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IVOA for AI-ready Astronomy: What Is Still Missing?

ChenZhou Cui

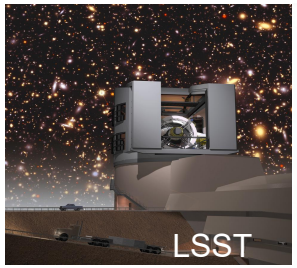
China-VO/NADC

Astronomy is Changing

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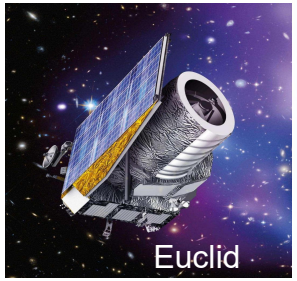


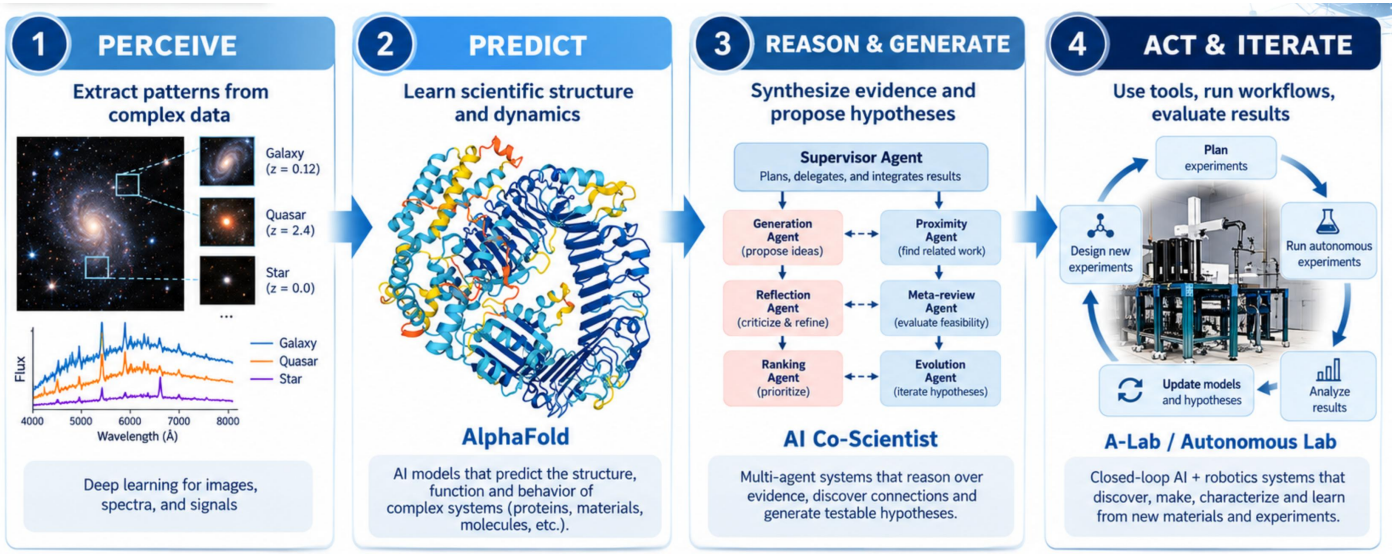












Modern surveys are not just "large datasets". They are high-dimensional, heterogeneous, time-dependent scientific ecosystems.

- Images + spectra + time series + simulations + catalogs
- Different resolutions, sensitivities, footprints and selection effects

The AI Revolution in Science

The frontier is moving from AI for data analysis to AI participating in the scientific discovery loop.

Its impact depends on open data, reusable models, interoperable tools and transparent provenance.

