The Physics at an Underground Laboratory, LNGS

Symposium on Science at PAUL (Paarl Africa Underground Laboratory)

Cape Town, South Africa, 13-19/01/2024

Marcello Messina Researcher at LNGS-INFN, Italy

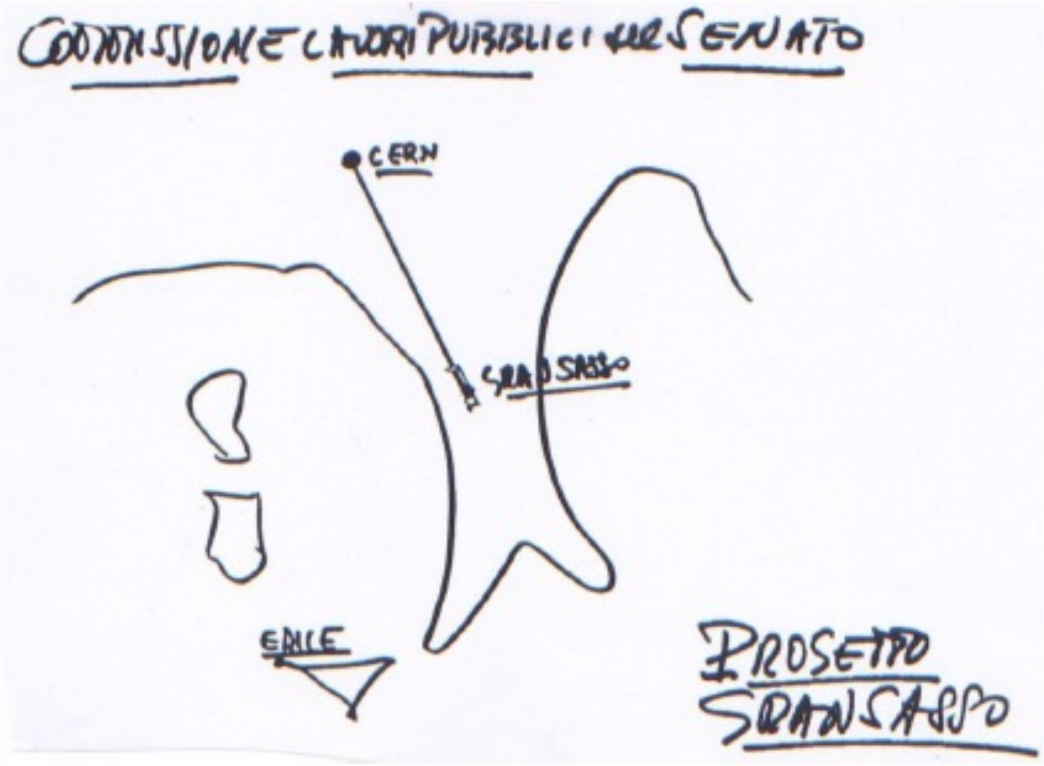
INFN LNGS

LABORATORI NAZIONALI del GRAN SASSO of INFN

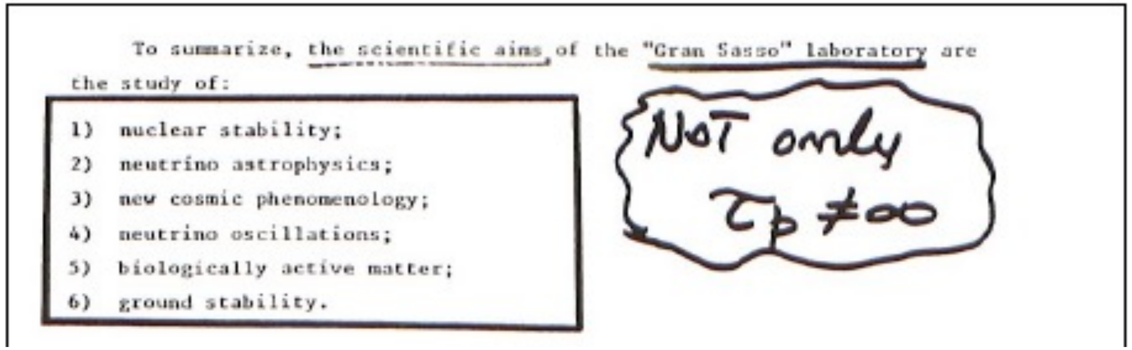
- In the last 35 years, LNGS has been the largest underground site for astroparticle physics worldwide.

- Its unique combination of technology, infrastructure, location, accessibility, and scientific community, made LNGS attractive to thousands of scientists from all around the world.

Above ground laboratory



Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).



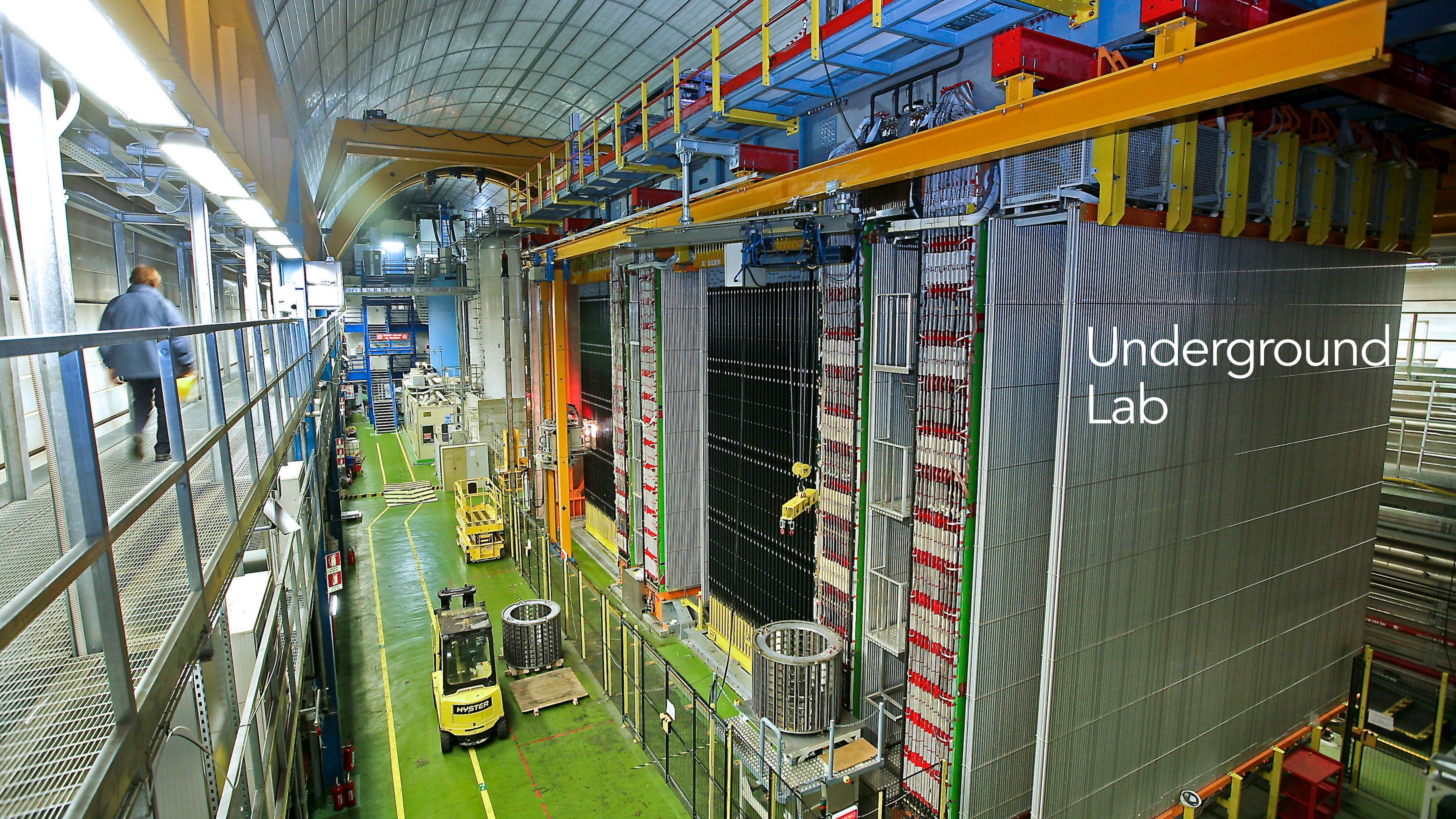
To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

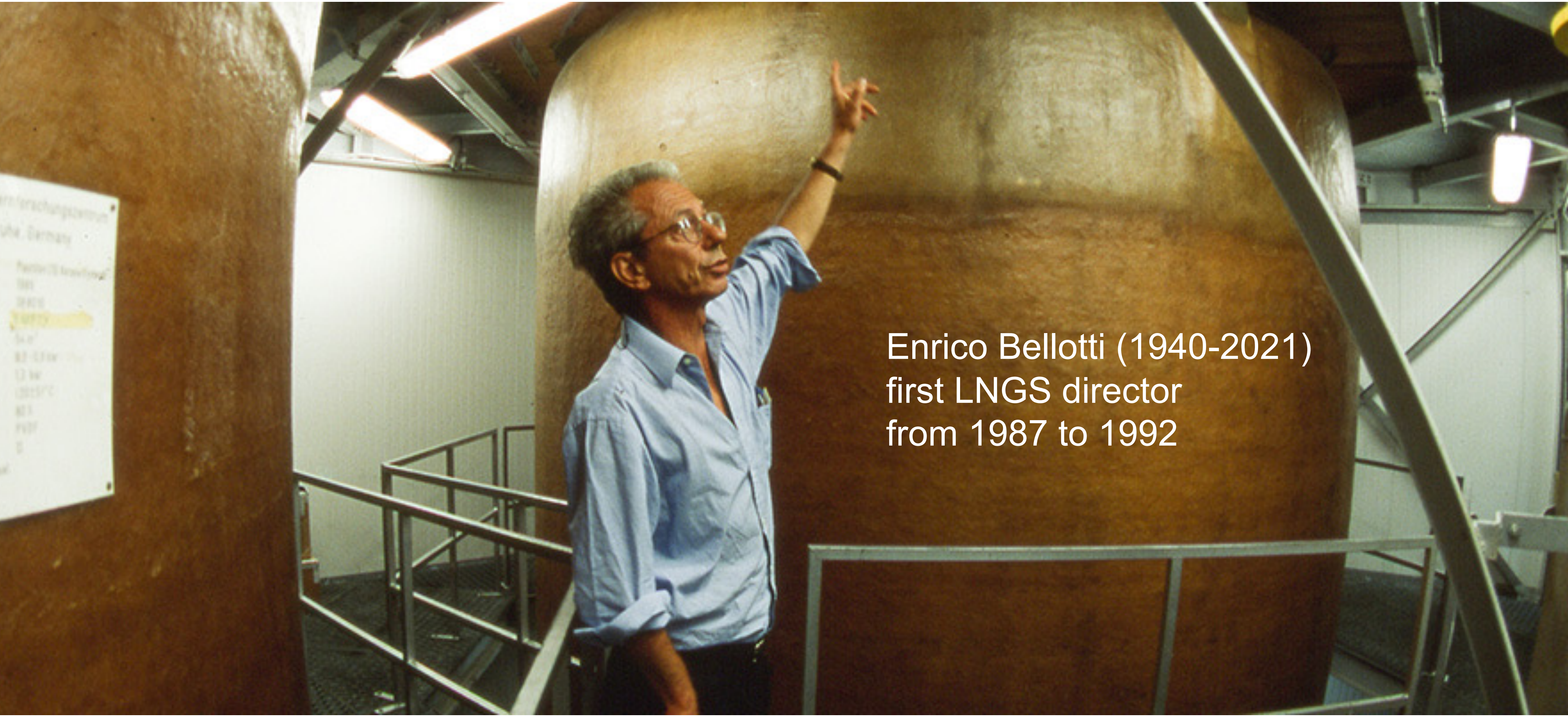
1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

