F. Cappuzzello
Università di Catania and INFN LNS

The nuclear matrix elements of 0νββ decay and the NUMEN project at INFN-LNS

4th Workshop on New Aspects and Perspectives in Nuclear Physics (HINPW4) 5-6 May 2017

"Karolos Papoulias" Conference Center, University of Ioannina

A successful collaboration between INFN-LNS and University of Ioannina

- ✓ Starting in 2013
- ✓ Several experiments performed
- ✓ Impacting low energy nuclear physics

A new MoU for the future activity

3 research lines

1. Double Charge Exchange within the NUMEN project
2. Elastic and inelastic scattering in inverse kinematics
3. Multinucleon transfer

Memorandum of Understanding

between

Istituto Nazionale di Fisica Nucleare (INFN)
Via Enrico Fermi, 40 – 00044 Frascati (Rome), Italy

and

University of Ioannina
Panepistimiou Avenue, GR-45110 Ioannina, Greece

and

University of Athens
Panepisthmiou Avenue 30, GR10679 Athens, Greece

and

Hellenic Insitute of Nuclear Physics
Panepistimiou Avenue, GR-45110 Ioannina, Greece

Dr. Giacomo Cuttone
Director of INFN-LNS

2 6 APR. 2017

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Rector of UoI

Prof. Th. Sfikopoulos
Vice Rector of UoA

Prof. Th. Sfikopoulos
Vice Rector of Research and Development

Prof. G. Lalazissis
President of HINP

The NUMEN project

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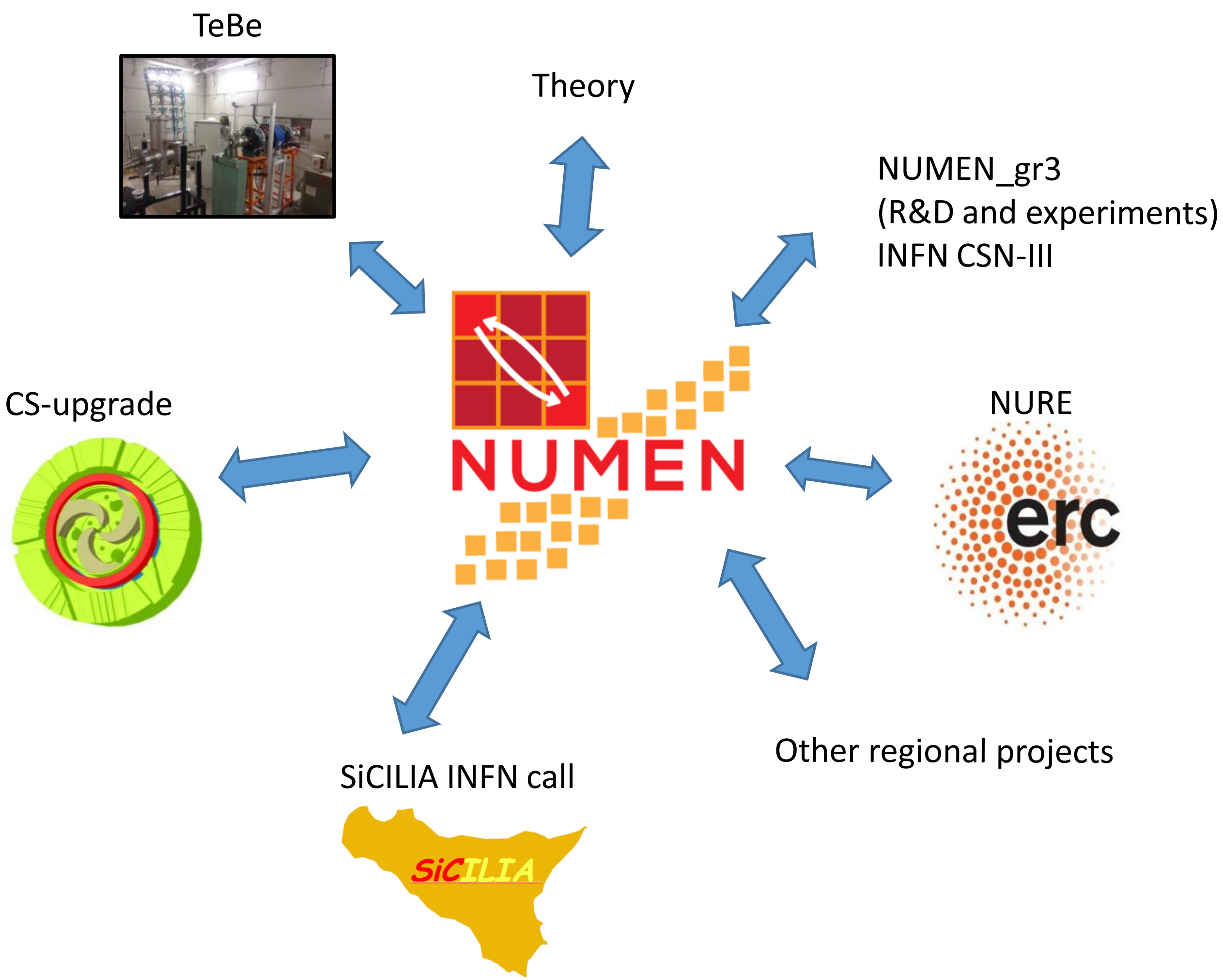
$$1/T^{0\nu}_{1/2}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

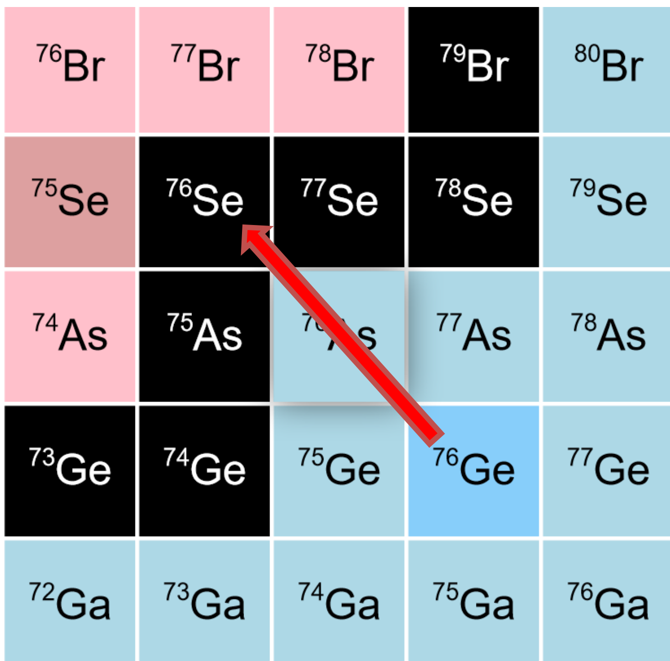
A broad view

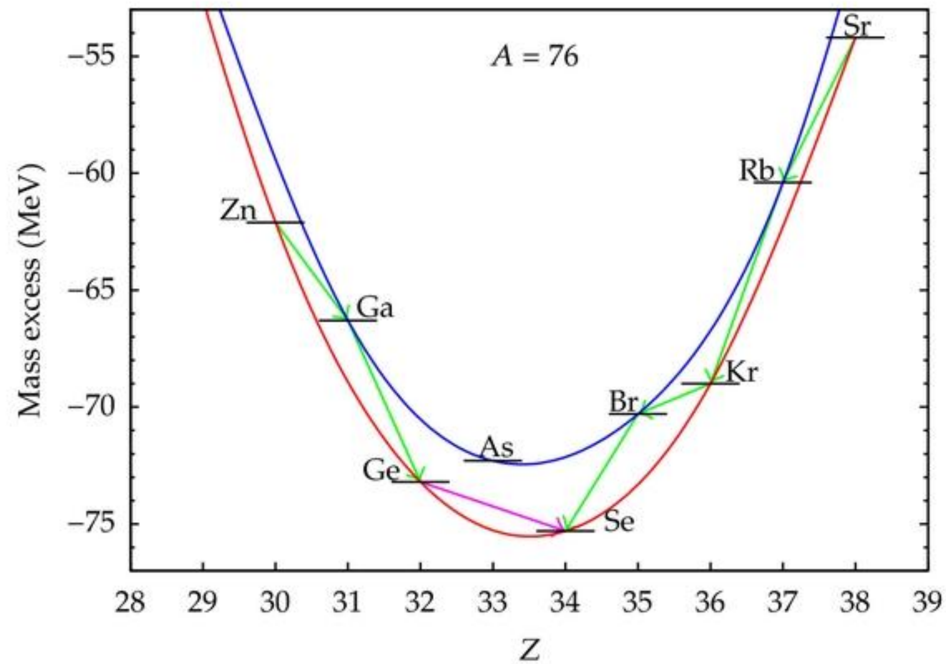

TeBe
Theory
NUMEN_gr3
(R&D and experiments)
INFN CSN-III
CS-upgrade
NUMEN
NURE
erc
SiCILIA INFN call
SiCILIA
Other regional projects

Physics case tutorial

Double β-decay

$$
{}^{A}_{Z}X_{N} \rightarrow {}^{\;\;\;A}_{Z-2}Y_{N+2} + 2e^{-} + (2\bar{\nu})
$$



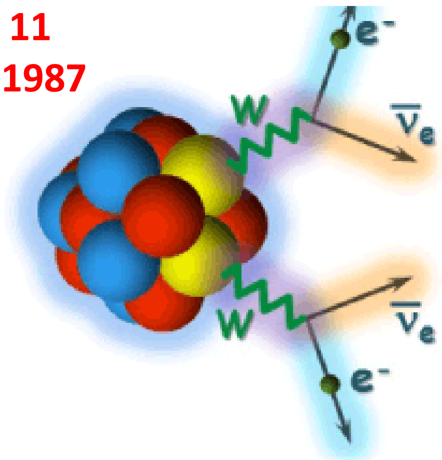


- ✓ Process mediated by the weak interaction observable in even-even nuclei where the single β-decay is energetically forbidden
- ✓ The role of the pairing force

