CUORE Cryogenic System Design

Angelo Nucciotti
Dip. di Fisica " G. Occhialini", Univ. di Milano-Bicocca
and INFN, Sezione di Milano-Bicocca, Italy

Outline

- **neutrinoless double beta decay**
- **thermal detectors**
- **the Cuoricino experiment**
- **the CUORE experiment**
  - design criteria and requirements
  - cryostat design
  - Dilution Unit and Pulse Tubes
  - static thermal analysis
  - 300K-4K cool down
  - base temperature cool down

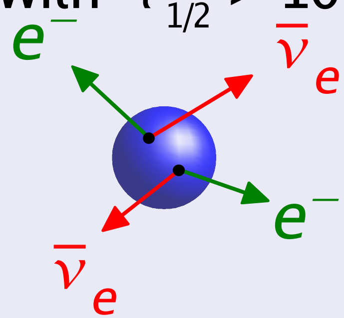
IOP/BCC Meeting on Cryocoolers, 17th March 2008, Southampton UK

Introduction: double beta decay

second order nuclear weak decay
of even-even nuclei
in *A* even multiplets:
^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe ...

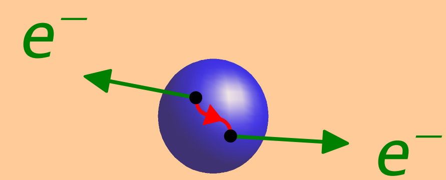
$\beta\beta$-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- allowed in Standard Model
- observed with $\tau_{1/2} > 10^{19}$ years



$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

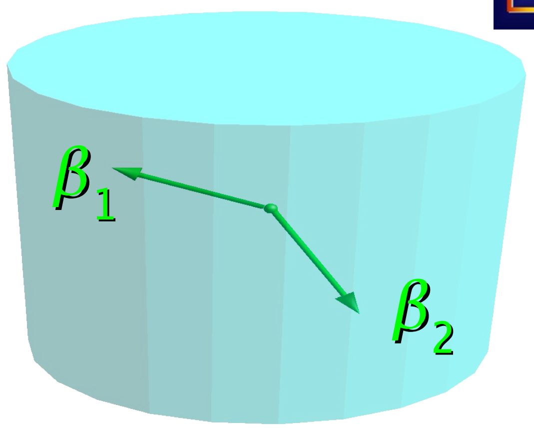
- not allowed in Standard Model
- expected $\tau_{1/2} > 10^{25}$ years
- only one *criticized* evidence to date



- **$\beta\beta$-0ν:implications**
  - neutrino must have **mass** to allow helicity non conservation $\Rightarrow \Delta H=2$
  - neutrino must be a **Majorana particle** to allow lepton number non conservation $\Rightarrow \Delta L=2$

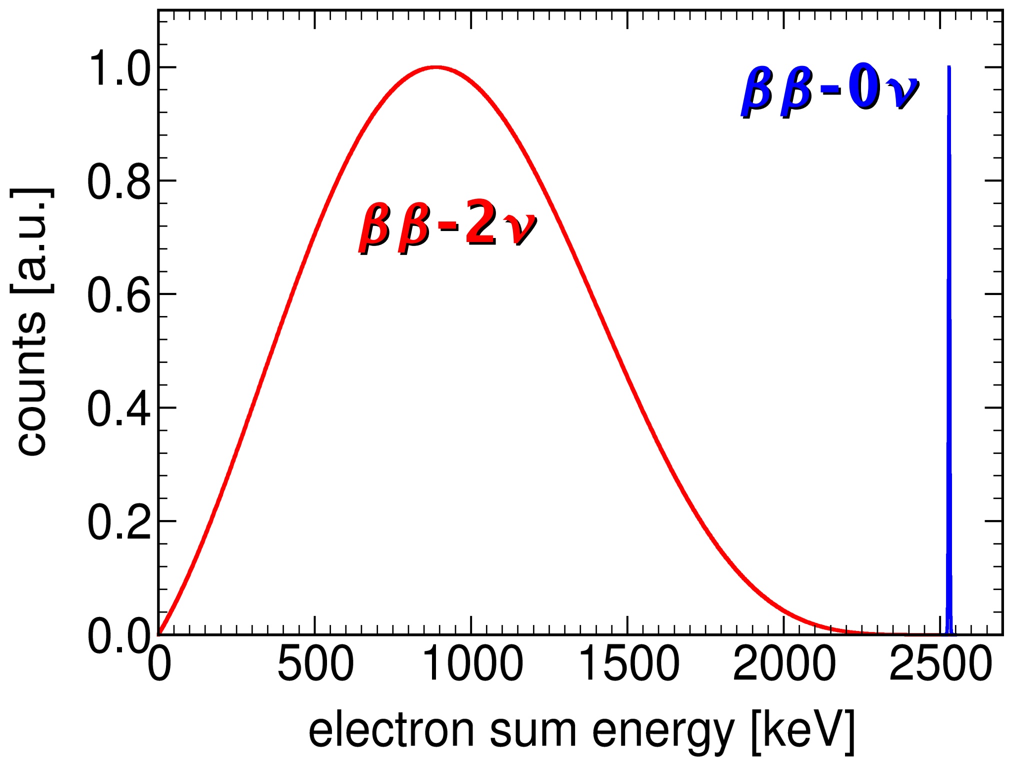
$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{matrix} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{matrix}$$

Experimental approaches for $\beta\beta$-0ν



Source ⊆ detector (calorimetry)

- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ▸ $\beta\beta$-0ν signature: a peak at transition energy $Q_{\beta\beta}$
- scintillators, bolometers, semiconductor diodes, gas chambers
  - ▲ large masses
  - ▲ high efficiency
  - ▲ many isotopes possible
- depending on technique
  - high energy resolution (bolometers, semiconductors)
  - moderate topology recognition (Xe TPC, semiconductors)



Source ≠ detector ...

Experimental sensitivity for $\beta\beta$-0ν

$$m_\nu \propto \sqrt{1/\tau_{1/2}^{0\nu}}$$

Experimental sensitivity to $\tau_{½}^{0\nu}$

- with **no** decay observed
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{½}$ at 1σ

$$\sum(\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

measuring time [y]

detector mass [kg]

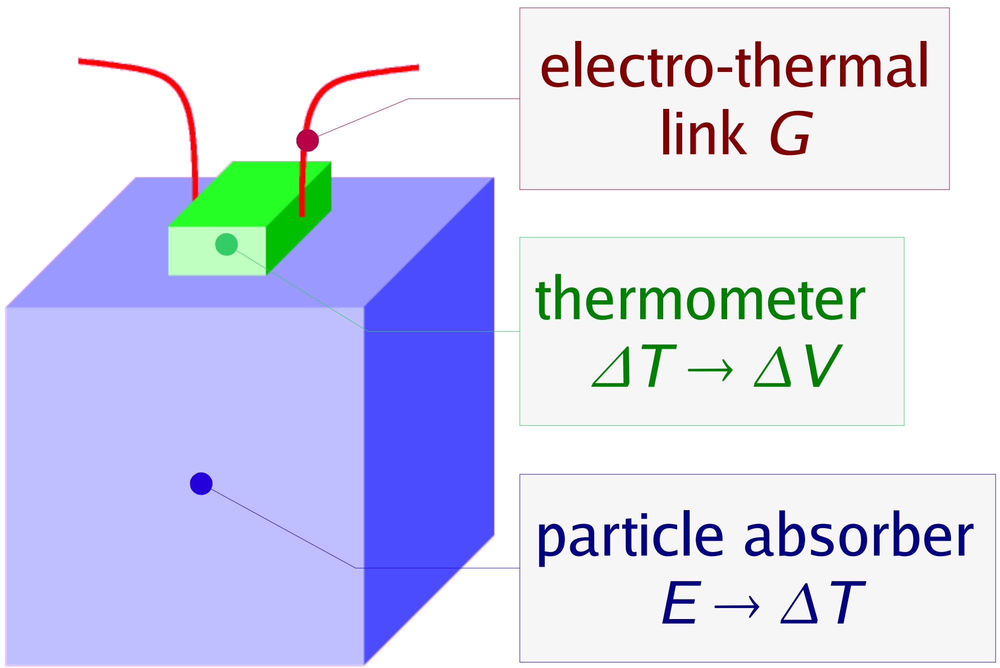
detector efficiency

isotopic abundance
atomic number

energy resolution [keV]

specific background [c/keV/kg/y]

Cryogenic detectors as calorimeters



Detection Principle

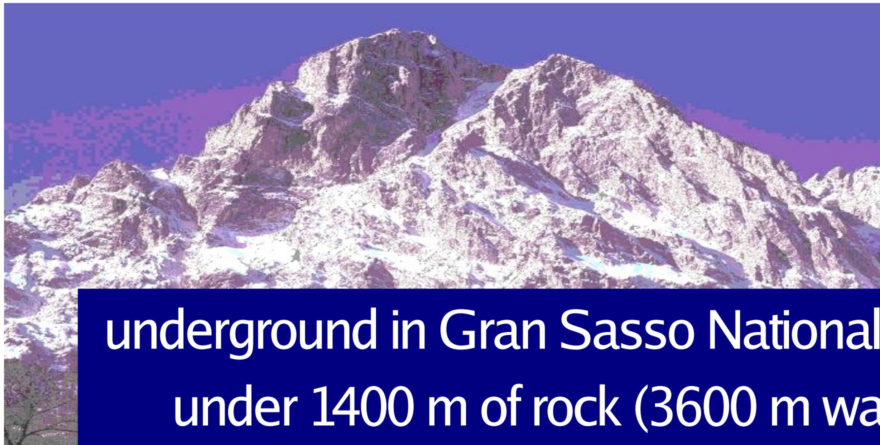
- complete energy thermalization
  - ⇨ **calorimetry**
- $\Delta T = E/C$ C thermal capacity
  - ⇨ low C
    - ⇨ low T (i.e. $T \ll 1$K)
    - ⇨ dielectrics, superconductors
- $\Delta T(t) = E/C\, e^{-t/\tau}$ with $\tau = C/G$ and G thermal conductance
- ultimate limit to sensitivity: statistical fluctuations of internal energy U
  $\langle \Delta U^2 \rangle = k_B T^2 C$

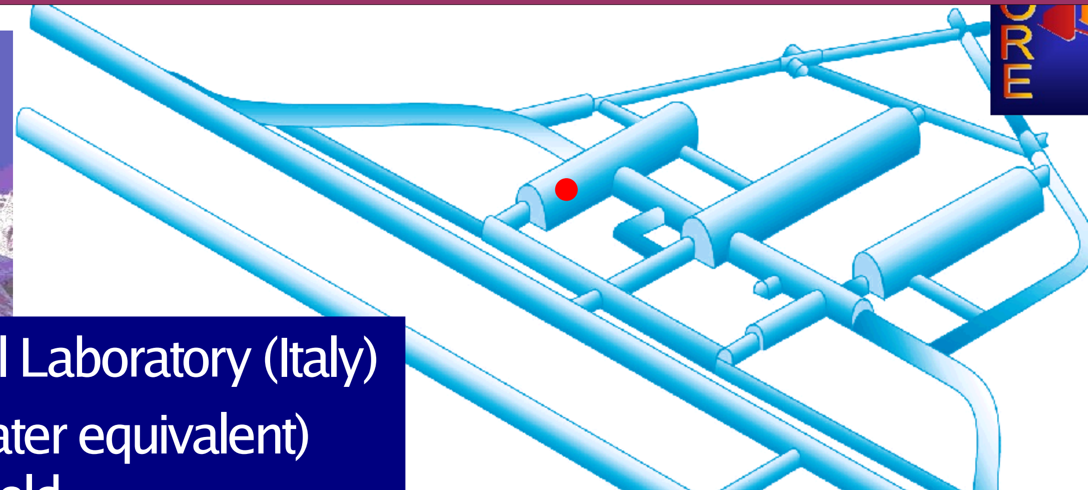
Properties

▲ high energy resolution
▲ large choice of absorber materials
▲ true calorimeters
▼ only energy and time informations
▼ slow $\tau = C/G \sim 1$ s

- example: 760 g of TeO_2 @ 10 mK
  $C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K
  1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu$K
  $\Rightarrow \Delta U \sim 10$ eV
  $G \sim 4\times10^{-9}$ W/K
  $\Rightarrow \tau = C/G \sim 0.5$ s

CUORICINO experiment set-up in LNGS

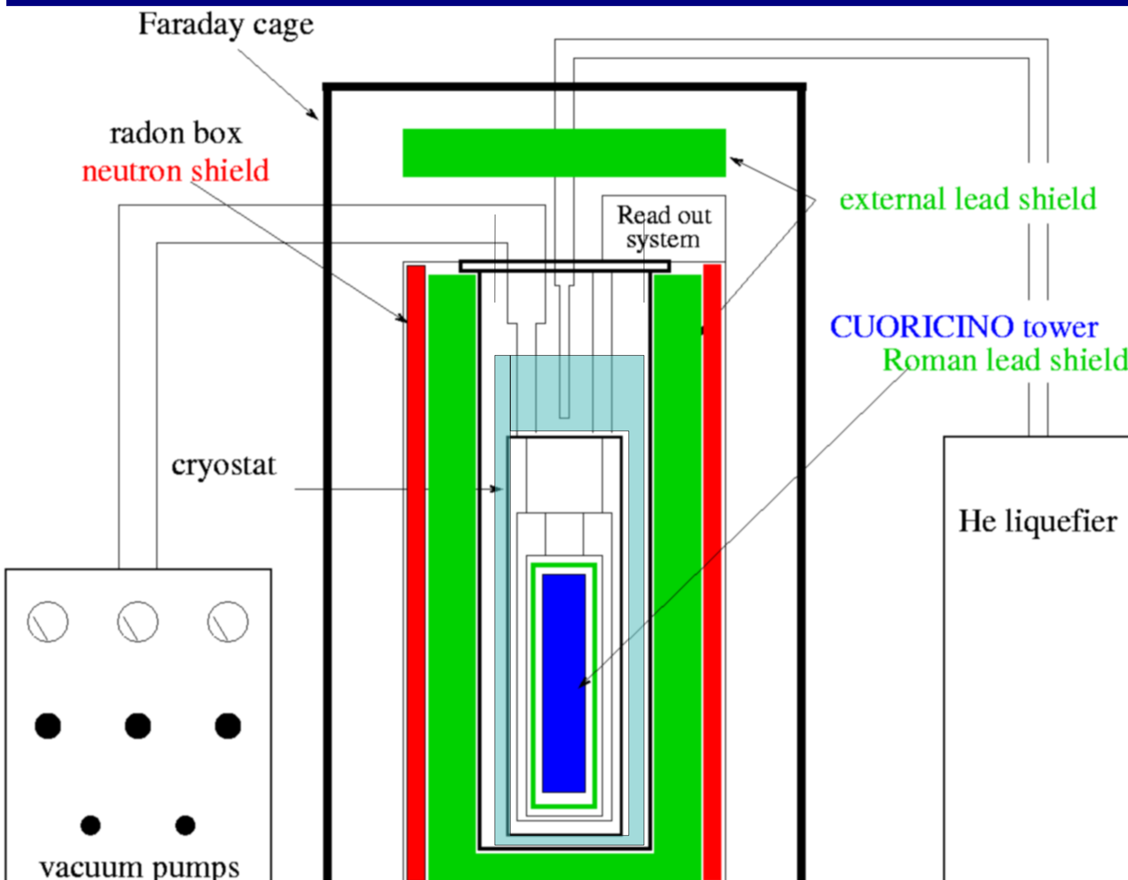


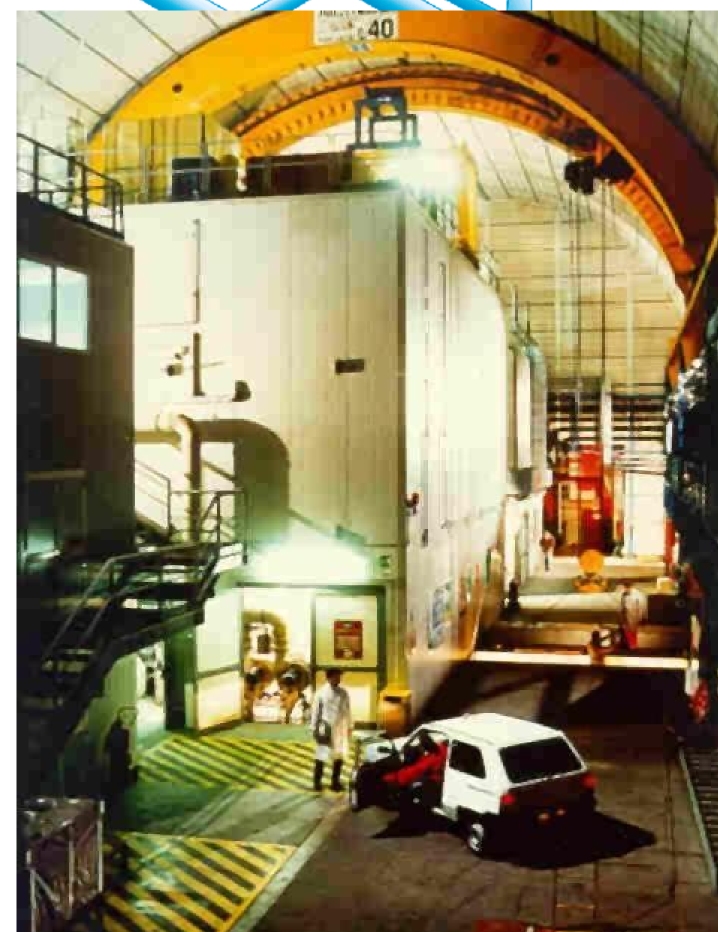


underground in Gran Sasso National Laboratory (Italy)

under 1400 m of rock (3600 m water equivalent)

