

Detección de raios cósmicos na estrutura de computación cuántica do CESGA [Qmio]

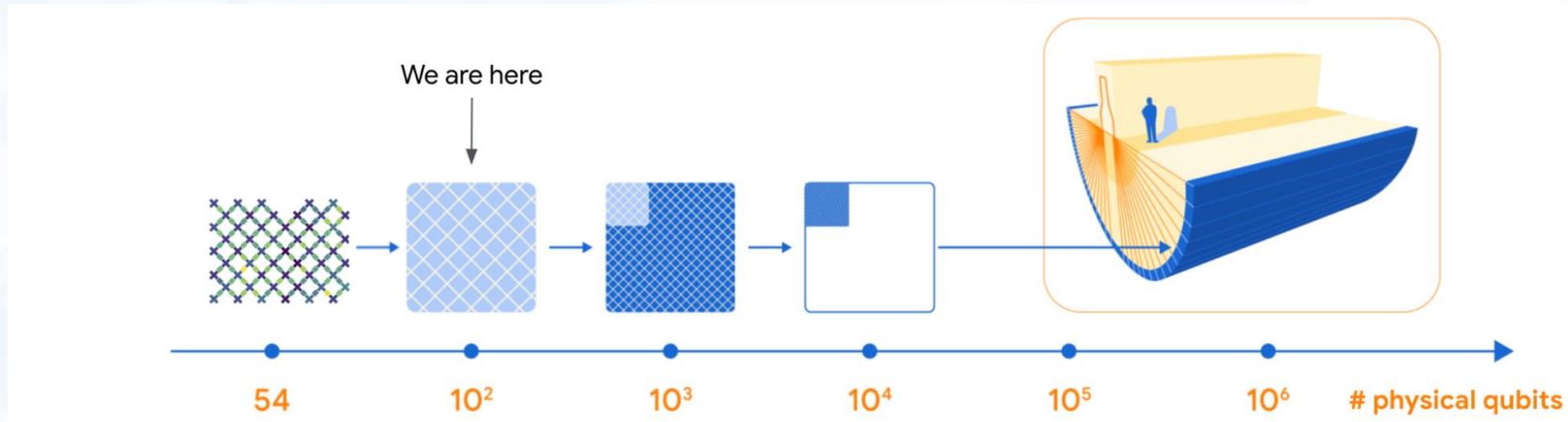
H. Álvarez Pol, Y. Ayyad Limonge, M. Caamaño Fresco, B. Fernández Domínguez

IGFAE - Instituto Galego de Física de Altas Enerxías

25/10/2023

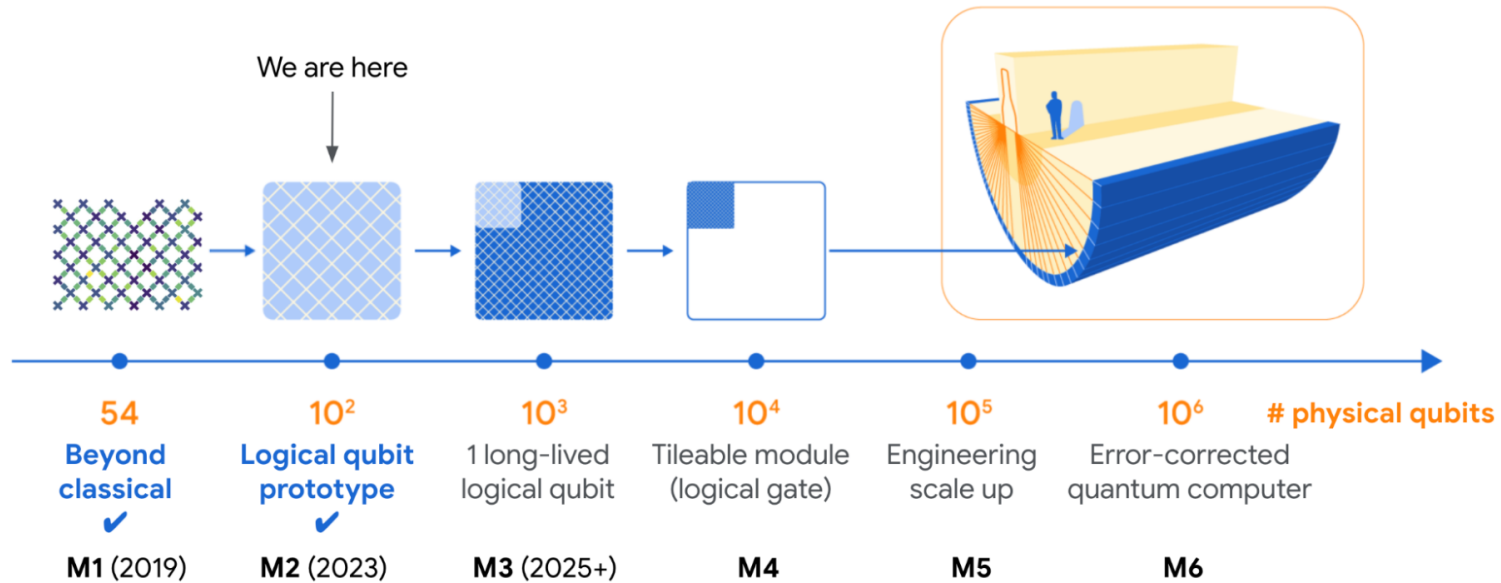
Corrección de erros na computación cuántica

- As computacións cuánticas requiren millóns de operacións lóxicas.
- A corrección de erros intrínsecos é posible, mais
 - So para unha moderada fracción dos cubits (<1% ?).
 - De producirse aleatoria e independentemente, sen correlacións.



Corrección de erros na computación cuántica

Quantum error correction	–	Enabled	At scale
# Physical qubits	10 – 100	100 – 1000	$10^4 – 10^6$
# Logical qubits	–	1	10 – 1000+
Logical error	10^{-3}	$10^{-2} – 10^{-6}$	$10^{-6} – 10^{-12}$



Google Quantum AI Team. “Suppressing quantum errors by scaling a surface code logical qubit”.
<https://blog.research.google/2023/02/suppressing-quantum-errors-by-scaling.html>

Efecto das radiacións ionizantes

A radiación ionizante produce un gran número de erros correlacionados e duraderos

- ioniza o medio, xerando fonóns de alta enerxía e electróns-ocos no medio [10 ns, 1 mm].
- Os fonóns desprazanse e o 57% da súa enerxía convértese en quasipartículas [300 ns, 3-6 mm]
- ... que termalizan radiando fonóns de baixa enerxía, rompendo pares de Cooper [1 ms, cm]
- Reduce os tempos de relaxación $T_1 < 1 \mu\text{s}$