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



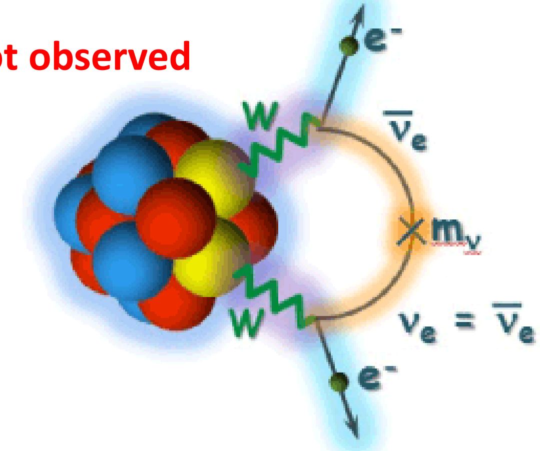
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. Within standard model
2. $T_{1/2} \approx 10^{19}$ to $2*10^{21}$ yr

$$1/T^{2\nu}_{1/2}(0^+ \to 0^+) = G_{2\nu}\left|M^{\beta\beta 2\nu}\right|^2$$

Neutrinoless double beta decay

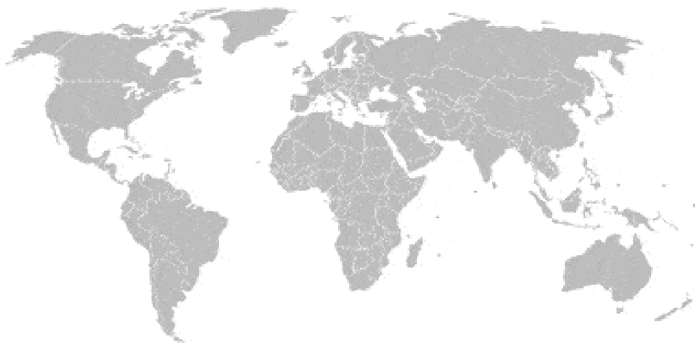
Still not observed



E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

1. Beyond standard model
2. Access to effective neutrino mass
3. Violation of lepton number conservation
4. CP violation in lepton sector
5. A way to leptogenesis and GUT

$$1/T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$



Search for 0νββ decay. A worldwide race

List not complete…

Experiment	Isotope	Lab
GERDA	^{76}Ge	LNGS [Italy]
CUORE	^{130}Te	LNGS [Italy]
Majorana	^{76}Ge	SURF [USA]
KamLAND-Zen	^{136}Xe	Kamioka [Japan]
EXO/nEXO	^{136}Xe	WIPP [USA]
CUPID - Lucifer	^{82}Se, ^{100}Mo	LNGS [Italy]
SNO+	^{130}Te	Sudbury [Canada]
SuperNEMO	^{82}Se (or others)	LSM [France]
CANDLES	^{48}Ca	Kamioka [Japan]
COBRA	^{116}Cd	LNGS [Italy]
DCBA	many	[Japan]
AMoRe	^{100}Mo	[Korea]
MOON	^{100}Mo	[Japan]

New physics for the next decades

but

requires

Nuclear Matrix Element (NME)!

$$\left|M_{\varepsilon}^{\beta\beta0\nu}\right|^{2}=\left|\left\langle\Psi_{f}\left|\hat{O}_{\varepsilon}^{\beta\beta0\nu}\right|\Psi_{i}\right\rangle\right|^{2}$$

- ✓ Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF .....

E. Caurier, et al., PRL 100 (2008) 052503
N. L. Vaquero, et al., PRL 111 (2013) 142501
J. Barea, PRC 87 (2013) 014315
T. R. Rodriguez, PLB 719 (2013) 174
F.Simkovic, PRC 77 (2008) 045503.

- ✓ Measurements (still not conclusive for $0\nu\beta\beta$):
  (π^+, π^-)
  single charge exchange (^{3}He,t), (d,^{2}He)
  electron capture
  transfer reactions
  muon nucleus scattering …

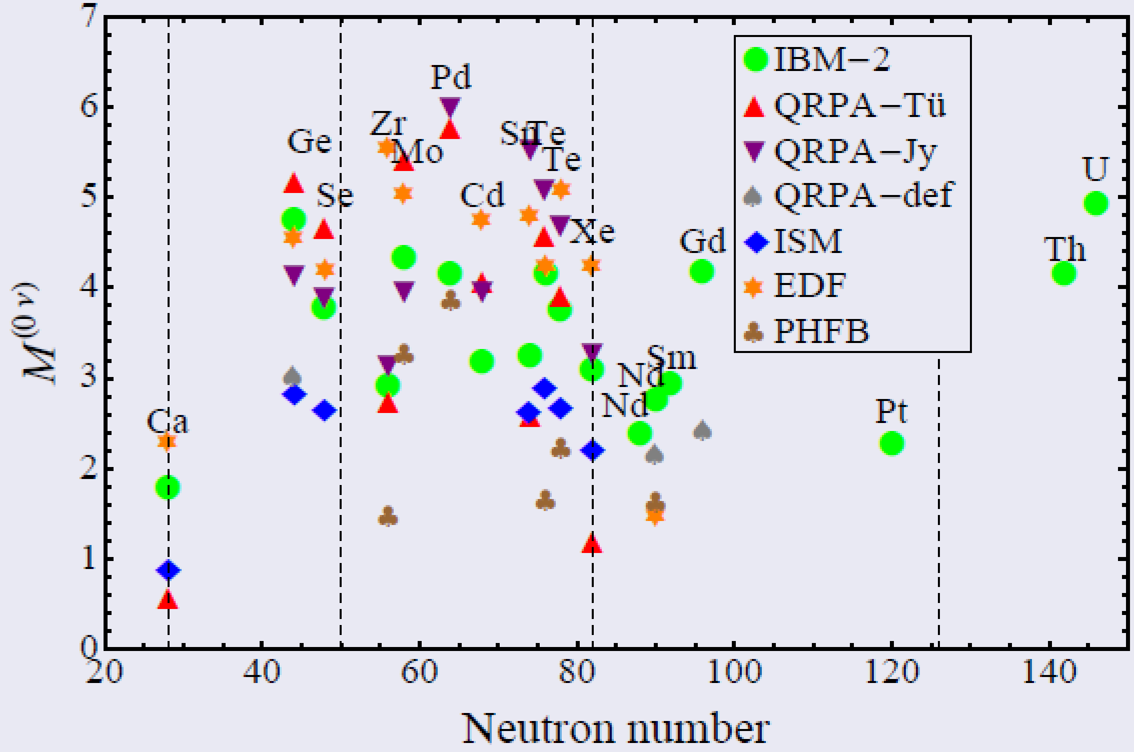
N. Auerbach, Ann. Of Phys. 192 (1989) 77
S.J. Freeman and J.P. Schiffer JPG 39 (2012) 124004
D.Frekers, Prog. Part. Nucl. Phys. 64 (2010) 281
J.P. Schiffer, et al., PRL 100 (2008) 112501

- ✓ A new experimental tool: heavy-ion Double Charge-Exchange (DCE)

State of the art NME calculations

Courtesy of Prof. F.Iachello

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



Far from satisfactory!

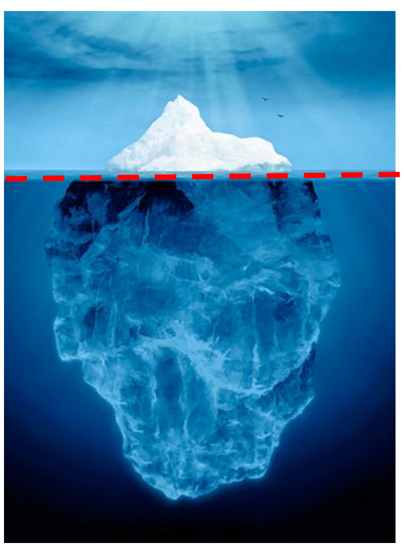
Heavy-ion DCE

- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order:

  Brink's Kinematical matching conditions *D.M.Brink, et al., Phys. Lett. B 40 (1972) 37*

- ✓ Meson exchange mechanism 2nd order
- ✓ Possibility to go in both directions

NUMEN

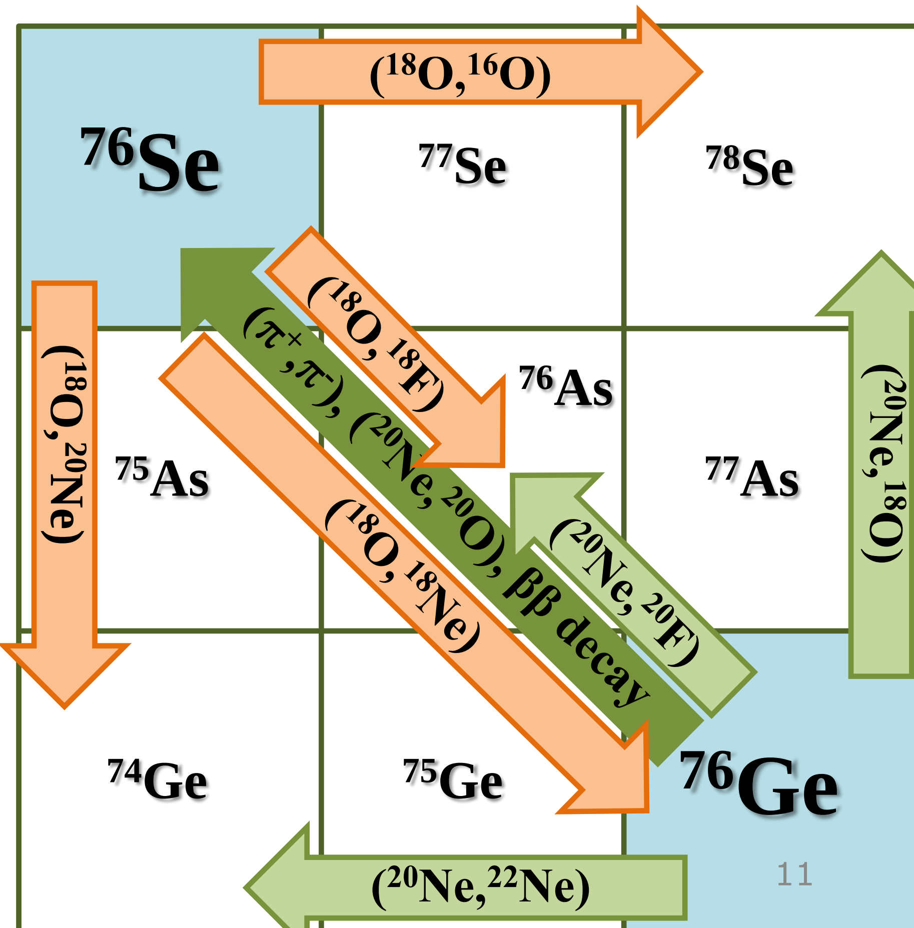


Tiny amount of DGT strenght in low lying states

Sum rule almost exhausted by DGT Giant Mode

RIKEN

RCNP



0νββ vs HI-DCE

Differences

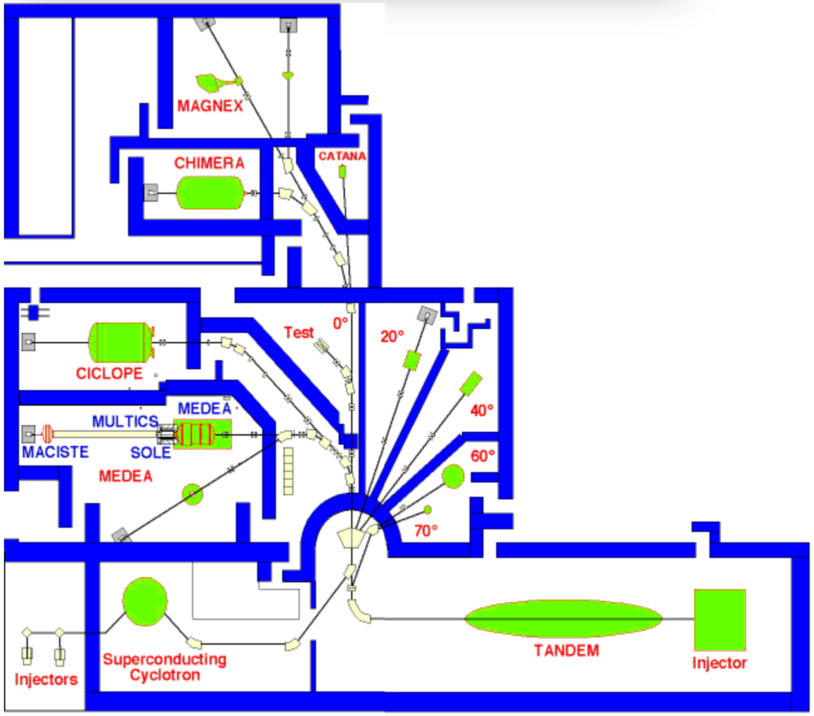
- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- DCE includes **sequential** transfer **mechanism**

Similarities

- **Same initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ decay are the same as those of the target/residual nuclei in the DCE
- **Similar operator:** Short-range Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with tunable weight in DCE
- **Large linear momentum** (~100 MeV/c) available in the virtual intermediate channel
- **Non-local** processes: characterized by two vertices localized in a pair of valence nucleons
- **Same nuclear medium**: Constraint on the theoretical determination of quenching phenomena on $0\nu\beta\beta$
- **Off-shell propagation** through virtual intermediate channels

DCE @ INFN-LNS

The LNS laboratory in Catania



Superconducting Cyclotron and MAGNEX spectrometer @ LNS

crucial for the experimental challanges

K800 Superconducting Cyclotron

- In operation since 1996.
- Accelerates from H to U ions
- Maximum energy 80 MeV/u.