⇒ cosmic rays shield

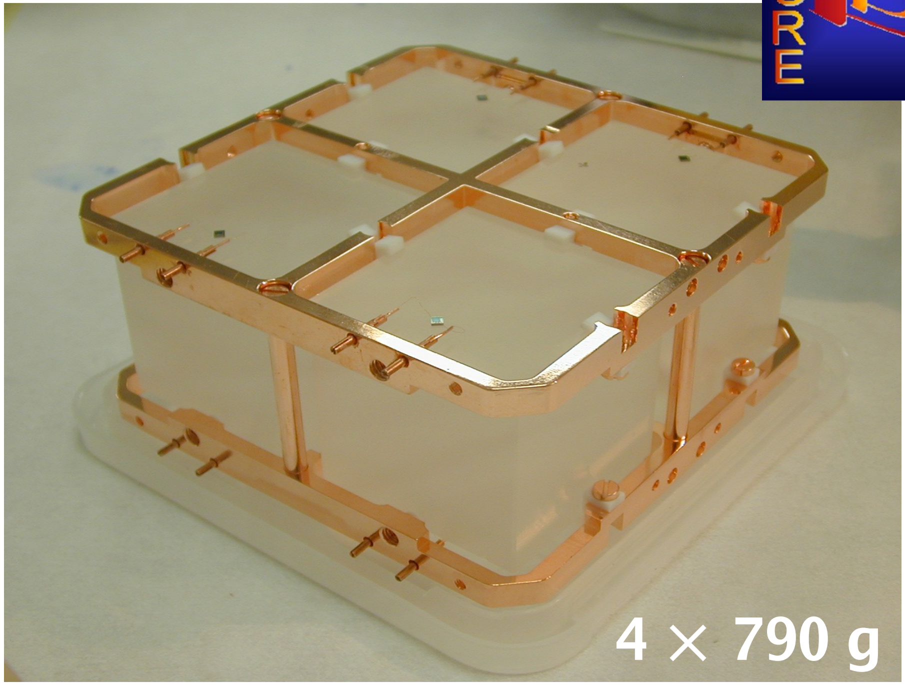


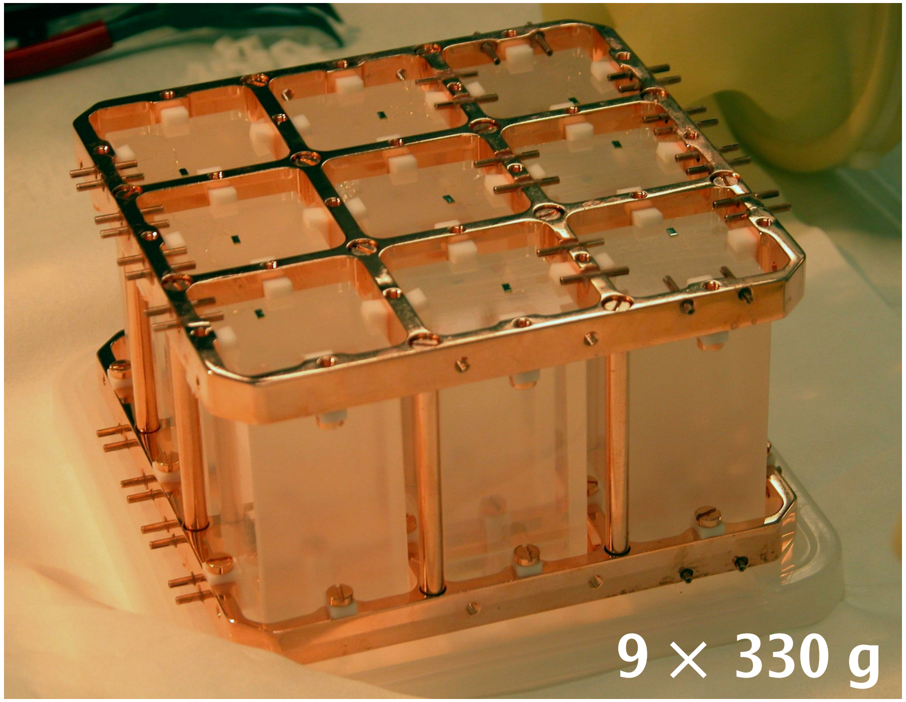


The CUORICINO experiment / 1

TeO_2 thermal calorimeters

- **Active isotope ^{130}Te**
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 keV
  - "short" predicted half life
    $\langle m_\nu \rangle \approx 0.3$ eV $\Leftrightarrow$ $\tau_{1/2}^{0\nu} \approx 10^{25}$ years
- **Absorber material TeO_2**
  - low heat capacity
  - large crystals available
  - radiopure



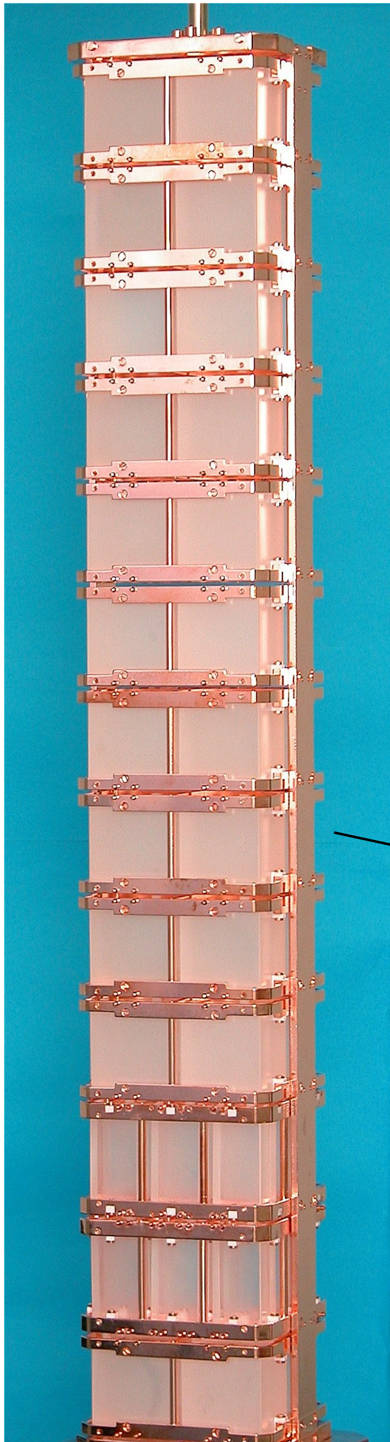


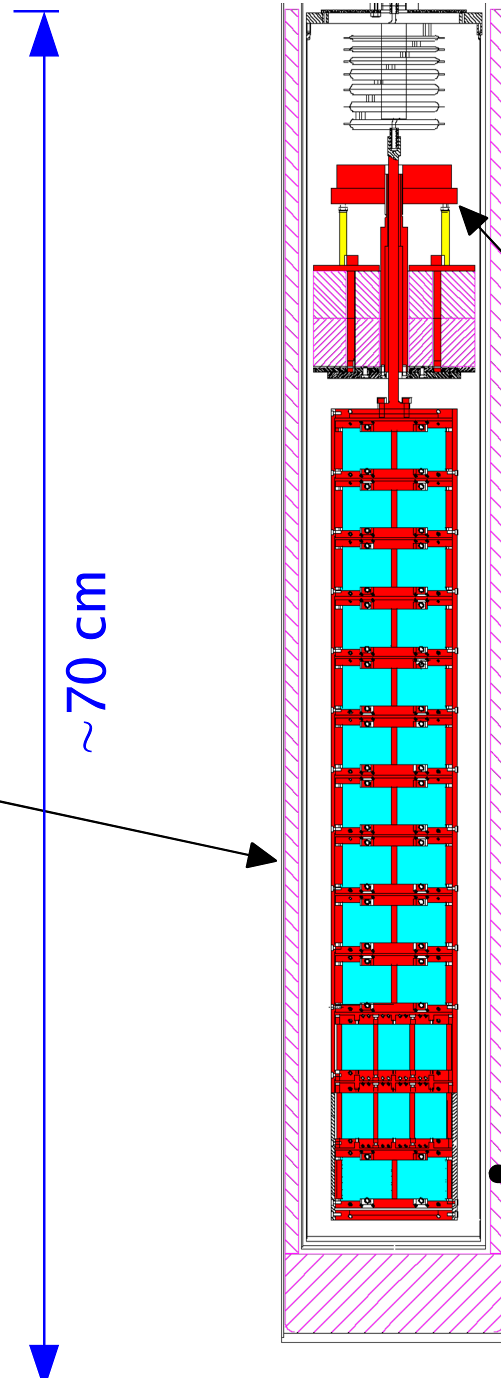
CUORICINO experiment @ LNGS

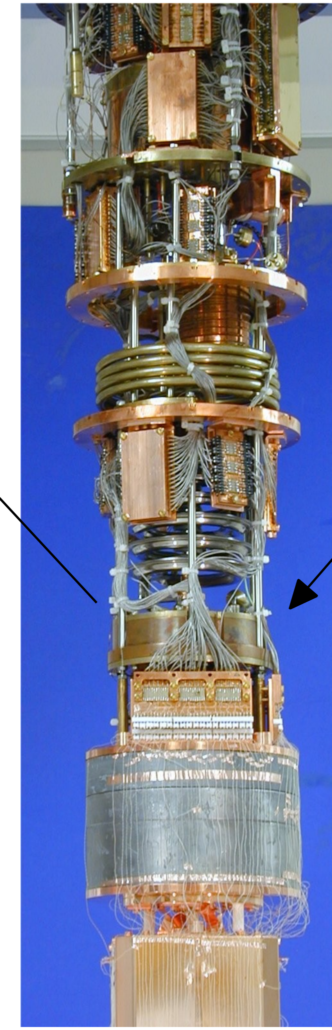
- 62 TeO_2 detectors in the ***tower*-like structure** foreseen for **CUORE**
- 11 modules: 4 × **790 g** crystals
- 2 modules: 9 × **330 g** crystals
- **total mass 41 kg**
- **intermediate size $\beta\beta$ experiment**
- **test for radioactivity**

The CUORICINO experiment / 2

Cuoricino *tower*: 62 TeO_2 crystals







mixing chamber
$T \approx 6$ mK

roman Pb shielding (1 cm lateral)

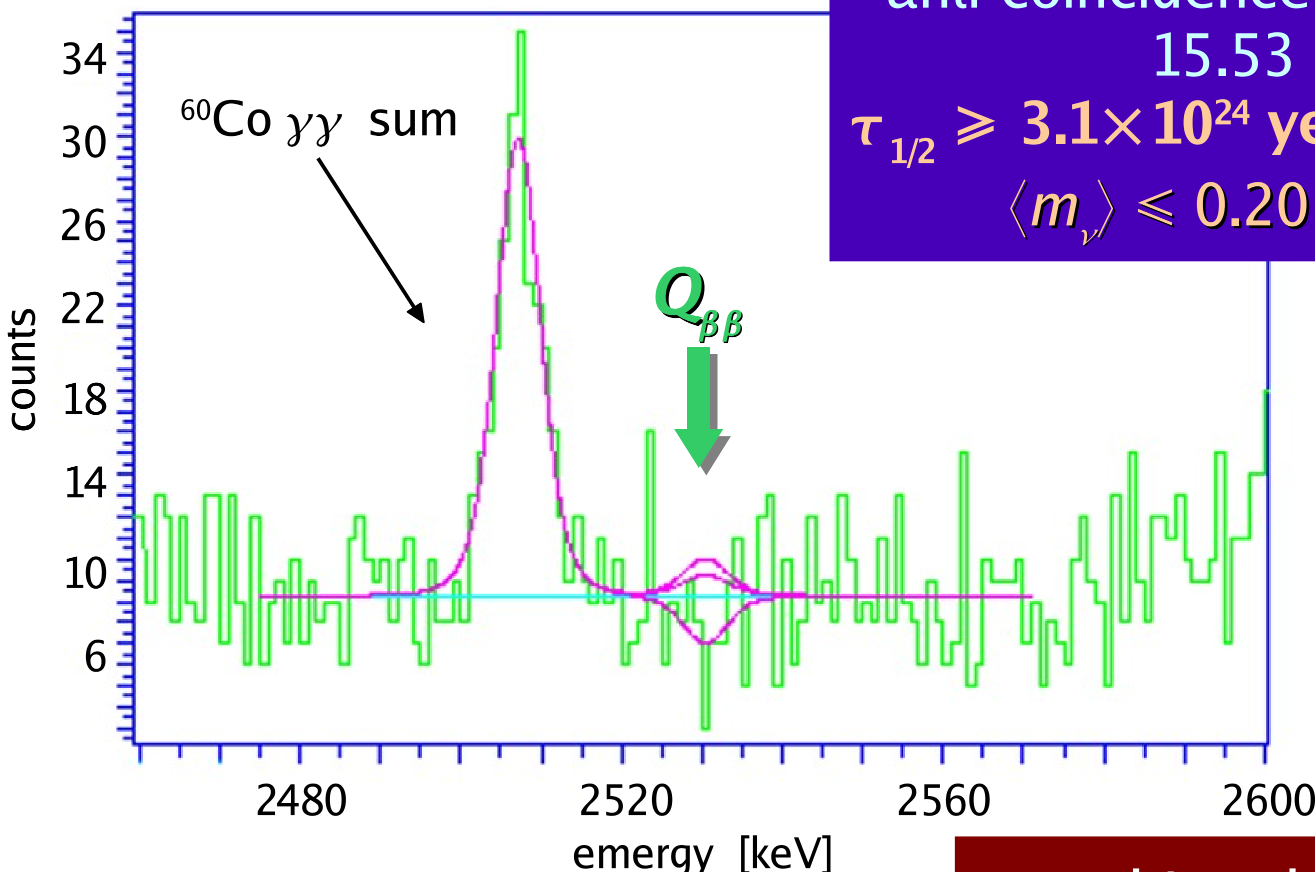
external shields:

- 10 cm Pb + 10 cm low act Pb
- neutron shield: B-polyethylene
- nitrogen flushed anti-radon box

The CUORICINO experiment / 3

- running since 2003
- total exposure 15.53 kg×y of ^{130}Te
- energy resolution FWHM $\Delta E = 8$ keV at $Q_{\beta\beta}$ (σ_E=1.3‰)

anti-coincidence sum spectrum
15.53 kg×y
$\tau_{1/2} \geqslant 3.1\times10^{24}$ years at 90% C.L.
$\langle m_\nu \rangle \leqslant 0.20 \div 0.68$ eV



