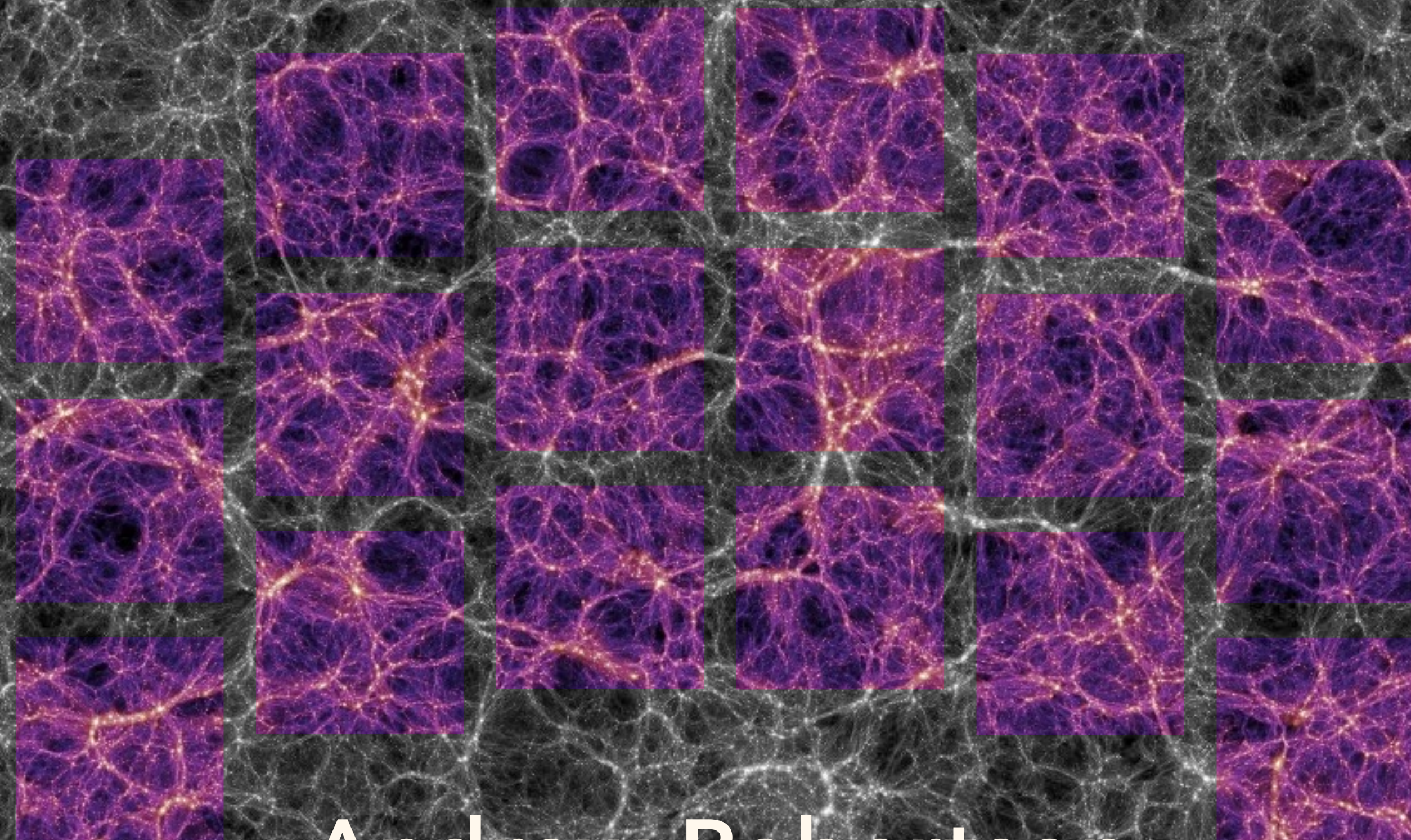


CALIBRATING GALAXY FORMATION MODELS FOR THE ROMAN ERA



Andrew Robertson

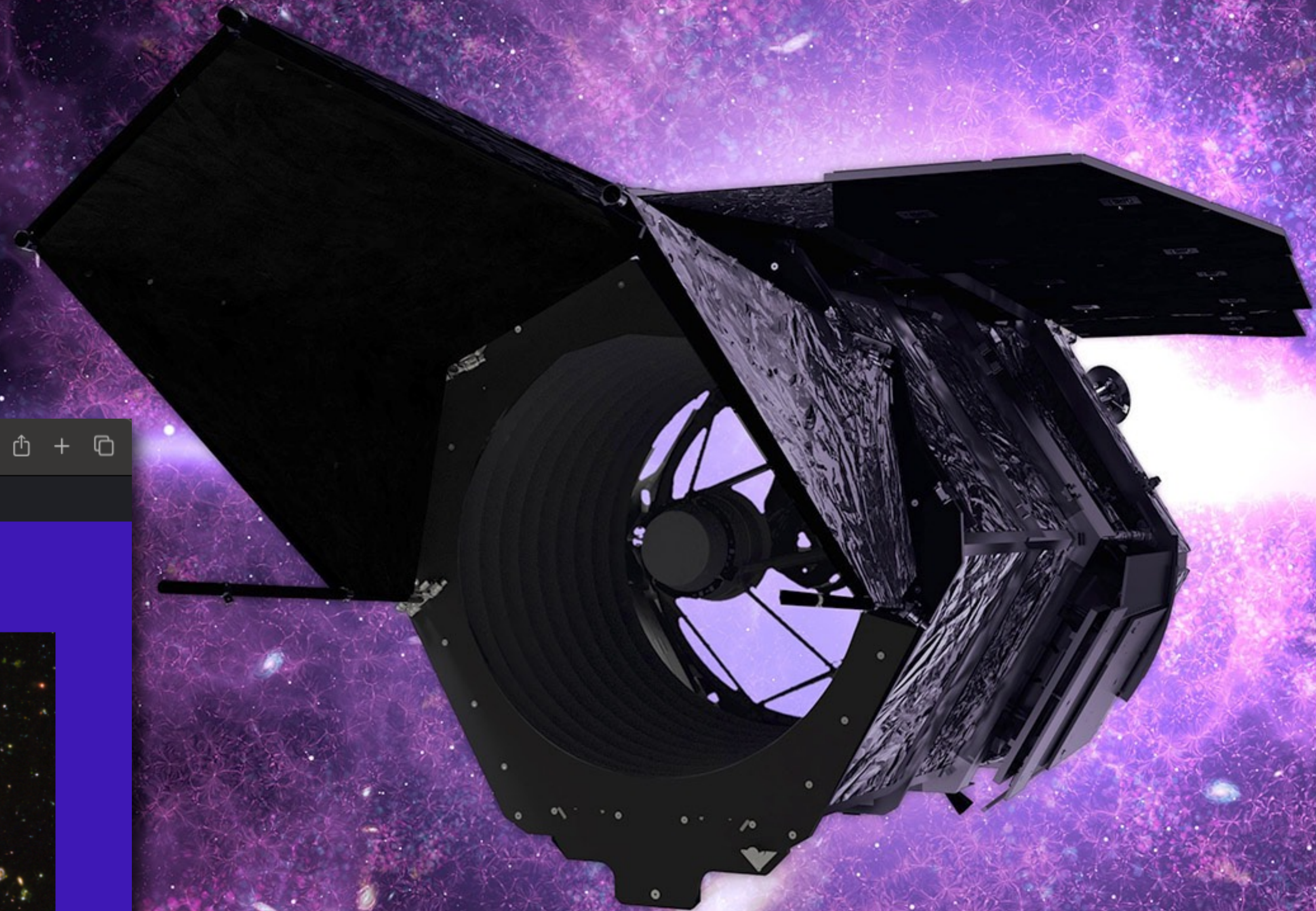
Carnegie Observatories

MockNYC, Flatiron Institute, January 13th 2026

Roman is coming soon!

Scheduled to launch by May 2027

Currently planned for launch on September 28th 2026



roman-grs-pit.caltech.edu

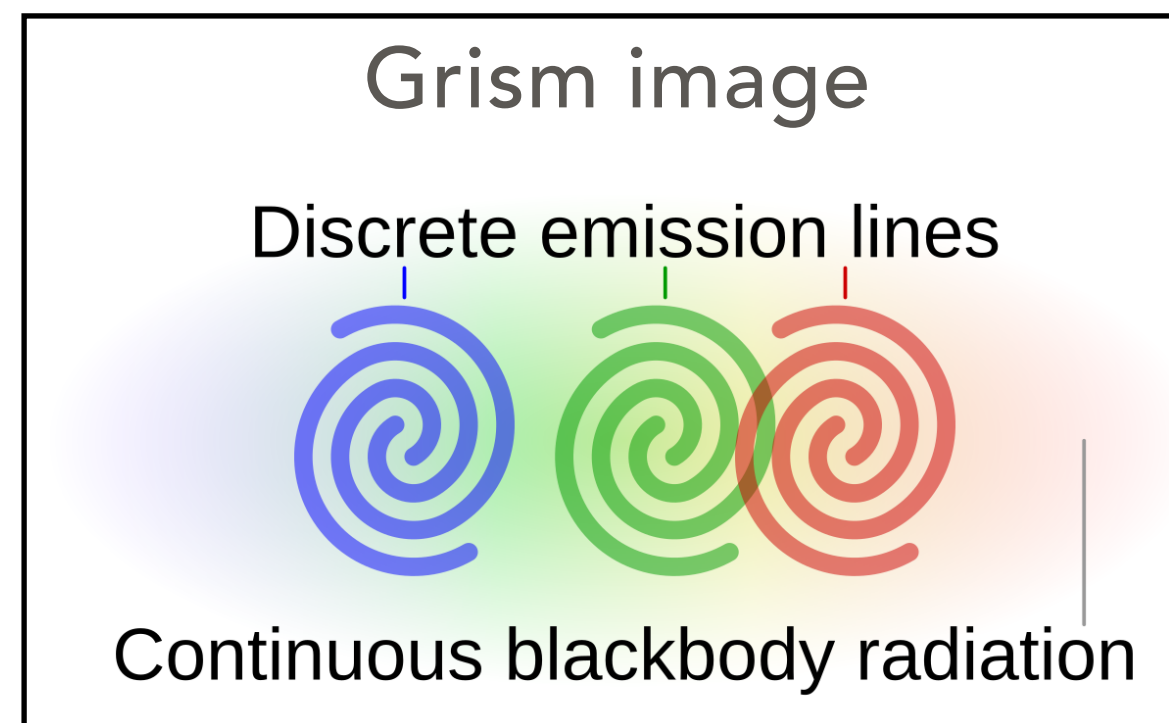
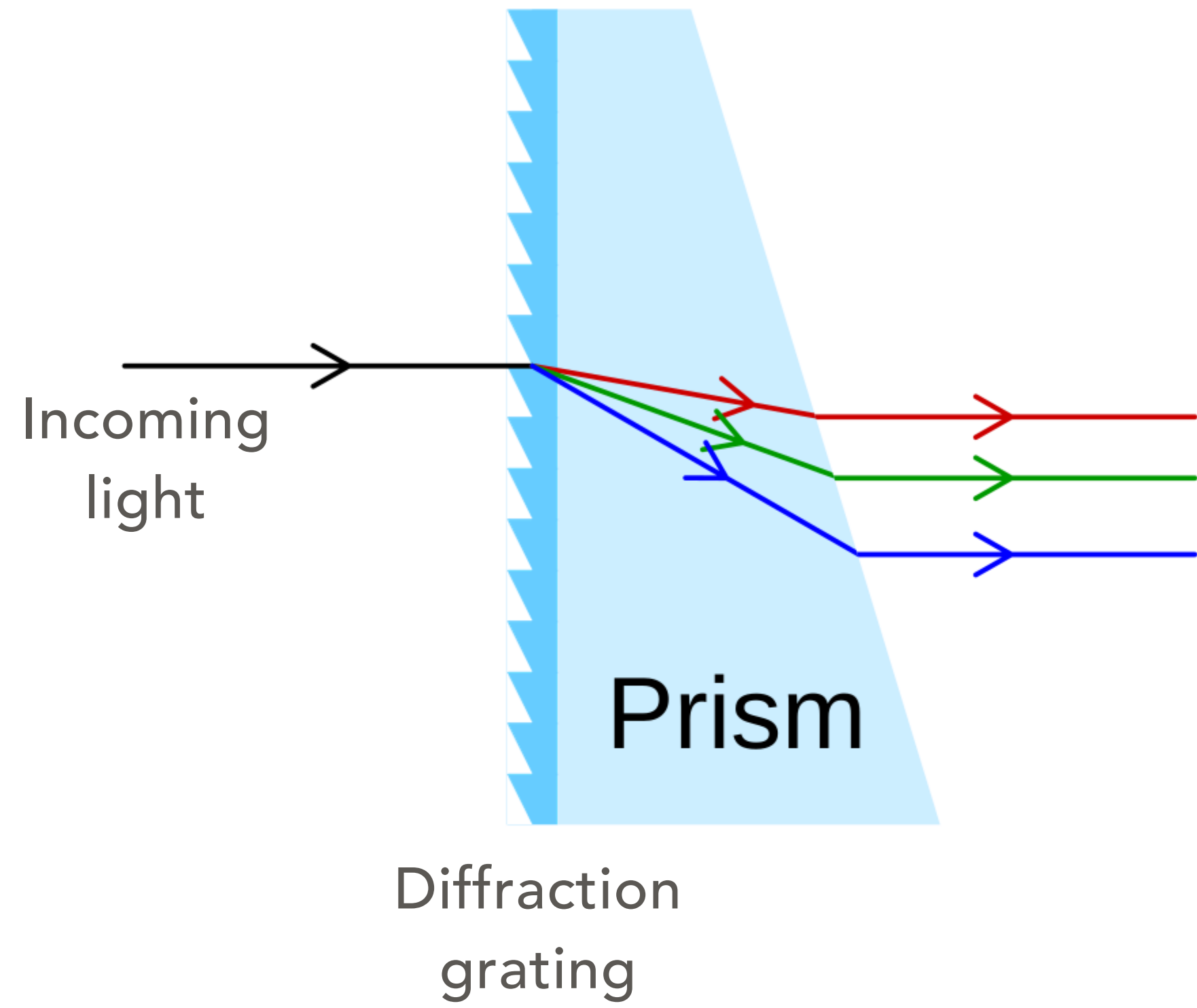
ipac

Roman GRS-PIT The Team Data Products Publications Code of Conduct Postdoc Positions Internal