What IVOA Has Already Achieved

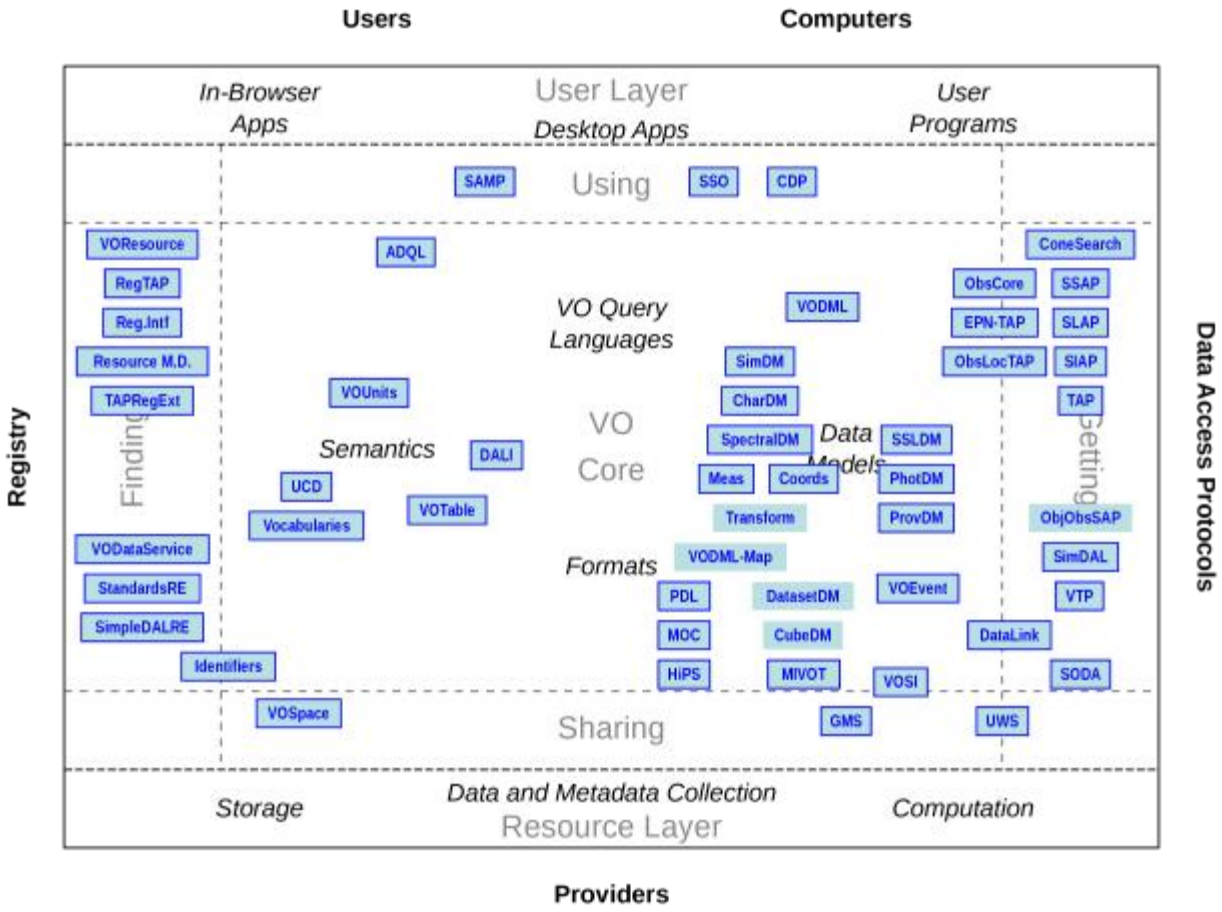
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IVOA Documents & Standards

https://ivoa.net/documents/

- Data
- Semantics
- Data Models
- Registry
- Data Access
- Authentication
- Formats





IVOA made distributed astronomical resources interoperable.

The Next Interoperability Frontier

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Classic VO

- Find data
- Access data
- Understand data
- Combine data

AI-ready VO

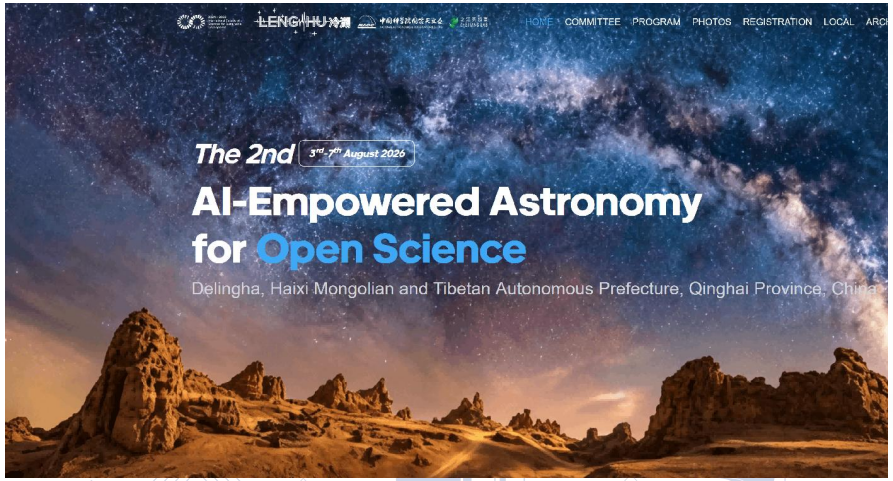
- Discover capabilities
- Invoke services
- Execute workflows
- Use models
- Verify results
- Orchestrate agents

