Advancing Cosmology through Artificial Intelligence

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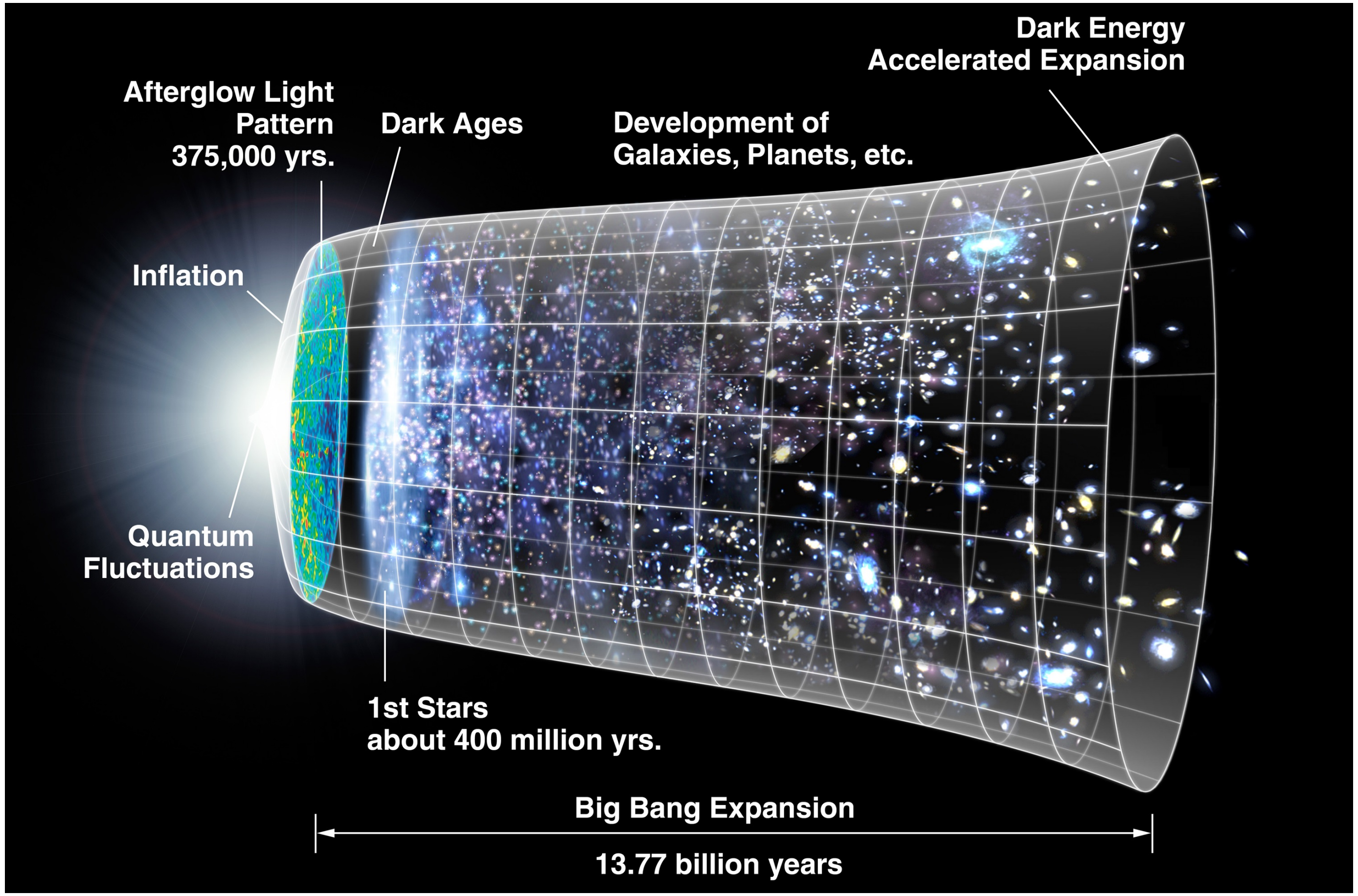
Big Data Cosmology: Opportunity & Bottlenecks

- Next-generation surveys (CSST, *Euclid*, LSST, SKA) are entering the PB data era



Three fundamental bottlenecks:

1. Front-end (Data → Observables):

- Limited precision in extracting weak signals
- Human-in-the-loop bottlenecks
- Inefficiency at survey scale

