



AI Needs in Compute/Data Intensive Research from High-Energy Physics and Radio Astronomy

The SPECTRUM Project Perspective

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24 June 2025

e-IRG Workshop under Polish EU Presidency



Funded by
the European Union

SPECTRUM is funded by the European Union - Grant Agreement Number 101131550



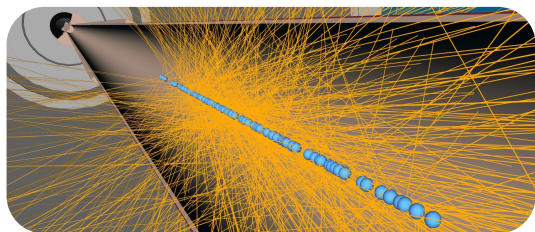
Outline

- The Exascale challenge in HEP and RA
- The role of the SPECTRUM Project
- Priorities for AI in HEP/RA

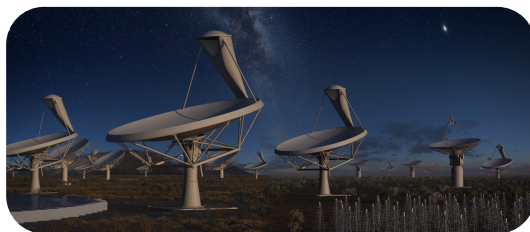
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The Exascale Challenge: A New Era for Science

High-Energy Physics (HEP) and Radio Astronomy (RA) are entering the Exascale era, driven by next-generation instruments



High-Luminosity Large Hadron Collider (HL-LHC)



Square Kilometre Array (SKA)



LOW Frequency ARray (LOFAR) 2.0

Volume

Exabytes of data requiring storage and analysis

Velocity

Data generated at terabytes/petabytes per second, demanding real-time processing

Variety

Complex, heterogeneous data from millions of sensors or thousands of antennas

Elevating Data-Intensive Science in Europe

CHALLENGE

The **computing** for the **next generation of scientific instruments** in High-Energy Physics and Radio Astronomy is an **unsolved problem**

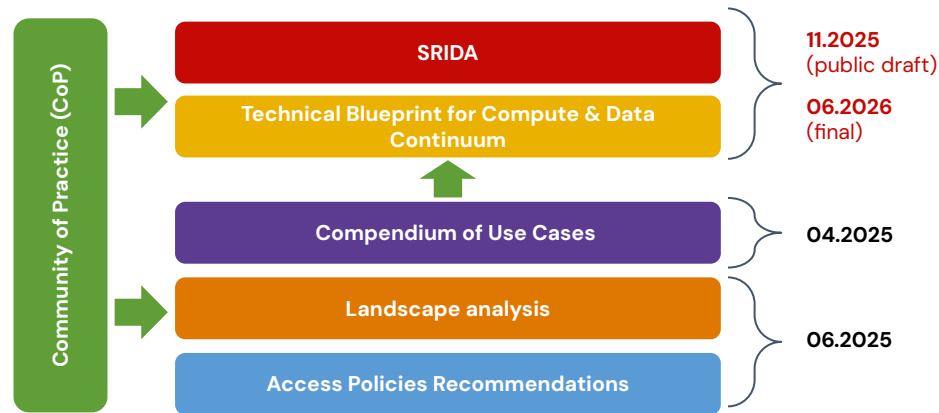


GOAL

Deliver a **Strategic Research, Innovation and Deployment Agenda (SRIDA)** and a **Technical Blueprint for a European compute and data continuum**.

IMPACT

- **Strengthening Europe leadership** in strategic technologies
- **Aligning efforts** and reduce fragmentation among initiatives
- **Enabling a federated ecosystem** that integrates diverse compute capabilities (HTC, Cloud, HPC, QUantum) allowing researchers to bring their analysis to the data



<https://www.spectrumproject.eu/kers>



The SPECTRUM Project is funded by the European Union Grant Agreement Number [101131550](#)
 Start date: 1 Jan 2024 - End date: 30 Jun 2026
More Info: [spectrumproject.eu](https://www.spectrumproject.eu)

AI in HEP and RA





The Broad Landscape of AI in Science

More than just chatbots, a wide range of AI capabilities to see, decide, and create

AI to See (Perception & Analysis)

- Process vast and complex data, finding meaningful patterns that would be impossible for humans to detect
- *Examples: Analyzing images from detectors and telescopes; Identifying faint signals hidden in noisy data*
- *Key Technologies: Convolutional Neural Networks (CNNs), Graph Neural Networks (GNNs)*

AI to Decide (Reasoning & Optimization)

- Make intelligent, real-time decisions based on the data it sees
- *Examples: Classifying which collisions to save; Detecting anomalies that could signal new physics; Optimizing telescope settings and scheduling to maximize scientific output*
- *Key Technologies: Boosted Decision Trees (BDTs), Unsupervised Anomaly Detectors*

AI to Create (Generation & Simulation)

- Generate new, realistic data or solutions that dramatically accelerate the pace of research
- *Examples: Creating ultra-fast simulations that reduce tasks from hours to seconds; Assisting scientists with complex coding and analysis*
- *Key Technologies: Generative Adversarial Networks (GANs), Large Language Models (LLMs)*



