# The EIC project at BNL

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Assemblea di Sezione, INFN Bologna
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**afferenti sigla EIC_NET Bologna, incluse sinergie progetti MAECI_EIC e AIDA innova (2.65 FTE)**

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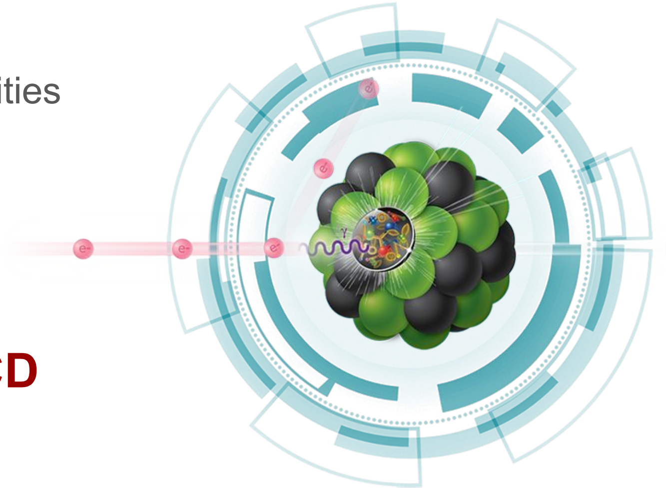
# The Electron-Ion Collider

**a machine that will unlock the secrets of the strongest force in Nature**

is a future electron-proton and electron-ion collider to be constructed
in the United States in this decade and foreseen to start operation in 2030

- **EIC constitutes the major US project in the field of nuclear physics**
  - and will surely be one of the most important scientific facilities for the future of nuclear and subnuclear physics
- **EIC will be the world's first collider for**
  - polarised electron-proton (and light ions)
  - electron-nucleus collisions
- **EIC will allow one to explore the secrets of QCD**
  - understand the origin of mass and spin of the nucleons
  - provide extraordinary 3D images of the nuclear structure

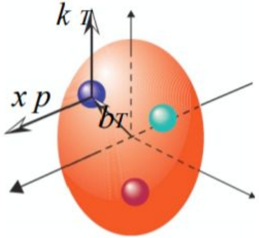


# The Physics of EIC

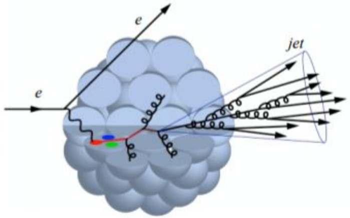
**is precision QCD Physics**

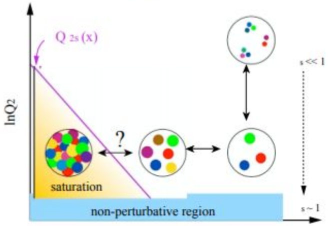
investigate universal dynamics of gluons

understand the emergence of hadronic matter and its properties




- **how are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?**
  - how do the nucleon properties emerge from them and their interactions?
- **how do colour-charged quarks and gluons, and colorless jets, interact with a nuclear medium?**
  - how do confined hadronic states emerge from these quarks and gluons?
  - how do the quark-gluon interactions create nuclear binding?
- **what happens to the exploding gluon density at low-x in hadronic matter?**
  - does it saturate at high energy, giving rise to a gluonic matter with universal properties?




**The Electron-Ion Collider aim is to <u>answer central questions in QCD</u> Physics**

**project formally approved!**

Department of Energy

# U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020


Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics

**WASHINGTON, D.C.** – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an

Secretary Brouillette approved Critical Decision-0, "Approve Mission Need," for the EIC on December 19, 2019.

accelerator technology, critical components of overall U.S. leadership in science," said **U.S.**

project formally approved!

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## Electron-Ion Collider Achieves Critical Decision 1 Approval

CD-1 milestone marks start of project execution phase for next-generation nuclear physics facility that will probe the smallest building blocks of visible matter

July 6, 2021

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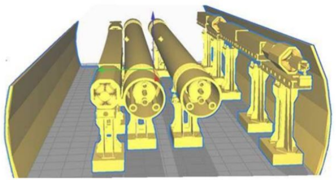
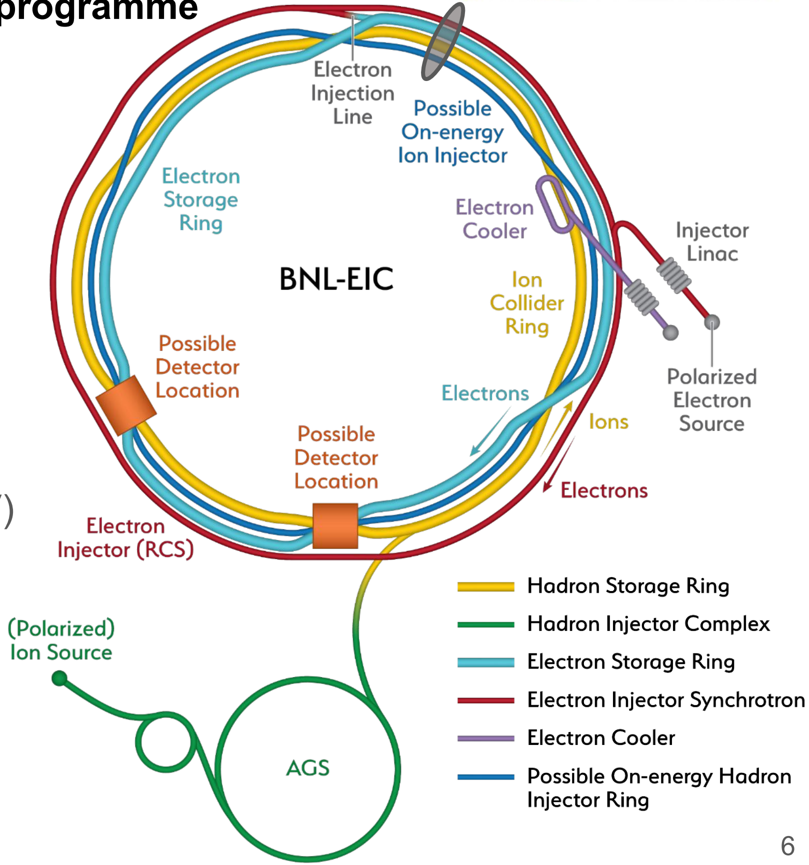
# Accelerator overview



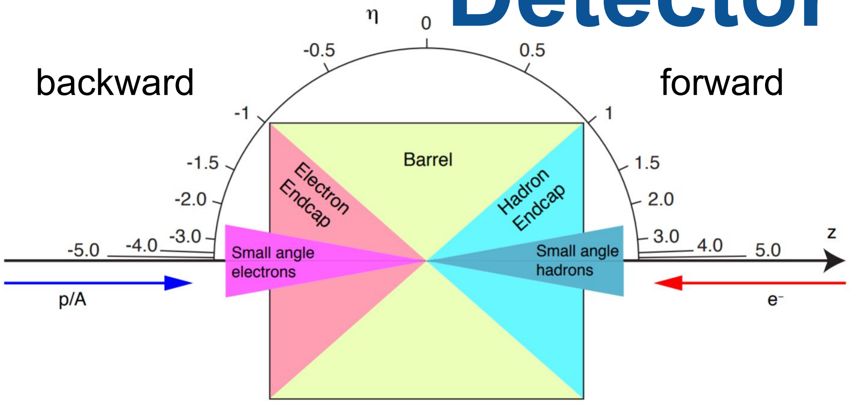
| | |
|---|---|
| √s | 20 – 141 GeV |
| $\mathcal{L}_{max}$ | $10^{34}$ $cm^{-2}$ $s^{-1}$ |
| $P(e^-)$ | 80% |
| P(h) | 80% |
| A | p – U |

**BNL-EIC satisfies the requirements**
**to fulfill the rich physics programme**




- **design using much of the RICH facility**
  - three accelerator rings
    - existing RHIC ring (275 GeV)
    - new Rapid Cycling Electron Synchrotron (18 GeV)
    - new Electron Storage Ring (18 GeV)
  - two injector complexes
    - existing Hadron Injectors
    - new Electron Injectors
  - two detector halls
  - hadron cooling facility

# Detector requirements




**main challenges**
**forward PID**
**EM cal at < 2% / √E %**

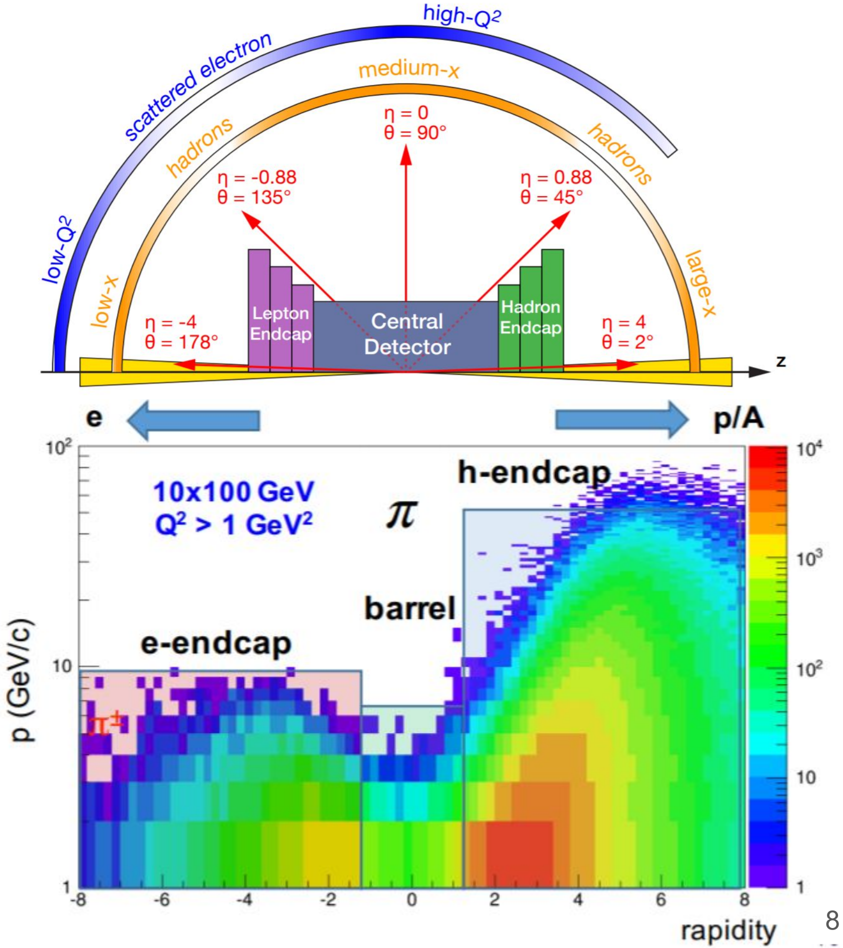
- **hermetic detector**
  - with low-mass inner tracker
  - moderate radiation hardness
- **good momentum resolution**
  - central: $\sigma_p/p = 0.05 \oplus 0.5$ %
  - forward: $\sigma_p/p = 0.1 \oplus 0.5$ %
- **and impact parameter resolution**
  - $\sigma = 5 \oplus 15 / p \sin^{3/2}$ μm
- **electron and jets**
  - $-4 < \eta < 4$

- **excellent EM resolution**
  - central: $\sigma_E/E = 10 / \sqrt{E}$ %
  - ⇨ backward: $\sigma_E/E < 2 / \sqrt{E}$ %
- **good hadronic energy resolution**
  - forward: $\sigma_E/E \approx 50 / \sqrt{E}$ %
- **excellent PID for π, K, p**
  - ⇨ forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c

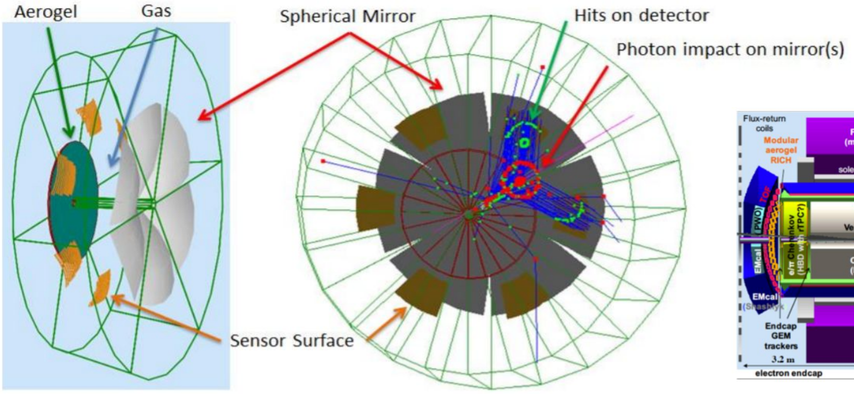
# Particle identification at EIC

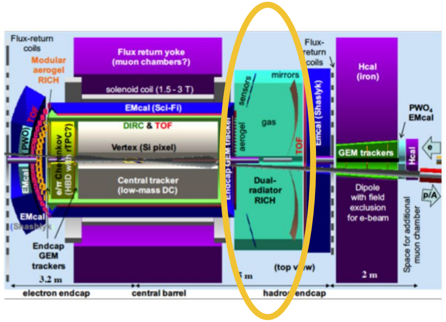
**one of the major challenges for the detectors**

- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range |η| ≤ 3.5
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands different technologies**



# dRICH proposal for forward PID

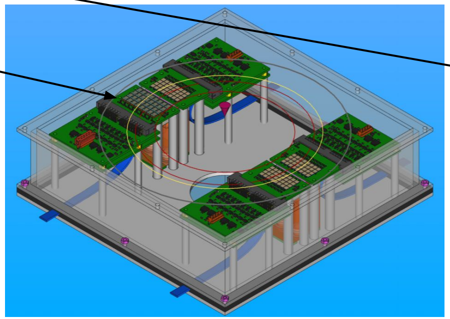


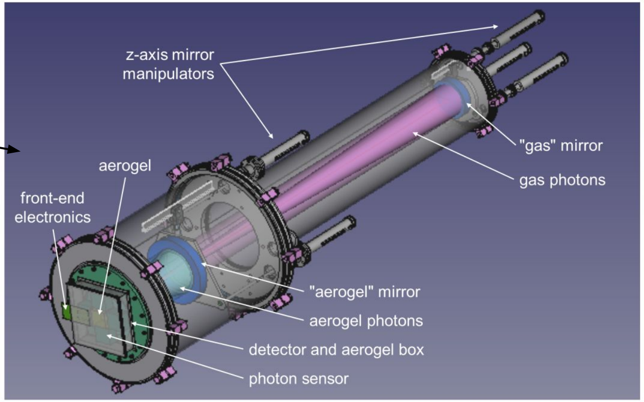




- **dual-radiator RICH (dRICH)**
  - aerogel (n ~ 1.02) + gas (n ~ 1.0008)
  - for PID in the hadronic endcap
    - $3 < p < 50$ GeV/c
    - $1.5 < \eta < 3.5$
  - 6 sectors x 0.5 m$^2$/sector photosensors
    - ~ 1 T magnetic field
    - sensors out of acceptance

**explore SiPM readout option**

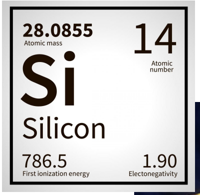
- **realisation of dRICH prototype, test beams**
  - design of electronics boards
  - SiPM studies
    - irradiation tests (@ Trento)
    - annealing at high T ~ 170°
    - operation at low T ~ −40°
  - DAQ for front-end readout
    - front-end based on ALCOR





# SiPM option for RICH optical readout

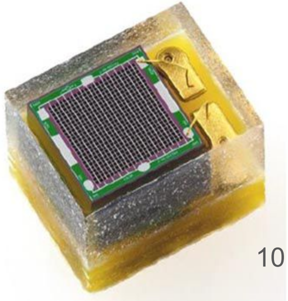
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field



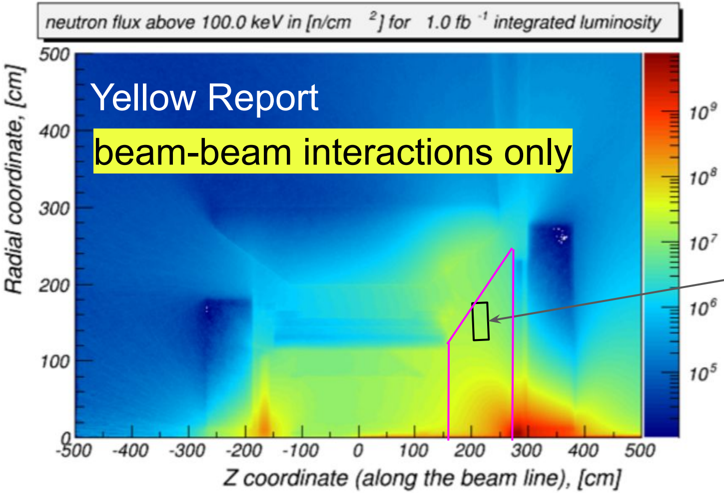

- **cons**

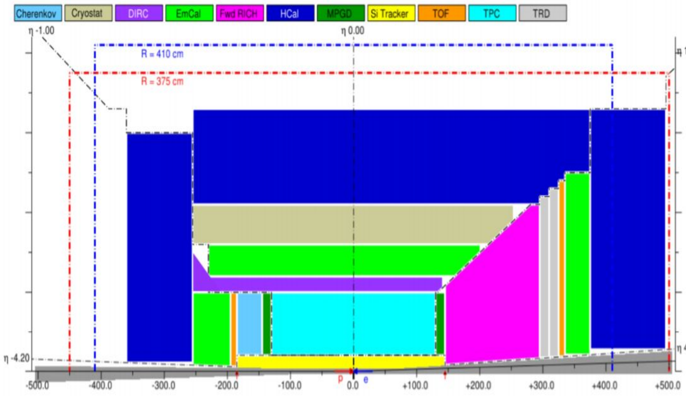
  large dark count rates

  not radiation tolerant



# Neutron fluxes and SiPM radiation damage




Most of the key physics topics discussed in the EIC White Paper [2] are achievable with an integrated luminosity of 10 $\text{fb}^{-1}$ corresponding to 30 weeks of operations. One notable exception is studying the spatial distributions of quarks and gluons in the proton with polarized beams. These measurements require an integrated luminosity of up to 100 $\text{fb}^{-1}$ and would therefore benefit from an increased luminosity of $10^{34}\text{cm}^{-2}\ \text{sec}^{-1}$.

