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Space Weather and Heliophysics Modelling in Europe

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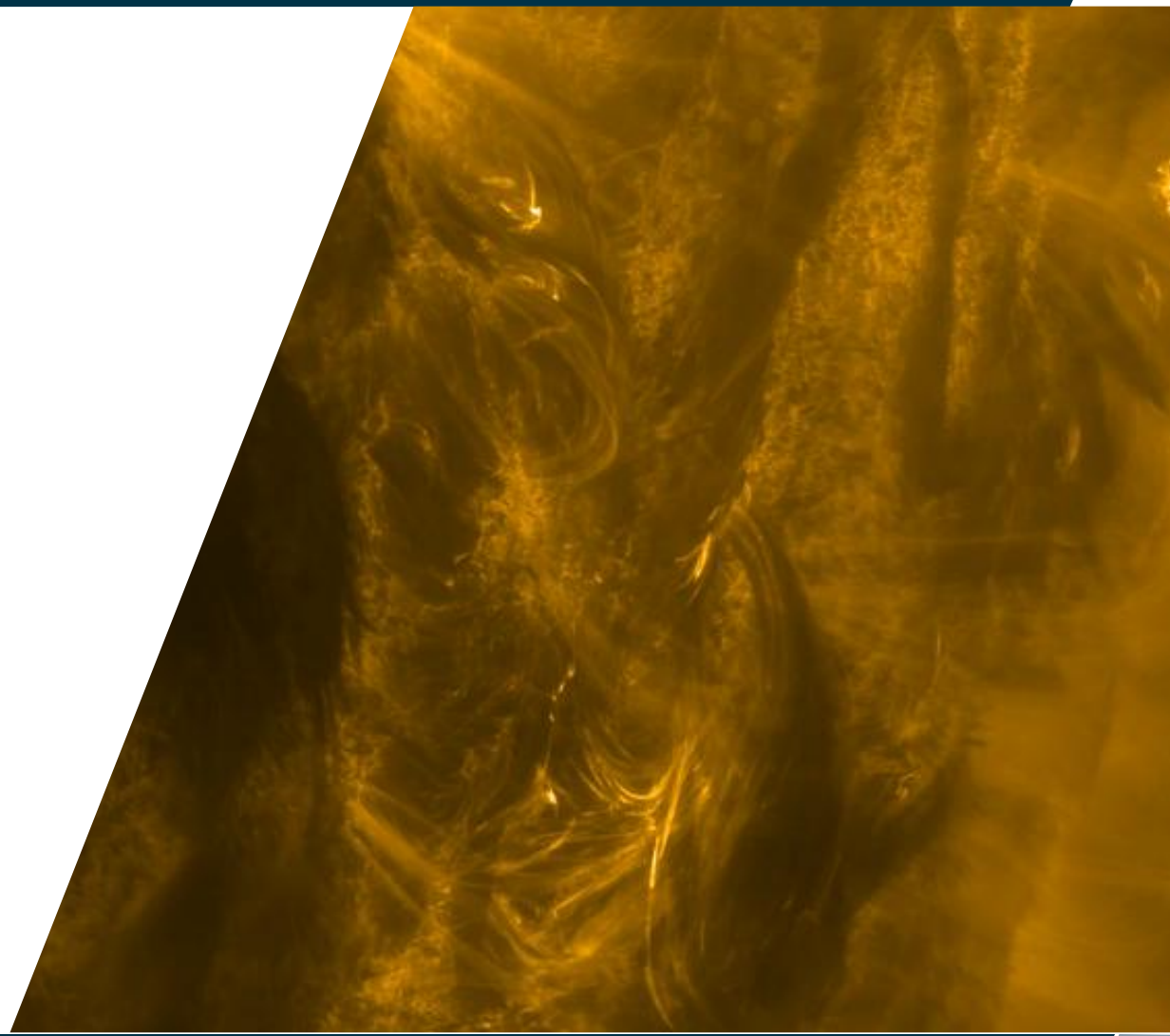
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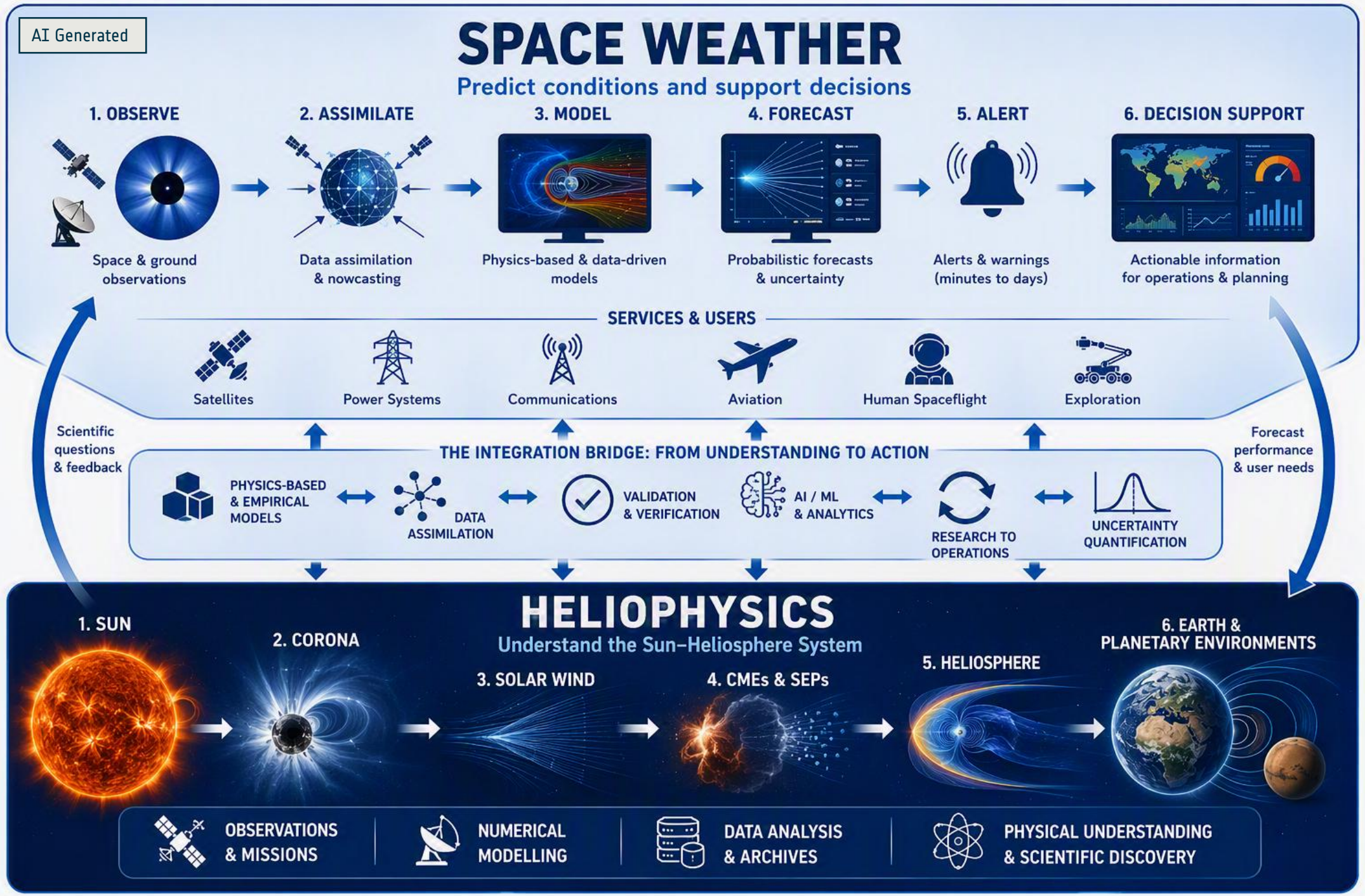
EUROPEAN SPACE AGENCY