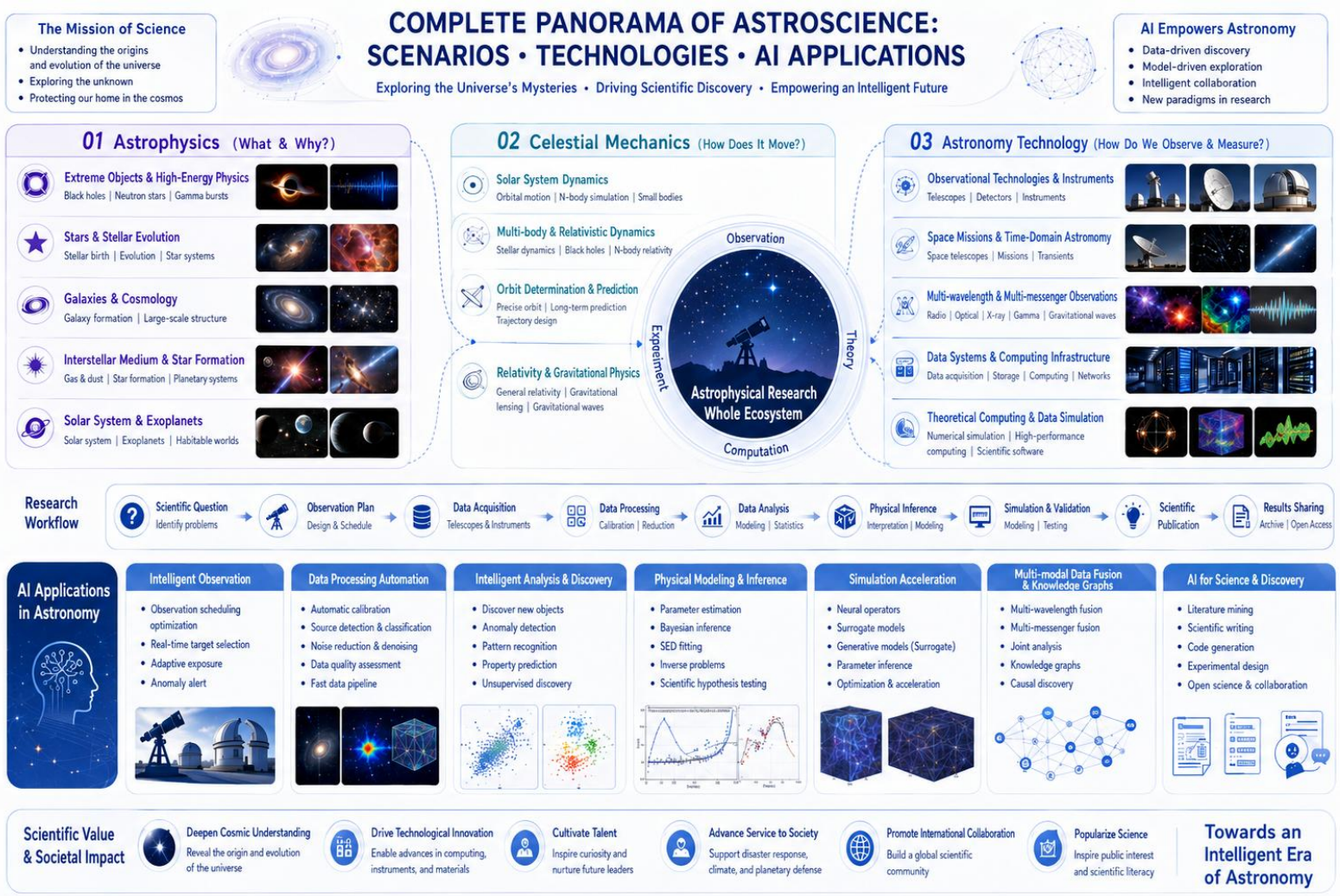
- IVOA was built to make astronomical resources interoperable.
- AI-era astronomy requires astronomical capabilities to become interoperable.

AI-ready Astronomy

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AI can assist discovery across the full research loop — from data preparation to interpretation and publication.