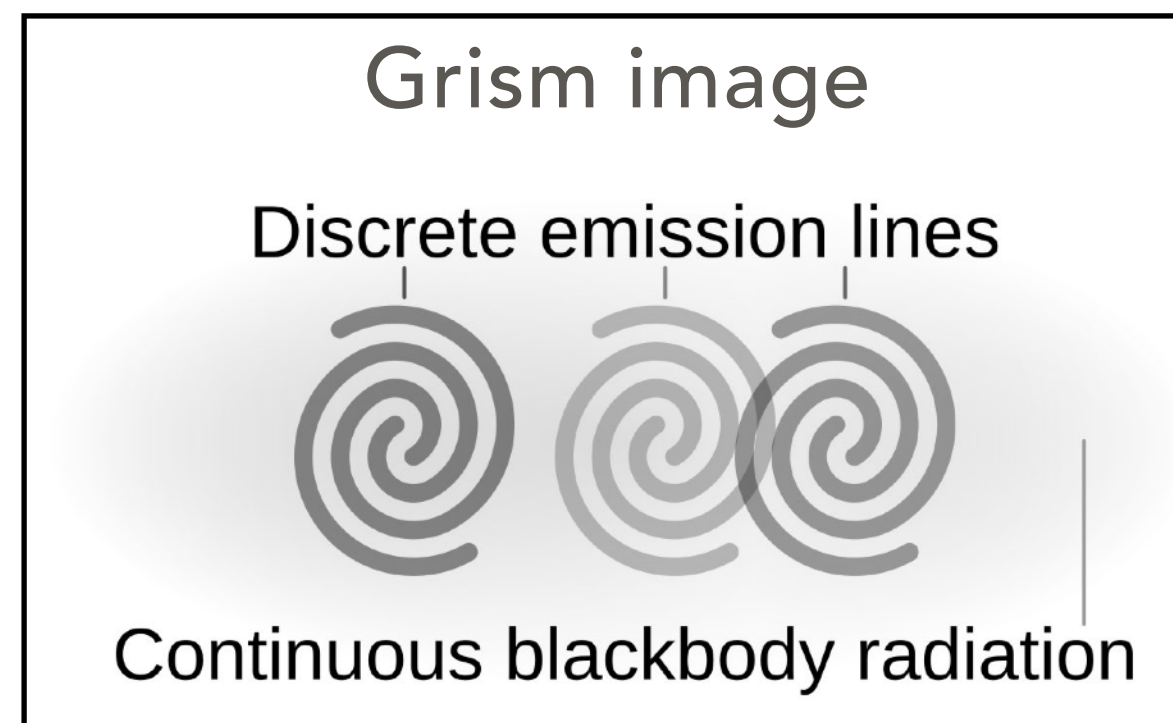
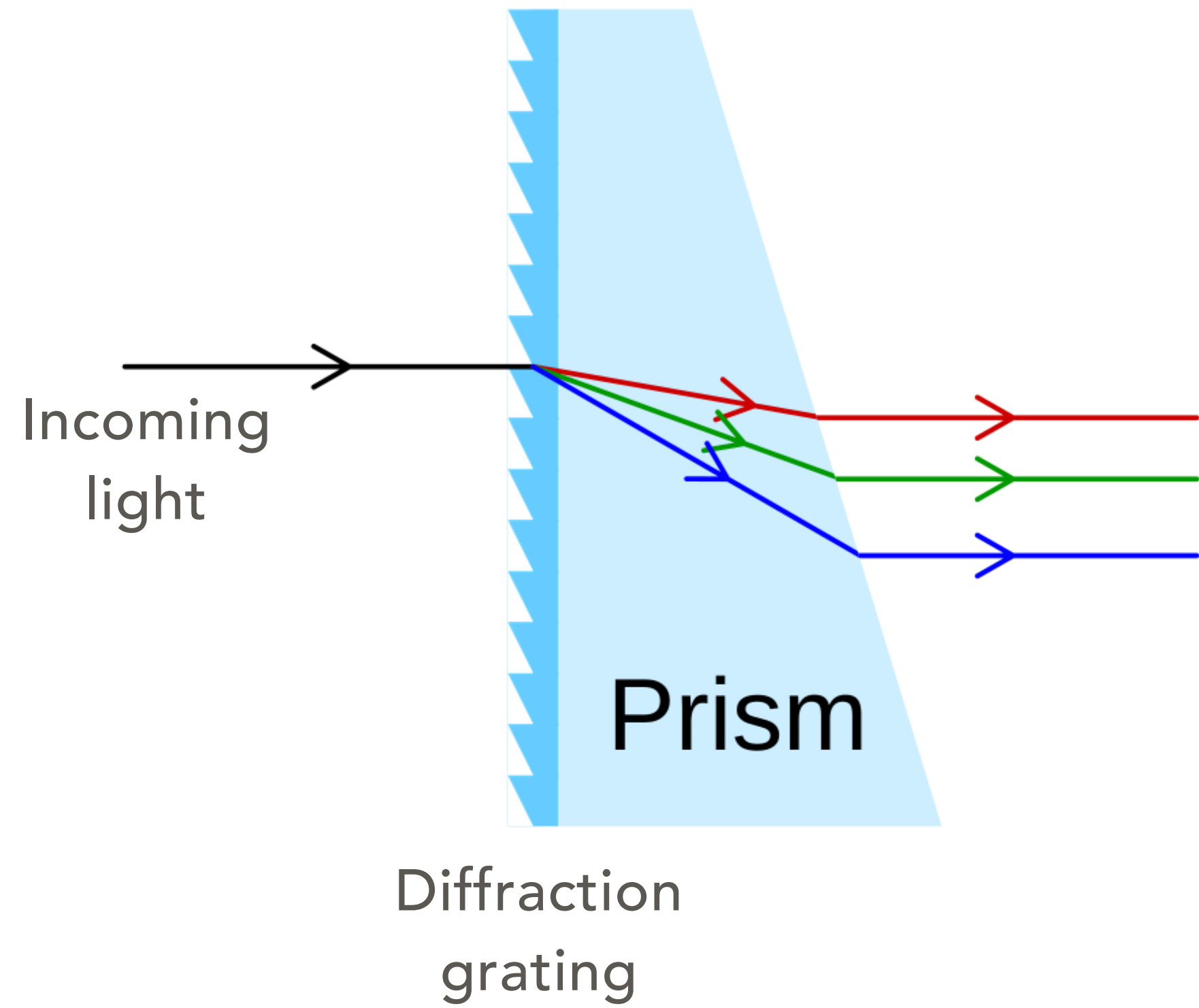
The Roman Galaxy Redshift Survey Project Infrastructure Team

The Nancy Grace Roman Space Telescope is NASA's next flagship mission in astrophysics. The Roman Galaxy Redshift Survey Project Infrastructure Team (GRS PIT) develops and maintains the infrastructural tools and capabilities needed to address the mission objective for the Roman GRS and to support community science collaborations. We work closely with the Roman project, and partner with the Science Centers, providing all necessary support to ensure mission success.

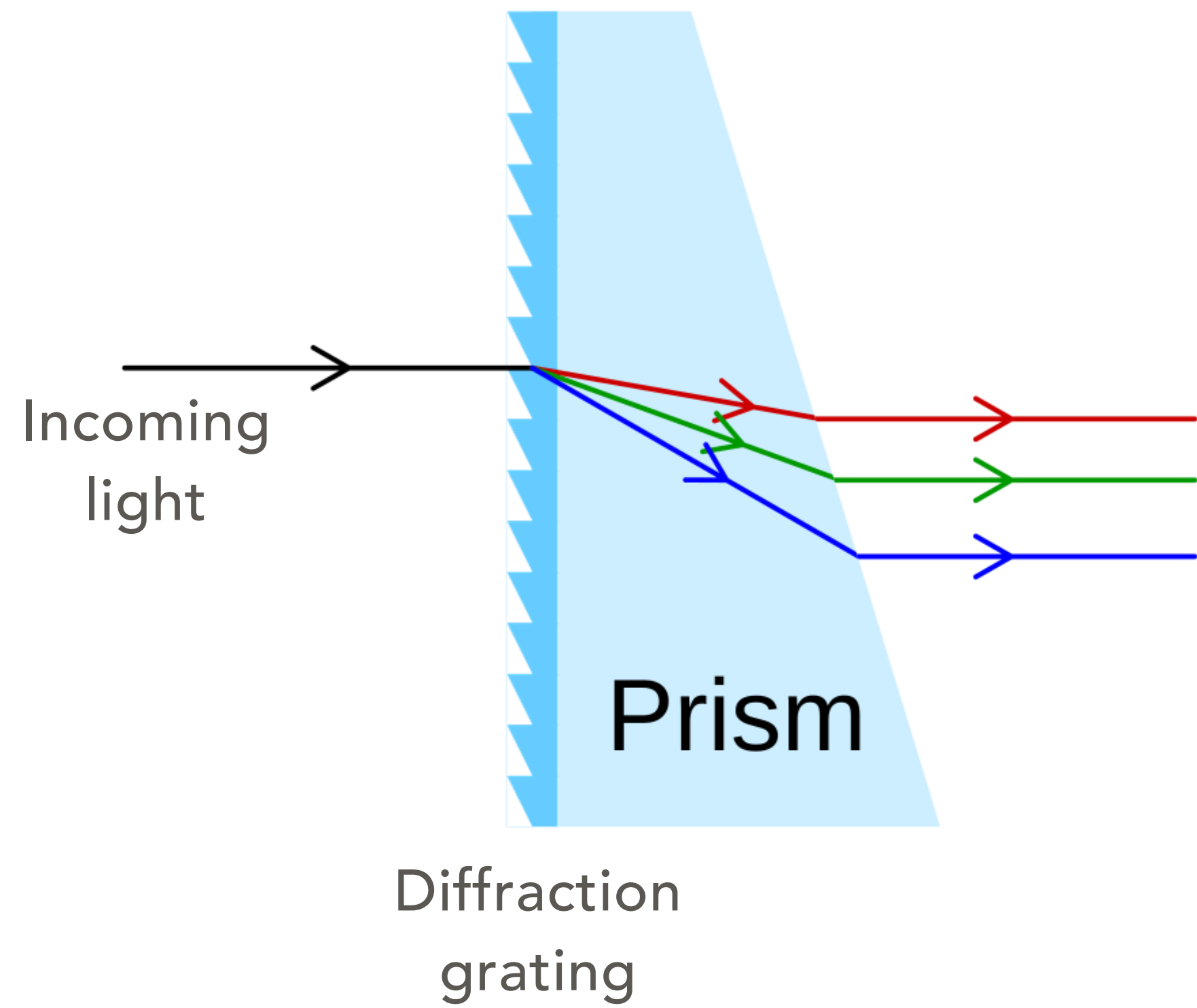
WHAT IS A GRISM?



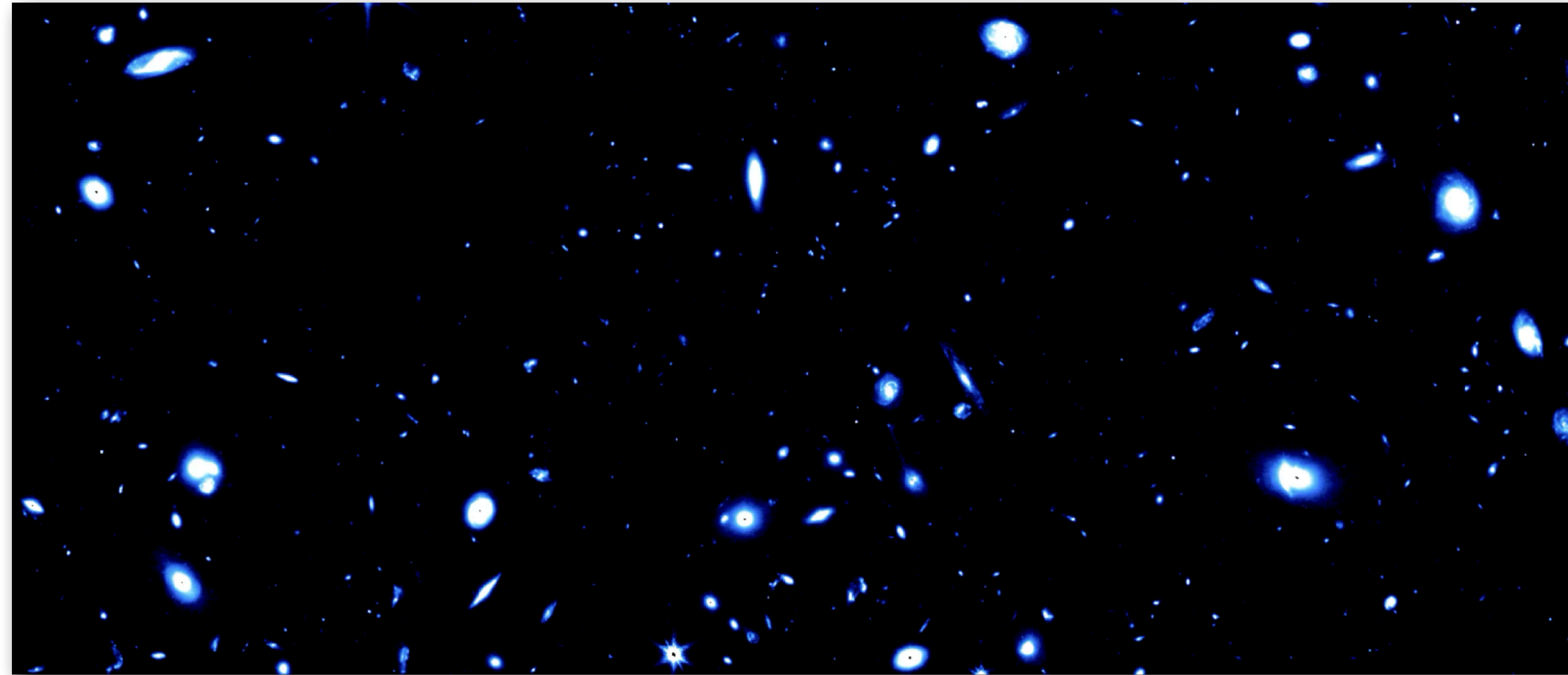
WHAT IS A GRISM?



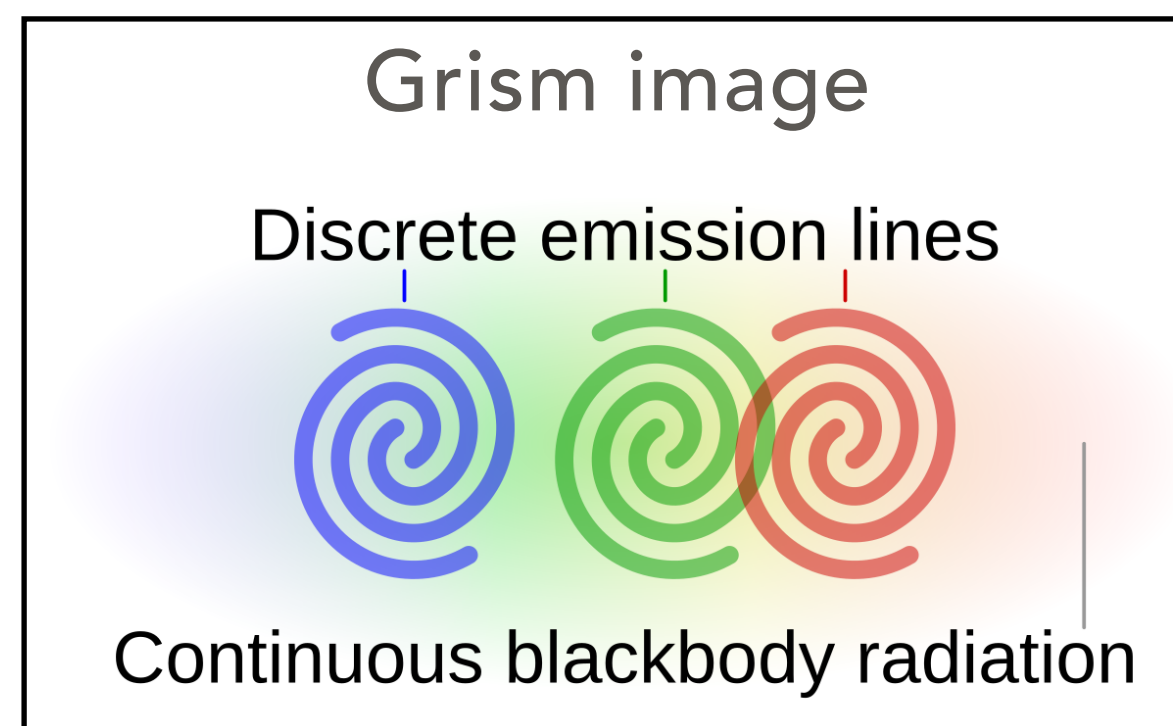
WHAT IS A GRISM?



