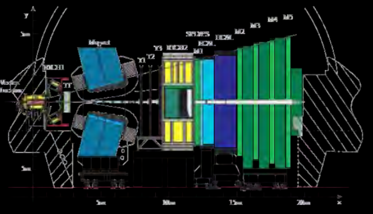
Dipole or solenoid in forward region



Magnet: 6T / 12m bore
System: 30-50 m long
Stored Energy: 50-60 GJ.

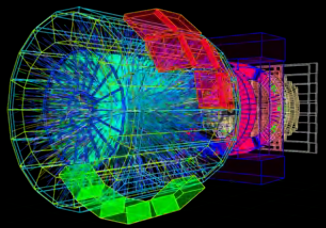
Trigger and Data Rates

LHCb



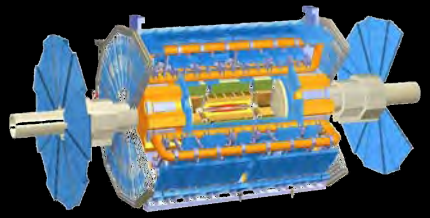
- 40 MHz — 40 Tb/s
- DAQ
- LLT
  μ, e, γ, h
- 5 - 40 MHz
- HLT
  Event reco
- 20 – 100 kHz
- Offline
- 2 GB/s

ALICE



- 50 kHz — 1 TB/s
- DAQ
- Reco
  +
  Compression
- 50 kHz
- Offline
- 75 GB/s

ATLAS

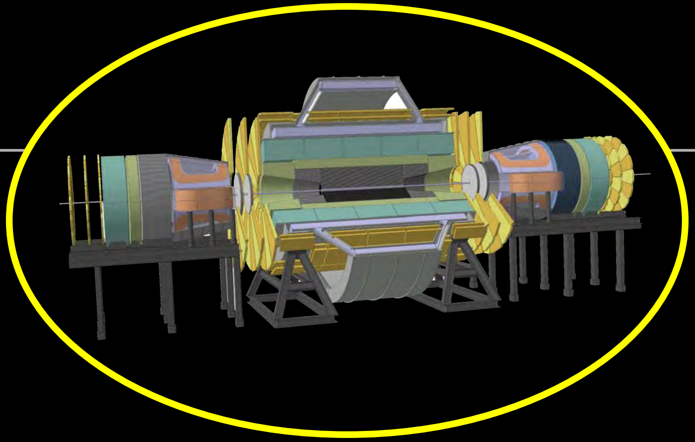


- 40 MHz — 20 Tb/s
- DAQ
- Level 0/1
- 0.5 - 1 MHz
- Level 2
- 5 - 10 kHz
- Offline
- 10 - 20 GB/s

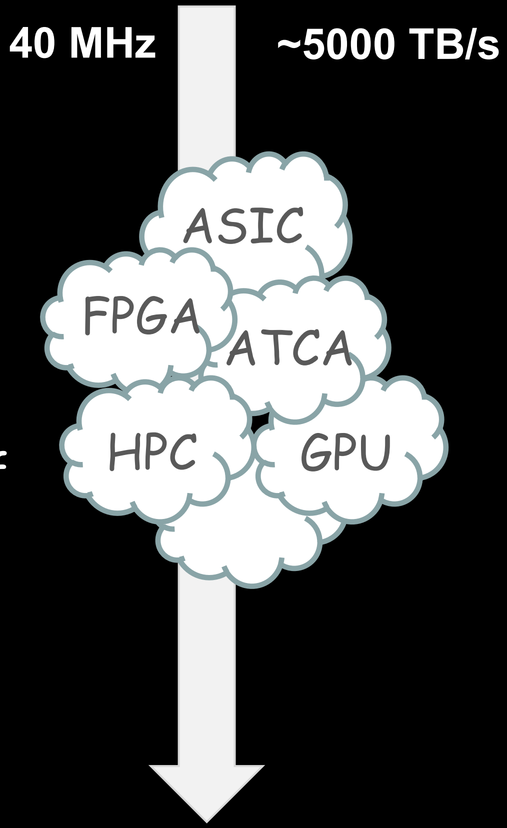
CMS

- 40 MHz — 40 Tb/s
- DAQ
- Level 1
- 1 MHz
- Level 2
- 7.5 – 10 kHz
- Offline
- 40 GB/s

At 100 TeV

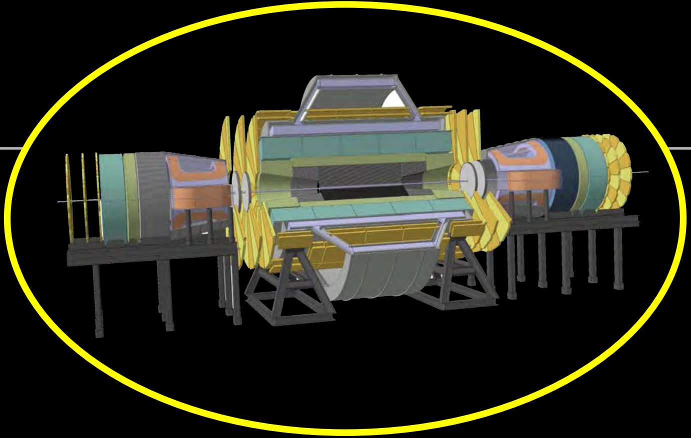


Larger detectors
Higher granularity
More data



- Tracking and calorimeter each have raw data rates of ~2,000 TB/s
- Using 10 Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Eb/s

At 100 TeV



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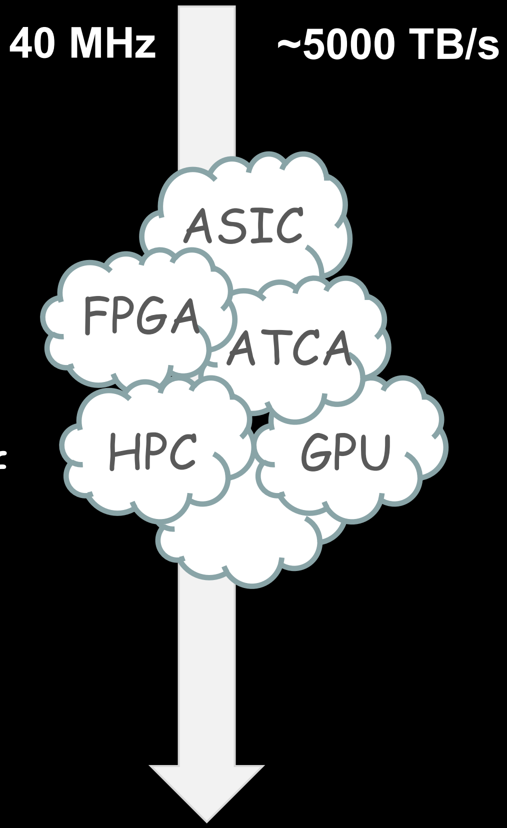

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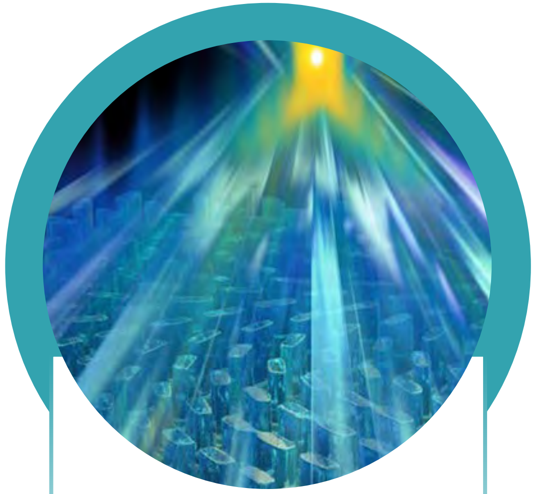
- Using 10 Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Eb/s

- Power budget for links, based on best current devices (~500mW for 10 Gb/s): 2MW for links alone
- Substantial R&D required for low-mass, rad-hard, low cost devices with no commercial applications

Science Technologies Will Play a Pivotal Role

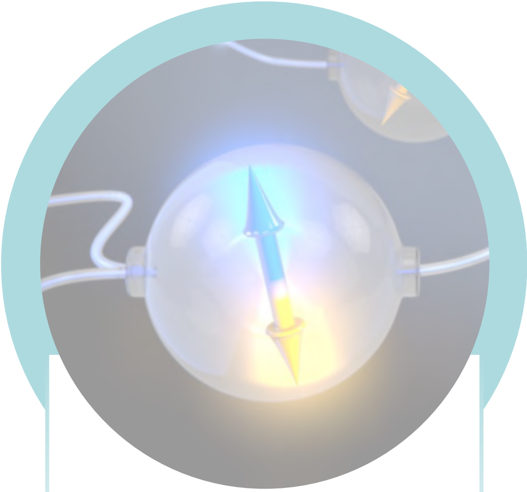
Directed R&D

Aimed at realizing high-priority projects



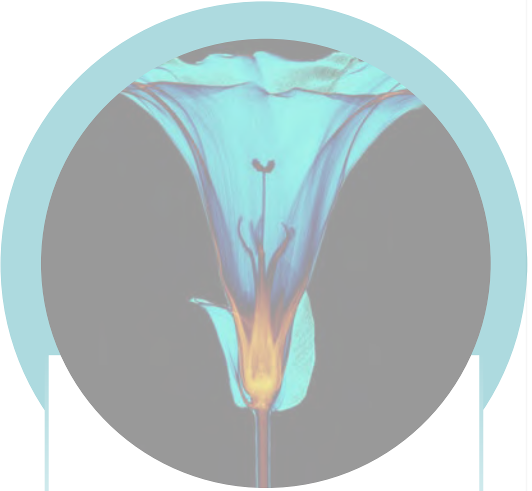
Generic R&D

Aimed at developing new methodologies and techniques, adopting emerging technologies



Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines

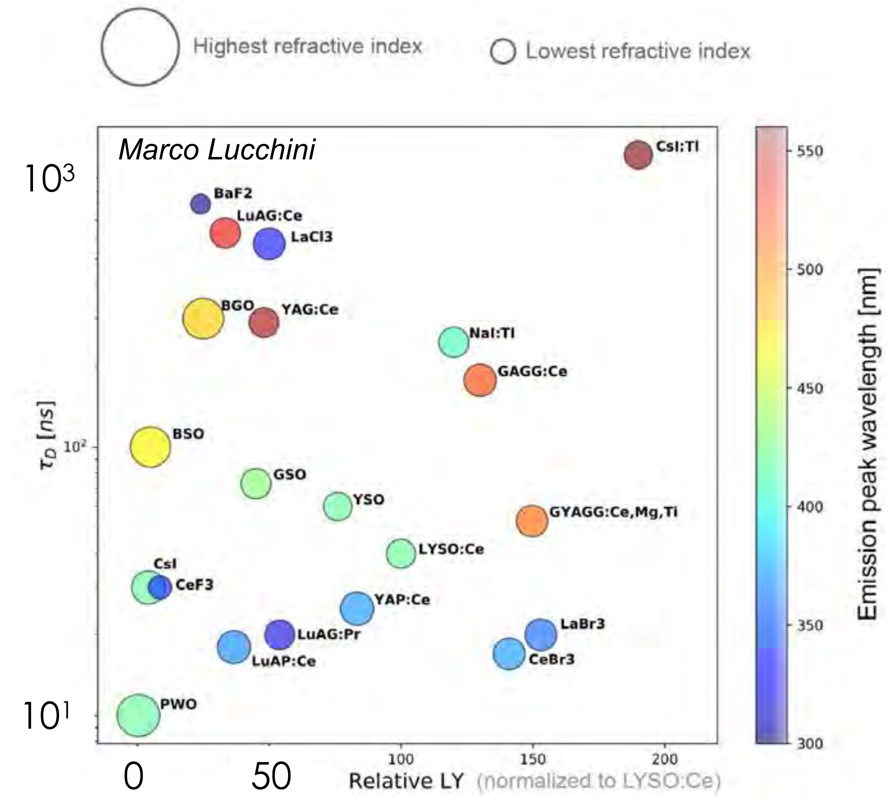


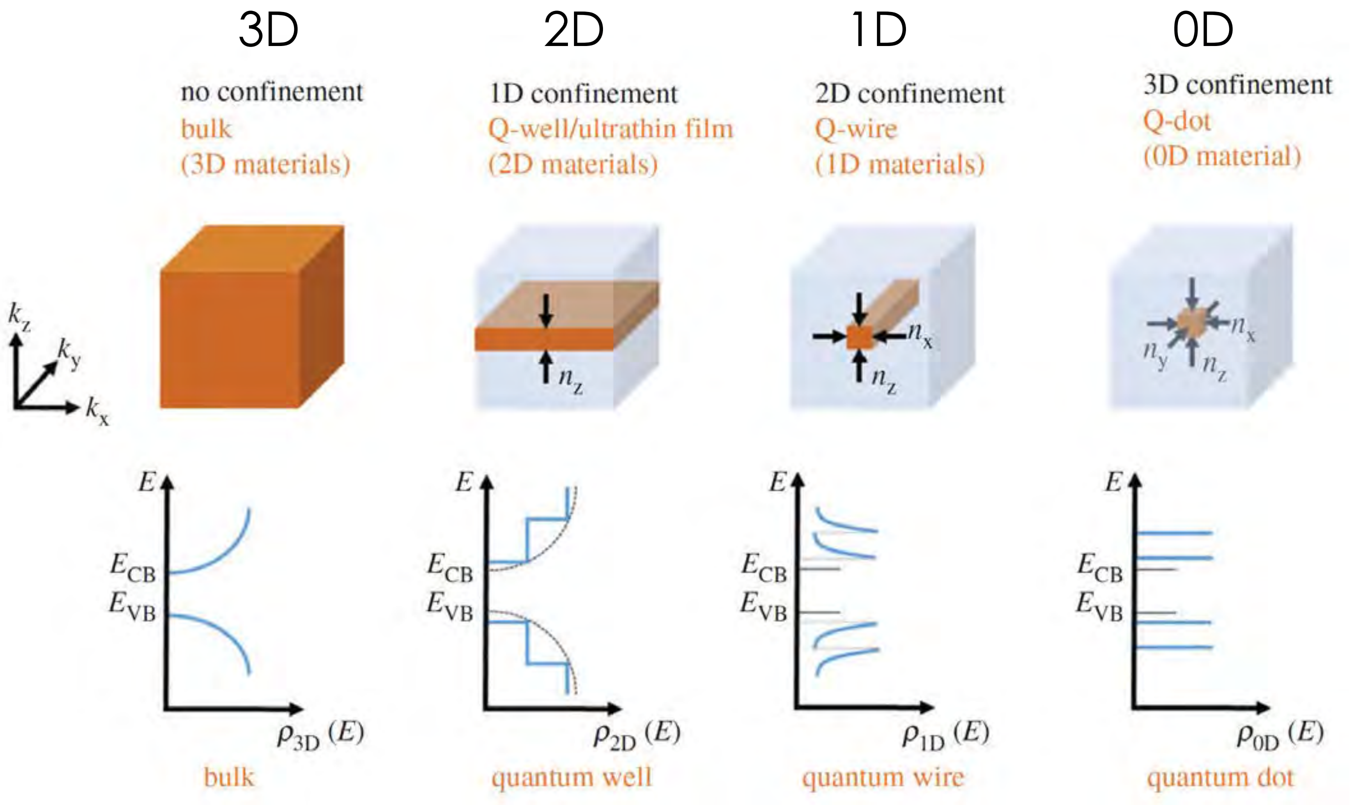
R&D That Inspires

Applying the techniques to other areas of science

Crystal Calorimetry

- Traditionally, crystal – fully absorbing – calorimetry has obtained the best energy resolution