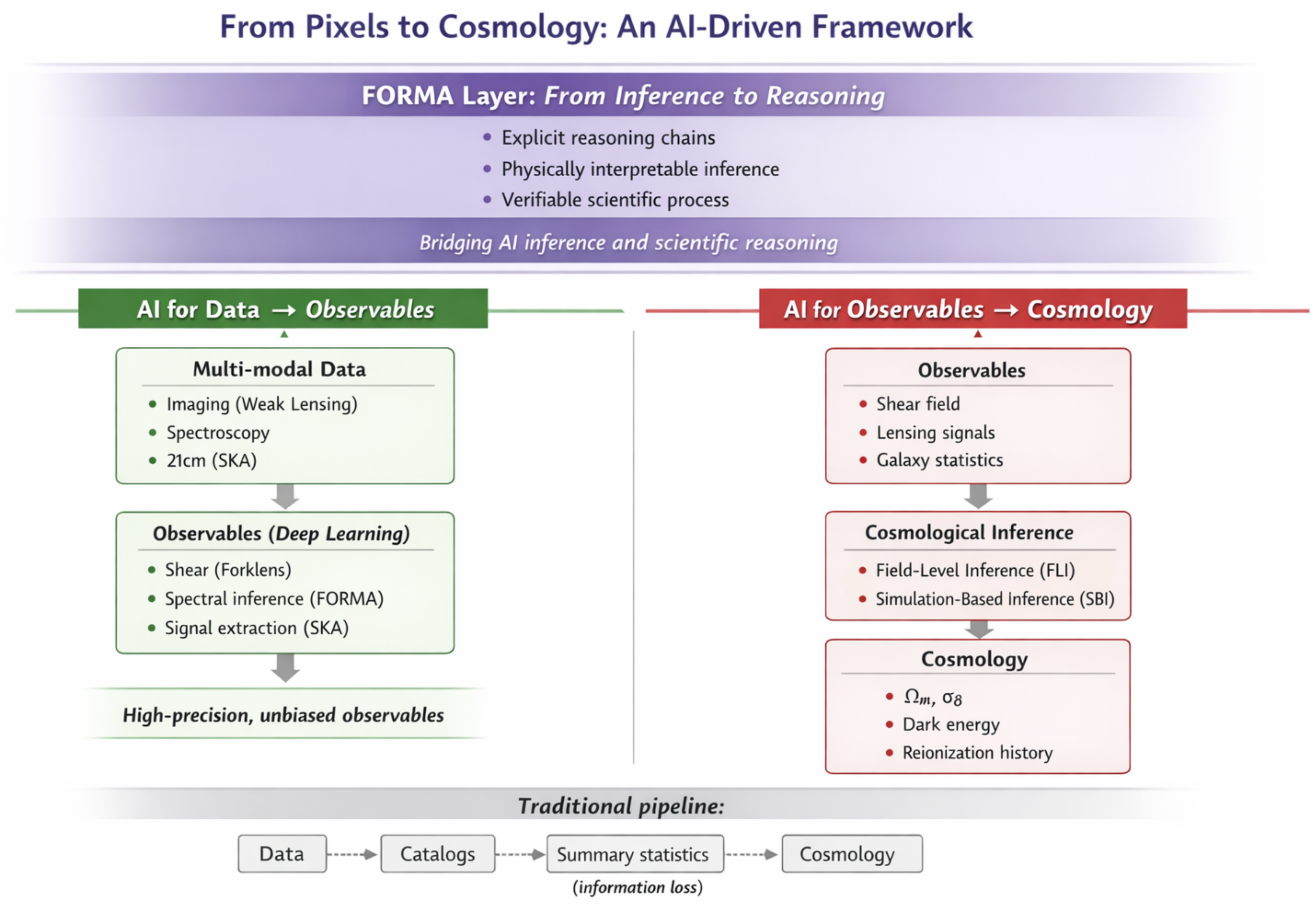
2. Back-end (Observables → Cosmology):

- Information loss (e.g. summary statistics)
- Intractable likelihoods
- Extremely high computational cost

3. **Trust Layer (Inference → Reasoning):**

- Black-box behavior of AI models
- Manual validation of AI outputs
- Auditable and interpretable reasoning

We need a New Inference Paradigm!



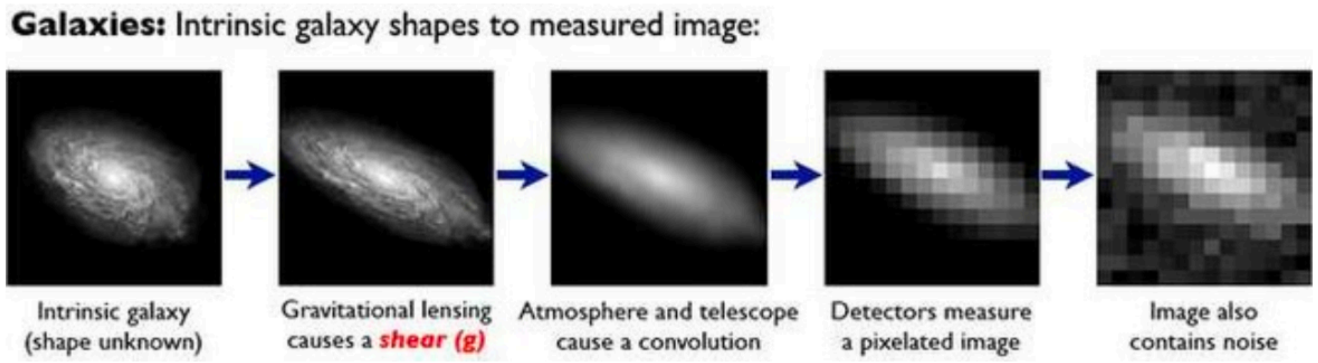
- **Front-end** enables high-precision, unbiased measurement from raw data
- **Back-end** enables high-dimensional, likelihood-free cosmological inference
- **Trust layer** formalizes scientific reasoning, transforming AI inference into auditable knowledge

AI transforms cosmology across three layers: perception, inference, and reasoning

- **AI for Data → Observables (Front-End)**
- AI for Observables → Cosmology (Back-End)
- From Inference to Reasoning (Trust Layer)

Forklens: DL Weak Lensing Shear Measurement

- Weak Lensing: a cornerstone cosmological probe



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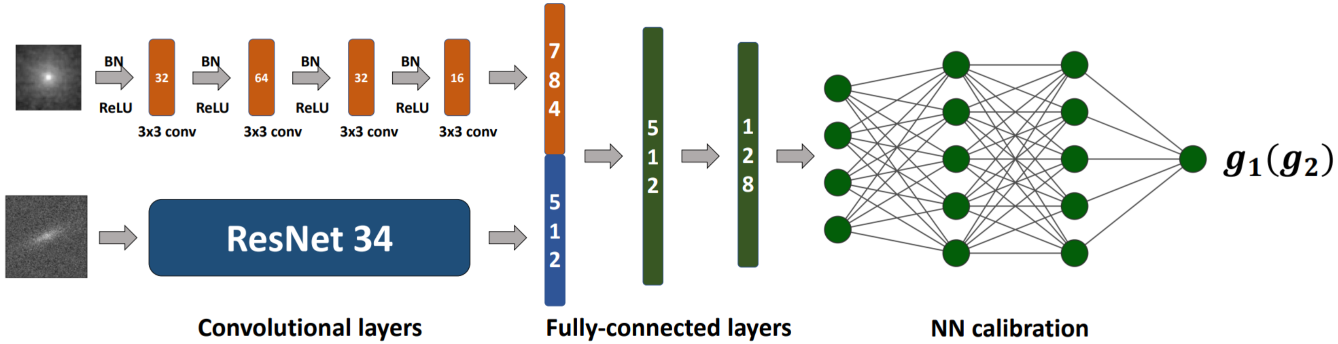

