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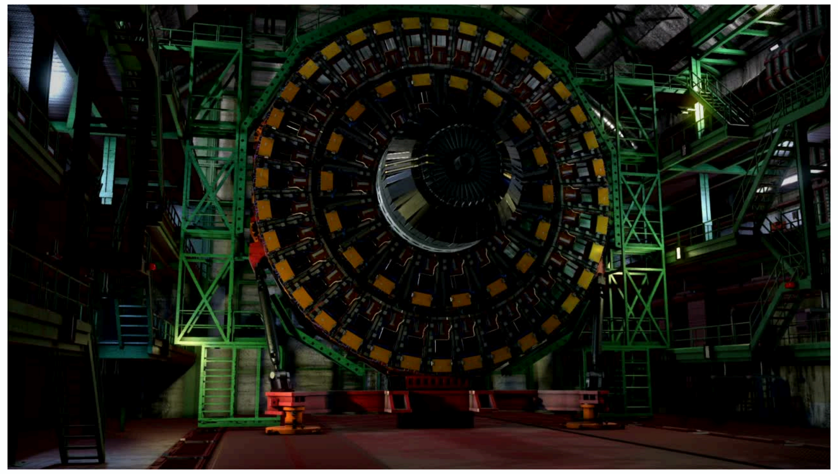
Direct Dark Matter Search 2: Axions and Other Light Dark Matter

Mert Dil

04.11.2024

Overview



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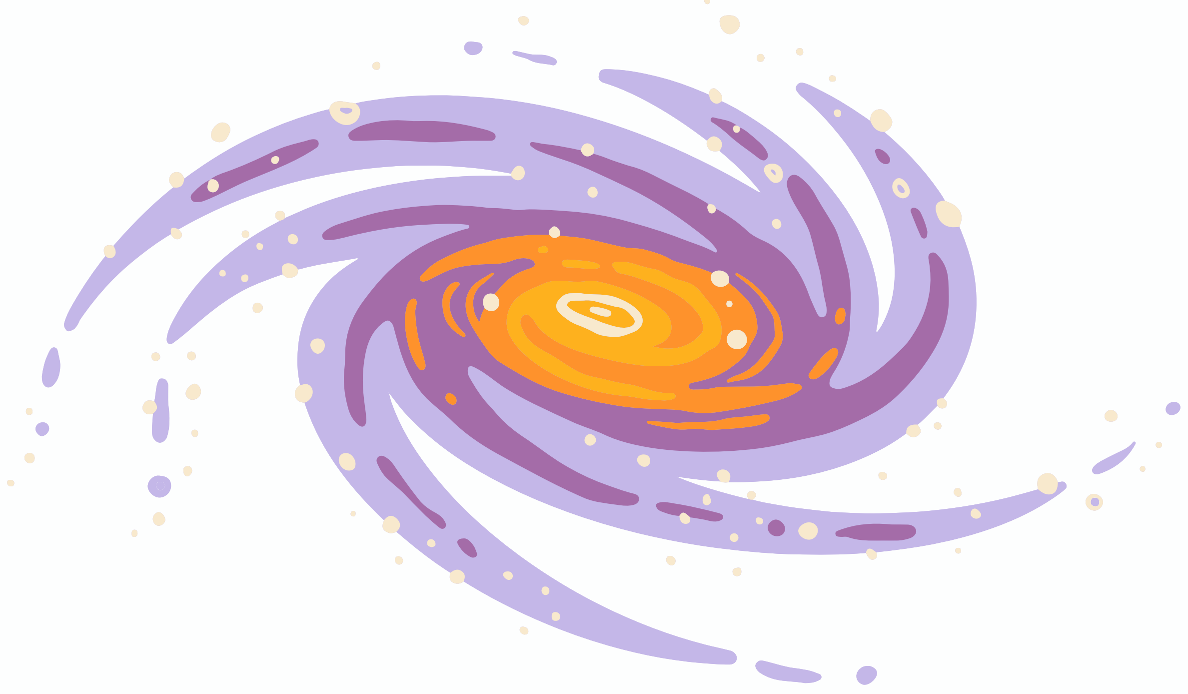
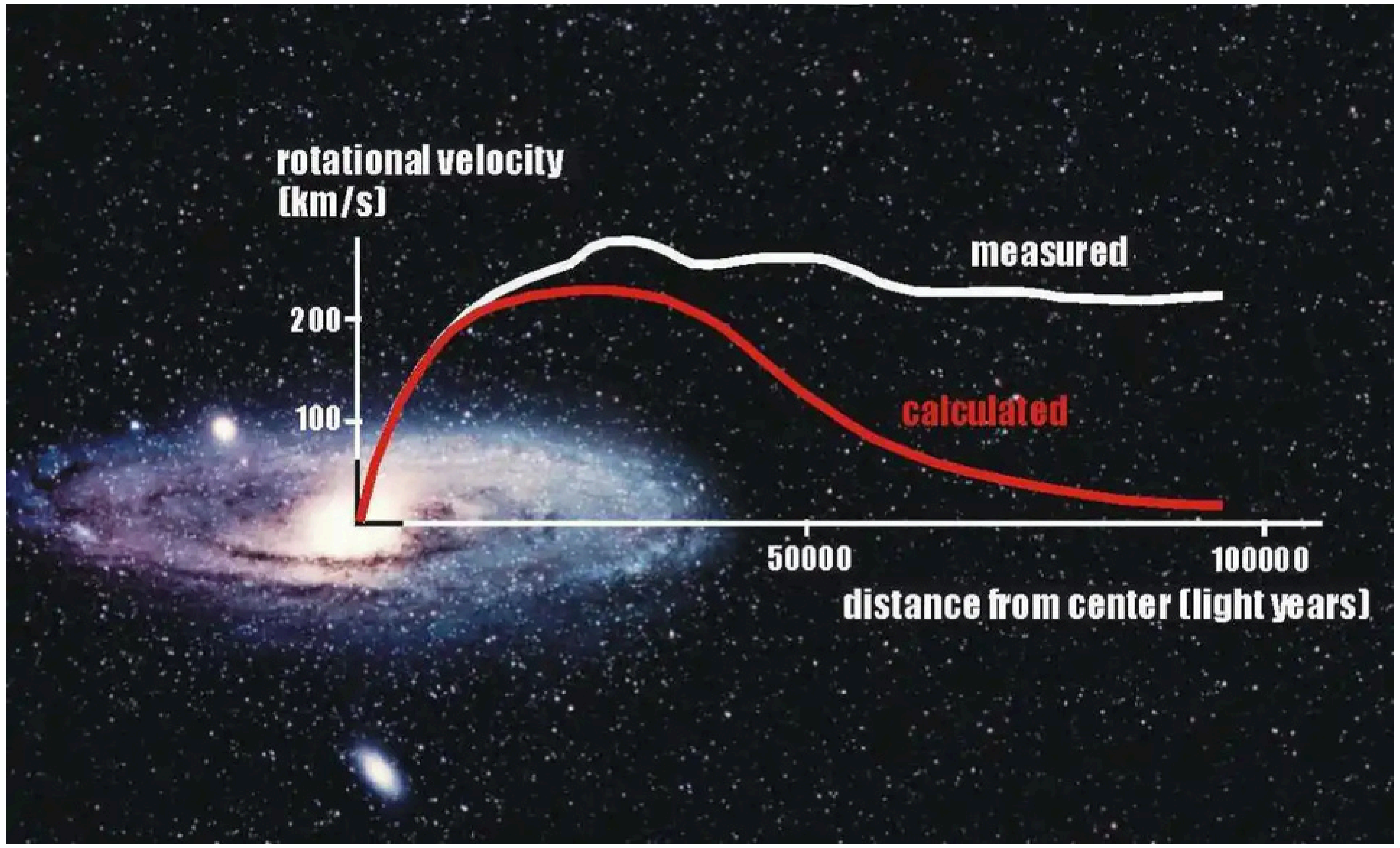
Structure

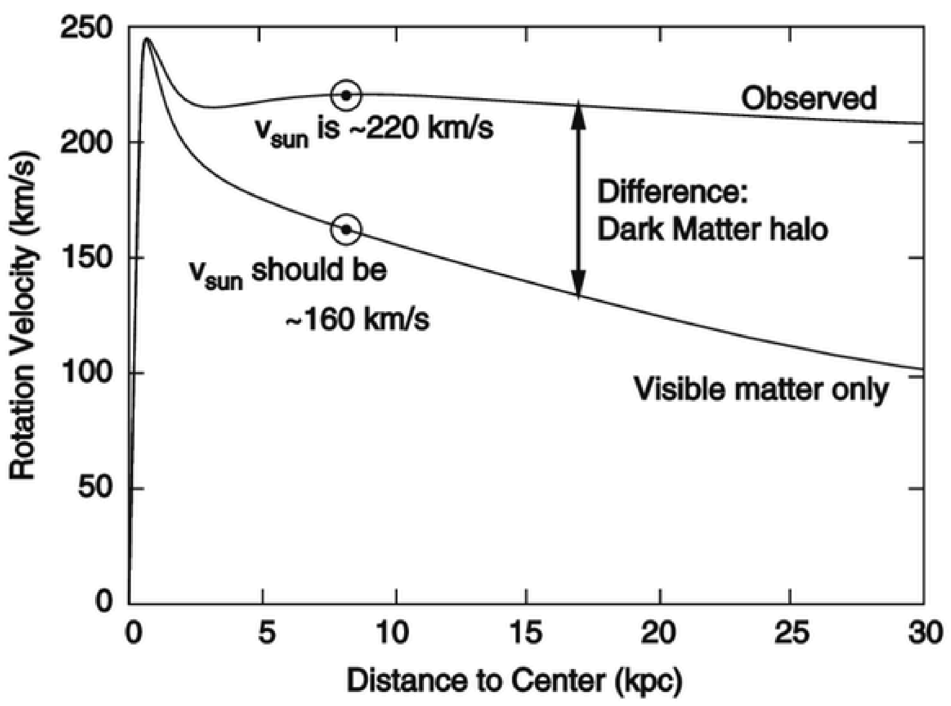


- Understanding Dark Matter
- Theoretical Basis of Axions and Light Dark Matter Candidates
- Experimental Detection Techniques
- Computational Advancements and Future Directions

Introduction to Dark Matter

- **Dark Matter (DM):** Hypothetical matter composing ~27% of the universe's total mass energy, invisible but crucial for gravitational effects.
- **Evidence:** Galaxy rotation curves, Cosmic Microwave Background (CMB) anisotropies, and gravitational lensing provide indirect evidence.





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Overview of Dark Matter Candidates

- Primary Candidates: Weakly Interacting Massive Particles (WIMPs), axions, and sterile neutrinos.
- Shift to Light DM: Increasing focus on sub-eV particles, given WIMP non-detections.

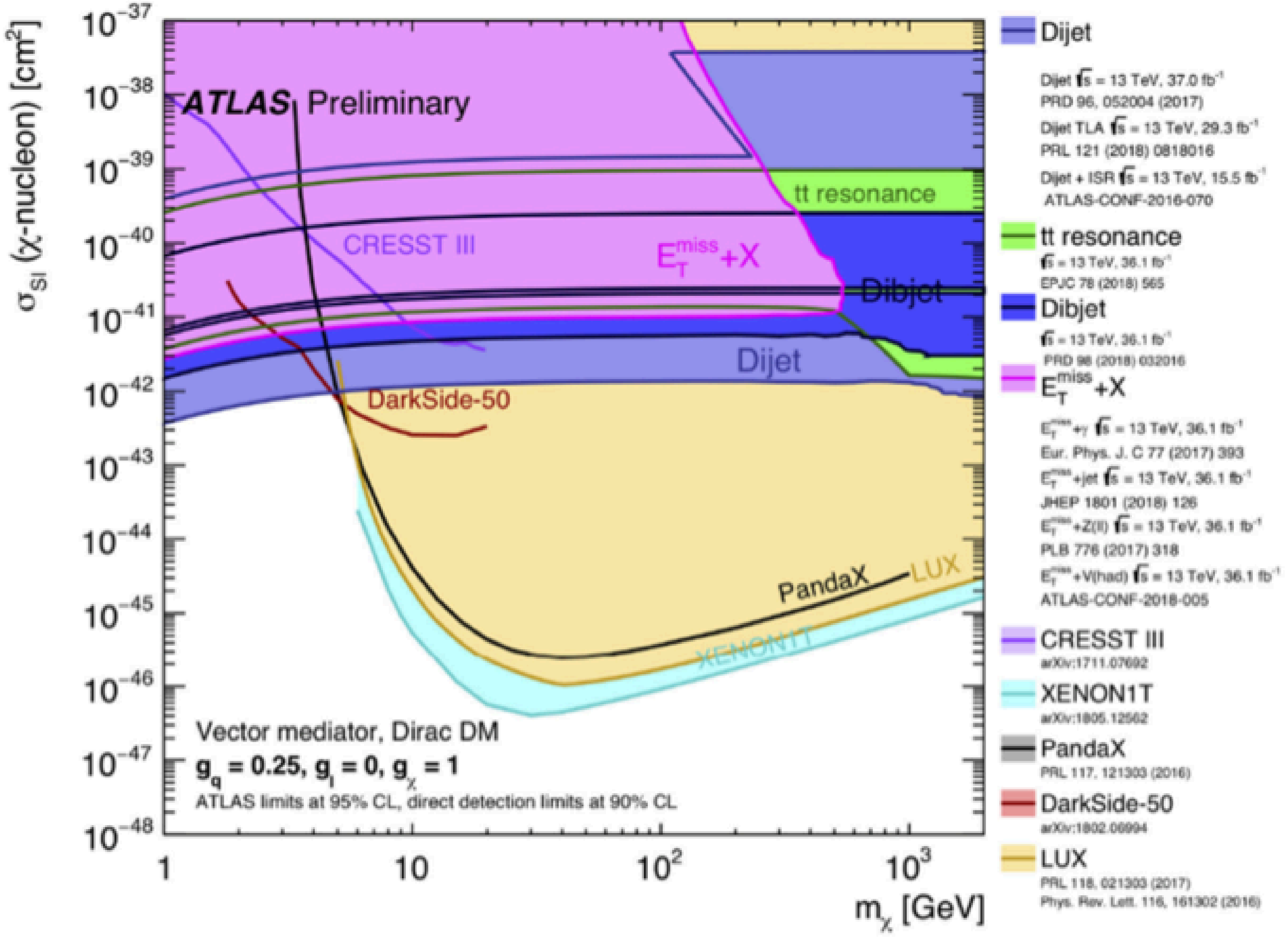

Figure : Limits from the Atlas detector for spin independent dark matter com- pared to limits from direct detection experiments. Figure taken from [31], ref- erences for displayed data see legend. The limits assume a specific dark matter model.).