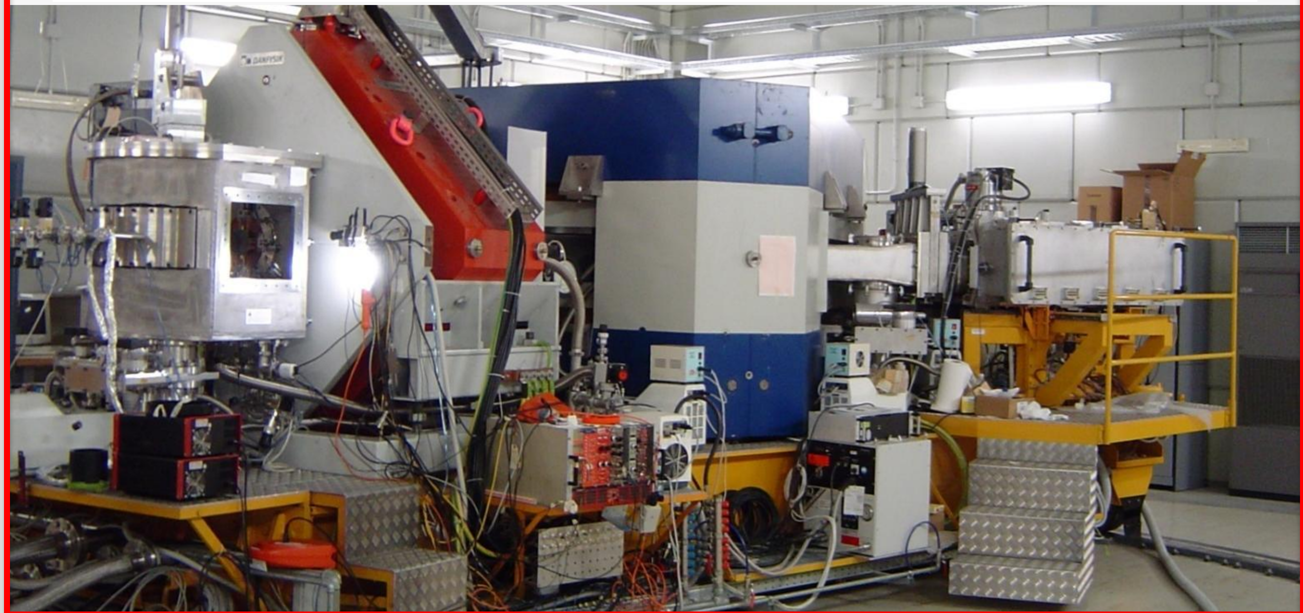
MAGNEX spectrometer

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167

Achieved resolution

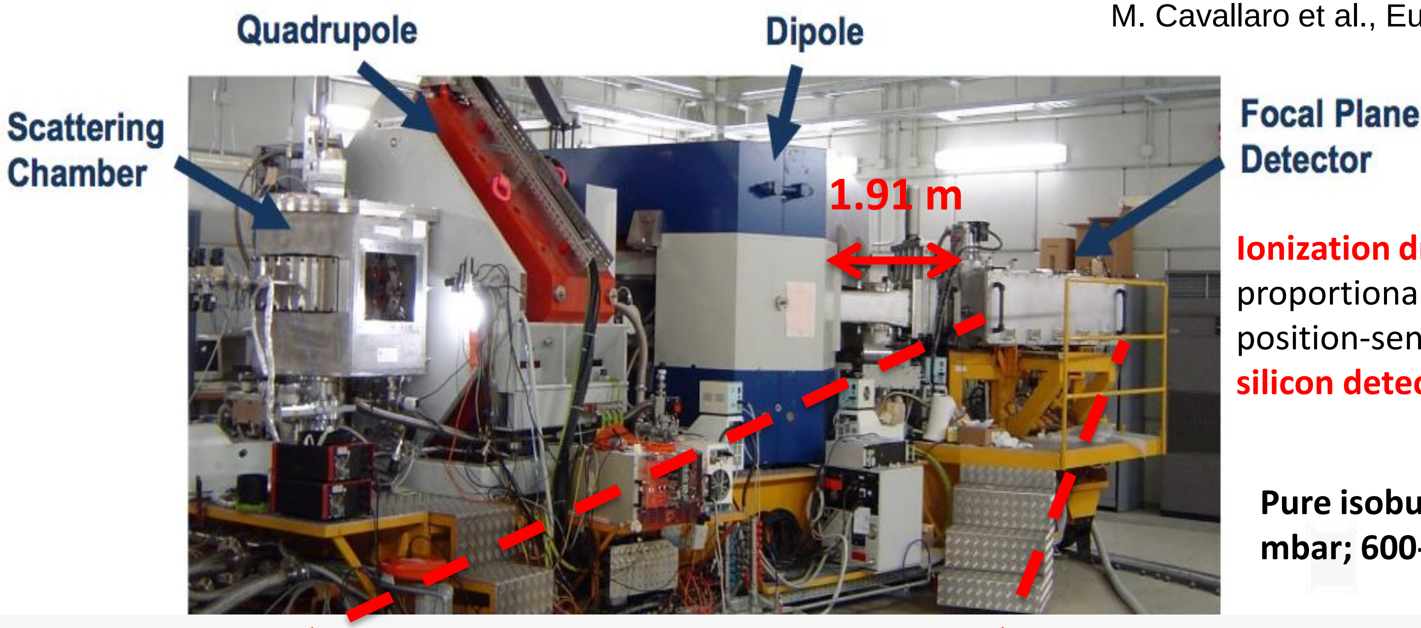
Energy **$\Delta E/E \sim 1/1000$**
Angle **$\Delta\theta \sim 0.2^{\circ}$**
Mass **$\Delta m/m \sim 1/160$**

Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68



The MAGNEX FPD

M. Cavallaro et al., Eur. Phys. J. A (2016) 48: 59

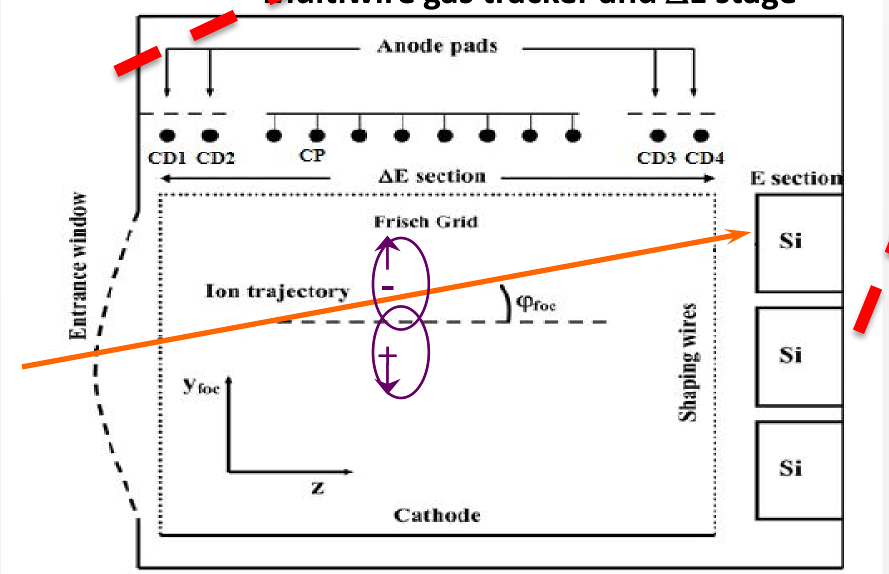


active area **140 x 20 cm^2**

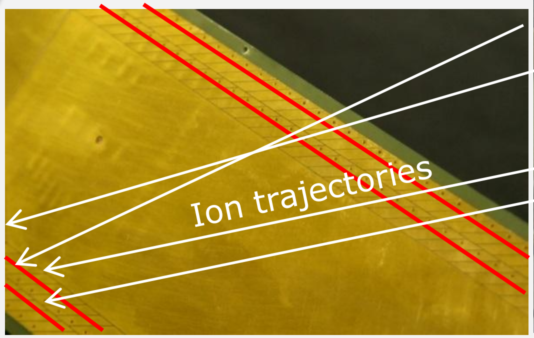
Ionization drift chamber, five independent proportional counters, four of which are position-sensitive and a **wall** of **stopping silicon detectors**

