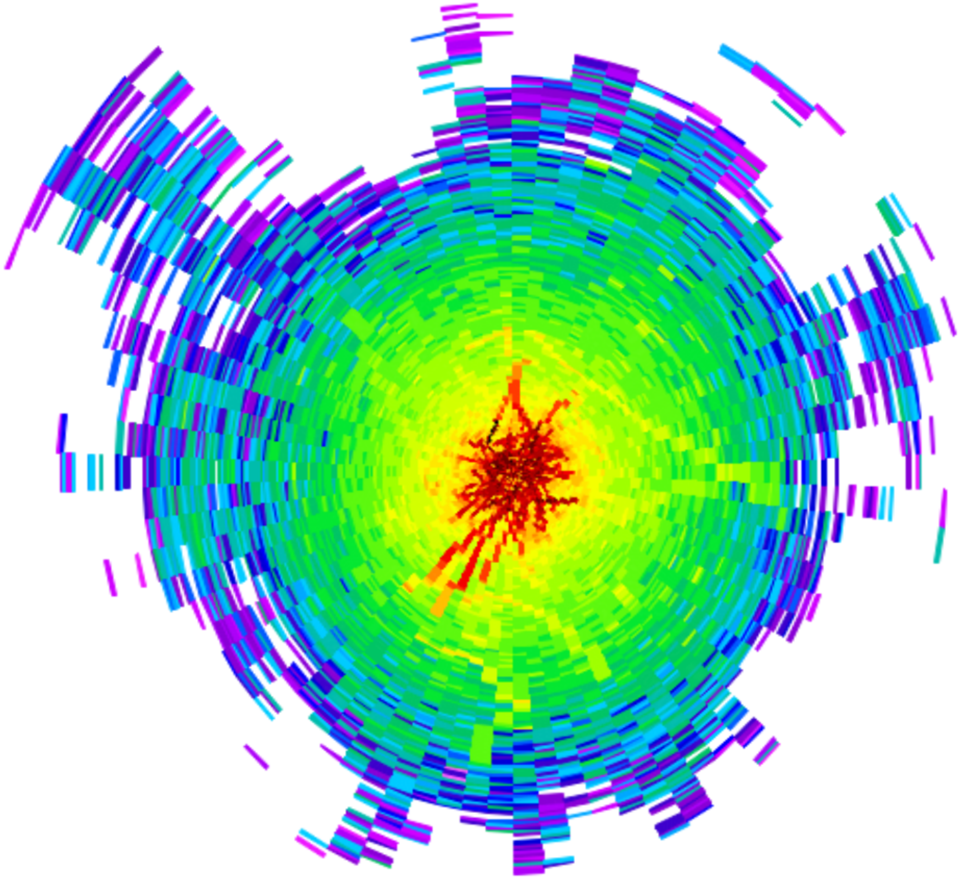
Gruppo2 activities @ LAE

A. Longhin

Univ. di Padova & INFN

CdL LNL, 6 May 2021



Gr2 @ PD

Fisica "dallo spazio" multimessenger,cosmology

EUCLID DE S. Dusini
CTA/MAGIC γ (Ch, terra) M. Mariotti
FERMI γ (CAL, sat) R. Rando
VIRGO GW L. Conti
ET J. P. Zendri

CUORE L. Taffarello
GERDA R. Brugnera

ββ0ν @ Gran Sasso

MOONLIGHT-2 P. Villoresi

Quantum science

QUAX G. Carugno

assioni

JUNO A. Garfagnini

Oscillazioni neutrini (reattori)

ICARUS A. Guglielmi
DUNE L. Stanco
T2K G. Collazuol
ENUBET F. Pupilli

Oscillazioni neutrini (acc)

Gr2 @ PD

LAE

Fisica “dallo spazio” multimessenger,cosmology

EUCLID DE S. Dusini
CTA/MAGIC γ (Ch, terra) M. Mariotti
FERMI γ (CAL, sat) R. Rando
VIRGO L. Conti
ET J. P. Zendri
GW

CUORE L. Taffarello
GERDA R. Brugnera
ββ0ν @ Gran Sasso

JUNO A. Garfagnini
Oscillazioni neutrini (reattori)
ICARUS A. Guglielmi
DUNE L. Stanco
T2K G. Collazuol
ENUBET F. Pupilli
Oscillazioni neutrini (acc)

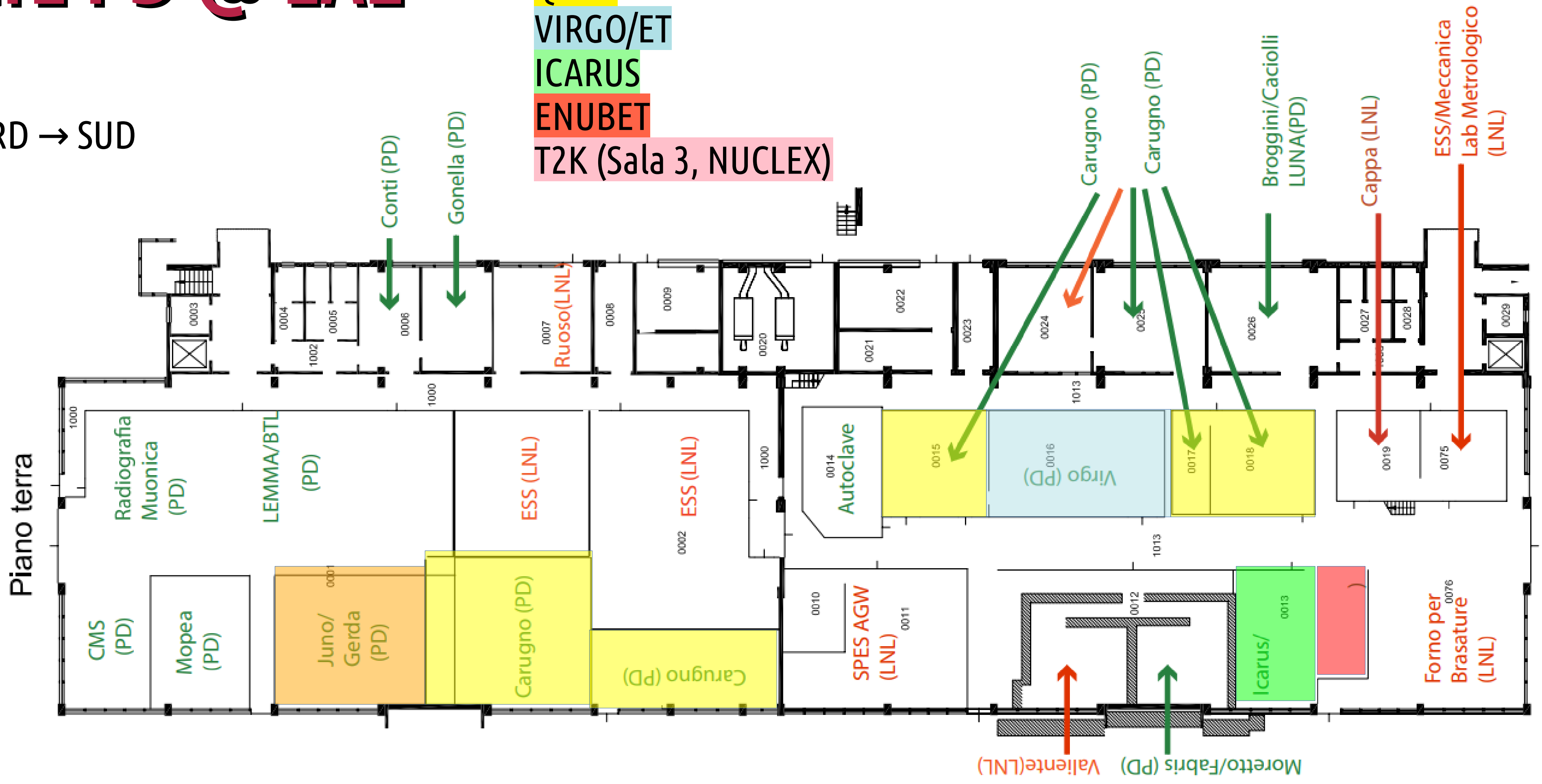
MOONLIGHT-2 P. Villoresi
Quantum science

QUAX G. Carugno
assioni

Gr2 PD @ LAE

JUNO/GERDA
QUAX
VIRGO/ET
ICARUS
ENUBET
T2K (Sala 3, NUCLEX)

NORD → SUD



Research group

Lab @INFN-LNL, HE building

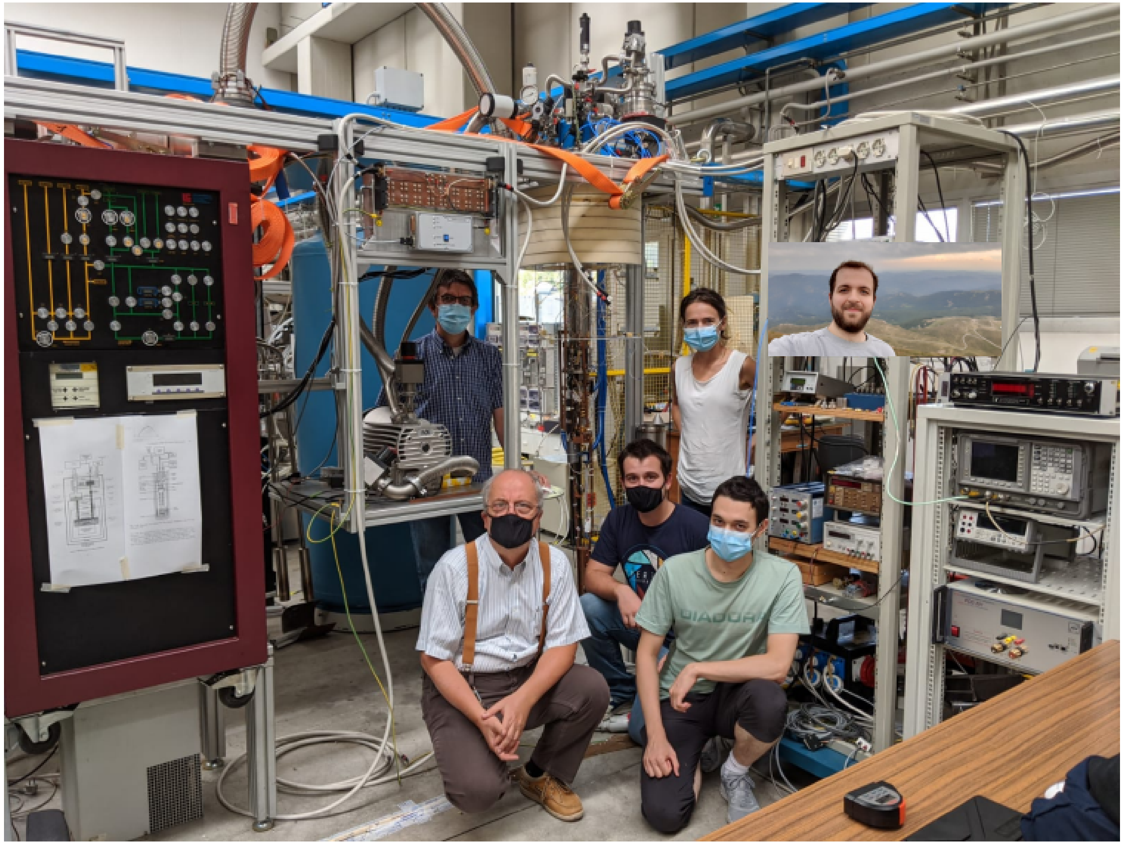
C. Braggio, DFA
G. Carugno, INFN-PD
A. Ortolan, G. Ruoso, INFN-LNL

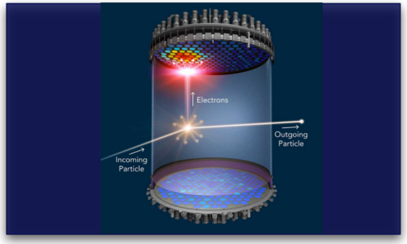
former PhD students: F. Chiossi, N. Crescini
PhD student: R. Di Vora

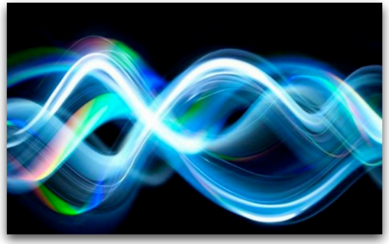
FUNDING ID:

QUAX	INFN-CSN2	2021-2025
SQMS	DOE, USA	2020-2024
TERAPOL	INFN-CSN5	2021-2022
ATTRACT	EU	2019-2020
SUPERGALAXY	FET-EU	2020-2024
DEMIURGOS	INFN-CSN5	2019-2021

QUAX







WIMP [1-100 GeV]
– number density is small
– tiny wavelength
– no detector-scale coherence

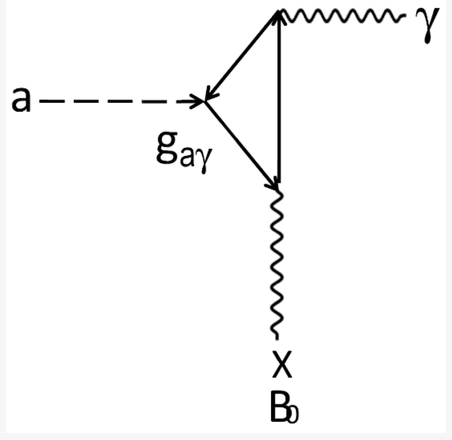
⟹ observable: **scattering** of individual particles

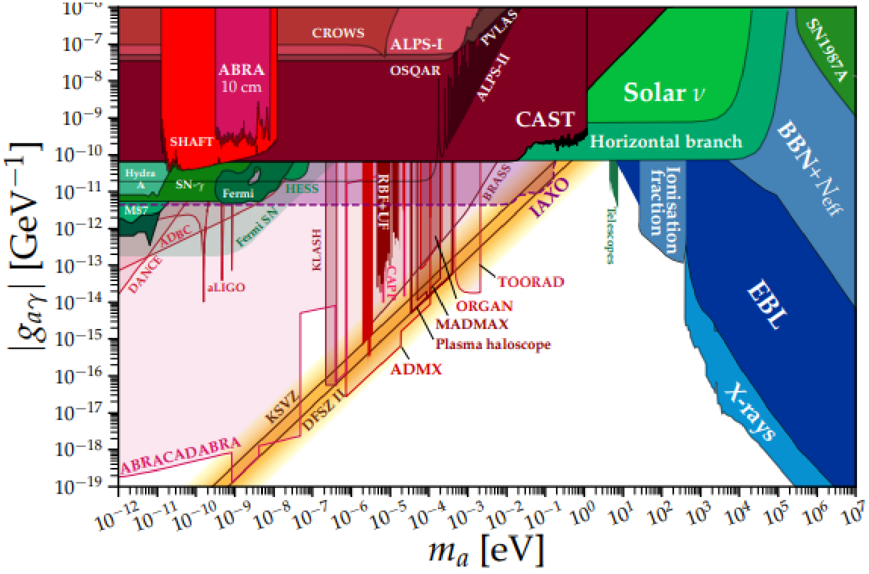
AXION [$m_A \ll$ eV]
– number density is large (bosons)
– long wavelength
– coherence within detector

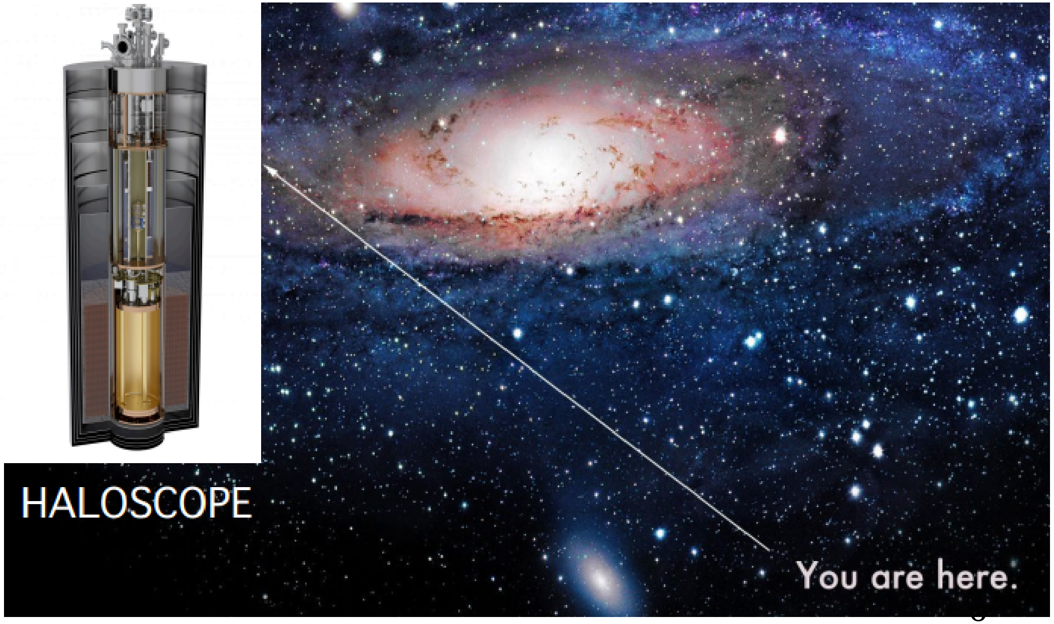
⟹ observable: classical, oscillating, **background field**

→ search for axion DM in the Galactic halo
→ the axion: weakly interacting, light particle
→ it manifests as an AC effective field

inverse Primakoff effect → axion-induced excess photons inside a microwave cavity in a static magnetic field



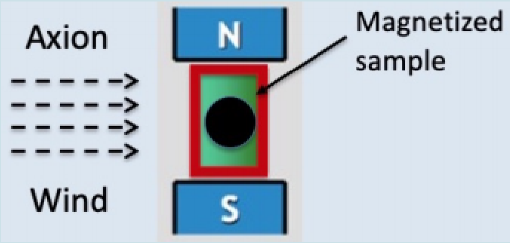




QUAERERE AXIONS: working principle

Detection of cosmological axions through their **coupling to electrons** or **photons**

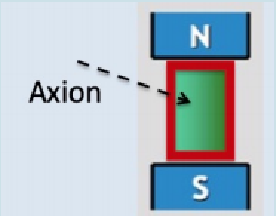
ELECTRON COUPLING – **QUAX**



the axion DM cloud acts as an **effective RF magnetic field** on the electron spin exciting **magnetic transitions** in a magnetized sample (YIG) $\rightarrow$ **RF photons**

$$P_{ax} = 3.3 \cdot 10^{-24}\,\mathrm{W} \left(\frac{V_{\mathrm{eff}}^{\mathrm{Sa}}}{2.3 \cdot 10^{-5}\,\mathrm{m}^3}\right) \left(\frac{B}{8\,\mathrm{T}}\right)^2 \times \left(\frac{g_\gamma}{-0.97}\right)^2 \left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm}^{-3}}\right) \left(\frac{f}{13.5\,\mathrm{GHz}}\right) \left(\frac{Q_L}{145\,000}\right)$$

PHOTON COUPLING – **QUAX** aγ

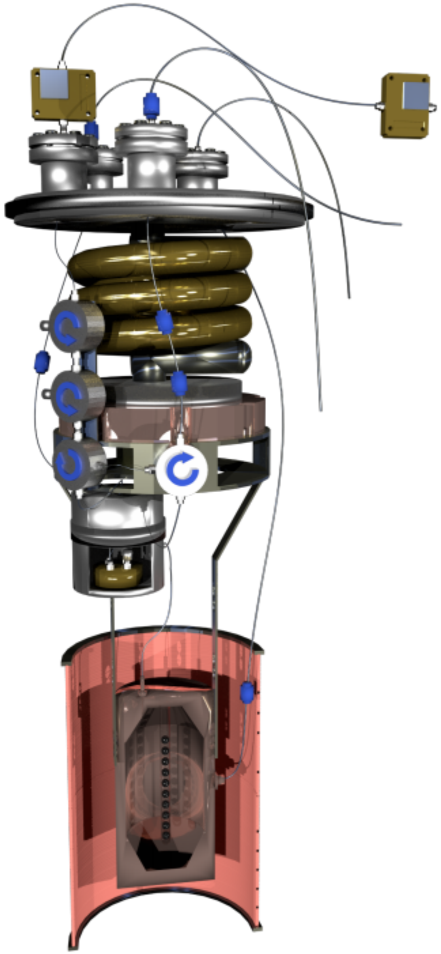


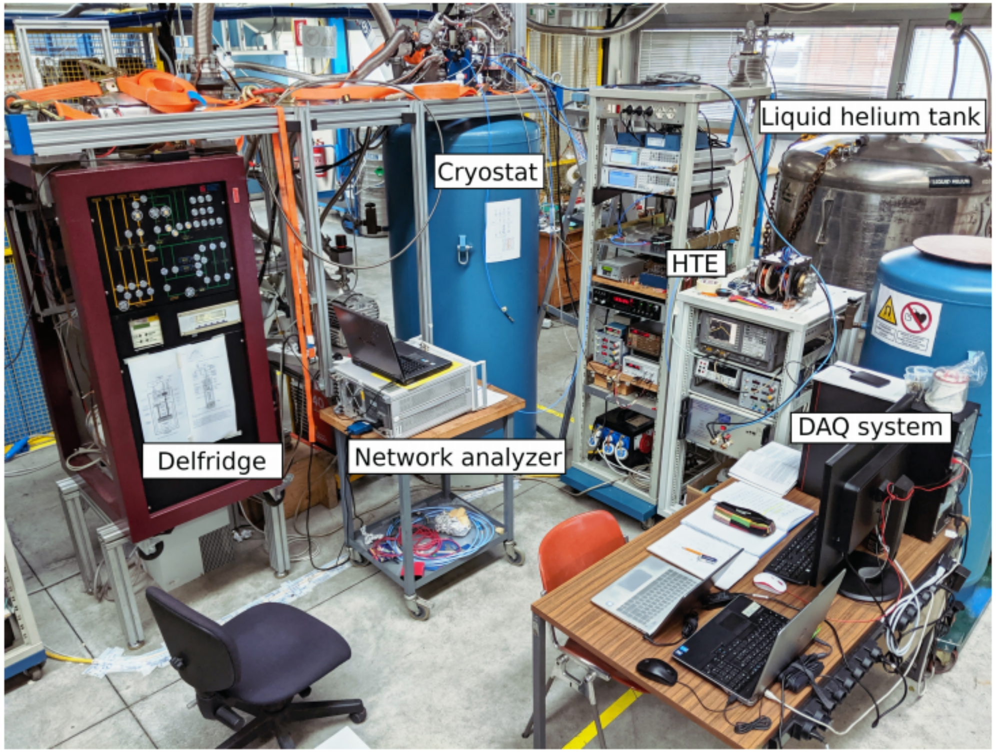
DM axions are converted into **RF photons** inside a **resonant cavity** immersed in a **strong magnetic field**

$$P_{out} = \frac{P_{in}}{2} = 8 \times 10^{-26} \left(\frac{m_a}{2 \cdot 10^{-4}\,\mathrm{eV}}\right)^3 \left(\frac{V_s}{1\ \mathrm{liter}}\right) \left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right) \left(\frac{\tau_{\min}}{10^{-6}\,\mathrm{s}}\right)\ \mathrm{W},$$

Nicolo’ Crescini: Premio Rossi 2021 per il PhD (presentazione recente in CSN2) →

https://agenda.infn.it/event/26309/contributions/133542/attachments/80685/105460/ncrescini_brunoRossi_030920.pdf