rsos.royalsocietypublishing.org R. Soc. open sci. 5: 180387

- Huge range of possibilities through **quantum engineering** of materials

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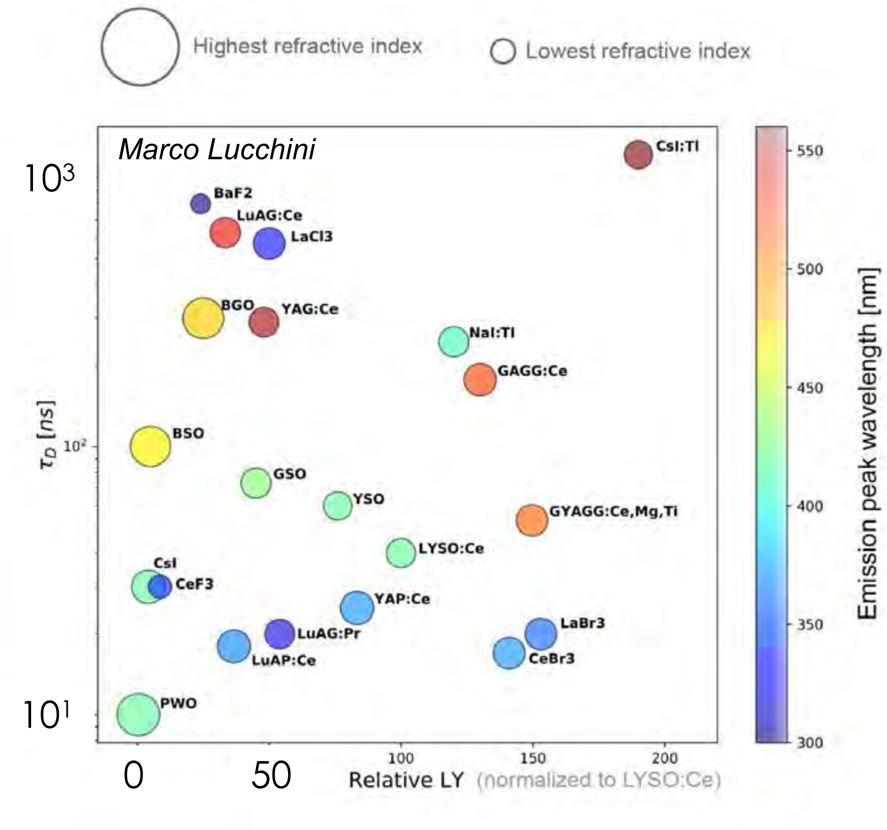
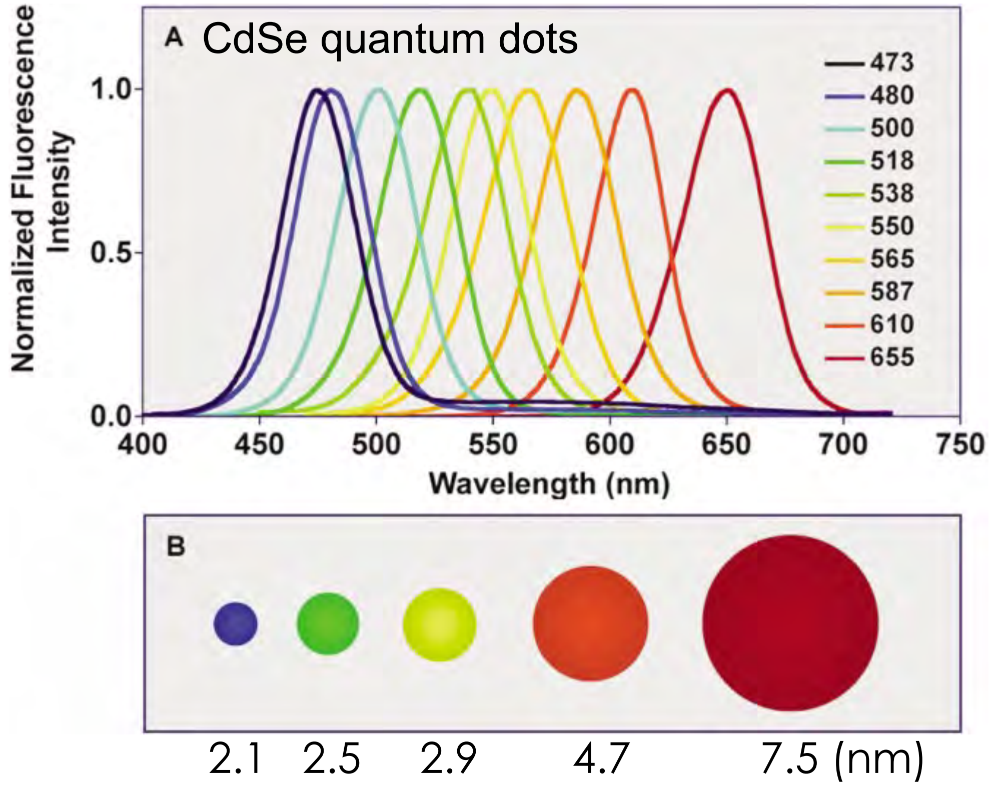


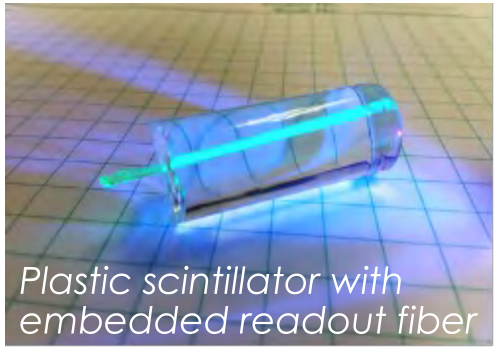


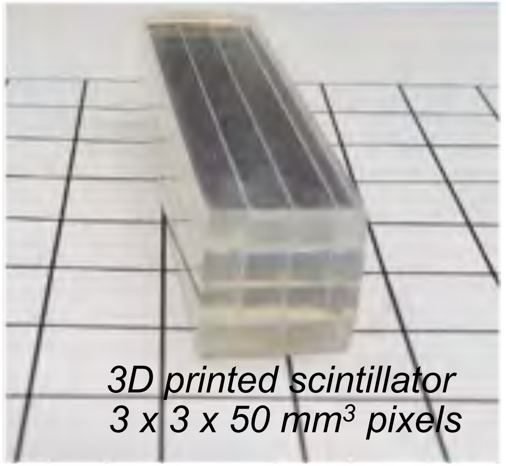
A. Smith, https://doi.org/10.1039/B404498N

- Huge range of possibilities through **quantum engineering** of materials

Creation of Scintillators with Light

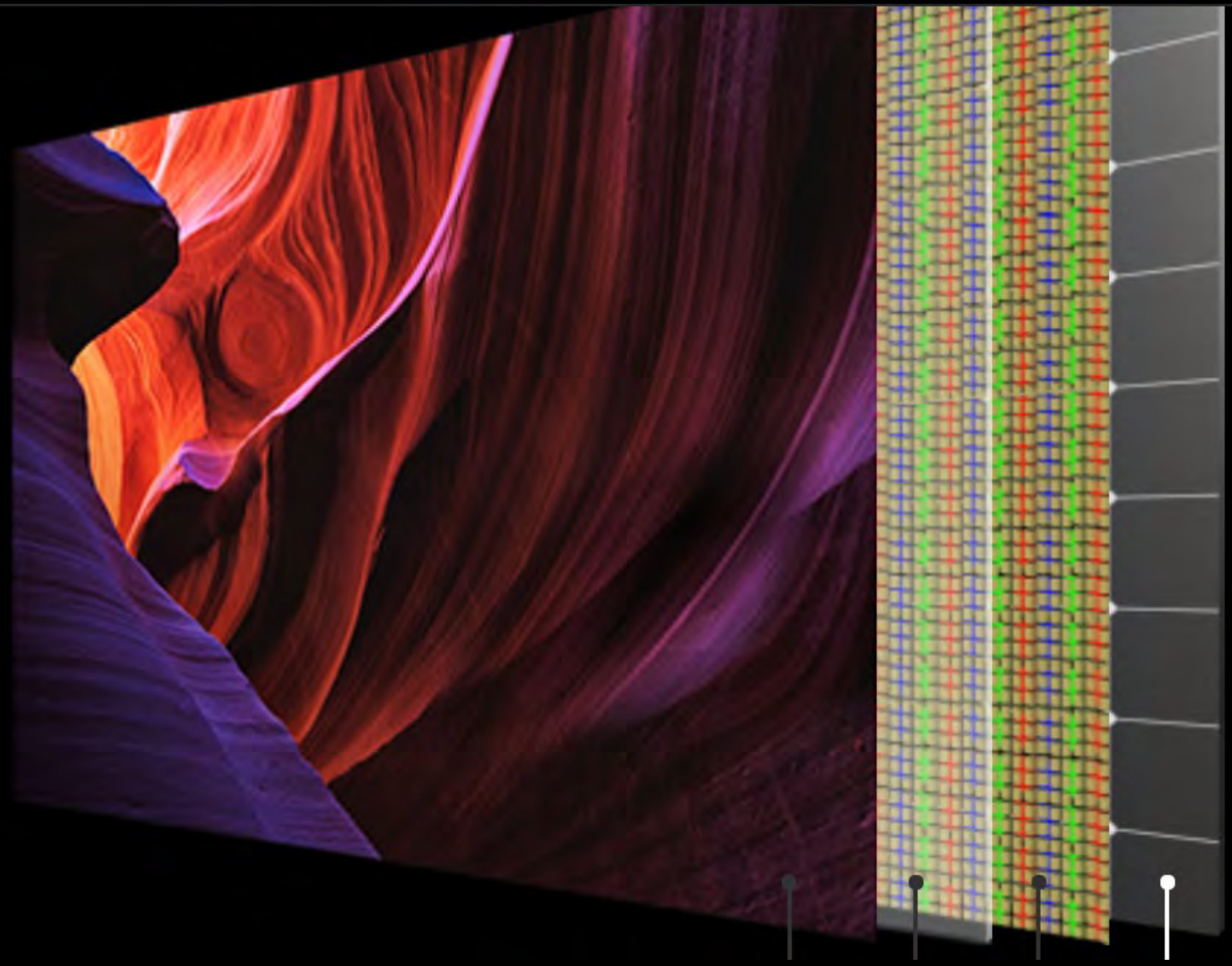
- Light-based **3D Stereolithography** (SLA):
  - Part is produced layer-by-layer from a liquid resin vat using just light
  - Near contactless manufacturing! Background free!
  - Significantly better optical properties than Fused Deposition Modeling
- Photocurable resins allows using UV or visible light:
  - Curing time from seconds to hours; large-scale production
  - Can be performed at room temperature
  - Resin formulations allows for embedding
- Can build **Optically Active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures





Low mass detector holder design under UV illumination (LEGEND)

Digression



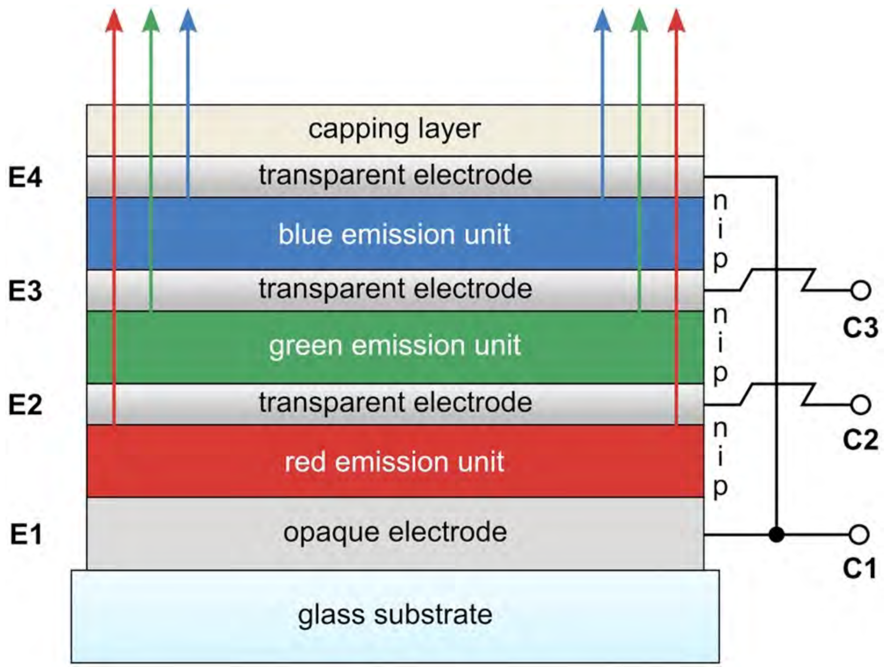
A closer look at technologies at industrial scale like Organic Light Emitting Diode (OLED)

- A series of organic thin films ink-jet printed between two conductors emitting light when a voltage is applied.
- Ubiquitous used in laptops, monitors, automotive, cell phones, …
- Anisotropic Conductive Film drives the pixels.

Spectroscopic photosensors

- Reverse the OLED design: spectroscopic photodetectors
  - Engineer organic materials that absorb the light with a specific wavelength
  - Transparent electrodes collect the signal
  - Cherenkov vs. scintillation separation
  - No loss of photosensor coverage
- Can be made on rigid and flexible substrates
- Organic semiconductors good starting point
  - Low cost & highly scalable
- Integrate with 3D printed scintillators
- Requires multi-disciplinary collaboration