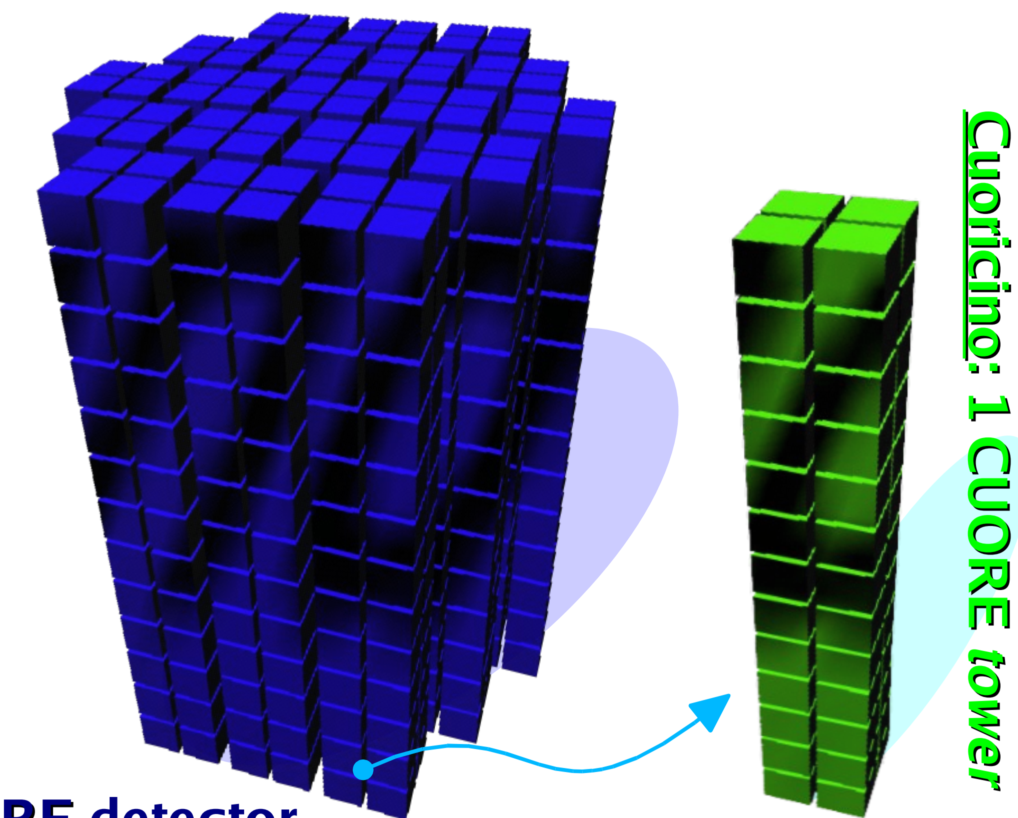
- probing the debated 0.4 eV claim
- most sensitive running experiment

The CUORE experiment

Cryogenic Underground Observatory for Rare Events

- array of 988 natural TeO_2 crystals 5×5×5 cm^3 (750 g) @ LNGS
  - **740 kg TeO_2** granular calorimeter ⇒ **200 kg of ^{130}Te**
- **aim**: improve a **factor 10** the Cuoricino sensitivity on $\langle m_\nu \rangle$
  - improve a factor 100 the sensitivity on $\tau_{1/2}$
- CUORE is the only fully approved second generation $\beta\beta$ experiment

International collaboration:
Italy, US, Spain, China, UK



CUORE detector
19 *towers* – 52 detectors each

CUORE Cryostat design and sensitivity for $\beta\beta$-0ν

- to improve a factor 100 the sensitivity on $\tau_{1/2}$
  - increase mass M ×18
  - reduce background bkg ÷100
  - increase measuring time t_{meas} ×5

Cryostat dimensions
Cooling powers
→ detector mass [kg]

Cryogenic system reliability and duty cycle
→ measuring time [y]

$$\sum(\tau^{0\nu}_{1/2}) \propto \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

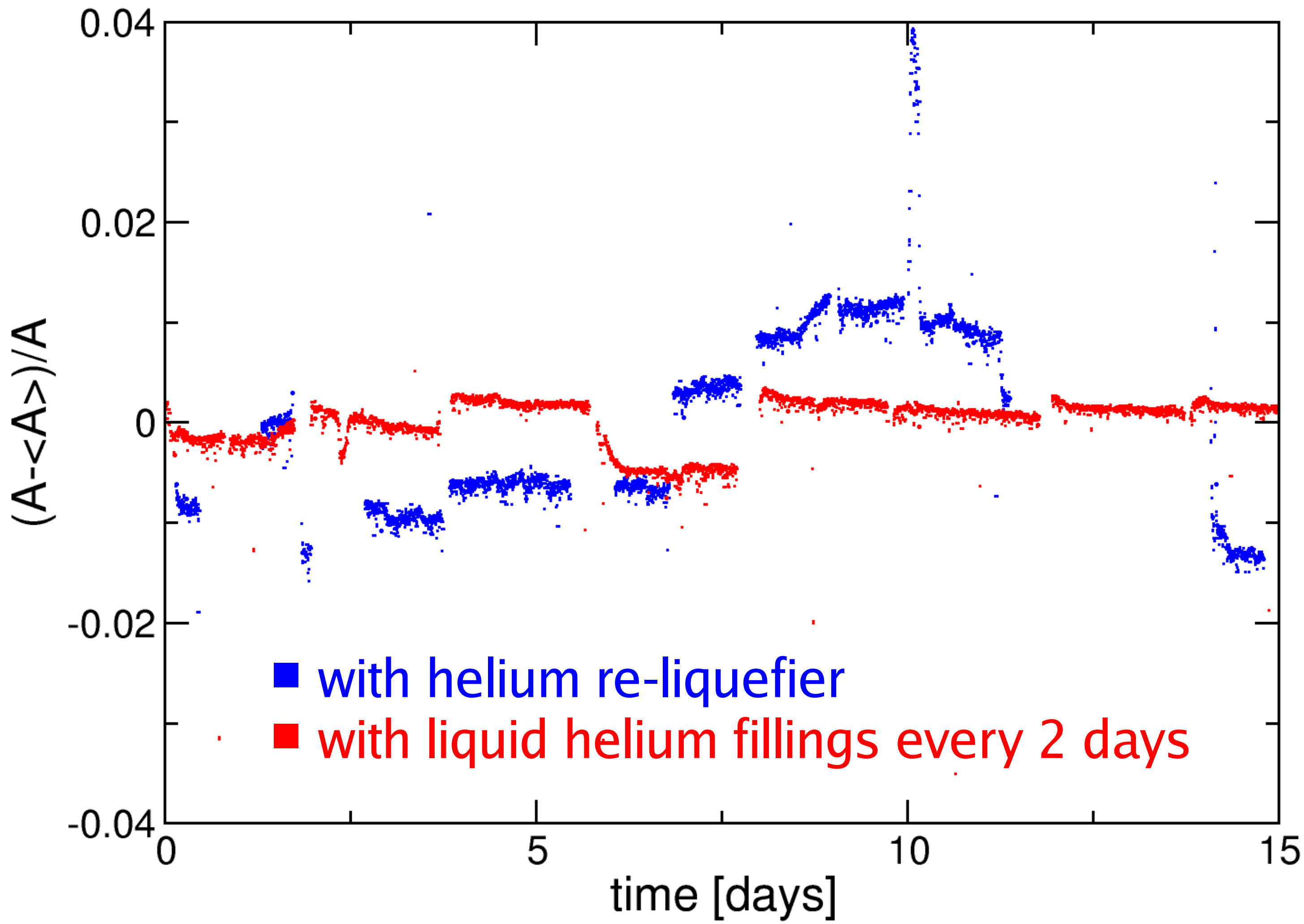
energy resolution [keV]
↑ **Cryostat system stability**
Mechanical vibrations

specific background [c/keV/kg/y]
↑ **Cryostat material selection**
Lead shieldings against environmental radioactivity

CUORE Cryostat specifications

- **cryogen-free**
  - Pulse Tubes (with spares)
- **base temperature <10mK**
  - high cooling power custom Dilution Unit (DU) without 1K pot
- **dimensions**
  - external: $\oslash \leq 1687$, $h \leq 3100$
  - experimental space: $\oslash \geq 900$, $h \geq 1385$
- **low radioactivity experimental space**
  - strict material selection
    - only selected pure copper
    - other selected materials only in small amounts (SS, TiAlSn...)
  - large cold lead shielding close to detector
  - small amount of Multi Layer Insulation (MLI)
- **heavy load support**
  - detector: total mass about 1 ton
  - lead shielding: total mass about 10 ton
- **low mechanical vibration input on detector**
  - independent detector suspension

Detector stability and duty-cycle in Cuoricino

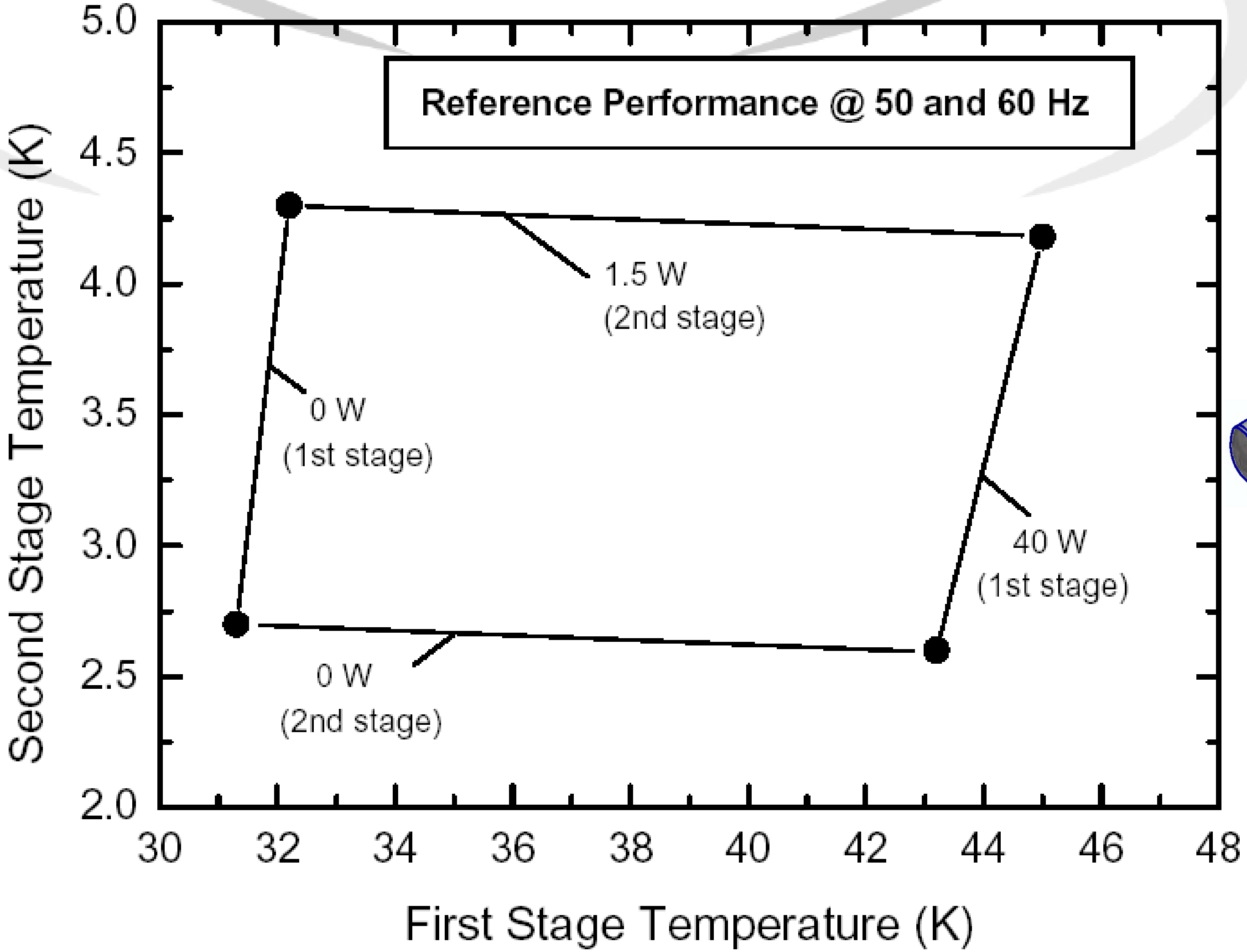


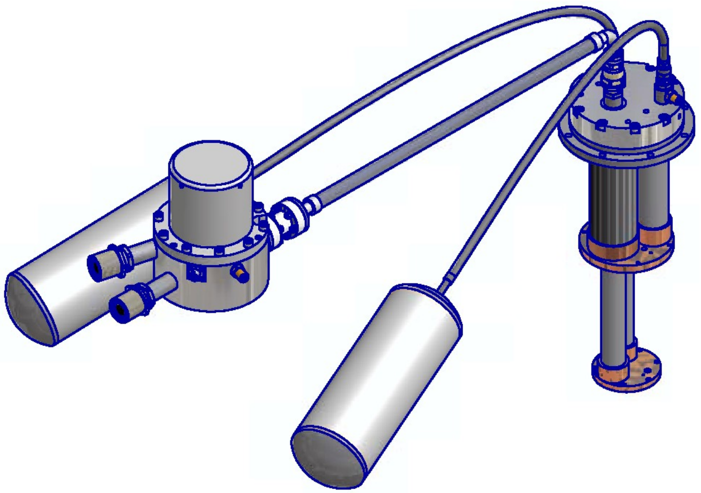
- use of LHe disfavoured because of
  - safety issues
  - LHe cost and logistic

▸ pulse tubes

Cryorefrigerators: Pulse Tubes

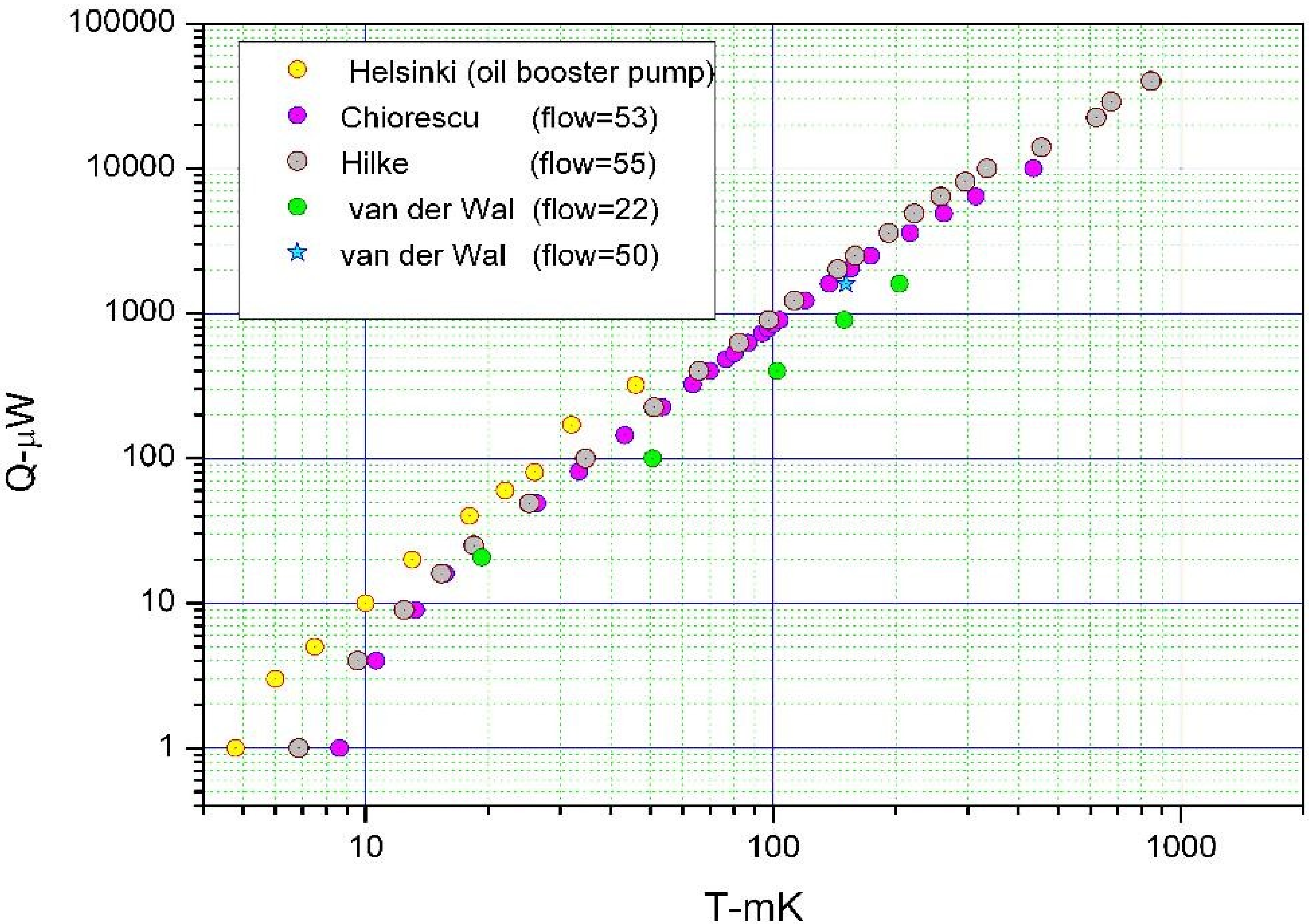
- **5** Pulse Tubes **PT415 with remote motor** (from Cryomech)
  - P = 1.5W (40W) @ 4.5K (44K)
  - use no more than 4: one PT should be kept as spare