- 1979: proposal by A. Zichichi to Italian Parliament
- 1982: Approval of LNGS construction
- 1987: construction completed
- 1989: Start data taking of first large experiment (MACRO)




MACRO


Underground
Lab
HYSTER



Enrico Bellotti (1940-2021)
first LNGS director
from 1987 to 1992

The Underground Lab in numbers

- 1400 m (3800 m.w.e. vertical depth)
- Muon rate ~ 1/(m^2 h)
- Surface: 17 800 m^2
- Volume: 180 000 m^3
- Ventilation: 1 vol / 3 hours
- 3 large experimental halls (~100x20x18 m^3)
- 22 experiments currently running
- Easy accessible via highway tunnel

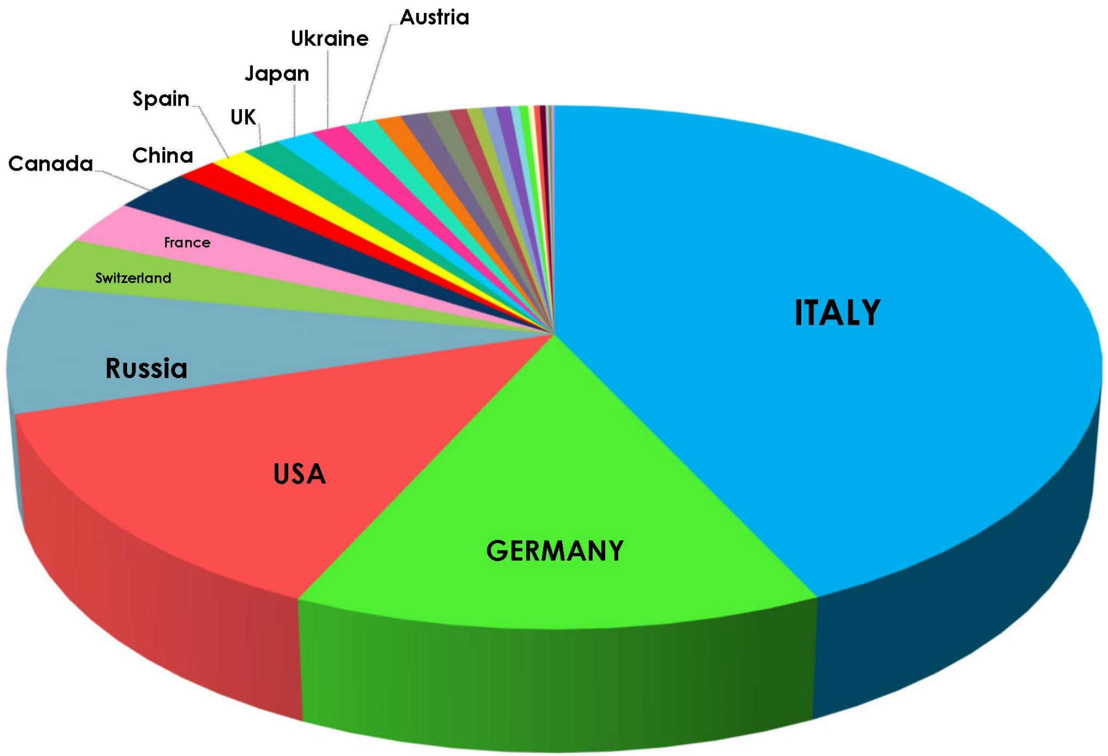
Worldwide LNGS access

Since its beginning, LNGS has always been characterized as an international Lab

Total users: N. 981

Italian users: N. 417

Foreign users: N. 564



* data source: 2019

Science network

LNGS is one of the corners of a high-level science and education triangle in the Gran Sasso area.

The University of L'Aquila and the Gran Sasso Science Institute are the primary partners of the LNGS development and culture promotion strategy.

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL GRAN SASSO

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

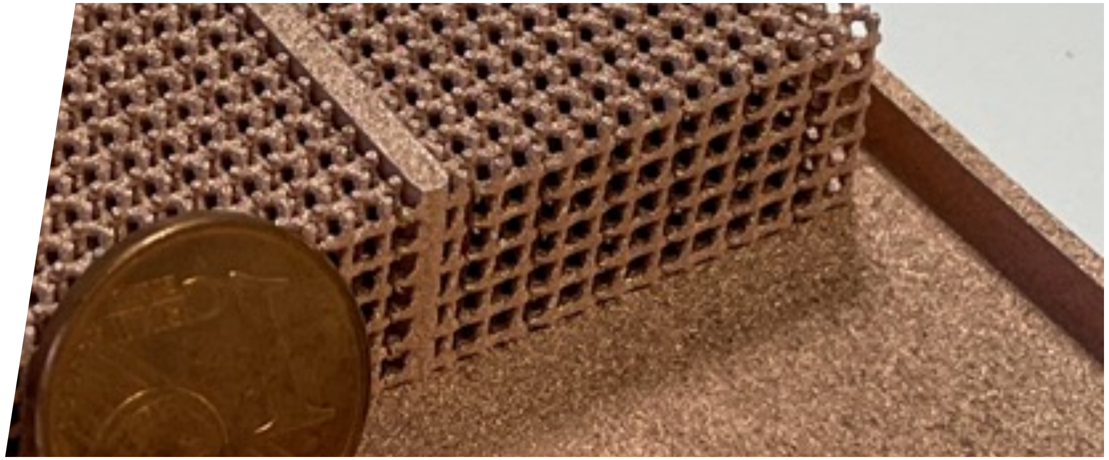
GSSI GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Integrated infrastructures

What makes LNGS a unique place for research is the combination of integrated infrastructures and support laboratories.

The low background lab STELLA (see talk from M.Laubenstein), the ICPMS trace identification facility, electronics and chemistry workshops,

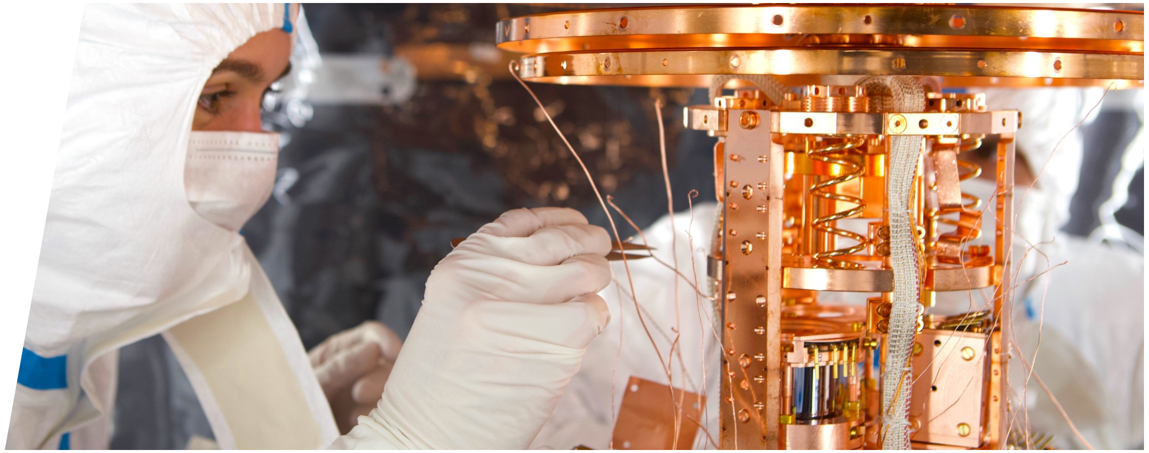
mechanical workshop (and the new additive manufacturing lab HAMMER) allow scientists advanced prototyping, contaminant identification and material selection, detector development, …



Physics topics which requires very low noise environment

The leading science research lines in this age of LNGS are:

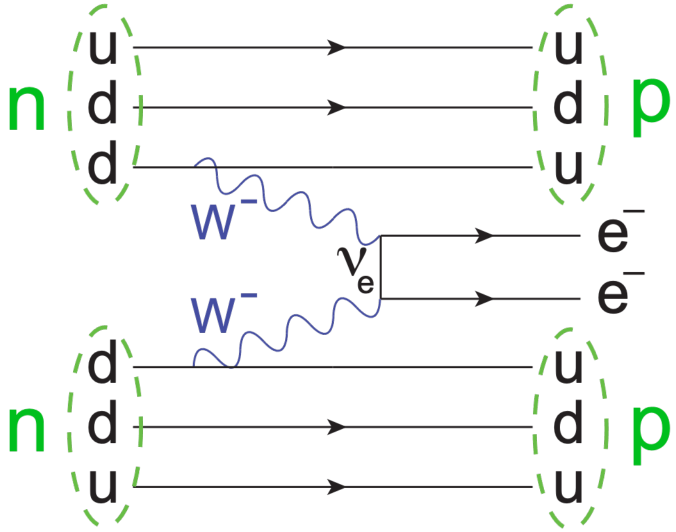
- neutrino physics
  - Majorana neutrino program (LEGEND, CUORE/CUPID,…)
- dark matter search
  - Direct DM search programs (XENON-nT, DarkSide, CRESST, DAMA, COSINUS, CYGNO, SABRE, NEWS,…)
- nuclear astrophysics
  - Bellotti Ion Beam Facility MV accelerator (open to the LUNA program, and more…)

