diagnostic technologies in high-sensitivity experiments to detect ultra-rare events

ICFDT8 8th International Conference on Frontier in Diagnostic Technologies

Giovanni Mazzitelli • LNF-INFN / Oct 19–21, 2026 Frascati

what we are talking about?

diagnostics in astroparticle physics

- **astroparticle physics** connects **particle physics, astrophysics and cosmology**, searching for signals such as **dark matter, neutrinos, cosmic rays, gamma rays, gravitational waves and rare decays**.

- many of these searches operate in an **ultra-rare or ultra-weak signal** regime: signals can be **sparse, transient or extremely small, and are often hidden by detector, environmental or physical backgrounds**.

how can we reliably measure a very small signal?

can we demonstrate that a signal-like observation is not explained by detector effects, environment or known backgrounds?

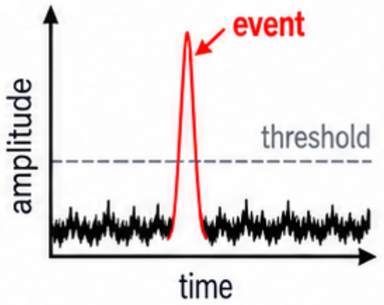
- this is why **diagnostics are part of the physics measurement**.

search paradigms in rare-event experiments

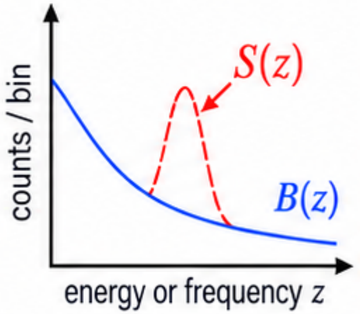
1. Search paradigms

A. Individually identifiable events

event-by-event identification



B. Statistical excess over background



No validated candidate / no significant excess → **Upper limit**

Validated candidate / significant excess → **Candidate signal / detection**

2. Sensitivity in a counting experiment

$$N_{\mathrm{sig}} = E \cdot \varepsilon \cdot \theta$$

- E: exposure
- ε: total signal efficiency
- θ: parameter of interest

$$\varepsilon = \varepsilon_{\mathrm{det}} \cdot \varepsilon_s$$

- $\varepsilon_{\mathrm{det}}$: detector / reconstruction efficiency
- ε_s: signal acceptance after selections

Background-dominated regime $(B' \gg 1)$

$$\theta_{\mathrm{UL}} \propto \frac{\sqrt{r_b}}{\varepsilon\sqrt{E}} \sim \frac{1}{\sqrt{E}}$$

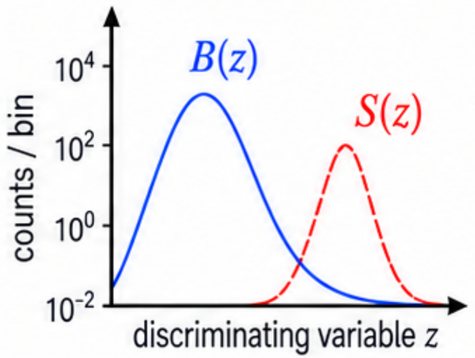
Sensitivity improves by reducing residual background and preserving signal efficiency.

Background-free regime $(B' \ll 1)$

$$\theta_{\mathrm{UL}} \propto \frac{1}{\varepsilon E} \sim \frac{1}{E}$$

If residual background after selections is $\ll 1$, the search recovers the more favorable 1/E scaling.

3. Role of diagnostics



$$S' = \varepsilon_s S$$
$$B' = r_b B$$

Reduce background leakage
Lower $r_b \rightarrow$ better sensitivity

Keep high signal acceptance
High $\varepsilon_s \rightarrow$ preserve sensitivity

In favorable cases: reach background-free

$$B' \ll 1 \rightarrow \theta_{\mathrm{UL}} \propto \frac{1}{\varepsilon E}$$

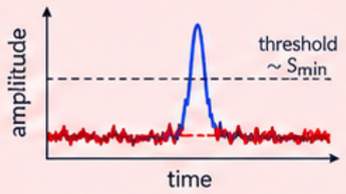
diagnostics improve sensitivity and **reliability** by reducing background leakage while preserving signal acceptance and, in favorable cases, recovering the **background-free 1/E sensitivity scaling**

diagnostics vs sensitivity

A signal-like fluctuation becomes physics only after independent controls agree

Intrinsic detector noise

What the primary detector measures and its irreducible noise



- Electronic noise, dark counts
- Energy / time resolution
- Threshold
- Irreducible instrumental background

Main effect on:

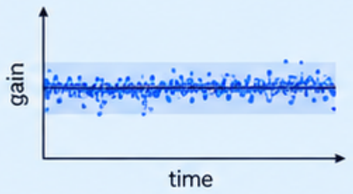
S_{min}

(minimum detectable signal)

Limited leverage once the detector is built (larger during design).

Detector health

Gain, baseline, noise, dead channels, trigger behaviour



- Gain and baseline stability
- Noise and channel quality
- Dead/noisy channels
- Trigger efficiency and stability

Main effect on:

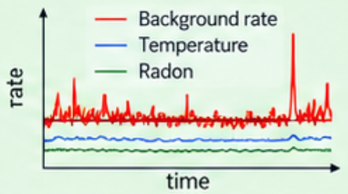
$E, \epsilon, B(x)$

(stability and usability)

Keeps the detector response stable and usable over time.

Environment

Temperature, pressure, radon, vibrations, magnetic / acoustic fields



- Environmental monitoring
- Correlations with background rate
- Identification of disturbed periods
- External backgrounds (neutrons, radon, ...)

Main effect on:

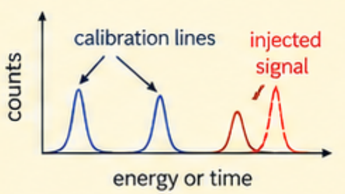
$B(x), E$

(time-dependent background)

Identifies and mitigates environment-induced backgrounds.

Calibration & timing

Sources, injected signals, clocks, synchronization



- Energy / time scale and resolution
- Detector response and linearity
- Trigger calibration (efficiency)
- Clock stability and synchronization (main detector + veto)

Main effect on:

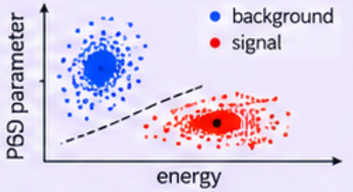
$\epsilon, B(x)$

(energy/time scale, response)

Keeps the detector response physically interpretable and synchronized.

Background identification & rejection

Pulse-shape discrimination, topology, fiducialisation, anticoincidence, vetoes (muons, ...)



- Pulse-shape discrimination (PSD)
- Event topology
- Fiducial cuts
- Veto detectors (muons, neutrons)
- Coincidences / anticoincidences
- Multivariate selections

Main effect on:

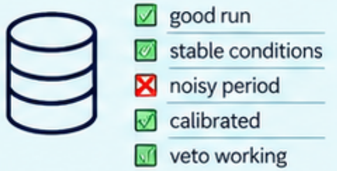
ϵ_s, r_b

(signal efficiency and rejection)

Separates signal-like from background-like events.

Data quality

Reproducible detector-state information propagated into analysis



- Run selection and quality flags
- Detector configuration and conditions
- Provenance and reproducibility
- Systematic uncertainties

Main effect on:

$E, \epsilon, B(x)$

(effective exposure and systematics)

Ensures a clean, well understood dataset for the analysis.

diagnostics determine **sensitivity and reliability**: not only how small a signal can be measured, but how confidently instrumental and background explanations can be constrained

some examples…

sensitivity tells us what we can see; diagnostics tell us whether we can trust it.

