The Next Paradigm of Discovery: Autonomous Closed-Loop Laboratories in Experimental Physics

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The ATTRACT Workshop
November 2025 | DESY

University of Hamburg

From Building Blocks to a New Proposal

I. The Building Blocks: Recent Advances in AI

1. **Adaptive Control:** Reinforcement Learning in Accelerators
2. **Data Comprehension:** Foundation Models in Particle Physics
3. **Embodied Agency:** Action Models in Industry

II. The Synthesis: A Unified Framework

4. **The Closed-Loop Library:** A Robot Scientist
5. **Core Advantages &** Requirements

III. The Proposal: Applications in Experimental Physics

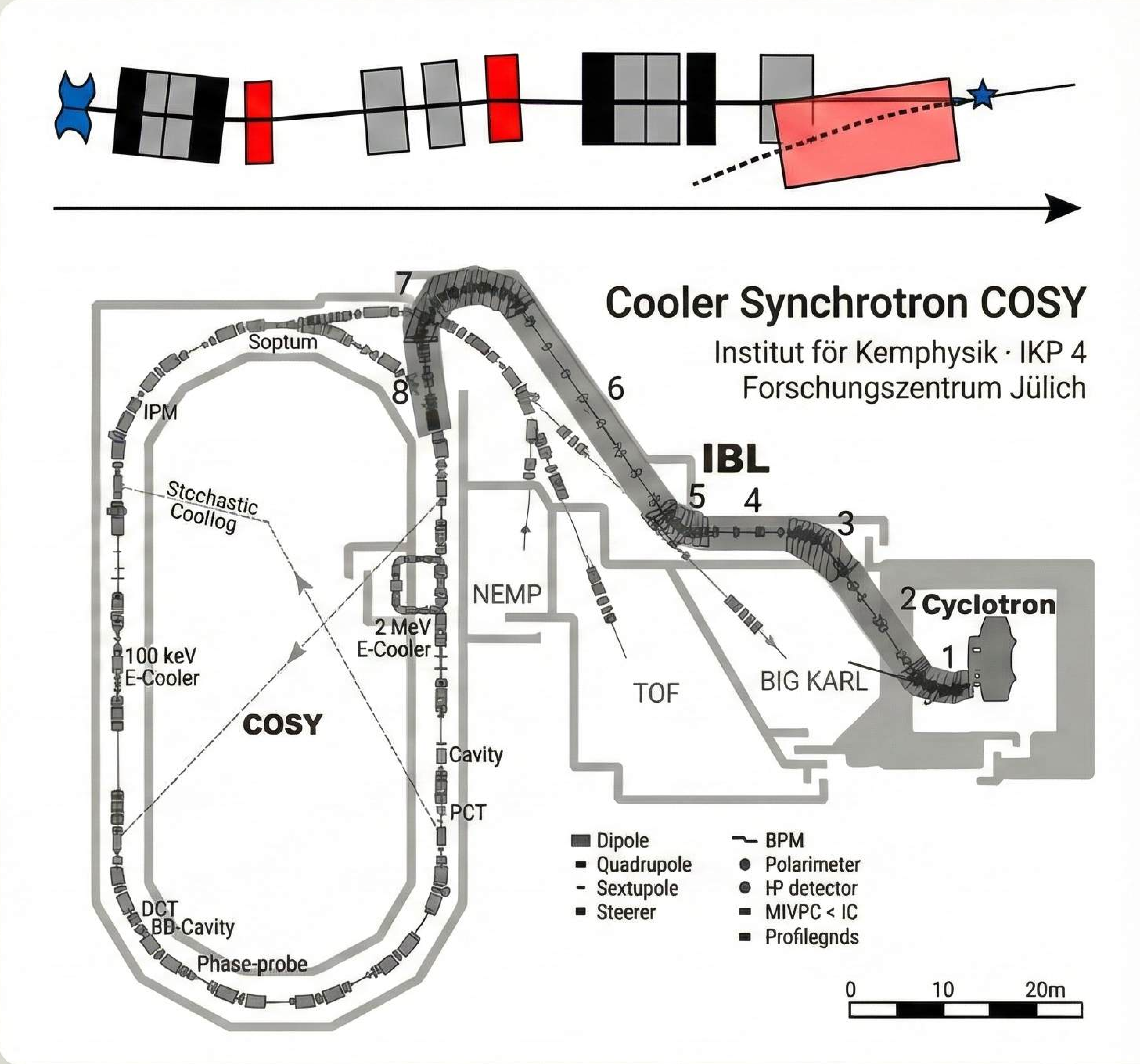
6. **Use Case I:** The Intelligent Particle Detector
7. **Use Case II:** The Autonomous Telescope Survey
8. **Path Forward**

Building Block 1: Reinforcement Learning for Adaptive Control

Key Concept: An AI agent learns to tune complex machine parameters, surpassing traditional algorithms and human experts in real-time.

Case Study: COSY Synchrotron

- Problem: Optimizing beam intensity requires navigating a high-dimensional, non-linear space of magnet settings.
- RL Solution: An agent directly interacts with the machine, observing the beam current (reward) and adjusting magnets (actions) to discover novel, effective optimization strategies.
- Demonstrated Capability: **Adaptive Control** in a complex physics environment.