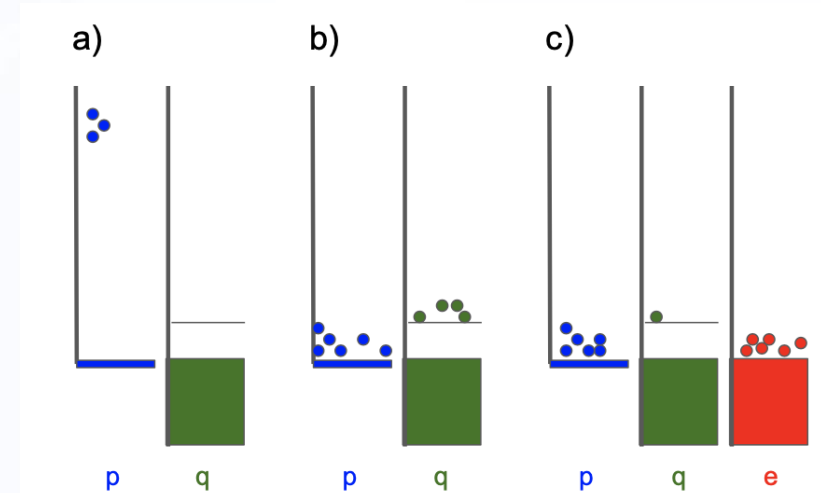
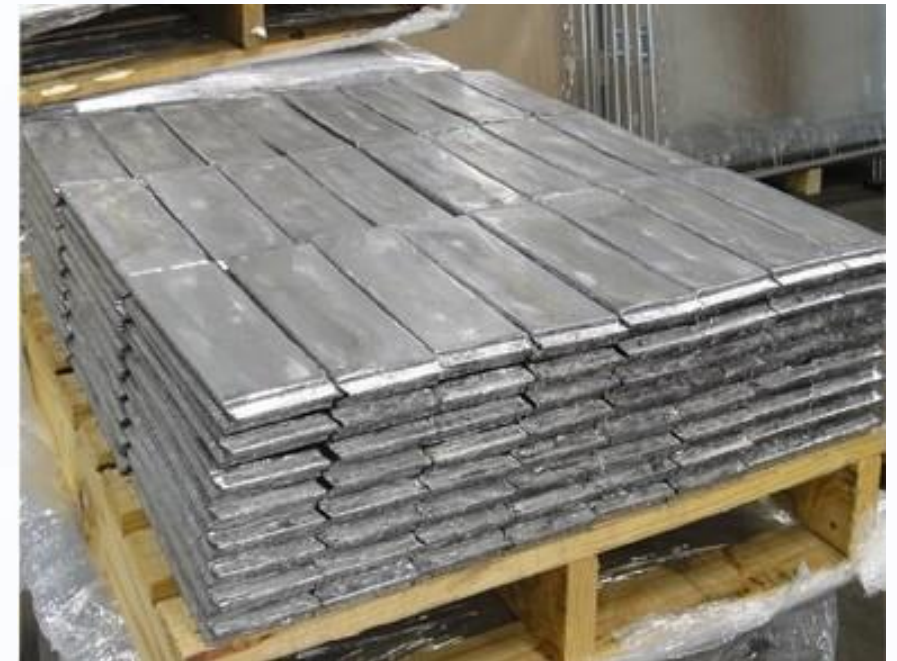
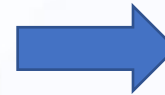
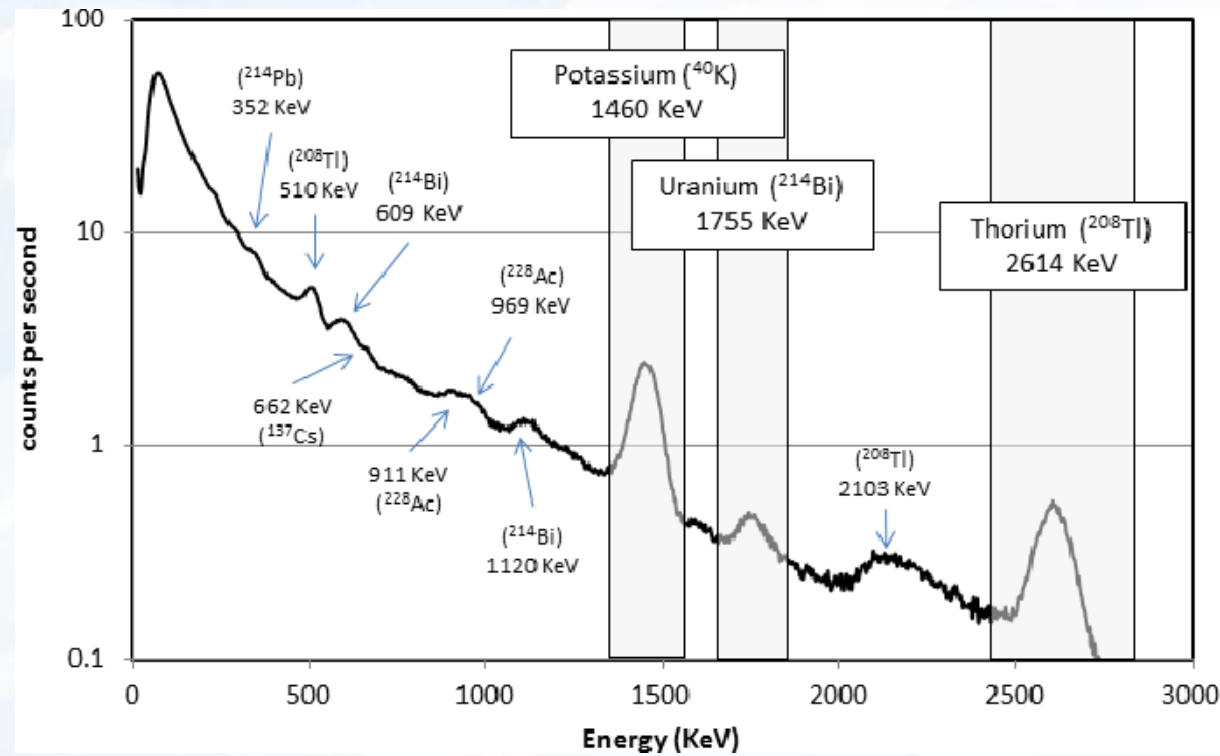


Fig. 1 Nonequilibrium phonon, quasiparticle, and electron excitations. **a** Schematic representation of the phonon (p) and quasiparticle (q) excitations after the radiation event, with only a few high-energy phonons. The vertical axis represents the state energy. **b** After relaxation, the phonon energy has down-converted to quasiparticle excitations in the superconductor and low-energy (subgap) phonons. About 57% of the initial energy remains in the quasiparticles. **c** With a normal metal structure, most of the energy has been channeled away from the superconductor and towards the normal metal electrons (e), which is designed not to affect the qubit.