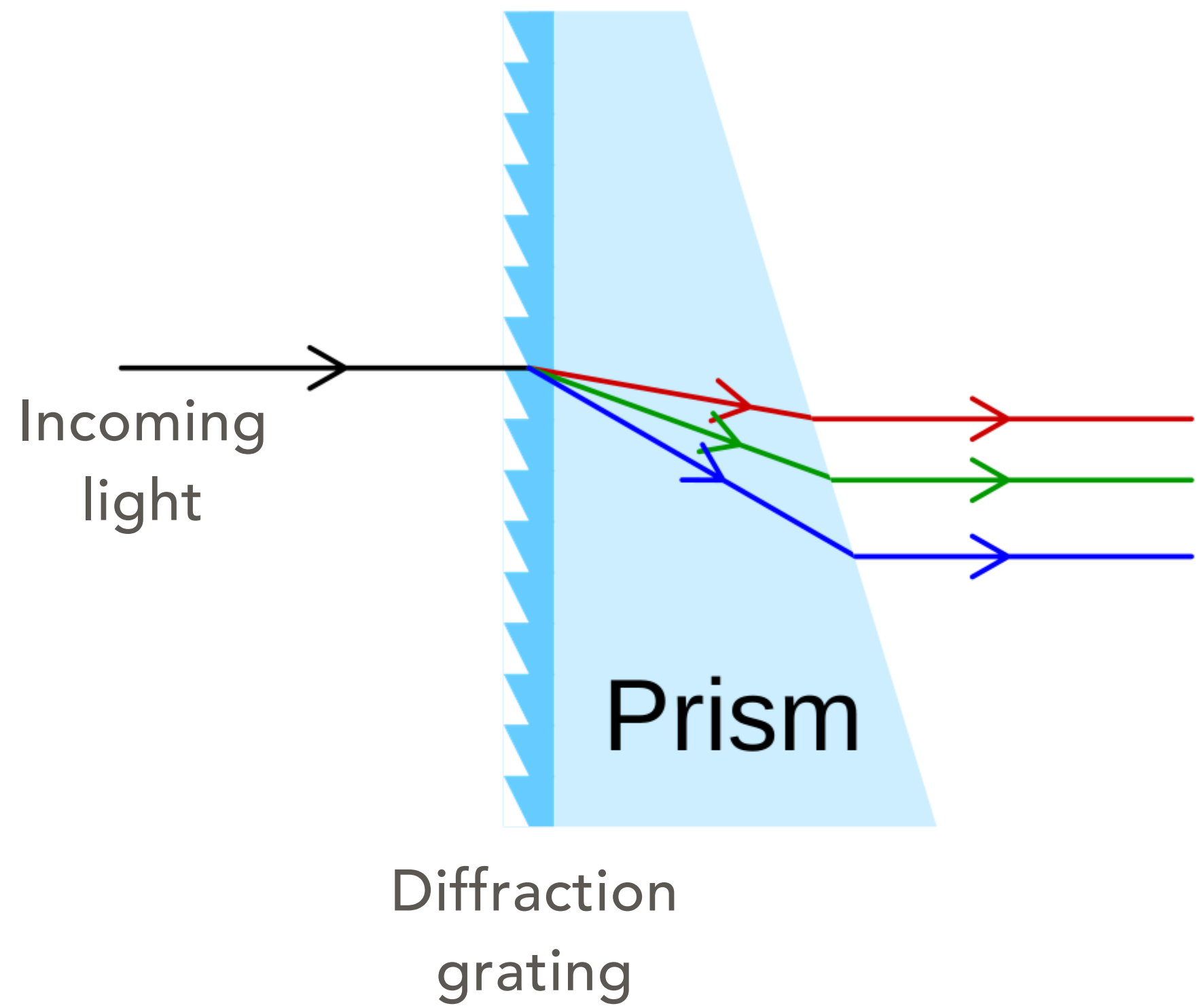
Direct image



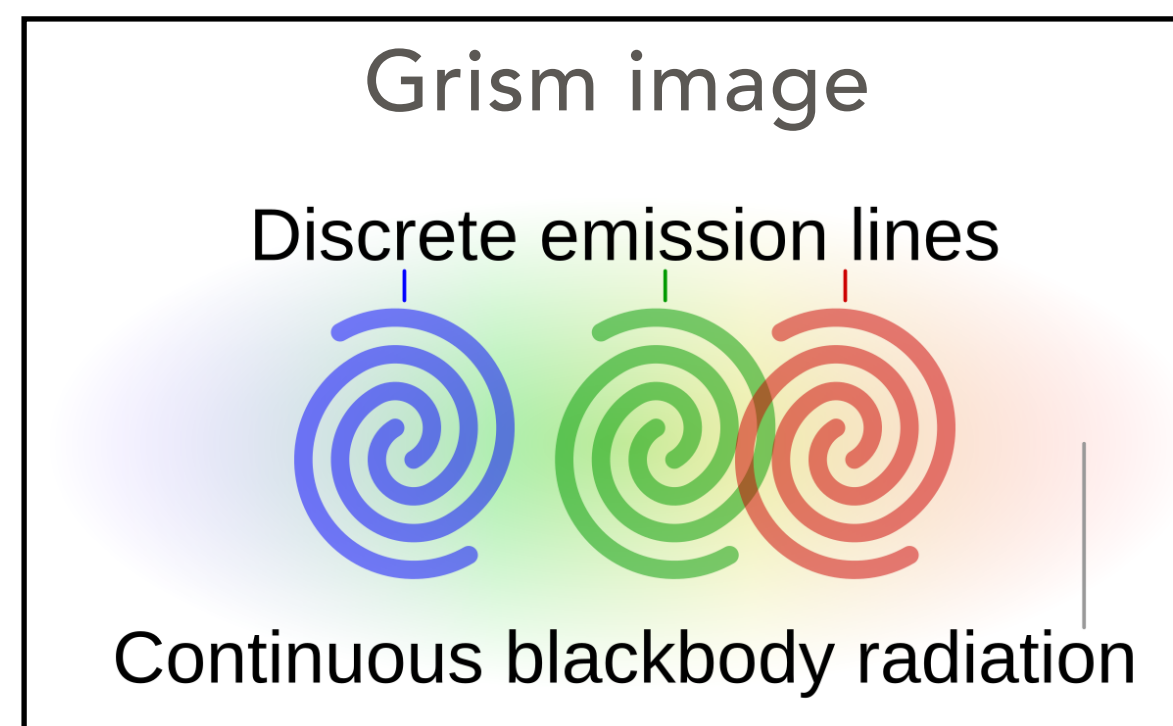
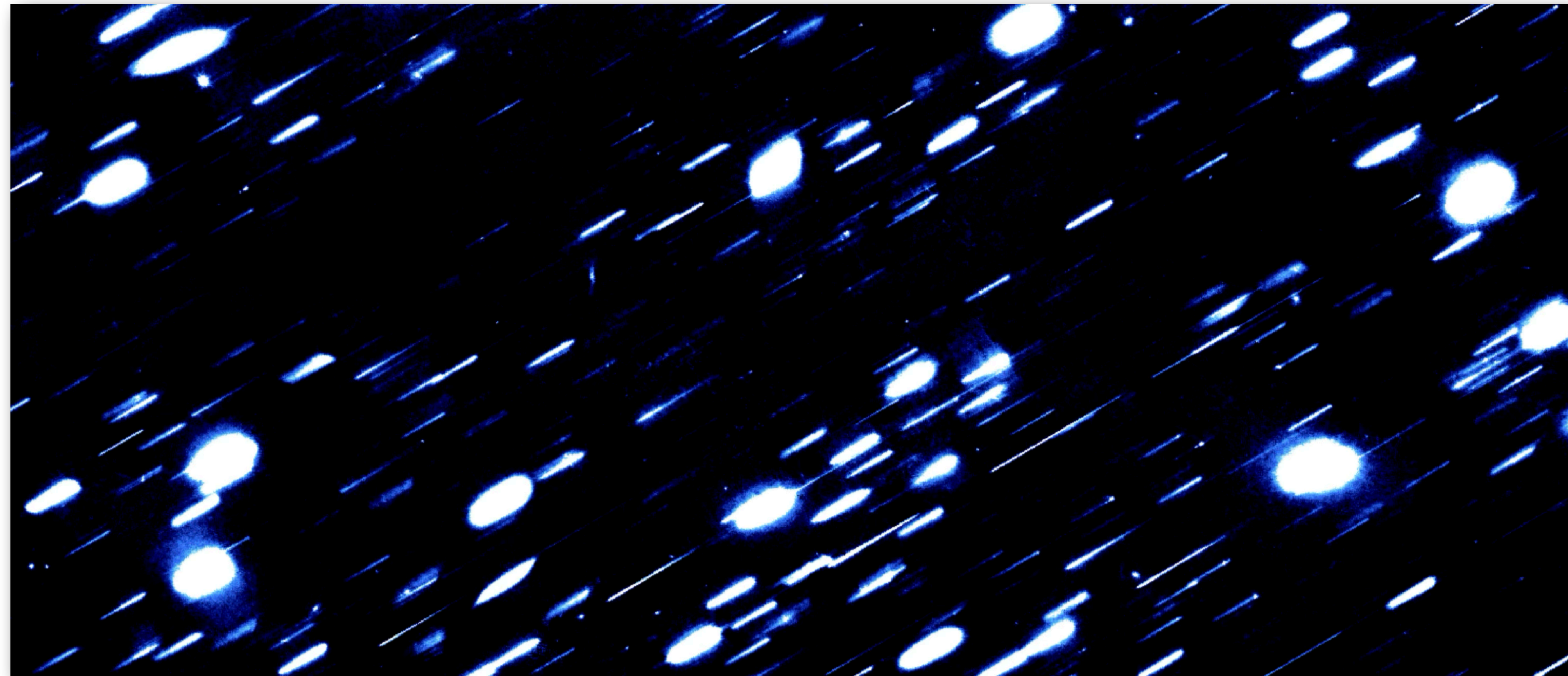
JWST/NIRISS
Kalina Nedkova



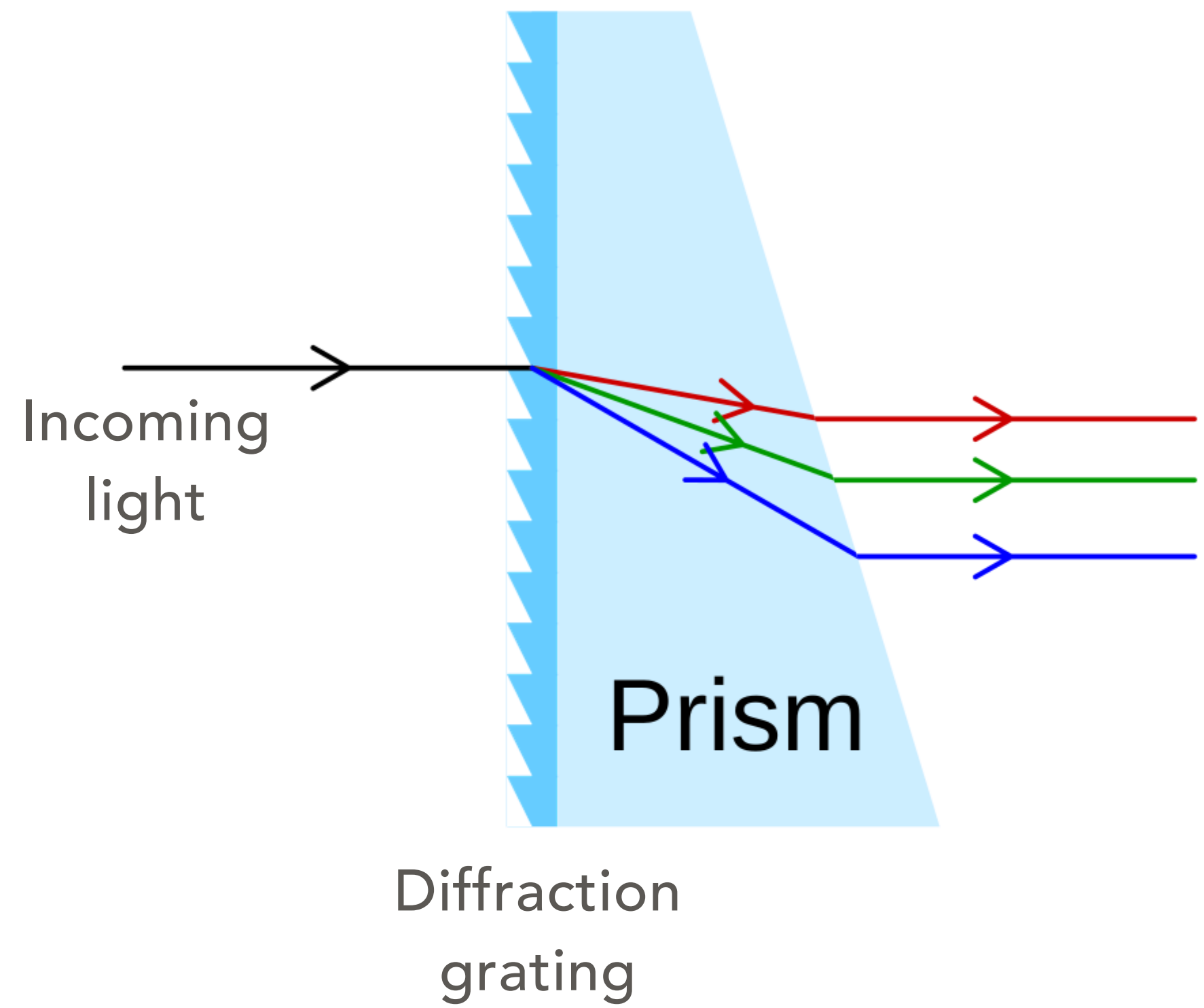
WHAT IS A GRISM?



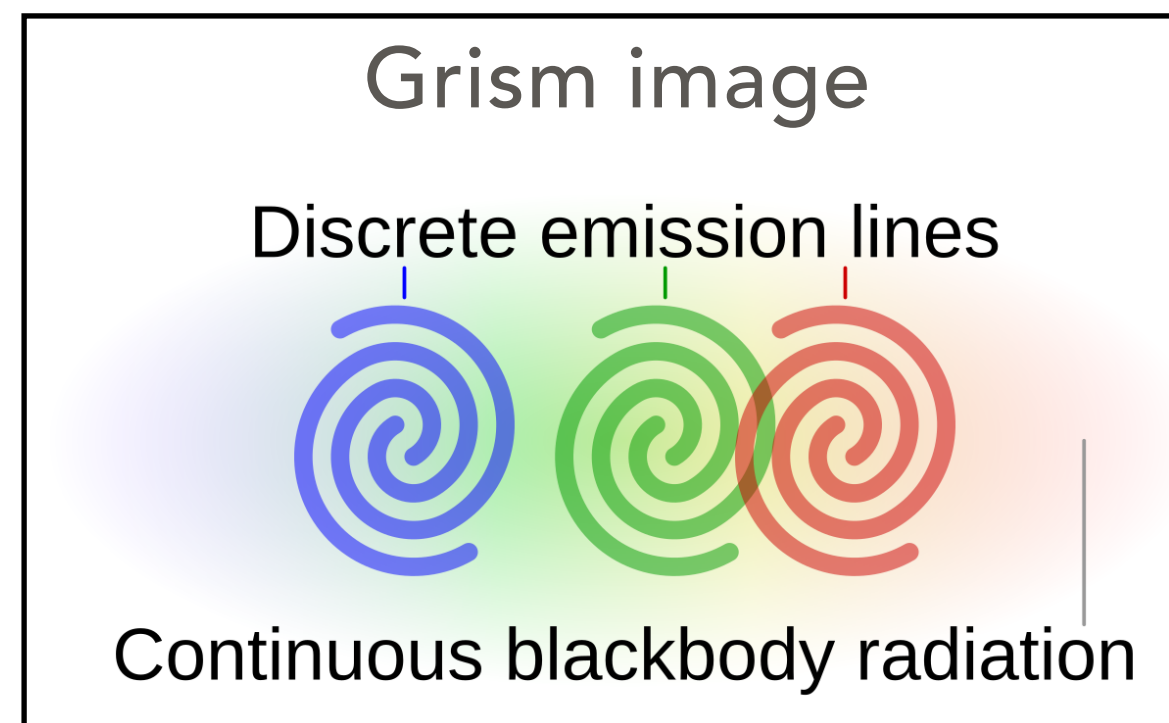
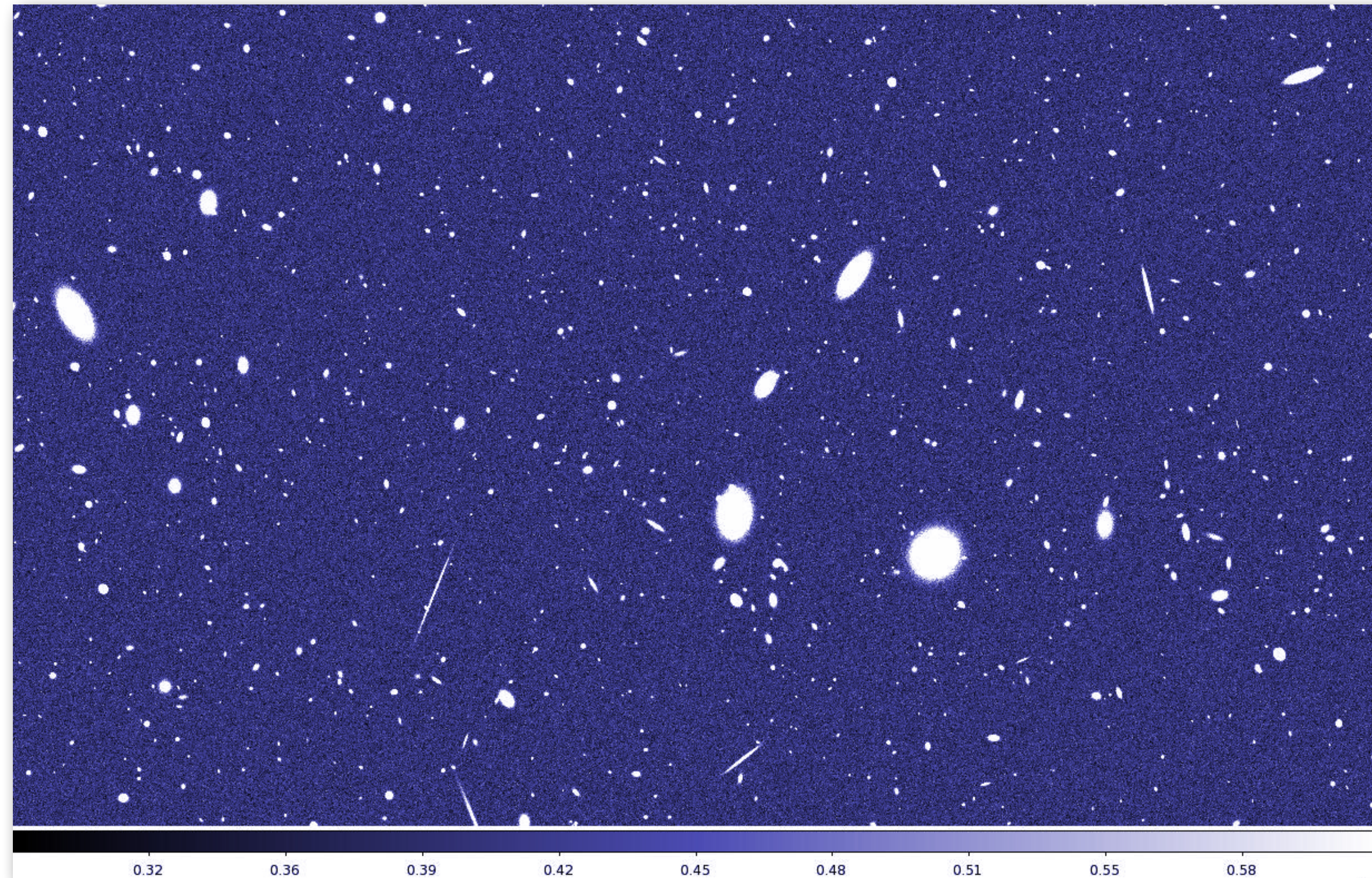
Grism image



WHAT IS A GRISM?

