Inferring the assembly and merger histories of galaxies

with the IllustrisTNG simulations and machine learning

Based on Eisert+ in prep.

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Marc Huertas-Company
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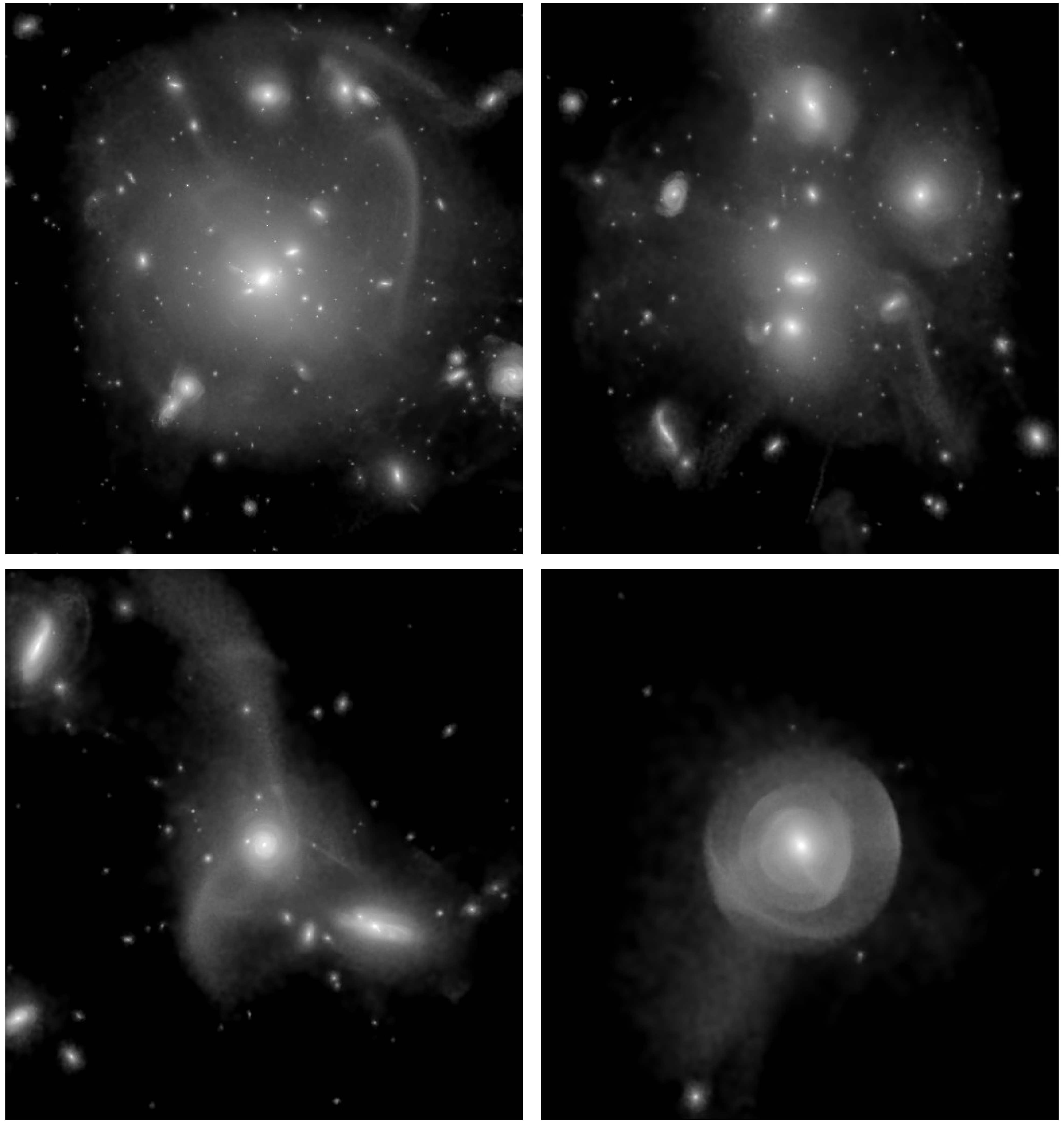
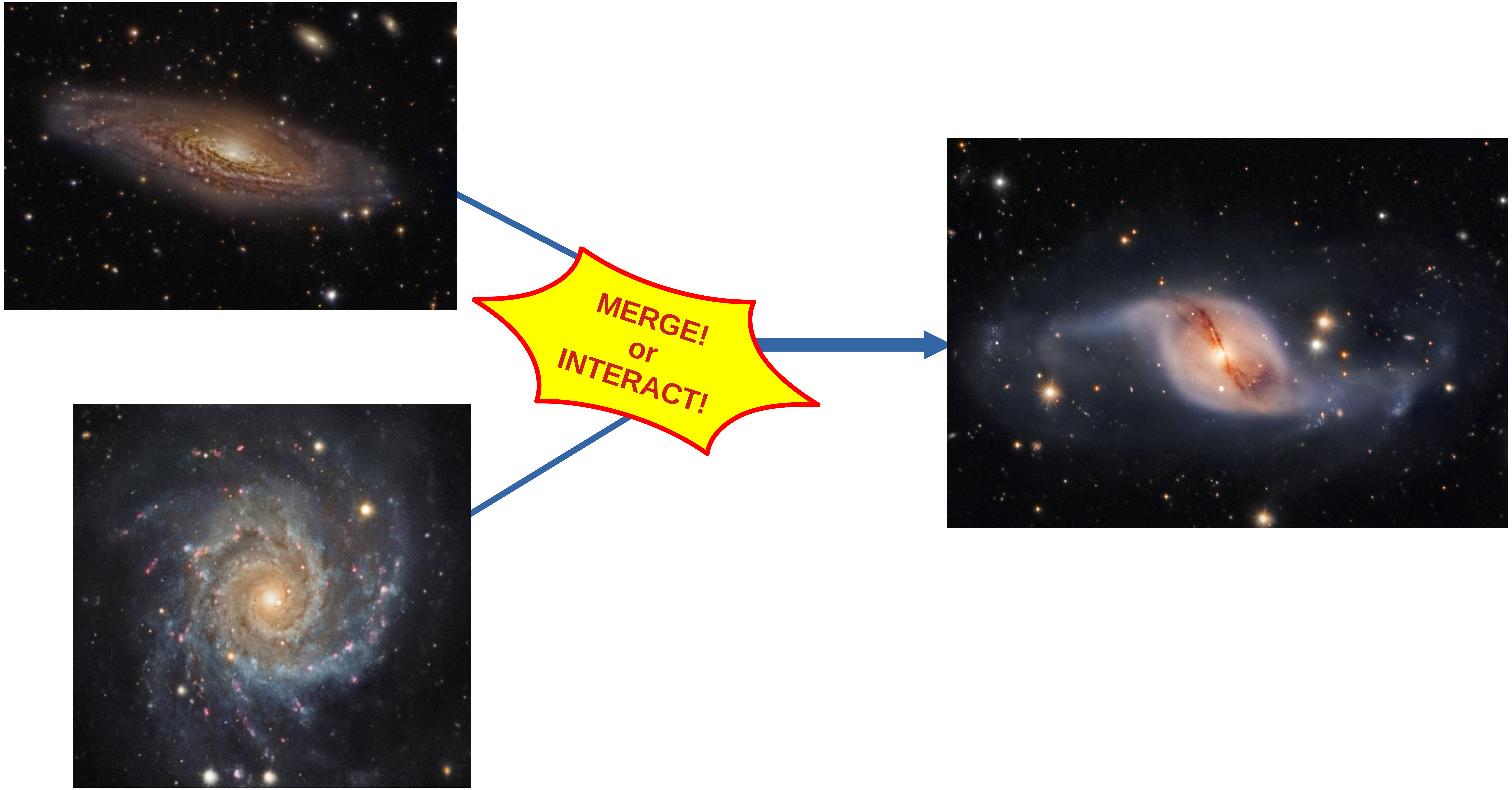
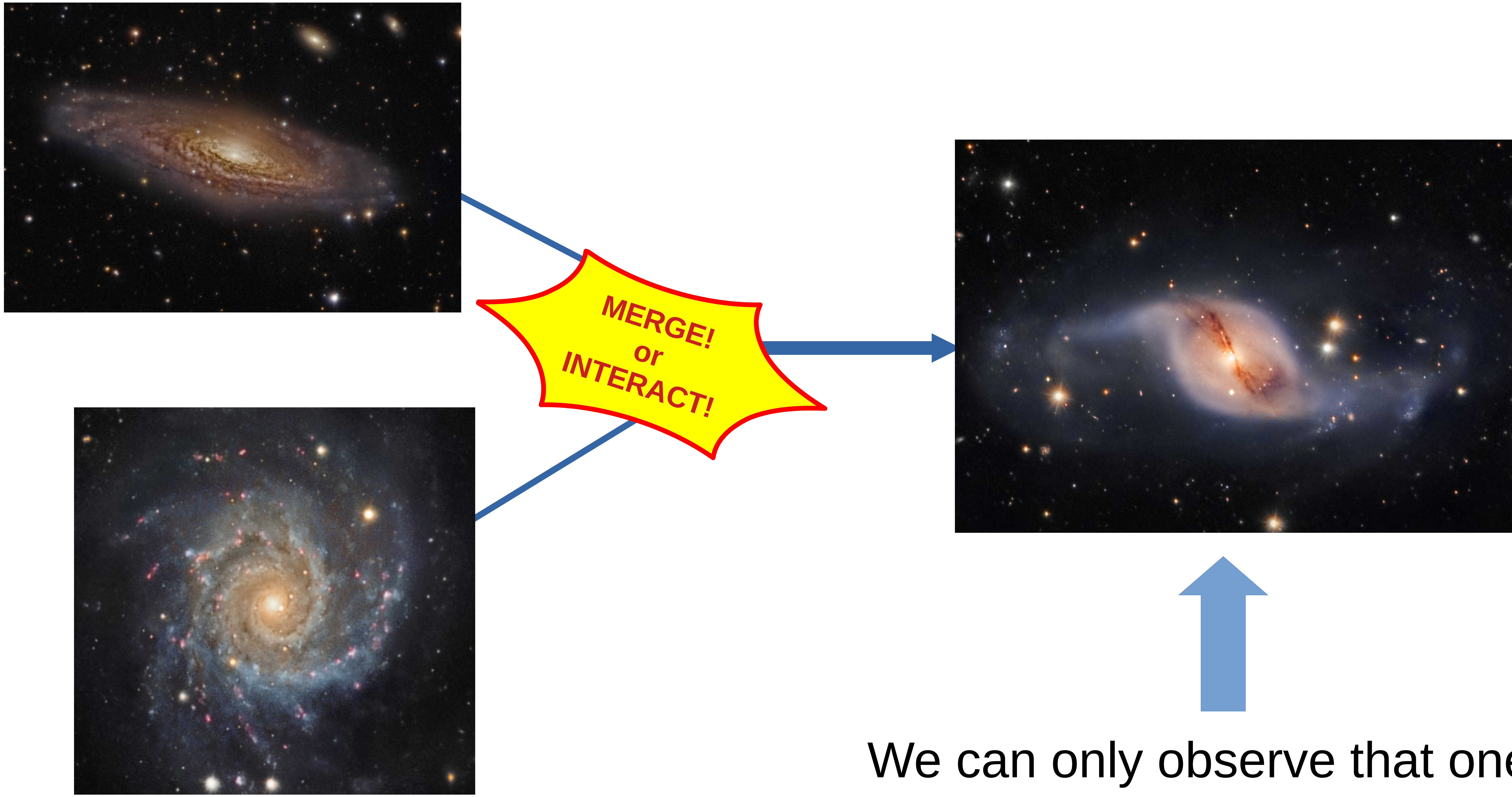
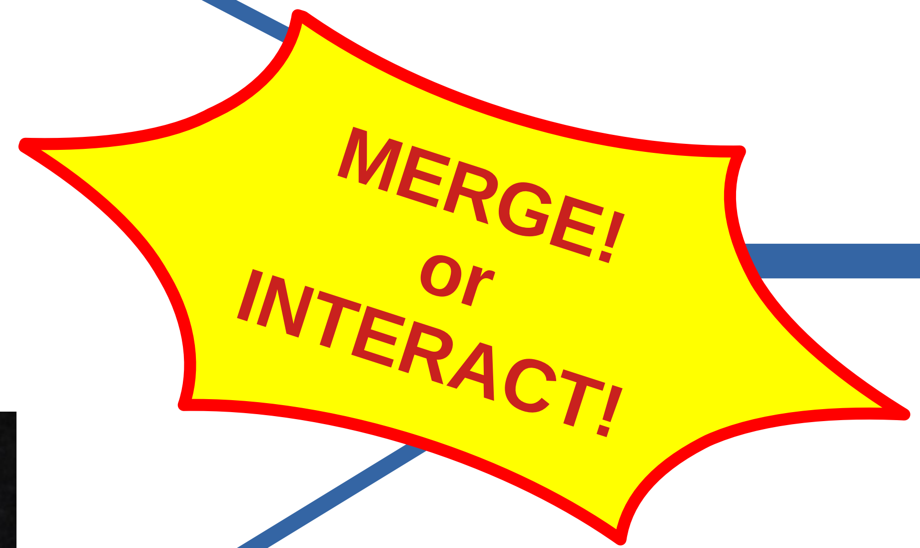



MERGE!
or
INTERACT!