What space weather & heliospheric modelling needs to deliver

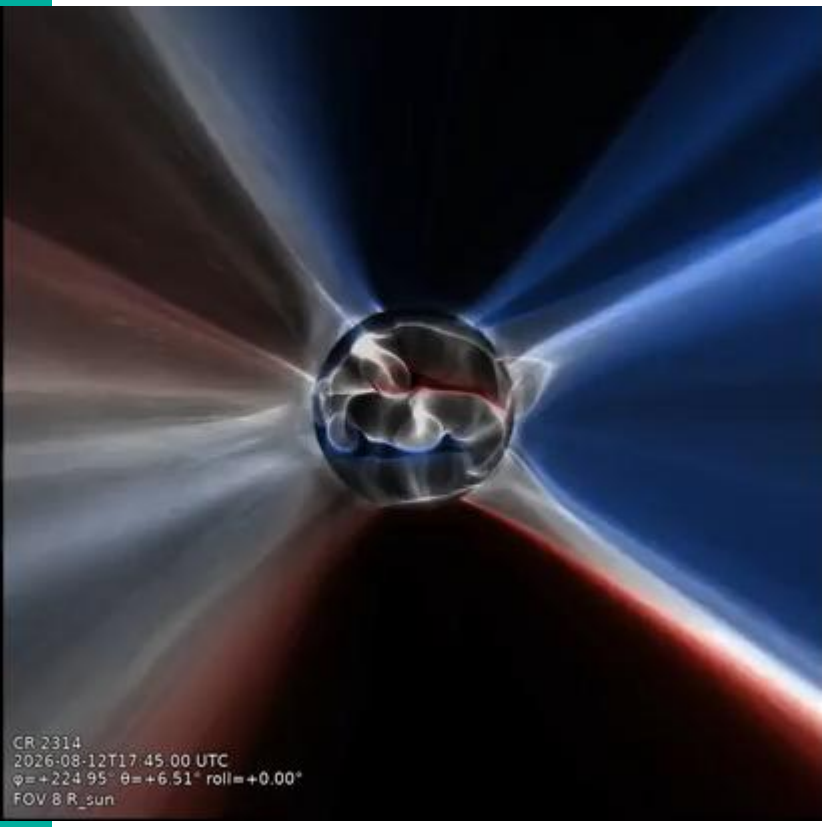
- From world-class components to a dependable European forecasting capability

- Europe has much of the science and technology it needs. The challenge for the coming decade is to make the whole greater, and more dependable, than the sum of its parts.




AI Generated
SPACE WEATHER
Predict conditions and support decisions
1. OBSERVE
2. ASSIMILATE
3. MODEL
4. FORECAST
5. ALERT
6. DECISION SUPPORT
Space & ground observations
Data assimilation & nowcasting
Physics-based & data-driven models
Probabilistic forecasts & uncertainty
Alerts & warnings (minutes to days)
Actionable information for operations & planning
SERVICES & USERS
Satellites
Power Systems
Communications
Aviation
Human Spaceflight
Exploration
Scientific questions & feedback
Forecast performance & user needs
THE INTEGRATION BRIDGE: FROM UNDERSTANDING TO ACTION
PHYSICS-BASED & EMPIRICAL MODELS
DATA ASSIMILATION
VALIDATION & VERIFICATION
AI / ML & ANALYTICS
RESEARCH TO OPERATIONS
UNCERTAINTY QUANTIFICATION
HELIOPHYSICS
Understand the Sun–Heliosphere System
1. SUN
2. CORONA
3. SOLAR WIND
4. CMEs & SEPs
5. HELIOSPHERE
6. EARTH & PLANETARY ENVIRONMENTS
OBSERVATIONS & MISSIONS
NUMERICAL MODELLING
DATA ANALYSIS & ARCHIVES
PHYSICAL UNDERSTANDING & SCIENTIFIC DISCOVERY