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Challenges:
- PSF convolution
- Noise bias
- Morphology–shear degeneracy

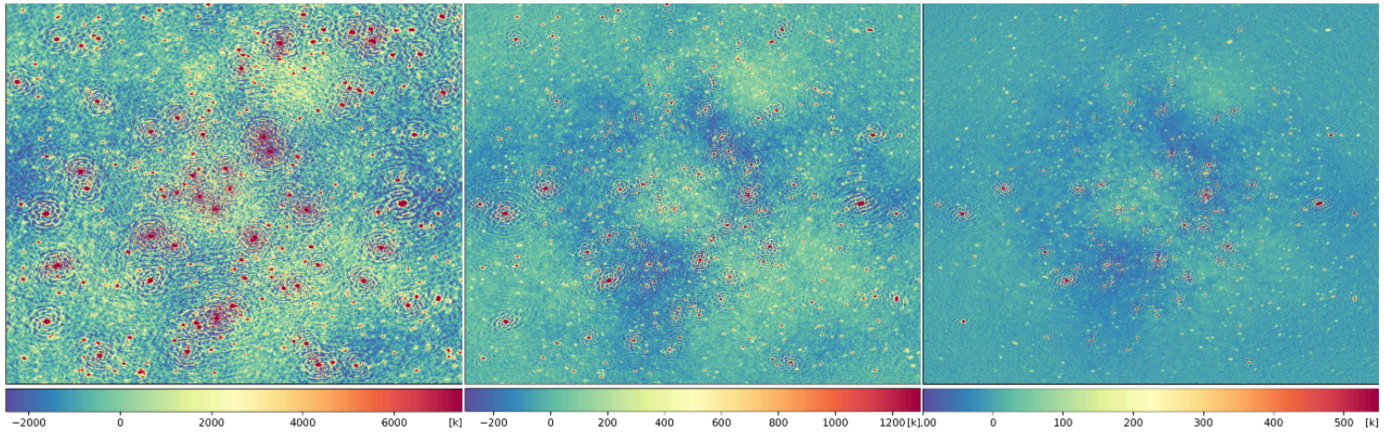
Forklens:
- CNN+NN shear estimation & calibration
- Dual-module CNN shape measurement
- No explicit bias calibration

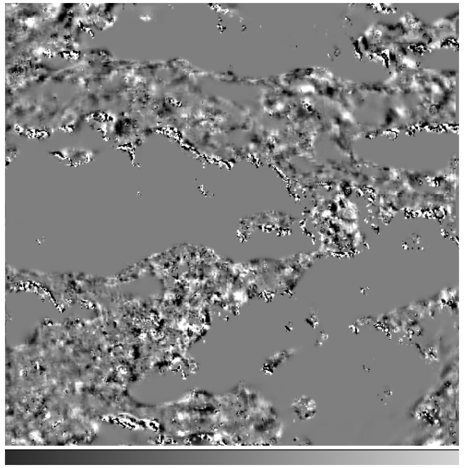
Performance:
- Accuracy: ~2×10^{-3}
- Speed: ~0.7 ms/galaxy

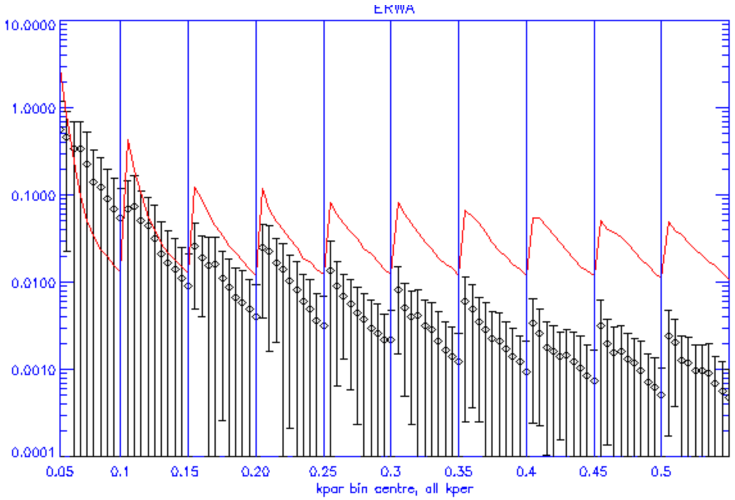
Enabling Stage-IV Precision Weak Lensing

ERWA: SKA Deep Learning Foreground Removal

- 21cm Cosmology: probing the Epoch of Reionization







Challenges:

- Foregrounds>> signal (~10^5 stronger)
- Ionosphere+instrumental noise

ERWA Approach:

- DL-based deconvolution + FG removal
- Learn non-linear foreground structures

Performance:

- Accurate signal recovery
- Competitive performance in SKA Data Challenge (4th in total/1st DL category)