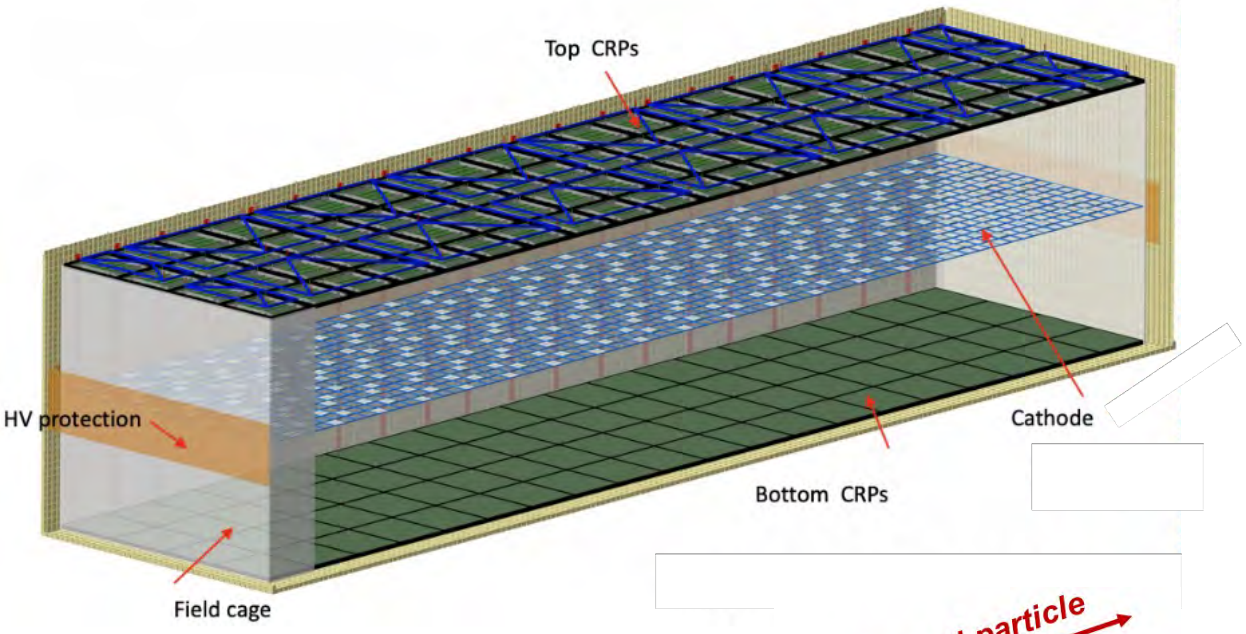
Stacked OLED

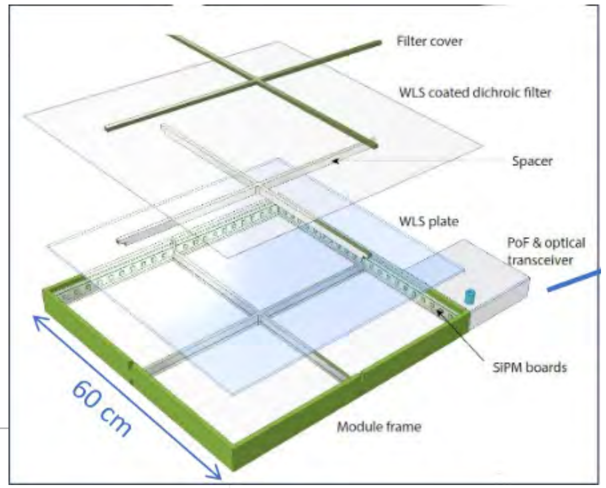


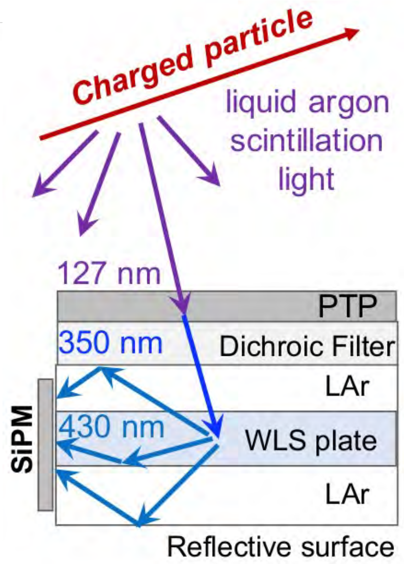
https://www.nature.com/articles/s41598-018-27976-z

https://www.sammobile.com/news/samsungs-new-foldable-and-udc-panels-reveal-an-exciting-future/

Photodetection in Liquid Argon







A.A. Machado, et al., JINST 11 (2016) 02, C02004

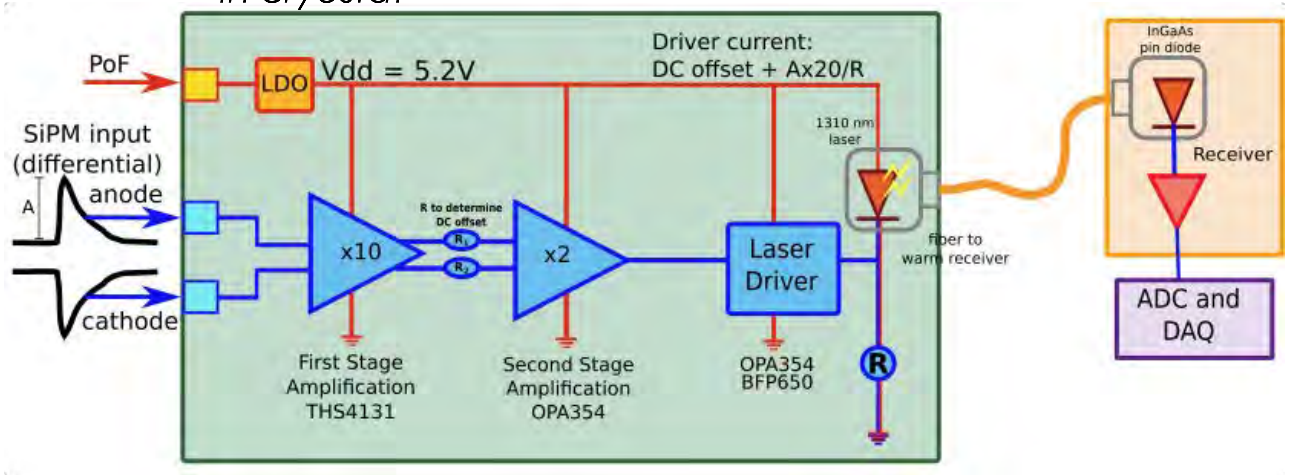
Not to scale.

- Photodetection in DUNE with an Arapuca:
  - trap wavelength-shift light (X-Arapuca uses total internal reflection)
  - Readout with SiPMs
- Coverage, on cathode side and two long membranes: ~14%.
- Total PDE of (1.8 +/- 0.1)% with improved scintillator material.
- Room for improvement …

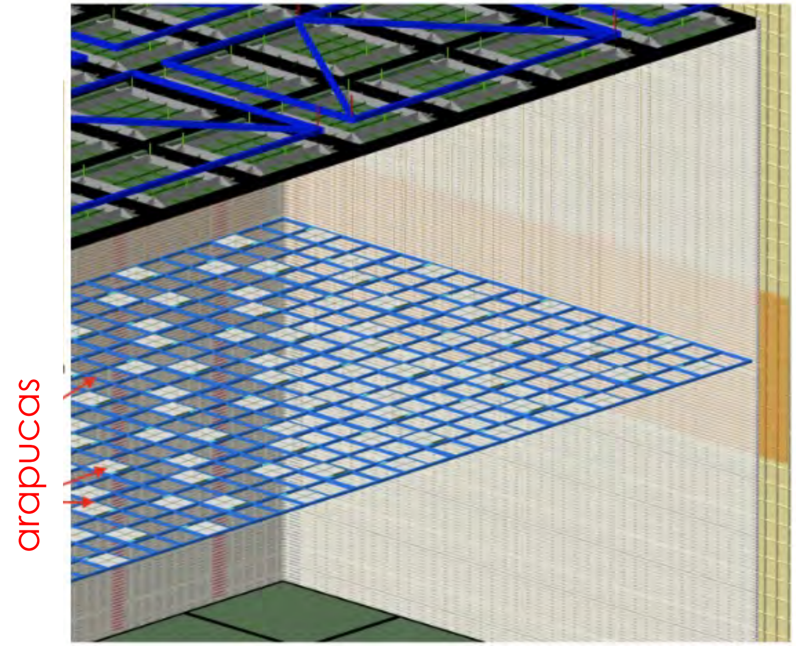
Powering

- Photodetection system distributed over the cathode plane, held at 300kV.
- Needs to be electrical isolated:
  - Power over Fiber (PoF)
  - Signal over Fiber (SoF)

In cryostat

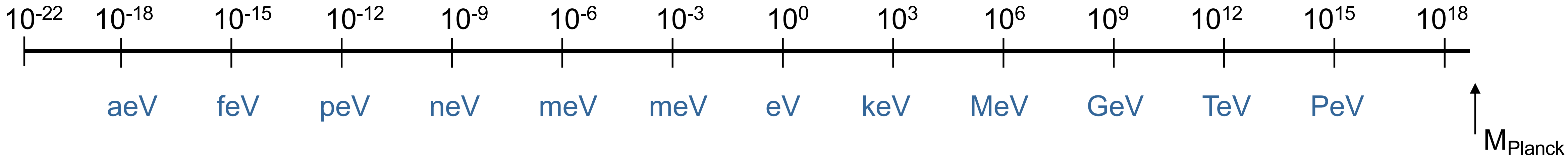


DUNE Vertical Drift



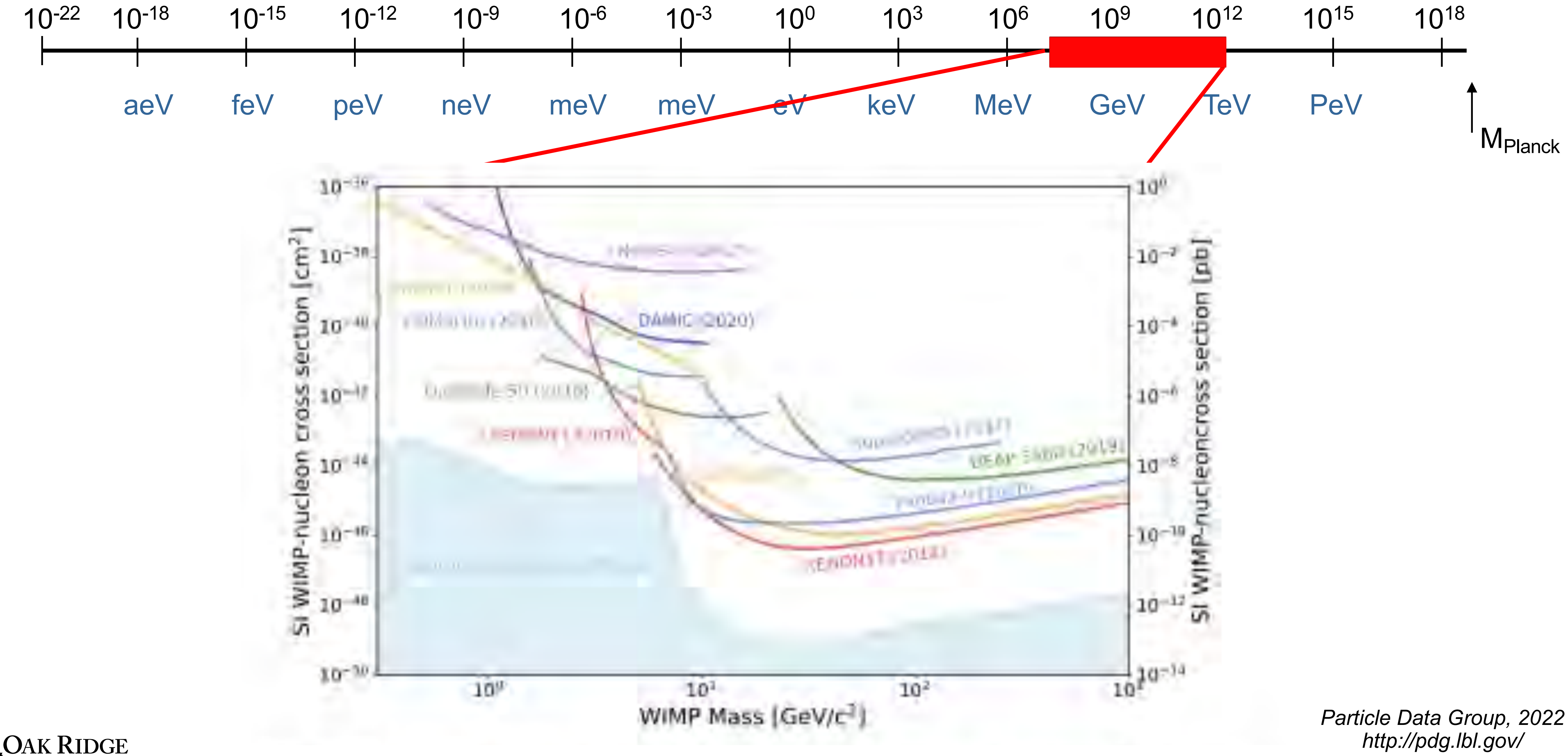
- A Low-dropout (LDO) regulator provides stable voltage for front-end electronics bias
  - Low Voltage - High Current
- A DC-DC converter provides higher voltage for the SiPM bias
  - High Voltage - Low Current
- Performance over fiber nearly as good as over copper

Dark Matter Searches



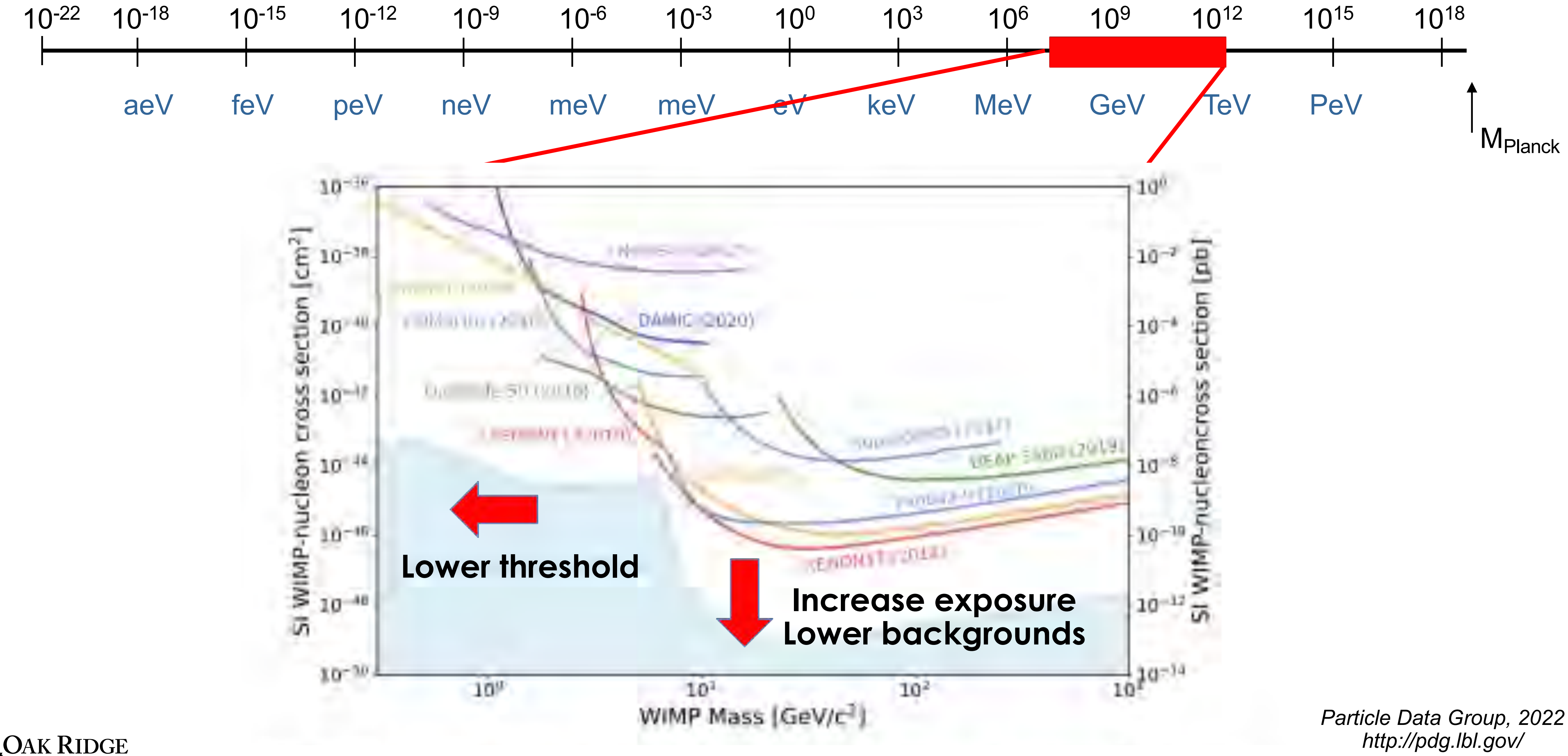
- The mass range for dark matter is in principle unconstrained
- Weakly Interacting Massive Particles were a favorite model