possible location of dRICH photosensors
neutron fluence for 1 $\text{fb}^{-1}$ → 1-5 $10^7$ n/cm$^2$ (> 100 keV ~ 1 MeV $n_{eq}$)

- radiation level is moderate
- magnetic field is high(ish)

R&D on SiPM as potential photodetector for dRICH, main goal
**study SiPM usability for Cherenkov up to $10^{11}$ 1-MeV $n_{eq}$/cm$^2$**

notice that $10^{11}$ $n_{eq}$/cm$^2$ would correspond to 2000-10000 $\text{fb}^{-1}$ integrated $\mathscr{L}$
quite a long time of EIC running before we reach there, if ever
it would be between 6-30 years of continuous running at $\mathscr{L} = 10^{34}\ \text{s}^{-1}\ \text{cm}^{-2}$

→ better do study in smaller steps of radiation load

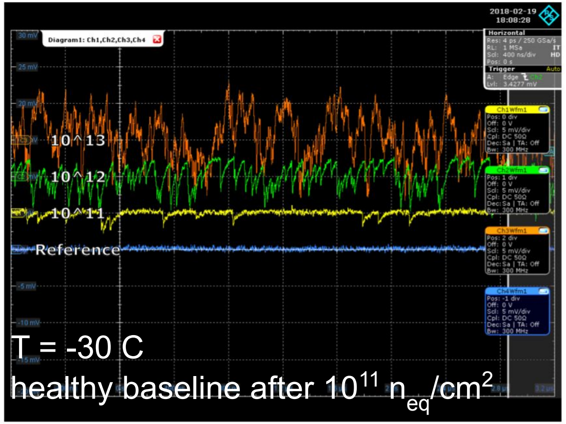
| | |
|---|---|
| $10^9$ 1-MeV $n_{eq}$/cm$^2$ | *most of the key physics topics* |
| $10^{10}$ 1-MeV $n_{eq}$/cm$^2$ | *should cover most demanding measurements* |
| $10^{11}$ 1-MeV $n_{eq}$/cm$^2$ | *possibly never reached* |

# SiPM radiation damage and mitigation strategies

Radiation damages increase currents, affects $V_{bd}$ and increase DCR
With very high radiation loads can bring to baseline loss, but…
**does not seem to be a problem up to $10^{11}$ $n_{eq}/cm^2$ (if cooled, T = -30 C)**

*Calvi, NIM A 922 (2019) 243*

$10^{11}$




If the baseline is healthy, single-photon signals can be be detected one can work on reducing the DCR with following mitigation strategies:

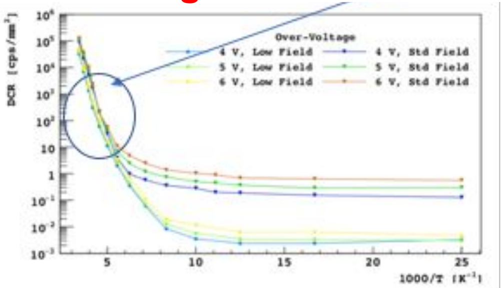
- Reduce operating temperatures (**cooling**)
- Use **timing**
- High-temperature **annealing** cycles

Key point for R&D on RICH optical readout with SiPM:

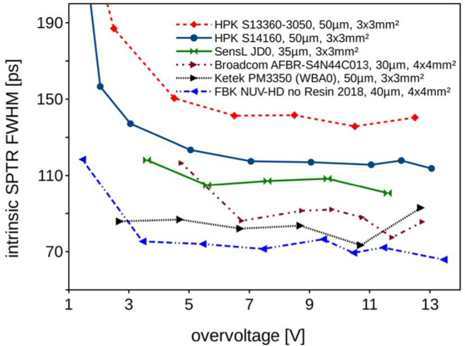
- demonstrate capacity to measure Single Photon
- keep DCR under control (ring imaging background)

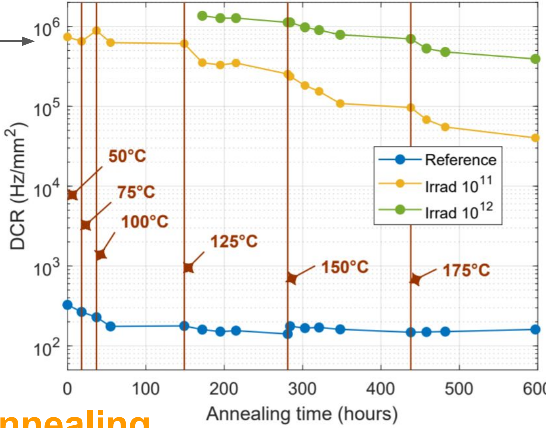
despite radiation damages

**cooling**




**timing**




20x less DCR

**annealing**

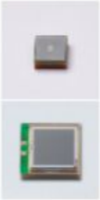
# where we are

*Garutti et al*: “Due to the increased DCR, the single photoelectron separation from noise is lost already at relatively low fluences $\Phi_{eq}$ ~ $10^{10}$ cm$^{-2}$. This limit depends on many factors related to the SiPM design and the operation conditions, so <u>it should be tested for each specific application.</u>“

this is what we are doing for the dRICH SiPM option

- **acquired multiple SiPM samples**
  - from different manufacturers
  - and of different types
- **developed electronic boards**
  - SiPM carrier boards
  - adapter boards
  - ASIC readout board
- **first irradiation campaign**
  - FBK prototypes
  - Hamamatsu sensors
  - NIEL: ~ $10^8$ $10^9$ $10^{10}$ and $10^{11}$
- **high-temperature annealing**
  - Hamamatsu up to T = 150 C
  - FBK up to T = 125 C
- **characterisation and operation**
  - I-V characteristics
  - DCR and signal sampling
  - low temperature operation
  - with ALCOR ASIC readout

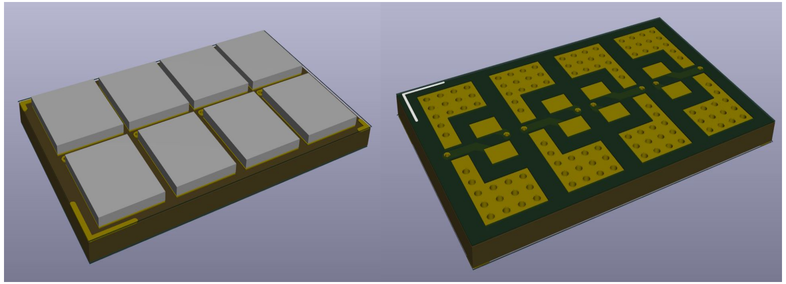
# Commercial SiPM sensors

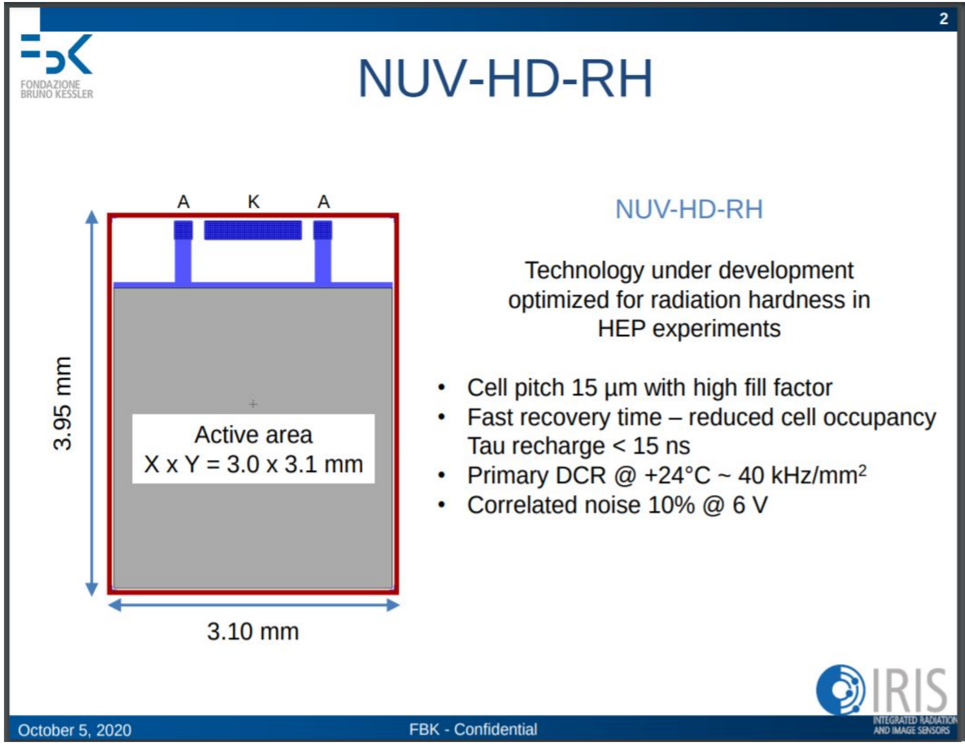


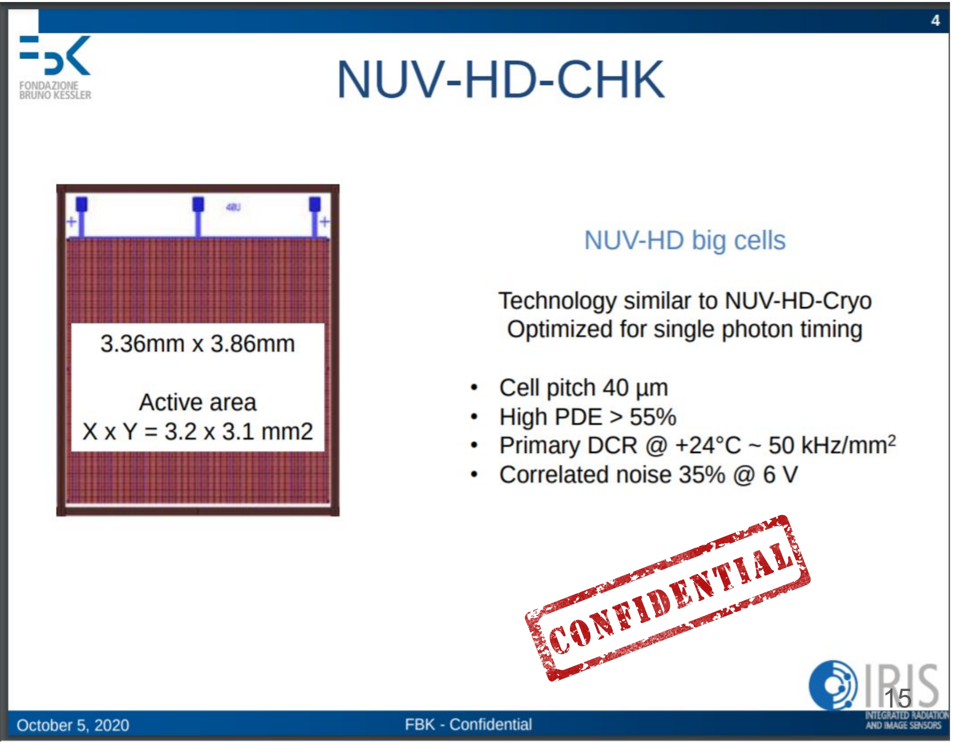
| board | sensor | uCell (µm) | $V_{bd}$ (V) | PDE (%) | DCR (kHz/mm$^2$) | window | notes |
|---|---|---|---|---|---|---|---|
| HAMA1 | S13360 3050VS | 50 | 53 | 40 | 55 | silicone | legacy model Calvi et. al |
| | S13360 3025VS | 25 | 53 | 25 | 44 | silicone | legacy model smaller SPAD |
| HAMA2 | S14160 3050HS | 50 | 38 | 50 | | silicone | newer model lower $V_{bd}$ |
| | S14160 3015PS | 15 | 38 | 32 | 78 | silicone | smaller SPADs radiation hardness |
| SENSL | MICROFJ 30035 | 35 | 24.5 | 38 | 50 | glass | different producer and lower $V_{bd}$ |
| | MICROFJ 30020 | 20 | 24.5 | 30 | 50 | glass | the smaller SPAD version |
| BCOM | AFBR S4N33C013 | 30 | 27 | 43 | 111 | glass | commercially available FBK-NUVHD |

# and FBK prototype sensors wire bonded on custom mini-tiles

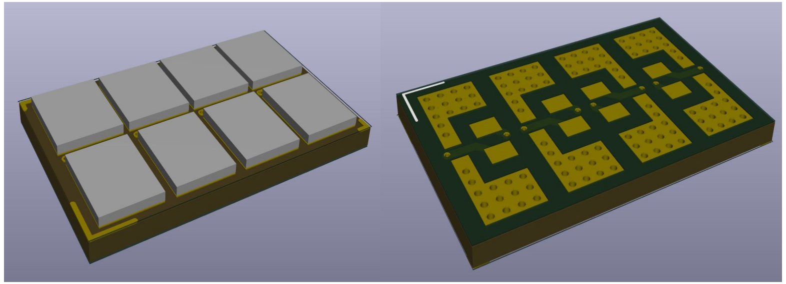
**FBK has developed for us custom mini-tiles hosting 2x4 prototypes each**

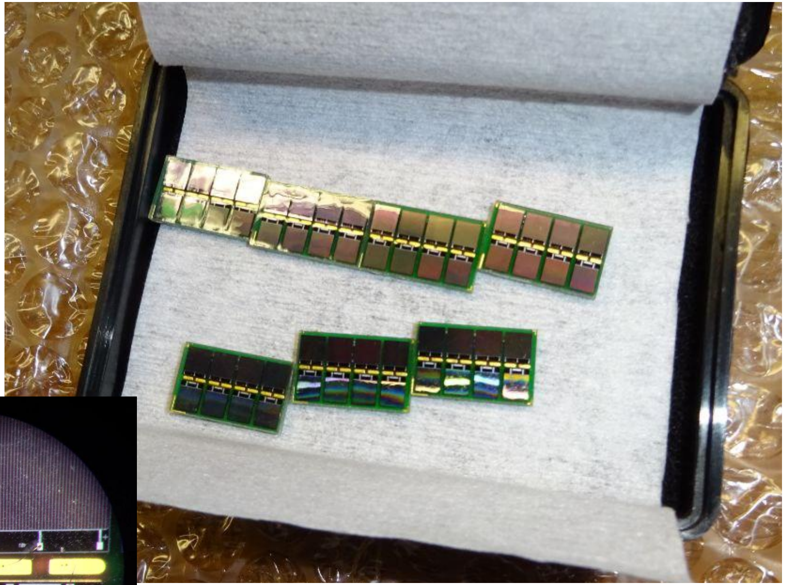


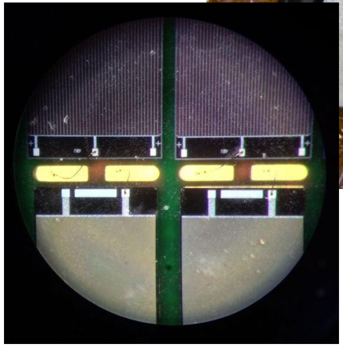


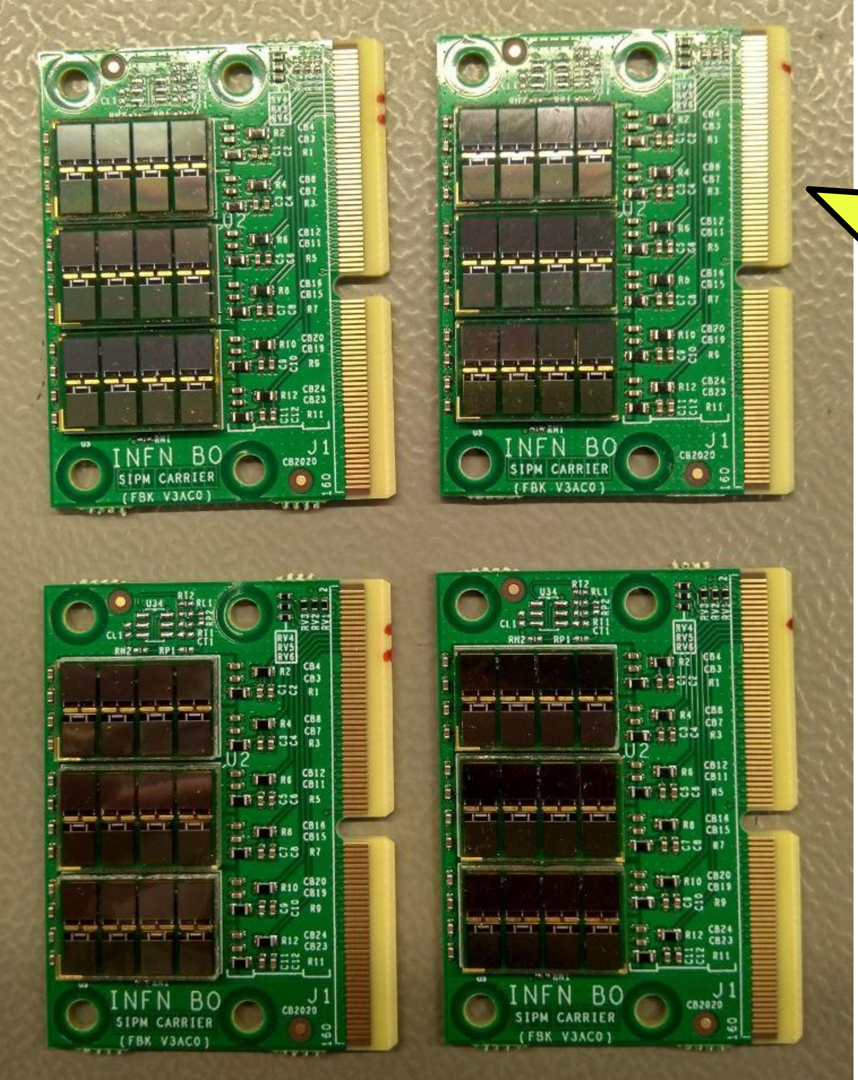




INFN BO
SIPM CARRIER
(FBK V3AC0)