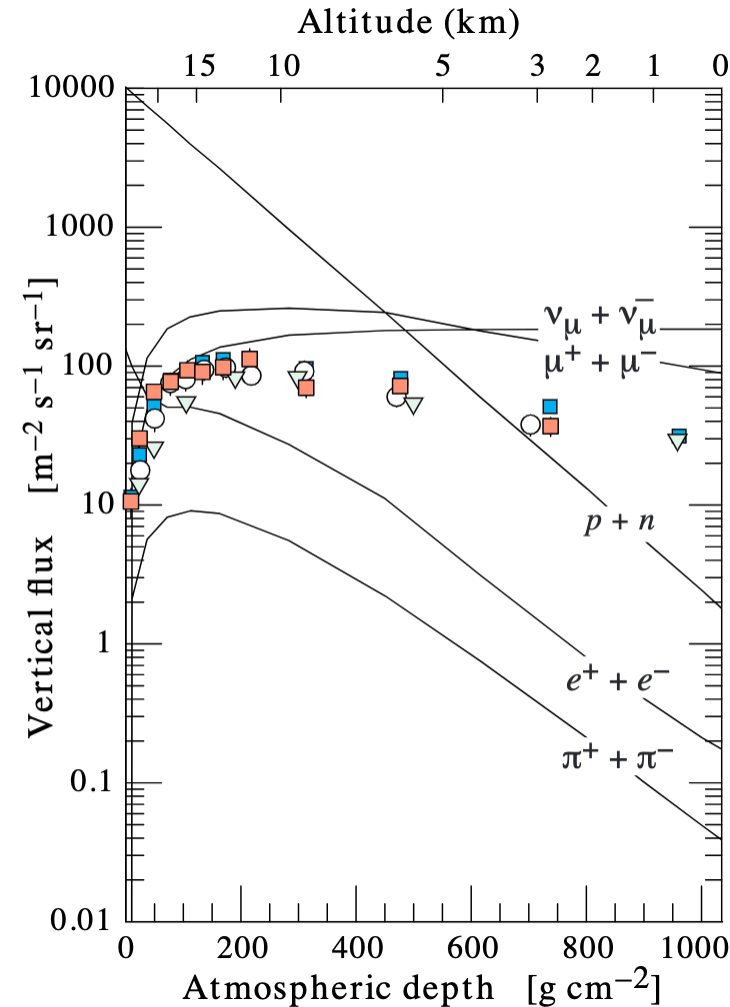
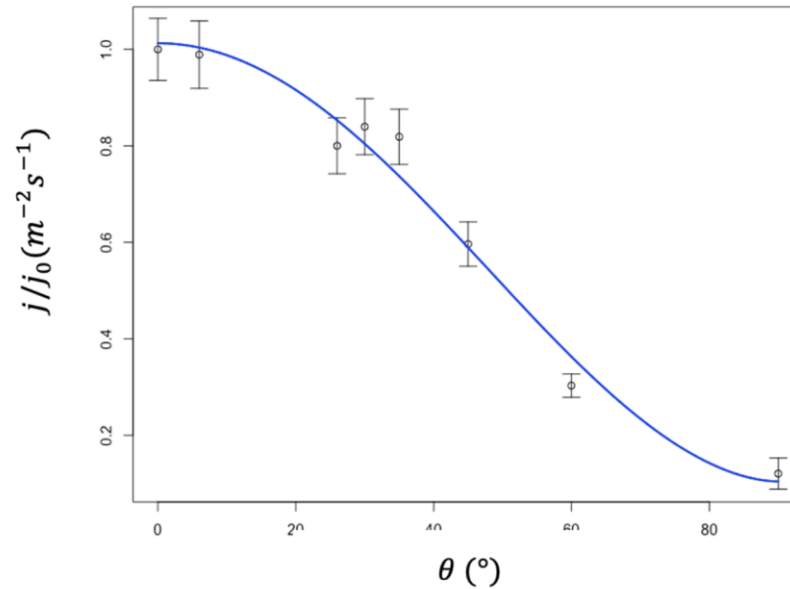
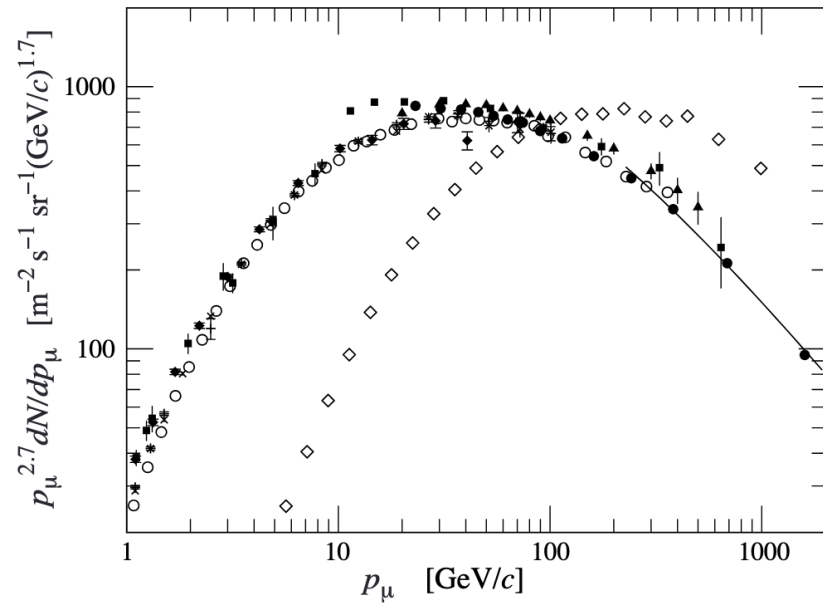
John M. Martinis. “Saving superconducting quantum processors from decay and correlated errors generated by gamma and cosmic rays”. Quantum Information 7: 90, xuño 2021 (<https://doi.org/10.1038/s41534-021-00431-0>). Open Access.

Radiación gamma ambiental



Blindaxe de chumbo (optimizada)

Radiación cósmica (muons)



Fluxo: ~ 1 muon por cm² e minuto

Enerxía depositada no substrato: ~ 4 MeV/cm

Detección de radiación cósmica en Qmio

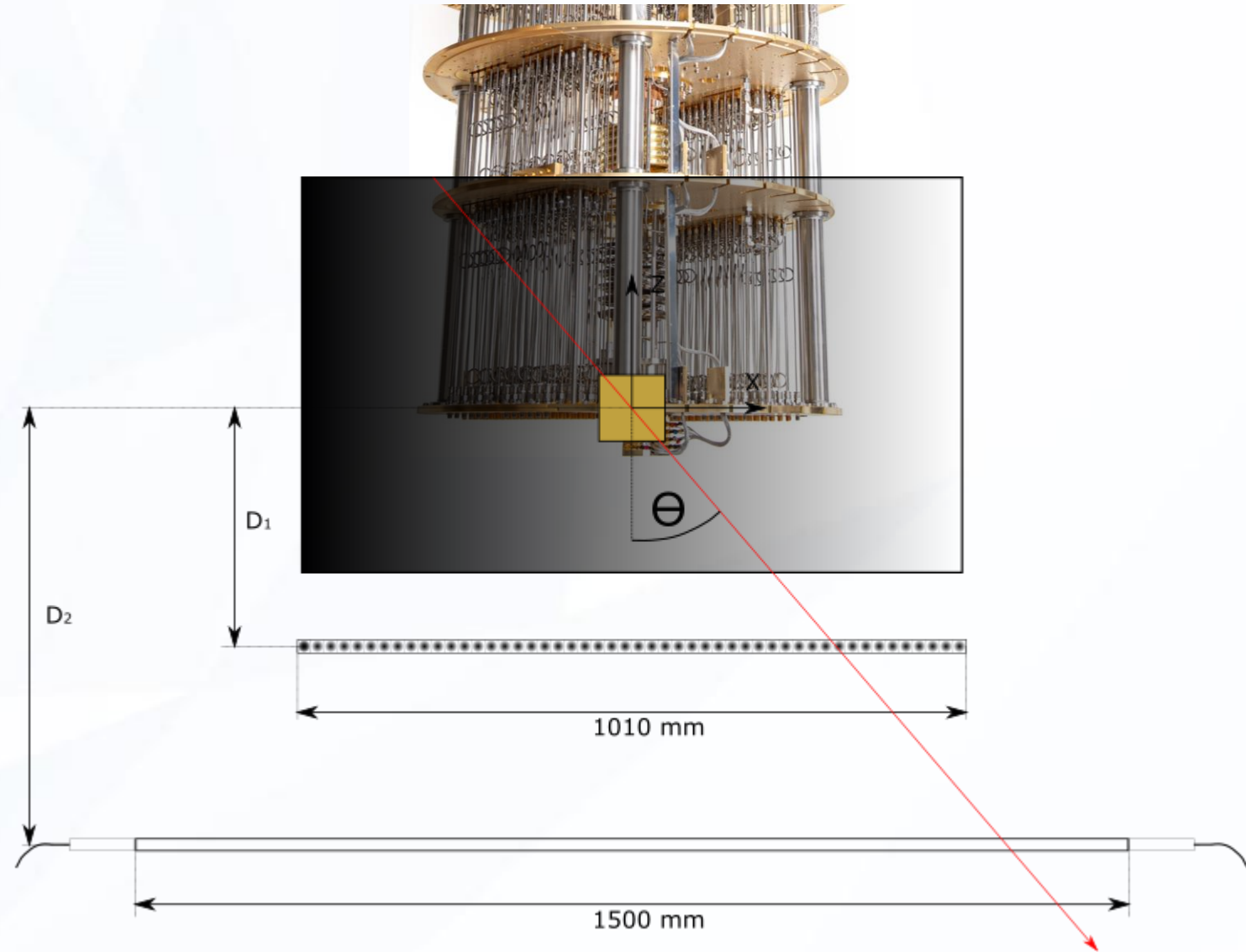
A radiación ionizante produce un gran número de erros **correlacionados**

- identifícase pola abundancia de erros, asumindo a orixe cósmica.
- **nunca se detectou en coincidencia** a radiación cósmica e os seus efectos no procesador durante unha computación.

