Detector Physics 2021/2022, Lecture 9

Cryogenic detectors: bolometers, noble liquids, etc.

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Cryogenic detectors: references

- Hans Kraus, Superconductive Bolometers and Calorimeters (Topical Review), Supercond. Sci. Technol. **9** (1996) 827–842

  https://www.csnsm.in2p3.fr/IMG/pdf/kraus_bolometer_calorimeter.pdf

- Thomas Patzak, 2019 NPAC Lectures

  https://npac.lal.in2p3.fr/wp-content/uploads/2019/Cours-S1/Detectors/Matter-Interaction-3.pdf

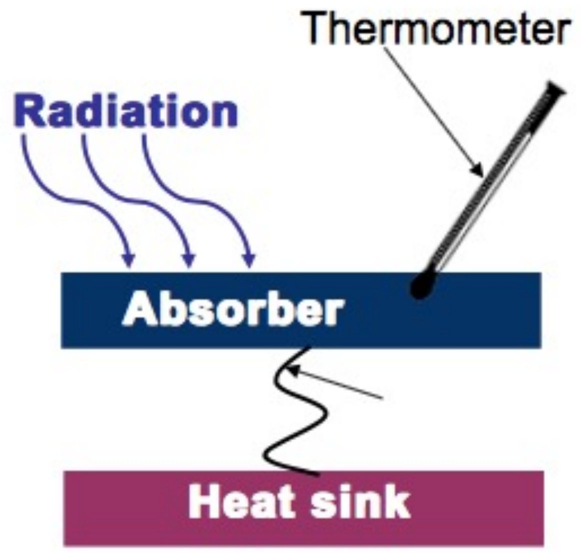
- Bernhard Brandl's Lectures, Leiden university

  https://home.strw.leidenuniv.nl/~brandl/DOL/DTL_06_2020_Bolometers.pdf

Bolometer

Bolometer : from Greek, *bole* (beam, ray) + *metron* (measure)

measures the amount of radiation
incident on an active area
by producing a corresponding electrical signal



Radiation absorbed →

change of temperature of the absorber →

change of resistance in the thermometer →

voltage drop across the thermometer (I=const)

a bolometer is a temperature transducer

Bolometer

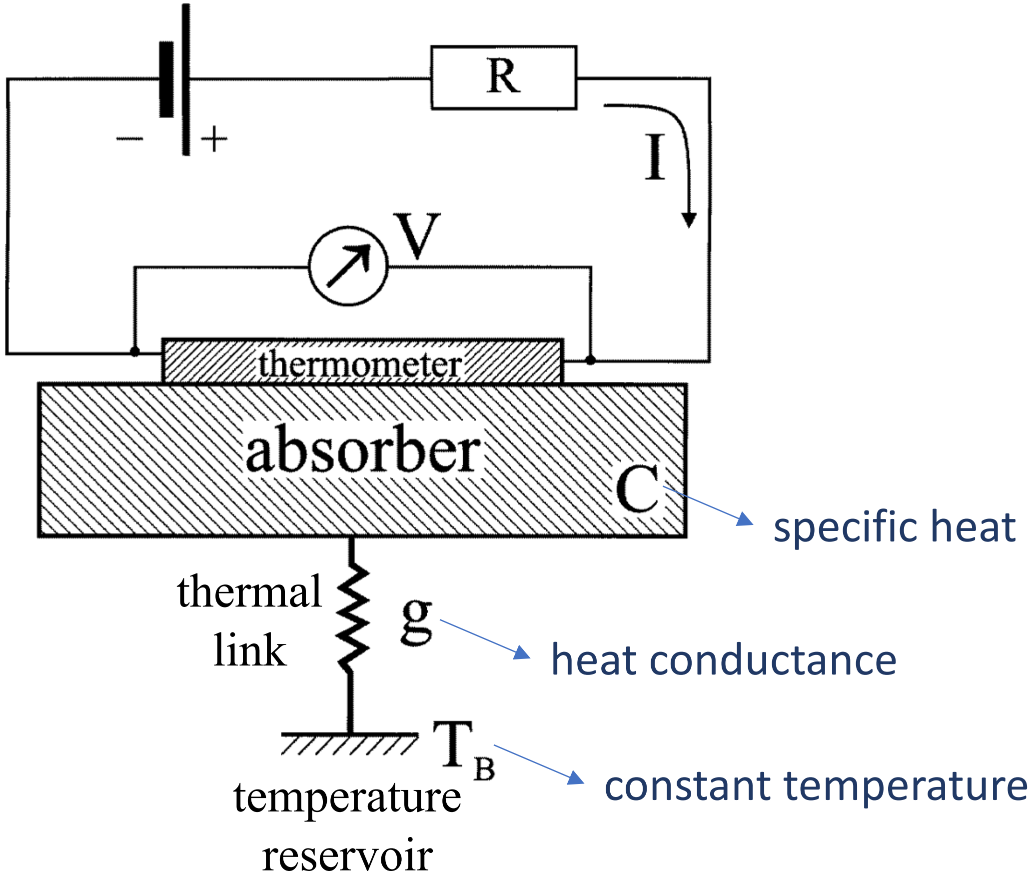
A **BOLOMETER** =

- an absorber for radiation or particles +
- a temperature transducer (thermometer) +
- a thermal link to a temperature reservoir

basic principle: $\boxed{\Delta E \rightarrow \Delta T \rightarrow \Delta R}$

Need

- low heat capacitance: $dT = dE/C$
- large temperature coefficient: $\alpha = dR/dT$



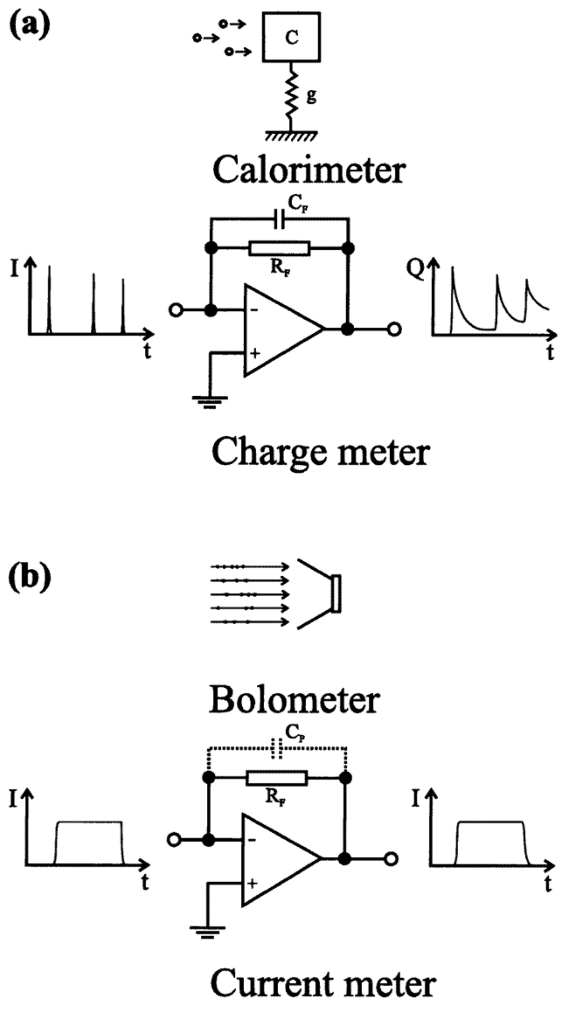
specific heat

heat conductance

constant temperature

Bolometer vs Calorimeter

Two operation modes of similar devices



Calorimeter: measure the energy of single quanta or particles.

Bolometer: measure a flux of particles or radiation.

Depending on the values of

- time between the arrival of the single particles τ_g
- time resolution of the device $\tau_F = C_F R_F$
- time during which the particle deposits its energy and causes a change of the detector output signal τ_p

Calorimetric mode: $\tau_g \gg \tau_F \gg \tau_p$
Bolometric mode: τ_F as short as possible but $\tau_F \gg \tau_p$
different design/operation mode/optimisation criteria

in practice: we always say ”bolometer”,
but when the purpose is energy measurement it’s a ”calorimeter”

Advantages

Bolometers

- Sensitivity over a wide range of wavelength (energy): cm (~meV) – visible (~eV) – X-ray (keV).
- Weak dependence of sensitivity on wavelength (or frequency): used as calibration devices for other detectors, favored as microwave detectors
- Easy to operate (low-background platforms, satellites)

Applications → **Space science**: infrared spectroscopy, radiometry, noctovision, pulse photometry, plasma diagnostics or measurement of phonon propagation, CMB

Calorimeters

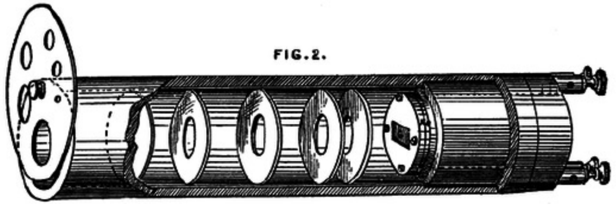
- Low Energy threshold and good resolution

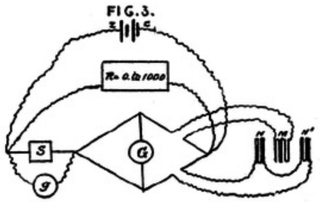
Applications → **Particle physics** detectors with low energy threshold and good resolution: search for rare processes such as ββ0ν decay, Dark Matter interactions with nuclei

Normal metal strips

Original construction by **Samuel P. Langley** (T., S. *The Bolometer* . *Nature* **25,** 14–16 (1881))

- for the study of solar radiation
- Platinum foils and ribbons





Metal has ~linear dependence of resistance on temperature, so

$$\Delta R = \alpha \, R_0 \, \Delta T \qquad \boxed{\alpha = \frac{1}{R_0}\left(\frac{dR}{dT}\right)}$$

α = temperature coefficient
~0.003 K^{-1} at room T

R_0=resistance at operating point

- Metals have high specific heat capacity → need **small size**
- **Nickel, Platinum** (for their mechanical properties), **Bismuth** (low heat capacitance)
- Metal strips of thickness in the range of 10 to 50 nm deposited by sputter deposition or by evap

$\alpha \propto T^{-1}$ → low temperature operation more favourable → cryogenic detector

Thermistors

Manganese, **Cobalt** or **Nickel** oxides sintered together and mounted on a sapphire substrate

- Temperature increase of the metal oxide films → increase of the density of free charge carriers → the film resistance reduces with increasing temperature

Mott's law: $R(T) = R_0 exp\left(\frac{T_0}{T}\right)^{1/4}$ → $\boxed{\alpha = -\frac{1}{4T_0}\left(\frac{T_0}{T}\right)^{5/4}}$

where T_0 depends on the density of states at Fermi level and on their localization radius

- ***α* ~ -0.05 K^{-1}** : one order of magnitude larger than for metal strip bolometers
- $\alpha \propto T^{-2}$: RuO_2 films studied at <100 mK.

Sensitivity close to that of semiconductor thermometers… (see next slide)

Semiconductor thermometers

Franck J. Low (1961 J. Opt. Soc. Am. 51 1300)

Germanium single crystal doped with gallium, operated at $\boxed{\textbf{T = 2 K}}$

- Advantages of low-temperature operation:
  - reduced blackbody background radiation
  - increased sensitivity: heat capacity reduced, very large dR/dT
- Achieved $\boxed{\boldsymbol{\alpha \sim -2\ K^{-1}}}$, vs $\alpha \sim -0.05\ K^{-1}$ for semiconductor thermometers at room temperature
- Since then, technological improvements to $\boldsymbol{\alpha \sim -4}$ **to** $\boldsymbol{-10\ K^{-1}}$

For semiconductors: $R(T) = R_0 exp\left(\frac{T_0}{T}\right)^B \rightarrow \boxed{\alpha = -\frac{B}{T_0}\left(\frac{T_0}{T}\right)^{B+1}}$

- *Heavily doped semiconductors: B~0.5*

Soon applied to IR spectroscopy, nowadays the standard for sub-mm

Composite bolometers

Absorber ≠ Thermometer

Advantage : large active area or volume AND fast response

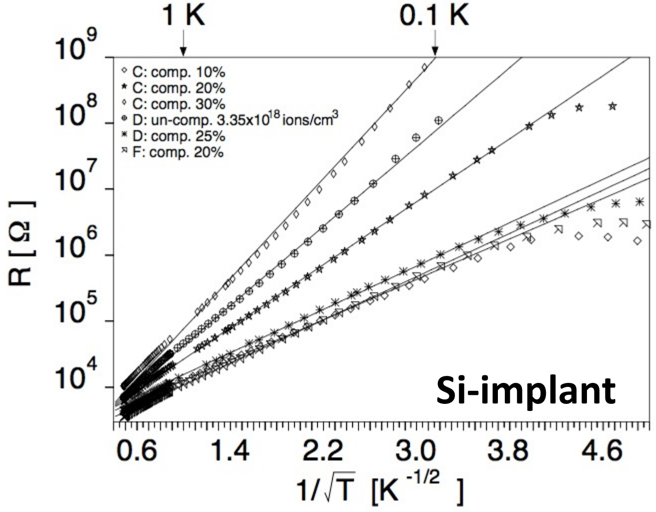
Choice of absorbers → **low C**

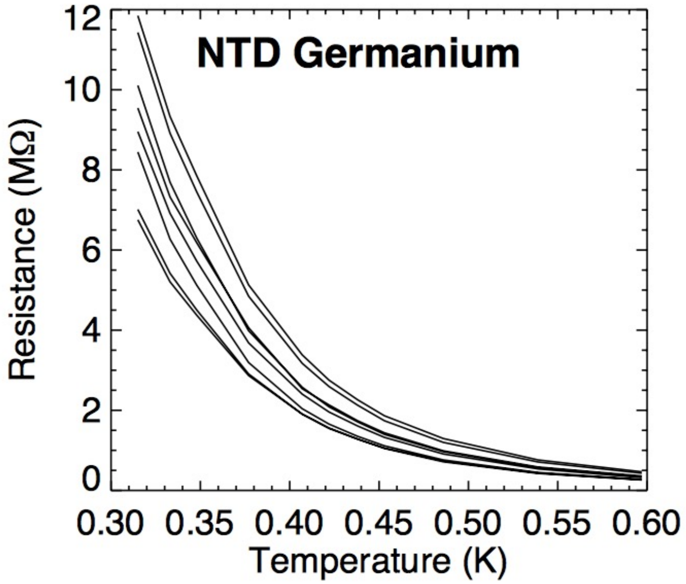
- **Metal film or grid / crystals**

Also look for good g (heat conductance)

Choice of thermometers → **large α**

- **Semiconductors** : **α ~ -4 to -10 K^{-1}**
  - Silicon-implanted thermistors (Milan/FBK)
  - Neutron Transmutation Doped Germanuim (Haller-Beeman)
  - NbSi thin film (CSNSM Orsay)
- **Superconductors** near transition: **α ~ 100 to 1000 K^{-1}**
  - Transition Edge Sensors (TES) … see next slide

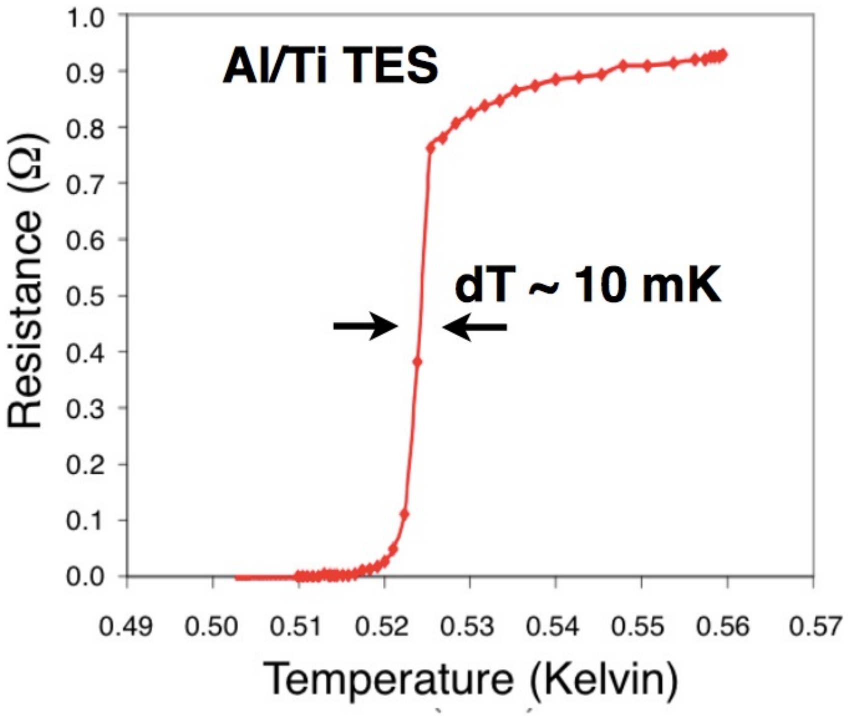




Superconducting phase transition thermometers

Transition Edge Sensors (TES)

- At transition between the superconducting and the normal-conducting phases, very large α can be achieved : **α ~ 100-1000**
- Key to use in astronomy was realisation (K. Irwin, 1995) that voltage bias keeps them automatically on transition
- Advantages:
    - ***Fabrication*** - TES's can be fabricated on bolometer
    - ***Linearity*** - Steepness of *R(T)* curve determines strength of electrothermal response



- Typically a metal bi-layer, superconducting transition tuned by thickness of normal / superconducting layers
- Typical combinations (e.g., **Al/Ti**, **Mo/Au**, **Al/Mn**, **Ti/Au**) require ~20-100 nm film thickness to achieve transitions of ~500 mK

Noise Equivalent Power (NEP)

Figures of merit to compare bolometers:

- ***NEP*** = power in a 1 Hz bandwidth (or 0.5 s integration time) one has to present to the detector in order to receive a response of the same signal height as the noise (➔ S/N = 1)

  Units [NEP] = W $Hz^{-1/2}$

- Detectivity: $D = NEP^{-1}$

- Specific detectivity: $D^{*} = D\sqrt{A}$ where A is the active area of the detector. (useful when the dominant noise is black body radiation, which depends on $\sqrt{A}$)

For calorimeter:

need to quote **minimal energy** which can be detected or the threshold energy per mass of the detector.