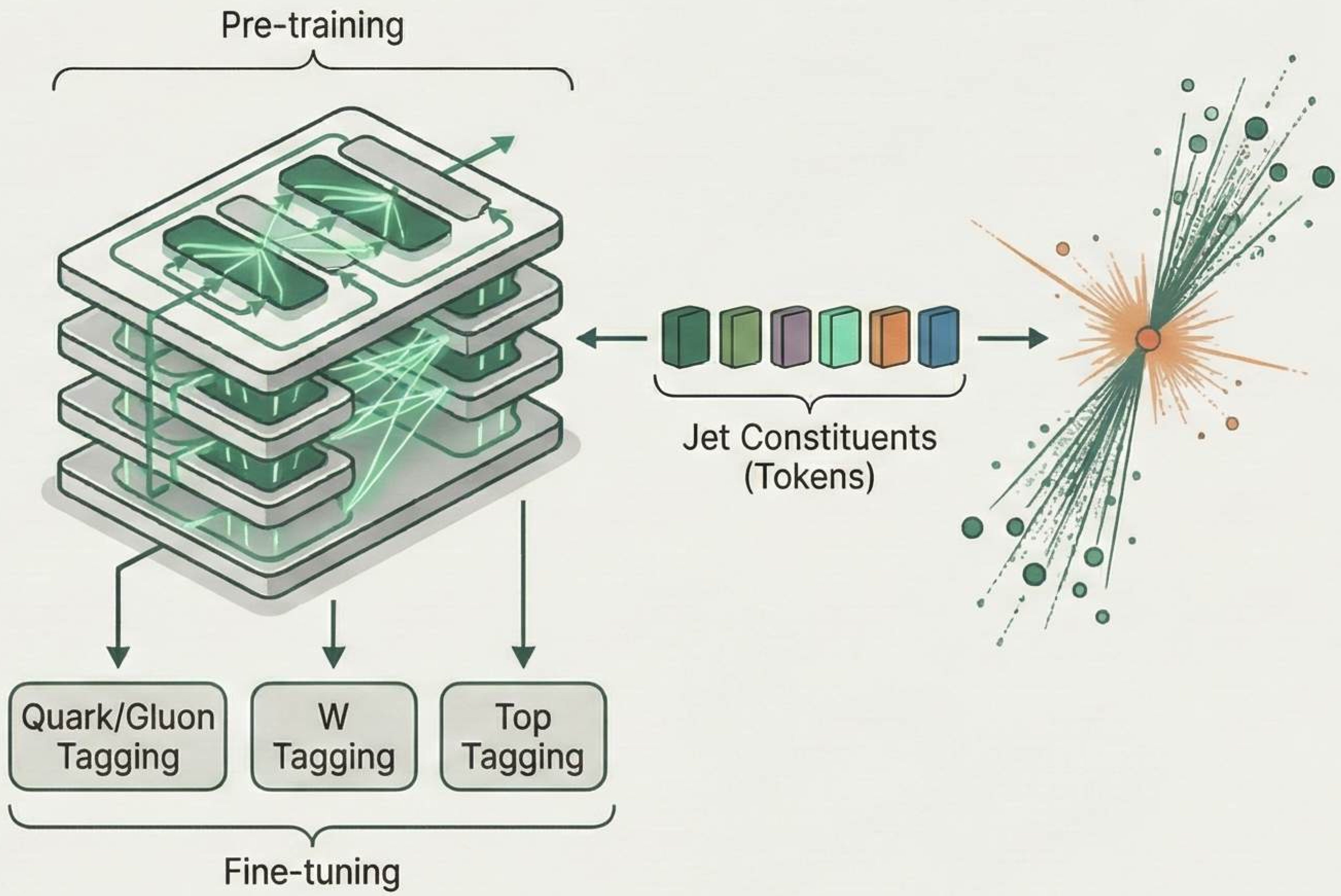
[A.Awal et al, "Injection optimization at particle accelerators via reinforcement learning: From simulation to real-world application" 2025]

Building Block 2: Foundation Models for Universal Data Comprehension

Key Concept: A single model, pre-trained on broad data, can be adapted to a wide range of downstream tasks without starting from scratch.

Case Study: OmniJet-Alpha

- **Problem:** Jet identification is crucial, but traditional methods are task-specific and require separate models.
- **Foundation Model Solution:** Treats particle jet constituents as ‘tokens’ in a sequence, allowing a Transformer to learn the fundamental structure of jets.
- **Demonstrated Capability:** Universal Data Comprehension, enabling a single model to excel at jet classification, anomaly detection, and more.



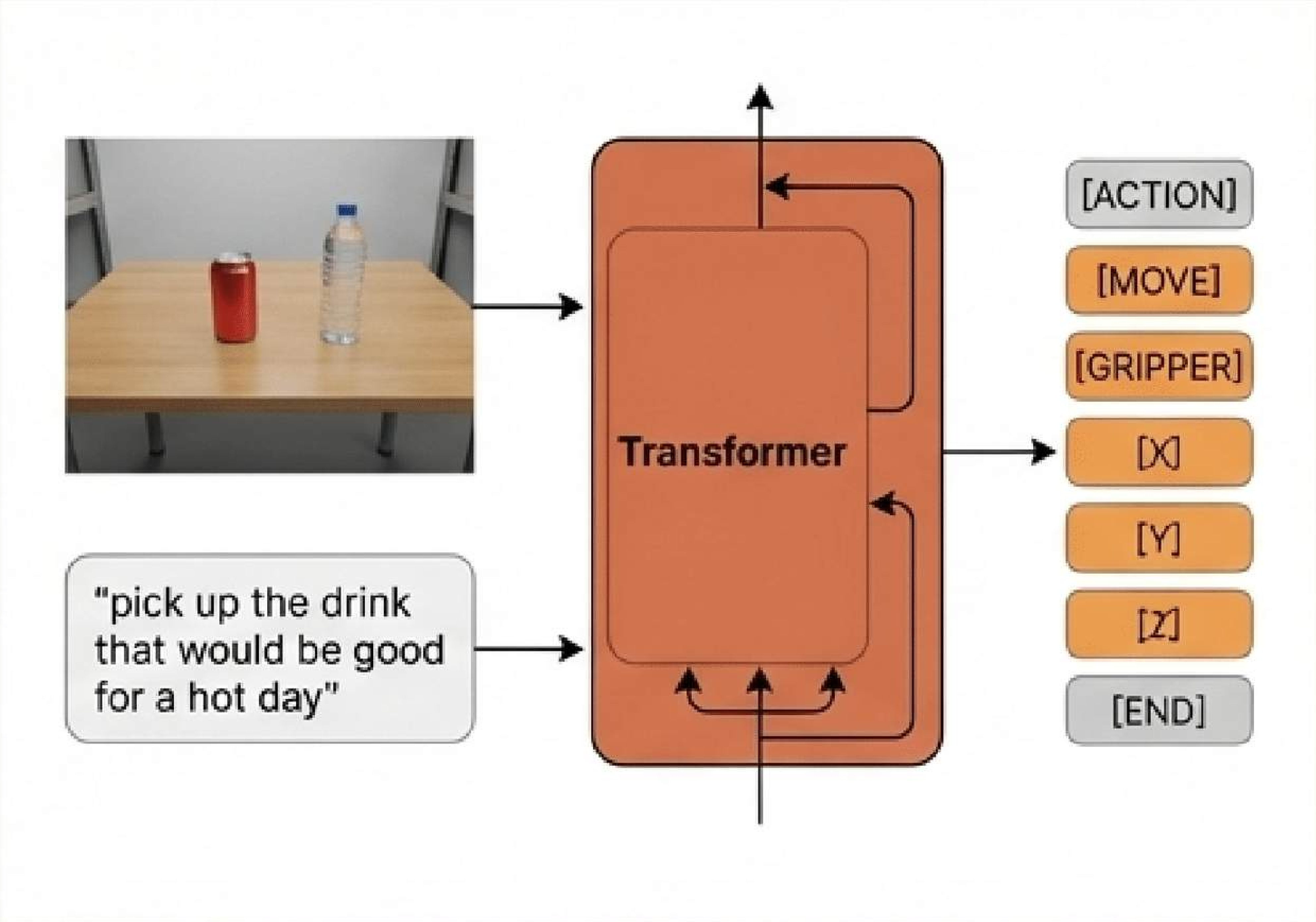
[Figures adapted from J.Brick, A.Hallin and G. Kasieczka, “OmniJet-Alpha: The first cross-task foundation model for particle physics” arxiv: 2403.05618]

Building Block 3: Vision-Language-Action Models for for Embodied Agency

Key Concept: Merging web-scale knowledge (vision, language) with robotic control, enabling robots to reason, plan, and act.