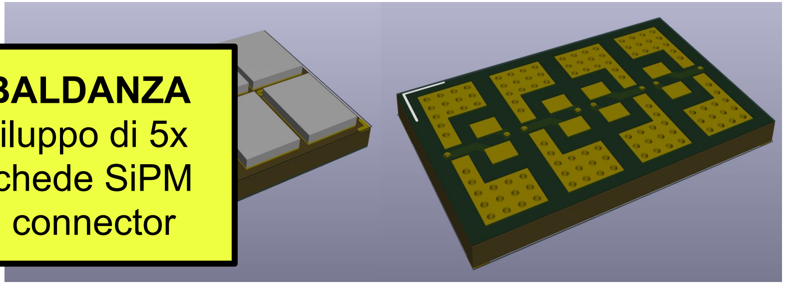


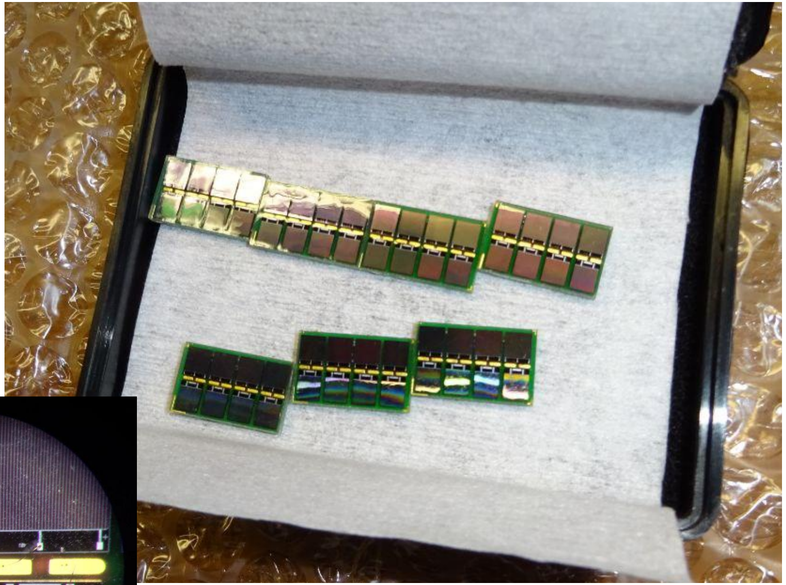


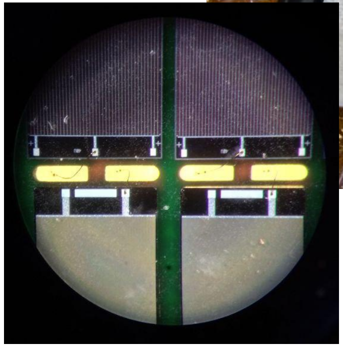





**CASIMIRO BALDANZA**
disegno e sviluppo di 5x
tipologie di schede SiPM
carrier edge connector







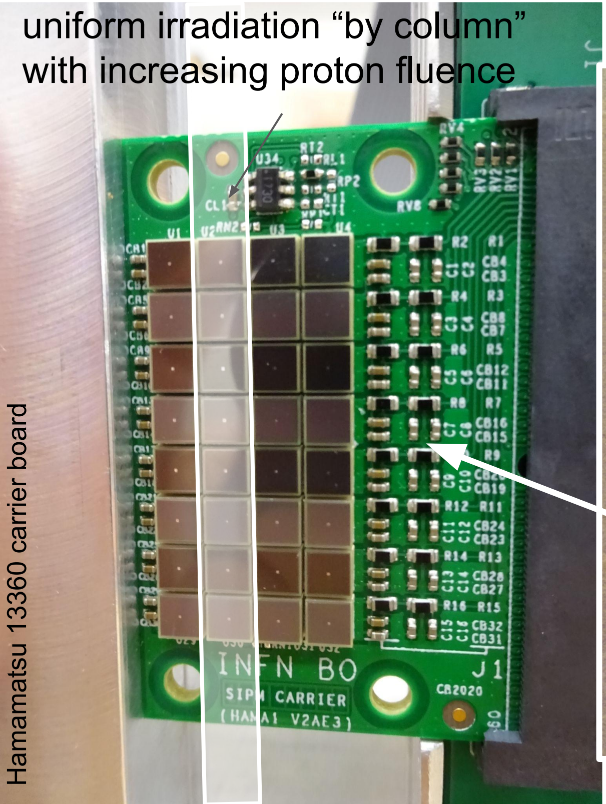
# 1st irradiation round in May 2021

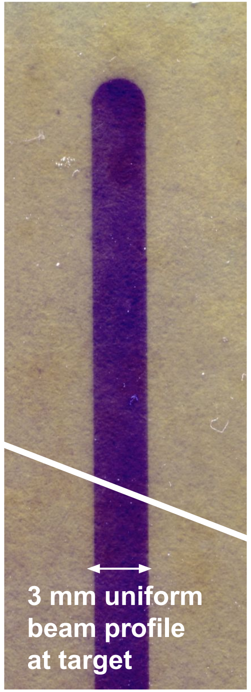
3x3 mm$^2$ SiPM sensors
4x8 "matrix" (carrier board)

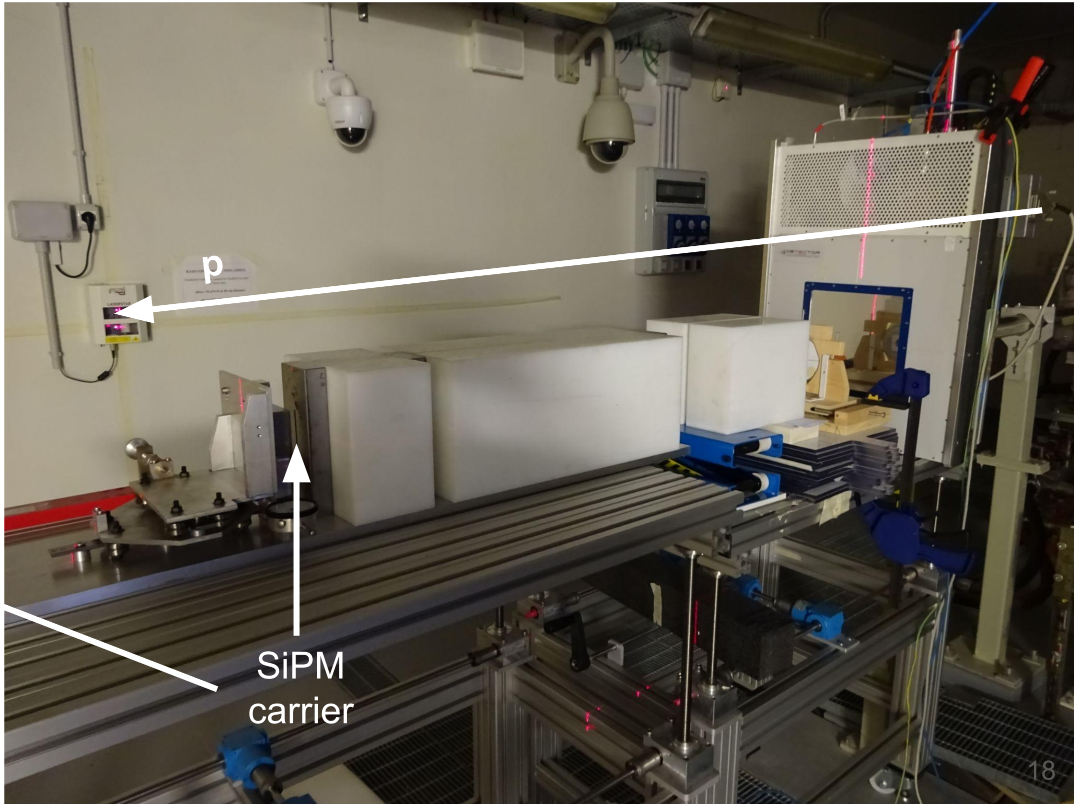
multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
**FBK** prototypes (rad.hard and timing optimised)

148 MeV protons → scattering system → collimation system → carrier board

uniform irradiation "by column"
with increasing proton fluence



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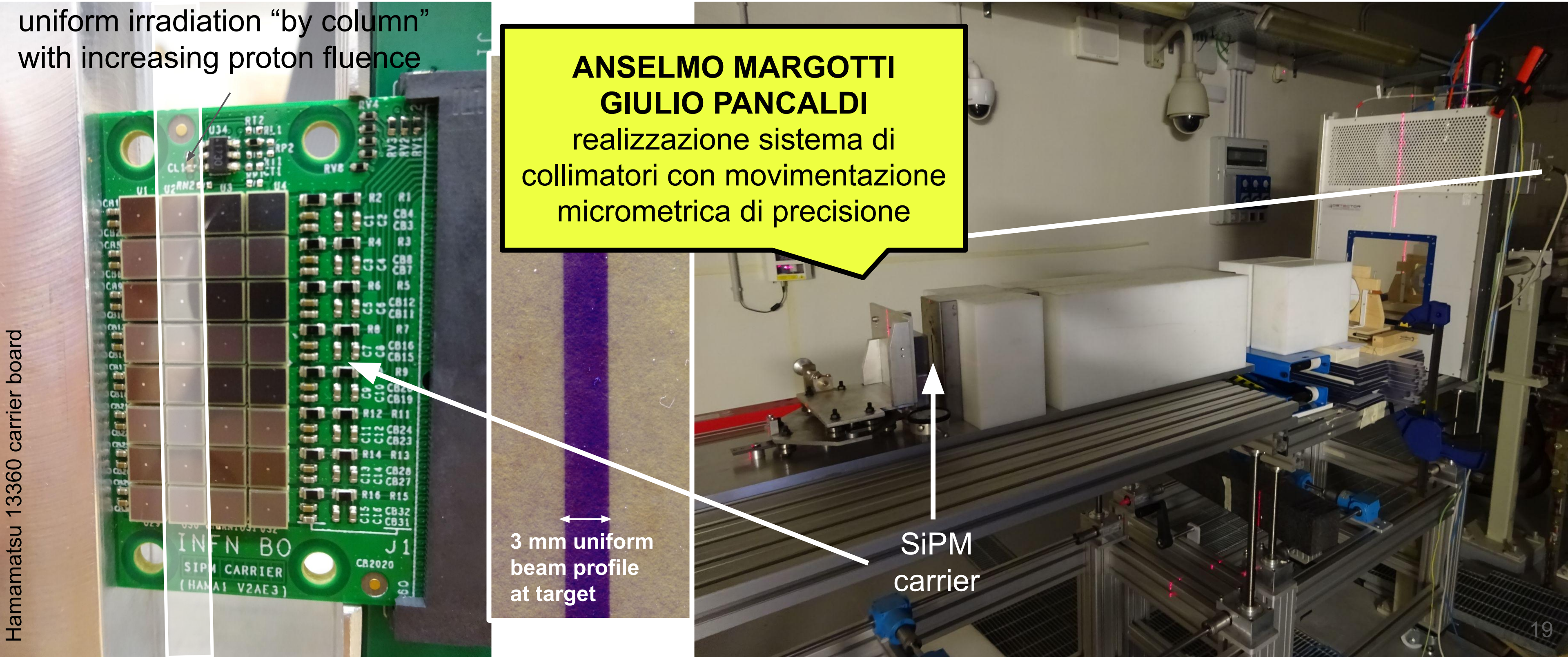
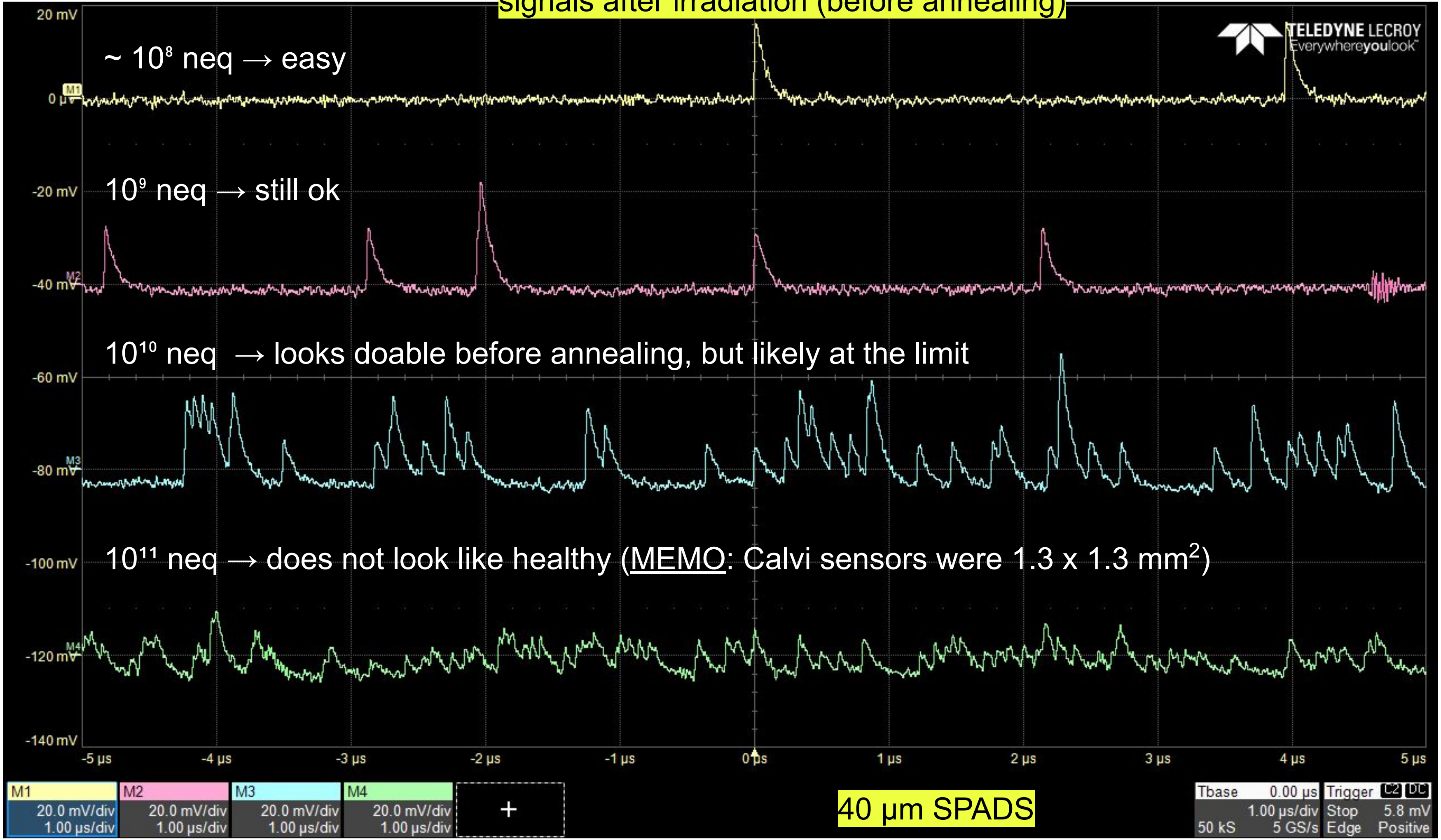