Noise

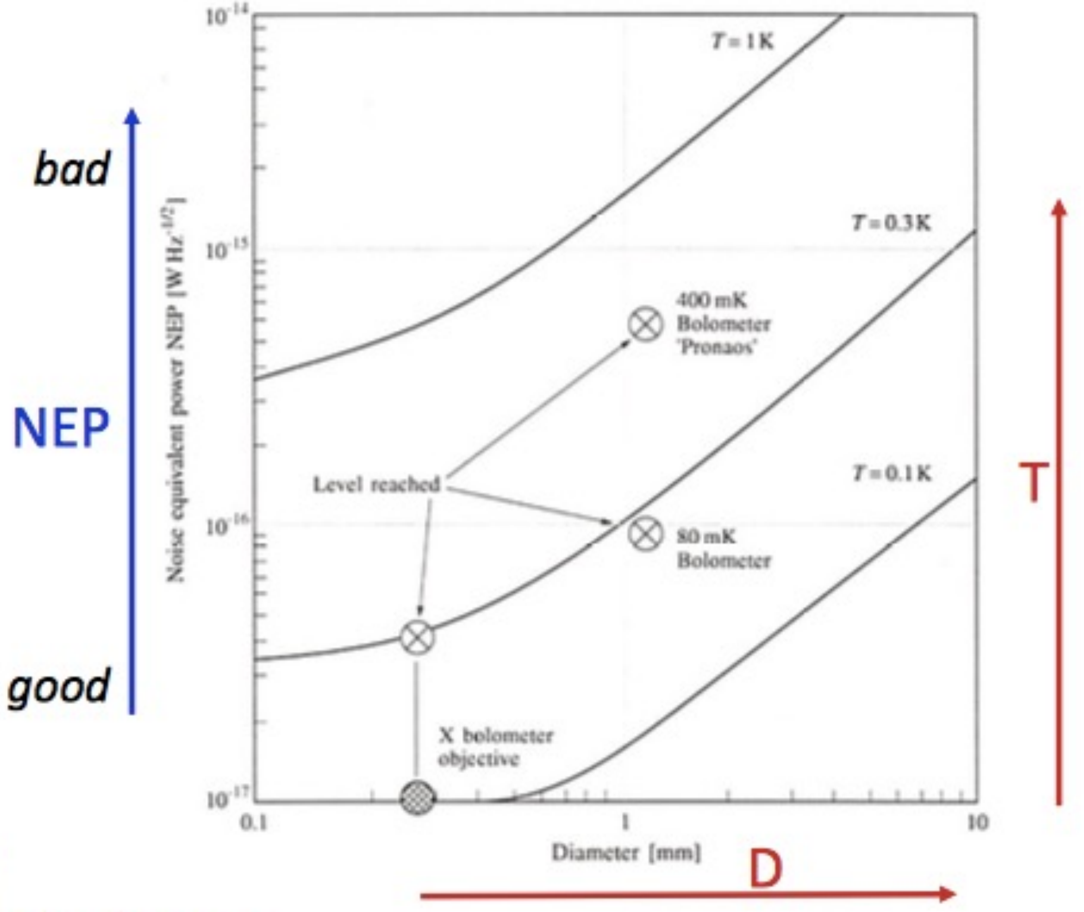
- Thermal noise: Energy fluctuations between the bolometer and the temperature reservoir across the thermal link
  $$\langle \Delta E^2 \rangle = k_B T^2 C$$
- Photon noise: photons radiated from the detector or impinging on it. Reduced by cooling. Background radiation in front of the observed radiative source cannot be eliminated. If photon nose dominates: Background Limited detector (BLIP)
- Amplifier noise: always present, but can be made negligibly small by cooling and by readout choice
- Johnson noise: random scattering of electrons while passing through the resistor. Decreases with T
- Load noise: can be made negligible by choosing large load resistance
- 1/f noise: depends on quality of the film and coupling with substrate
- Excess noise: various sources associated with the environment

To calculate the **total NEP**, all single noise contributions must be added in quadrature since they are uncorrelated

For a calorimeter, resolution $\Delta E_{rms} = \xi \sqrt{\tau}\, NEP(0)$

where:
NEP is at 0 frequency
τ=C/g
ξ depends on ratio f-dependent and f-indep. contributions to NEP

NEP Performance of Bolometers



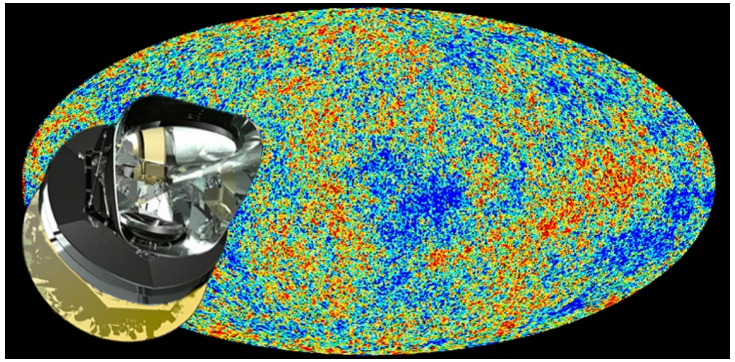
(from Puget & Coron 1994 for the SAMBA mission).

Conclusions:

- the colder, the better
- the smaller, the better

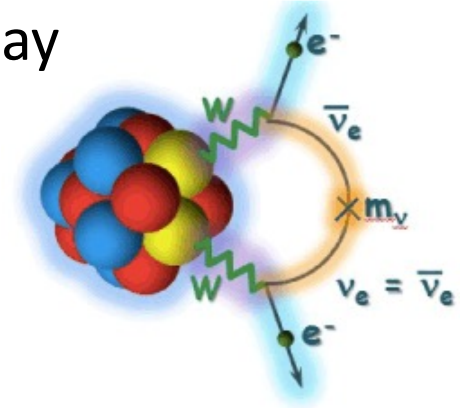
Bolometer applications

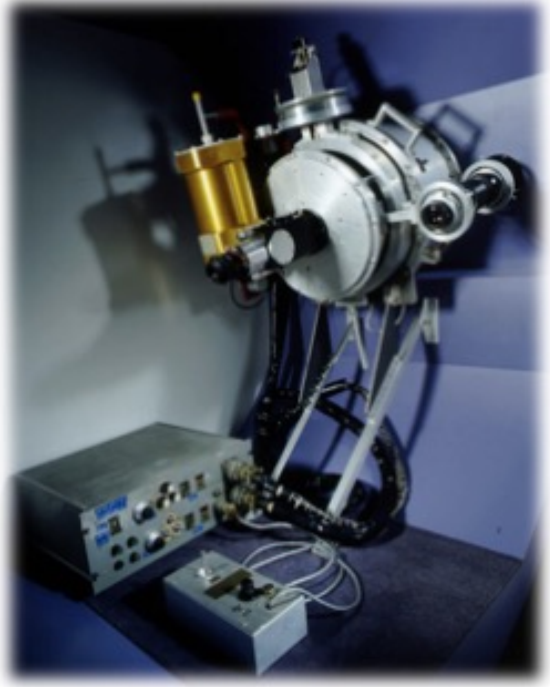
I will briefly discuss



- Cosmic Microwave Background measurements

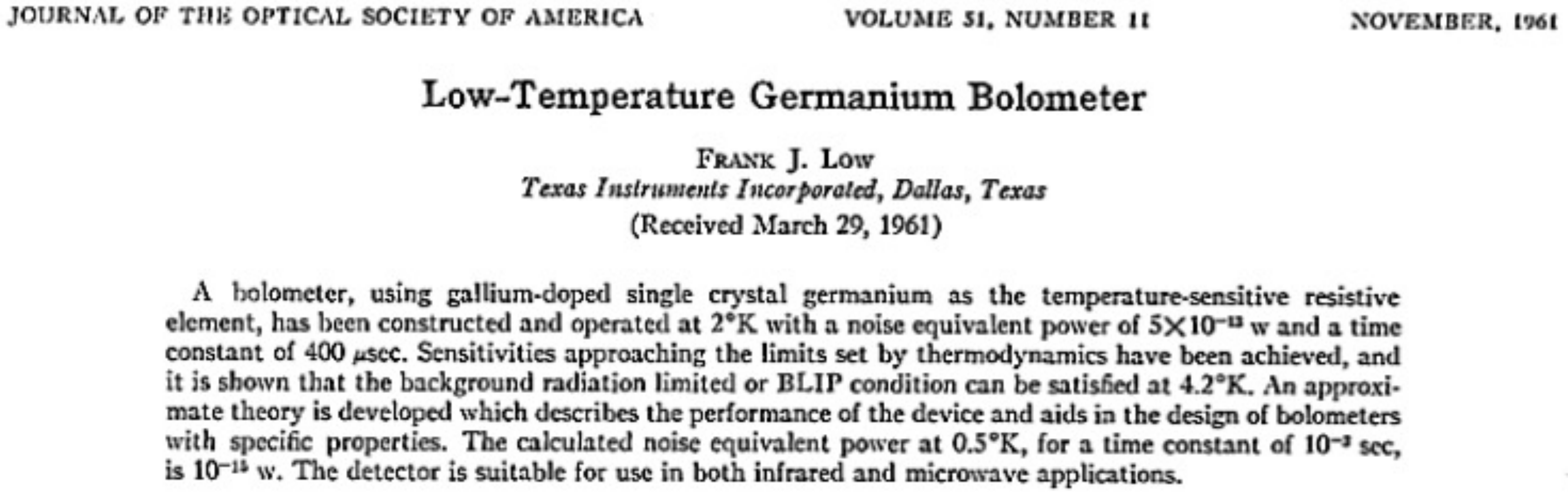
- Direct searches for Dark Matter
- Search for neutrinoless double-beta decay





The Beginnings

The father of astronomical bolometers is Frank Low (1933-2009). He invented the Ge:Ga bolometer in 1961.



JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 51, NUMBER 11 NOVEMBER, 1961

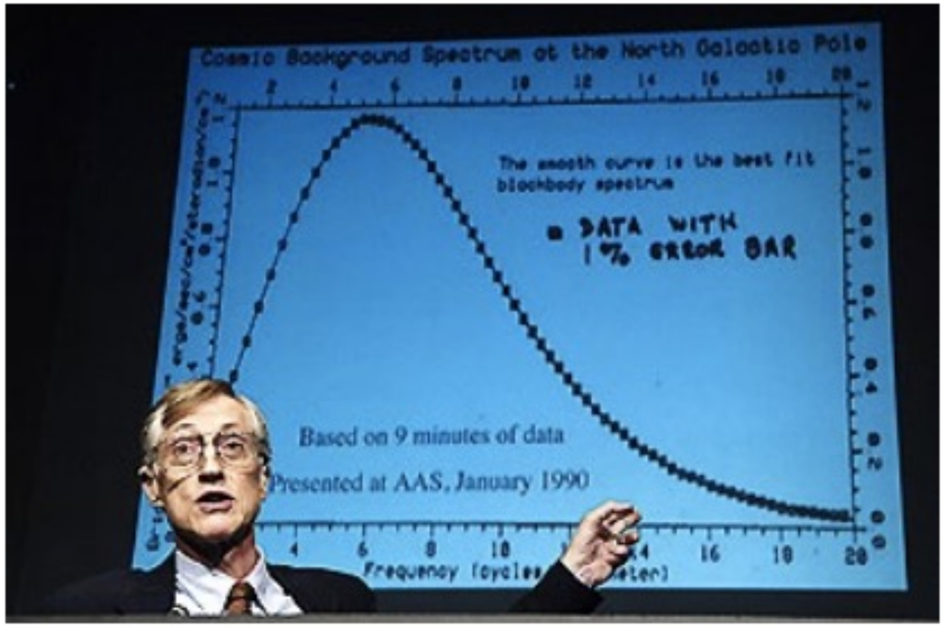
Low-Temperature Germanium Bolometer

Frank J. Low
Texas Instruments Incorporated, Dallas, Texas

(Received March 29, 1961)

A bolometer, using gallium-doped single crystal germanium as the temperature-sensitive resistive element, has been constructed and operated at 2°K with a noise equivalent power of 5×10^{-13} w and a time constant of 400 μsec. Sensitivities approaching the limits set by thermodynamics have been achieved, and it is shown that the background radiation limited or BLIP condition can be satisfied at 4.2°K. An approximate theory is developed which describes the performance of the device and aids in the design of bolometers with specific properties. The calculated noise equivalent power at 0.5°K, for a time constant of 10^{-3} sec, is 10^{-15} w. The detector is suitable for use in both infrared and microwave applications.

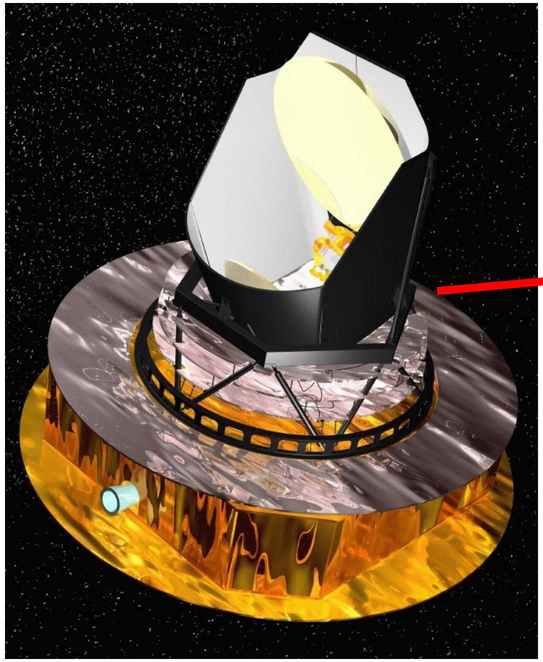
A milestone in the History of Bolometers

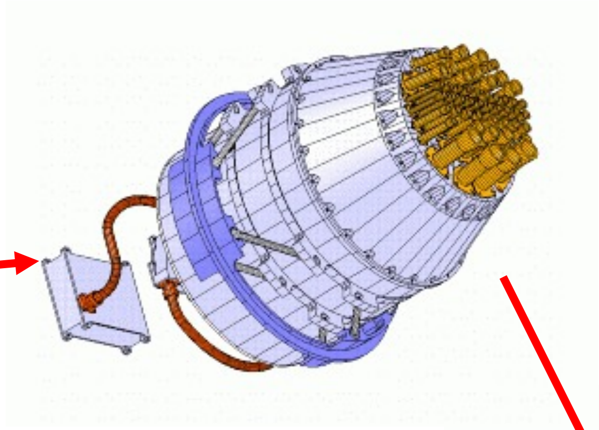


See John C. Mather (Applied Optics 21, 1125, 1982);
PI of the Far Infra Red Absolute Spectrophotometer (FIRAS) on COBE
and Nobel prize winner in Physics 2006 (with George Smoot)

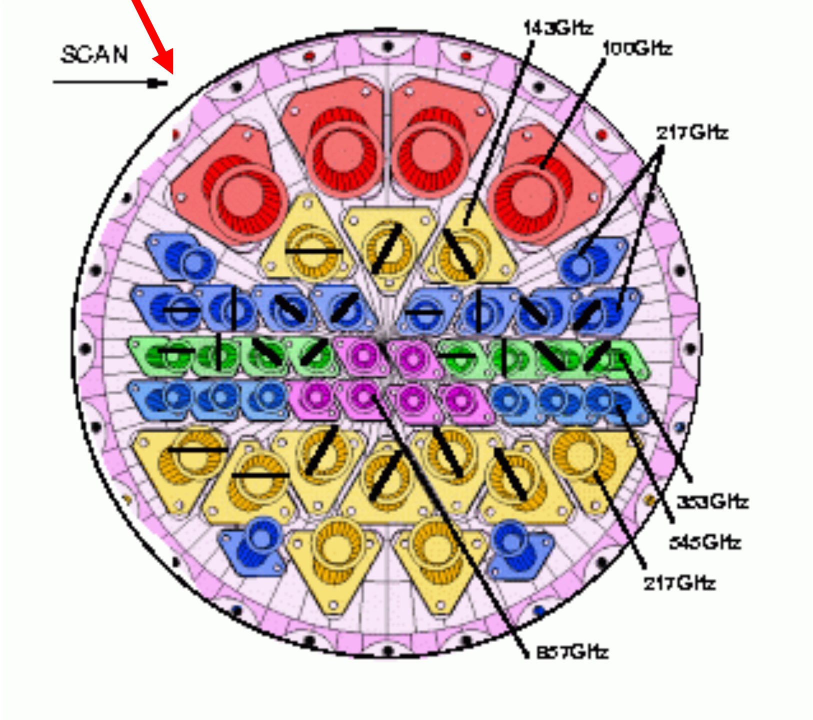
17-4-2020 Detection of Light – Bernhard Brandl 8

Planck

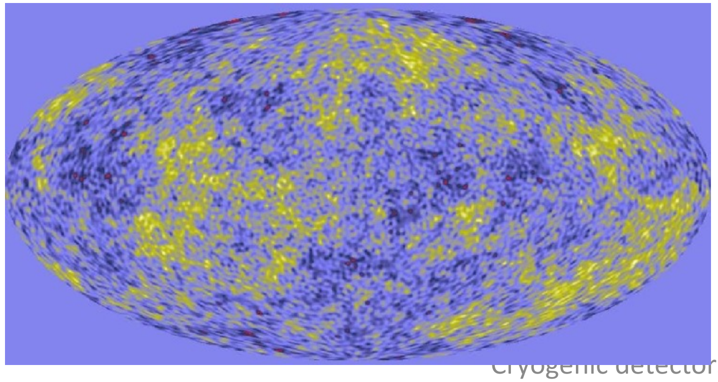




Planck **HFI**
(**H**igh **F**requency **I**nstrument)
- 52 bolometers
- at 100 mK
- 100 – 587 GHz (farIR-mm) in 6 bands