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Theoretical Basis of Axions

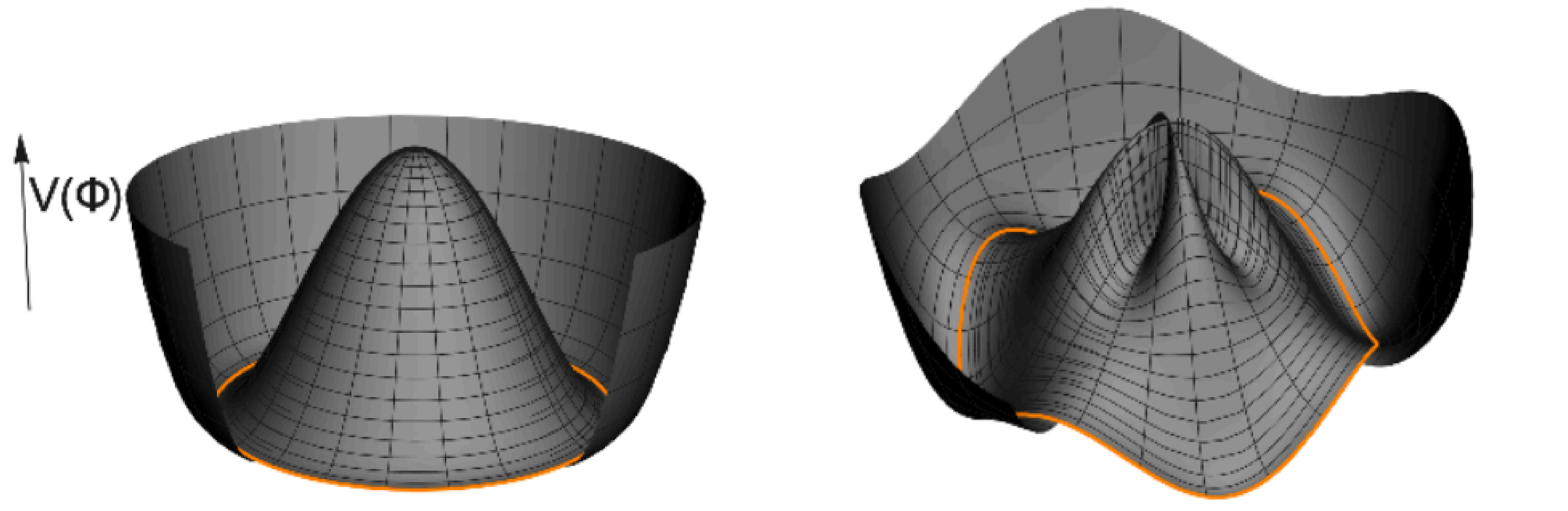


Figure “Sombrero” potential of the Peccei-Quinn field Φ is shown schematically before (left) and after (right) the QCD phase transition. The axion corresponds to the angular direction of this potential. The potential on the right is shown for the case of colour anomaly N = 4.

Origin

Proposed as a solution to the strong CP problem via the Peccei-Quinn mechanism.

Properties

Axions are ultra-light particles, postulated to form part of DM.

Axions as Dark Matter Candidates

- Production: “Misalignment” mechanism leading to axion generation in the early universe.
- Cold DM Fit: Axions match cold DM criteria with distinctive experimental signatures.

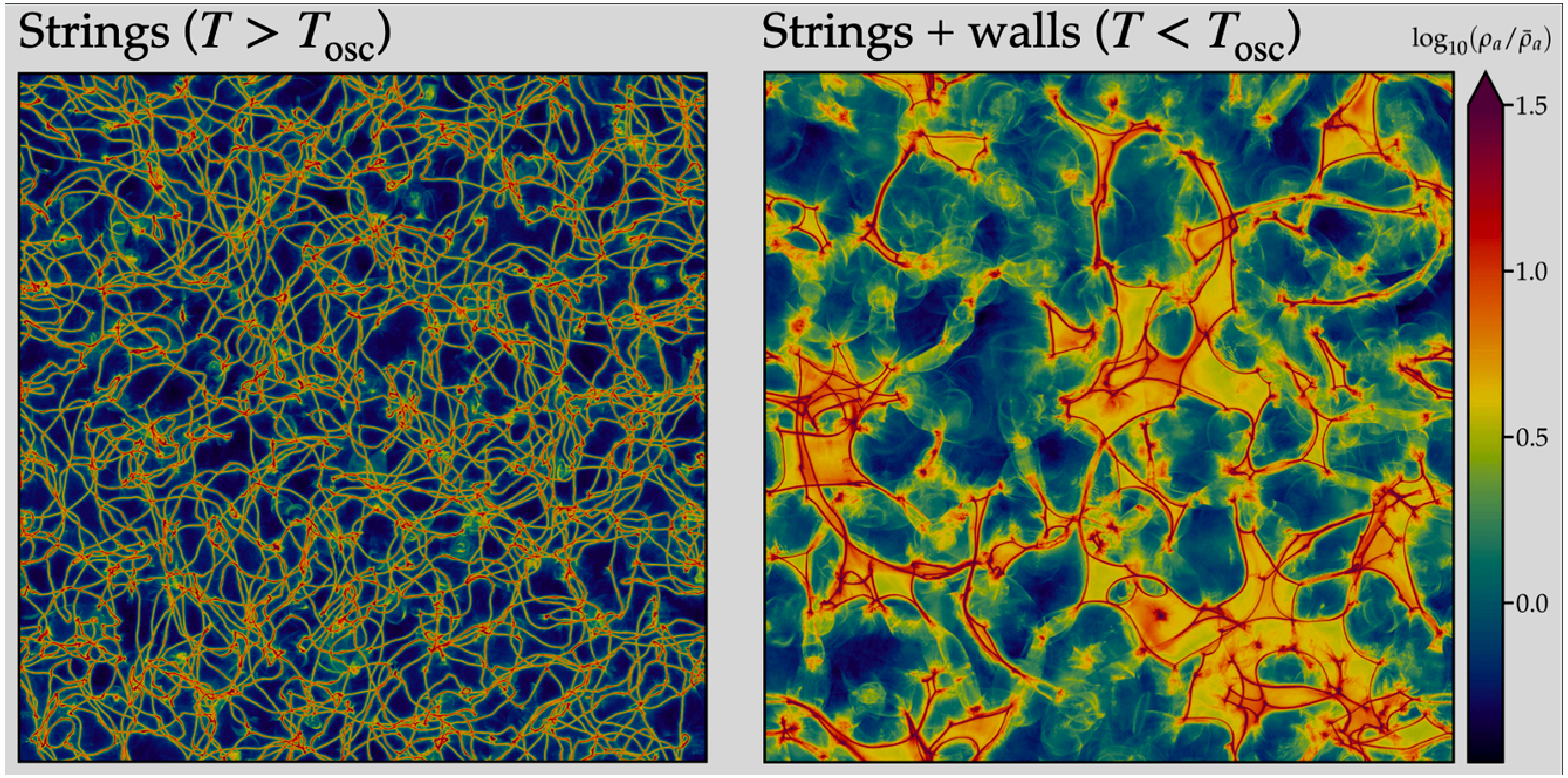
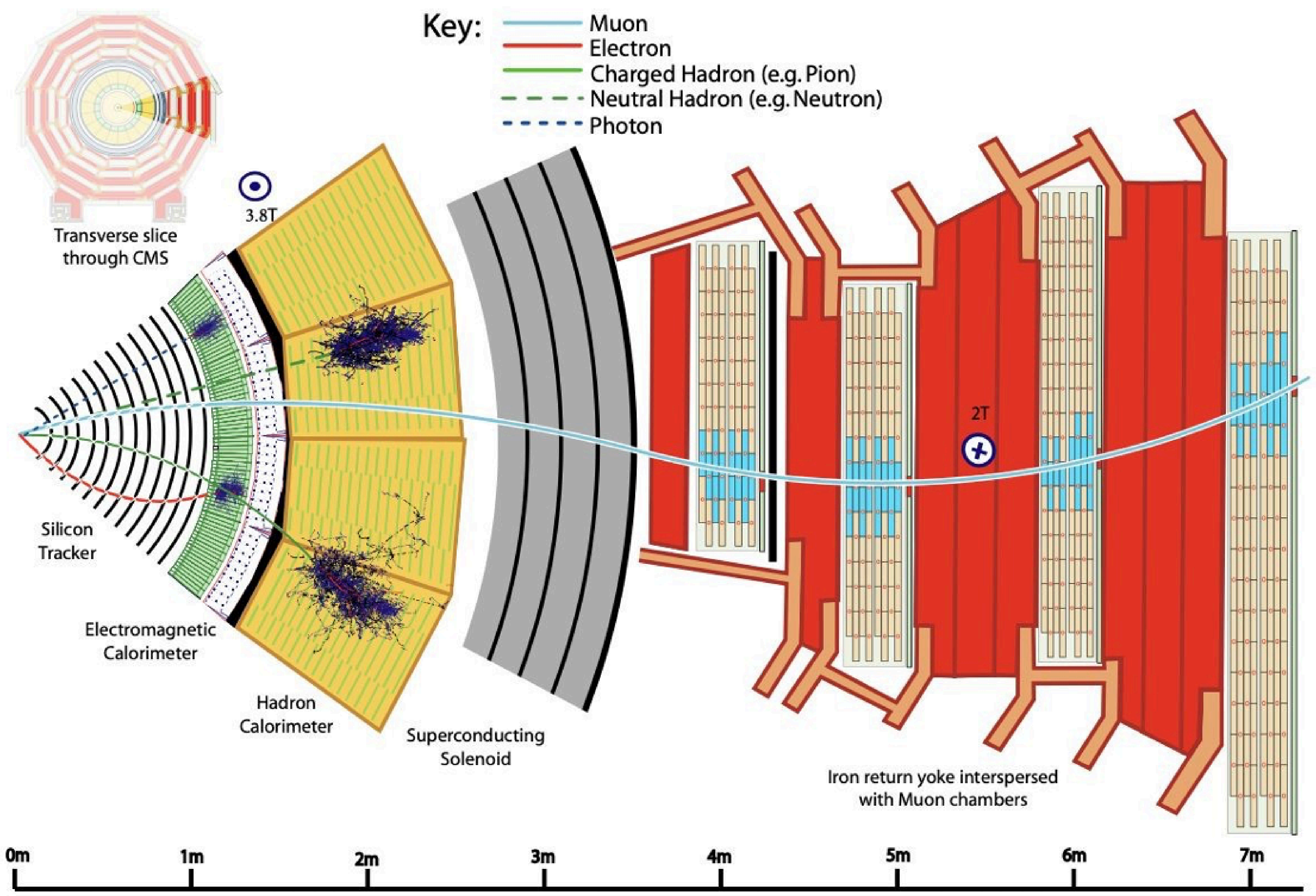


Figure :Visualisation of a post-inflation axion simulation before and after the axion becomes dark matter at Tosc. The colour scale is logarithmic and corresponds to the axion energy density integrated along a third spatial axis extending into the page. The reddish linear objects are cosmic strings, visible in both panels, and the yellowish surfaces connected to them are domain walls, visible only in the right-hand panel which is for a time after the axion’s mass has become relevant. Wavefronts in the axion string radiation are visible, especially from the cusps of the cosmic strings.

CMS Detector's Role in Dark Matter Search

- **CMS at CERN:** Primarily designed for high-energy collisions but adapted for indirect DM searches.
- **MET Measurement:** Tracks missing transverse energy to infer the presence of non-interacting particles.



A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. The muon and the charged pion are positively charged, and the electron is negatively charged.