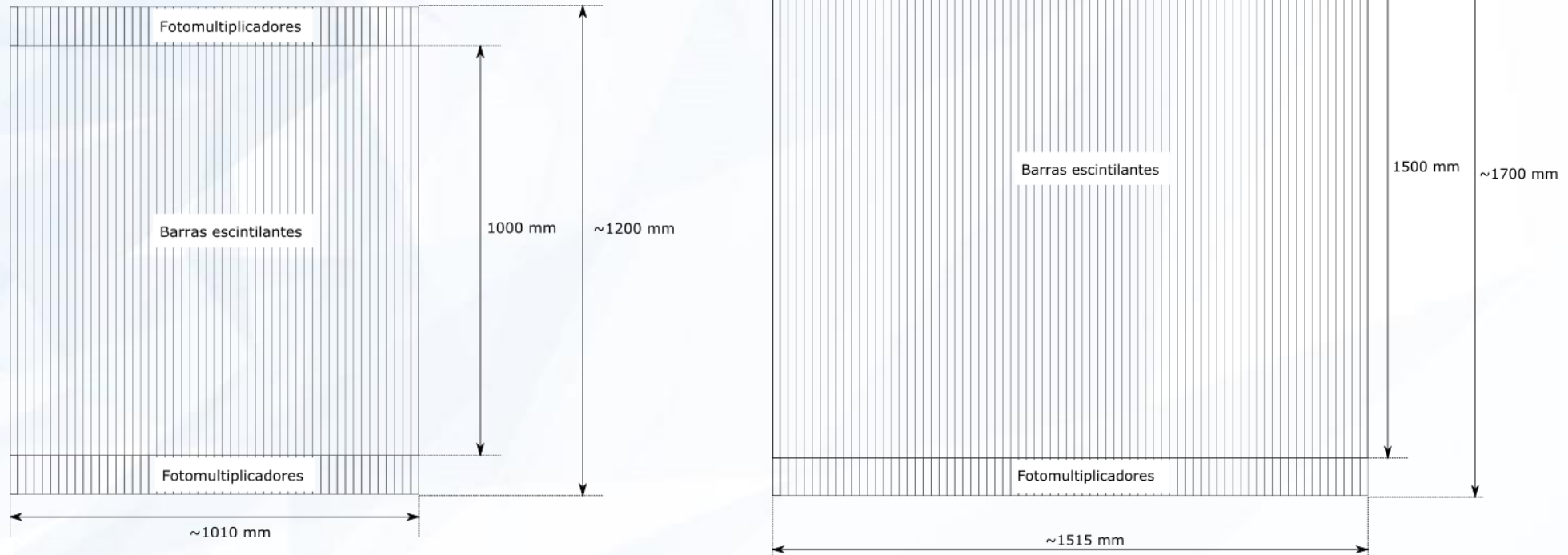


Detector de cósmicos de alta eficiencia e resolución para o marcado do paso da radiación cósmica en Qmio

Esquema do detector



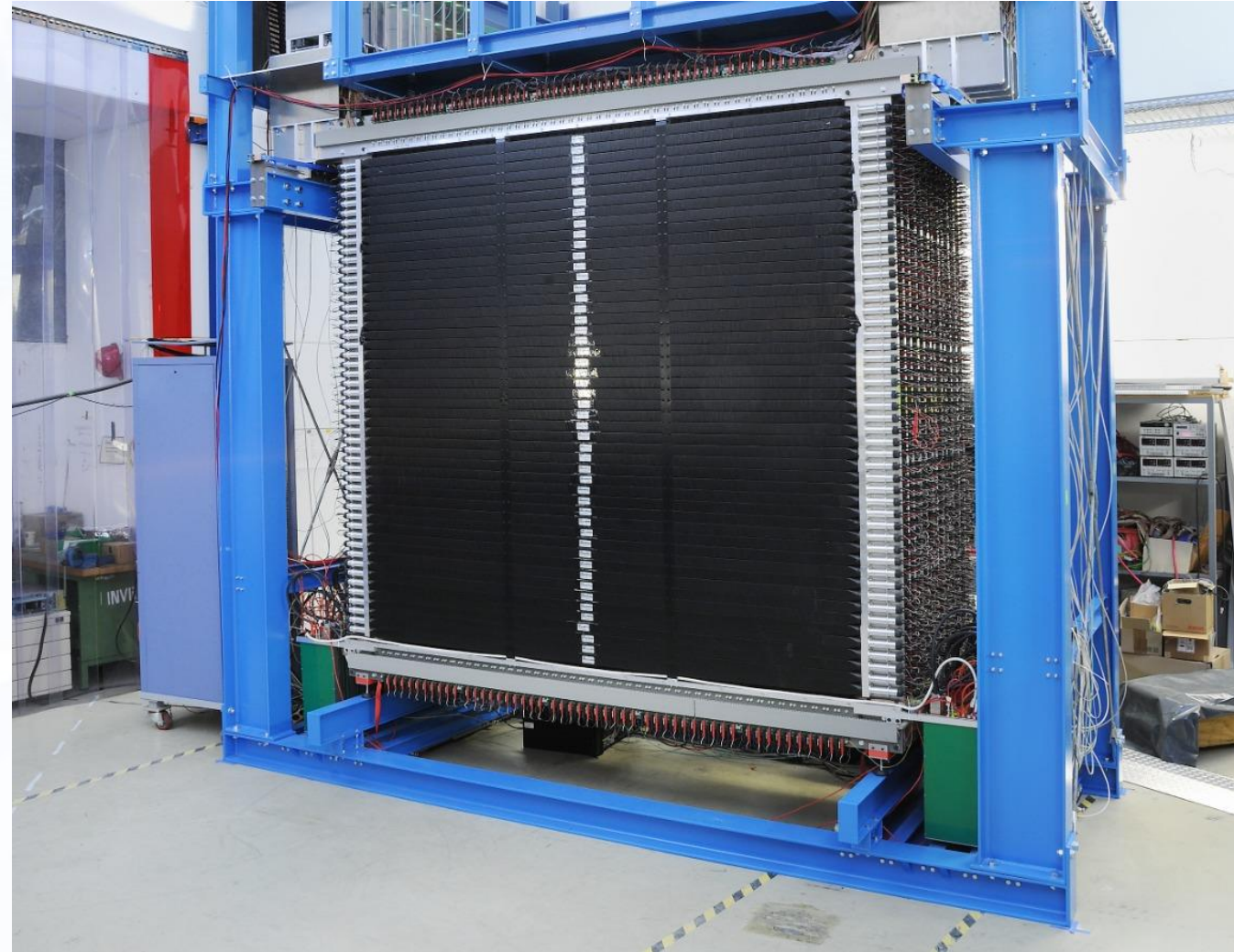
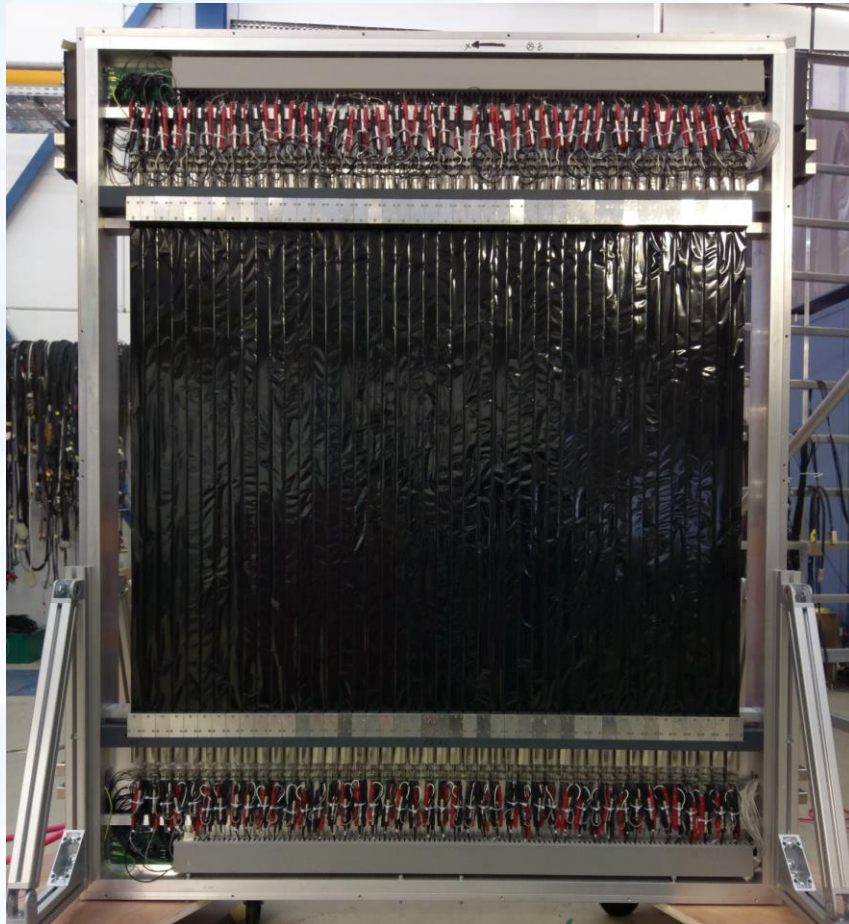
Esquema do detector