# signals after irradiation (before annealing)



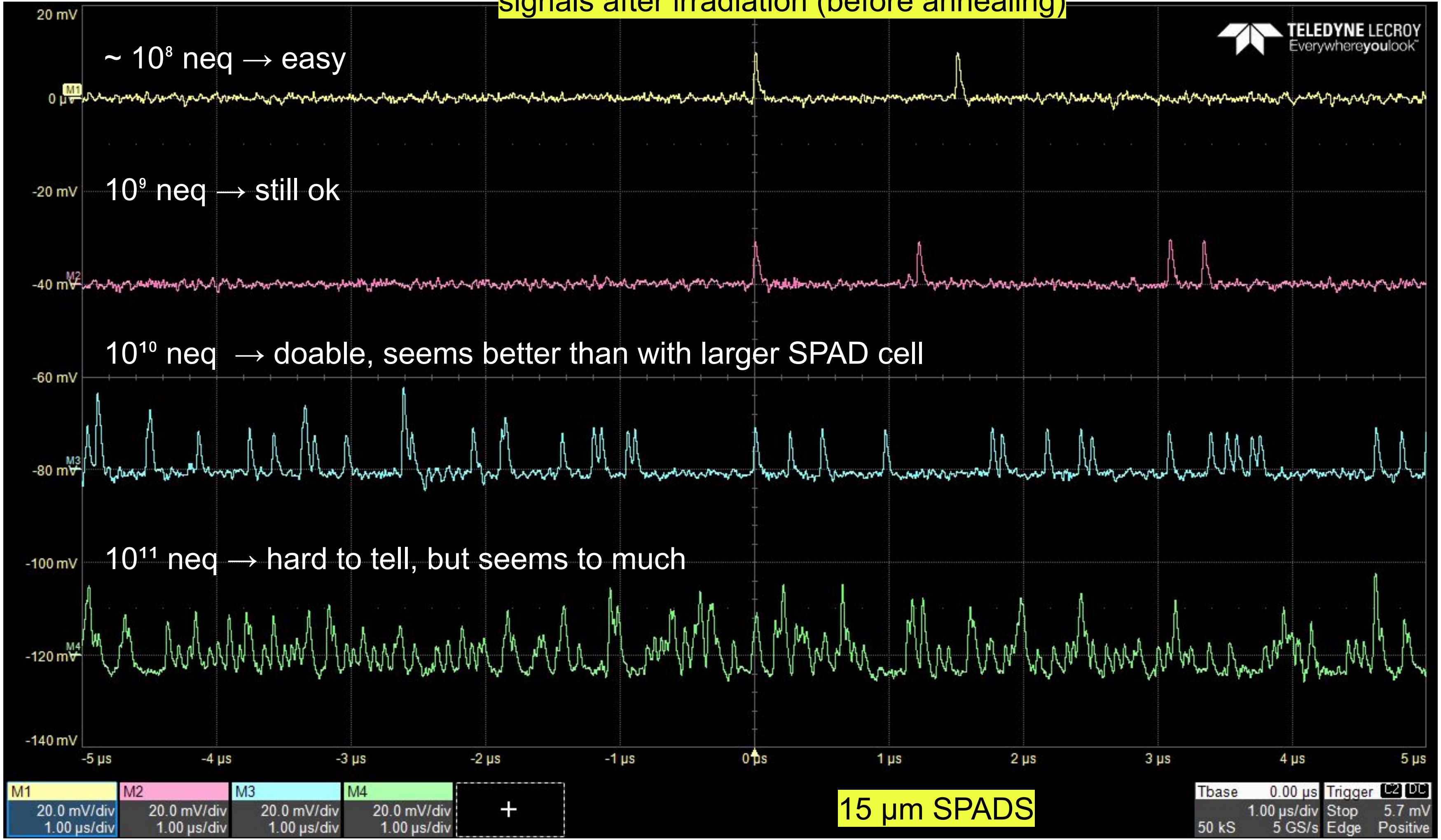

**FBK #3** (T = -30 C)

**NUV-HD-CHK** (row A)

# signals after irradiation (before annealing)

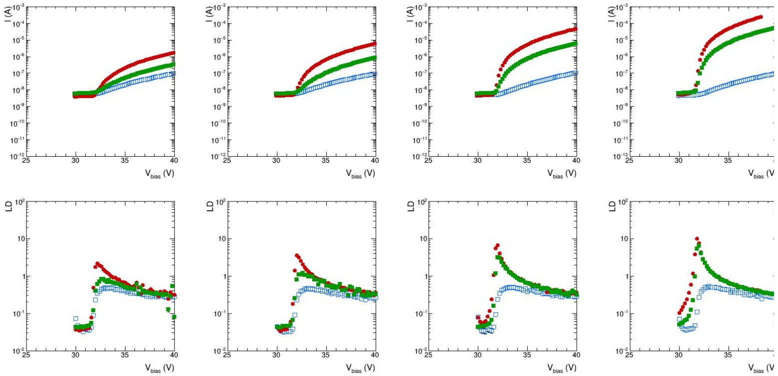
FBK #3 (T = -30 C)

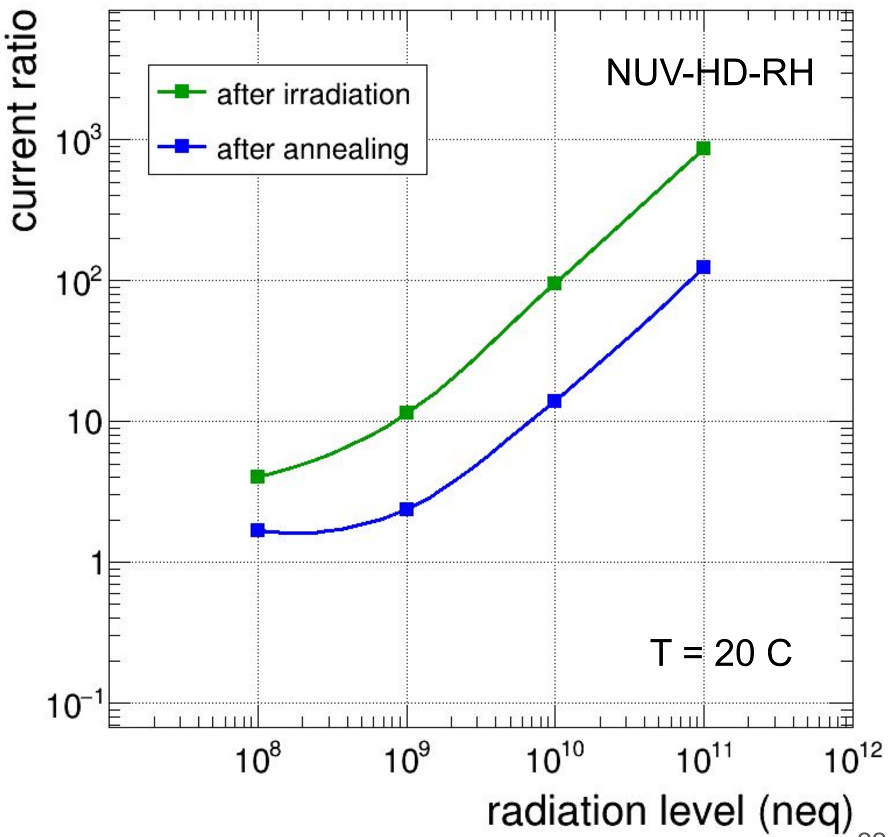
**NUV-HD-RH** (row B)



# FBK characterisation after 1 week of annealing at T = 125 C

new
irradiated
annealed





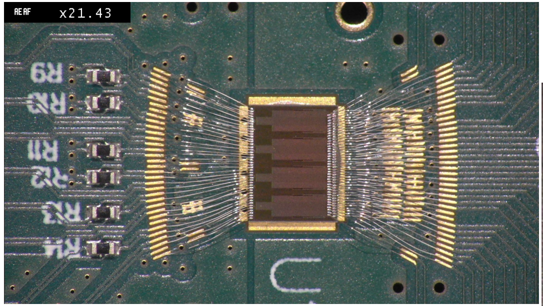

annealing reduced dark current by a factor of ~5-10, in line with expectations

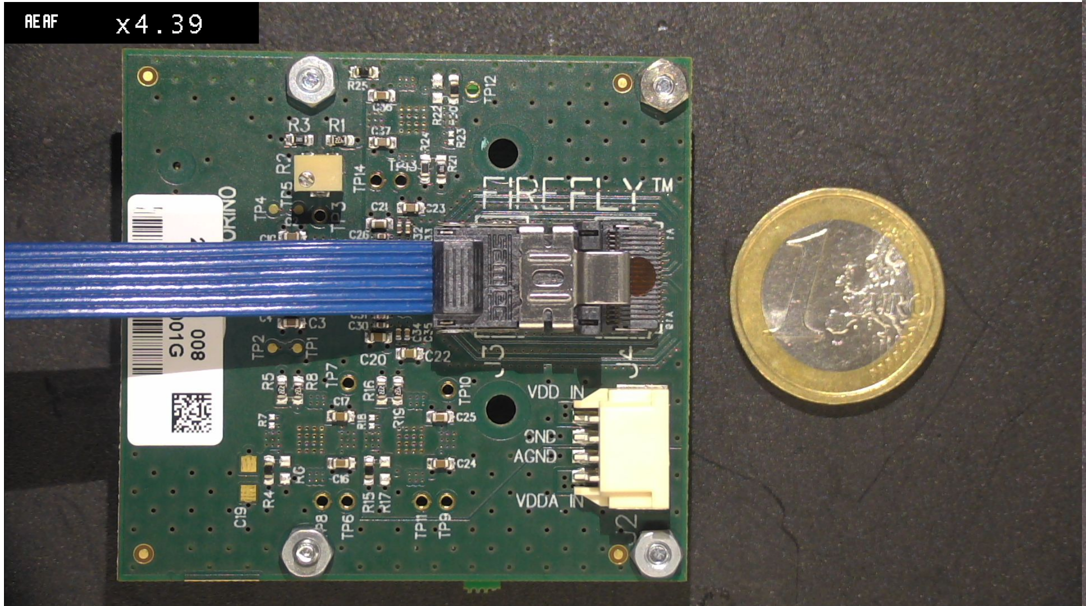
SiPM irradiated up to $10^{11}$ now behave like if they were irradiated by $10^{10}$

FBK annealing stopped at 125 C at the time
little issue related to the solder paste used during assembly (T = 138 C) did not allow to reach T = 175 C
→ needed reworking of the carrier boards, DONE
→ annealed up to T = 150 C, characterisation to be done

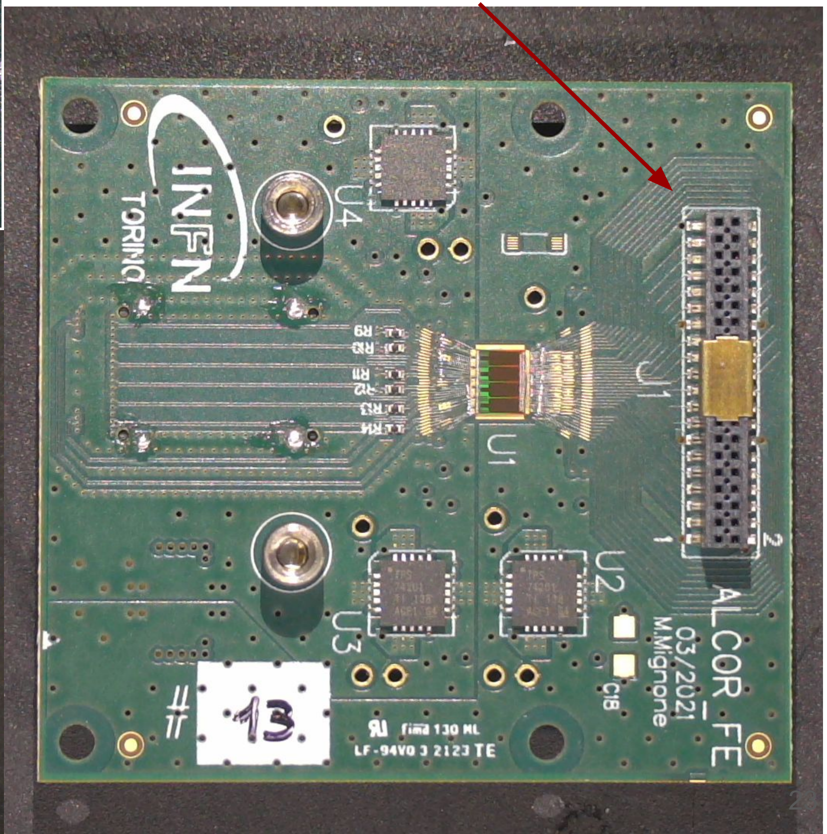
# ALCOR – A Low Power Chip for Optical sensor Readout

ALCOR-FE frontend board for testbeam with bonded ALCOR chip and FireFly cable



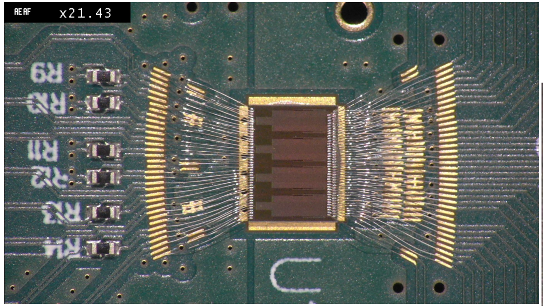



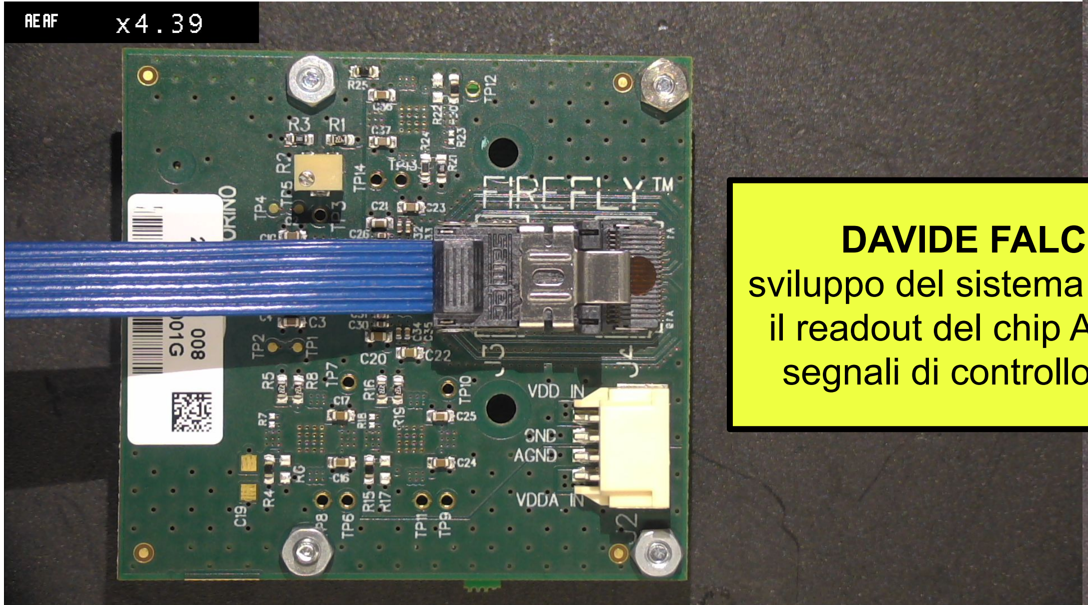

connector to adapter-CA board

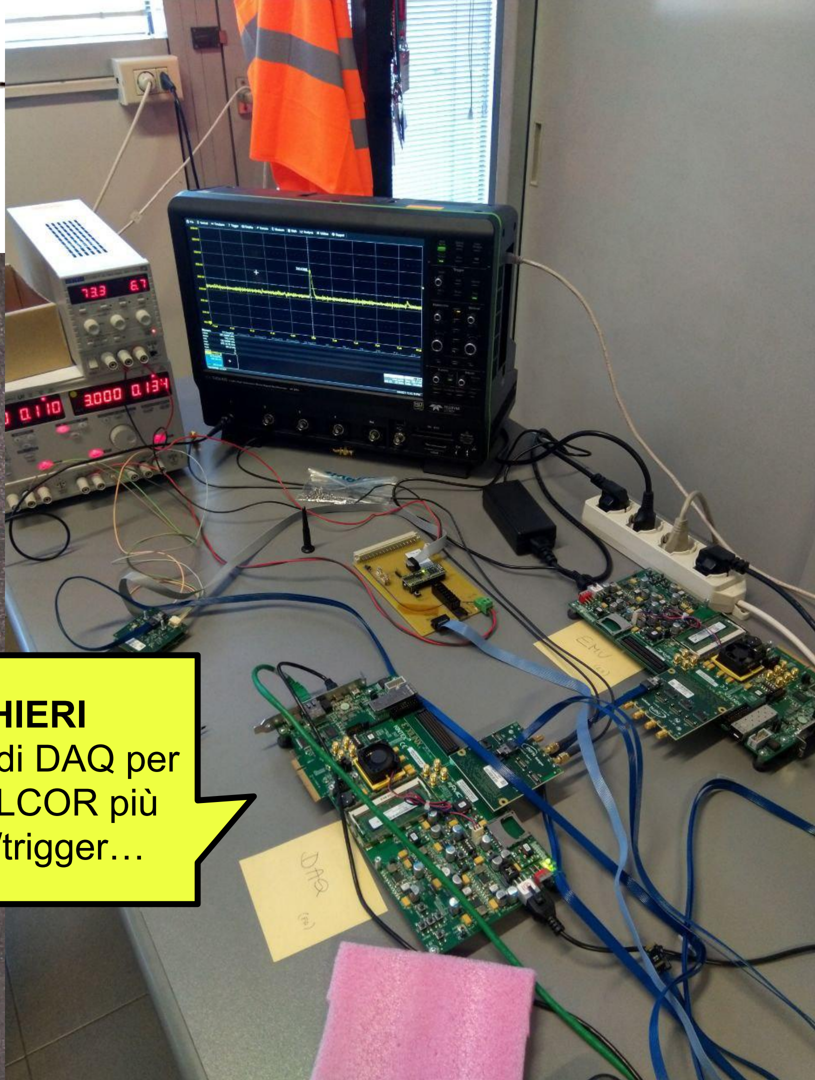


# ALCOR – A Low Power Chip … Readout

ALCOR-FE frontend board for testbeam with bonded ALCOR chip and FireFly cable



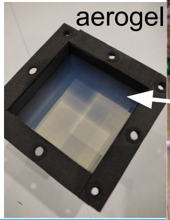



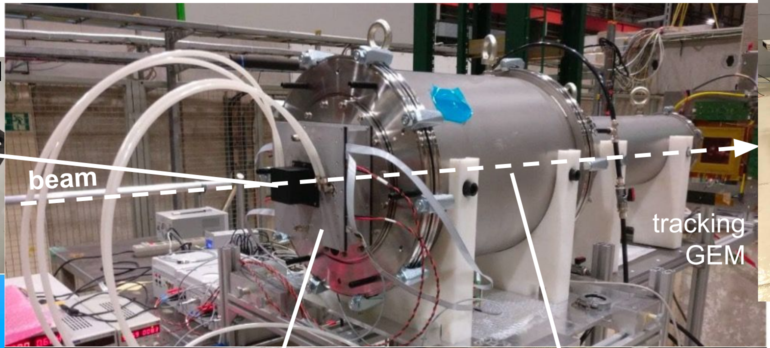
**DAVIDE FALCHIERI**
sviluppo del sistema di DAQ per il readout del chip ALCOR più segnali di controllo/trigger…

