Photon Detectors

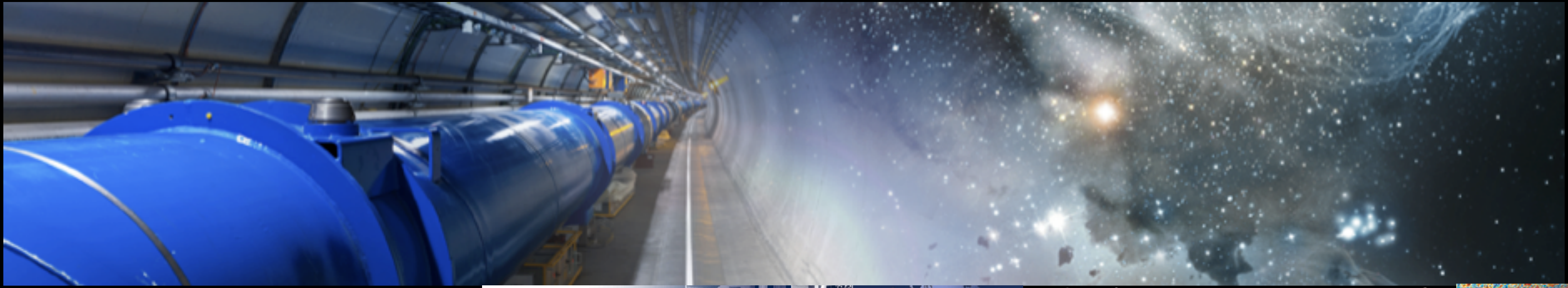
James Turrell
Rendering for Aten Reign, 2013
Guggenheim Museum

> “Light is not so much something that reveals, as it is itself the revelation.”
>
> James Turrell

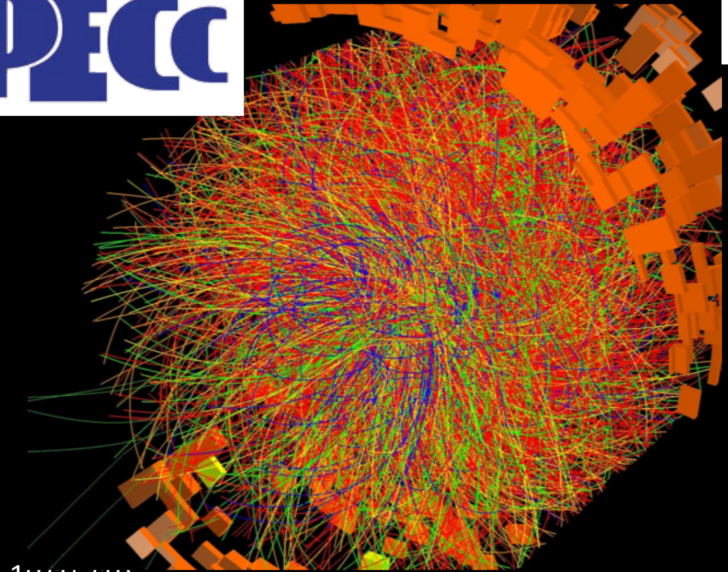
Daniela Bortoletto

The Physics

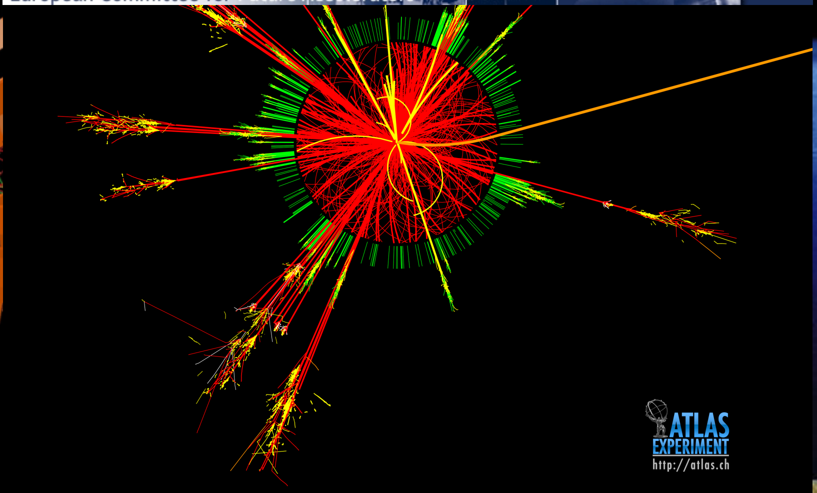
- There are profound connections between the physics goals of nuclear, particle, and astroparticle physics

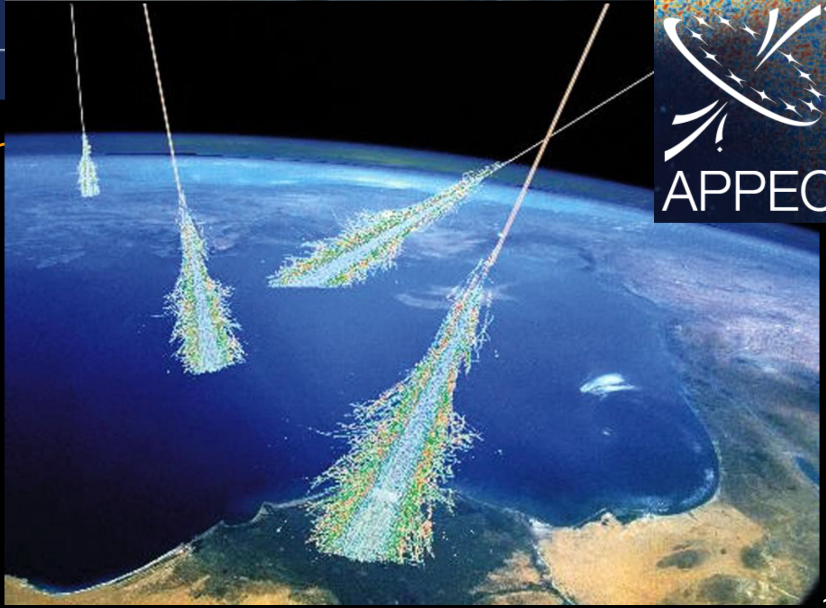


NuPECC



ECFA
European Committee for Future Accelerators





APPEC

Future Strategies

Nuclear theory

RECOMMENDATIONS

The training of the next generation of nuclear scientists

BUILD

APPA
PANDA
FAIR
NUSTAR
CBM

SPIRAL2
ISOL Facilities
HIE-ISOLDE
SPES
ELI-NP
NICA

SUPPORT

The full exploitation of existing and emerging facilities

ALICE and the heavy-ion programme at the LHC with the planned experimental upgrades

The completion of the detector AGATA in full geometry

The construction, augmentation and exploitation of Europe's world-leading ISOL facilities

CARRY OUT

R&D Programmes for possible future facilities

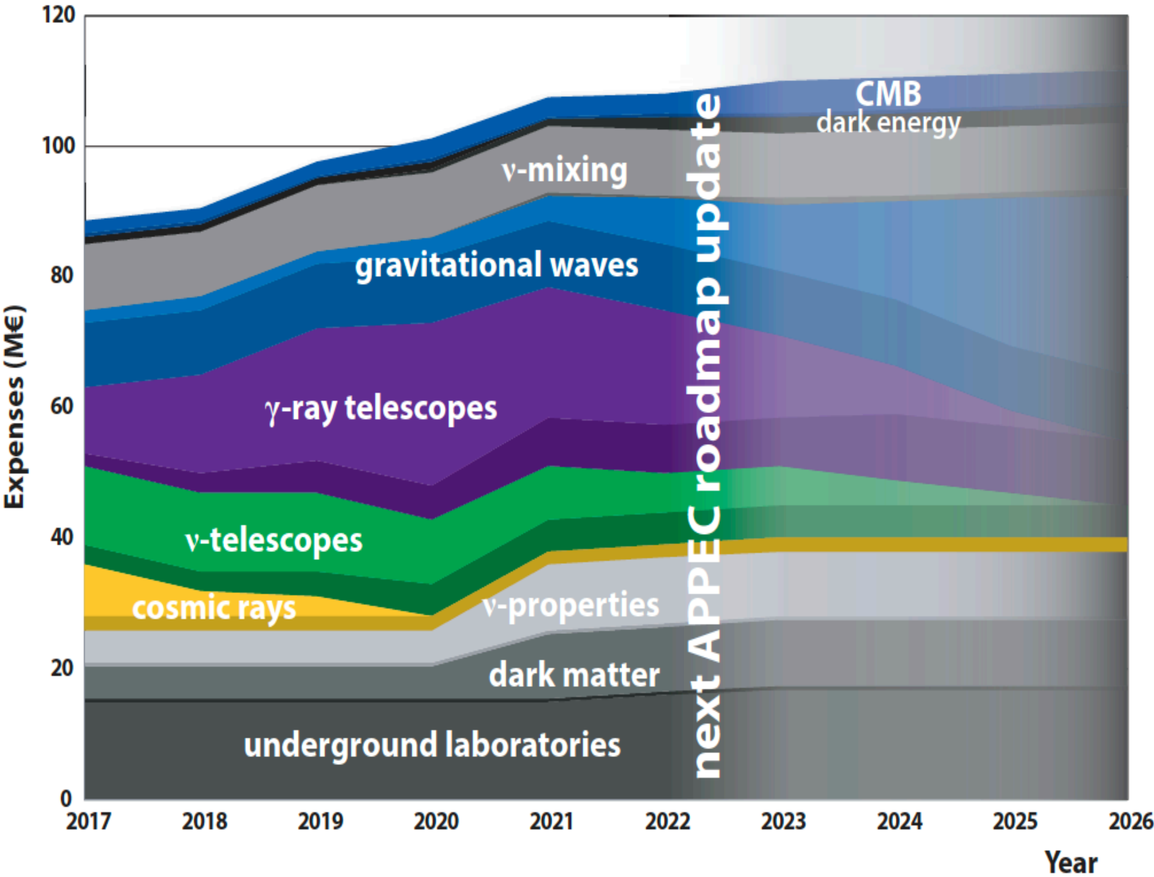
Vigorous programmes on nuclear applications

NuPECC
European Science Foundation

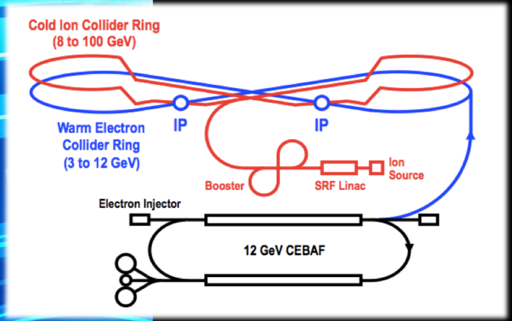
NuPECC
Long Range Plan 2017
Perspectives
in Nuclear Physics

APPEC

European Astroparticle Physics Strategy 2017-2026



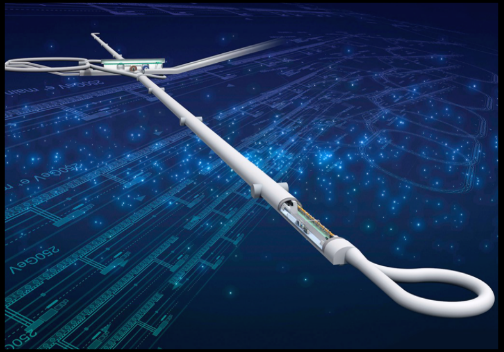
Future Colliders – Ongoing European Particle Physics Strategy



Electron Ion Collider (EIC)
e < 25 GeV, p < 250 GeV

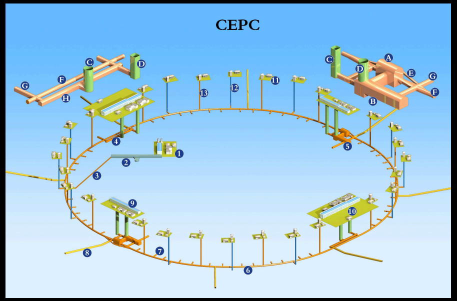
2025

2030

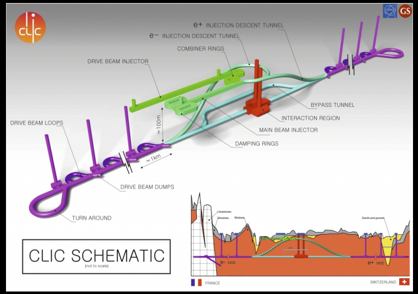


International Linear Collider (ILC)
e^+e^- $E_{cms} < 1$ TeV

2035

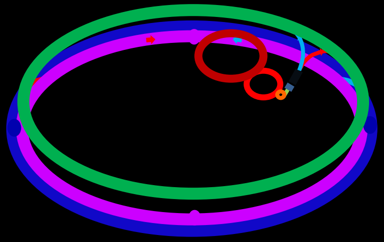


Circular Electron Positron Collider (CepC) $E_{cms} < 250$ GeV



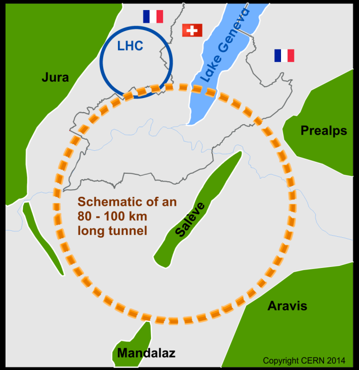
Compact Linear Collider (CLIC)
e^+e^- $E_{cms} < 3$ TeV

2040



Super pp Collider (SppC)
E_{cms} ~100 TeV

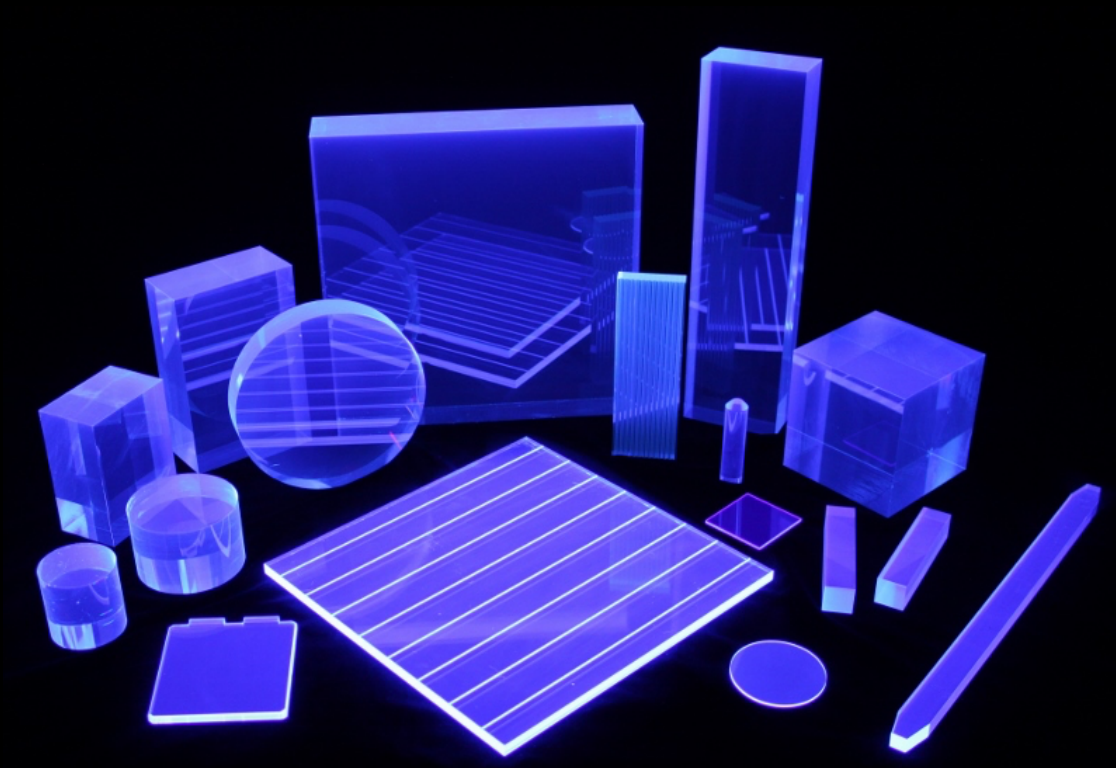
2045



Future Circular Collider (FCC)
pp, E_{cms} ~100 TeV
e^+e^- $E_{cms} < 350$ GeV
AA E_{cms} ~40TeV

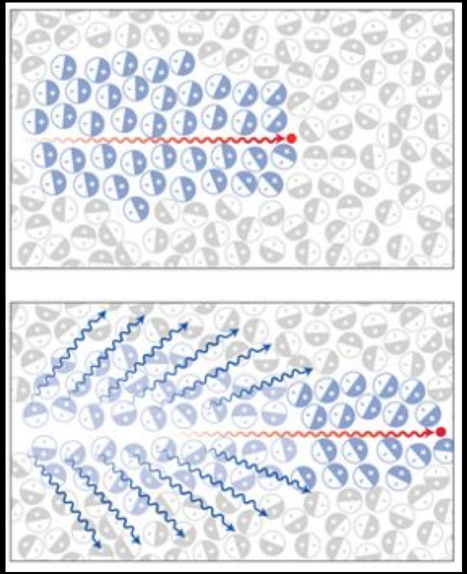
Light in particle and nuclear physics

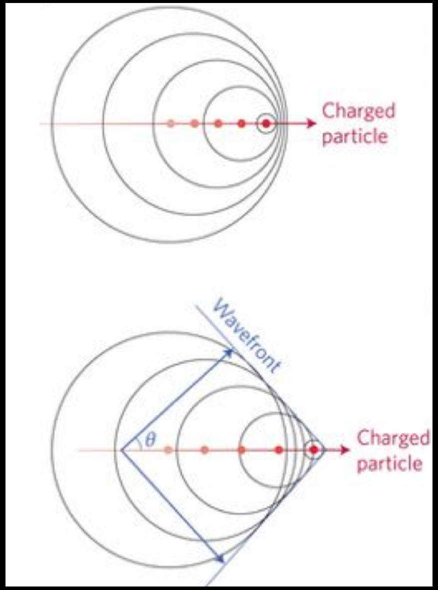
- Detection of scintillation photons
  - A wide range of different media: organic (plastic, liquid) and inorganic (crystals, cryogenic liquids) scintillators in use
  - Typical emission spectra in visible to UV light
  - Typically a few 10 to a few 100 eV of energy deposit needed per photon
- Applications in nuclear- and particle physics:
  - Trigger detectors for slow detectors (e.g. drift chambers)
  - Time of flight counters (TOF-Counter)
  - Calorimeters
  - Position detectors (scintillating fibres)
  - Detection and spectroscopy of thermal and fast neutrons
  - Neutrino detectors (liquid scintillators)



Light in particle and nuclear physics

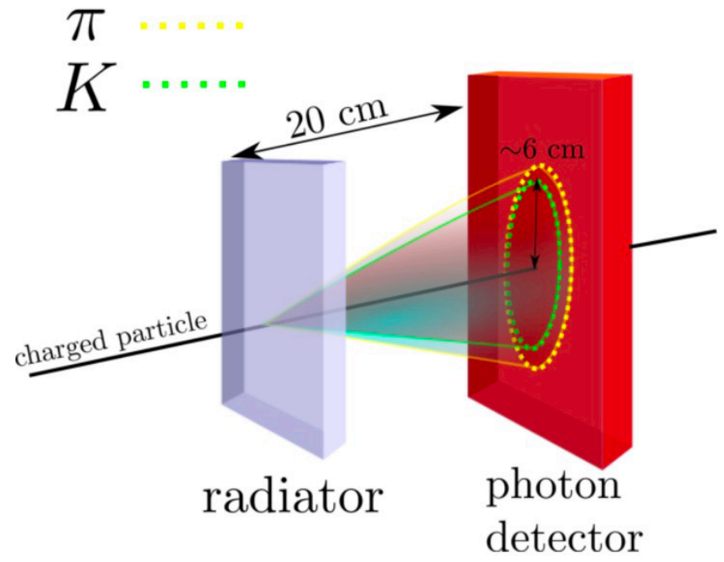
- Detection of Cherenkov photons
  - wide range of solid transparent Cherenkov media - crystals, aerogel, Water/Ice
- Applications:
  - Particle identification
  - Neutrino detection with water Cherenkov detectors