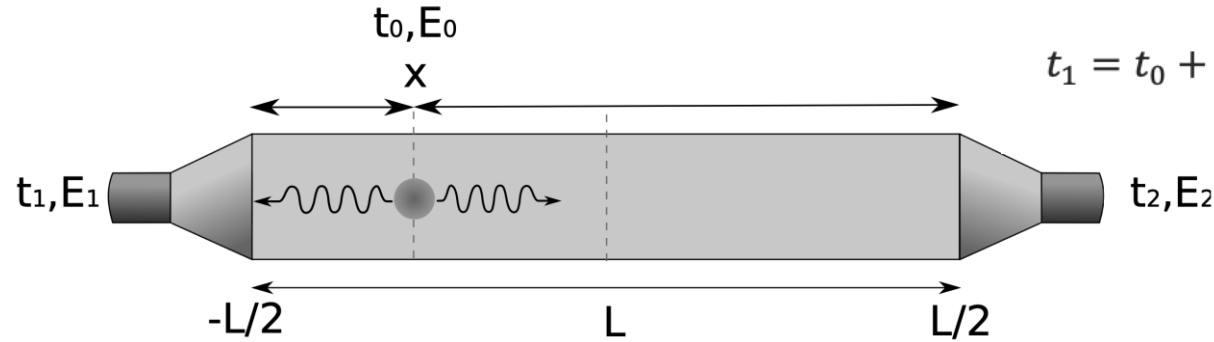
- 50 (75) barras escintilantes de 1 (1,5) m de lonxitude
- 100 (150) fotodetectores + sistema de alto voltaxe
- Electrónica: TDC (ADC) + FPGA + PC

Detectores NeuLAND e TOFD de R³B

Esquema do detector

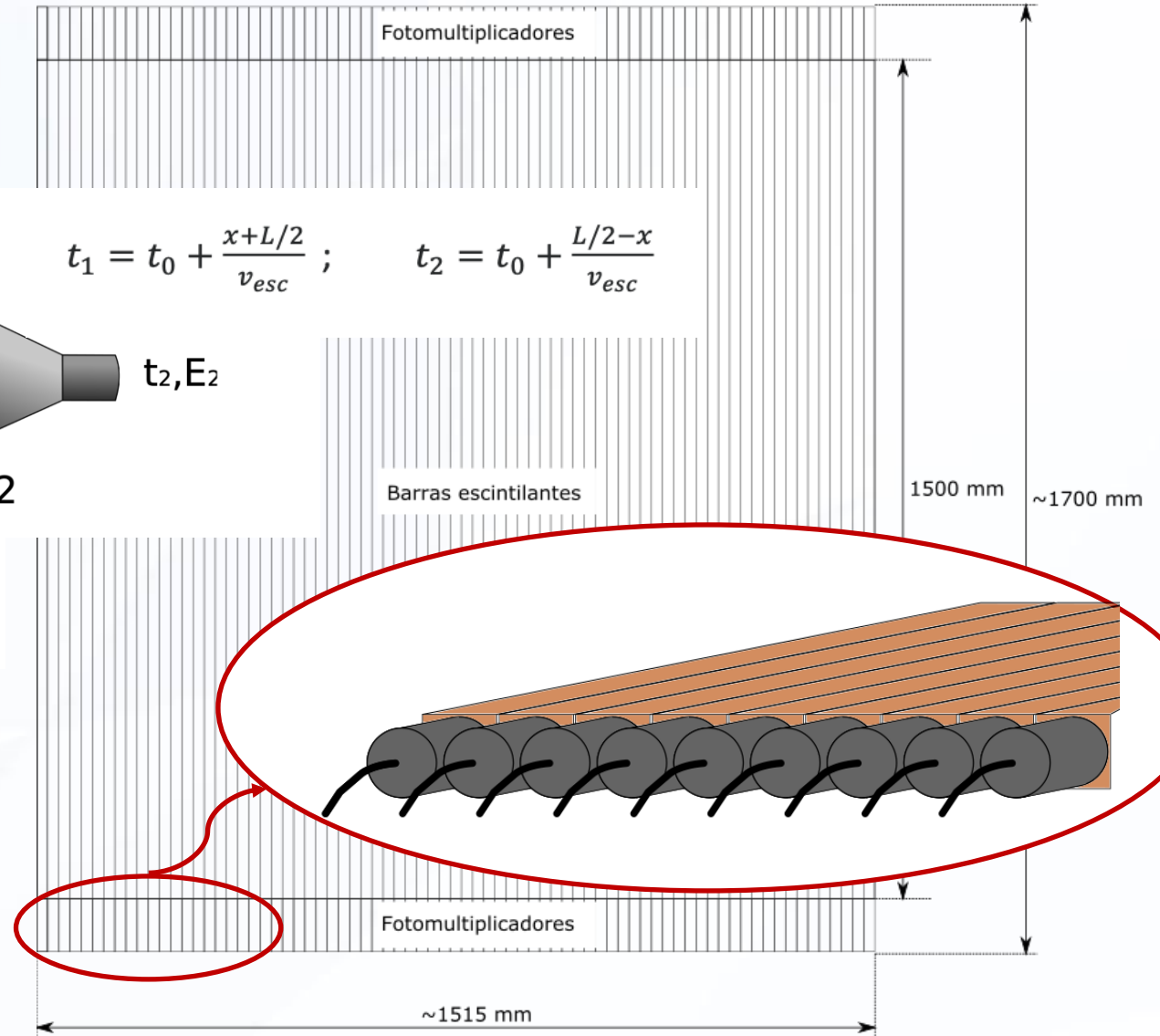


Funcionamento do detector



$$x = \frac{v_{esc} (t_1 - t_2)}{2} ; \quad t_0 = \frac{t_1 + t_2}{2} - \frac{L}{2 v_{esc}}$$