We can only observe that one!

What can this observation tell us about the assembly history?



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What are we observing?

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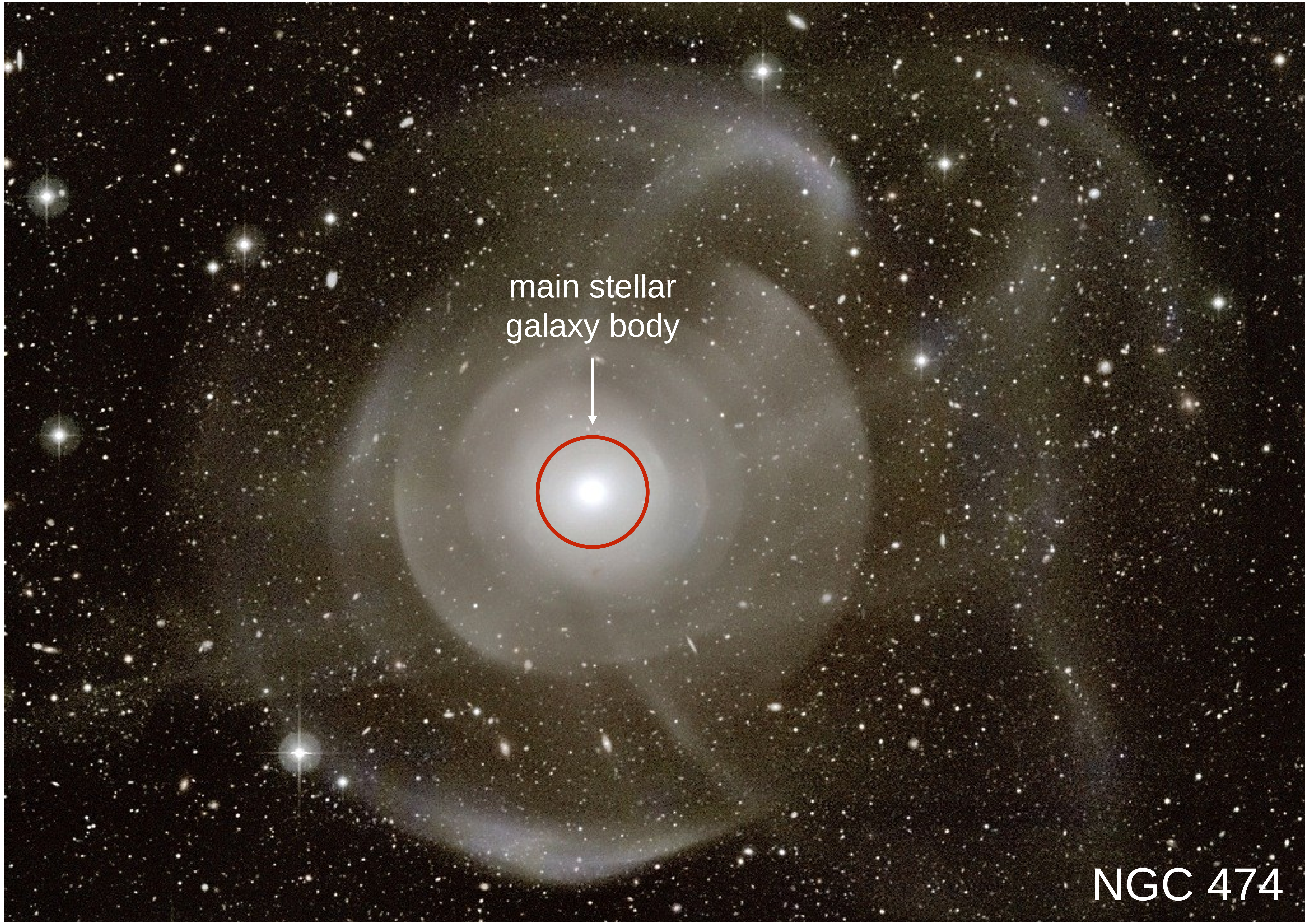
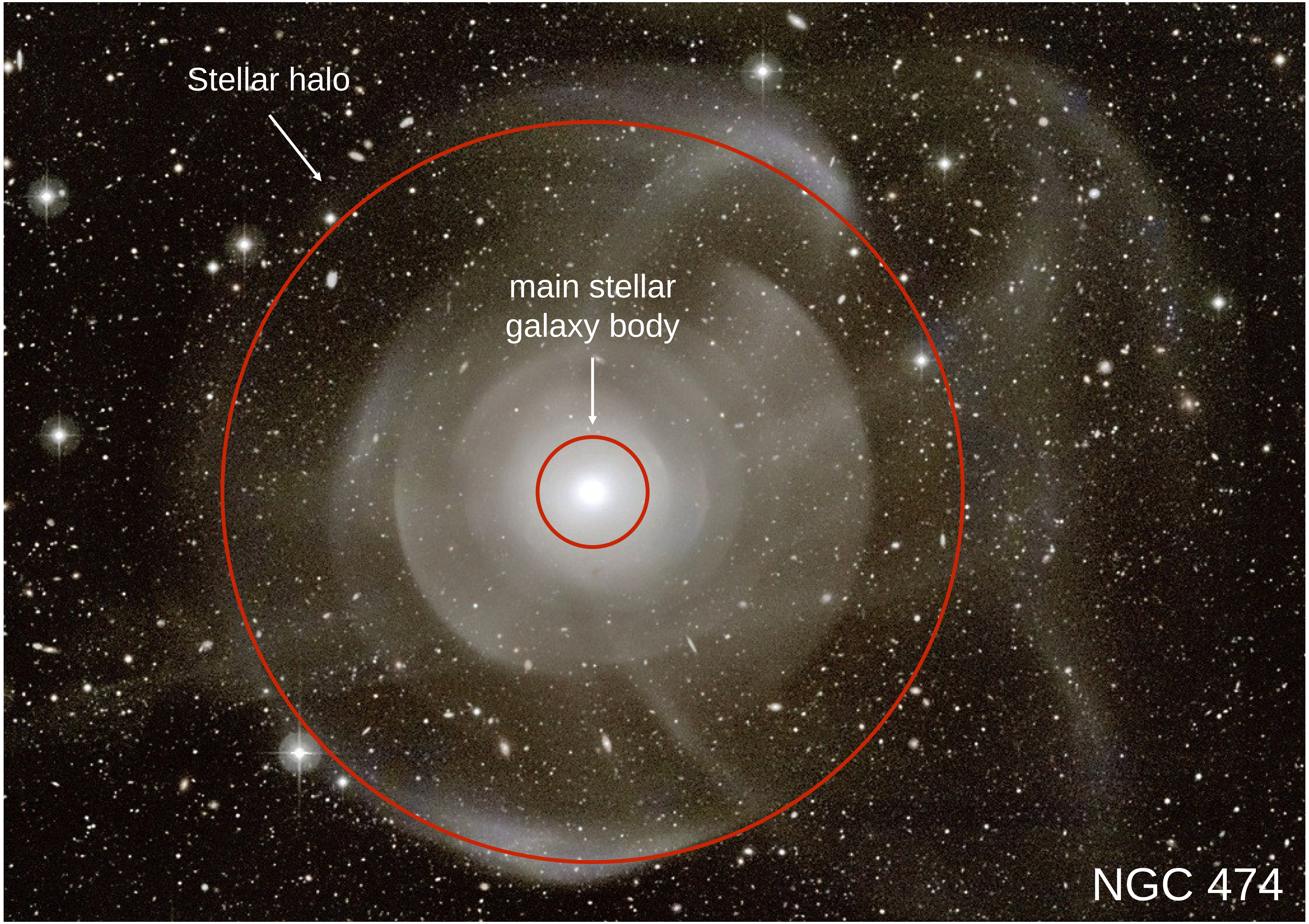


“EASY”:
Observable morphology and/or properties of the bright main galaxy body

e.g. SDSS

What are we observing?



"EASY":
Observable morphology and/or properties of the bright main galaxy body

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HARD:
Observable faint stellar halo surrounding them

no large sample available yet!

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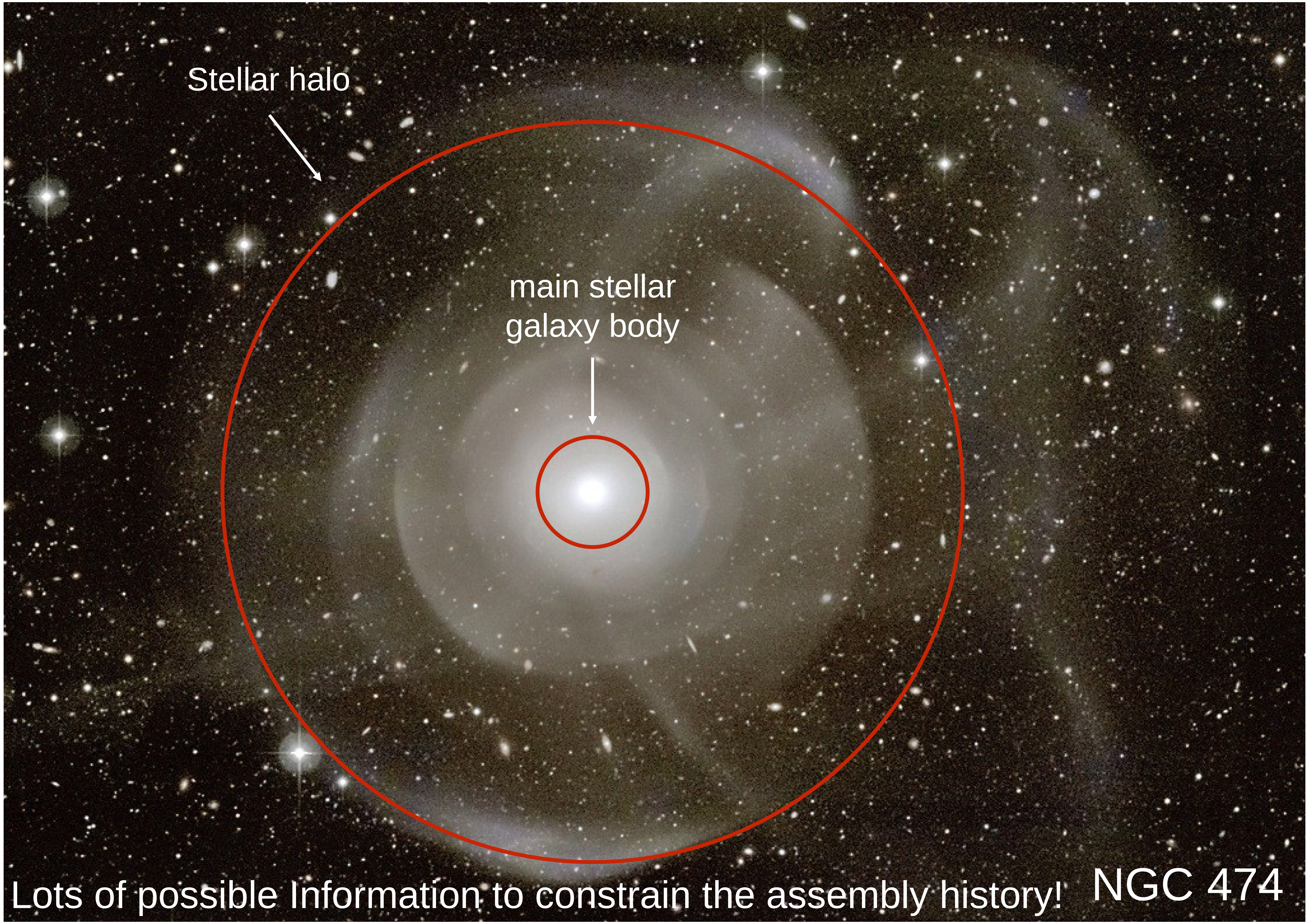

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The problem…

We can only observe galaxies at one specific point in time…

How to learn something about their histories?