$\beta = v_p/c > c/n(\lambda)$

$$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$



BELLE 2 ARICH DETECTOR

Light in particle and nuclear physics

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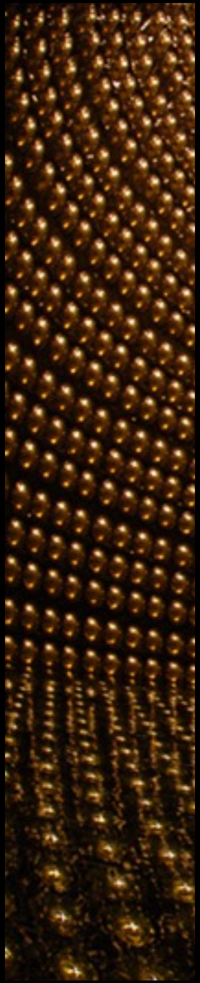
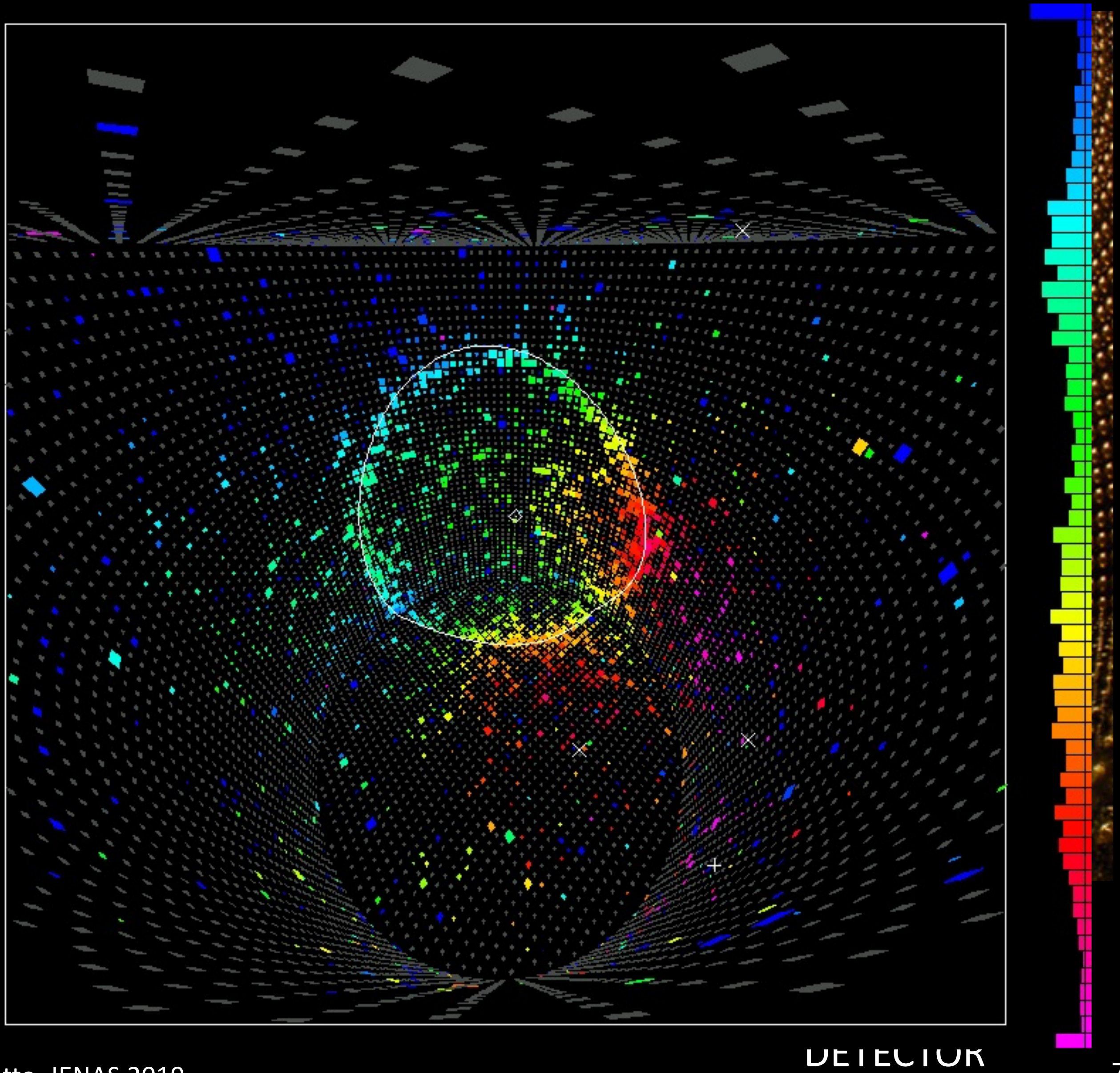
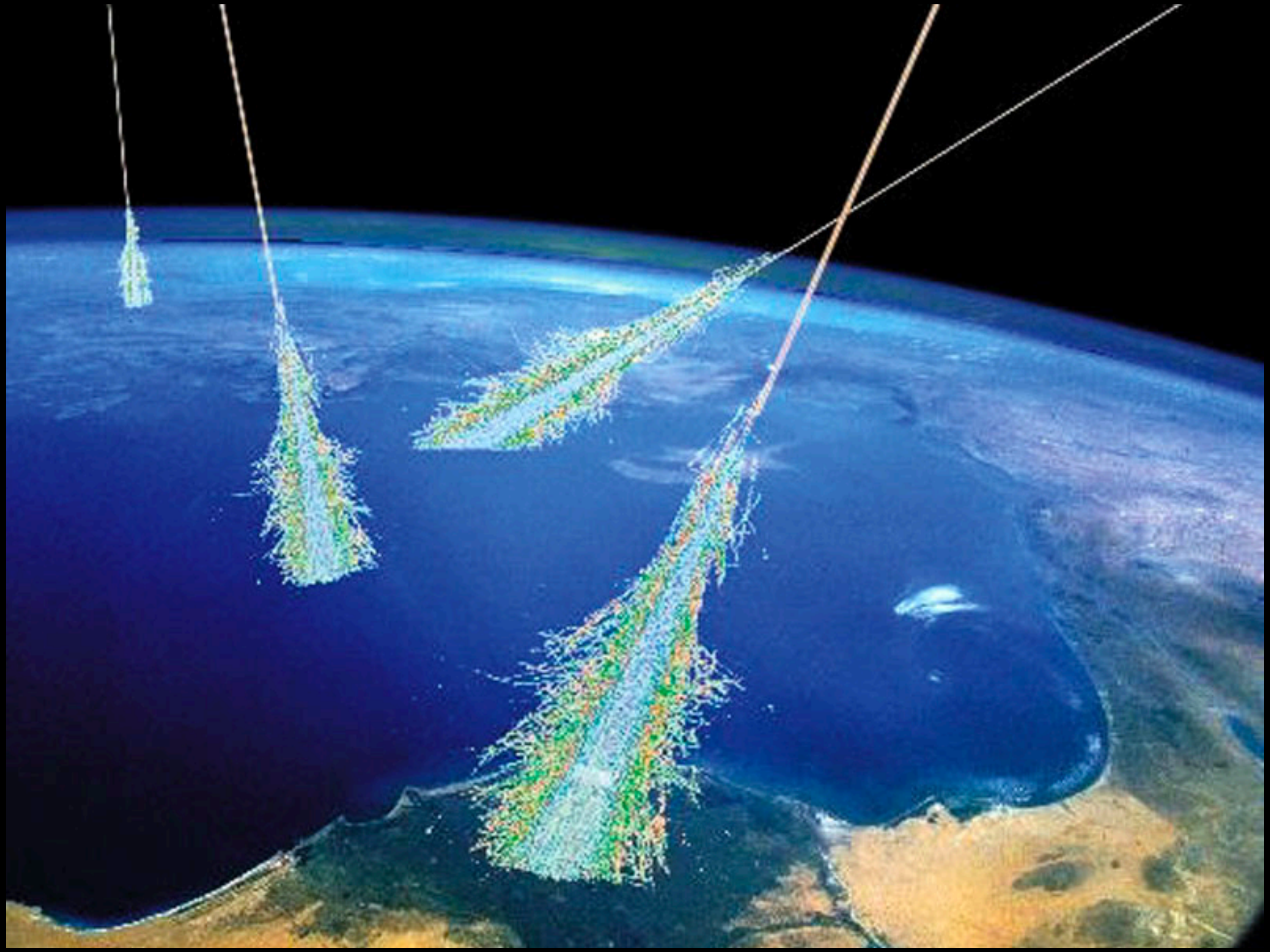




Light in astro-particle physics

- Low energies (charged particles <10^{14} eV & gamma rays <10^{10} eV)
  - Particle detectors in space or on balloons
- For high energies (charged particles >10^{14} eV & gamma rays >10^{10} eV)
  - Atmosphere as calorimeter
    - Imaging Atmospheric Cherenkov Telescopes
    - Fluorescence Telescopes
    - Detectors on the ground
- Neutrino Telescopes:
  - use atmosphere, water, ice, earth crust, or dedicated large detector volumes.
- Dark Matter experiments



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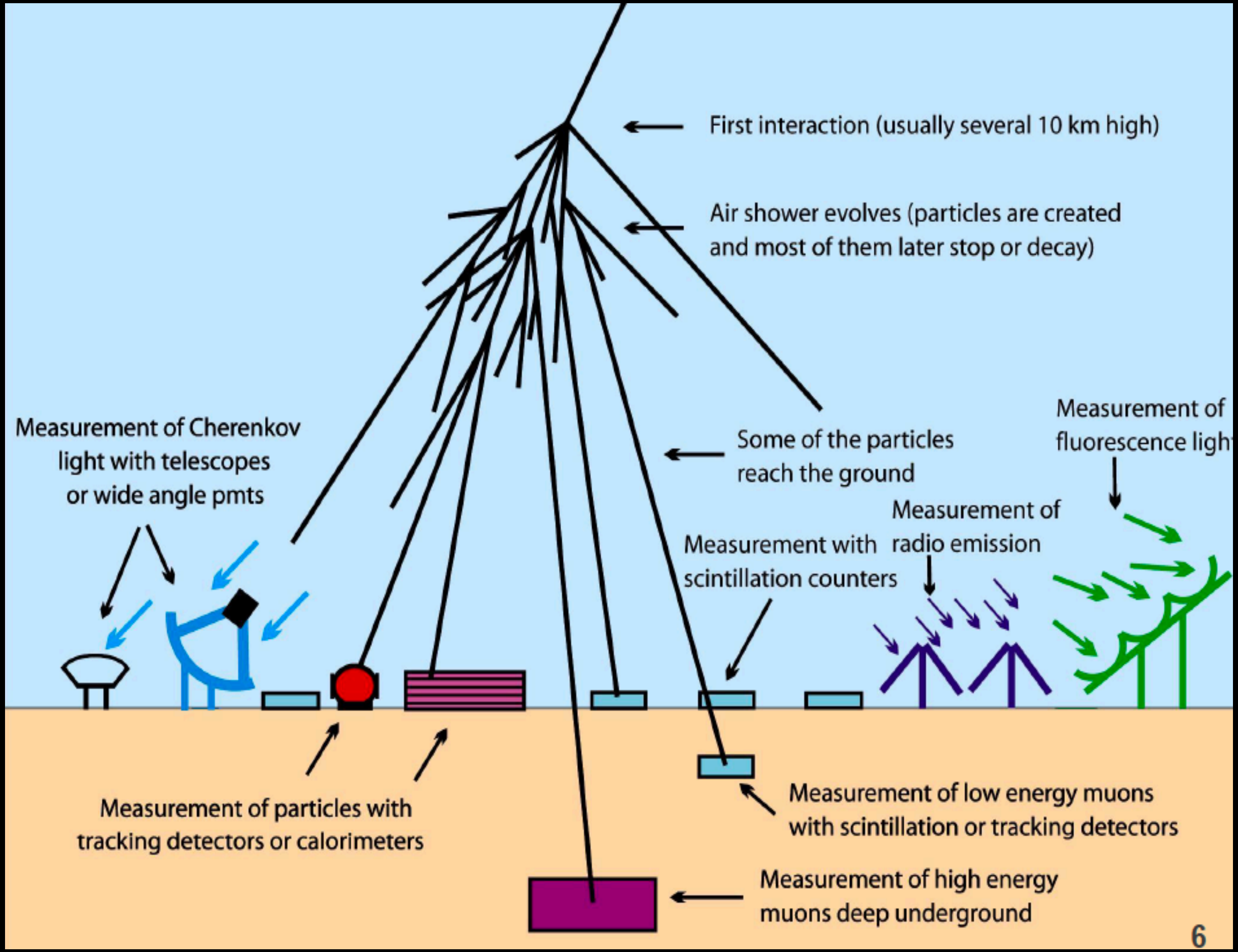
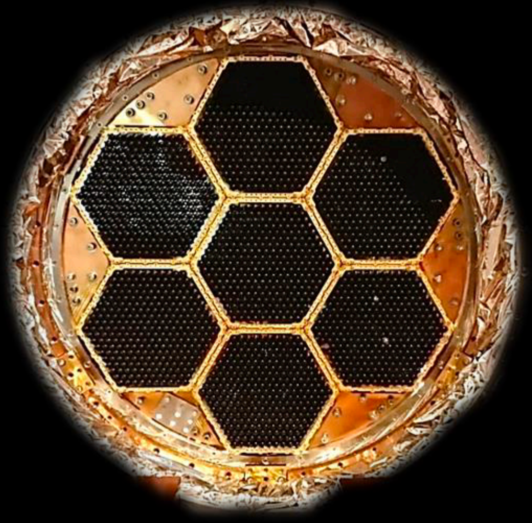


CMB and Dark Energy experiments

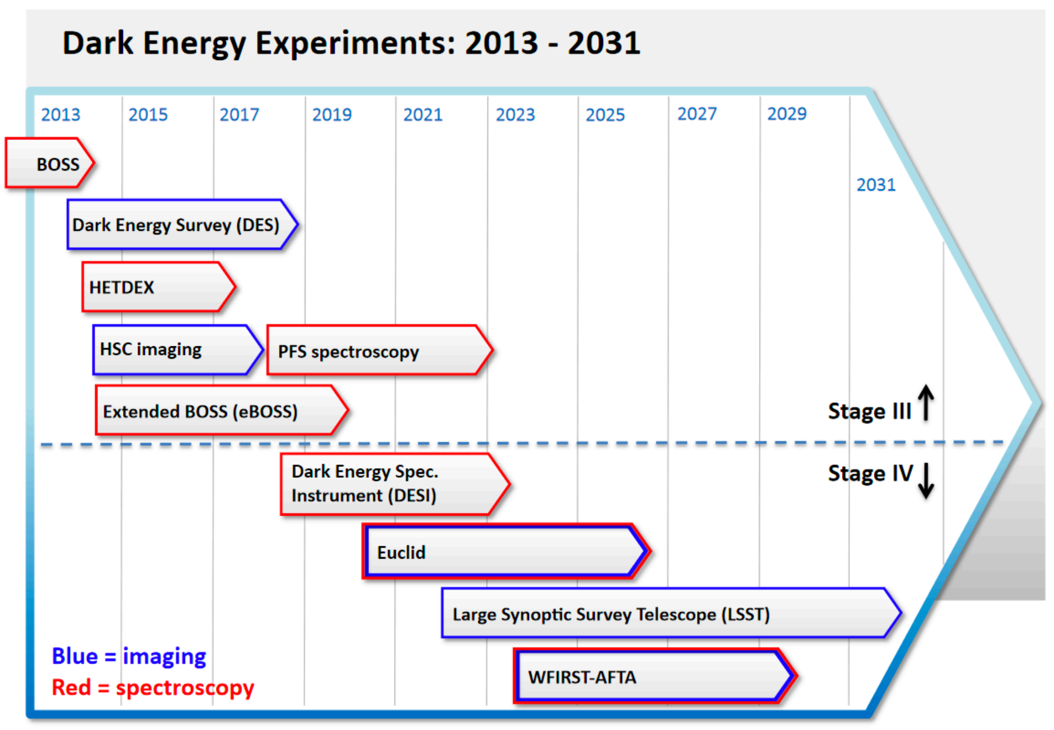

Atacama Cosmology Telescope (6 m)


South Pole Telescope (10 m)

- Transition Edge Sensor
  - Widely used in stage-2 and stage-3 CMB experiments



- Microwave Kinetic Inductance Detectors



CCDs

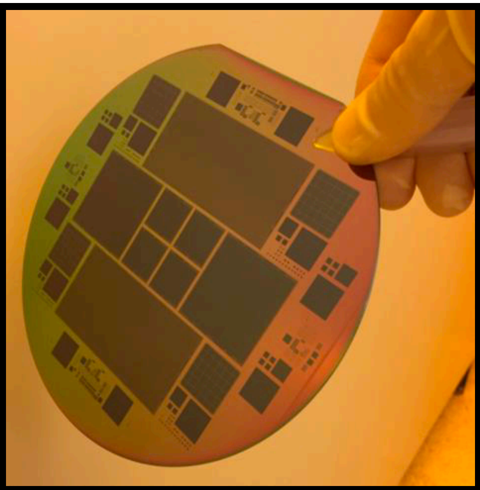
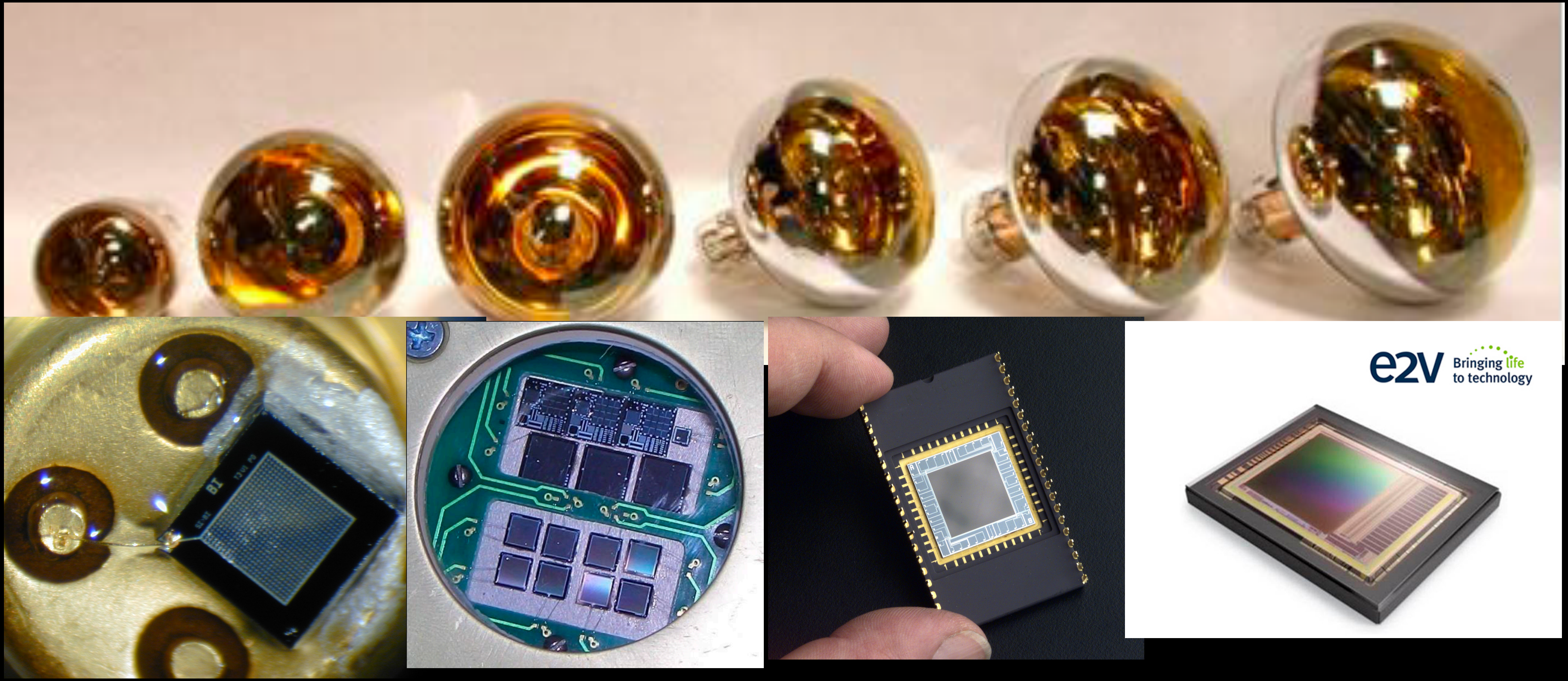
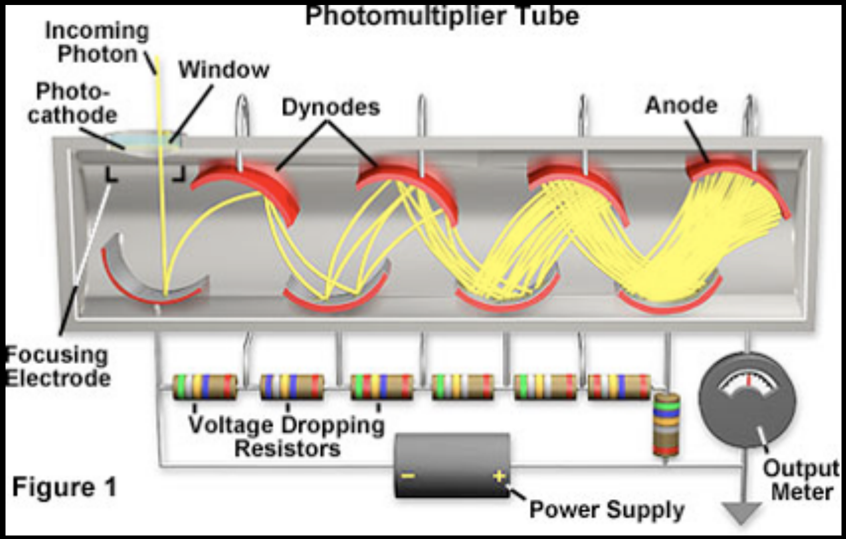


Photo Detectors

- Impossible to cover all photodetectors used now and needed for the next generation of experiments



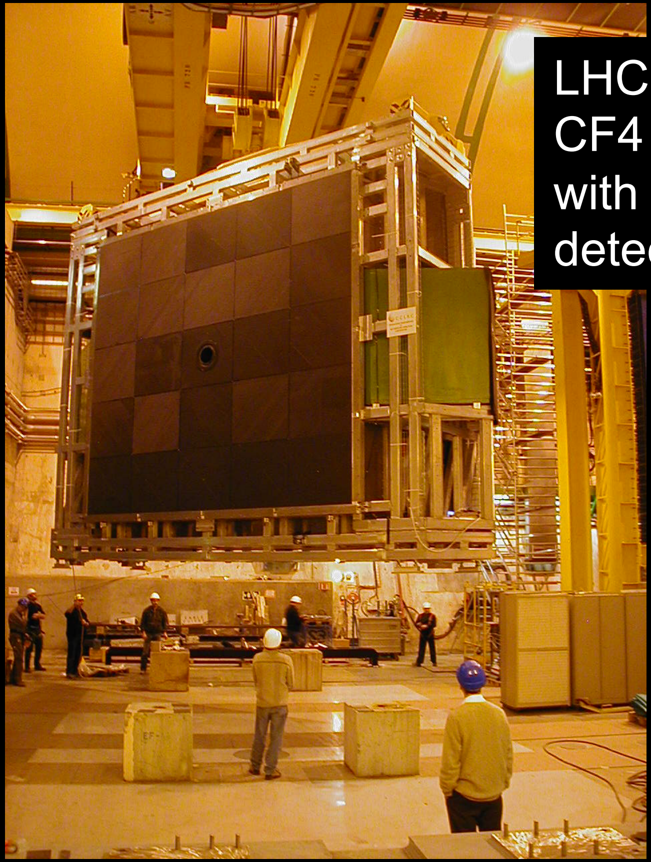
PMTs



- Position information is now available with multi anode PMTS
- Many PMTs are employing a silicon sensors as an anode:
  - Hybrid Photon Detector, HPD
  - Hybrid avalanche photon detector HAPD

Requirements for RICH photo-detectors

- Photon detectors critical for RICH performance
  - Detect and spatially resolve single photon with high efficiency
  - Sensitivity in particular in UV region
  - Spatial resolution (pixel size, readout channels...)
  - Time resolution (sub-ns, 50ps in case of “Time of propagation” counters, 3D counters)
  - Low dark rates (trigger-less readout)
  - Large area coverage (many m.) and low costs per area
- Challenges in modern RICH detectors
  - very high photon rates (high interaction rates, large track multiplicity in heavy ion experiments)
  - life time, integrated charge
  - radiation environment (neutrons,γ, ionizing particles)
  - magnetic stray fields



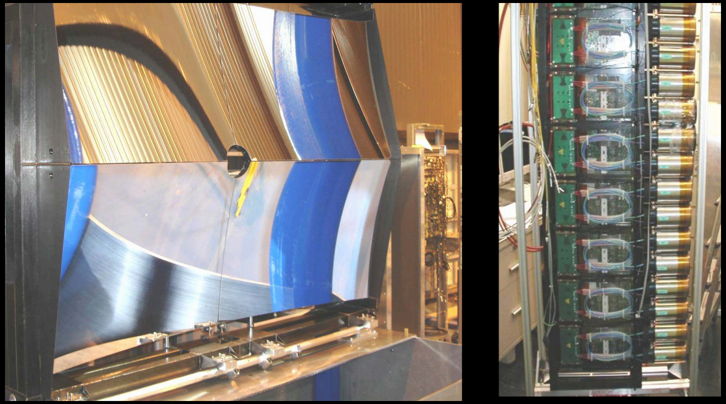
LHCb RICH2
CF4 gas radiator
with hybrid photon
detectors (HPDs)

Photon Detection (PD) Options:

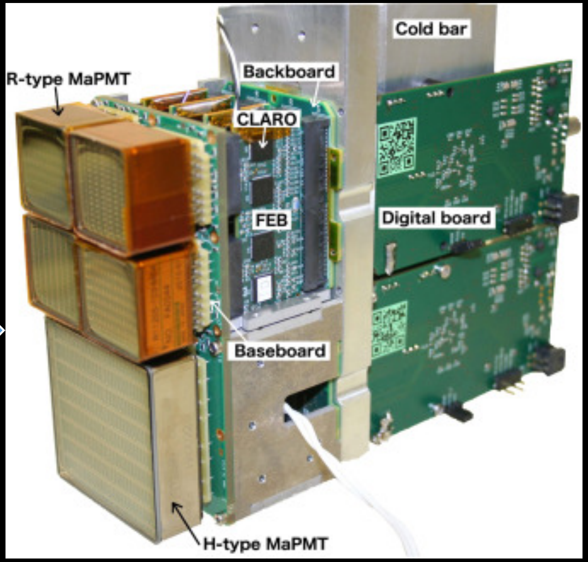
- gas detectors (GEM, MPGD)
- vacuum tube detectors (PMTs, MaPMTs)
- Silicon detectors (APDs, SiPMs)