Data Fusion: Beyond Catalog Cross-Matching

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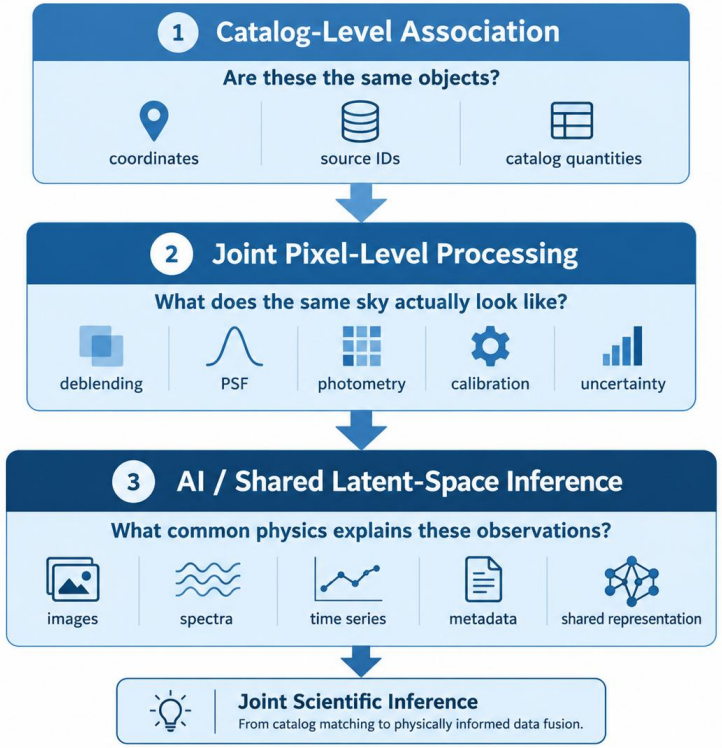
Same Sky — Different Instruments

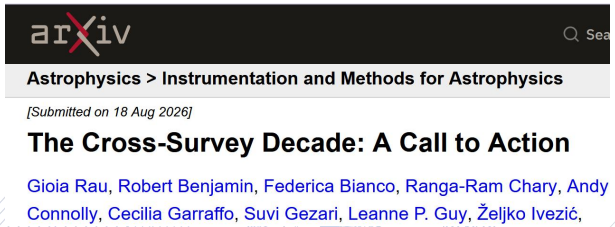
Rubin · Euclid · Roman · CSST



resolution · wavelength · PSF · cadence

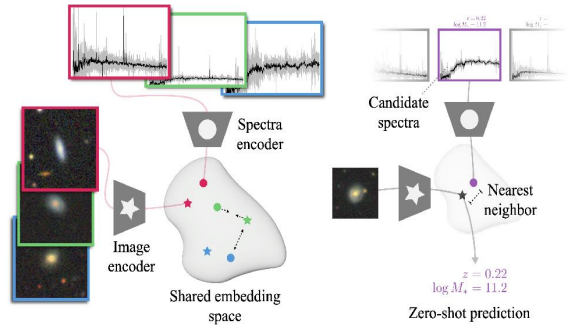
The bottleneck has moved from the telescopes to the infrastructure between them





AstroCLIP

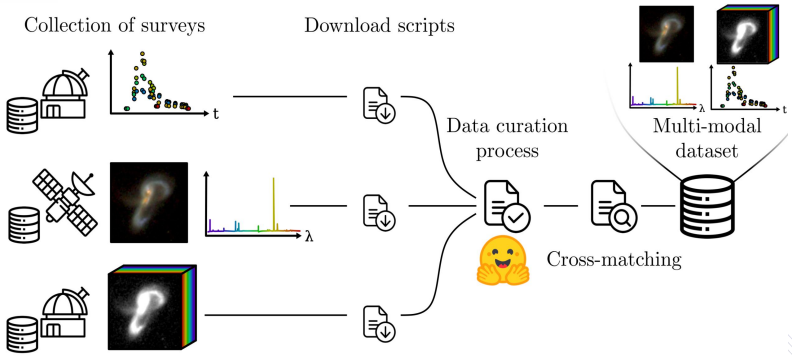
Images + spectra → shared physical representation



Liam Parker, et al. 2024. AstroCLIP: a cross-modal foundation model for galaxies

Multimodal Universe

An AI-ready data substrate with common schemas, metadata, and cross-matching utilities.



https://github.com/MultimodalUniverse/MultimodalUniverse

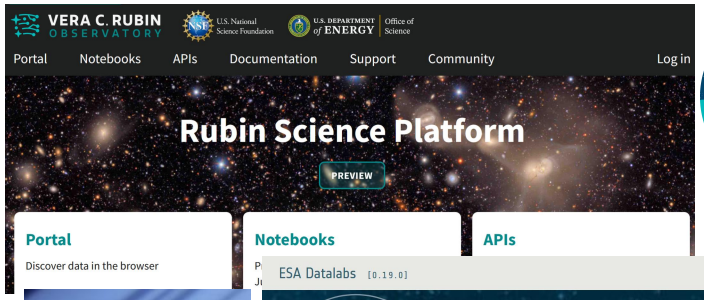
From “Bring Compute to the Data” to “Bring Intelligence to the Data”

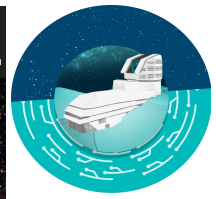
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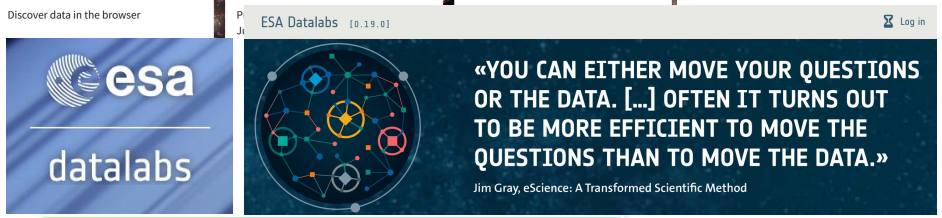
A seamless astronomy science platform integrating data, software, storage, compute and network resources.