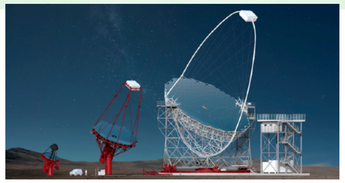
Intrinsic detector noise
What the primary detector measures and its irreducible noise



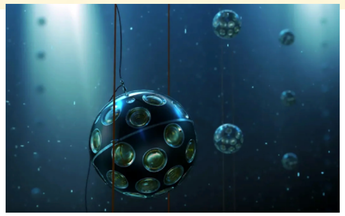
Detector health
Gain, baseline, noise, dead channels, trigger behaviour



Environment
Temperature, pressure, radon, vibrations, magnetic / acoustic fields



Calibration & timing
Sources, injected signals, clocks, synchronization



Background identification & rejection
Pulse-shape discrimination, topology, fiducialisation, anticoincidence, vetoes (muons, …)



Data quality
Reproducible detector-state information propagated into analysis



KM3NeT
ns timing and continuously reconstructed detector geometry enter directly into event reconstruction

CUPID
heat/light discrimination, pulse shape and vetoes directly control ϵ_s and r_b

QUAX-FLASH
the noise floor directly sets the smallest extractable signal

LIGO / Virgo
auxiliary channels, state vectors, vetoes and DQ flags are essential to validate candidates

XENONnT/LZ
purity, electron lifetime, gains, liquid level and channel status determine stable detector response

CTAO/CYGNO
environmental conditions affect detector response

intrinsic detector noise

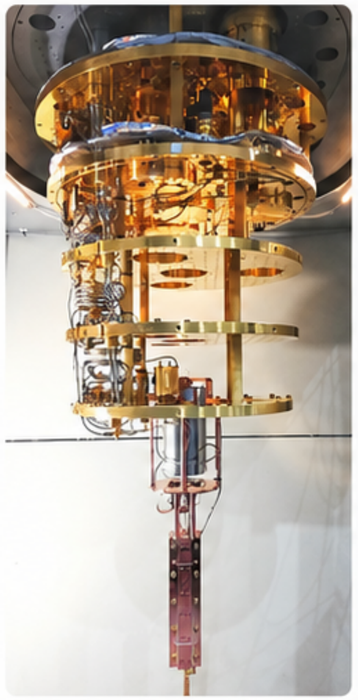
Intrinsic detector noise
What the primary detector measures and its irreducible noise

FLASH/QUAX — resonant detector for HFGW & axion searches

FLASH is part of the global GravNet collaboration for HFGW search / QUAX is an operating axion haloscope

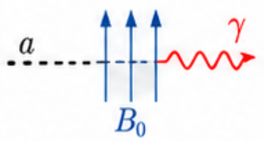
1. Resonant cavity concept

Same detector family, different weak couplings



Axion conversion

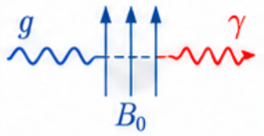
$a + B_0 \rightarrow \gamma$



axion-photon conversion in a static magnetic field

Gertsenshtein effect

$g + B_0 \rightarrow \gamma$

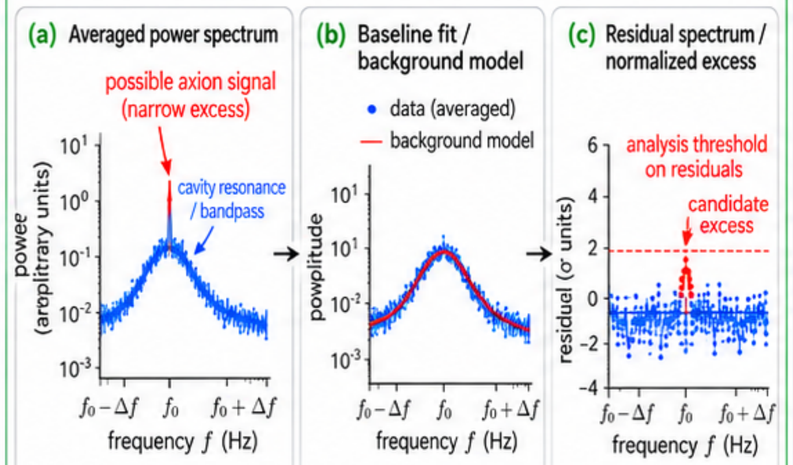


HFGW to electromagentic conversion in a static magnetic field

Resonant cavity + strong magnetic field + ultra-low noise readout

2. Axion haloscope search (QUAX-style)

Frequency-domain excess search after baseline subtraction



- Search for statistically significant narrow excesses
- No excess → upper limit; candidate excess → rescan / confirmation
- Noise floor sets the smallest detectable signal power

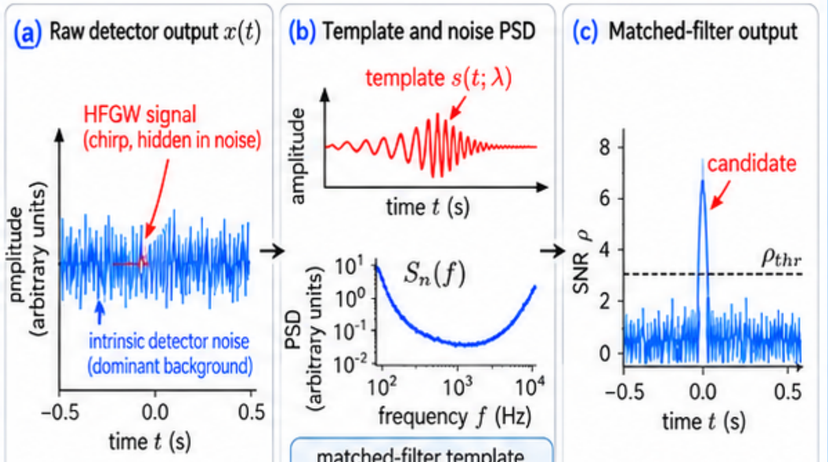
$$\mathrm{SNR} = \frac{P_a}{\delta P_{\mathrm{noise}}}$$

P_a : signal power from axion conversion at the cavity output

$\delta P_{\mathrm{noise}}$: rms noise power per frequency bin (after averaging)

3. Transient HFGW search (FLASH / GravNet-like)

Time-domain waveform search with matched filtering



matched-filter template

$$q(f) \propto \frac{s^*(f)}{S_n(f)}$$

- Optimal filtering weights the waveform by the detector noise PSD
- Sensitivity is set by the minimum waveform amplitude giving $\rho > \rho_{thr}$
- Instrumental transients can mimic the matched-filter response

$$\rho^2 = 4\int_0^\infty \frac{|s(f)|^2}{S_n(f)}\,\mathrm{df}$$

$s(t;\lambda)$: template waveform with parameters λ
$S_n(f)$: one-sided noise PSD
ρ : matched-filter SNR
ρ_{thr} : detection threshold

intrinsic noise sets the **ultimate sensitivity**, while **diagnostics** provide the **reliability** needed to establish that the noise floor is stable and understood

axion search at QUAX

Intrinsic detector noise
What the primary detector measures and its irreducible noise

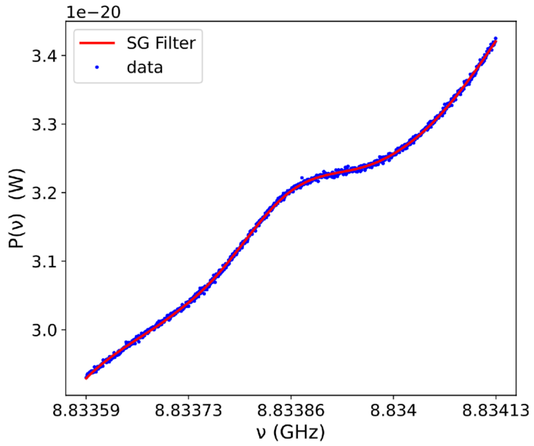


FIG. 5. FFT cavity power spectrum (blue dots) and SG filter (red line). $\nu_c = 8.833862$ GHz, $Q_L = 32540$.