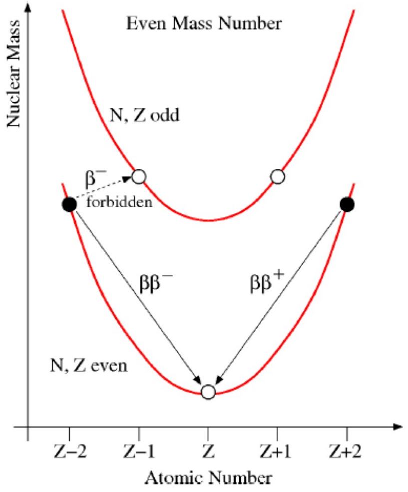


And much more…

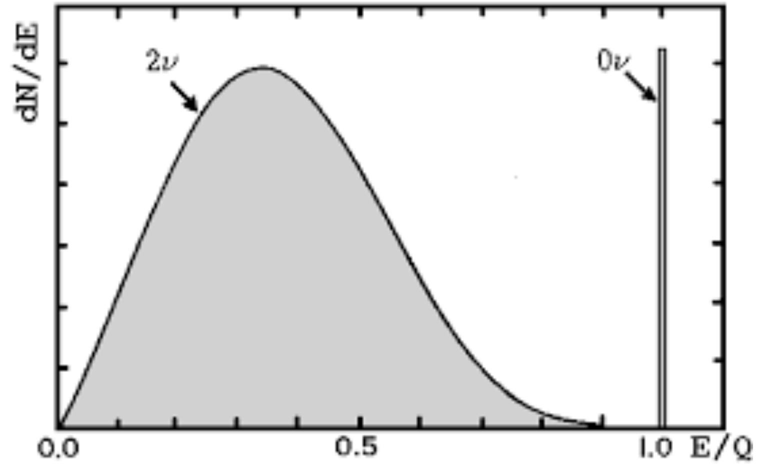
- Gravitation and General Physics
  - Precision measurements
  - Tests in highly reduced seismic noise environment
- Geophysics and geology
  - Underground water, trace radioactivity
  - Antineutrinos from the earth
- Quantum Computing
  - Low background studies
- Biology
  - Effects of very low doses on living organisms

Production of Leptons in the framework of Majorana neutrino theory (Neutrino-less double-beta decay)





$$\Gamma_{\beta\beta}^{0\nu} = \frac{1}{T_{\beta\beta}^{0\nu}} = G^{0\nu} \cdot |M^{0\nu}|^2 < m_{\beta\beta} >^2$$

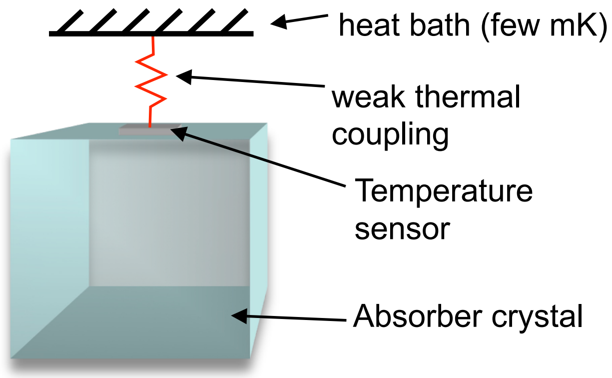


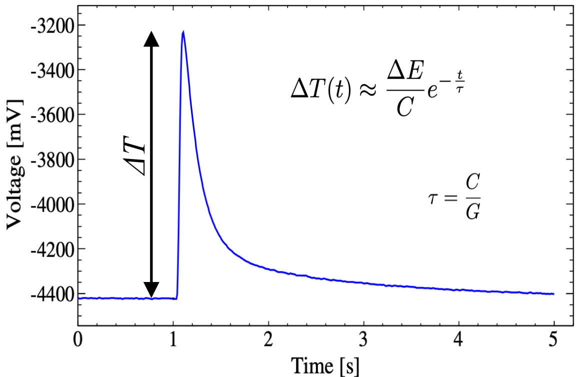
$$m_{\beta\beta} = \sum_i U_{e,i}^2 \cdot m_i$$

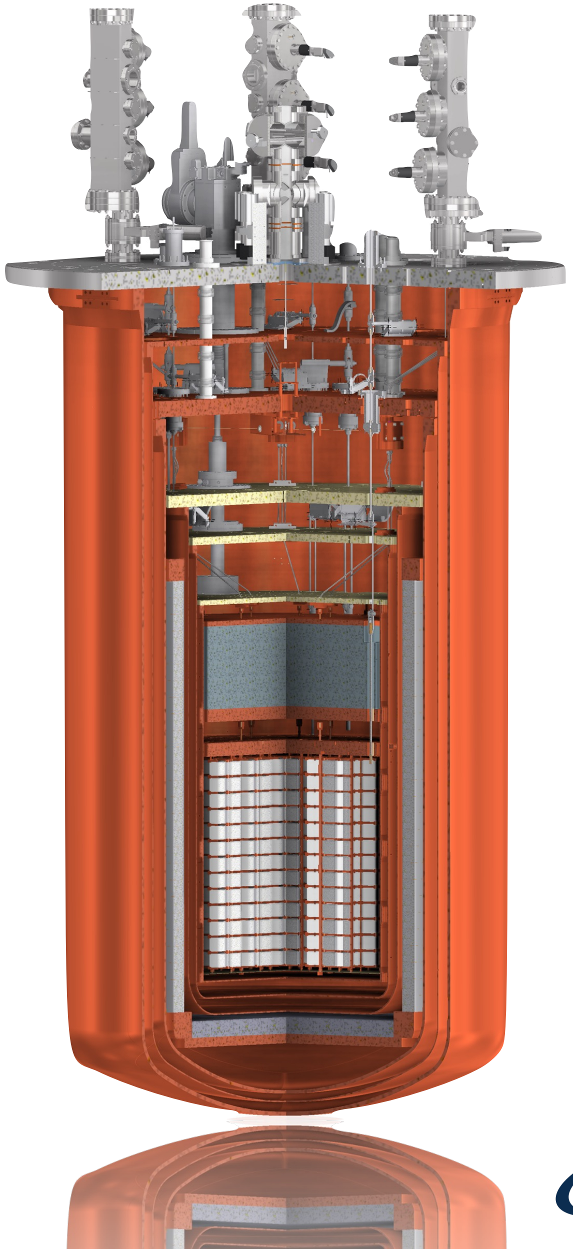
CUORE
Cryogenic Underground Observatory for Rare Events

The challenge was to build a cryogenic system with an experimental volume of ~1 m^3 in which operates a huge LTD array in a low radioactivity and low vibrations environment. 10 years of hard work!

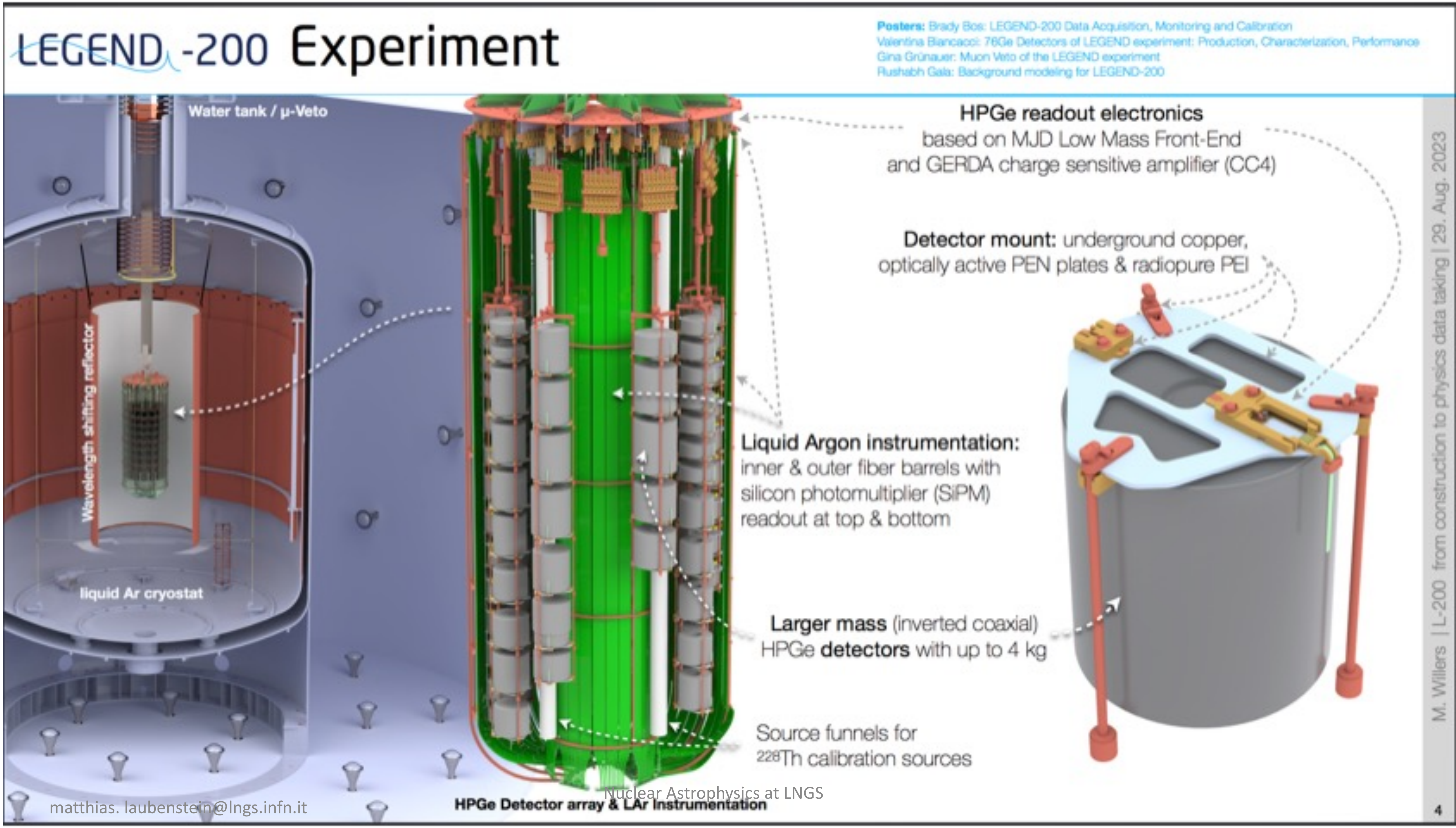
- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
- Mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tonnes (Pb, Cu and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- Target energy resolution: 5 keV FWHM @ 2615 keV
- Projected sensitivity in 5 years (90% C.L.): $T_{1/2} > 9 \times 10^{25}$ yr