Method: Robotic Transformer 2 (RT-2)

- Robot actions (e.g., `move gripper to [x,y,z]`) are tokenized into a sequence, just like words.
- This approach connects the tokenization method in OmniJet-Alpha (for particles) to tokenization for physical actions, creating a unified vocabulary for both data and action.
- Demonstrated Capability: **Embodied Agency**—translating abstract understanding into physical action.



Footnote: Figure adapted from A. Brohan et al., arXiv:2307.15818 (2023).

The Synthesis: A Framework for the Autonomous Scientist

The Unifying Idea: We can integrate these AI advancements into a single, closed-loop system capable of autonomous experimentation and discovery.

This is More Than Automation

The goal is not simply to reduce human labor in routine tasks. The advantages are more fundamental:

Explore Vast Parameter Spaces

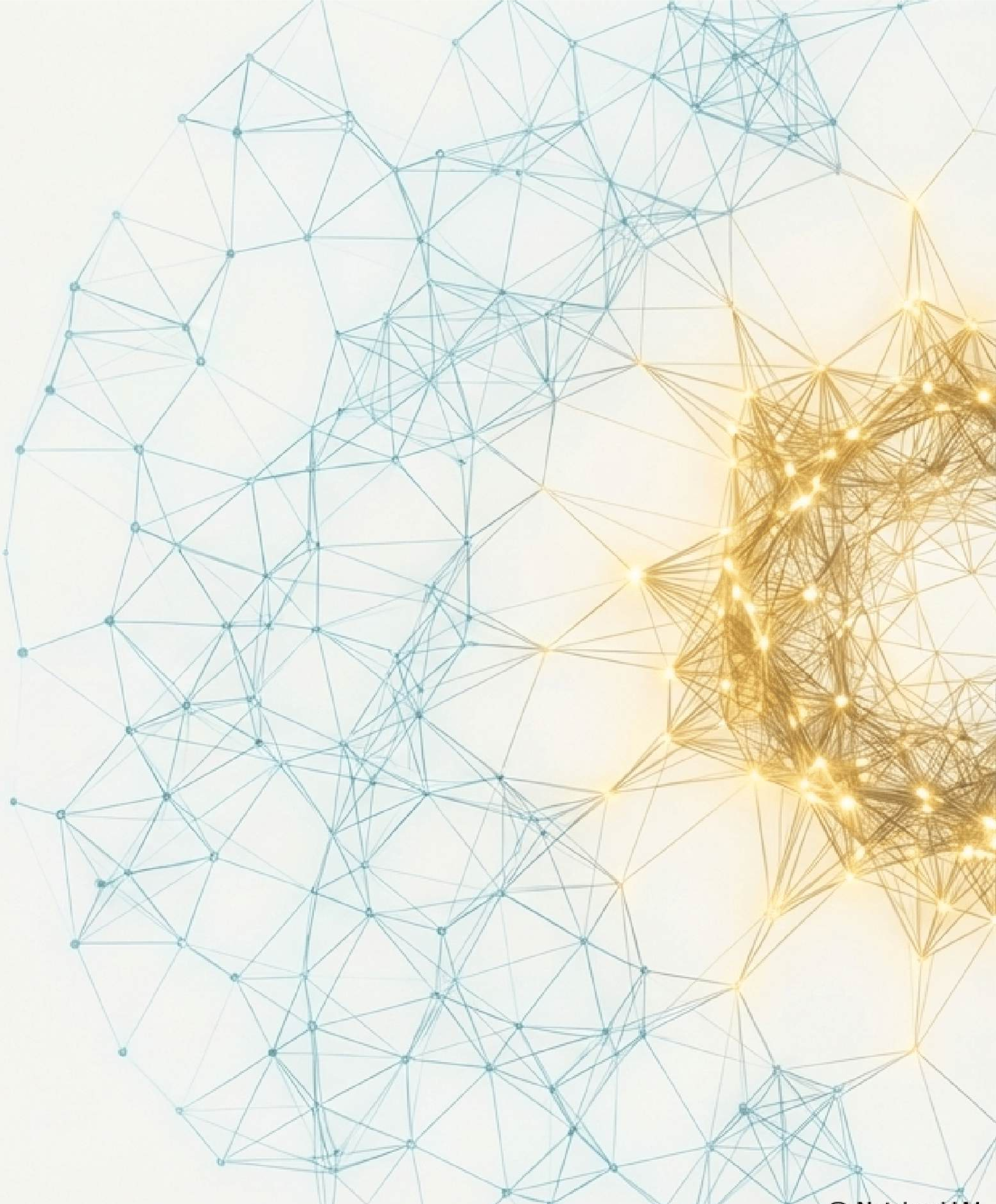
Autonomously navigate and optimize in domains too complex for humans.

Accelerate the Discovery Loop

Tightly couple hypothesis, experimentation, and analysis, reducing discovery cycles from months to hours.

Enable Serendipitous Discovery

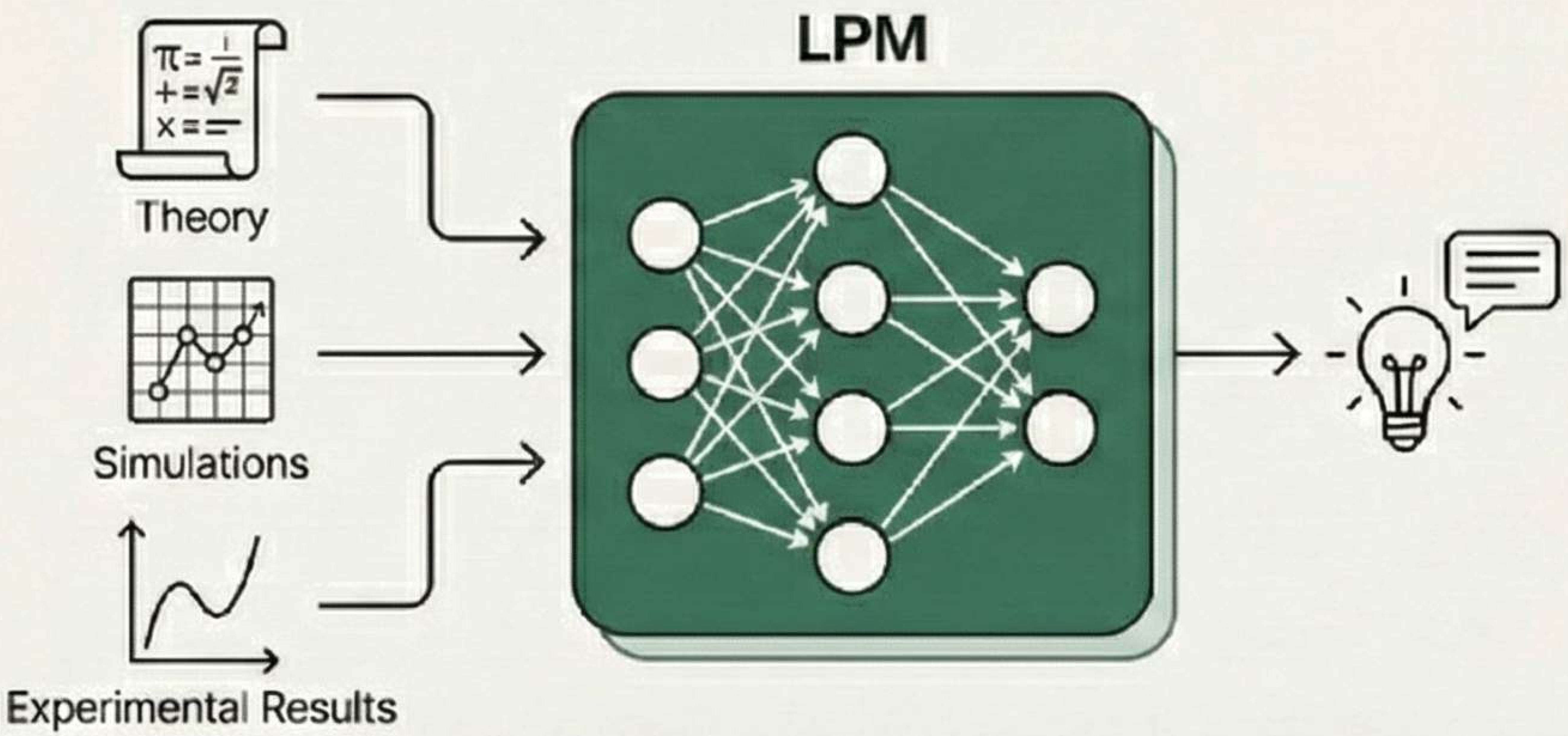
By continuously exploring and analyzing, the system can uncover unexpected correlations and novel phenomena we didn't know to look for.