Cryorefrigerators: dilution unit

- **high cooling power cryogen-free custom Dilution Unit**
  - DRS-CF-2000 from Leiden Cryogenics
  - P = 5 (>1.5×10^3) μW @ 12 (120) mK
  - T_{base} < 6 mK without loads



Cryo-refrigerators R&D

- High cooling power cryogen-free DU R&D at Leiden Cryogenics
  - first high power cryogen-free DU ever!
  - J-T heat exchanger design
  - ^{3}He pre-cooling heat exchangers on PT
  - construction of heat exchangers is in progress
  - open issues:
    - effect of vibrations on base temperature
- PT415 characterization in Milano
  - cooling power measurements (especially at high T)
  - vibration measurements
  - radioactivity measurements
  - open issues under investigation:
    - rotating valve low vibration mounting
    - cold stage high thermal conductance low vibration coupling

Thermal specifications

Stage	T [K]	Available Cooling power [W]	Cooling Power Budget for Systems: Dilution Unit DU [W]	Suspension [W]	Wiring WS [W]	Calibration DCS [W]	Available to Cryostat
40K	40-50	*1.60E+02*	-	1.00E+01	1.00E+01		1.40E+02
IVC	4-5	*6.00E+00*	4.00E+00	2.00E-01	1.00E+00	3.00E-01	5.00E-01
Still	0.6-0.9	*5.00E-03*	-	1.20E-03	5.00E-04	5.50E-04	2.75E-03
Cold Pl.	0.05-0.1	*2.00E-05*	-	1.00E-05	3.00E-06	1.10E-06	5.90E-06
Mixing Ch.	0.01	5.00E-06	-	1.00E-06	0.00E+00	1.20E-06	2.80E-06

note on **40K and IVC** cooling power:

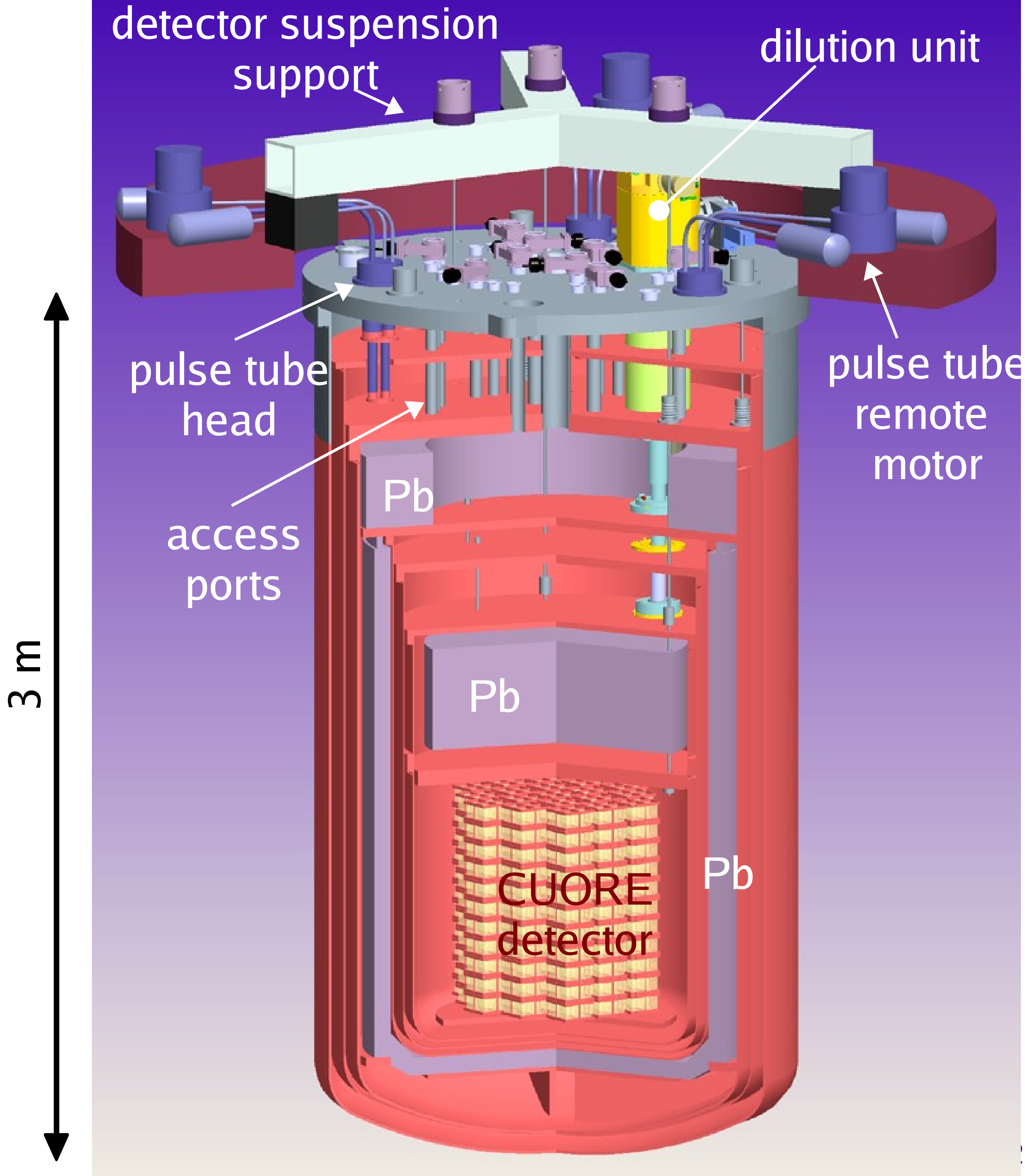
The total cooling power reported here is for 4 Pulse Tubes running at the reference working temperatures of 45K and 4.5K.

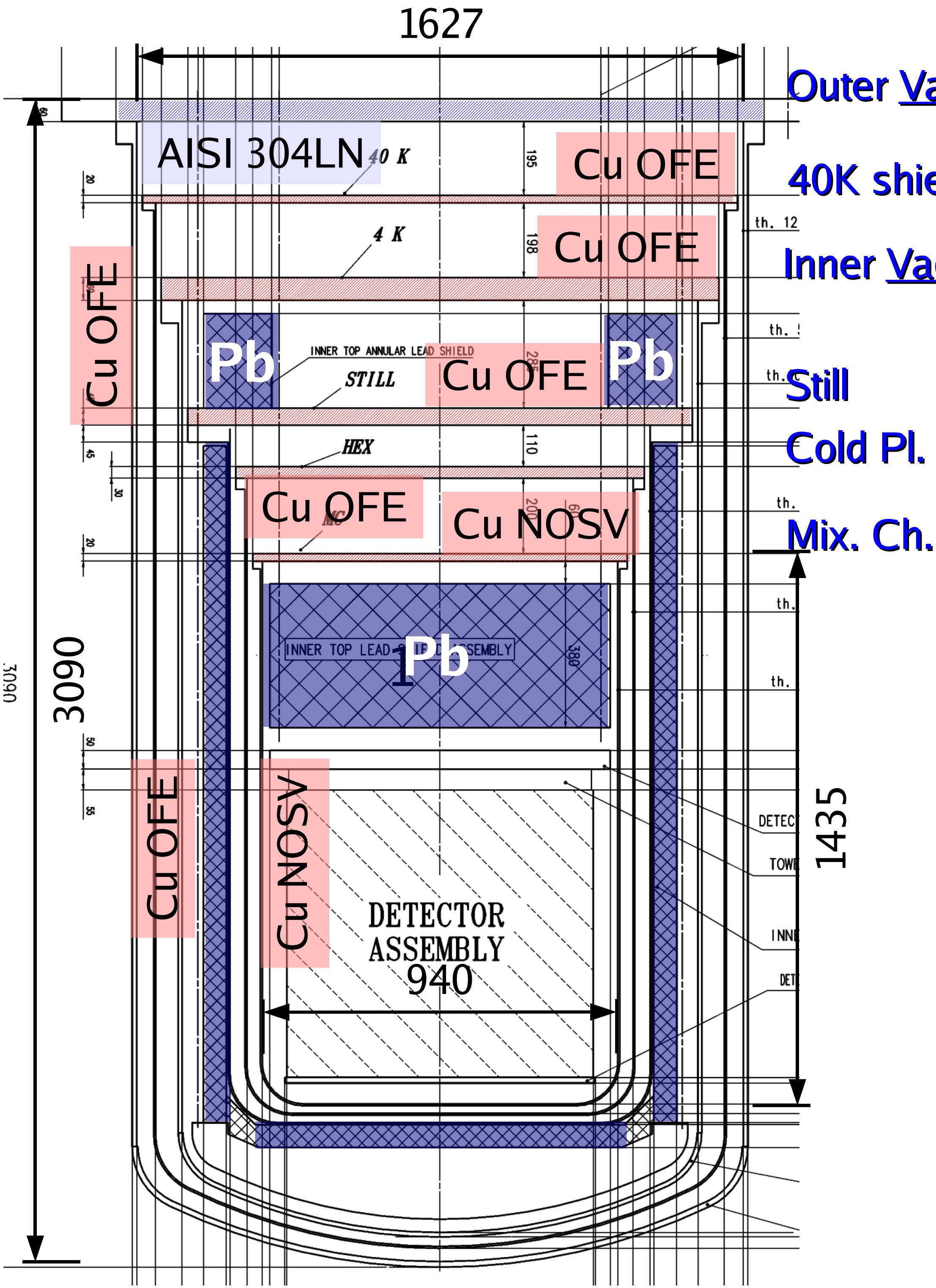
note on **DU Still** cooling power:

The Still cooling power depends on the He3/He4 flow rate (it is about 40mW/(mmole/s)).
The 5mW cooling power mentioned here allows the user to control the flow rate between 0.1 and 4mmole/s by adding extra Joule heating power.

note on **DU Cold Plate** cooling power:

Specification cooling power is 125 microW. The 20 microW cooling power mentioned here is a safe upper limit to avoid side effects on the DU Mixing Chamber temperature.


detector suspension support
dilution unit
pulse tube head
pulse tube remote motor
access ports
Pb
Pb
Pb
CUORE detector
3 m