LHCb Upgrade

RICH 1 Upgrade



PDs: Hybrid Photon Detector with 1 MHz max. readout rate



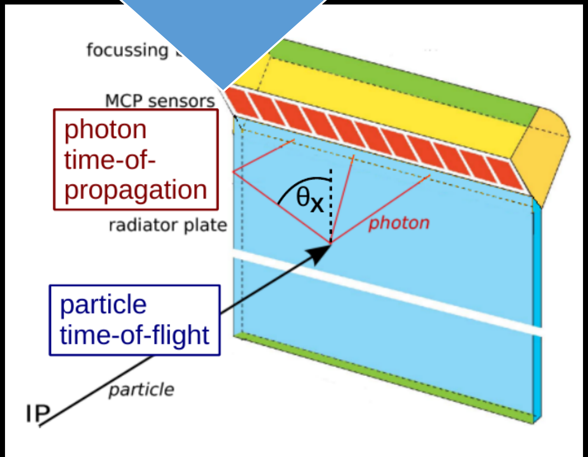
LHC: LS 2 (now)

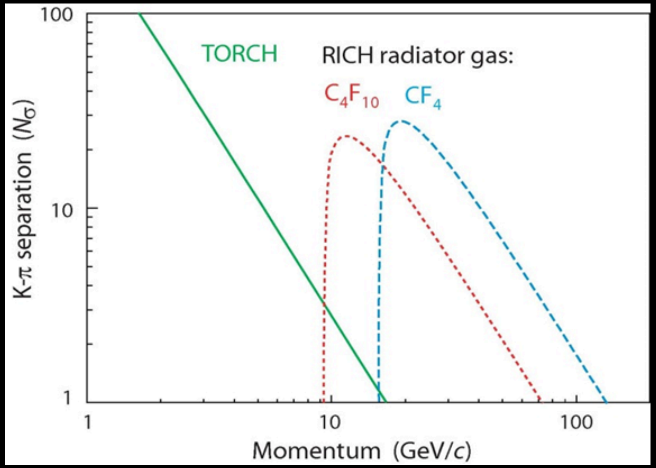
Multi-anode PMTs from Hamamatsu

Upgrade IA: New optics, photo detectors, new electronics

LS3: 2025

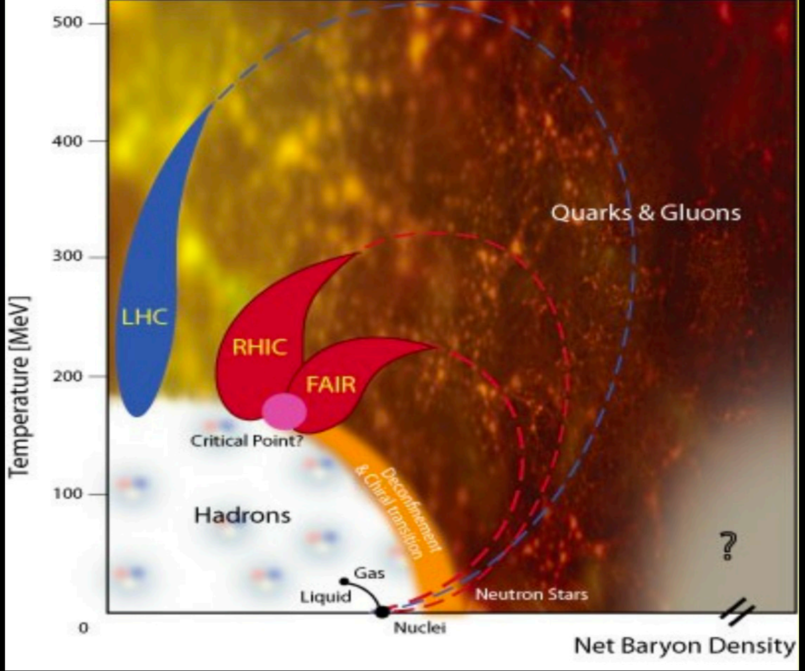
TORCH (Time Of internally Reflected CHerenkov light) ToF resolution ~10-15 ps (per track) using micro channel plates

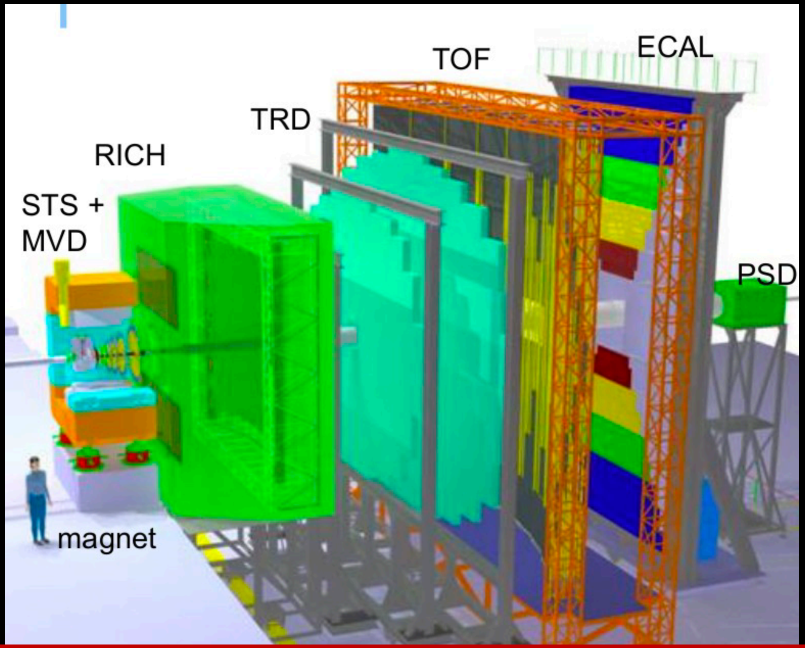




CBM RICH DETECTOR

- CBM - “Compressed Baryonic Matter”, a future heavy ion experiment being build at FAIR
- Goal: study QCD phase diagram at large density and moderate temperature in Au+Au fixed target collisions up to 35 GeV
- e/π separation key for studies of ρ and J/ψ decays
- π-suppression factor >100 up to 8 GeV
- RICH detector only after significant material (from silicon tracking detector)
- High rate (up to 100 kHz photon rate per pixel)

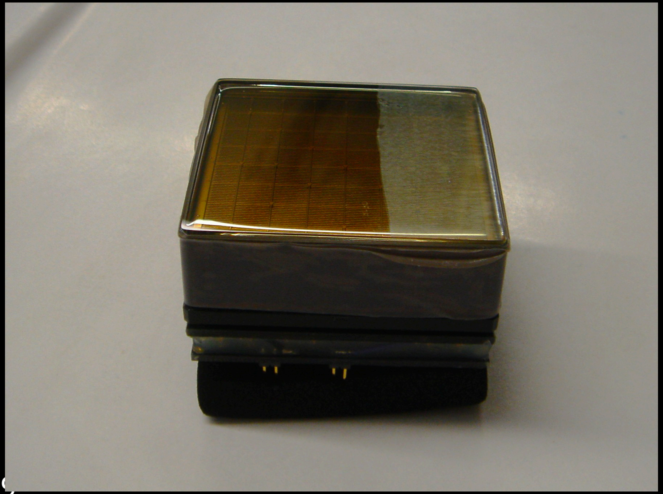




CO_2 gas radiator and MAPMT photodetectors (1100 Hamamatsu H12700 ordered)

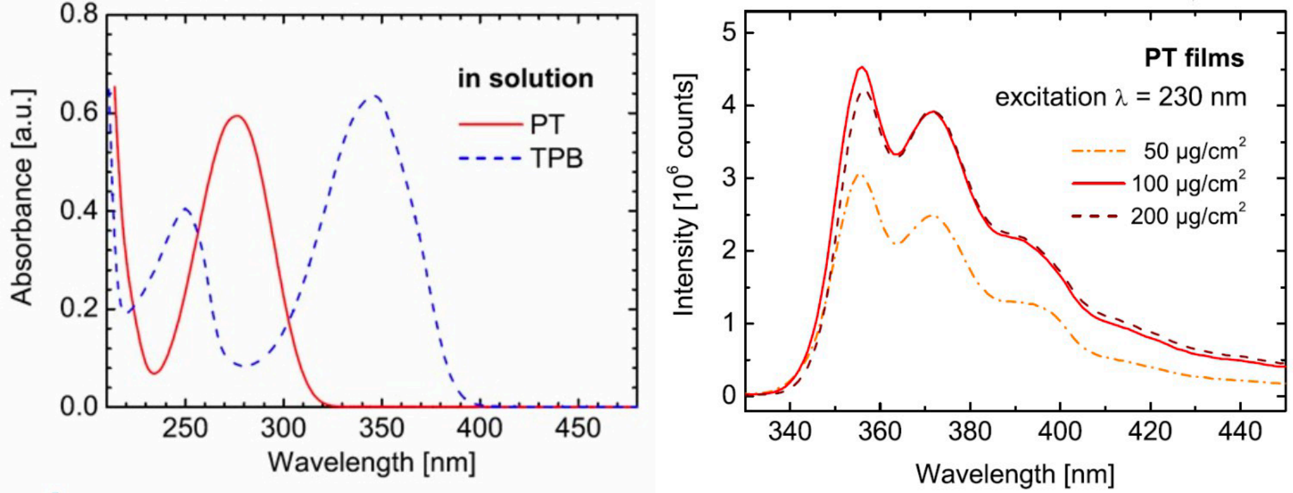
MaPMT Improvements for CBM

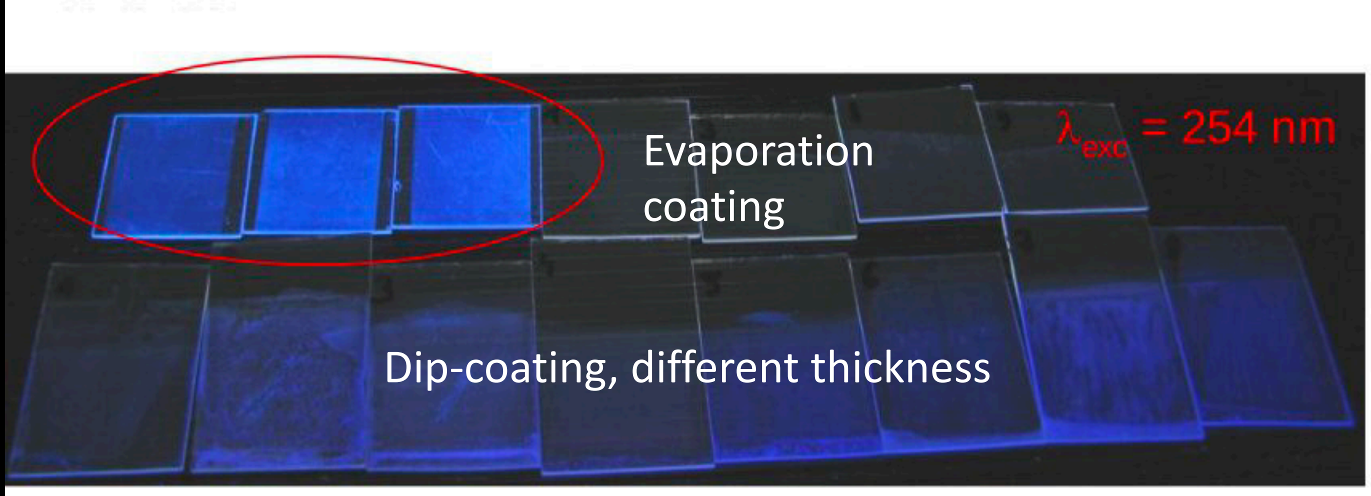
- Quantum efficiency in UV can be significantly increased by
  - Coating the MaPMTs with a wavelength shifting film
  - Promising candidate: p-Terphenyl (PT)
  - Absorb UV-photons in region for cathode is not sensitive any more (isotropically) re-emit photons in region of larger sensitivity



Absorption of p-Terphenyl (red) in UV, below 230nm

Reemission around 360nm





Evaporation coating

Dip-coating, different thickness

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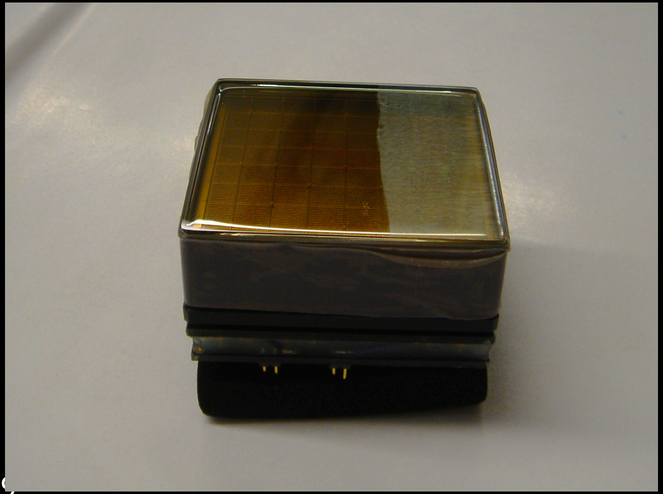
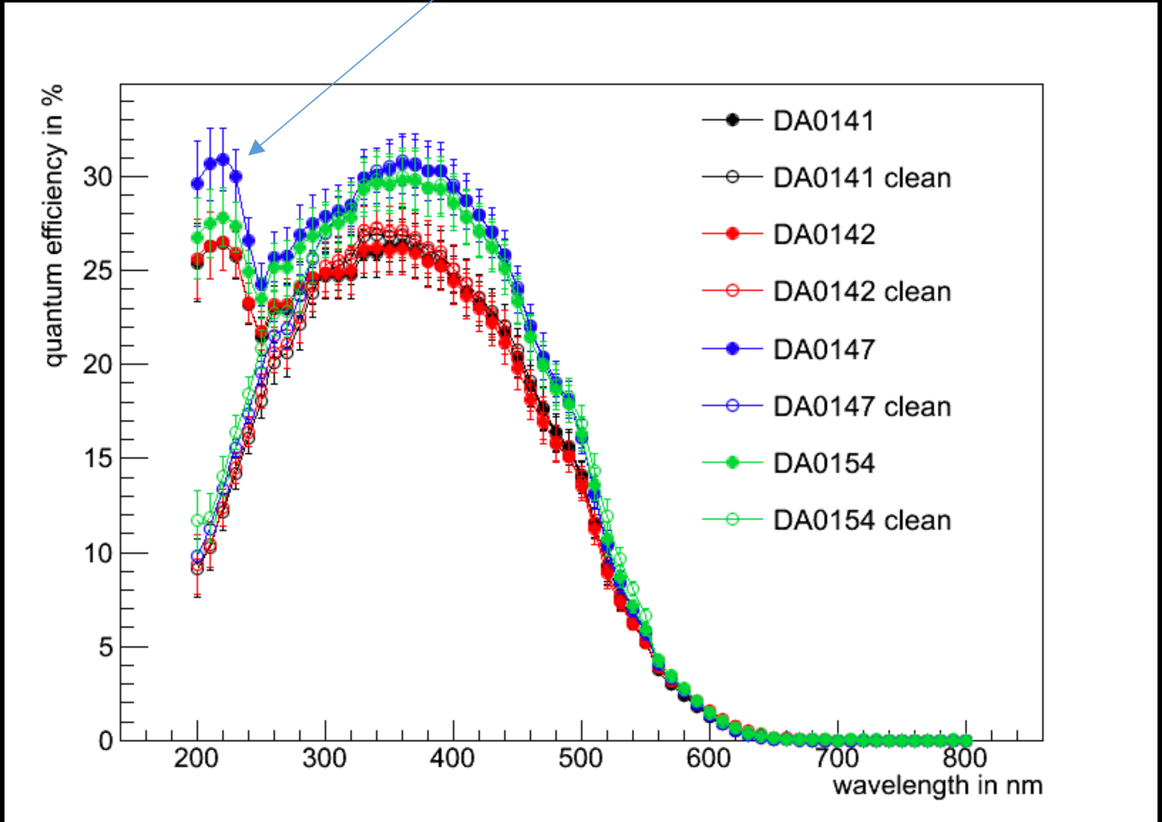
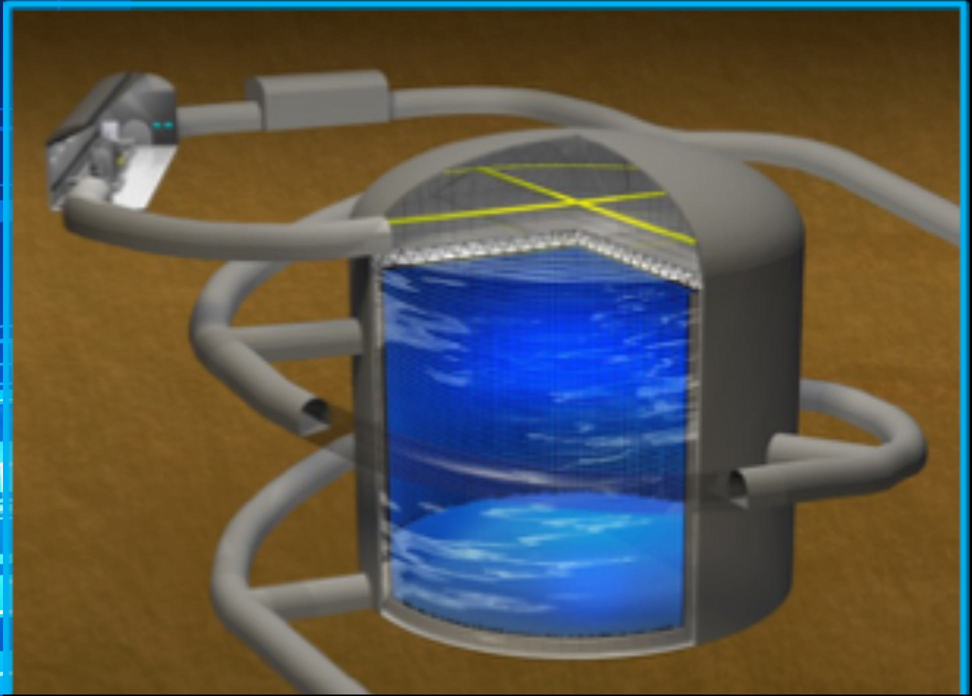


Gain due to WLS



HYPERK

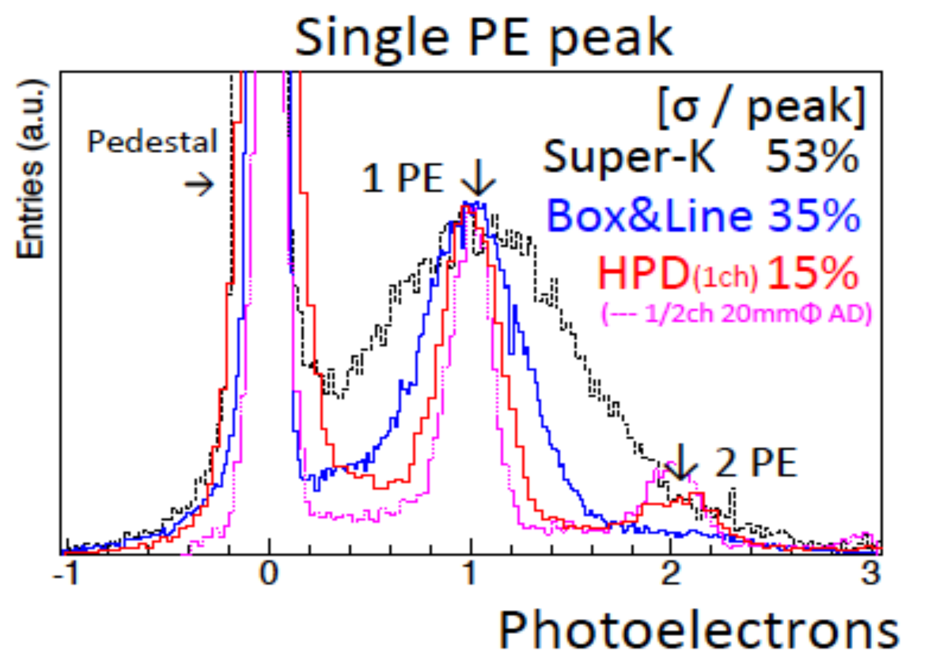


- 260 kton ultrapure water
- 190 kton fiducial mass: 10×SK
- Innermost volume viewed by 40,000 of new 50 cm PMT
  - ~x2 high detection efficiency
  - 50% improvement in time & charge resolution
  - ~x2 high pressure bearing for 60m

Hamamatsu
R12860
Box and line PMT

Hamamatsu
R12850
HPD (Hybrid Photo Detector)

Prototypes installed in SK

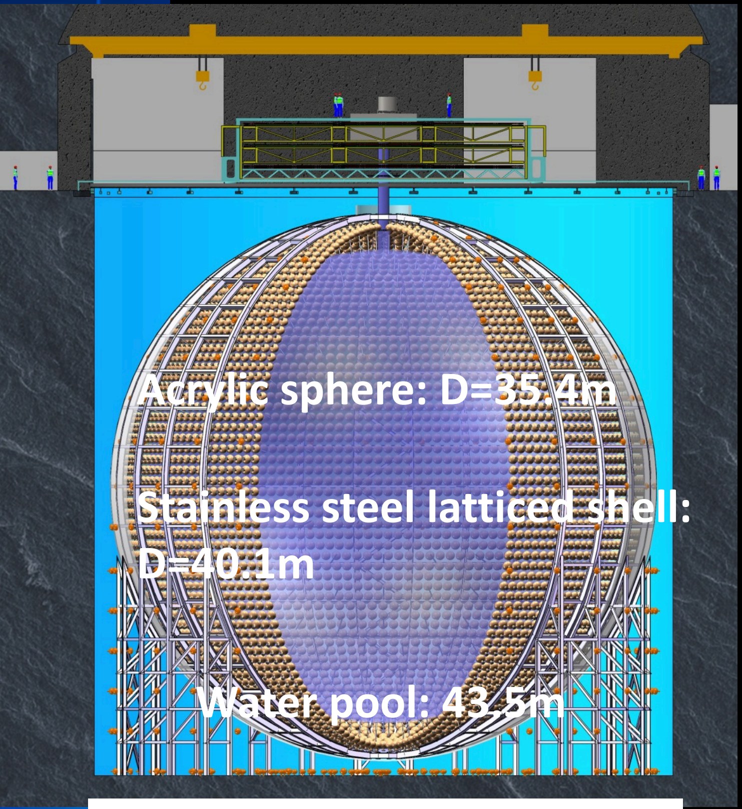


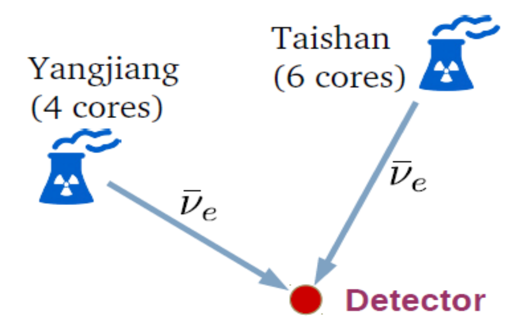
Alternative option:
50% 20’’ MPTs and 50% multi PMTs (ala KM3NET)

- Construction start in 2020
- Operation in 2026

JUNO

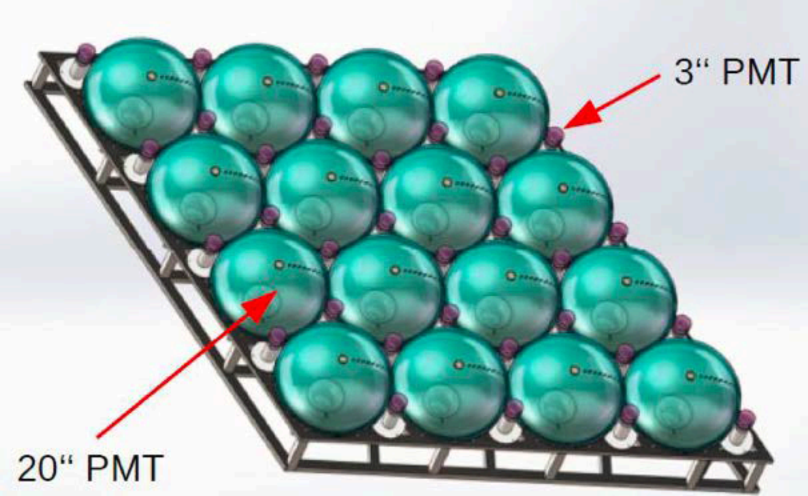
- Jiangmen Underground Neutrino Observatory
- Central detector: ~ 20 kton of scintillator (**Largest scintillator detector ever built !)**
- Unprecedented energy resolution (3% at 1 MeV)
- Light detection: 18000 20'' PMTs and 25000 3'' PMTs
  - 15k MCP-PMT (75%) from NNVT (China) and 5k (25%) from Hamamatsu
- The detector overburden is about 700 m