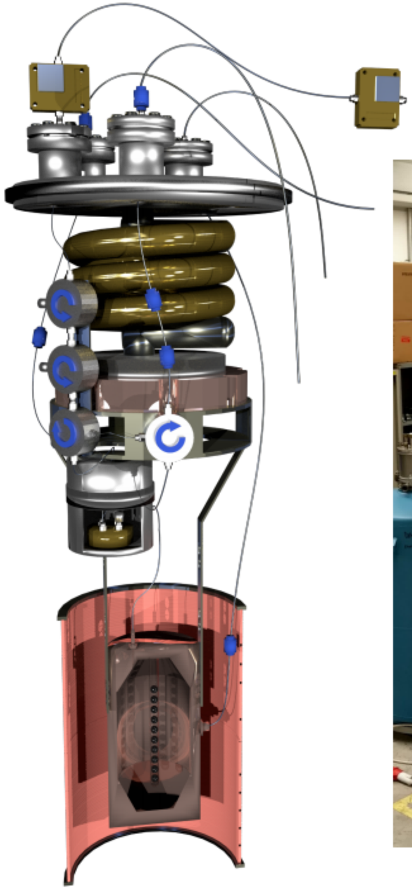


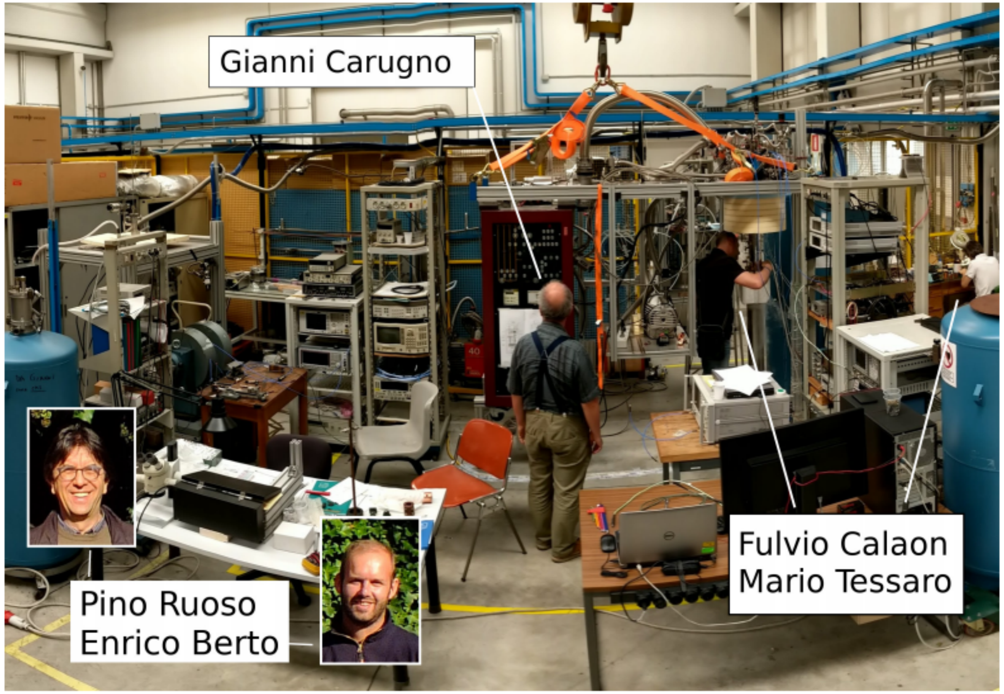


8

Nicolo’ Crescini: Premio Rossi 2021 per il PhD (presentazione recente in CSN2) →

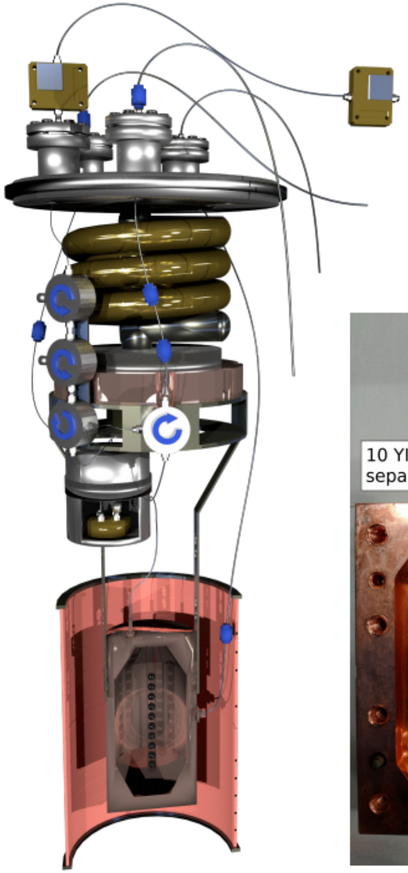
https://agenda.infn.it/event/26309/contributions/133542/attachments/80685/105460/ncrescini_brunoRossi_030920.pdf

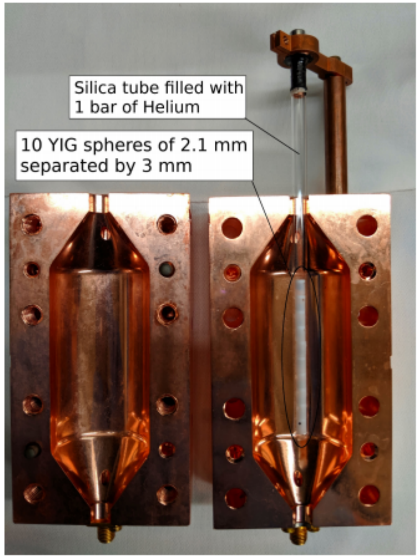


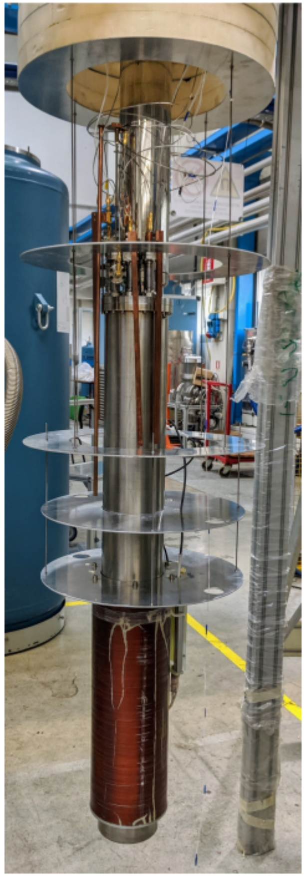


Nicolo' Crescini: Premio Rossi 2021 per il PhD (presentazione recente in CSN2) →

https://agenda.infn.it/event/26309/contributions/133542/attachments/80685/105460/ncrescini_brunoRossi_030920.pdf





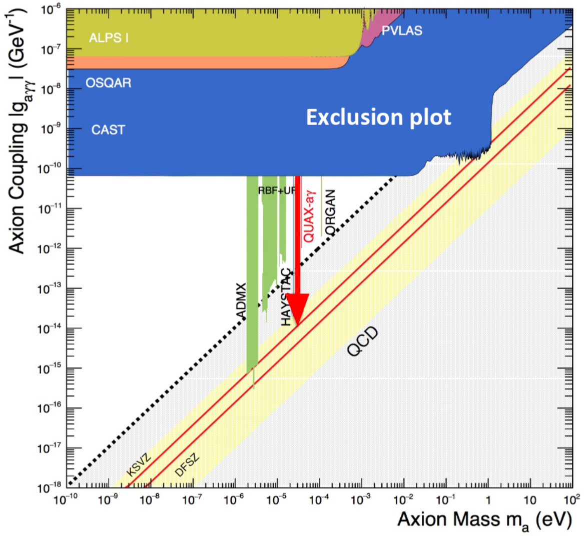


10

QUAX: physics results

QUAX-ag : axion-photon coupling

Results obtained by the QUAX-aγ set-up are competitive with other experiments



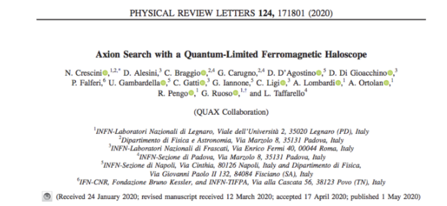
First test with JPA in 2020 reached a **sensitivity of 3 x KSVZ** in a sharp window -> **article in preparation**

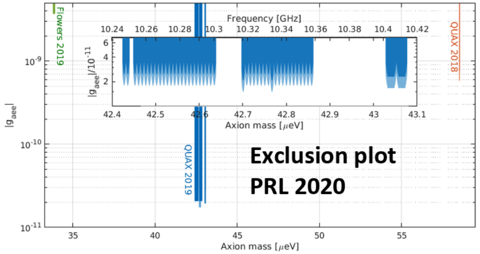
QUAX-aγ will start **a search with mass scanning** employing the **Josephson Parametric Amplifier** and a **higher Q cavity**

3

QUAX limit on axion electron coupling

2018	First limit in the parameter space $\{m_a, g_{aee}\}$ obtained from an experiment searching for axions as the main Dark Matter component (Haloscope) → EPJC 78:703 (2018)
2019/20	First operation of a ferrimagnetic haloscope with mass scanning through magnetic field tuning ⍰ PRL 124, 171801 (2020)





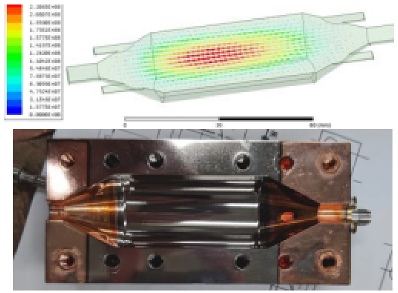
	QUAX 2018	QUAX 2019/20	QUAX (final)
• Material volume	2.6 mm^3	**42 mm^3**	10^5 mm^3
• System total noise temp.	15 K	**1 K**	counter (T_{eff} <1 mK)
• Relaxation time	0.1 ms	**0.3 μs**	2 μs

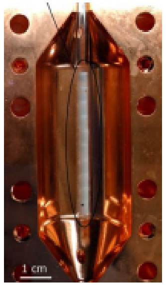
Set-up with 10 YIG spheres giving 42 mm^3 of volume and JPA readout, field sensitivity 5 10^{-19} T

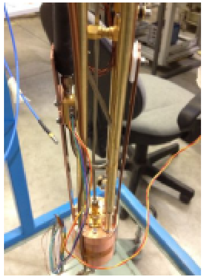
QUAX e' passato da un R&D (nato in seno a WhatNext) a essere un esperimento finanziato dalla CSN2 per produrre risultati di fisica. Nuovo magnete a 14 T. Migliorie nella criogenia.

QUAX: activities in the laboratory

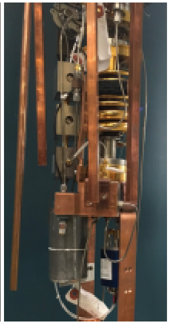
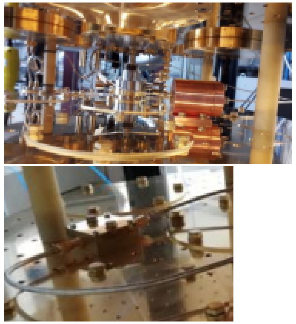
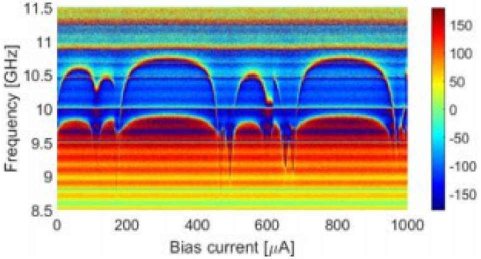
- we develop **high Q** ($\gtrsim 10^6$) microwave cavities, compatible with **strong magnetic fields** ($B \gtrsim 8\,\mathrm{T}$)

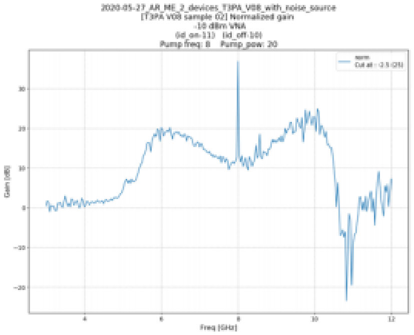




- **we use the best preamplifiers (research, not commercially available)** $\rightarrow$ JPA (Josephson Parametric Amplifier) key element in **qbit** readout, TW (Travelling Wave) JPA (thanks to collaboration with N. Roche, Grenoble)



12

QUAX: expertise and other activities

QUANTUM SENSING	JPA (Josephson Parametric Amplifiers) amplifiers, SQUID, TW JPA, microwave SPD (single photon detector)
Microwave resonators	photonic cavities, hybrid (magnon-photon) systems, NC and SC cavities (Nb and type II SC)
LASER systems LAB (former ALICE clean room)	Femtosecond and picosecond mode-locked lasers, CW tunable narrow linewidth Ti:Sa lasers, MOPA lasers
CRYO TESTBEDS	dilution refrigerators (mK), superfluid He vessel, liquid helium cryosystems, pulse tubes (> 4K)
MATERIALS SCIENCE	RE (rare-earth) doped materials, YIG (Yttrium Iron Garnet), AF-TI (Antiferromagnetic Topologic Insulators), SC
Magnetic fields	2T, 8 T SC magnets — 14T to come!

More initiatives

SUPERGALAX

Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.

Part of SQMS: the US Quantum Technology initiative

13

Experimental activities of Virgo and ET at LNL

wide array of experimental investigations and technological developments in support of Gravitational Wave detectors

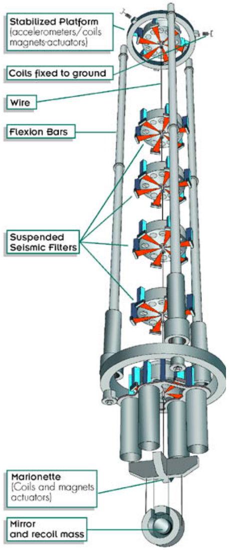
INFN and Uni Padova : Bazzan, Bonavena, Bordignon, Chiarini, Ciani, Conti, Zendri & undergrads

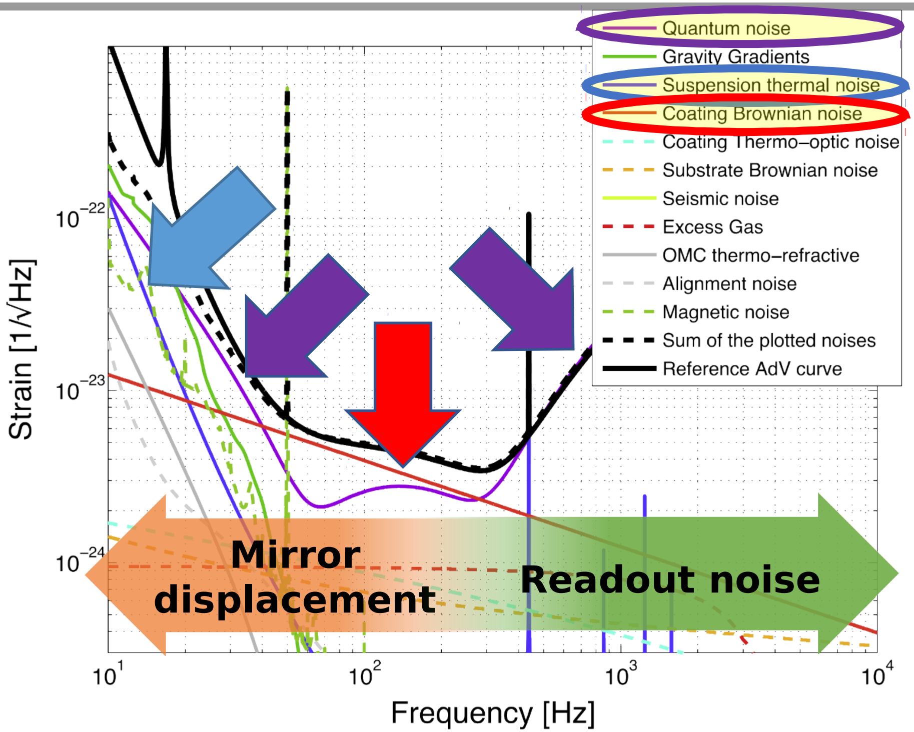
TIFPA and Uni Trento : Grimaldi, Perreca

VIRGO

ET EINSTEIN TELESCOPE

Gravitational wave detectors and their enemies





Two main challenges:
Measure vanishingly small displacements
Make sure the displacements is from gravitational waves only!

The Virgo&ET laser lab at LAE@LNL

4 benches/experiments:

Virgo related (@1064nm)

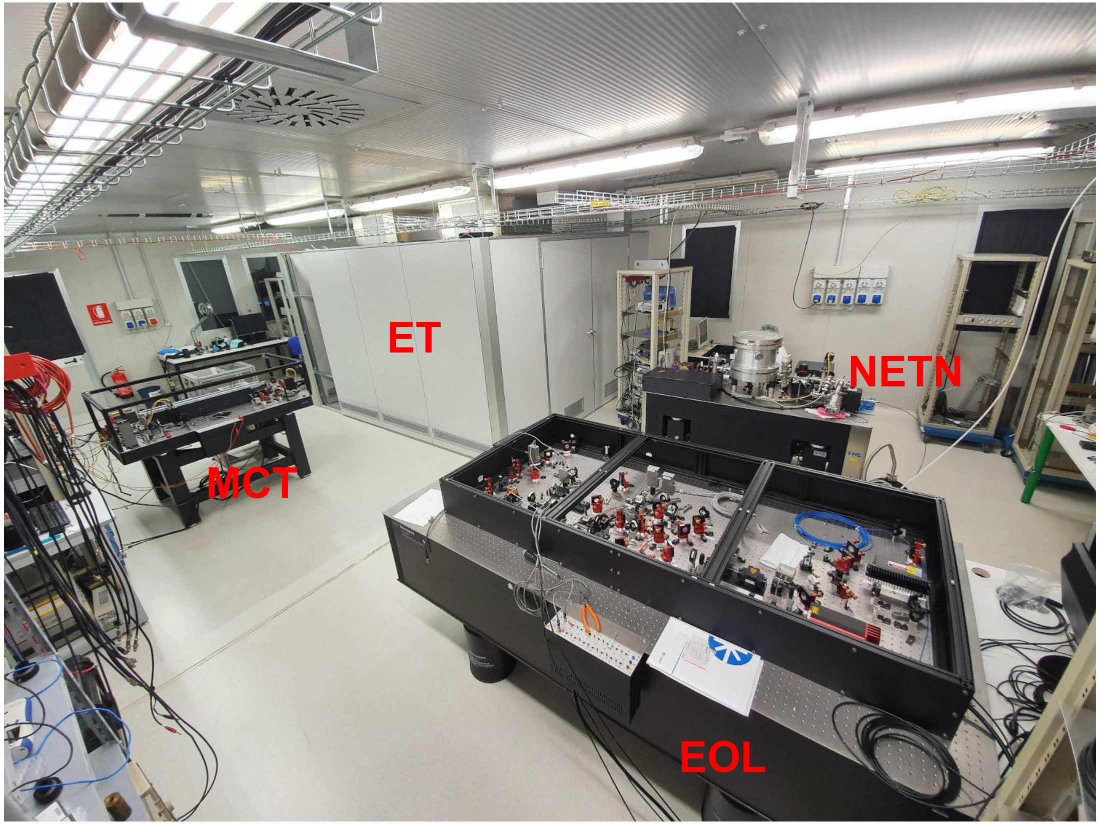
1. Electro-optical lens : EOL
2. Mode-converter telescope: MCT

Einstein Telescope related (@1550nm)

3. Cryogenic characterization of materials: ET

Transversal to both Virgo & ET (@1064nm)

4. Non-equilibrium Thermal Noise: NETN



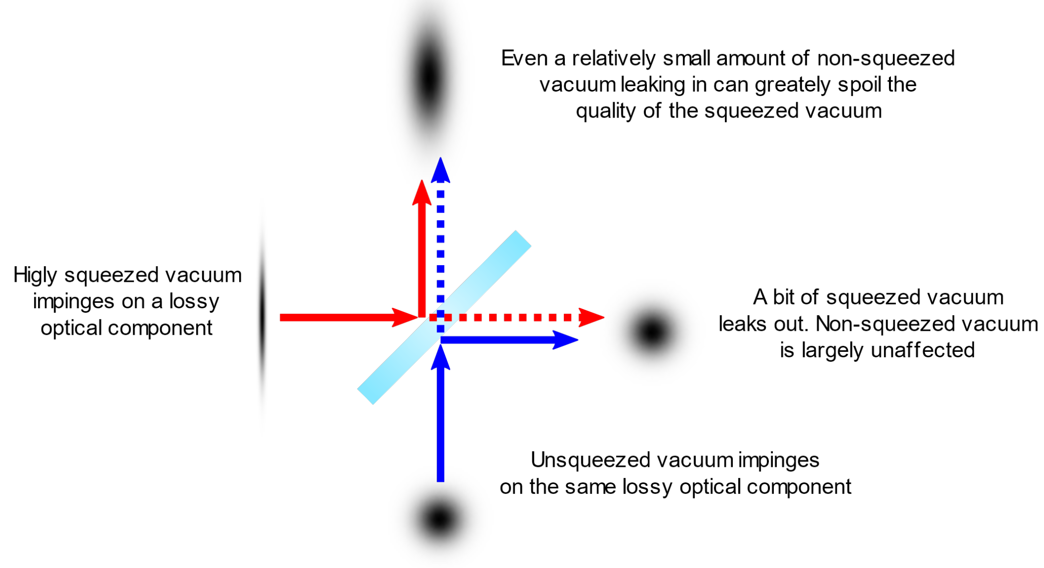
Main strength and expertise:

- Laser optics
- Opto-electronics
- adaptive optics (not the "astronomical" type…)
- Fast/quiet electronics
- Optical materials
- Cryogenics

Electro-optic lens & Mode-converter telescope

Advanced Virgo employs Squeezing (SQZ) since the run O3 (ie from 2019).

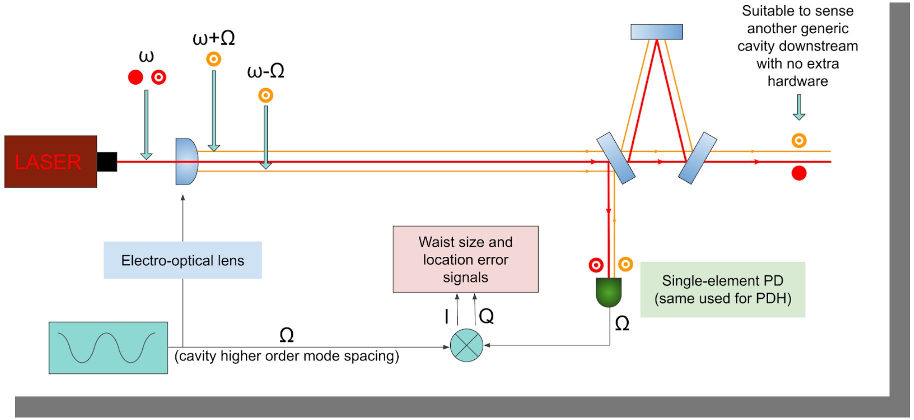
Optical losses are of major concern for SQZ as they couple (non-squeezed) quantum fluctuations thus spoiling the quality of squeezed vacuum. To reduce losses, the sqz states need to be mode-matched to the interferometer beam.