Dark Matter Searches



Particle Data Group, 2022
http://pdg.lbl.gov/

Dark Matter Searches



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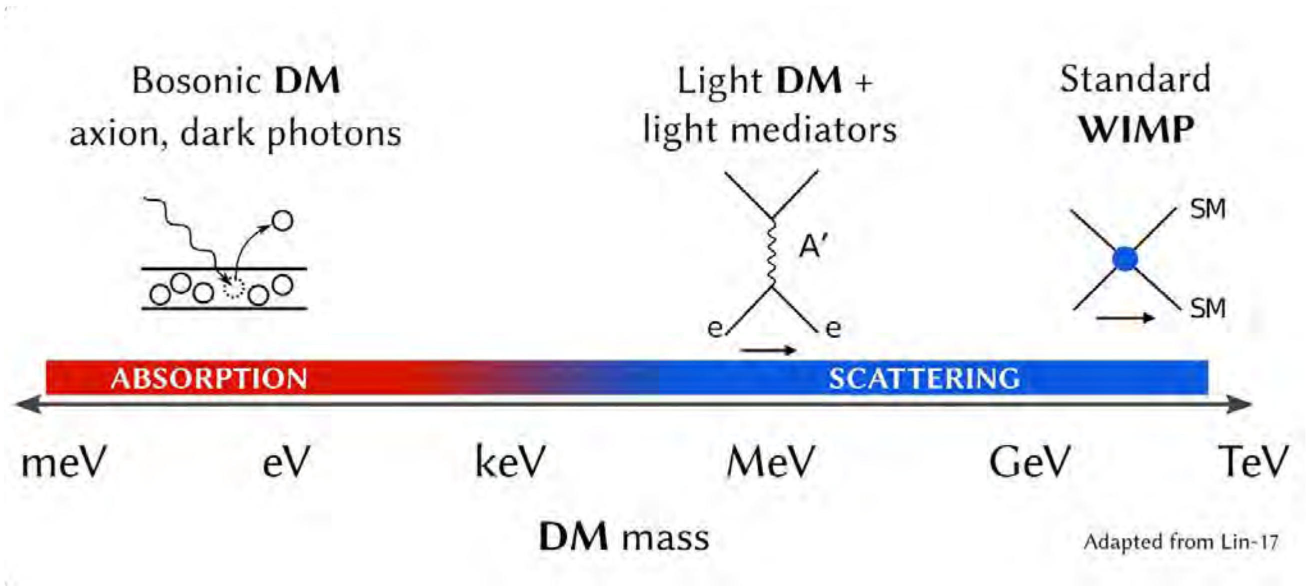
Dark Matter Searches

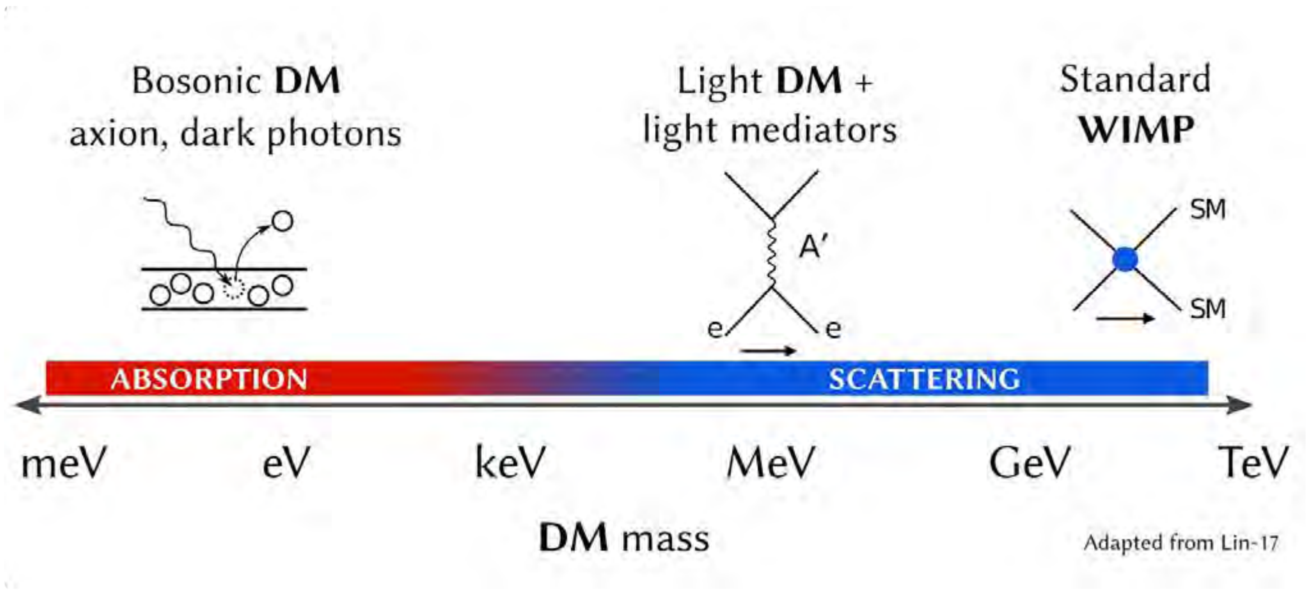


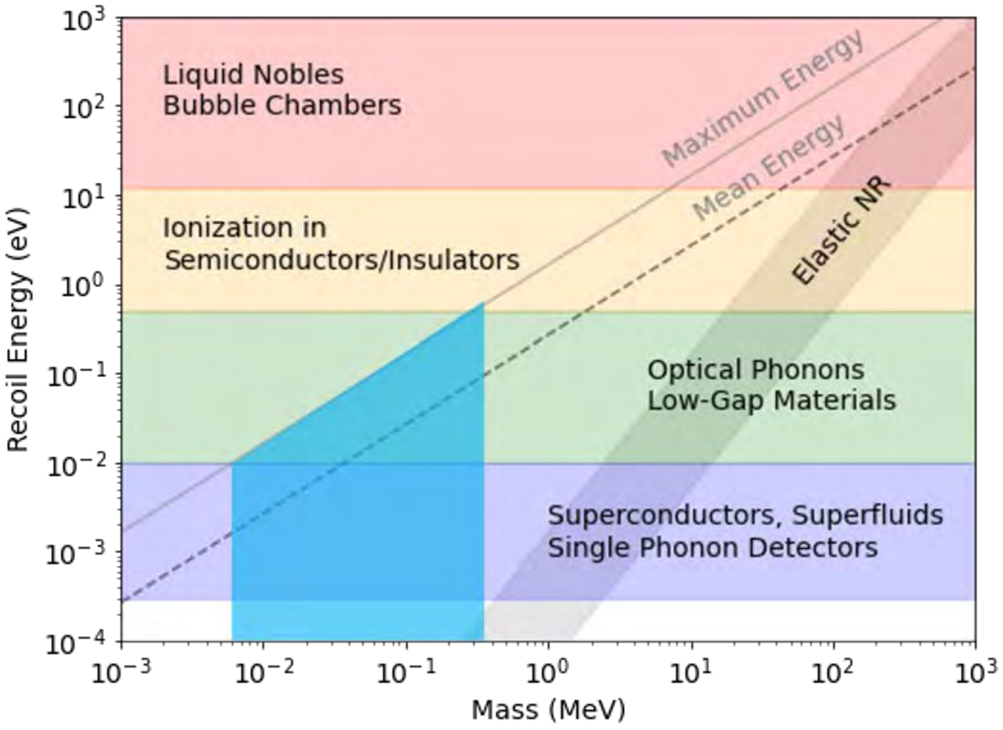
Field-like

Particle-like

Oak Ridge National Laboratory

Dark Matter Searches





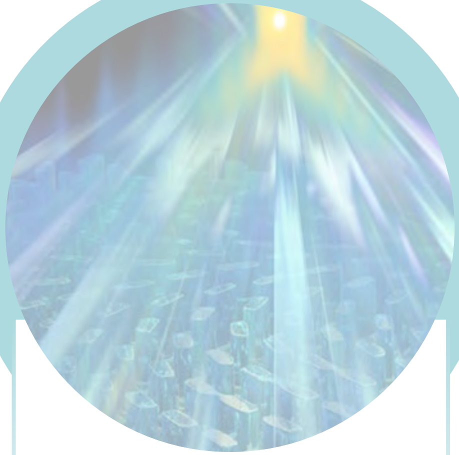
Field-like **Particle-like**

- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise

Science Technologies Will Play a Pivotal Role

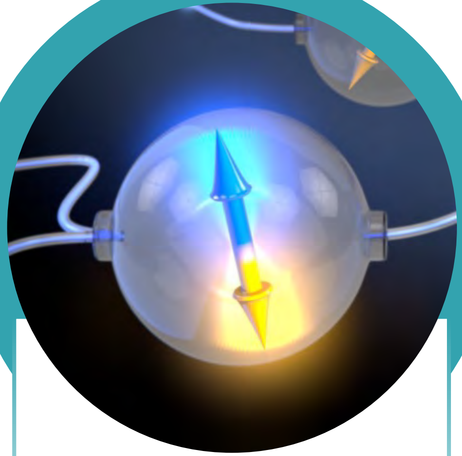
Directed R&D

Aimed at realizing high-priority projects



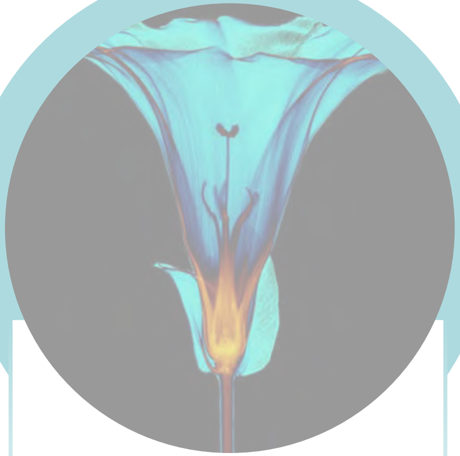
Generic R&D

Aimed at developing new methodologies and techniques, adopting emerging technologies



Inspired R&D

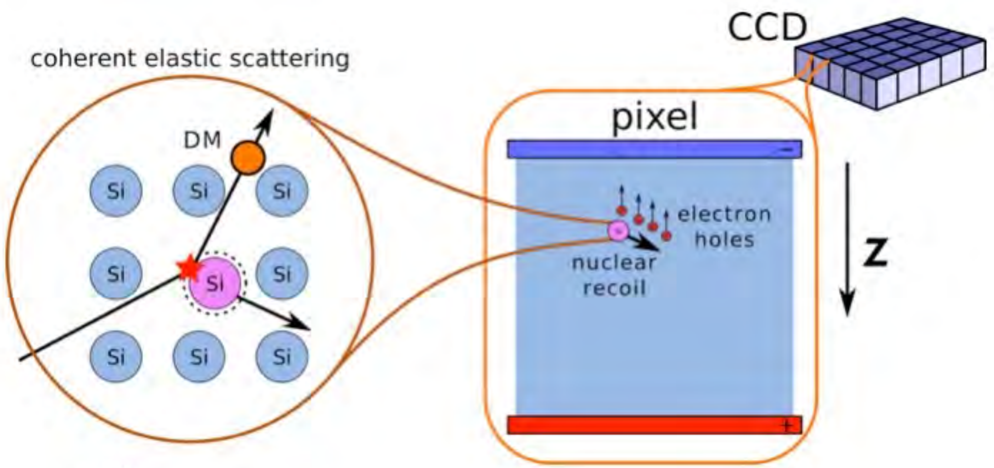
Building on emerging technologies and advances in industry and other science disciplines



R&D That Inspires

Applying the techniques to other areas of science

Light Dark Matter in Silicon



- Dark matter interaction in charge-coupled device (CCD)
  - First application: nuclear recoil on Si (DAMIC)

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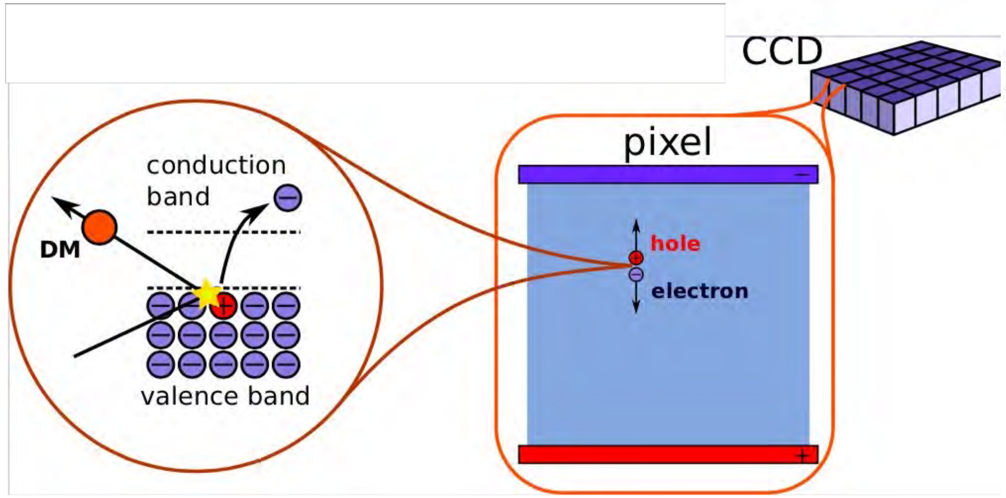
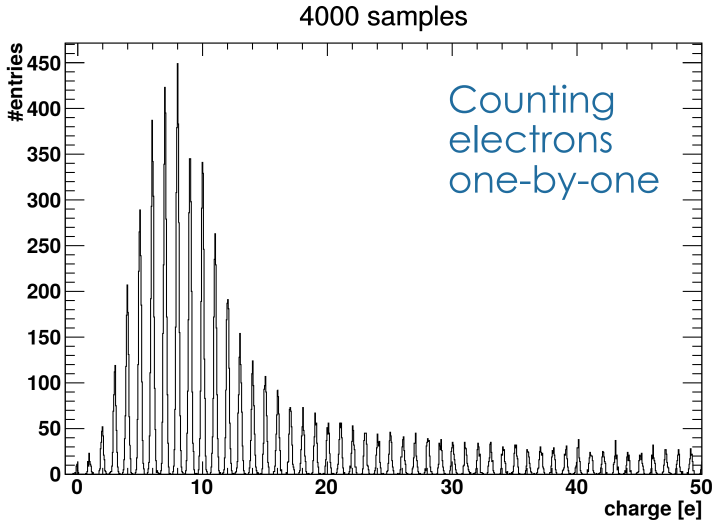