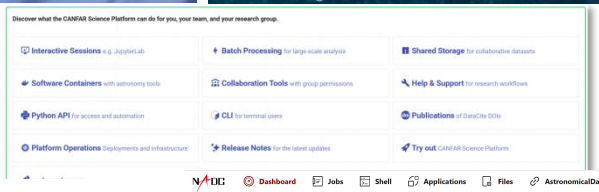
Representative Science Platforms

Rubin Science Platform · ESA Datalabs · CANFAR/CADC · AstroNexus



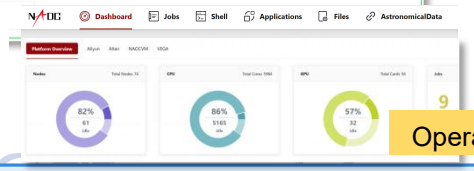




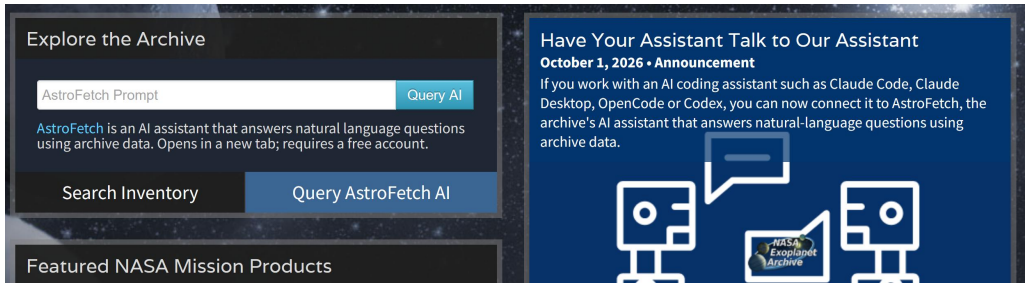


CANFAR

AstroNexus 天枢



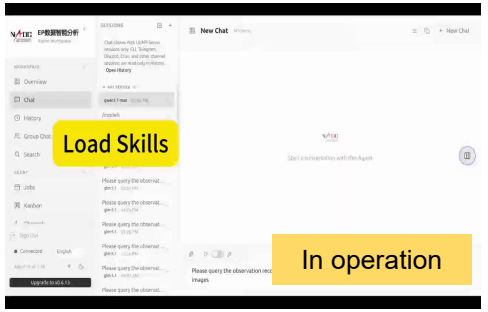
Operational resource dashboard



AstroFetch AI — NASA Exoplanet Archive

Natural language · ADQL · literature · observation planning

AstroFetch



NADC–EP Transient Verification Agent

A production multi-agent workflow for transient vetting in the Einstein Probe Science Center. Multiple agents collaborate on data access, multi-source analysis, evidence checking and report generation.

AstroFabric / NADC Agent Platform

Agents + Models + Skills + Knowledge Bases + Data Services

From AI-assisted work to shared scientific intelligence infrastructure.