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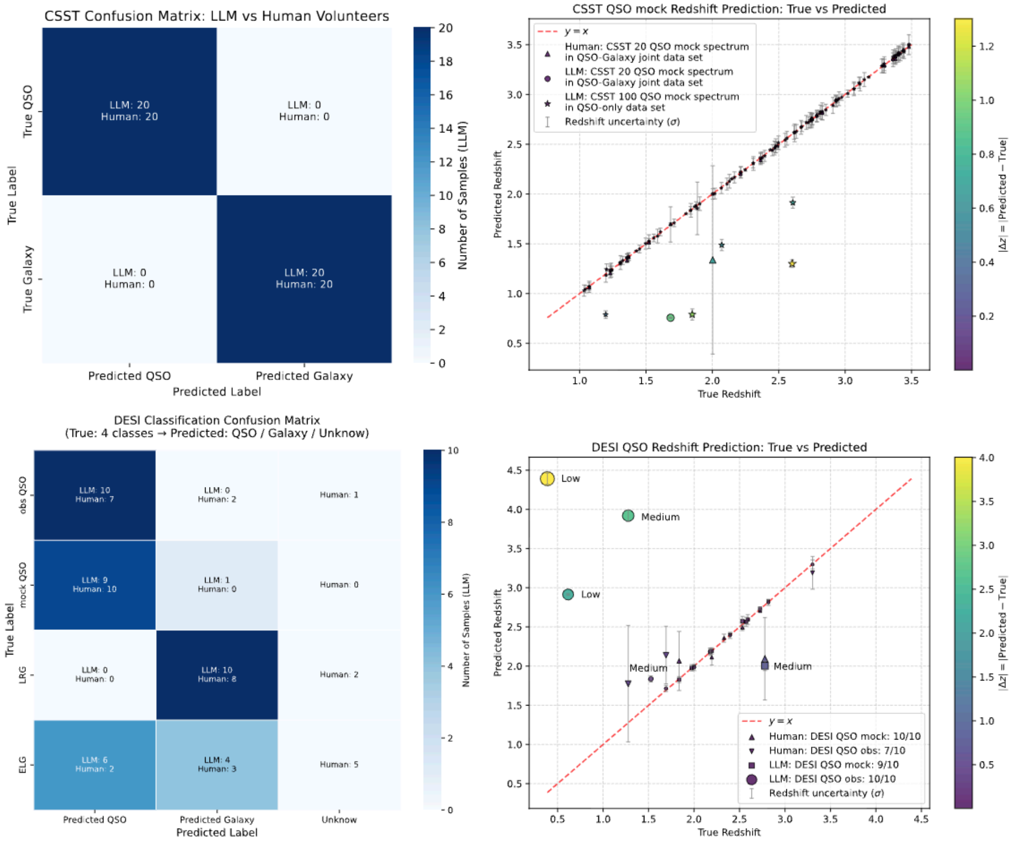
Enabling 21cm Cosmology from Contaminated Data

FORMA: LLM-Dirven Spectral Analysis

- Stage IV Spectroscopic surveys face new bottlenecks



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Challenges:
- Massive spectroscopic data
- Human-dependent validation

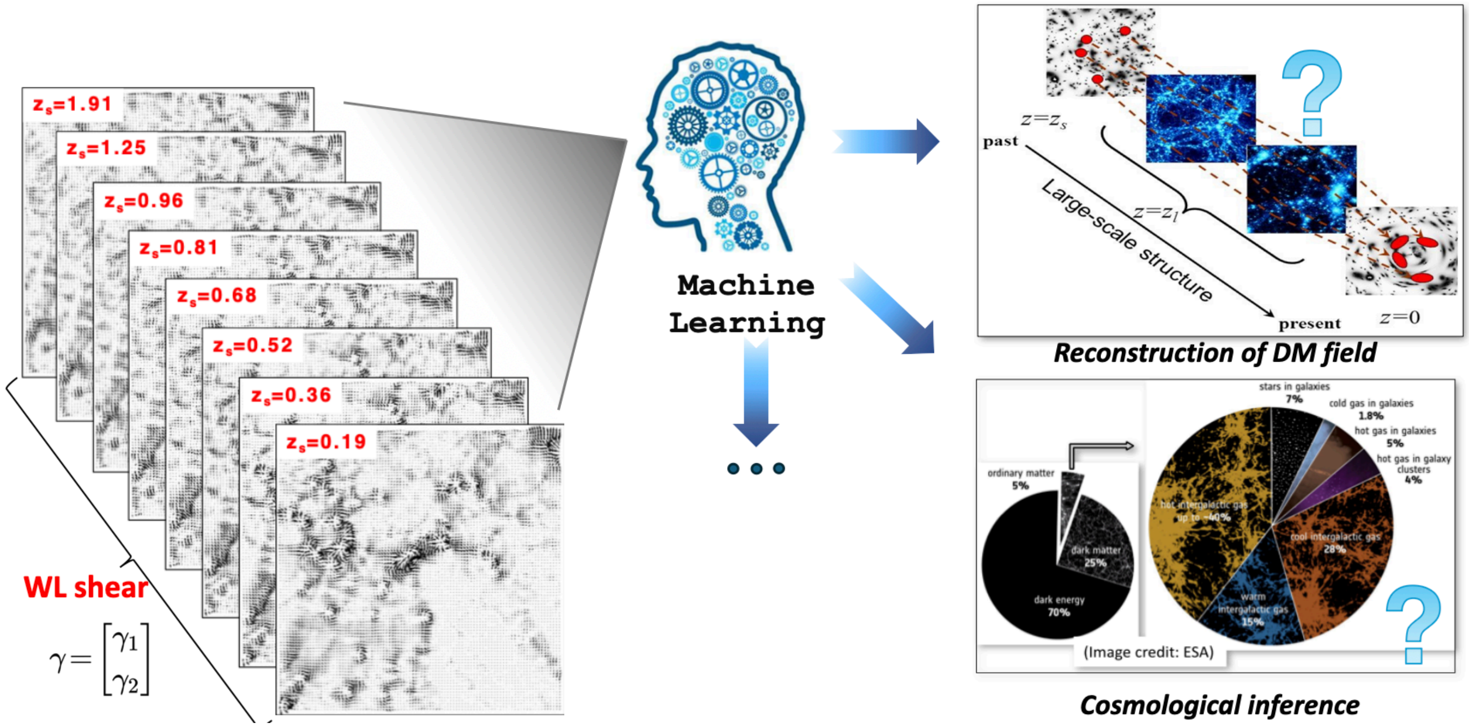
FORMA: **LLM-Driven**
- Automated spectral analysis at survey scale
- Removes human-in-the-loop bottleneck
- Consistent and scalable inference

Result:
- CSST: 100% classification accuracy for QSO and LRG; 95% of QSO redshifts meet $|\Delta z| < 0.1$
- DESI: Correctly identified 95% QSOs and all LRGs