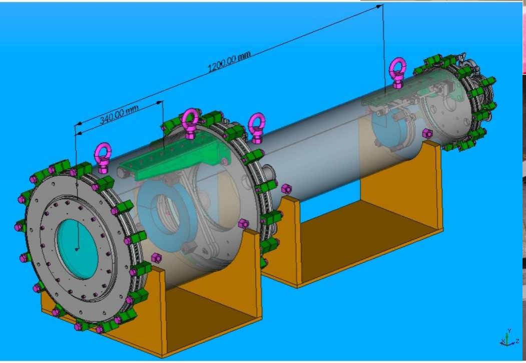
# SiPM tested with beams at CERN

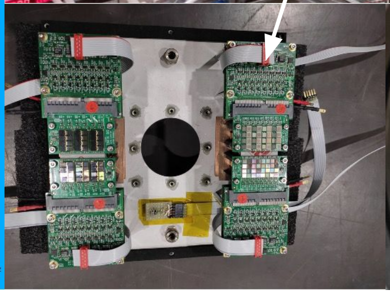
**first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN**

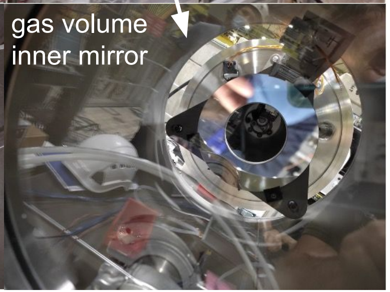
dRICH prototype @ CERN-SPS



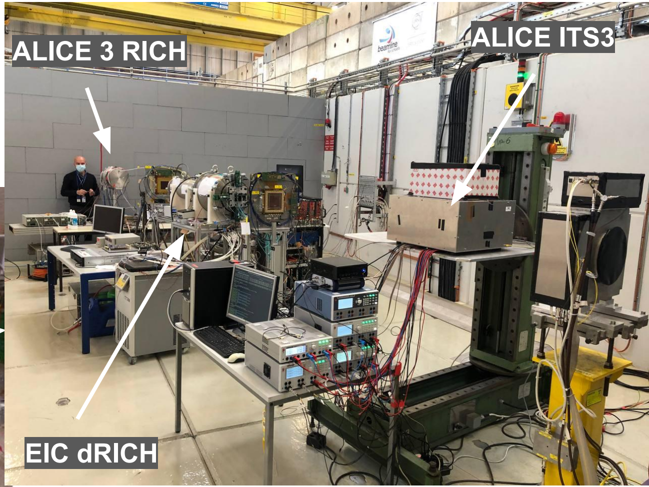



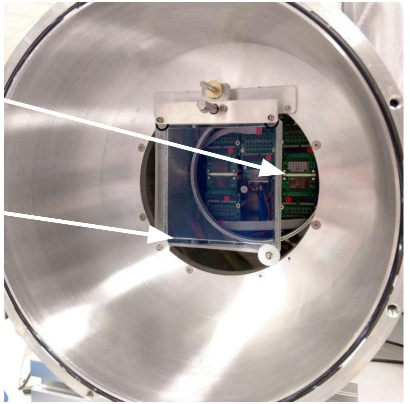



ALICE and EIC at CERN PS T10 October 2021




EIC SiPM with ALCOR readout

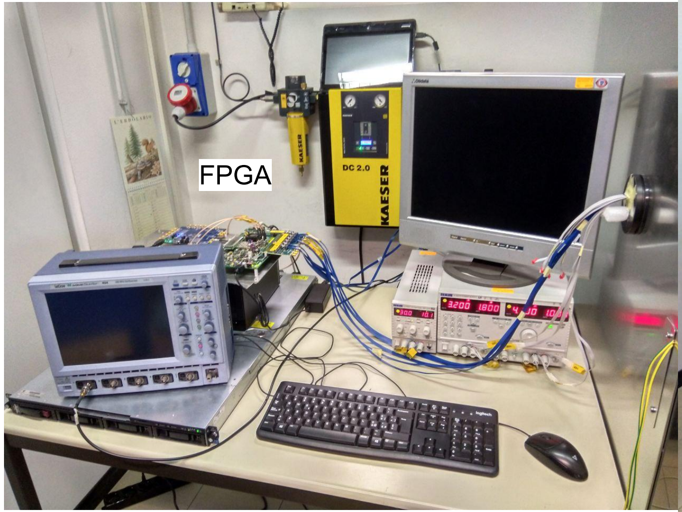
ALICE 3 aerogel Chiba sample



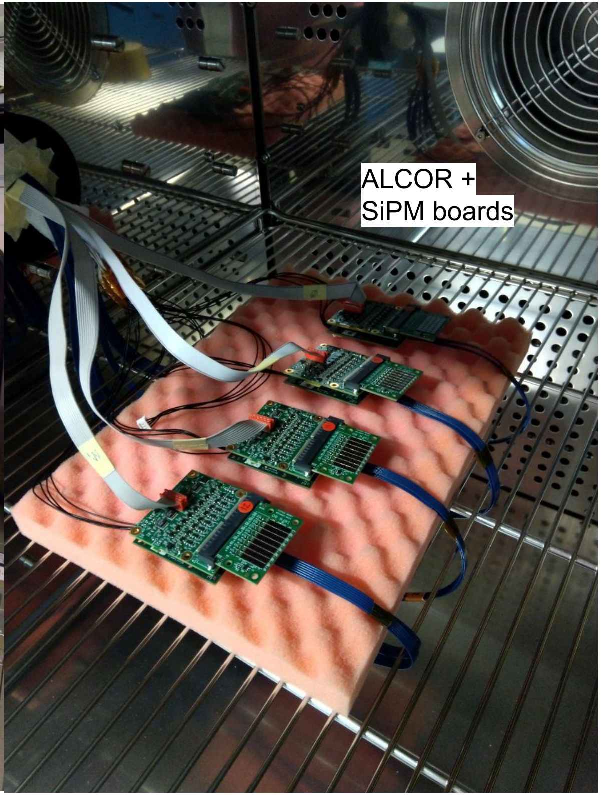
perhaps too optimistic / ambitious for the program of 2021
some troubles with electronics, not really a successful beam test for the SiPM readout
**but we have anyway learned something, stay positive for 2022!**

# SiPM+ALCOR setup in Bologna

permanent EIC SiPM setup in the INFN Bologna Silicon Labs
characterisation of performance of SiPM with full (ALCOR) readout system
**measure many SiPM in one go!**








the following results have been obtained with this setup

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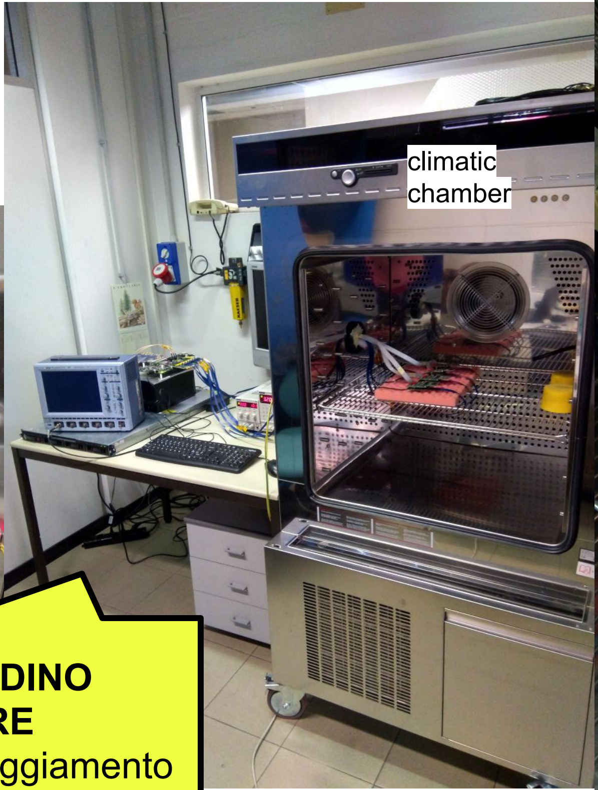
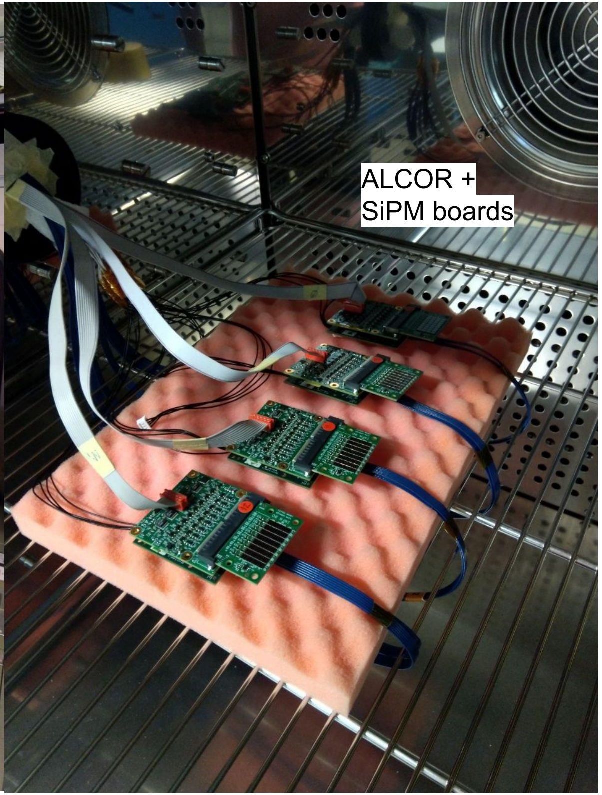


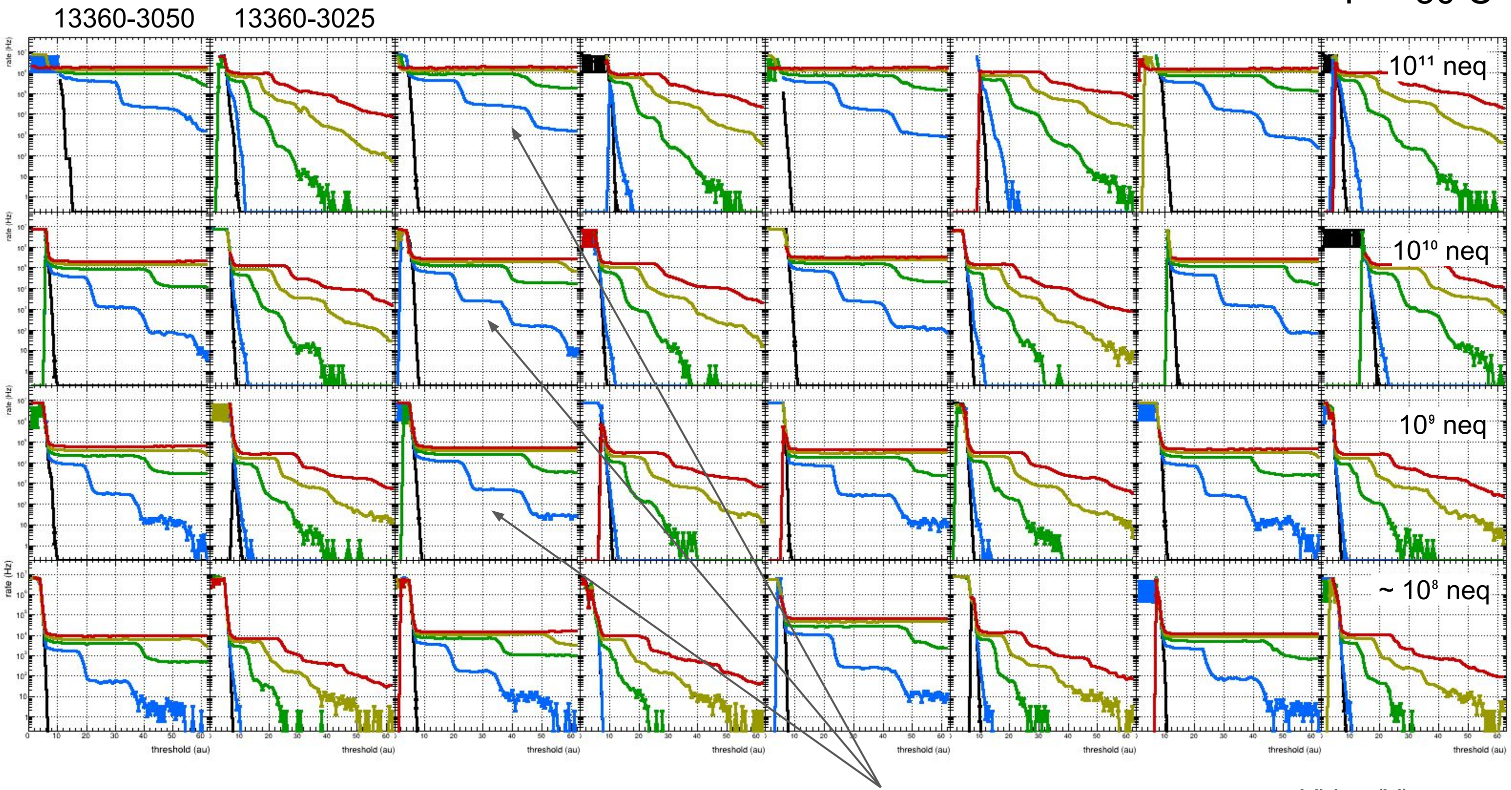

**ANTONIO PALADINO**
**IL DIRETTORE**
per lo spazio, l'equipaggiamento nel Laboratorio Silici e il supporto

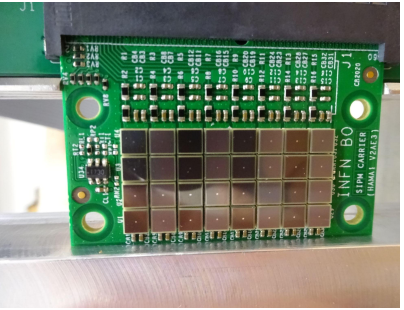
the following results have been obtained with this setup

# Hamamatsu (HAMA1 #2) threshold scans

PRELIMINARY

T = -30 C



**irradiated board after annealing**

still working!

clear single-photon separation up to $10^{11}$

Vbias (V)