INFN

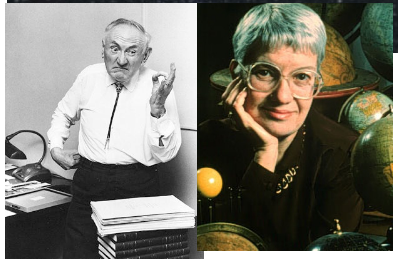


matthias. laubenstein@lngs.infn.it

Hints towards Dark Matter existance

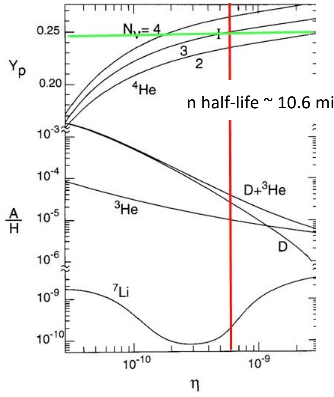
Astrophysical Observatior

Beginning of the story

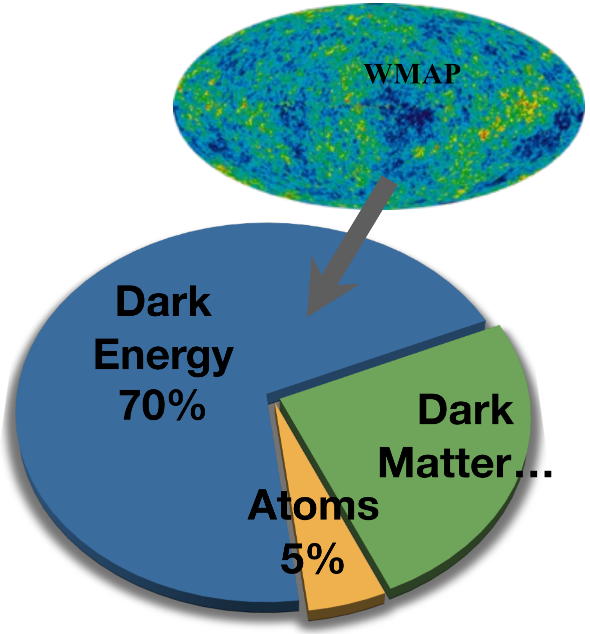


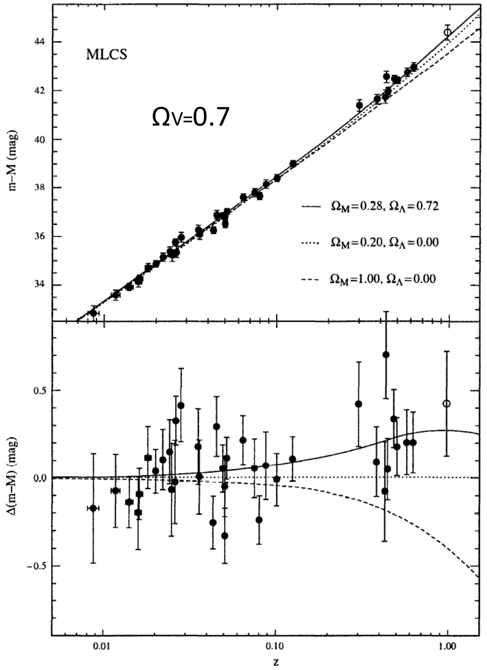
Ω_m=0.3

BBN



Ω_b=0.01-0.02



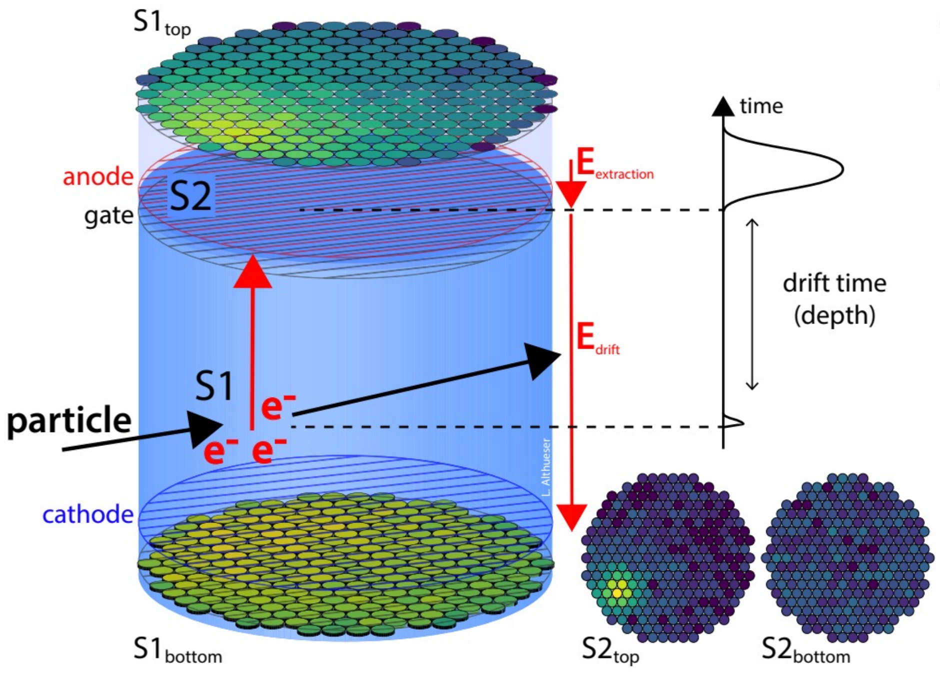


All consistent with ~25% dark matter (give or take).

Possible candidates:

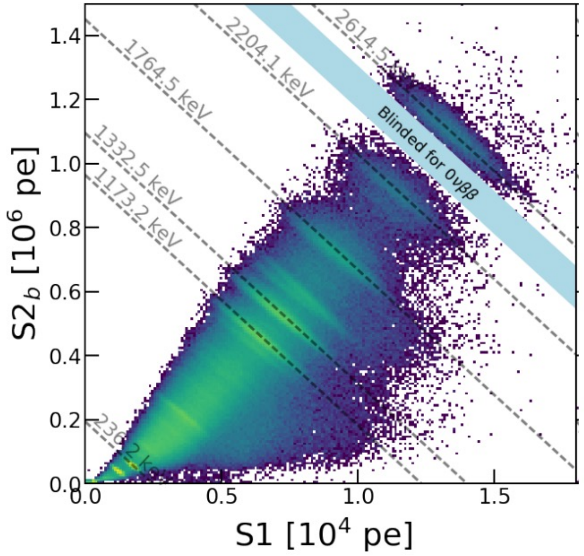
WIMPs

Dual-Phase Time Projection Chamber



Scintillation and **ionization**:

- Prompt light signal (**S1**)
- Secondary light in GXe from drifted charges (**S2**)
- Position reconstruction (**x, y, z**), calorimetry (**E**) and interaction type (**ER**/**NR**)



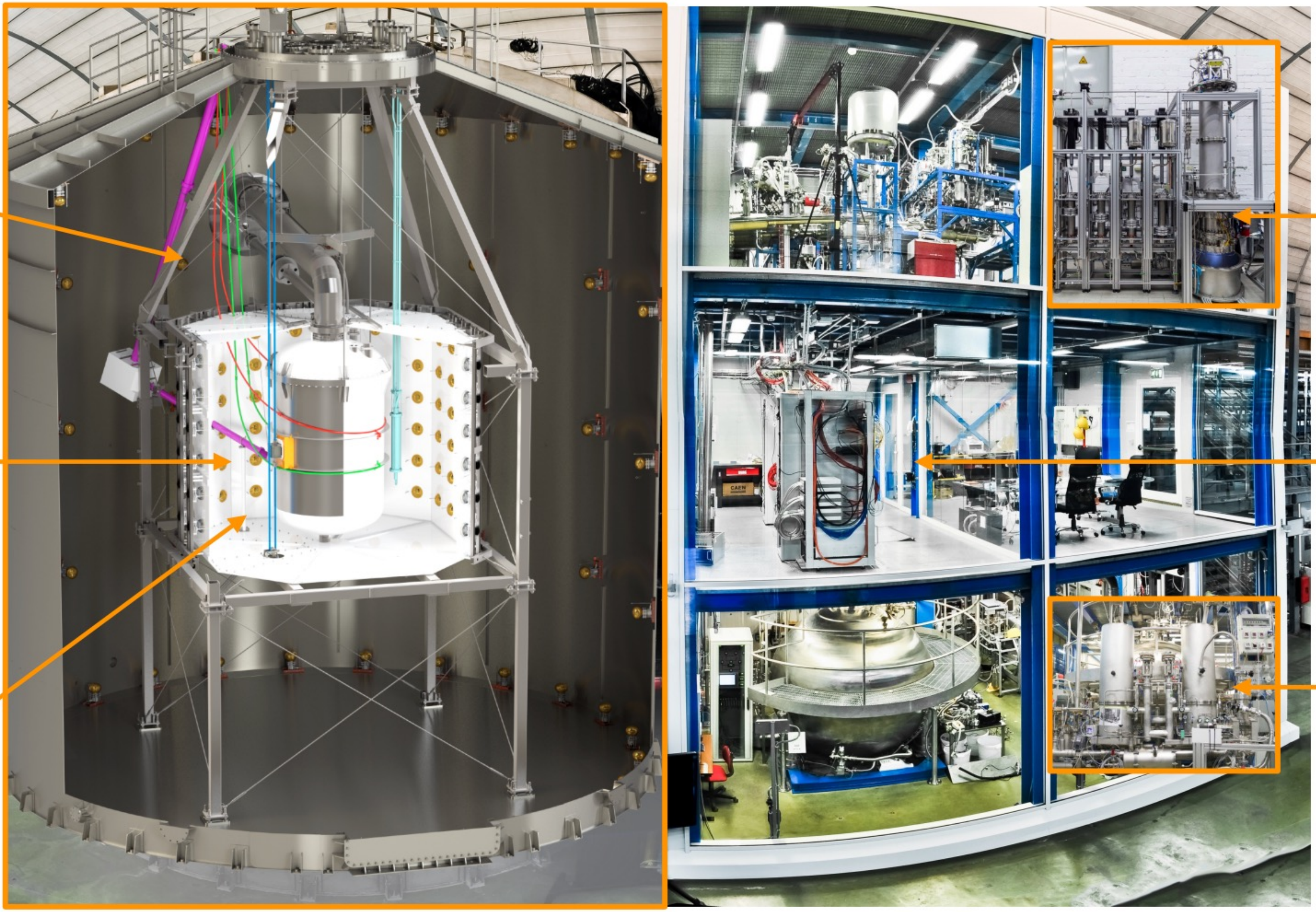
This technology works well with LXe and LAr which naturally started two different family of detectors:
XENON10-XEON100-XENON1T-XENONnT(running)-DARWIN (far future)
Dark Side(in construction phase)-ARGON200 (far future)