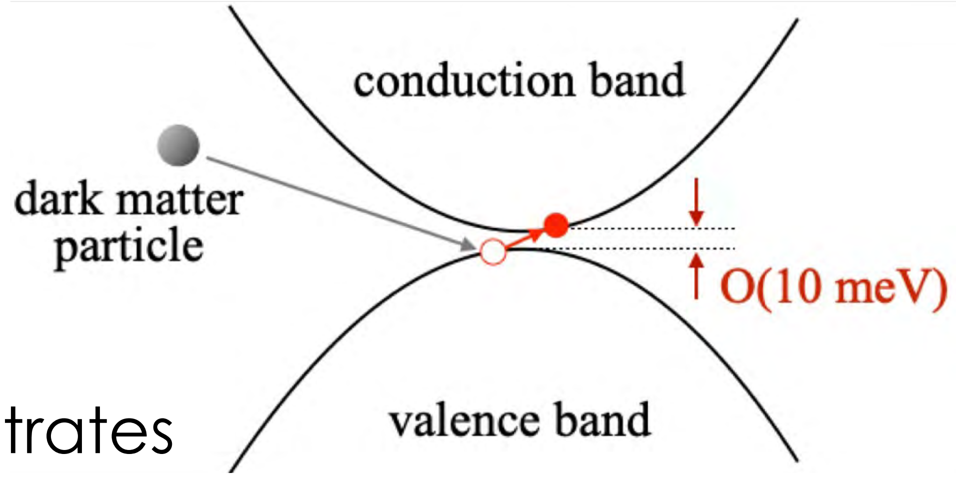


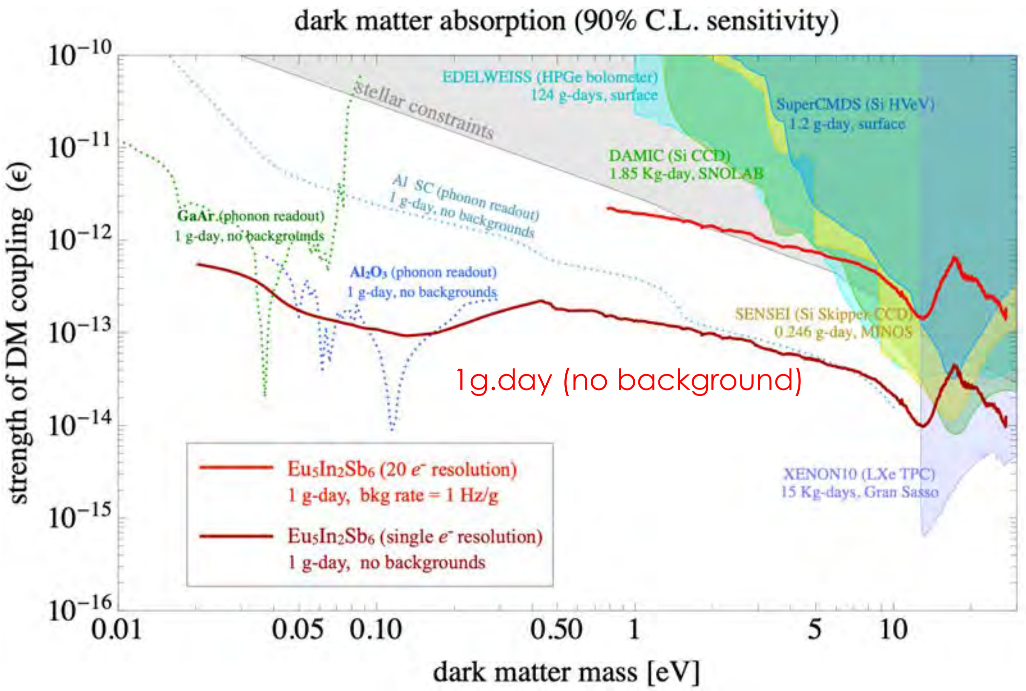
- Dark matter interaction in charge-coupled device (CCD)
  - First application: nuclear recoil on Si (DAMIC)
- Revival of an old idea, the 'Skipper CCD', reading the charge in each pixel multiple times
  - Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)
  - Pixel value = $\frac{1}{N}\sum_{i=1}^{N} Q_i$
  - Energy threshold is bandgap (1.1eV)
  - Readout noise 0.1 e^-
- OSCURA: 10kg detector
- Background control will be the main challenge

The Oscura Experiment arXiv: 2202.10518
Chavarria (arXiv:2210.05661)

Lowering the bandgap

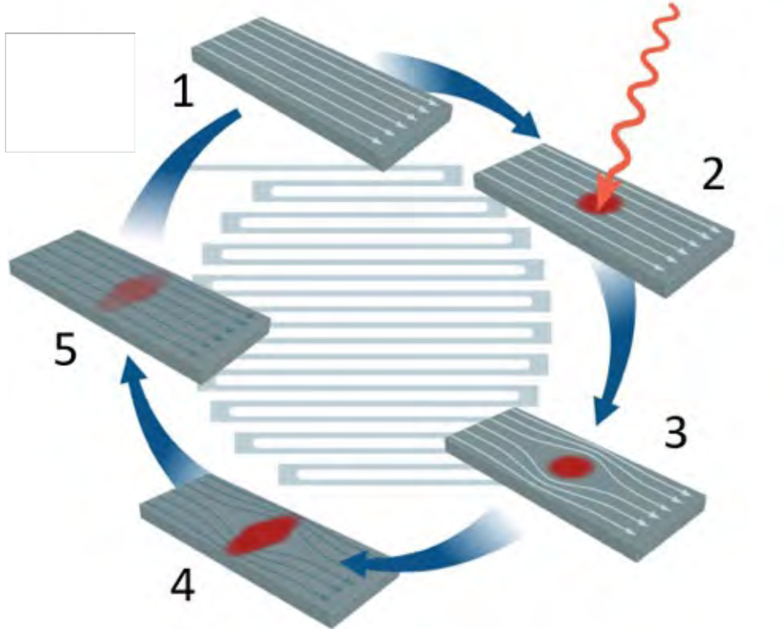
- Engineering novel single crystal semi-conductors with bandgaps of O(1-100 meV)
- Single crystal synthesis allows for scalable substrates
- Materials have anisotropic band structures to give sensitivity to daily DM modulation effects ($Eu_5In_2Sb_6$)
- Charge readout scheme with O(1) electron resolution that is device independent.





SPLENDOR: Search for Particles of Light dark MattEr with Narrowgap semiconDuctORs

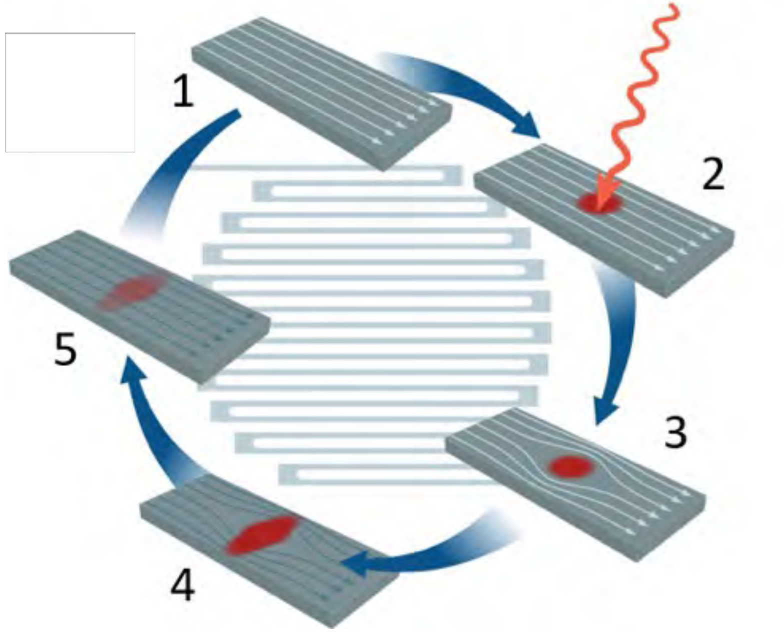
Superconducting Nanowire Single Photon Detector (SNSPD)

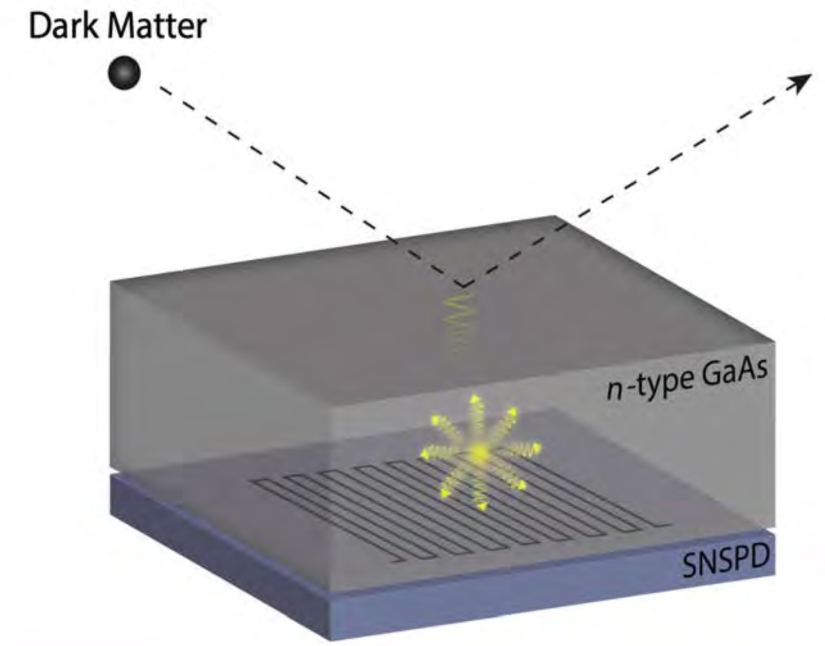


1. Bias $I < I_C$
2. Singe γ absorption
3. Hotspot generation
4. High current density, resistive barrier
5. Dissipation – restoration

- High Efficiency, 98% @ 1550nm
  - *Reddy et al., Optica (2018)*
- UV – mid-IR operation
- Superb timing resolution, 2.6 ps FWHM
  - *Korzh et al., Nature Photonics (2020)*
- Low dark counts, 10^{-5} cps
  - *Chiles et al, Phys. Rev. Lett. (2022)*
- High even rate, 1.2 Gcps in 63-element
  - *M. Shaw, doi.org/10.1117/12.2563483 (2020)*

Superconducting Nanowire Single Photon Detector (SNSPD)





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GaAs bandgap 1.52 eV

OAK RIDGE National Laboratory

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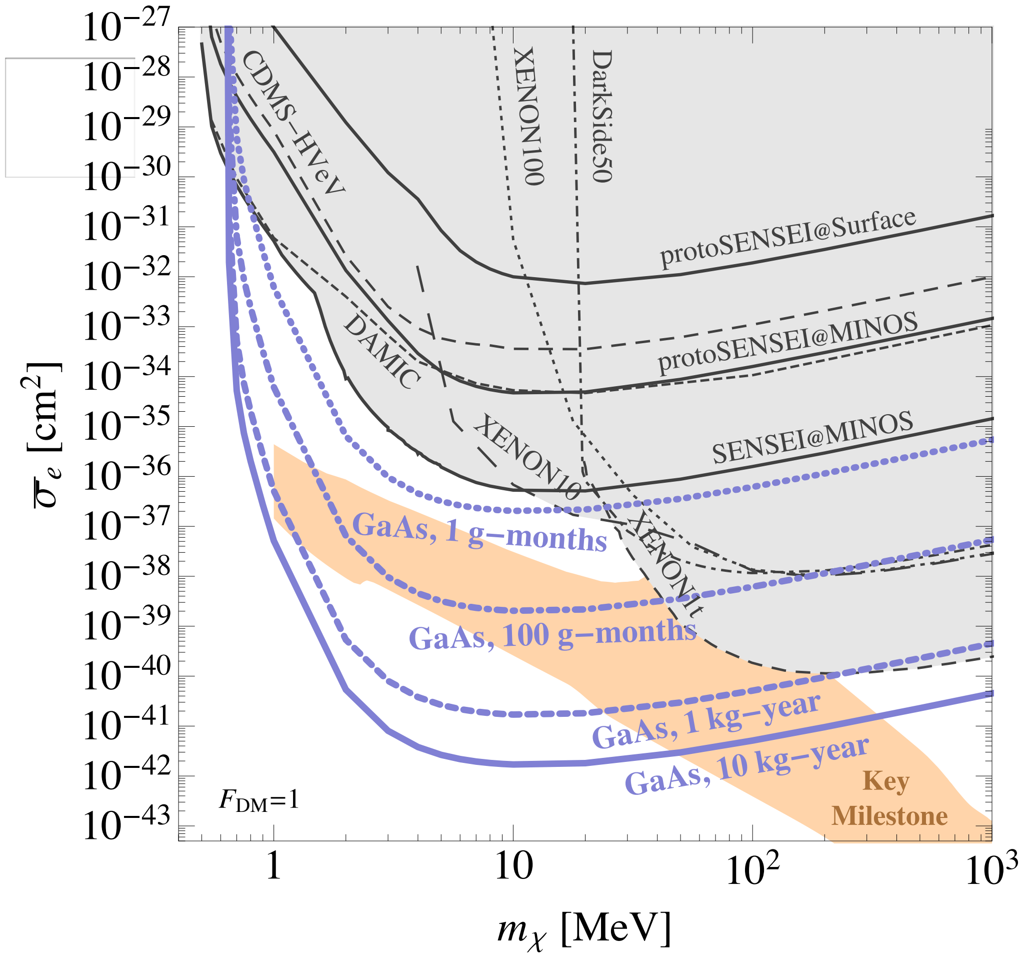
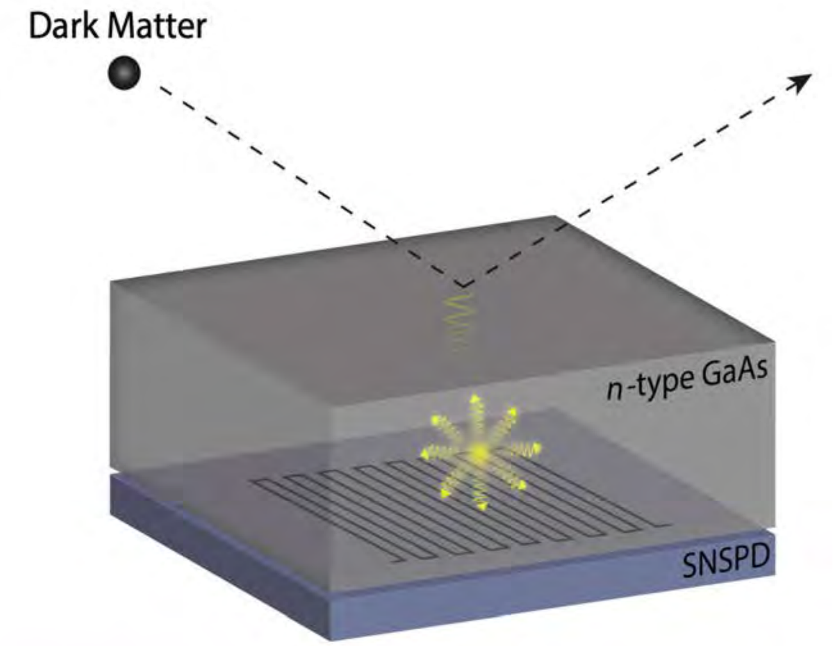
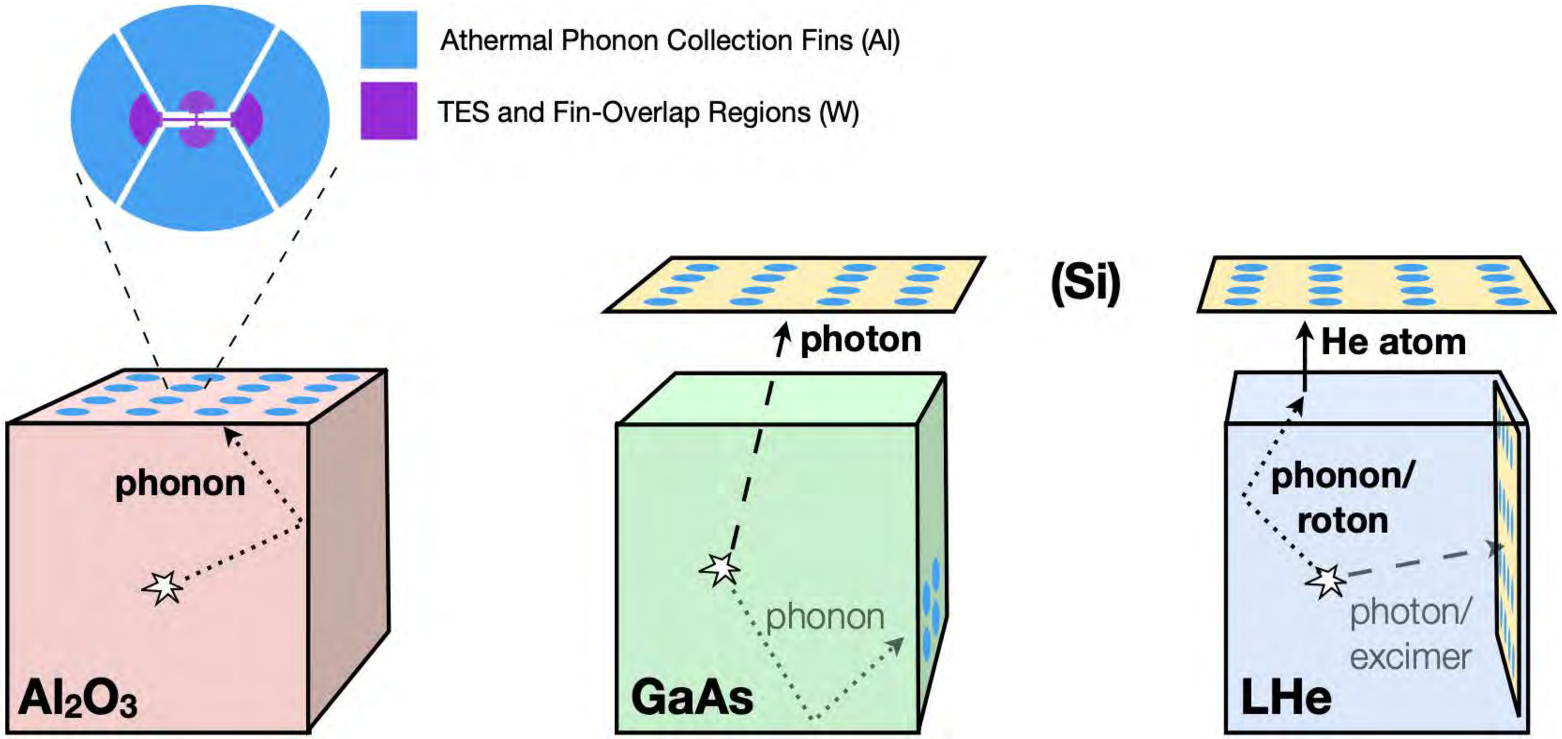