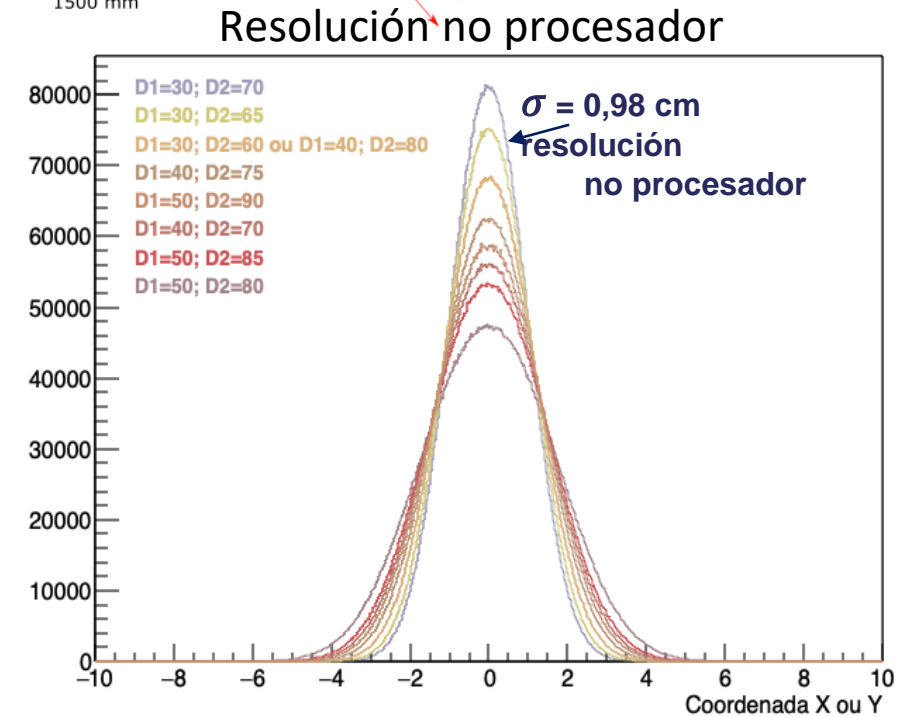
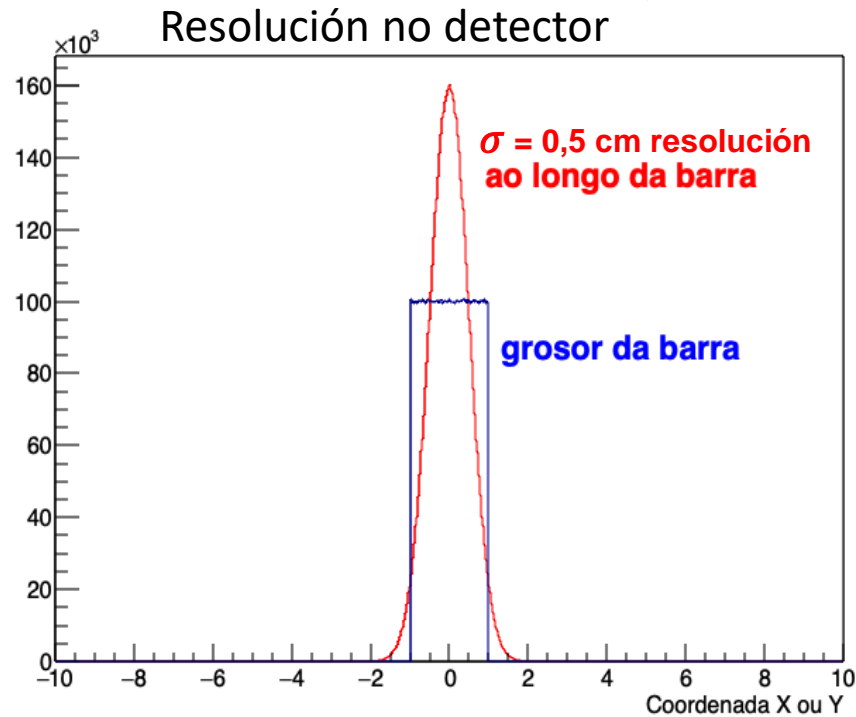
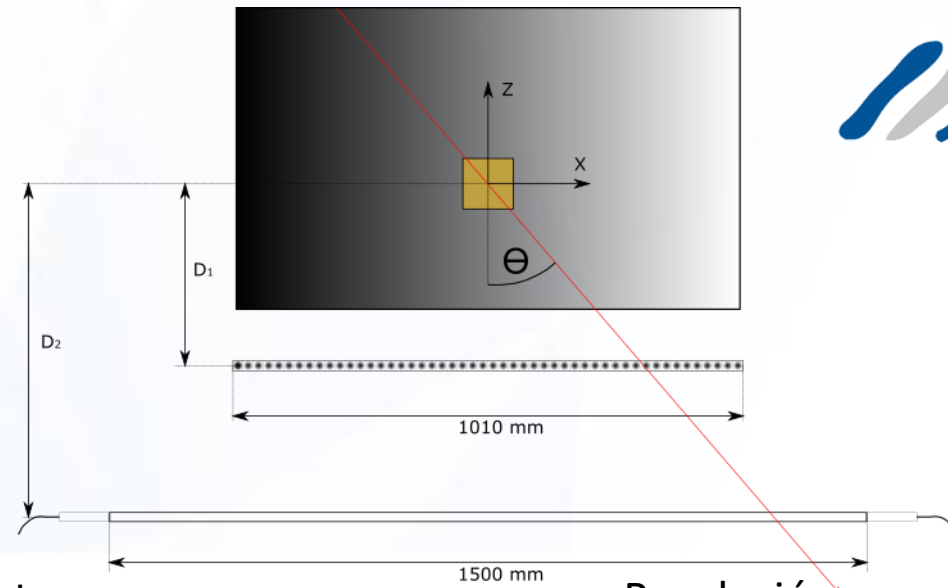
$$t_1 = t_0 + \frac{x + L/2}{v_{esc}} ; \quad t_2 = t_0 + \frac{L/2 - x}{v_{esc}}$$



- Eficiencia xeométrica:** > 85%
- Eficiencia instrínseca:** > 99%
- Resolución temporal:** < 100 ps
- Resolución espacial (σ):** < 1 cm

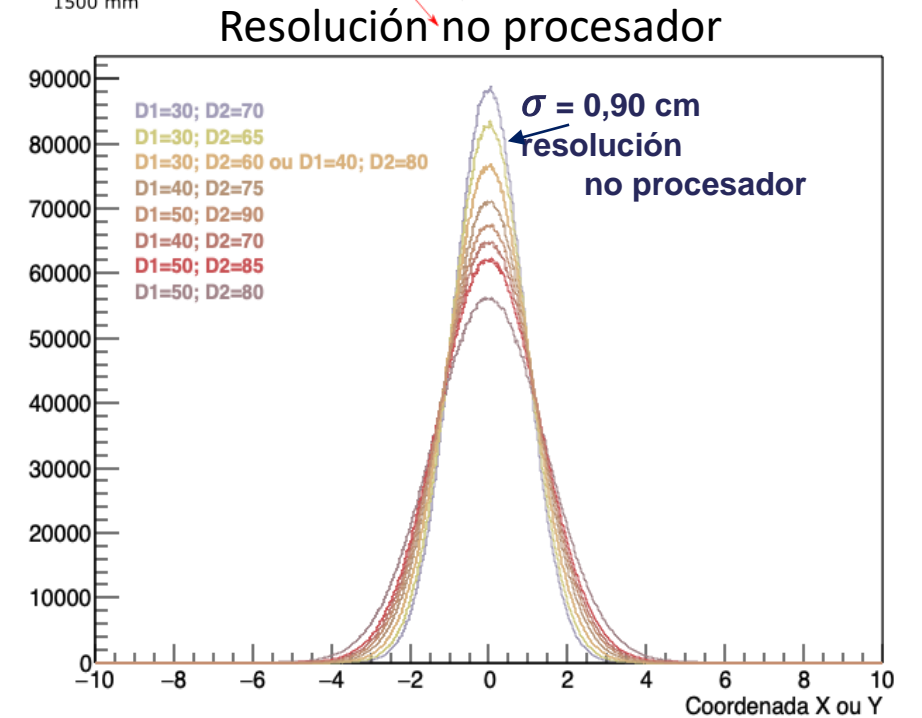
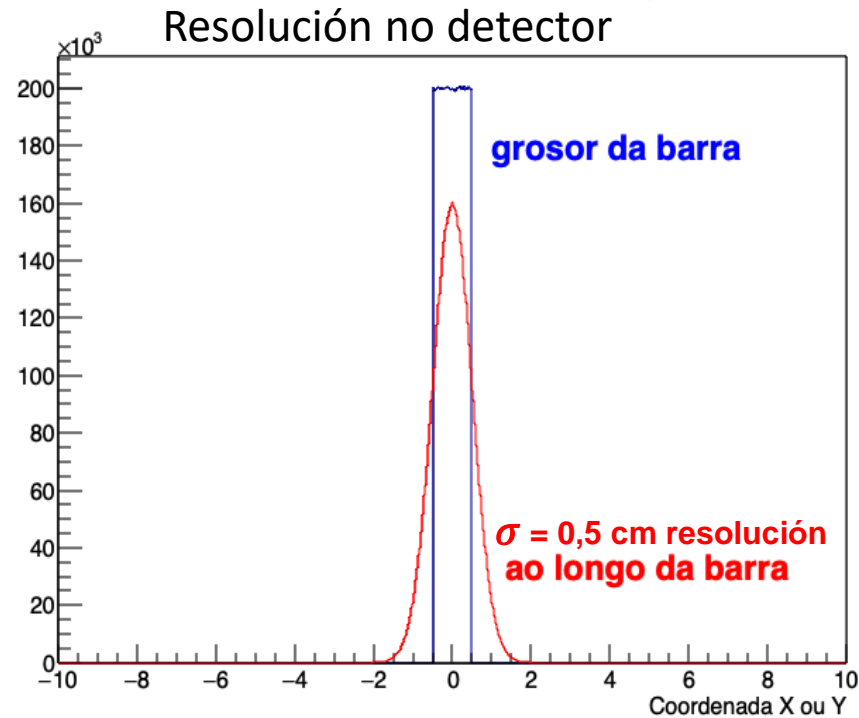
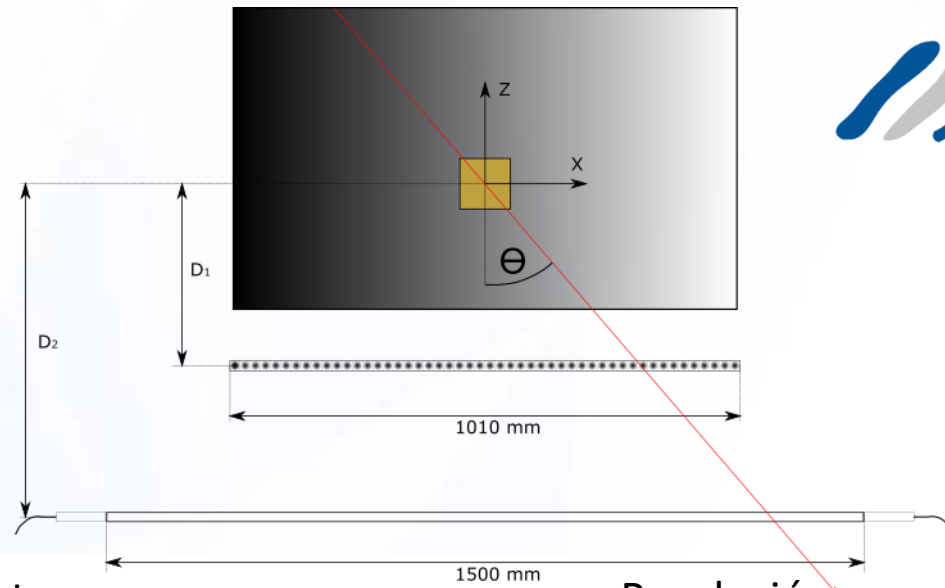
Resolución en posición