The Components of a Physics Robot Scientist

The Brain: Large Physics Models (LPMs)

- Foundation models trained specifically on multimodal physics data: theory, simulations, experimental results, academic papers.
- An LPM serves as the core reasoning engine, capable of generating hypotheses and interpreting results within the context of physical laws.



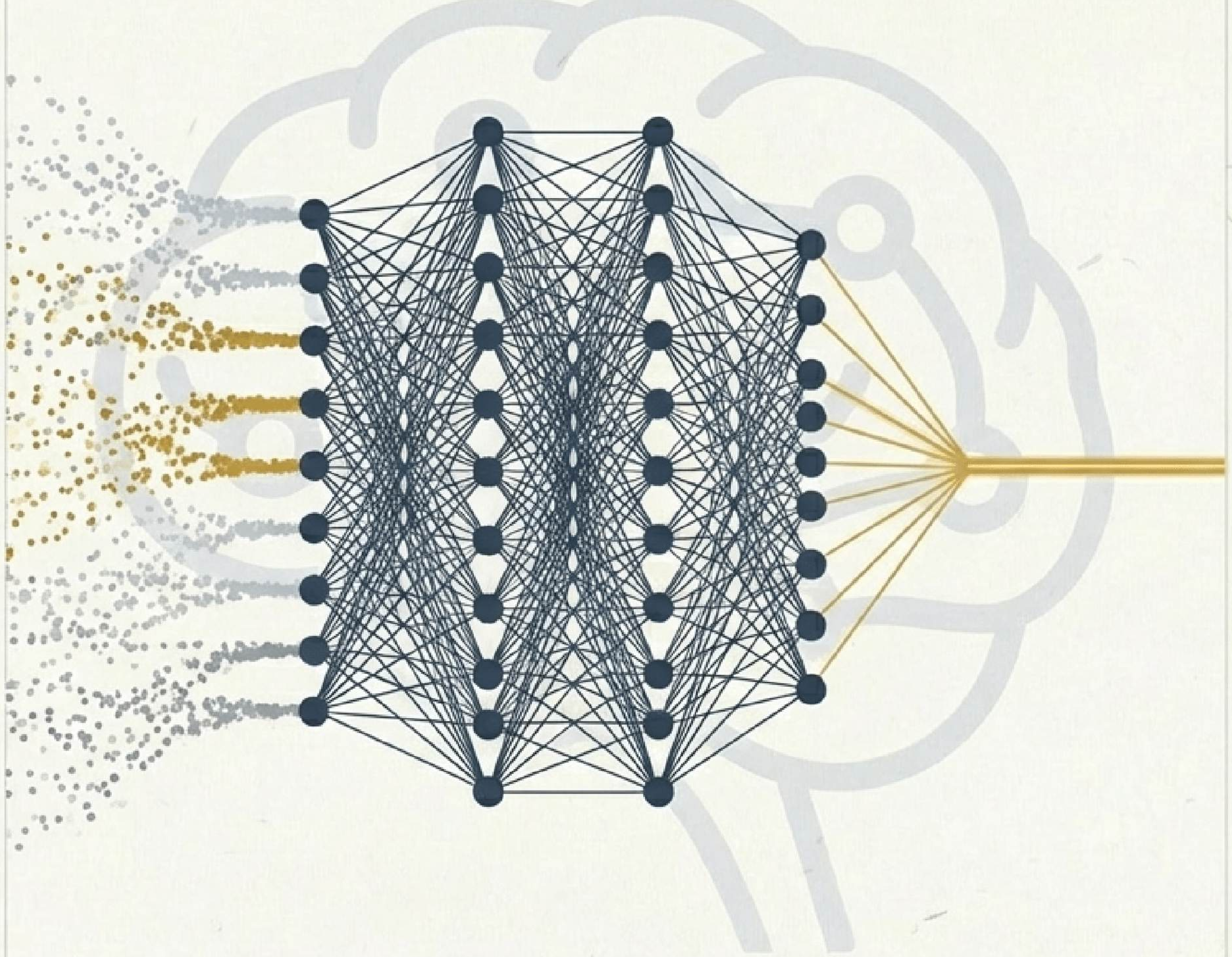
The Eyes: Advanced Detector Systems

- Our modern trackers, calorimeters, and CCDs are already sophisticated digital eyes. The framework integrates integrates their data streams directly into the Brain.

The Arms: Precision Actuation & Control

- This includes digital control of accelerator magnets, telescope pointing systems, and robotic sample handlers.

[Further info: K.Barman, S.Caron, G.Kasieczka et al "Large Physics Models: Towards a collaborative approach with Large Language Models and Foundation Models" arxiv: 2501.05382]



Cognition: The Large Physics Model (LPM).