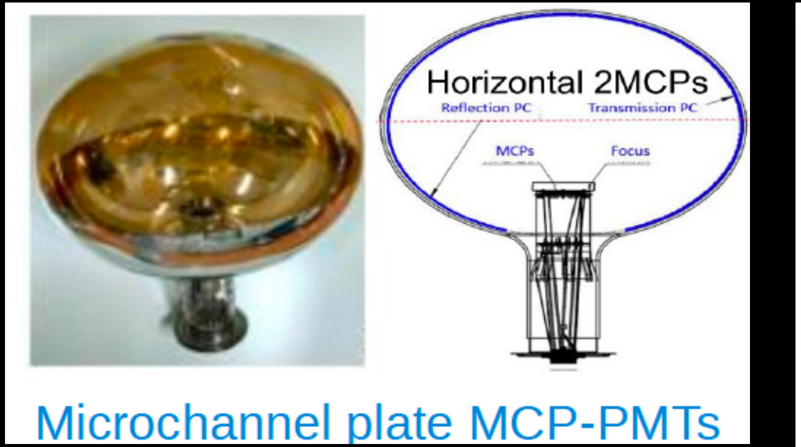


- Determination of the neutrino mass hierarchy with good sensitivity (3σ after 6 years)
- Precision measurement the neutrino mixing parameters: $\sin 2\theta_{12}$ (from 4.1 % to 1%), Δm^2_{12} (from 2.3% to <1%)
- 2018 - 2019 Detector assembly & installation
- 2020 Liquid scintillator filling
- 2020 Start of data taking

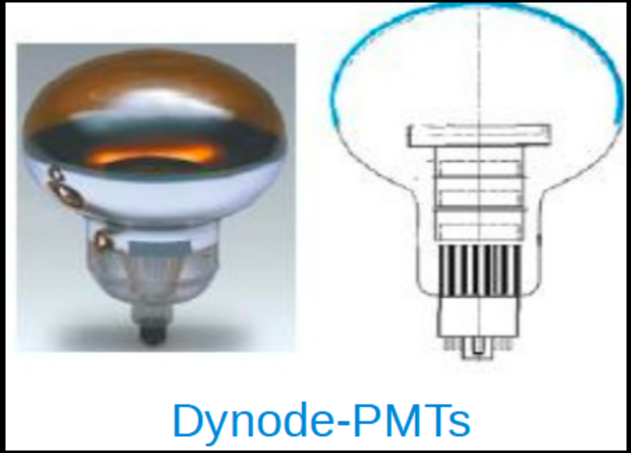
JUNO PMT DEVELOPMENT AND PRODUCTION



- Two complementary technologies for 20”:
  - 15000 MCP-PMTs from NNVT in China
  - 5000 dynode PMTs from Hamamatsu



Microchannel plate MCP-PMTs



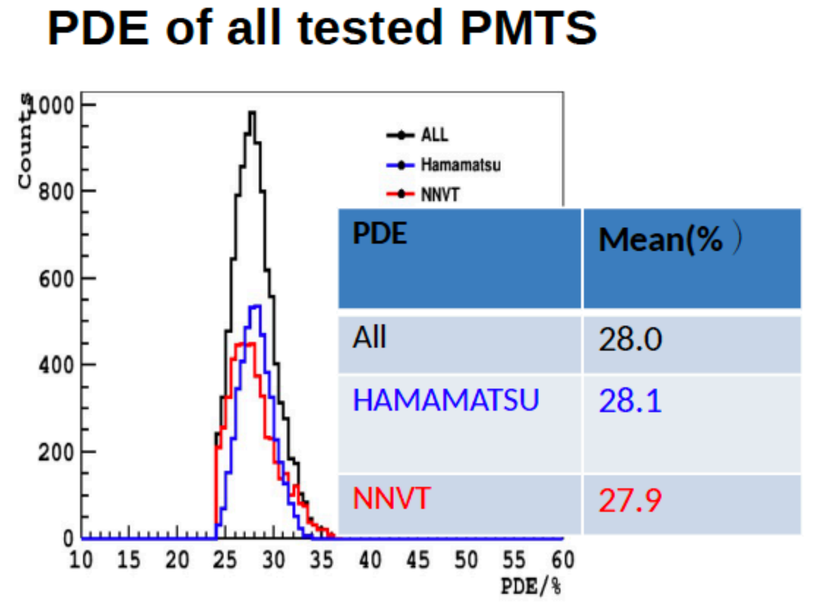
Dynode-PMTs

- Commercial testing facility

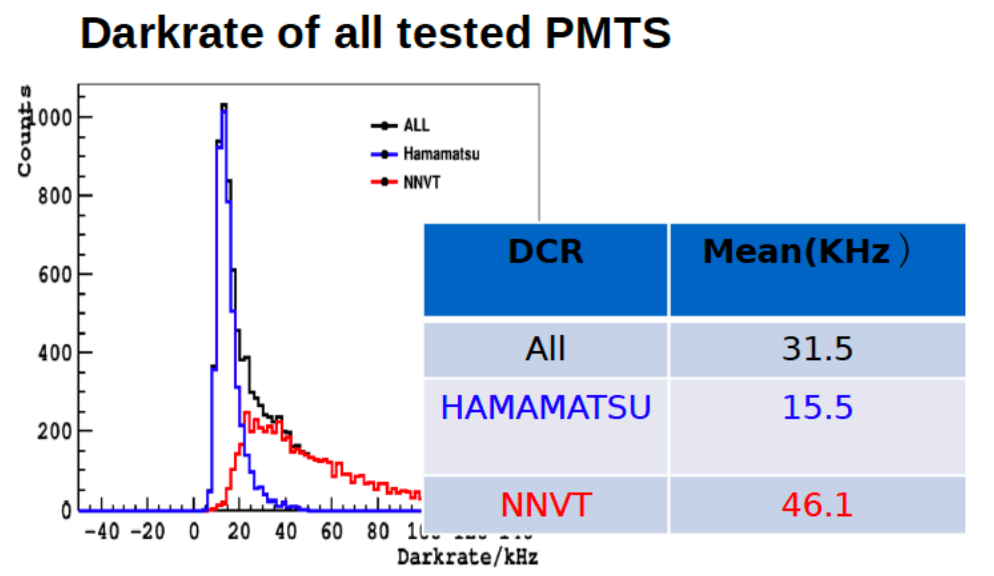
- 5000 dynode and 8000 MCP PMTS delivered.
- 11000 PMTs tested in the containers and 1500 in the scanning stations

JUNO PMT DEVELOPMENT AND PRODUCTION

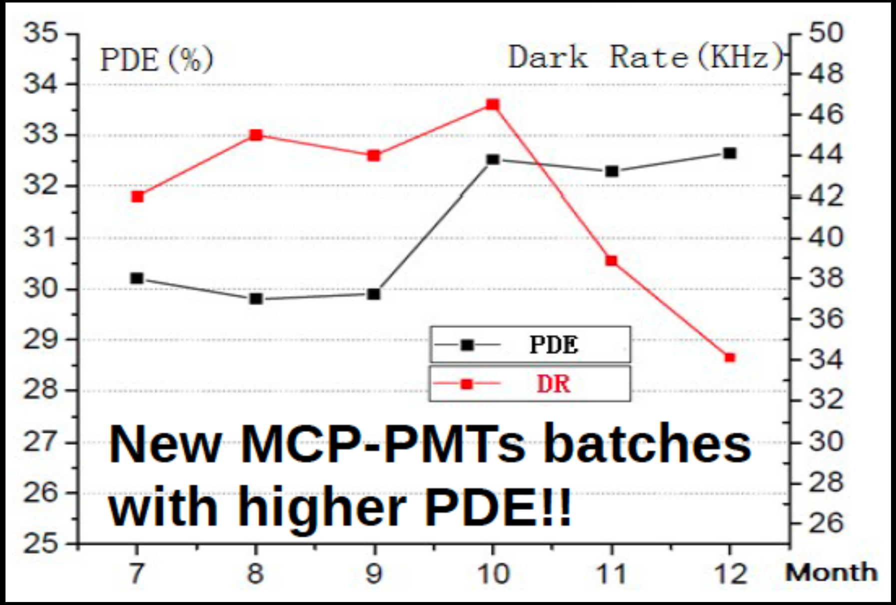
- Commercial testing facility


PDE of all tested PMTS

PDE	Mean(%)
All	28.0
HAMAMATSU	28.1
NNVT	27.9

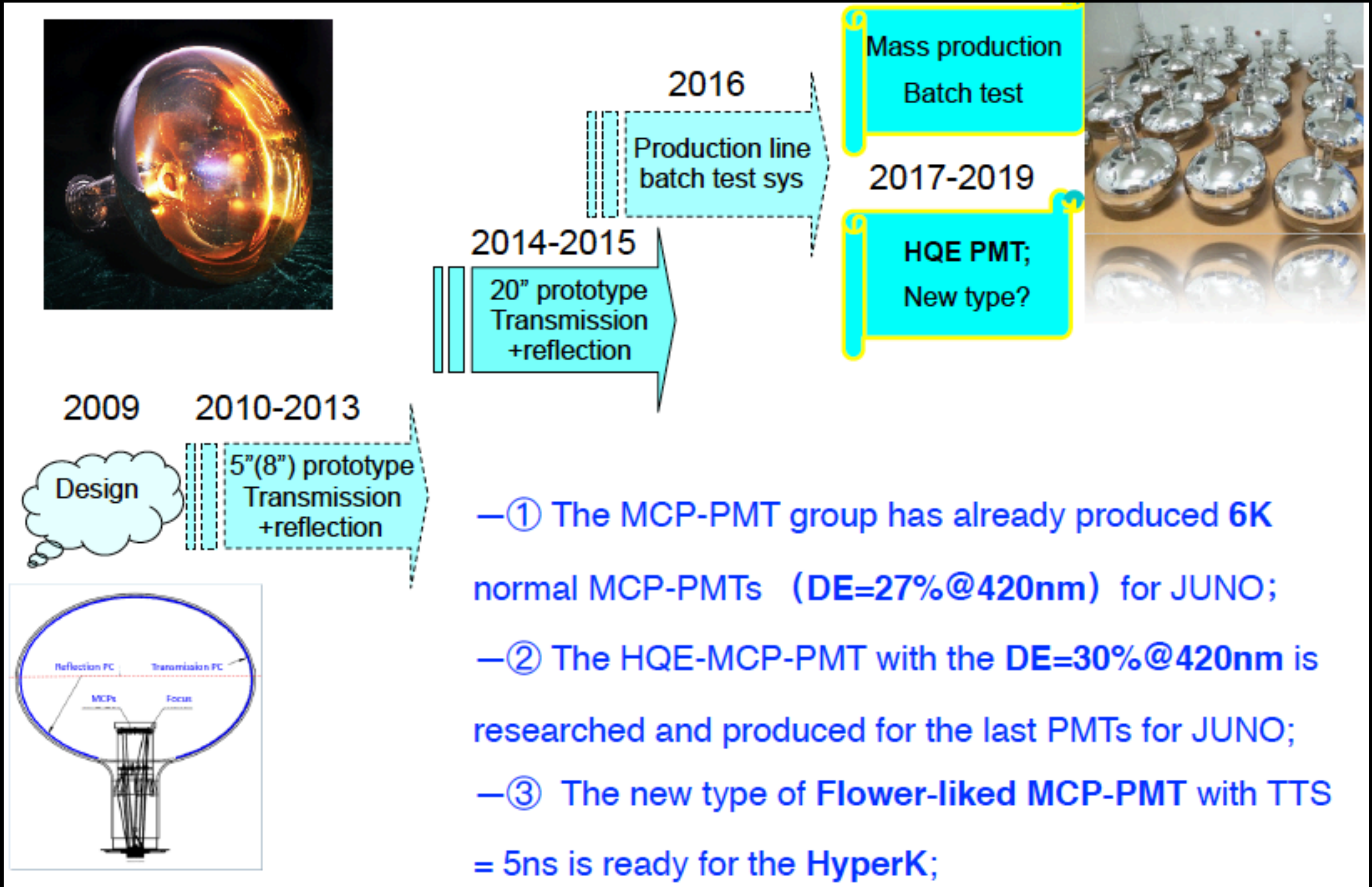

Darkrate of all tested PMTS

DCR	Mean(KHz)
All	31.5
HAMAMATSU	15.5
NNVT	46.1



New MCP-PMTs batches with higher PDE!!

PMT ADVANCES AT NNVT



2009
Design

2010-2013
5”(8”) prototype
Transmission
+reflection

2014-2015
20” prototype
Transmission
+reflection

2016
Production line
batch test sys

Mass production
Batch test

2017-2019
HQE PMT;
New type?

—① The MCP-PMT group has already produced **6K** normal MCP-PMTs （**DE=27%@420nm**） for JUNO;

—② The HQE-MCP-PMT with the **DE=30%@420nm** is researched and produced for the last PMTs for JUNO;

—③ The new type of **Flower-liked MCP-PMT** with TTS = 5ns is ready for the **HyperK**;

KM3NET

KM3NeT

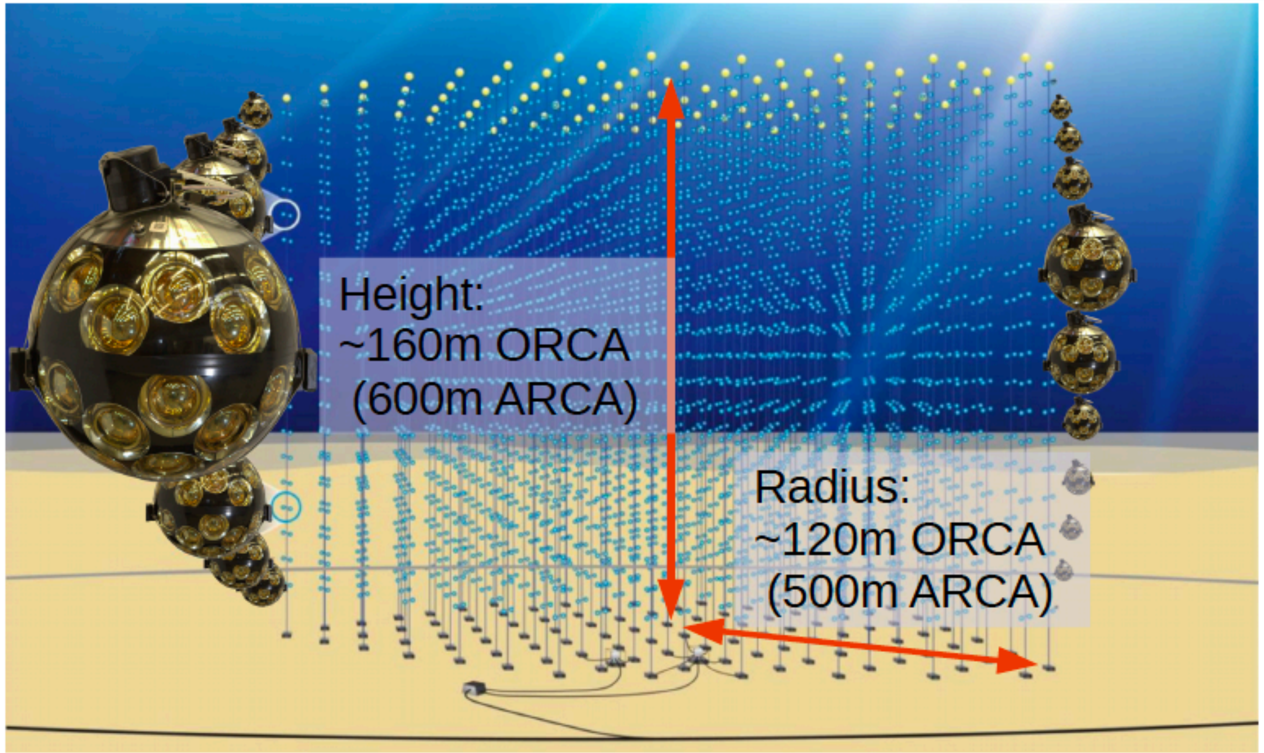
- ORCA: The origin of cosmic neutrino (high energy- PeV ν)
- ARCA: Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory : Oceanography, bioacoustics, bioluminescence, seismology

KM3NET

ORCA will consist of one dense **KM3NeT Building Block:**

115 detection lines
Total: 64k * 3” PMTs

	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton



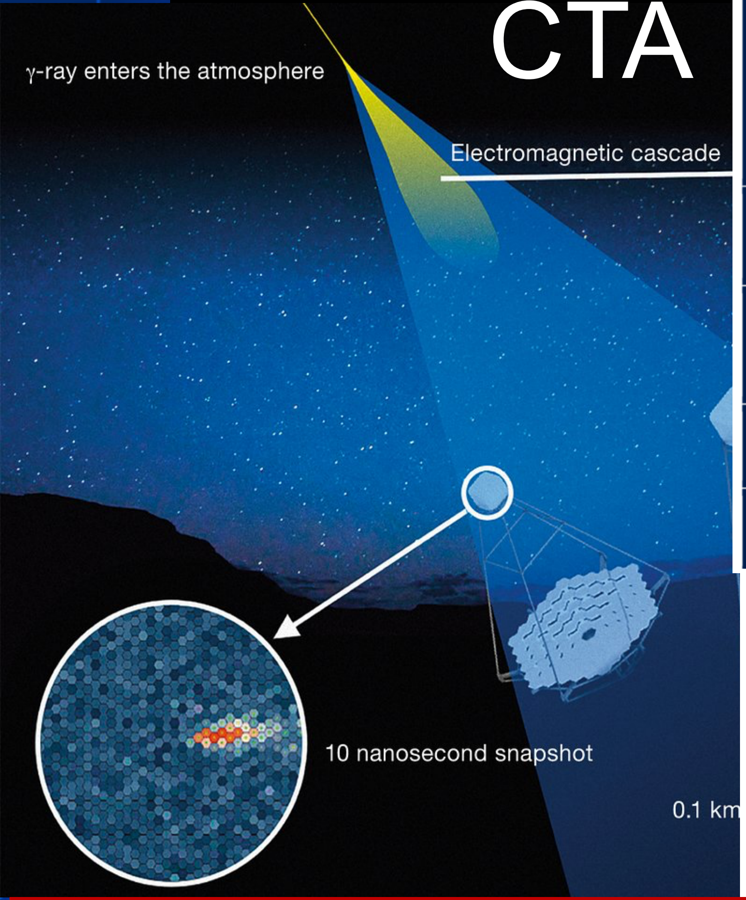
Directional information

Will also be used for the ICECUBE Telescope Upgrade

Imaging Atmospheric (or Air) Cherenkov Telescopes

Future IACT

CTA



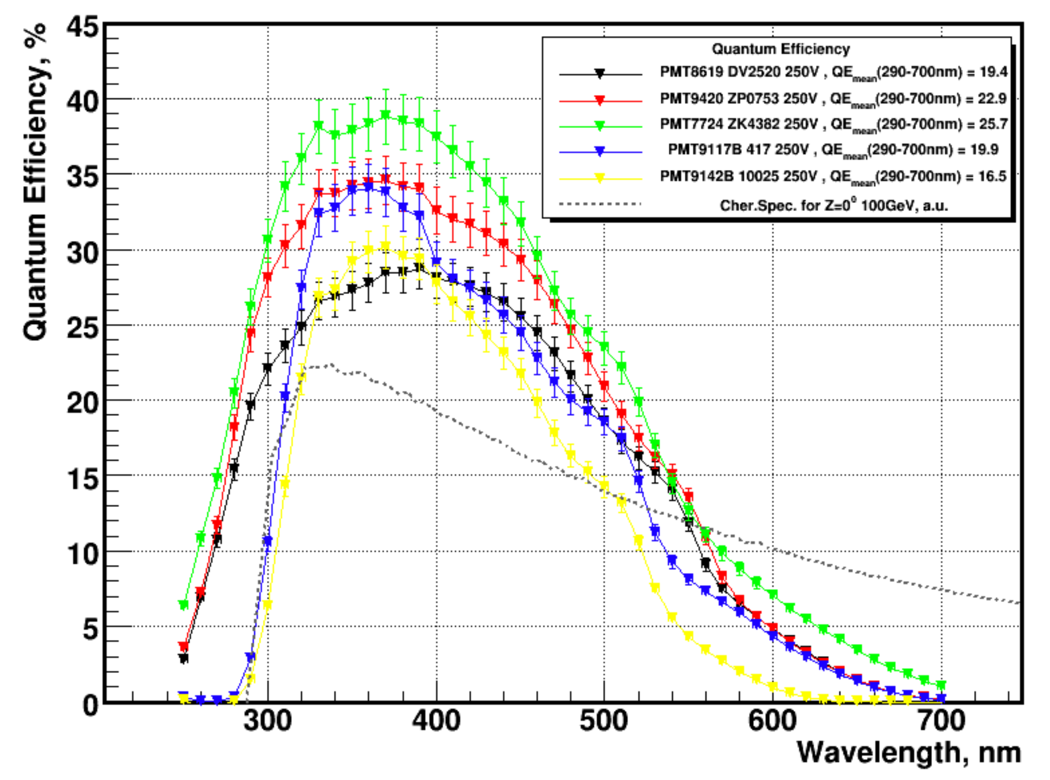
	Large-Sized Telescope (LST)	Medium-Sized Telescope (MST)			Small-Sized Telescope (SST)		
		FlashCam	NectarCam	SCT	ASTRI	GCT	SST-1M
Required energy range	20 GeV – 3 TeV	80 GeV – 50 TeV			1 TeV – 300 TeV		
Energy range (in which subsystem provides full system sensitivity)	20 GeV – 150 GeV	150 GeV – 5 TeV			5 TeV – 300 TeV		
Number of telescopes	4 (South) 4 (North)	25 (South) 15 (North)			70 (South) 0 (North)		
Optical design	Parabolic	Modified Davies-Cotton		Schwarzschild-Couder	Schwarzschild-Couder		Davies-Cotton
Effective mirror area (including shadowing)	370 m^2	88 m^2		41 m^2	8 m^2	8.9 m^2	7.5 m^2
Focal length	28 m	16 m		5.6 m	2.15 m	2.28 m	5.6 m
Total weight	103 t	82 t		80 t	19 t	11 t	8.6 t
Field of view	4.3 deg	7.5 deg	7.7 deg	7.6 deg	10.5 deg	8.3 deg	8.8 deg
Number of pixels in Cherenkov camera	1855	1764	1855	11328	2368	2048	1296
Pixel size (imaging)	0.1 deg	0.17 deg	0.17 deg	0.067 deg	0.19		0.24 deg
Photodetector type	PMT		PMT	SiPM	SiP		SiPM

PMT

SiPM

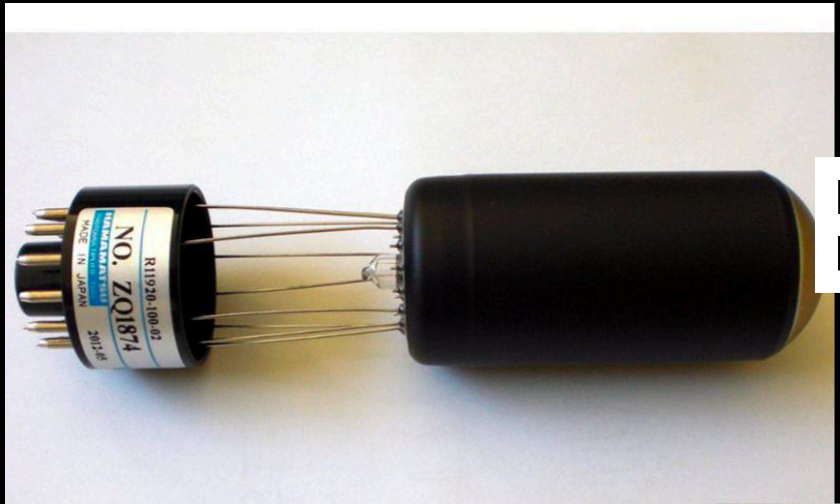
Low energies limitation:
- Photon Collection large telescopes with >20 m diameter
- energy threshold: 20 GeV

IACT PMT Instrumental improvements



- CTA PDE improvement program with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).