Barras de 2 cm de grosor



Resolución en posición

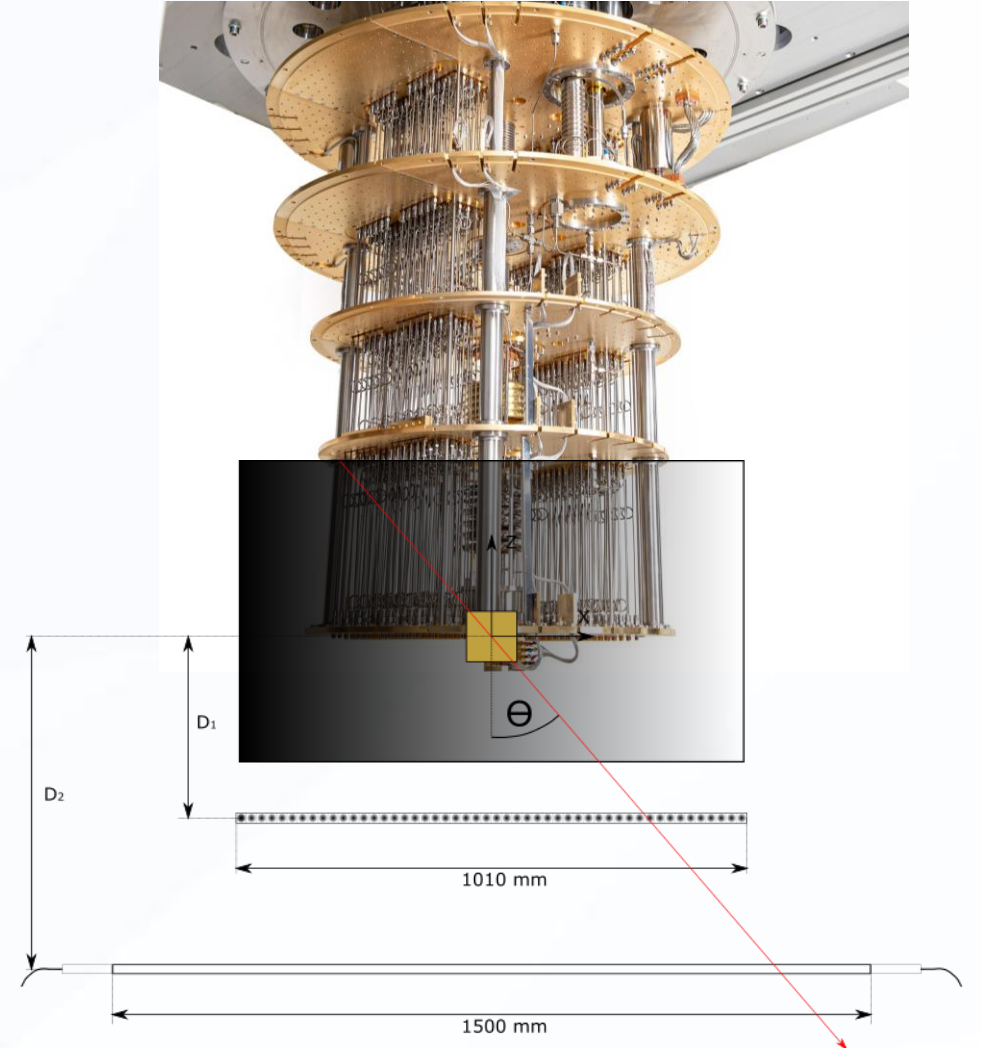
Barras de 1 cm de grosor



Resolución en posición

Distancia ao procesador (cm)	Distancia entre planos (cm)	Resolución no procesador para $\sigma_{\text{longo}} = 0,5 \text{ cm}$ (σ , cm)	Resolución no procesador para $\sigma_{\text{longo}} = 1 \text{ cm}$ (σ , cm)
30	40	0,98	1,80
	35	1,05	1,92
	30	1,15	2,08
40	40	1,15	2,08
	35	1,26	2,24
	30	1,40	2,46
50	40	1,34	2,36
	35	1,47	2,56
	30	1,65	2,84

Barras de 2 cm de grosor



Moving forwards...

... The repetition code results demonstrate that low logical error rates are possible in a superconducting system, but **finding and mitigating highly correlated errors such as cosmic ray impacts will be an important area of research moving forwards.**

TeamGoogle Quantum AI.

Suppressing quantum errors by scaling a surface code logical qubit.

Nature 614, 676-681 (2023).

<https://doi.org/10.1038/s41586-022-05434-1>

... many interesting experiments.

The energy pulses from cosmic and gamma rays are clearly an important issue for superconducting qubits, since qubit errors and correlations in time and space will kill error correction by many orders of magnitude... **There are many interesting experiments to do soon to demonstrate that an effective solution is possible.**

J. Martinis, “Saving superconducting quantum processors from decay and correlated errors generated by gamma and cosmic rays”

Quantum Information (2021) 7:90;

<https://doi.org/10.1038/s41534-021-00431-0>

Agradecido pola atención!