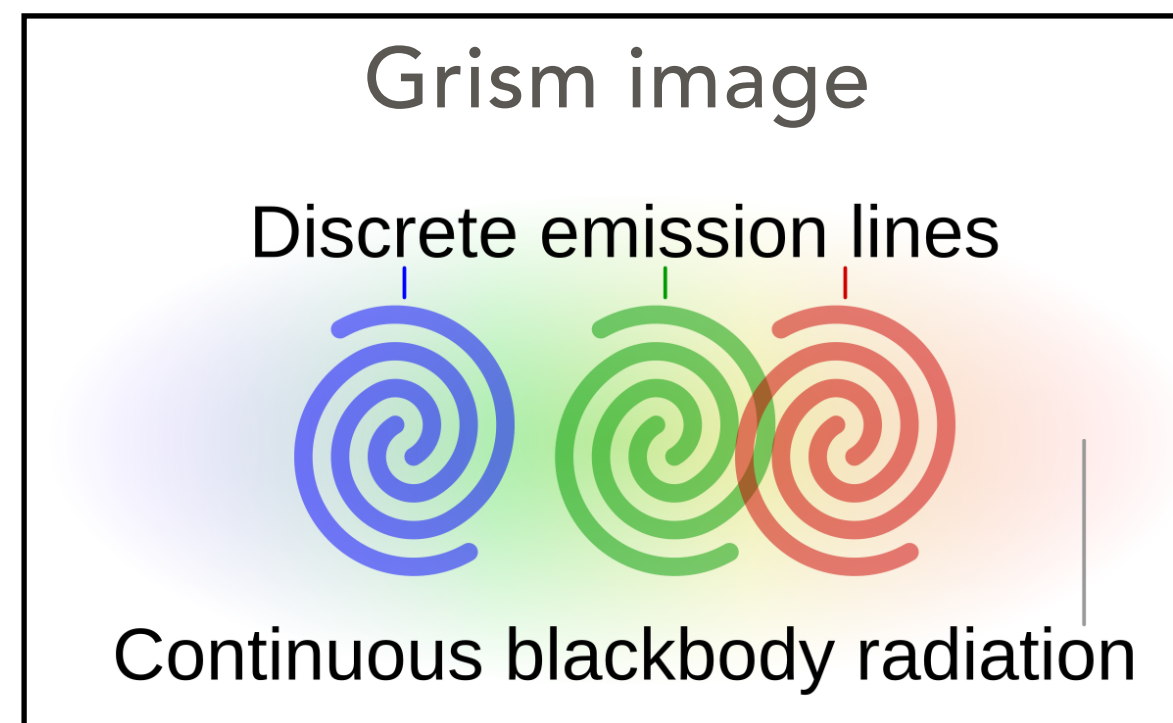
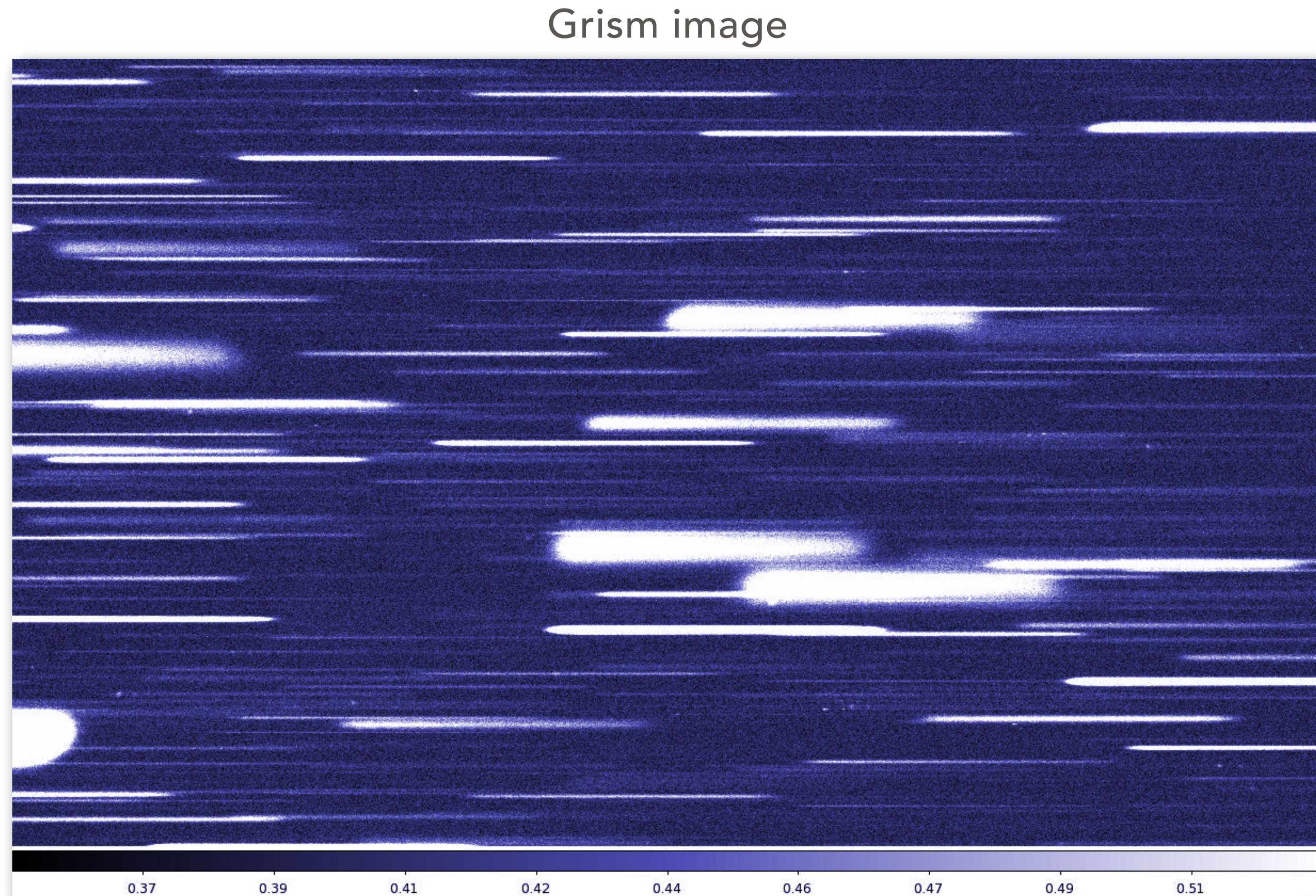
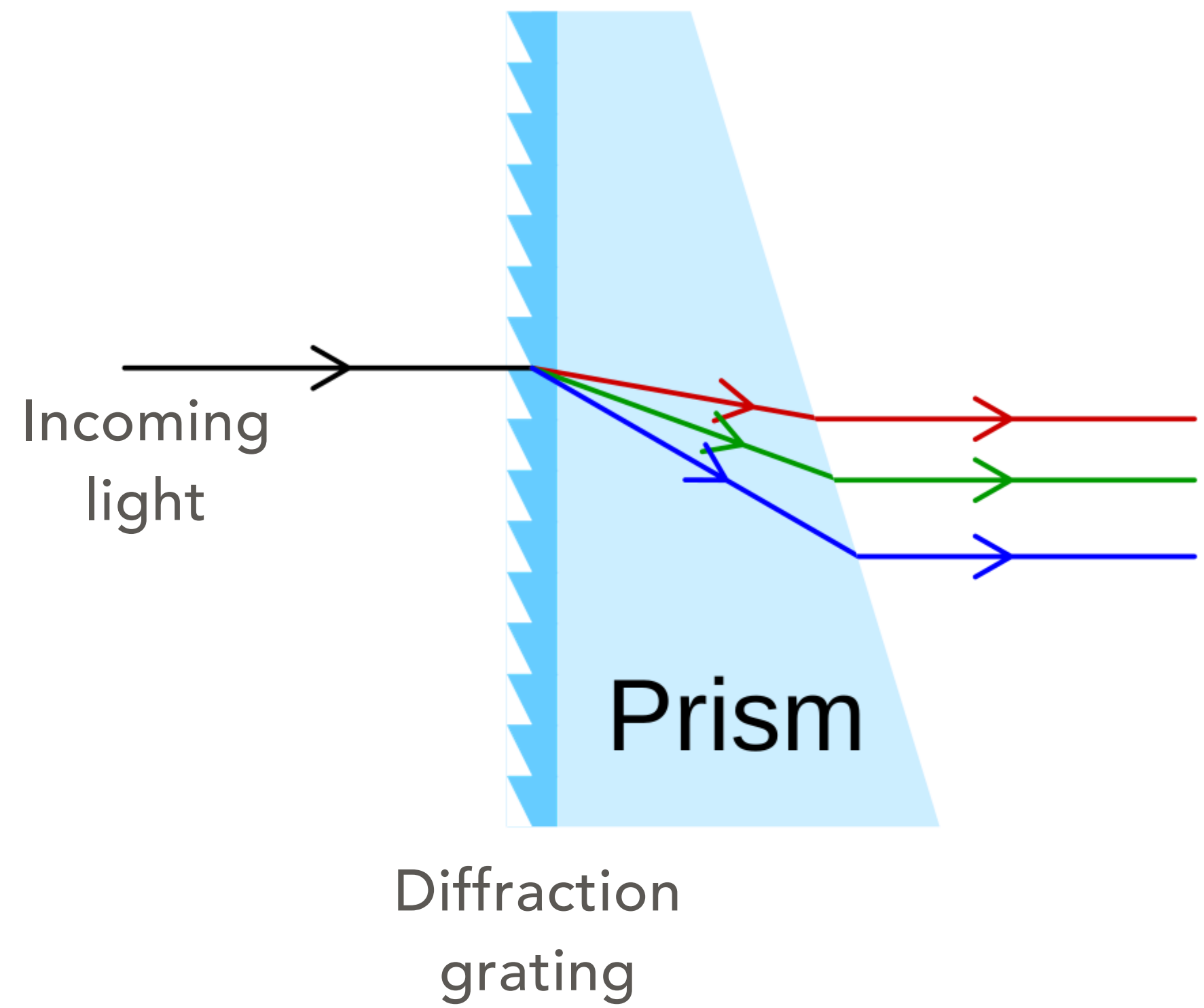


Direct image



Roman Simulation
IPAC/STScI/Goddard

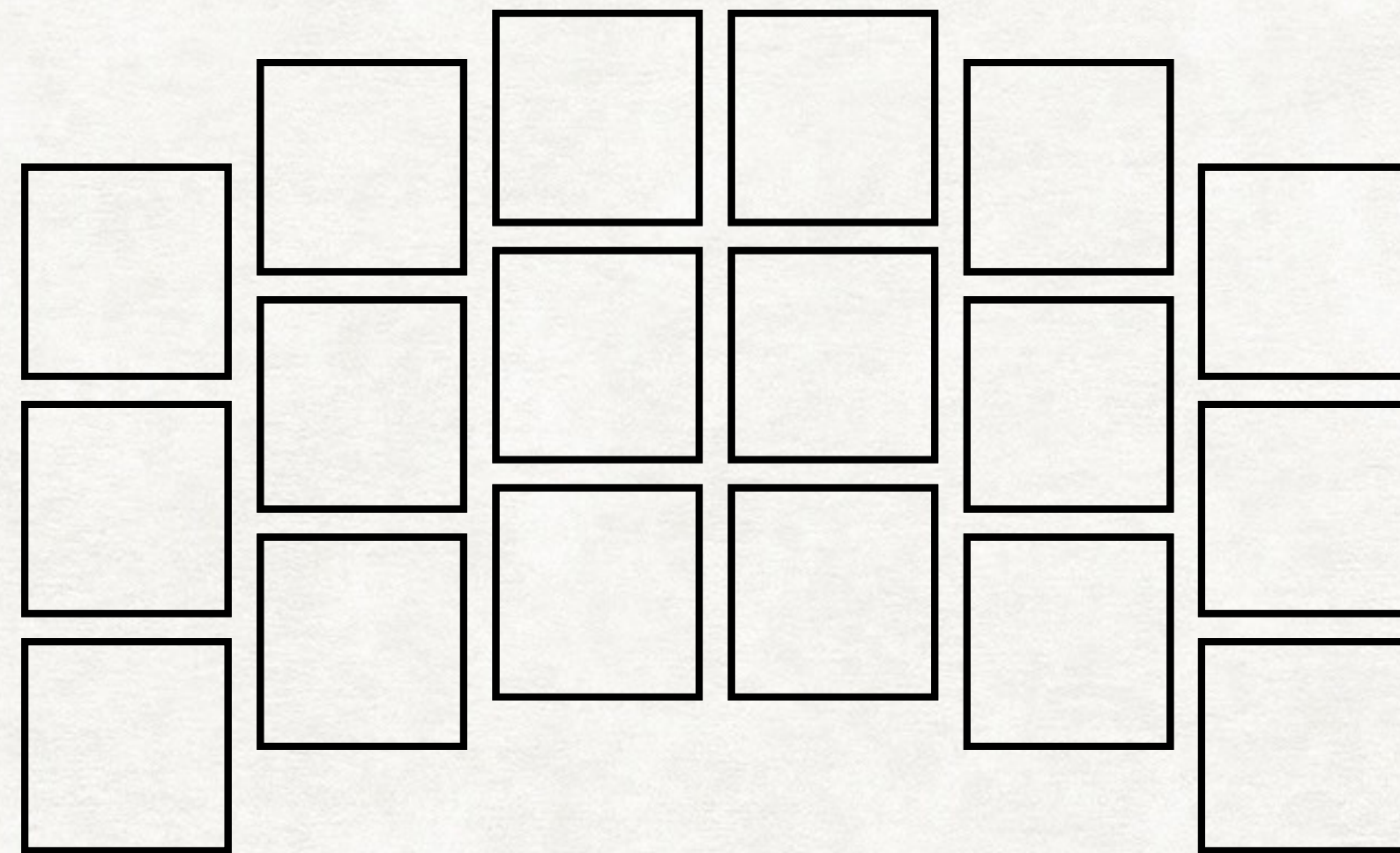
WHAT IS A GRISM?



Roman Simulation
IPAC/STScI/Goddard

STRATEGIES TO MITIGATE THIS

Survey Strategy



Analysis

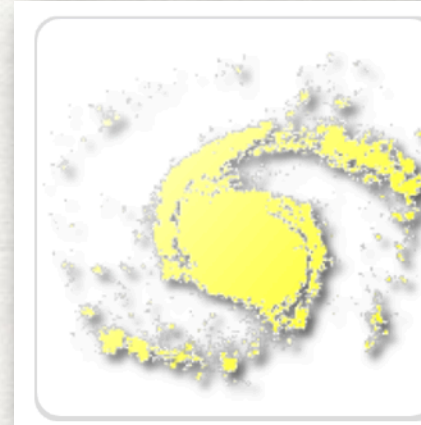
Probabilistic deblending

Model for problem with
nuisance parameters

Forward model
everything!