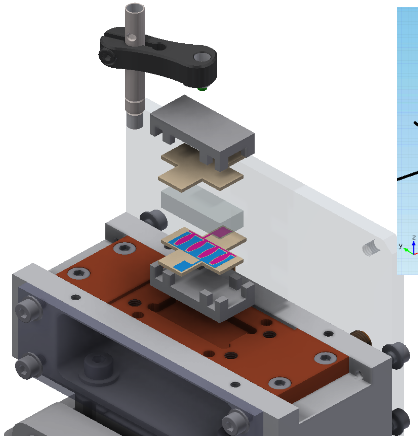
We are developing 2 technologies for sensing (and correcting) the mismatch, for the next run O4 of Advanced Virgo. The goal is to reduce to <3% the optical losses due to mode mismatch (now order 10%)

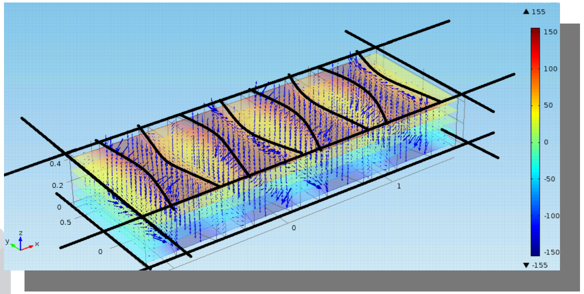
Electro-Optic Lens

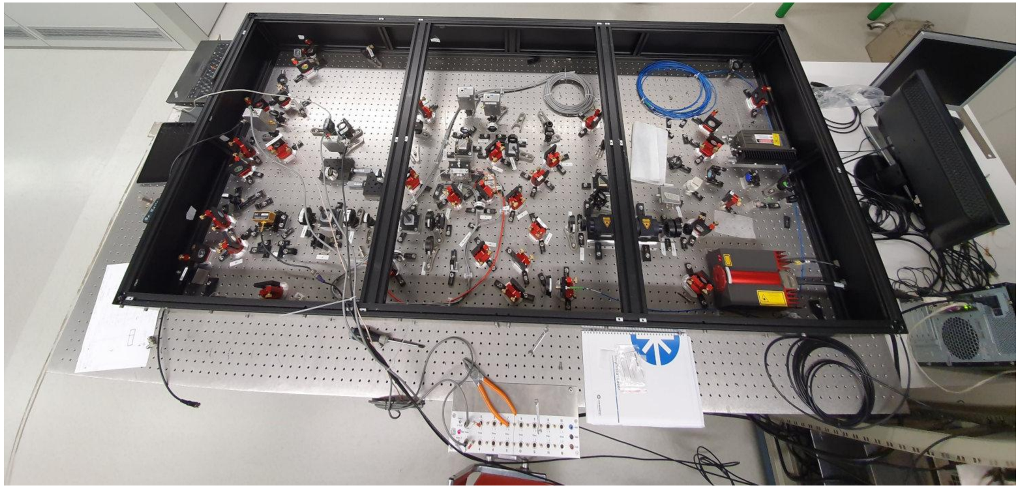
Development of an innovative technique for sensing the mode mismatch between an optical cavity and a laser beam



The technique is based on the realization of a custom electro-optical lens, capable of changing focal length at frequencies up to ~100 MHz





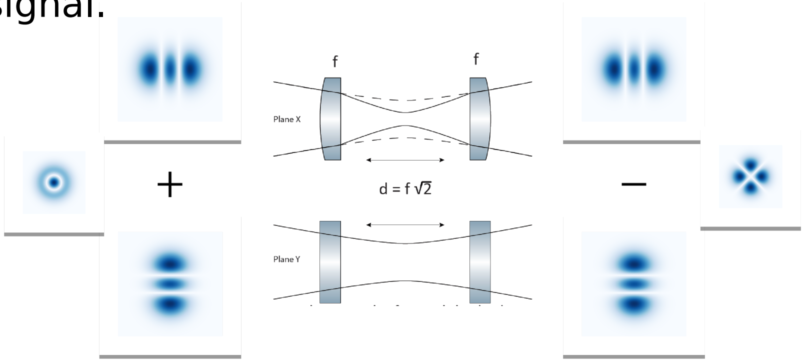


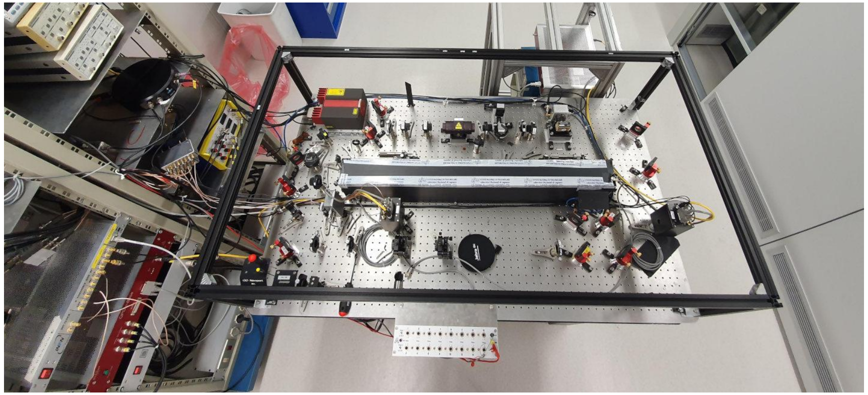
Mode Converter Telescope and Actuator

TIFPA collaboration

The sensor

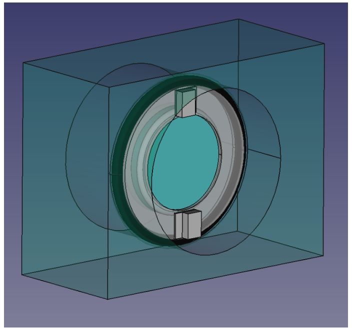
Testing an astigmatic telescope configuration that allows to optically convert the LG10 mode to and HG11 and to use the standard Quadrant Photodiode to detect the Mode mismatch error signal.

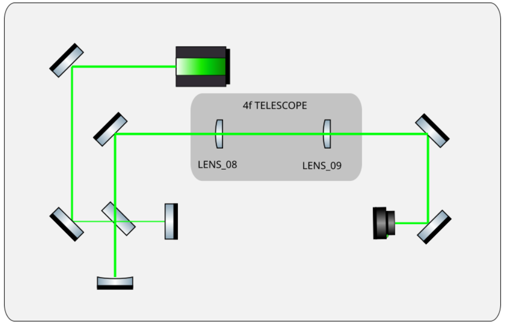




The actuator

We are developing a new optical actuator based on a thermomechanical deformation of mirrors.





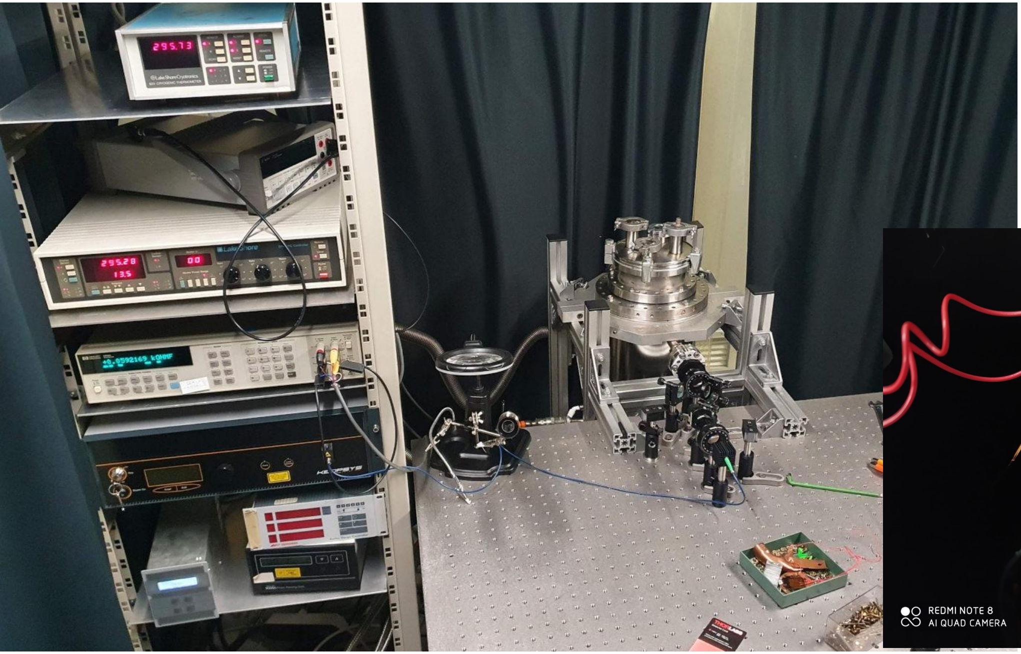
The curvature characterization of this actuators will be performed at LNL, using a compact Shack-Hartmann setup.

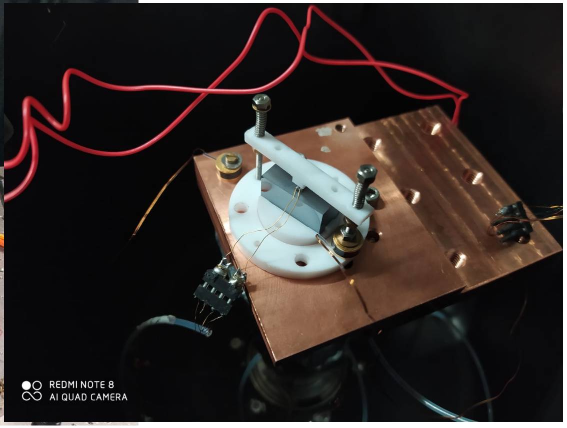
Cryogenic characterization of materials for ET

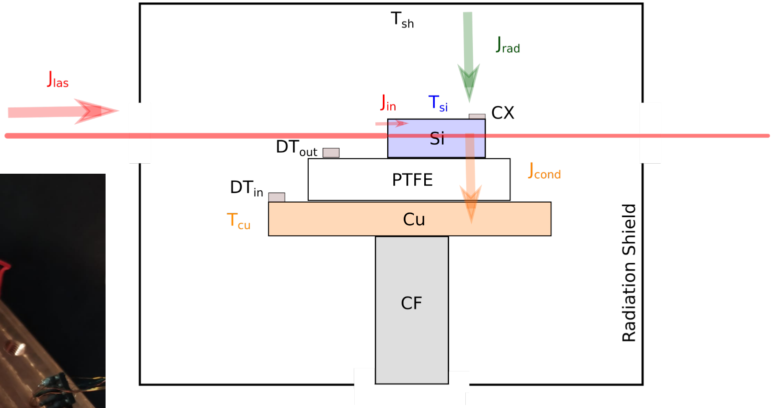
To lower thermal noise, Einstein Telescope will use cryogenics: this requires new materials and lasers. Silicon is a good candidate material at cryogenic T, but it is not transparent to the wavelength (1064nm) used in Virgo-Ligo-Kagra! Need to move to 1550nm: optical properties unknow at the level needed for GW detectors

@LAE: facility to test optical grade silicon samples from different manufacturers/processes.

- Assessing optical absorption by means of bolometric measurements

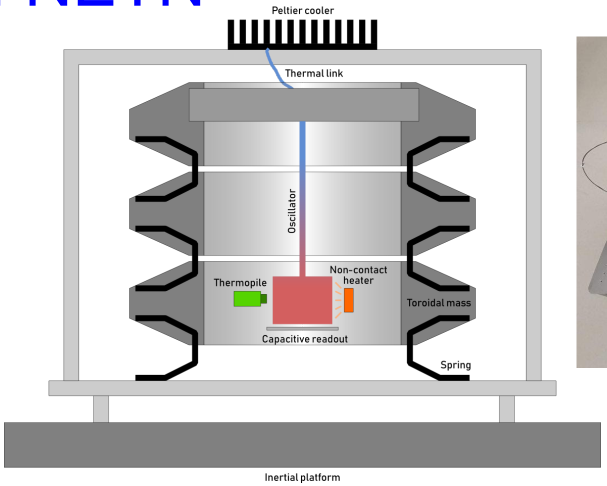


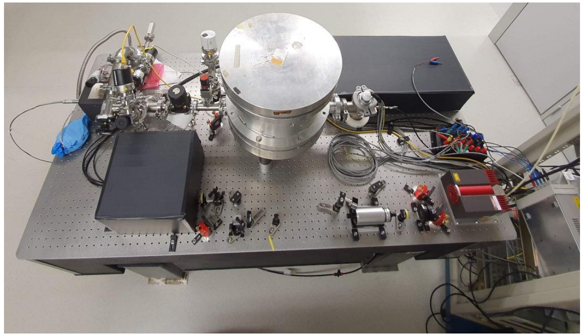


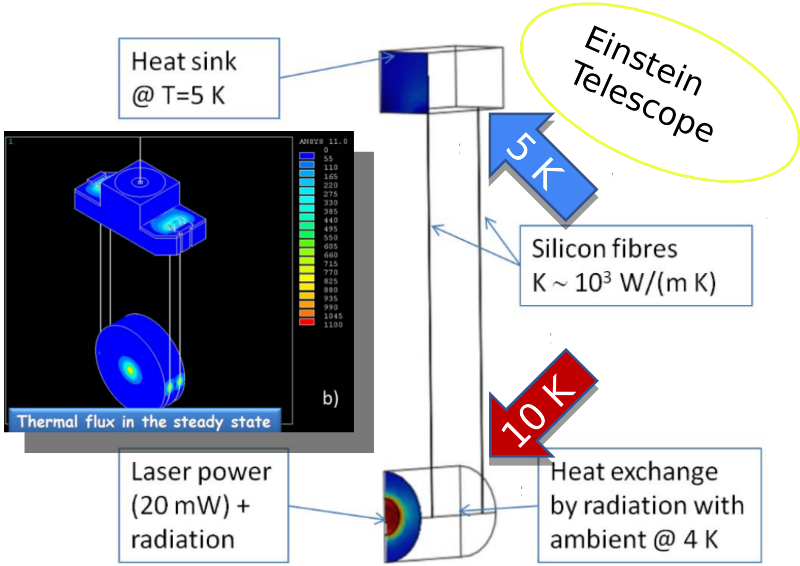


Non-equilibrium Thermal Noise: NETN

- Thermal noise is well understood and measured in terms of Fluctuation-Dissipation Theorem (FDT)
- FDT assumes thermodynamic equilibrium
- Not a valid assumption in many experiment!
- No valid theory to describe non-equilibrium

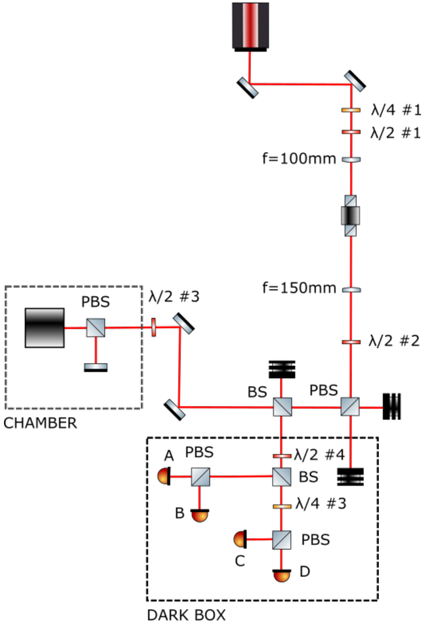






@LAE : Facility with thermal-noise limited macroscopic oscillator; ability to control thermal gradients

- Objectives:
  - Measurement of TN out of equilibrium
  - Establish a phenomenological base to help develop a viable theory
- Collaborations:
  - Experimentalists @ENS Lyon
  - Theoreticians @DFA, PoliTo and University of Luxemburg

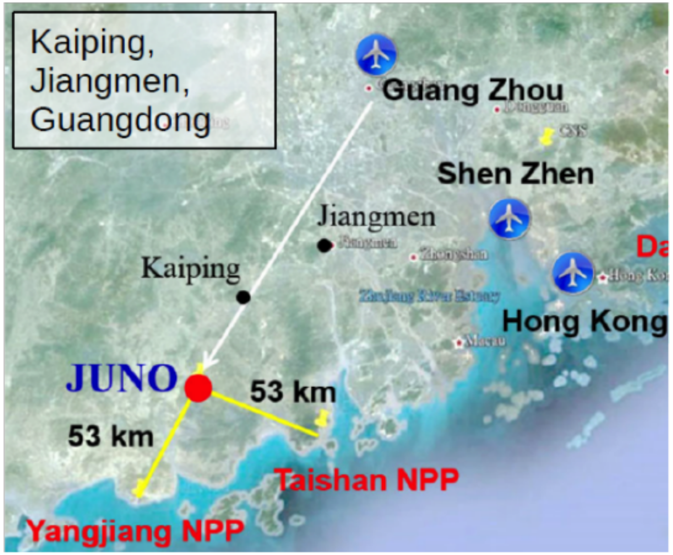


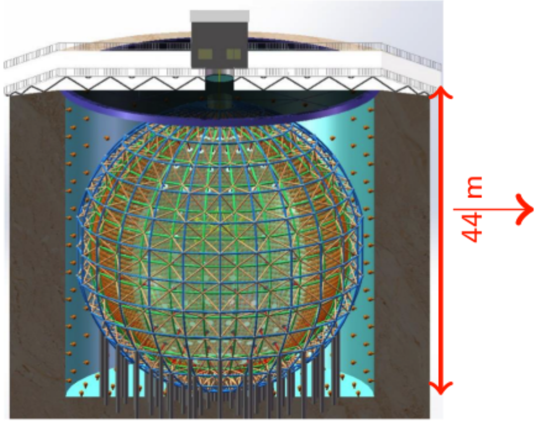
JUNO

669 members from **17** countries and **77** institutes

Jianmeng Underground Neutrino Observatory (JUNO) in one slide

- the largest ever built liquid scintillator (LS) detector for neutrino and rare events physics (including dark matter)
- main target : determination of the neutrino mass hierarchy, one of the still unanswered questions in neutrino physics
- thanks to the large mass (20 kt) and overburden (700 underground), JUNO will be able to exploit several neutrino physics channels





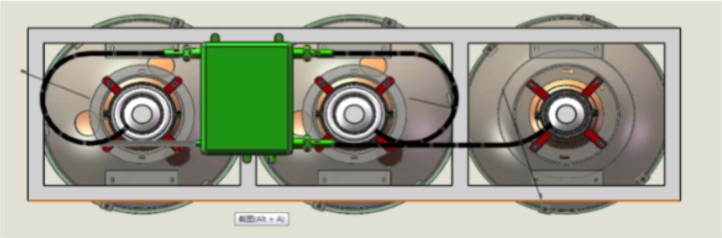
20 kton LS detector
700 m overburden
3% energy resolution (@1 MeV)
20000 large PMTs (20")
25600 small PMTs (3")
supernova neutrinos
geo-neutrinos
proton decay searches

https://arxiv.org/abs/2104.02565

JUNO

JUNO largePMT Electronics Readout Scheme

LPMT installation module



electronics designed by INFN-Padova
developed and tested in parternship
with IHEP-Beijing

project co-funded by MAECI (Italy)
and NSFC (China)

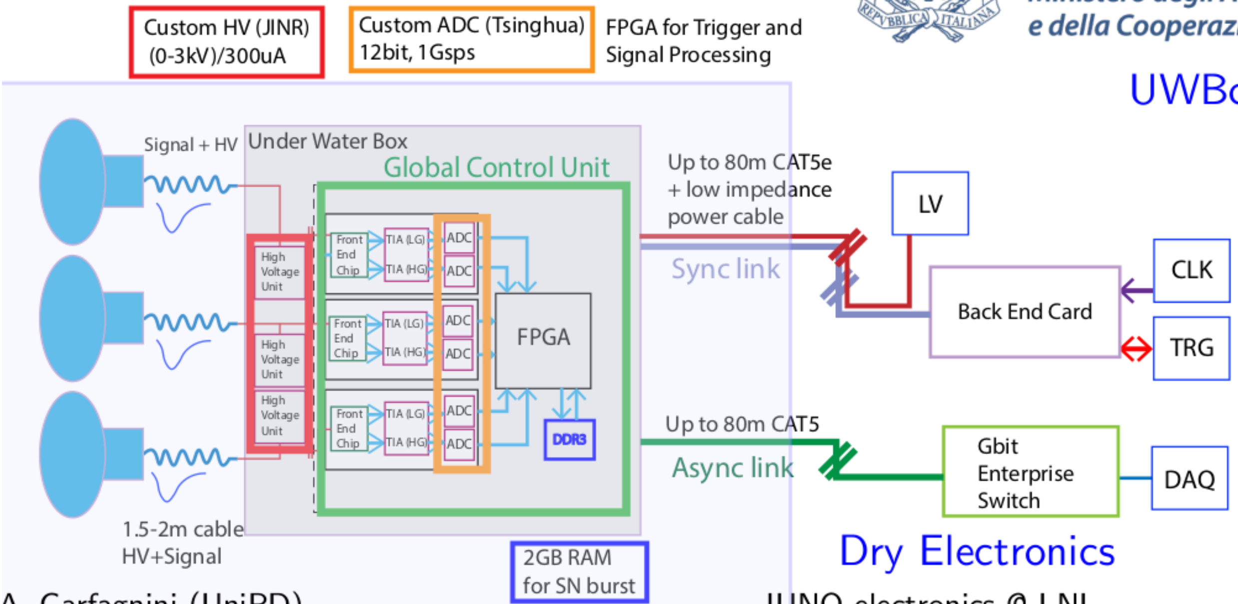
Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

Padova responsible of firmware.

Design of the electronics.

Big investment of CSN2 on the electronics

Under Water Electronics



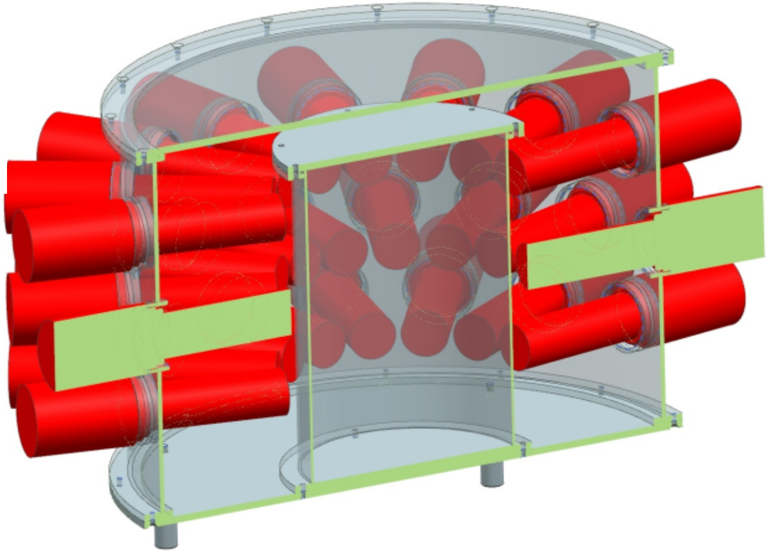
UWBox with electronics

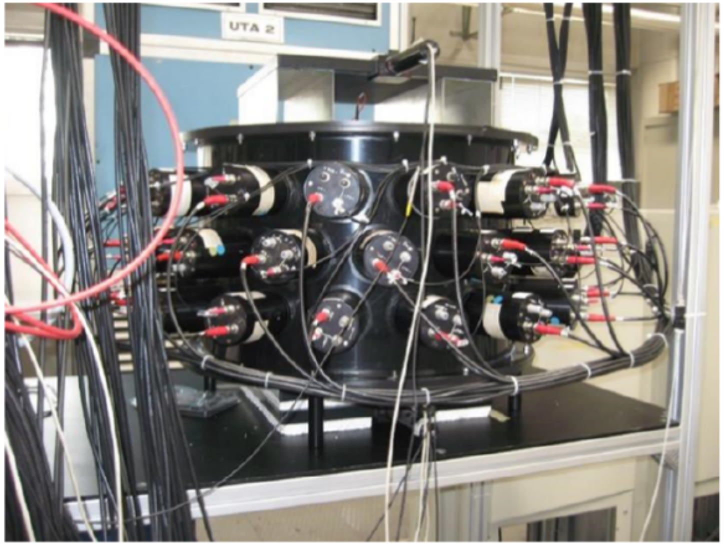
JUNO

JUNO Electronics Test Setup in Legnaro

- developed and built to test, debug and characterize the final JUNO electronics
- it consists of

- about 17 liters of Linear-Alkyl-Benzene (LAB) liquid scintillator
- 48 Philips XP2020 (diameter of 2") PMTs with their bases
- 3 plastic scintillators for external cosmic rays trigger
- a black support structure to reduce external light going inside the system

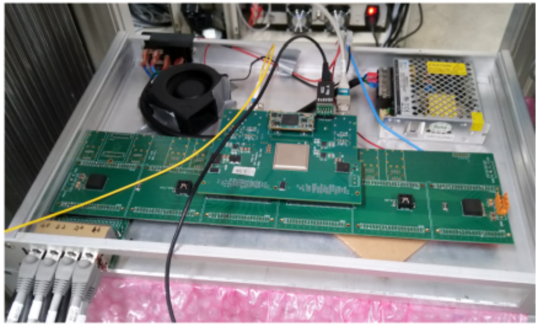




JUNO

JUNO electronics LNL test setup

BEC + TTIM



39 PMT channels acquired by 16 GCUs
All GCU SYNC outputs connected to one BEC/TTIM
Trigger validation inside TTIM
All GCU ASYNC outputs connected to GBit Enterprise Switch → two 40 GBit optical fiber uplink to DAQ server

GCU v2.4 inside cooling box

JUNO LNL setup : PMT calibration

- picoseconds laser pulses are ntroduced in the setup using an optical fiber
- it provides light at 405 nm and it is used to calibrate the PMT gain (with single p.e.)
- an additional LED is controlled with an external, tunable, square pulse