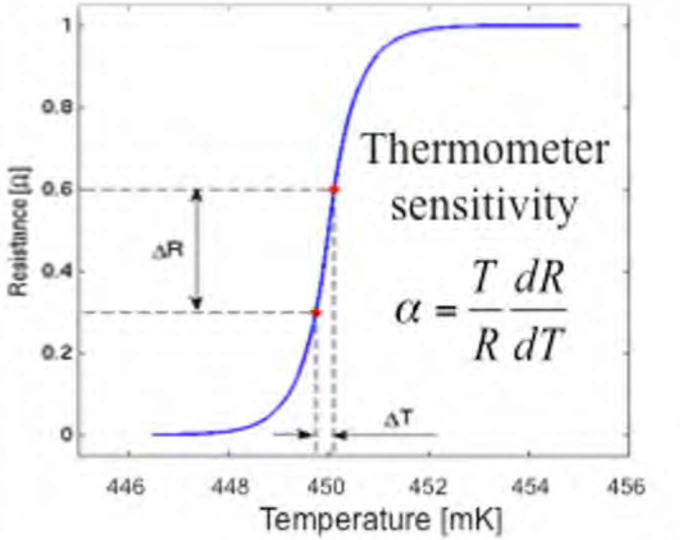


GaAs bandgap 1.52 eV

Phonon Detection

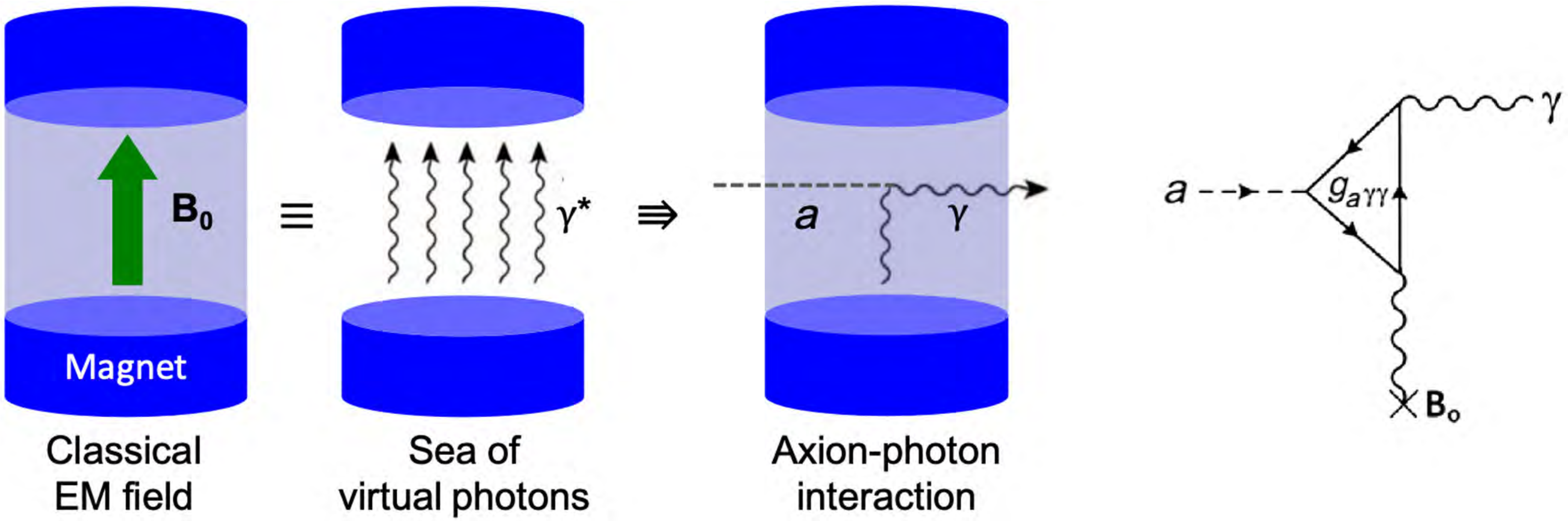
- For dark matter masses < 100 MeV, dark matter scatters coherently with the entire crystal, producing a single phonon.
- Vibrational energy scale in crystals is O(100 meV)
- The kinematics of optical phonon production all of the kinetic energy of the DM can potentially be used for phonon creation





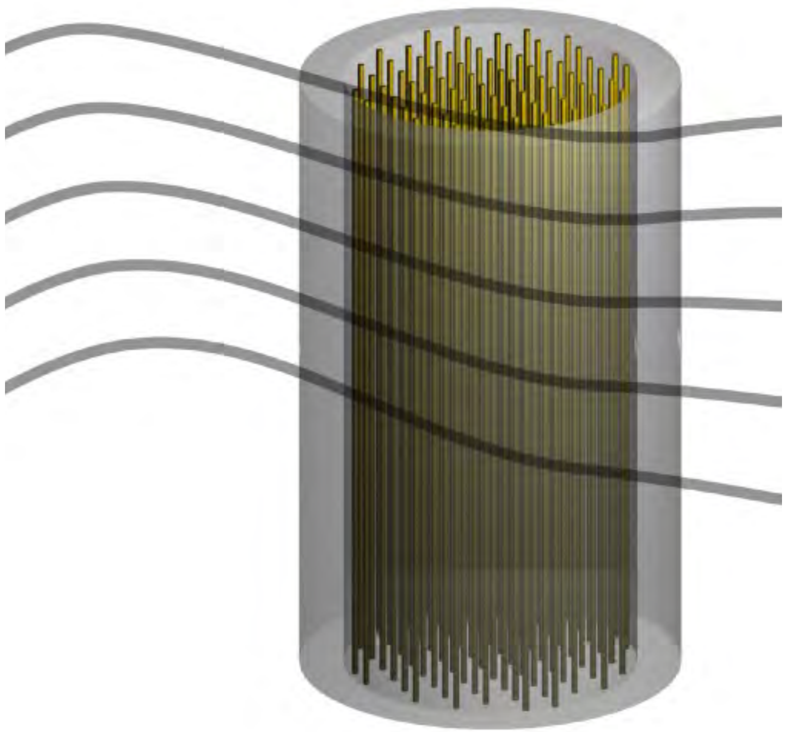
Resonance Techniques

- A common search technique is using resonant cavities through the Primakov effect



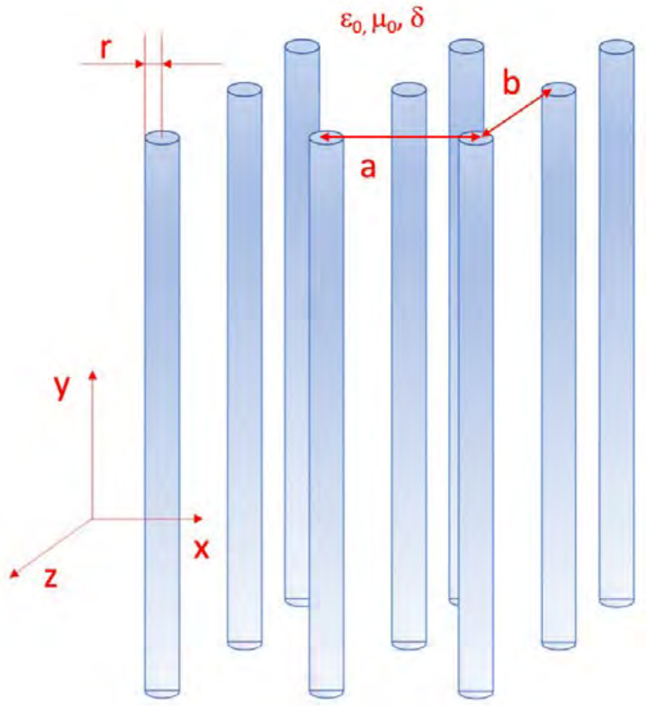
- Tuning resonant frequencies and integration times are limiting factors in their ultimate reach.

A Tunable Plasma Haloscope



M. Lawson et al., PRL 123 (2019) 141802

- A wire array of metamaterials exhibits plasmonic behavior, and can act as a resonator for a dark matter axion experiment:
  - Enables going to higher frequencies
  - Faster scanning times, no tuning difficulties

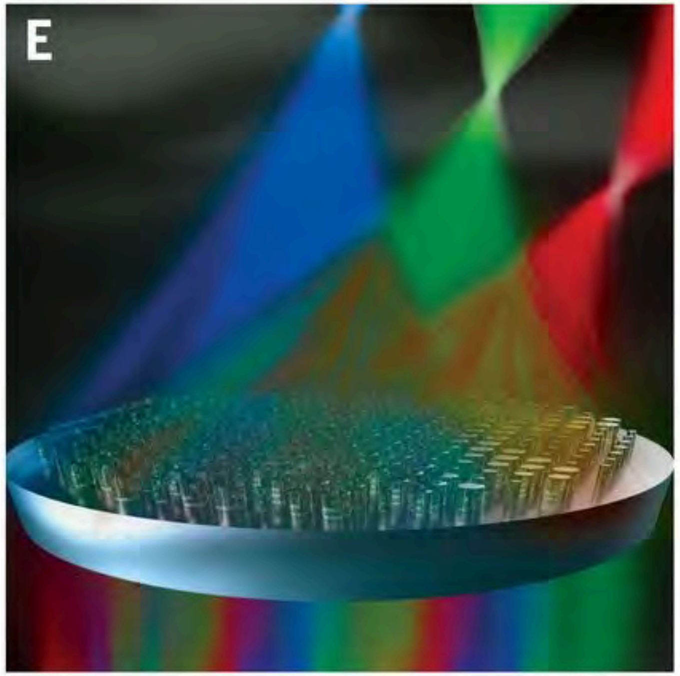


$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2pi}{a^2 \log(a/r)}$$

OAK RIDGE National Laboratory

Nanophotonics

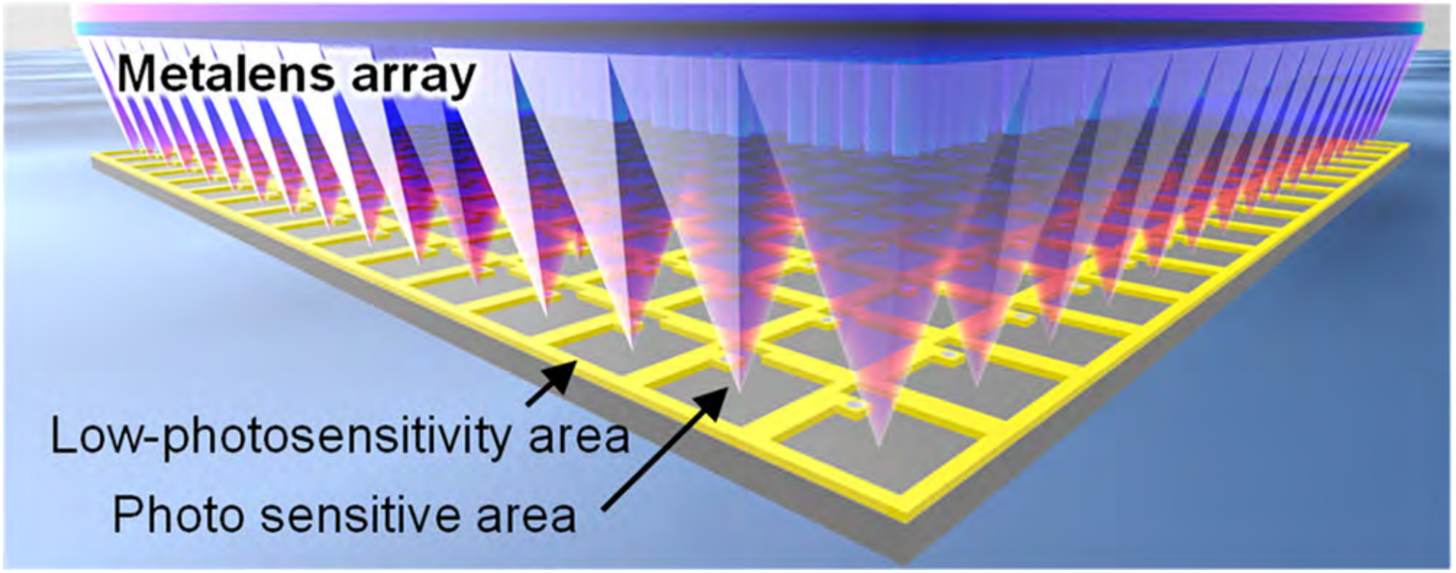
- Arrays of sub-wavelength spaced nanostructures that can manipulate light wavefronts
- Control of phase, amplitude, polarization, wavelength, diffraction, …
- Large-areas through standard photo-lithographic process
- Low cost and very versatile