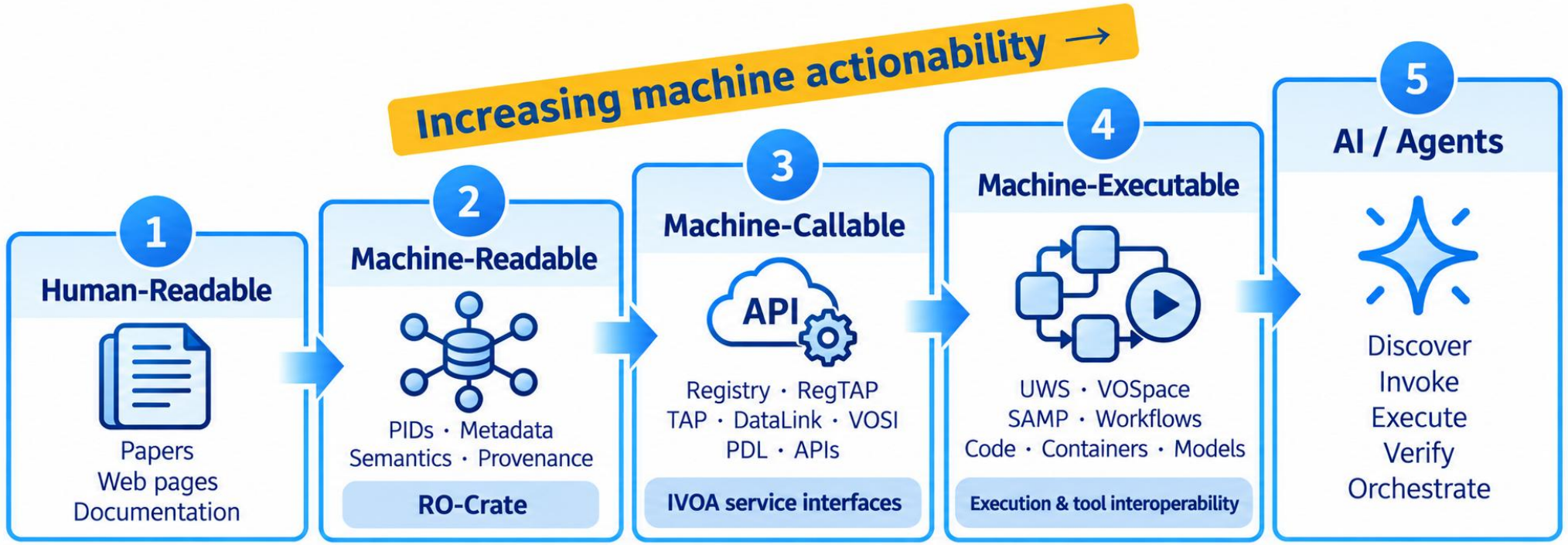
AstroFabric



Agents need not only data access — they need interoperable scientific capabilities.

From Human-Readable to Machine-Actionable

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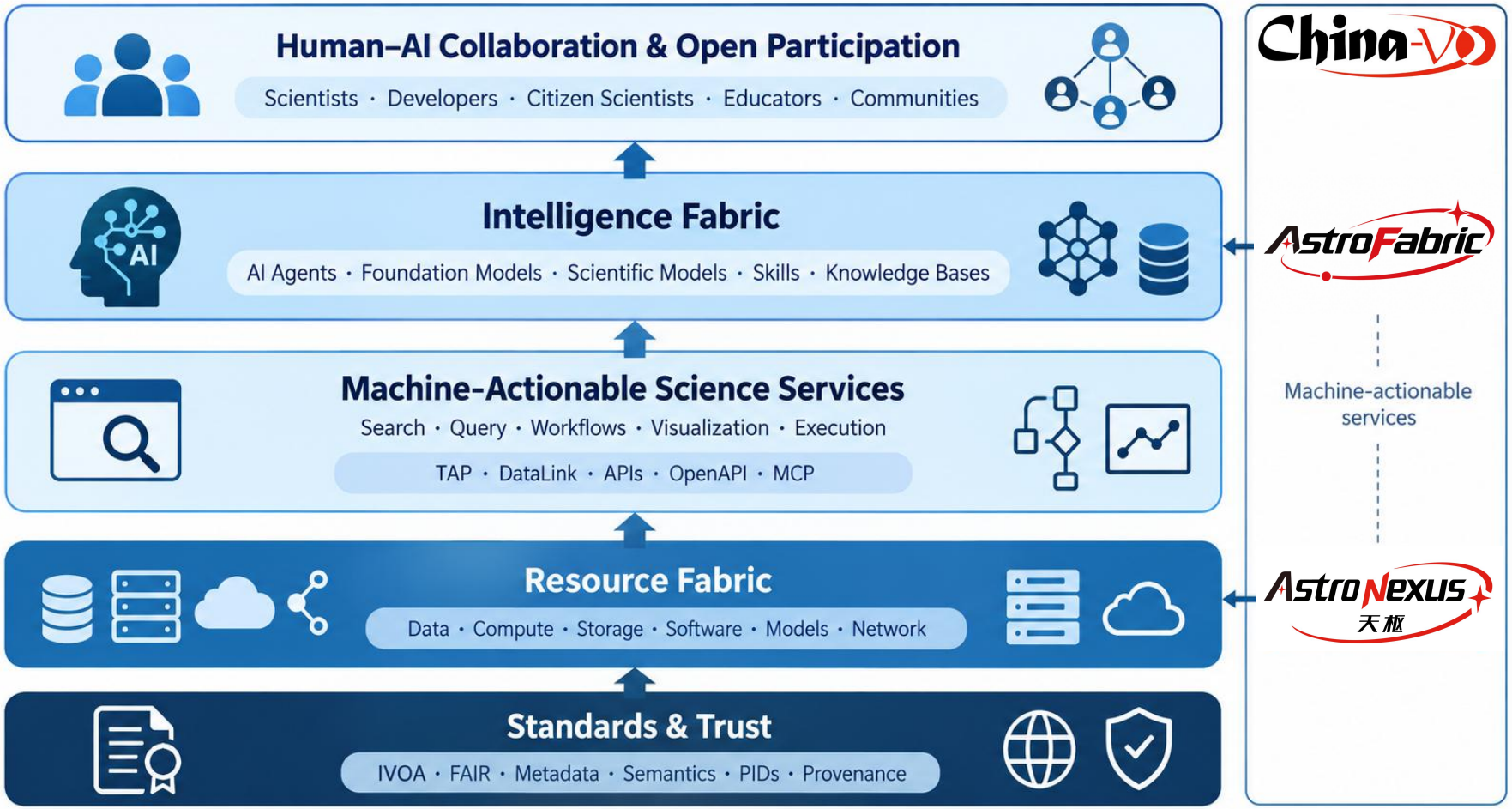