Enabling Large-Scale Spectroscopic Pipelines

- AI for Data → Observables (Front-End)
- **AI for Observables → Cosmology (Back-End)**
- From Inference to Reasoning (Trust Layer)

Field-Level Inference: Beyond Summary Statistics



Traditional approach:

- 2PCF → Gaussian approximation

Limitation:

- Discards non-Gaussian information
- Introduces reconstruction biases

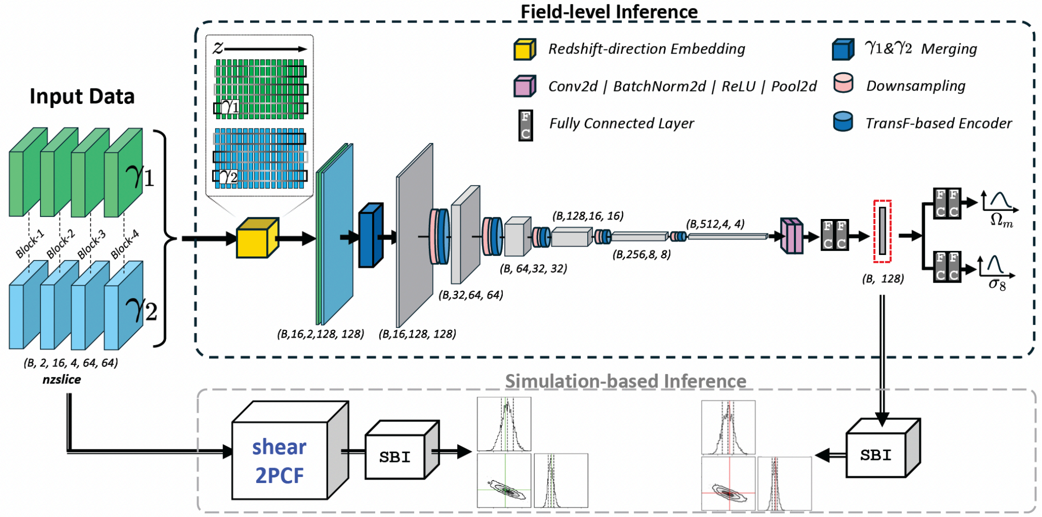
Field-Level Inference (FLI):

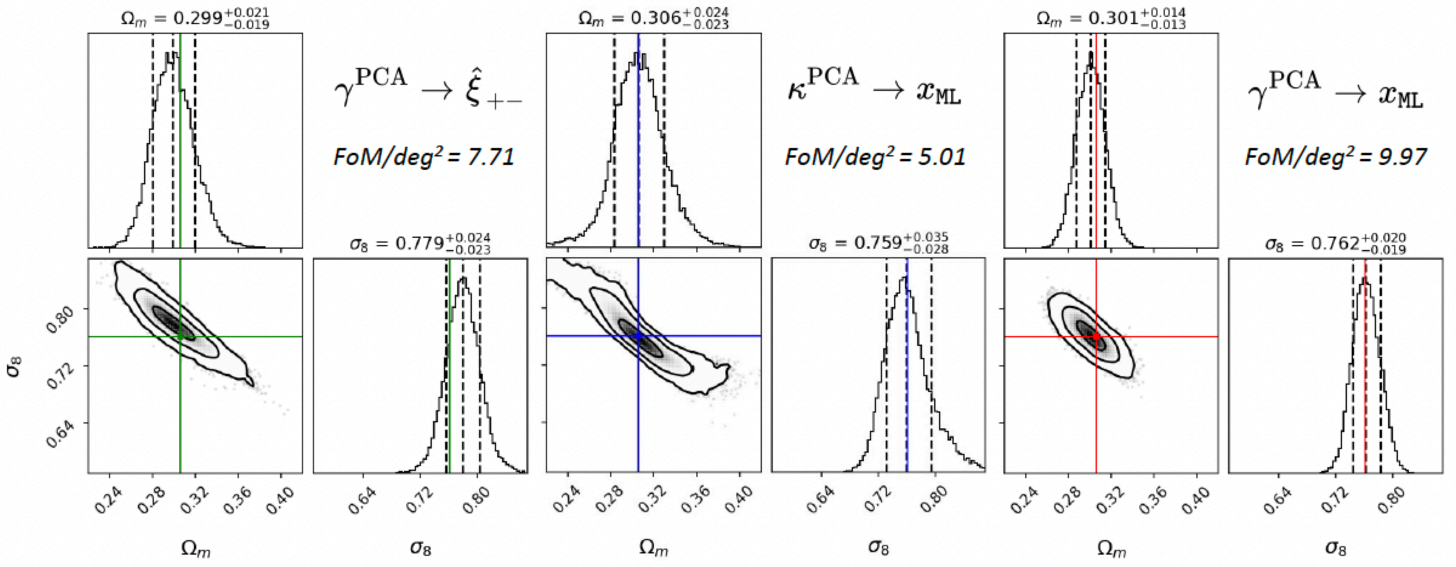
- Directly map shear field → cosmology

Cosmology without Summary Statistics

Shear-to-Cosmology: Lossless Inference

- **Framework: FLI for feature extraction+SBI for posterior distribution**





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Key advantages:

- No mass reconstruction (avoid noise & E/B mixing)
- Full spatial information retained

Result:

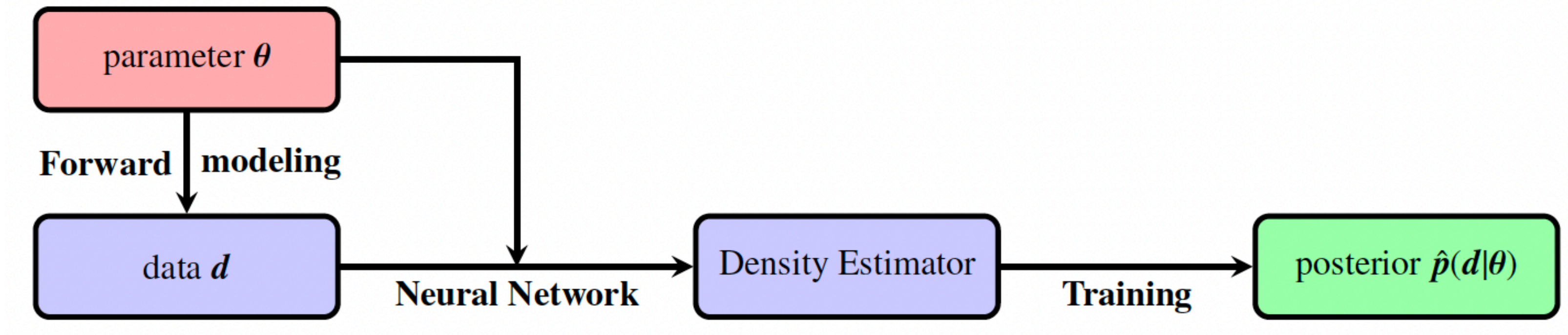
- +36.4% information vs 2pt statistics
- ~2× improvement vs KS-based methods

Direct Inference from Fields, not Compressed Observables

Simulation-Based Inference (SBI)

Challenges: Likelihoods are intractable for complex observables

Solution: Learn posterior directly from simulations



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Workflow:

- Simulate across parameter space
- Train neural density estimator
- Perform fast inference

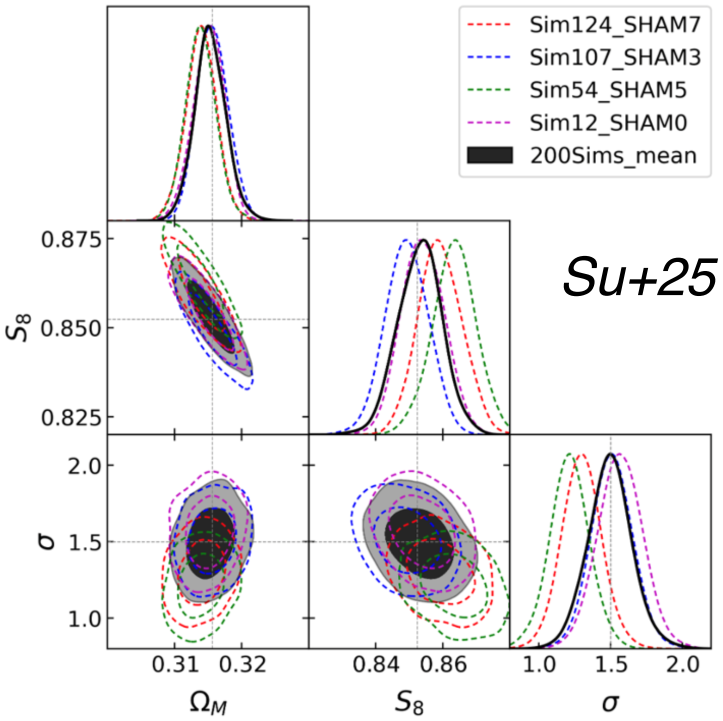
Advantages:

- Likelihood-free
- Captures non-Gaussianity
- Scalable to complex probes

A Universal Cosmological Inference Engine

SBI: Across Cosmological Probes

Void lensing:
- Sensitive to gravity & DE



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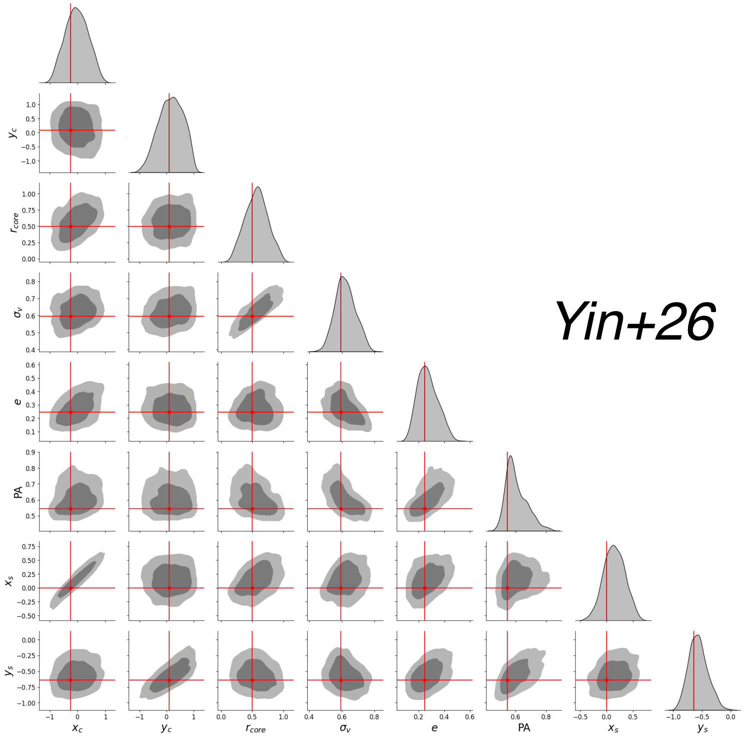
Cluster strong lensing:
- Precise mass reconstruction