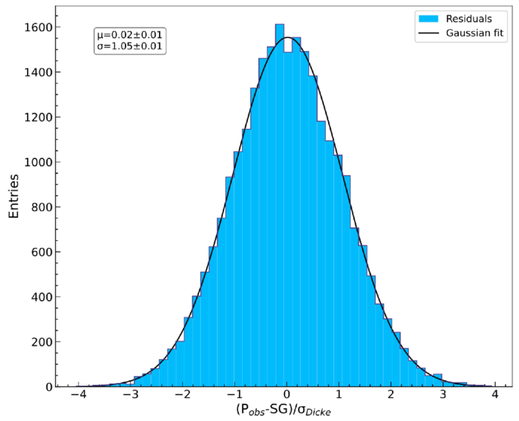
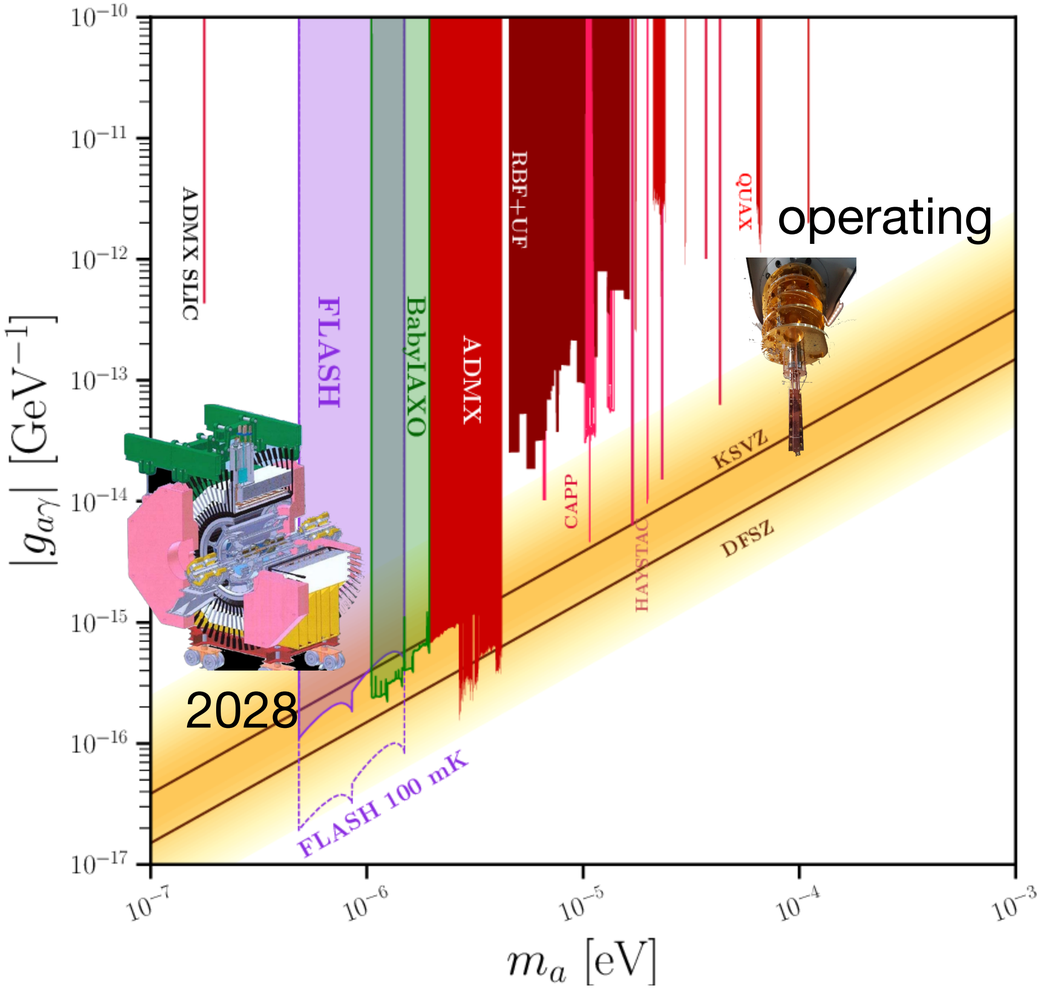


FIG. 6. Distribution of the cumulative residuals normalized to σ_{Dicke}.

$$\sigma_{\mathrm{Dicke}} = k_B T_{\mathrm{sys}} \sqrt{\Delta\nu/\Delta t}$$

where Tsys, is the system noise temperature, Δν is the bin width (500 Hz) and Δt is the integration time (3764 s)



noise characterization provides the **sensitivity and reliability** required to turn a weak spectral excess into a statistically interpretable signal or upper limit

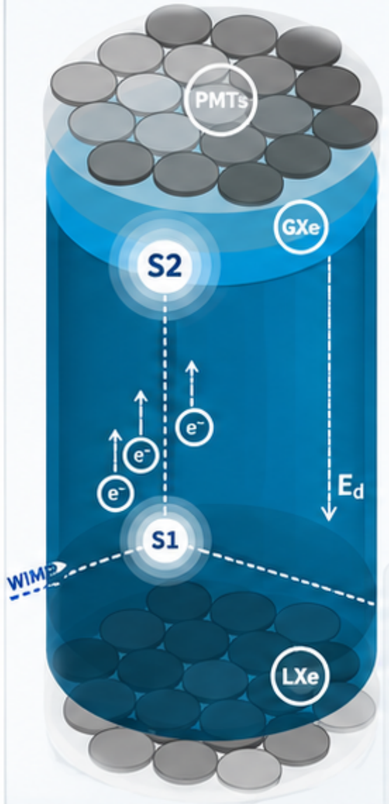
detector health

Detector health
Gain, baseline, noise, dead channels, trigger behaviour

XENONnT — dual-phase liquid Xe TPC for dark matter search

related: LZ • PandaX-4T • DARWIN

Dual-phase LXe TPC



interaction
energy deposit

↓

S1 + e⁻
light + charge

↓

S2
gas electrolum.