SENSE ROADMAP



Hamamatsu CTA PMT now

Electron Tubes Enterprises CTA PMT now

- ph.e. collection efficiency increased from 85% to 95%, as well as the QE has further increased towards ~40%
- After pulsing level has been reduced from a typical 0.3% to 0.02 %
- Further improvements possible: new photo-cathode K_2CsSb and smoother deposition

SiPM

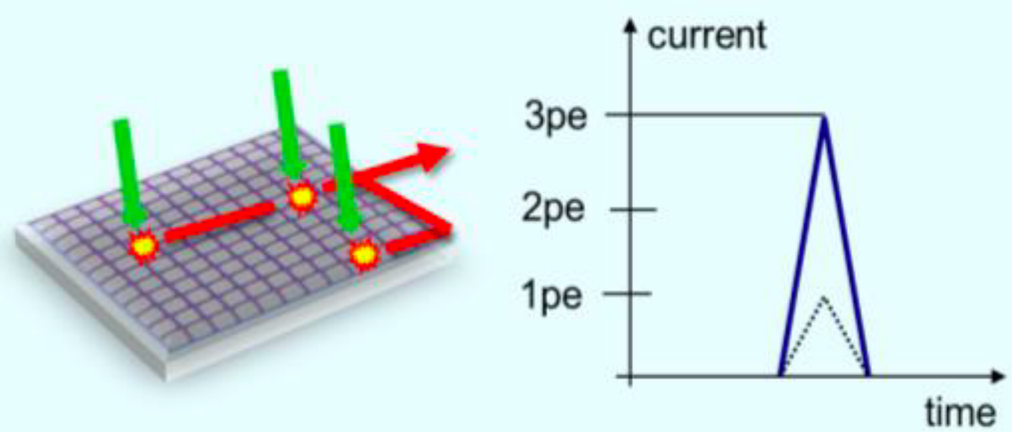

Philips
KETEK
MPI-HLL
CPTA
1.1mm
MePhi/
Pulsar
SensL
Zecotek
Hamamatsu
RMD
Excelitas
AdvanSiD
NDL
NanoFab
Korea

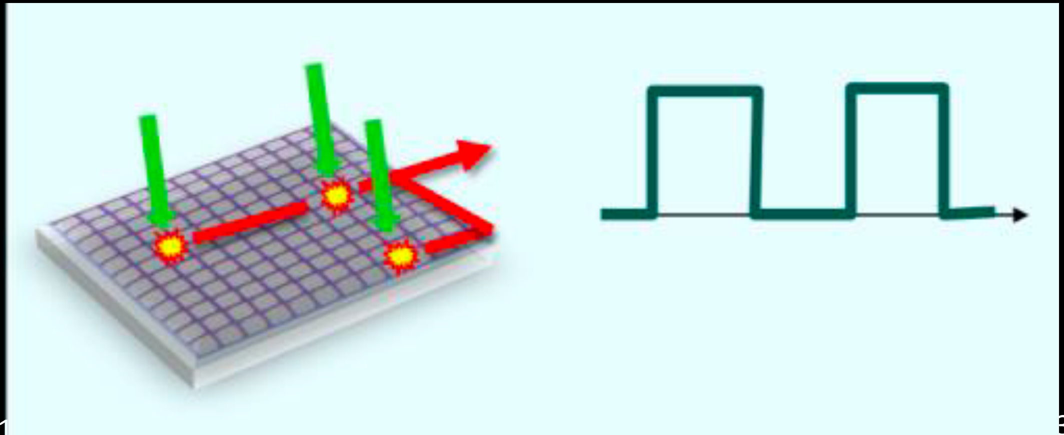
SiPM

- Array of compact independent Avalanche Diodes (SPAD), with integrated quenching circuit, operating in Geiger mode outputting the sum of cell signal (analog sum or digital sum)
- Great progress in the last 15 years

- ANALOG
- SPADs connected in parallel through a decoupling resistor, which is also used for quenching avalanche
  - Amplitude of output signal ∝ n(photons)
  - Custom technology (or CMOS) optimized SPAD performance.

- DIGITAL
  - SPAD signal digitized at pixel level.
  - Integrated digital architecture allows data processing on the sensor.
  - CMOS technology with active quenching via a transistor
  - Optimized signal treatment, quenching/reset and processing





SiPM

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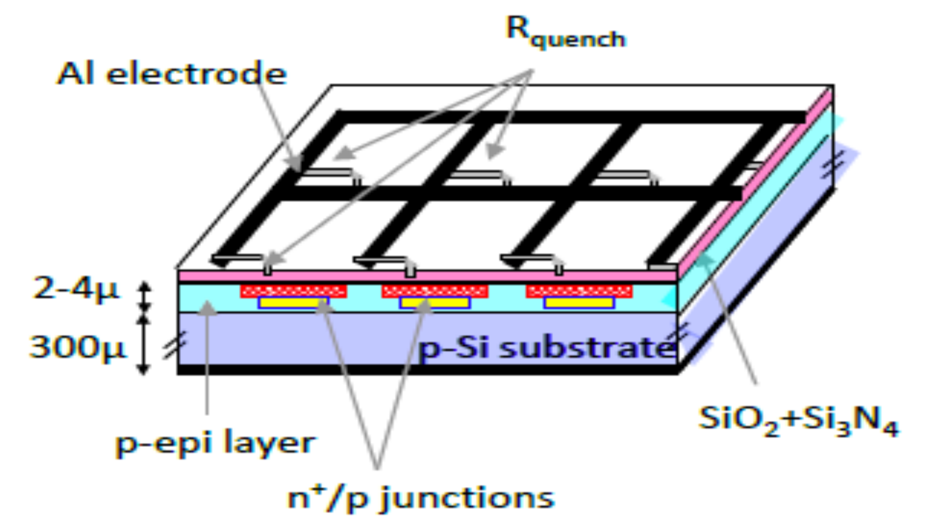

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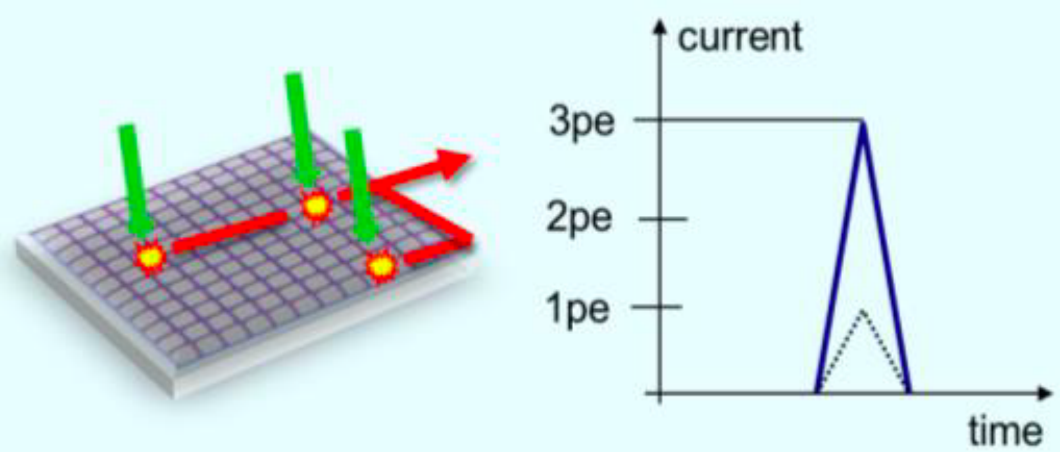
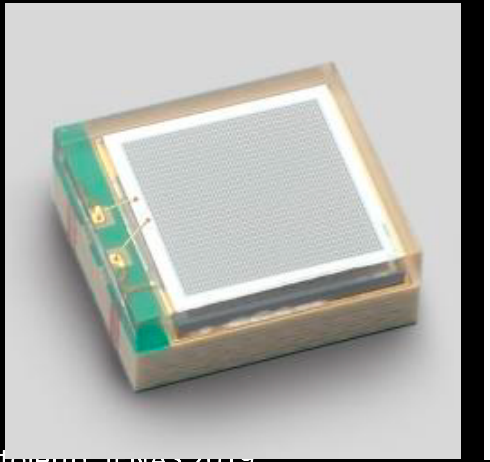
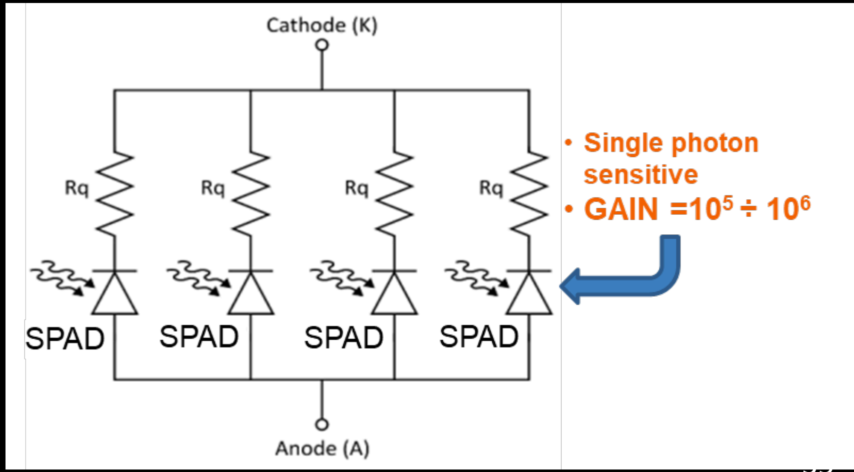
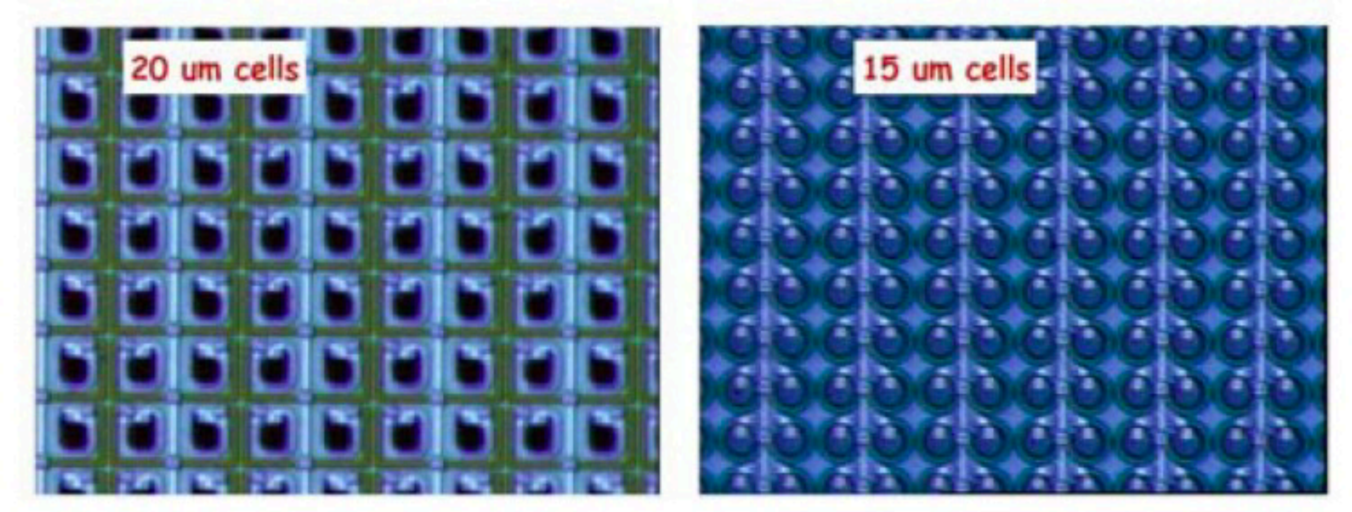




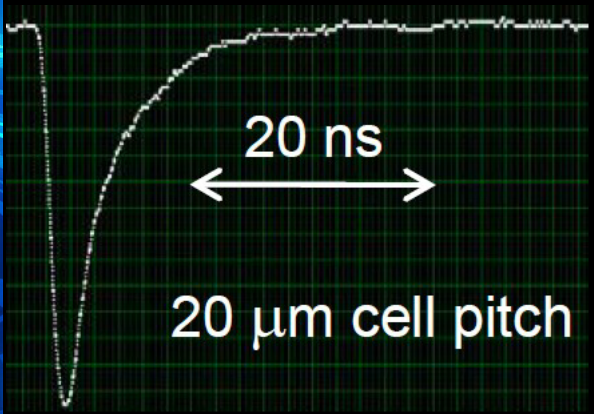


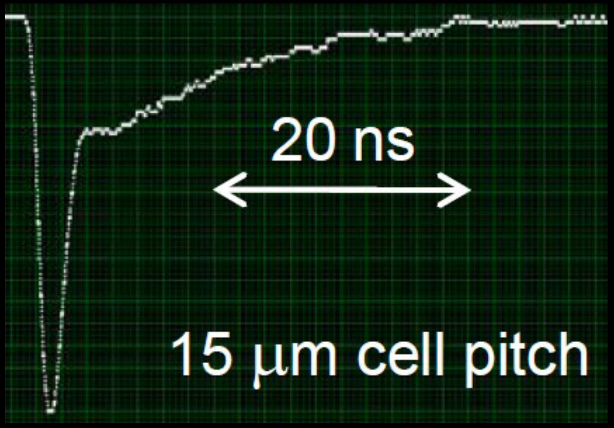
Improvements: smaller cells

- Smaller cells
  - tiny cells (10-15 μm) HPK, FBK, NDL, MPI-LL, …
  - micro cells (few μm) Zecotek, Amplification Techn.

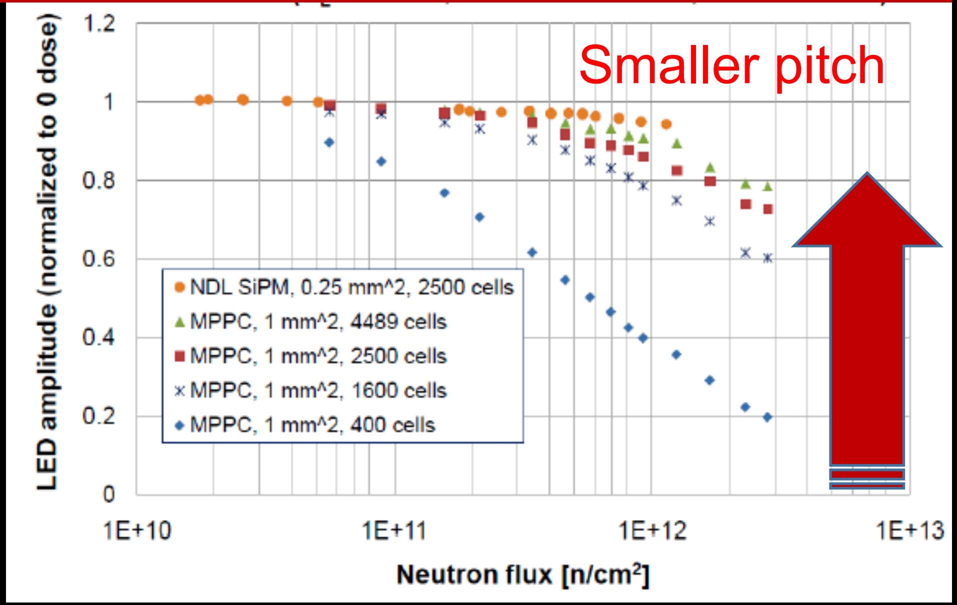


Better timing

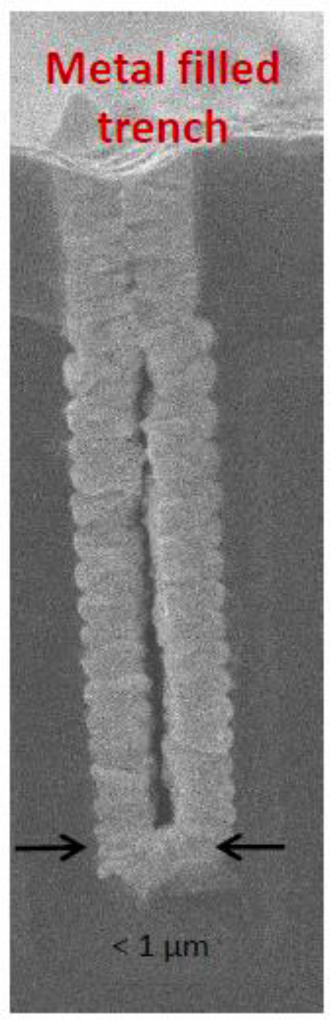




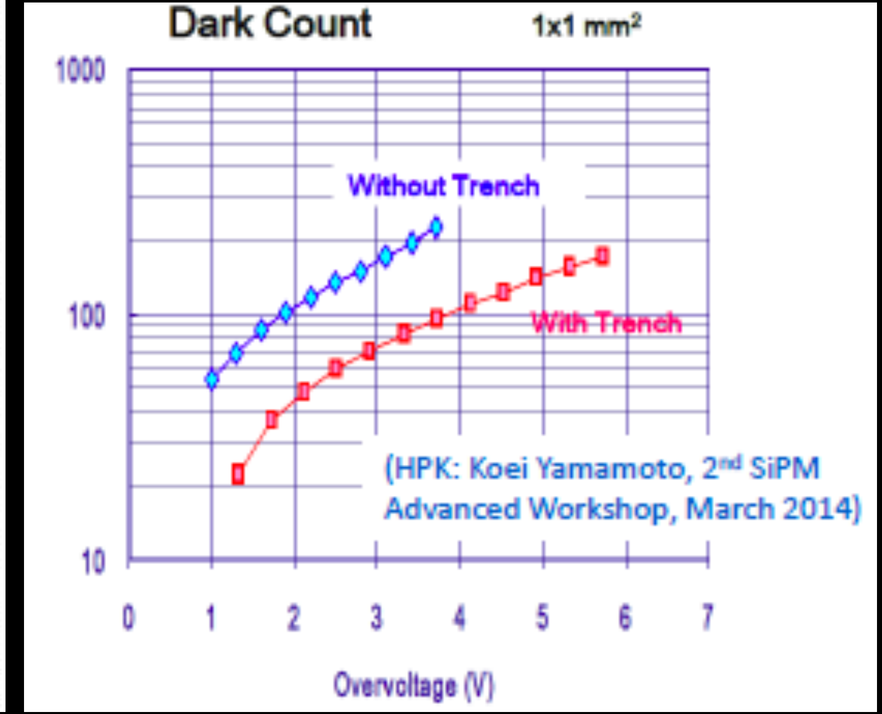
Increased radiation hardness



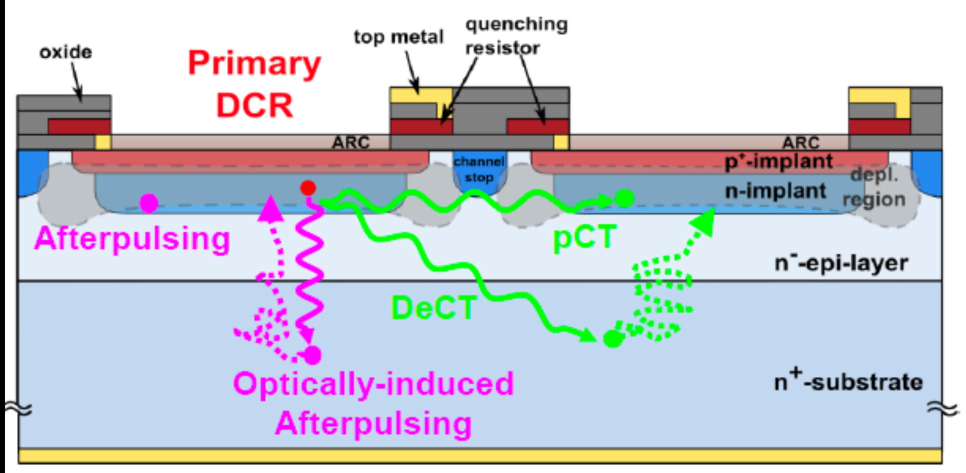
Improvements: Trenches & substrates



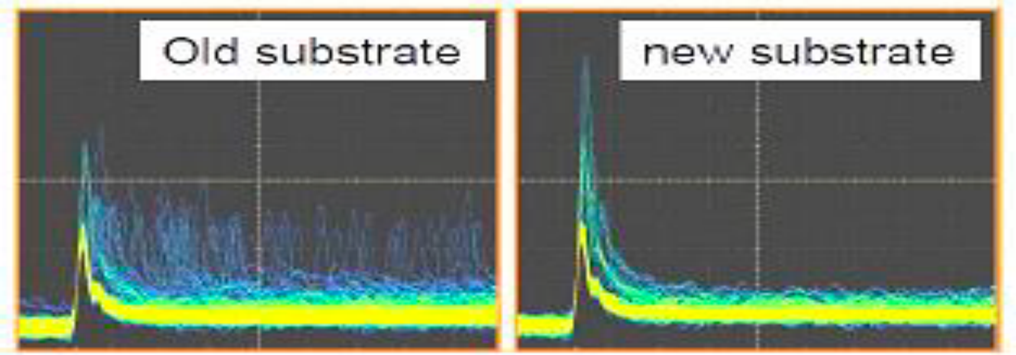
Cross Talk reduction with trench filled with non-transparent material (tungsten)



(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)



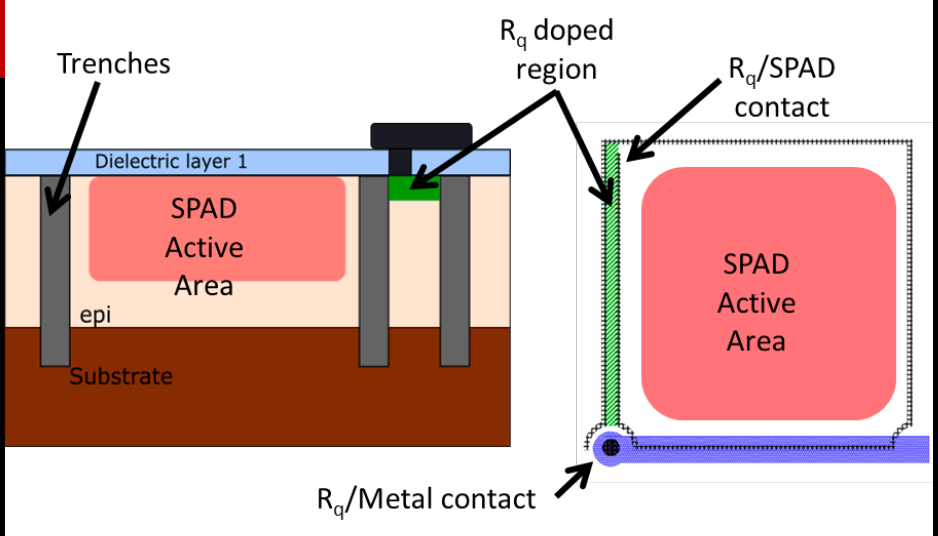
After pulsing and delayed X-talk reduction with improved substrates (minority carrier lifetime reduced x100)