USLASERS

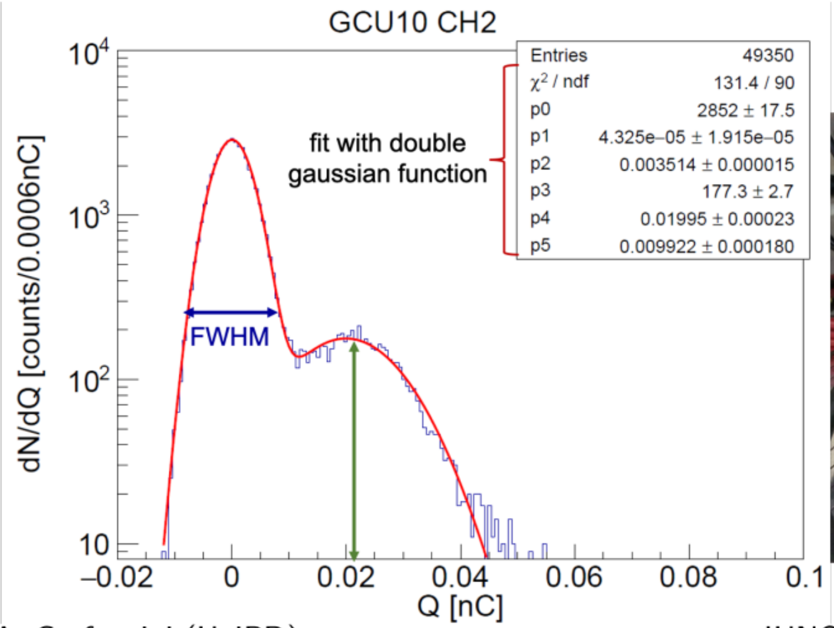
D405-20 • 405nm 20mW laser diode•

Features

- Device: 405nm laser diode
- Power: 20mW
- Package Type: 5.6mm TO
- PIN configuration Style B

• Absolute Maximum Rating (Tc=25°C)

Characteristics	Symbols	Rating	Unit
Optical power	Po	20	mW
Reverse Voltage (Laser)	V	2	V
Reverse Voltage (PIN)	V	30	V
Operating Temperature	Top	-10 to +70	°C
Storage Temperature	Tstg	-40 to +85	°C

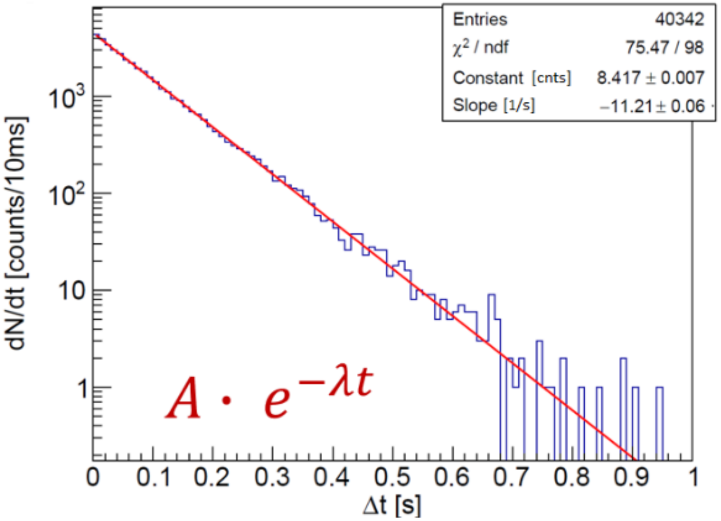


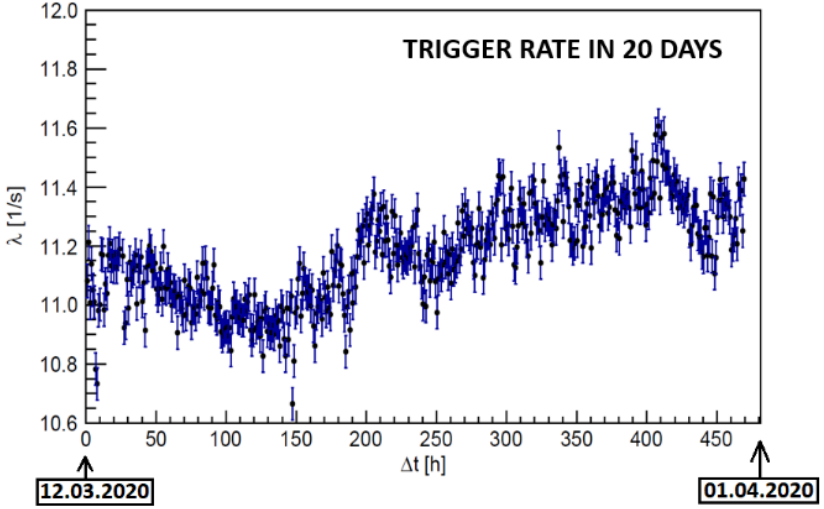
JUNO

1) Long term running with cosmic muons

System stability test

- several long runs (up to few months) have been collected
- selecting cosmic muons traversing our detector
- events are grouped (1 hour) based on timestamp
- time difference between consecutive events is fitted by simple exponential
  $\rightarrow$ trigger rate is extracted and plotted over time
- study: stability of the system (baseline, noise, synchronization)





JUNO

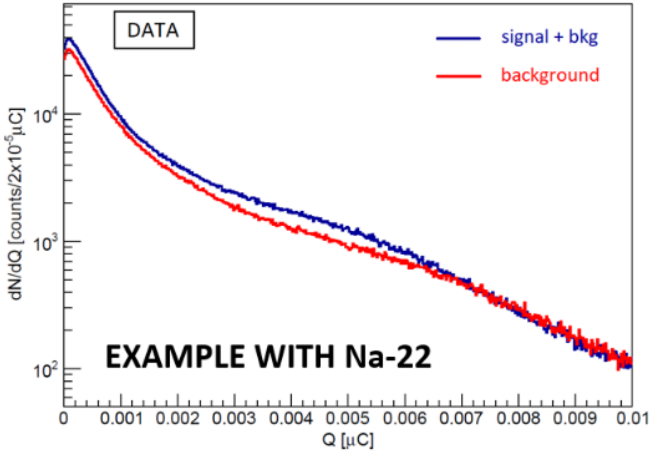
3) Calibration with γ sources

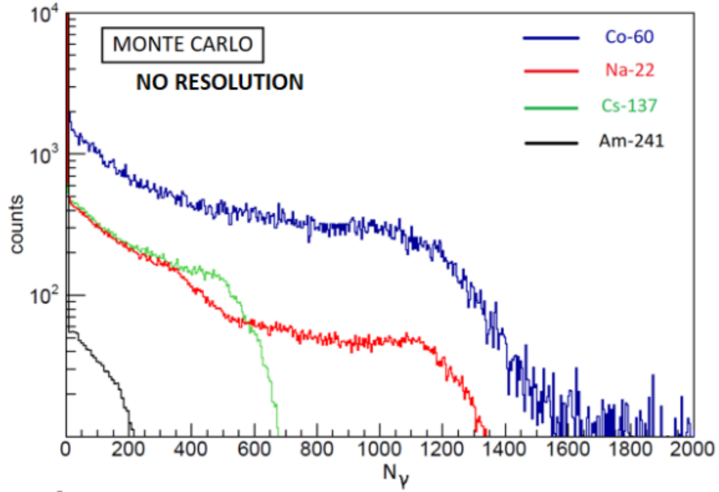
Sum over all channels

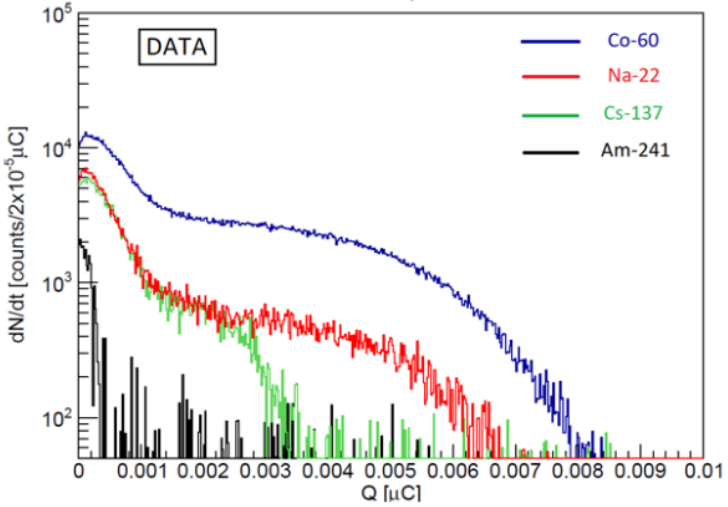
Measurements with the apparatus

- due to the small size of the LS vessel, no full-energy peak is detected
- calibration is based on the Compton continuum edge
- Trigger: OR of 3 PMT channels. Threshold: 6σ

1 acq. w/o any radioactive source ν: 1.97kHz
4 with different sources: Am-241 (ν: 2.00kHz), **Cs-137** (ν: 2.45kHz), **Na-22** (ν: 2.39kHz), **Co-60**(ν: 3.30kHz)







JUNO

3) Calibration with γ sources

Measurements with the apparatus

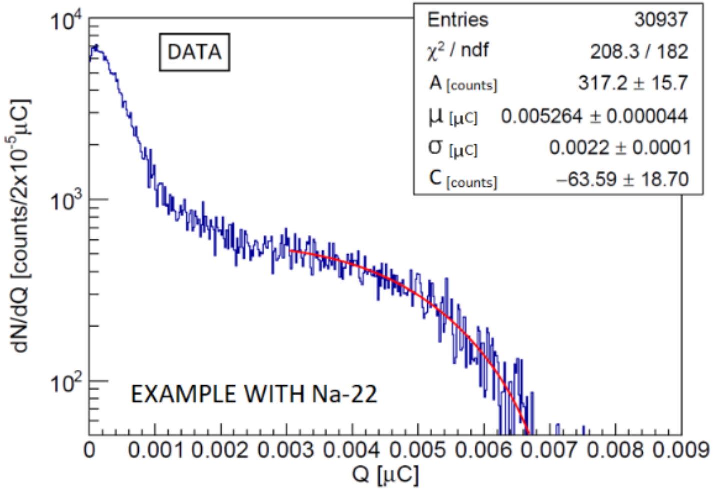
- calibration is based on the Compton continuum edge:

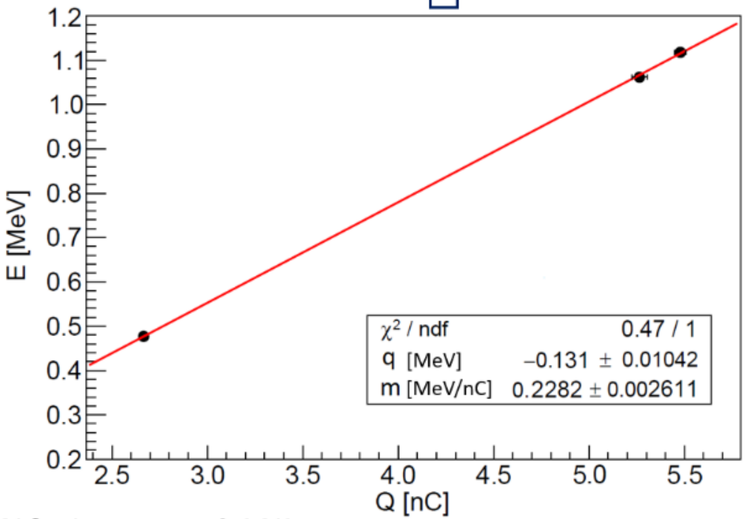
$$\max(E_e) = \frac{2E_\gamma^2}{2E_\gamma + m_e}$$

- the Compton edge energy, E_e is extracted with a fit using the complementary error function

source	A [counts/$2 \cdot 10^{-5} \mu$C]	μ [$10^{-5} \mu$C]	σ [$10^{-5} \mu$C]	C [counts/$2 \cdot 10^{-5} \mu$C]	$E_{e,max}$ [keV]
^{137}Cs	359 ± 9	267 ± 2	82 ± 3	9 ± 4	477
^{22}Na	317 ± 16	526 ± 4	220 ± 10	-64 ± 19	1062
^{60}Co	1225 ± 8	548 ± 3	180 ± 4	12 ± 8	1118

$$Erfc(x) = \frac{2A}{\pi} \int_{\frac{x-\mu}{\sigma}}^{\infty} e^{-t^2} dt + C$$





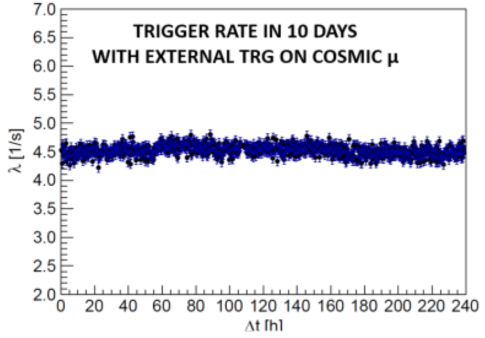
JUNO

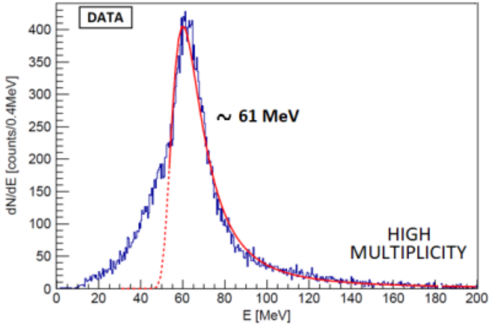
4) Extrapolation to μ deposited energies

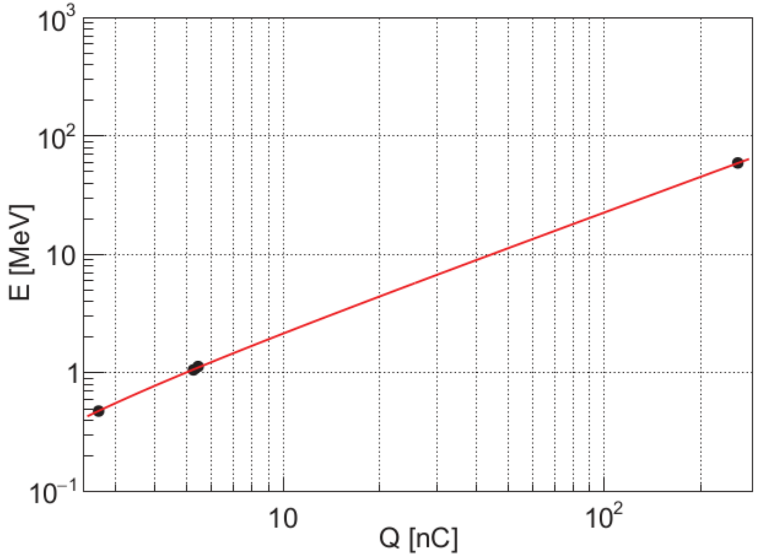
New μ measurement

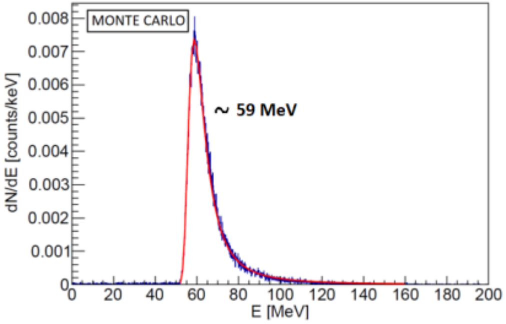
- a new 10 days long runs with external trigger was performed
- reconstructed charge has been compared to the Monte Carlo prediction
- the average reconstructed charge fit perfectly with the γ calibration data $\rightarrow$ fantastic linearity of the apparatus and of the electronics

Fit at low-E (sources) estrapolated to 60 MeV with perfect match









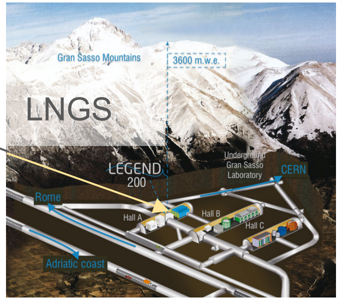
JUNO

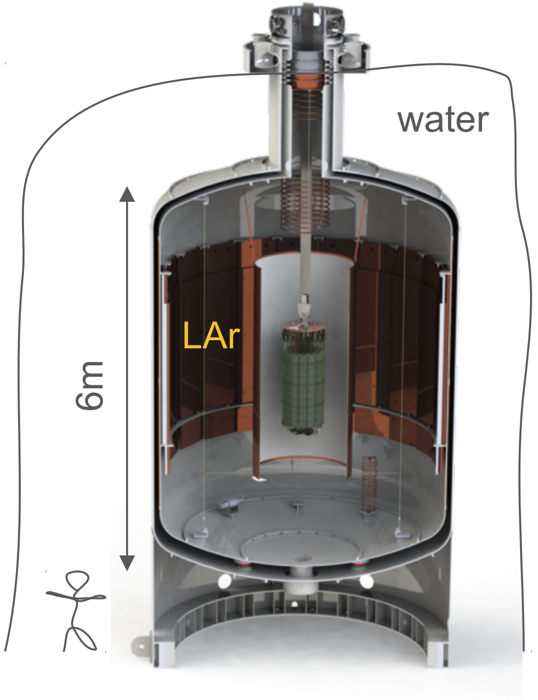
Summary and Outlook

- the JUNO 48 PMT setup operational in Legnaro is working very well
- the setup allowed
  - to test and debug the JUNO electronics full chain (several integration tests - GCU/BEC/TTIM - have been performed in the past)
  - develop/test and debug the CGU firmware
- the system is now used to prepare for the large number of channels integration test (700 GCU ➜ 2100 readout channels) that will test all the JUNo electronics before the installation in the experiment in China
- the system will be very important during the installation (2022) and commissioning phase (2023) of the experiment to debug possible firmware bugs and test new firmware versions (2024-2030) before deploying it in the JUNO experiment

GERDA & LEGEND

GERDA now
LEGEND200
LNGS Hall A



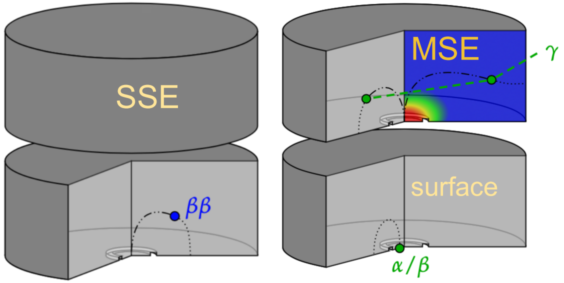


Experimental Setup

- Search for neutrinoless double-beta decay of ^{76}Ge
- High Purity Germanium (HPGe) detectors submersed in Liquid Argon (LAr)
- LAr cryostat surrounded by Water Cherenkov Muon Veto

Background suppression

- Multi-detector events discarded
- Scintillation light of LAr for vetoing (light guiding fibers coupled to SiPMs)
- Pulse shape discrimination (PSD) to veto multi-site (MSE) and surface events
  - double-beta signal shape (single-site event SSE) has to be well-known to discriminate from background

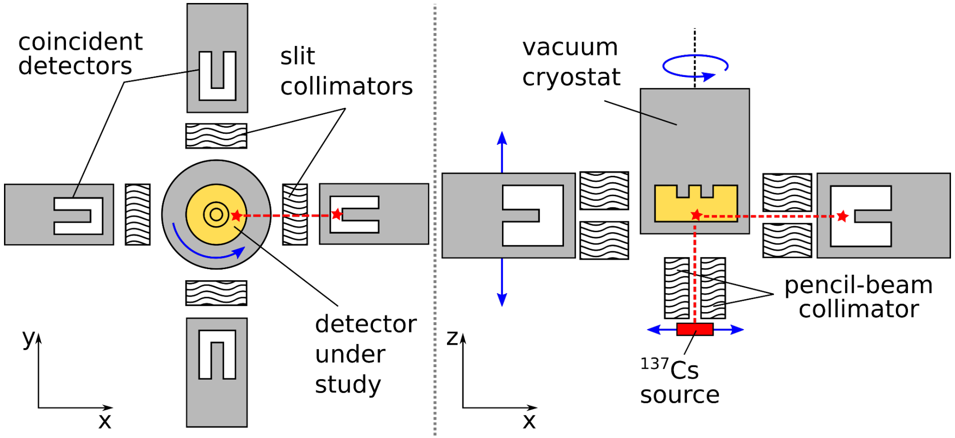


signal

background discarded by PSD

Compton Table

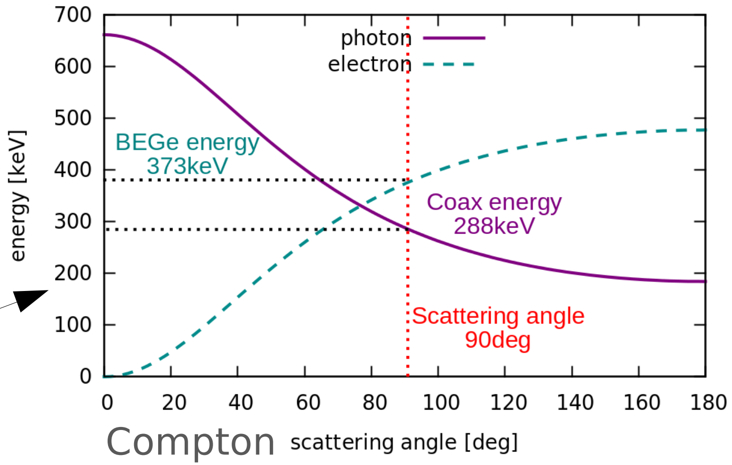
- Germanium detector response
- goal: collect samples of single-site SSE interactions with known interaction location
- take data of detector under study in coincidence with other detectors (up to 4) mounted laterally
- select single Compton scattered events through collimation and offline energy selection as proxy for SSE



sketch of the setup and its functionality

BeGe = under test (central)
Coax = trigger (cross)

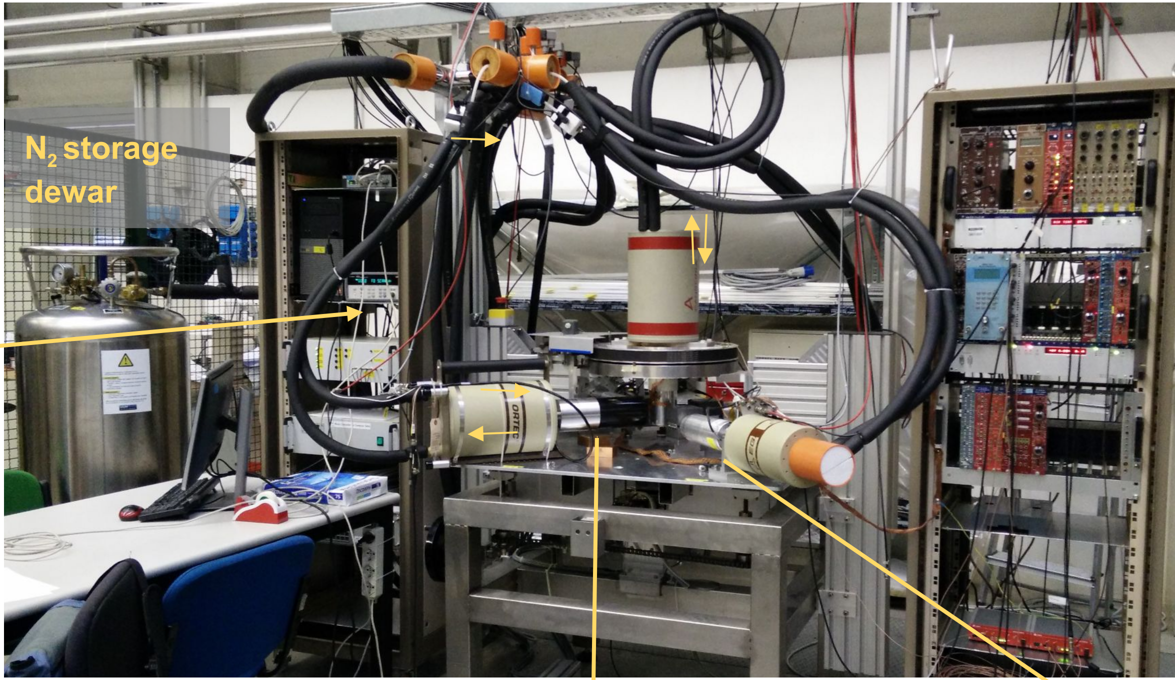
Coax for trigger from GASP

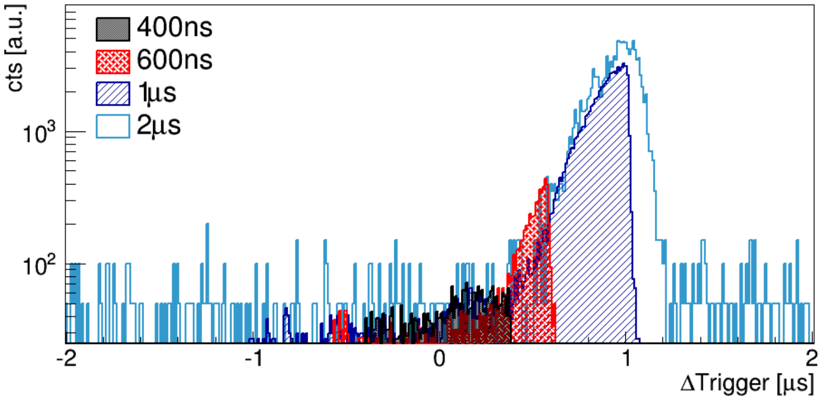


Compton

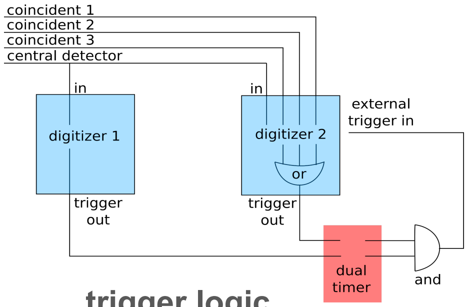
Compton Table

- automated N_2-filling system monitored and controlled by Agilent Keysight data-logger
- ^{22}Na β^+ source (511keV gammas back-to-back) for trigger calibration