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We can only observe galaxies at one specific point in time…

How to learn something about their histories?

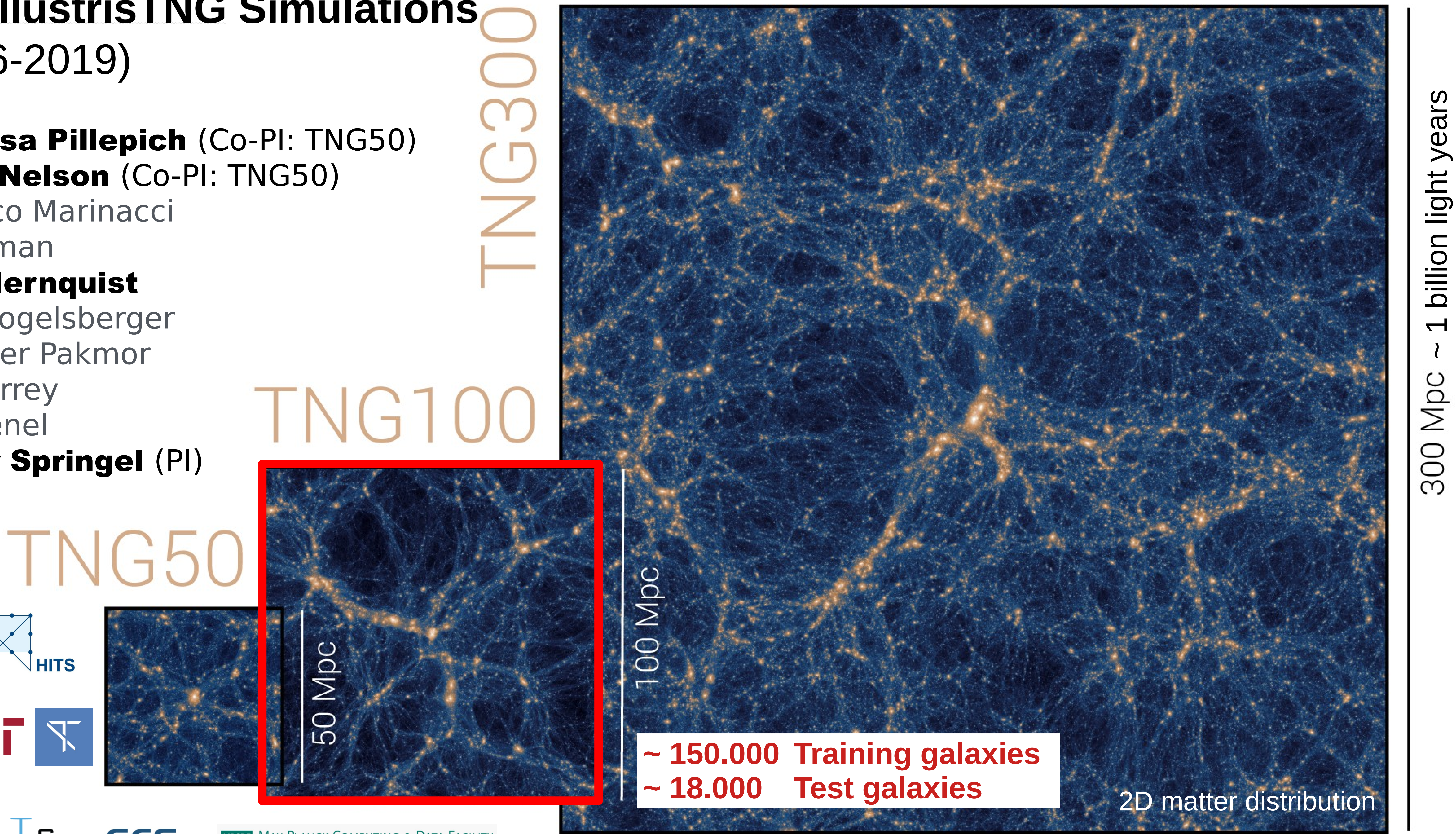
A solution…

Study galaxies via (full) cosmological simulations!

Get observables and the history for each simulated galaxy and train a Neural Network to it!

The IllustrisTNG Simulations
(2016-2019)

- **Annalisa Pillepich** (Co-PI: TNG50)
- **Dylan Nelson** (Co-PI: TNG50)
- Federico Marinacci
- Jill Naiman
- **Lars Hernquist**
- Mark Vogelsberger
- Ruediger Pakmor
- Paul Torrey
- Shy Genel
- **Volker Springel** (PI)



Max-Planck-Institut für Astrophysik

Physical processes (unobservables) x

esp. merger histories i.e.

- Average mass ratios of mergers
- Average time of mergers
- Time of latest major merger
- Fraction of ex-situ stars

Cosmological Simulations (e.g. IllustrisTNG)

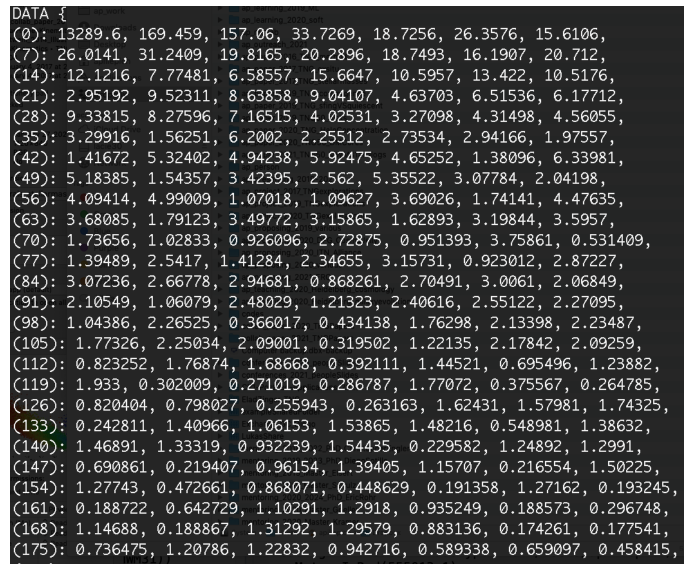
Potential loss of information

?

Galaxy properties (observables) c

Integral properties:

- Stellar mass
- Redshift
- Diskyness
- Galaxy size
- Average stellar age
- Integrated Color
- Stellar Metallicity



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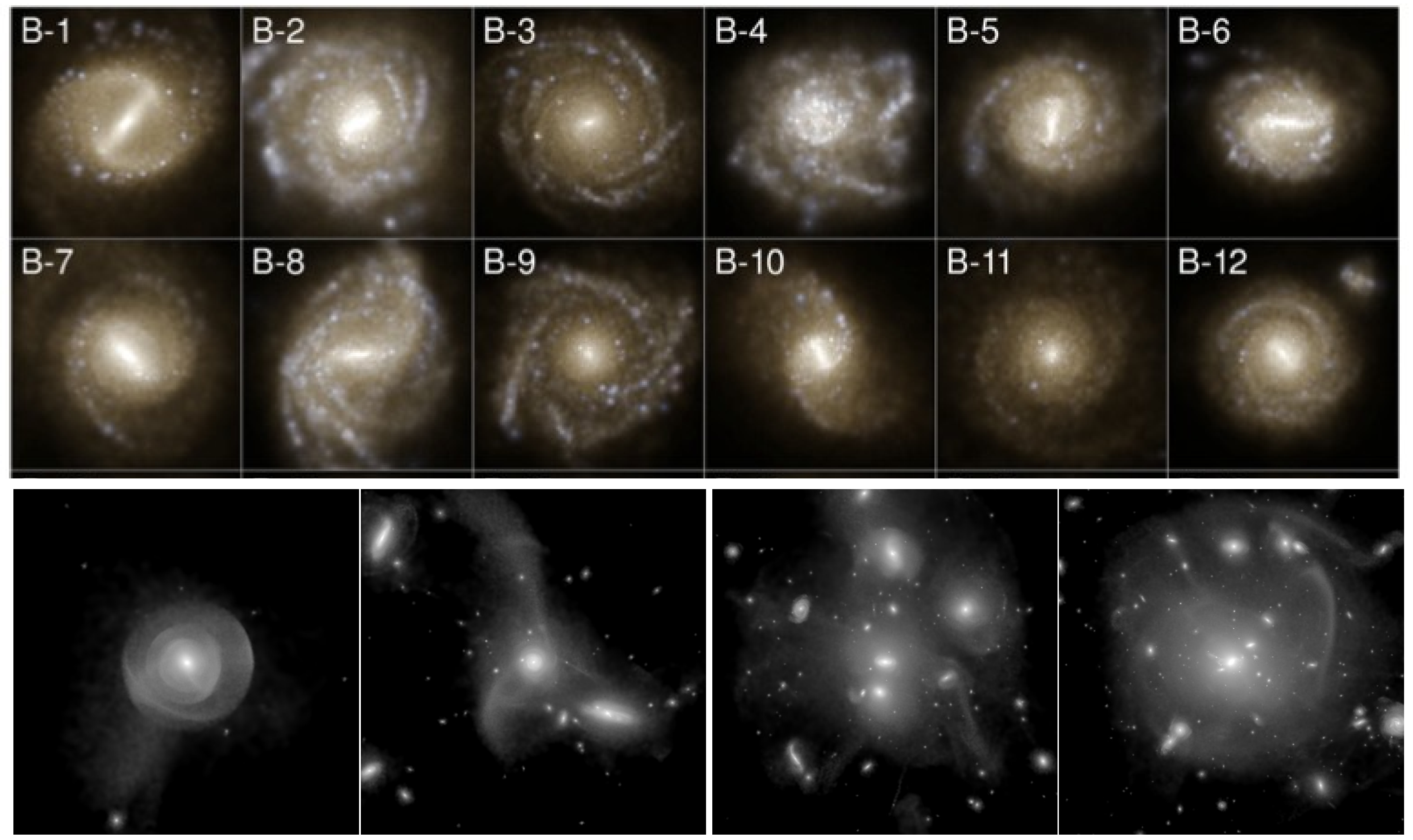
Galaxy stellar maps:



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esp. merger histories i.e.

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- Fraction of ex-situ stars

Cosmological Simulations (e.g. IllustrisTNG)

→

Potential loss of information

?