Examples of AI Applications in HEP

- **Smarter Detectors**
 - AI tunes detector settings in real-time, squeezing every bit of information from the 10× higher particle rates
- **Lightning-Fast Triggers**
 - AI-based “triggers” sift through 40 million events per second, keeping only the interesting collisions
 - Saves storage space and ensures we capture rare phenomena
- **Ultra-Fast Simulations**
 - AI accelerates complex physics simulations—from hours to seconds—so scientists can test new ideas quickly
- **Clearer Collision Pictures**
 - AI reconstructs particle tracks more accurately, even in the busiest events
 - Removes background noise, revealing the true physics signals
- **Spotting the Unexpected**
 - AI hunts for anomalies—unusual patterns that could hint at new particles or undiscovered laws of nature
- **Smarter Operations & Maintenance**
 - Predictive AI tools flag potential hardware issues early, reducing downtime and keeping the accelerator running smoothly

Examples of AI Applications in RA

- **Smarter Telescopes**
 - AI picks the best settings and observing times, so each telescope run gathers maximum science
- **Faster & Cleaner Data**
 - Handles huge data streams in the cloud
 - Removes noise and interference automatically
 - Delivers real-time results so exciting moments aren't missed
- **Sharper Cosmic Pictures**
 - AI sharpens blurry images and highlights key details
 - Can even “fill in the blanks” to reveal hidden structure
- **Spotting Cosmic Signals**
 - AI quickly finds and labels radio sources—stars, galaxies, and more—building detailed sky maps for astronomers
- **Catching Sudden Events**
 - Instantly flags fast radio bursts and other rare flashes
 - Aids searches for new or mysterious signals—even potential alien messages
- **Uniting Many Telescopes**
 - AI combines data from multiple dishes, giving us crystal-clear, wide-angle views of the universe



Priority 1: Real-Time AI for Instantaneous Discovery

- **Challenge**

- Discoveries are lost forever if we can't make decisions on petabytes of data in microseconds

- **Strategic Need (FastML)**

- Embed AI decision-making directly into our instruments on specialized, low-power hardware (FPGAs)
- Transform detectors from simple sensors into intelligent, autonomous discovery engines

- **Required Investment**

- Support for hardware/software co-design tools
- Access to next-generation AI accelerator testbeds



Priority 2: Building Trustworthy & Rigorous AI

- **Challenge**

- "Black-box" AI is insufficient for science. For a result to be published, it must be understood, trusted, and have its uncertainties quantified

- **Strategic Need (XAI & UQ)**

- Develop AI that can explain its reasoning (Explainable AI – XAI)
- Create AI that provides robust error bars for its predictions (Uncertainty Quantification – UQ)

- **Required Investment**

- Targeted research programs for science-centric XAI and UQ
- Community-wide benchmarks to validate model trustworthiness



Priority 3: Scalable & Energy-Efficient Infrastructure

- **Challenge**

- The entire scientific workflow, from massive-scale simulations to training next-generation Foundation Models, requires enormous computational power and has a significant energy footprint

- **Strategic Need**

- A federated compute continuum that integrates Europe's premier HPC, HTC, Cloud, Quantum to train foundation models and support the full data processing and analysis lifecycle
- A "Green AI" approach that prioritizes performance-per-watt to ensure sustainability

- **Required Investment**

- Funding for platforms that orchestrate AI workloads across the federated continuum
- Prioritizing energy efficiency in all future ICT procurement



Priority 4: Sustainable & Interoperable AI Solutions

- **Challenge**

- AI models developed in research often remain one-off prototypes. They must be engineered into robust, reproducible, and maintainable tools for long-term use

- **Strategic Need**

- Adopt professional Machine Learning Operations (MLOps) to manage the entire AI lifecycle (versioning, deployment, monitoring)
- Ensure all data, models, and software are FAIR (Findable, Accessible, Interoperable, Reusable)
- Develop a skilled workforce capable of building and maintaining these advanced systems

- **Required Investment**

- Support for common, open-source platforms
- Funding for dedicated MLOps support roles within research collaborations
- Coordinated training programs (e.g., summer schools, workshops) to build a new generation of AI-literate researchers

Summary

- The data deluge from HL-LHC, SKA, and LOFAR 2.0 is forcing a paradigm shift and AI has the potential to augment the entire scientific workflow
- Key Investment Priorities for the Future
 - **Real-Time & Trustworthy AI:** Fund foundational research in **FastML**, **XAI**, and **UQ** to ensure our AI is both fast and scientifically rigorous
 - **Federated Compute Continuum:** Invest in **energy-efficient** and **federated compute capabilities** to train foundation models and support AI-powered scientific workflows
 - **Sustainable Ecosystems:** Support **open platforms**, dedicated **MLOps roles**, and **coordinated training programs** to make our AI solutions robust, **reproducible (FAIR)**, and self-sufficient

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(Some) Resources

- SPECTRUM D3.1 Community of Practice – Interim report, March 2025 ([pdf](#))
- SPECTRUM D5.1 Compendium of Use Cases, April 2025 ([pdf](#))

- Strategic White Paper on AI Infrastructure for Particle, Nuclear, and Astroparticle Physics: Insights from JENA and EuCAIF, 2025 ([pdf](#))

- Exploratory meeting on enabling AI in HEP experiment and theory: software/tools, operations, wider engagement and skills capacity, 2024 ([pdf](#))

- AI Applications in Radio Astronomy, 2024 ([pdf](#))



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Thank you! Questions?

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