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MET Technique for DM Detection in CMS

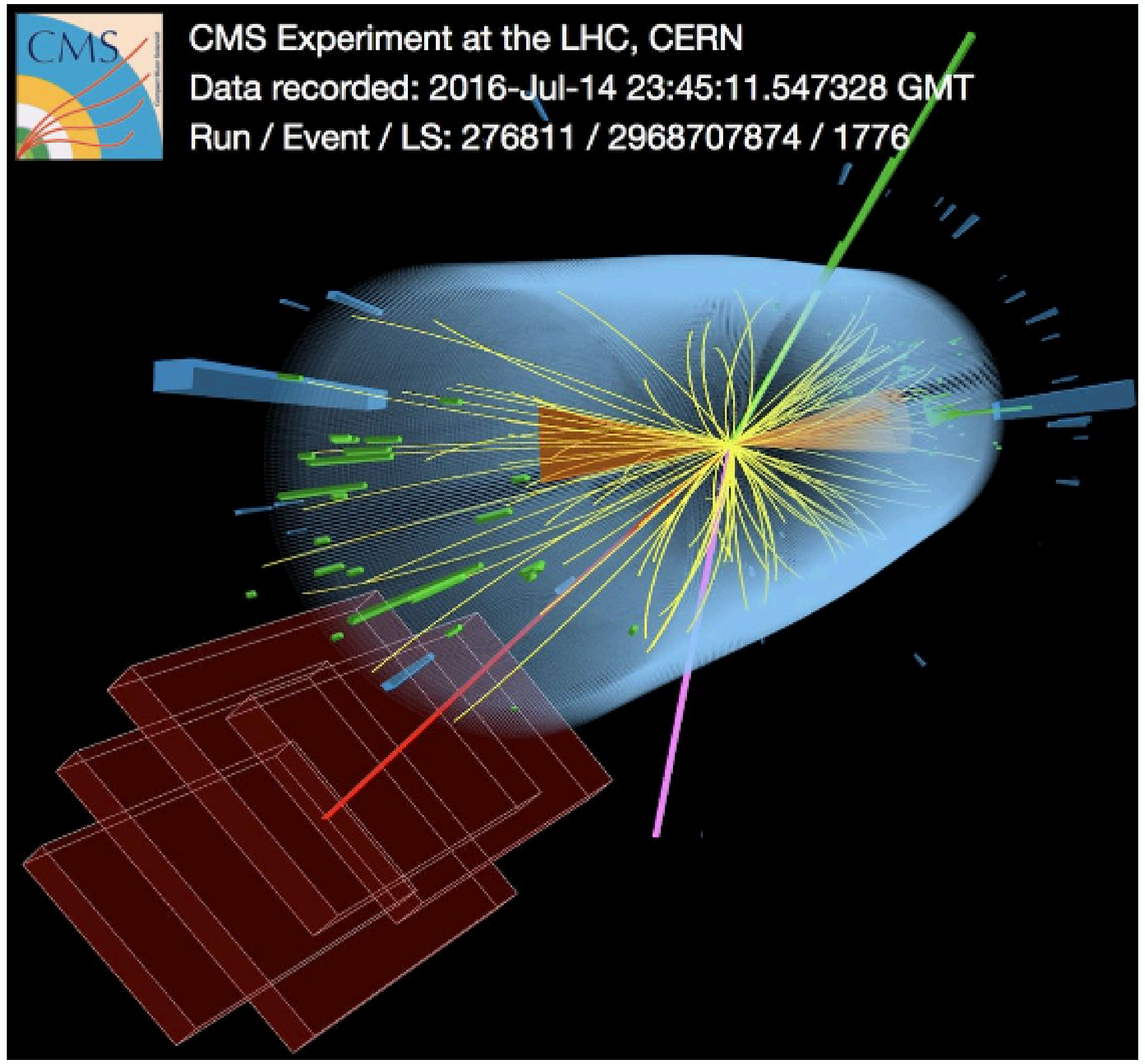
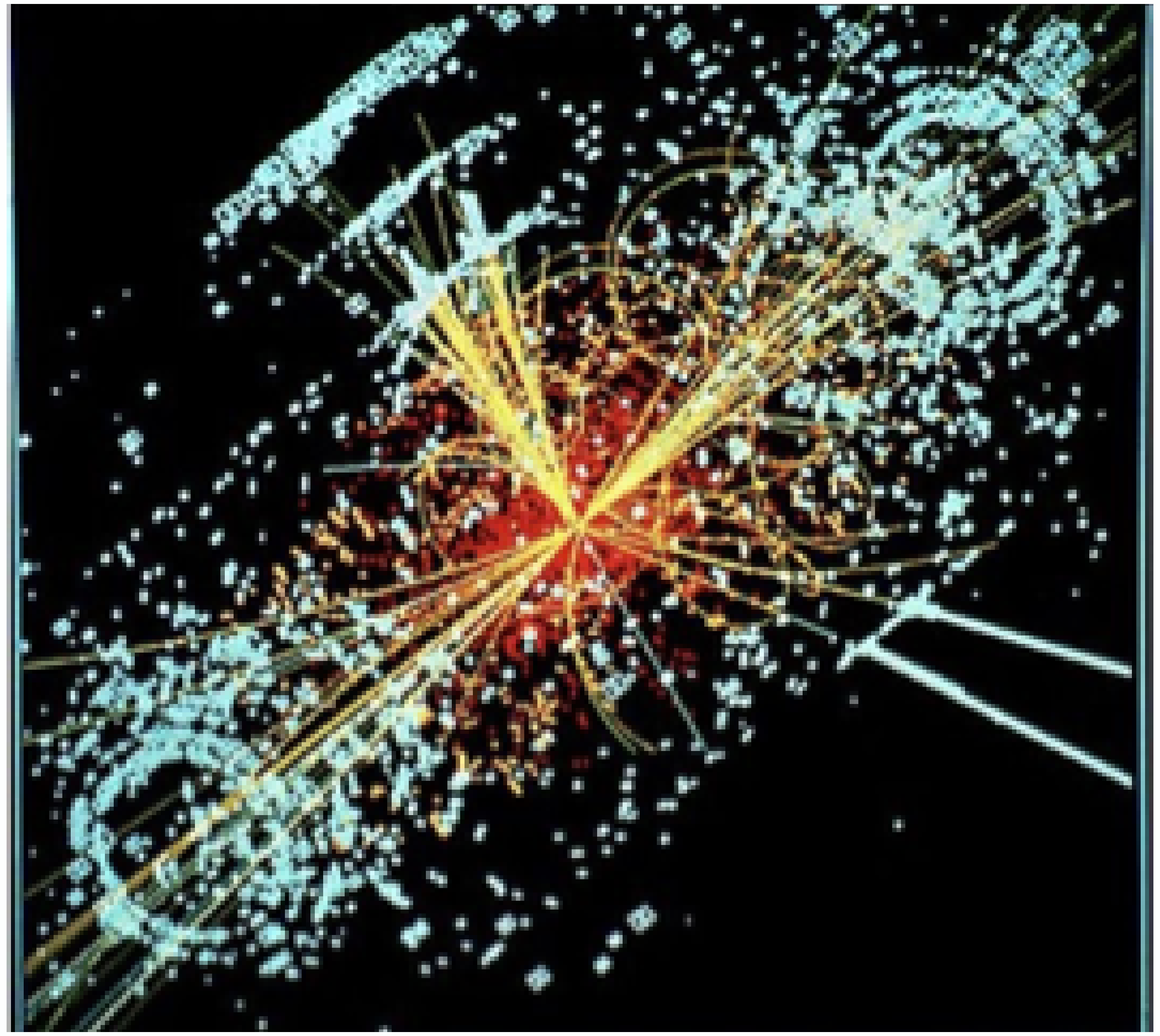


Figure : Display of an LHC collision detected by the CMS detector that contains a reconstructed top quark-antiquark pair. The display shows an electron (green) and a muon (red) of opposite charge, two highly energetic jets (orange) and a large amount of missing energy (purple).

- Missing Transverse Energy (MET): Essential in identifying particles not detected electromagnetically.
- Dark Matter Signature: Energy discrepancies hint at invisible particles in high-energy collisions.



Detection Techniques for Axions

- Axion-Photon Conversion: Primakoff effect enables axion detection through magnetic field interactions.
- Experiments: Use resonant cavities and haloscopes to test axion-photon coupling.

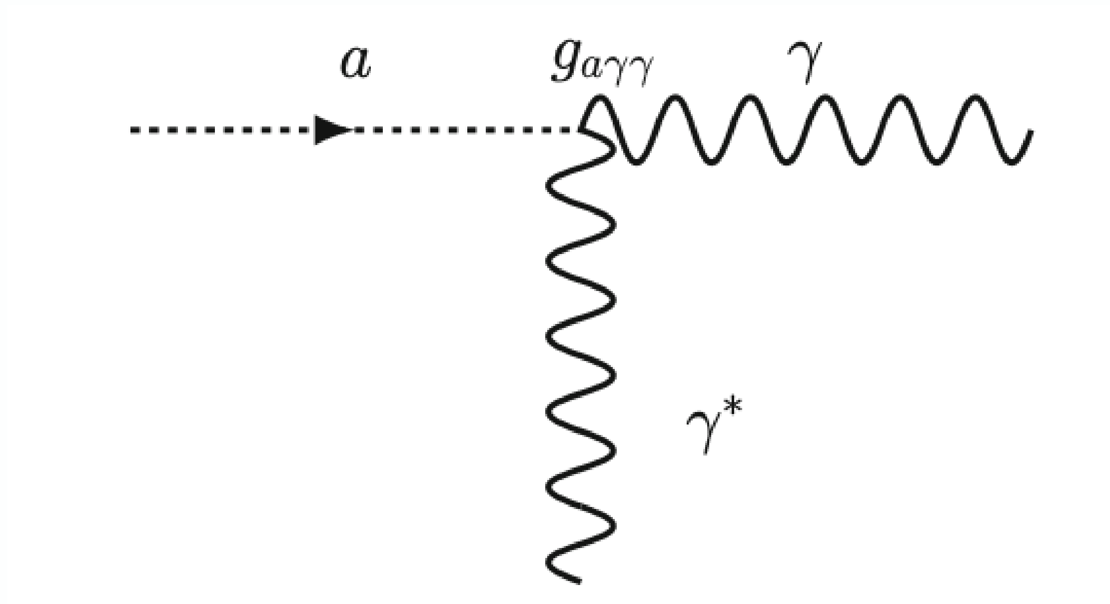


Fig: Feynman diagram illustrating the inverse Primakoff effect, where an axion a is converted into a real photon γ by interacting with a virtual photon γ ⋆ sourced by a magnetic field (a virtual photon is one that does not need to satisfy the energy-momentum relationship or "on-shell" dispersion equation, see discussion in Refs. [1–5]). The axion-photon interaction is parameterized by the axion-photon coupling constant gaγγ, see Eqs. (2.63) and (2.64)