Satellite to measure CMB anisotropies and B-modes
Launched 2009 – end 2013

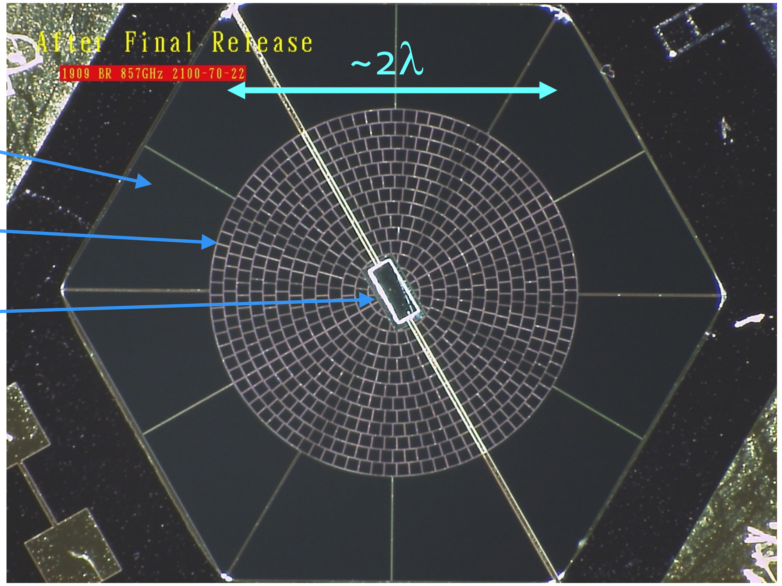


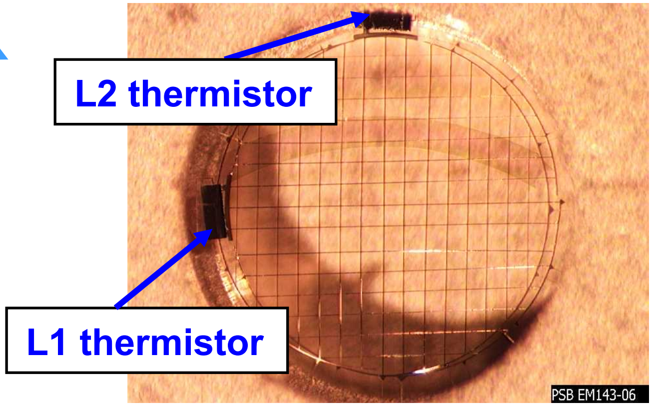
Planck bolometers
Spider web bolometers (Caltech-JPL)

low C ←
C dominated by thermistor
Au determines g

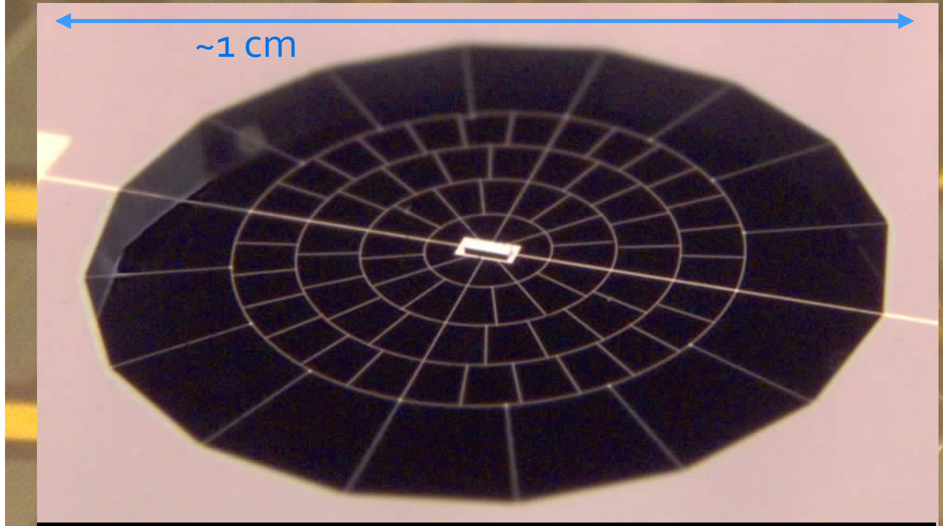
- Absorber: Si_3N_4
  - ➢ e~1µm, l~5µm, cell~100µm
  - ➢ Metallization Au
- Ge NTD thermometer
- Polarisation Sensitive Bolometer (PSB)
  - ➢ 2 bolometers in 1 module
  - ➢ Metallization in one direction

Detectors of
- **Boomerang**
- **QUAD**
- **BICEP1**
- **Planck-HFI**

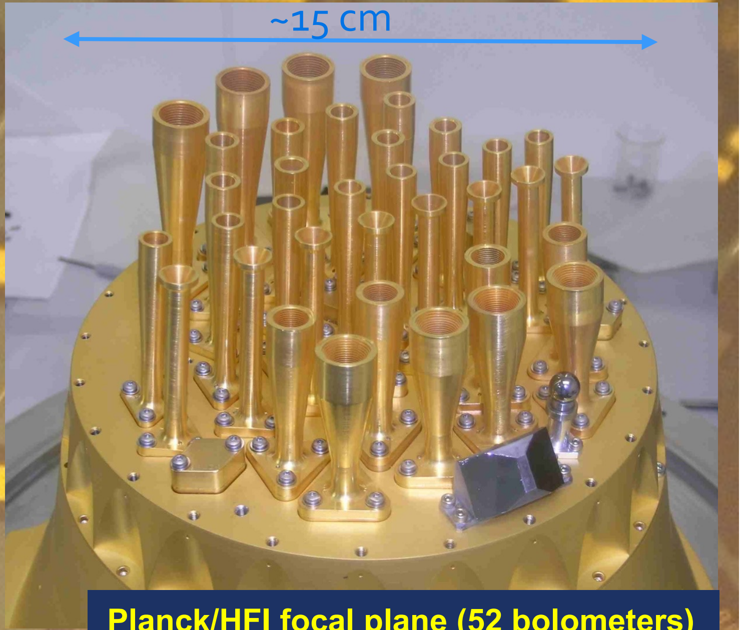




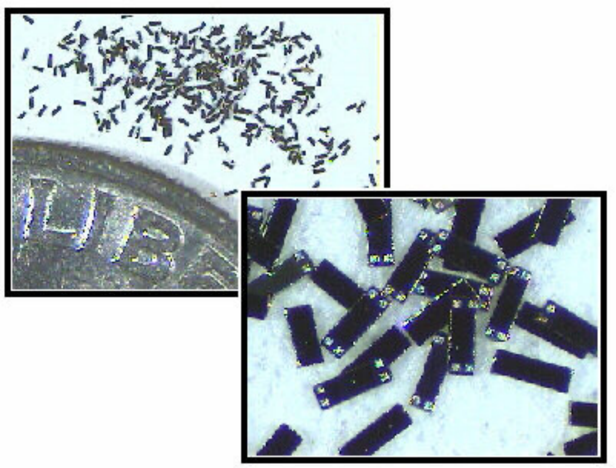
NTD Bolometers for Planck & Herschel



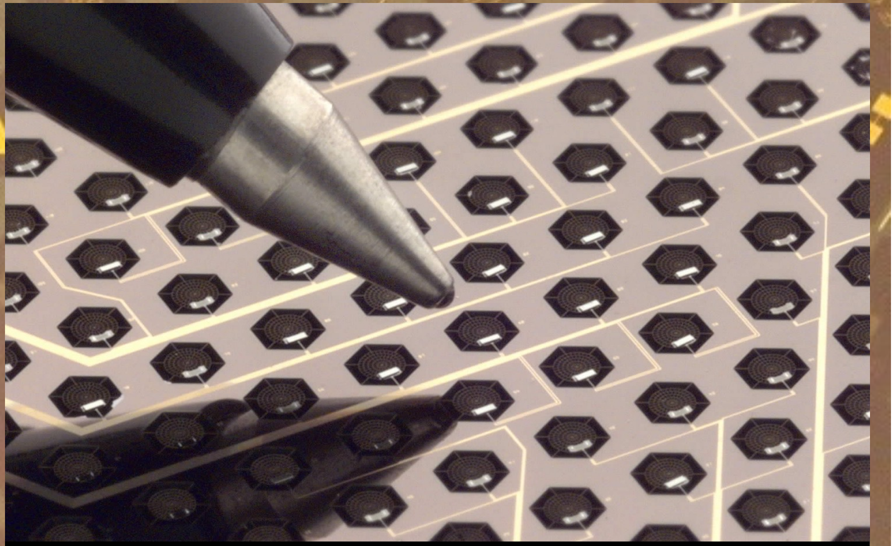
143 GHz Spider-web Bolometer



Planck/HFI focal plane (52 bolometers)



NTD Germanium

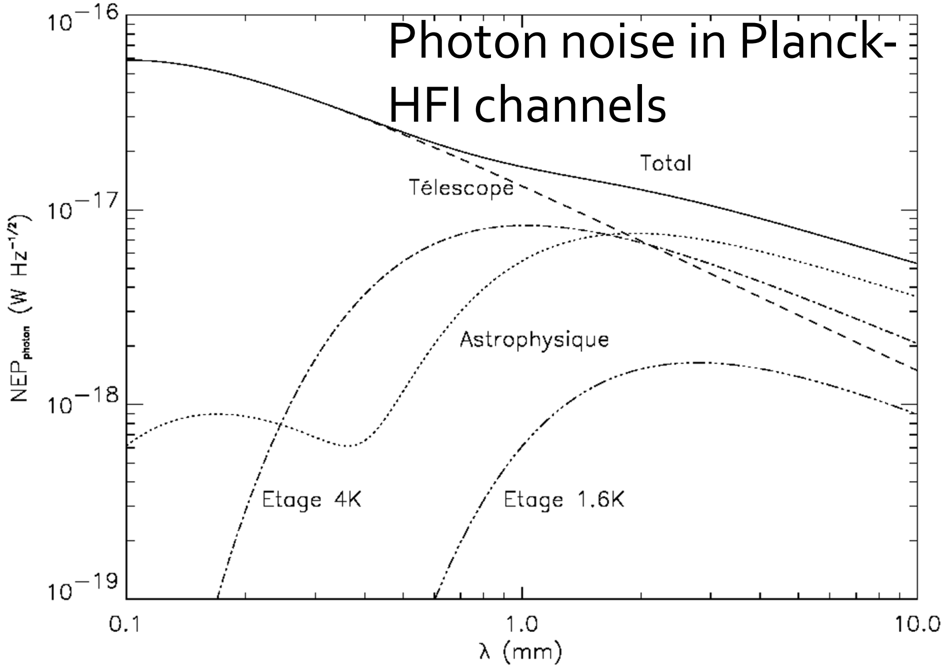


Herschel/SPIRE Bolometer Array

(From J. Bock, JPL)

Spider web bolometer performances

- at 300mK
  - NEP = $1,5.10^{-17}$ W/Hz$^{1/2}$
  - τ = 11ms
  - C = 1pJ/K
- at 100mK:
  - NEP = $1,5.10^{-18}$ W/Hz$^{1/2}$
  - τ = 1,5ms
  - C = 0,4pJ/K



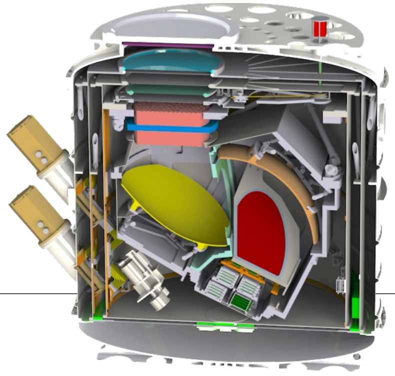
Photon noise in Planck-HFI channels

CMB photon noise limited detectors!

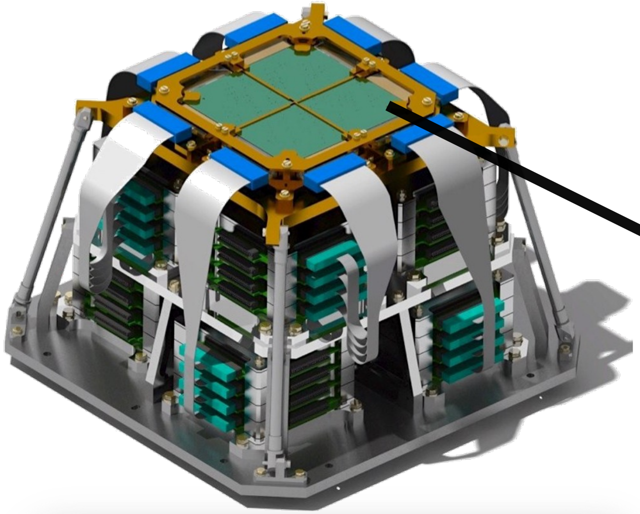
Sensitivity improvement ⇒ increase of detector number

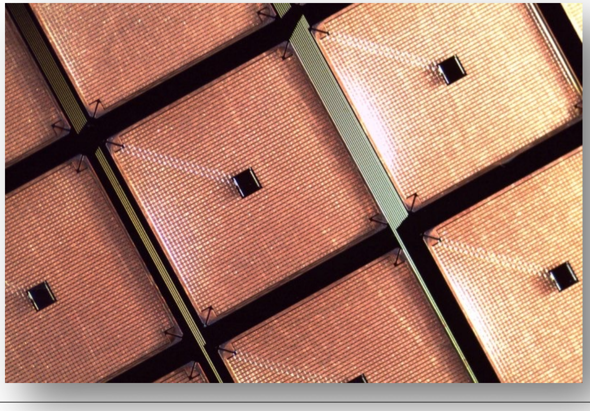
Bolometer arrays

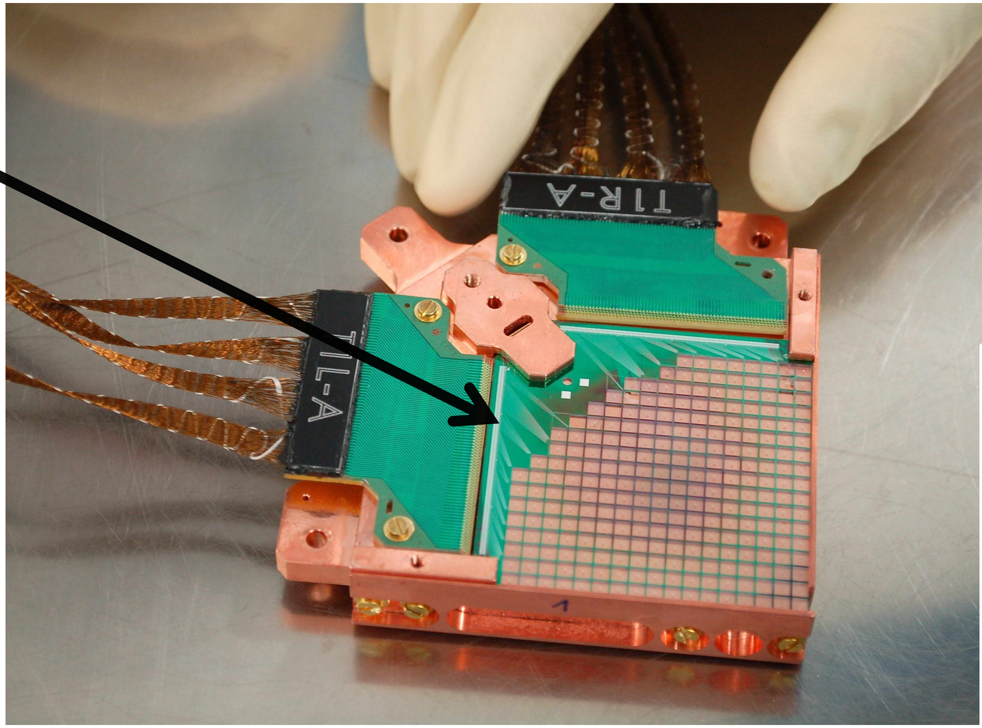
Example:
248 TES QUBIC (France)

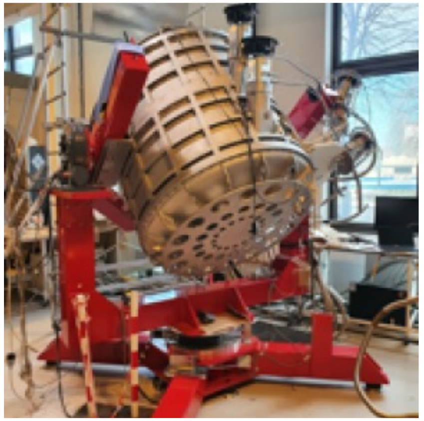


- Superconducting NbSi (CSNSM, C2N, APC)