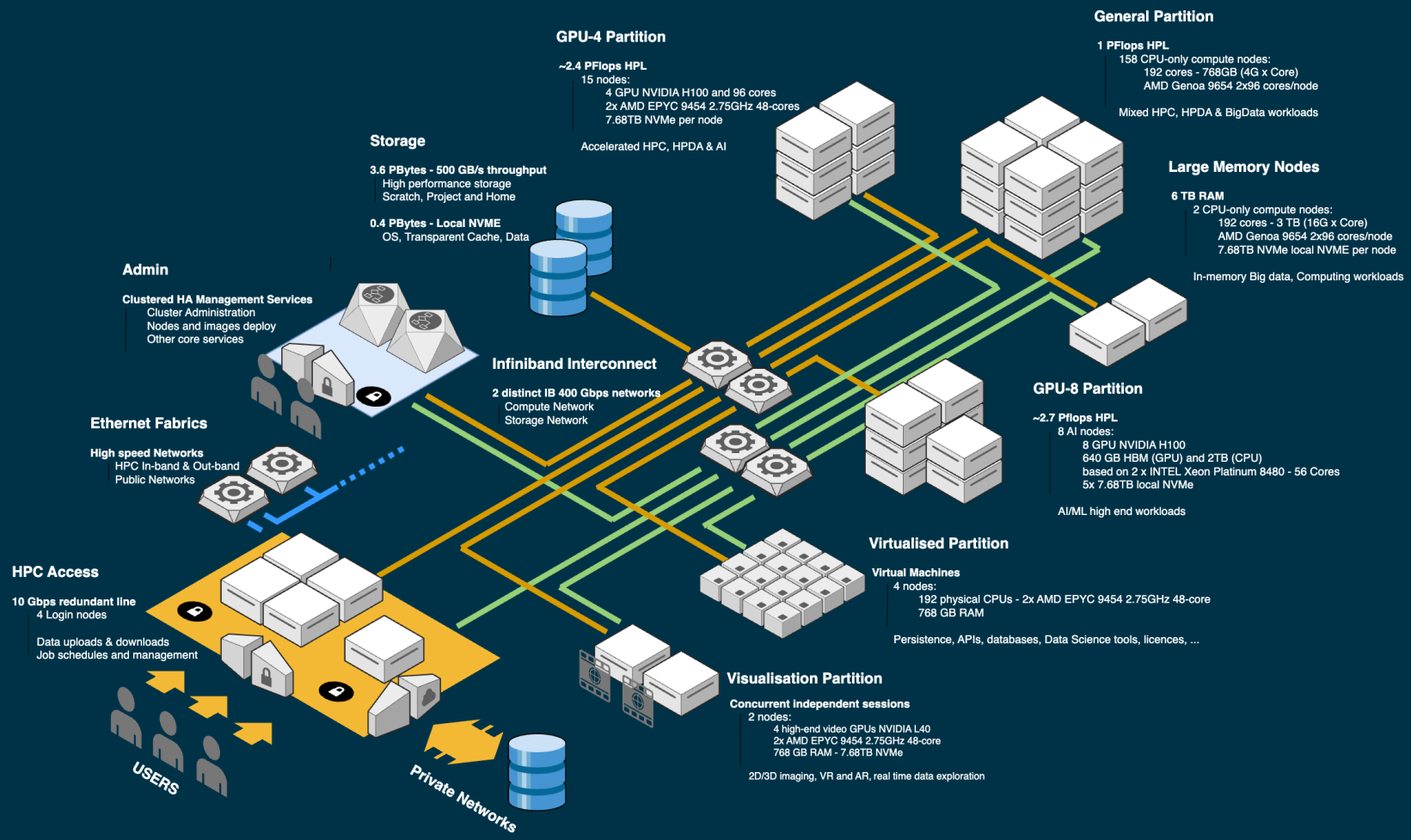
Europe is not starting from zero. There is a diversity of approaches



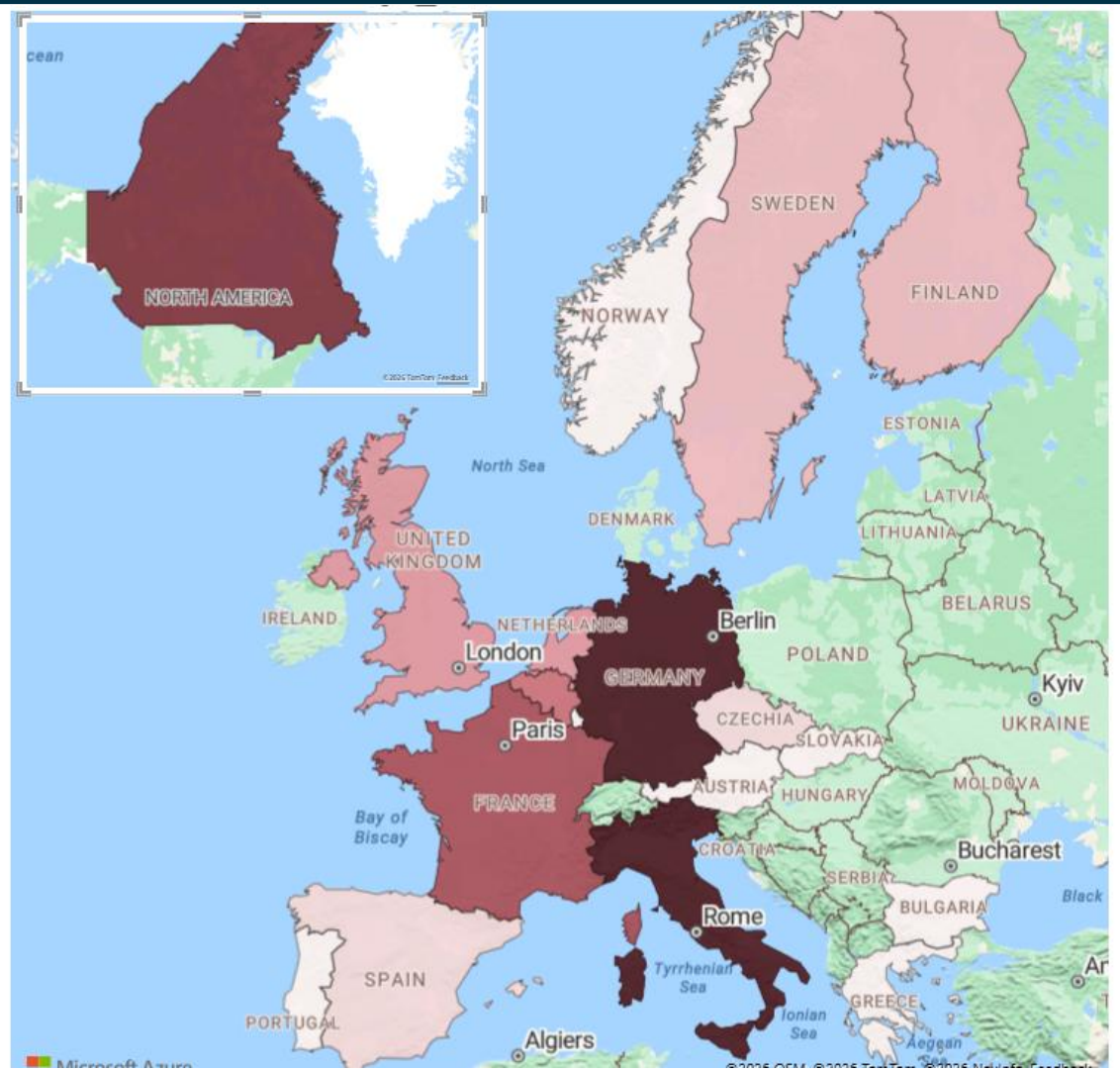
- Strong European expertise across the full space weather system.
- Important physics-based, empirical and data-driven models.
- Existing integration capability through VSWMC.
- Growing use of AI/ML, HPC, ensembles and data assimilation.
- New observations and missions creating an opportunity for major improvement.