Galaxy properties (observables) c

Integral properties:

- Stellar mass
- Redshift
- Diskyness
- Galaxy size
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- Integrated Color
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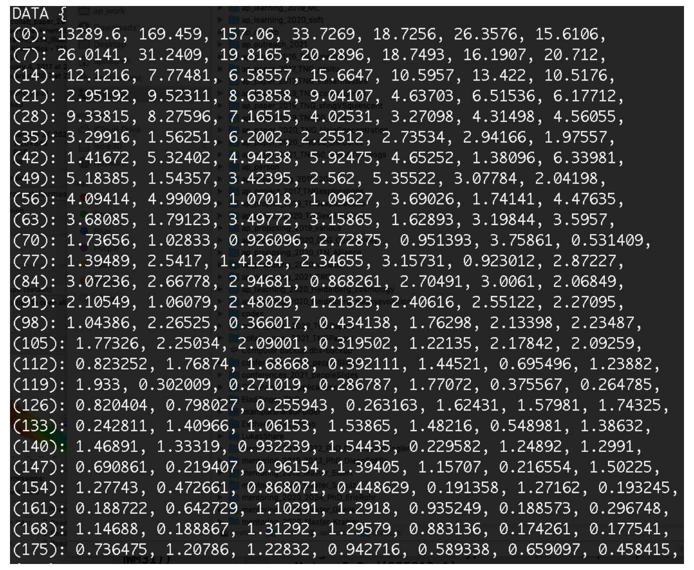

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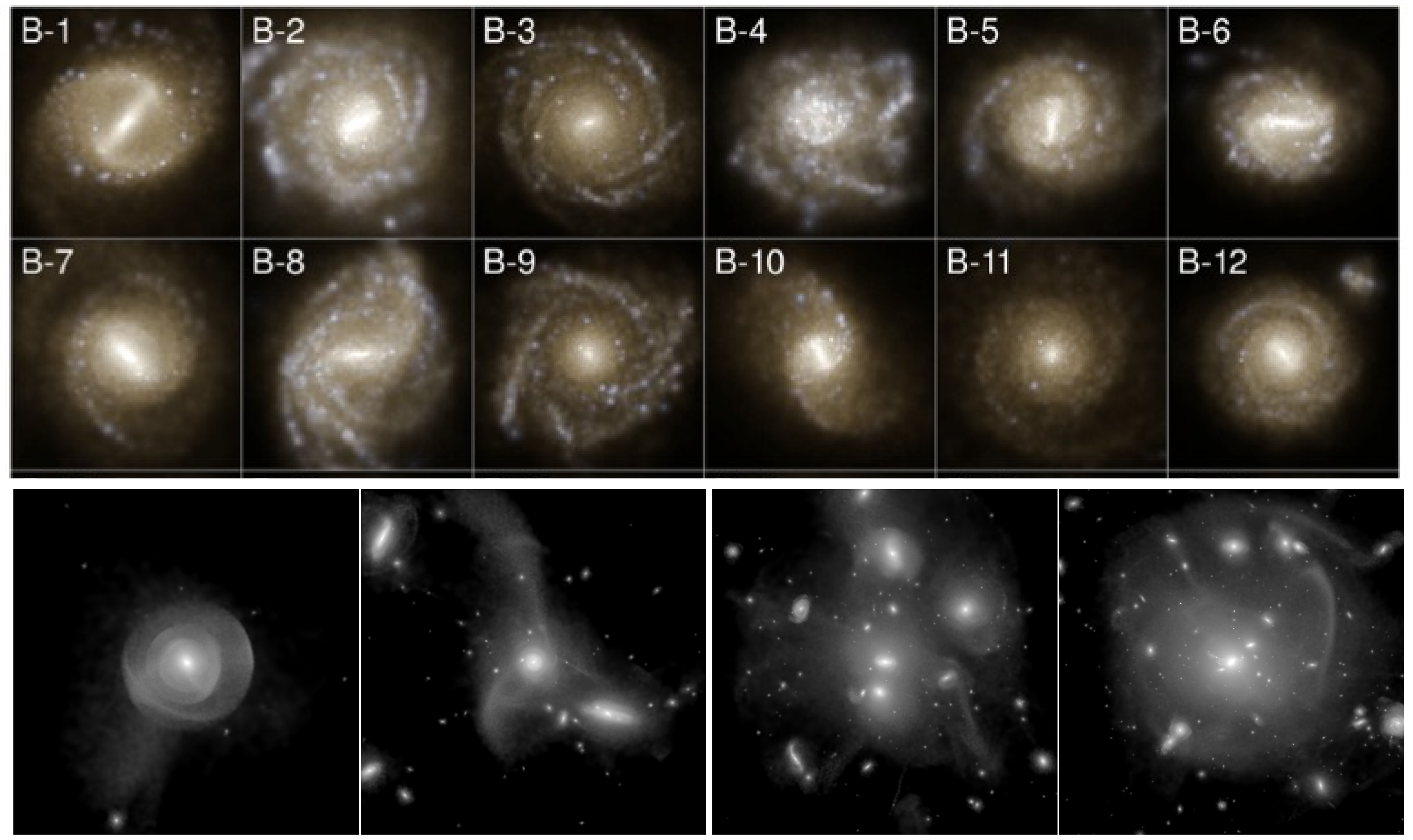

Approach #1: Scalars to scalars

Physical processes (unobservables) x

Cosmological Simulations (e.g. IllustrisTNG)

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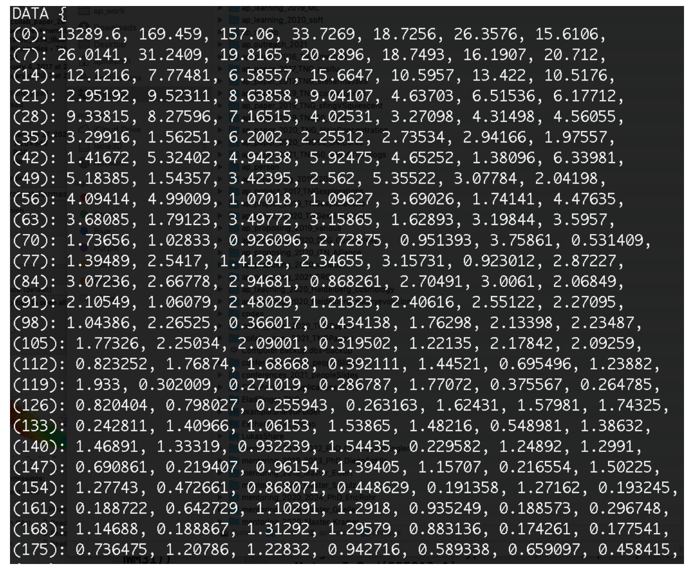

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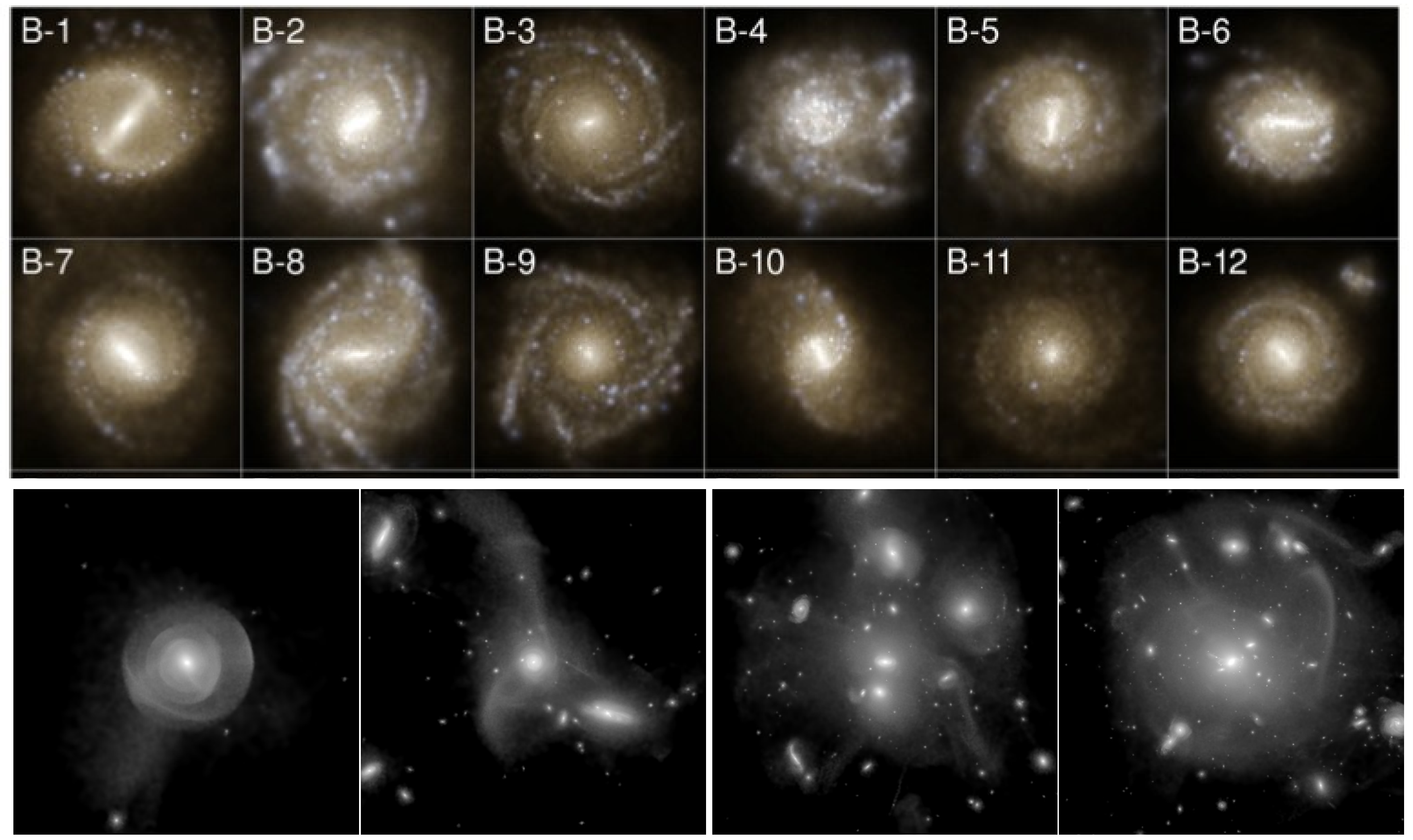

Approach #2: Maps to scalars

Physical processes (unobservables) x

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Cosmological Simulations
(e.g. IllustrisTNG)
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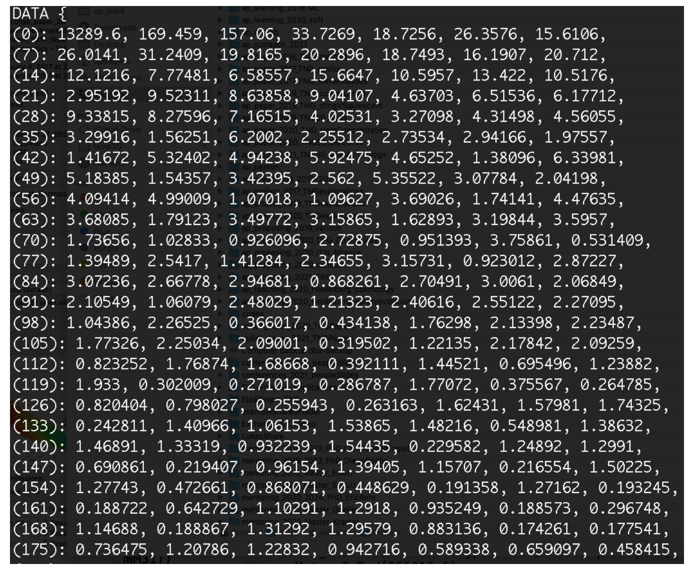