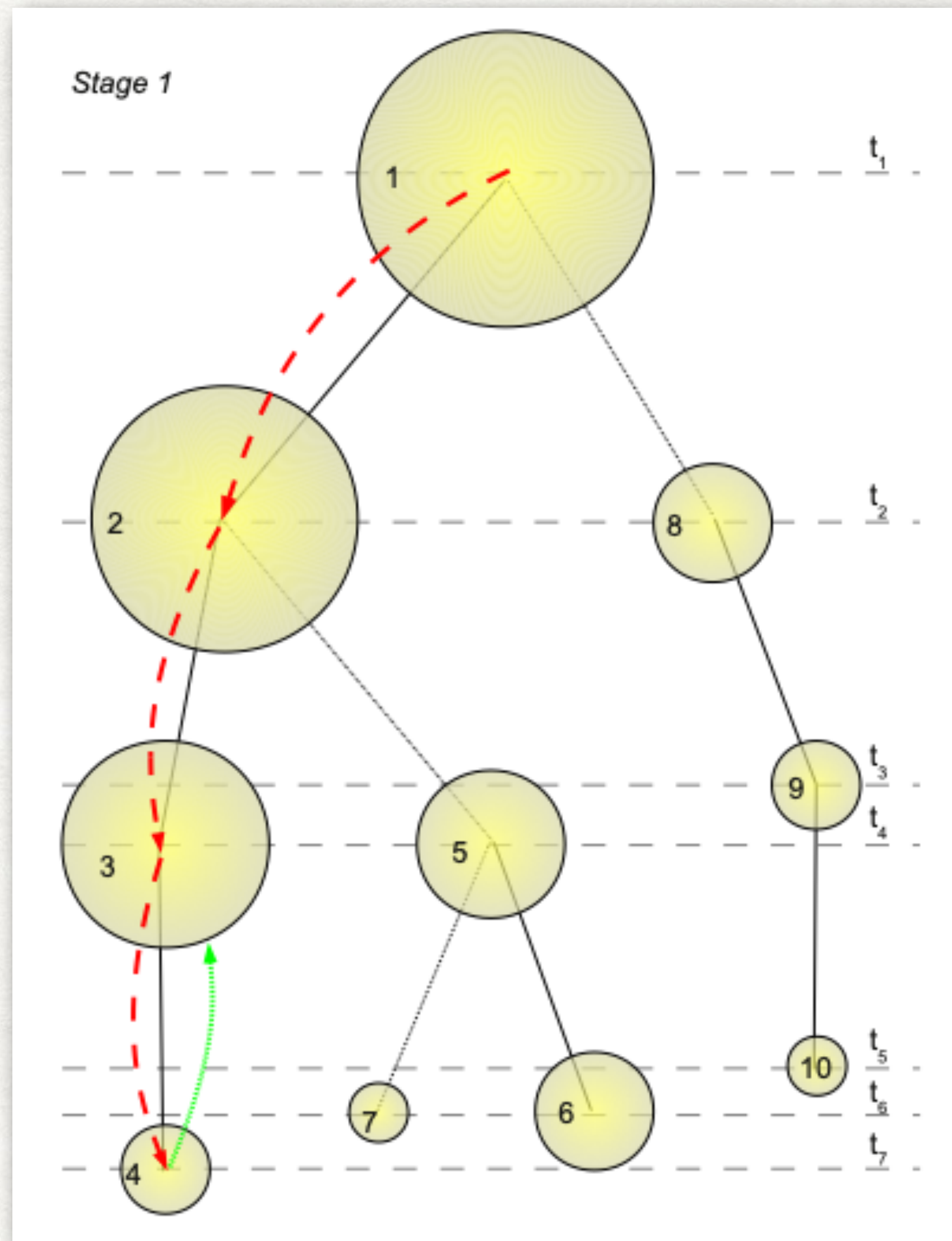
**WE WANT TO TEST THESE
ON REALISTIC MOCKS!**

WHAT IS A SEMI-ANALYTIC MODEL?



Galacticus

The Galacticus galaxy formation model



- Populates dark matter halos (e.g. from a dark matter only simulation) with galaxies
- Takes as input the "merger tree" for each halo
- Evolves a set of differential equations for the "movement" of baryons within galaxies (+prescriptions for galaxy mergers)
- An example: gas outflows from disk due to stellar feedback

Circular velocity

Rate of gas outflow

$$\dot{M}_{\text{outflow}} = \left(\frac{V_{\text{circ}}}{V_{\text{outflow}}} \right)^{\alpha} \dot{M}_{\star}$$

Star formation rate

power-law exponent controlling circular velocity (~ halo mass) dependence of feedback efficiency

Free parameters

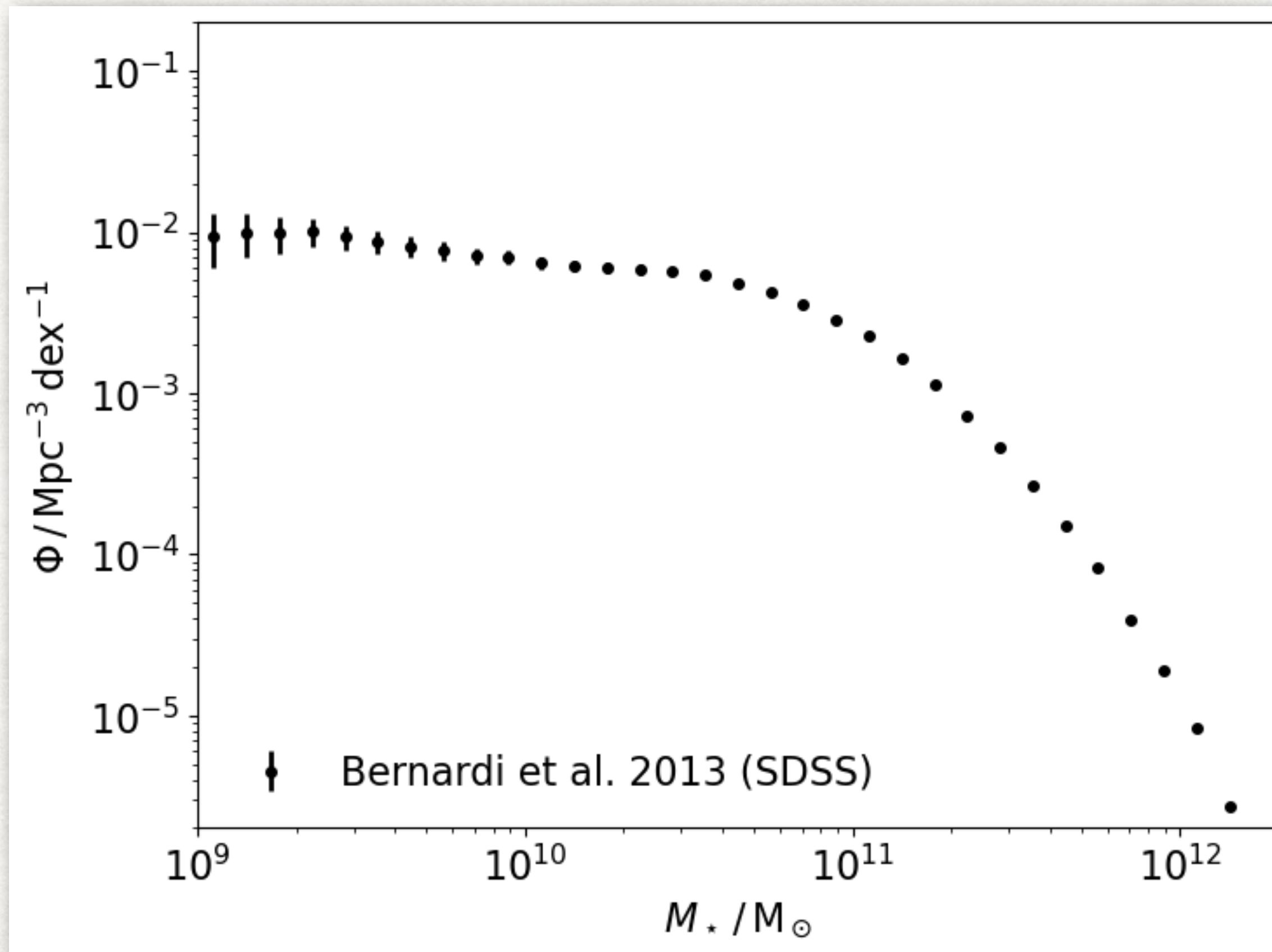
Characteristic circular velocity associated with outflows

"CALIBRATING" A SEMI-ANALYTIC MODEL

- Decide which observable(s) to try and match
- For a given set of model parameters, simulate a population of galaxies, calculate the relevant observables and compare
- Update the model parameters to try and improve the match between model and data

EXAMPLE

- low-redshift stellar mass function

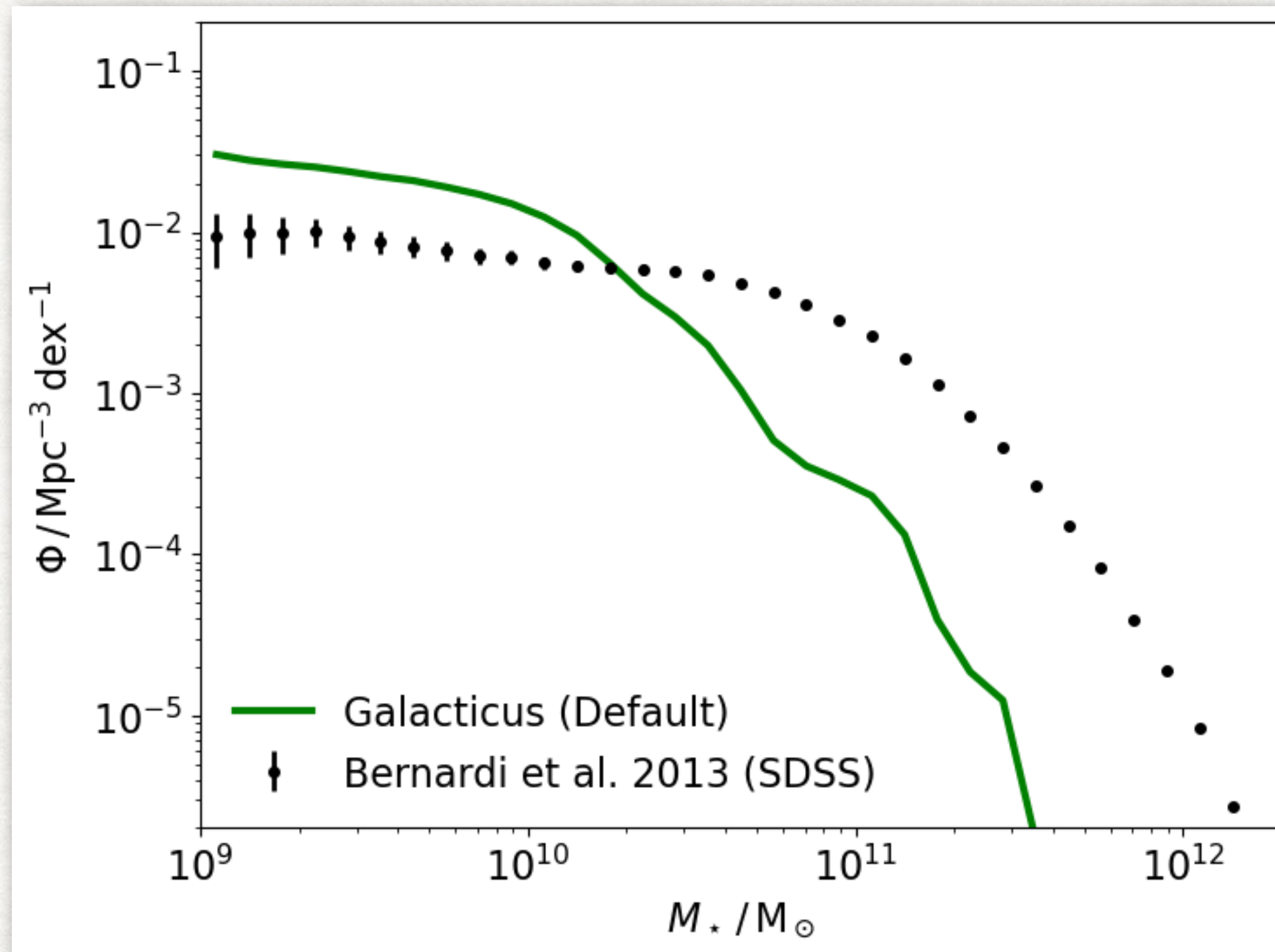


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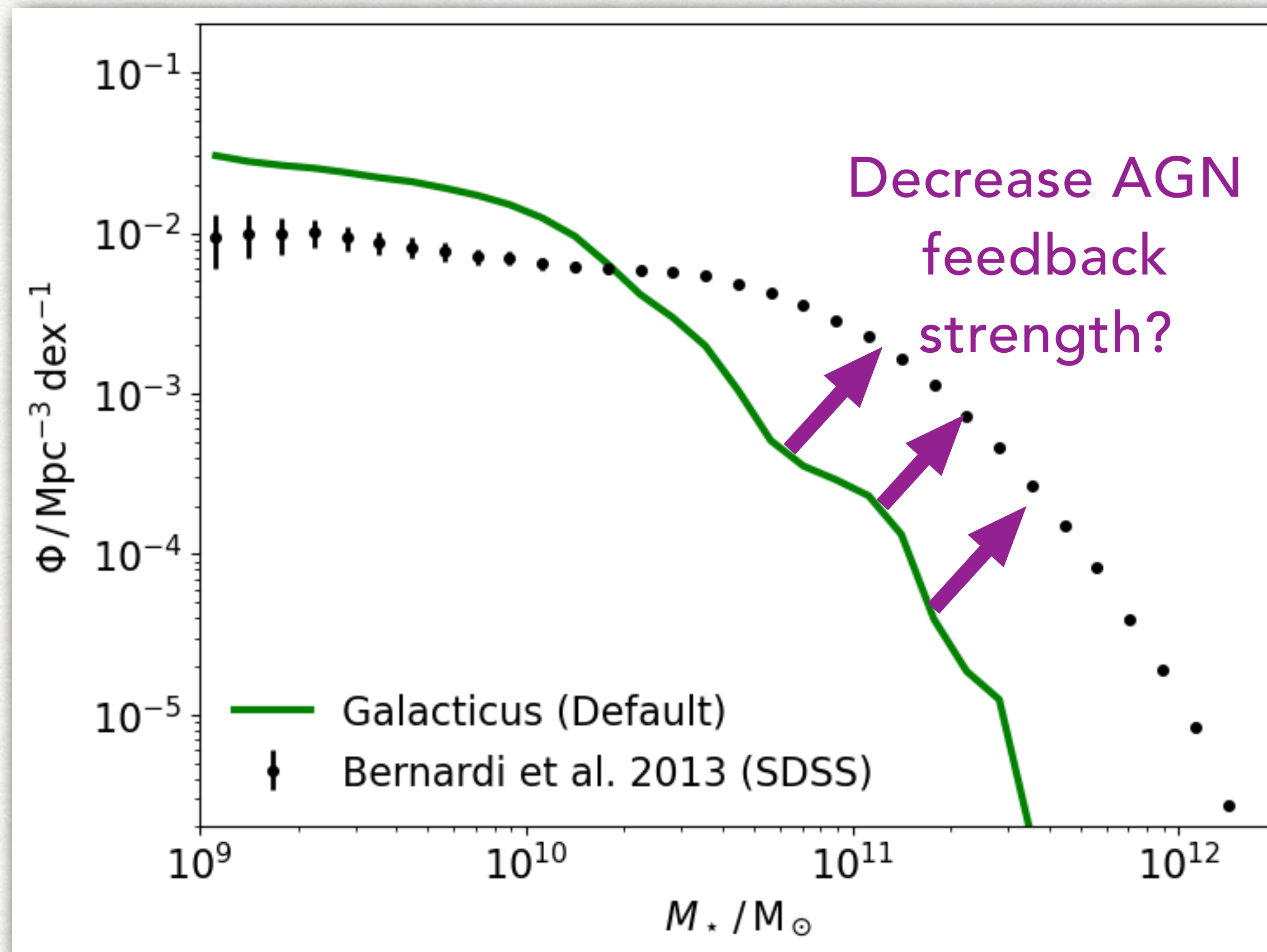


"CALIBRATING" A SEMI-ANALYTIC MODEL

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EXAMPLE

- low-redshift stellar mass function
- could make an informed guess about how to change the parameters