XENONnT, running

New ER and NR calibration systems

Larger TPC with 3x active volume

Gd-loaded water Cherenkov neutron veto



Radon distillation column

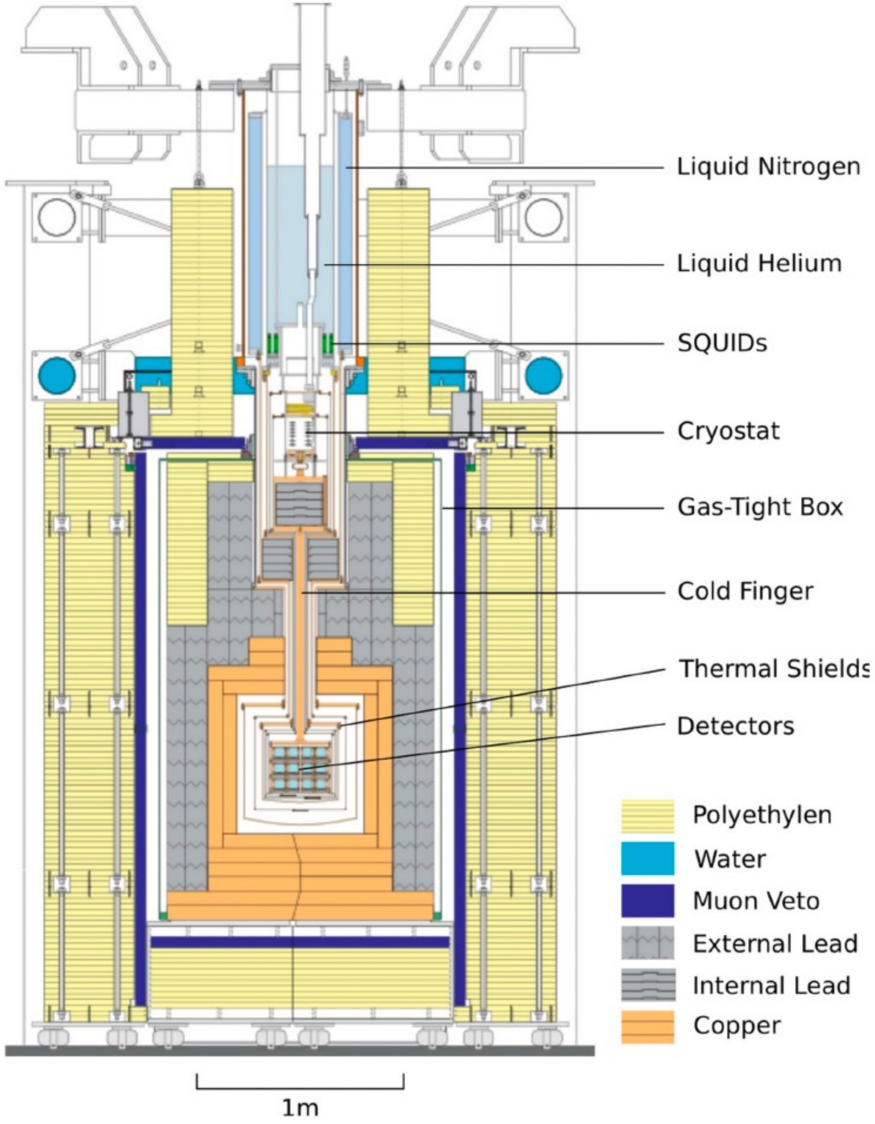
Upgraded DAQ with high-energy readout

Liquid xenon purification

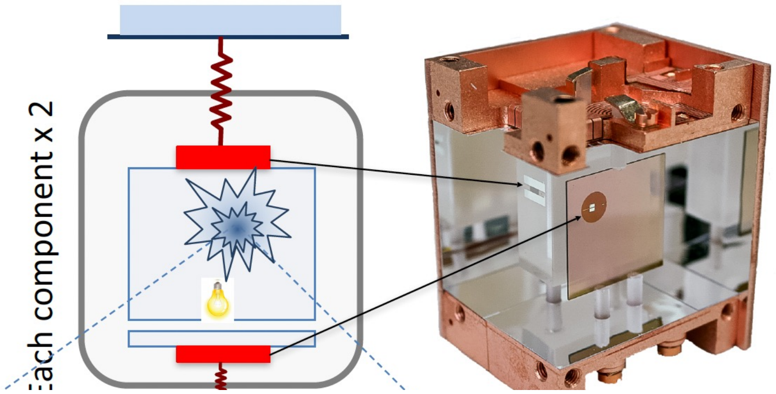
Dark Side under construction

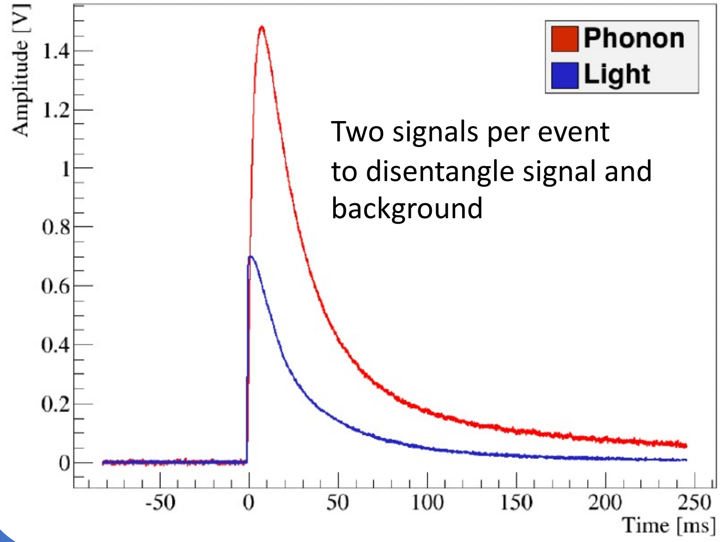
The next phase of DM direct search with liquefied noble element

The CRESST Experiment



CRESST detector module

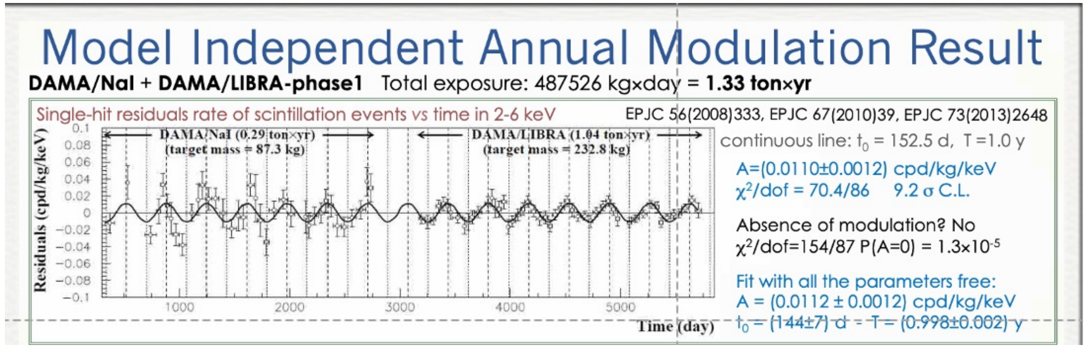




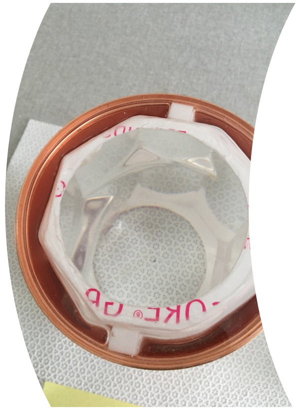
CRESST goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at ~15 mK using Scintillating $CaWO_4$ crystals as target and Safire crystals as cryogenic light detector

NaI: the legacy of the scintillating crystals

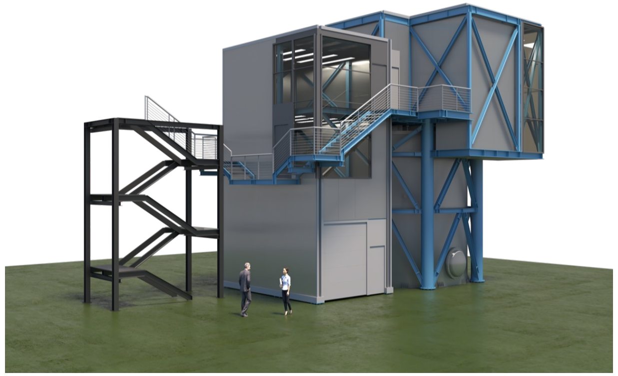
- DAMA/Libra: DM claim since long time.