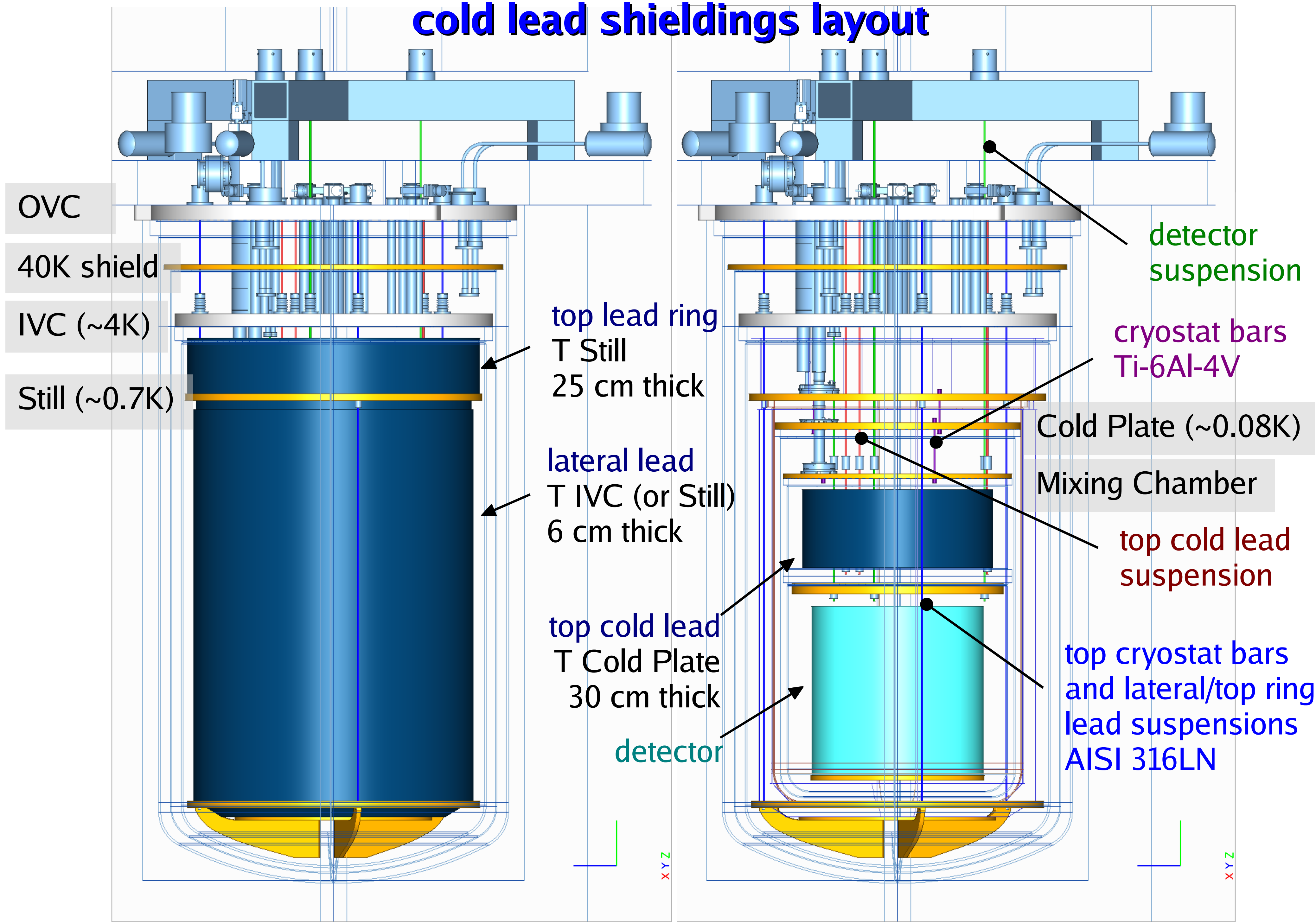
MATERIALS

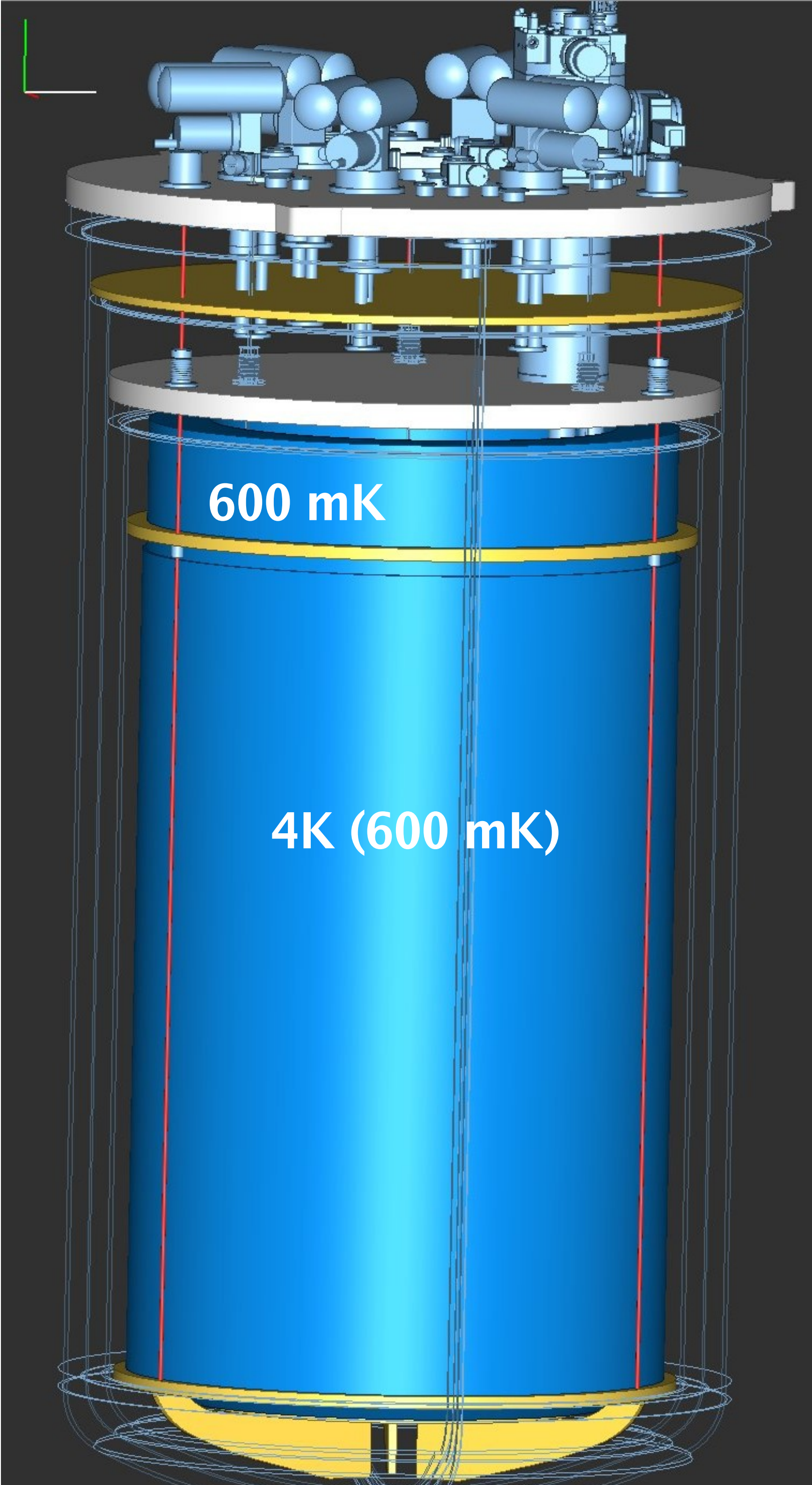
- everything *large* is out of Cu
  - low H2 content Cu for *T*<0.05K
- <u>everything</u> is out Cu inside Pb shield
- exceptions:
  - OVC and IVC top flanges out of 316LN
  - tie rods (316LN and low *G* materials)

COLD LEAD SHIELDINGS

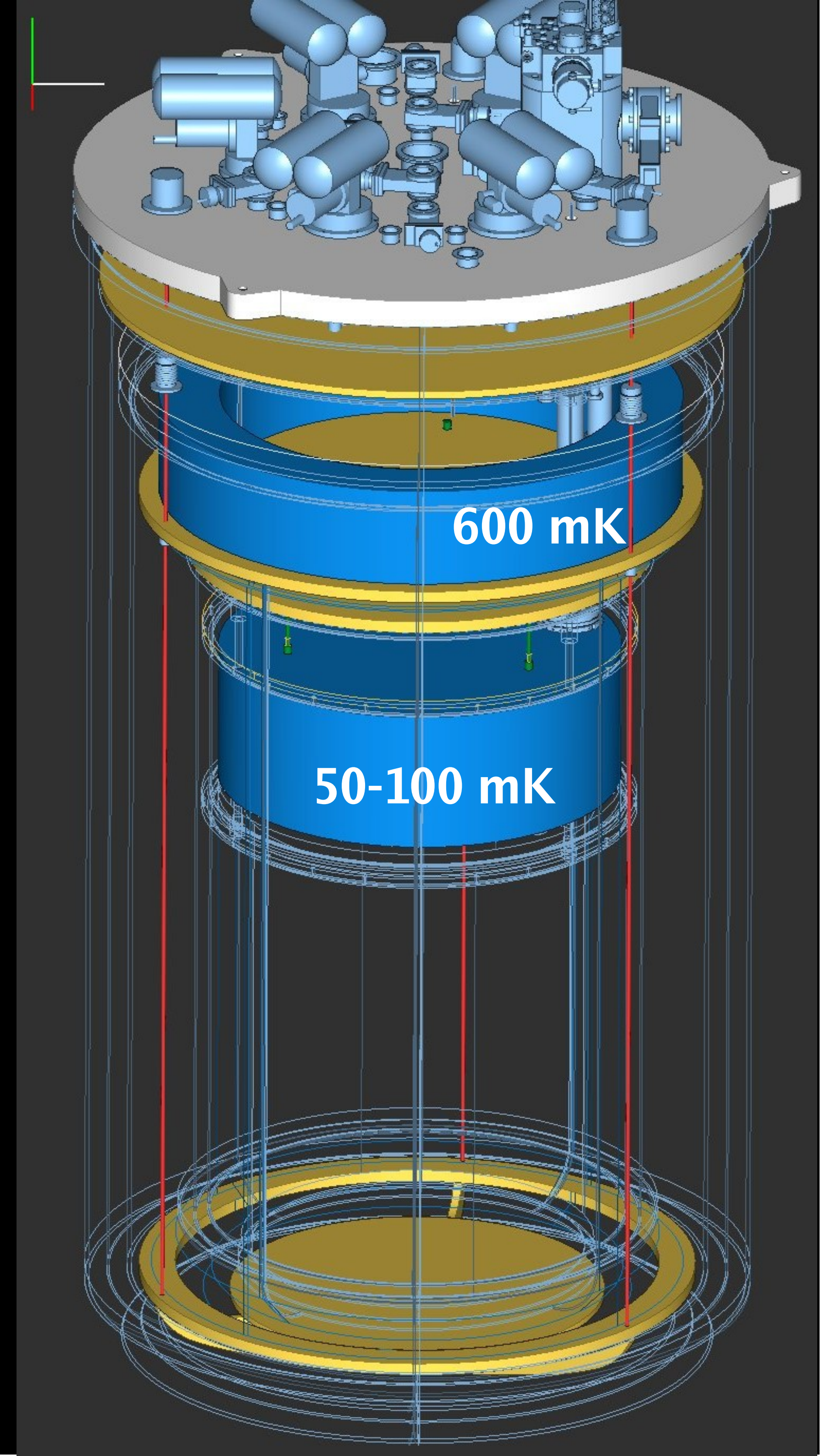
- Top cold Pb disk
  - independently suspended
  - at Cold Plate temperature (or Still?) to minimize heat load on MC
- Top Pb ring at Still temperature
- Lateral Pb at 4K

cold lead shieldings layout

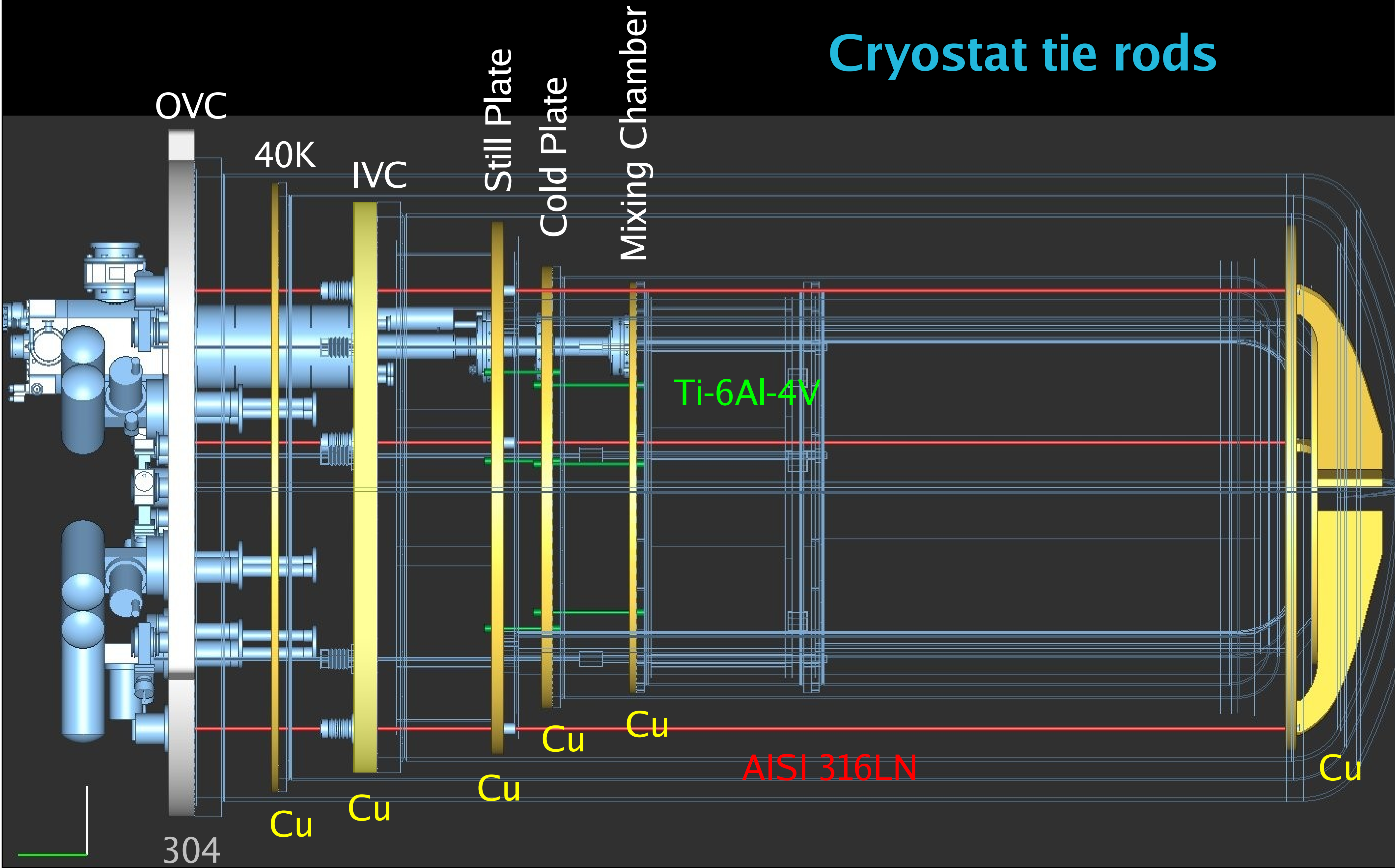




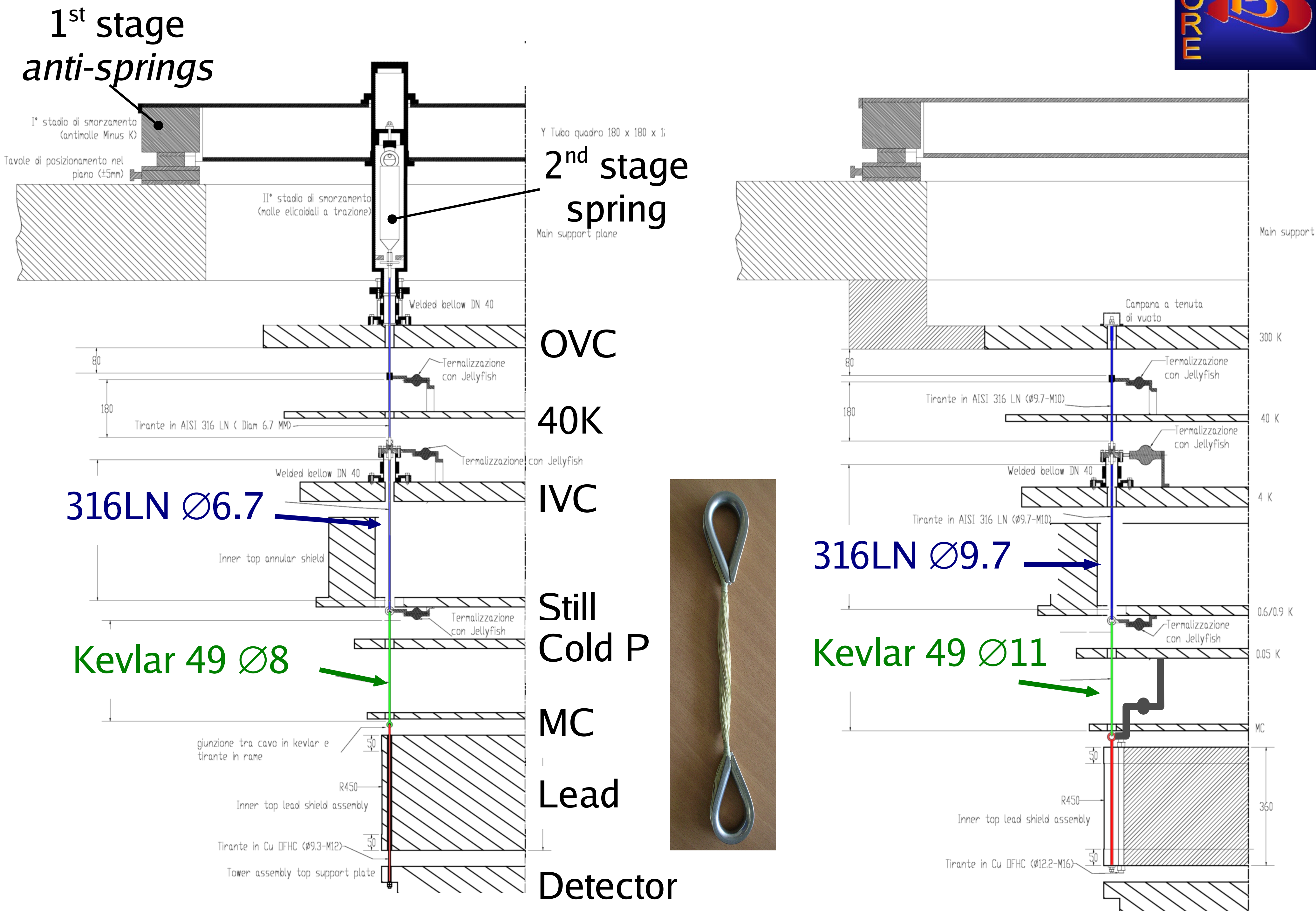
cold lead shieldings



Cryostat tie rods



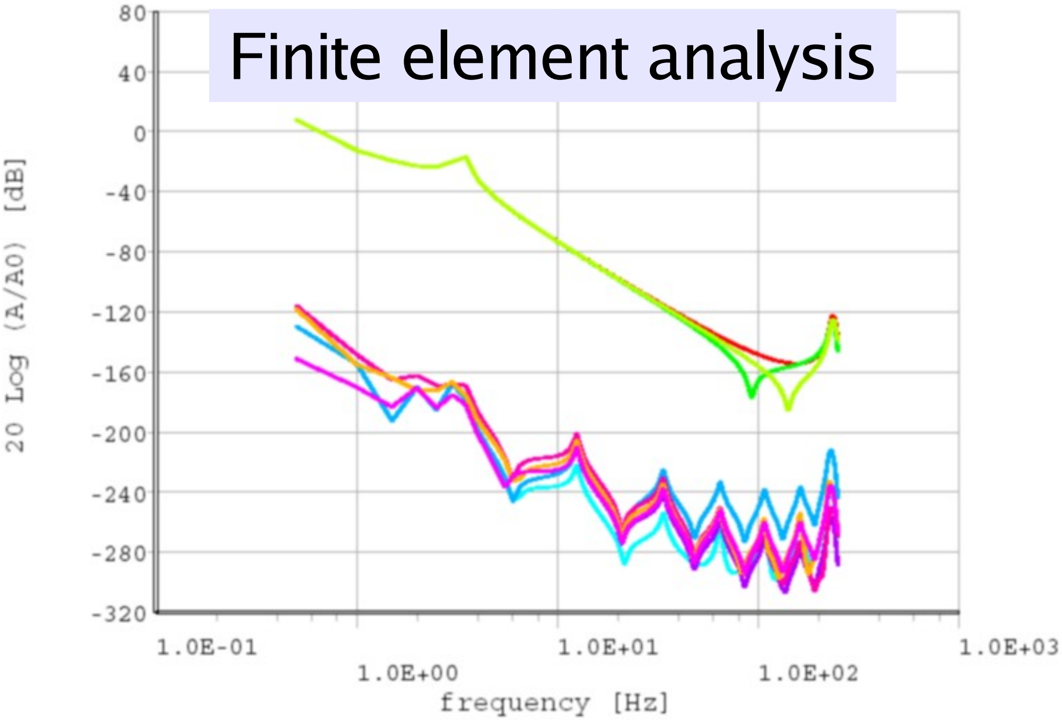
Detector and cold lead shield suspensions / 1