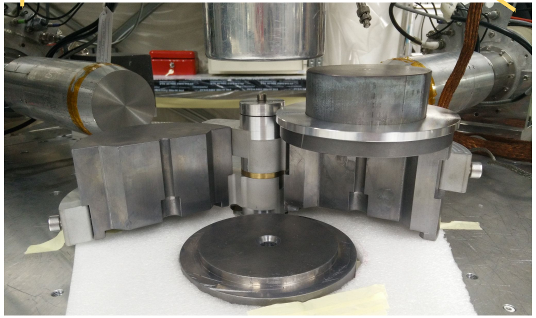




^{22}Na - dual timer gate calibration



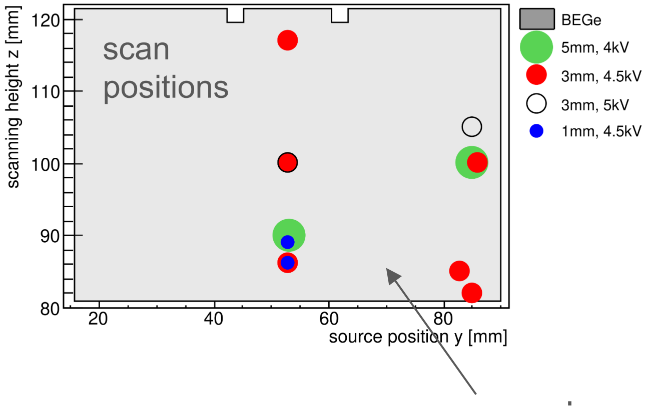
trigger logic



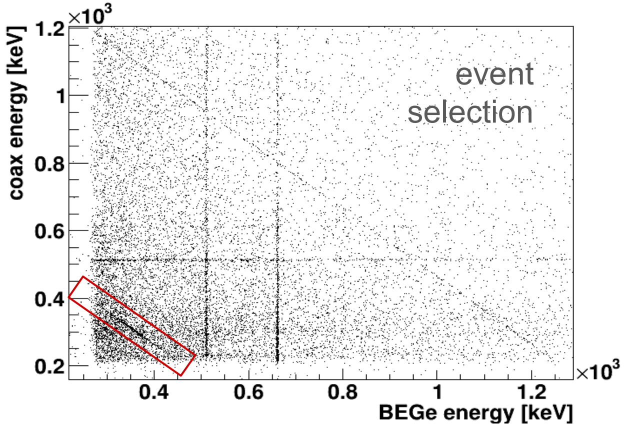
^{137}Cs 780MBq source collimator

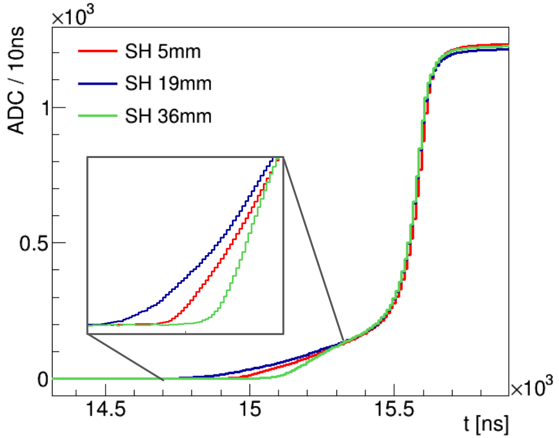
Compton Table

- samples & average pulse shape changing
  - scan height (manual)
  - scan depth (remotely controllable)
  - detector high voltage (remotely controllable)
- initial part of pulse changes with position and HV

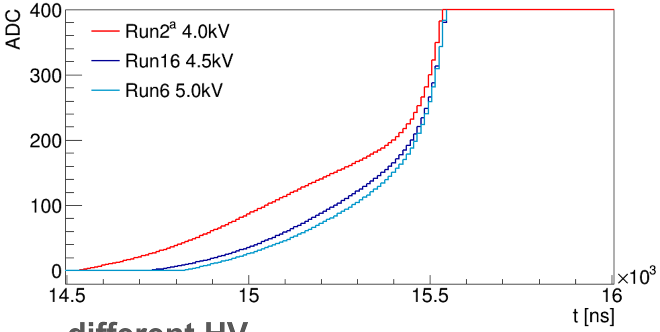


germanium detector under study





different scan height



different HV

average pulse shape

Compton Table

Conclusion

- study detector response to single Compton events with known interaction location in the context of GERDA (now LEGEND)

Future prospects

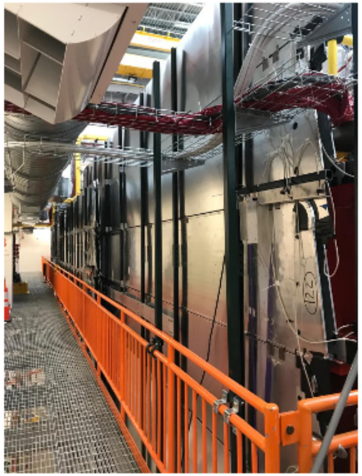
- comparison of different detector geometries
  - BEGe detector - GERDA geometry
  - pin-point-contact detector - MAJORANA geometry
  - inverted coaxial detector - LEGEND geometry
- improve scanning speed
  - mount pairs of pixelated detectors to measure the scanning height instead of collimating coincident detectors

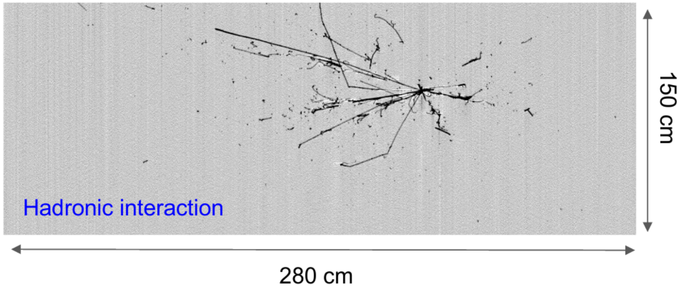
ICARUS

Status of Icarus detector

- TPC, PMT, trigger and DAQ installation activities complete, with latest achievements during Covid-19 restricted operations.
- Bottom CRT and 7 out of 8 walls of side CRT installation complete.
- 24/7 shifts since February 14th 2020. Remote only shifts since March 17th 2020.

CRT East walls complete



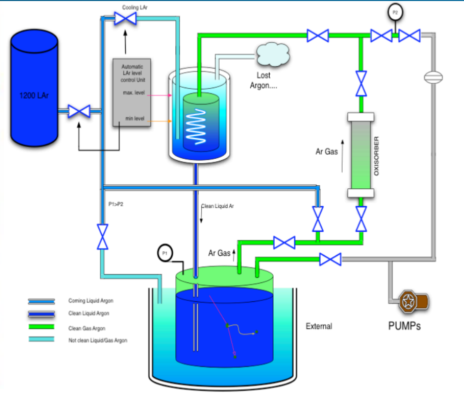


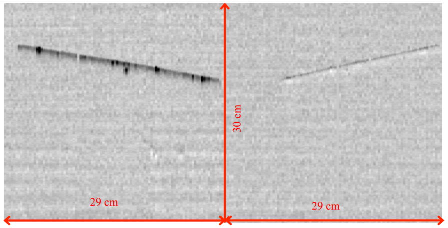
Fermilab

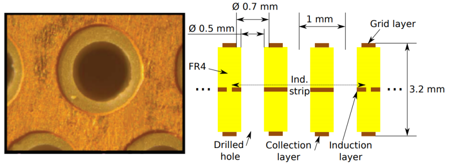
14 A. Fava _ NeuTel 2021 2/24/2021

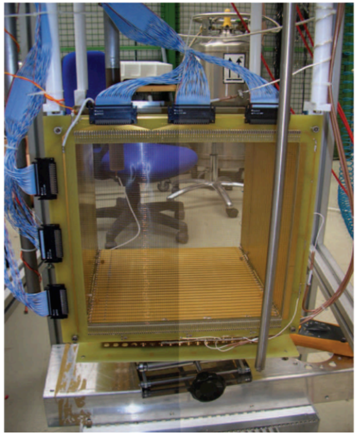
ICARINO

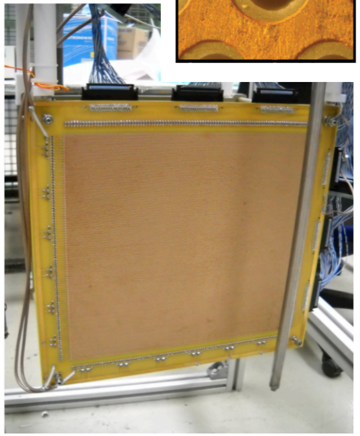
- Test facility for liquid Argon TPC, located in LAE building
- TPC is roughly a cube of 30 cm size -> 38 kg LAr active mass
- Built by ICARUS group in 2005, used for several tests
  - Measurement of very large (~20 ms) electron lifetime (JINST 2010 5 P03005)
  - First operation of multilayer 2D LEM readout in a LAr-TPC (JINST 2018 13 T03001)
  - Several other tests of LAr cryogenics (recirculation, purification), anode readout and electronics. Crucial for development towards ICARUS operation at LNGS and currently at FNAL







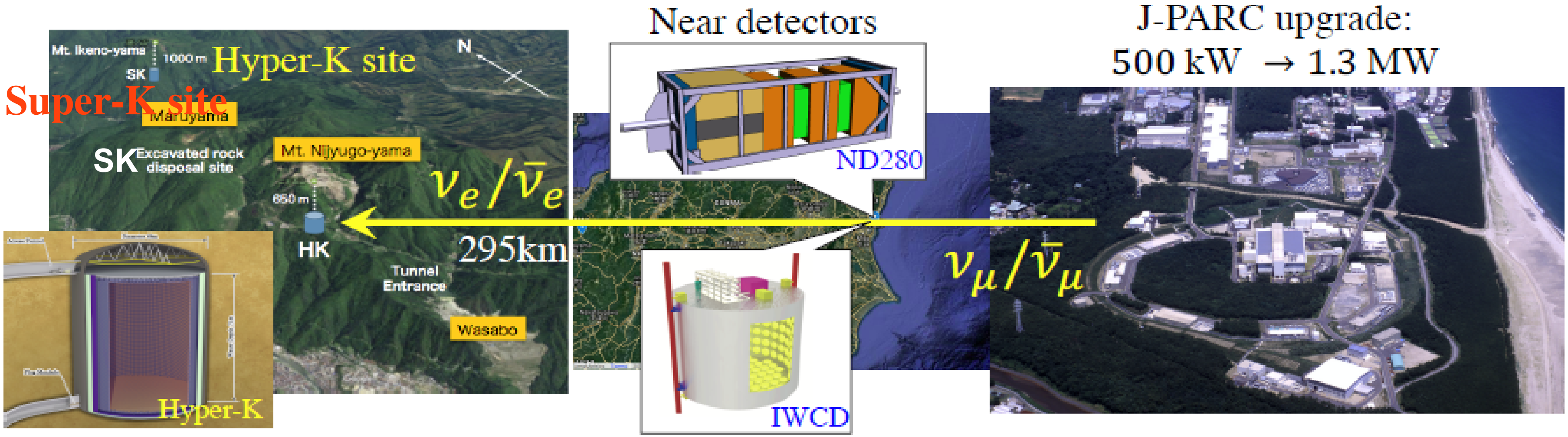




Current activity: LARISA

- The LARISA experiment (starting grant for F. Varanini) will use the ICARINO test facility for testing a 3-plane LEM readout in liquid Argon
- This is a further development of the previous 2D test, largely using the same infrastructure
- PCB-based LEM can be a cheaper, more robust and scalable alternative to wire-based readout for LAr-TPC. Great interest from DUNE, towards possible use for one DUNE module
- It is performed with the collaboration and support of the CERN group (F. Pietropaolo et al.), which is also testing 3D readout schemes
- LARISA will test a different approach, with PCBs only metalized on one face. It will characterize the focusing effect of the charge build-up on un-metalized PCB surface
- Approximate timeline
  - Simulation is being finalized, LEM design is ongoing
  - Data-taking expected during summer 2021
  - Analysis must be completed by the end of the year

T2K & SuperK & HyperK



Momento molto intenso per attivita` neutrini in Giappone

- **T2K** near detector upgrade in fase di costruzione
- **Super-K** entra in questi giorni nella nuova fase H_2O+Gd
- **Hyper-K** e` stato approvato all'inizio dell'anno

Gruppo locale in espansione

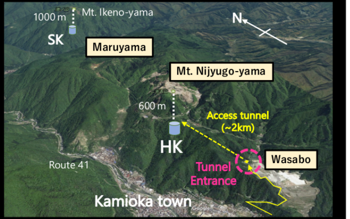
Staff: **G.Collazuol, M.Grassi, M.Laveder**, **A.Longhin**, **M.Mezzetto**,
Post-Doc: **M.Lamoreux** (INFN Fellini), Assegnisti: **N.Ospina, G.Cogo**
Dottorandi: **F.Iacob**, **M.Pari, C.Delogu**

- In stretta collaborazione per T2K-upgrade @ LNL: **M.Cicerchia, T.Marchi, F. Gramegna**

G.Collazuol
CdS INFN PD
2020/7/15

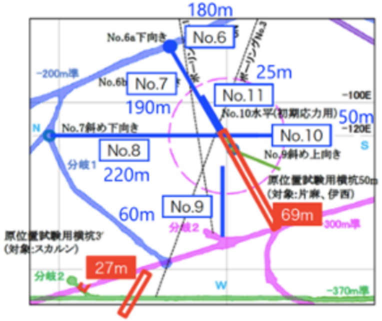
HK: construction/procurement

Entrance Yard Construction



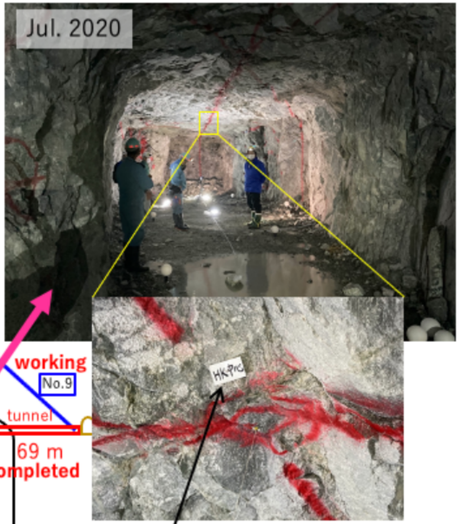
- Construction of entrance yard in Wasabo is completed.
- Construction of the waste water treatment facility at the entrance yard.

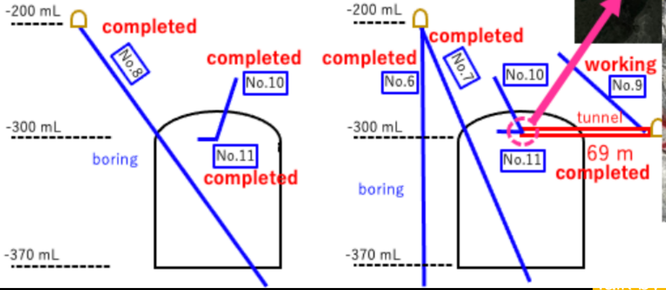
Neutel2021 - 24 Feb 2021



Survey tunnel

Near the center of the (future) HK dome





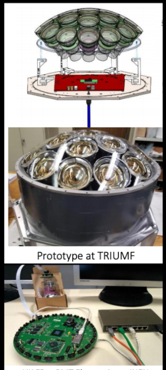
Hyper-K Detector Construction has Started

PMTs for the Inner Detector	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

2020/12 First six PMTs delivered to Kamioka

- Production has started on time for the 50cm PMTs with Box&Line dynode.
- 300 PMTs by March, 20,000 PMTs in total by 2026 according to the Japanese budget profile.

mPMTs



Prototype at TRIUMF

HK FD mPMT Electronics at INFN

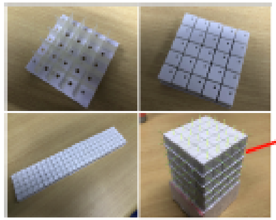
mPMT is a vessel which houses and protects an array of 19 3" PMTs:

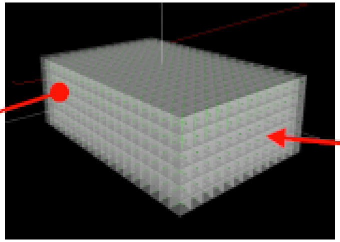
- improves the granularity and timing;
- additional intrinsic directional information.
- Far detector "hybrid" photocoverage: 20" PMTs and mPMTs.
- IWCD will be instrumented only with mPMTs.
- Different constraints on far detector and IWCD mPMTs.

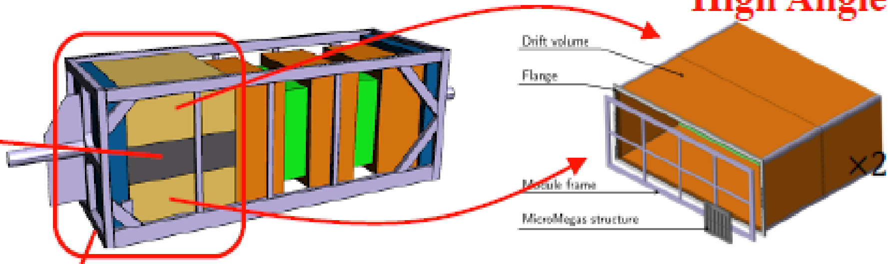
arXiv:1901.03750

Near Detector Upgrade

- **Large angle acceptance** to constrain neutrino interaction models
- Measurement of **short tracks** to identify non-QE, NC γ etc.





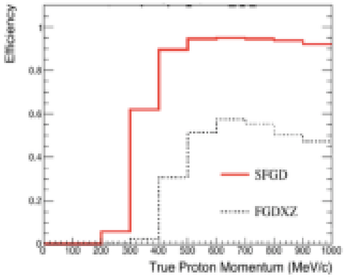


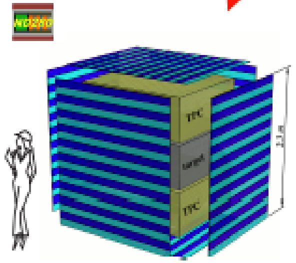
High Angle TPC

Improve reconstruction of hadron (short) tracks

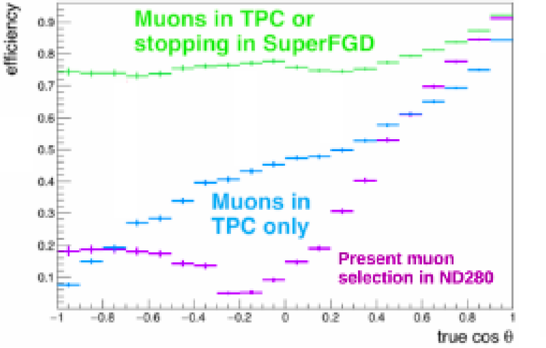
SuperFGD

(scintillator target tracker)
~$2m^3$, ~2M cubes, ~60k ch





TOF

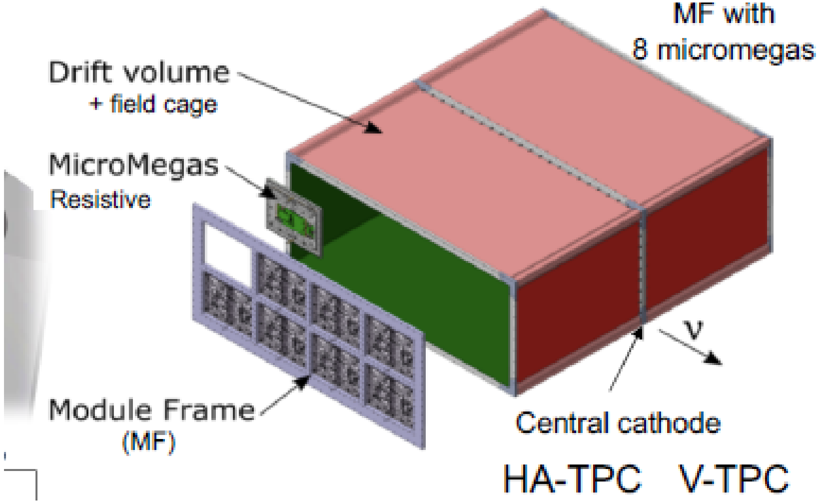


- **3D imaging super-fine grain detector**
  - Improved target tracking
  - Improved proton detection threshold
  - neutron detection capabilities

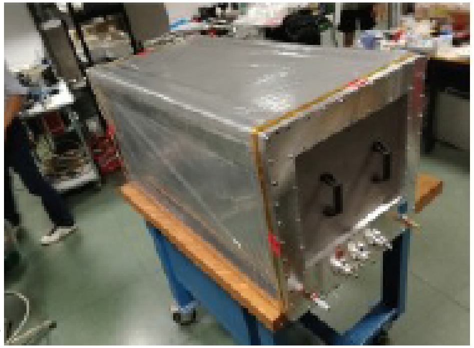
- **Improved high angle acceptance**
  - High Angle TPC's
- x2 in statistics for equal p.o.t.
- Time of Flight for background reduction

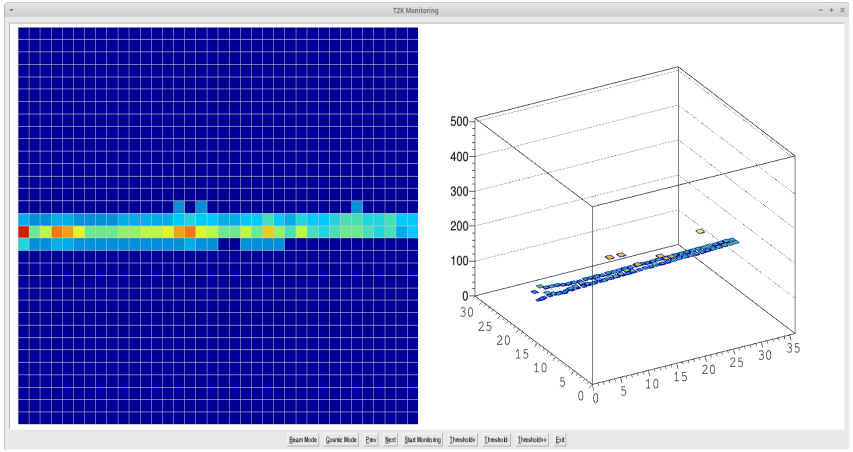
Near Detector Upgrade - HATPC

Importante coinvolgimento INFN Pd
in costruzione delle TPC orizzontali
(High Angle TPC):
→ **coordinamento progetto** HA-TPC (G.Collazuol)
→ disegno e **costruzione Field Cage** con INFN-LNL e INFN-Ba



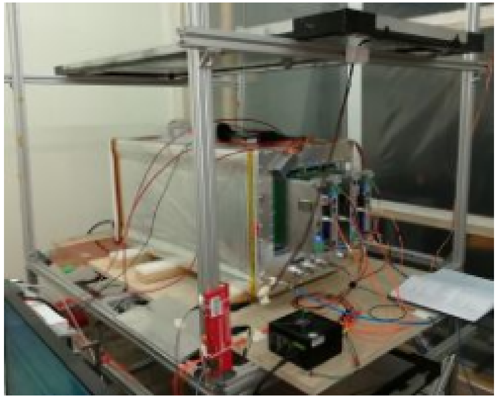
- progettazione HA-Field Cages
- realizzazione e test prototipi

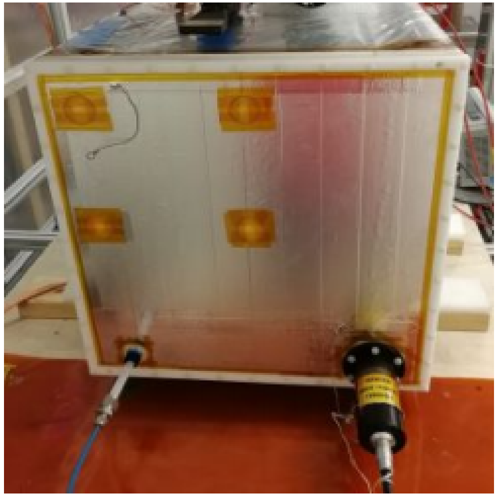




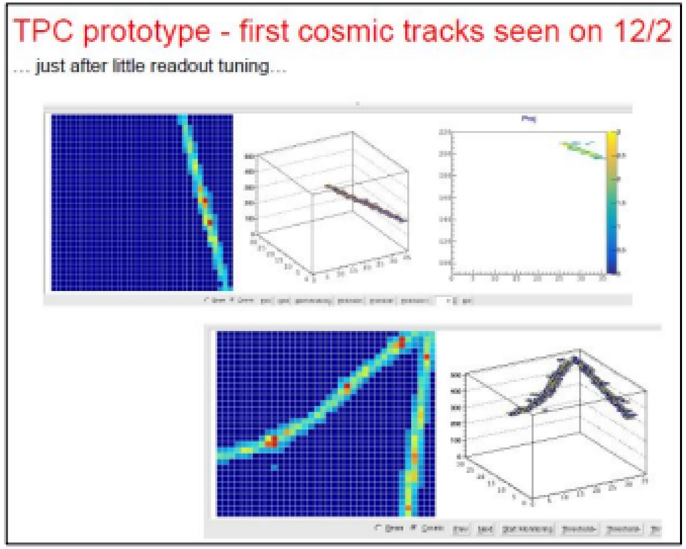
A.