Machine-actionable science means that machines can not only read scientific resources, but discover, invoke, execute and combine them.

Standards + semantics + APIs + provenance + executable workflows turn interoperable scientific resources into agent-actionable science.

Towards an AI-Ready Virtual Observatory

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Open to humans. Actionable by machines. Usable by AI agents. Trustworthy for science.

What Is Still Missing?

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A. Data Fusion & Representation Interoperability

- Object → Pixel / Measurement → Multimodal / Learned Representation

B. Capability & Tool Interoperability

- Discover → Invoke → Compose → Orchestrate

C. Executable Science & Model Interoperability

- Job → Workflow → Execution Environment → Model → Inference

D. Trust, Semantics, Identity & Governance

- Provenance · Capability Semantics · Authorization / Delegation · Quality · Accountability

The next challenge is extending IVOA's mature resource and service interoperability toward agent-actionable scientific capabilities.

From Cross-Matching to Multimodal Data Fusion

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Fusion level	Existing IVOA foundation	Coverage* today	Key gaps for fusion
1. Object / Catalog Association	TAP · ADQL · VOTable · UCD · VOUnits	Strong foundation	Probabilistic association · match-confidence semantics · provenance of association results · cross-survey quality semantics
2. Pixel / Measurement-Level Fusion	ObsCore · SIA · DataLink · SODA + Coords · Meas · PhotDM · ProvenanceDM	Partial coverage	**Machine-readable description of:** reprojection · PSF matching · calibration alignment · masks · uncertainty propagation · joint measurements **+ interoperable processing semantics and provenance**
3. Multimodal / Learned-Representation Fusion	UCD · Vocabularies · VO-DML · MIVOT · ProvenanceDM	Emerging foundation for this use case	Multimodal semantics · representation/embedding metadata · model/task description · training/inference provenance · applicability · uncertainty · interoperable shared representations

** "**Coverage**" here refers to IVOA support for the fusion use case, not the maturity of the individual standards.*

IVOA provides strong building blocks for accessing and describing pixels, but does not yet standardize cross-survey scientific pixel-level fusion.

The next frontier may be from object interoperability to measurement and representation interoperability.

From Service Discovery to Capability Interoperability

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What IVOA already describes

Resource & capability discovery

- VOResource · RegTAP

Rich I/O semantics & constraints

- PDL

Standard & endpoint

- standardID · interface · accessURL

Input parameters & basic semantics

- ParamHTTP · UCD · unit · datatype · use

Features & resource limits

- TAPRegExt and protocol-specific extensions

Availability & service metadata

- VOSI

Machine-readable usage examples

- DALI /examples

Dataset-linked service invocation

- DataLink service descriptors

Application / tool messaging

- SAMP

What agents still need

Scientific task / capability semantics

What scientific action does this capability perform?

Task-level scientific contracts

beyond parameter syntax and constraints

Scientific applicability & preconditions

When is this capability scientifically appropriate?

Quality, uncertainty & resource expectations

Side effects & machine-readable failure/recovery semantics

Capability composition semantics

Can output A safely become input B?

Generic agent/tool binding

leveraging rather than replacing existing VO standards

IVOA already describes how services are found, accessed and parameterized.
The AI-era gap is describing when and why a capability should be used, and how capabilities can be safely composed.

Executable Science & Model Interoperability

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Executable Science

Existing IVOA foundations

- ✓ UWS — asynchronous job lifecycle
- ✓ VOSpace — distributed storage / data exchange
- ✓ DataLink — linking data to processing services
- ✓ PDL — I/O semantics and constraints
- ✓ SAMP — application/tool interoperability
- ✓ ProvenanceDM — execution provenance

Still missing

- ○ Workflow description & composition
- ○ Workflow-level semantic typing
- ○ Portable execution-environment description
- ○ Software/dependency/environment metadata
- ○ Generic resource requirement declaration
- ○ Reproducible execution packaging
- ○ Workflow discovery & reuse profile

** Workflow interoperability is not a new concern for IVOA; what is new is its importance in agent-driven science.*

IVOA should standardize astronomy-specific interoperability metadata — not reinvent general workflow, container or AI technologies.