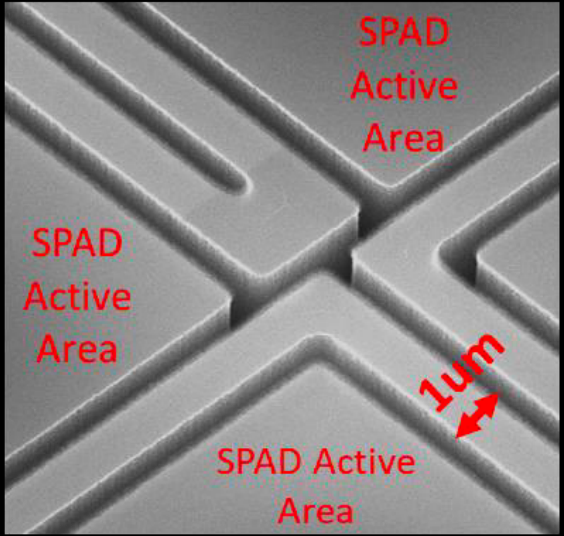


Improved Quenching Technology

- Silicon Resistor (SiR-SiPM): quenching resistor integrated in the silicon substrate by means of a semi-conductive channel

FBK

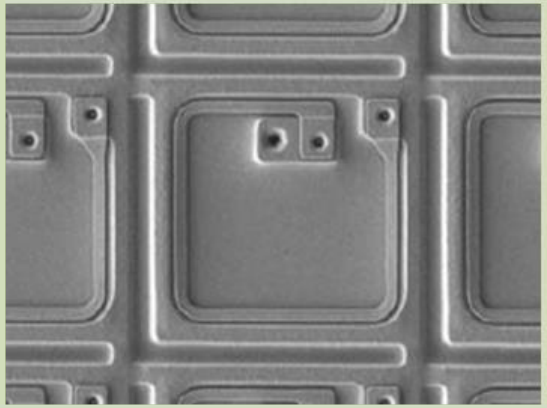




Advantages

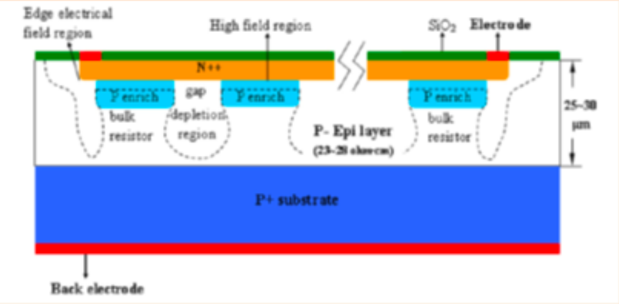
- Simpler, faster, more reliable and cheaper fabrication process (30% less steps, no poly deposition; no Si/Poly contact)
- Significantly reduced R_q dependence on the temperature
- Small FF reduction (from 83% down to 77%)
- ARC is easily customizable (single layer of oxide, no poly, reduced surface morphology)

Thin Metal Film Resistor

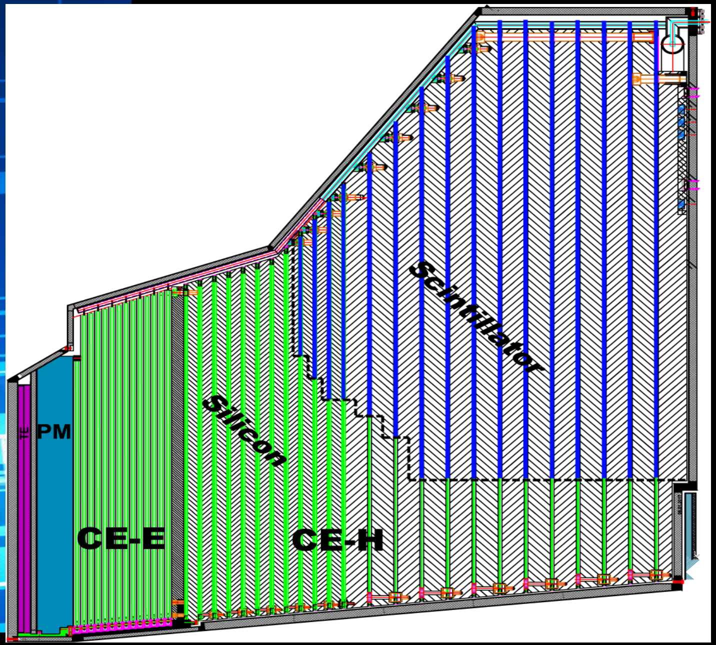


Bulk Silicon Resistor

Max Plank Institute, Beijing Normal University



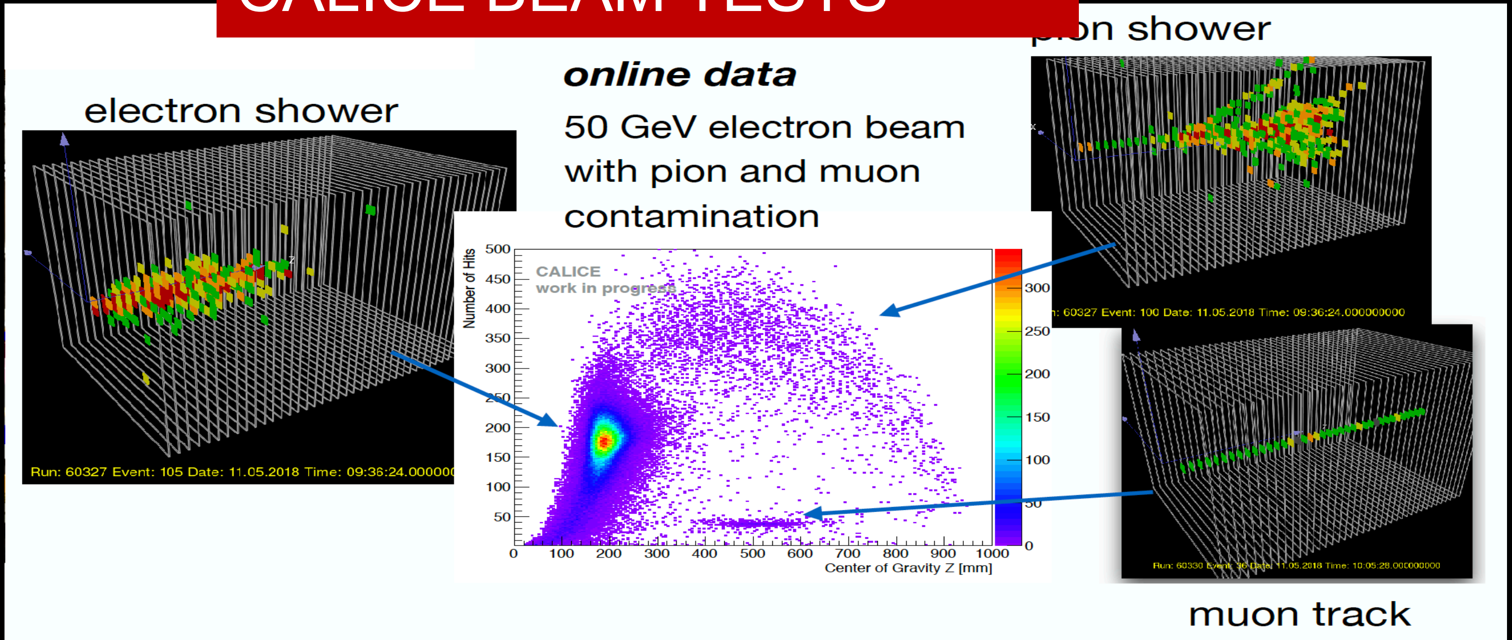
CMS High Granularity Calorimetry

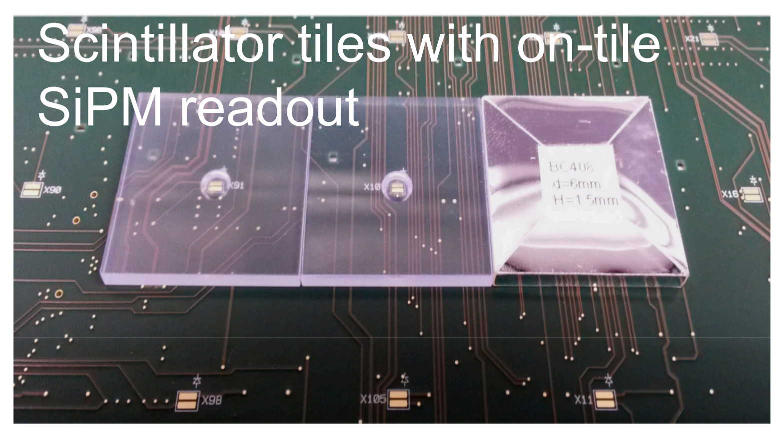


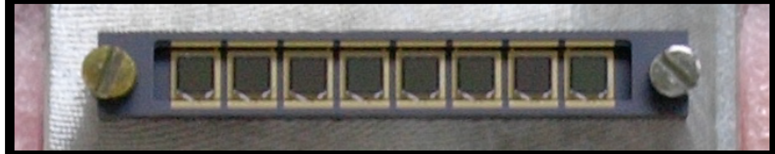
- Silicon in front region: 600 m^2 Si
- SiPM-on-Tile in back: 520 m^2,~ 400k SiPM
- Radiation hard to TID< 3 kGy, Neutron fluence < 8 x10^{13} n$_{eq}$/cm^2

- 16,000 Hamamatsu SiPMs in the phase I upgrade of the CMS hadron calorimeter
- GLUEx at JLAB early adopter of SiPMs for calorimetry

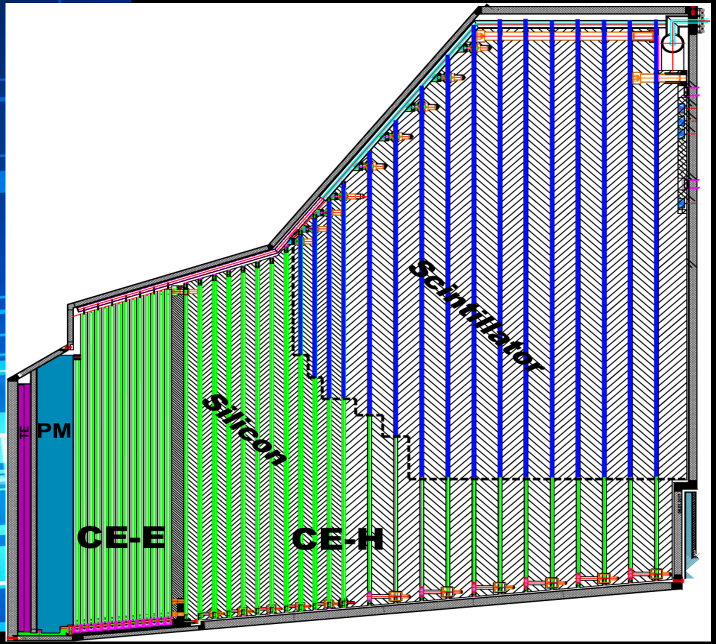
CALICE BEAM TESTS




Scintillator tiles with on-tile SiPM readout


Irradiation program to investigate radiation hardness

CMS High Granularity Calorimetry



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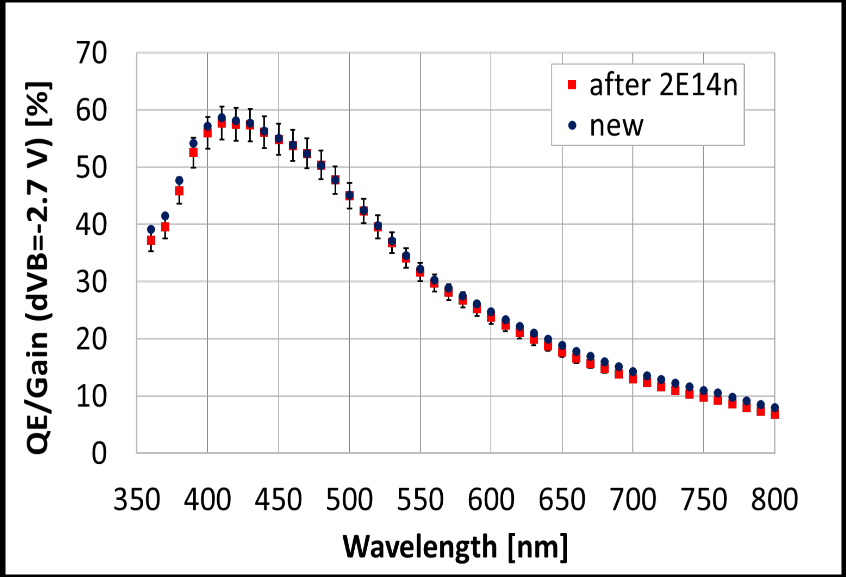
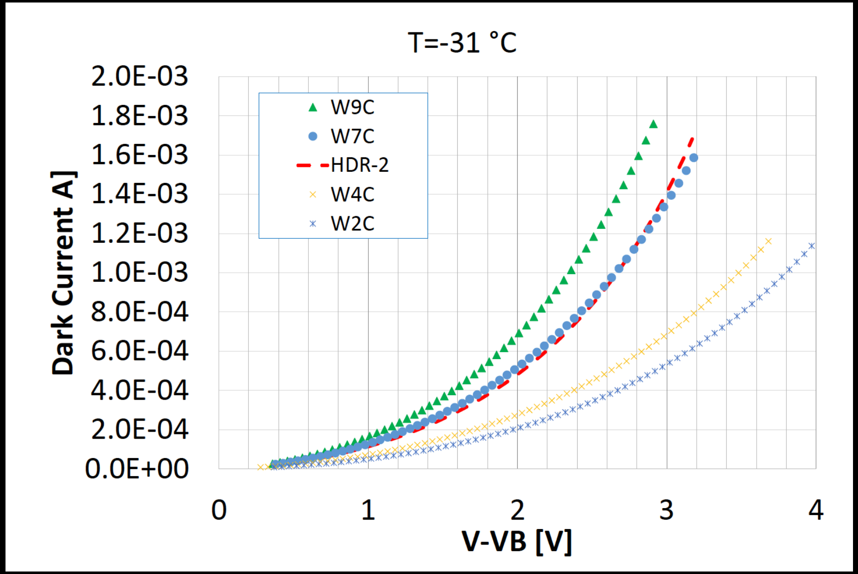


FBK thin epi after 2E14



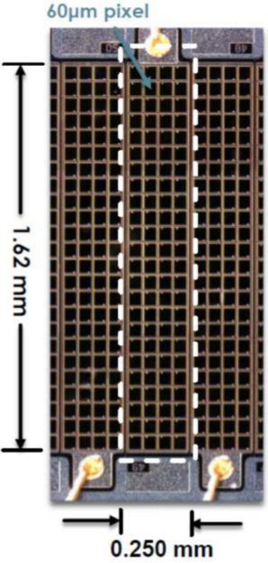
Currents reach 2 mA at 3V over voltage leading to self heating

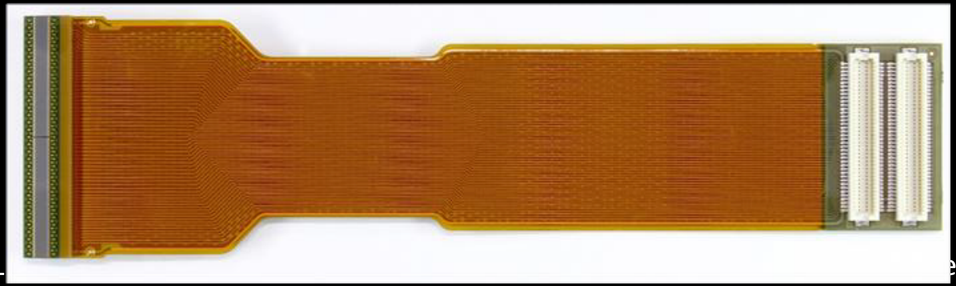
- Other issues:
  - Large Dark Current linear with the fluence
  - Breakdown voltage shift due to change in doping concentration
  - Self heating of the SiPMs due to the large gain
  - Loss of PDE in front p+ layer and/or the protective resins used

Fiber trackers: LHCb

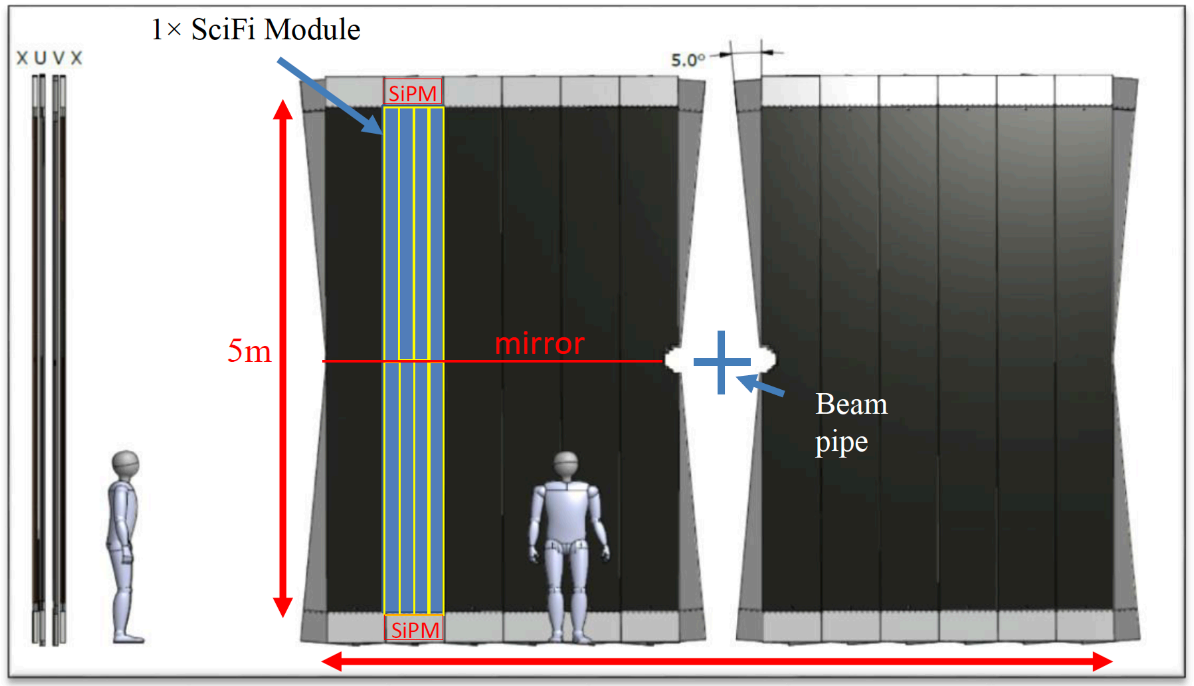
- Under construction for installation in 2020

340 m^2 total area
11,000 km of scintillating fibers (250 µm diameter)
4096 SiPM arrays:
525k SiPM channels





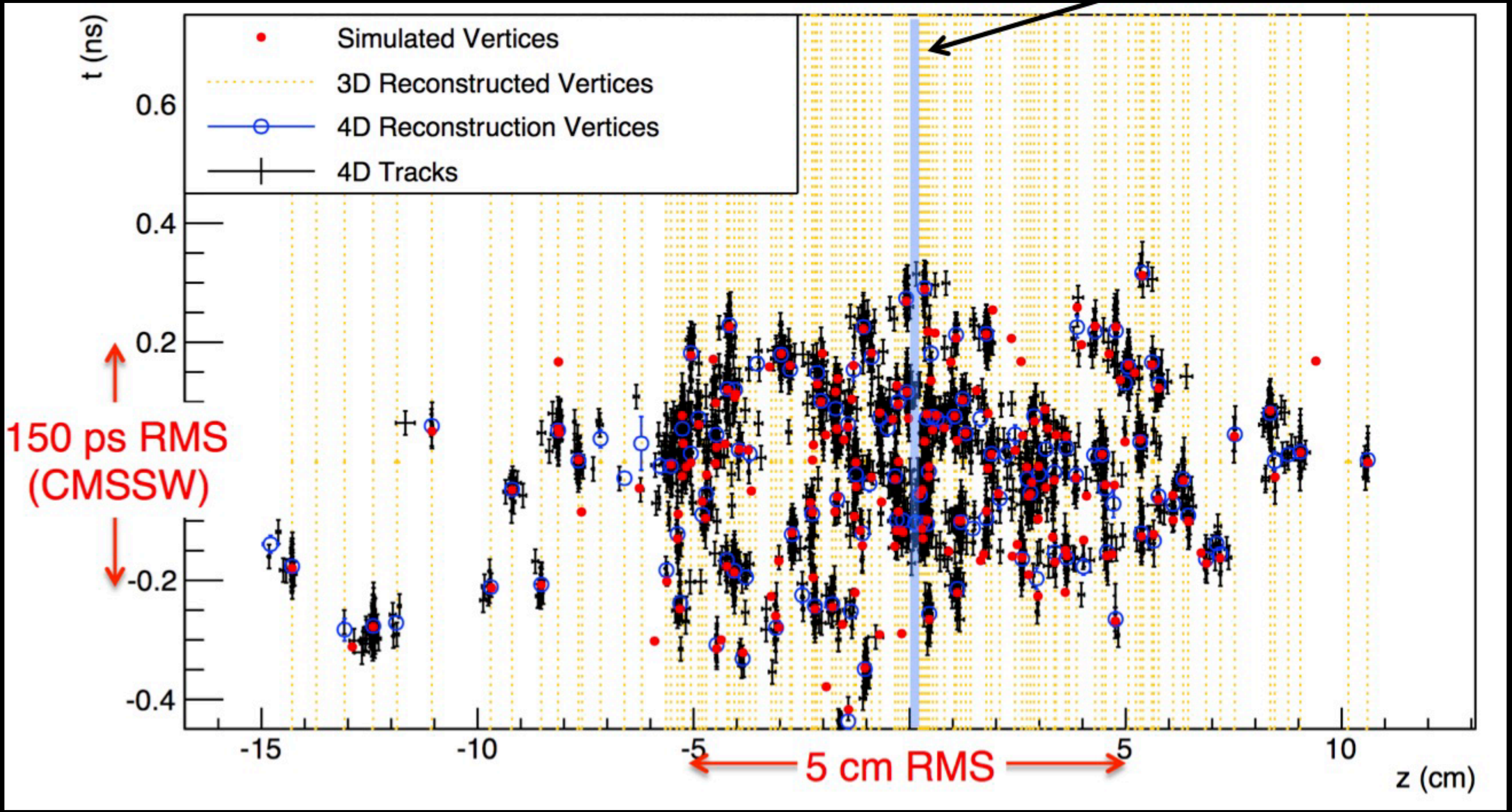
Operated at -40 C to reduce radiation damage induced noise



- SiPMs are glued on 3D printed Titanium bar
- Connection to FE-electronics via Flex-PCB
- 524k SiPM channels in total
- 4096 SiPM arrays

Timing detectors for High-Lumi LHC

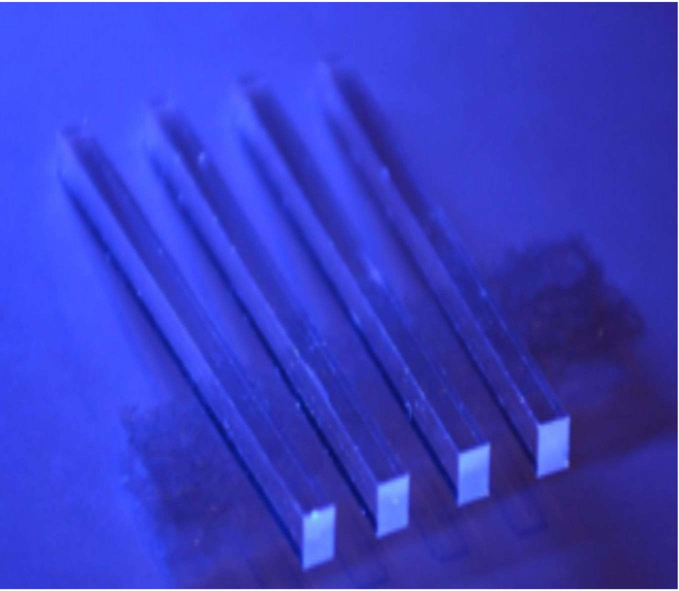
- The goal: Improve association of particles to primary vertices in high-pileup environments
- Requires ~ 30 - 50 ps time resolution to result in a pileup suppression of a factor 4 - 5