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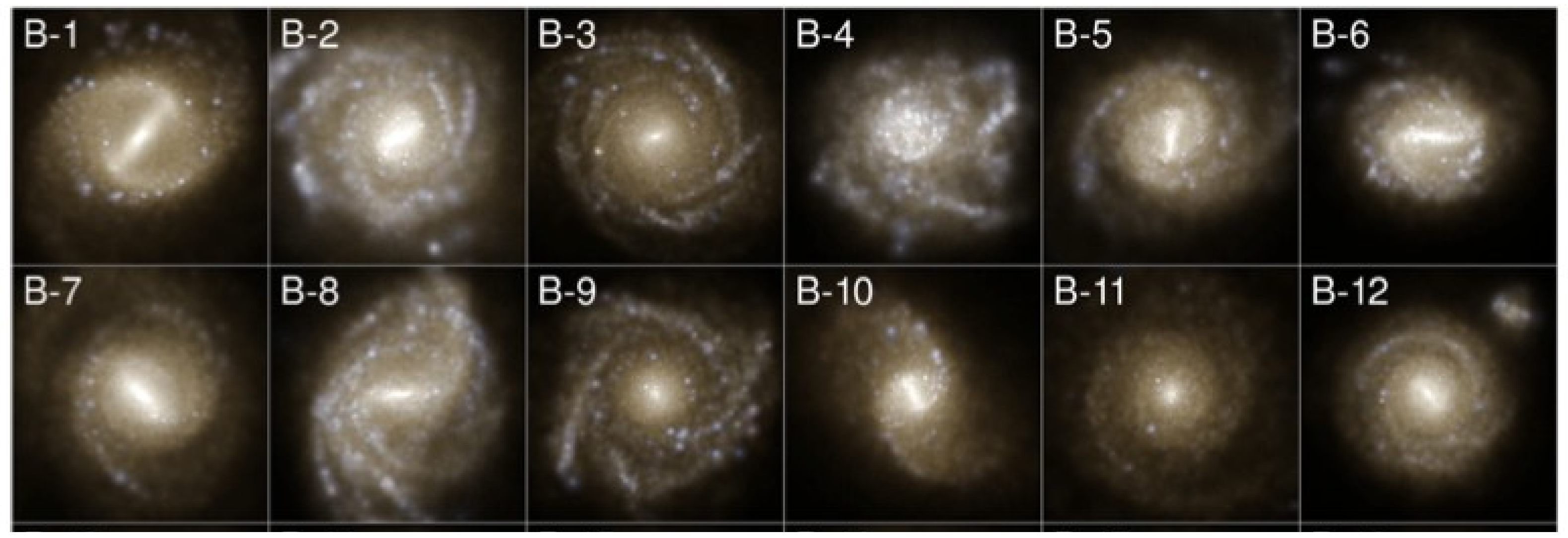
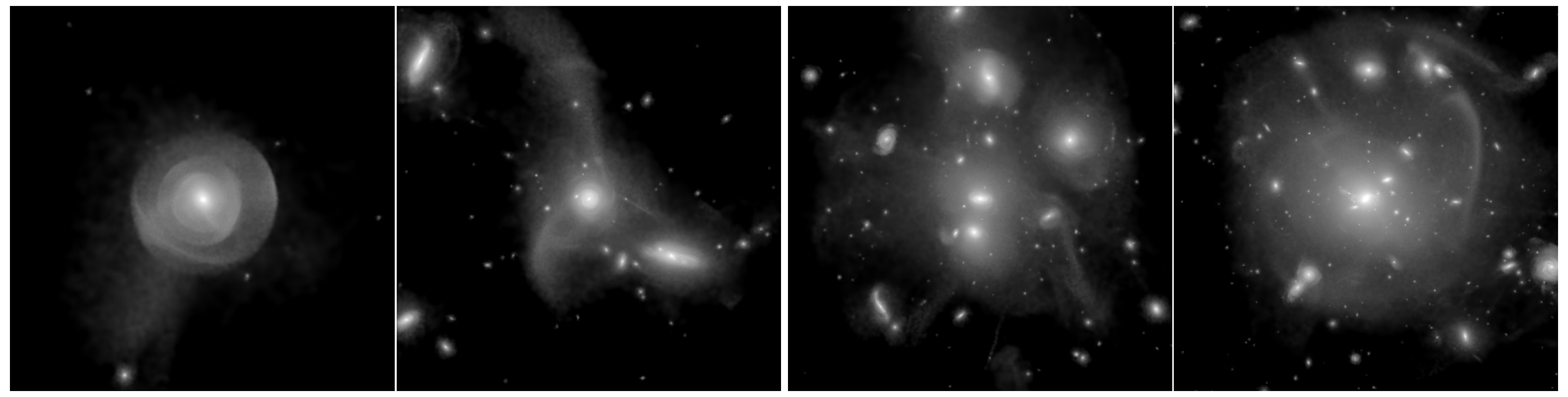
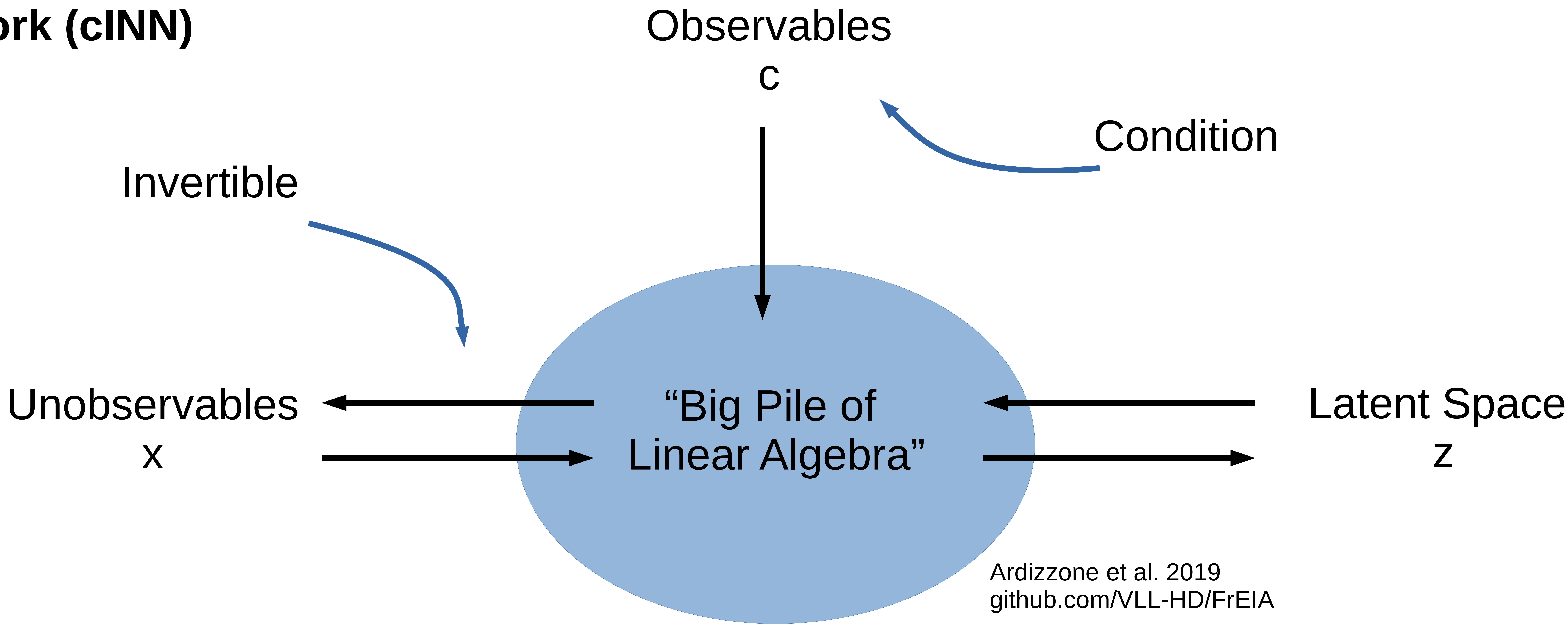




Approach #1: Scalars to scalars

Look for the posterior distribution p(x|c)
to account for ambiguities connected to such inverse Problems!

Conditional Invertible Neural Network (cINN)



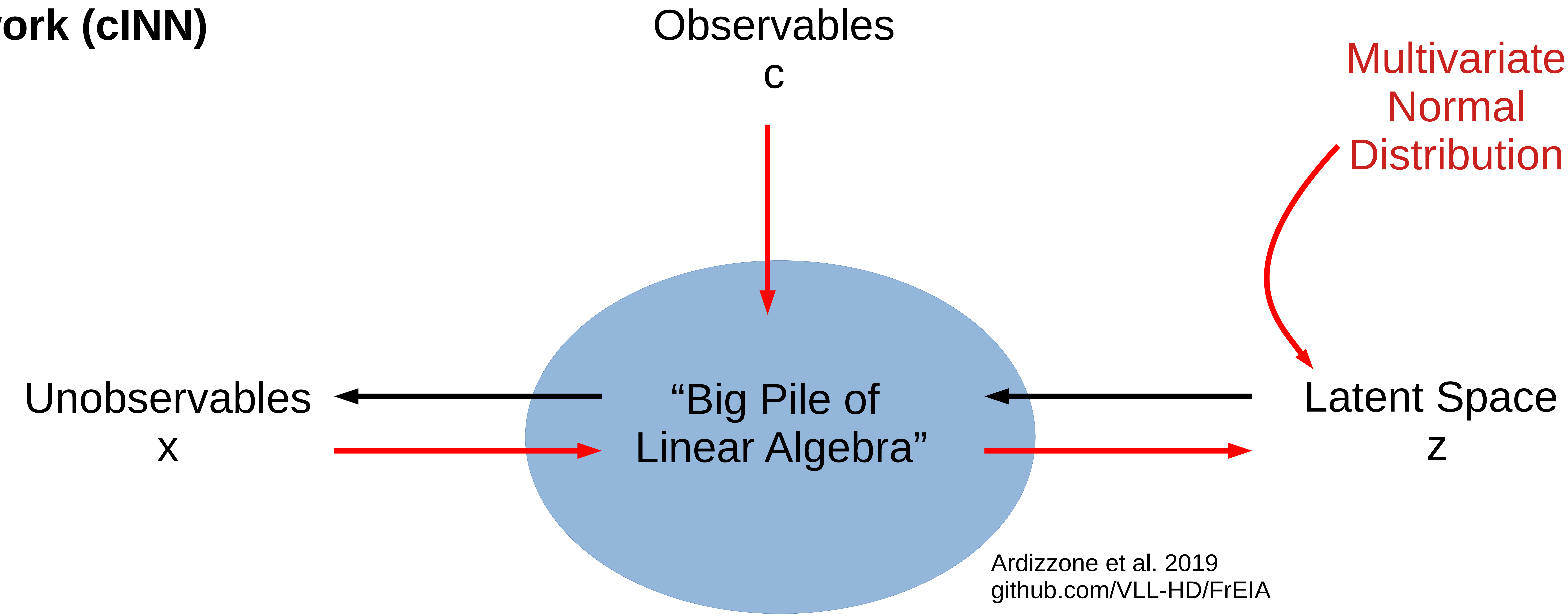
Ardizzone et al. 2019
github.com/VLL-HD/FrEIA

$$f(x; c, \theta) = z$$

$$f^{-1}(z; c, \theta) = x$$

Store information into z which would be otherwise lost!