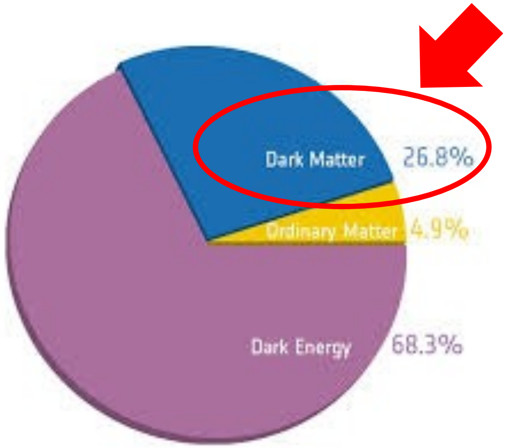




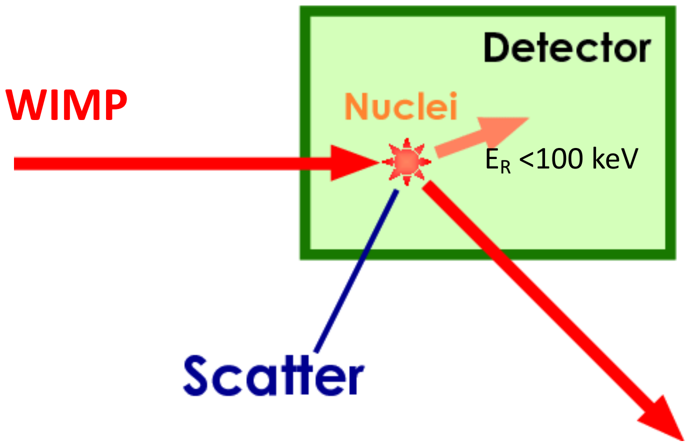
Integration and test at APC

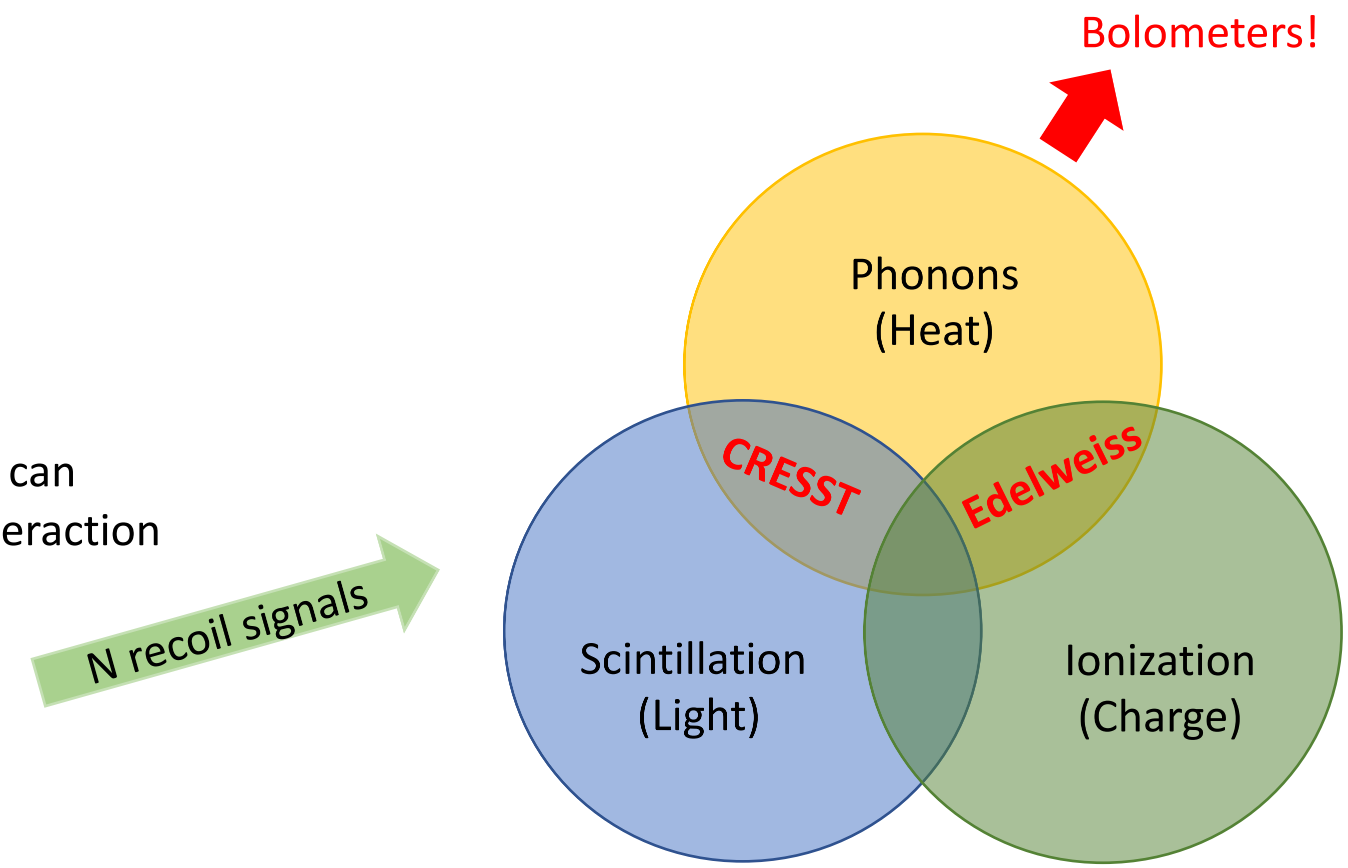
Direct detection of Dark Matter

→ 2nd semester lectures
by Davide Franco



What is its nature?
If **W**eakly **I**nteracting **M**assive **P**articles, we can detect the the recoil of nuclei from their interaction




N recoil signals

Bolometers!

Phonons (Heat)

Scintillation (Light)

Ionization (Charge)

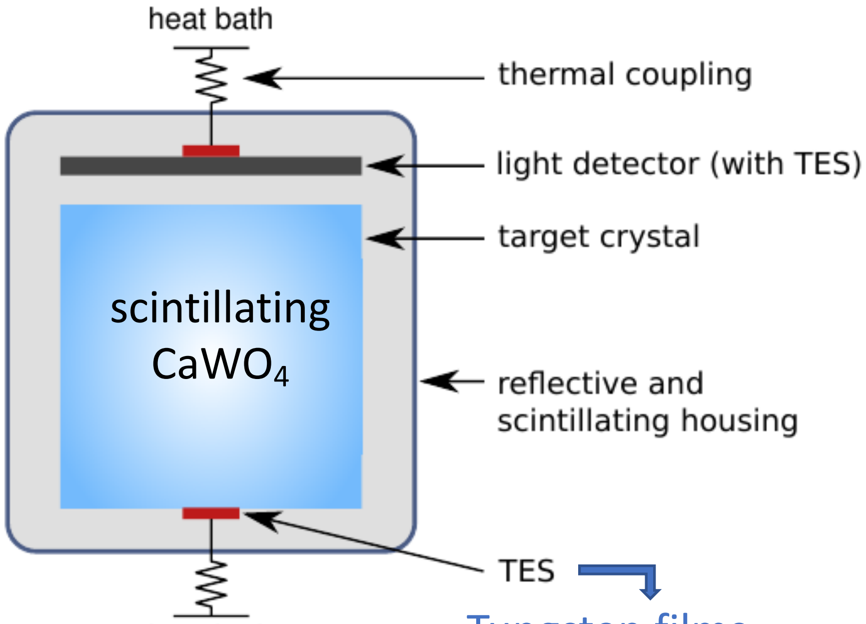
CRESST

Edelweiss

Direct detection of Dark Matter: CRESST

Cryogenic Rare Event Search with Superconducting Thermometers

https://www.cresst.de/



heat bath

thermal coupling

light detector (with TES)

target crystal

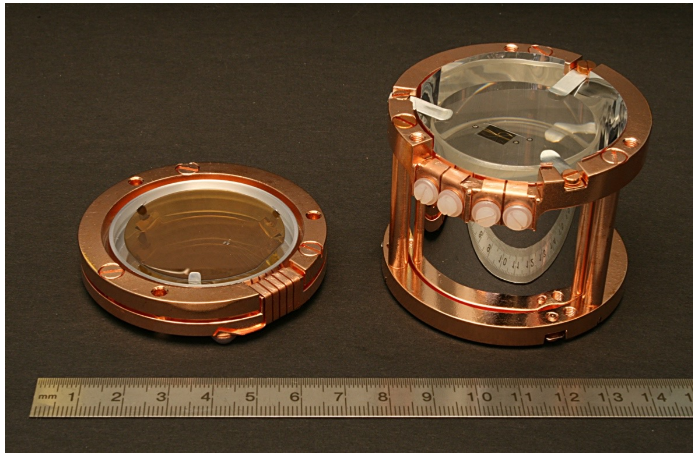
scintillating $CaWO_4$

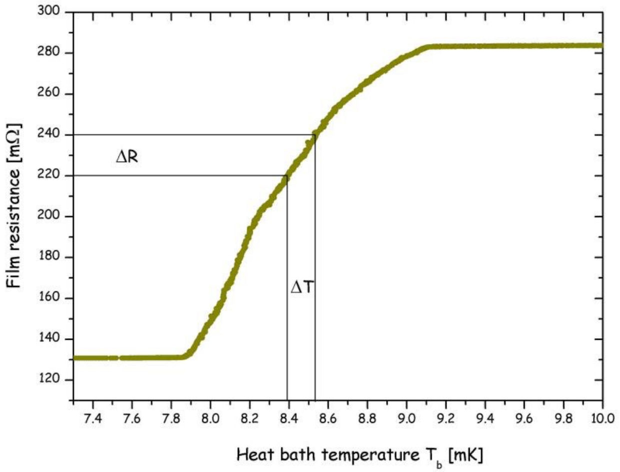
reflective and
scintillating housing

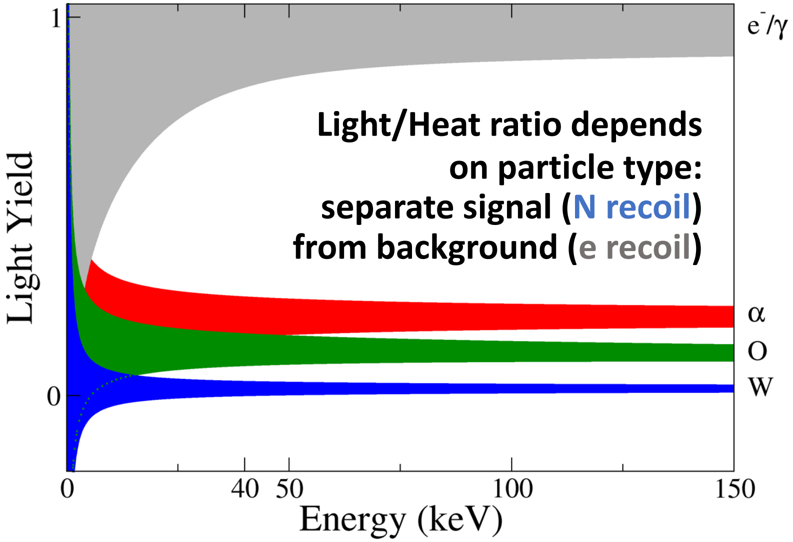
TES

heat bath

Tungsten films



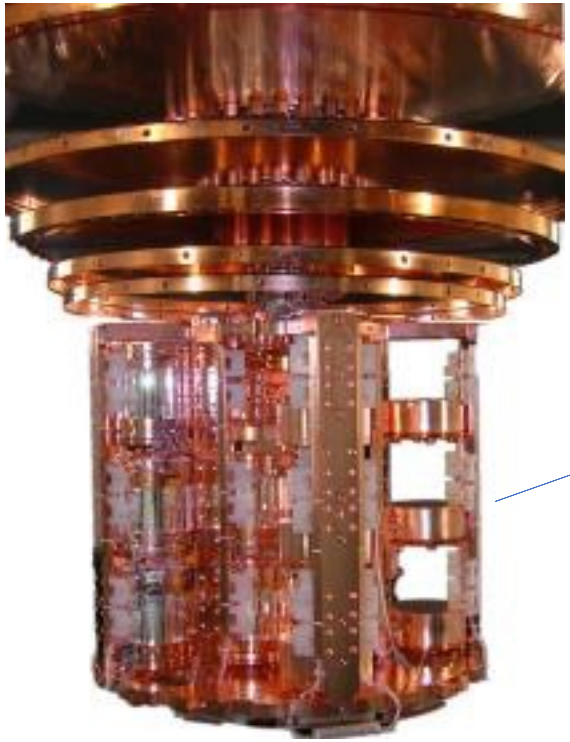


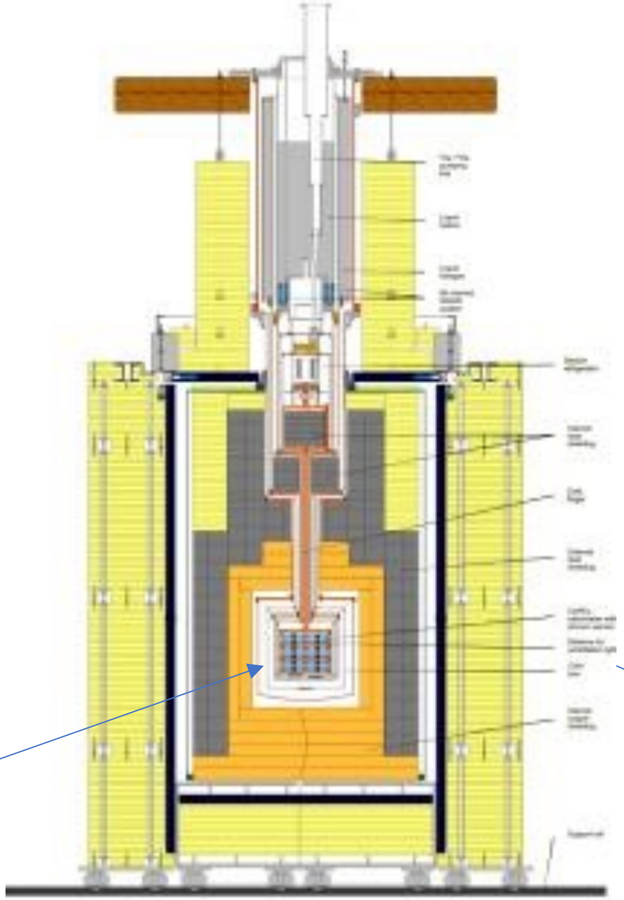


Light/Heat ratio depends on particle type: separate signal (N recoil) from background (e recoil)

Direct detection of Dark Matter: CRESST

Detector Modules:
up to 33 crystals (10 kg)



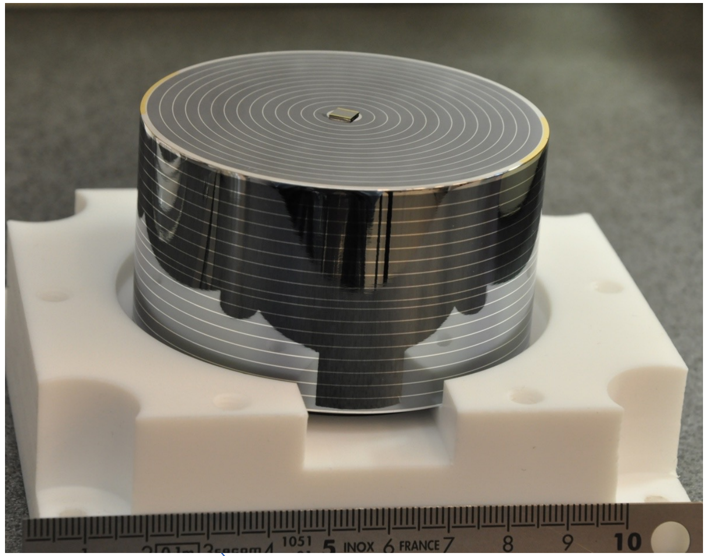


Cryostat

Experimental Hall at
Gran Sasso National Laboratories,
Italy

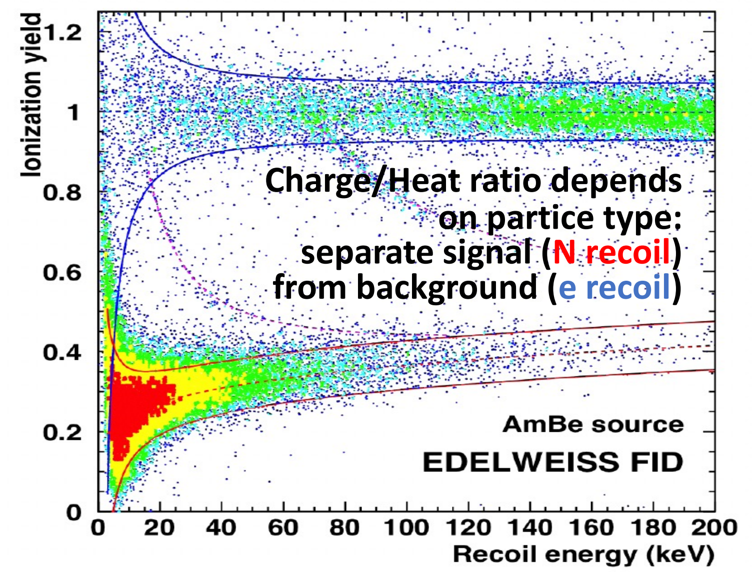
Direct detection of Dark Matter: Edelweiss-III

36 **Ge crystal** (870g)
FID (Fully InterDigit detectors)
with Charge readout on
the whole surface
+ NTD thermistors

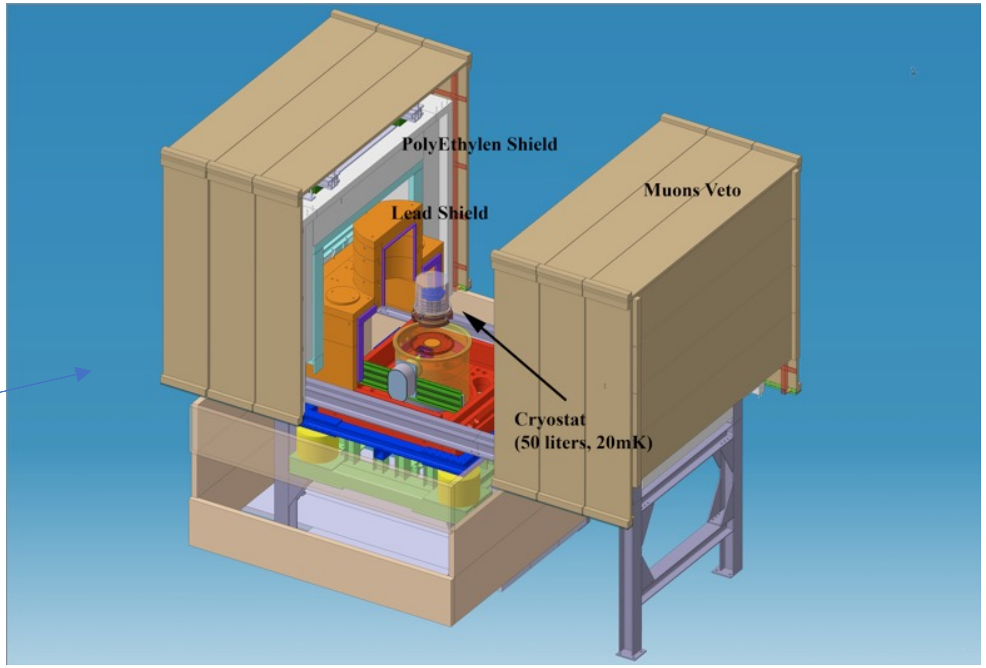


Expérience pour détecter les WIMPs en site souterrain
http://edelweiss.in2p3.fr/

Schematic view of the experiment
@ Laboratoire Souterrain de Modane,
France

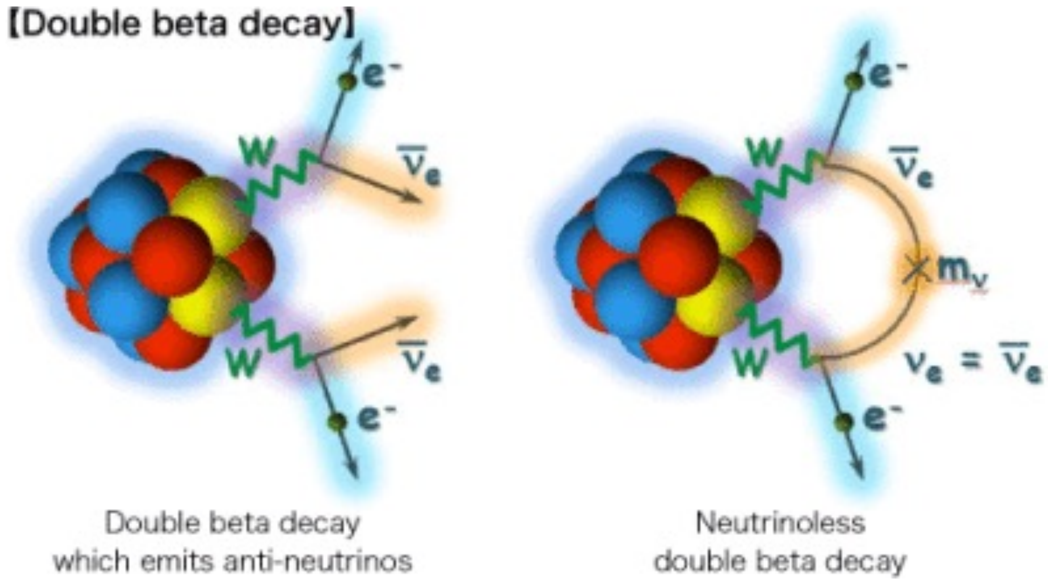


Charge/Heat ratio depends on particle type: separate signal (N recoil) from background (e recoil)