Pure isobutane; pressure range: 5-100 mbar; 600-800 V, wires ϕ =20 μm

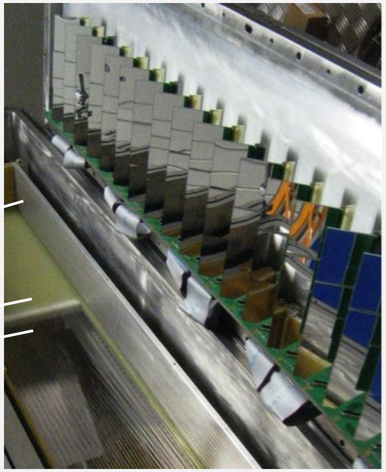
Multiwire gas tracker and ΔE stage



View of the stripped anode



Wall of 60 stopping 7 X 5 cm^2 Silicon detectors

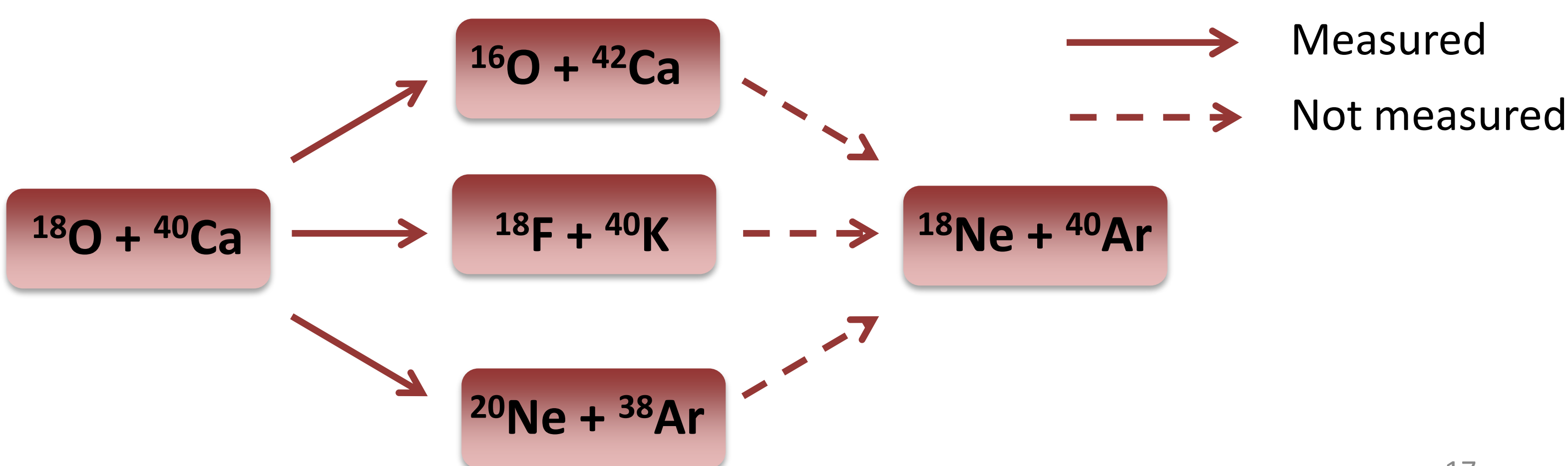


$(^{18}O,^{18}Ne)$ DCE reactions at LNS

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV

First pilot experiment

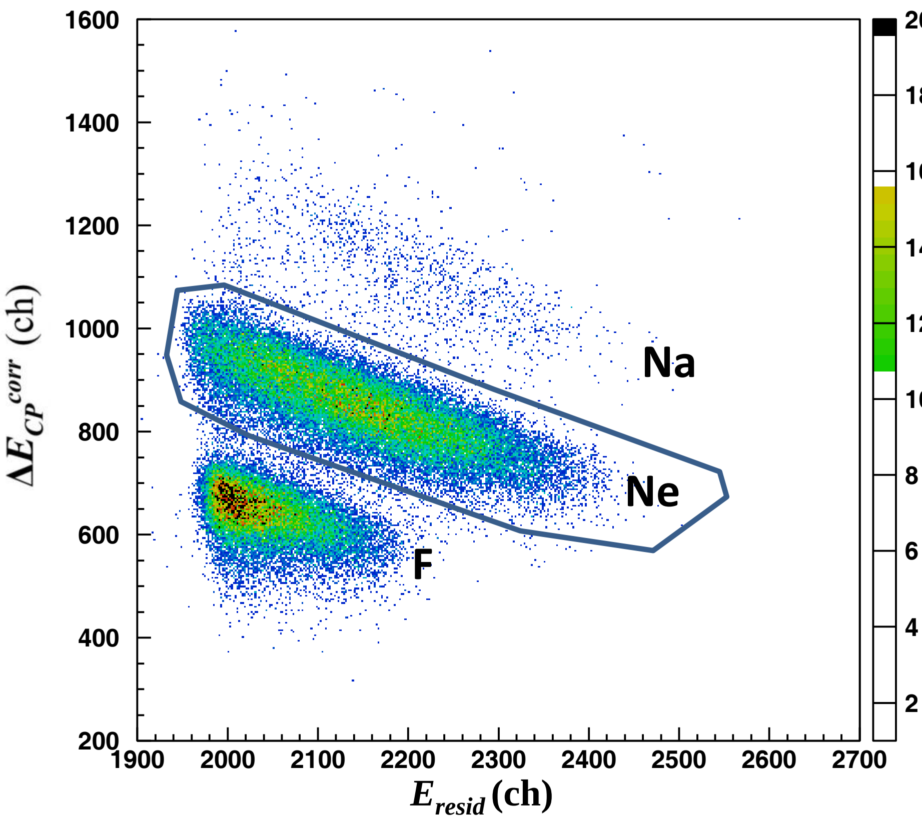
- $^{18}O^{7+}$ beam from Cyclotron at **270 MeV (10 pnA, 3300 μC in 10 days)**
- ^{40}**Ca** solid target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer ($0° < \vartheta_{lab} < 10°$)
- Unique angular setting: $-2° < \theta_{lab} < 10°$ corresponding to a momentum transfer range **from 0.17 fm^{-1} to about 2.2 fm^{-1}**



NUMEN

Particle Identification

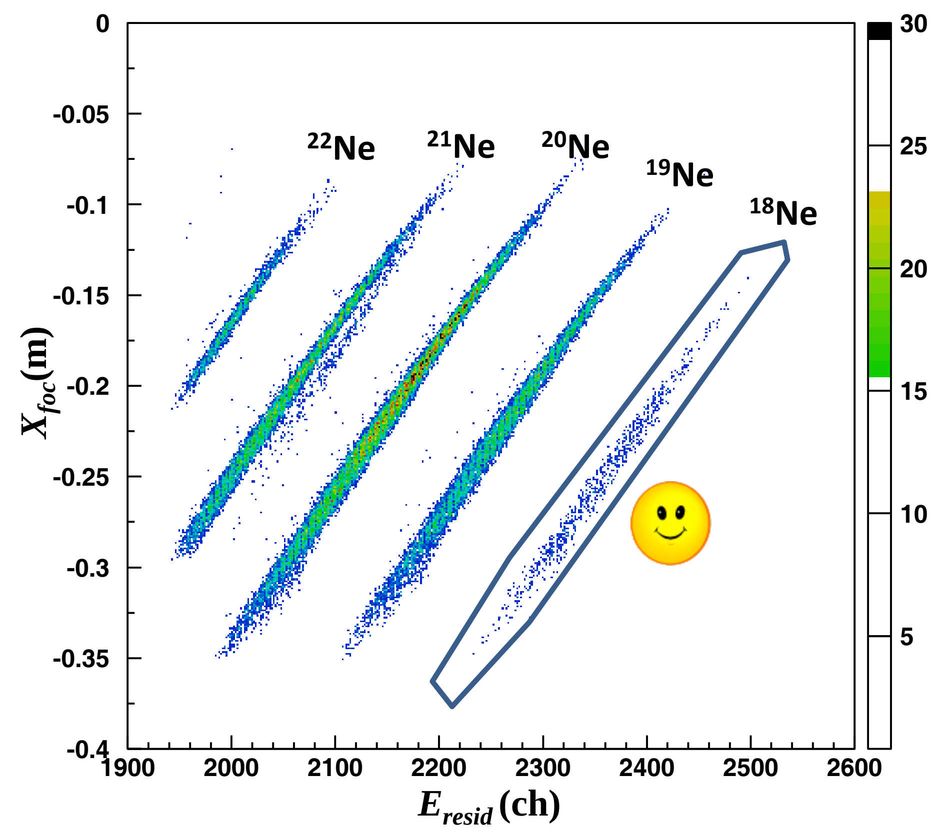
Z identification



A identification

$$Br = \frac{p}{q}$$

$$X_{foc}^2 \ \mu \ \frac{m}{q^2} E_{resid}$$



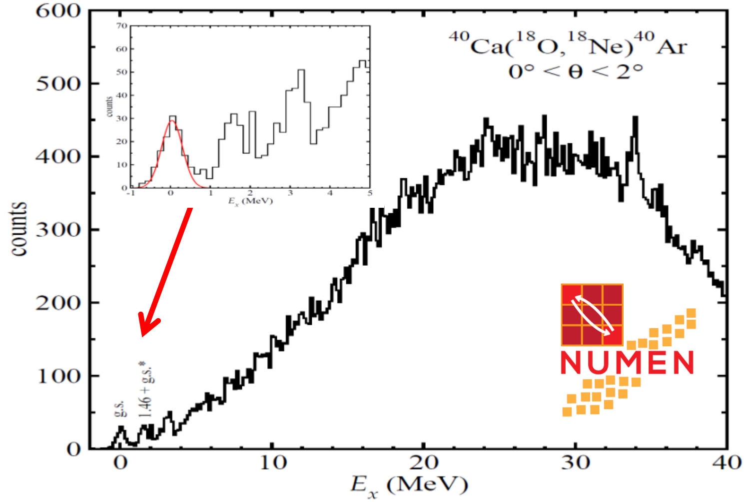
F. Cappuzzello et al., NIMA621 (2010) 419

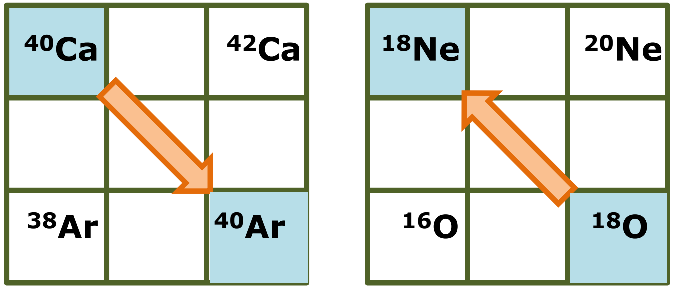
F. Cappuzzello, et al. NIMA638 (2011) 74