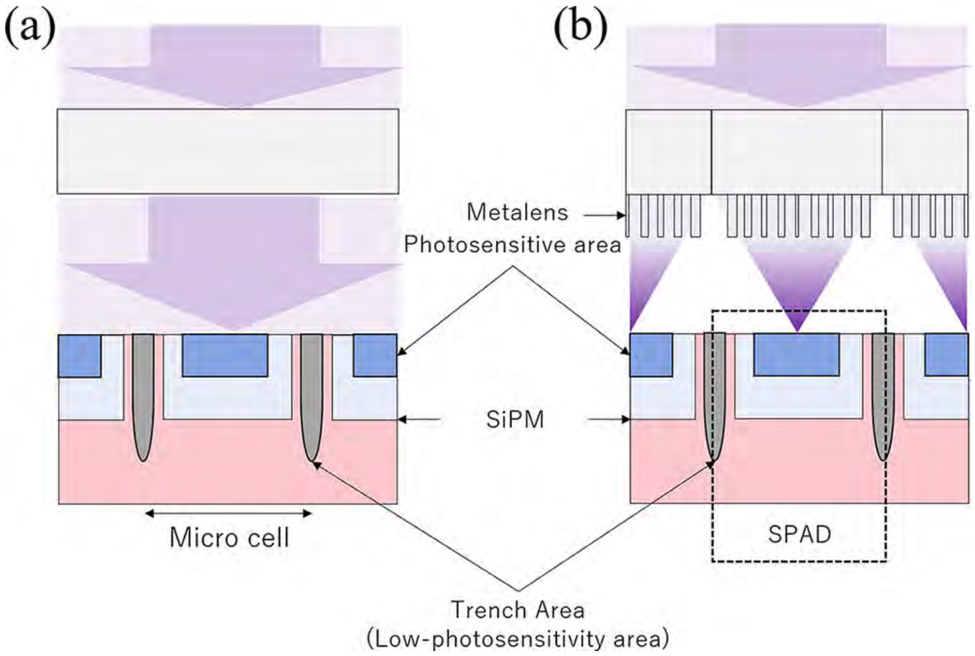


M. Khorasaninejad, F. Capasso, Science 358 6367 (2017) DOI: 10.1126/science.aam8100

https://serious-science.org/federico-capasso-optical-properties-of-surfaces-3795

Nanophotonics

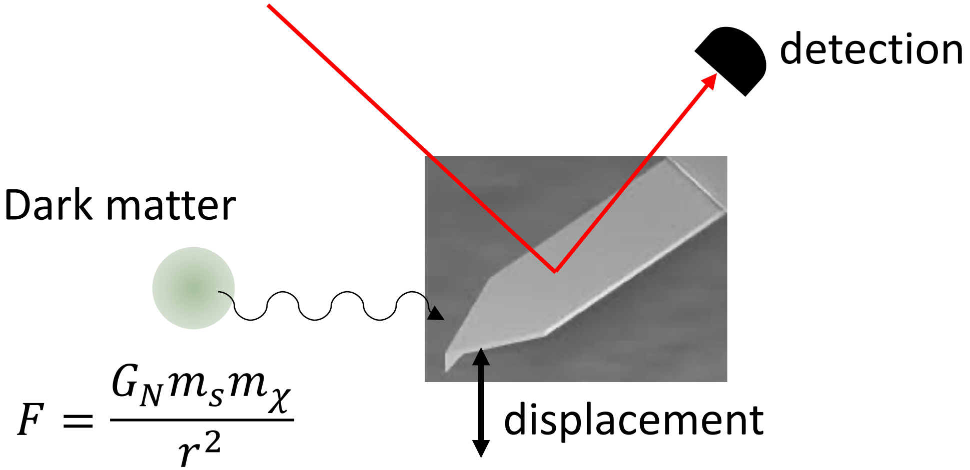




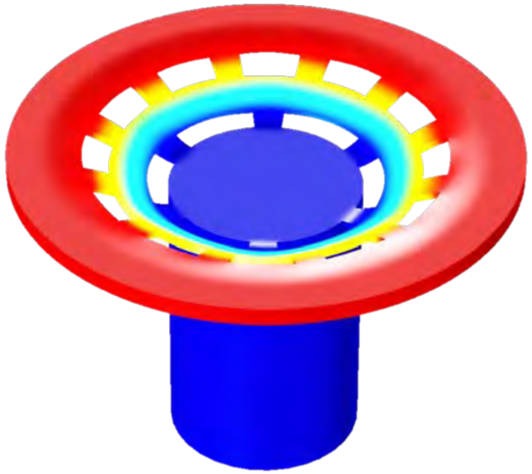
S. Uenoyama, R. Ota, ACS Photonics 2021, 1548–1555
https://doi.org/10.1021/acsphotonics.1c00257

- Improved detection efficiency, timing resolution.
- Possibility for wavelength sensitivity?

Gravitational Quantum Probe



$$F = \frac{G_N m_s m_\chi}{r^2}$$

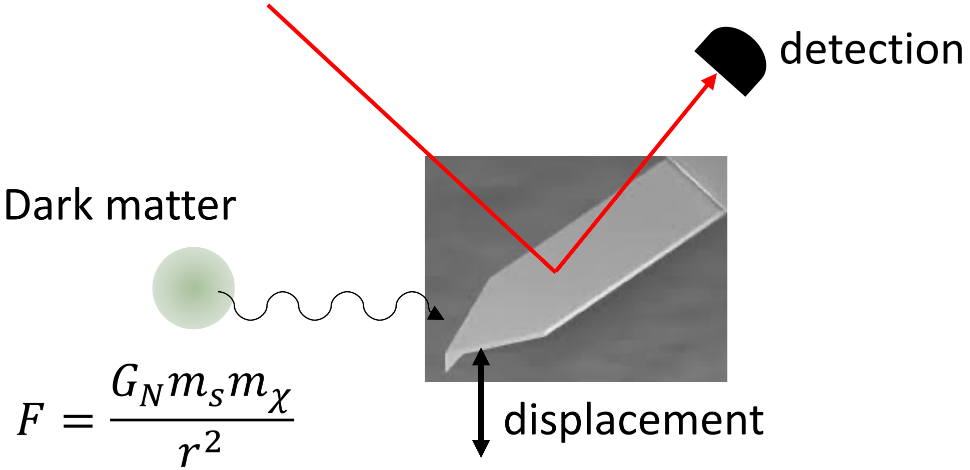


Test mass

- Gravitational coupling is the only guaranteed interaction channel for Dark Matter!
- Use Micro-electromechanical System (MEMS) technology
  - Bulk Silicon 70 mg accelerometer with soft tethers
  - Readout with dual squeezed light source

Carney et al. 2021 Quantum Sci. Technol. 6 024002

Gravitational Quantum Probe



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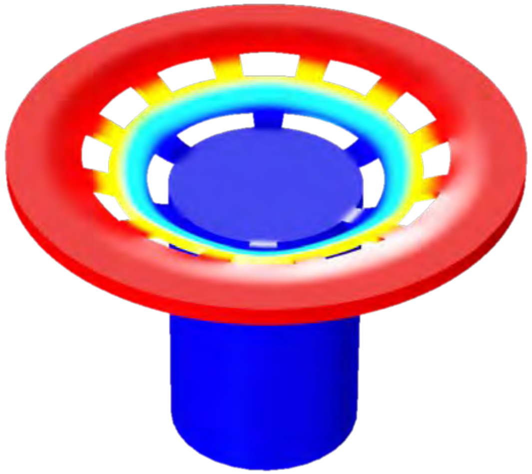

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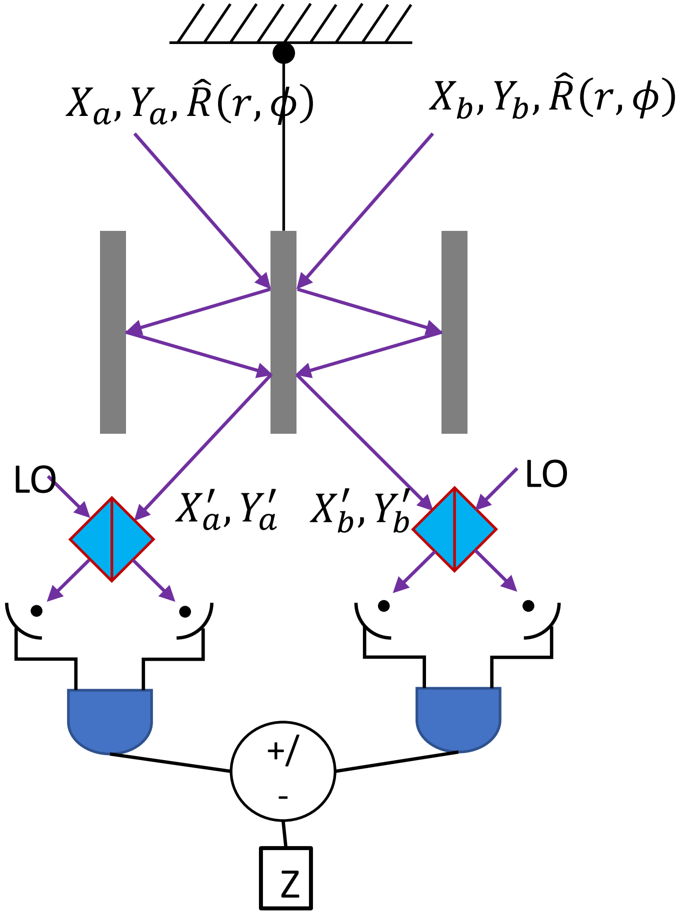


Backaction evasion techniques

Carney et al. 2021 Quantum Sci. Technol. 6 024002

Fundamental Constants and Quantum Sensors

- Clocks (atomic, nuclear, molecular, highly charged ions) measure with extreme precision atomic and molecular spectra

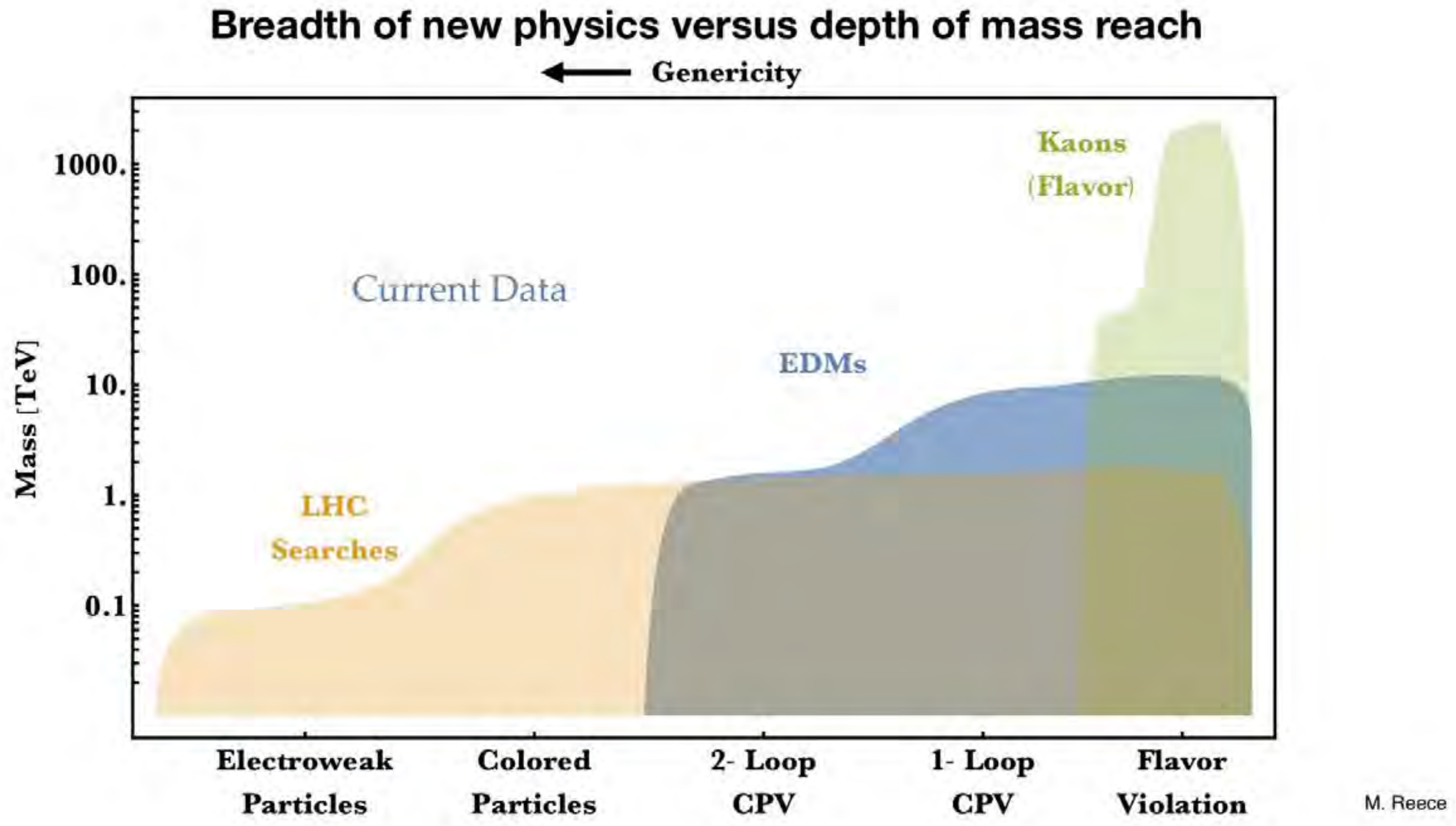
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{\mu_p}{\mu_e}$$

- Ionic, atomic and molecular systems hold great promise:
  - Fundamental physics laws
  - Searches for BSM Physics
  - Fundamental physics constants

https://www.nationalacademies.org/amo
Search for new physics with atoms and molecules, Rev. Mod. Phys. 90, 025008 (2018)

Precision Experiments

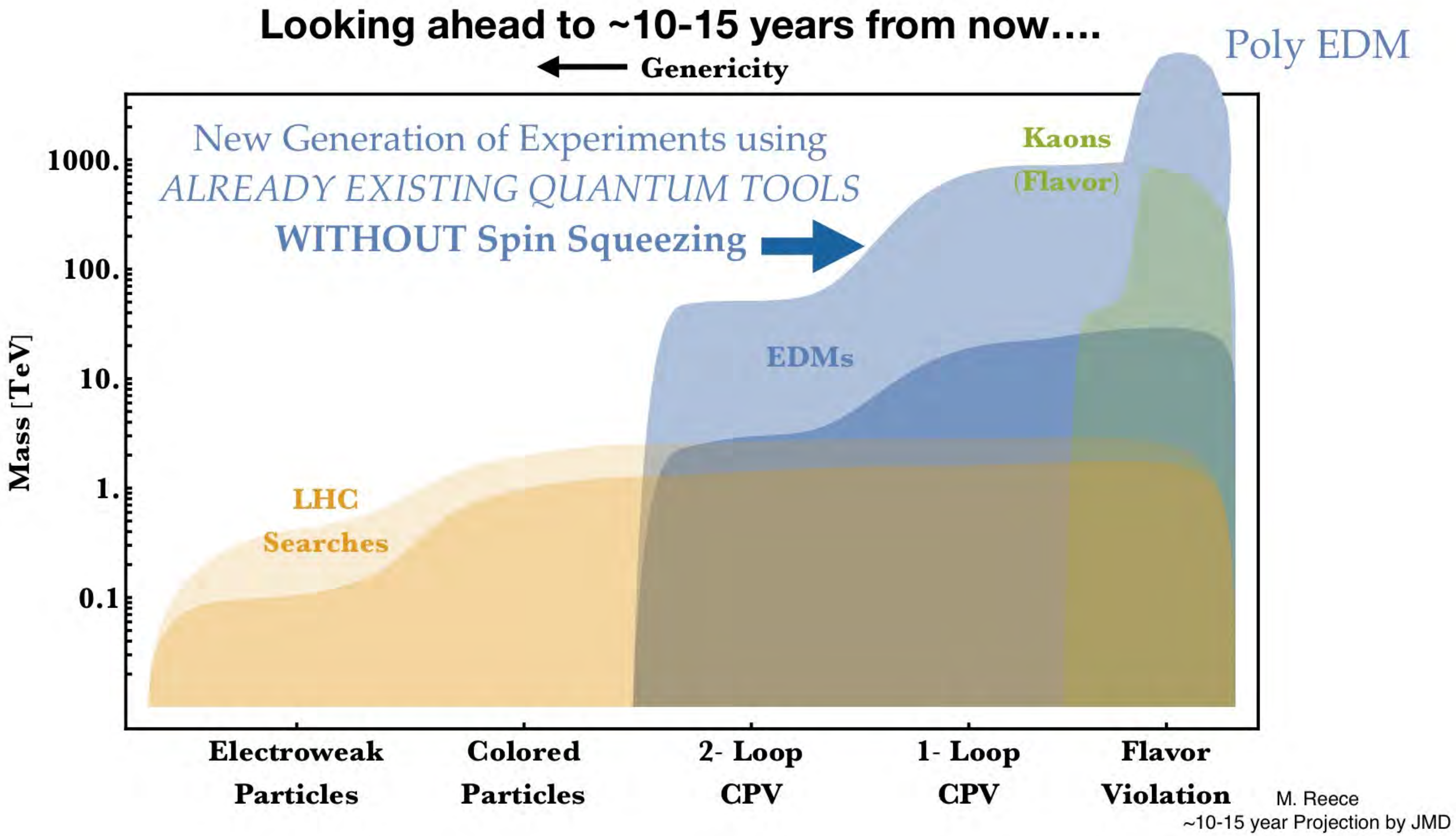
- Future colliders have direct discovery potential but are not the only source to explore very high energy scales.