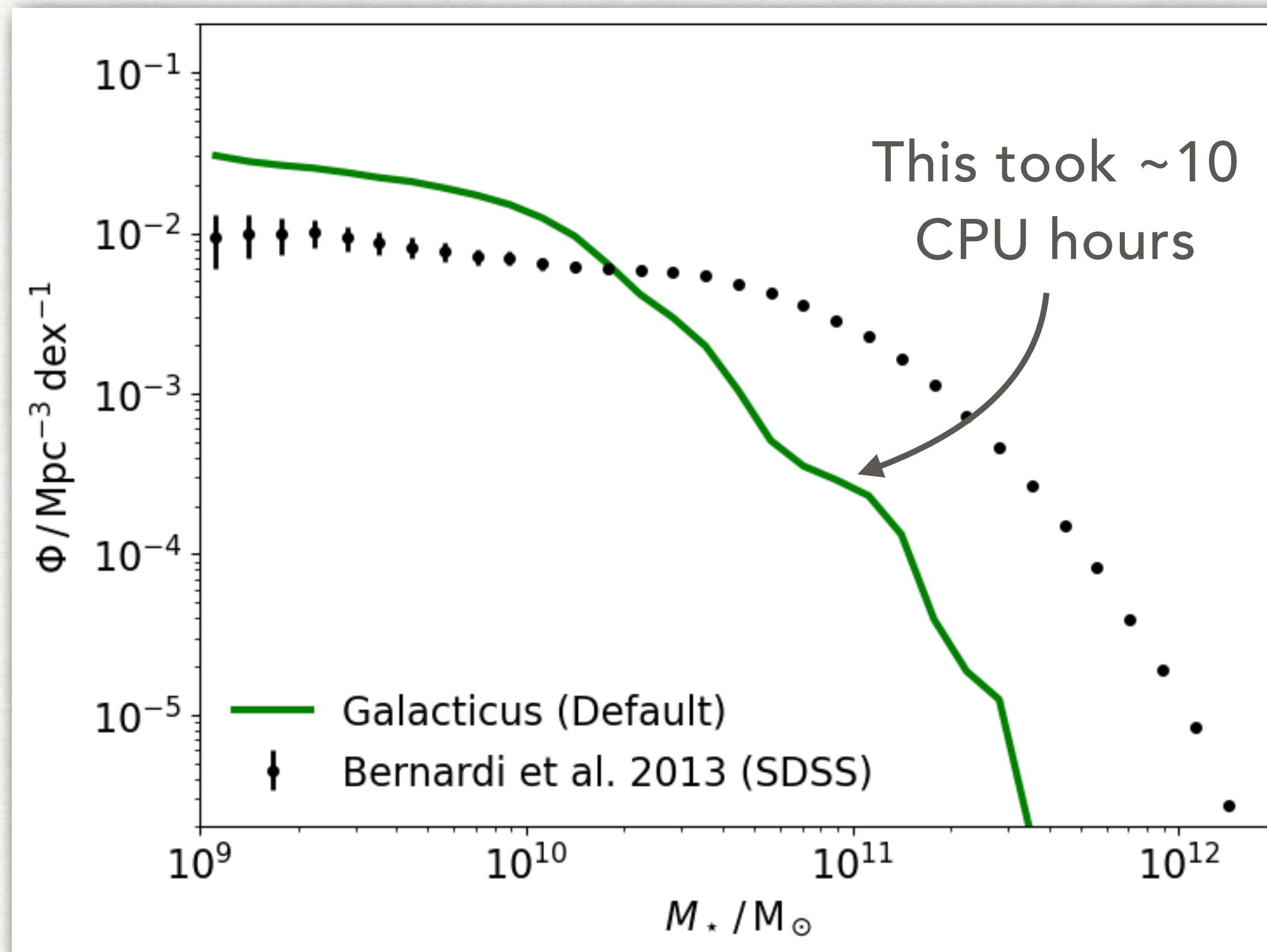


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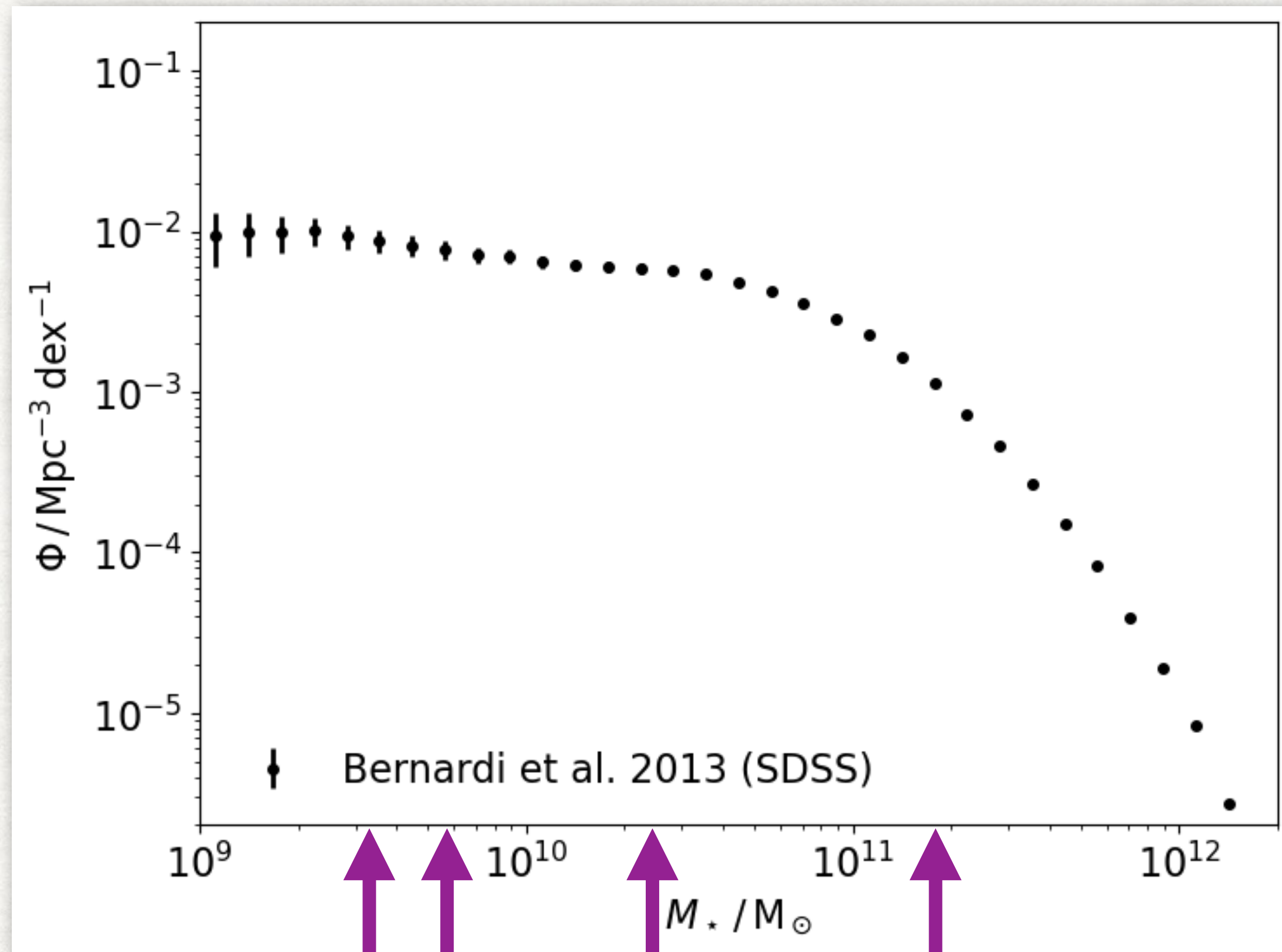
EXAMPLE

- low-redshift stellar mass function
- could make an informed guess about how to change the parameters
- but really we want something automated



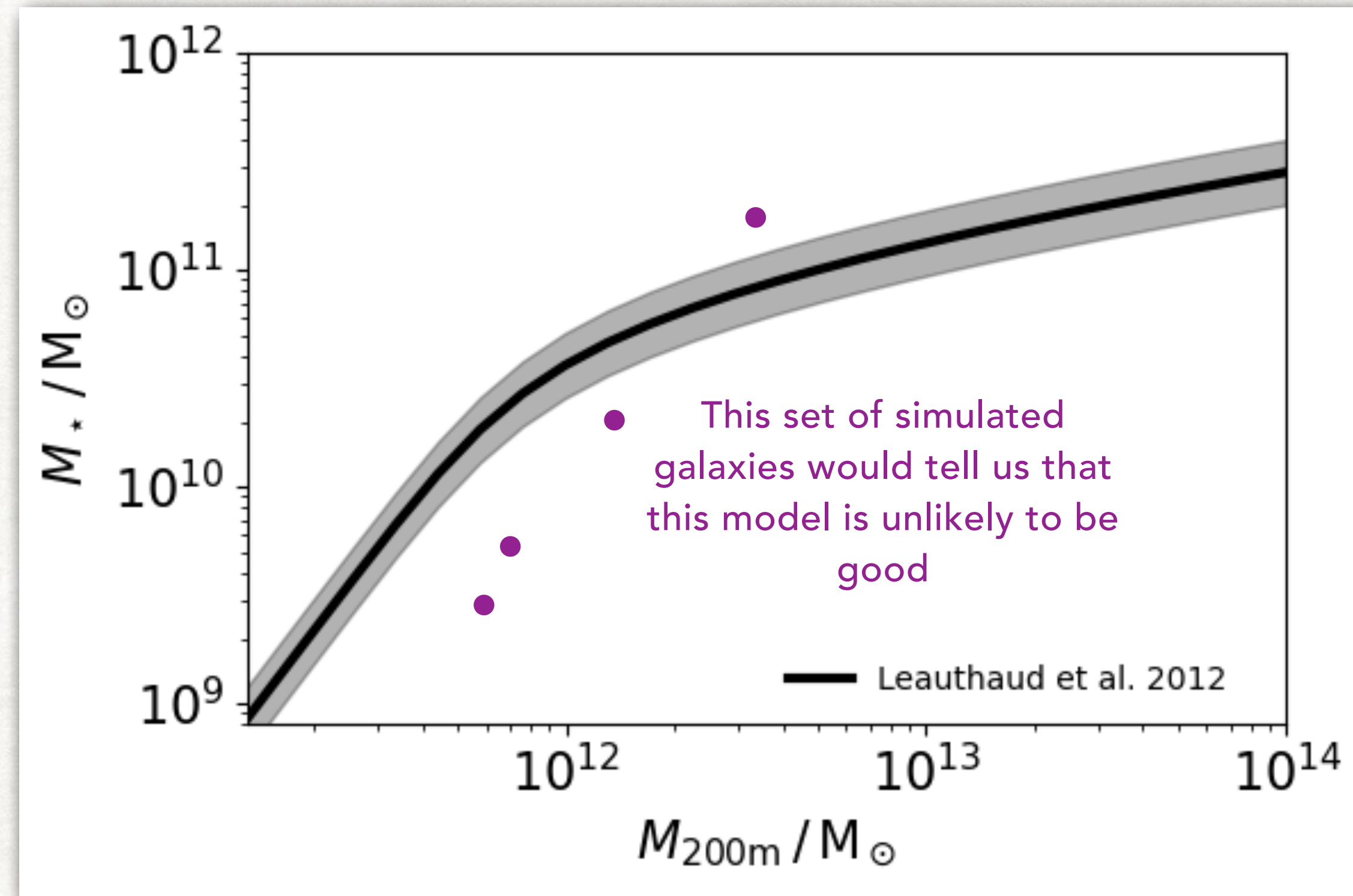
HOW TO SPEED UP A LIKELIHOOD EVALUATION?

- Simple! Just simulate fewer galaxies...



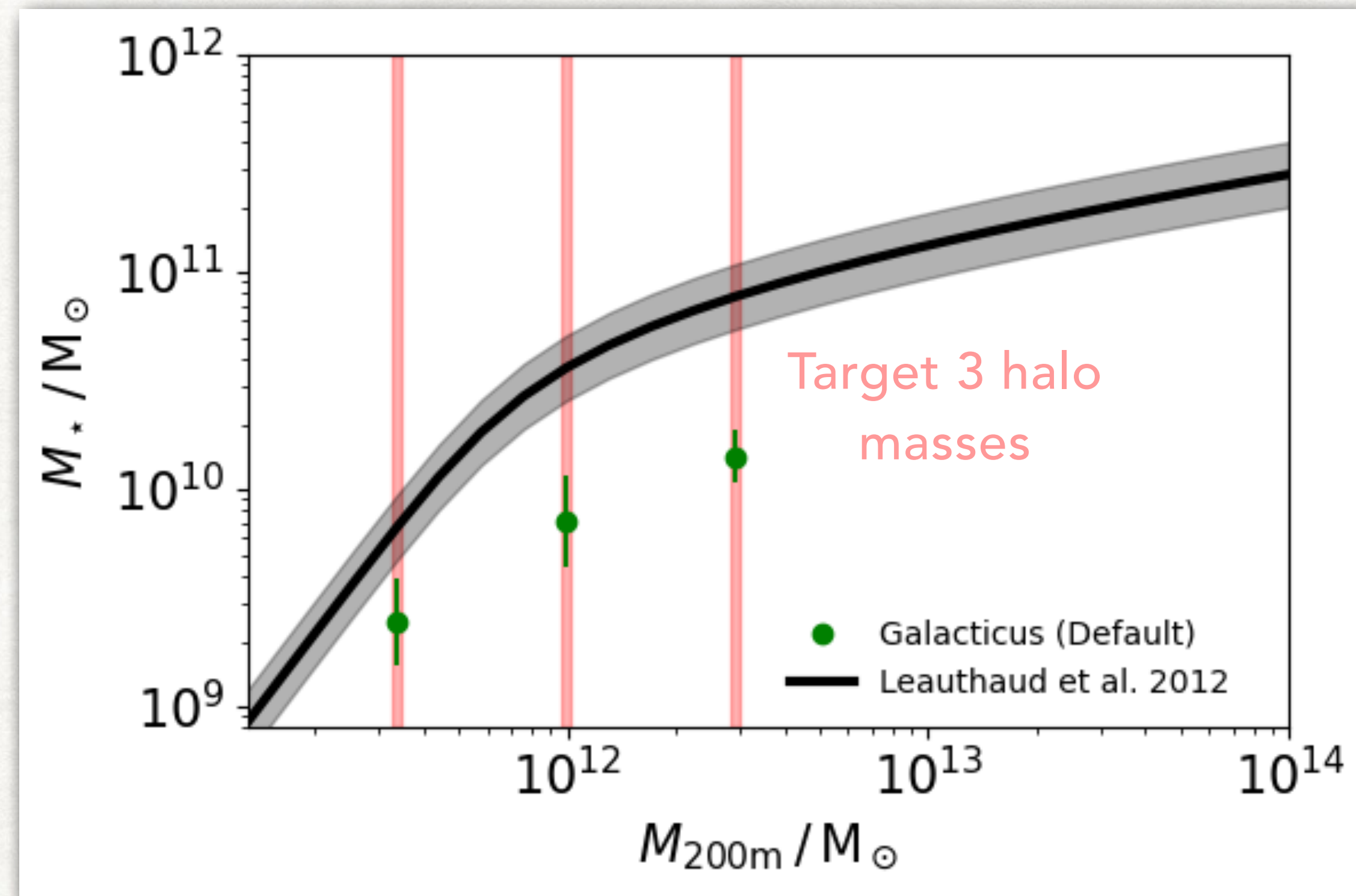
HOW TO SPEED UP A LIKELIHOOD EVALUATION?