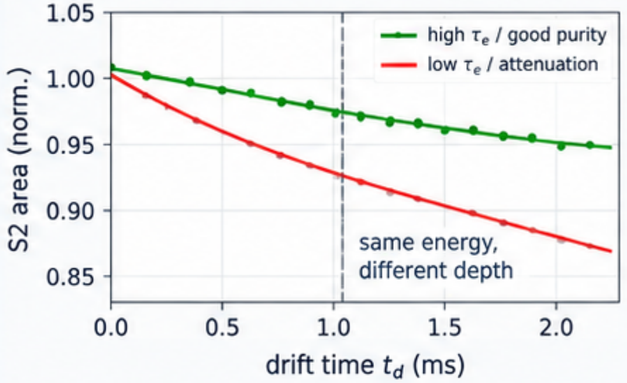
$$S2(t_d) = S2_0 \exp(-t_d / \tau_e)$$

t_d : electron drift time
τ_e : electron lifetime (xenon purity)

lower purity → depth-dependent S2 correction

Response stability

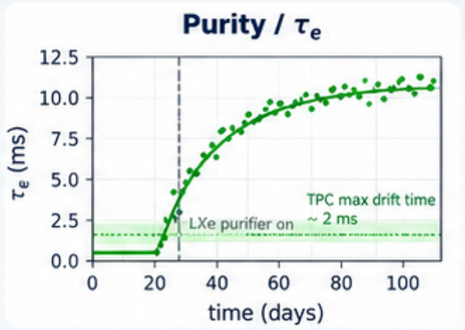
same physical event → same reconstructed response

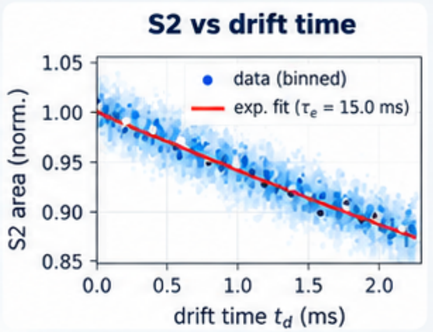


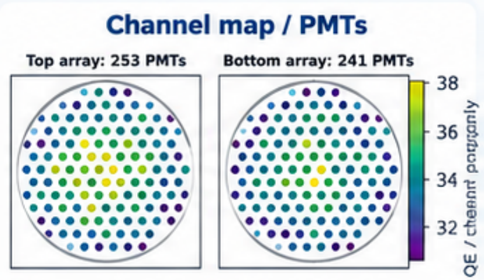
What must be monitored

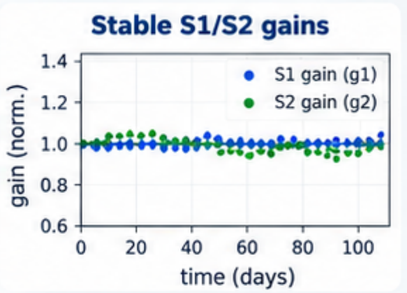
- **Purity / electron lifetime**
  charge survival and S2 correction
- **g1, g2, PMT gains**
  energy scale and discrimination variables
- **Liquid level / fields**
  extraction and electroluminescence stability
- **Channel status**
  dead/noisy PMTs and reconstruction quality

Health monitoring → analysis quantities









Main effect on sensitivity quantities

E	ε	$B(x)$
usable exposure	**overall efficiency**	**background model**
exclude unstable periods	trigger/reconstruction/ selection	avoid response-induced distortions

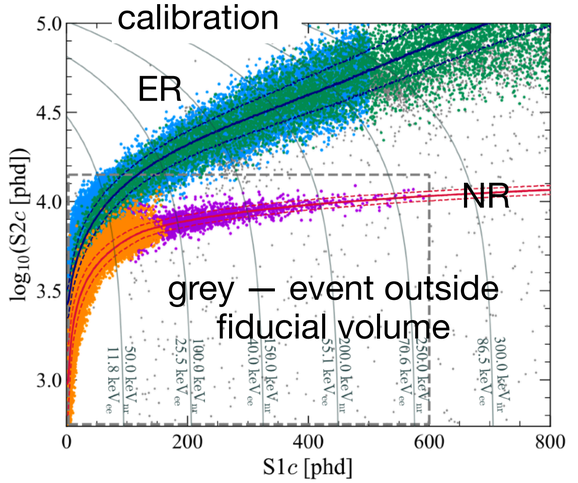
detector-health diagnostics preserve **reliability and comparability** by keeping the detector response stable, measured and correctable over the full exposure

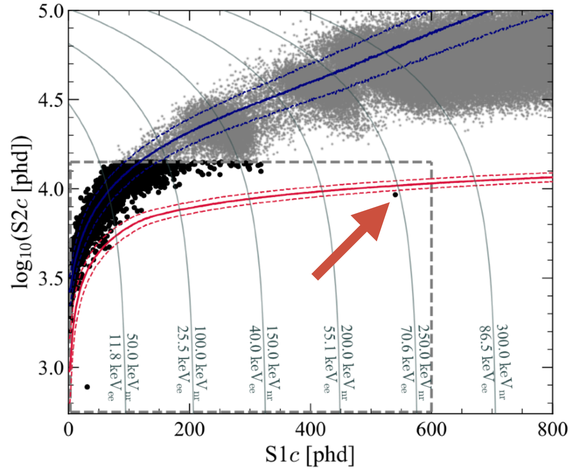
LUX-ZEPLIN (LZ) signal-like event!

Detector health
Gain, baseline, noise, dead channels, trigger behaviour

LZ high-energy candidate: intriguing, but not yet evidence

- **different analysis strategy**: the standard XENONnT DM search is optimized for low-energy elastic nuclear recoils, with significant efficiency mainly below ~**60–70 keV$_{NR}$; it is therefore not directly sensitive to the LZ candidate at~248 keV$_{NR}$**
- **LZ deliberately extends the NR search to high energy**: the response is calibrated with high-energy neutron data and the **analysis window and background model are extended up to ~270 keV$_{NR}$**, targeting NREFT and inelastic-DM scenarios.
- **no obvious instrumental or background explanation was found**: detector response, calibration history, muons, accidentals, neutron backgrounds and ER leakage were all explicitly checked.
- **but one event is still one event**: the excess (3.4σ local / 2.6σ global) is intriguing, not evidence. Confirmation requires **more LZ exposure and, ideally, an independent high-energy NR analysis by XENONnT/PandaX**.





reliability requires that a **signal-like event survives detector diagnostics,** background checks and independent controls before it can be interpreted as physics

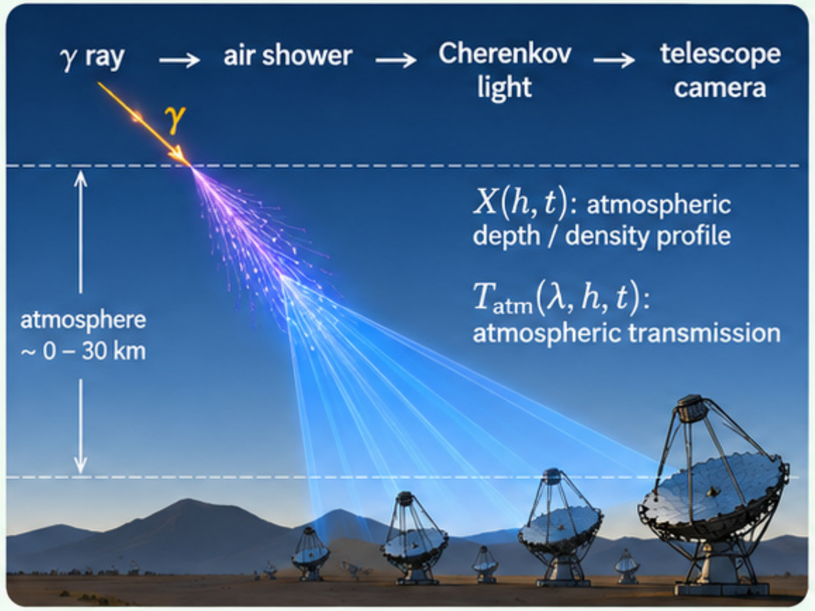
environment

Environment
Temperature, pressure, radon, vibrations, magnetic / acoustic fields

CTAO — cherenkov telescope array observatory studying Universe through gamma radiation

CTAO has sites in both the Northern and Southern Hemispheres
related: Pierre Auger • LHAASO • SWGO

1. From gamma ray to measured light



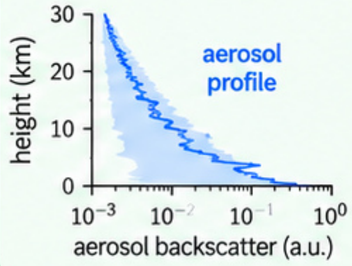
$$N_{\mathrm{pe}} \propto E_\gamma \, Y_{\mathrm{Ch}} \, T_{\mathrm{attm}}$$

N_{pe}: detected photoelectrons; E_γ: gamma-ray energy; Y_{Ch}: Cherenkov-light yield

Both shower development and light transmission depend on the atmosphere.