Neutrinoless double-beta decay (0νββ)

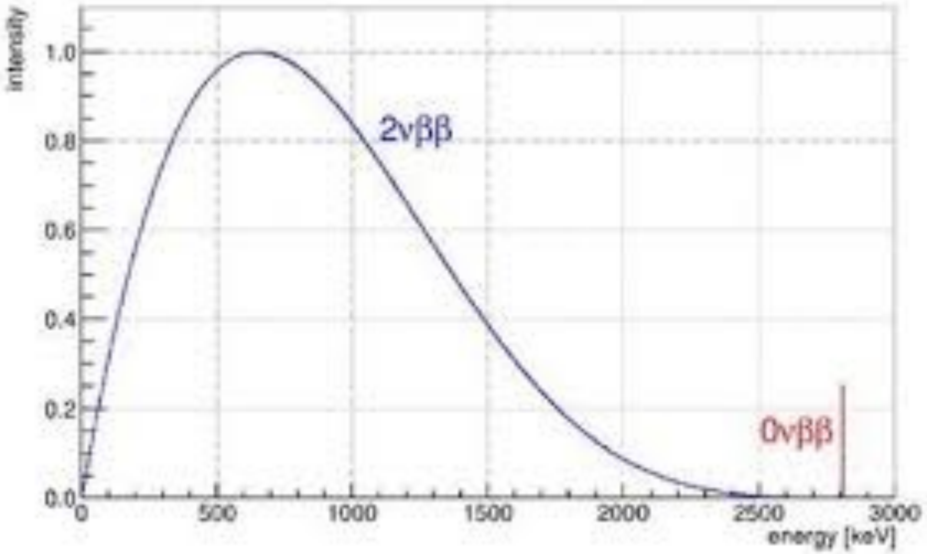
→ 2nd semester lectures
by Véronique Van Elewyck



2νββ
Observed with several isotopes

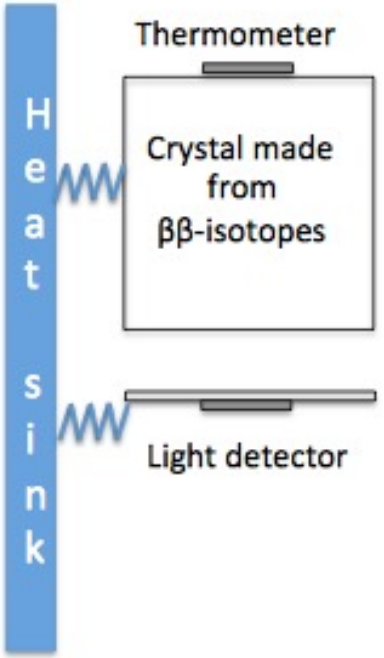
0νββ
Possible only if ν is
a Majorana particle
→ test of neutrino
nature

Experimental signature:
Peak at the endpoint in the sum
of the two electron energies



Need extremely good energy resolution
➔ BOLOMETERS

Bolometers for 0νββ



0νββ emitters: ^{130}Te, ^{82}Se, ^{100}Mo & few others

Crystals: TeO_2 , ZnSe, $ZnMoO_4$, $CaMoO_4$

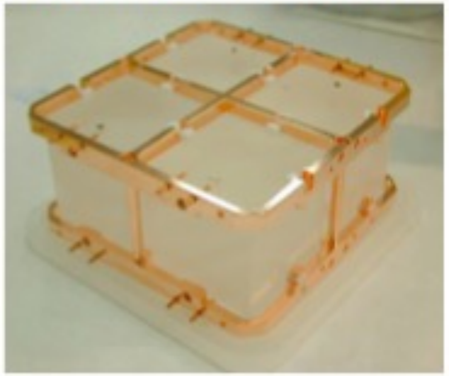
Operation at <20 mK:

$$C \propto T^3$$

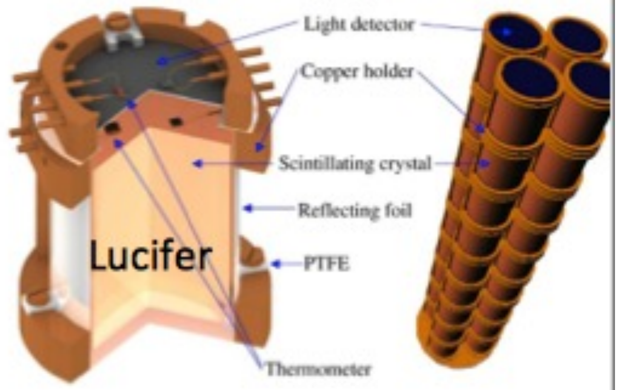
$$\Delta T \propto \Delta E / C$$

$$TeO_2: \quad \Delta E \cong 5 keV (FWHM) \, at \, Q_{\beta\beta} = 2528 \, keV$$

Cuore
(w/o light detection)



Lucifer, Lumineu, Amore
(with light detection)



S. Schönert (TUM): Challenges in neutrinoless double beta decay experiments – NOW, September 8, 2014

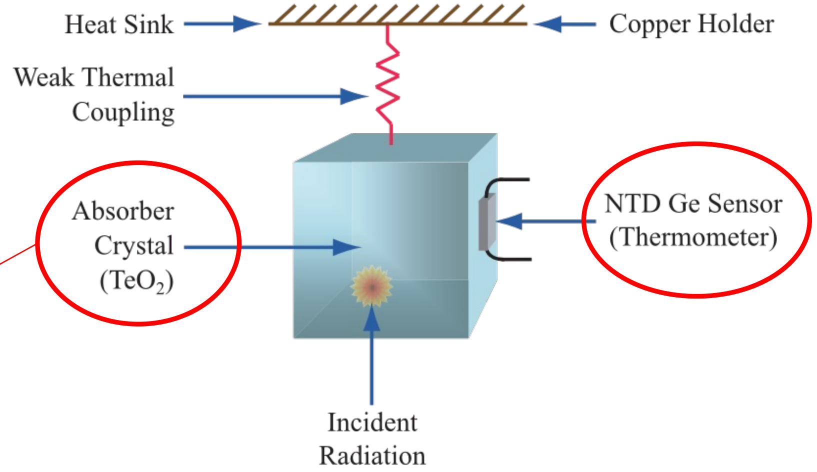
Bolometers for 0νββ: CUORE

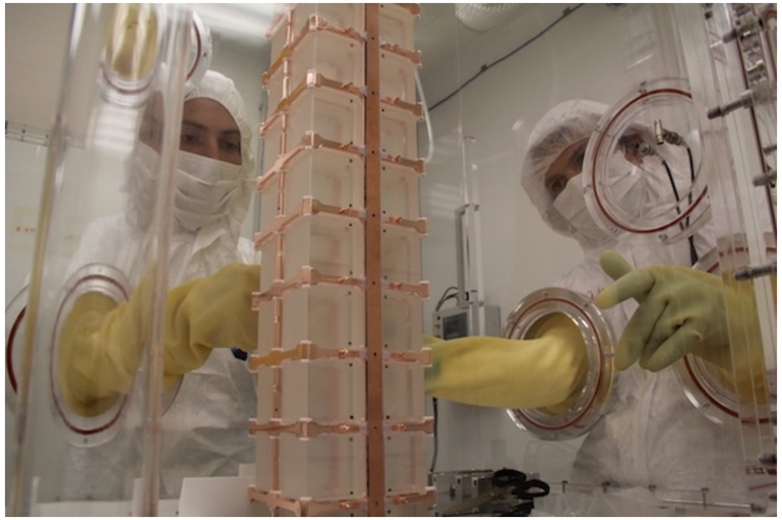
Cryogenic Underground Laboratory for Rare Events

https://cuore.lngs.infn.it

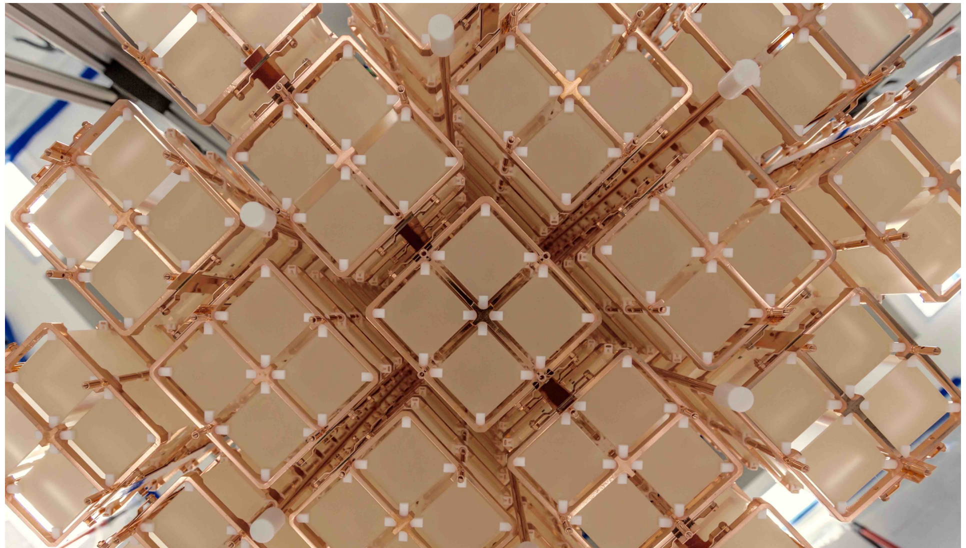
0νββ isotope: ^{130}Te

the crystal can be grown from the isotope

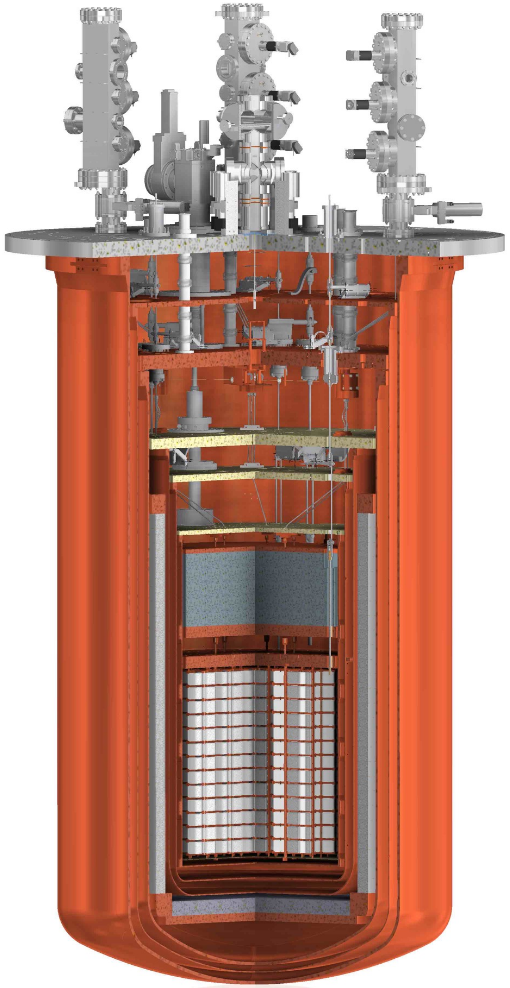




Assembling the CUORE-0 tower in a glove box

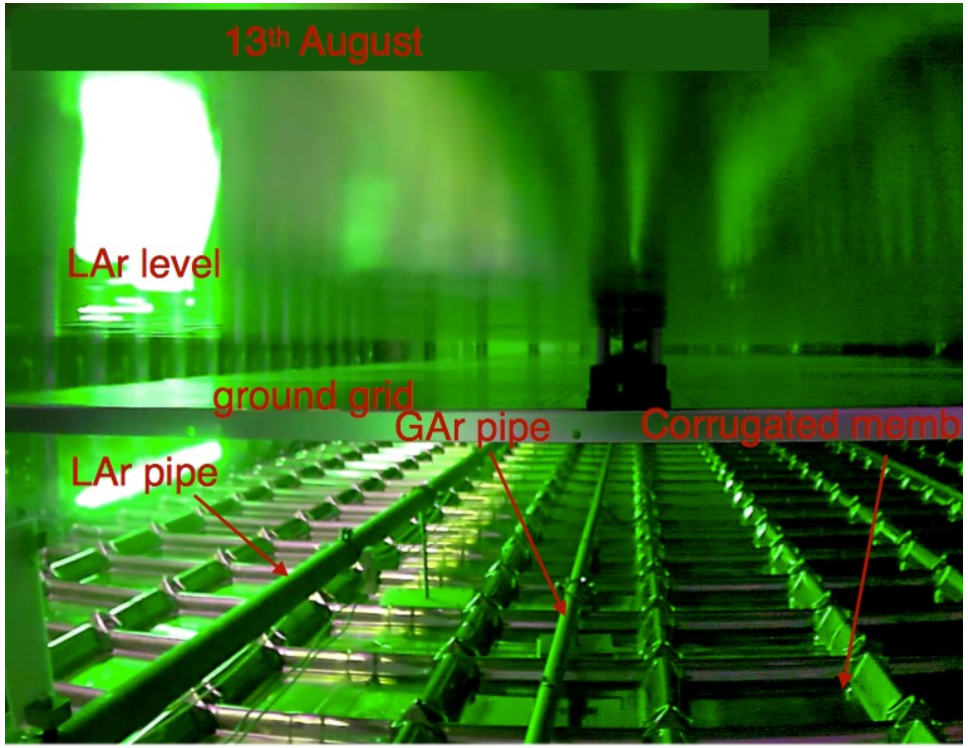


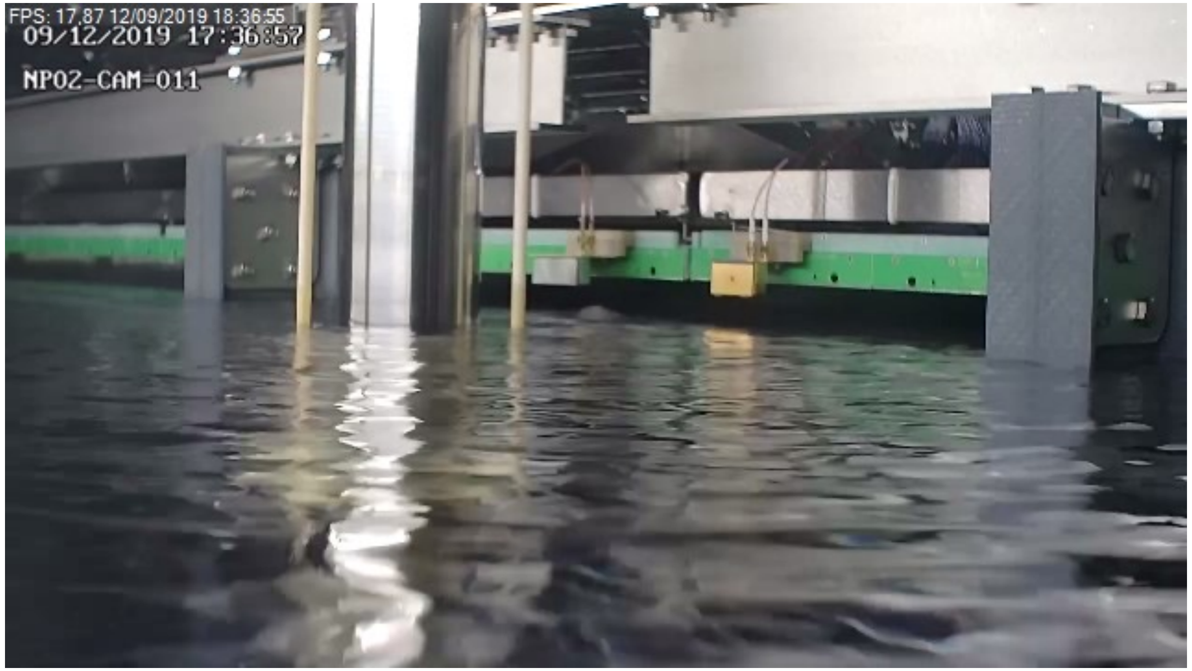
Bottom view of the 19 towers (988 bolometers, 741 kg, 206 kg of ^{130}Te)



The detector inside the cryostat (10 mK) @LNGS

Liquefied noble gases





Liquefied noble gases

Liquid Xenon (T = 165 K), **Liquid Argon** (T = 87.3 K)

- Dense, relatively inexpensive, easy to purify (scalable to Large Masses)
- High **ionisation** yield
- High **scintillation** yield
- Transparent to their own scintillation
- High electron mobility and low electron diffusion
- Discrimination electron/nuclear recoils (ER/NR): ionisation/scintillation

suitable for Time Projection Chambers

➔ Neutrino and Dark Matter Detectors

Liquefied noble gases

Property	**Xenon**	**Argon**
Z	54	18
A	131.3	39.95
Boiling point (K)	165	87.3
Density (g/cm^3)	3.0	1.4
Ionization work function W (eV) $=E/(N_{ex}+N_i)$	16.4	23.7
e- drift velocity at 500 V/cm (mm/µs)	1.7	1.64
Scintillation wavelength (nm)	175	128
Scintillation yield (Nphotons/MeV)	42000	40000
Fast (singlet) scintillation decay time (ns)	4.3	7
Slow (triplet) scintillation decay time (ns)	22	1500