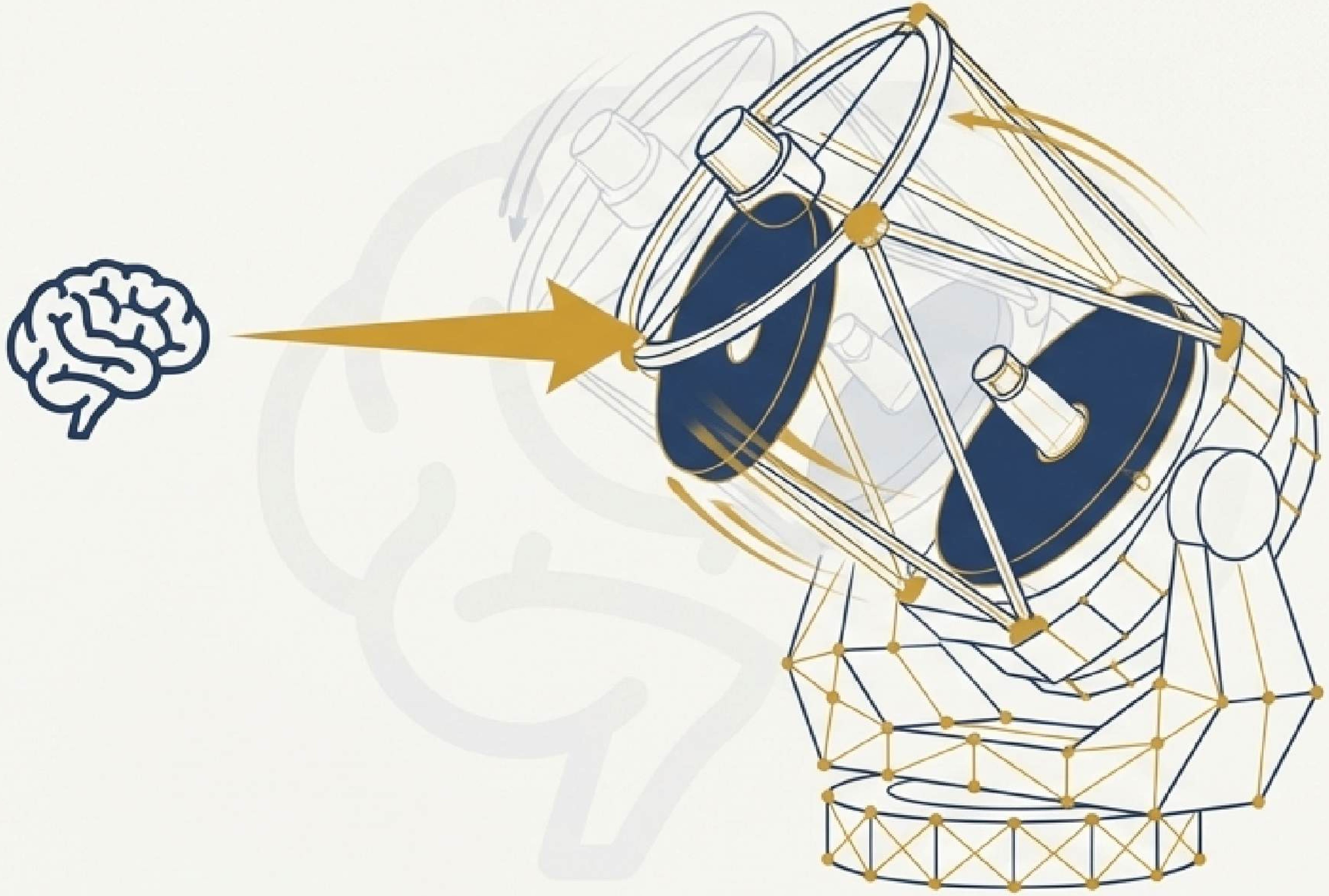
- **Centralized Knowledge:** Acts as a repository for information from all data modalities.
- **Cross-Modal Reasoning:** Reasons across diverse data types in unprecedented ways.
- **Vision-Language-Action (VLA) Integration:** Transfers rich semantic understanding directly into low-level control decisions.
- **Advantage in Physics:** Abundant simulated data mitigates the typical training data bottleneck.

Action: A Non-Optional Requirement

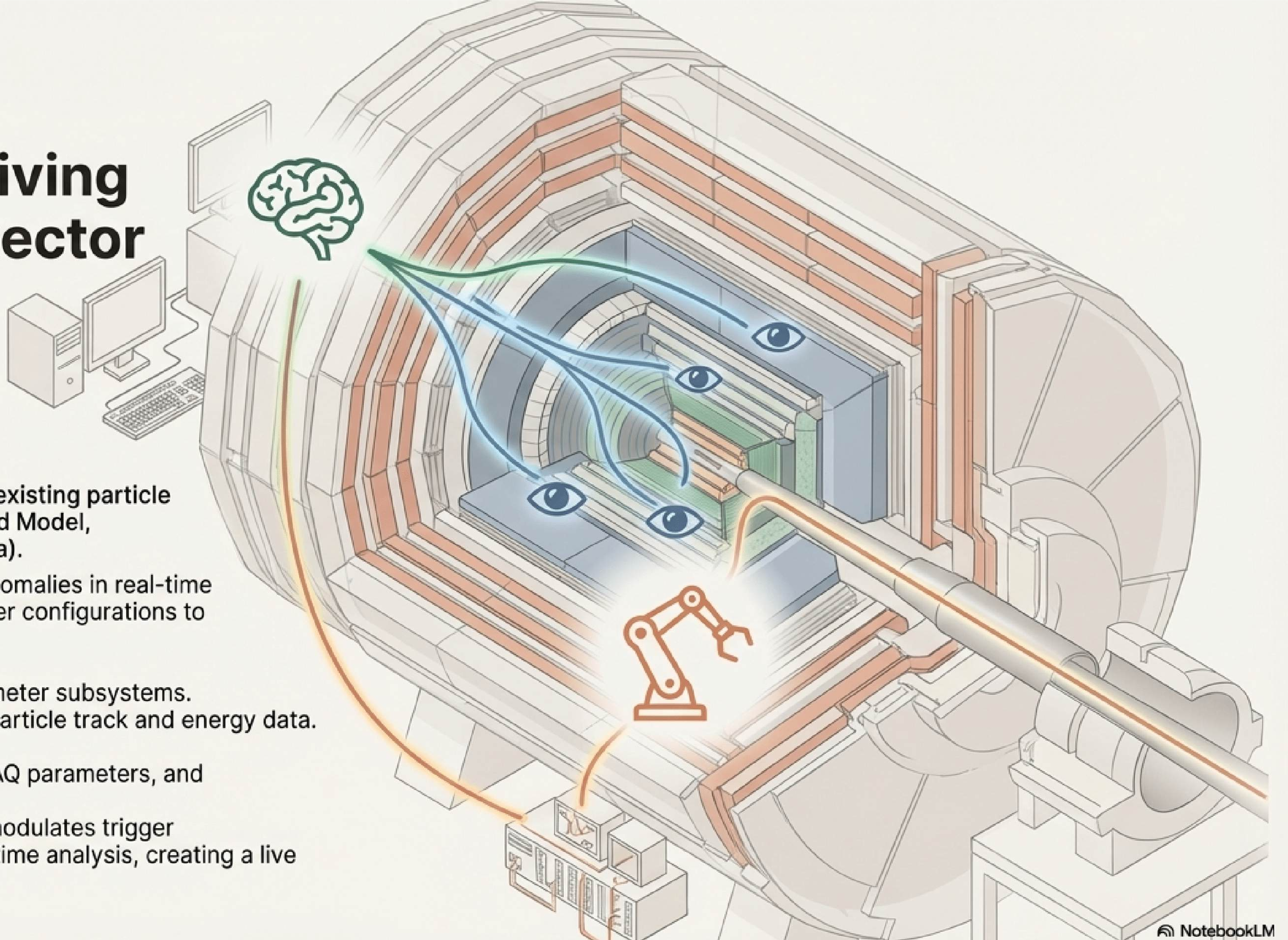
To complete the cycle, the system must intervene and verify in the real world. Without physical execution, the setup collapses into an inference and data analysis problem.