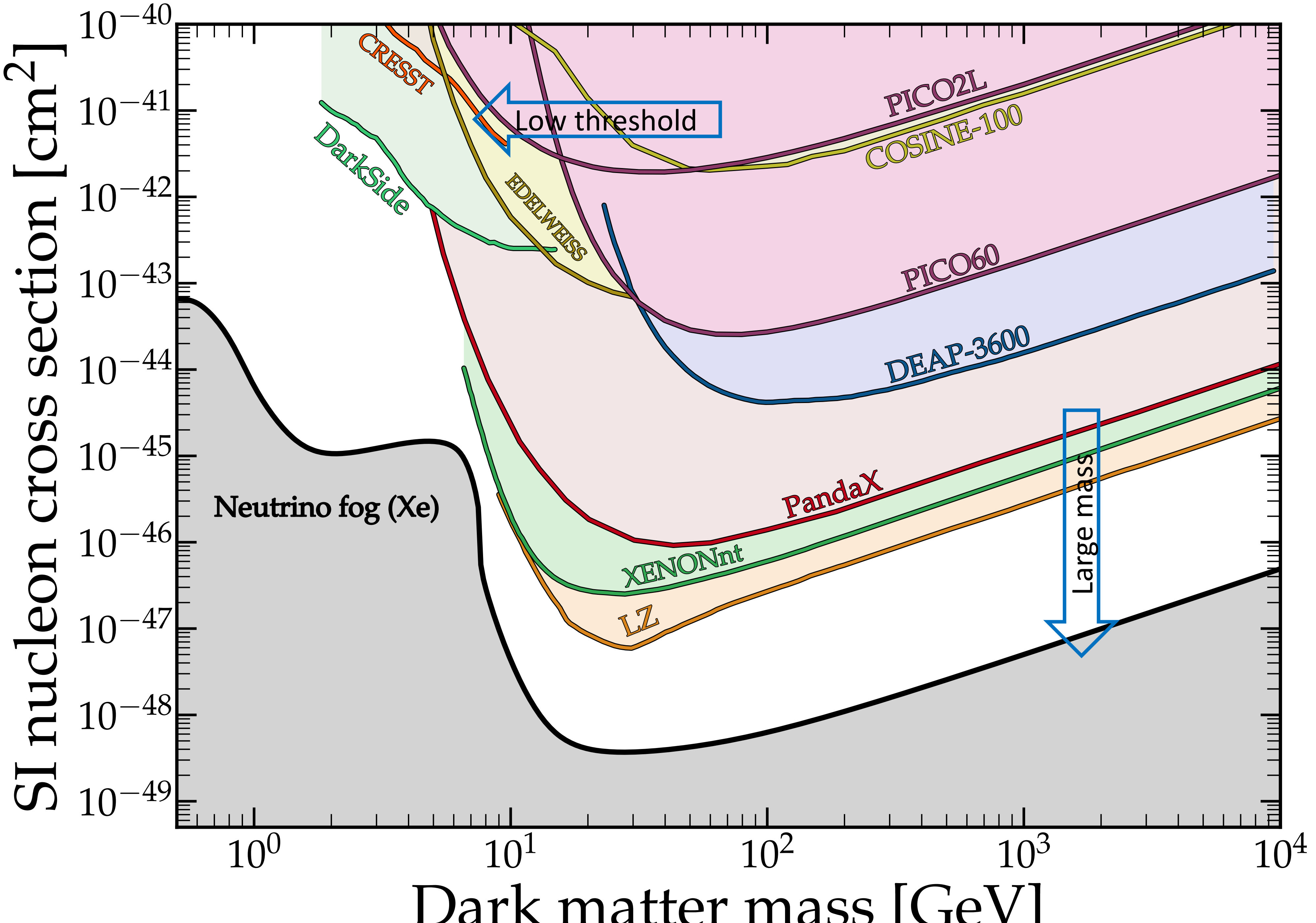


- SABRE project decided to test this signal investing in the technology of ultra-clean crystals, with great success.



- COSINU experiment: bet on a new technology where clean NaI crystals are used as calorimeter (phonons) and scintillation source.





SI nucleon cross section [cm^2]
Dark matter mass [GeV]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^0
10^1
10^2
10^3
10^4
CRESST
DarkSide
EDELWEISS
Low threshold
PICO2L
COSINE-100
PICO60
DEAP-3600
PandaX
XENONnt
LZ
Large mass
Neutrino fog (Xe)

The Lab. with largest DM direct search activity

- Cygnus: directional Dark Matter search with gas TPC
- NEWS: directional Dark Matter search with emulsions

Historical minimum of neutrino physics

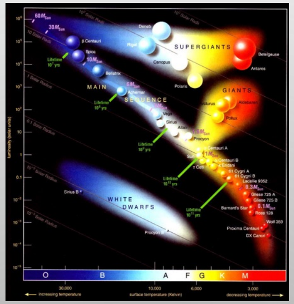
- Large Volume Detector (LVD): what remains of neutrino detectors at LNGS, dedicated to the SN explosion monitor

Off main stream

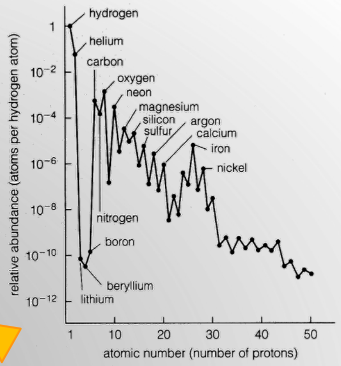
- Studies of Q-Bit: interaction with environment can affect the life-time of quantum state/information
- PTOLEMY: development of detector technology for possible future relic neutrino detection.

NUCLEAR ASTROPHYSICS

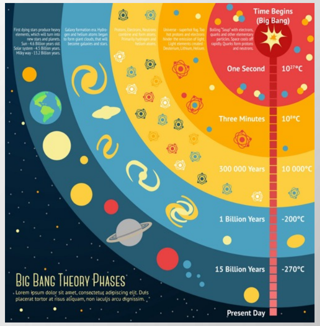
Stellar evolution



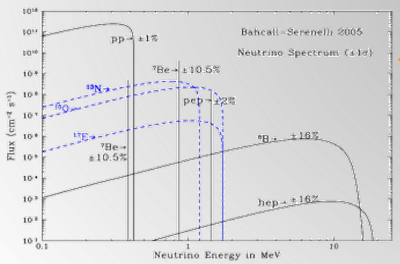
Nucleosynthesis



Evolution of early universe

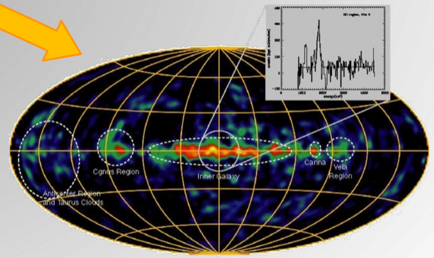


Nuclear cross sections



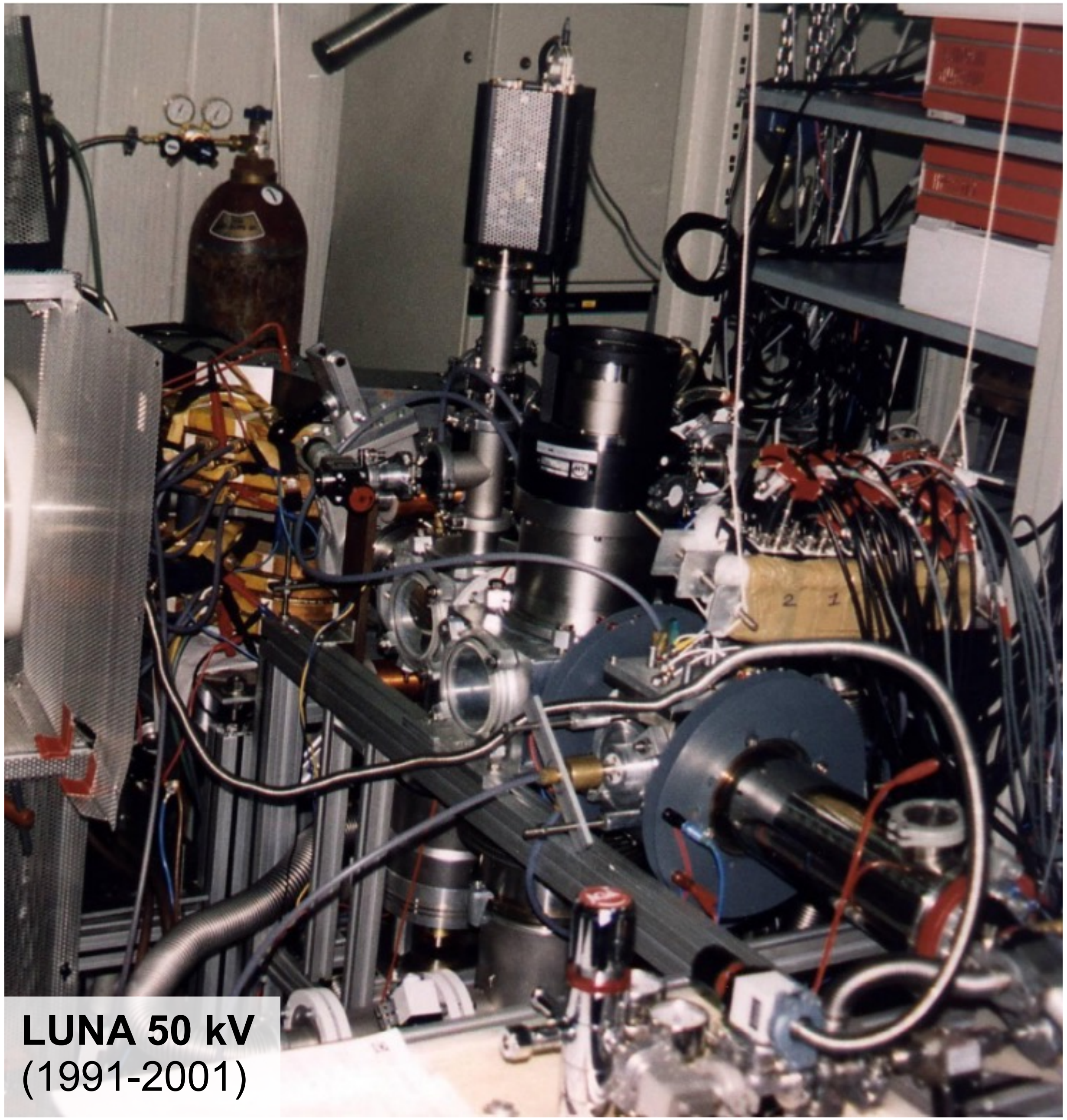
Solar neutrinos

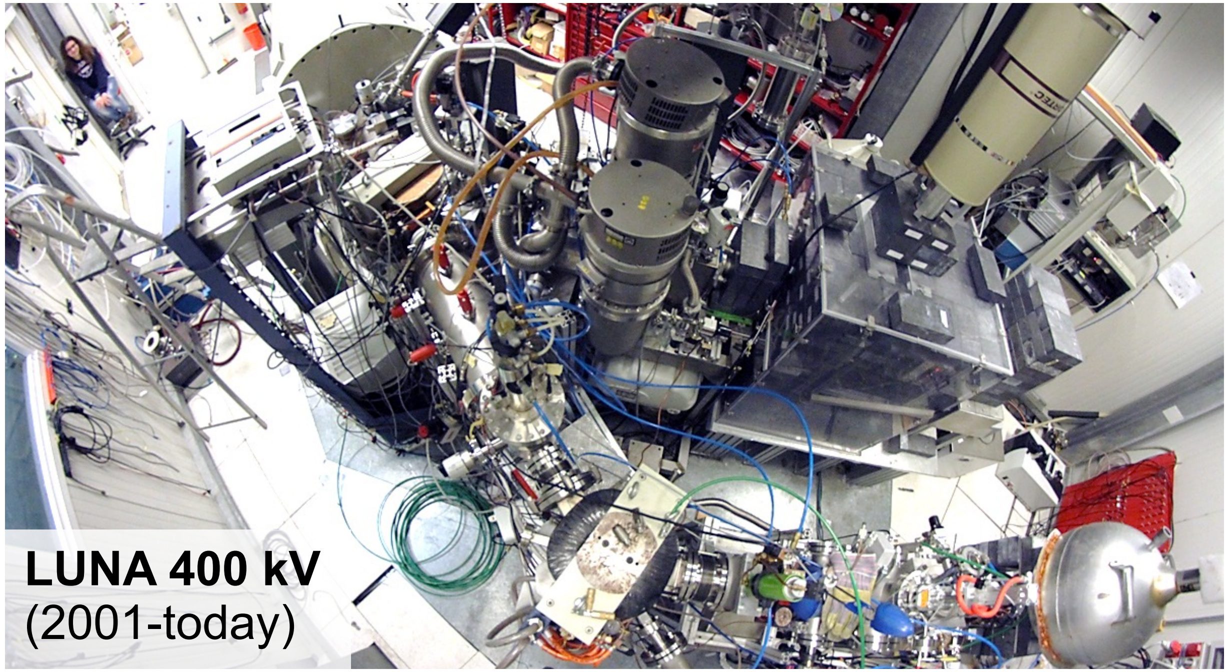
Solar system



(Oberlack et al., 1996; Pluschke et al., 2001)

Astronomy


LUNA 50 kV
(1991-2001)


LUNA 400 kV
(2001-today)


LUNA MV (LNGS-IBF)
(today-????)