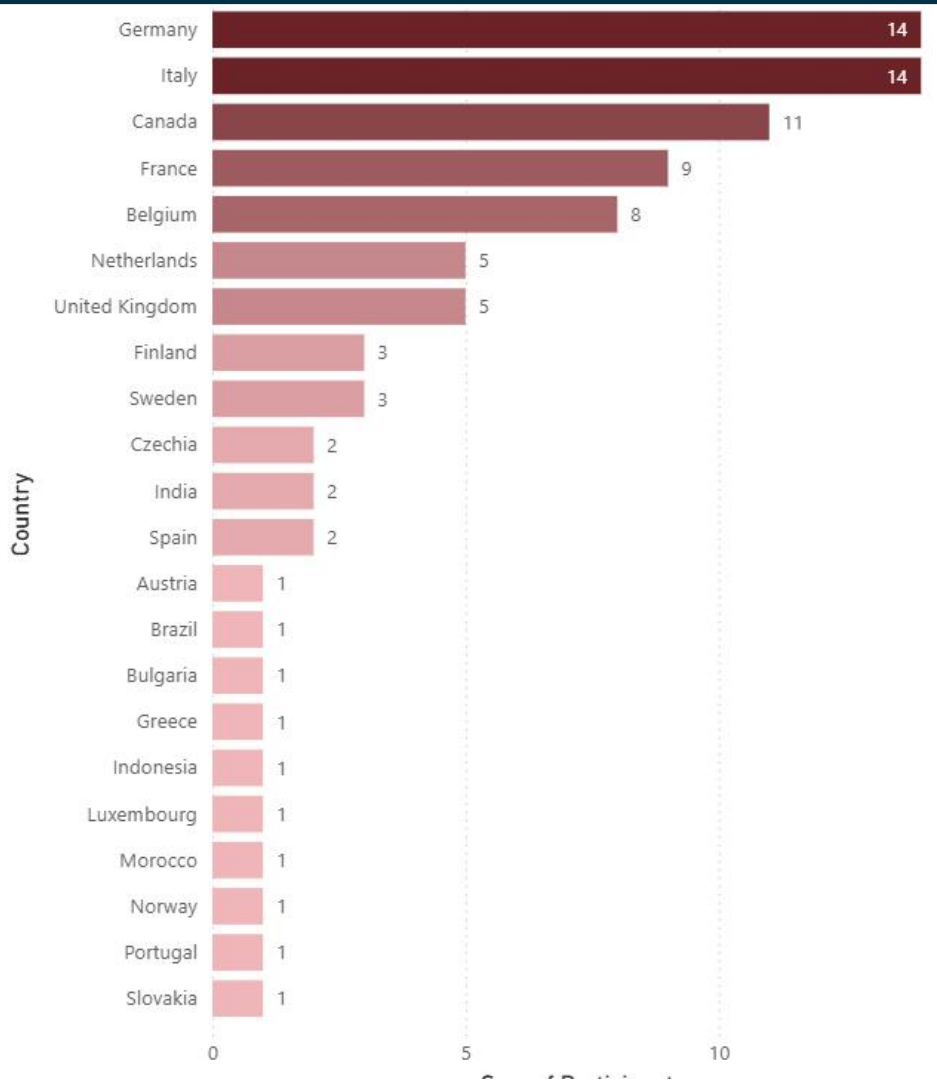
Solid infrastructure: ESA Space HPC system





SWE & HELIO modelling expertise





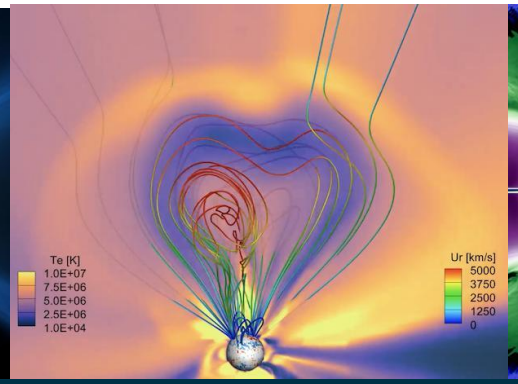
Capabilities are not yet an integrated system

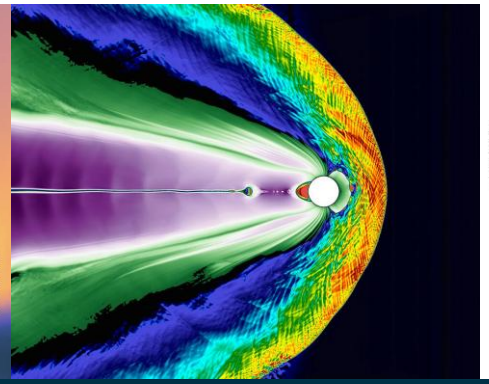
A collection of good models is not yet an operational forecasting system.

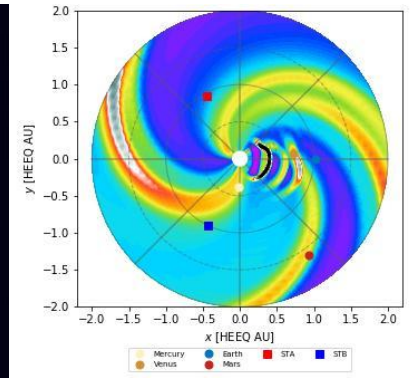
Excellent components separated by gaps:

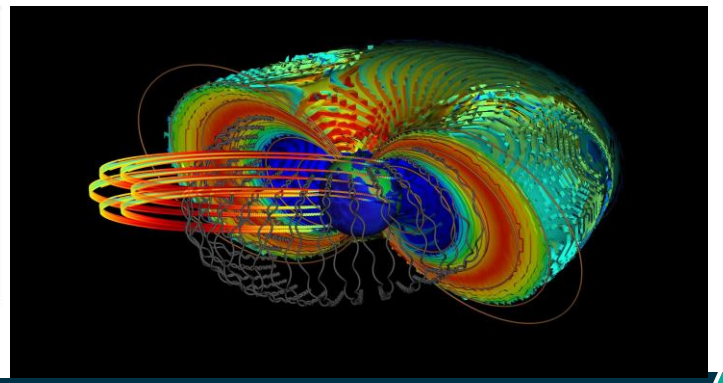
- Models developed under time-limited research projects
- Non-standard interfaces and inputs
- Uneven validation and uncertainty reporting
- Limited maintenance after project completion
- …