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Información adicional

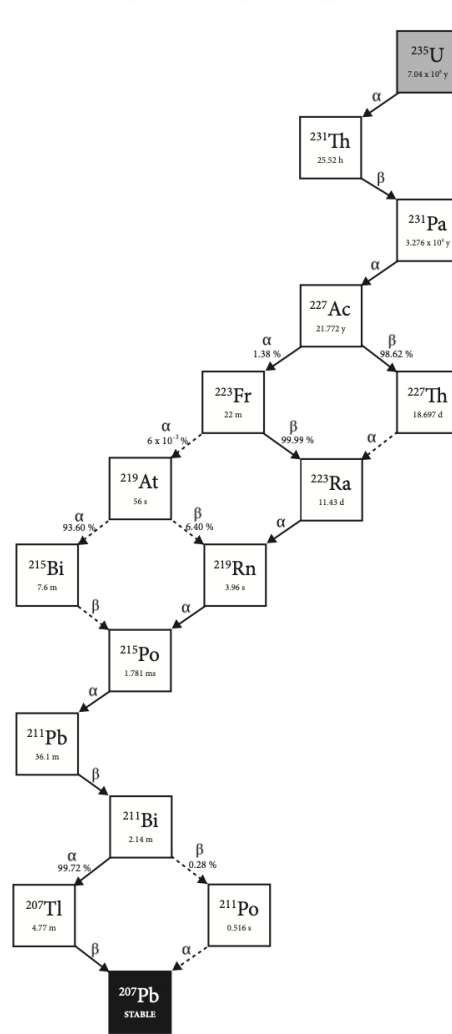
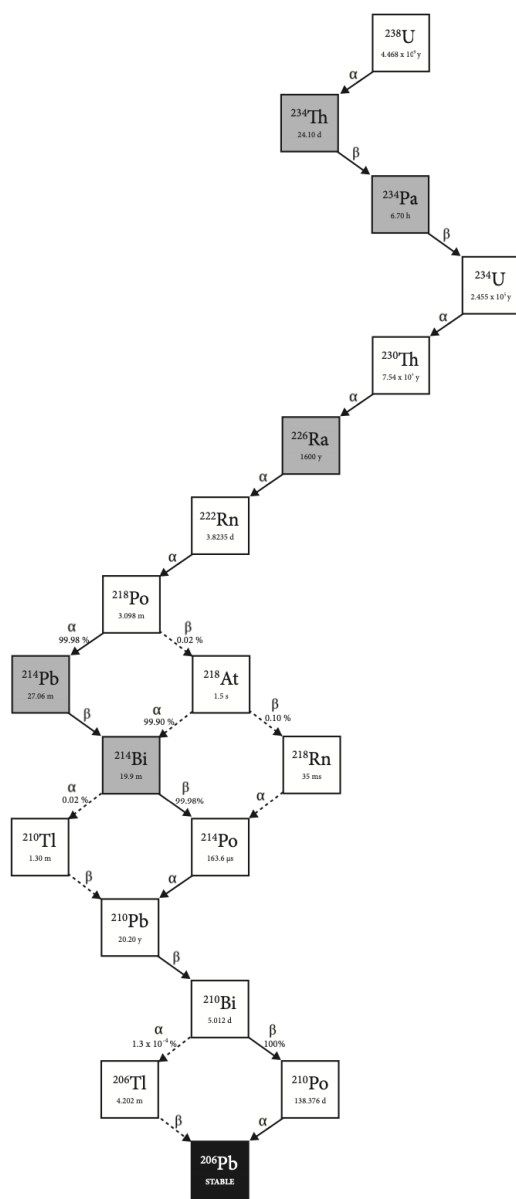


Figure 3.9: Actinium radioactive series [26]. It represents the successive decays from the parent nucleus ^{235}U until the stable nucleus ^{207}Pb is reached (black square). The easiest nuclei to detect by gamma spectroscopy, because of their outstanding photopeaks, are filled in grey (considering a small-sized germanium detector).

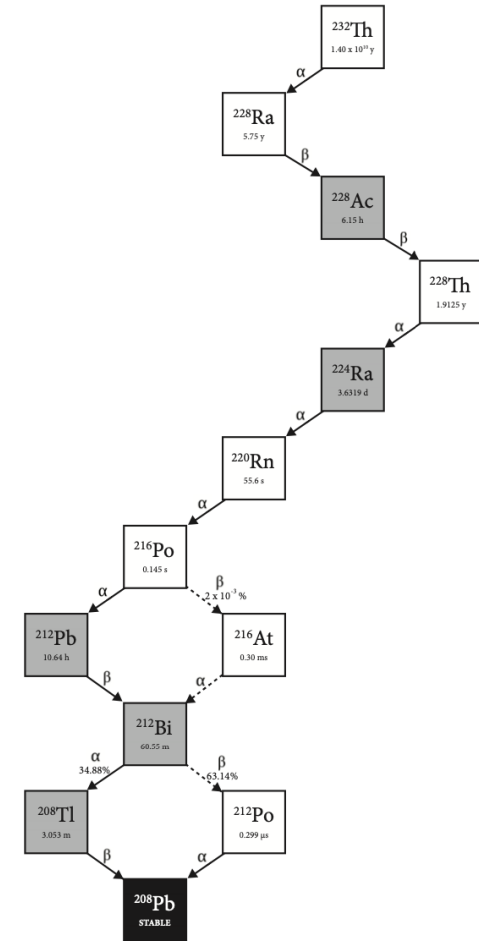


Figure 3.10: Thorium radioactive series [26]. It represents the successive decays from the parent nucleus ^{232}Th until the stable nucleus ^{208}Pb is reached (black square). The easiest nuclei to detect by gamma spectroscopy, because of their outstanding photopeaks, are highlighted in grey (considering a small-sized germanium detector).

Figure 3.8: Uranium radioactive series [26]. It represents the successive decays from the parent nucleus ^{238}U until the stable nucleus ^{206}Pb is reached (black square). The easiest nuclei to detect by gamma spectroscopy, because of their outstanding photopeaks, are highlighted in grey (considering a small-sized germanium detector).

CÁLCULO DA LONXITUDE DO DETECTOR					
Distancia (cm)	Ángulo cenital / % de cósmicos	Lonxitude (cm)	Distancia (cm)	Ángulo cenital / % de cósmicos	Lonxitude (cm)
30	45° / 81,8 %	60	50	45° / 81,8 %	100
	55° / 91 %	86		55° / 91 %	143
	65° / 96,6 %	129		65° / 96,6 %	215
40	45° / 81,8 %	80	60	45° / 81,8 %	120
	55° / 91 %	114		55° / 91 %	171
	65° / 96,6 %	172		65° / 96,6 %	257

Táboa 1: Cálculo da lonxitude total (diámetro no caso de detector circular) que permite cubrir un determinado ángulo cenital de 45°, 55° e 65° para os raios cósmicos que cruzan o procesador, en función da distancia do plano detector. Inclúese o porcentaxe da distribución entrante da radiación cósmica cuberto dentro de ese ángulo cenital.

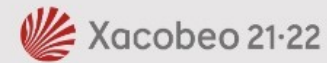
COBERTURA ANGULAR E PORCENTAXE DE COSMICOS NA ACEPTANCIA

Distancia ao procesador (cm)	Angular cenital máximo para o plano 1 (graos)	Angular cenital máximo para o plano 2 (graos)	Porcentaxe da distribución entrante (plano 1)	Porcentaxe da distribución entrante (plano 2)
30	59,0	68,2	93,66 %	97,73 %
40	51,3	61,9	88,06 %	95,23 %
50	45,0	56,3	81,83 %	91,94 %
60	39,8	51,3	75,53 %	88,06 %
70	35,5	47,0	69,54 %	83,97 %
80	32,0	43,2	64,16 %	79,77 %

Táboa 2: Cobertura angular (angulo cenital máximo detectable) e porcentaxe da distribución de radiación cósmicos incidente no dispositivo cuántico detectable en función da distancia entre os planos de detección e o procesador. A información avalíase para cada plano por separado por mor do seu diferente tamaño nesta proposta.

A iniciativa do Polo de Tecnoloxías Cuánticas de Galicia conta con financiamento de:

Fondos REACT EU



Despregamento dunha infraestrutura baseada en tecnoloxías cuánticas da información que permita impulsar a I+D+i en Galicia.

Apoiar a transición cara a unha economía dixital.

Operación financiada pola Unión Europea, a través do FONDO EUROPEO DE DESENVOLVEMENTO REXIONAL (FEDER), como parte da resposta da Unión á pandemia da COVID-19.

PROGRAMA OPERATIVO
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Unha maneira de facer Europa