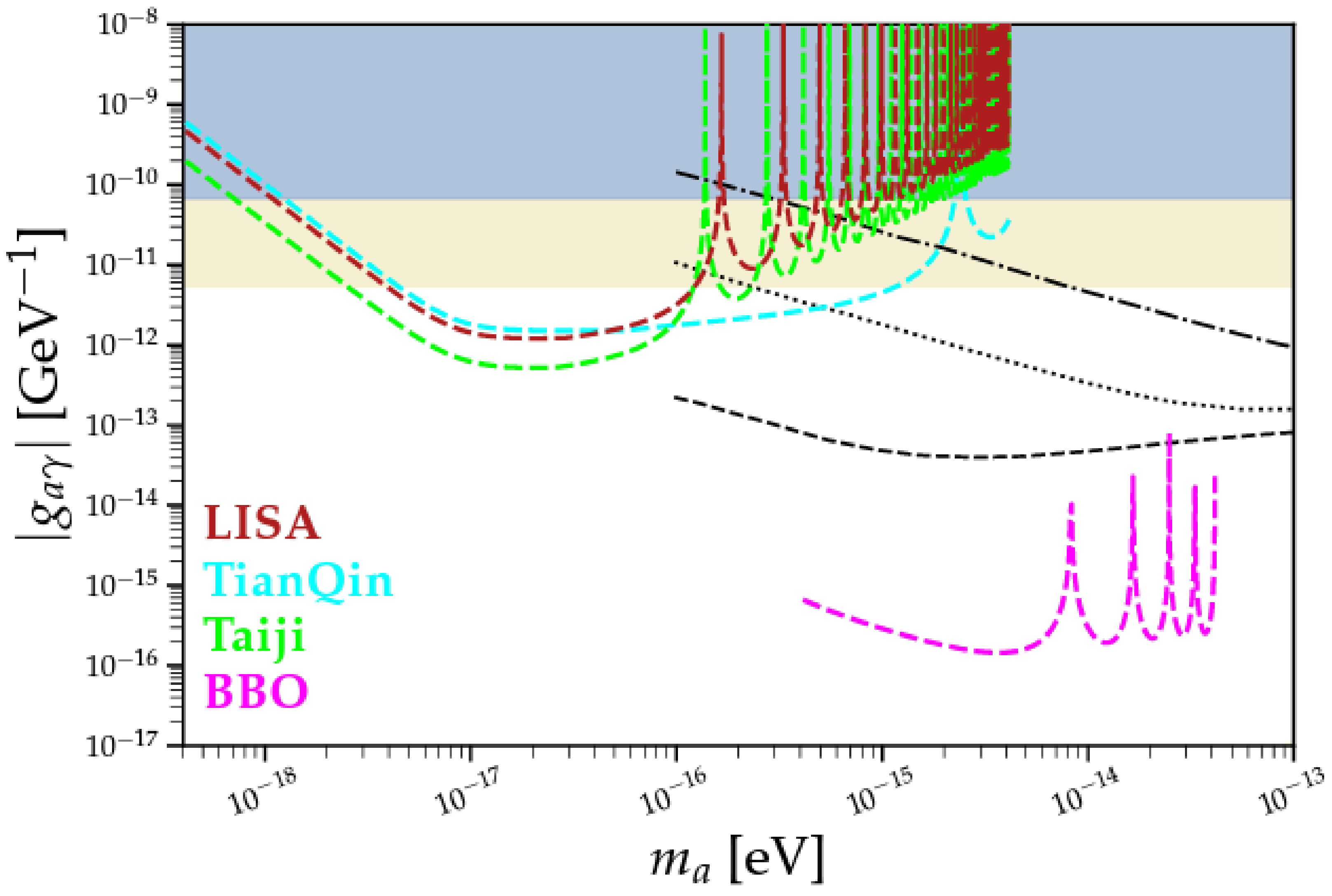


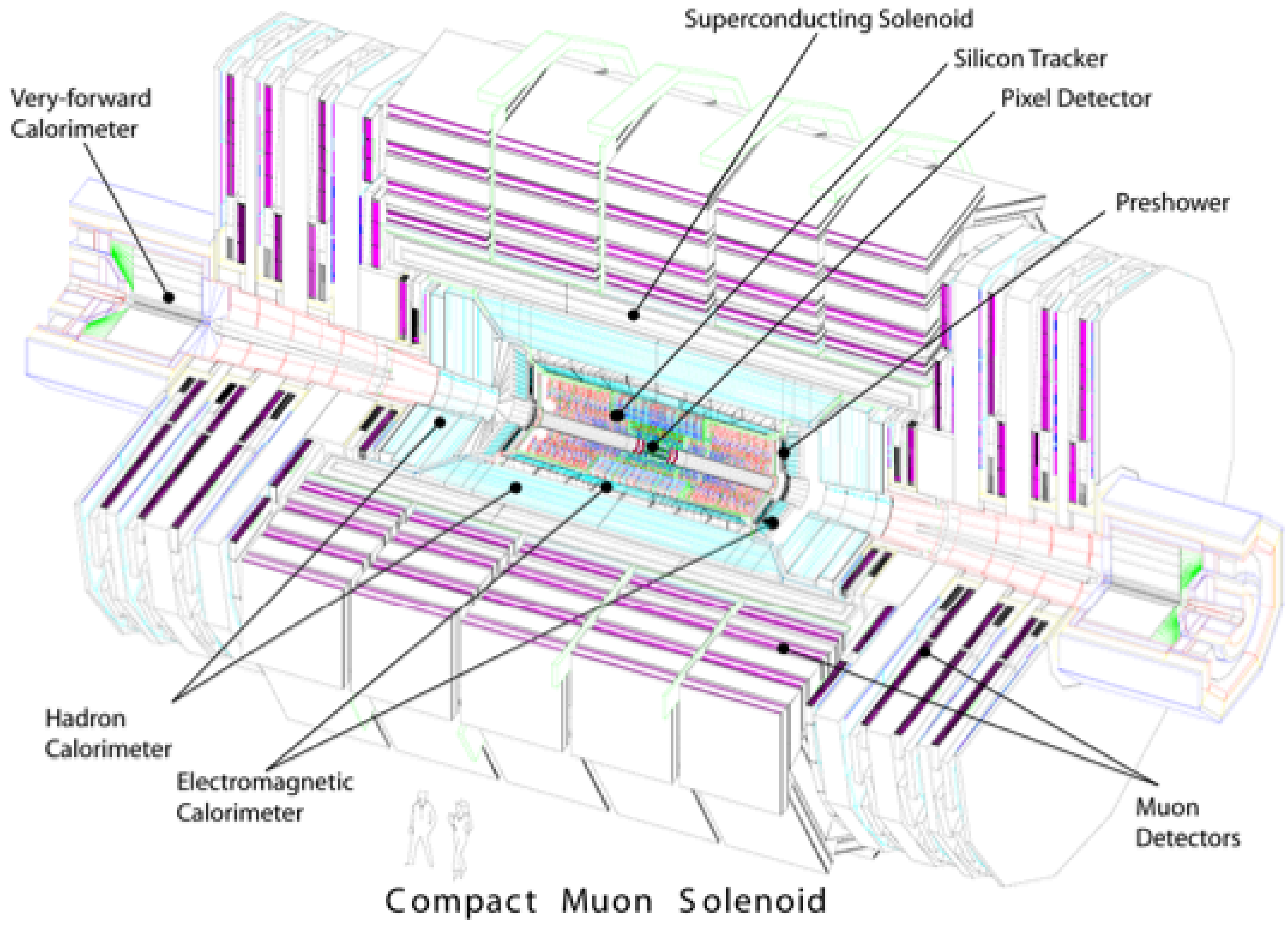
FIG.: Sensitivityestimatesofvarious GW space-baseddetectors(showninbrown,cyan, limeand magentarespectivelyforLISA,TianQin,Taijiand BBO)totheaxion-photoncouplinggay. Inlightblue andlightyellow,weshowtherespectiveconstraintfrom CAST[37]andobservationsofSN1987A[38] (from [39]).Finally, indashed-dotted,dottedanddashed blacklines,weshowrespectivelytheexpected sensitivityofadvancedLIGO,DECIGOandCosmic Explorerdetectors, from[14] (whichhavebeenrescaled forconsistentnumericalvalueofρDM).

	LISA	TianQin	Taiji	BBO
Laser frequency ν_0 (Hz)	2.82×10^{14}	2.82×10^{14}	2.82×10^{14}	6×10^{14}
Arm length L (m)	2.5×10^9	$\sqrt{3} \times 10^8$	3×10^9	5×10^7
Integration time $T_{\rm obs}$ (year)	4.5	$5 \times 1/2$	5	4
Frequency band (Hz)	$[10^{-4} - 1]$	$[10^{-4} - 1]$	$[10^{-4} - 1]$	$[10^{-1} - 10]$

Table: Experimentalparametersof interestforLISA,TianQin,TaijiandBBO, from[15–17,30,35,36].The timeof integrationofTianQinsuffersfroma1/2factorbecausethedetectorplaneisfixedthroughouttheorbit, implyingitwillbeblindedbytheSunduringhalfoftheorbit.Thetimeof integrationofBBOispurelypresumed.

CMS Detector

- **Particle Reconstruction in CMS:** Paths and interactions of charged particles, electromagnetic particles, strongly interacting particles, and muons.
- **Subsystems of CMS:** The CMS experiment comprises four key subsystems: the muon system, a 3.8 T solenoid magnet, a calorimetric system, and a tracking system.



A schematic overview of the CMS detector showing the layered structure of different subsys- tems including the tracking system, the calorimetry, the solenoid magnet and the muon system

Novel Axion Detection Approaches

- Technological Advances: Quantum sensing and improved photon-coupling technologies.
- Increased Sensitivity: Enabling detection across a broader mass range.

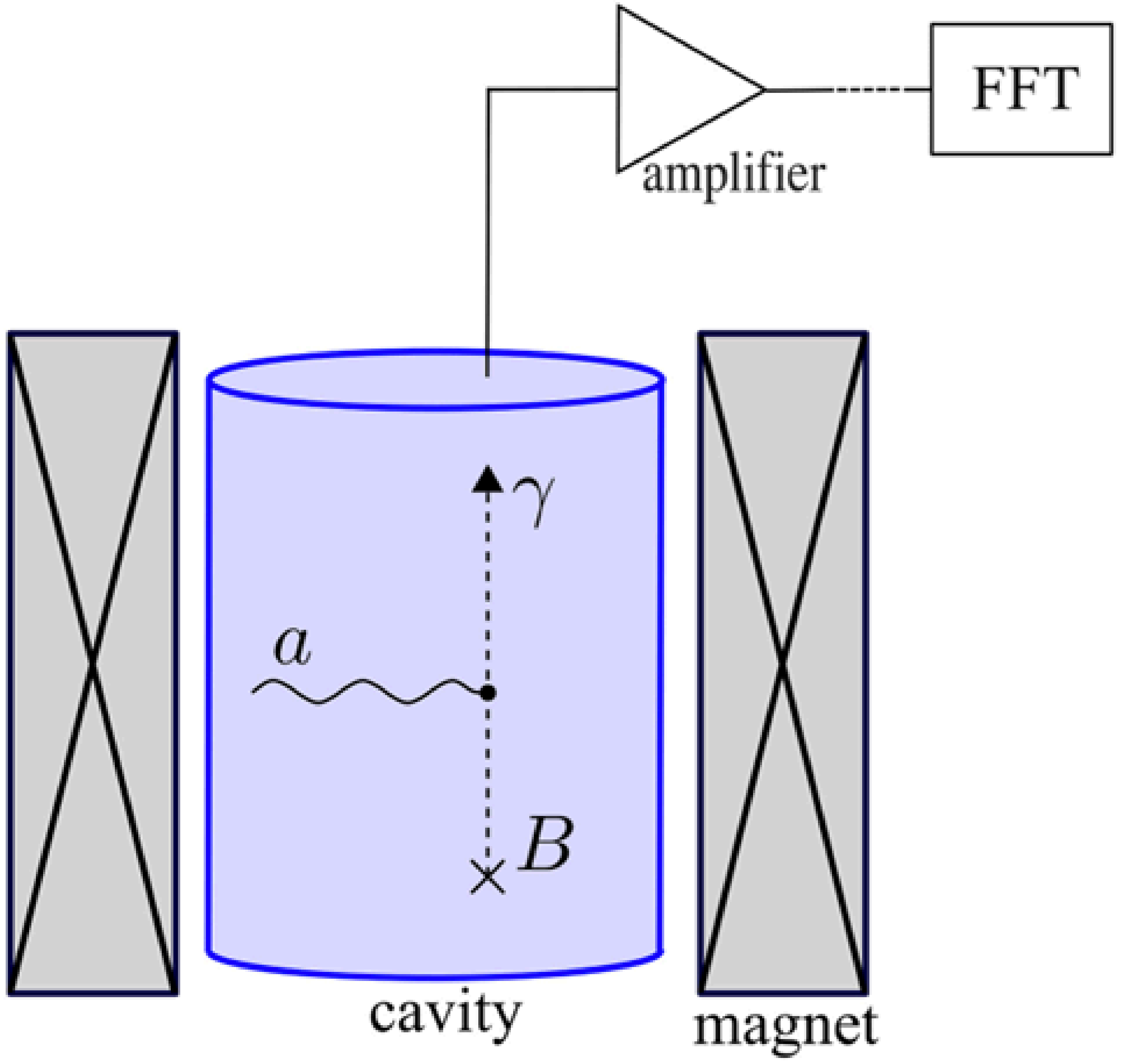


Fig: A conceptual schematic of the ADMX haloscope. Aresonant cavity is placed in a strong magnetic field created by a superconducting magnet inside a dilution refrigerator. Darkmatter axions are converted to photons via the electromagnetic interaction in Eq. (3). The resulting electromagnetic signal occupies a narrow band near the axion Compton frequency va. It is coupled out of the cavity and into a sensitive amplifier and detection chain. The search for the unknown axion mass is performed by tuning the cavity resonance.

Hidden Photons as Light Dark Matter Candidates

- Concept: Light particles that weakly couple to standard photons.
- Detection: Sensitive coupling methods are expanding research in light DM.