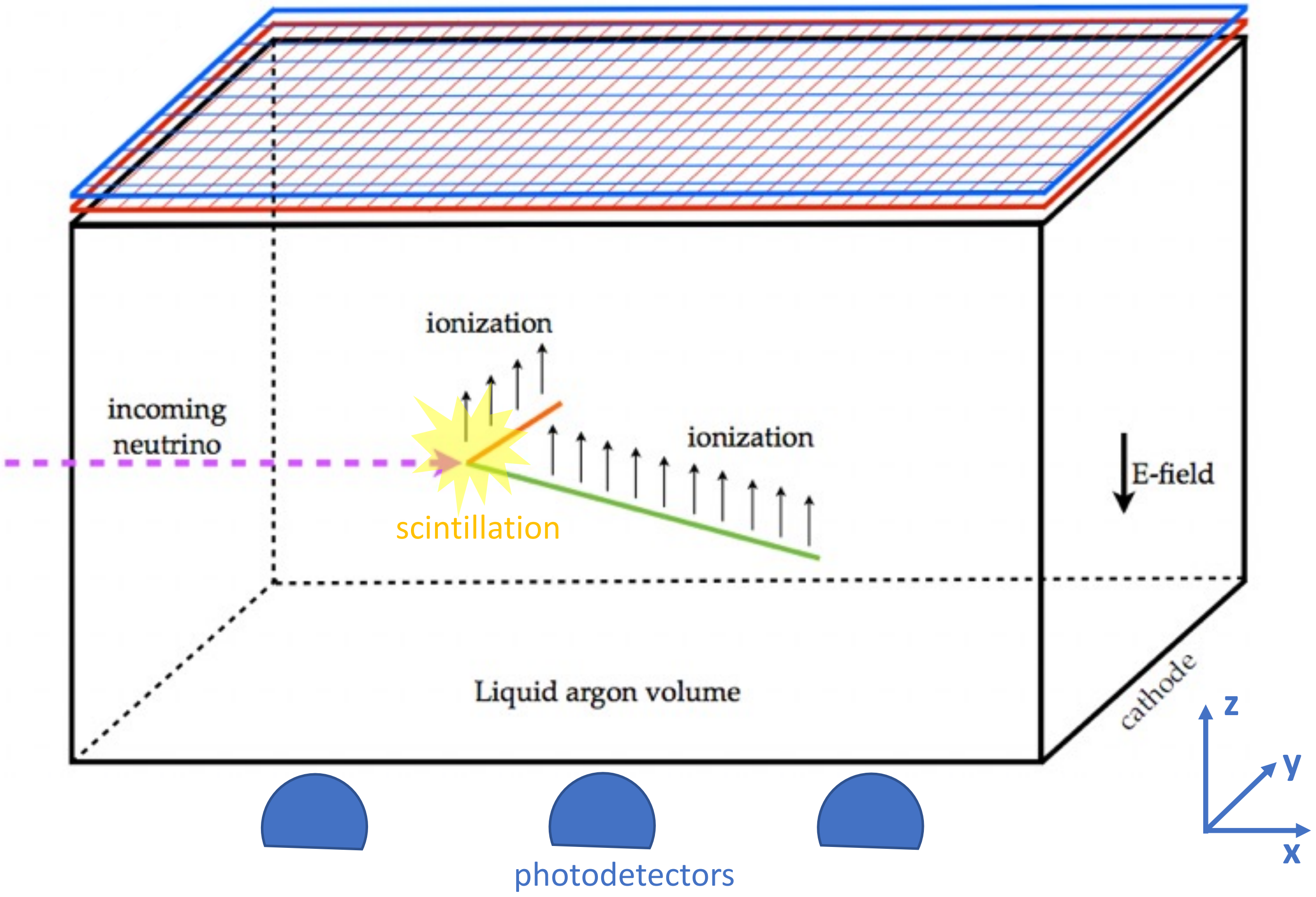
Liquefied noble gases Time Projection Chambers

Basic principle:

- Scintillation → event timing (t_0)
- Ionization charge drift time → z coordinate
- Ionization charge arrival position at anode plane → x,y coordinates
- Light and/or ionization meas. → deposited Energy

Information on

- Position (full 3D reconstruction)
- Energy deposition
- Particle Identification



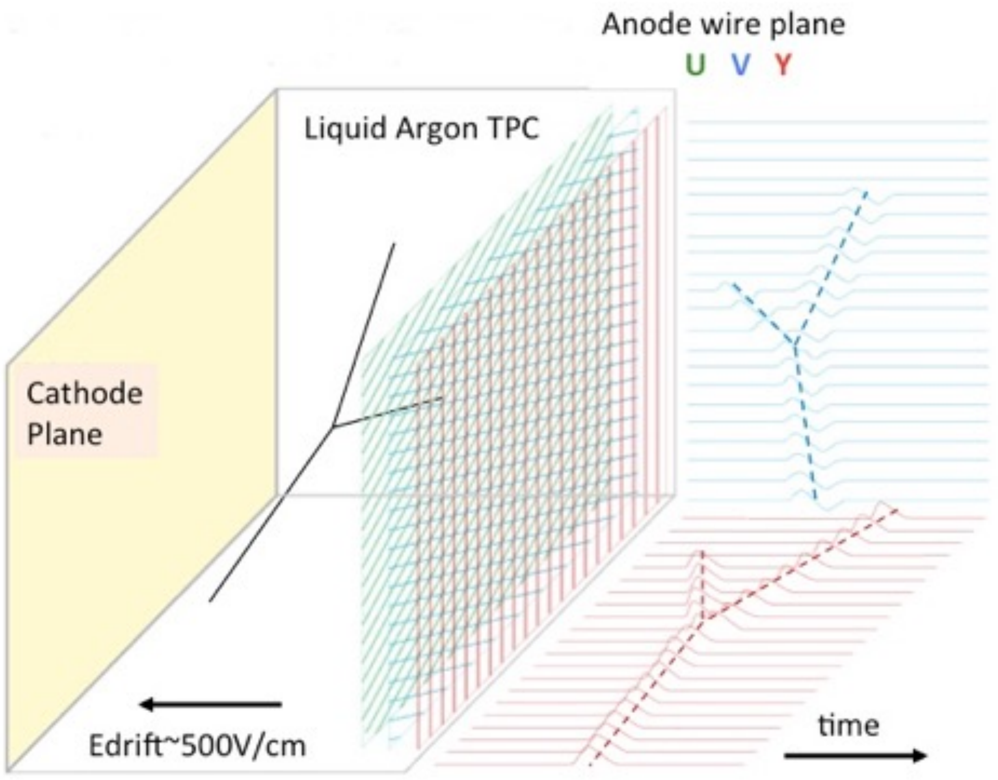
Liquid Argon TPC for neutrino experiments

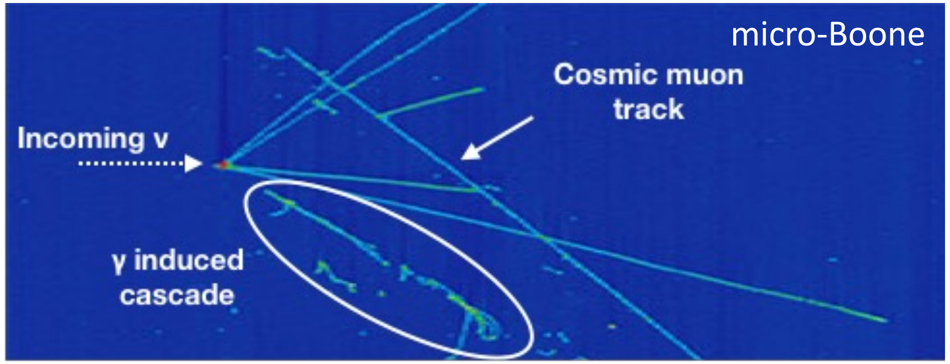
Energies:

GeV (accelerator ν) / **MeV** (SuperNova ν)

Signal

- scintillation light (→ trigger/timing + complementary calorimeter information)
- ionisation electrons, drifted to readout planes by an E-field and read-out by 1 induction and 2 collection wire planes (→ position, timing, energy)



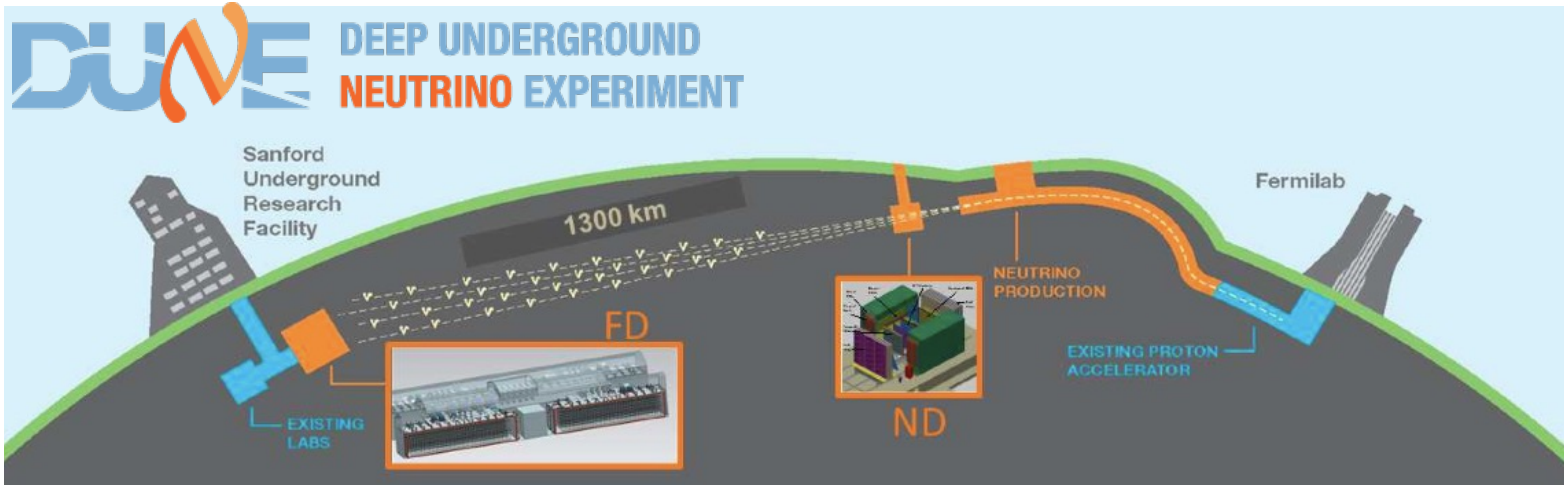


Features

- Large and homogeneous active volume
- 3D-imaging with ~mm resolution
- Accurate calorimetry
- PID from dE/dx and event topology

Liquid Argon TPC for neutrinos: DUNE

A 40-kt LAr Far Detector at SURF (4300 m.w.e. depth)
with a 1.2-2.3 MW beam from FNAL (1300 km baseline) and a Near Detector

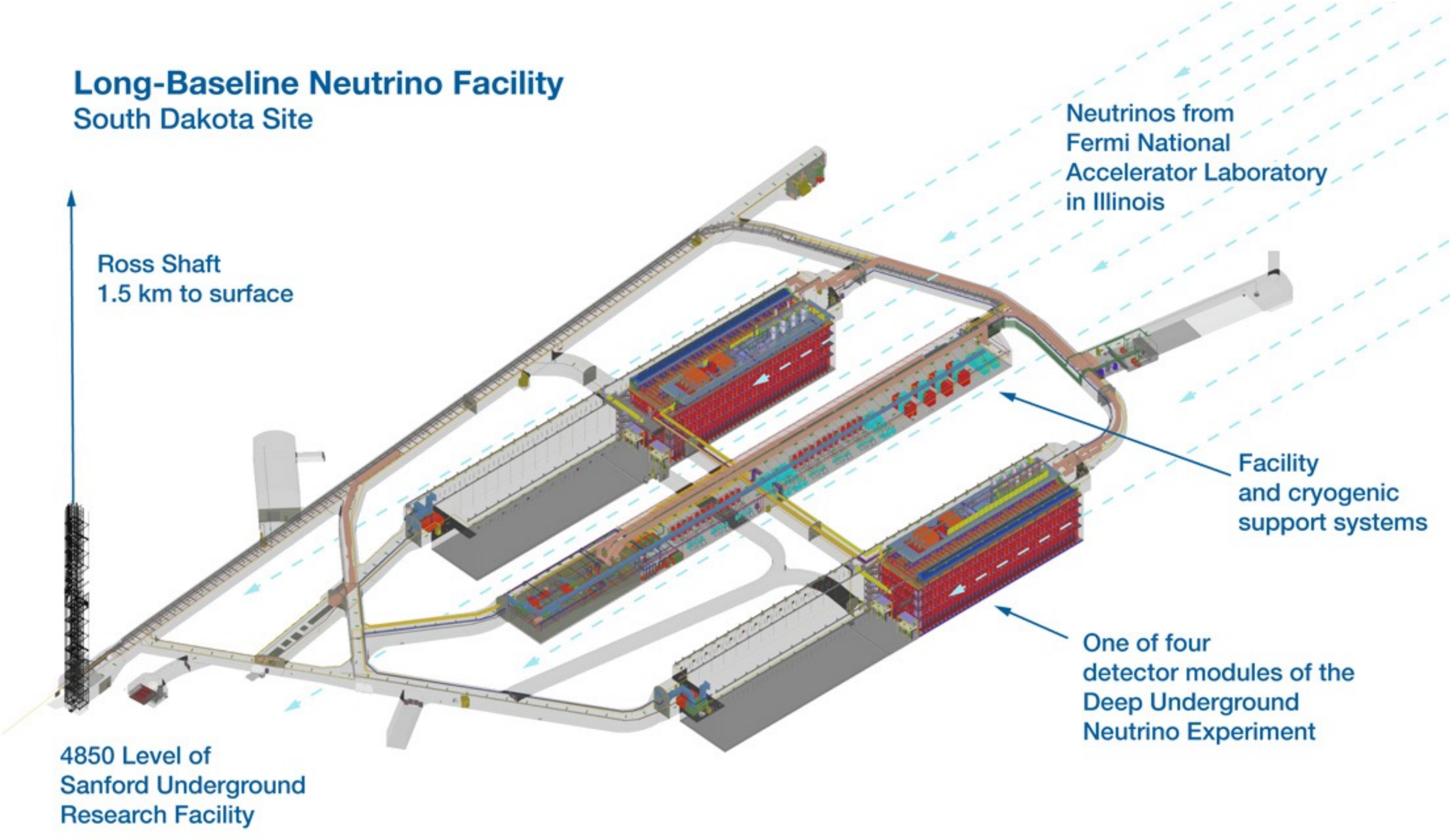


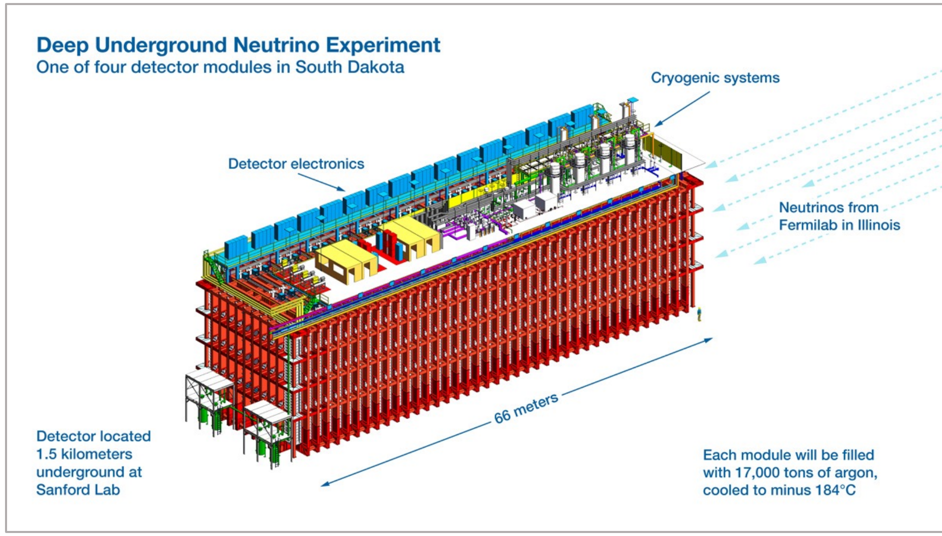
Physics goals:

- Precise measurement of neutrino oscillation parameters (MH, δ_{CP}, θ_{23})
- Searches for nucleon decay
- Neutrinos from SuperNovae core collapse
- Physics beyond the Standard Model

https://www.dunescience.org

Liquid Argon TPC for neutrinos: DUNE



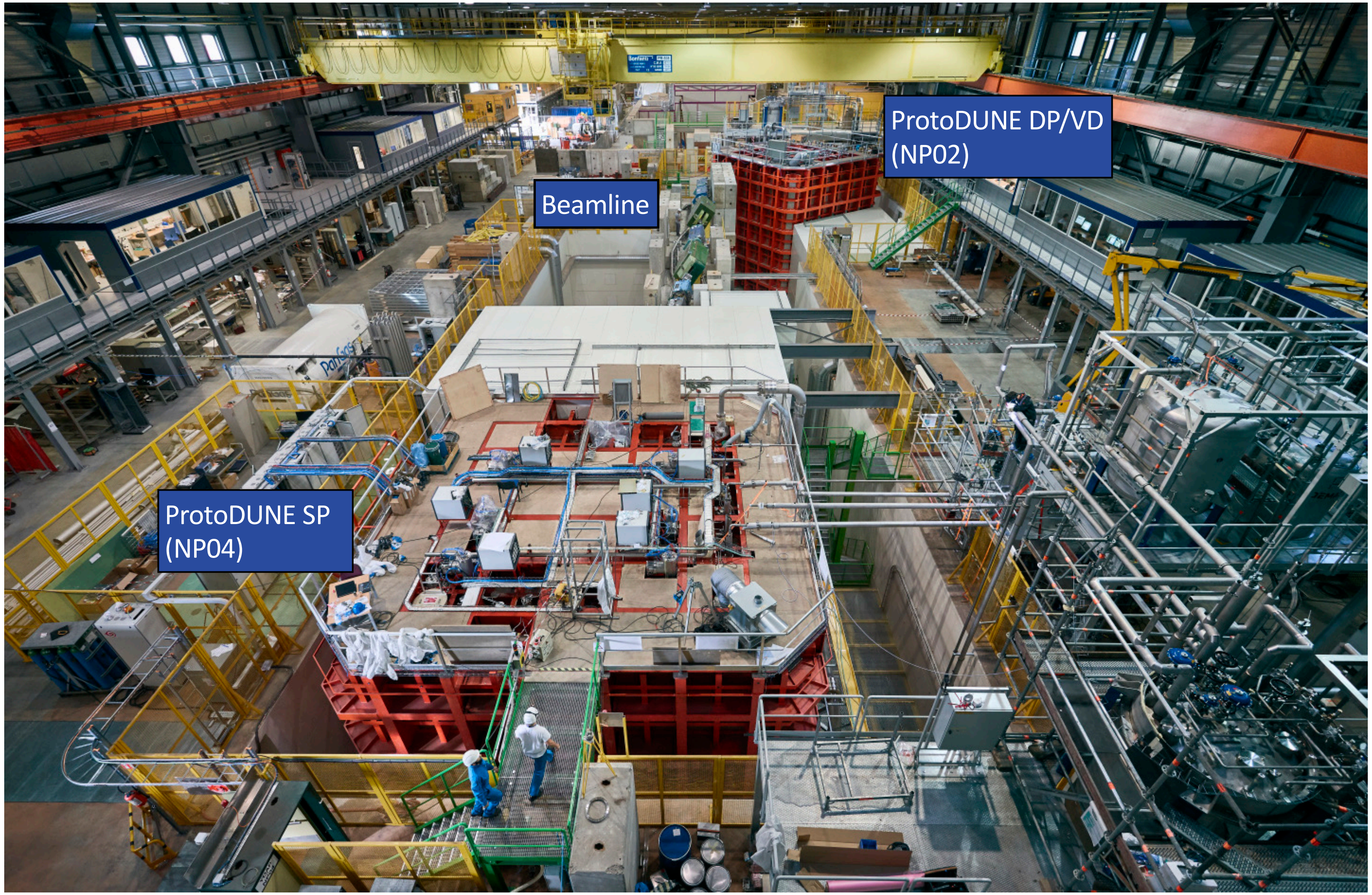


4 x 17.4 kton (10 kton fid.) Liquid-Argon (LAr) TPCs

4 cryogenic modules, 66m long

Liquid Argon TPC for neutrinos: ProtoDUNEs

Full-scale prototypes (6x6x6 m^3 fid) built and operated at the CERN Neutrino Platform



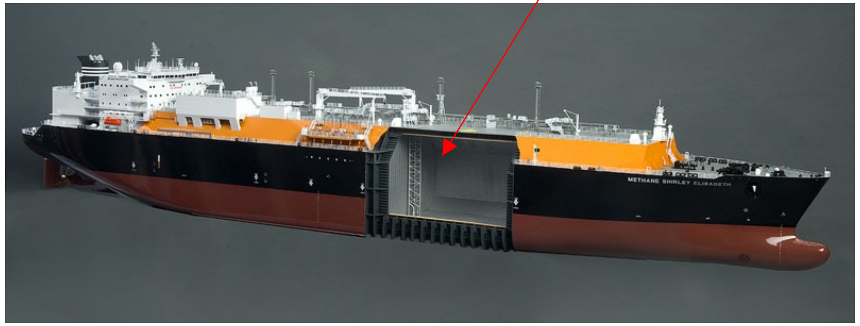
→ Cosmic rays

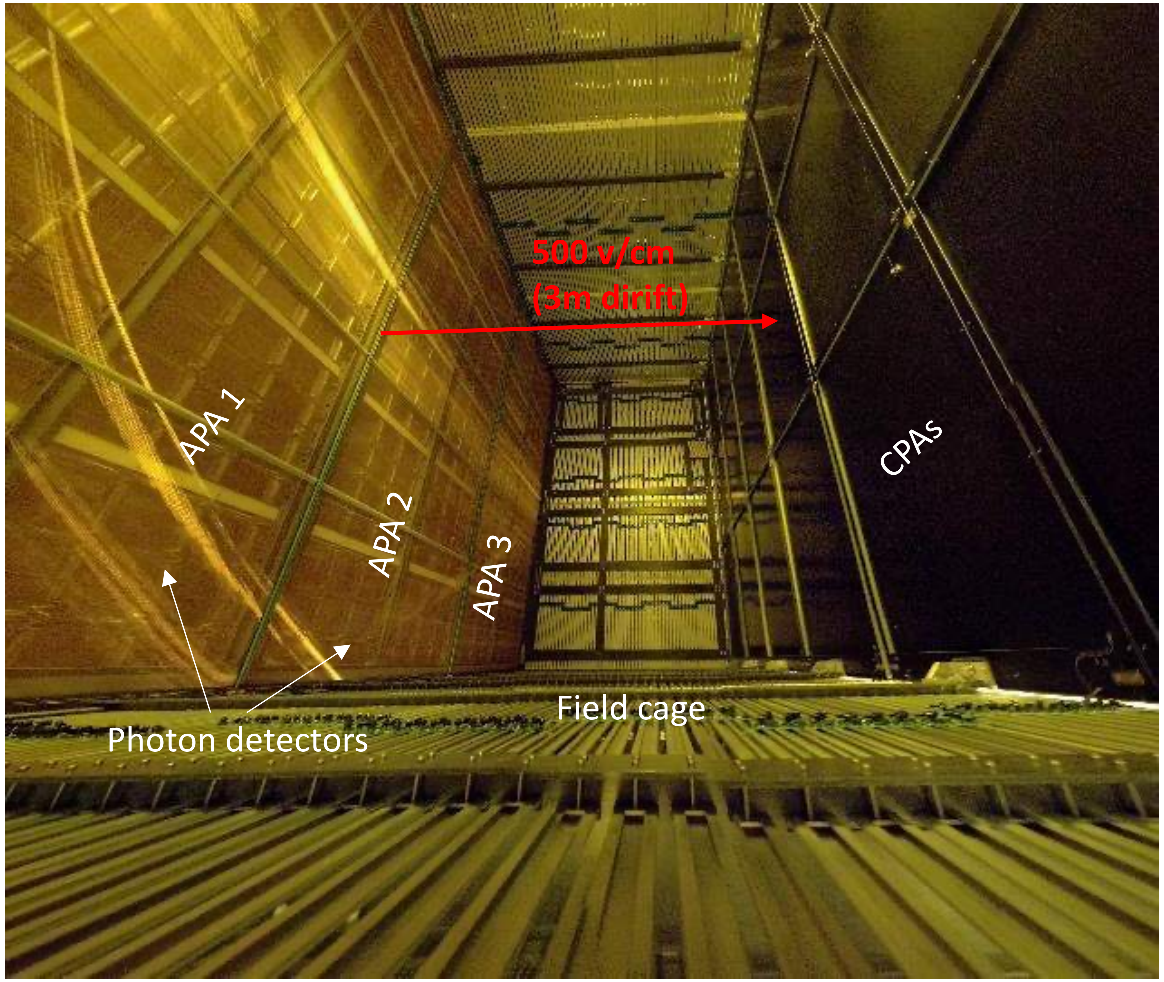
→ Known charged particle beams

Liquid Argon TPC for neutrinos: ProtoDUNEs

Inside the ProtoDUNE cryostat

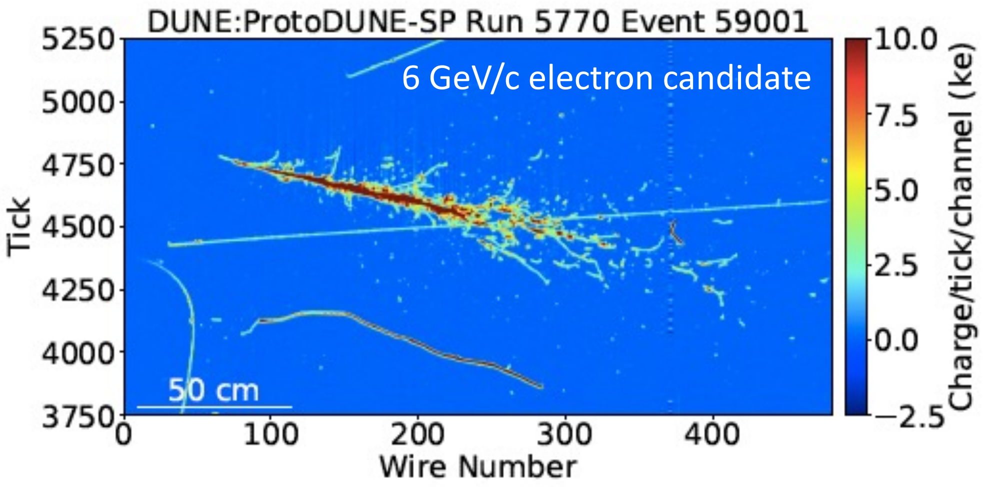
insulation technology (corrugated membrane)
from LNG tanker



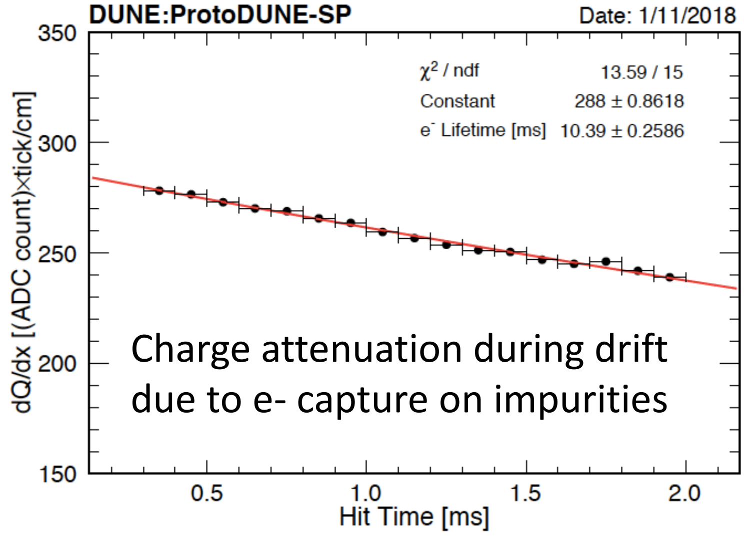


APA = Anode Plane Assembly
charge collection wires (3 views)
+ photodetectors

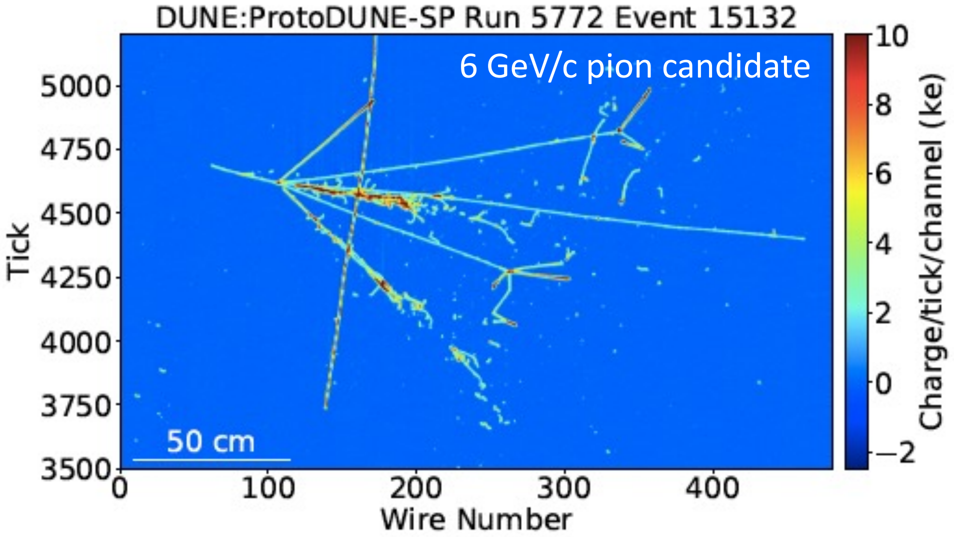
ProtoDUNE performances



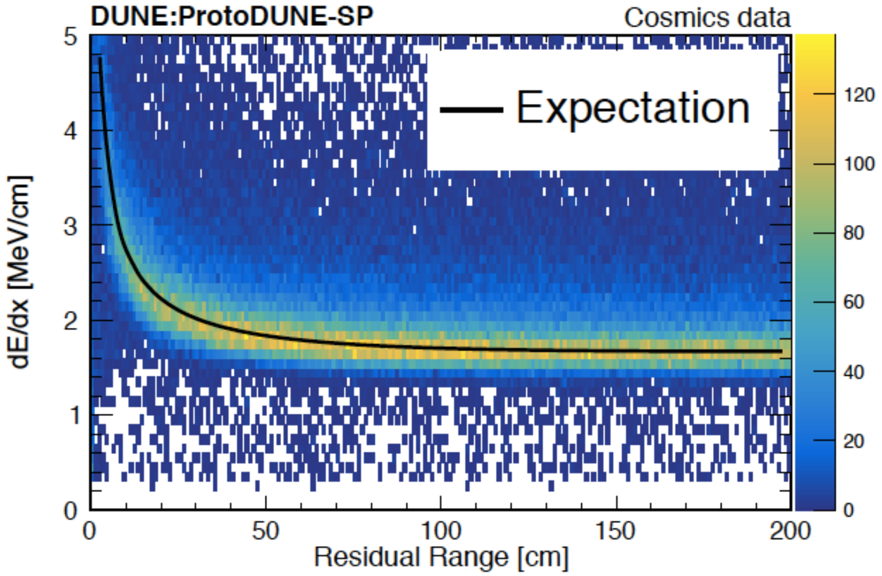
6 GeV/c electron candidate



Charge attenuation during drift due to e- capture on impurities



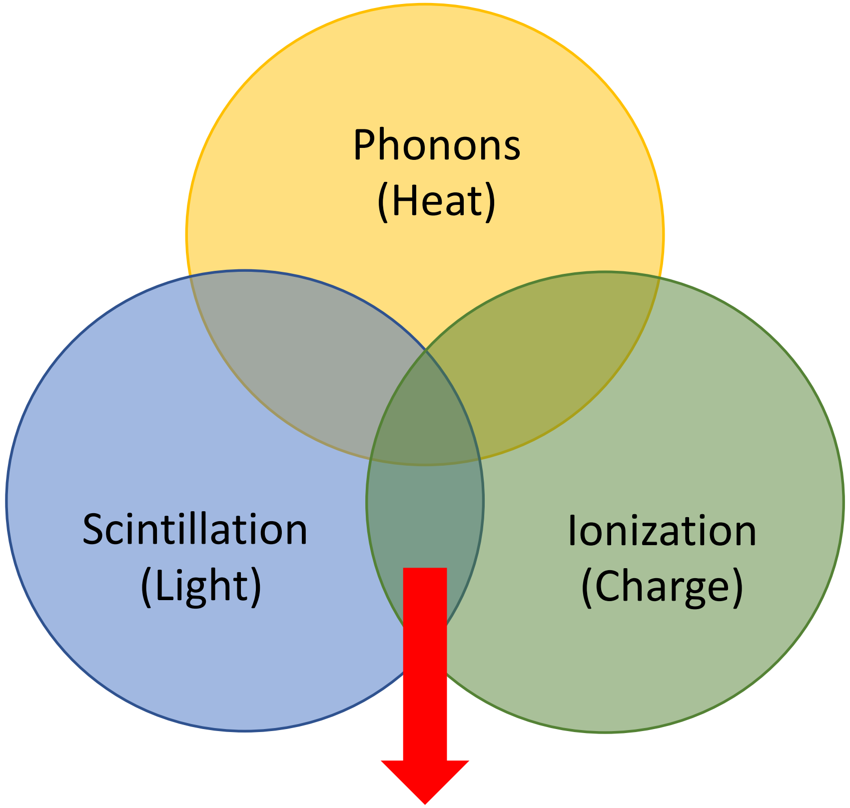
6 GeV/c pion candidate



dE/dx allows for particle identification

Liquefied noble gas TPCs for Dark Matter

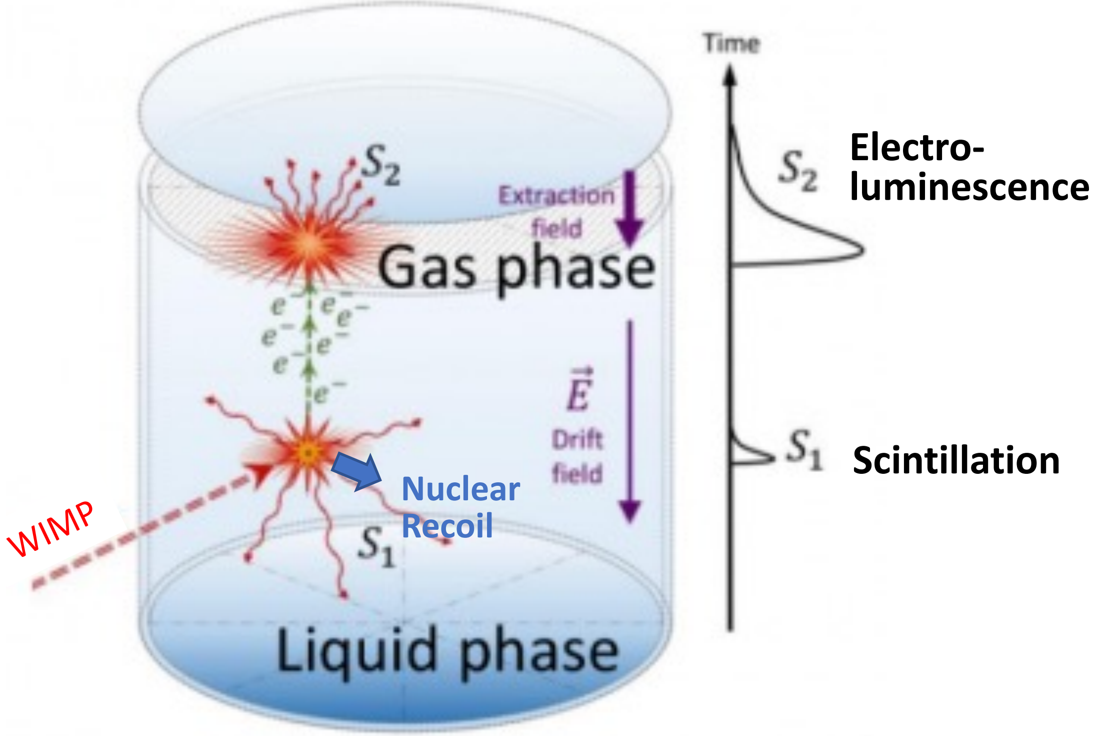
→ 2nd semester lectures by Davide Franco



LAr or LXe TPCs!