2. Atmospheric diagnostics

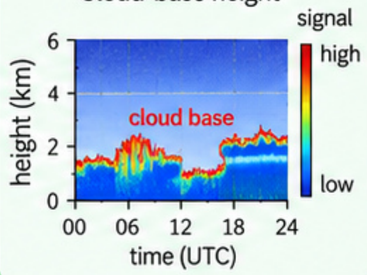
Raman LIDAR
Aerosol / transmission profile (vs. height)



All-sky / cloud camera
Cloud coverage and type (whole sky)



Ceilometer
Cloud-base height



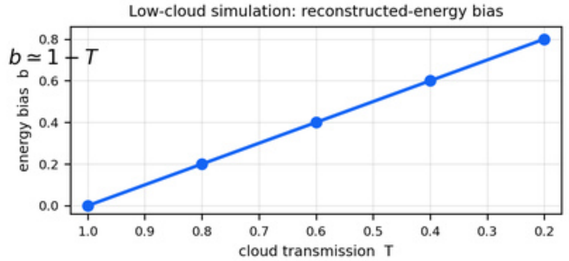
Weather station
Temperature, pressure, humidity, wind

T	12.3 °C
p	680 hPa
RH	23 %
wind	6 m/s (NW)

Continuous monitoring defines usable observation conditions.

3. Impact on the response

Published CTA / IACT simulations



Quantitative impact

- **Energy resolution:**
  < 9% clear sky; < 13% for T >= 0.6, E > ~2 TeV
- **Corrected flux:**
  < 20% systematic uncertainty for T >= 0.6 in 2-30 TeV
- **Atmospheric calibration:**
  transmission and molecular profiles affect energy scale, flux and usable exposure

Main effect on:
B(x), E, ε

Refs: Sobczynska et al., Astropart. Phys. 120 (2020) 102450;
Ebr et al., arXiv:1709.04273; Pecimotika et al., PoS(ICRC2021)773.

atmospheric diagnostics preserve **reliability and comparability** by keeping the detector response calibrated under changing observing conditions

run-to-run normalization

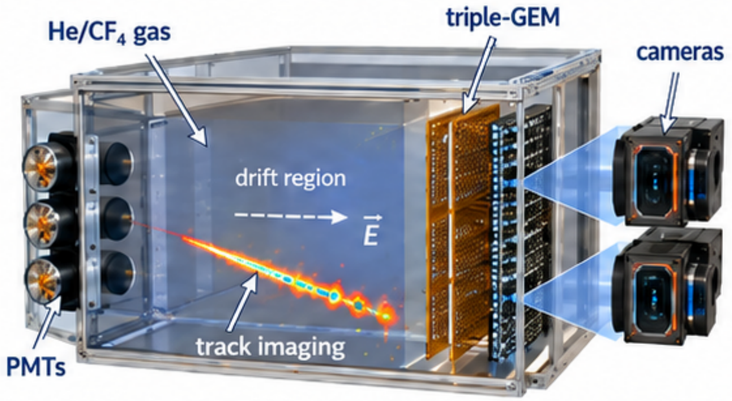
CYGNO - directional dark matter search

environment & data quality
pressure / response normalization / combined datasets

CYGNO LNGS as part of the international CYGNUS programme for directional dark-matter searches

1. The detector and the source of variability

Optical-readout gaseous TPC



atmospheric pressure | temperature | gain / HV | gas conditions

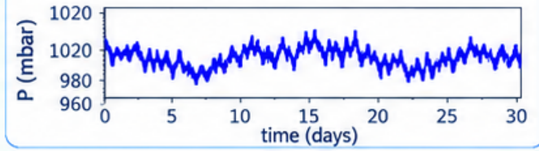
- Gas gain and track observables depend on pressure and operating conditions
- The same physical event can look different in different runs
- Without corrections, different runs are not directly comparable

$response = response(P, T, HV, gas)$

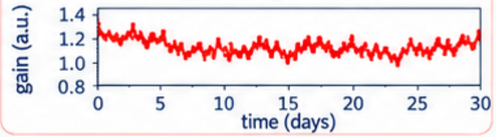
2. Diagnostics and correction

Monitor → correlate → derive correction

(a) Monitor environmental conditions
atmospheric pressure P(t)

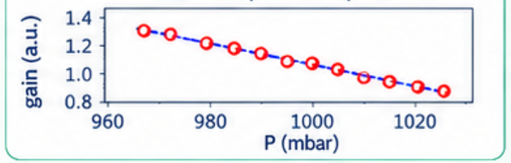


(b) Monitor detector response
gain / signal G(t)



correlate the variations

(c) Measured dependence
detector response vs pressure



derive correction function

(d) Apply run-by-run correction

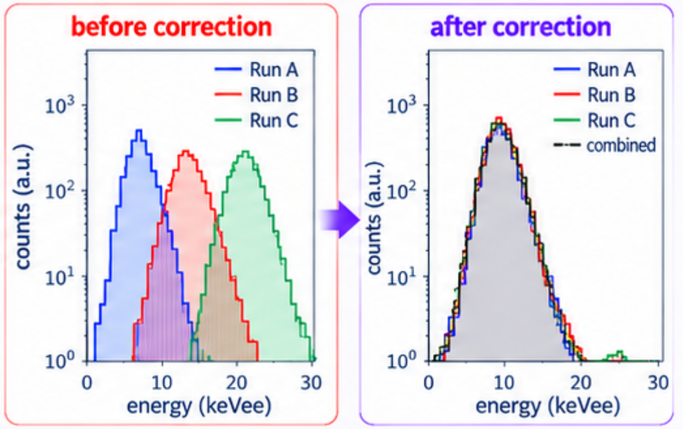
$x_{corr} = f(x_{raw}, P, T, \ldots)$

e.g. $x_{corr} = x_{raw} / C(P, T, \ldots)$ with C from data

Diagnostics convert environmental variations into a measurable correction.

3. Why it matters

Combining heterogeneous runs into one dataset



Run A E_A + Run B E_B + Run C E_C → corrected response → one homogeneous dataset

$$E_{usable} = \sum_i E_i$$

Common detector response
Runs taken at different conditions are put on the same scale.

Larger usable exposure
Corrected runs can be safely combined: $E_{usable} = \sum_i E_i$.