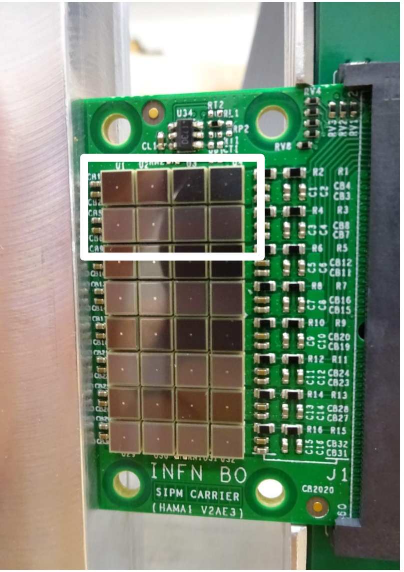
**48 50 52 54 56**

# Hamamatsu (HAMA1) grand comparison

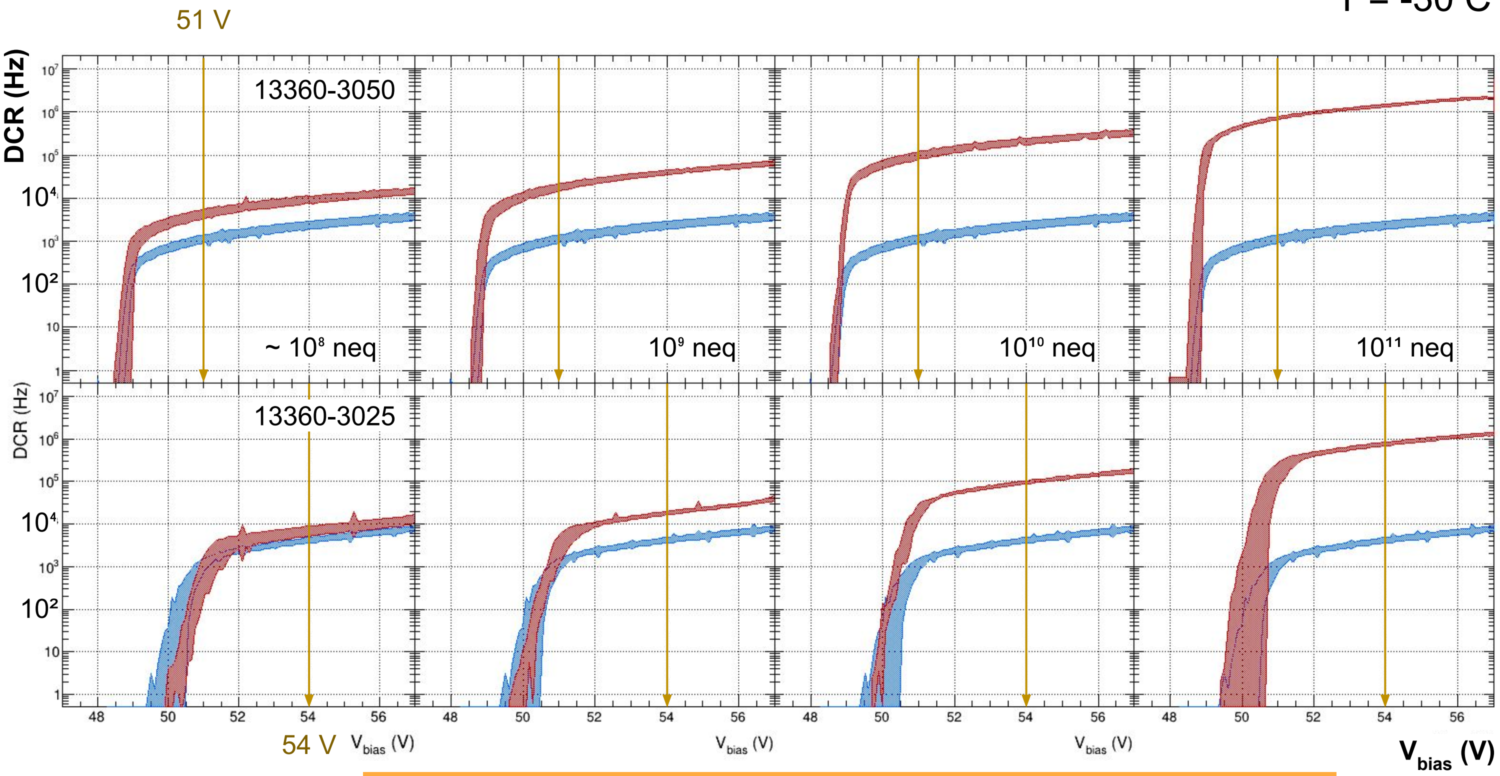
PRELIMINARY

T = -30 C

not irradiated board




irradiated board after annealing




| values at the indicated Vbias | new | ~ $10^8$ neq | $10^9$ neq | $10^{10}$ neq | $10^{11}$ neq |
|---|---|---|---|---|---|
| **13360-3050** | 1.1 kHz | 4.4 kHz | 18 kHz | 100 kHz | 730 kHz |
| **13360-3025** | 2.4 kHz | 7.0 kHz | 18 kHz | 95 kHz | 770 kHz |

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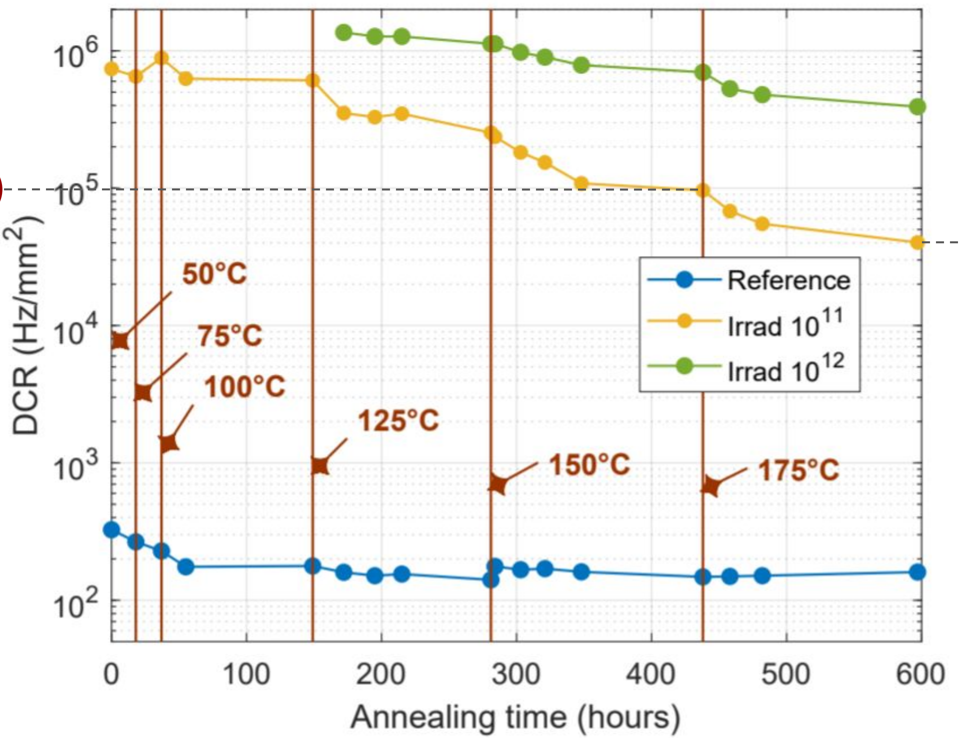
# Hamamatsu (HAMA1) grand comparison

**measured ~ 750 kHz DCR**
after $10^{11}$ neq dose
and T = 150 C annealing
in line with Calvi

**could reduce by another 3x factor**
with T = 175 C annealing
if we believe in Calvi (we do)

**could reduce by a further 2(4)x factor**
operating at T = -40(-50) C
we know DCR decreases by 2x every 10 C

900 kHz
in 3x3 mm$^2$




350 kHz
in 3x3 mm$^2$

| values at the indicated Vbias | new | ~ $10^8$ neq | $10^9$ neq | $10^{10}$ neq | $10^{11}$ neq |
|---|---|---|---|---|---|
| **13360-3050** | 1.1 kHz | 4.4 kHz | 18 kHz | 100 kHz | 730 kHz |
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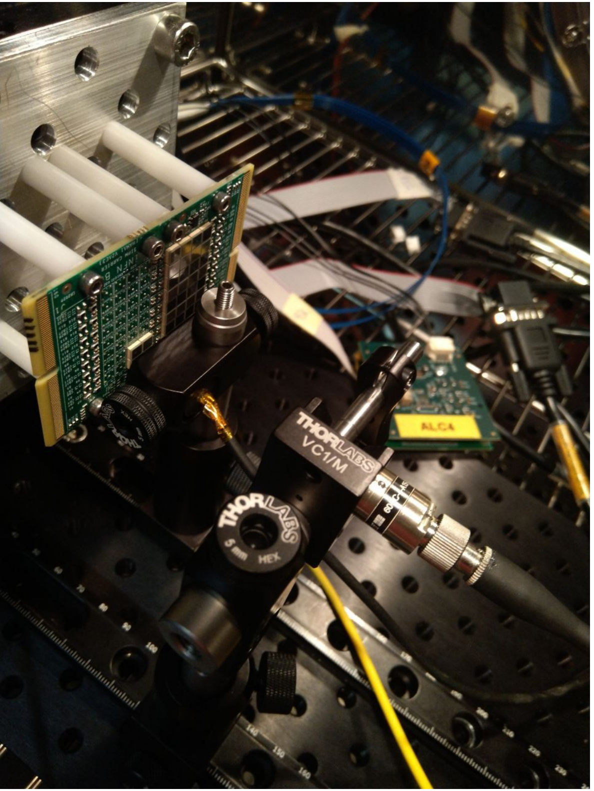
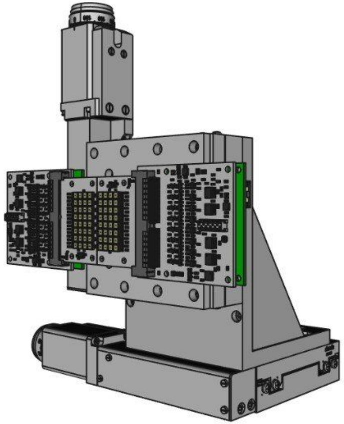
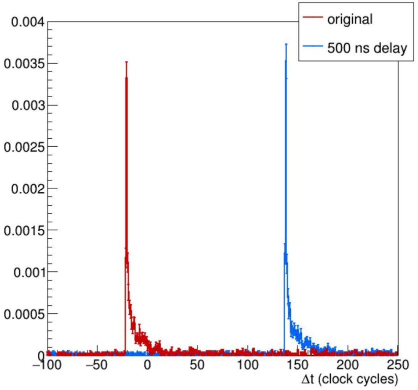
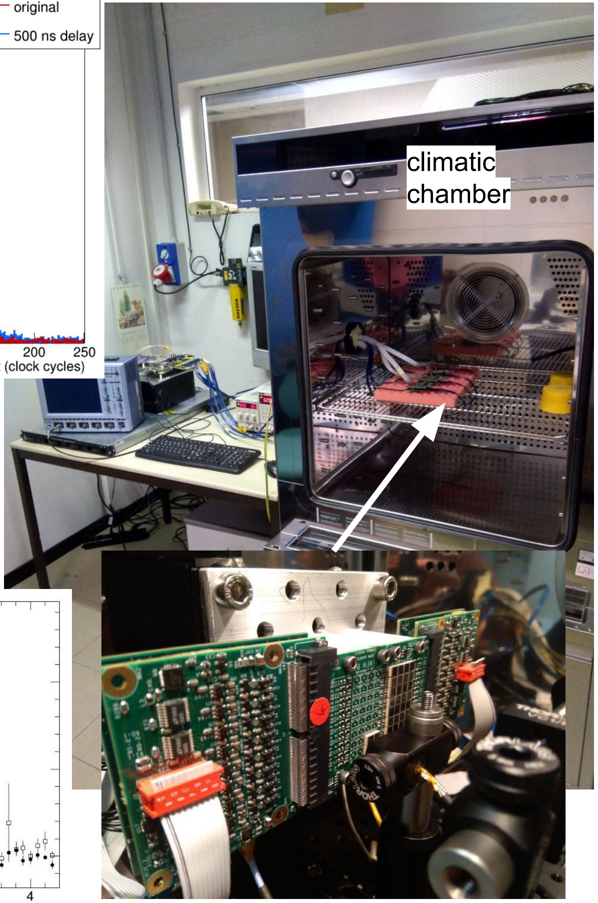
# SiPM+ALCOR setup in Bologna



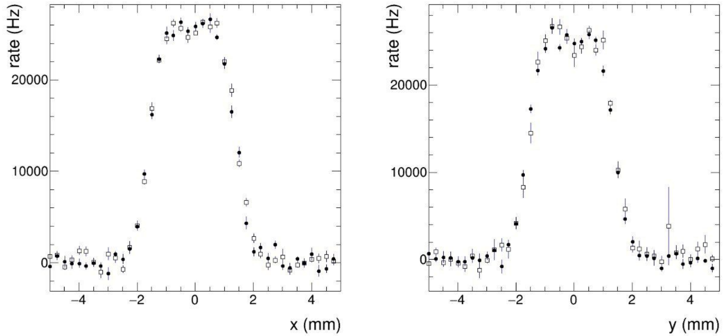



time correlations



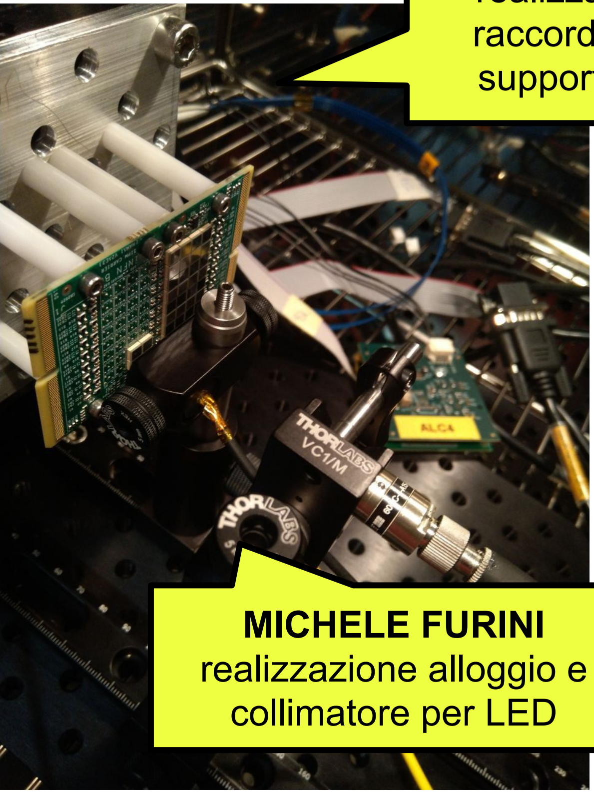

position scan

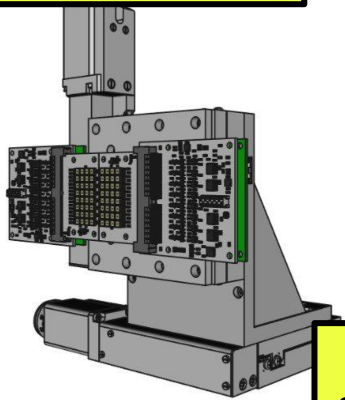


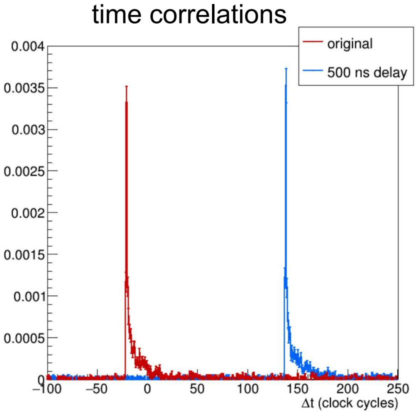

Bologna setup **upgraded** with pulsed LED and movimentation inside the climatic chamber