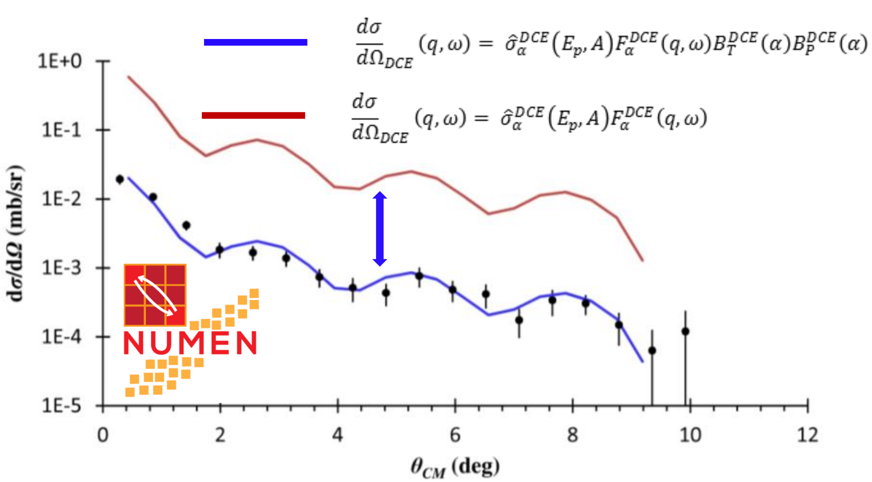
M.Cavallaro et al. EPJ A (2012) 48: 59

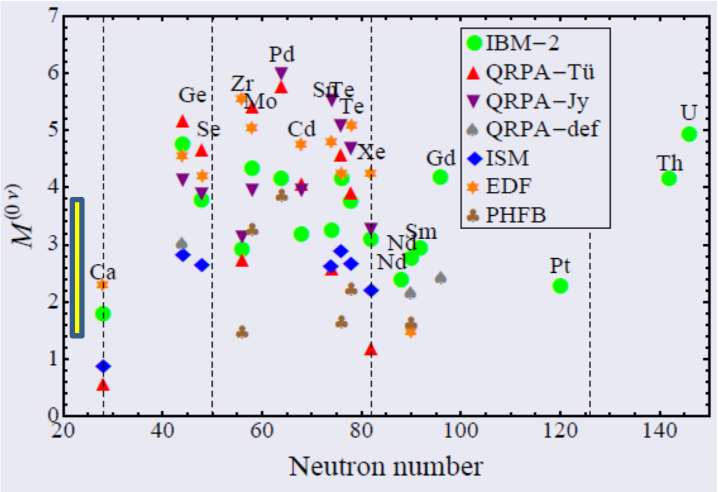
D.Carbone et al. EPJ A (2012) 48: 60

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV







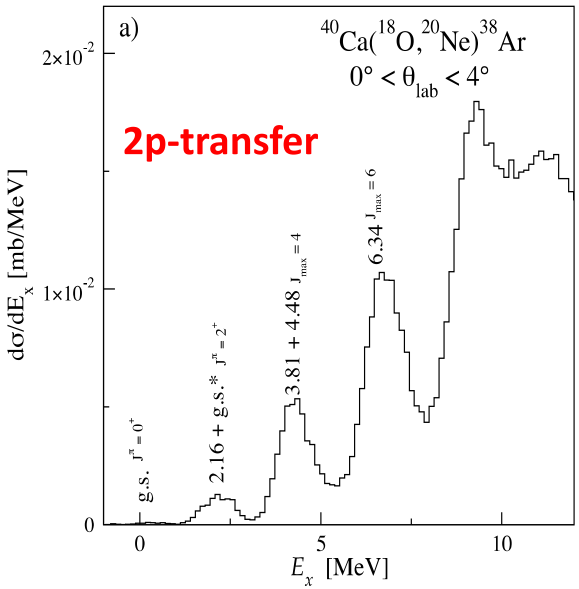


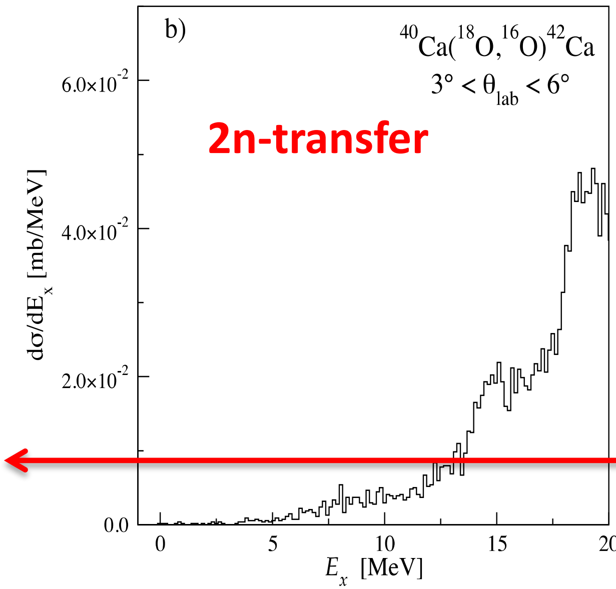
$$\left| M^{0\nu\beta\beta}\left({}^{40}Ca\right) \right|^2 = 0.37 \pm 0.18$$

F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145

Pauli blocking about 0.14 for F and GT

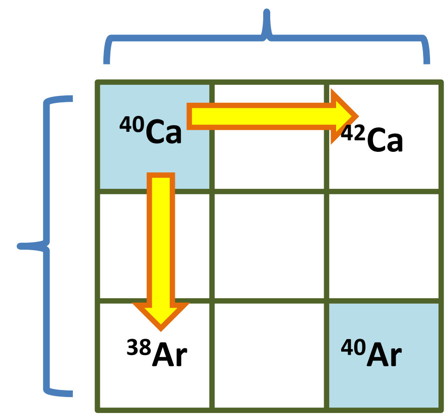
The role of the transfer reaction and the competing processes



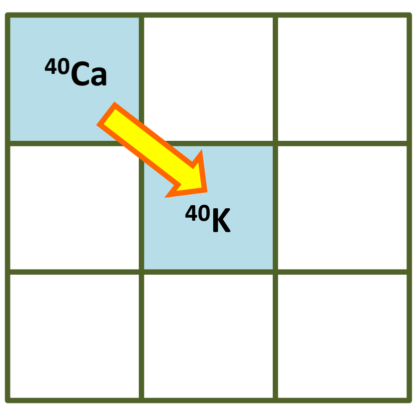


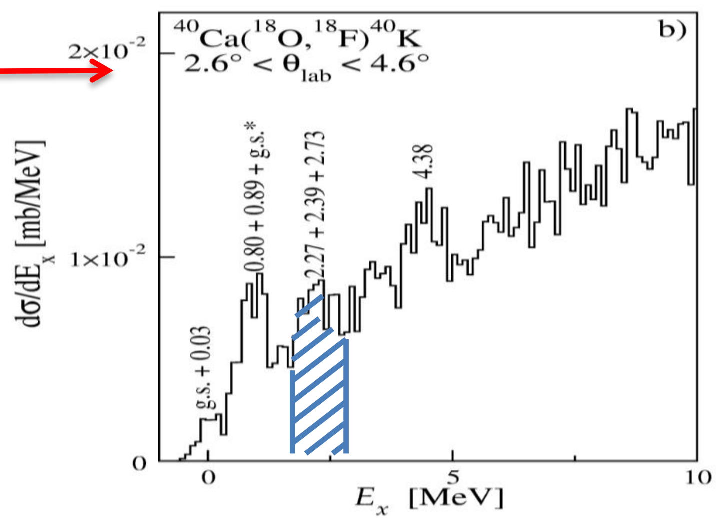
Less than 1% effect in the DCE cross section

Very weak



single charge exchange





x-section (2MeV < E_x < 3MeV) ≈ 0.5 mb/sr

Extracted B(GT) = 0.087

B(GT) from (^{3}He,t) = 0.083

Y. Fujita

Moving towards hot-cases:

Caveat

- The (^{18}O,^{18}Ne) reaction is particularly advantageous, but it is of *$\beta^+\beta^+$* kind;
- None of the reactions of *$\beta^-\beta^-$* kind looks like as favourable as the (^{18}O,^{18}Ne).
  (^{18}Ne,^{18}O) requires a radioactive beam
  (^{20}Ne,^{20}O) or (^{12}C,^{12}Be) have smaller B(GT)
- The reaction Q-values are normally more negative than in the ^{40}Ca case
- In some cases gas or implanted target will be necessary, e.g. ^{136}Xe or ^{130}Xe
- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus $\rightarrow$ Coincident detection of γ-rays

Much higher beam current is needed

NUMEN

Present technology is not enough…

The challenge: to detect with good energy, mass and angular resolutions rare events at very high rates of heavy ions!

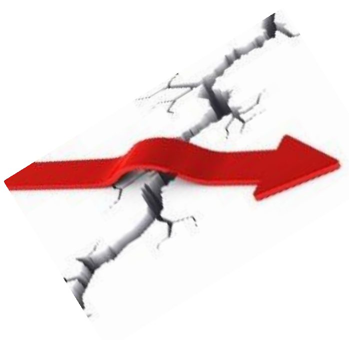
- **Upgraded set-up to match about 100 times more beam current than the present**
- **Substantial change in the technologies used in CS and in the MAGNEX detector**

The Goals of the Research Program

Main goal (Holy Grail):

Extraction from measured cross-sections of *"data-driven"* information on NME for all the systems candidate for $0\nu\beta\beta$

Secondary goals:



- Constraints to the existing theories of NMEs
- Model-independent comparative information on the sensitivity of half-life experiments
- Complete study of the reaction mechanism

Status and perspectives of NUMEN

The Phases of NUMEN project

- **Phase1**: The experimental feasibility
- **Phase2**: "hot" cases optimizing the experimental conditions and getting first results (approved)
- **Phase3**: The facility Upgrade (Cyclotron, MAGNEX, beam lines, …..)
- **Phase4** : The systematic experimental campaign

Time table

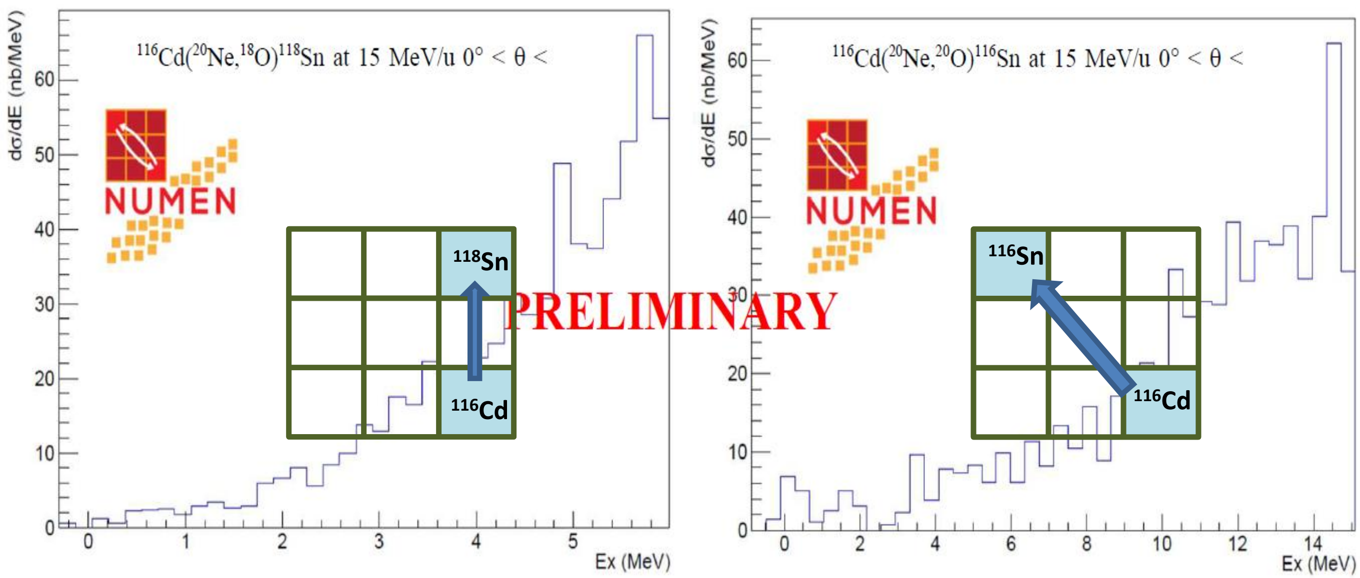
year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Phase1	done									
Phase2				Approved						
Phase3										
Phase4										

Recent NUMEN experiments

Facing some hot cases in Phase 2

		2016				2017				2018			
Reaction	**Energy (MeV/u)**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
^{116}Sn (^{18}O,^{18}Ne) ^{116}Cd	15-30	Exp											
^{116}Cd (^{20}Ne,^{20}O) ^{116}Sn	15-25		Test		Exp		Exp						
^{130}Te (^{20}Ne,^{20}O) ^{130}Xe	15-25								Exp				
^{76}Ge (^{20}Ne,^{20}O) ^{76}Se	15-25												
^{76}Se (^{18}O,^{18}Ne) ^{76}Ge	15-30												
^{106}Cd(^{18}O,^{18}Ne) ^{106}Pd	15-30												

Results from a test run on $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ March 2016