Detector and cold lead shield suspensions / 2

MINUS-K isolator with Negative Stiffness Mechanism

- **Mechanical vibration filter**
  - pendulum ~0.4 Hz
  - two stages longitudinal filter

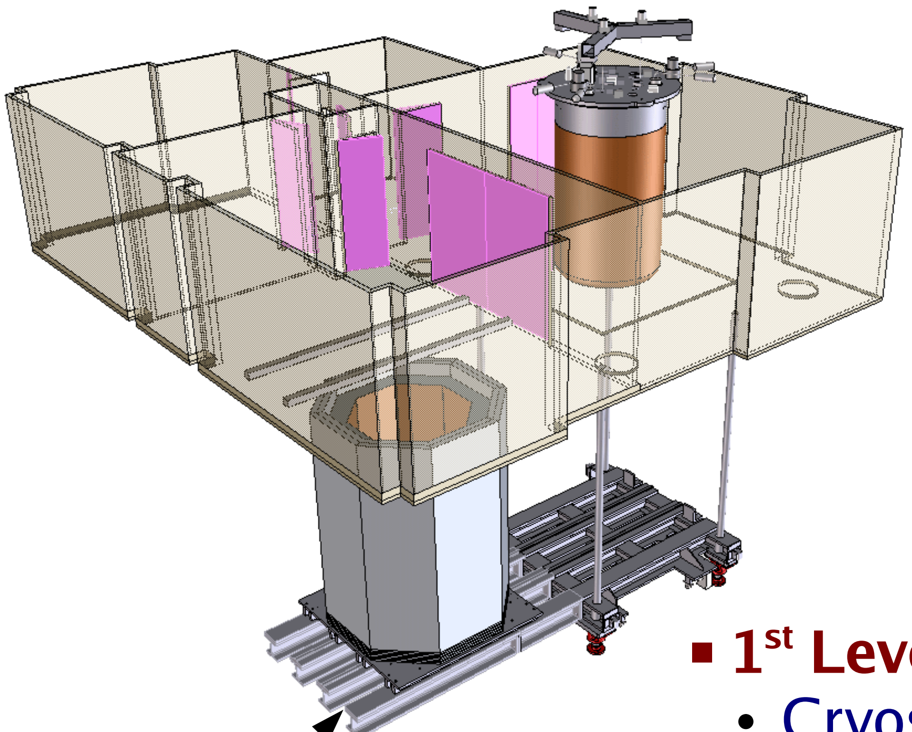


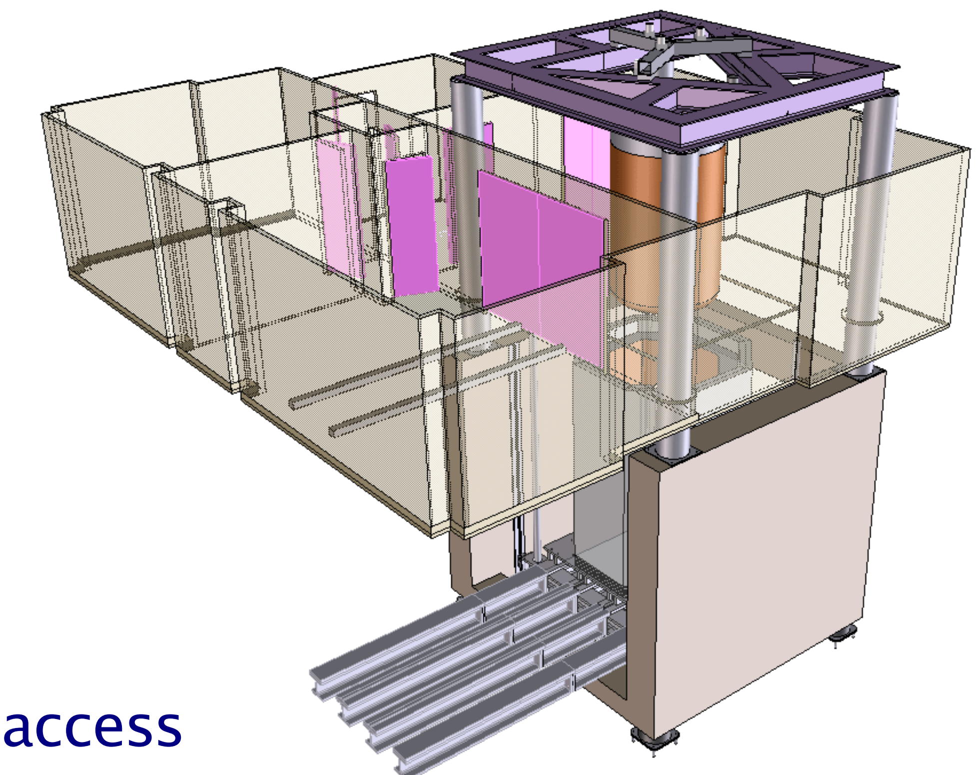
Mass inventory

Vessels	material	mass [kg]	Tot mass [kg]
OVC flange	SS 304L	1122	
OVC shield	Cu OFE	1943	**3065**
40K flange	Cu OFE	308	
40K shield	Cu OFE	681	**989**
IVC flange	Cu OFE	870	
IVC shield	Cu OFE	1152	**2022**
Still flange	Cu OFE	543	
Still shield	Cu OFE	351	**894**
Cold plate flange	Cu OFE	234	
Cold plate shield	Cu OFE	297	**531**
MC flange	Cu NOSV	131	
MC shield	Cu NOSV	270	**401**
Lead shields			
Still top ring	Pb	1718	
Still lateral	Pb	5408	
lead support	Cu OFE	243	**7369**
Cold plate top	Pb	2745	
lead support	Cu OFE	570	**3316**
Detector			
crystals	TeO2	751	
top+bottom	Cu NOSV	285	
frames	Cu NOSV	579	**1615**

External lead shielding and hut

- **2^{nd} Level**
  - Top flange access
  - Suspension access
  - DU Gas Handling
  - Electronics & DAQ



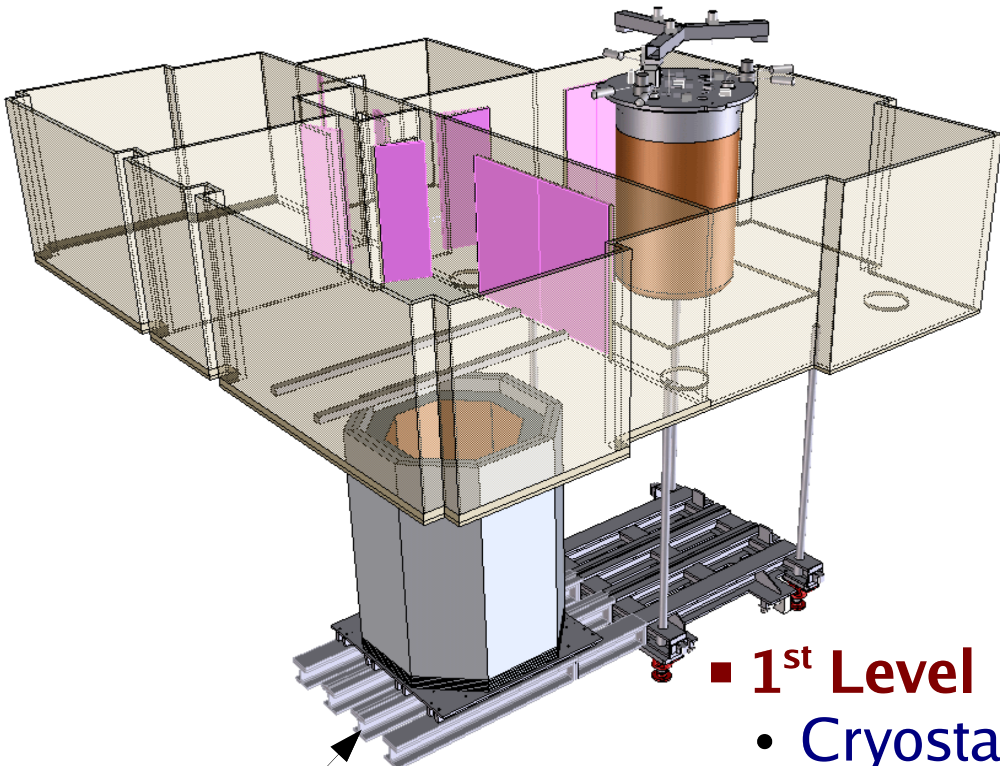


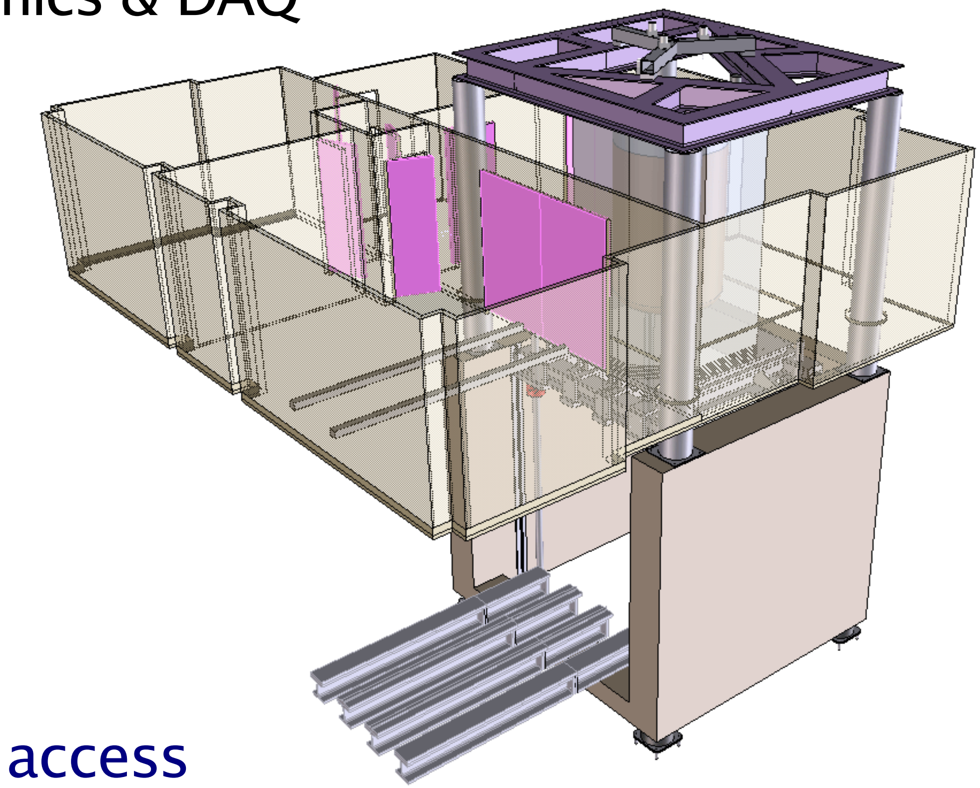
20 tons external lead shielding

- **1^{st} Level**
  - Cryostat access
  - Clean room
- **ground floor**
  - services (pumps,...)
  - shields and screens storage

External lead shielding and hut

- **2nd Level**
  - Top flange access
  - Suspension access
  - DU Gas Handling
  - Electronics & DAQ



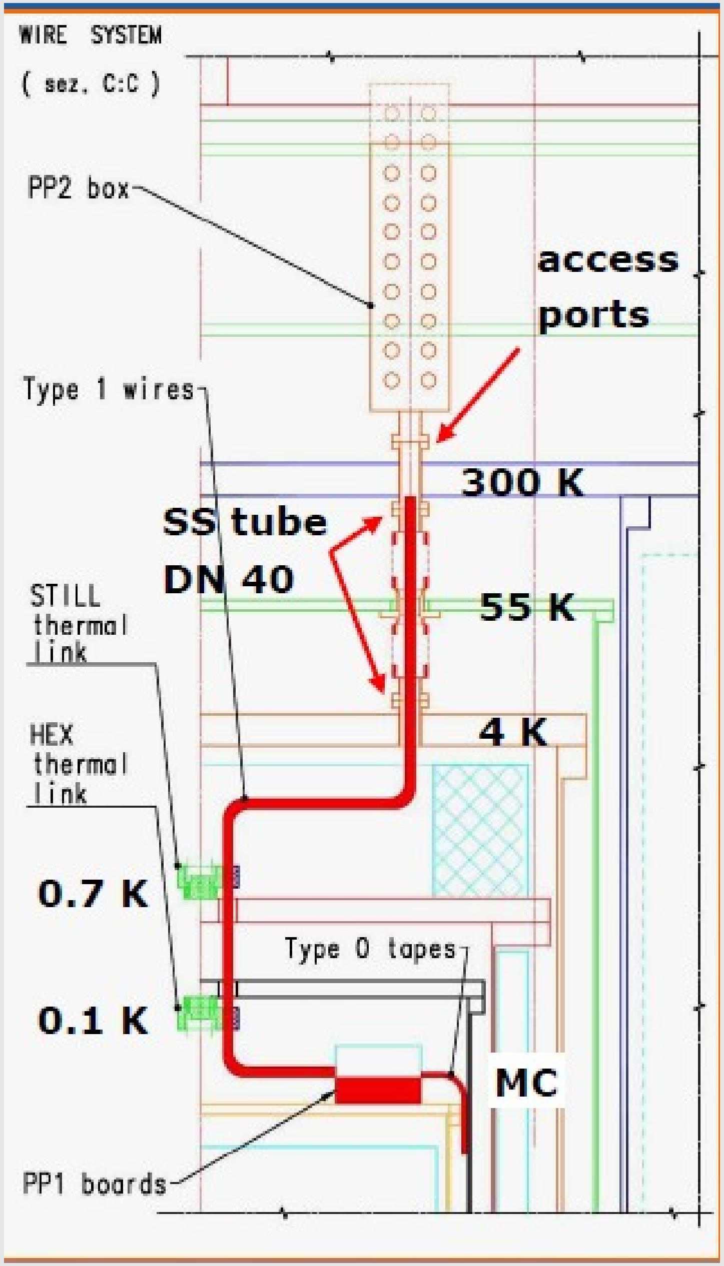


20 tons external lead shielding

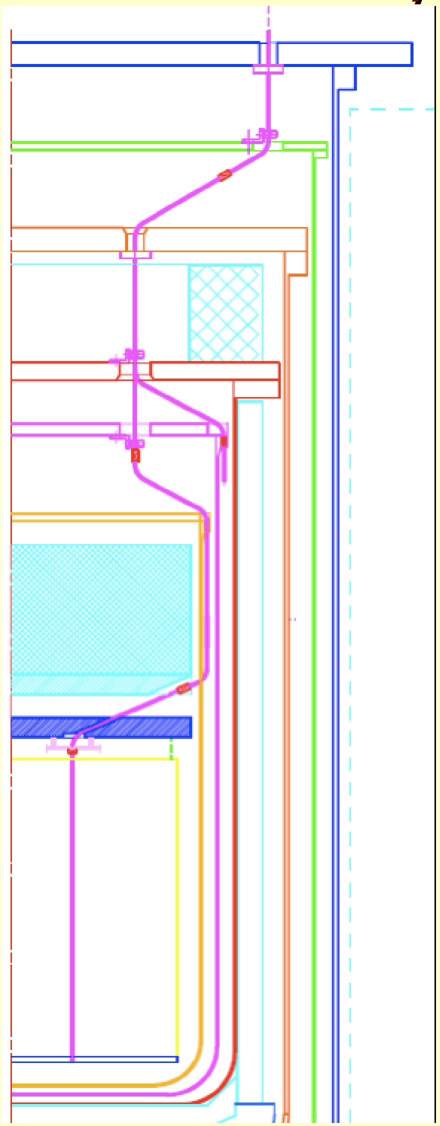
- **1st Level**
  - Cryostat access
  - Clean room
- **ground floor**
  - services (pumps,...)
  - shields and screens storage