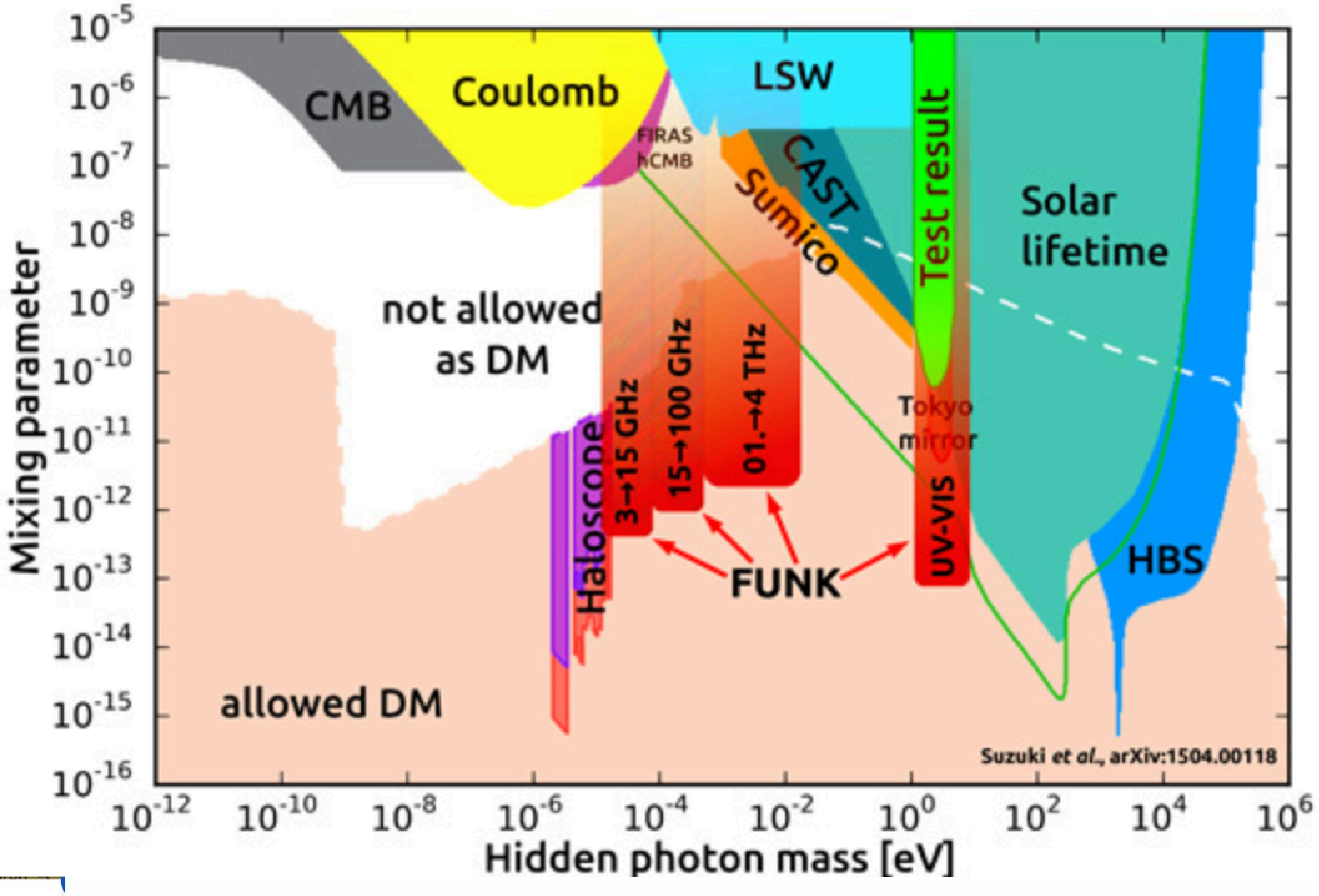
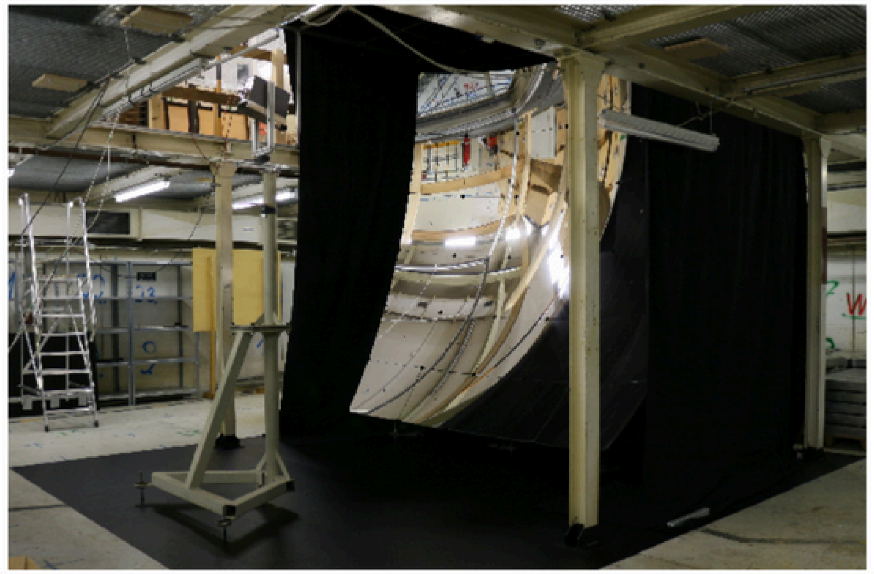


Fig.: The expected sensitivity of the FUNK experiment in various photon-energy ranges (in red)



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Detector's Sensitivity Enhancements on CMS

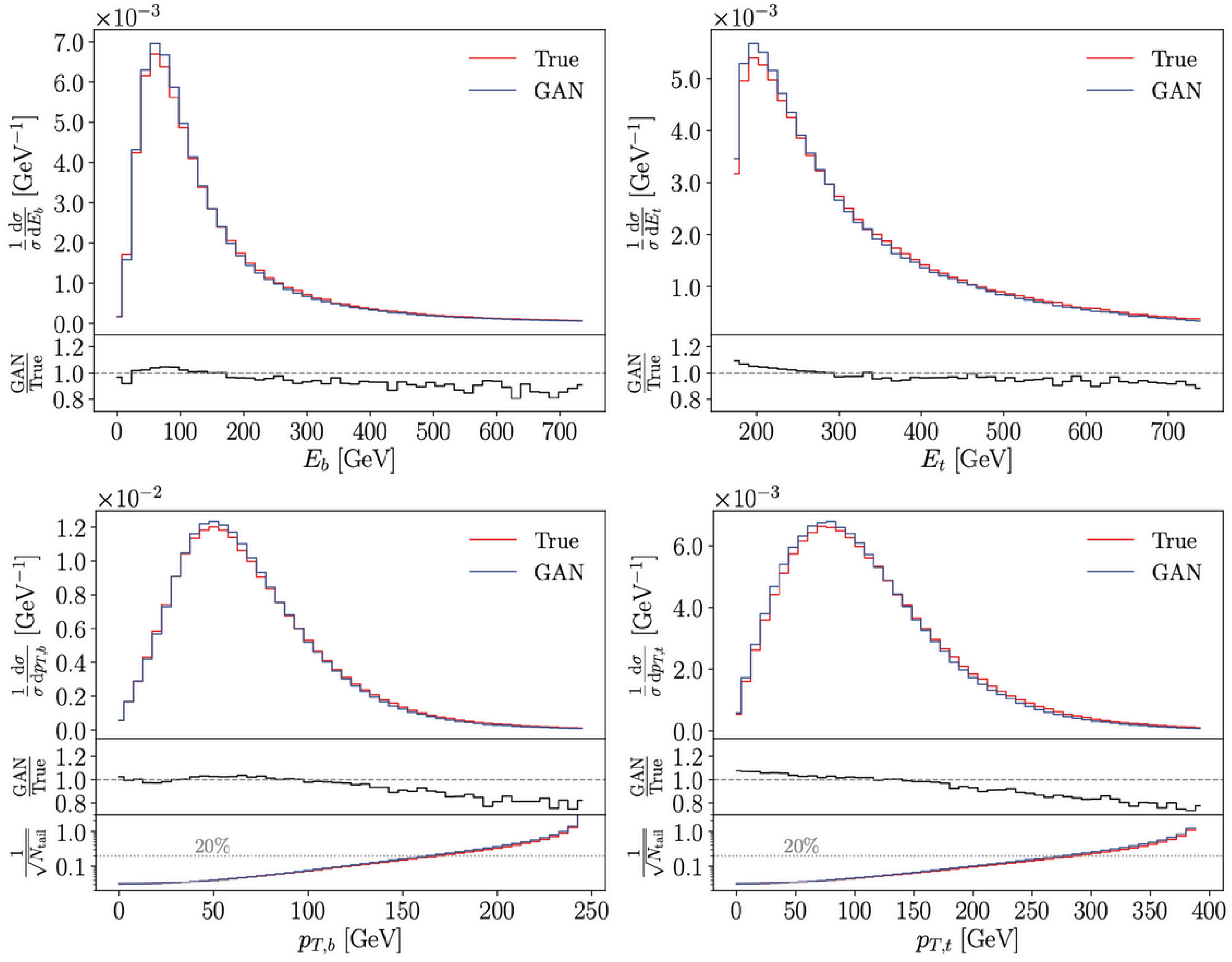


Figure : Energy (top) and transverse momentum (bottom) distributions of the final- state b-quark (left) and the decaying top quark (right) for MC truth (blue) and the GAN (red). The lower panels give the bin-wise ratio of MC truth to GAN distribution. For the pT distributions we show the relative statistic uncertainty on the cumulative number of events in the tail of the distribution for our training batch size.

MET Calibration Improvements:

Enhanced detection of low-mass particles.

Complementary Role:

Supports axion-focused detectors with additional sensitivity.

Advanced Computational Methods in DM Analysis

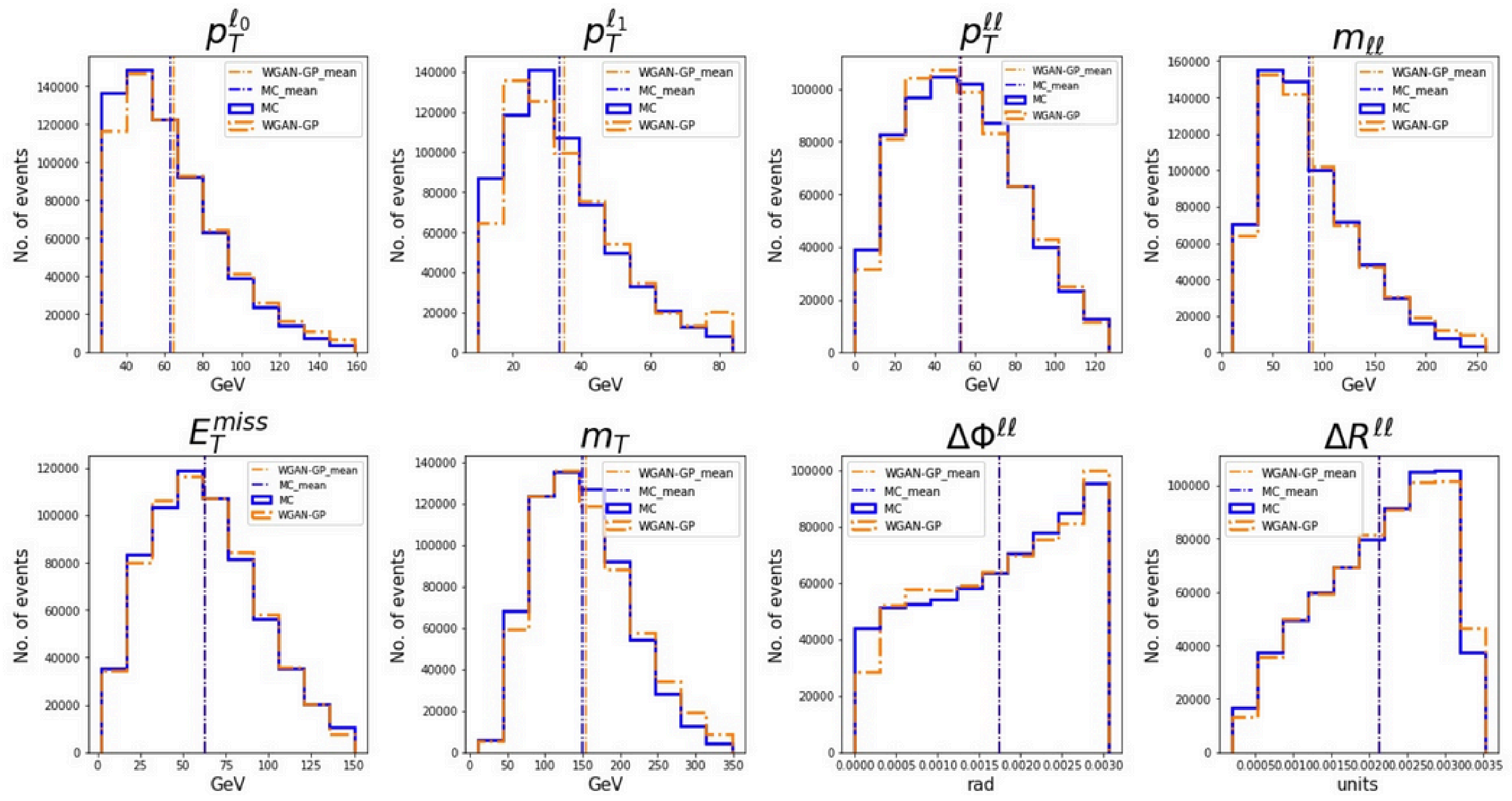
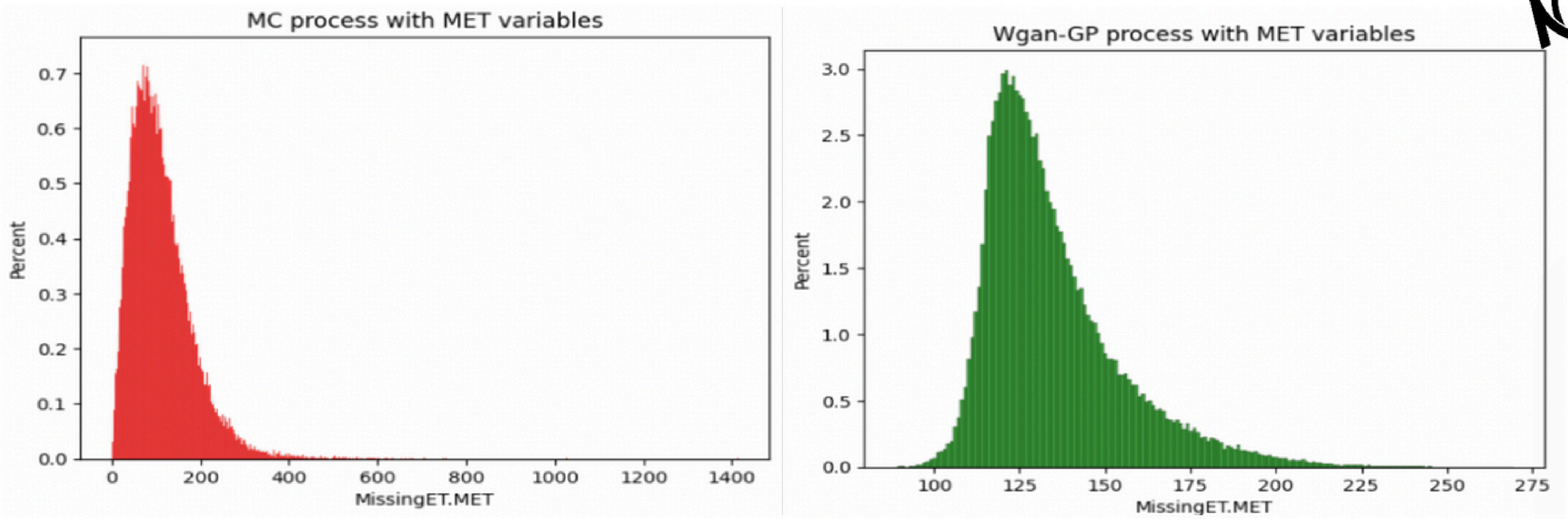


Fig. . Results on the best performing epoch of the WGAN-GP, with WGAN-GP generated event (in orange) and original MC (in blue) and their associated mean values.