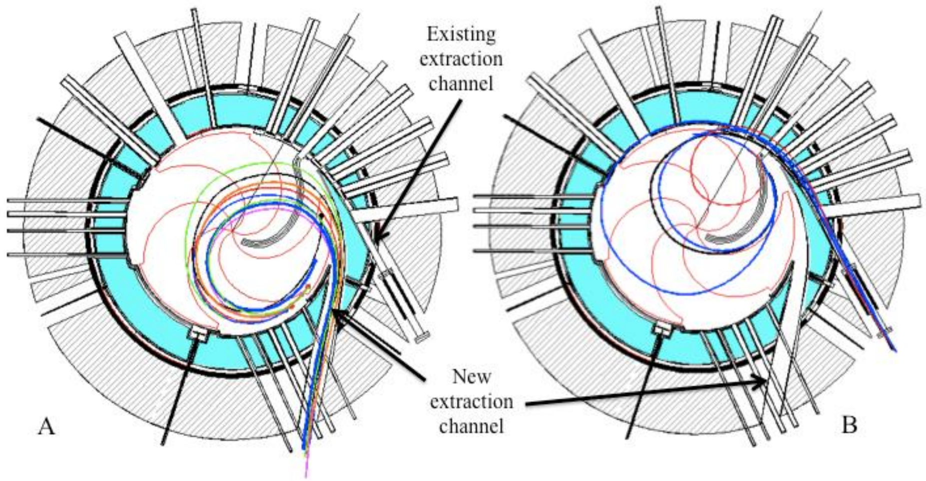


$$\sigma(^{116}Cd_{gs} \rightarrow {}^{118}Sn_{gs}) < 1/3^{*}\ \sigma(^{116}Cd_{gs} \rightarrow {}^{116}Sn_{gs})$$

Recent NUMEN R&D

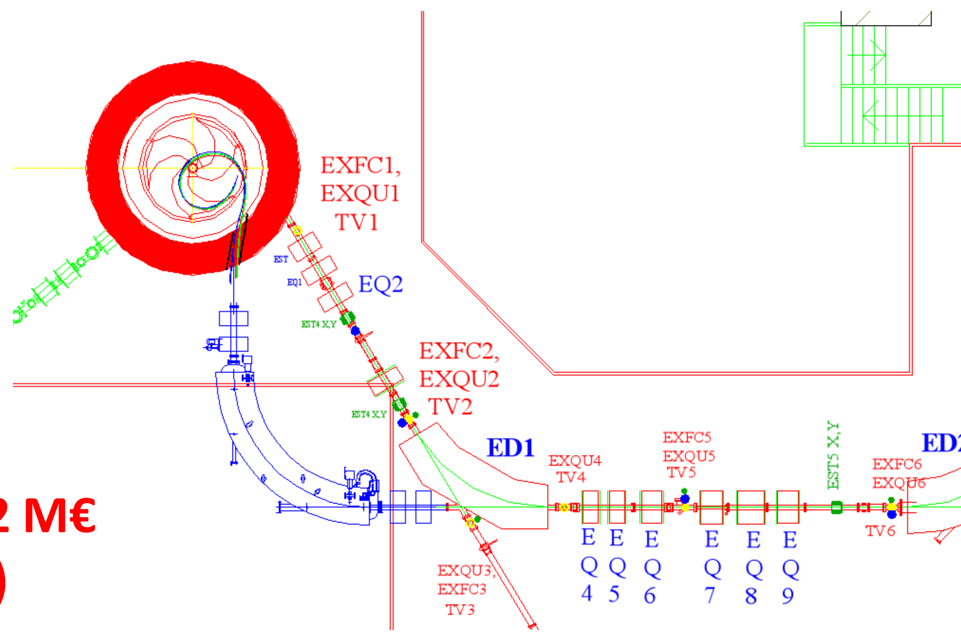
Major upgrade of LNS facilities: The CS accelerator

- The **CS** accelerator current (from 100 W to 5-10 kW);



Extraction by stripping

- The **beam transport line** transmission efficiency to nearly 100%



TDR of the project approved 11.2 M€
Cryostat tender started (~4.1M€)

Studied cases – expected intensities

Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	eμA	eμA	eμA	pps	watt
^{12}C q=5+	30	200	30 (4+)	45 (6+)	$4.7 \cdot 10^{13}$	2700
^{12}C q=4+	45	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	8100
^{12}C q=4+	60	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	10800
^{18}O q=6+	20	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	3600
^{18}O q=6+	29	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	5220
^{18}O q=6+	45	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	8100
^{18}O q=6+	60	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	10800
^{18}O q=7+	70	200	30 (7+)	34.3 (8+)	$2.7 \cdot 10^{13}$	5400
^{20}Ne q=7+	28	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	4800
^{20}Ne q=7+	70	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	10280
^{40}Ar q=14+	60	400	60 (14+)	77.1 (18+)	$2.7 \cdot 10^{13}$	10280

Purchase of the SC Magnet

Cost and technical analysis
Dec. 2015 -> completed in Sett. 2016
(RUP appointed in Sept. 2016)

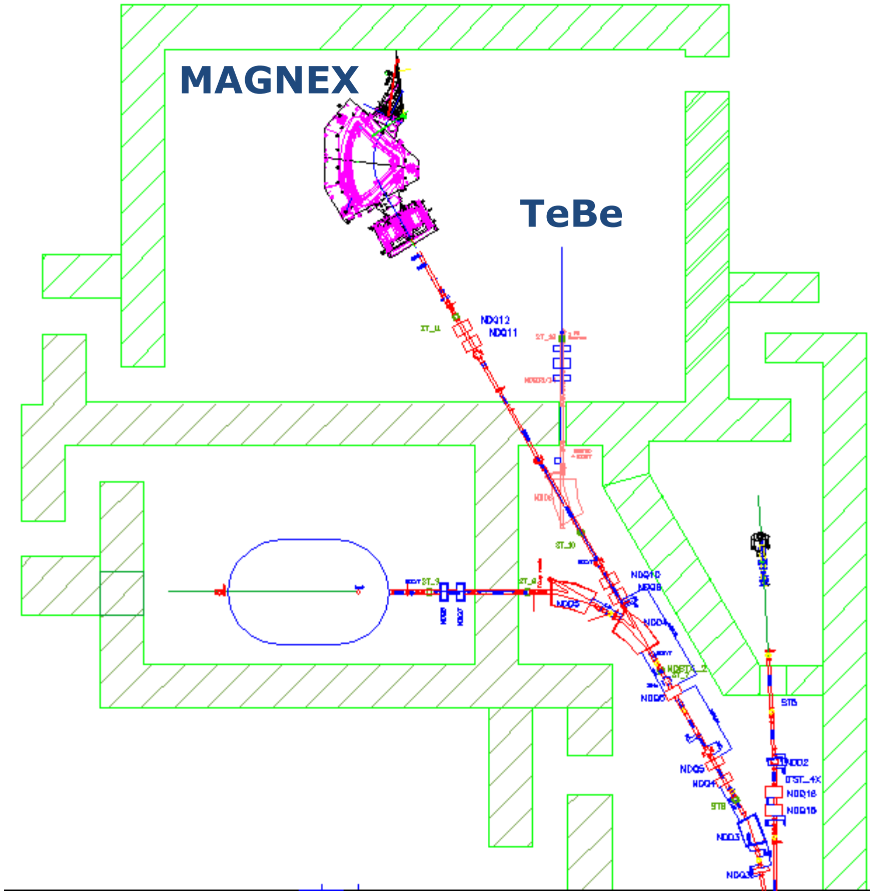
Tender and contract:
Nov. 2016 -> Sept. 2017

Design and Construction:
Oct. 2017 -> June 2020

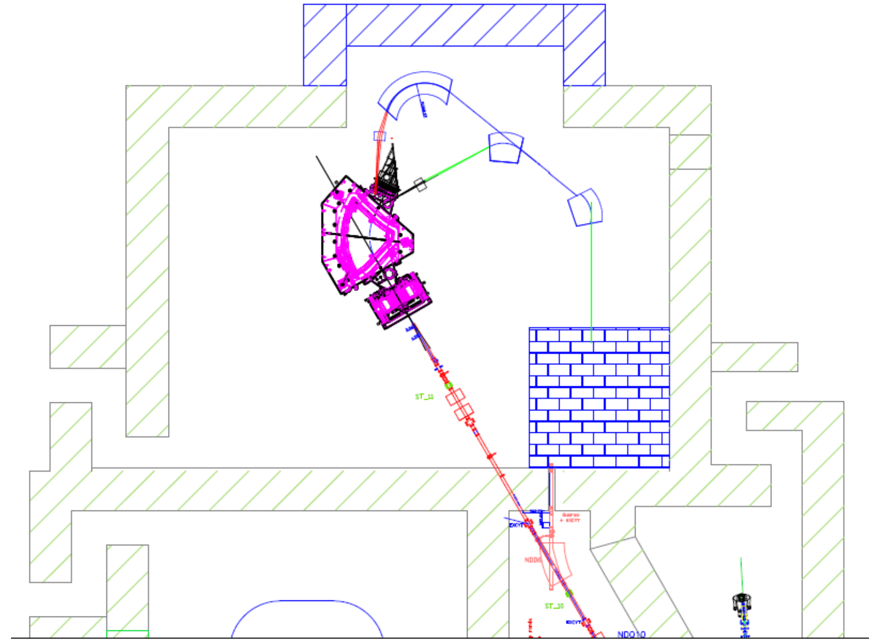
Installation - Test and Commissioning
July 2020 -> Apr. 2021