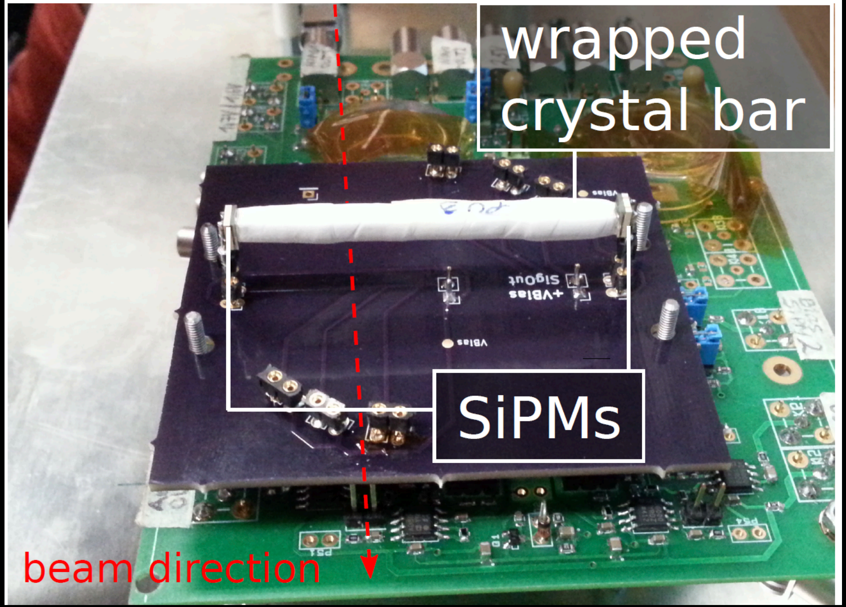


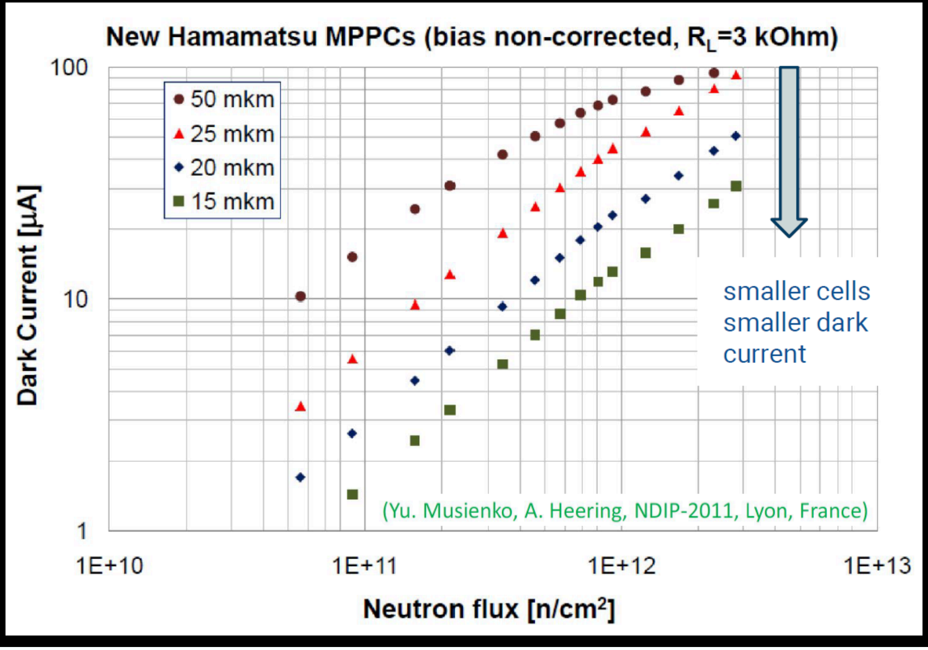
In the barrel region of CMS: 40 m^2 to cover, moderate (for LHC) radiation conditions: ~ 2 x 10^{14} n_{eq}/cm^2 for 4000 fb^{-1}

The CMS Barrel Timing Layer

- The technological solution:
  - LYSO crystals with SiPM readout
  - Excellent radiation hardness, fast (rise time ~ 100 ps) and large signal



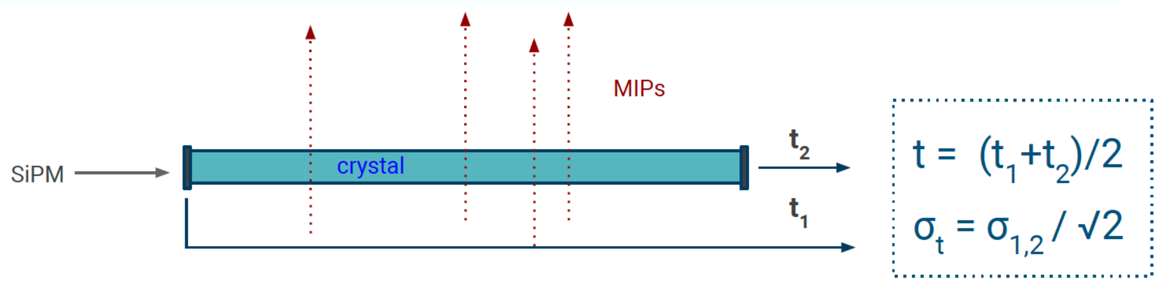




(Yu. Musienko, A. Heering, NDIP-2011, Lyon, France)

Small cell SiPM for high dynamic range and reduced impact of dark rate, large (3x3 mm^2) area for signal amplitude

In test beams: 30 ps achieved

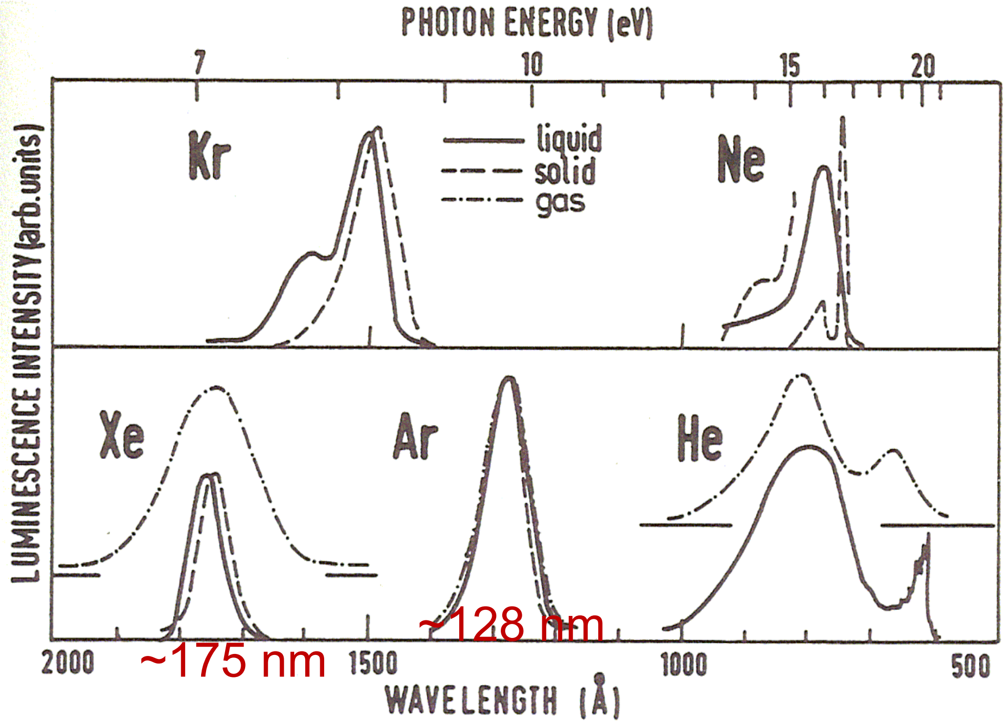


$t = (t_1+t_2)/2$

$\sigma_t = \sigma_{1,2} / \sqrt{2}$

Cryogenic operation of SiPMs

- Several particle detectors use liquified noble gasses as target:
  - Xe = 165 K, LAr = 87 , LNe = 27 K
  - Liquified noble gasses show:
    - Very high light yield O(10 pe/keV)
    - Very high electron lifetime O(10 ms)
- Beam experiments
  - Neutrino Long and Short baseline experiments at FNAL: DUNE/ICARUS
  - MEG/MEG-II
- Low Background experiments
  - Dark Matter detectors: DarkSide-20k, Xenon-nT
  - Double beta detectors: NEXO



- VUV light detection challenges
- Thermal issues
- Low radioactivity content

~175 nm

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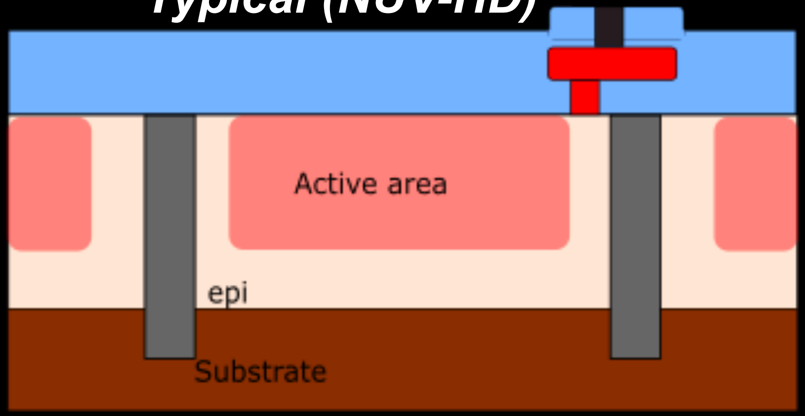
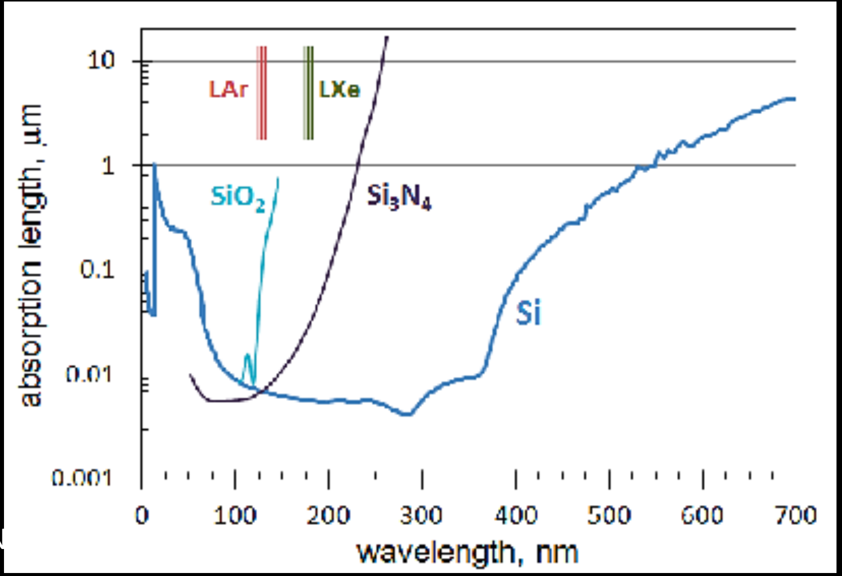
Typical (NUV-HD)



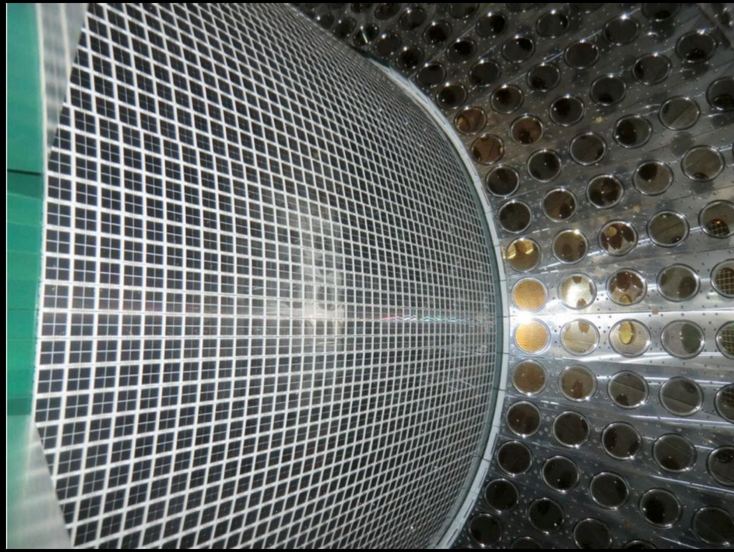
Multi stack of $Si_3N_4$and SiO_2 layers

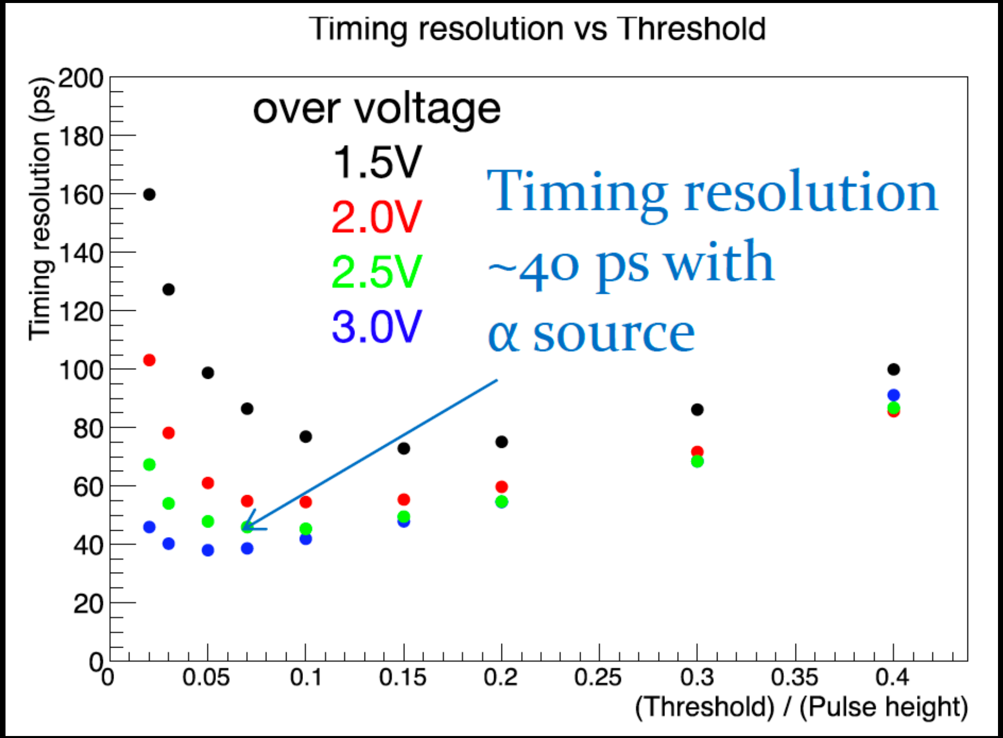
- Anti-Reflective Coating (ARC)
- VUV light can reflect on SiPM and absorbed in the dielectric layers protecting the SiPM



The MEG II LXe calorimeter

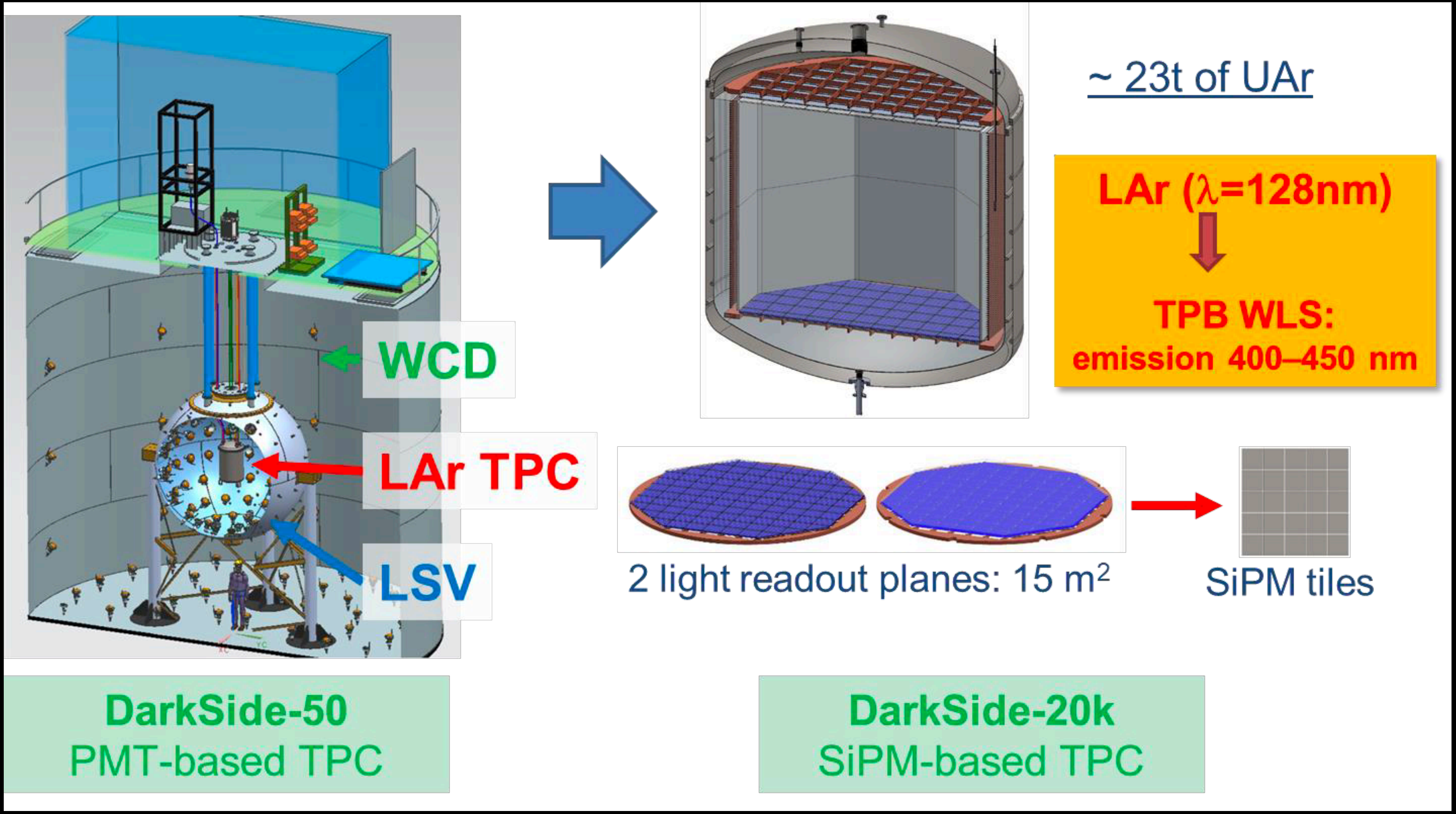
- $\mu \rightarrow e\gamma$ is a flavor violating decay which is forbidden in SM
- PMTs at γ entrance face are replaced with SiPMs
  - Granularity is improved →better position resolution
  - Uniform coverage → better energy resolution
  - reduced material
- Key requirement: VUV sensitive photon detectors (liquid Xe scintillation ~ 174 nm)
  - Bialkali (K-Cs-Sb) photo-cathode,
  - VUV-transparent quartz window
  - Protection layer (resin) is removed • Contact layer thinned down
- Sensitive to VUV light (QE ~15%)
- 4092 discrete arrays of 4 6x6 mm^2 SiPMs developed with Hamamatsu




Timing resolution vs Threshold

Timing resolution ~40 ps with α source

SiPMs in Dark Side


WCD

LAr TPC

LSV

~ 23t of UAr

LAr (λ=128nm)

TPB WLS:
emission 400–450 nm

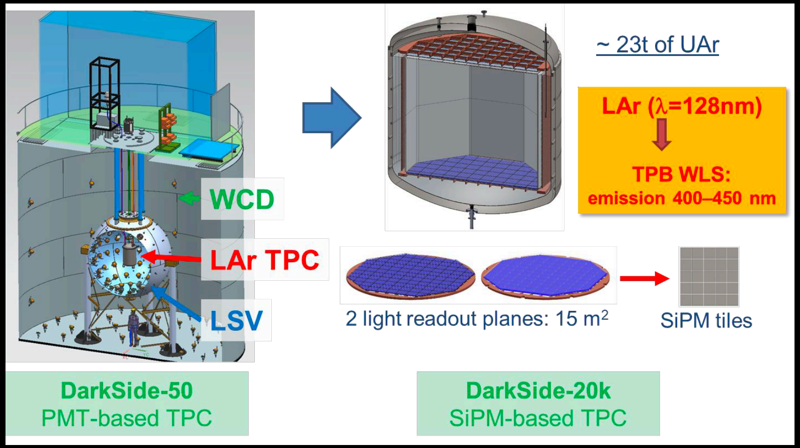
2 light readout planes: 15 m^2

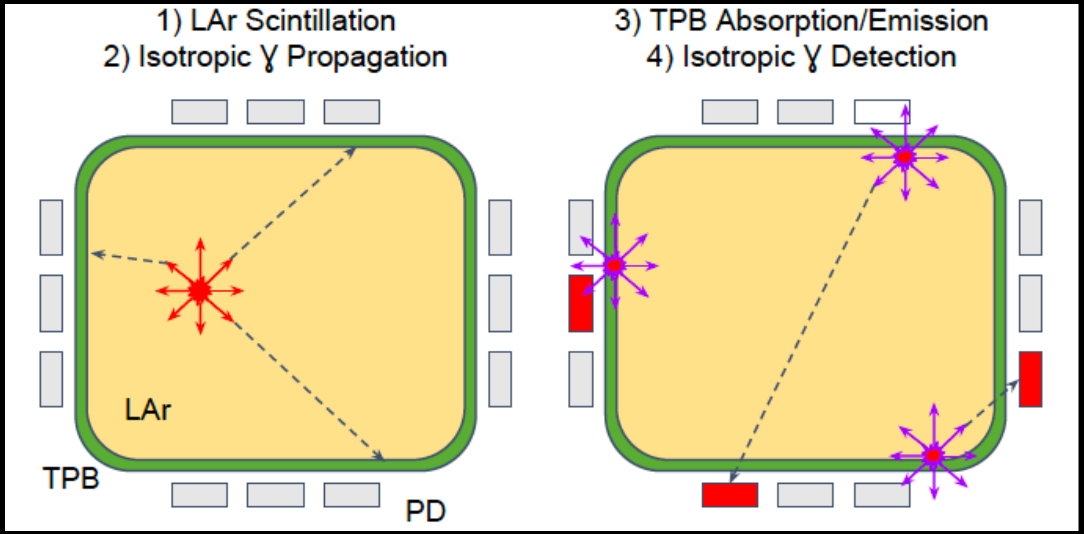
SiPM tiles

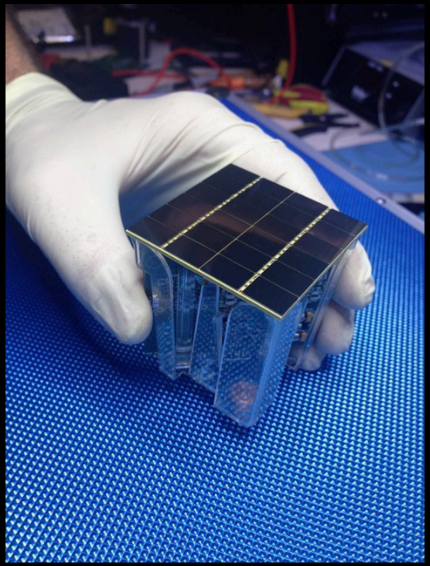
DarkSide-50
PMT-based TPC

DarkSide-20k
SiPM-based TPC

SiPMs in Dark Side

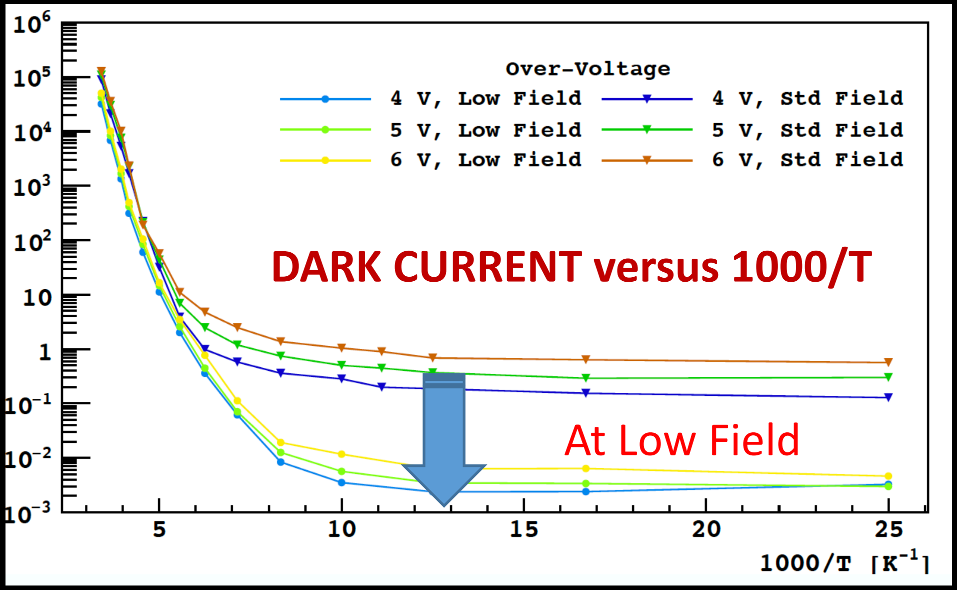






- Higher photo-detection
- efficiency
- Better single photon resolution
- Lower background
- Lower cost
- High dark rate
- Requires electronic development to combine SiPMs and reduced preamps etc