NR Energies: **<100 keV**

Dual-Phase TPCs for Dark Matter



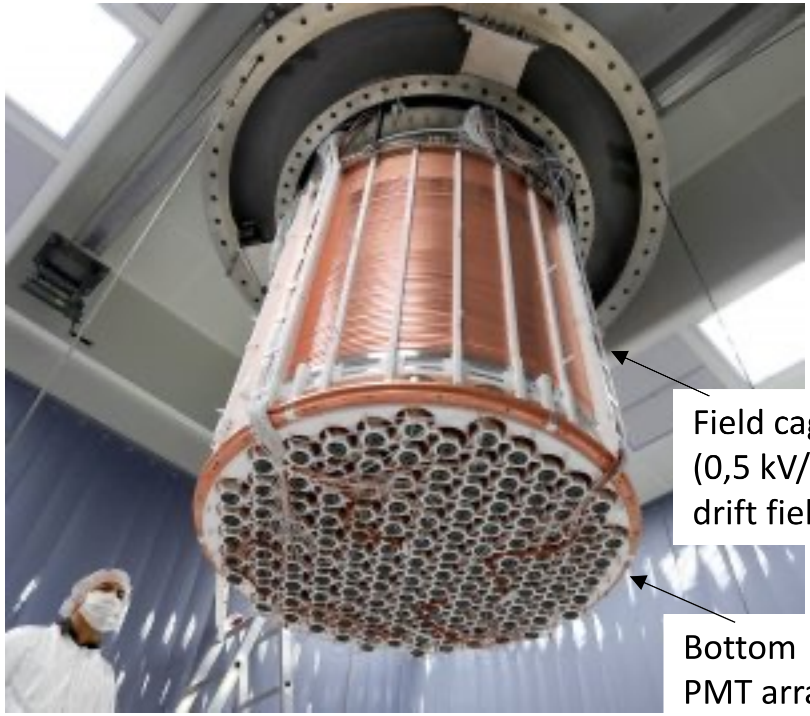
- 3D position reconstruction
- Energy
- Background rejection from S1/S2 (and S1 pulse shape in LAr), event topology

Liquid Xenon TPC for DM: XENON

http://www.xenon1t.org

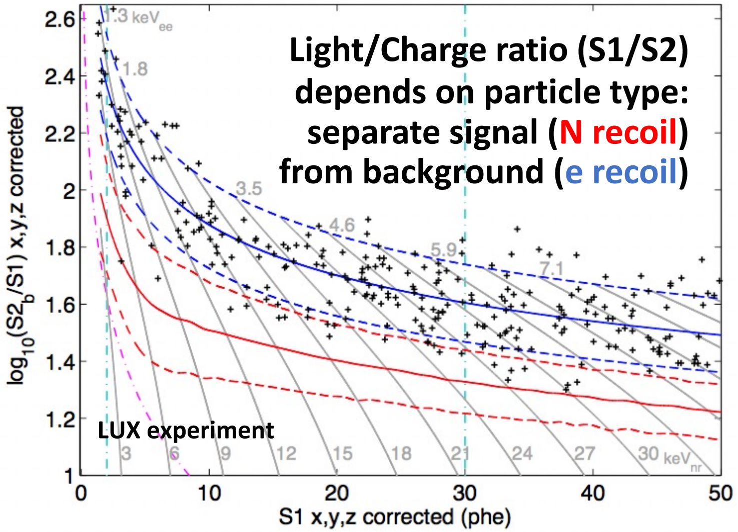
3500 kg of **LXe** (1.3 ton fid.)

@Laboratori Nazionali
del Gran Sasso, Italy



Field cage
(0,5 kV/cm
drift field)

Bottom
PMT array



Light/Charge ratio (S1/S2) depends on particle type: separate signal (N recoil) from background (e recoil)

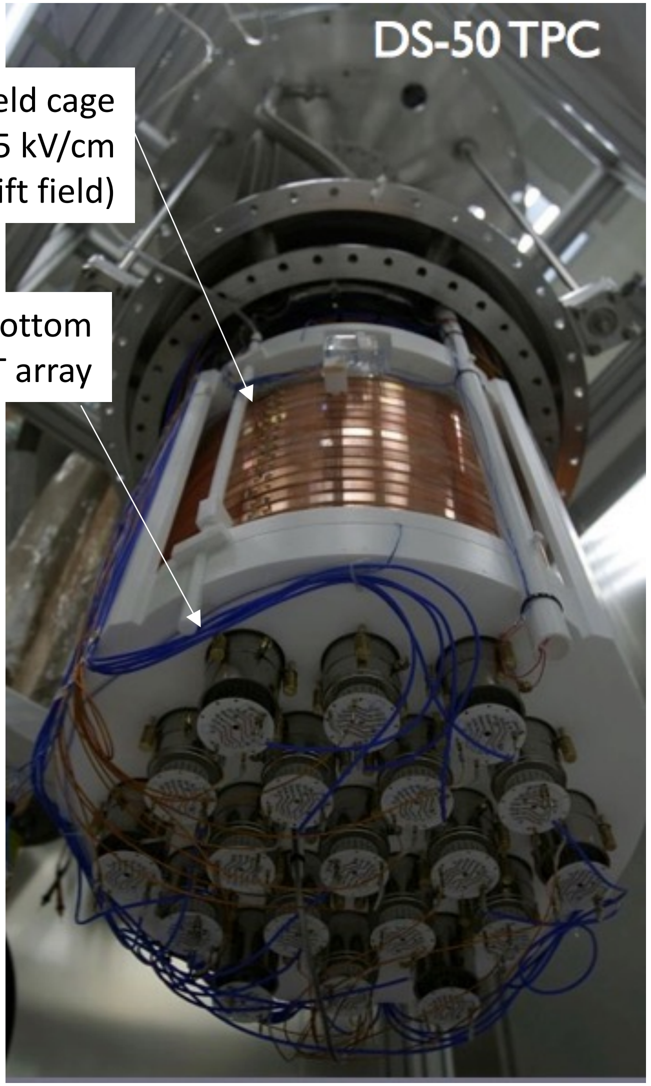
XENON-1t sets the strongest exclusion limits for WIMP mass > 6 GeV

LAr TPC for DM: DarkSide

http://darkside.lngs.infn.it

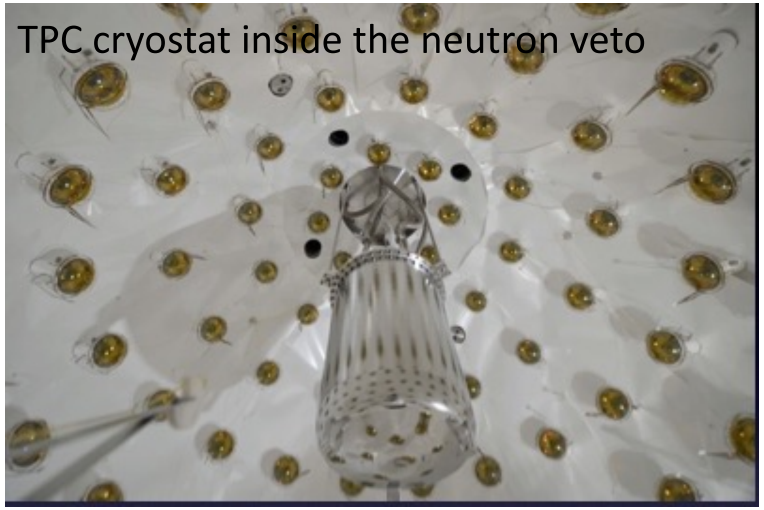
50 kg of **LAr** (36.9 kg fid.)

@Laboratori Nazionali
del Gran Sasso, Italy

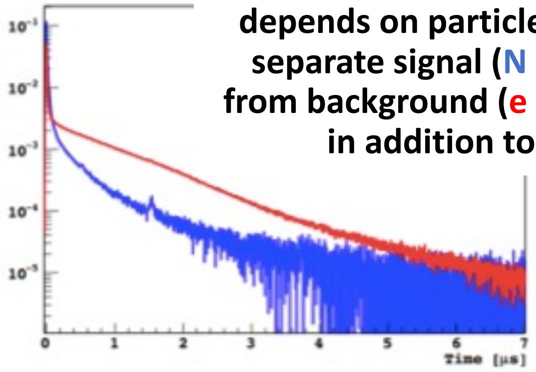


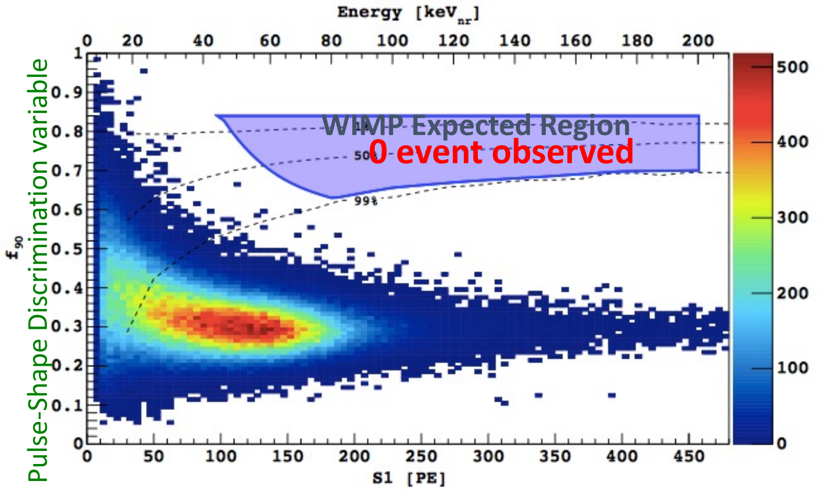
Field cage
(0,5 kV/cm
drift field)

Bottom
PMT array


TPC cryostat inside the neutron veto

Scintillation pulse shape (long/short τ component) depends on particle type: separate signal (N recoil) from background (e recoil) in addition to S1/S1

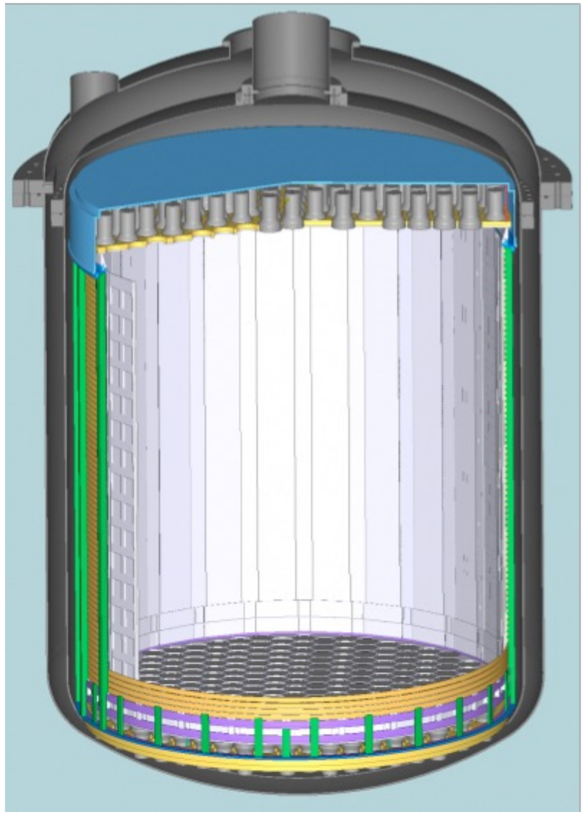




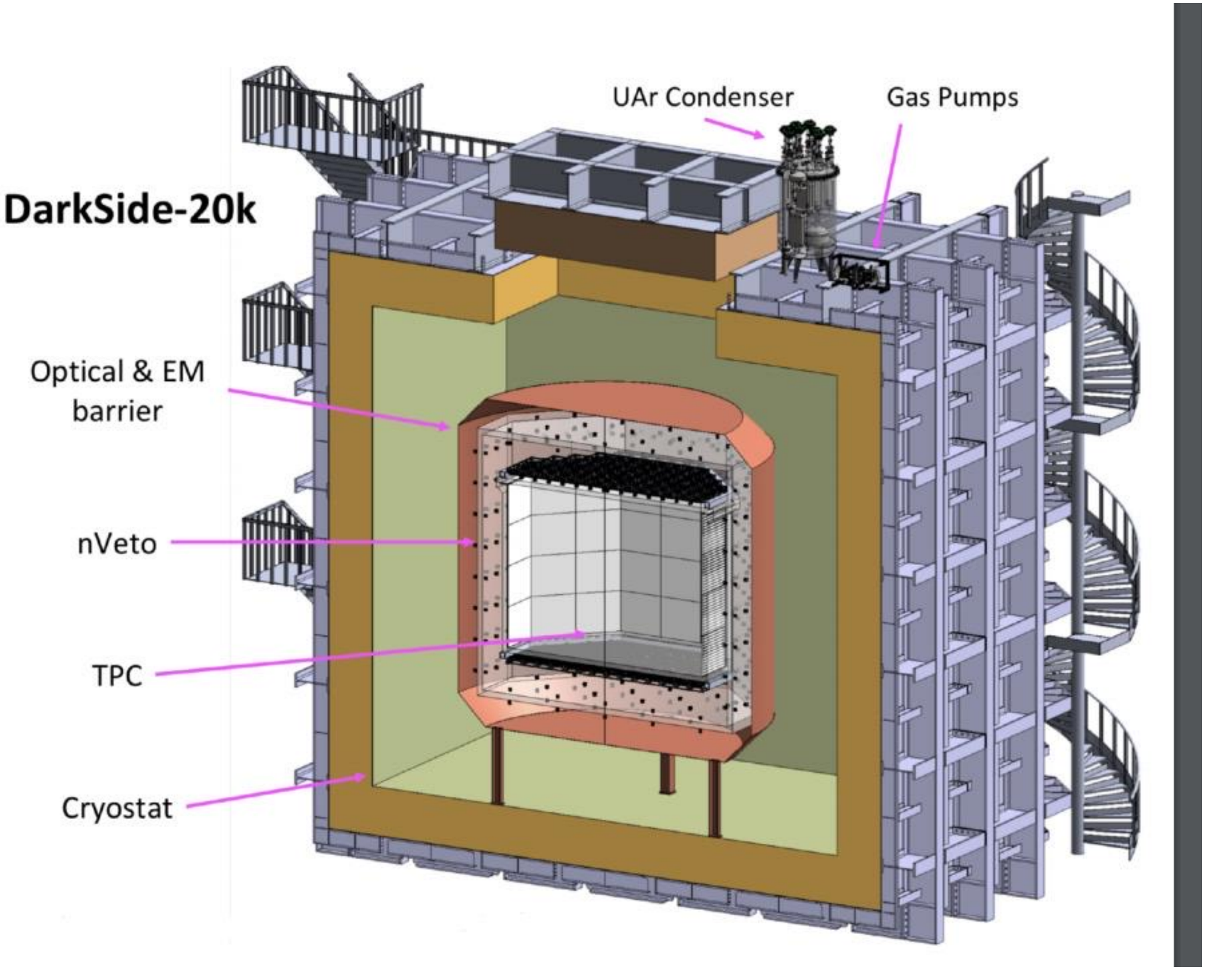
Demonstrated background-free technology scalable to large mass

Direct Searches for Dark Matter: the future

Dual-Phase Noble Liquid TPCs → Larger Mass ➔ sensitivity x10



XENONnT (8 t)



DarkSide-20k (20 t) ; ARGO (300 t)

Summary on cryogenic detectors

Bolometers

- Convert incident radiation to a temperature change
- Absorber: low C ; Thermistor: high α=dR/dT (doped semiconductors, superconductor TES)
- Benefit from low Temperature operation
- Used in cosmology and (astro)particle physics

Liquefied noble gases

- Scintillation + Ionization
- Large mass TPCs with 3D reconstruction + calorimetry + PID
- Used for Neutrino physics, Direct Dark Matter Searches

Exercise 1

Suppose you want to build a high performance bolometer based on a cubic thermo-element (0.45mm on a side) made of gallium-doped germanium connected to the heat sink via two cylindrical thin brass leads, each 1cm long. The bolometer is to be operated at $T = 2.7$K.

Assume also that the detector is blackened so that its quantum efficiency is $\eta = 0.55$ (all other detector properties are unaffected by this process).

The thermal conductance G between the bolometer pixel and heat sink depends on the thermal conductivity κ, wire cross-section A and length L as $G = \kappa A/L$. The value of κ at the operating temperature is 2×10^{-2} W cm^{-1} K^{-1}.

The thermal noise power depends on quantum efficiency and thermal conductance as

$$NEP_T = \frac{(4k_B T^2 G)^{1/2}}{\eta}$$

To obtain a good performance, suppose that you want the detector to have a thermal-noise limited NEP_T of 4.5×10^{-15} W Hz$^{-1/2}$. Calculate the conductance G of the cylindrical leads, and hence their radius in order to achieve this performance.

(reminder : $k_B = 1.38 \times 10^{-23}$ J K^{-1})

(adapted from https://home.strw.leidenuniv.nl/~brandl/DOL/Ex7_2018.pdf)

Exercise 2

Compute the number of detected scintillation photons and ionization electrons when a 1 GeV muon interacts in a Liquid Argon TPC at a distance of 3m from the anode plane.

The drift field is E_{drift}=500 V/cm and the electron lifetime is 3 ms.

The excitation/ionization ratio is 0.21. We will assume $N_\gamma=N_{ex}$ and $N_e=N_i$ and neglect recombination effects*.

The photodetector coverage is 10% and their QE 20%.

(* the recombination of ionization electrons with ions producing additional scintillation photons can be as large as 50% at this value of E_{drift}. We will not consider it in this exercise.)

End of the Detector lectures

Don’t hesitate to contact us if you have questions!
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tonazzo@in2p3.fr