Forms of Action:

- Live mechanical manipulation.
- Dynamic alignment and real-time recalibration.
- Electronic reconfigurations.



Proposal I: The Self-Driving Particle Detector



Brain: An LPM trained on all existing particle physics knowledge (Standard Model, simulation libraries, past data).

Function: Identifies subtle anomalies in real-time data and proposes new trigger configurations to investigate.

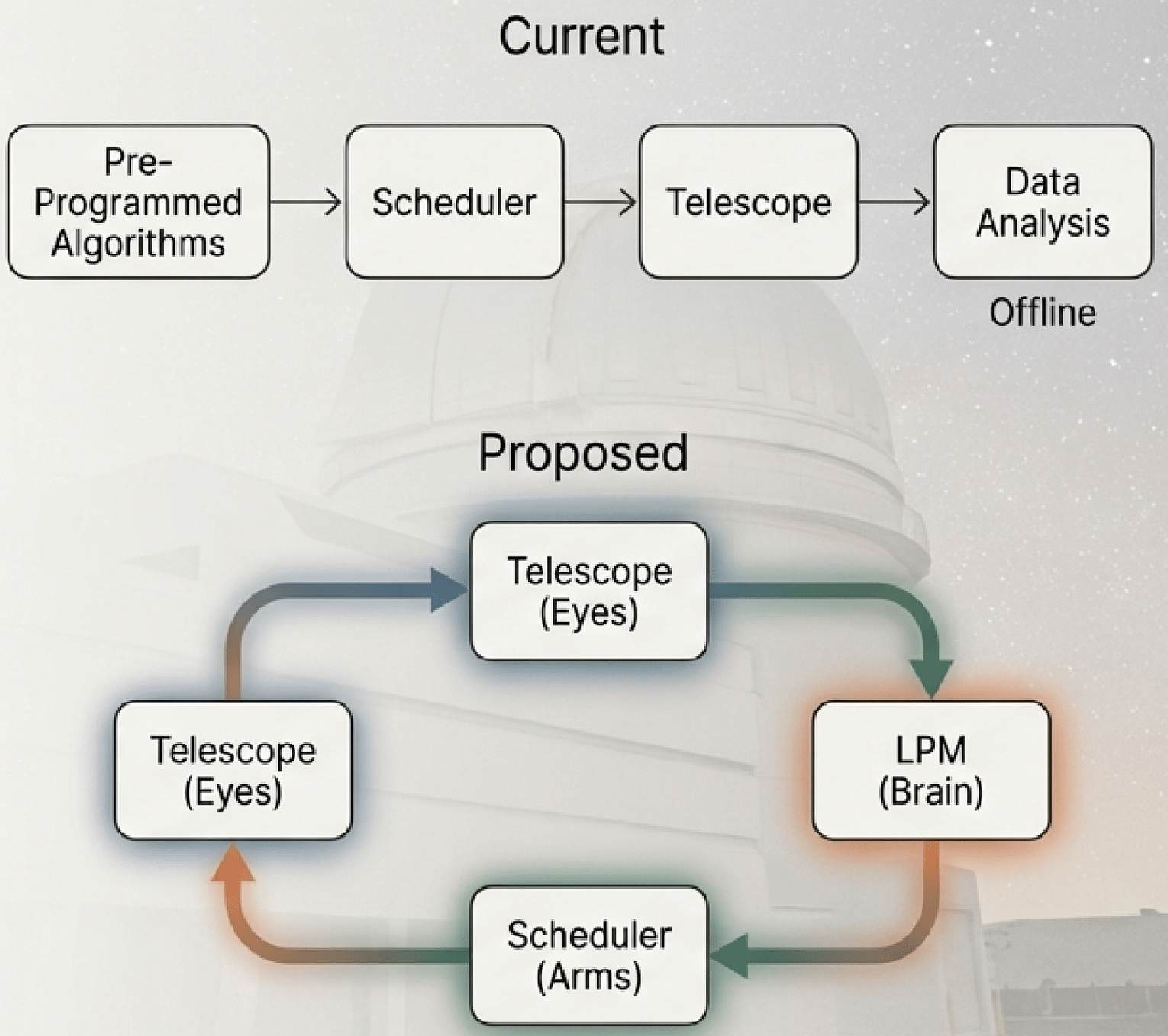
Eyes: The tracker and calorimeter subsystems.
Function: Provide real-time particle track and energy data.

Arms: The trigger system, DAQ parameters, and calibration tools.
Function: The LPM directly modulates trigger thresholds based on its real-time analysis, creating a live discovery loop.

Proposal II: The Autonomous Sky Survey

- **Brain:** An LPM trained on astrophysical data.
  Function: Analyzes incoming transient alerts (supernovae, etc.) and identifies targets of unique scientific opportunity.

- **Eyes:** The telescope's camera and image processing pipeline.
- **Arms:** The telescope's pointing scheduler.
  Function: The LPM dynamically re-tasks the telescope, overriding the pre-planned survey to perform immediate follow-up observations on a highly unusual event.



Autonomous Science Framework Comparison

Feature	Current High-Level Automation	Proposed Autonomous Framework
Goal	Execute pre-defined scripts & optimize fixed metrics.	Discover novel phenomena & generate new hypotheses.
Data Flow	Fragmented: acquire data, offline human analysis, then issue new commands.	Unified, real-time closed loop. Analysis directly and immediately informs action.
Decision Making	Human-in-the-loop for all strategic scientific decisions.	Human-on-the-loop. The system makes tactical scientific decisions autonomously.
Adaptability	Reacts to pre-programmed conditions.	Learns, adapts, and explores based on live data.
Outcome	Efficiency and optimization.	Efficiency, optimization, AND **serendipity**.