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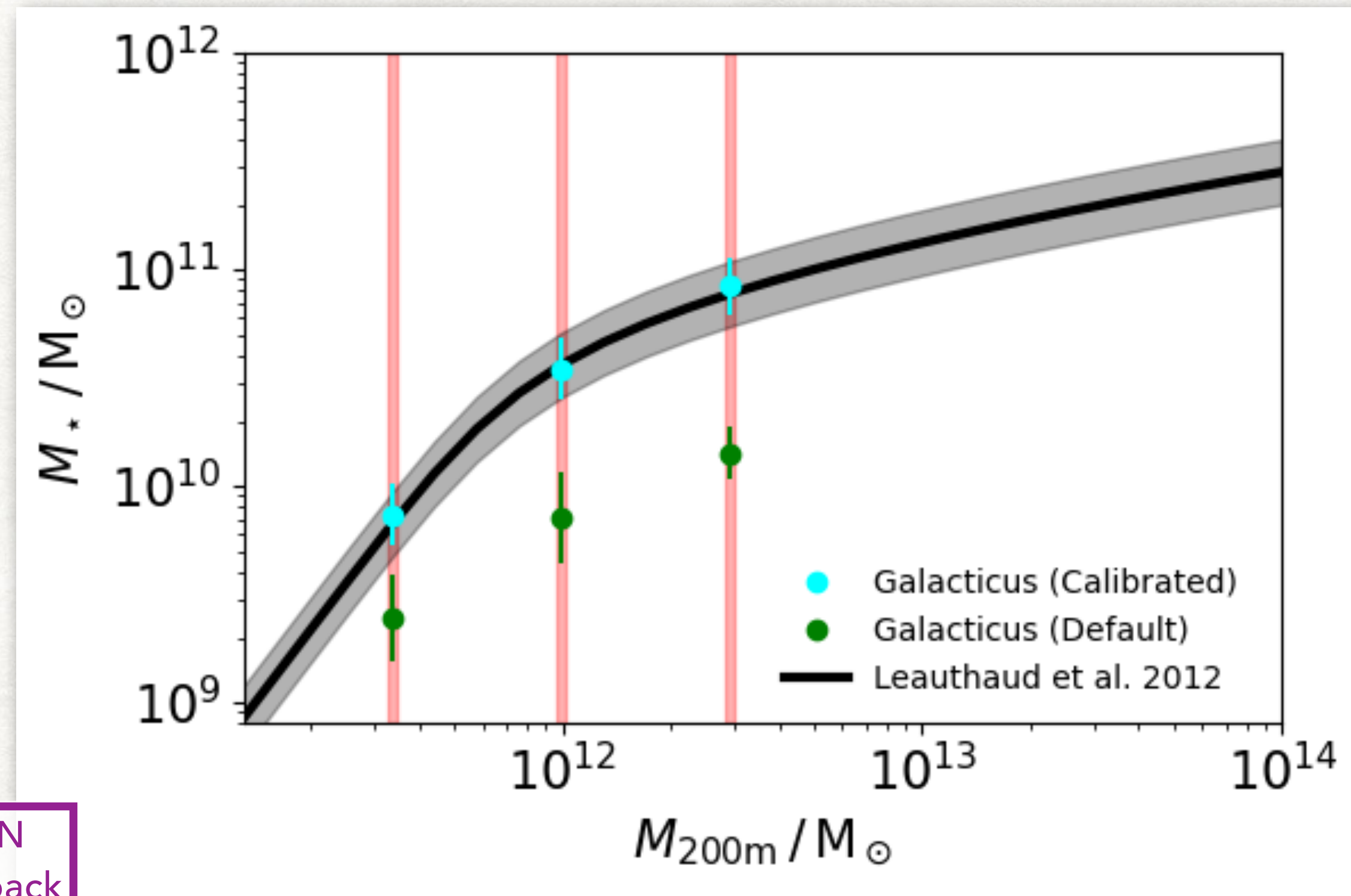
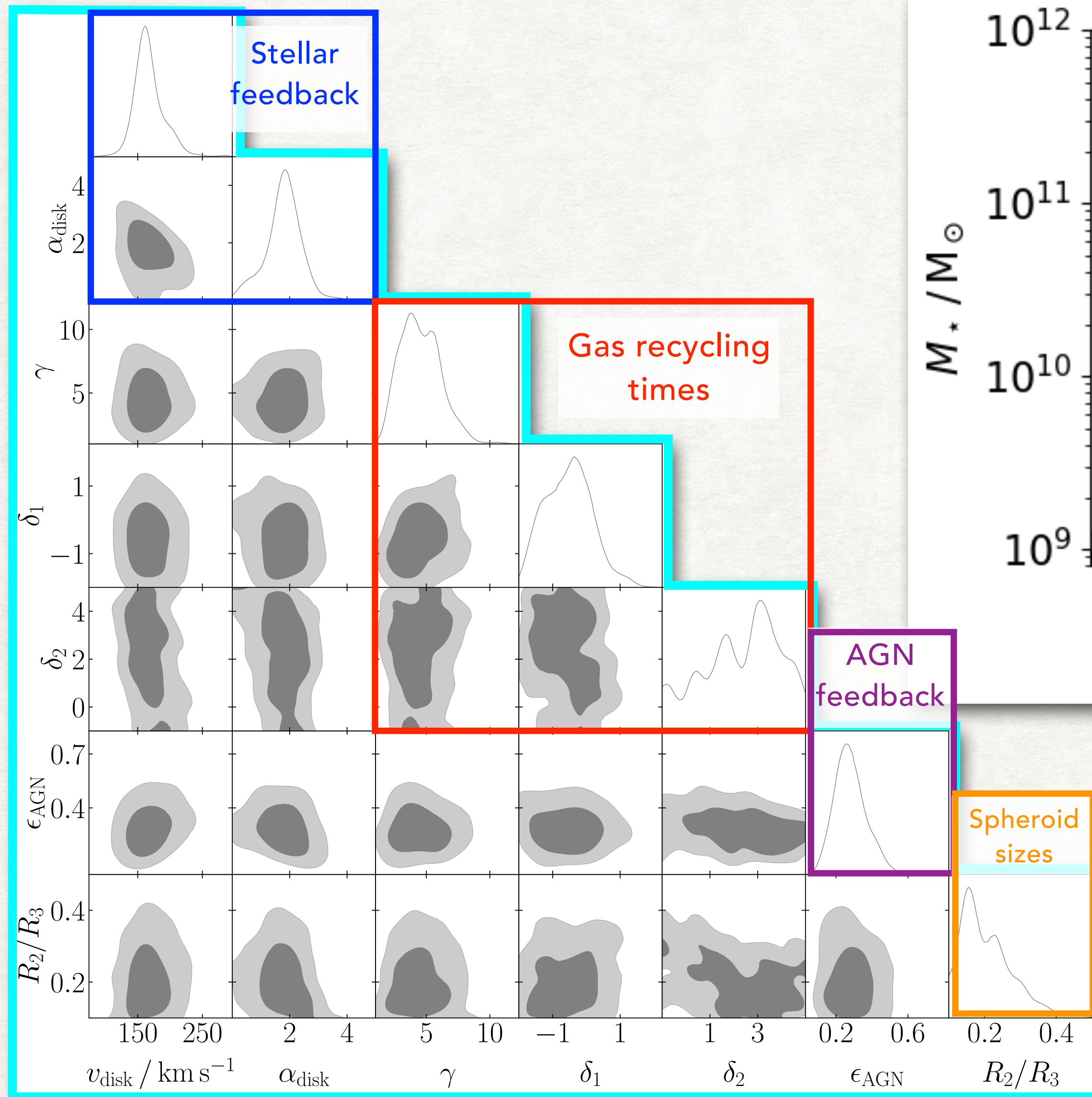


HOW TO SPEED UP A LIKELIHOOD EVALUATION?

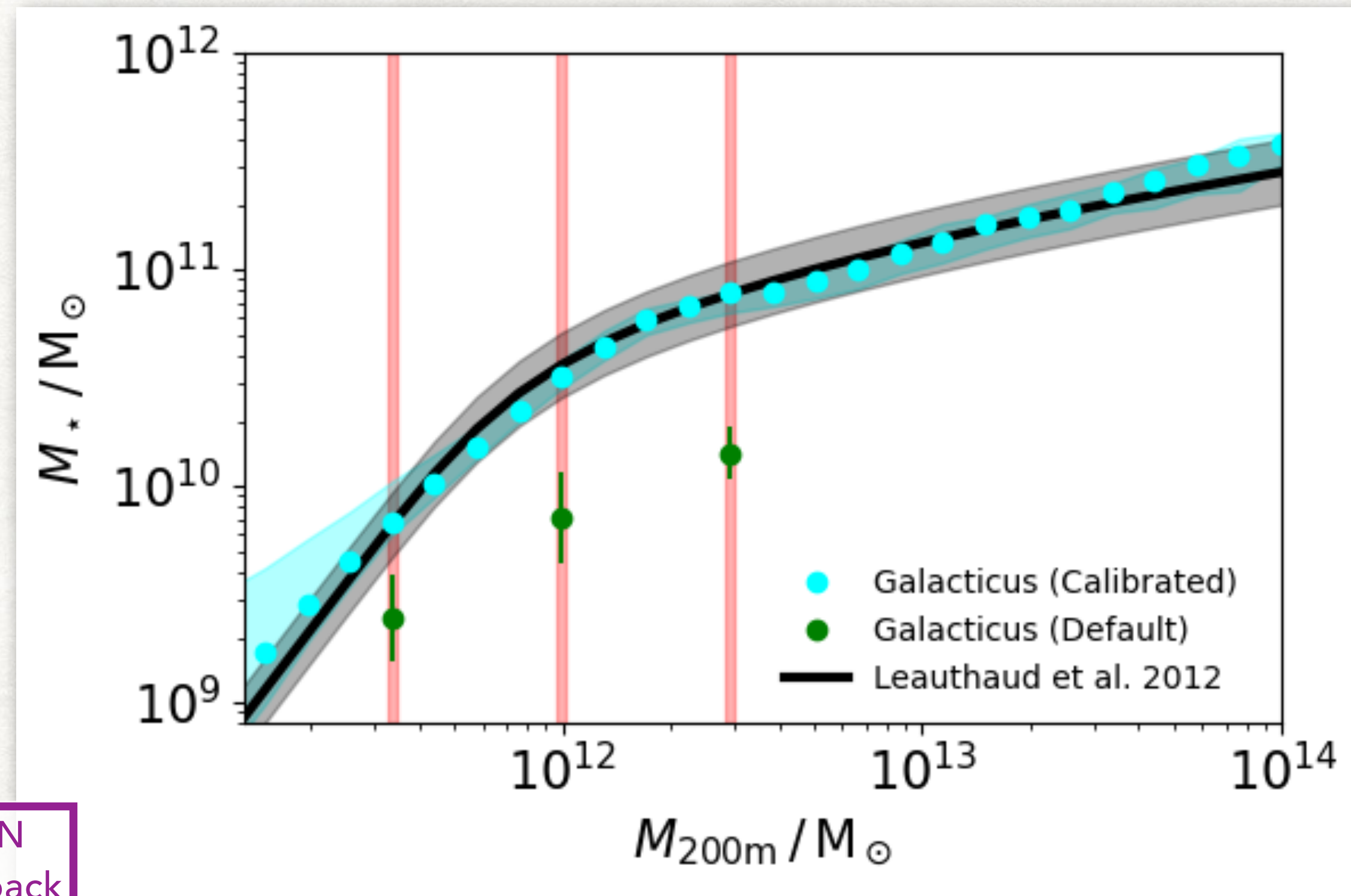
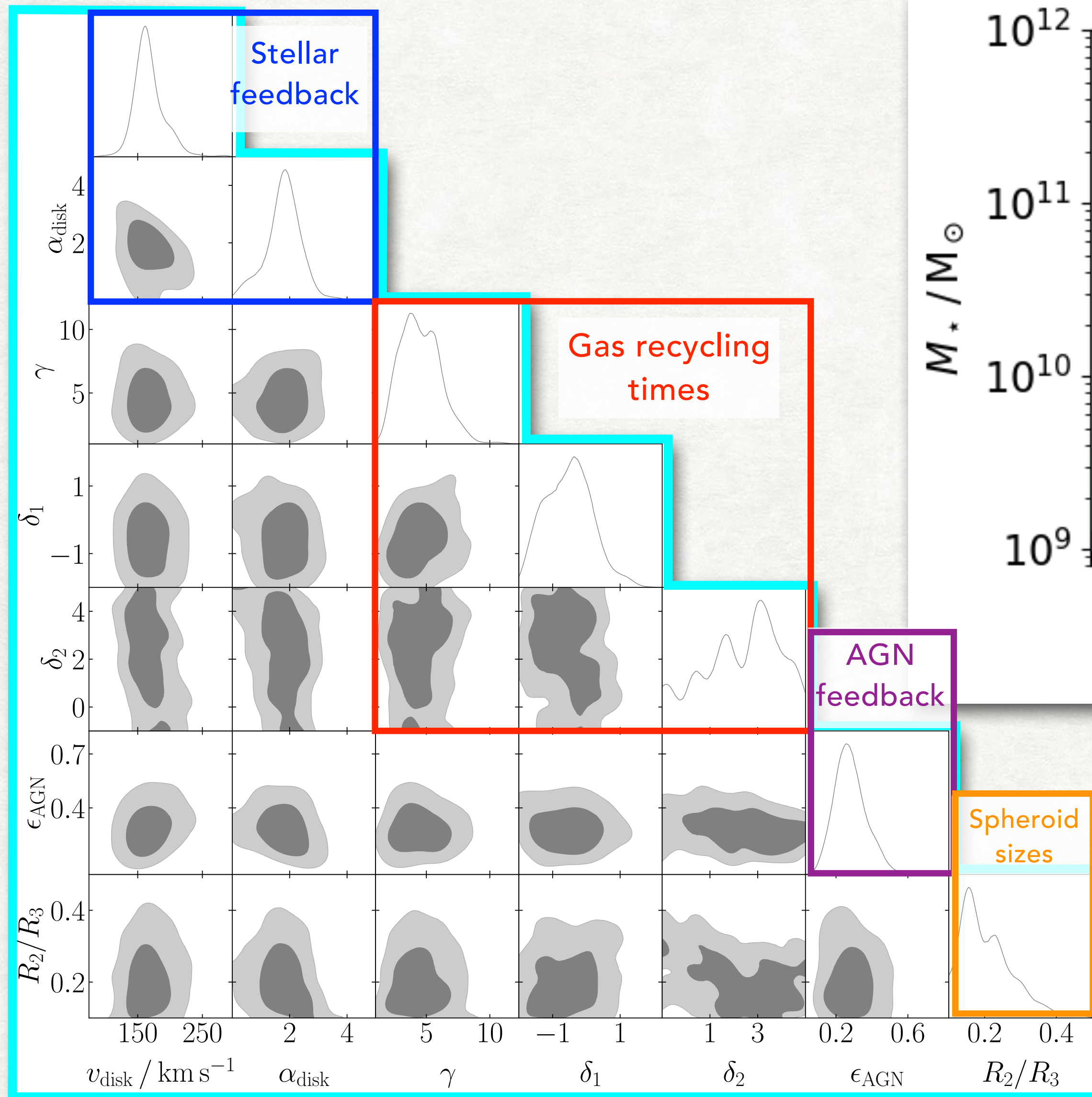
- Simple! Just simulate fewer galaxies...
- 3 different halo masses, 9 halos of each mass, takes \lesssim a minute
- Can now afford to run an MCMC!