Other systems to integrate in the cryostat

2600 NbTi read-out wires

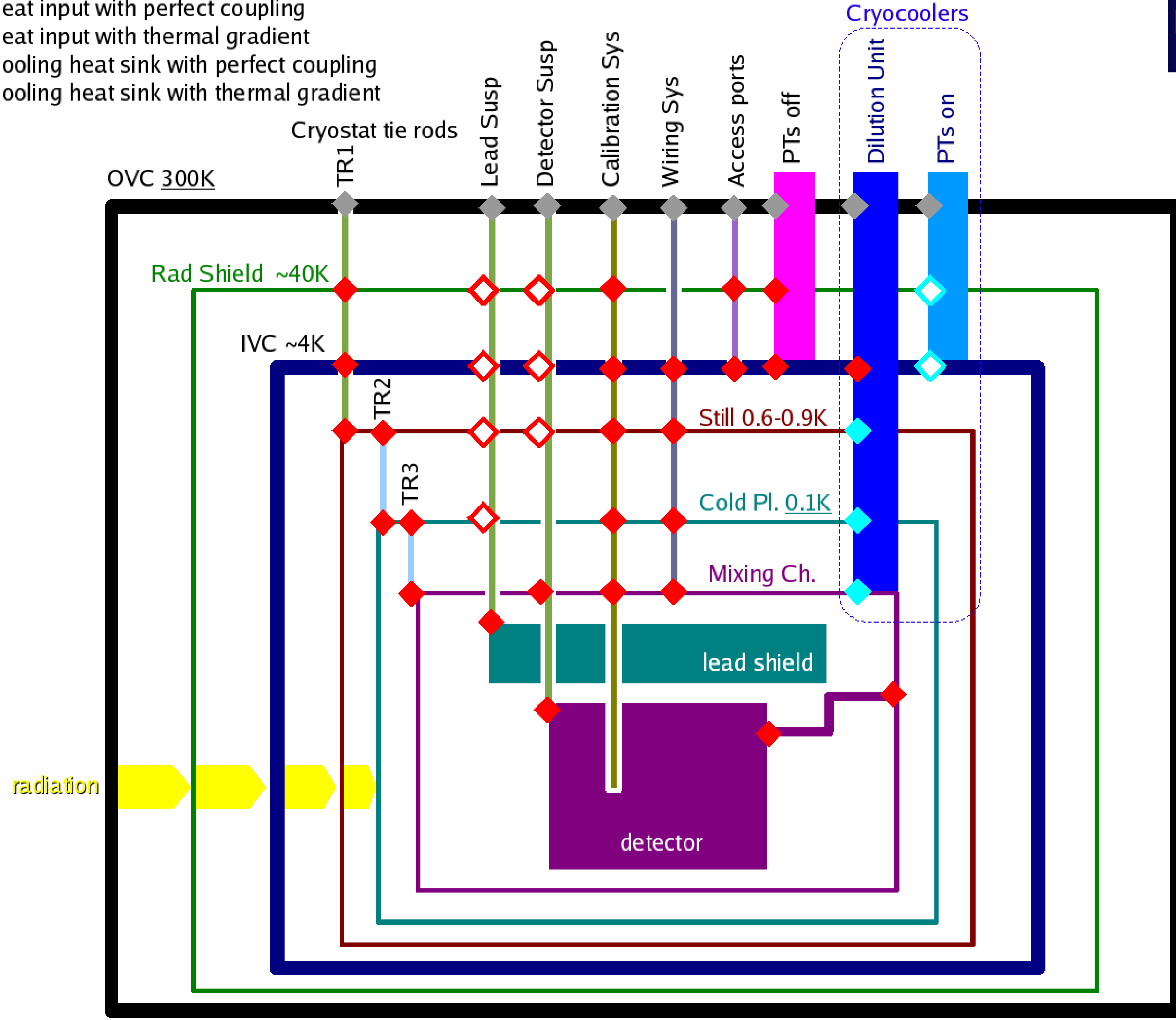


12 tubes for inserting γ calibration sources inside the detector array



Thermal model / 1

- ◆ Heat input with perfect coupling
- ◇ Heat input with thermal gradient
- ◆ Cooling heat sink with perfect coupling
- ◇ Cooling heat sink with thermal gradient

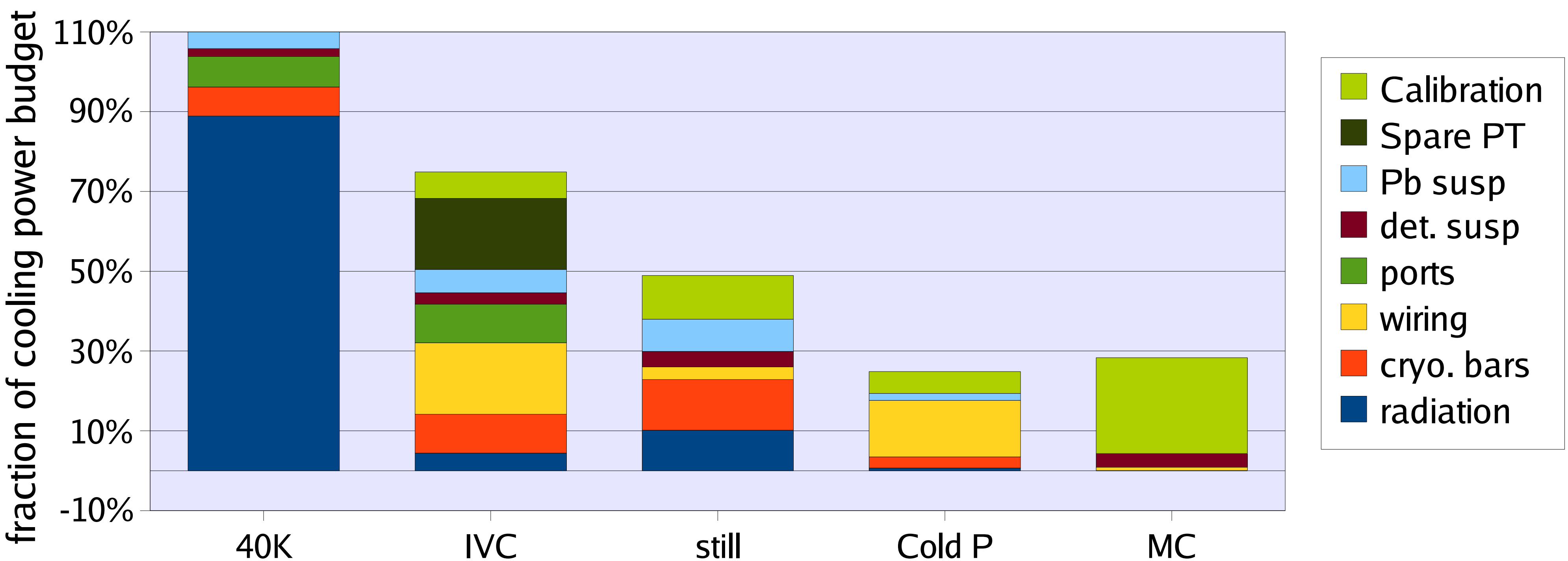


Thermal model / 2

	radiation	cryo. bars	wiring	ports	det. susp	Pb susp	Spare PT	DCS	He3	TOT [W]
40K	1.07E+02	8.67E+00		9.17E+00	2.45E+00	5.03E+00	1.72E+01		-	**1.49E+002**
IVC	1.99E-01	4.39E-01	8.06E-01	4.36E-01	1.28E-01	2.63E-01	8.00E-01	*3.00E-01*	1.00E+00	**4.37E+000**
still	5.08E-04	6.35E-04	1.58E-04		1.96E-04	4.01E-04		*5.50E-04*	-	**2.45E-03**
Cold P	1.33E-07	5.57E-07	2.83E-06			3.51E-07		*1.10E-06*	-	**4.97E-06**
MC	8.04E-11	2.67E-09	4.17E-08		1.71E-07			*1.20E-06*	-	**1.42E-06**

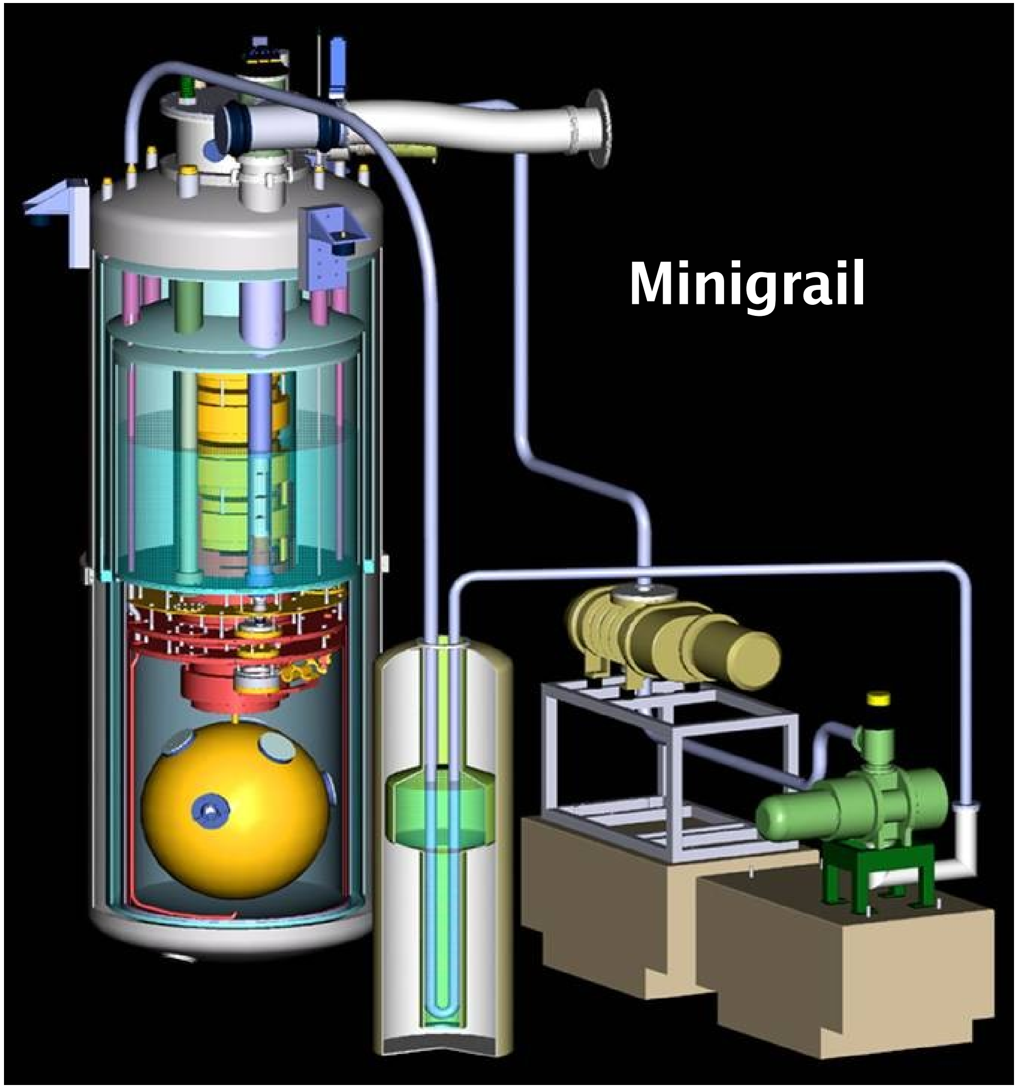
- still power 30 mW
- ^{3}He flow = 1 mmol/s
- 3 active Pulse Tubes

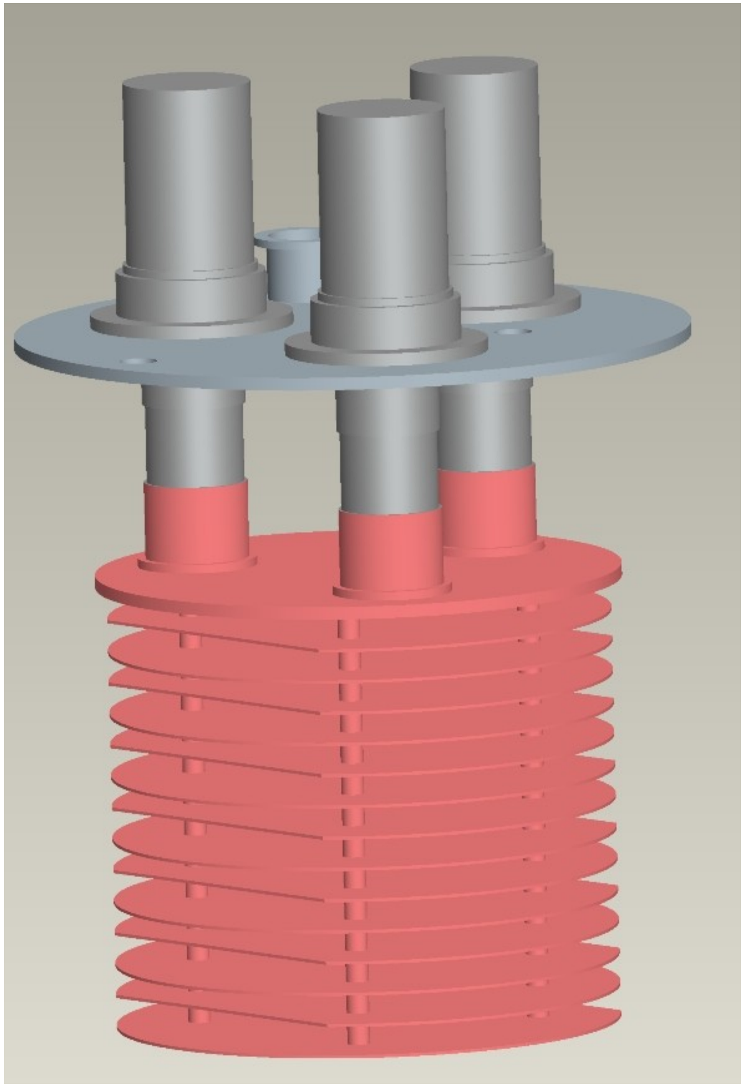
Temperatures [K]	
40K shield	**41.56**
IVC	**4.12**
DU still	**0.62**
DU Heat-ex	**0.07**
DU MC	**0.008**