A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

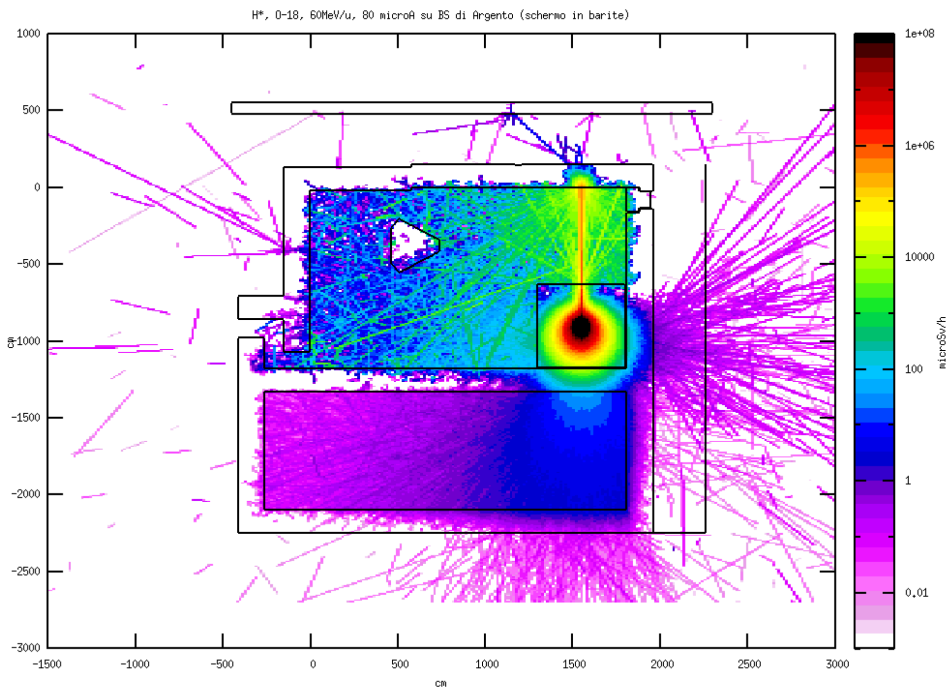


Future MAGNEX hall

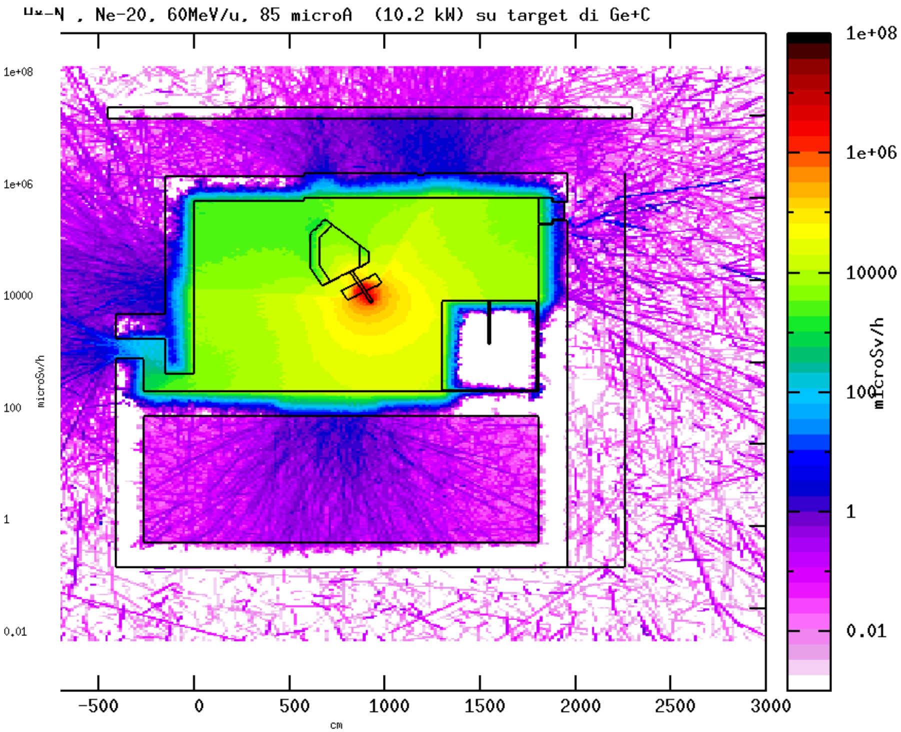


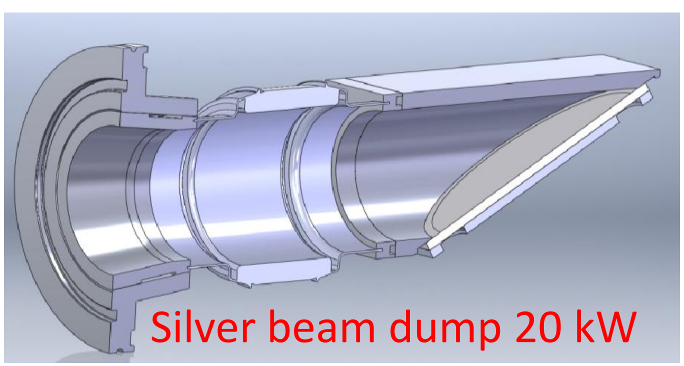
A challenging beam dump inside the MAGNEX hall

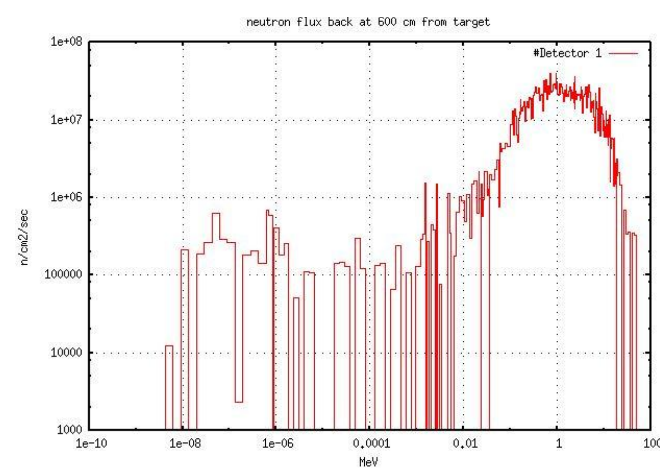
85 μA beam of ^{18}O on Ag



85 μA beam of ^{20}Ne on ^{76}Ge+C







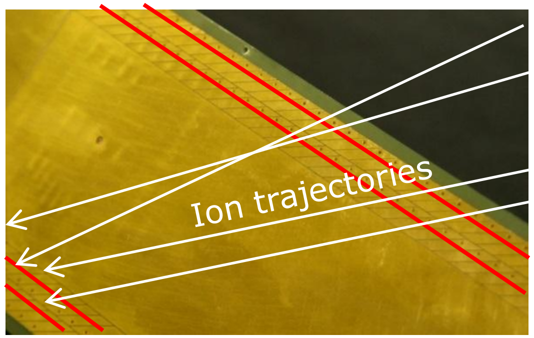
From S.Russo (LNS radioprotection service)

The new focal plane detector

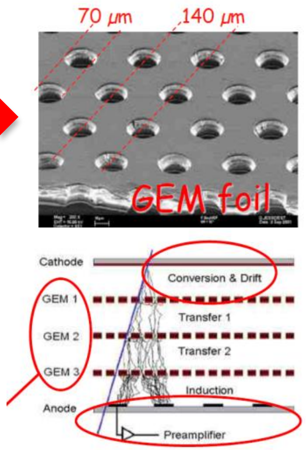
Major upgrade of LNS facilities: MAGNEX

- The **MAGNEX focal plane** detector rate (from 2 kHz to several MHz)

From multi-wire tracker



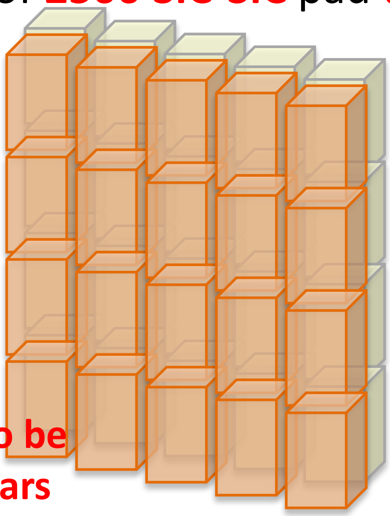
To micro-pattern tracker



- **R&D key issue : MPGD-based tracker at low pressure and wide dynamic range**
- **INFN-LNS, collaboration with INFN-CT, UNAM**

From wall of **60** Si pad

To wall of **2500 SiC-SiC** pad **telescopes**



About 10^{14} ions to be collected in 10 years

A big challenge!

0.9 M€ call approved by INFN CSN5 (SICILIA)

collaboration with CNR, STM, FBK

SiC detectors in INFN

SiCILIA

Si**l**icon **C**arbide Detectors for **I**ntense **L**uminosity **I**nvestigations and **A**pplications

Call INFN 2016

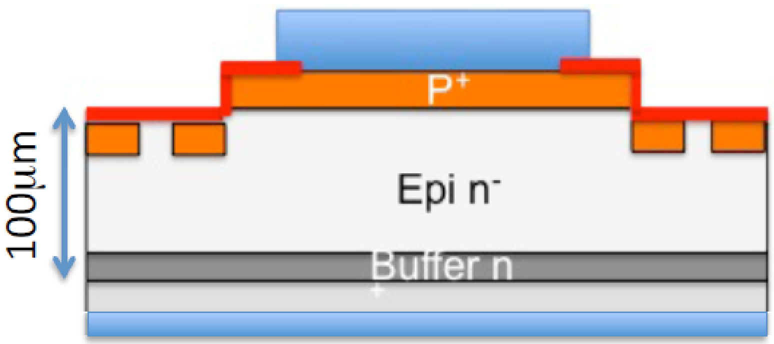
SiCilia strategy

Schottky junctions =>

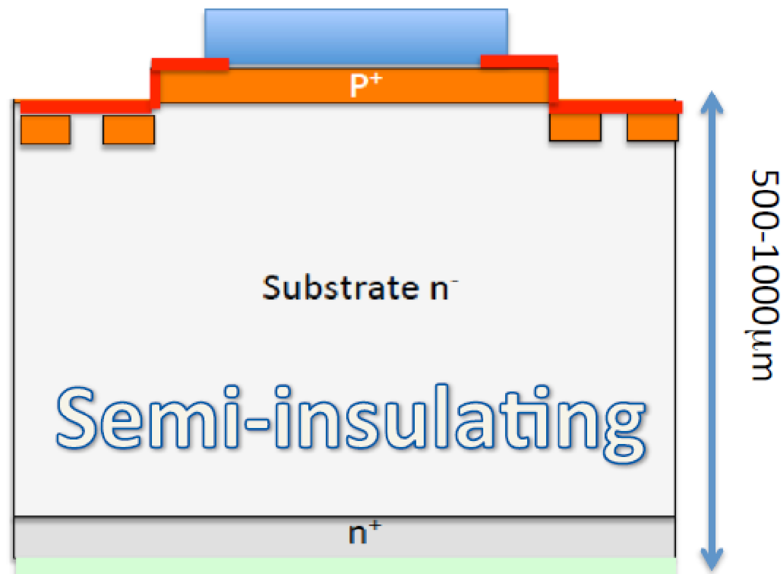
p-n junctions =>

STMicroelectronics

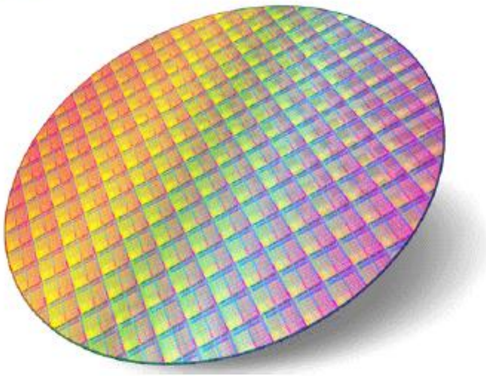
Detector Δ E



Detector E



Silicon Carbide detectors

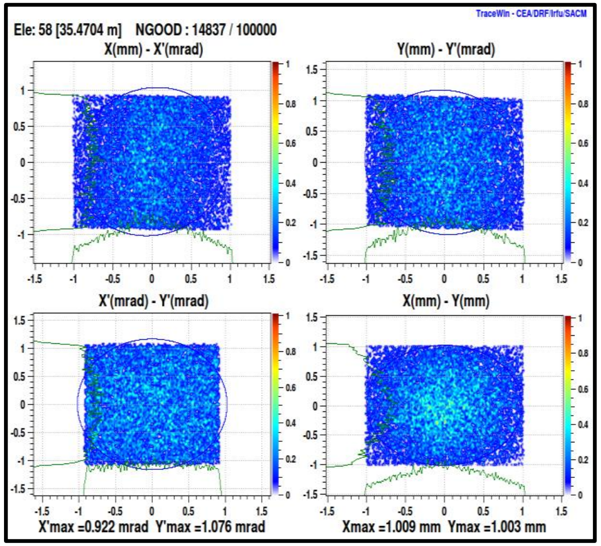


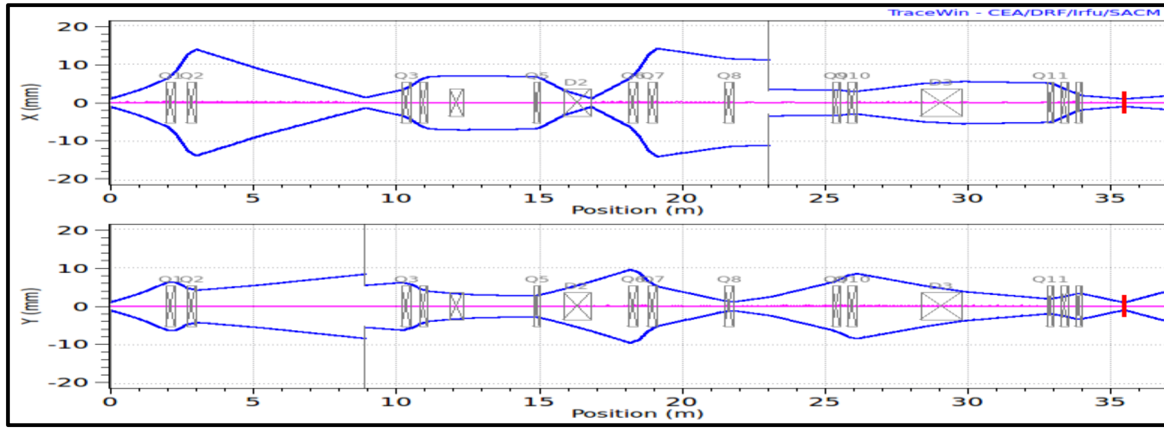
First new detector prototypes from STM already in house to be tested under beam