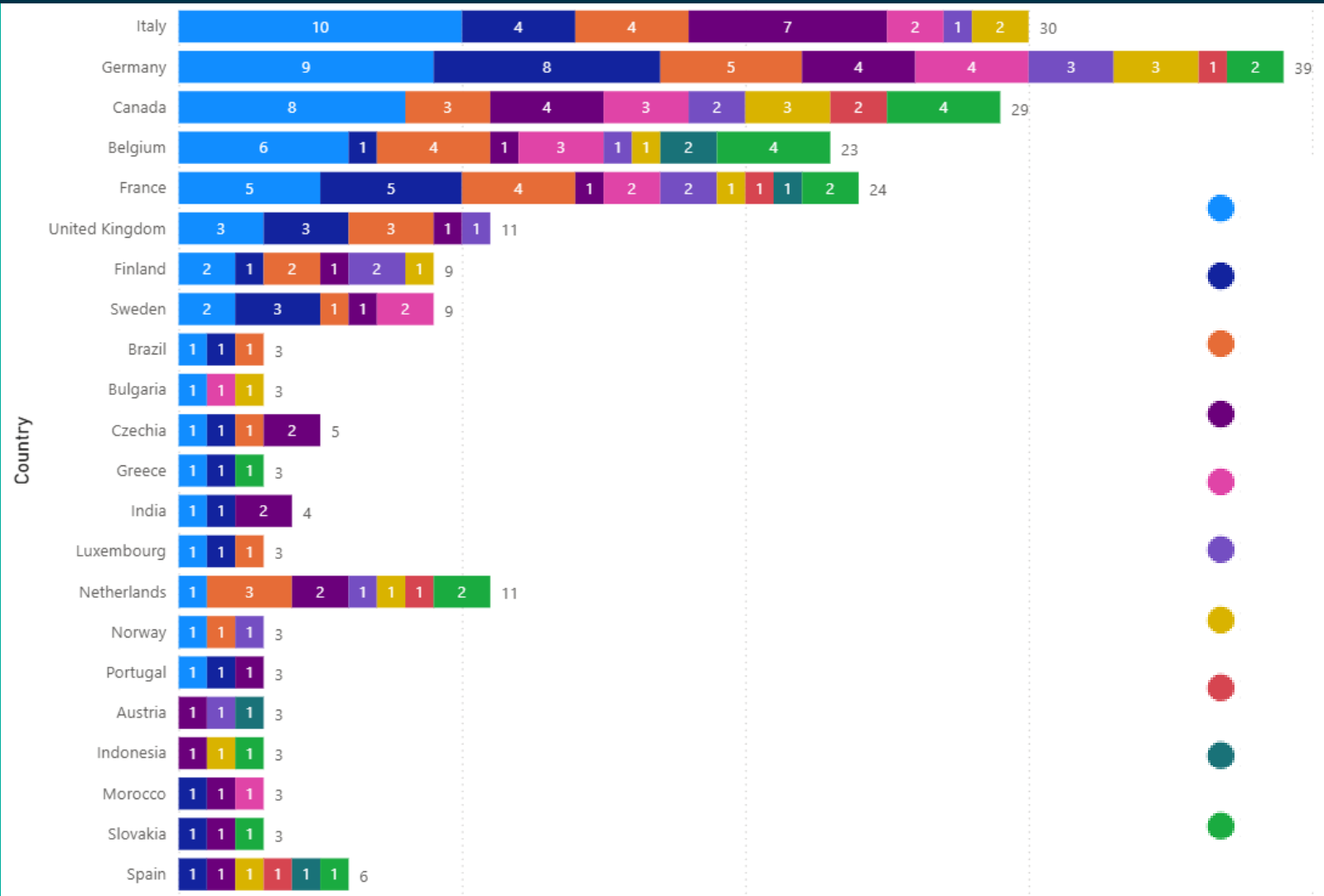






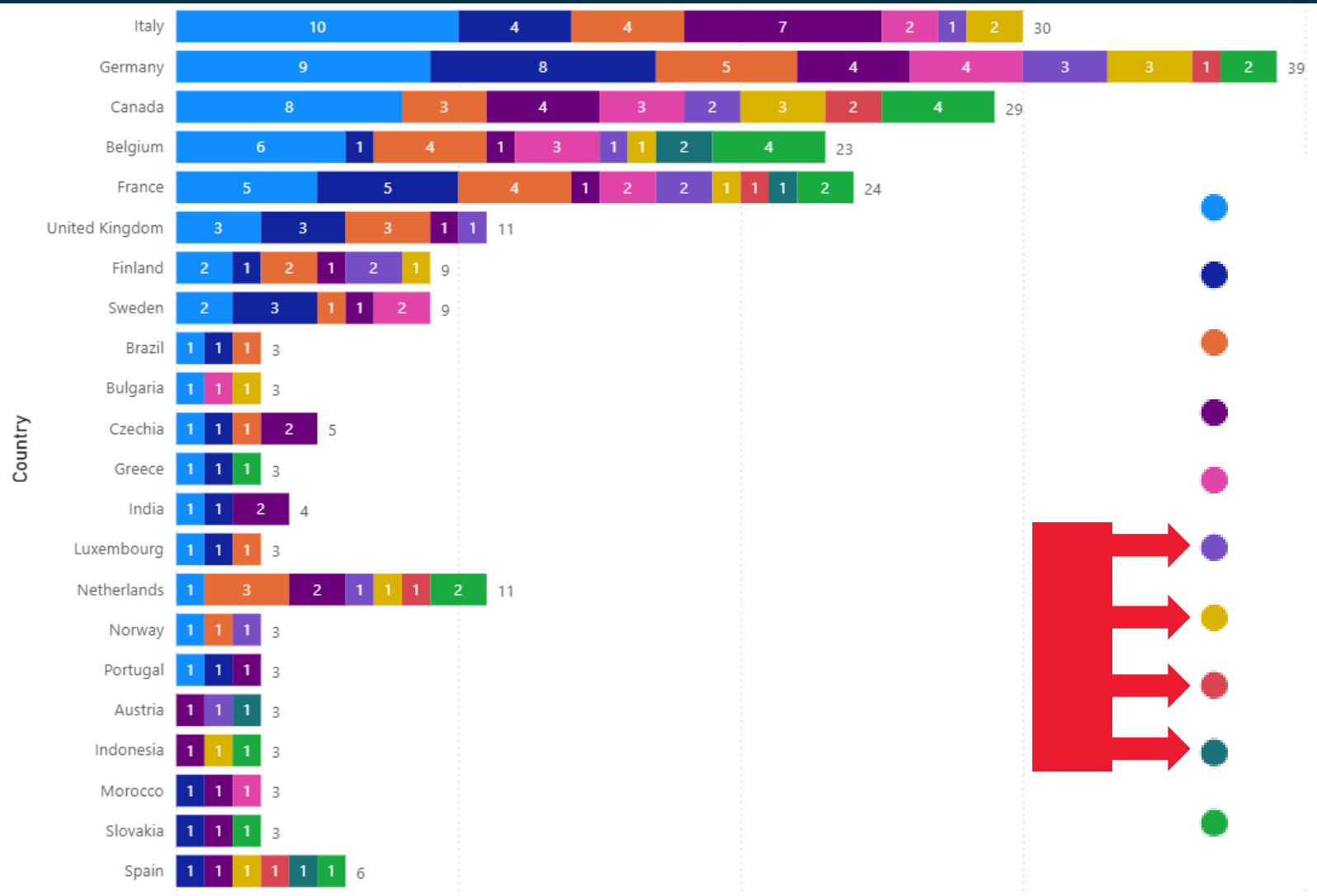


Technical and scientific expertise



- Model development
- Artificial Intelligence / Machine Learning
- Modelling data analysis
- Instrument data analysis
- Parallel computing