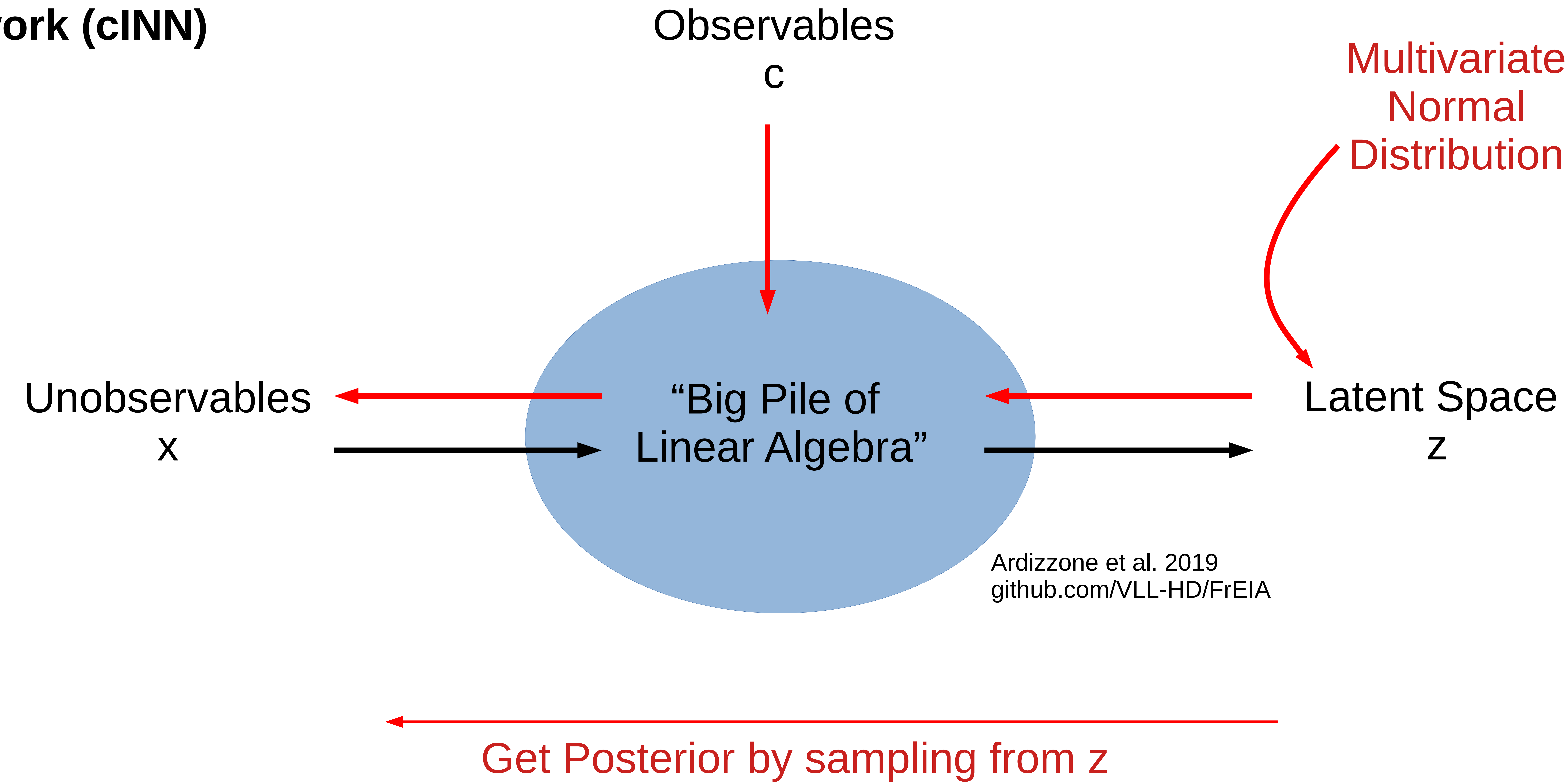
Conditional Invertible Neural Network (cINN)



Training with Maximum Likelihood Loss

$$\mathcal{L} = \mathbb{E}_{\mathrm{i}}\left[\frac{||f(\mathbf{x_i};\mathbf{c_i},\theta)||_2^2}{2} - \log|J_{\mathrm{i}}|\right]$$

Conditional Invertible Neural Network (cINN)



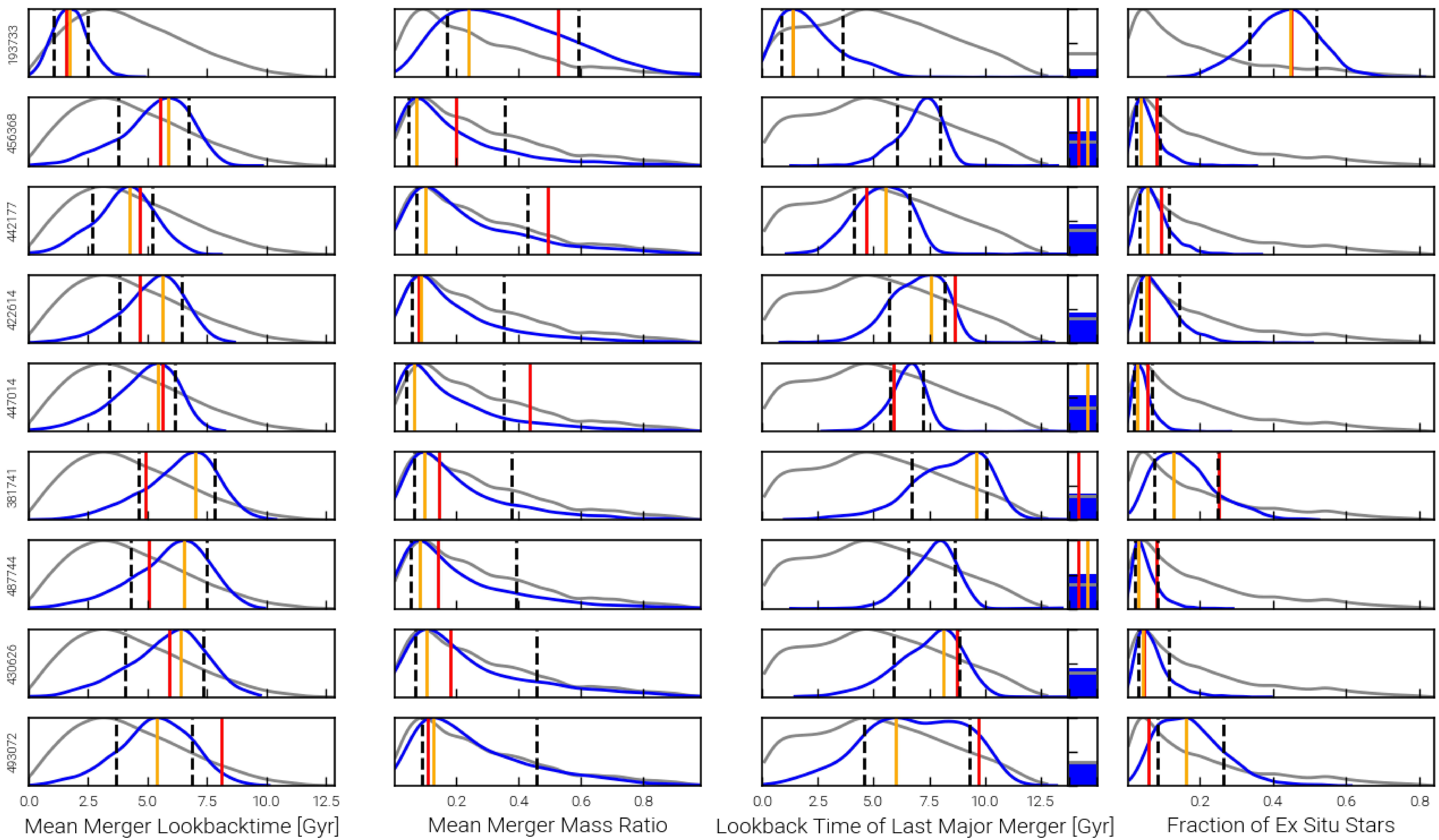
$$f^{-1}(z; c, \theta_{opt}) \rightarrow p(x|c)$$

Conditional Invertible Neural Network (cINN) Posteriors

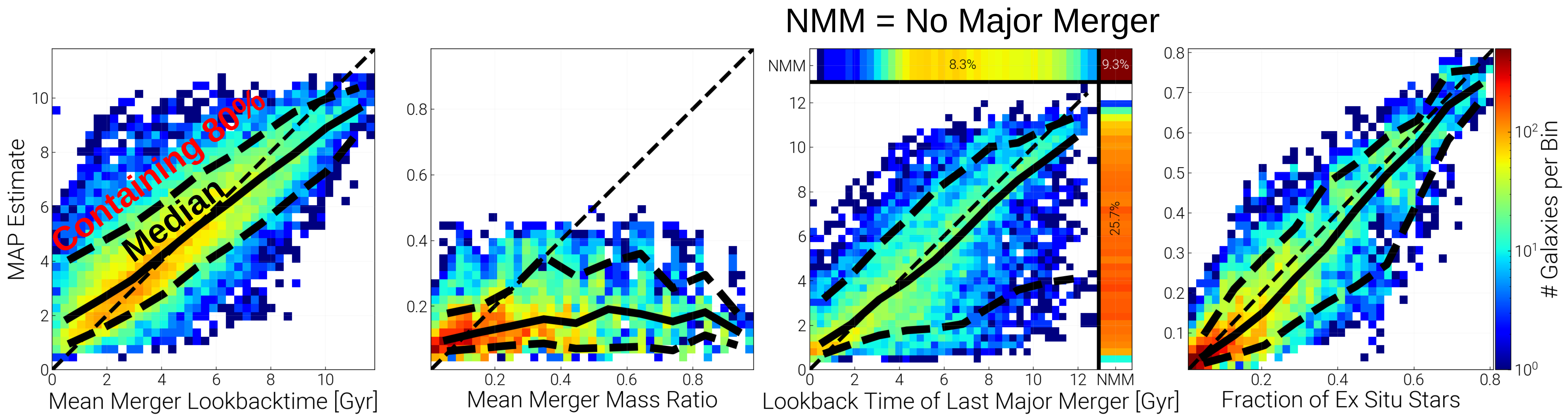
1 row = 1 example galaxy

Prior
Posterior
Ground Truth
Max. a posteriori estimate (MAP)

Mean Merger Lookbacktime [Gyr] | **Mean Merger Mass Ratio** | **Lookback Time of Last Major Merger [Gyr]** | **Fraction of Exsitu Stars**

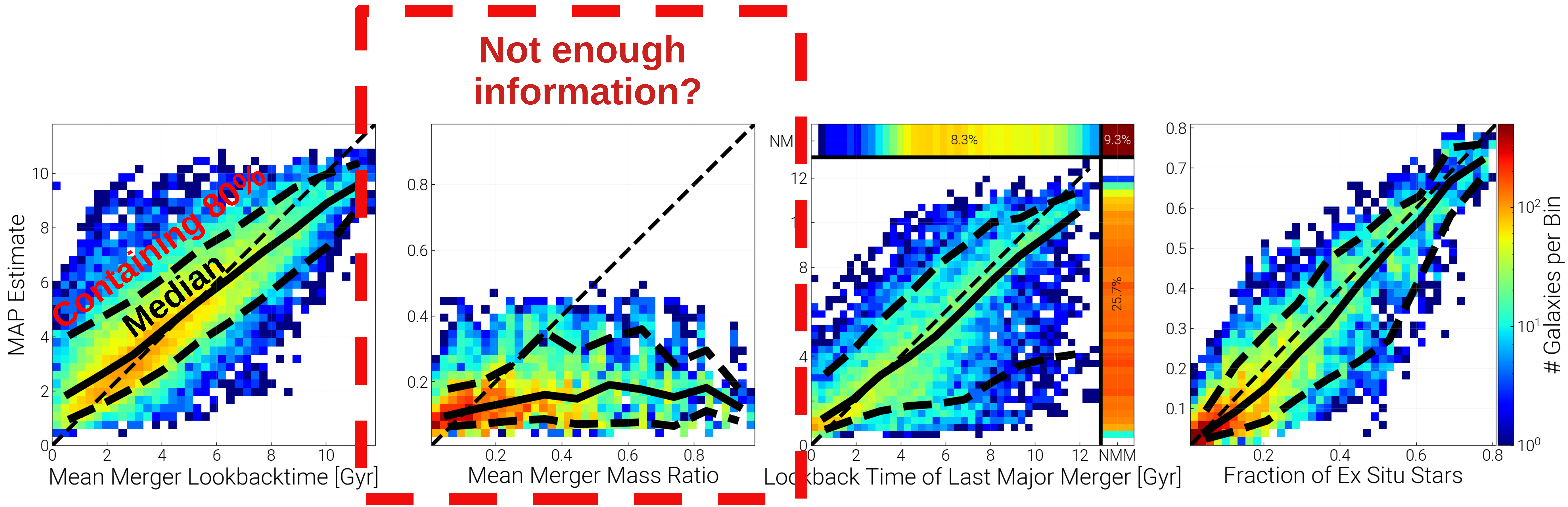


cINN Results



TNG100
Redshift <= 1
Log Total Stellar Mass > 10.0
~ 150.000 Training galaxies
~ 18.000 Test galaxies
Logarithmic colorbar