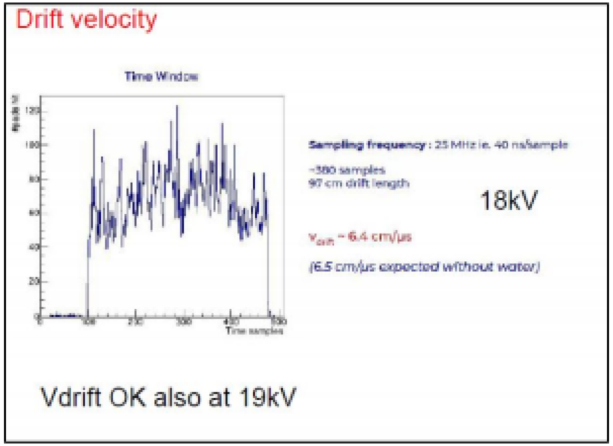
Prototype at CERN ⟶ T2K lab facility @ Neutrino Platform Area (Activity 2019 Q4 – 2020 Q1)





- TPC assembled (Resistive Micromegas + Electronics + DAQ)
- HV and gas long term tests at CERN ⟶ studied and solved HV problems (discharges externally around cathode region) ⟶ adjusted external ground layout
- Gas quality measurements (long term measurements)
- Data taking with Cosmic Rays
  ⟶ early characterization: OK
  ⟶ full characterization: need more data
  (activities at CERN frozen due to covid19)





A. Longh

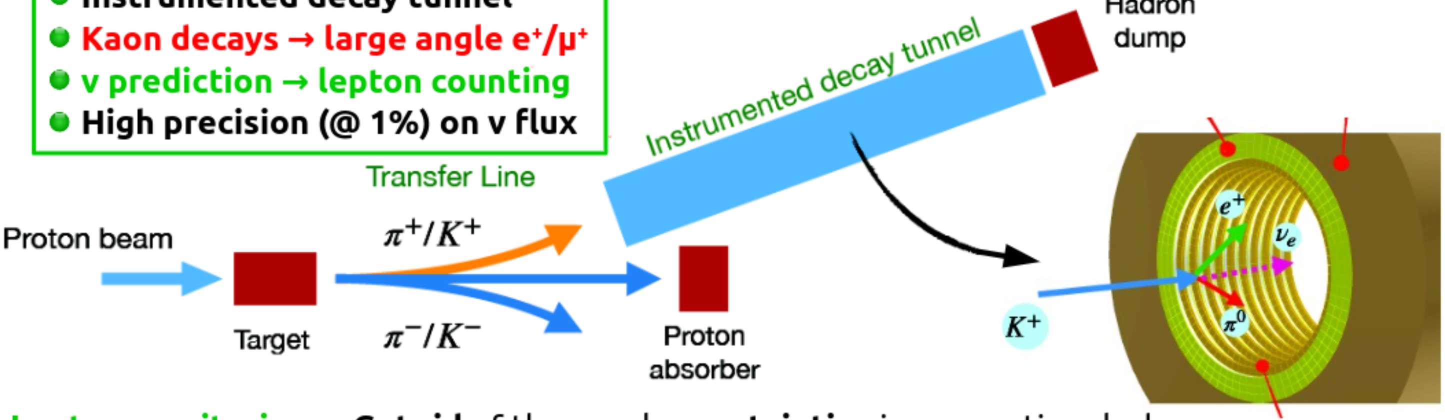
ENUBET

NP06/ENUBET

A new narrow-band neutrino beam for high precision cross section measurement in the DUNE/Hyper-K era

- **ERC Cons. Grant (2016-2021)** [ENUBET, PI: A. Longhin, UniPD (host) + INFN]
- *Grant MIUR – Bando FARE (2017-2021)* [ENUBET/NUTECH]
- Since April 2019, ENUBET is also a **CERN Neutrino Platform experiment: NP06**

- **Instrumented decay tunnel**
- **Kaon decays → large angle e^+/μ^+**
- **ν prediction → lepton counting**
- **High precision (@ 1%) on ν flux**



Lepton monitoring → **Get rid** of the usual **uncertainties** in conventional ν beams (Hadro-production, protons on target, beam-line efficiency)

Main goals
1) Design/simulate the layout of the **hadronic beam-line**
2) Build/test a **demonstrator** of the **instrumented decay tunnel**

ENUBET

ENUBET: instrumented decay tunnel

Requirements:

- Allow **$e^+/\pi^{\pm,0}$ separation** in the GeV energy region
- **Suppress** background from **beam halo** (μ, γ, non collimated hadrons)
- Sustain O(MHz) rate and **suppress pile-up effects** (recovery time ≤ 20 ns)
- **Cost-effective** (to instrument a 40m long decay tunnel)

Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Lateral light readout with WLS+SiPM

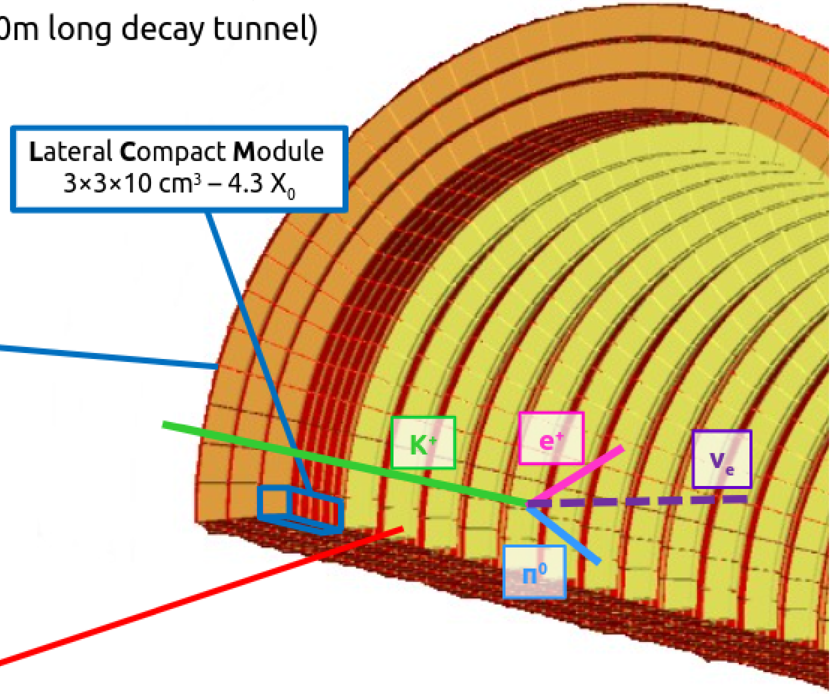
→ $e^+/\pi^\pm/\mu$ separation

Integrated photon veto (t0-layer)

Plastic scintillators

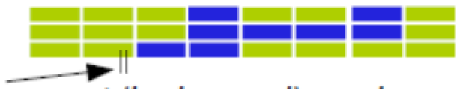
Rings of 3×3 cm^2 pads readout by SiPM

→ π^0/γ rejection



e^+ (signal) topology

π^0 (background) topology

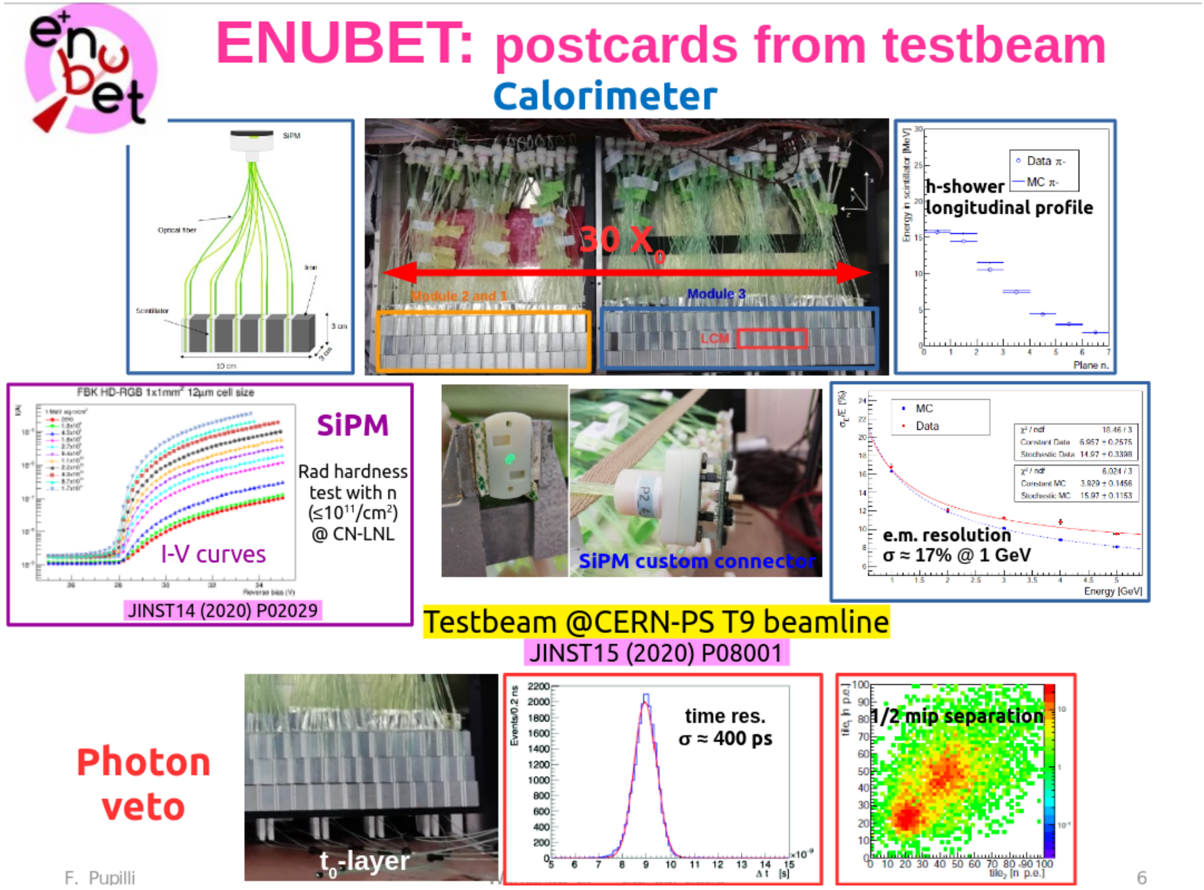


π^+ (background) topology

ENUBET

An intense testbeam activity

CERN-PS (x7) INFN-LNL CN INFN-LNF BTF

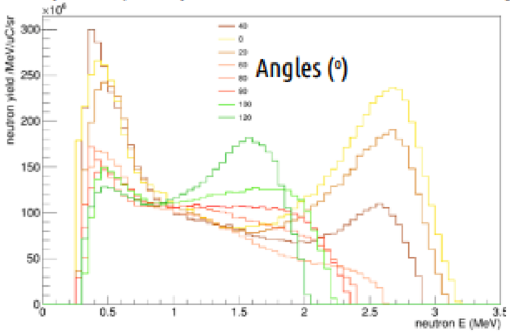


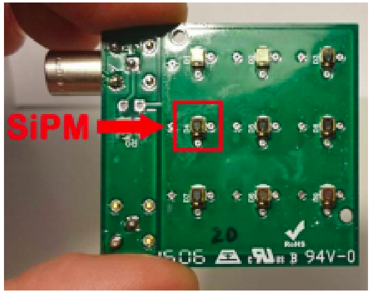
ENUBET

SiPM irradiation @ INFN-LNL (Legnaro)

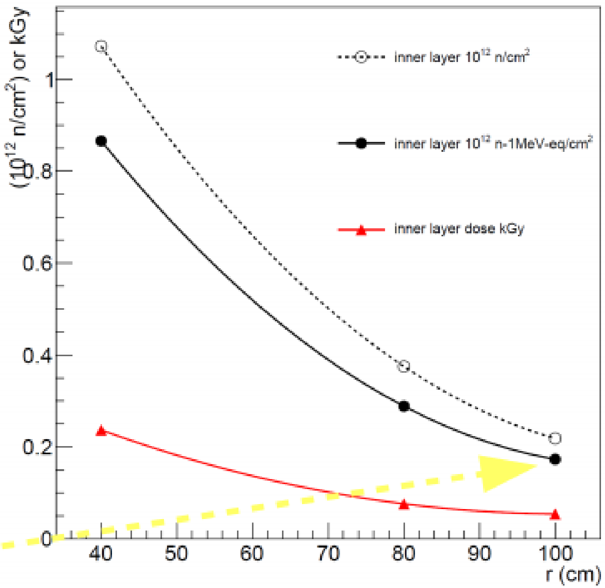
- SiPM were irradiated at the CN Van de Graaf on July 2017
- 7MV and 5 mA proton currents on a Be target
- $^{9}Be(p,n)^{9}B$, $^{9}Be(p,np)2\alpha$, $^{9}Be(p,np)^{8}Be$ and $^{9}Be(p,n\alpha)^{5}Li$
- → 1-3 MeV n with fluences up to $10^{12}/cm^2$ in a few hours

n spectra (from previous works at the same facility)

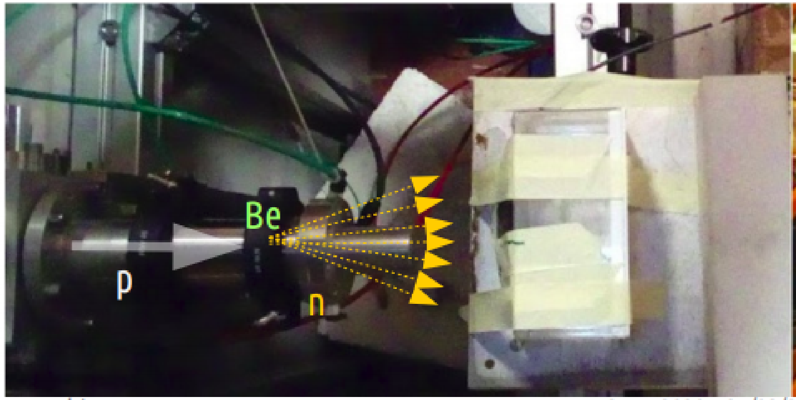


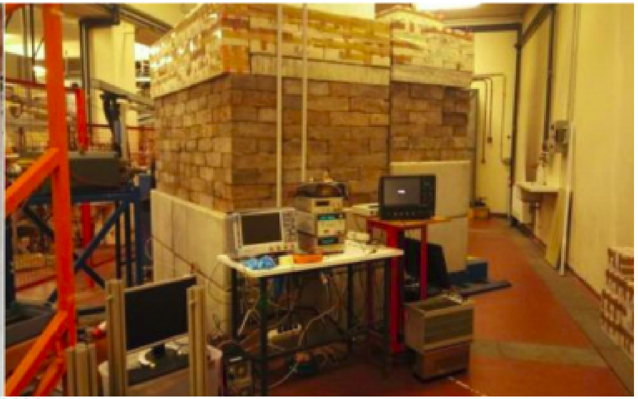


Expected n doses from K decays (FLUKA)



→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm²** 1 MeV-eq (max non ionizing dose for 10^4 ν_e^{CC} at a 500 t ν detector at r = 1 m)



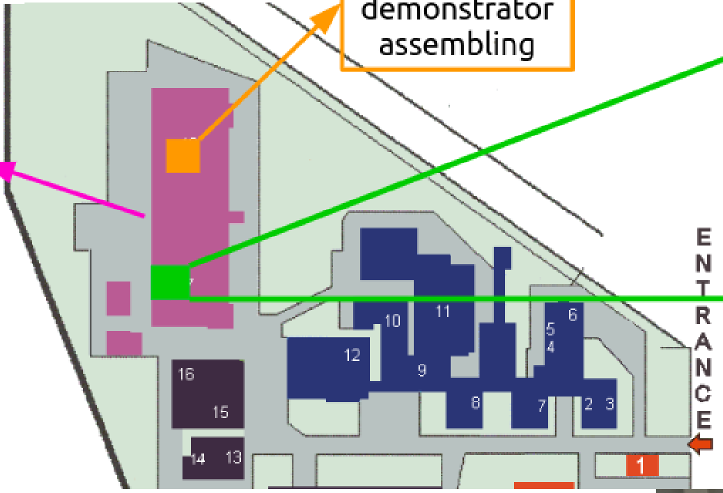


The ENUBET lab @ INFN-LNL

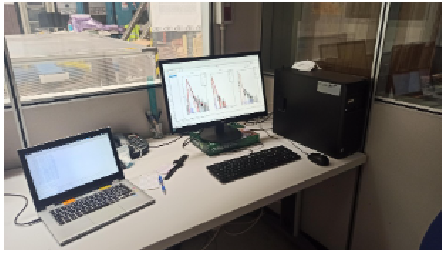
ENUBET

Area for demonstrator assembling

High energy building "LAE"



A. Longhin
G. Collazuol
F. Pupilli
M. Pari
C. Delogu
F. Iacob


Office/DAQ

Lab space

Digitizer

CAEN V1743
- 16 ch
- 12 bit
- 3.2 GS/s
- 2.5 Vpp dynamic range

CAEN V2718 VME-PCI Optical link bridge + **A3818** PCI controller

Multichannel Analyzer

CAEN DT5781
- 2 channels

Laser

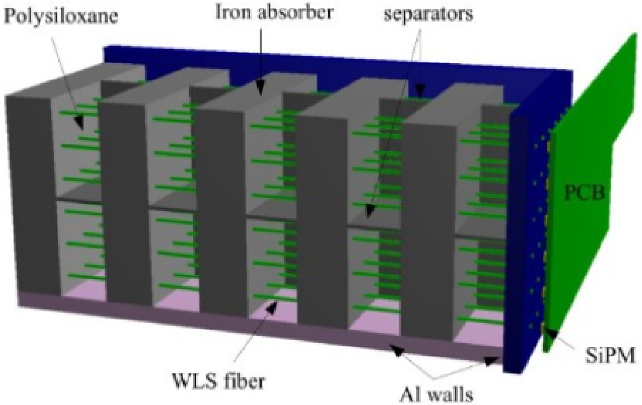
ALPHALAS Picosecond Pulse Laser Diode
- 405 nm
- <40 ps pulse width

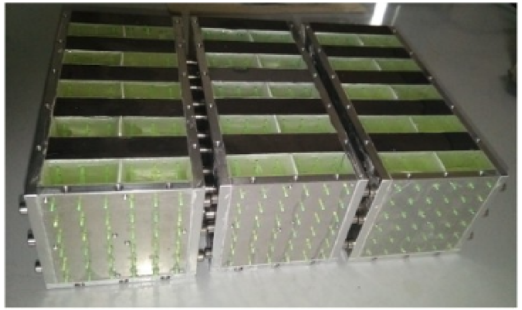
Polysiloxane-based scintillators

NIMA 956 (2020) 163379

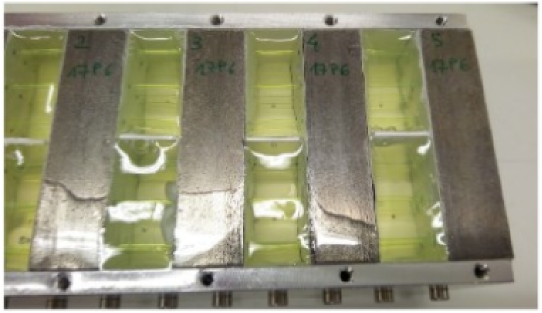
Polysiloxane resin instead of plastic with suitable dyes for scintillation

- A $13X_0$ shashlik calorimeter prototype tested in 2017-18 @ CERN (**first application** in HEP!)
- **Pros:** increased **radiation hardness** (no yellowing), **simpler** (just pouring+reticulation)

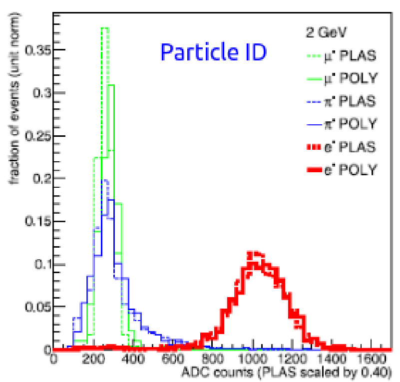


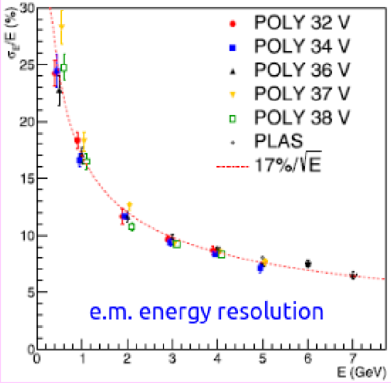


Scintillator prepared by **S. Carturan**



Light yield ~1/3 wrt plastic, but similar calorimetric performance



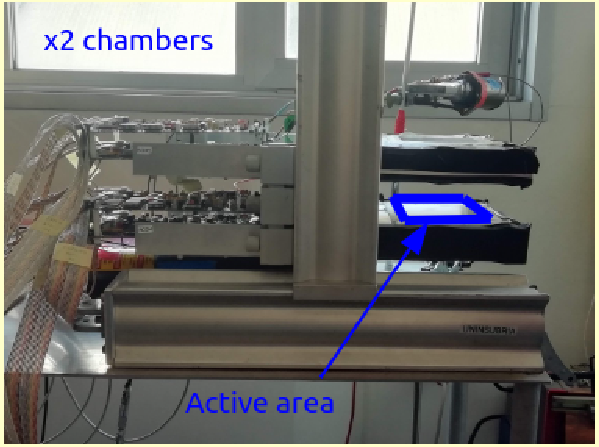


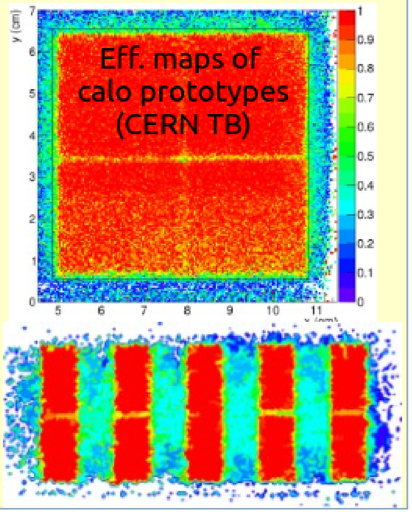
50

Silicon strip detectors

for particle tracking
and high resolution
efficiency maps
Developed for AGILE
NIMA 501 (2003) 280

- **Active area**: 10x10 cm^2
- **$\sigma \approx 30\ \mu m$**

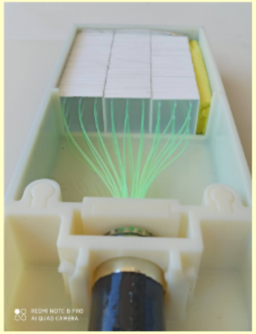


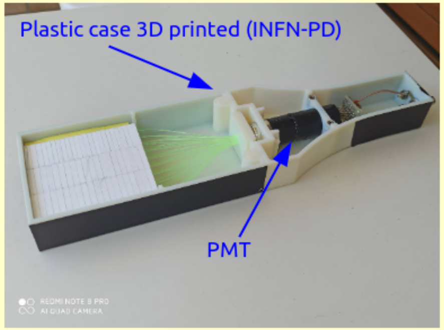


Trigger scintillator

3D printed at INFN mech. Workshop. Uses tiles developed for shashlik calorimeters R&D in collaboration with INR Moskow

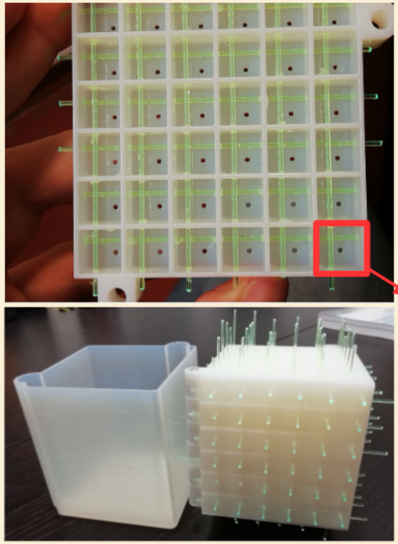
- **Active area**: ~10x10 cm^2





More collateral detector R&D
(work in progress)

Polysiloxane-based high granularity neutrino targets. 3 views. Same idea of the new T2K near detector (SuperFGD) but without the need of assembling millions of mechanically independent cubes → pouring into a frame.