Machine Learning Role:
Anomaly detection with GANs in complex datasets.

Generative Models:
Simulate DM-like events to better predict experimental outcomes.

Case Study: WGAN-GP in CMS Dark Matter Search



(a) MC process with MET (b) WGAN-GP process with MET

Fig. Comparisons with MET between MC and WGAN-GP process)

WGAN-GP

Stabilizes training and anomaly detection for DM signals in MET.

Application

Used in CMS for reliable DM candidate identification.

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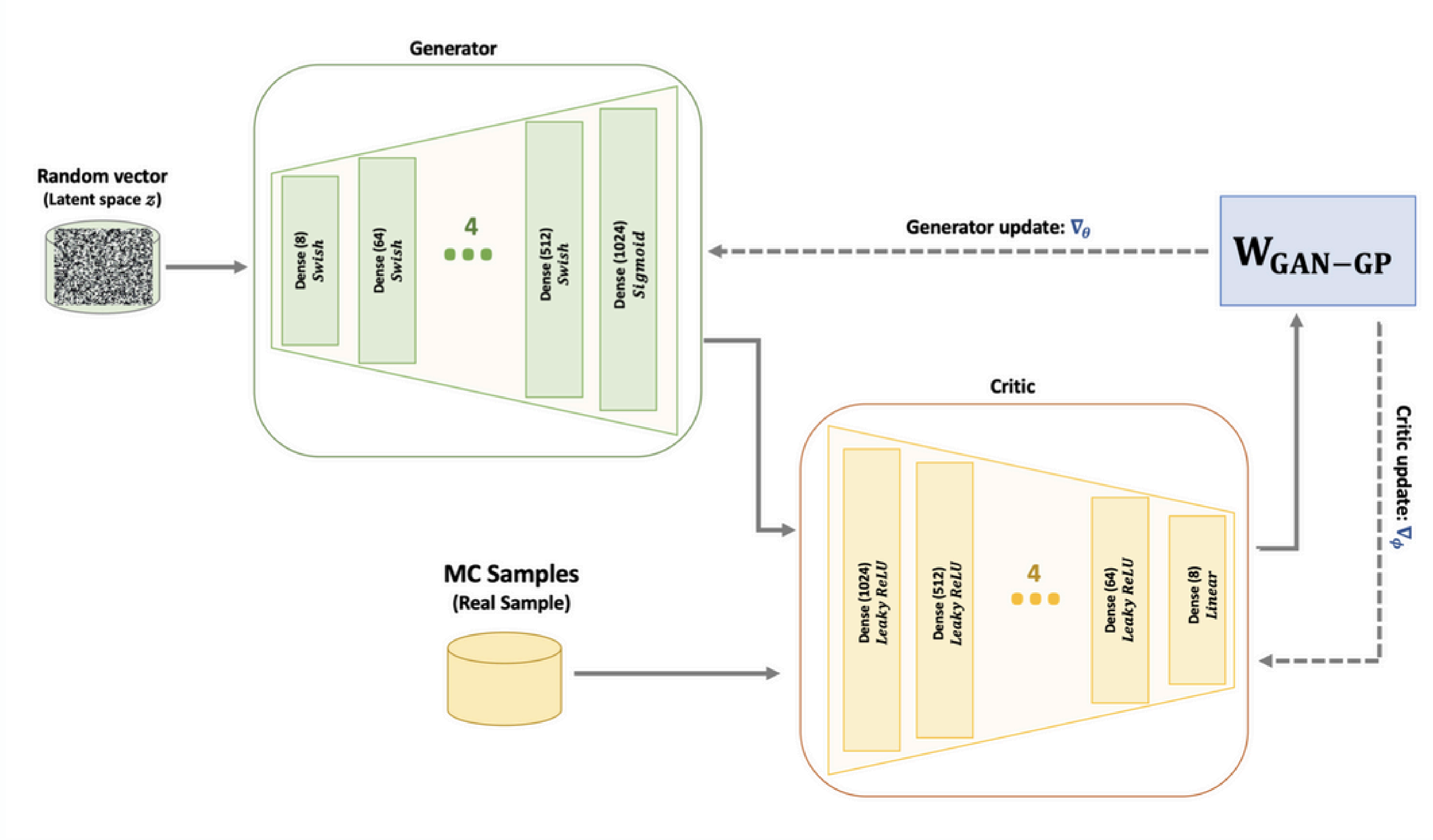
Application of GAN Models in Dark Matter Research

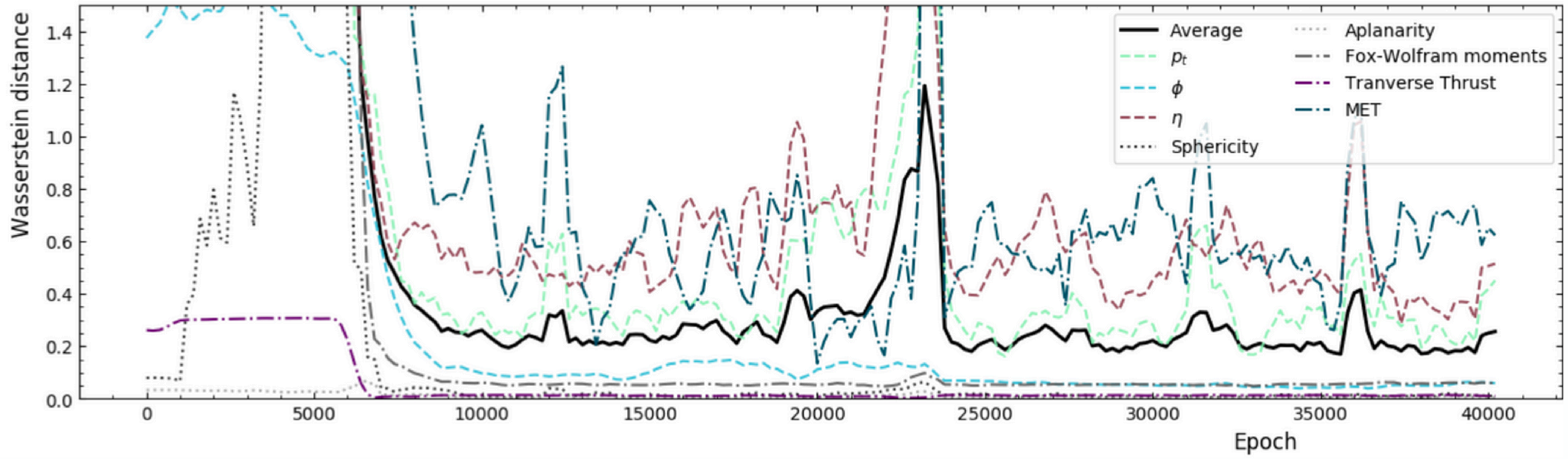


Fiigure: The WGAN-GP Network architecture with a generator (G) and a critic (C). This network is build via a connection of outputs of (G) to inputs of critic (C) whilst penalizing gradient weights with values above 1.

Enhanced Accuracy:
WGAN-GP captures DM patterns more effectively than GANs.

Future Developments:
Real-time anomaly detection improvements.

Optimization of Computational Models



Fiigure: Evolution of our performance metric (solid black) as a function of training. EM distances for some of the individual quantities are superposed

Shift to PyTorch & more complex training model

Enables more efficient data handling and model training.

Significance:

Real-time analysis critical for large datasets in high-energy physics.

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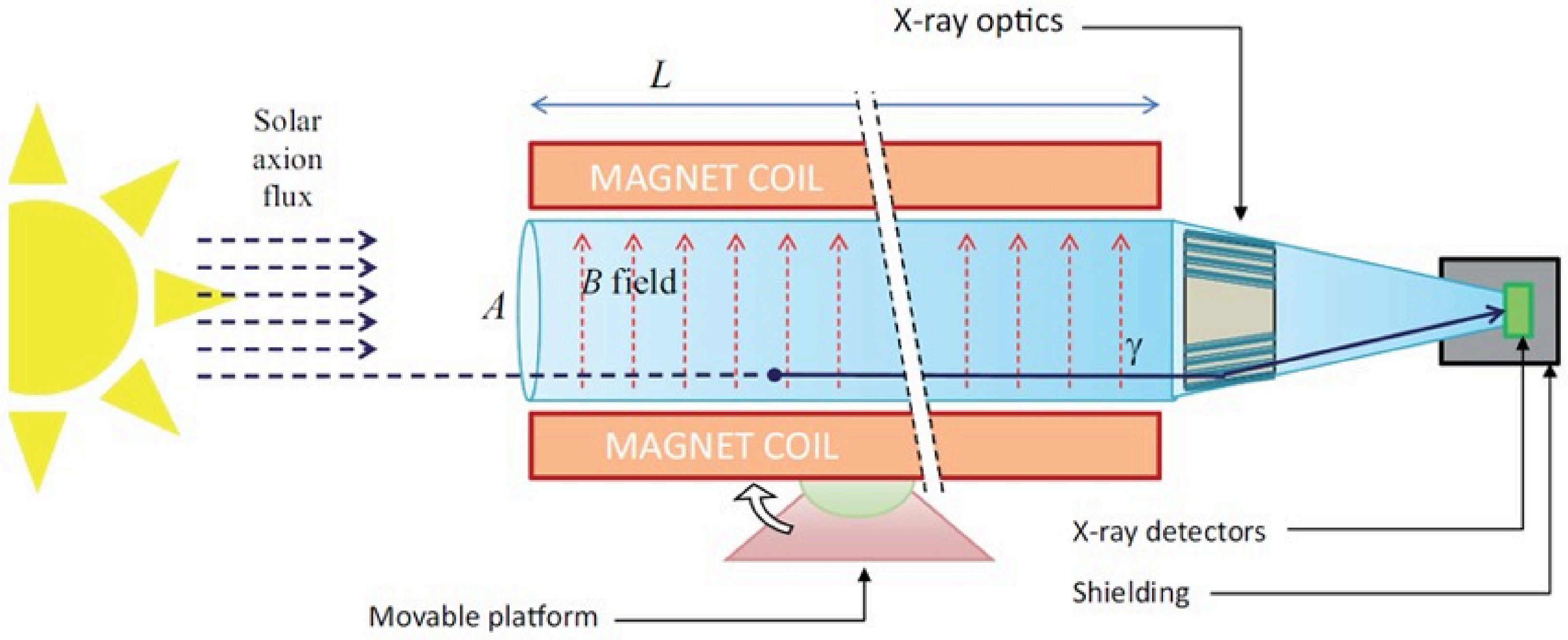
Future Directions in Axion Detection

- Innovations: Quantum computing and larger resonant cavities to expand axion detection.
- IAXO: Aimed at detecting lower mass ranges than current experiments like ADMX.