cINN Results



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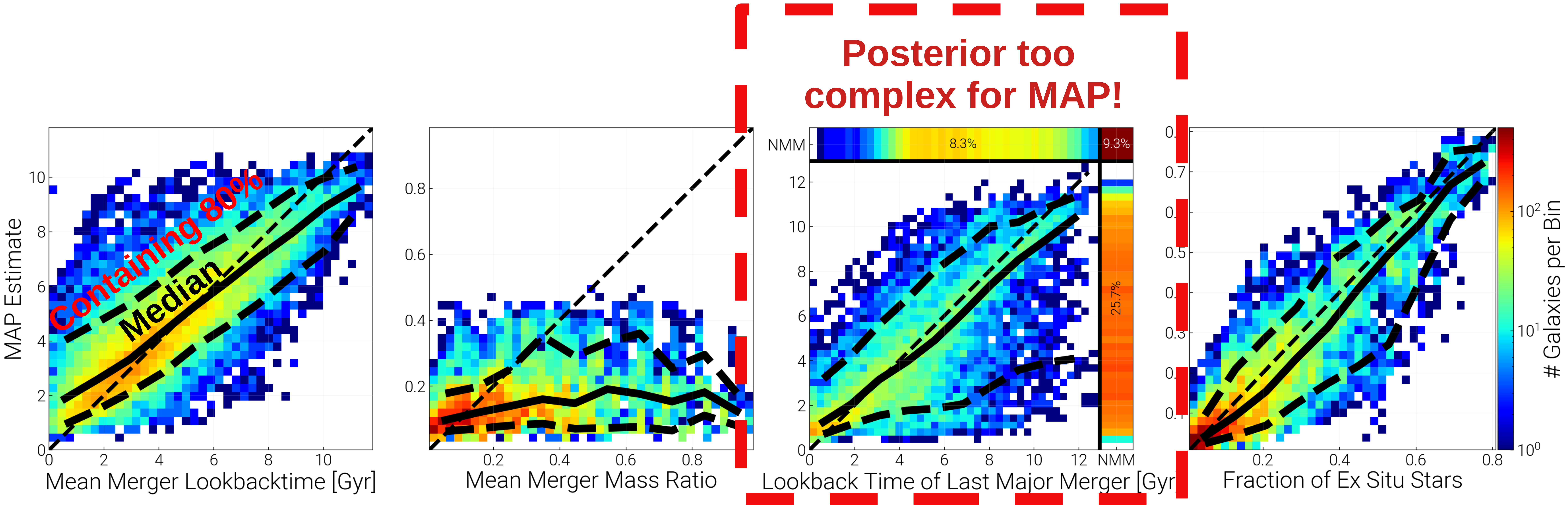

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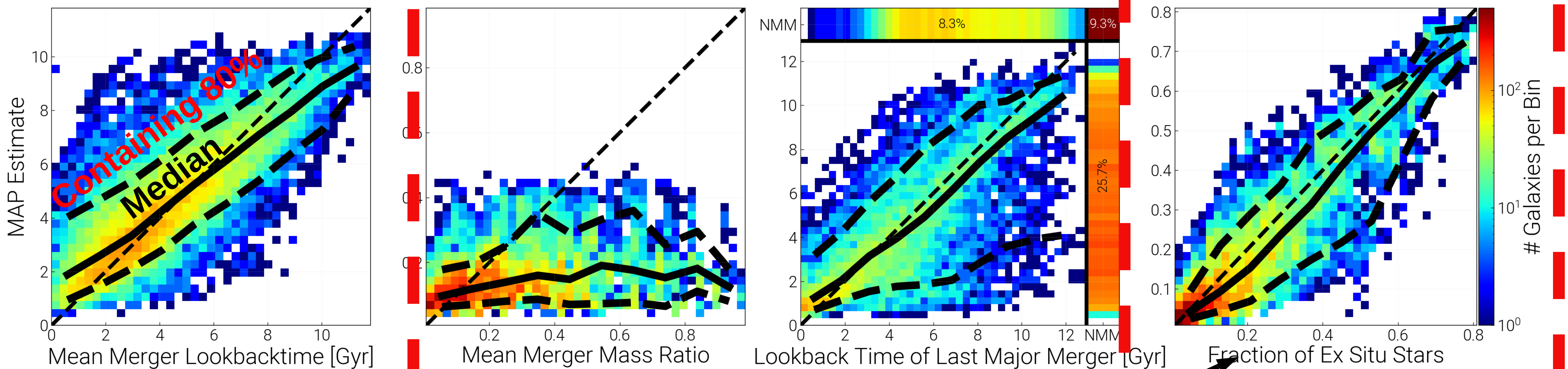
Working point predictions for
Mean Merger Lookback time
and
Stellar Exsitu Fractions

cINN Results



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Working point predictions for
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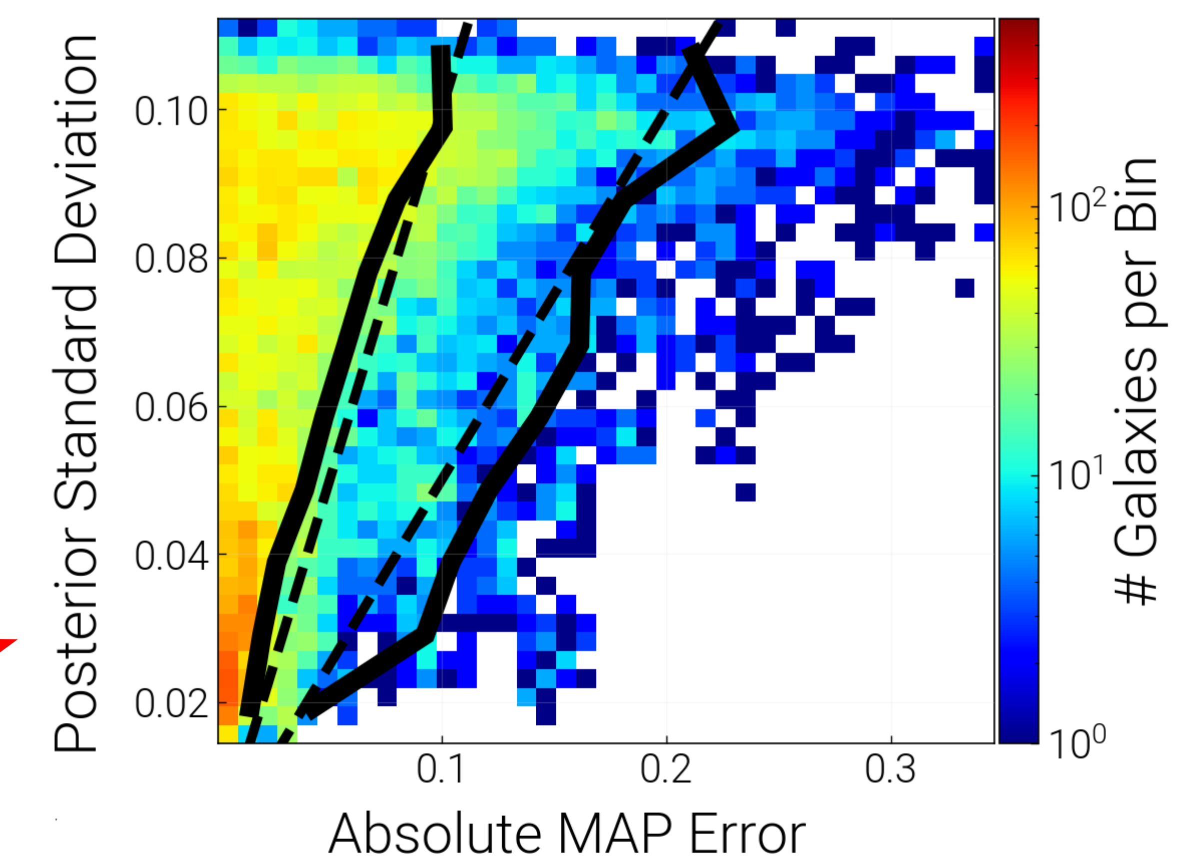
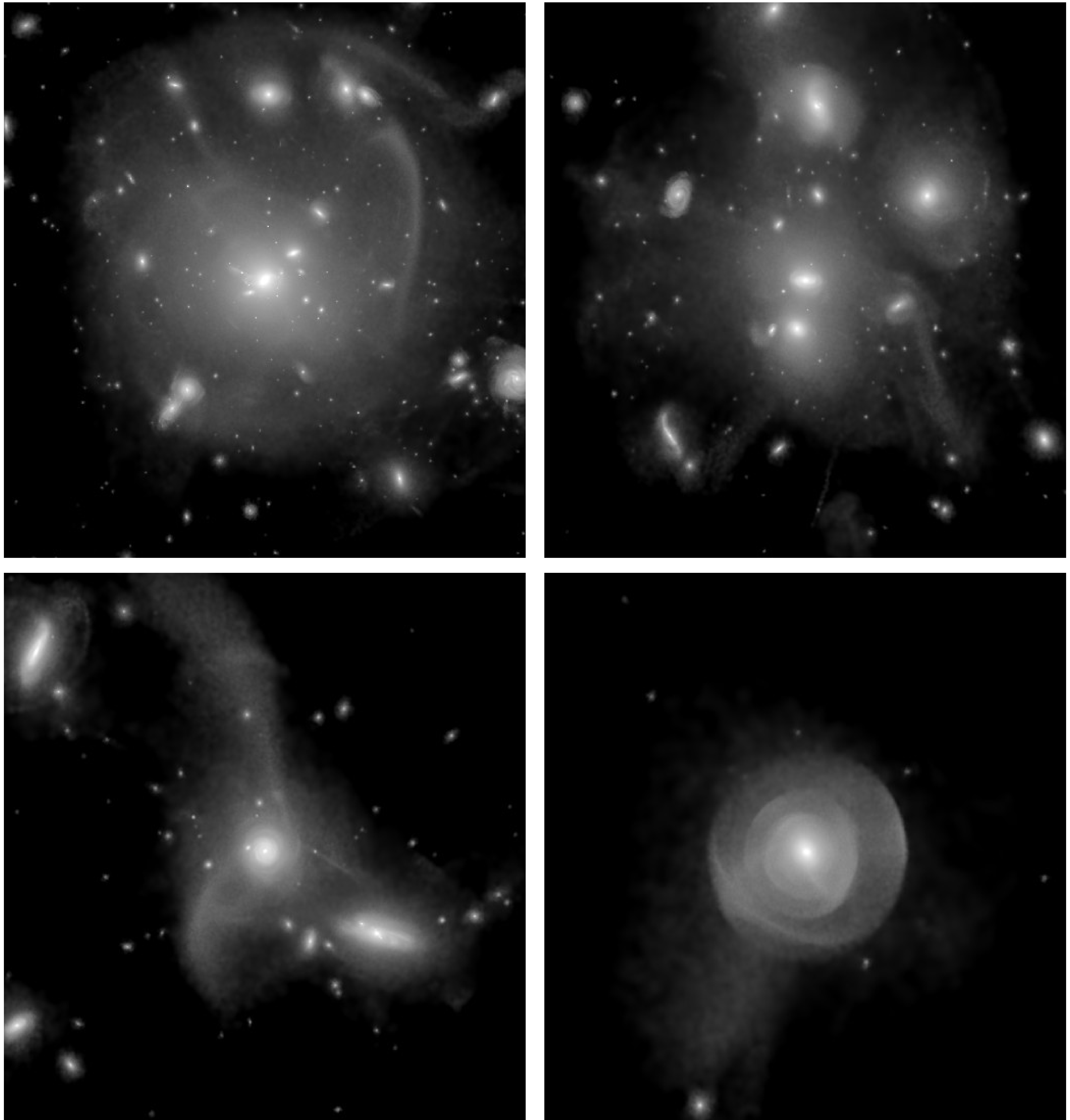
+ Errorbars from the Posteriors!