- Model operationalisation (R2O)
- Informatics and software engineering
- Medium and long-term planning
- Model operations and maintenance
- Project management

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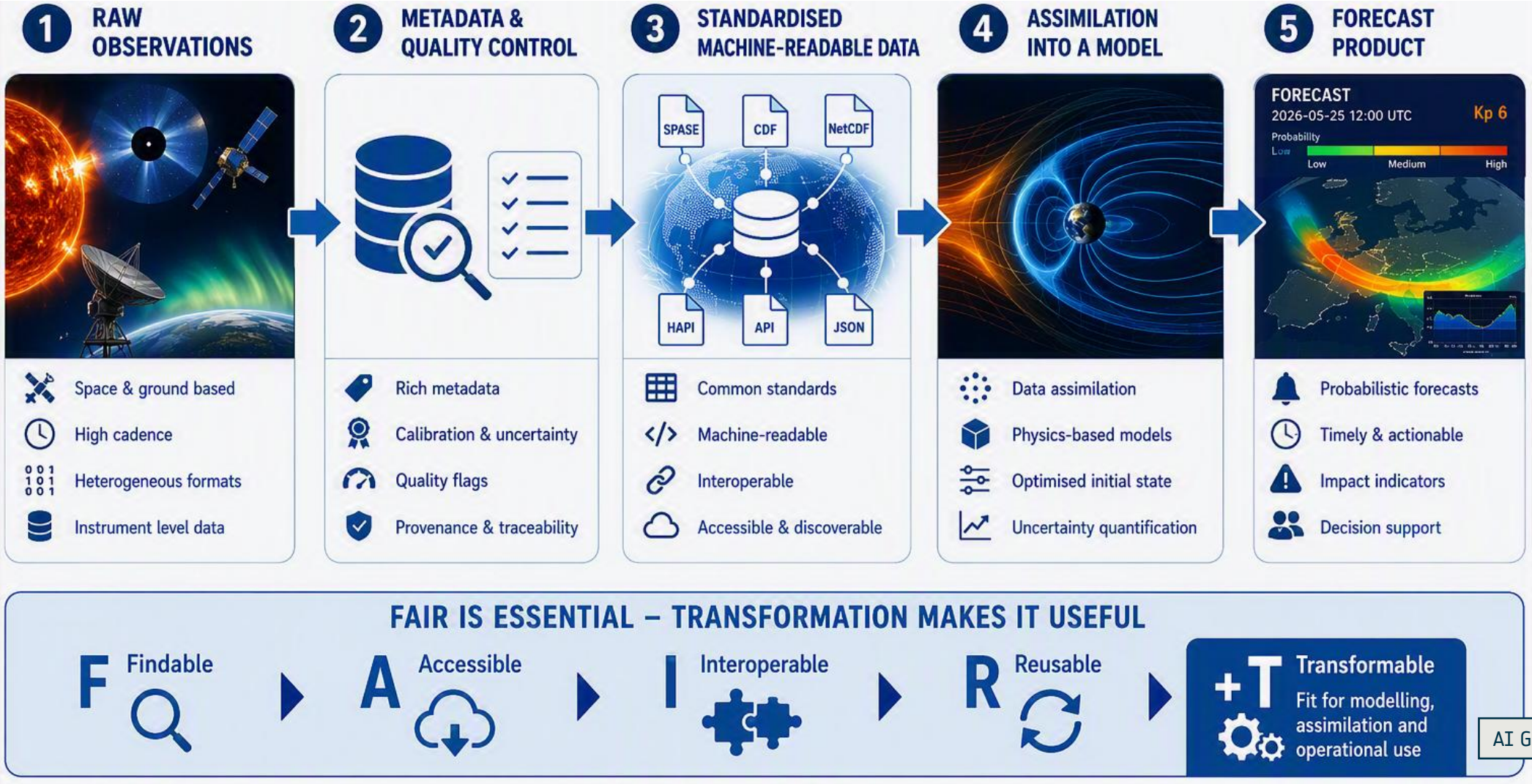
Outcomes of the workshop