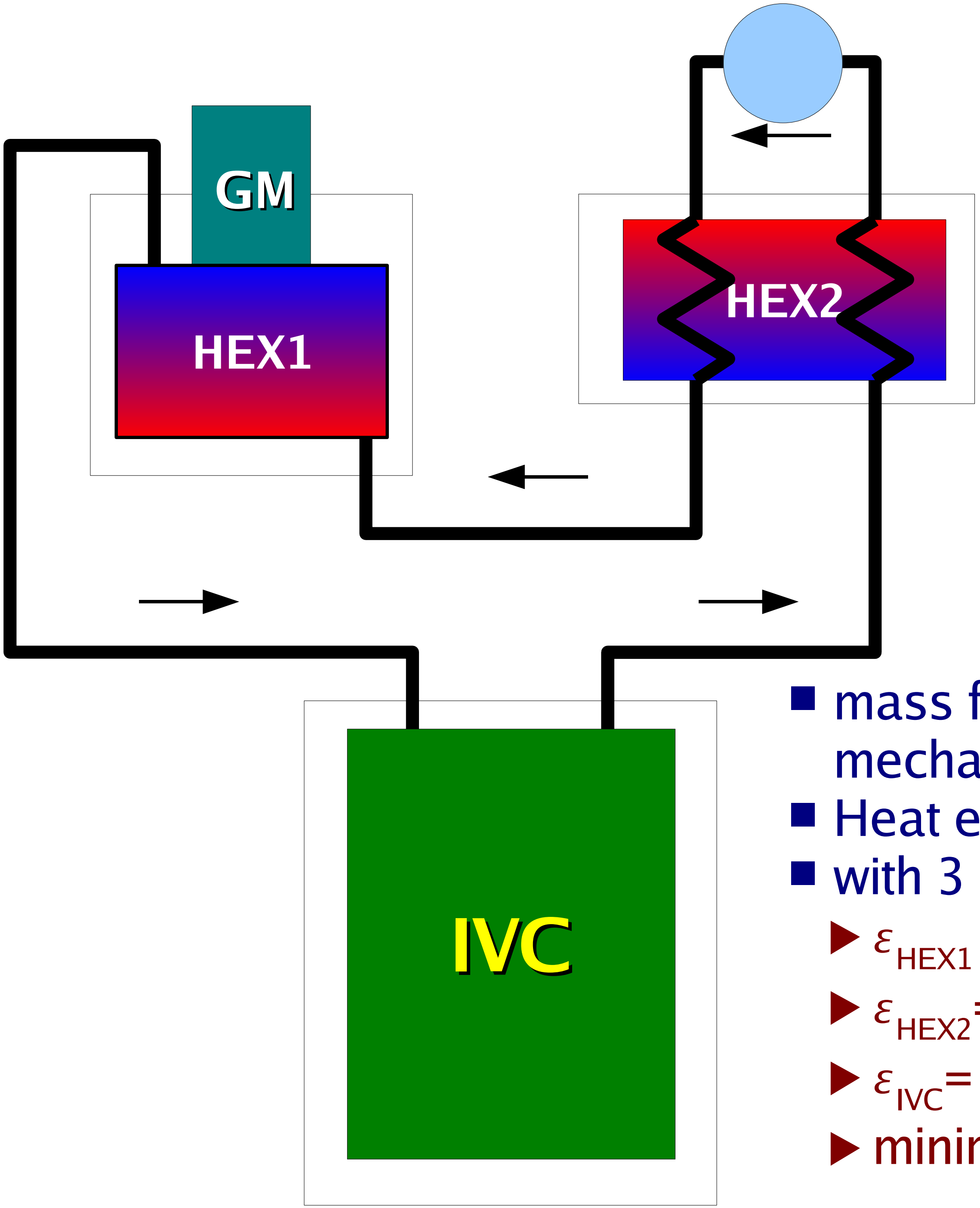
Cooling down: from 300K to 4K / 1

- 40K shield cooled by the 5 PT415
- IVC cooled by forced helium flow and the 5 PT415
- helium cooled by **up to 3 GM AL600** (600W@77K)
- helium circulated by 2 roots





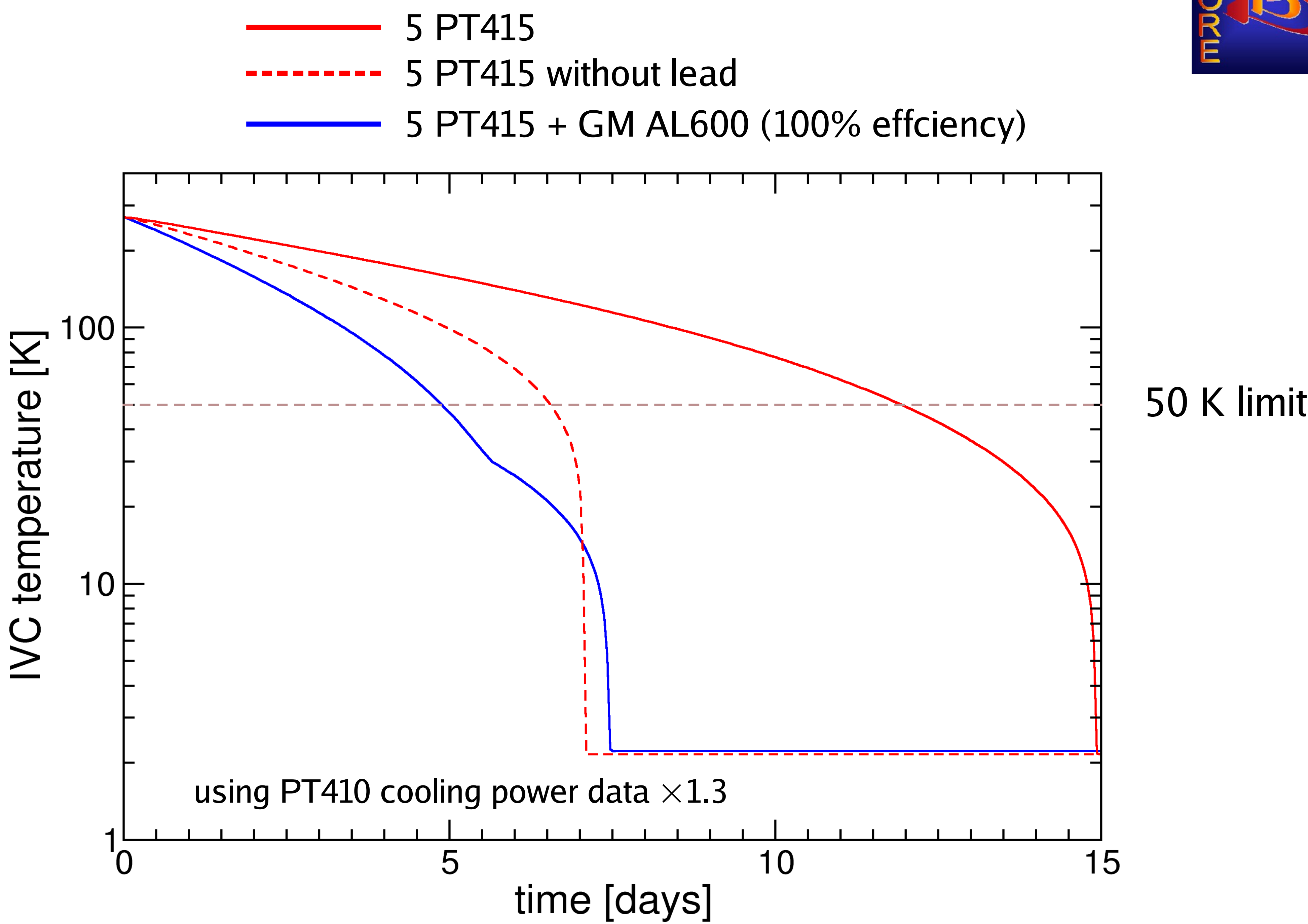
Cooling down: from 300K to 4K / 2



Using the GM instead of the liquids requires one more Heat Exchanger

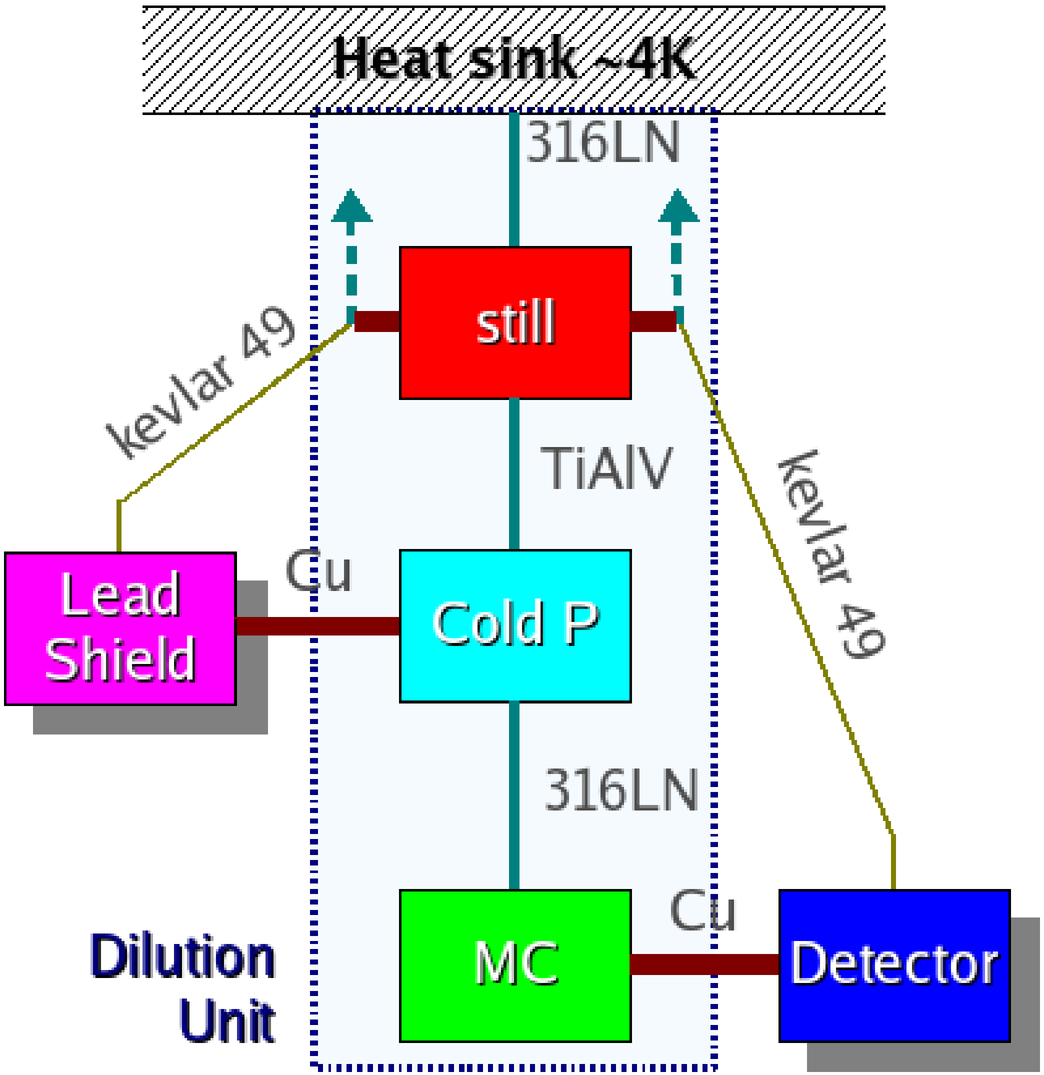
- mass flow limited to avoid mechanical stresses in the IVC
- Heat exchanger efficiency is crucial
- with 3 AL600
  - $\varepsilon_{HEX1} = 1.0$
  - $\varepsilon_{HEX2} = 0.95$
  - $\varepsilon_{IVC} = 0.9$
  - minimum $T_{IVC} \approx 50K$ reached in 3 days

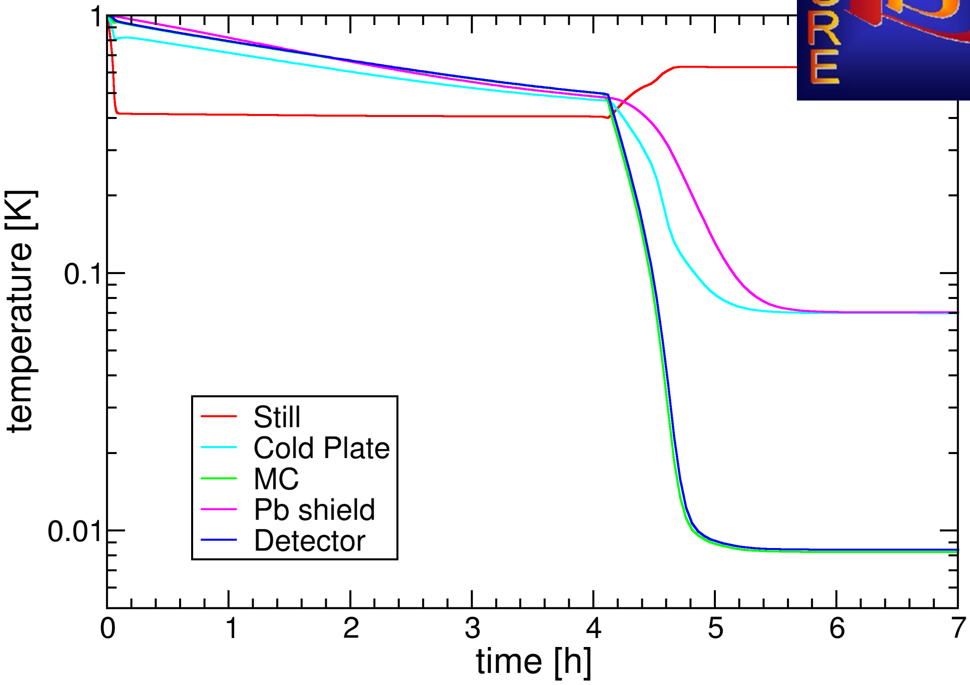
Cooling down: from 300K to 4K / 3



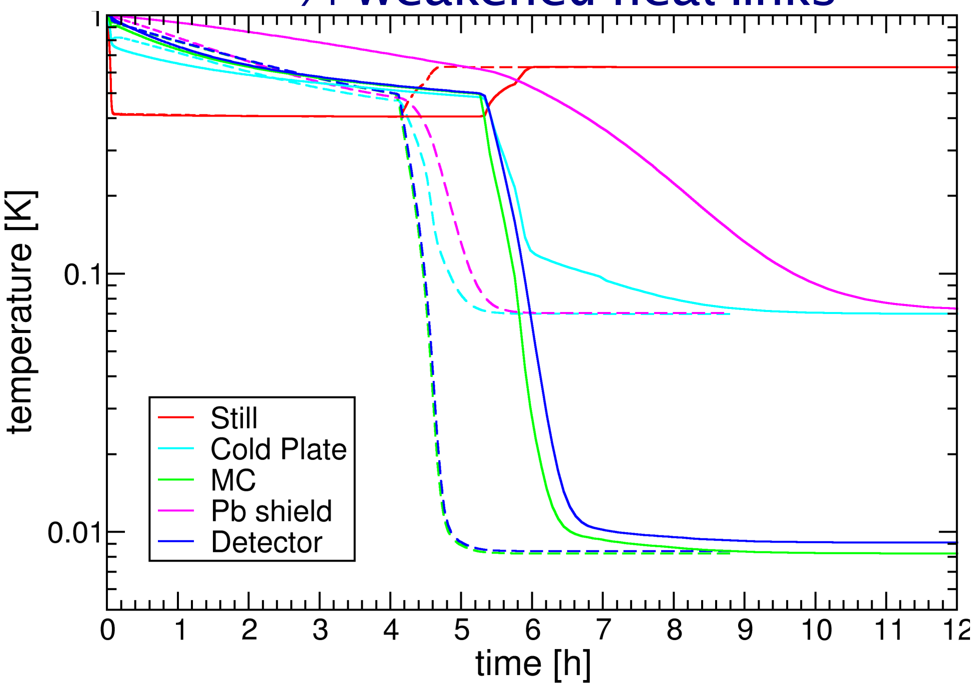
Cooling down: from 1K to base temperature

- simplified thermal block diagram
- DU model differential equations
- without residual heat leaks in Cu or Pb





¼ weakened heat links



Conclusions

- **The project is challenging!**
  - **first attempt ever to cool down a mass this large to 10 mK**
- Cryostat design is almost completed
  - the tender for Cryostat production is in progress
  - Fast cooling with GM is still in the conceptual design phase
  - Design of other systems (suspensions, wiring, calibration...) is in progress
- Pulse Tube characterization is in progress
  - check performances
  - measure mechanical vibration and design thermal couplings
- DU construction is in progress
- DU and Cryostat should delivered to LNGS by the end of 2008
  - Commissioning should take place during 2009
  - The Cryogenic system should be completed by the end of 2009
- **The CUORE experiment should start data taking in 2011**