Reduced systematic uncertainty
Environmental variations are accounted for, leading to smaller systematics and better sensitivity.

diagnostics provide **comparability** by normalizing data taken under different conditions, **increasing usable exposure and reducing systematic uncertainties**

calibration & timing

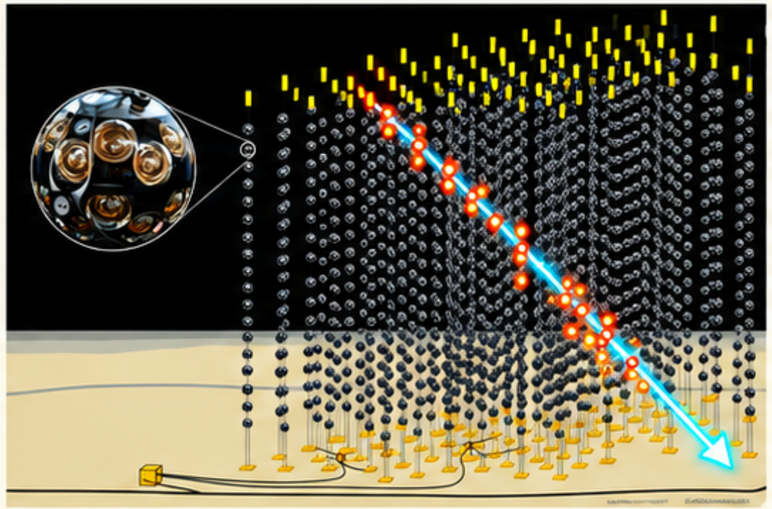
Calibration & timing
Sources, injected signals, clocks, synchronization

KM3NeT — a deep-sea neutrino telescope: nanosecond timing and dynamic geometry calibration

KM3NeT consists of two detector sites in the Mediterranean Sea. related: IceCube / IceCube-Gen2 • Baikal-GVD

1. From photons to a track

Each hit contributes time, position and charge



$$\{ t_i , \vec{r}_i(t) , q_i \} \rightarrow \text{track fit}$$

t_i: hit time, $r_i(t)$: DOM position, q_i: hit charge

- PMT hit times, positions and charges feed the fit
- Detector geometry changes with sea currents
- Timing + geometry are part of the measurement

2. Calibration infrastructure

Continuous timing and positioning calibration

White Rabbit clock sub-ns synchronization → **< 1 ns**

Nanobeacons / 40K / muons relative timing calibration → timing calibration

Acoustic positioning DOM positions → **~ 10 cm**

Compass + tilt sensors orientation → **~ 3°**

Calibration continuously updates when and where each photon was detected.

3. Published performance

Representative calibration figures from KM3NeT documentation

- Relative timing offsets stable within ~1 ns — ~ 1 ns
- Acoustic positioning accuracy ~10 cm — ~ 10 cm
- Orientation known to ~3° — ~ 3°
- Position calibration consistent with muon-based checks at the ~10 cm level — ~ 10 cm

Main effect on: E, ε, B(x)
timing / geometry calibration preserve response and angular reconstruction

Refs: S. Biagi et al., EPJ Web Conf. 116 (2016) 05002; F. Bretaudeau et al., PoS(ICRC2023)1033; A. Sánchez Losa et al., PoS(ICRC2023)1062.

timing and geometry calibration provide the **reliability** required to reconstruct when and where each photon was detected

background identification & rejection

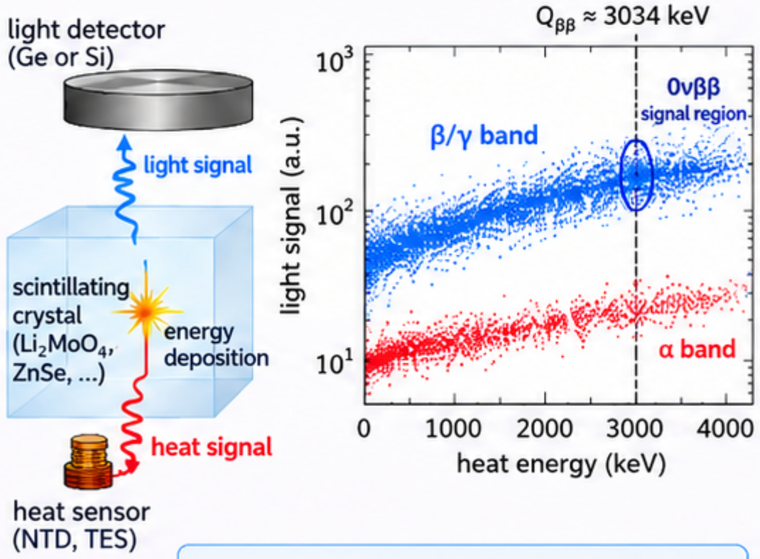
Background identification & rejection
Pulse-shape discrimination, topology, fiducialisation, anticoincidence, vetoes (muons, ...)

CUPID — search for neutrinoless double-beta decay (0νββ) in Li_2MoO_4 scintillating crystals

CUPID is the planned upgrade of CUORE at LNGS
related: LEGEND • nEXO • KamLAND-Zen

1. Heat + light give particle identification

Scintillating bolometers separate α from β/γ events



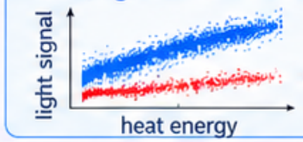
$\{E_{heat}, E_{light}\} \rightarrow$ particle ID

- Scintillation light adds particle ID
- β/γ and α populate distinct bands
- 0νββ lies in the β/γ-like band

2. Rejection tools and selection

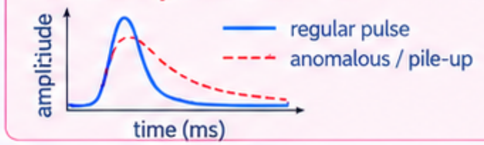
Keep signal-like events, suppress background-like events

Heat/light discrimination



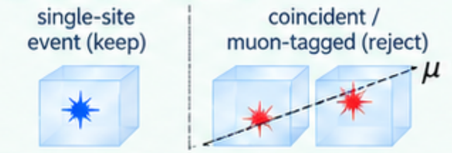
0νββ signal regigaln → reject α-like events

Pulse-shape discrimination



→ reject non-physical pulses

Coincidence / vetoes



→ reject coincident events

ε_s = accepted signal fraction
r_b = accepted background fraction (background leakage)

$S' = \varepsilon_s S$ $\quad B' = r_b B$

Goal: $\varepsilon_s \rightarrow 1$, $r_b \rightarrow 0$

3. Published performance

Representative numbers from CUPID demonstrators and prototypes

- **α rejection > 99.9%** with equally high β/γ acceptance in the ROI — > 99.9%
- **Energy resolution:** 5.3 keV FWHM at 2615 keV (calibration), 6.5 keV in physics data — 5.3 / 6.5 keV
- **Muon-veto prototype detection efficiency: (98 ± 1)%** — (98 ± 1)%
- **ROI background down to ~ 10^{-4} counts/(keV kg yr)** in CUPID-0 — ~ 10^{-4}

Main effect on: ε_s, r_b
particle identification, pulse shape and vetoes preserve signal efficiency while suppressing background leakage