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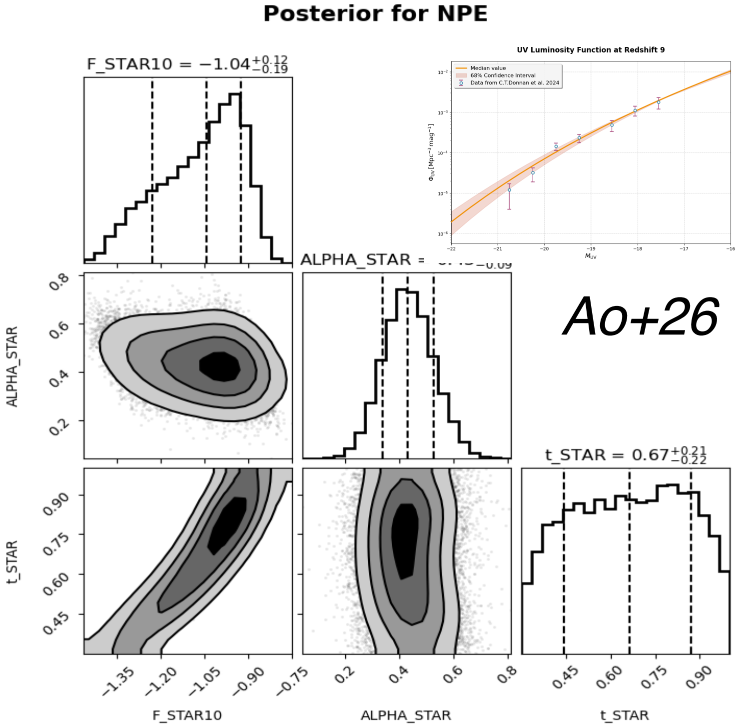
High-z UVLF:
- Constrains EoR history



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Result:
- Unbiased inference
- Orders-of-magnitude speedup

One Framework, Multiple Probes

- AI for Data → Observables (Front-End)
- AI for Observables → Cosmology (Back-End)
- **From Inference to Reasoning (Trust Layer)**

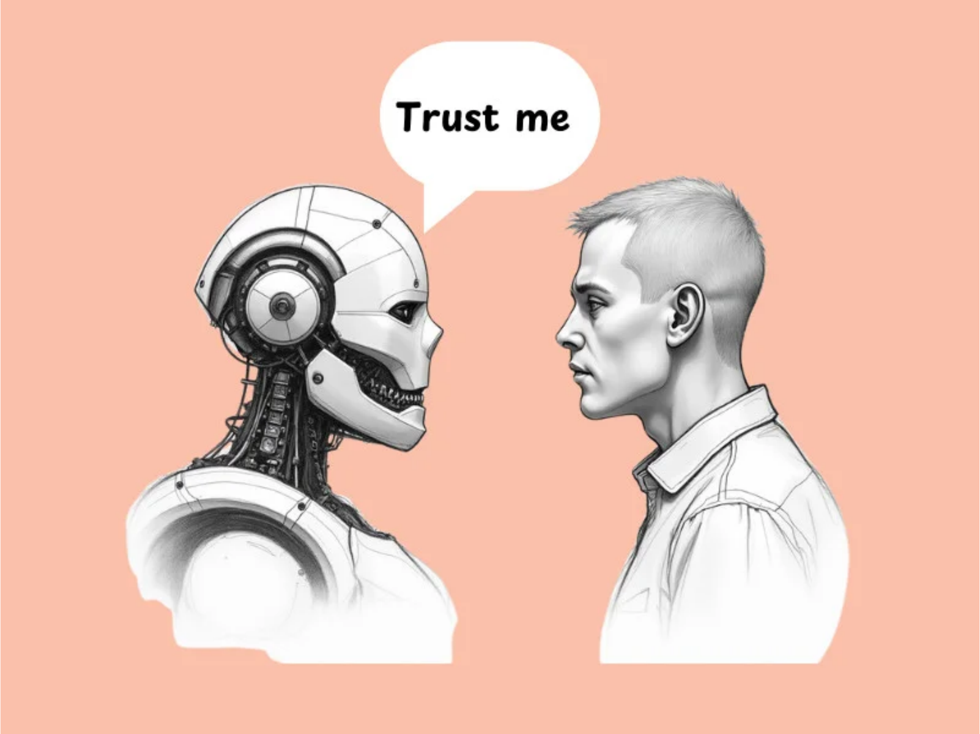
Can We Trust AI Cosmology?

AI enables:

- End-to-end inference
- Likelihood-free modeling

But introduce:

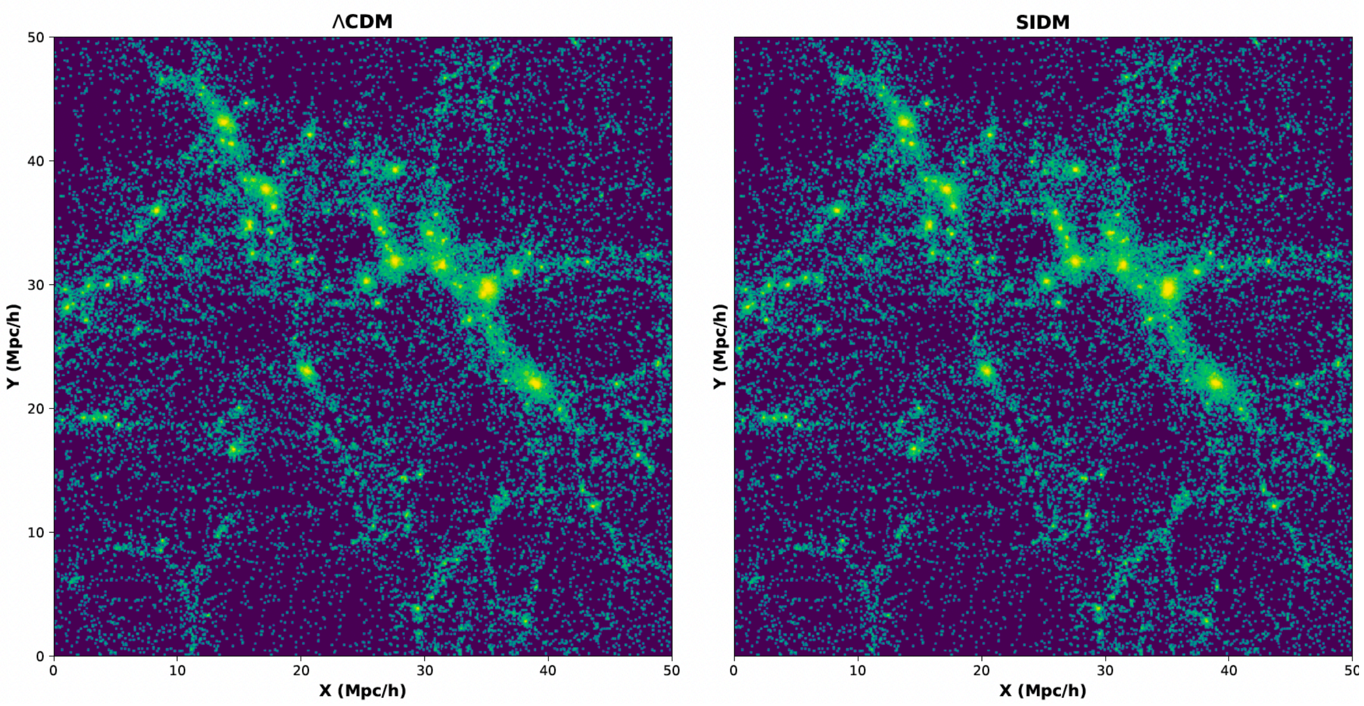
- Black-box behavior
- Lack of interpretability
- Limited physical transparency