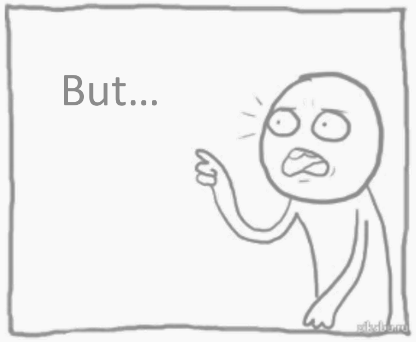
Challenges in Nuclear Astrophysics

Below a certain energy, the counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

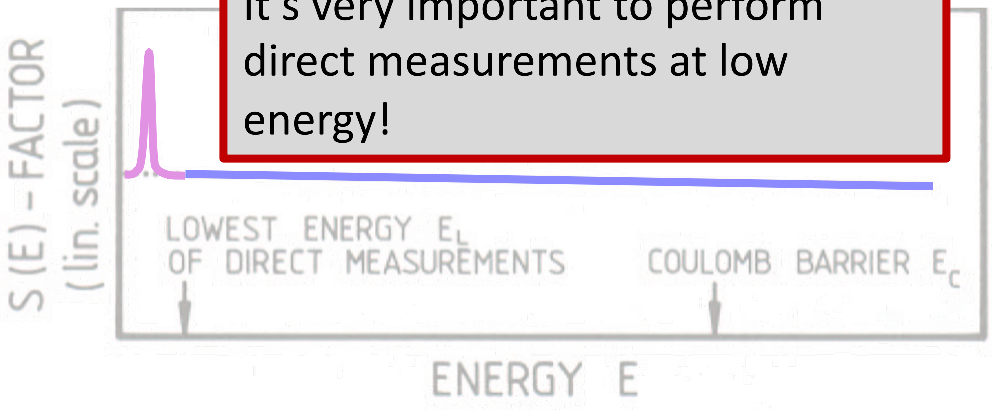
introducing the **astrophysical S-factor S(E)** and factorizing the **Coulomb interaction term** apart:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

it is possible to measure the cross section at high energy and extrapolate the astrophysical factor *S(E)* in the interesting energy range (Gamow window)



unexpected low-energy resonances may be present in the extrapolation region!



It's very important to perform direct measurements at low energy!

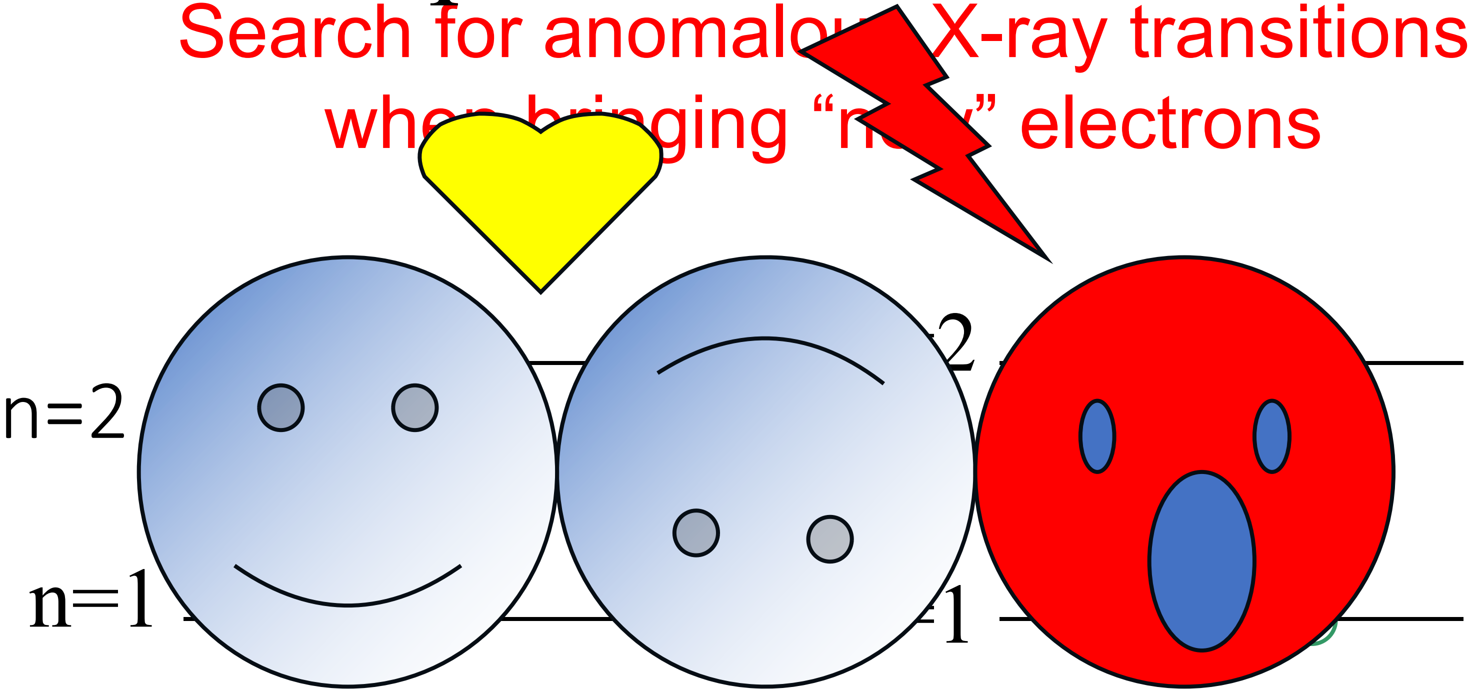
Testing fundaments of Quantum Mechanics

The VIP experiment

An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using atomic physics methods

Experimental method:

Search for anomalous X-ray transitions
when bringing “new” electrons



Normal 2p –>1s transition

Energy 8.04 keV

2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Theories of Violation of Statistics

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

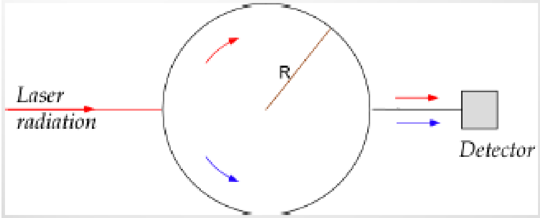
"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible………….

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only bose and fermi statistics occur in Nature."