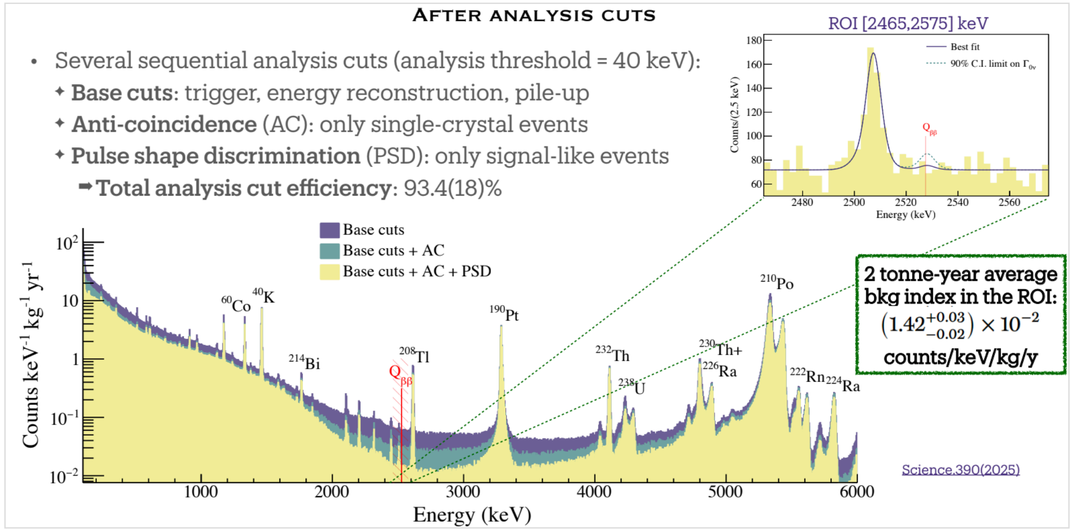
Refs: CUPID-Mo performance & prospects (EPJC 2020); Optimization of the first CUPID detector module (2022); CUPID muon-veto prototype (2025); CUPID-0 background model (2019).

particle identification and vetoes improve **sensitivity and reliability** by keeping signal acceptance high while suppressing background leakage

CUPID pile-up control

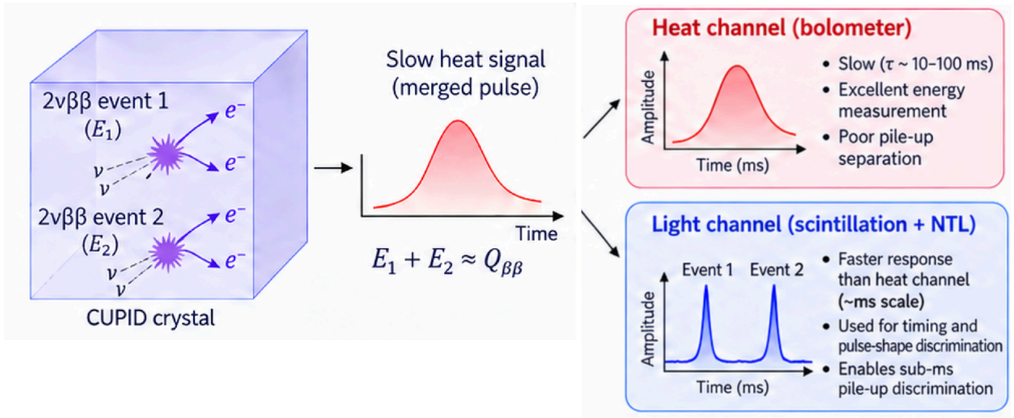
Background identification & rejection
Pulse-shape discrimination, topology, fiducialisation, anticoincidence, vetoes (muons, ...)

while CUORE has achieved world-leading sensitivity to 0νββ decay, CUPID (CUORE Upgrade with Particle IDentification), based on ^{100}Mo, must address a new background near $Q_{\beta\beta}$: pile-up from unresolved 2νββ decays.



why CUORE is much less affected: ^{130}Te has a much longer 2νββ half-life, $T_{1/2} \sim 7.7\times10^{20}$y, versus 7.1×10^{18} y for ^{100}Mo. Together with the natural \ ^{130}Te abundance in CUORE, this gives a 2νββ rate of only ~ 0.03 mHz/crystal, compared with ~2.6 mHz/crystal in CUPID. Thus 2νββ pile-up is not a dominant CUORE background.

- **problem**: the slow thermal response can merge two independent 2νββ decays into a single event with $E_1+E_2 \sim Q_{\beta\beta}$
- **why it matters**: ^{100}Mo has a relatively high 2νββ rate; unresolved coincidences can become an irreducible-looking background in the 0νββ ROI.
- **solution**: use the **faster scintillation-light channel** for **pulse-shape discrimination**;
- **goal**: **reduce pile-up** from **3x10^{-4} to 5x10^{-5}** counts/(keV kg yr).



fast-light diagnostics improve **sensitivity and reliability** by identifying unresolved 2νββ pile-up that can mimic a 0νββ event

data quality

LVK - gravitational-wave observatories

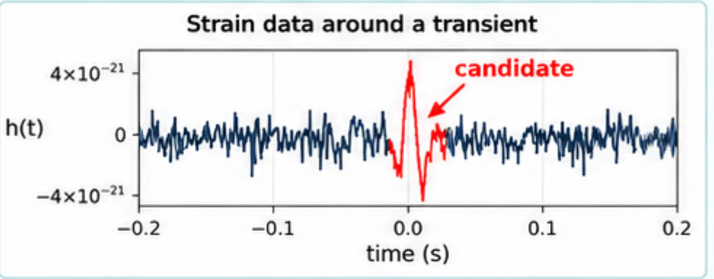
Data quality
Reproducible detector-state information propagated into analysis

LIGO in the United States, Virgo in Italy and KAGRA in Japan

1. Strain transient → candidate

A trigger in h(t) is not yet an astrophysical event





h(t) + detector state + auxiliary channels

no DQ concern → **validated**

DQ flag / veto → **vetoed**

Candidate validation uses detector state and independent witnesses.

2. Data-quality workflow

DQ information is propagated into the analysis

state vectors
- science mode; calibration valid
- DAQ OK; no hardware injections

↓

auxiliary channels
- seismic, acoustic, magnetic, controls
- alignment and weather monitors

↓

DQ flags / vetoes
- known bad segments
- noise-correlated intervals

↓

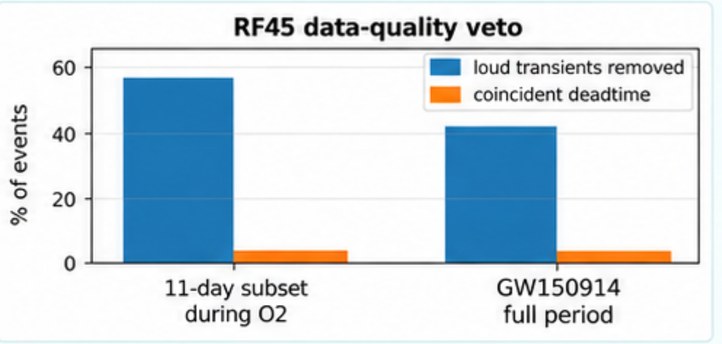
candidate validation
- event-by-event checks
- background estimation

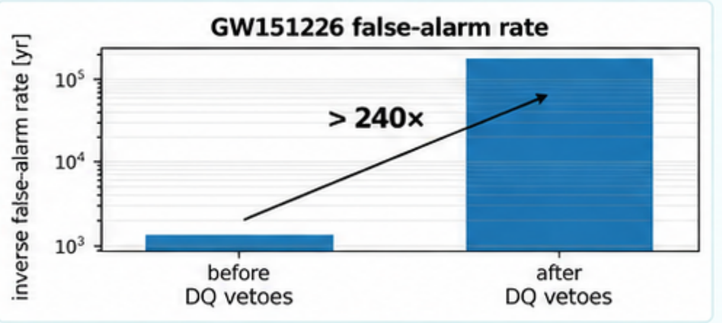
↓

DQ flags define usable data and veto unsafe intervals

3. Published impact

Real detector-characterization results





GW150914 PEM checks
Ambient fluctuations too small to explain the strain. **< 6%**