The new Test Bench (TeBe)

TeBe Experimental point in the MAGNEX H

Low emittance beam line for test of tracking detectors

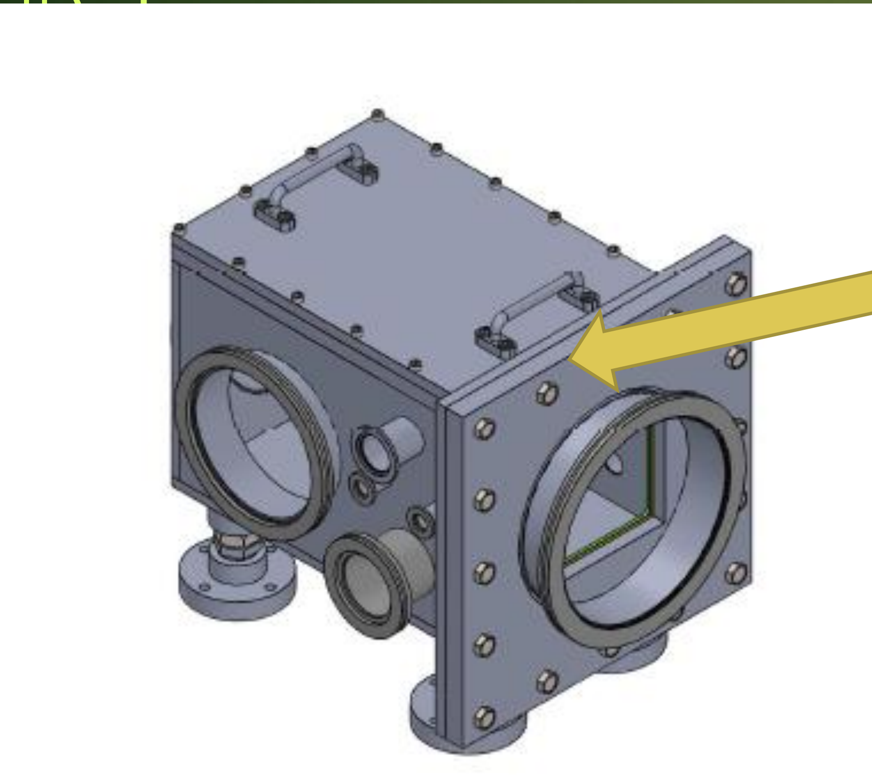


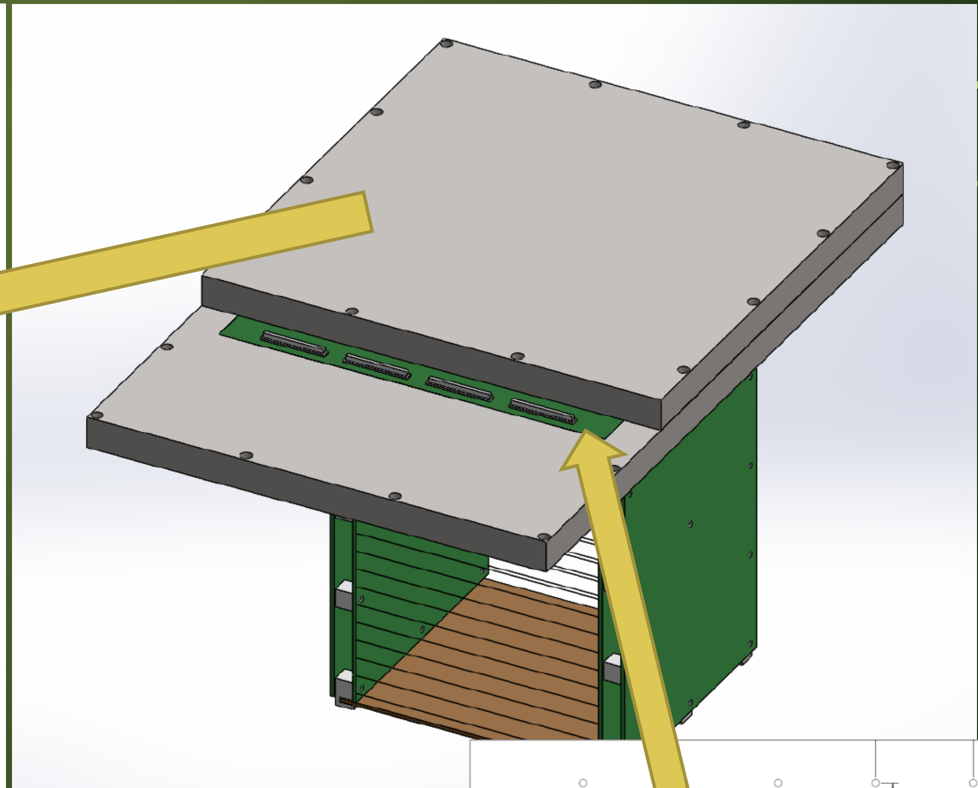


Final assembly and commissioning this week

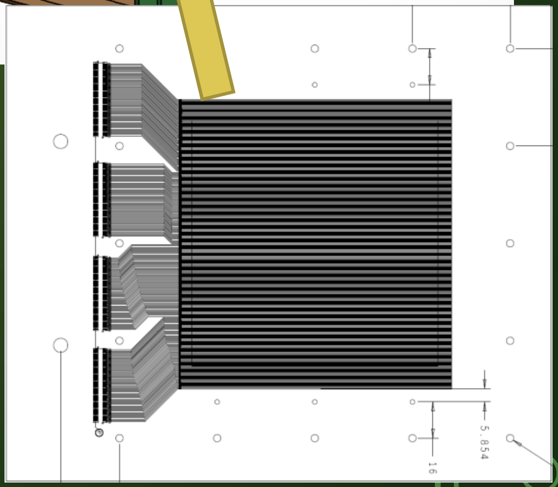
DETECTOR CHAMBER PROTOTYPE

TEST PLATFORM FOR ALL BRAND NEW SOLUTIONS





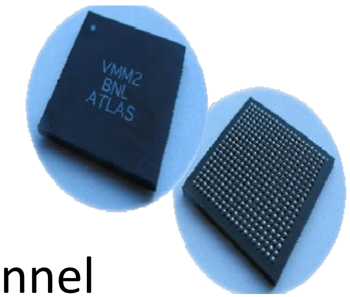
- Scalable to final size;
- Minimization of FE-RO Electronics;
- No need for vacuum connector;
- Read-out Electronics in air;
- Optimization of the electric field;
- Easy of maintenance.



The new electronics

Front-end and read-out electronics

ELECTRONICS PROTOTYPES



1) ASIC front–end chip:

for FPD chip **VMM2(3)** in collaboration with Brookhaven National Laboratory (8x10^4 transistor/channel for 64 channels)

2) Read – out: new generation of **FPGA** and System On Module (**SOM**)

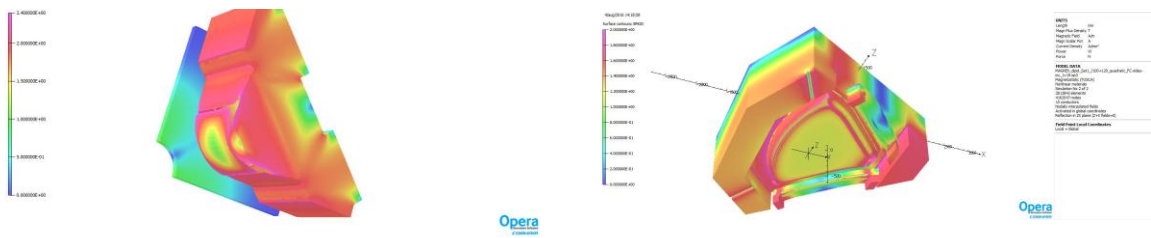
Number of channels

- Gas tracker ~ 2000 ch
- SiC-SiC ~ 6000 ch
- γ-ray calorimeter ~ 2500 ch

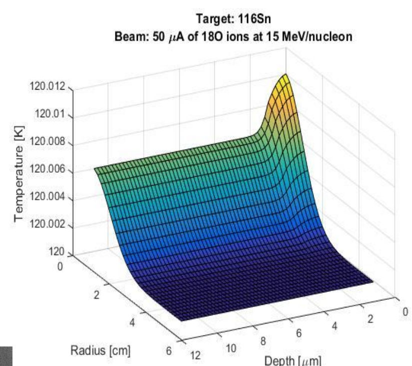
Tot ~ 10500 ch

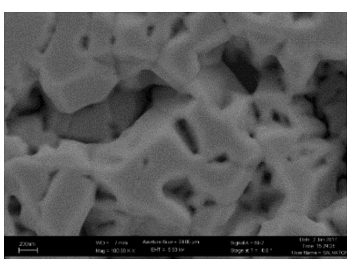
Other upgrades

- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)



- The **target** technology for intense heavy-ion beams





- An **array of scintillators for γ-rays** measurement in coincidence with MAGNEX

Other upgrades

- **Nuclear reaction theory** (formal development and calculations)
- **Plan_B for particle identification**
- **Simulations**
- **Data Acquisition**
- **Data Reduction**

Conclusions and Outlooks

- **NUMEN represents a challenging perspective** for the future of LNS in nuclear science
- **The project** turns around the MAGNEX and the Cyclotron upgrade toward high intensity
- It is playing an important role for **attracting worldwide researchers at the LNS**
- It is playing an important role for nuclear physics in Italy. **INFN-LNS was recently included** in the restricted list of **italian strategical research projects**
- **Results** of relevance for $0\nu\beta\beta$ physics already got in **the initial campaigns**
- **A big technological challenge**

Conference on Neutrinos and Nuclear Physics (CNNP2017)

15-21 October 2017
Catania (Italy)

http://agenda.infn.it/event/CNNP2017

Registration open