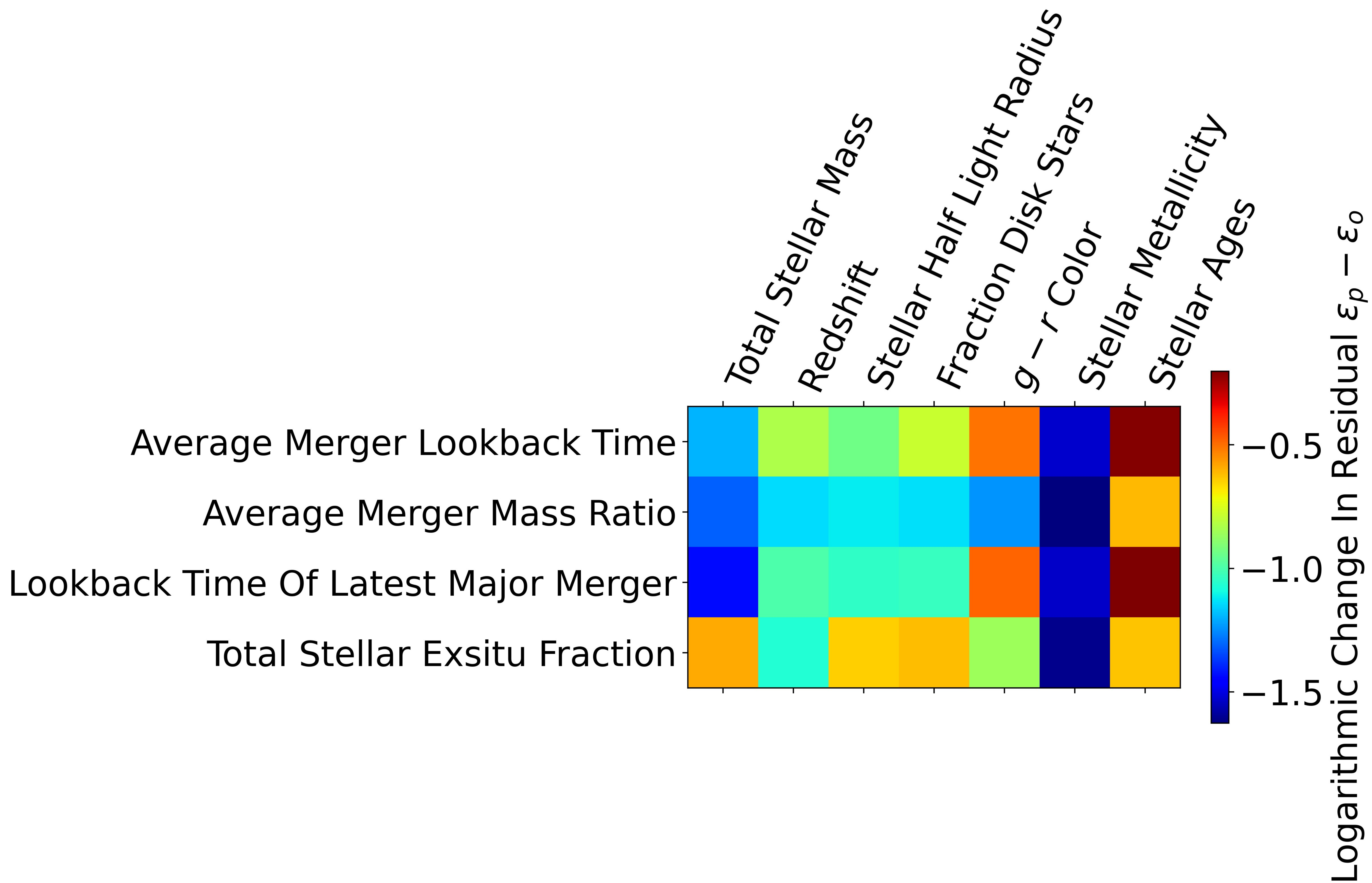


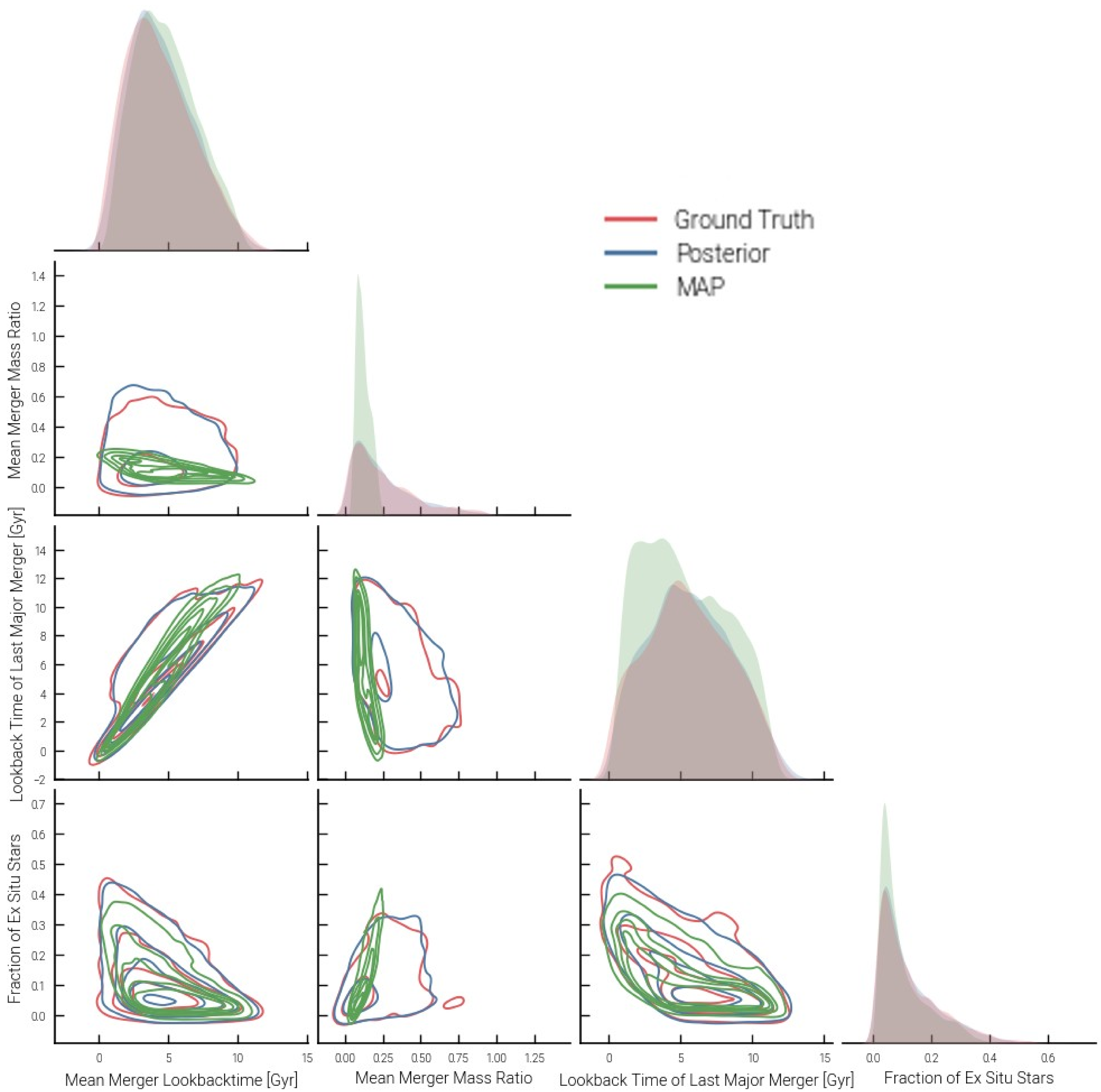


Summary & Outlook

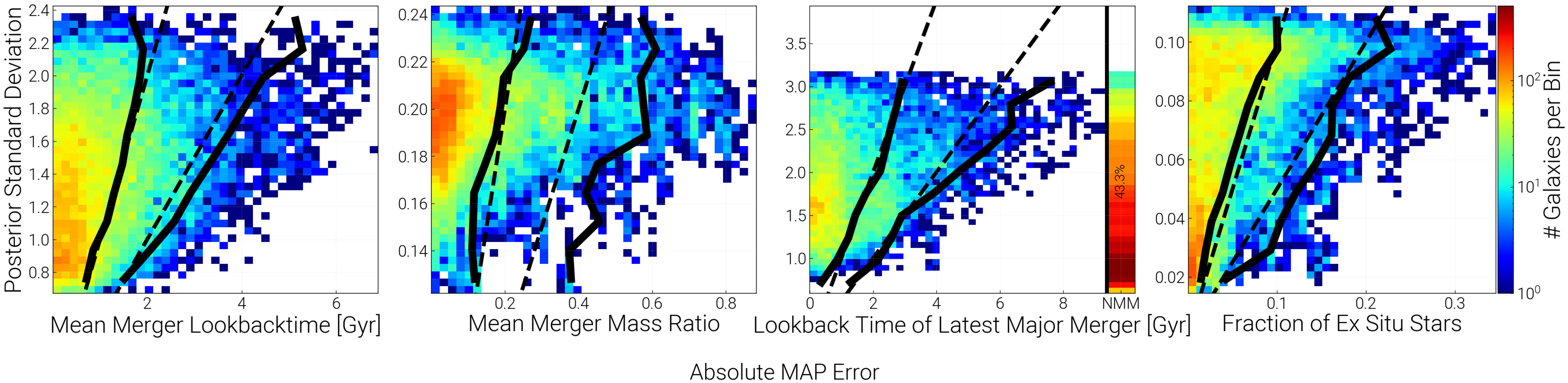
- We are able to construct well behaving posteriors for the average merger lookback time and stellar exsitu fractions from a simple set of scalar observables!
- In the full paper:
  - Convergence Analysis
  - Closer look at the mass ratios and the lookback time of the latest major merger
  - Sensitivity Analysis
- Approach #2:
  Use Light Maps as input
- Get representations via contrastive learning
- Infer more parameters; maybe even the merger tree or maps of unobservable physical quantities
- Apply the models to real observational data!

Supplementary


Total Stellar Mass
Redshift
Stellar Half Light Radius
Fraction Disk Stars
$g-r$ Color
Stellar Metallicity
Stellar Ages
Average Merger Lookback Time
Average Merger Mass Ratio
Lookback Time Of Latest Major Merger
Total Stellar Exsitu Fraction
−0.5
−1.0
−1.5
Logarithmic Change In Residual $\epsilon_p - \epsilon_o$



Ground Truth
Posterior
MAP
Mean Merger Mass Ratio
Lookback Time of Last Major Merger [Gyr]
Fraction of Ex Situ Stars
Mean Merger Lookbacktime [Gyr]
Mean Merger Mass Ratio
Lookback Time of Last Major Merger [Gyr]
Fraction of Ex Situ Stars


Posterior Standard Deviation
Mean Merger Lookbacktime [Gyr]
Mean Merger Mass Ratio
Lookback Time of Latest Major Merger [Gyr]
NMM
43.3%
Fraction of Ex Situ Stars
Galaxies per Bin
Absolute MAP Error

Embedding of the galaxies into a 2D representation with UMAP