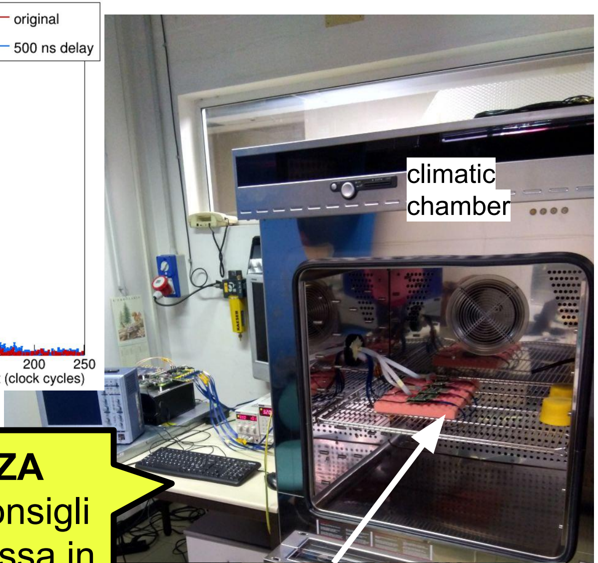
# SiPM+ALCO… a

**TOMMASO FADANNI**
realizzazione piastra di raccordo e colonnine di supporto schede SiPM

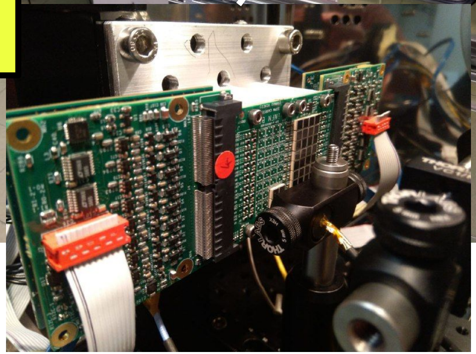


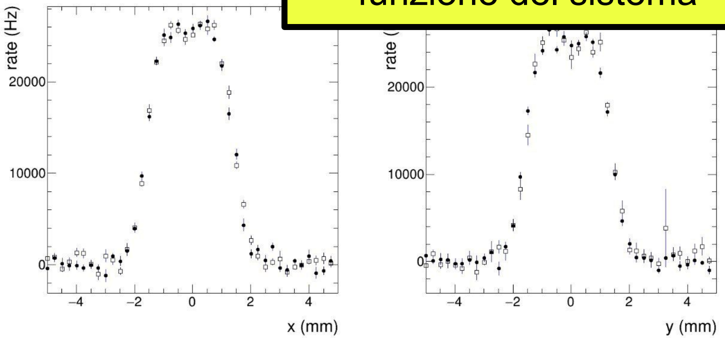


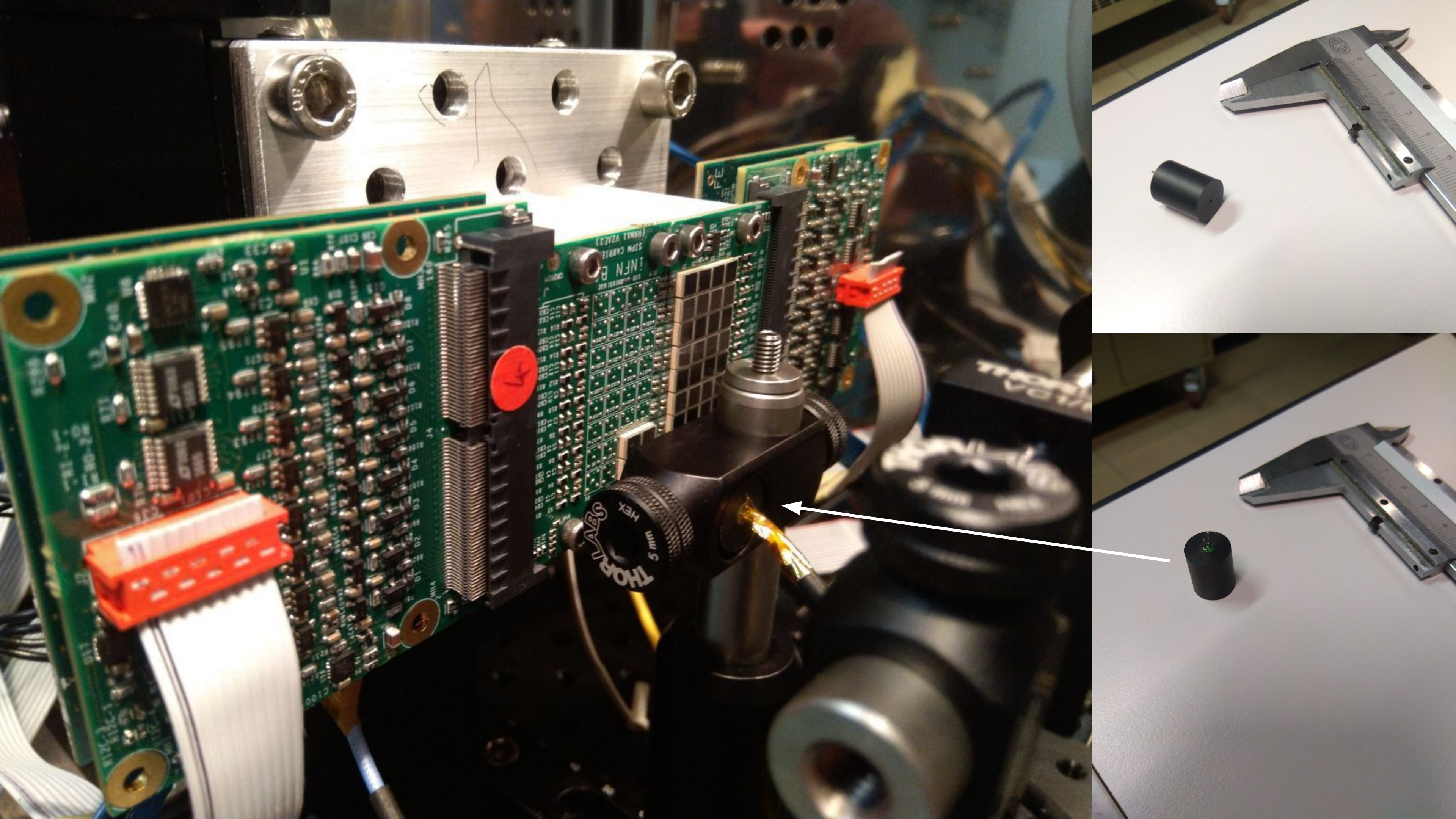

**DANIELE CAVAZZA**
supporto tecnico e consigli a 360 gradi per la messa in funzione del sistema



**MICHELE FURINI**
realizzazione alloggio e collimatore per LED



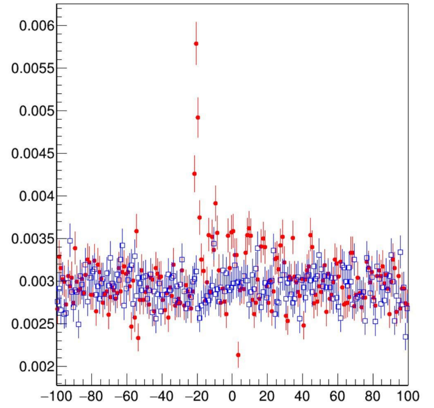

Bologna setup **upgraded** with pulsed LED and movimentation inside the climatic chamber

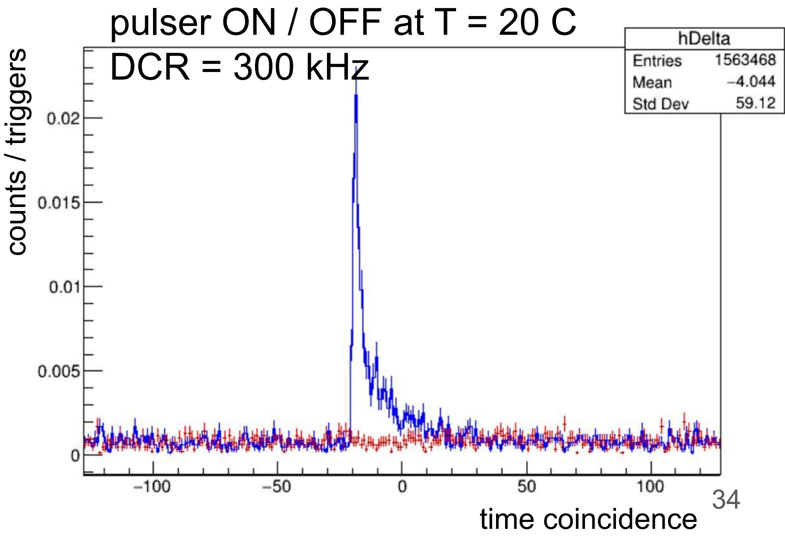

THORLABS
HEX
5 mm

# SiPM + ALCOR response with light

- **use the complete electronics built in 2021 for laboratory tests**
  - SiPM carrier + adapter + ALCOR + readout
  - mount everything in the climatic chamber
  - with an LED / laser in front of the sensor
  - plus movimentation to inspect all sensors
- **study response of SiPM to pulsed light**
  - pulsed LED / laser
  - measure increase of rates
  - measure time coincidences
  - compare sensors with different NIEL
- **system setup is complete in Bologna**
  - the goal is to have it as a permanent test bench
  - to be used to test SiPM response for 2022 irradiation plan
    - ie. relative variation of PDE
  - to be used to get ready for test beam
  - first measurements performed

NIEL received $10^{11}$ + annealing

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PRELIMINARY

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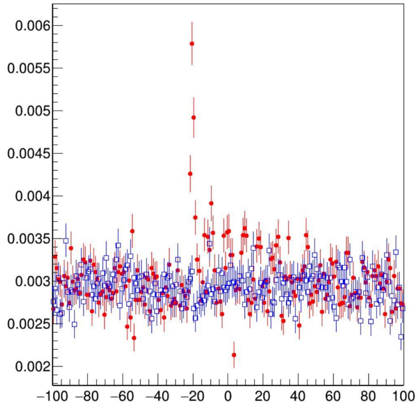
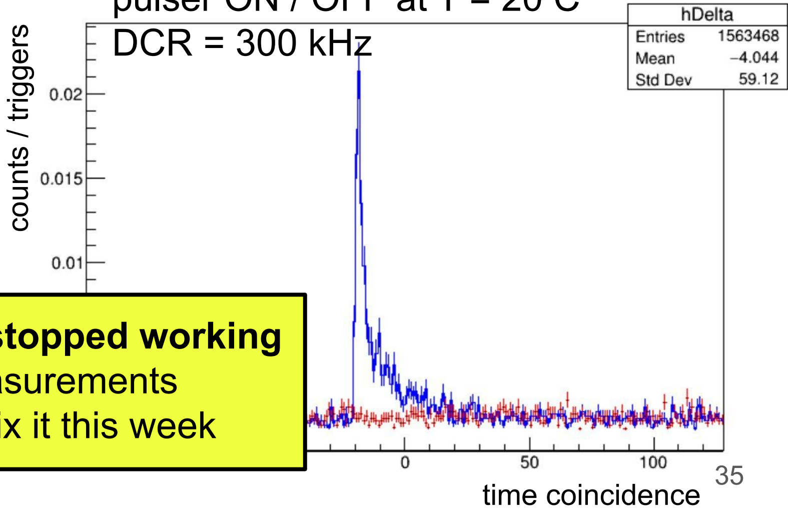
    - ie. relative va
  - to be used to get r
  - first measurement

NIEL received $10^{11}$ + annealing




unfortunately, the **climatic chamber stopped working** a month ago… big delay in measurements servicing supposed to come and fix it this week

PRELIMINARY

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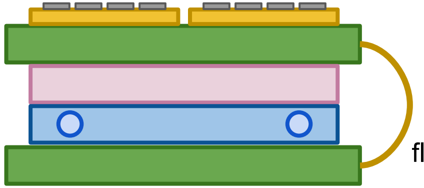
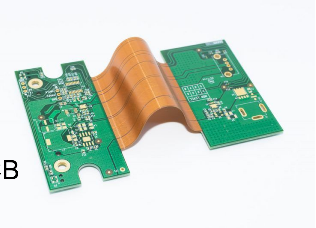
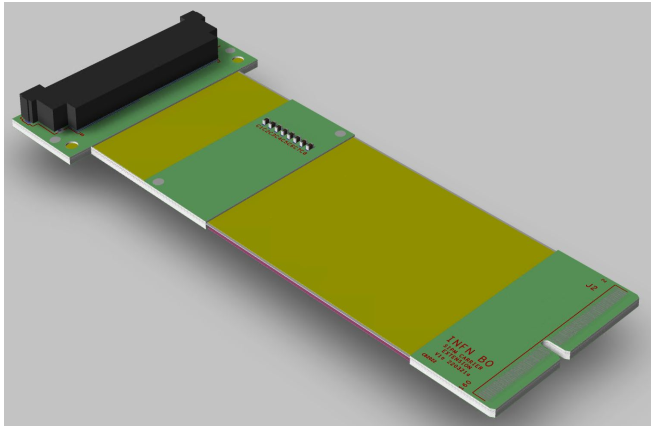
# dRICH SiPM proto-readout-tile

proto-readout-tile
(Peltier cell?)
cooling
front-end ASIC



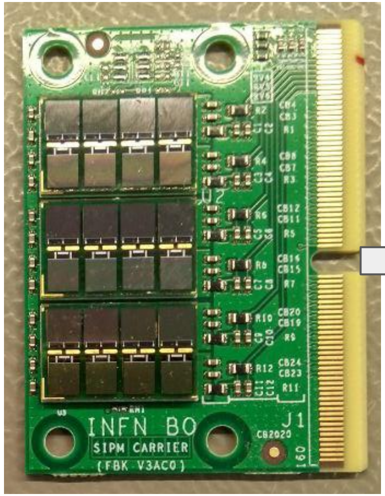
flex PCB

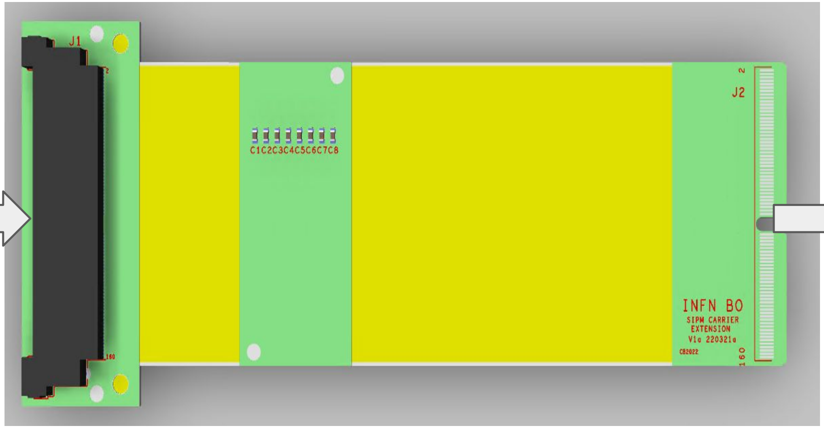


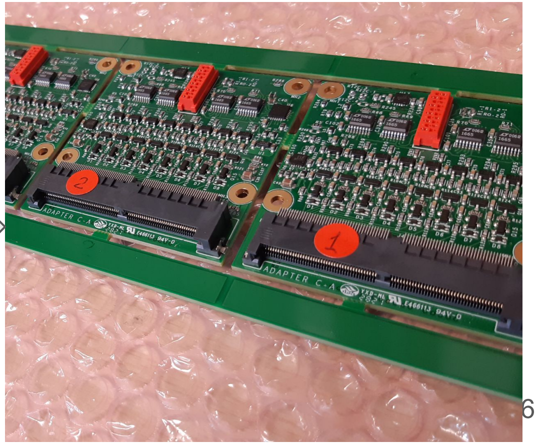



**PCB-flex-PCB prototype extension cord** to test

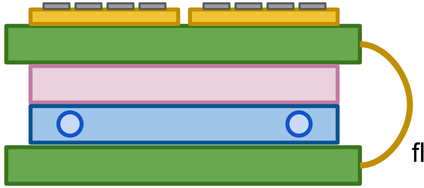
- bending capabilities (static), hopefully smaller that R = 2 mm
- signal integrity over longer path to ASIC
- design optimisations towards proto-readout-tile