Challenge: trustworthy scientific inference

SIMAgent: AI Assistant for Simulation

Challenges: Adapting Beyond-ΛCDM simulation is highly non-trivial and time-consuming



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SIMAgent: co-pilots simulation workflow

- **Literature-to-Code:** Automatically mapping models to specific code structures
- **Autonomous Code Navigation:** Pinpointing modifications within full codebase
- **Intelligent Synthesis:** Generating technical reports and modification suggestions for human verification

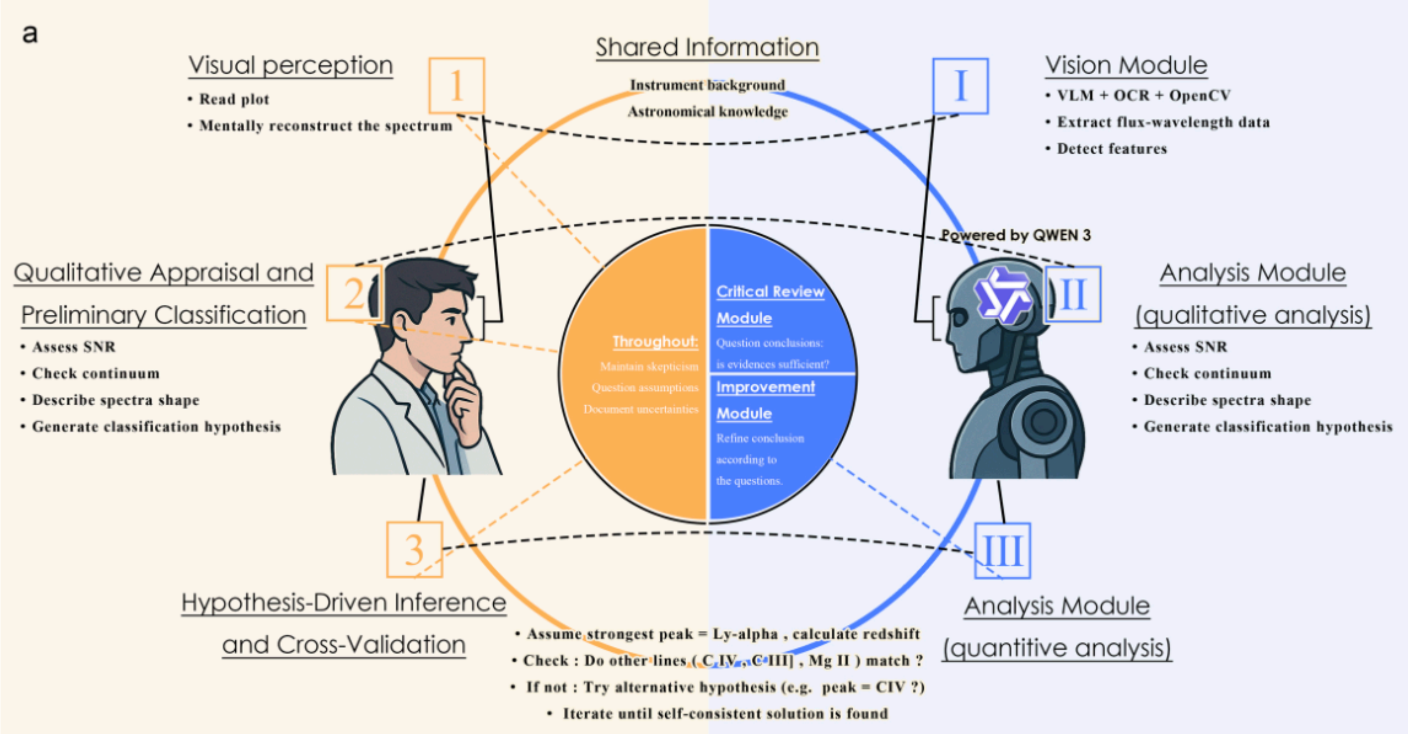
Result:

- Validated for multiple DM simulations (CDM, WDM, FDM, SIDM..)
- Compilable, fully runnable code with results matching theoretical expectations

From Black-Box Prediction → Auditable Scientific Reasoning

FORMA: LLM-based Scientific Reasoning

Motivation: Scientific inference requires explicit reasoning, but traditional AI models lack interpretability



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FORMA (LLM-based framework):
- Visual: Extracts features from spectral images
- Qualitative Analysis: generates redshift and classification hypotheses
- Hypothesis Inference: Validates hypotheses

Capabilities:
- Interpretability
- Verifiable reasoning steps
- Human-aligned scientific logic

From AI Inference → LLM-driven Scientific Reasoning

Summary

- A **New Paradigm** for AI-Driven Cosmology

- AI transforms cosmology at three fundamental levels:

Perception → DL enables high-precision, unbiased measurement

Inference →FLI+SBI enables high-dimensional, likelihood-free inference

Reasoning → LLM-driven framework formalizes scientific reasoning

A Lossless, Trustworthy, and Reasoning-Driven Paradigm

for the PB-data Era