Not only better science, but better support infrastructure

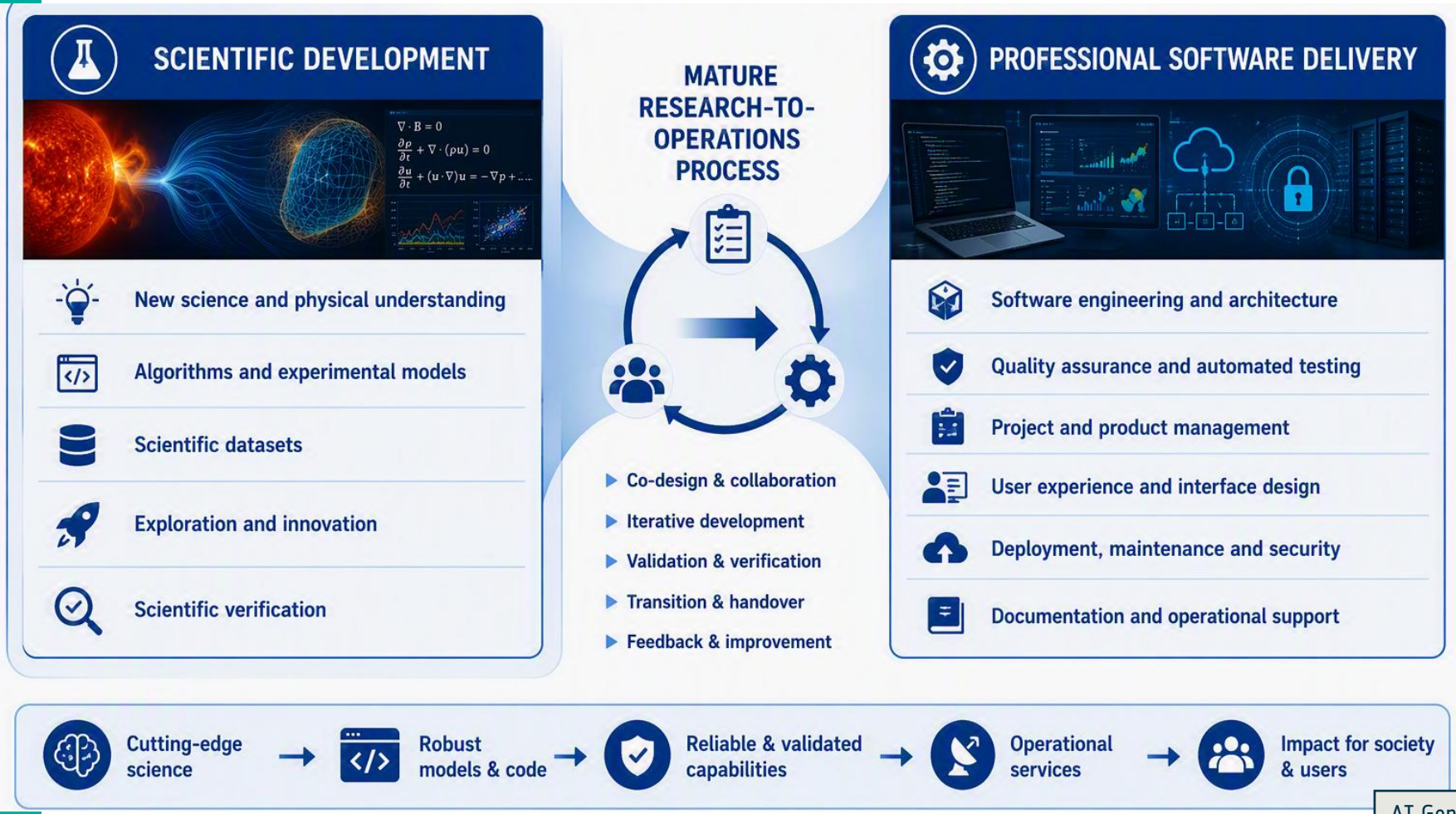
Five consolidated outcomes:

1. **DATA** Assimilate diverse observations systematically.
2. **AI/ML** Combine physics-based models with AI/ML rather than treating them as competing approaches.
3. **UNCERTAINITY** Quantify uncertainties and trace their propagation through coupled chains.
4. **BENCHMARKING** Create common datasets, metrics and benchmark cases.
5. **R2O** Adapt Research-to-Operations processes to iterative scientific software development.

Making data model-ready



From scientific models to professional software



- Excellent science does not automatically produce operational software.
- Scientists should not be expected to become software engineers, user-interface designers or operational service managers.
- Equally, engineers need support from scientists to make scientific choices.

A mature Research-to-Operations process

A mature R2O process requires:

- evaluation of entry and exit criteria
- professional engineering
- performance benchmarks
- assessment of uncertainty and limitations
- reproducible testing and configuration control
- operational demonstrations with users
- continuous monitoring after transition.

Quality is not a single review at the end of the development. It is a quantitative and repeatable process embedded throughout development, transition and operation.

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R2O framework provides:

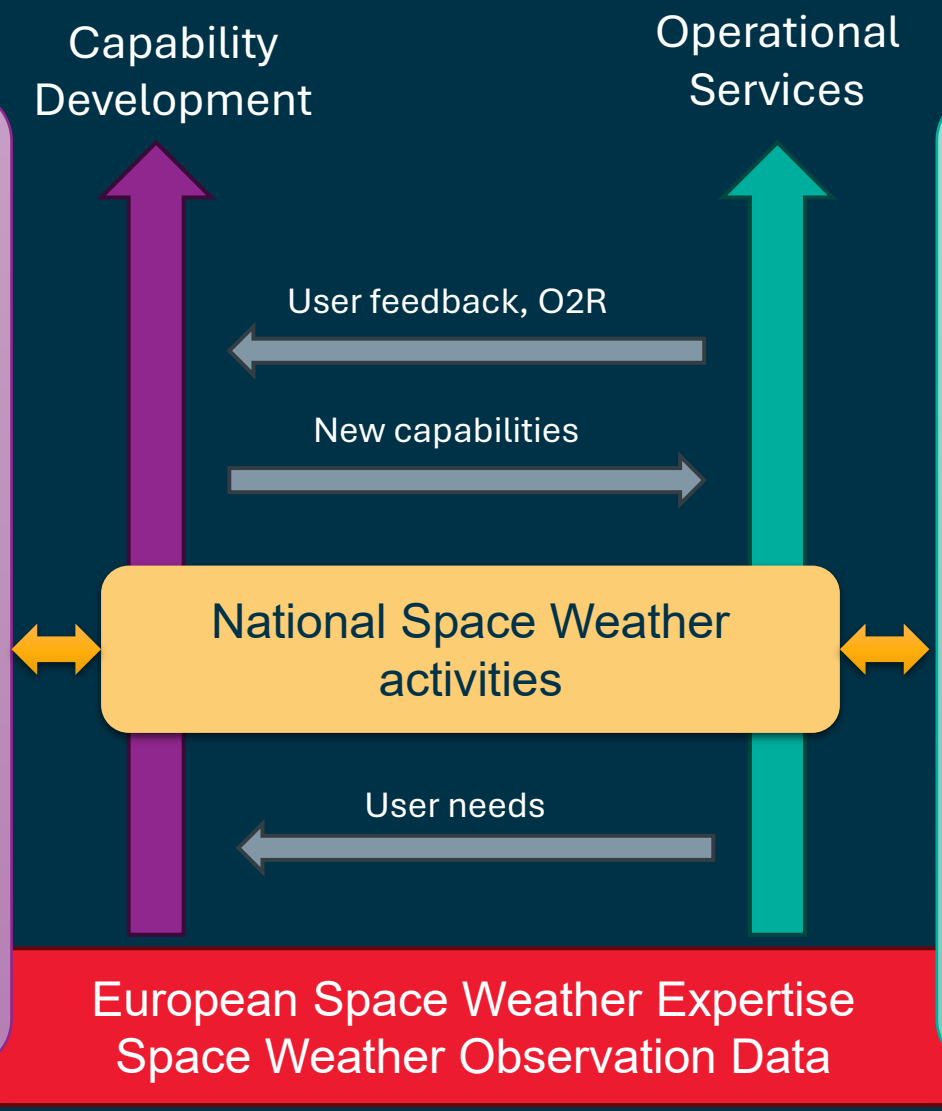
- Standardised and transparent criteria
- Verified and validated data
- Robust engineering
- End-user at the centre of the development
- Justified background for the development
- Stamp of quality and maturity for funding