Y. Nakai, M. Reece: Physics Today, Nov. 2018
DOI:10.1063/PT.6.3.20181114a

Squeezed Precision Experiments

- Nascent Quantum techniques provide a compelling reason



J. Doyle, Argonne workshop, Dec. 2017,
Y. Nakai, M. Reece: Physics Today, Nov. 2018
DOI:10.1063/PT.6.3.20181114a

Science Technologies Will Play a Pivotal Role

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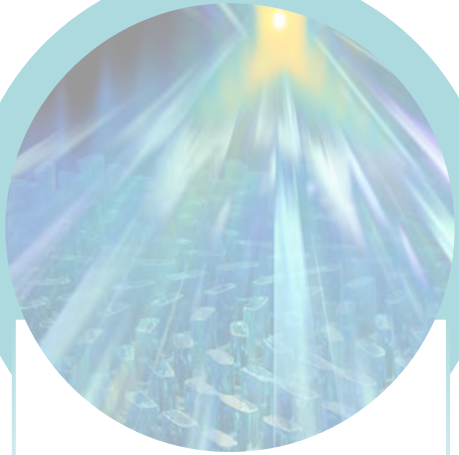

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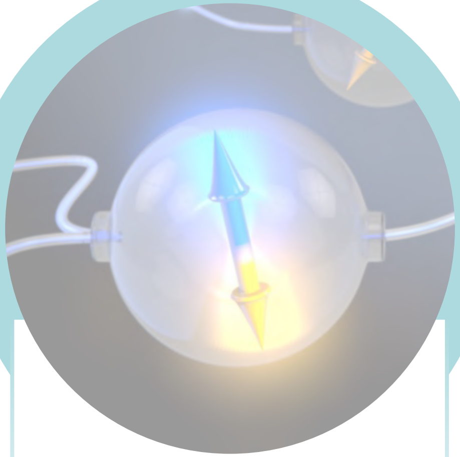
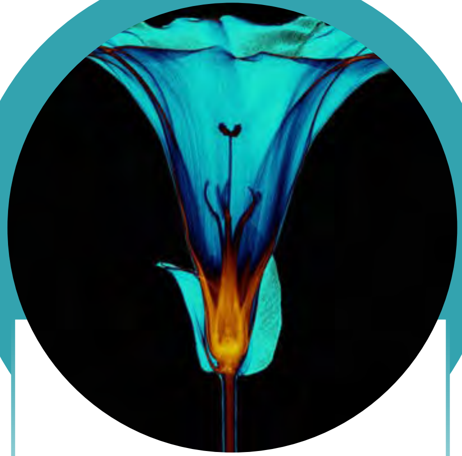


Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines



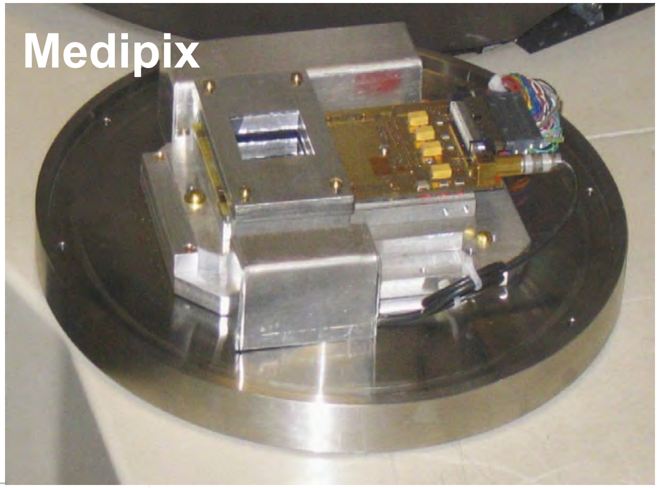
R&D That Inspires

Applying the techniques to other areas of science

R&D That Inspires: Advancing Cryo-Electron Microscopy

- The quest for obtaining the best image resolution of biological material avoiding sample damage and destruction by the electron beam
- Enter the development of the pixel chips for the LHC experiments and their evolution into the Medipix and Timepix families

CMOS node	**250 nm**
Pixel Array	**256 x 256**
Pixel pitch	**55 mm**
ENC	**110 e^{--}**
Minimum detectable charge	**~500 e^{-}**



Noiseless direct detection of electrons in Medipix2 for electron microscopy, *NIM* A546 (2005) 160–163
Direct electron detection methods in electron microscopy, *NIM A*513 (2003) 317-321

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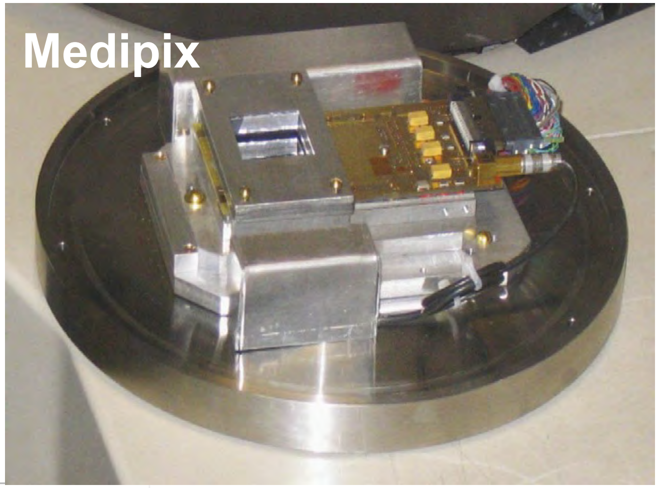
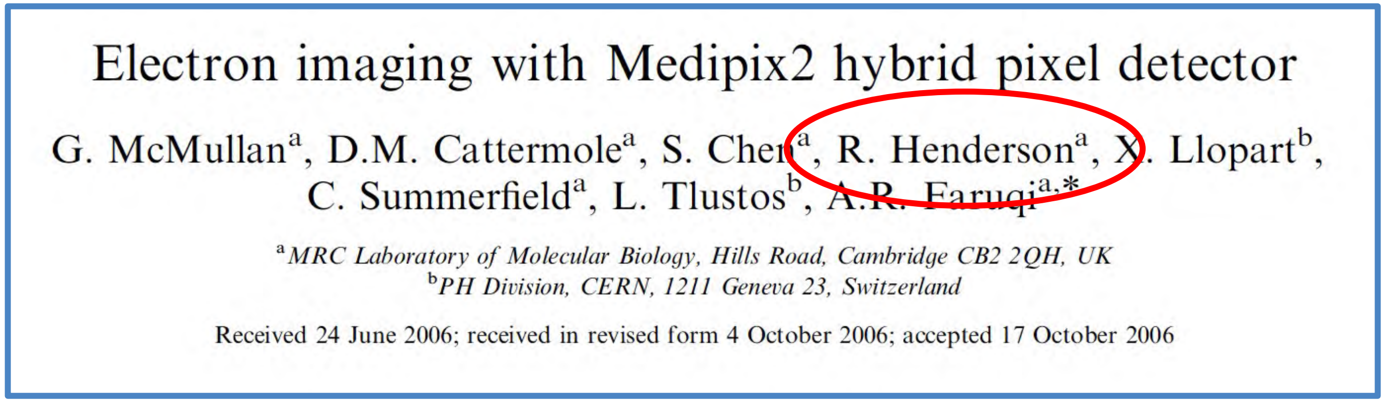




Electron imaging with Medipix2 hybrid pixel detector

G. McMullan[a], D.M. Cattermole[a], S. Chen[a], R. Henderson[a], X. Llopart[b], C. Summerfield[a], L. Tlustos[b], A.R. Faruqi[a,*]

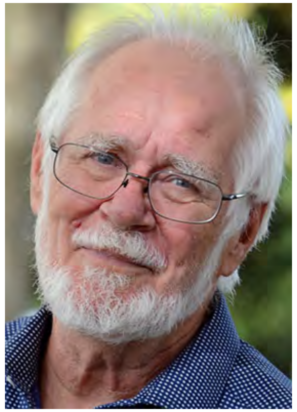
[a] *MRC Laboratory of Molecular Biology, Hills Road, Cambridge CB2 2QH, UK*
[b] *PH Division, CERN, 1211 Geneva 23, Switzerland*

Received 24 June 2006; received in revised form 4 October 2006; accepted 17 October 2006

Ultramicroscopy, **107** (2007) 401-413

Noiseless direct detection of electrons in Medipix2 for electron microscopy, *NIM* A546 (2005) 160–163
Direct electron detection methods in electron microscopy, *NIM A*513 (2003) 317-321

2017 Nobel Prize in Chemistry

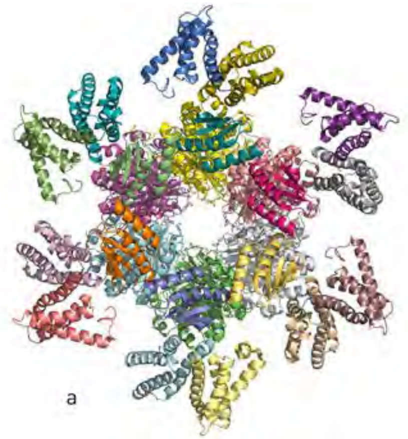


Jacques Dubochet
University of Lausanne

Joachim Frank
Columbia University

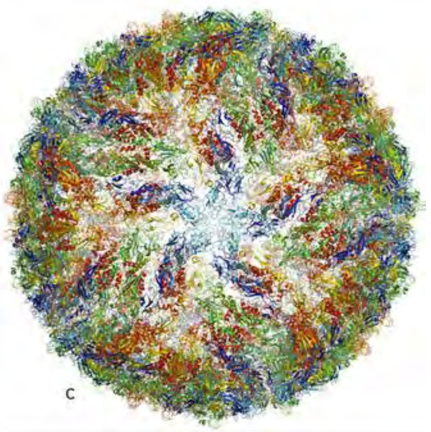
Richard Henderson
MRC Lab, Cambridge

"For developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution".

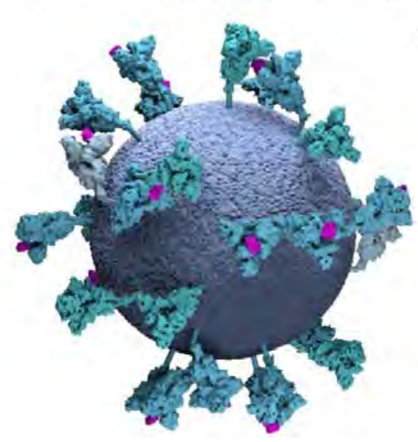


Protein for circadian rhythm

Ear pressure sensor



Zika virus



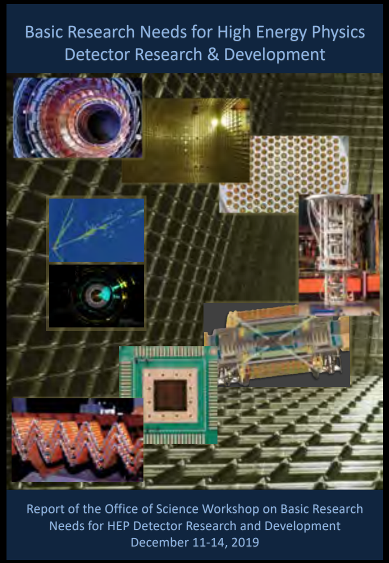
3.5 Å resolution

SARS-CoV-2 virus
Nature volume 588, pg. 498 (2020)

Currently use CMOS technology; Medipix helped advance the technology

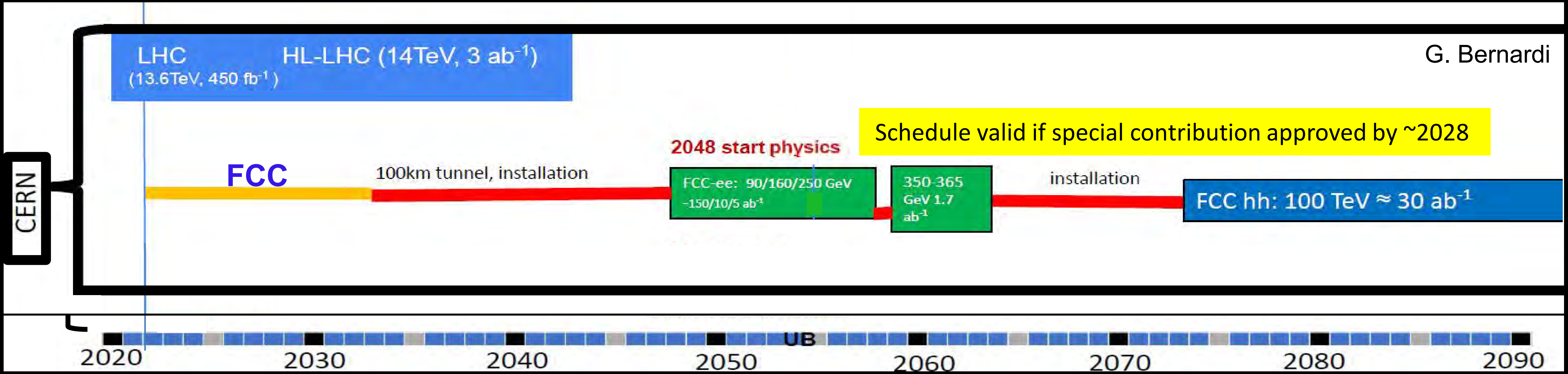
Closing Thoughts

- We arguably live in one of the most exciting times for fundamental physics; we have come so, so far but some of the most fundamental questions remain unanswered.
- We very much live in a data driven world
- Technology is taking a very prominent role:
  - Basic Research Need workshop in the US
  - ECFA detector and accelerator roadmap



- Our program can only be realized – in a cost-effective manner – by investing in innovative technologies, and get to physics earlier!

Closing Thoughts



- Timescales are long, costs are high, ….

Closing Thoughts

https://www.pottermore.com/writing-by-jk-rowling/pensieve

Who Celebrates its 16th Birthday in a few months?

https://www.pottermore.com/writing-by-jk-rowling/pensieve

Perspective

September 2005
First iPOD Nano

February 2006
First MacBook Pro

June 2007
First iPhone

To Realize Our Vision

To Realize Our Vision

To Realize Our Vision

Thank You