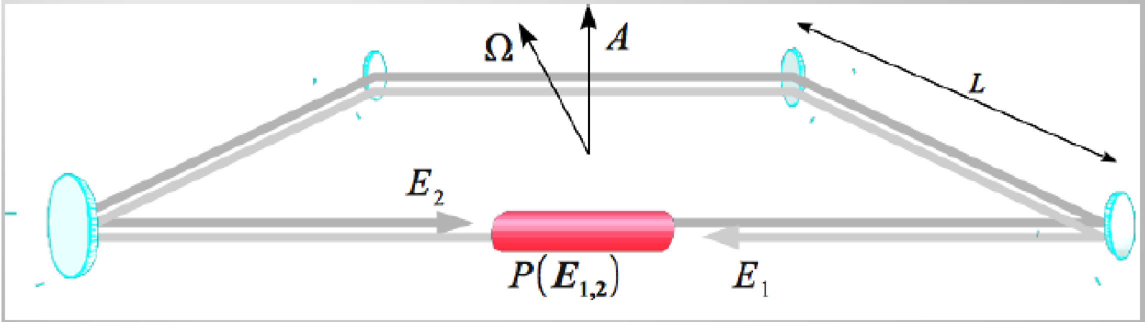
GINGER experiment

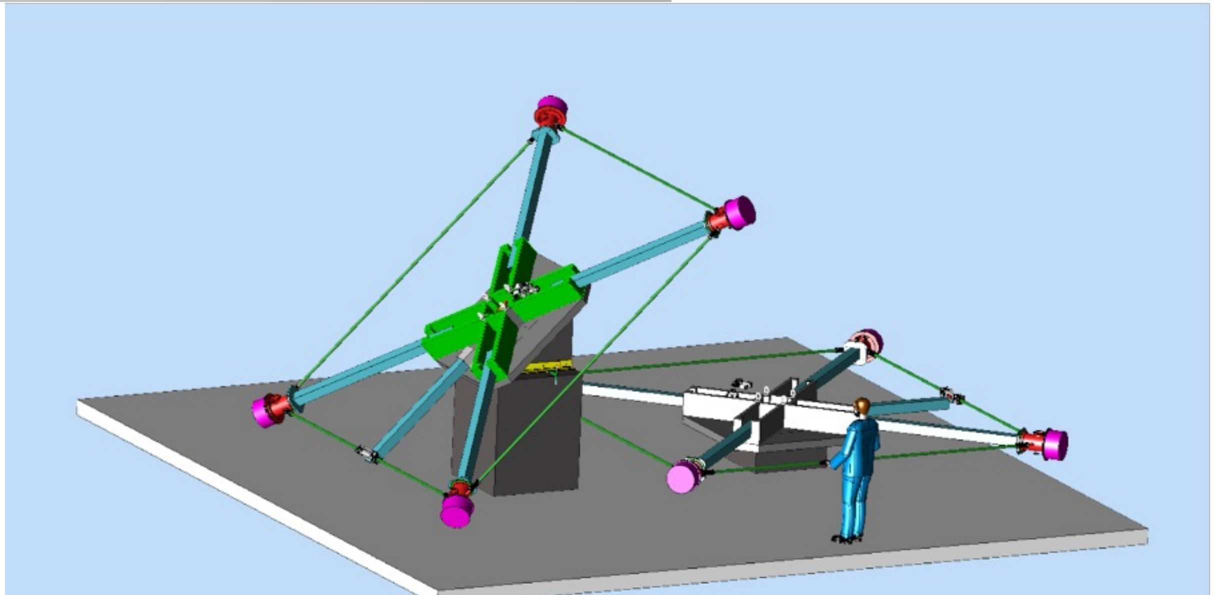
Ring Laser Gyroscope array

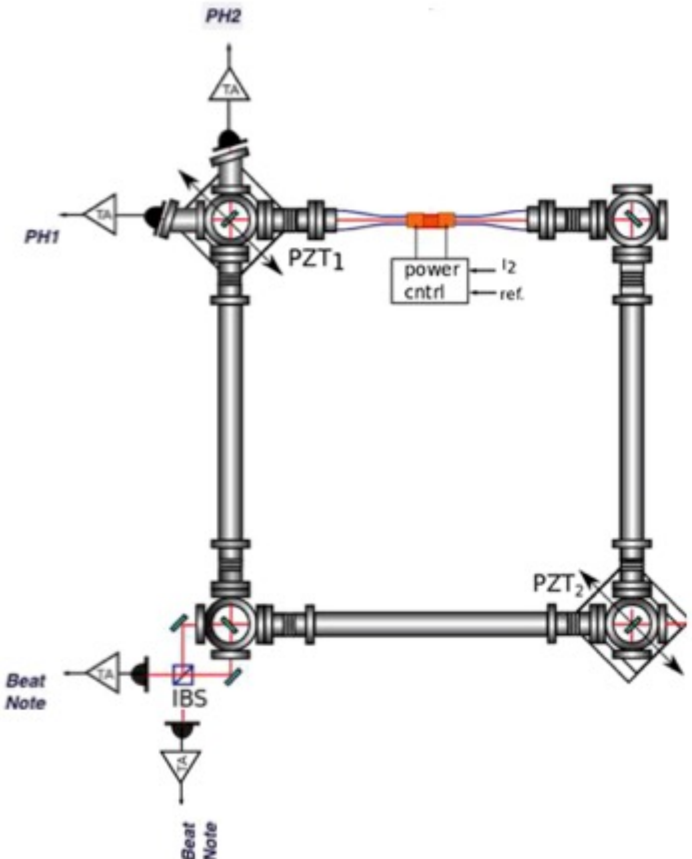
The Sagnac Effect and the ring-laser



$$f_{Sagnac} = \left| f_{CW} - f_{CCW} \right| = \frac{4\vec{A}\cdot\vec{\Omega}}{\lambda p}$$

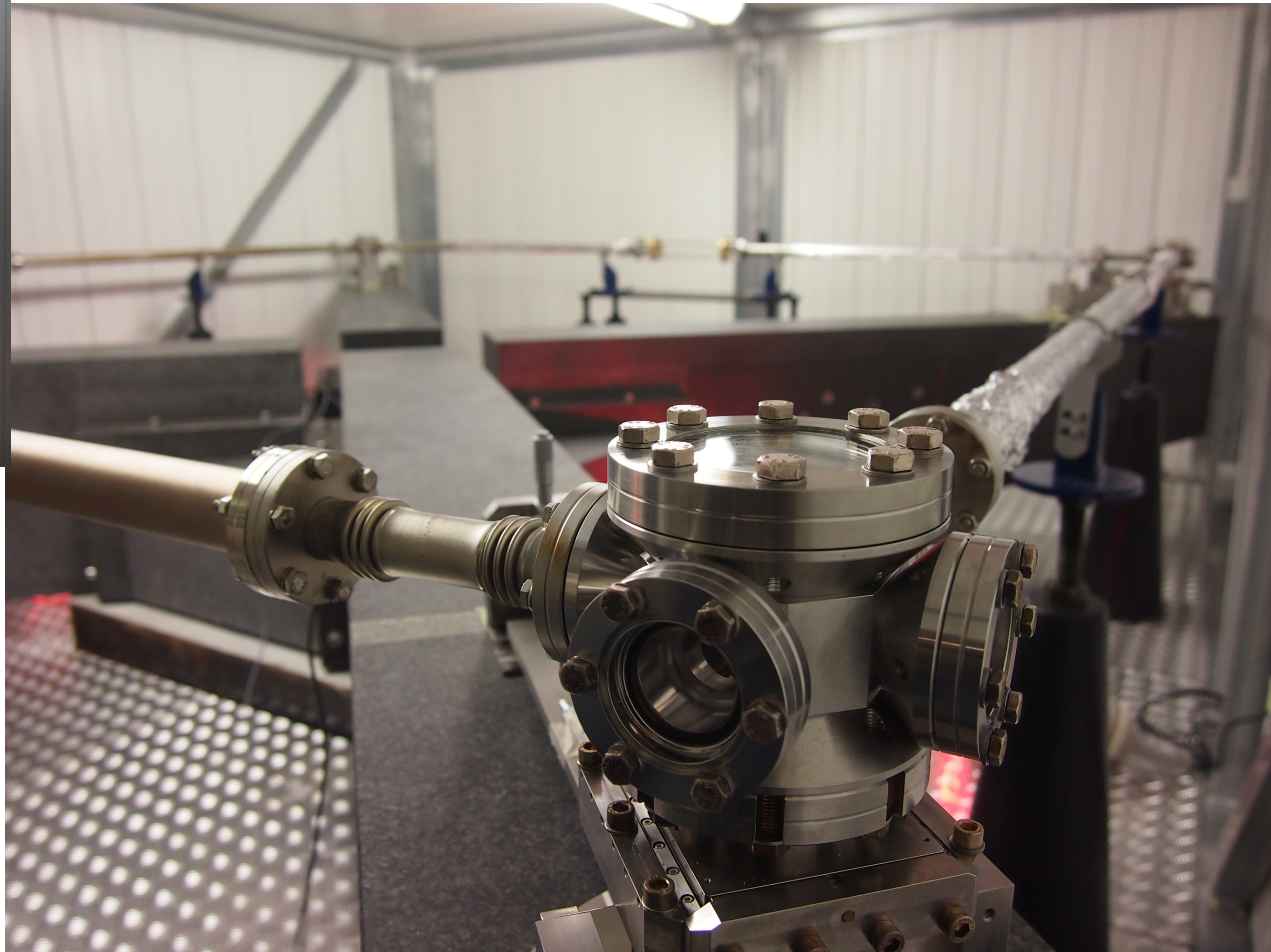






GINGER experiment

Ring Laser Gyroscope array



Whenever you have an underground facility there are biologists that aim at doing some studies

For detailed discussion see second morning session on Wed

Summary of *in vitro* and *in vivo* experiments at LNGS

LRE: *Low Radiation Environment*
RRE: *Reference Radiation Environment*

Yeast	**Saccharomyces cerevisiae** *cultured for 1 week (~120 generations) at LRE and RRE (University of Rome)*	**Mutation induction** (*hprt* locus)	**Satta *et al., Mutat Res* 1995**
Cultured mammalian cells	***Long term experiments (months)***		
Cultured mammalian cells	**Chinese hamster V79 cells** *cultured for up to 9-10 months (>120 generations) at LRE and RRE (RRE: Istituto Superiore di Sanità, Rome; external LNGS laboratory)*	**Cell growth** **Antioxidant enzymes activity** **Apoptosis** **Mutation induction** (*hprt* locus)	**Satta *et al., Radiat Environ Biophys* 2002** **Fratini *et al., Radiat Environ Biophys* 2015**
Cultured mammalian cells	**TK6 human lymphoblasts** *cultured for up to 6 months at LRE and RRE (Istituto Superiore di Sanità Rome)*	**Cell growth** **Micronuclei induction** **Antioxidant enzymes activity**	**Carbone *et al. Radiat Environ Biophys* 2009**
Cultured mammalian cells	***Short term experiments (weeks)***		
Cultured mammalian cells	**A11 mouse hybridoma cells** *(short term experiments, few weeks) RRE (Istituto Superiore di Sanità Rome)*	**Cell proliferation** **caspase-3 activation** **PARP1 cleavage**	**Fischietti *et al., Front Public Health* 2021**
Fly	***Drosophila melanogaster*** *(RRE: L'Aquila University)*	**Life span** **Ferility** **DNA repair *(mutants)***	**Morciano *et al., J. Cell Physiol.* 2018** **Morciano *et al., Radiat. Res.* 2018** **Esposito *et al., Front Public Health* 2020**
Fly	***Drosophila melanogaster*** (*RRE: external LNGS laboratory*)	**Chromosome breaks** **DNA repair (*mutants*)**	**Porrazzo *et al., Int. J. Mol. Sci.* 2022** **Morciano *et al., Frontiers in Physics* 2023** **Ampollini M. *et al Frontiers in Physics* 2023**

P. Morciano-Cosmic Silence Collaboration

LNGS BIOLOGY FACILITIES

One above ground faciliy and two underground facilities

Above ground

Underground

No atmospheric pressure difference

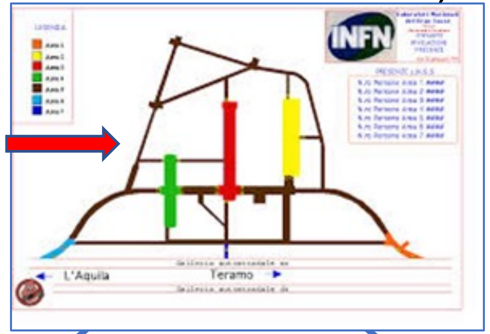
Reference Radiation Environment, RRE

SMALL ANIMALS

CULTURE CELLS

Chemistry and Chemical Plant Service

Low Radiation Environment, LRE



Cosmic Silence

SMALL ANIMALS

Pulex

CELL CULTURE

P. Morciano-Cosmic Silence Collaboration

Conclusions

- An underground facility is something very precious.
- It is not trivial to stop cosmic rays. You don’t build a mountain above your laboratory at the occurrence
- It is worth pointing out that even though one site is not the deepest and the largest still a lot of fundamental physics can be done. This can help to grow a school in a new field but also to make measurements at the frontier of knowledge.

To conclude

In fundamental research is way more important the path than the goal