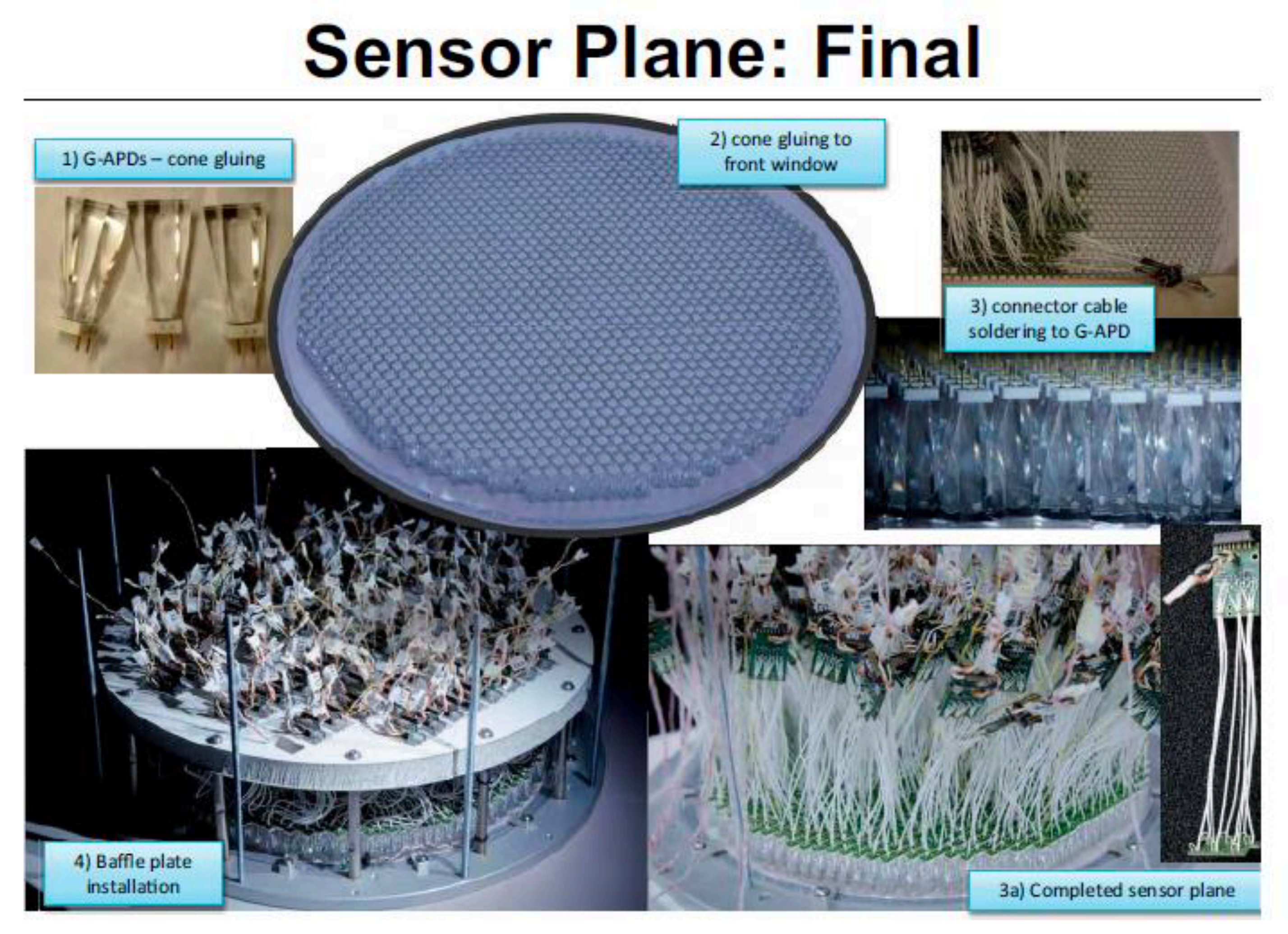
FBK NUV-HD low field PDE at 300 K



Technology transfer between FBK and LFOUNDRY

IACT using SiPMs

- FACT telescope camera
- 1440-pixel MPPC



Sensor Plane: Final

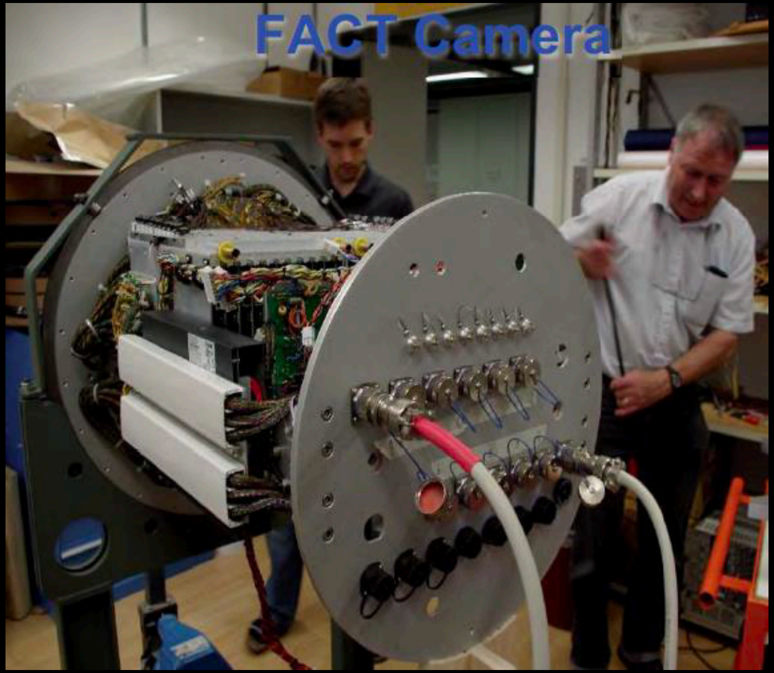
1) G-APDs – cone gluing

2) cone gluing to front window

3) connector cable soldering to G-APD

3a) Completed sensor plane

4) Baffle plate installation



- Keep gain of the SiPMs constant despite temperature larger T variation (>25 C).
- Implementation of a feedback system that adjusts the applied voltage to the sensor temperature and current drawn

SiPMs in CTA

CTA SSTs are using SiPM

Small size telescopes

SST 1M **ASTRI** **GCT**

Science drivers

Highest energies (> 5 TeV)
Galactic science, PeVatrons

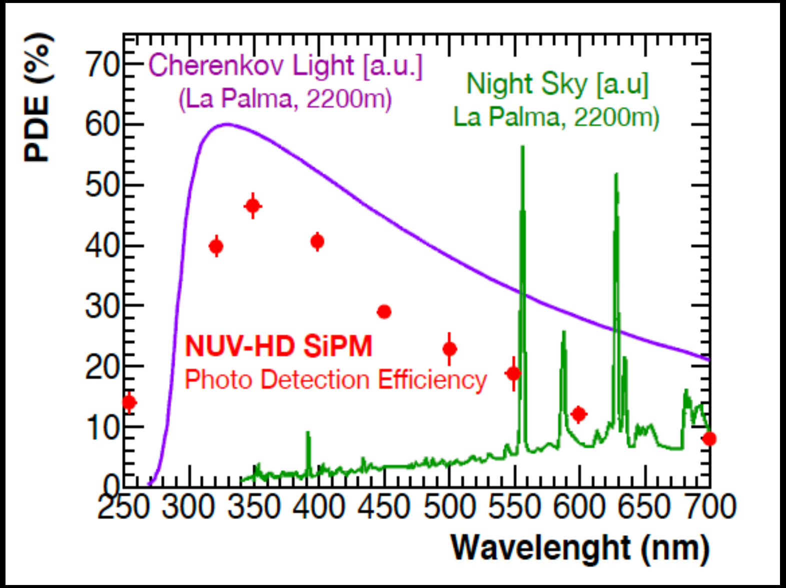
Array layout

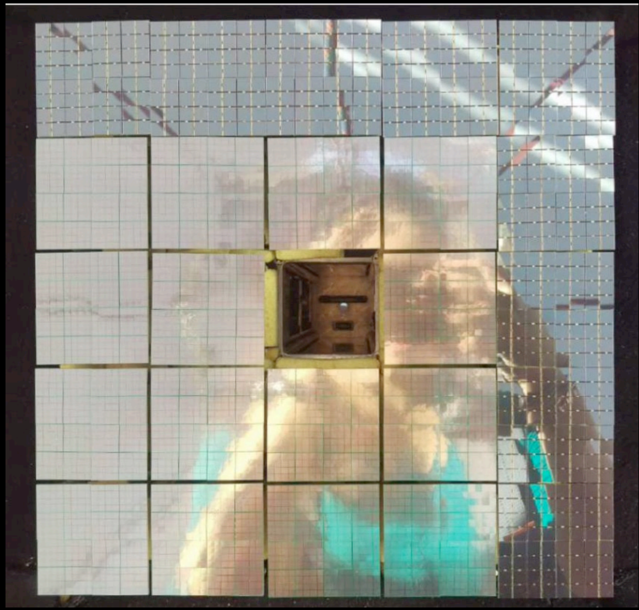
South site: 70 SST
North site: -

- Smaller areas (SiPM <1cm^2), hence higher pixel angular resolution
- Higher photo-detection efficiency at UV wavelengths (c.a. 50%)
- Fast response O(1-10) ns
- Not damaged by moonlight, can be operated during bright Moon nights enhancing the DAQ duty cycles
- Can be operated with bias voltages <100V
- Low power consumption (μW)
- Light-weight
- Noisy, dark count rates O(10-100) KHz/mm^2 at room temperature, but below the expected average night sky background.

SiPMs for CTA

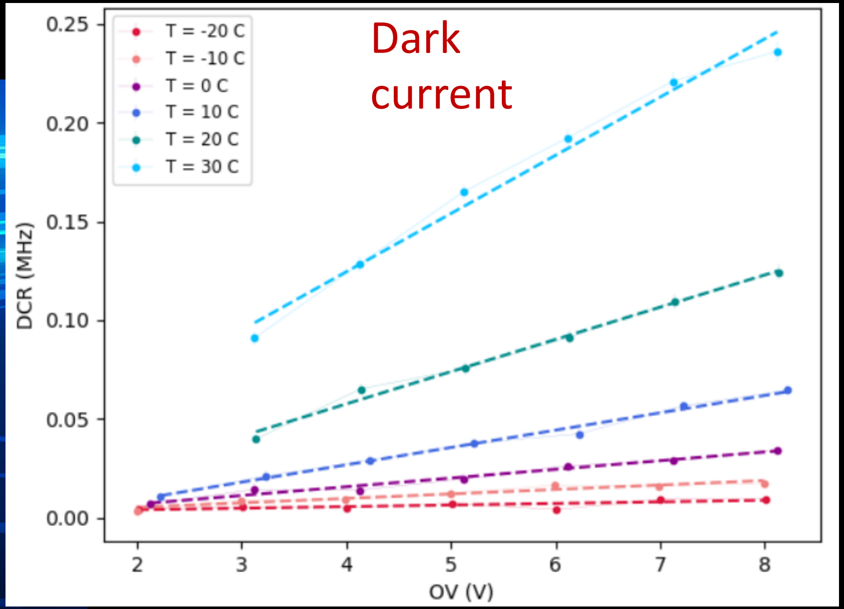
- Produced at FBK (Trento, IT)
- p-n SiPM
- Active area: 6.03 x 6.06 mm^2 with 30 x 30 μm^2 Microcells
- Fill Factor: 76%
- High PDE (50%) for UV photons
- NUV-HD technology successful, further improvements are ongoing



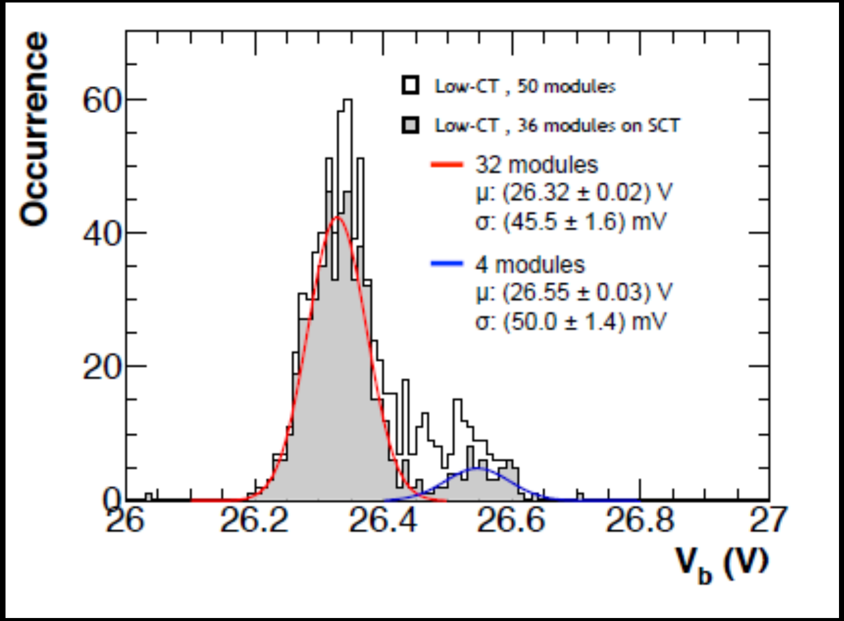


PSCT camera

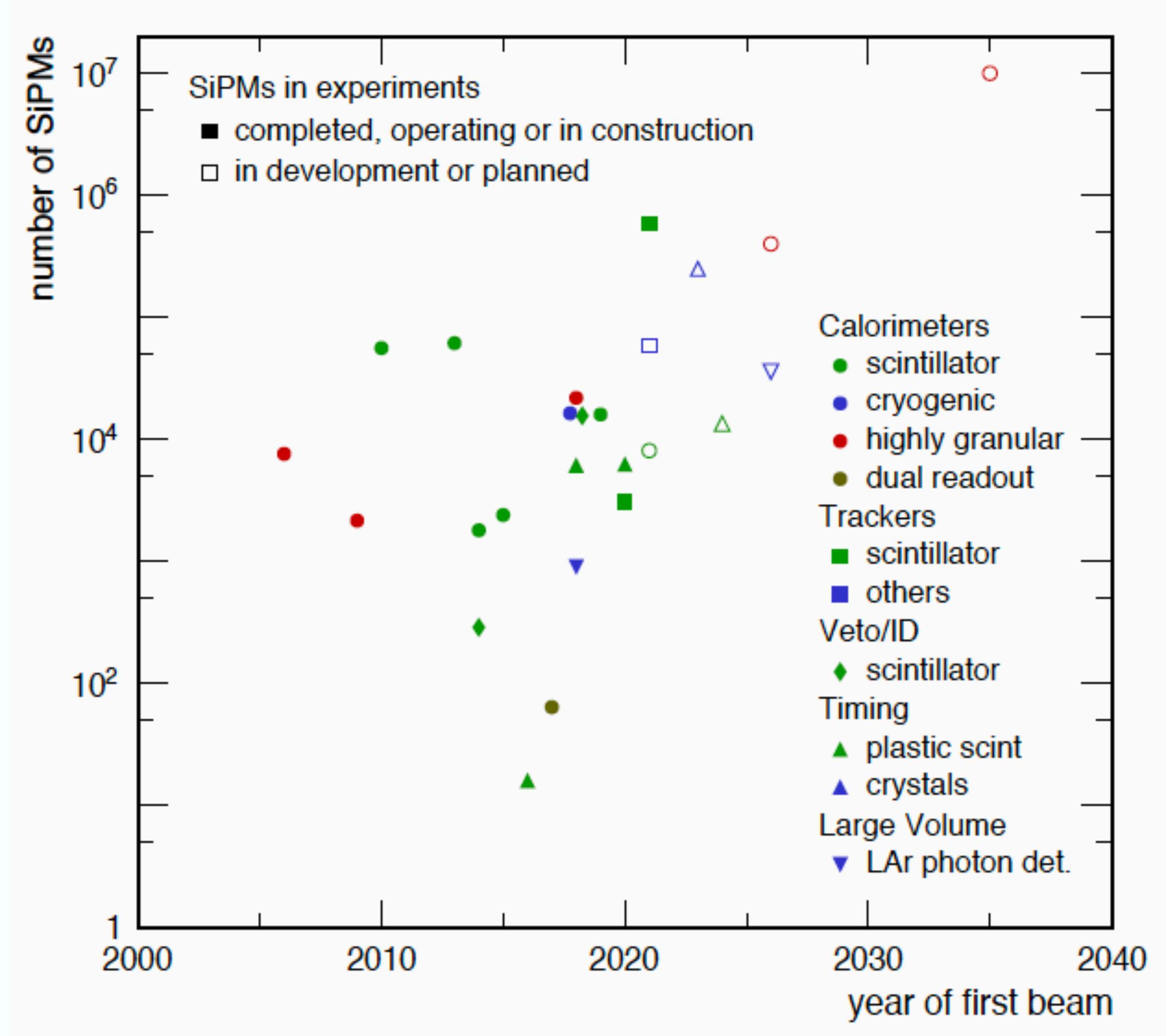
- 15+1 HAMAMATSU modules
- 9 FBK modules (top and right)
- Central module removed to allocate a alignment module for the telescope pointing procedure
- First light on Jan 23 2019

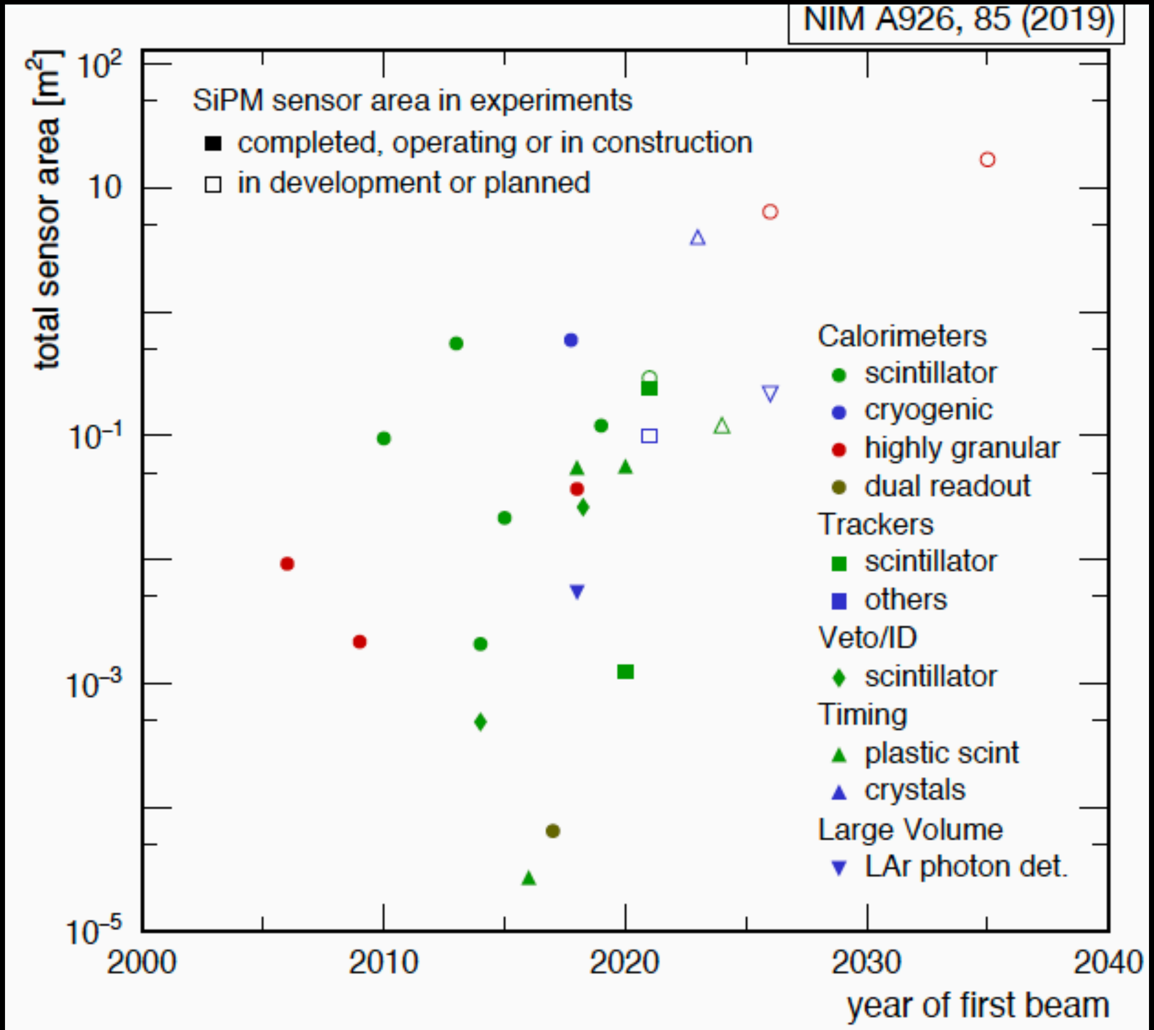


Dark current



Evolution of SiPM-based Systems




NIM A926, 85 (2019)

Conclusions

- Amazing advances in technology
- R&D is still required to achieve the ultimate performance needed for future projects:
  - Radiation hardness
  - Lower cross talk
  - Noiseless amplification
  - 100 % photon detection efficiency (PDE) over a wider range of wavelength
  - no degradation in lifetime
  - Readout and mechanical support
- ECFA, APPEC and NuPECC are interested in similar photodetectors at least for some applications.
- Cooperation will facilitate improved interactions with companies and accelerate progress

JENAS-2019
Joint ECFA-NuPECC-ApPEC Seminar
jointly organized by LAL, IPNO, IRFU and LPNHE

October 14-16, 2019
Auditorium Pierre Lehmann, bât. 200, Faculté d'Orsay

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