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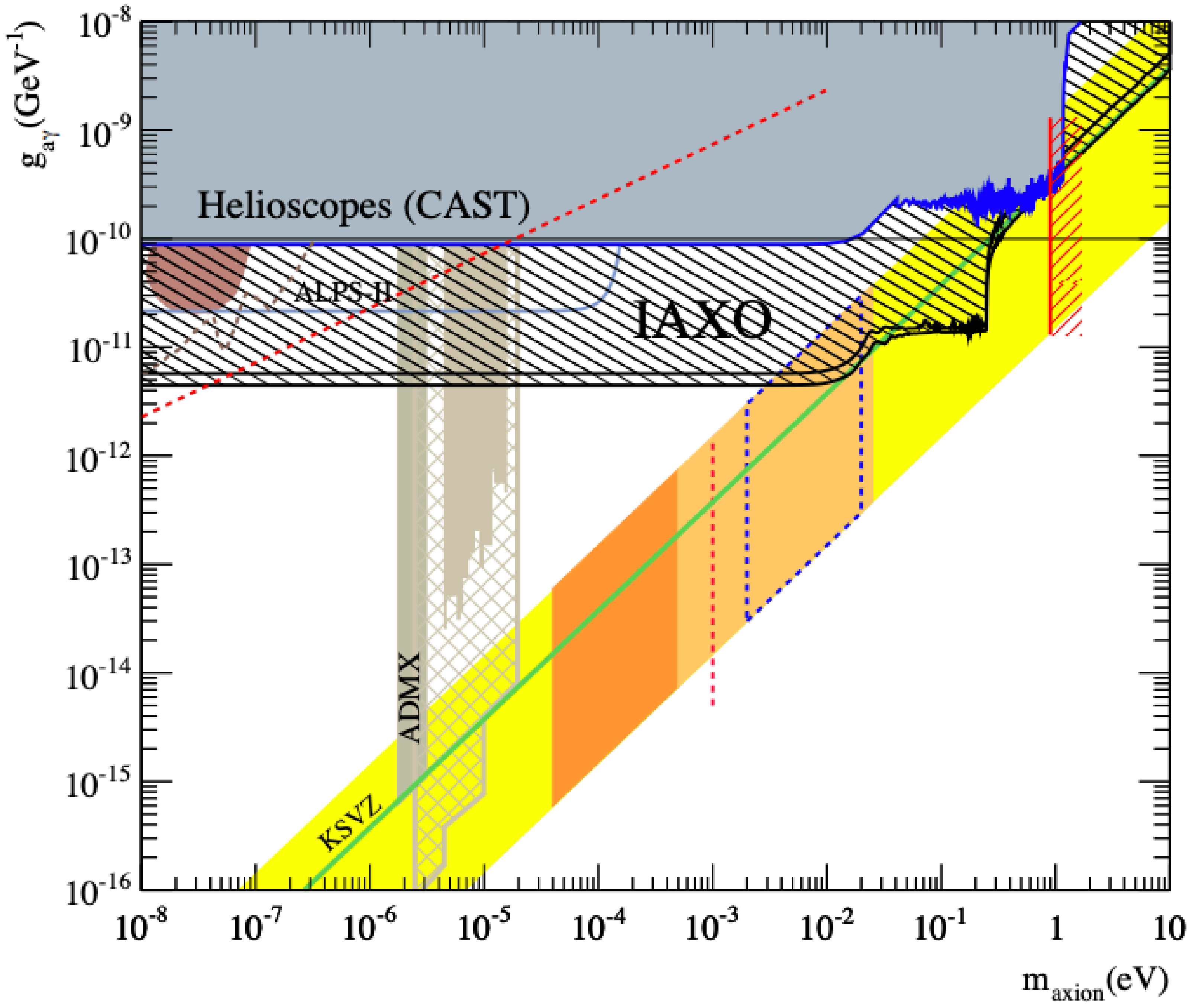


Figure Expected sensitivity of IAXO compared with current bounds from CAST and ADMX. Future prospects of ADMX (dashed brown region) and ALPS-II [40] (light blue line) are also shown. Additionally, theoretically favored regions are shown for axions within the yellow model band (classical axion window in dark orange, mixed axion-WIMP DM in light orange, white dwarf cooling hint within the area surrounded by the dashed blue line) and for ALPs at low masses (brown dashed line for transparency hint, red dashed diagonal line for ALP cold DM). For more details on these well motivated regions of the axion paramter space see Reference [2].

Technical Challenges in Light DM Detection

Core Issues

Detector sensitivity, noise isolation, and interaction strength barriers.

Mitigation

Advanced algorithms and improved calibration techniques.

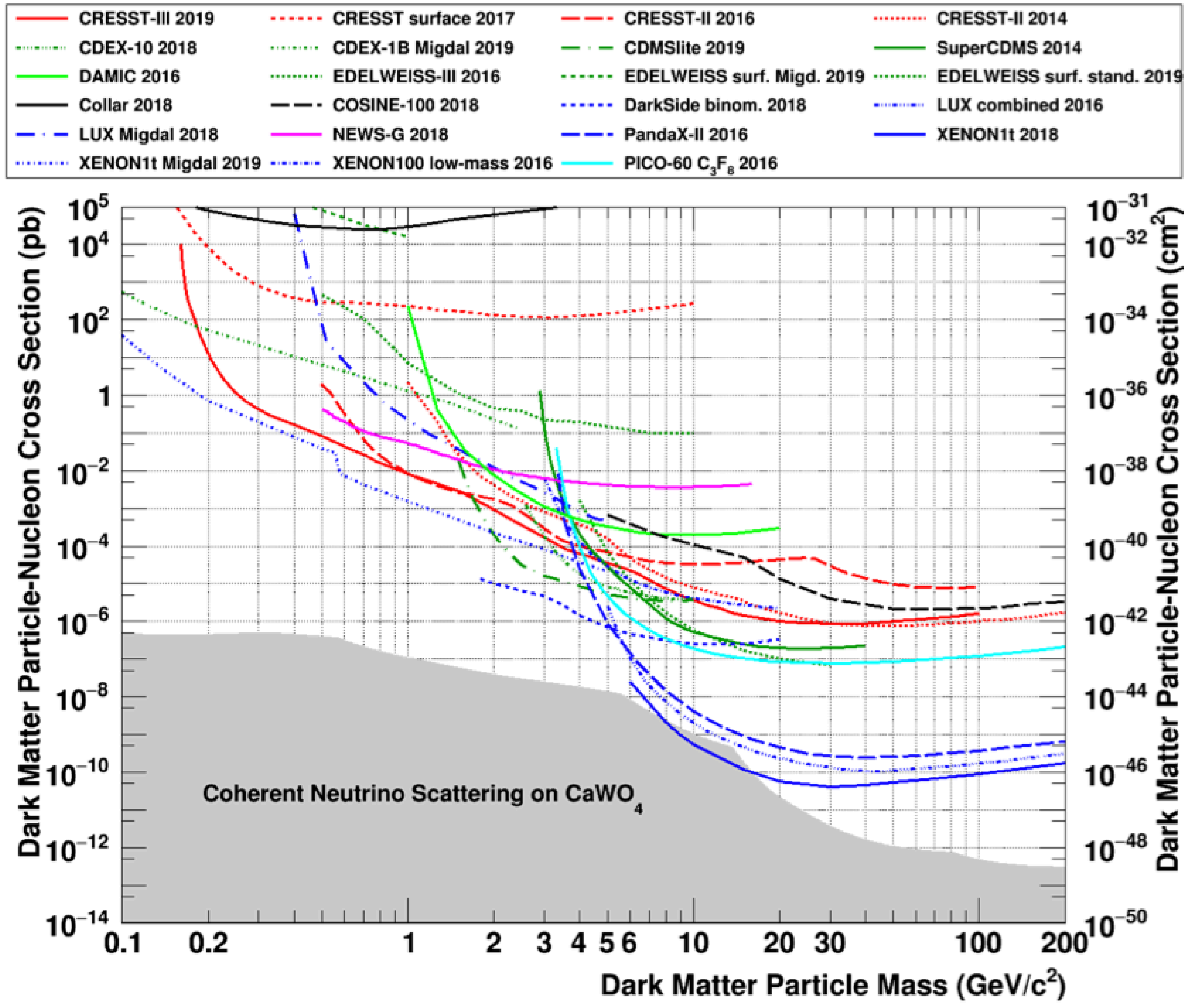
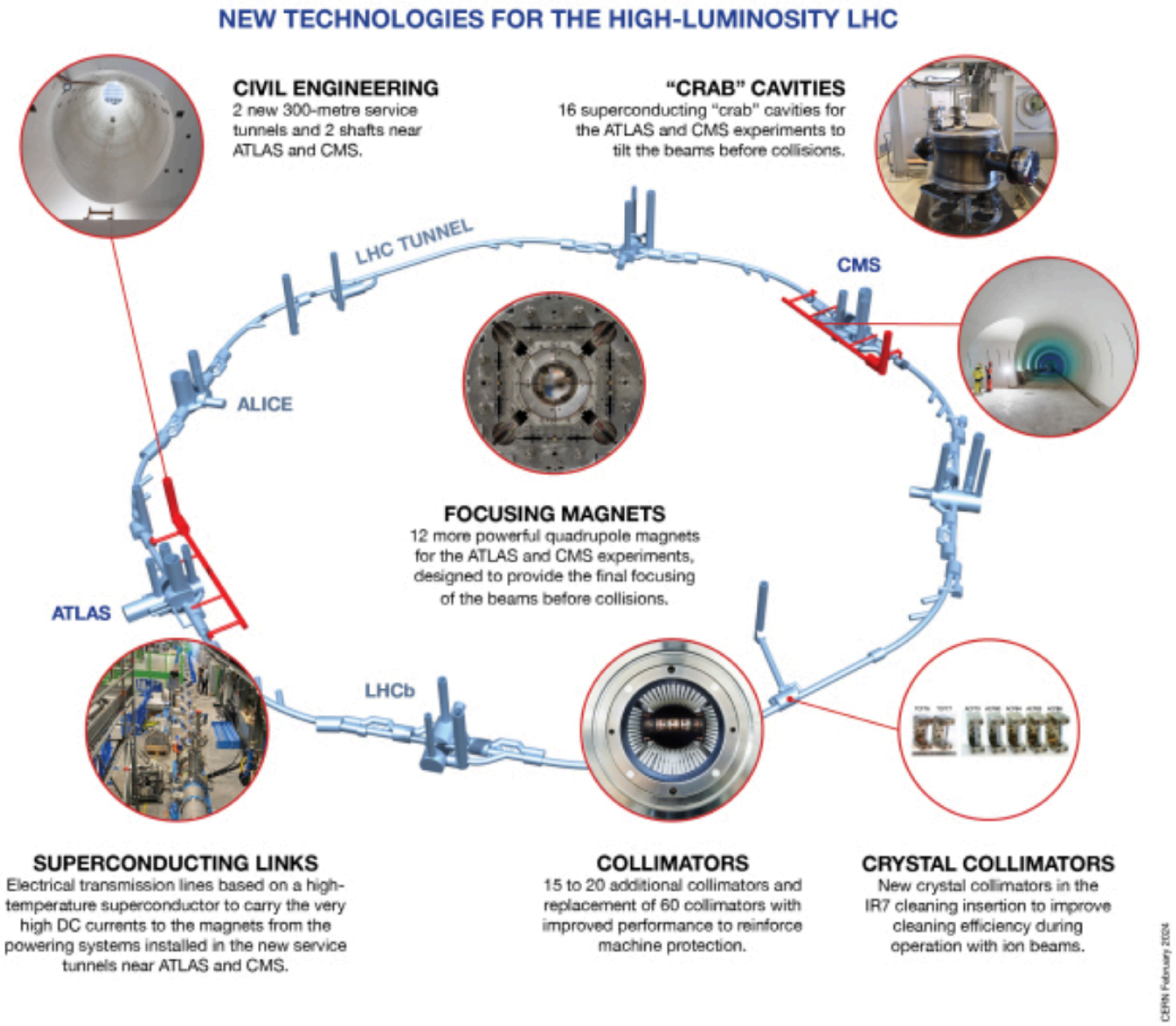