1x1x1 cm^3

ENUBET

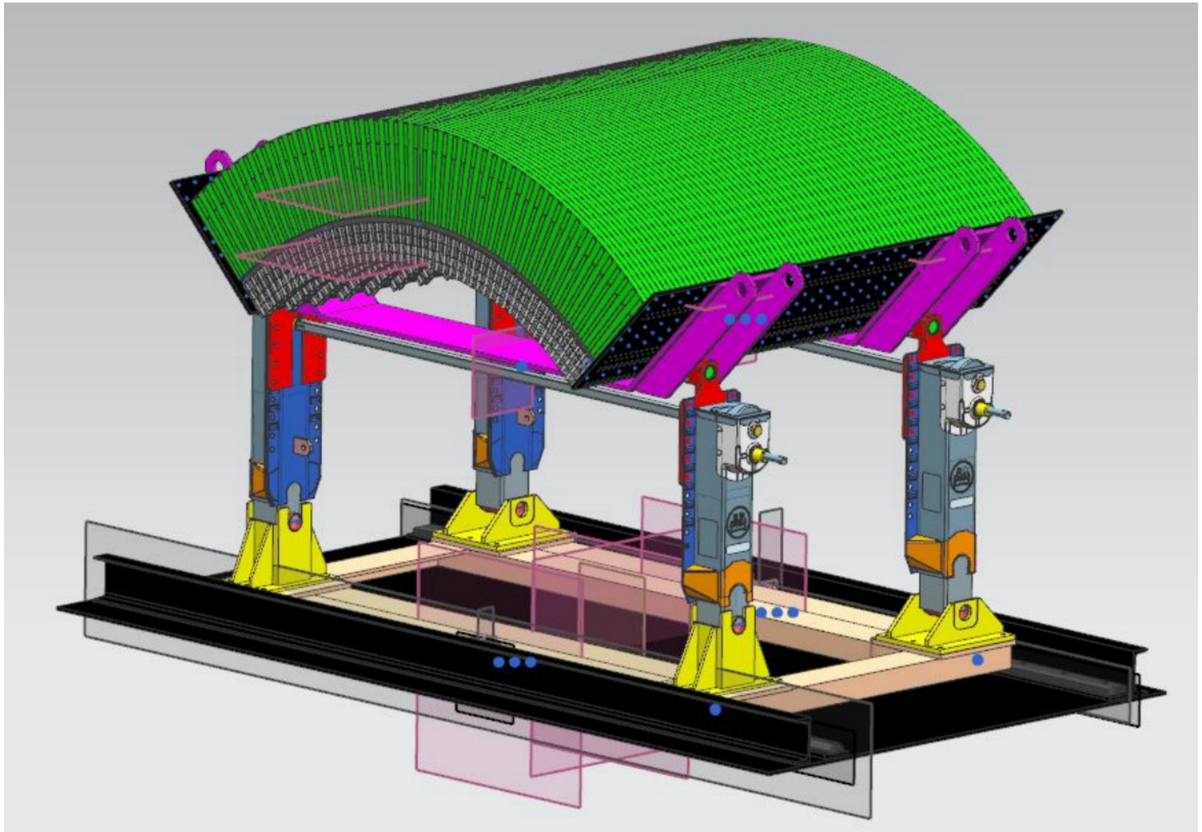
Final demonstrator due to the ERC.

A portion of the instrumented decay tunnel

Proof of performance/feasibility and cost effectiveness

Assembly will be in a new area in the north part of LAE.

Will be tested in 2022 at CERN-PS East Hall.



CERN-SPSC annual report
https://cds.cern.ch/record/2759849/files/SPSC-SR-290.pdf

Spunti finali

Il LAE e’ **un’ambiente prezioso per le attivita’ di Gruppo 2** in generale e per Padova in particolare.

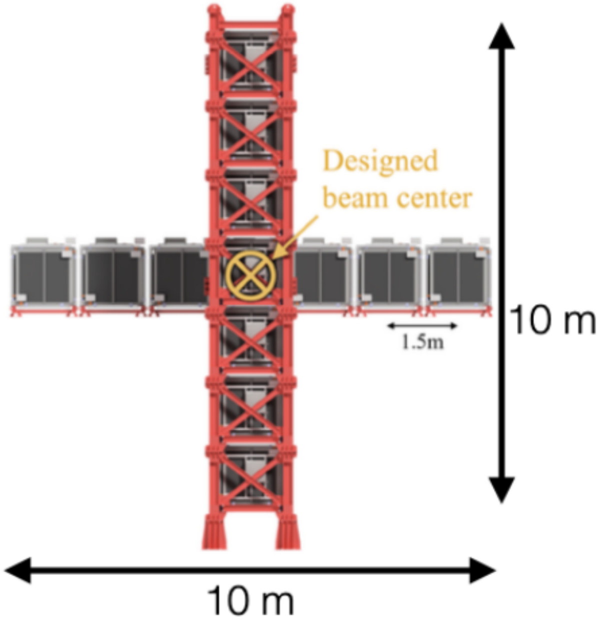
Esperimenti che fanno fisica (QUAX), costruzione/test/sviluppo di sistemi di rivelatori per grandi apparati su cui la CSN2 sta investendo molto (JUNO, LEGEND, DUNE, HYPER-K, ET, VIRGO upgrades), progetti ERC (ENUBET).

Rafforzare l’integrazione con LNL come gia’ succede per per QUAX e T2K ?

Bonus slides

Hyper-Kamiokande near detectors

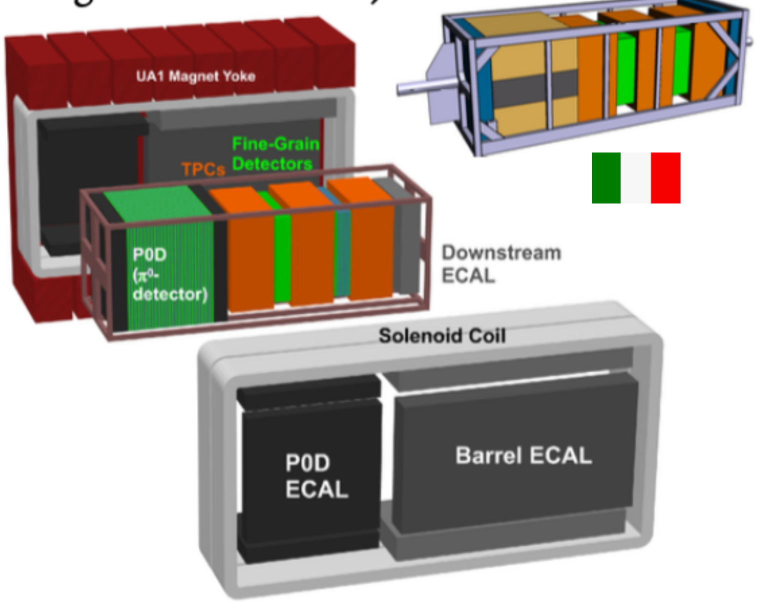
On-axis Detector (INGRID)



measure beam direction, monitor event rate.

Existing

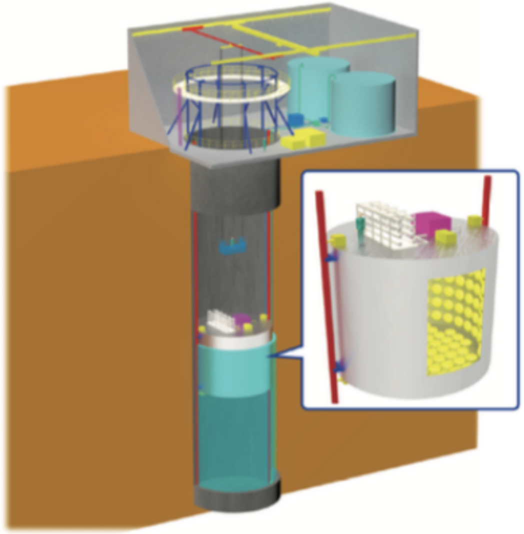
Off-axis Magnetized Tracker (ND280→ND280 Upgrade→HK magnetize detector)



charge separation (wrong-sign background), recoil system.

being upgraded.

Off-axis spanning intermediate water Cherenkov detector (IWCD)

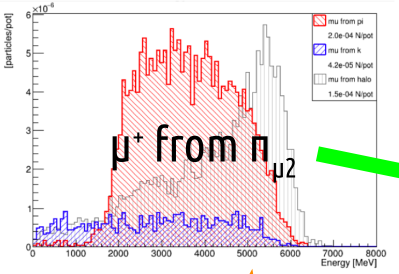


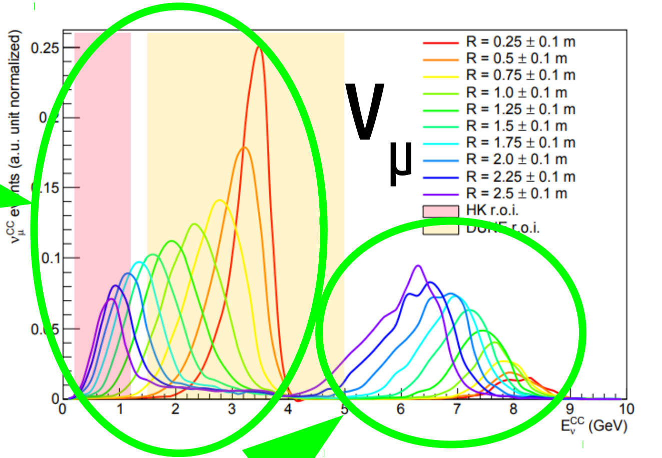
intrinsic backgrounds, electron. (anti)neutrino cross-sections, neutrino energy vs. observables, H_2O target.

To be built

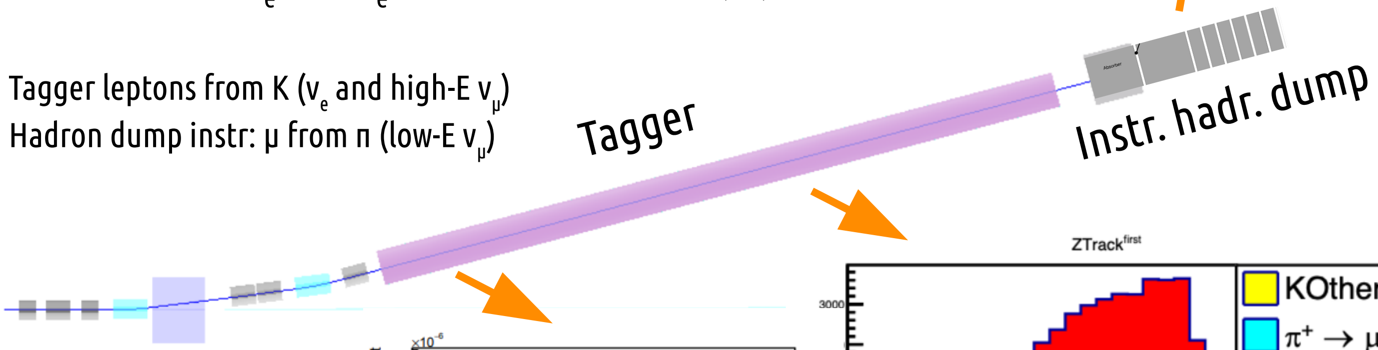
Systematics: NP06/ENUBET

Unprecedented control of flux by monitoring the leptons in an instrumented decay tunnel in a narrow band beam.
Measure the ν_e and $\bar{\nu}_e$ cross sections at O(%)



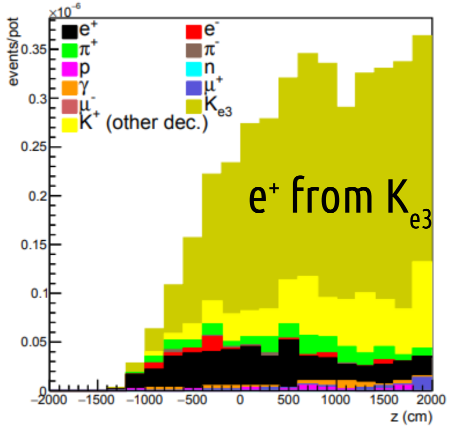


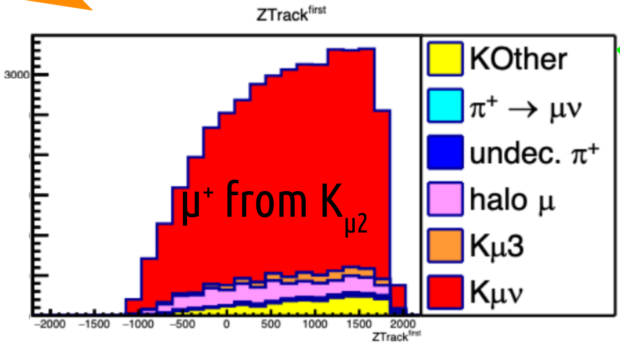
Tagger leptons from K (ν_e and high-E ν_μ)
Hadron dump instr: μ from π (low-E ν_μ)

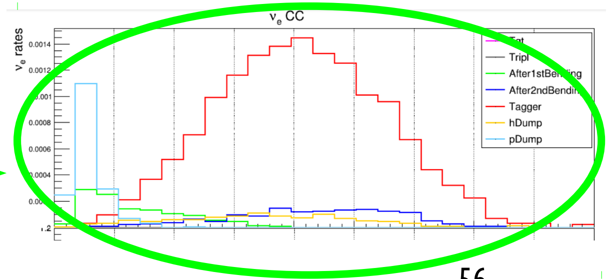


E_ν has a well defined dependence on the position of the interaction vertex in the neutrino detector. Constrain shape & normalization.

Single particle level lepton "counting"







Activities

Marco Bazzan, *Giacomo Ciani*, Livia Conti,
Matteo Pegoraro, Jean-Pierre Zendri

- Gravitational wave science is a very interdisciplinary enterprise
- Our group is pursuing a wide array of experimental investigations and technological developments in support of GW detectors

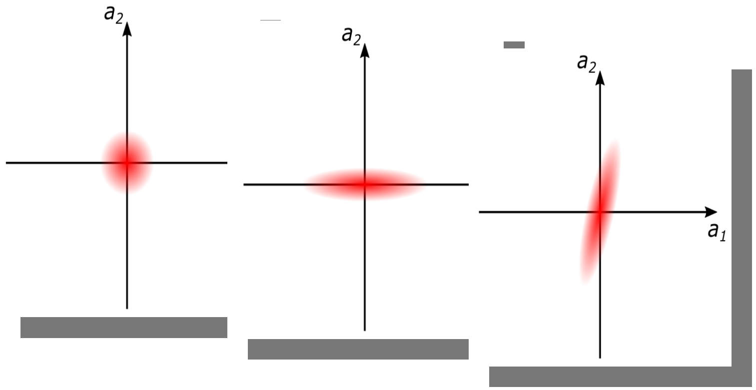
- Main strength and expertise:
  - Laser optics
  - Opto-electronics
  - adaptive optics (not the "astronomical" type…)
  - Fast/quiet electronics
  - Optical materials
  - Cryogenics

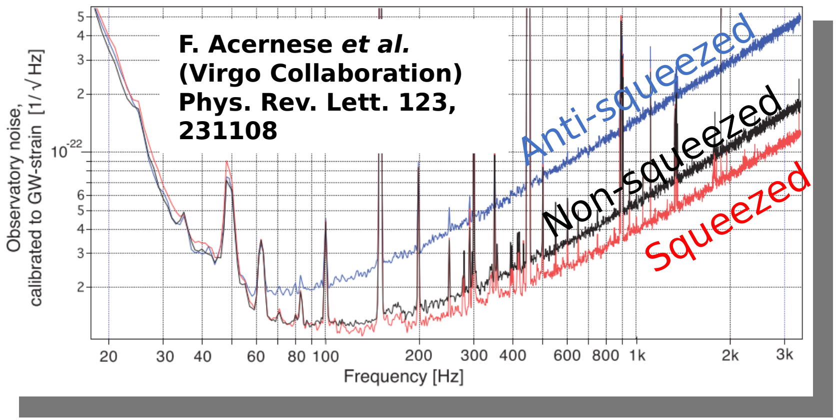
Our clean optics lab at Legnaro National Labs

Da G. Ciani
https://agenda.infn.it/event/21880/

Fighting quantum noise with vacuum squeezing

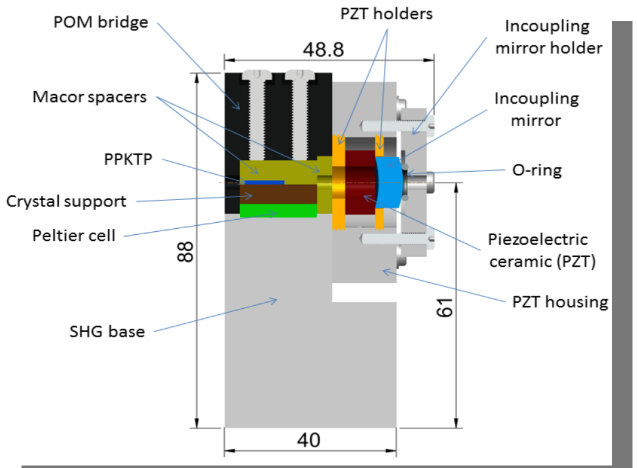
- True source of quantum noise: quantum vacuum fluctuations entering the “dark port” and mixing with the carrier
- Solution: inject vacuum with reduced quantum fluctuation
- Two quadratures that obey an uncertainty relation:
  - phase (causes shot noise, high frequencies)
  - amplitude (causes radiation pressure, low frequencies)
- ***Who is your worst enemy?*** Can “squeeze” one quadrature at the expense of the other (so far, we have been improving shot noise at high frequency… and it works!)
- ***Or win on the whole ground*!** decide which one as a function of frequency.
  - For example, the squeezing angle can be rotated as a function of frequency by reflecting the *squeezed vacuum beam* on a detuned cavity (a.k.a filter cavity)

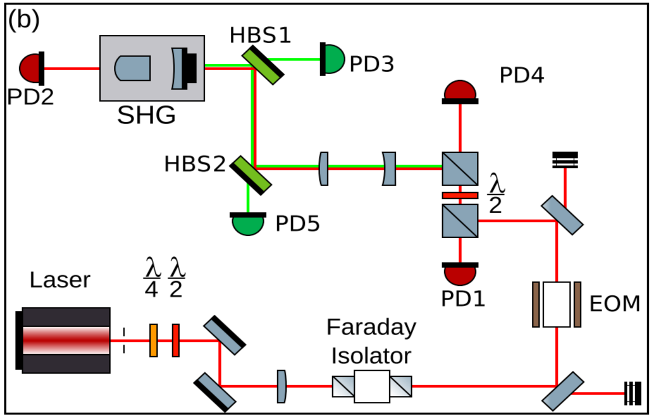


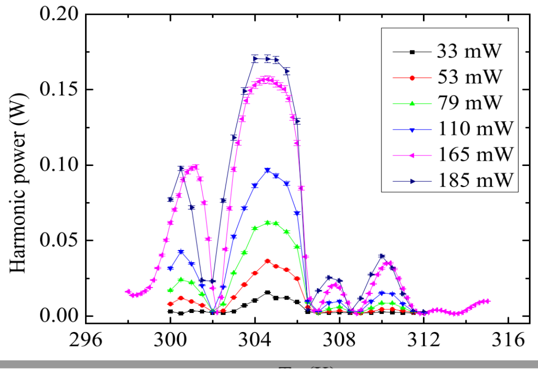


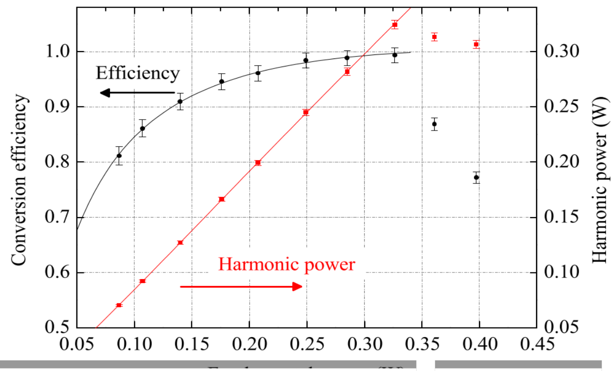
Optimizing squeezing generation process

- Custom-built **Second Harmonic Generator** based on intracavity non-linear crystal
  - used to frequency halving/doubling (key to squeezing production)
- Record 99% efficiency demonstrated (M. Leonardi et al 2018 Laser Phys. 28 115401)
- Currently developing a novel technique for ultra-low crystal absorption measurements



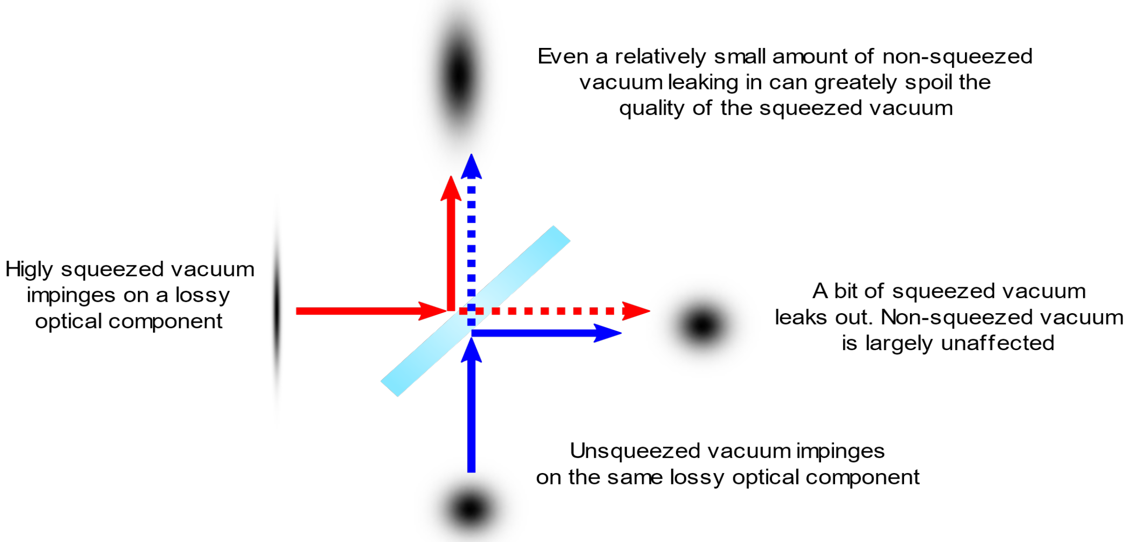




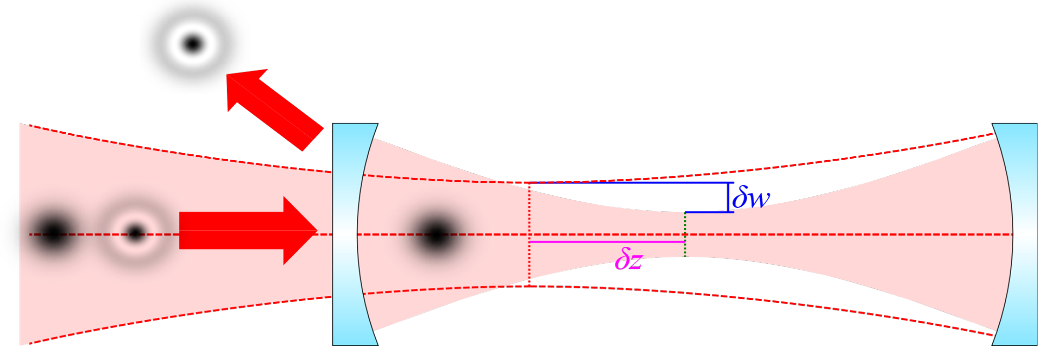


Mode matching sensors for squeezing

- Optical losses are the enemy: if photon can escape the system, then (non-squeezed) quantum fluctuation can enter from the reverse path



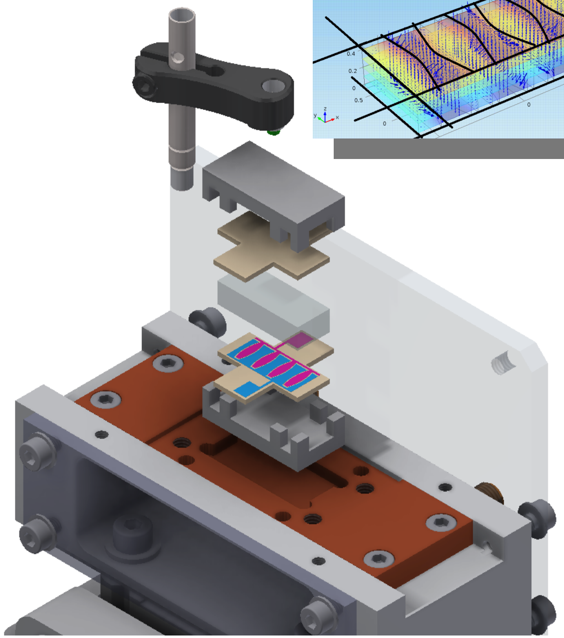
- Mode matching is one of the critical sources of loss, and real time sensing (and correction) at the ~1% level becomes critical.