Quality is not a single review at the end of the development. It is a quantitative and repeatable process embedded throughout development, transition and operation.

A Vision for European Institutional Space Weather Activities

Governance: ESA, Space Agencies
Execution: Academia, institutes, industry
Advice to ESA: Space Weather Working Team (SWWT)

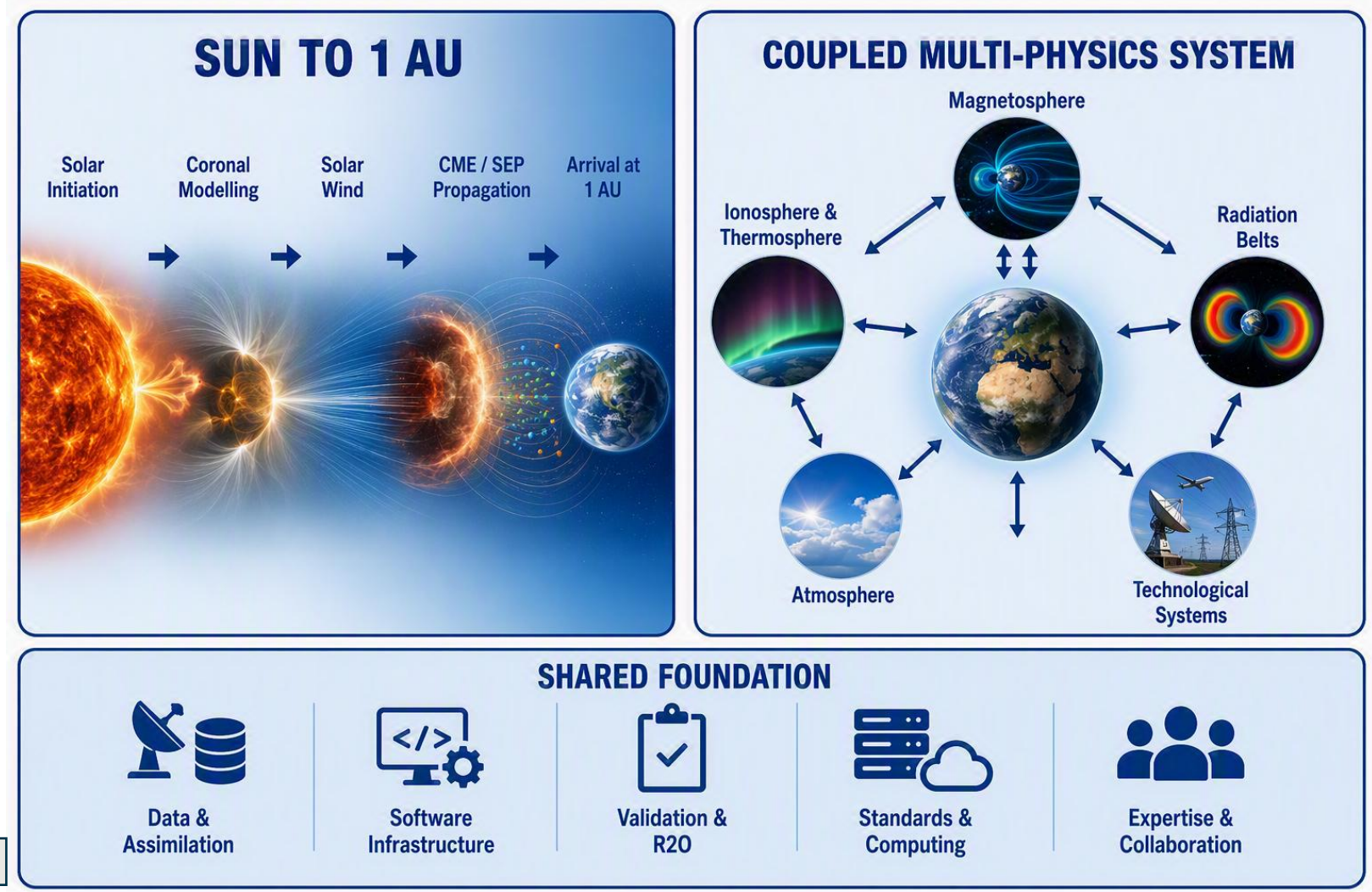
Key activities:
- R&D, R2O
- New innovation models
- New observation systems:
  - Space missions
  - Ground based sensors
- Data utilization studies
- Development of new models
- Verification, validation and testing of new products with users
- Preparing mature capabilities for transition into operational services



Governance: EU (TBC)
Execution: Networking of European expertise, commercial actors
Management: Entrusted to space agencies

Key activities:
- Operational public service provision
- User interfacing and support
- Operational data acquisition:
  - Operation of existing observation systems
  - Procurement of recurring systems
  - Data buy
  - International collaboration
- Interfacing with commercial services

Roadmap to 2040 : challenges and foundation



AI Generated

Closing message

Europe has excellent science, models and data. The next step is to connect these strengths through professional software, mature Research-to-Operations processes and resilient access to critical observations.

- **Advance the science across two complementary modelling challenges**
- **Build professional infrastructure around scientific innovation**
- **Sustain, validate and protect the resulting European capability**

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THANK YOU!

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