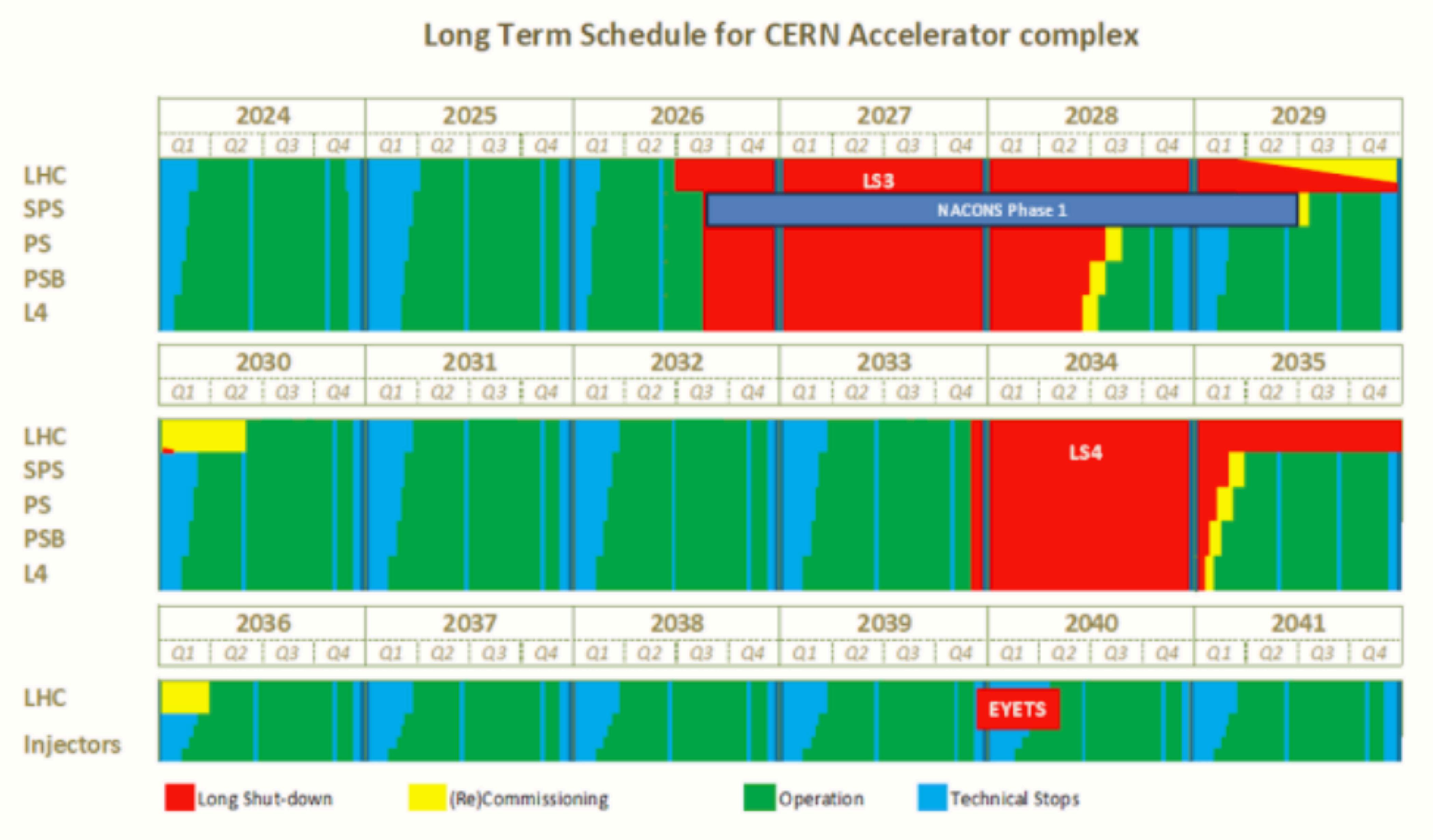
Fig: Current dark matter exclusion limits from direct detection experiments. The plot contains limits published after the results of this work—the lim- its assumes standard values as discussed in section 1.3.3.1 regarding dark matter abundance and velocity. The shown limits are CRESST-III 2019 [80], CRESST surface 2017 [81], CRESST-II 2016 [82], CRESST-II 2014 [83], CDEX-10 2018 [84], CDEX-1B Migdal 2019 [85], CDMSlite 2019 [75], SuperCDMS 2014 [86], DAMIC 2016 [67], EDELWEISS-III 2016 [87], EDELWEISS surf. Migd. 2019 and EDEL- WEISS surf. stand. 2019 [88], Collar (H) [89], COSINE-100 2018 (NaI) [90], Dark- Side binom. 2018 [64], LUX combined 2016 [55], LUX Migdal 2018 [58], NEWS-G 2018 (Ne + CH4) [68], PandaX-II 2016 [62], XENON1t 2018 [59]), XENON1t Migdal 2019 [57], XENON100 low-mass 2016 [91], PICO-60 C3F8 2016 [70]. A grey area: experimental sensitivity at which one or more events from coherent neu- trino scattering are expected for a dark matter search with CaWO4 [92]. Coherent neutrino scattering forms an irreducible background for most direct dark matter search experiments.

Summary of Key Findings

- Candidate Viability: Axions and hidden photons are promising DM candidates.
- CMS Impact: The detector's versatility highlights its role in DM search efforts.



Long-Term Prospects for Light DM Research



Future Designs
Enhanced detectors, advanced computations, and theoretical insights.

Interdisciplinary Importance
Links between physics, computation, and engineering.

Closing Remark

DM detection remains vital for understanding cosmic structures.

CMS's high-energy reach is critical to modern astrophysical research.

Acknowledgments & References

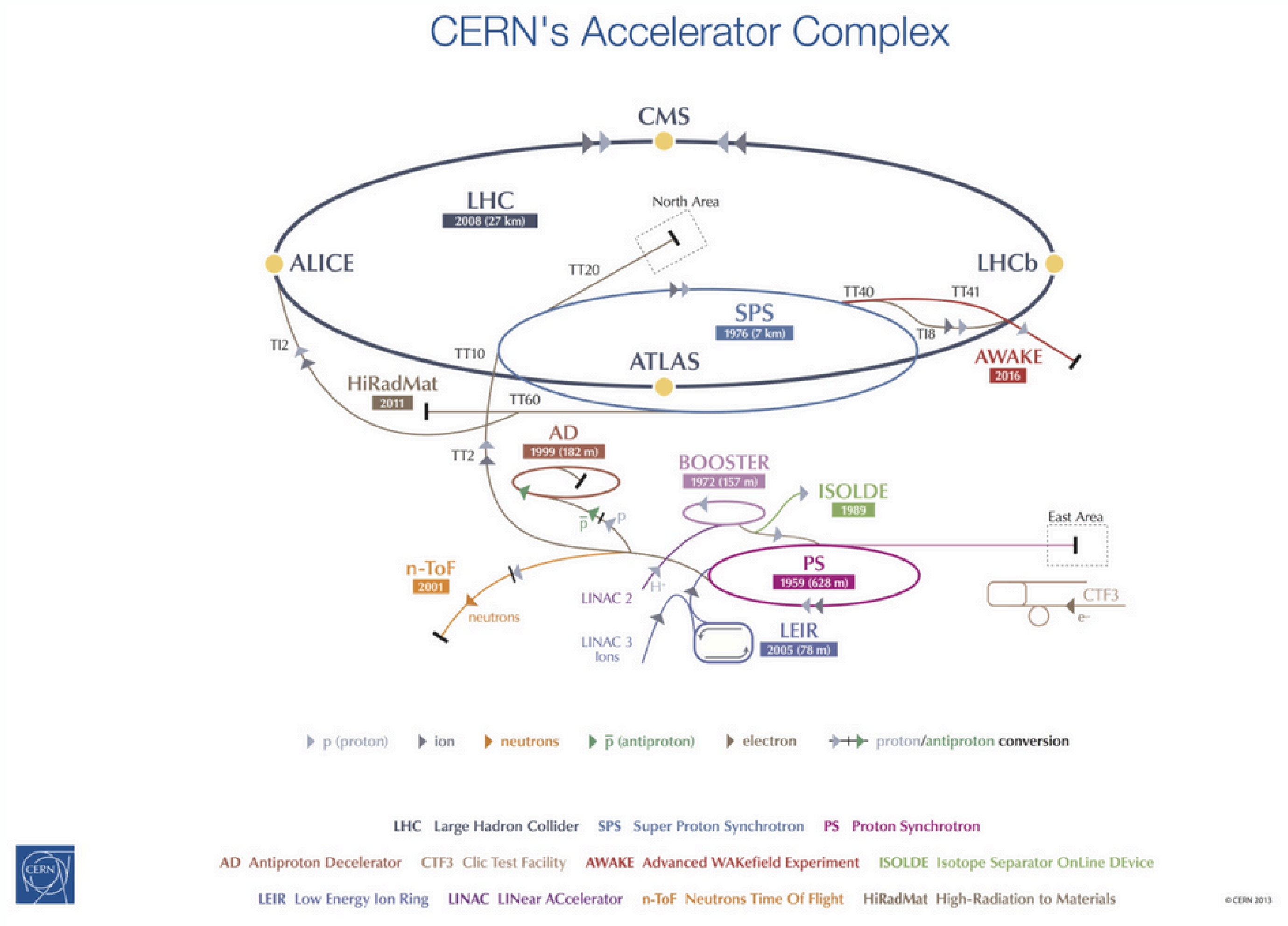


Figure 2.1: An illustration of the accelerator complex at CERN [17]

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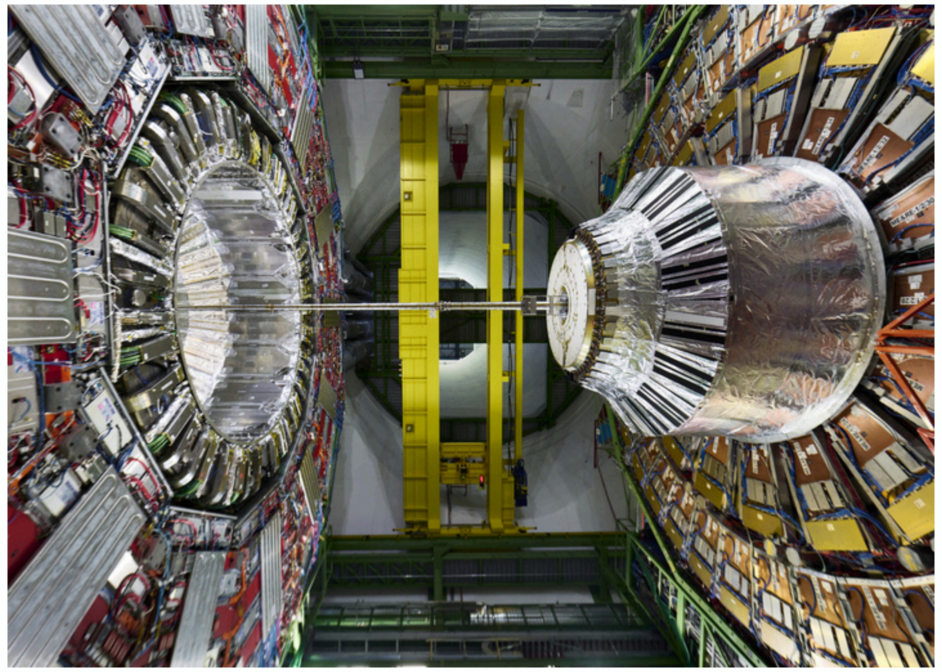
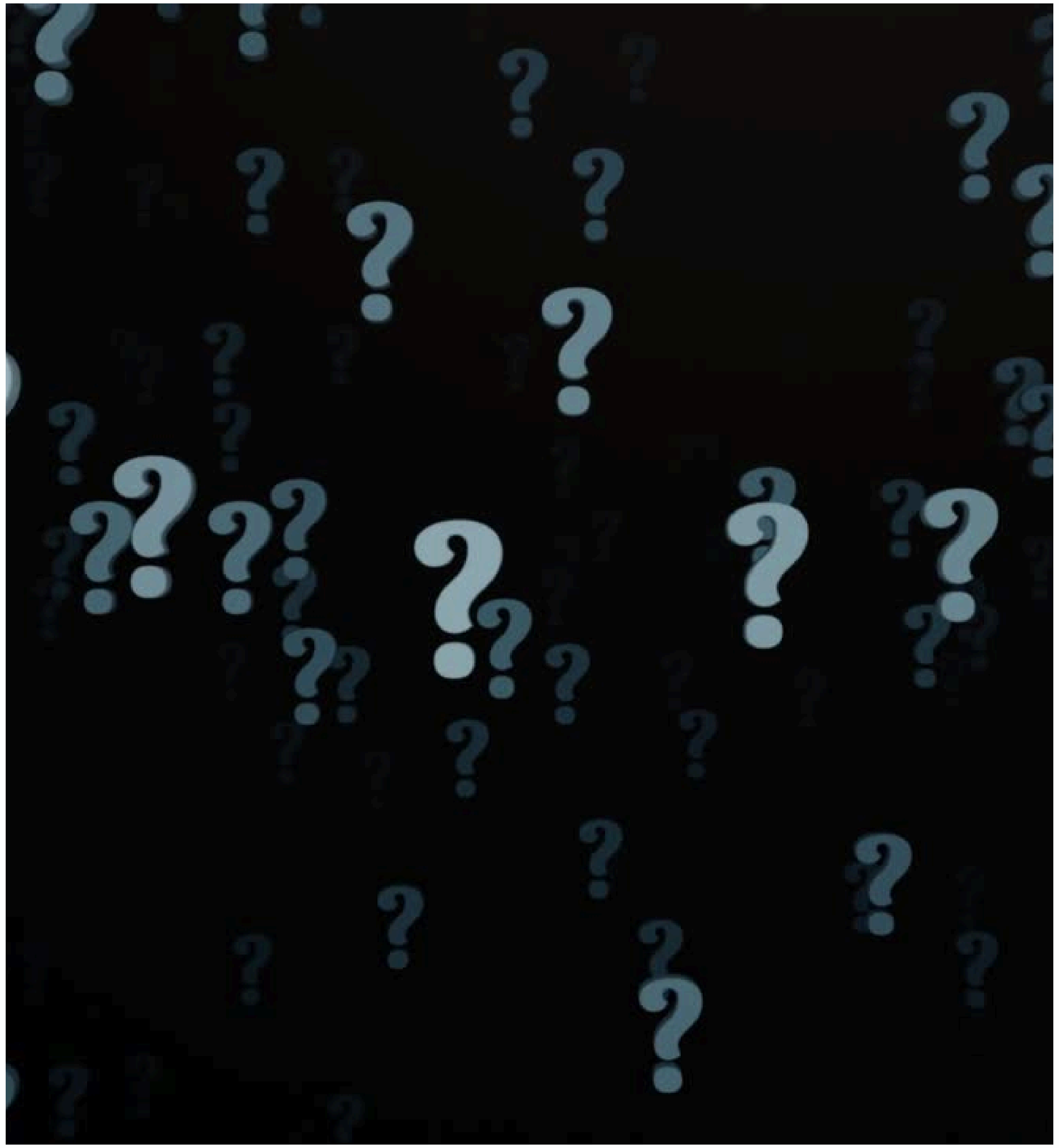


Q&A

Interactive session to address audience inquiries.



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