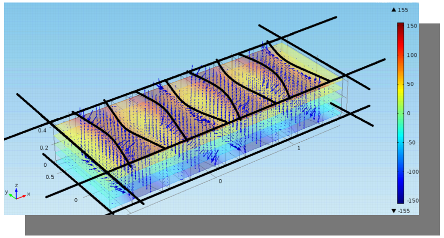


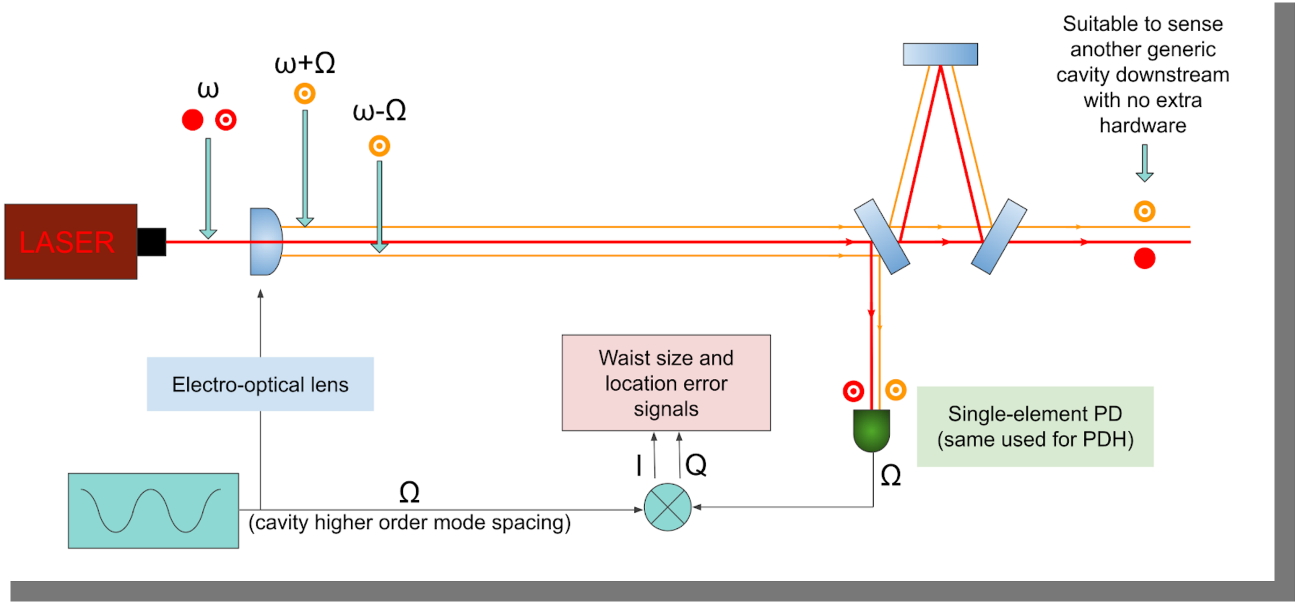
- Little development in the past due to non-critical nature (before squeezing came in!)

Online sensing of laser-cavity mode-matching

- Mode-mismatch is a primary source of optical losses, the worst enemy of an effective squeezing
- Development of an innovative sensing technique



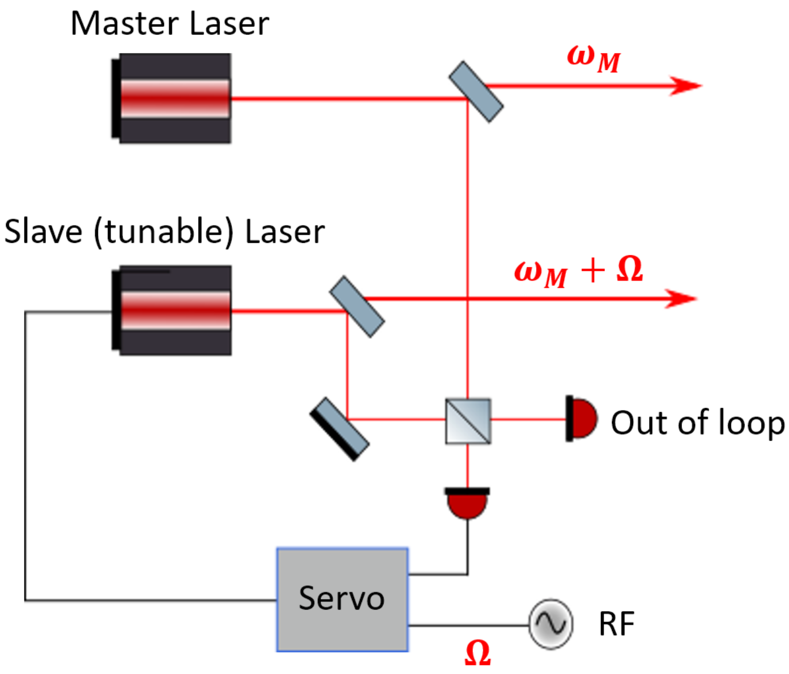




- Realization of a custom electro-optical lens capable of changing focal length at frequencies up to ~100 MHz
- Requires expertise in laser optics, RF electronics, solid state physics
- Collaboration with UniTN/TIFPA on alternative techniques

GHz Optical Phase Locked Loop

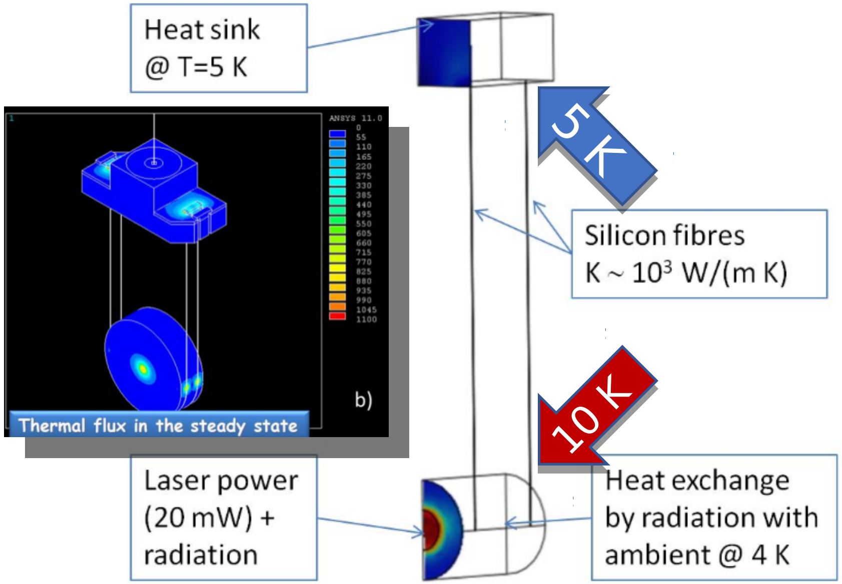
- Squeezing and control beams need to be phase-locked to the main interferometer carrier with high precision and selectable frequency offset
- Implementation of frequency-dependent squeezing requires offset up to ~GHz

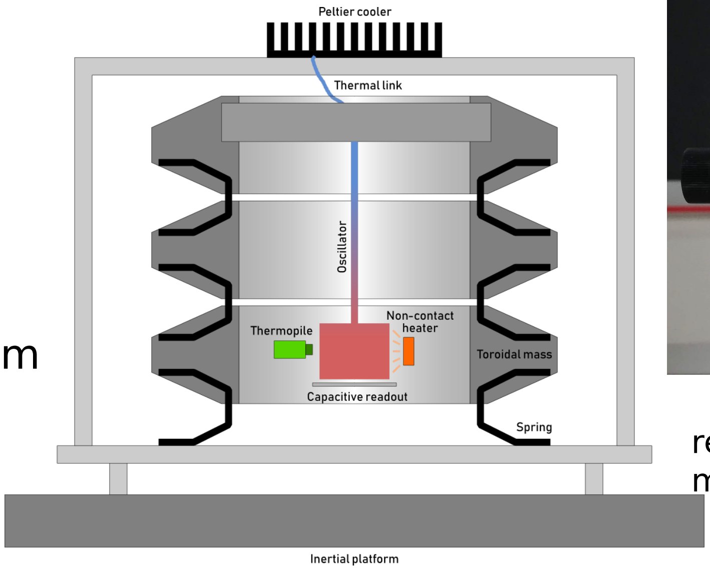


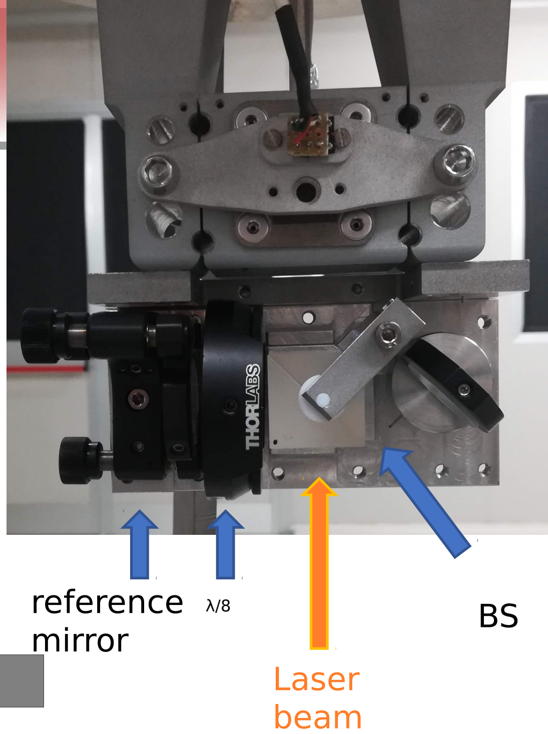
- Offset frequencies allowed: 1.5MHz ÷ 1.5GHz
- Bandwidth 50-100 kHz, limited by the internal resonances of the laser PZT actuator (can be improved using an EOM as actuator)
- Achieved residual RMS phase noise of order mrad (100 kHz bandwidth)
- Fiber optic version (being tested).
- Autolocking system for long term operation

Out of Equilibrium thermal noise

- Thermal noise is well understood and measured in terms of fluctuation-dissipation theorem (FDT)
- FDT assumes thermodynamic equilibrium
- Not a valid assumption in many experiment!
- No valid theory to describe non-equilibrium

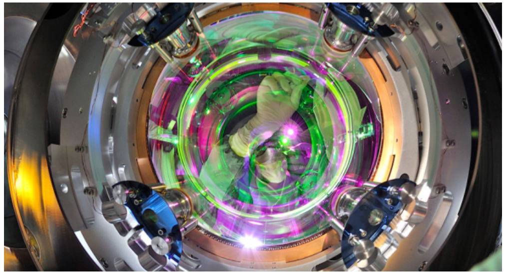






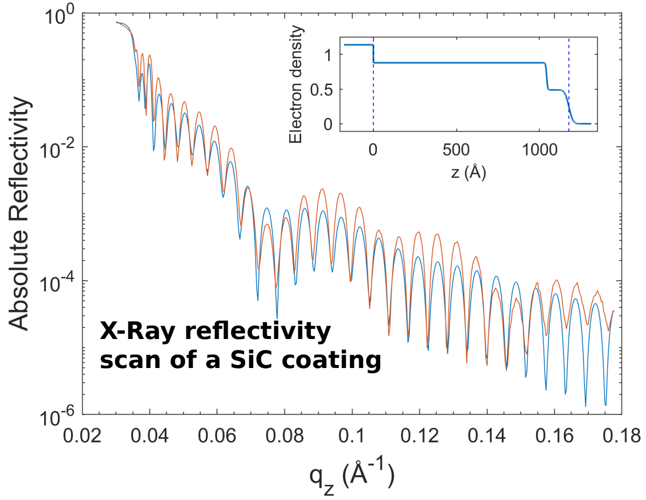
- Facility with thermal-noise limited macroscopic oscillator
- Ability to control temperature and thermal gradients
- Objectives:
  - Measurement of TN out of equilibrium
  - Establish a phenomenological base to help develop a viable theory
- Collaborations:
  - Experimental @ENS Lion
  - Theroretical colleagues @DFA, PoliTo and University of Luxemburg

Coating research



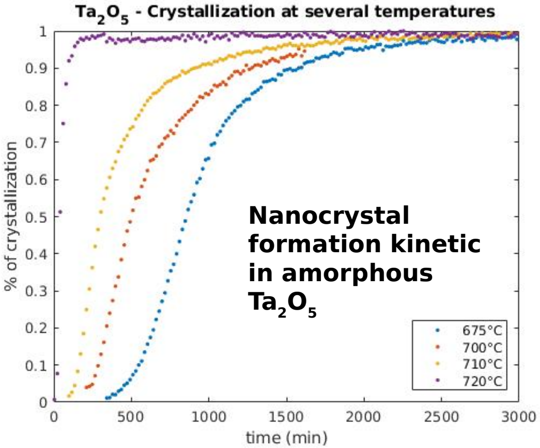
SCIENTIFIC CASE:

- Thermal noise and optical absorption in advanced optical coatings
- Investigation on the physical origin
- Development of new materials



ACTIVITIES:

- Fabrication (Sputtering, Thermal treatments)
- Characterization (Rutherford Backscattering, X-Rays, Optical...)

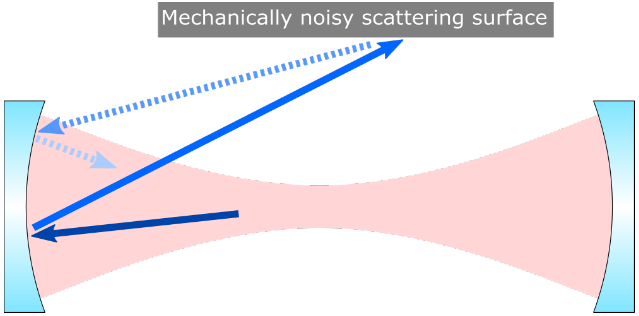


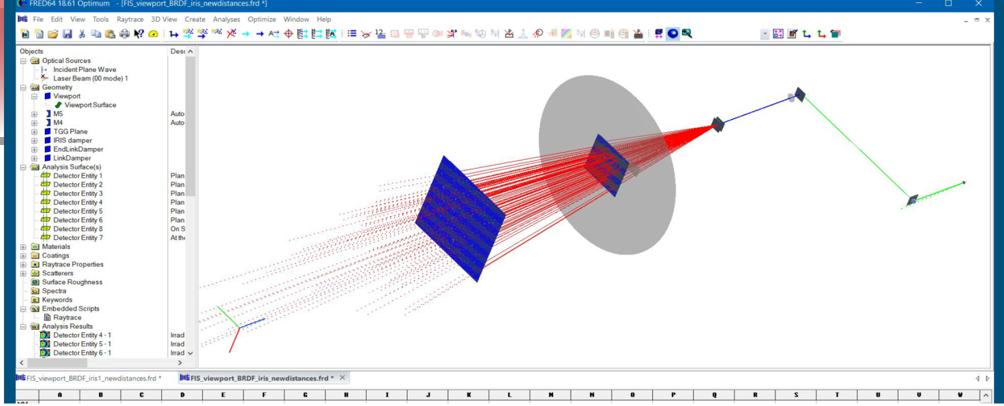
HIGHLIGHTS:

- Interdisciplinary effort (takes advantage of the peculiar expertise of the FISMAT group at DFA and LNL on thin films science)
- Key aspect in GW technology
- Wide network of collaborations (Europe, USA, Japan)

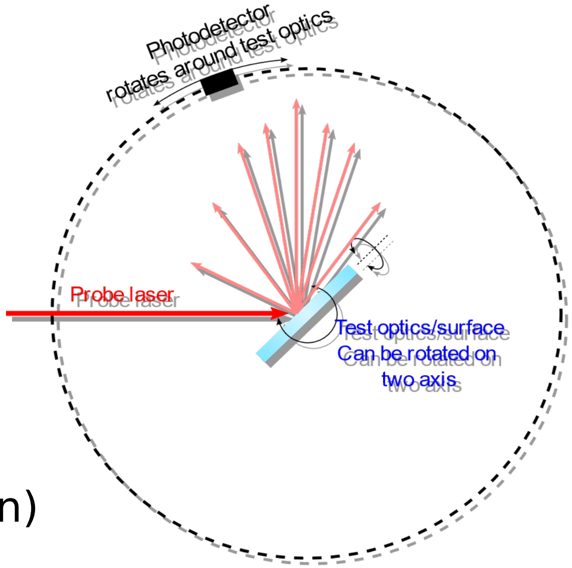
Old enemy, new fight: stray light

- the main sources of “unexplained noise”





- Difficult to model, control and suppress
- Activities:
  - Numerical simulations of squeezing subsystem with commercial raytracing software (FRED)
  - Building a facility do characterize optics and other surfaces’ scattering properties (BRDF/BTDF – Bidirectional Reflectance/Transmittance Distribution Function)



Integrating sphere to measure total scattering

Cryogenic optics characterization

- Going cryogenic to fight thermal noise (e.g Einstein Telescope) requires new materials and lasers
  - Fused silica's (current state of the art) mechanical loss increase at low T

- Silicon is a good candidate material at cryogenic T…
  - Low mechanical losses, high thermal conductivity, low thermal expansion
- …but, it is not transparent to 1064nm! Need to move to 1550nm: optical properties unknow at the level needed for GW detectors

- Currently building a cryogenic, 10W@1550 nm facility to test optical grade silicon samples from different manufacturers and processes.
  - Assessing optical absorption by means of bolometric measurements

Correlated activities: SUPERGALAX

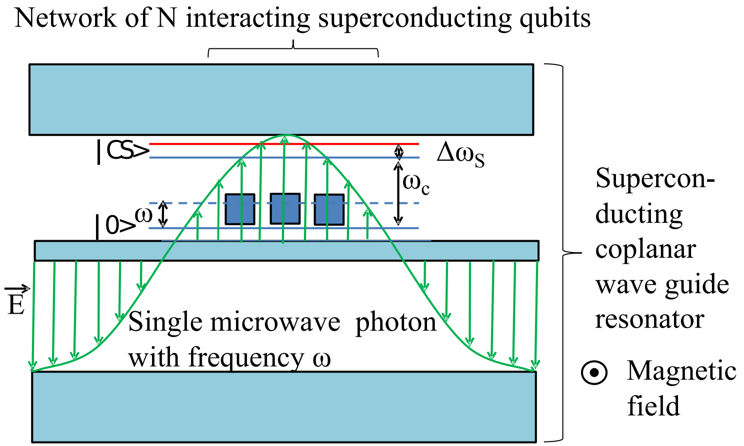
SUPERGALAX

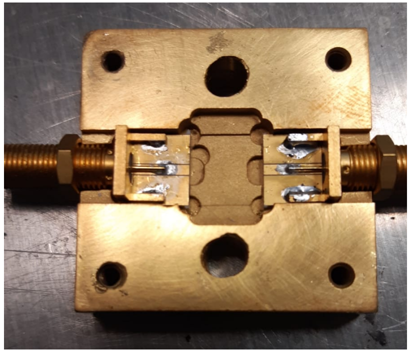
FET OPEN SUPERGALAX

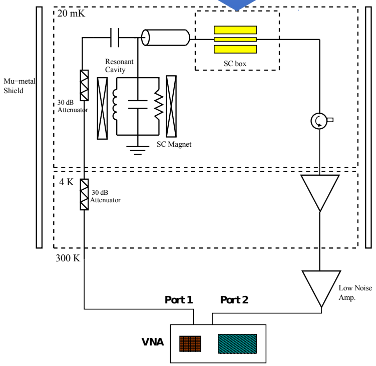
- CNR (IT, PI, exp)
- INRIM (IT, exp)
- INFN (IT, axion exp)
- KIT (DE, exp)
- Leibniz IPHT (DE, exp)
- RUB (DE theory)
- LU (UK, theory)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.

Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.







In a device based on array of qubits signal noise is suppressed by √N.

Zagoskin et al., «Spatially resolved single photon detection with a quantum sensor array» SCIENTIFIC REPORTS | 3 : 3464 | DOI: 10.1038/srep03464

67

Correlated activities: US QT Initiative

Quantum technologies Initiative proposed to DOE for the creation of a System Center

5-6 Centers out of 10 to be financed

QUAX PD/LNL Group involved within search for Axion Dark Matter

HIGH Q-FACTOR cavities in STRONG B-FIELDS

Photonic cavities (copper + dielectric): cavities hosting sapphire cylinders or rods that shape the cavity mode, reducing the dissipation on the cavity walls $\rightarrow 10^6$

Hybrid cavities (SC and copper surface) $\rightarrow 3 \times 10^5$ at 5 T.

A quantum-limited FMR HALOSCOPE

The most sensitive RF spin magnetometer ever realized. Operation of this instrument led to the best reported limit on the coupling of DM axions to electrons, and corresponds to a field sensitivity of 5.5×10^{-19} T.

68