Refs: Abbott et al., CQG 33, 134001 (2016); Abbott et al., CQG 35, 065010 (2018); Virgo public DQ documentation.

data-quality diagnostics provide **reliability** by excluding instrumental explanations and **validating** the data around a strain transient

offline computing

from acquisition to reproducible physics

Computing model
reproducible reconstruction, calibration, simulation, data quality and reprocessing

1. Preserve unique data

Acquisition and archiving are part of the physics strategy



Example computing centre: CNAF / CINECA

- unique and unrepeatable data (e.g. cosmic events) constrain uptime and dead time
- data may be acquired in extreme or inaccessible conditions (space, deep sea, ice, underground), limiting interventions and setup changes
- offline requires complete raw data, metadata and detector conditions
- integrity, provenance and recovery directly protect the physics sample

E_raw -> E_usable starts from preservation

2. Reconstruct, calibrate, simulate

Offline gives physical meaning to the raw data

raw data + conditions + templates / Monte Carlo -> reconstructed event

calibration constants
energy scale, timing, alignment, detector response

↓

conditions database
environment, detector state, channel status, quality flags

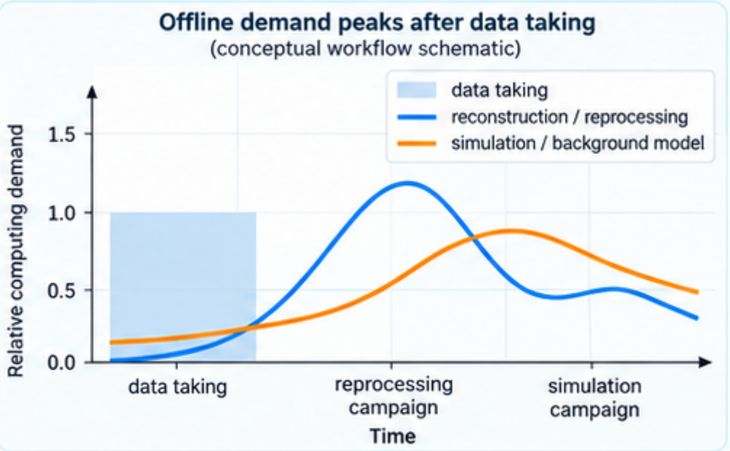
↓

templates and Monte Carlo
needed not only for systematics, but also to identify candidate events (e.g. GW, air showers, rare-event topologies)

offline estimates: $B(x)$, ε, ε_s, r_b
background model, efficiencies and systematics

3. Reprocess and scale resources

Offline campaigns are discontinuous and resource-intensive



- new calibrations or detector-response updates can require repeated re-reconstruction
- resource usage is discontinuous, with peaks during reprocessing campaigns
- computing infrastructure must absorb bursts, not only average annual volume

Main effect on: E, ε, B(x), systematics

calibration, conditions, simulation and reprocessing provide **reproducibility**, turning raw detector output into a traceable and **repeatable physics measurement**

conclusion

diagnostics turn detector performance into physics

- **sensitivity**: the smallest measurable signal is set by the detector noise, **but the effective sensitivity also depends on usable exposure, efficiency, background knowledge and systematic uncertainties.**

- **reliability:** detector health, environment, calibration, timing, background rejection and data quality **are therefore not ancillary systems, but they determine which data can be trusted and used for physics.**

- **comparability**: diagnostics also make data taken at different times and under different conditions comparable, **increasing usable exposure and reducing systematic uncertainties**.

- **reproducibility**: calibration, detector conditions, simulations, templates, data-quality information and reprocessing turn raw detector output into a **reproducible physics measurement**.

$$\text{detector} + \text{diagnostics} + \text{offline computing} \longrightarrow \text{physics result}$$

diagnostics turn detector performance into sensitivity, reliability, comparability and reproducibility the conditions required for an ultra-rare signal to become a physics result

references

selected references for the diagnostic technologies / ultra-rare events talk

GENERAL / STATISTICS

[1] APPEC, European Astroparticle Physics Strategy 2017-2026; Mid-term update (2023).
[2] Cowan, Cranmer, Gross & Vitells, EPJC 71 (2011) 1554, arXiv:1007.1727.
[3] Feldman & Cousins, PRD 57 (1998) 3873.

RESONANT / HFGW / AXION

[4] Alesini et al., Phys. Dark Univ. 42 (2023) 101370 — FLASH.
[5] Rettaroli et al., PRD 110 (2024) 022008, arXiv:2402.19063 — QUAX-LNF.
[6] Allen et al., PRD 85 (2012) 122006 — matched filtering.
[7] Amaral et al., arXiv:2603.24645 — GravNet conceptual design.

DARK MATTER / LIQUID-XE TPCs

[8] XENON Collab., EPJC 84 (2024) 784 — XENONnT detector.
[9] XENON Collab., PRD 111 (2025) 062006 — reconstruction/calibration.
[10] XENON Collab., arXiv:2502.18005 — standard WIMP search.
[11] LZ Collab., arXiv:2609.02823 — extended NR energy window.

CTAO / ATMOSPHERE

[12] Acharya et al., Astropart. Phys. 43 (2013) 3 — CTA concept.
[13] Ebr et al., arXiv:1709.04273 — CTA atmospheric calibration.
[14] Sobczynska et al., Astropart. Phys. 120 (2020) 102450 — clouds / IACTs.
[15] Pecimotika et al., PoS(ICRC2021)773 — CTA in clouds.

CYGNO / STABILITY & ENVIRONMENTAL RESPONSE

[15bis] CYGNO / stability & environmental response — F.D. Amaro et al., NIM A 1065 (2024) 169473.

KM3NeT / TIMING & GEOMETRY

[16] Kieft, EPJ Web Conf. 116 (2016) 06002 — timing calibration.
[17] Sanchez Losa et al., PoS(ICRC2023)1062 — nanobeacons.
[18] Bretaudeau et al., PoS(ICRC2023)1033 — dynamic position/orientation.

CUPID / BACKGROUND REJECTION

[19] Armengaud et al., EPJC 80 (2020) 44 — CUPID-Mo performance.
[20] CUPID Collab., EPJC 82 (2022) 810 — first CUPID module.
[21] Huang et al., JINST 16 (2021) P03032 — CUPID-Mo PSD.
[22] Azzolini et al., EPJC 79 (2019) 583 — CUPID-0 background.
[23] Moore et al., JINST 20 (2025) P08020 — CUPID muon-veto prototype.

CUPID / PILE-UP

[24] Enhanced light signal for suppression of pile-up in Mo bolometers, EPJC 83 (2023), DOI:10.1140/epjc/s10052-023-11519-6.
[25] CUPID Collab., EPJC 85 (2025) 737 — CUORE upgrade with particle ID.
[26] CUPID Collab., EPJC 86 (2026) 633 — CUPID sensitivity.

LVK / DATA QUALITY

[27] Abbott et al., CQG 33 (2016) 134001 — GW150914 transient noise.
[28] Abbott et al., CQG 35 (2018) 065010 — data-quality vetoes.
[29] Abbott et al., SoftwareX 13 (2021) 100658 — open data / DQ flags.

COMPUTING / INFRASTRUCTURE

[30] Berghoefer et al., arXiv:1512.00988 — APPEC computing model.
[31] Bagnasco, EPJ Web Conf. 295 (2024) 04047 — LVK computing.
[32] INFN-CNAF / CINECA institutional pages — data-centre references.