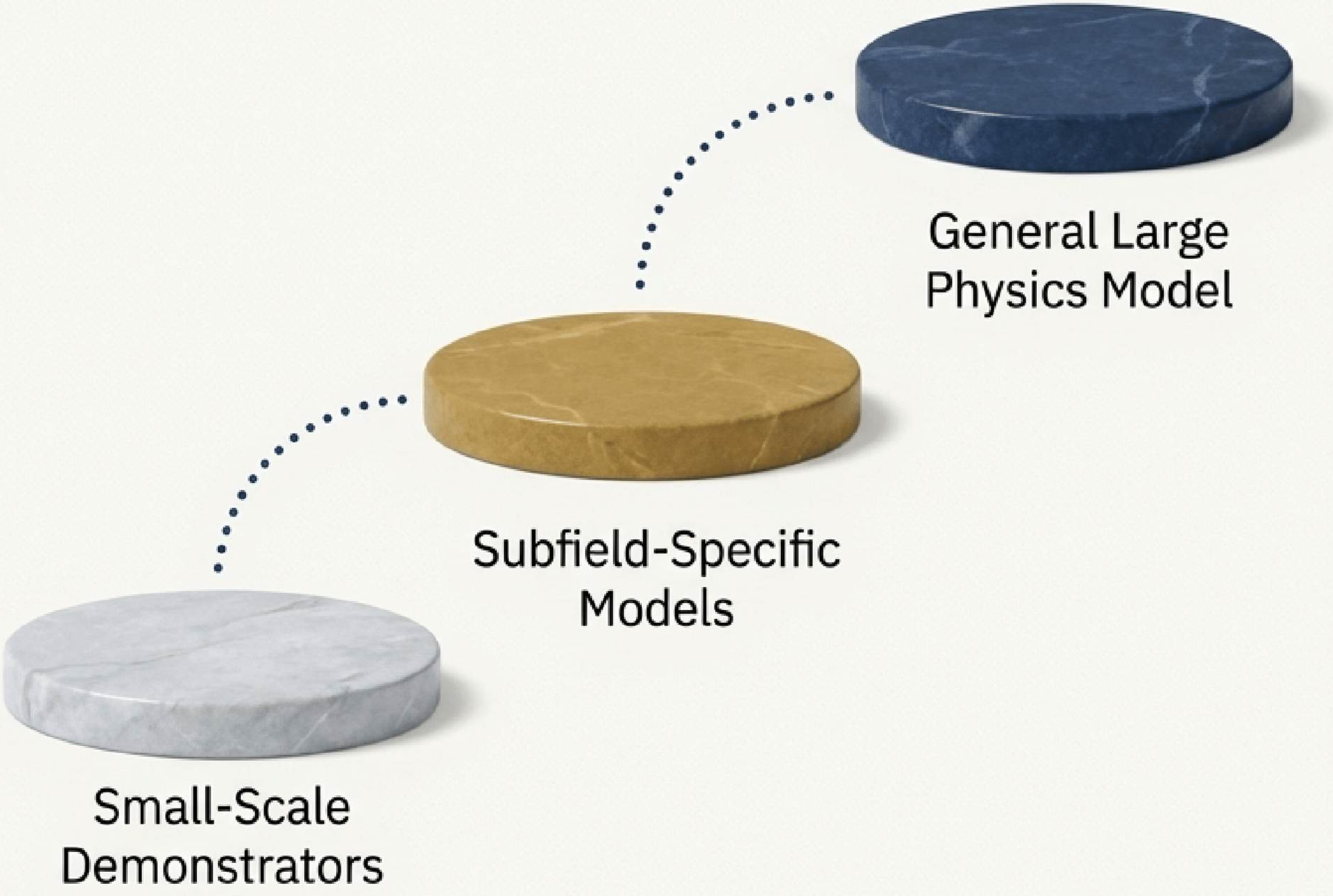
A Feasible Path Forward.

Key Strategy:

Building small-scale demonstrators for specific tasks within each subfield (particle physics, astrophysics) is the most effective first step.

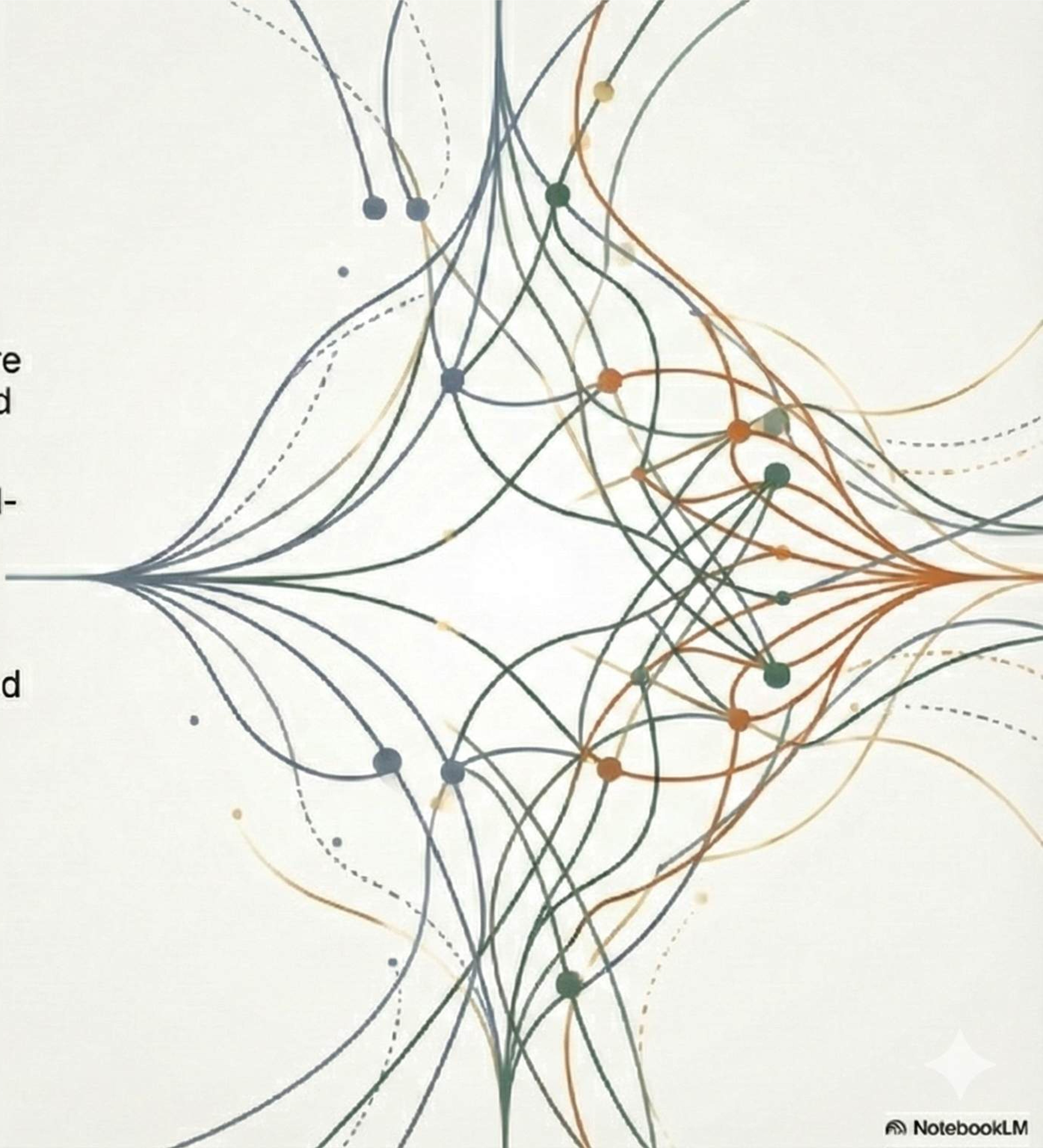
Benefits:

- Provide proof of concept.
- Evaluate feasibility and performance.
- Demonstrate potential impact to the community.