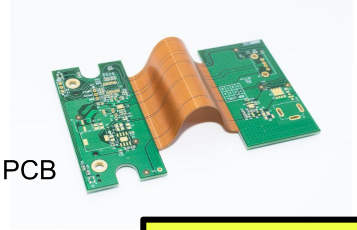


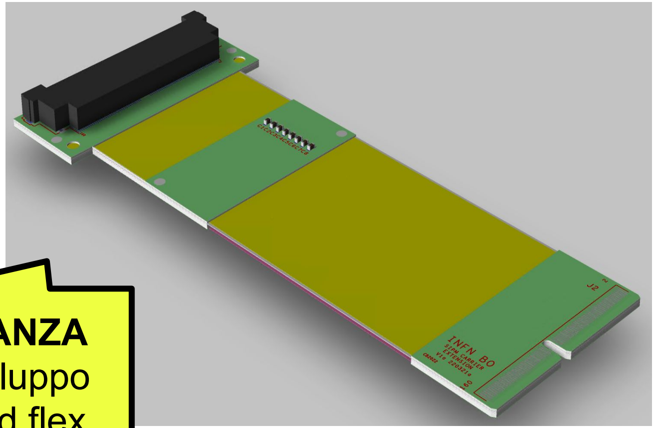



# dRICH SiPM proto-readout-tile



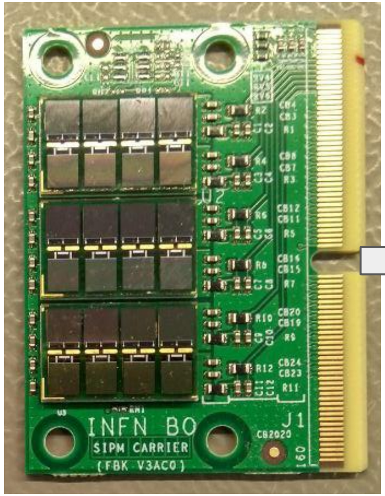



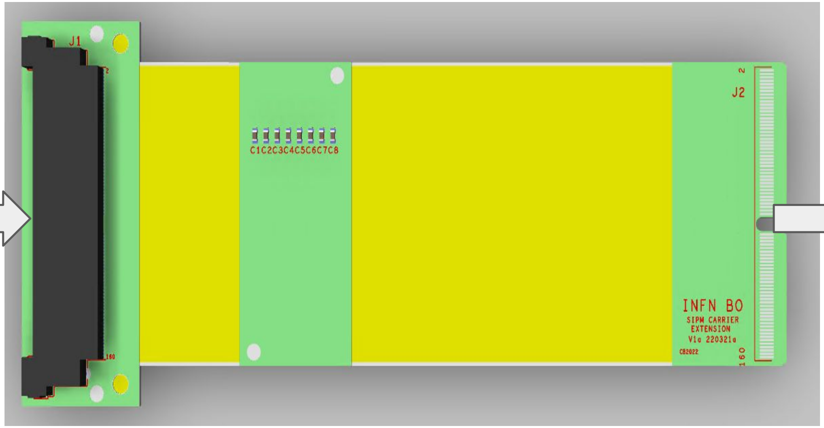



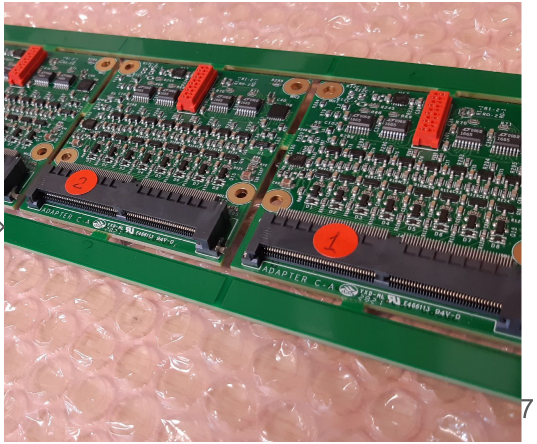

**CASIMIRO BALDANZA**
R&D, disegno e sviluppo
delle extension cord flex
a breve in realizzazione

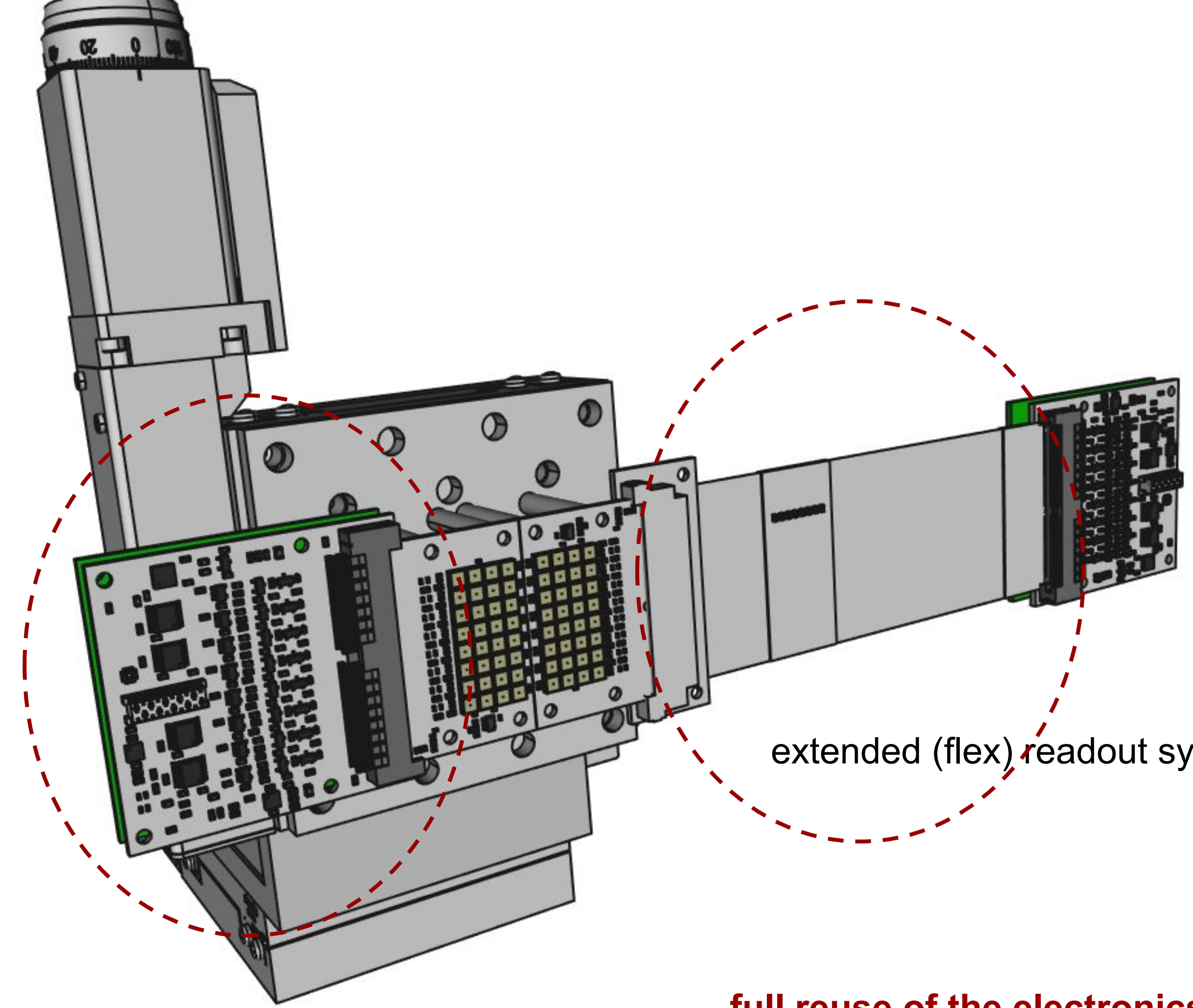
**PCB-flex-PCB prototype extension cord** to test

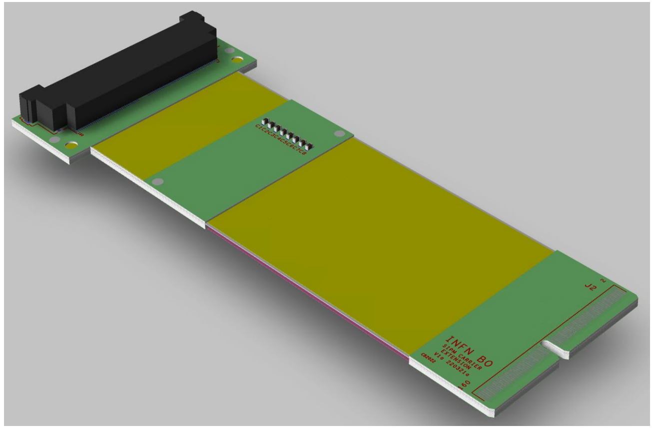
- bending capabilities (static), hopefully smalle
- signal integrity over longer path to ASIC
- design optimisations towards proto-readout-



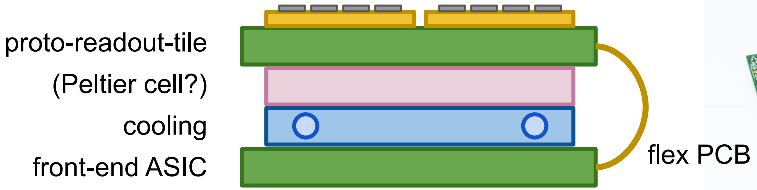



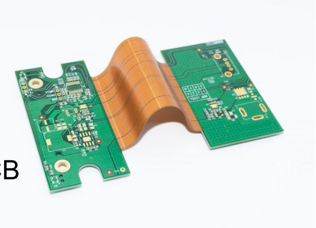


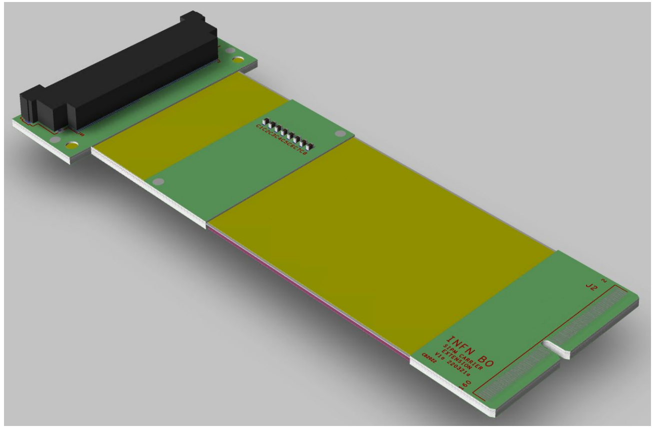



**full reuse of the electronics and systems developed so far**

# dRICH SiPM proto-readout-tile

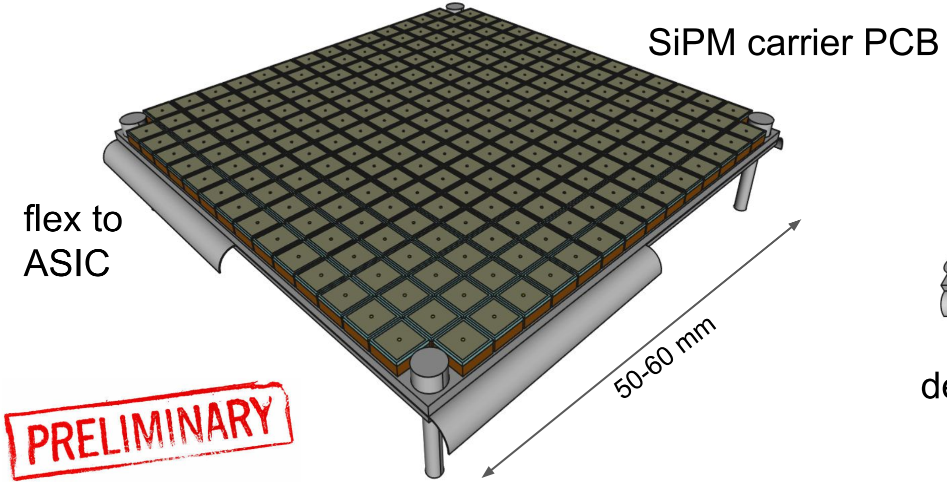


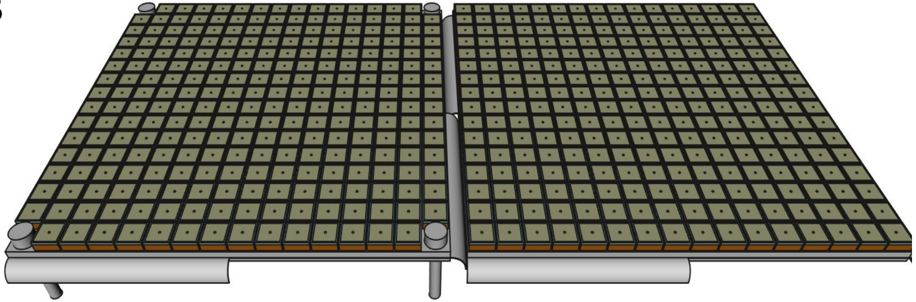





**PCB-flex-PCB concept will be integrated in proto-readout-tile**

- design and realise a large SiPM carrier board (256 pixels)
- form-factor following latest dRICH readout studies
- many details still to be defined, towards the end of the year



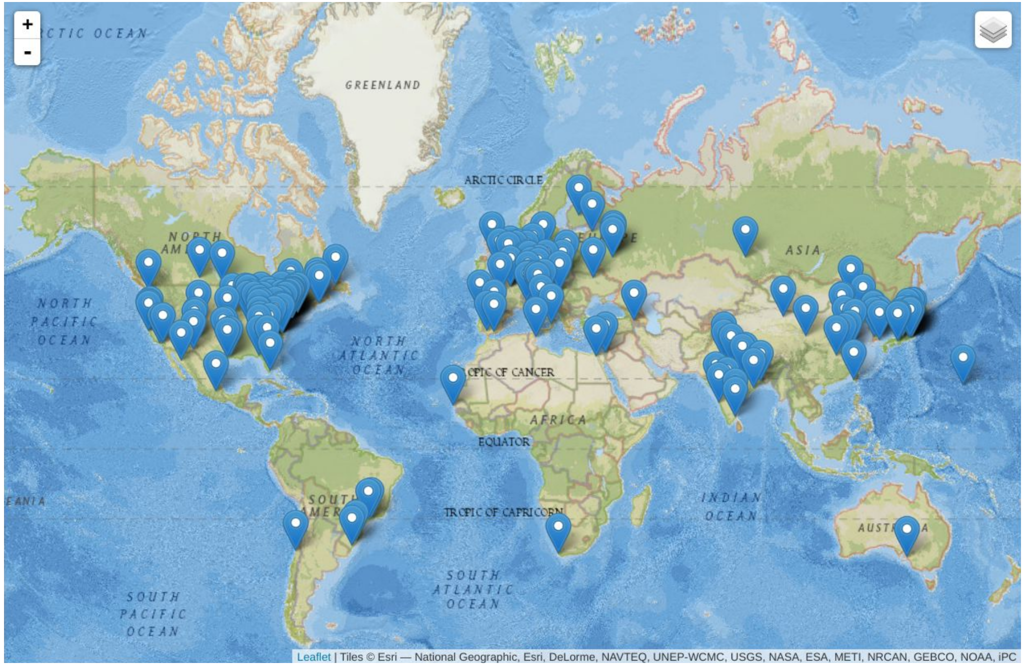



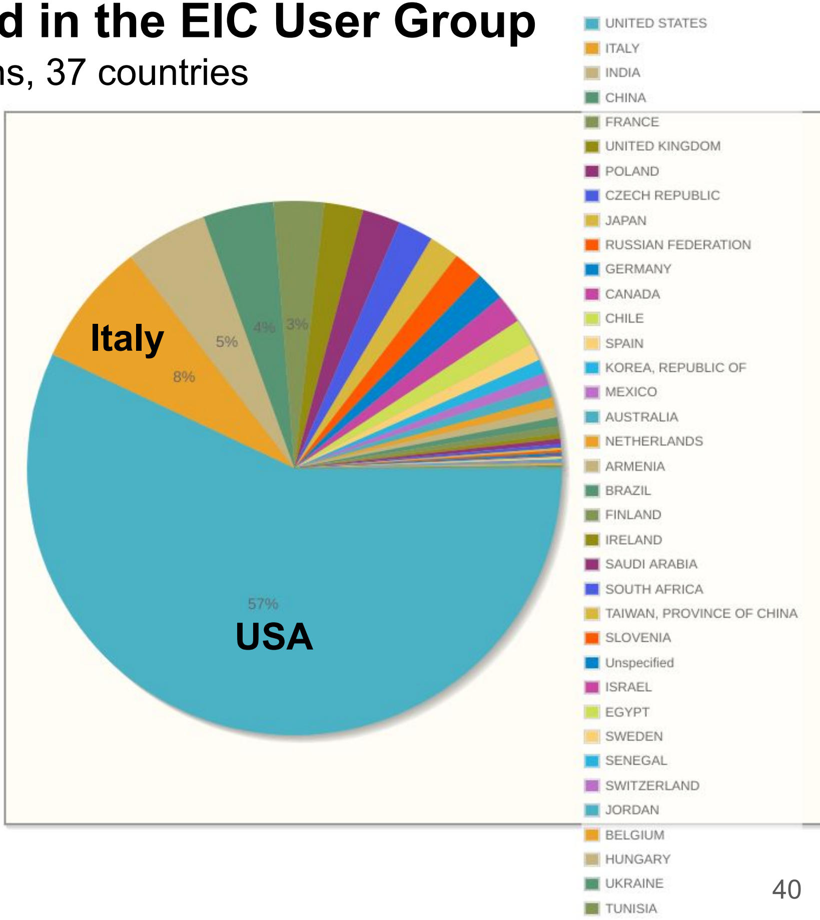
design optimised to test layout that maximises coverage
with colling and electronics behind sensors

# The EIC Community

**International Community organised in the EIC User Group**

1313 members, 267 institutions, 37 countries



# Yellow Report initiative

**GOAL: advance the state and detail of the documented physics studies (White Paper) and detector concepts (Detector and R&D Handbook) in preparation for the realization of the EIC**

415 authors, including
Antonioli, Preghenella e Noferini




arXiv:2103.05419 [physics.ins-det]

# Call for Collaboration Proposals for Detectors at the Electron-Ion Collider

Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerat
announce the Call for Collaboration Proposals for Detectors to be located at the Elec
the capacity to host two interaction regions, each with a corresponding detector. It is
detectors would be represented by a Collaboration.

**Detector 1** is within the scope of the EIC project and should be based on the "referen
Group (EICUG) in the Yellow Report (YR) and included in the EIC Conceptual Design R
on the EIC community White Paper and the National
are expected to support most but not all of the acquisition of
Detector 1. It is currently planned to be located at Interaction Point 6 (IP6) on the Relativistic Heavy-Ion Collider

**Deadline for submission is December 1, 2021.**

ATHENA

**INFN participation**
in the ATHENA detector proposal

**convener of PID Working Group**
Roberto Preghenella

**member of election committee**
Pietro Antonioli

**co-authors from Bologna**
Agrawal Neelima, Antonioli Pietro
Baldanza Casimiro, Cappelli Laura
Cavazza Daniele, Chiarusi Tommaso
Falchieri Davide, Giacalone Marco
Giacomini Francesco, Margotti Anselmo
Noferini Francesco, Pellegrino Carmelo
Preghenella Roberto, Rignanese Luigi
Rubini Nicola, Strazzi Sofia

# Giornate Nazionali EIC_NET

Giornata nazionale EIC_NET 2019

**Bari, 2019**

**Frascati, 2020**
**online**


Giornata nazionale EIC_NET 2020


Giornata nazionale EIC_NET 2021

**Torino, 2021**

**Responsabile Nazionale**
Pietro Antonioli

**incontro annuale** in cui i gruppi INFN interessati alla futura sperimentazione a EIC in USA discutono **stato e prospettiva del coinvolgimento italiano** nel progetto scientifico internazionale

**first National EIC_NET day**
Bari, 7-8 November 2019

**last National EIC_NET day**
Torino, 20-21 December 2021

**next National EIC_NET day**
Catania, 30 June - 1 July 2022

# Thank you a tutte le persone che ci hanno supportato e aiutato


difficile riuscire ad elencare tutte le persone in Sezione che ci hanno supportato e aiutato senza dimenticarsi proprio di nessuno…

- **l'officina meccanica**
  vassoi per SiPM (Zucchini), sistema collimatore (Pancaldi), vecchio sistema movimentazione (Margotti), pannelliera per cavi (Furini), tappi camera climatica (Pancaldi), piastra carrier (Fadanni), collimatore LED (Furini)
- **il laboratorio elettronica e STG**
  realizzazione schede SiPM carrier (Baldanza), strumentazione e cavi (Travaglini, Torromeo), supporto setup di misura (Cavazza), realizzazione sistema DAQ (Falchieri)
- **l'amministrazione e i RUP**
  supporto spedizione materiale (Raimondi), ciclo acquisti (Travaglini, Margotti)
- **il gruppo CMS e altri colleghi**
  spazio nel loro laboratorio per allestire setup di misure "wating for" laboratorio silici (Guiducci, Giacomelli, Fabbri), consigli per camera climatica / essiccatore (Sbarra), strumentazione in prestito e consigli vari (Rinanese)
- **il Direttore e tutti coloro che si sono adoperati per il lab. silici**
  spazio ed equipaggiamento