AI Model Profile

A model can already be represented as a VO resource. The missing piece is a dedicated interoperability profile describing its scientific behavior. An agent needs to know:

- ○ Scientific task / intended use
- ○ Input modality and schema
- ○ Output schema and semantics
- ○ Model identity and version
- ○ Training domain / training-data provenance
- ○ Evaluation metrics
- ○ Applicability and limitations
- ○ Uncertainty / confidence information
- ○ Inference interface
- ○ Citation, license and usage policy

Model Resource
Identity · Version · Task · Inputs · Outputs
Training provenance · Evaluation · Applicability
License · Inference endpoint

Trust, Semantics, Identity & Governance

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Provenance

Existing

- **ProvenanceDM**: Entity, Activity, Agent

AI-era profiling / validation

- Model & version, Prompt/context, Tool calls, Retrieved evidence, Intermediate results, Agent decisions, Human intervention, Uncertainty

Can existing ProvenanceDM profiles capture agent decision chains?

Semantics

Existing

- UCD, Vocabularies, VO-DML/Data Models, MIVOT, PDL

Needed

- Scientific task / intent, Capability semantics, Scientific applicability, Preconditions / effects, Quality / uncertainty semantics, Composition semantics

Identity & Delegation

Existing

- SSO, OAuth / OpenID, Credential Delegation Protocol, GMS

AI-era questions

- Agent identity, Scoped authorization, Delegation limits, Credential/token propagation, Revocation, Service-to-service authorization, Audit trail, Human approval boundaries

Governance & Quality

Existing

- Registry validation, Rights / licensing, Provenance, Access-control foundations

AI-era questions

- Trusted models / services, Scientific quality & uncertainty, Accountability, Usage policy, Human oversight, Auditability

Who did what, on whose authority, using which evidence and model — and can we reproduce it?

Existing Foundations and AI-Era Gaps

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AI-era requirement	Existing IVOA foundation	Coverage today	Possible next step
Catalog association	TAP · ADQL · VOTable · UCD · VOUnits	Strong foundation	Association use cases / richer probabilistic & quality semantics
Pixel / measurement fusion	ObsCore · SIA · DataLink · SODA · Coords · Meas · PhotDM · ProvenanceDM	Partial coverage	Fusion use cases + processing-semantics profile
Multimodal / learned representations	UCD · Vocabularies · VO-DML · MIVOT · ProvenanceDM	Emerging for this use case	Representation / embedding metadata profile
Agent capability discovery & use	VOResource · RegTAP · PDL · VOSI · DataLink · SAMP	Substantial building blocks	Agent-oriented capability profile + composition semantics
Workflow interoperability	UWS · VOSpace · DataLink · PDL · SAMP · ProvenanceDM	Partial foundation	Workflow profile + execution-environment metadata
AI model interoperability	VOResource / Registry · PDL · ProvenanceDM	No dedicated profile	AI model interoperability profile
AI / agent provenance	ProvenanceDM	Strong generic foundation	Profile & validate for agent decision chains
Agent identity / authorization	SSO 2.0 · OAuth/OpenID · Credential Delegation · GMS	Partial foundation	Scoped authorization / delegation experiments

Many of the gaps are missing profiles that connect existing standards for agent-driven science.

A Practical IVOA Action Plan

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Reuse → Profile → Integrate → Prototype → Standardize only when necessary

NOW — Understand & Map

2026–2027

- Collect AI-native astronomy use cases
- Map them onto existing IVOA standards
- Classify each gap: integration / profile / extension / new standard
- Establish a cross-WG AI-ready interoperability activity
- Publish a Use Cases & Gap Analysis Note

NEXT — Profile & Prototype

- Data-fusion use cases & profile feasibility
- Agent-oriented capability profile
  VOResource · RegTAP · PDL · VOSI · DataLink · SAMP
- Workflow / AI-model interoperability prototypes
- ProvenanceDM profile for AI/agent workflows
- Scoped authorization & delegation experiments

THEN — Interoperability Tests

- Reference implementations
- Cross-archive / cross-platform agent workflows
- Interop exercises / plugfests
- Validate composability, portability and trust
- Document demonstrated gaps

LATER — Standardize Selectively

- Only standardize where implementations demonstrate a genuine interoperability need.
- Extend existing IVOA standards where appropriate
- Adopt/profile wider technology standards where possible
- Focus IVOA standardization on astronomy-specific interoperability

- From data access → capability access
- From catalog cross-match → multimodal data fusion
- From human-facing VO → agent-actionable VO

What should IVOA standardize, what should it profile or adopt, and what should it leave to the wider technology ecosystem?