The Future is Autonomous

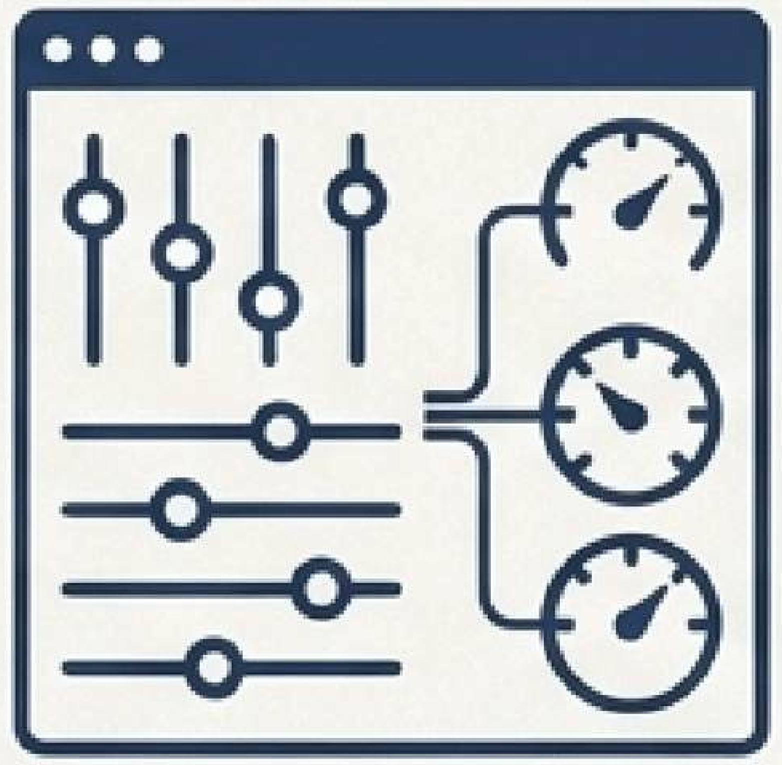
- **The Convergence:** We are at a unique moment where mature AI paradigms for control, comprehension, and action can be unified.
- **The Framework:** By synthesizing these into a closed-loop system, we have the blueprint for a ‘robot scientist’ in experimental physics.
- **The Impact:** This new paradigm moves us beyond simple automation to accelerate the scientific method itself, enabling us to explore complex systems and uncover the unexpected.



Thank You.

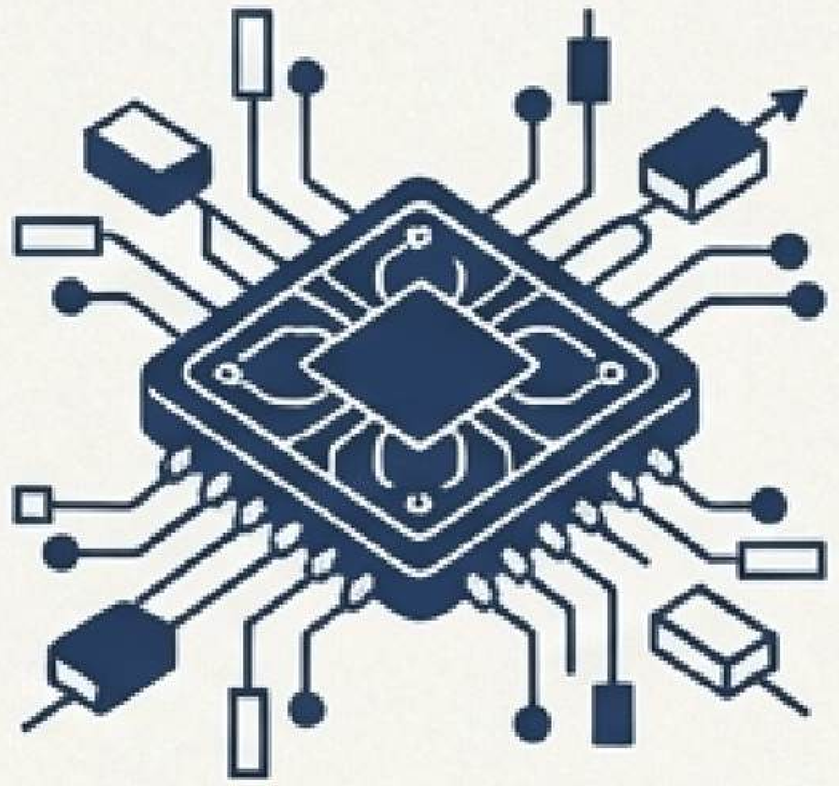
Backup

The Arms of a Particle Detector



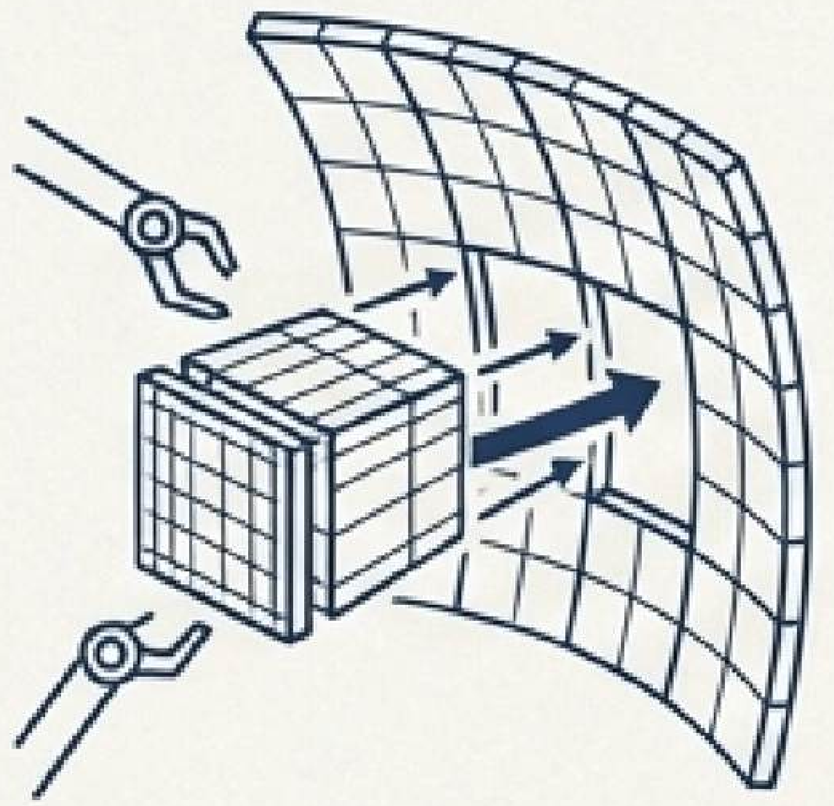
1. Detector Control Systems (DCS)

The LPM makes on-the-fly decisions to dynamically adjust operating conditions like voltages, temperatures, and tracker alignment. (Example: ATLAS dynamic alignment)



2. Electronics-Level Reconfiguration

The LPM commands mode-switches in front-end hardware (ASICs, MAPS) to alter data reduction, timing, or granularity on demand.



3. Active Geometry (Validated via Simulation)

End-to-end simulations can optimize the placement of detector modules for specific physics goals, creating an operational plan for a future robotic controller.