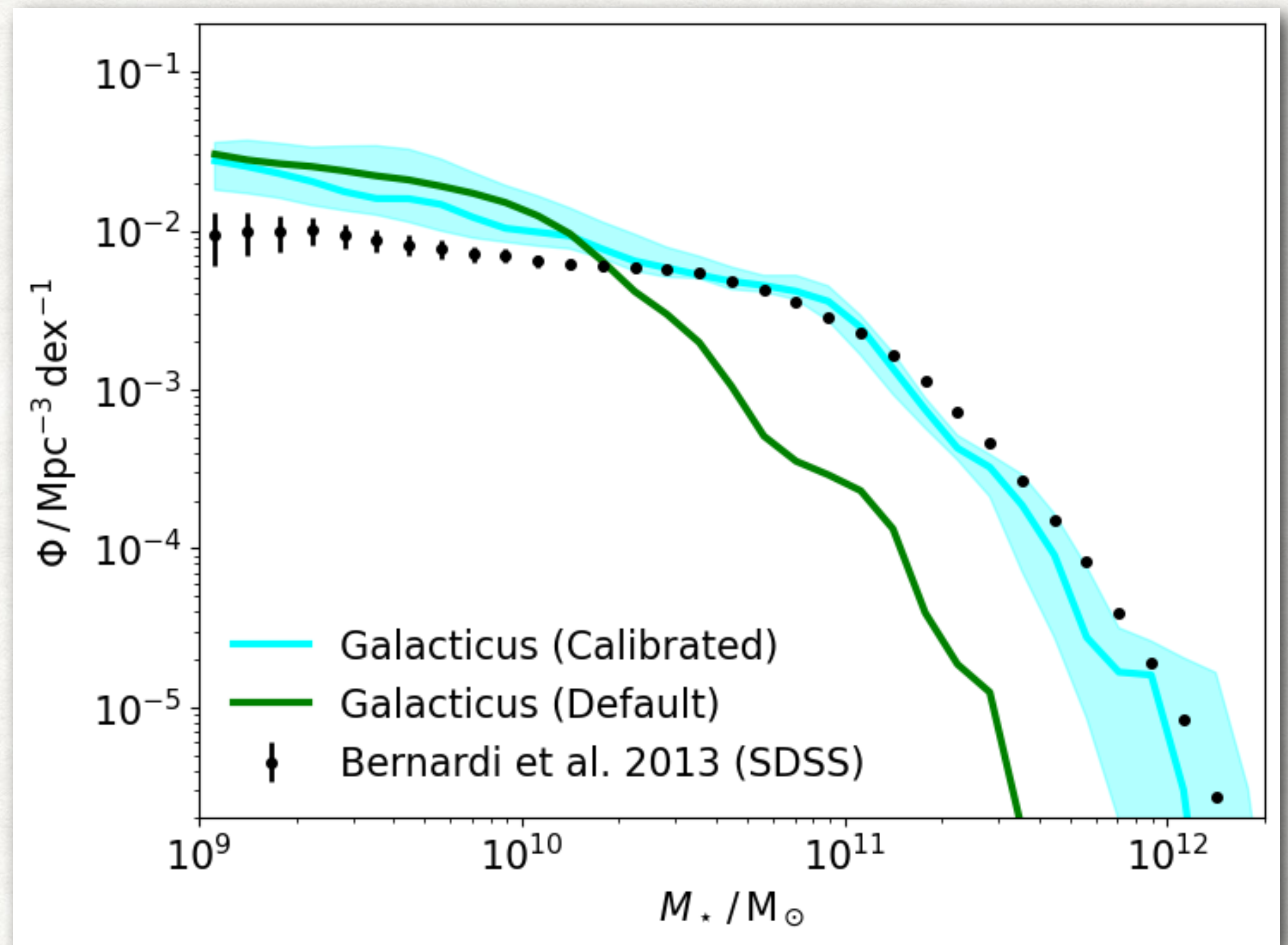
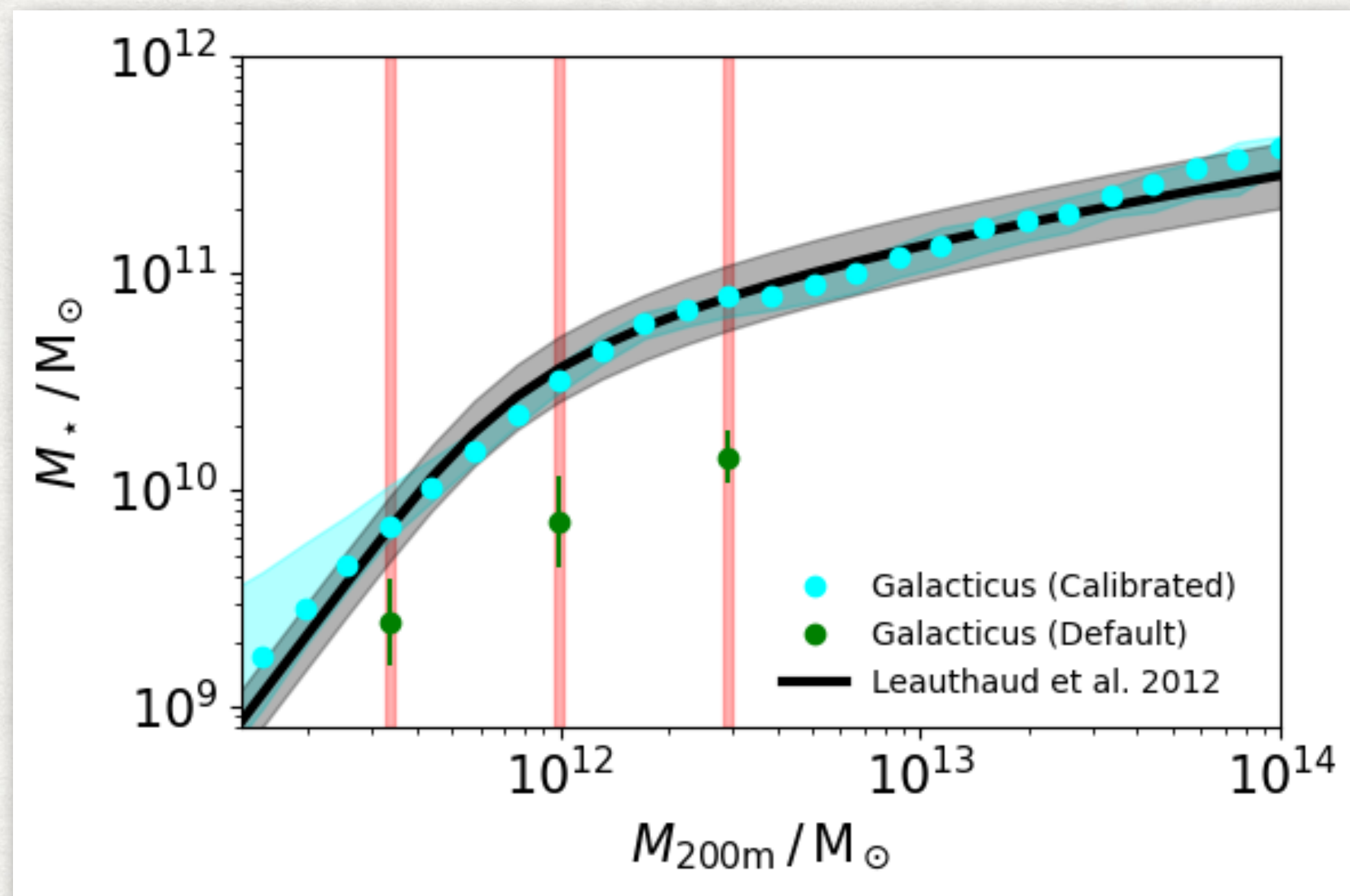
EXPLORE MODELS USING MCMC



BEST-FIT MODEL

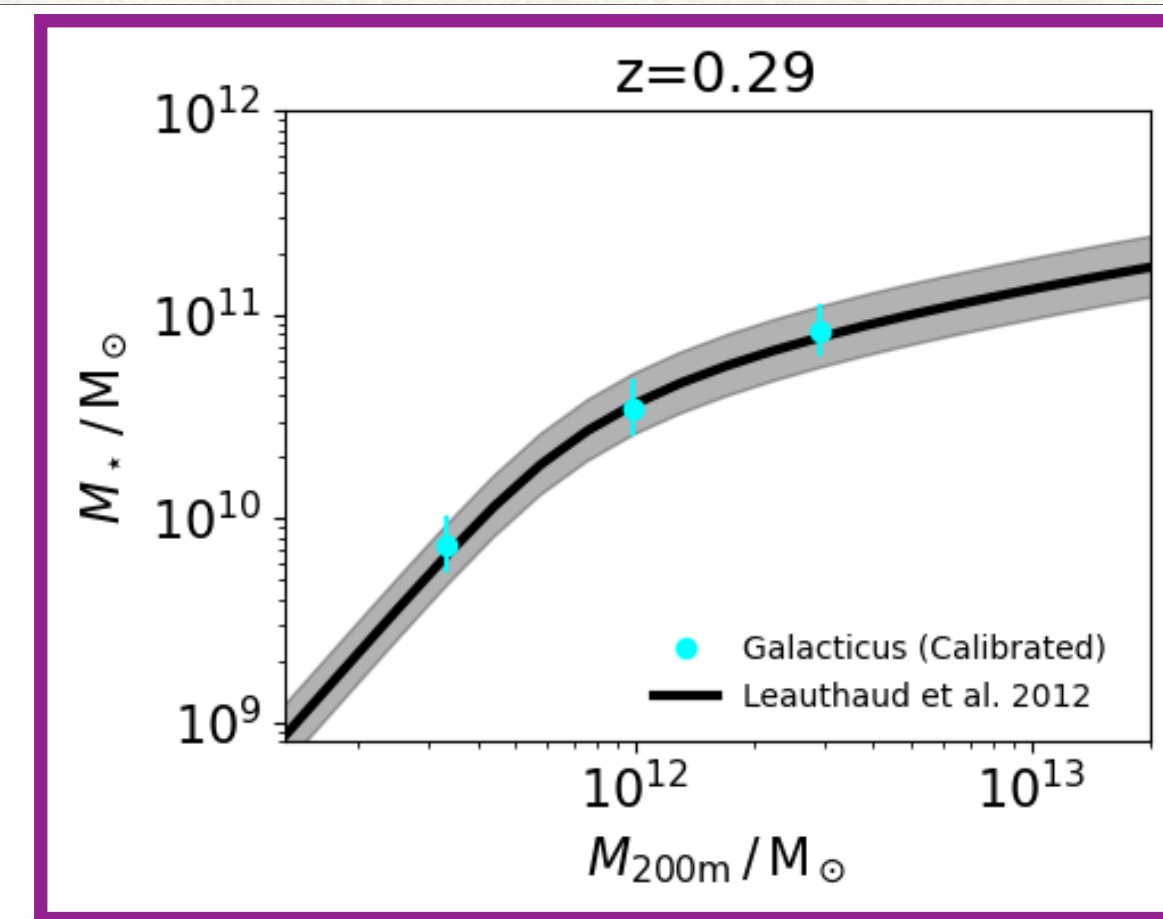
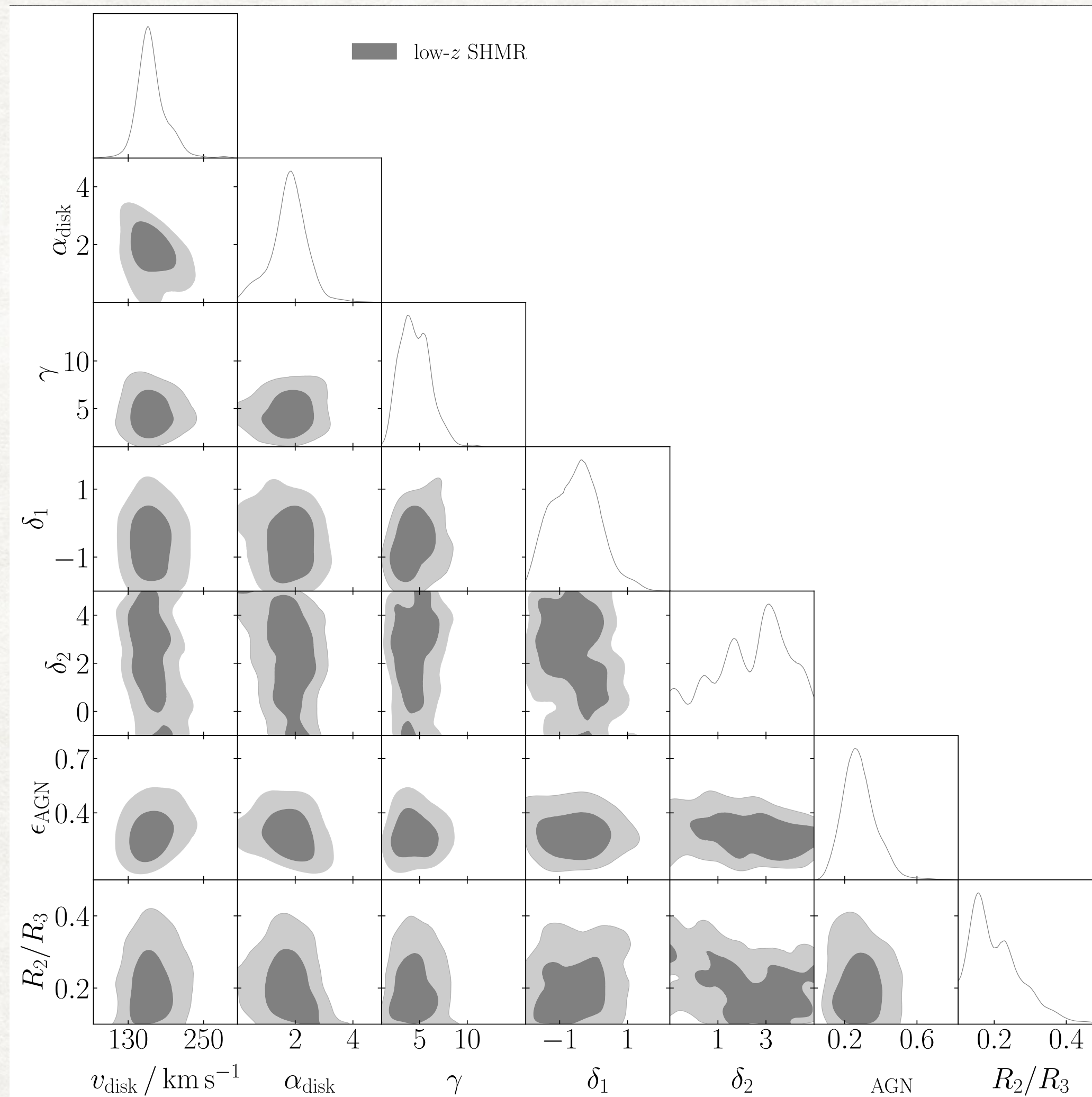


BACK TO THE STELLAR MASS FUNCTION



FITTING TO ADDITIONAL DATASETS

low-redshift
stellar mass - halo mass relation



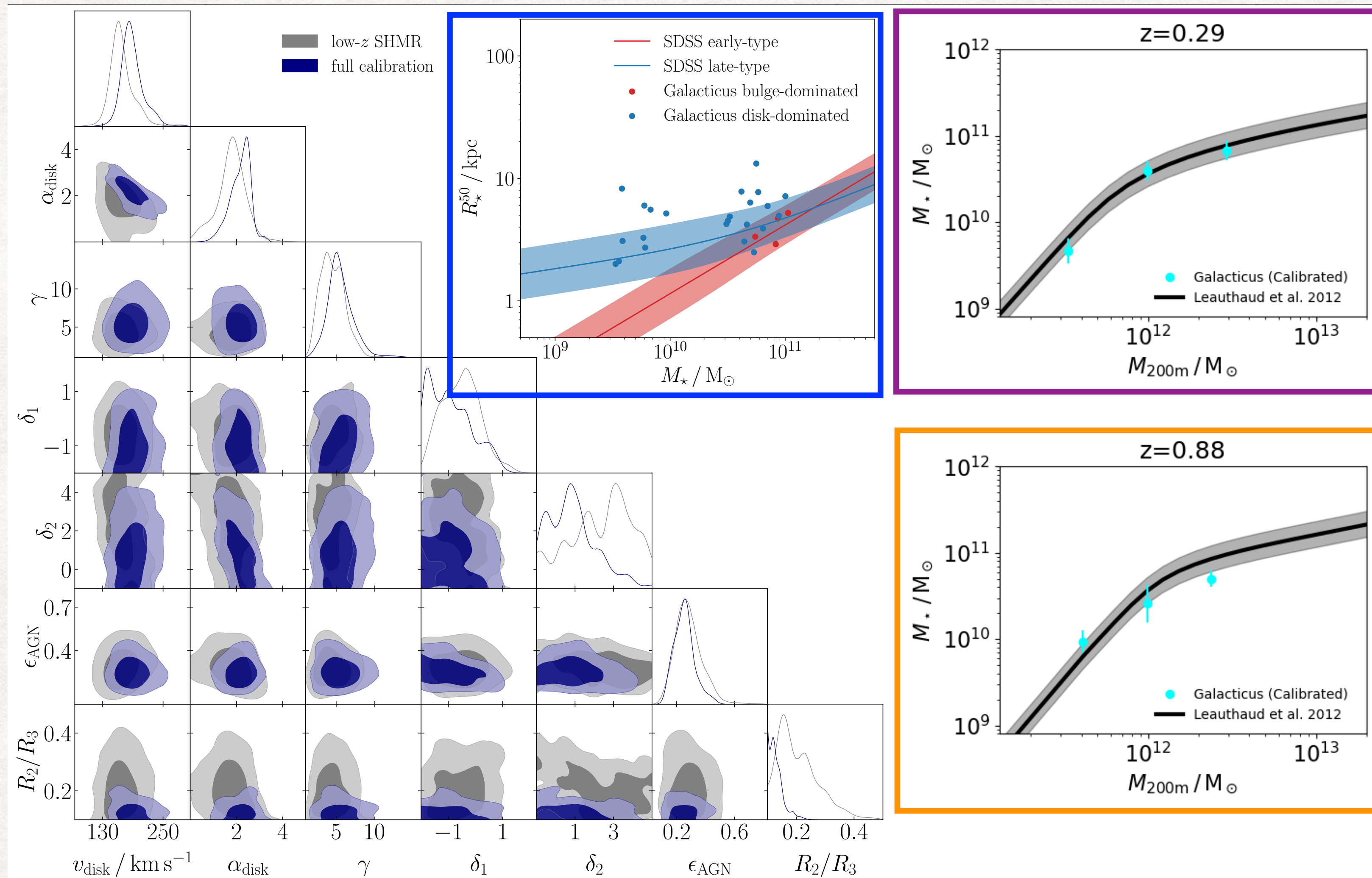
FITTING TO ADDITIONAL DATASETS

low-redshift

stellar mass - size relation

low-redshift

stellar mass - halo mass relation



higher-redshift
stellar mass -
halo mass
relation

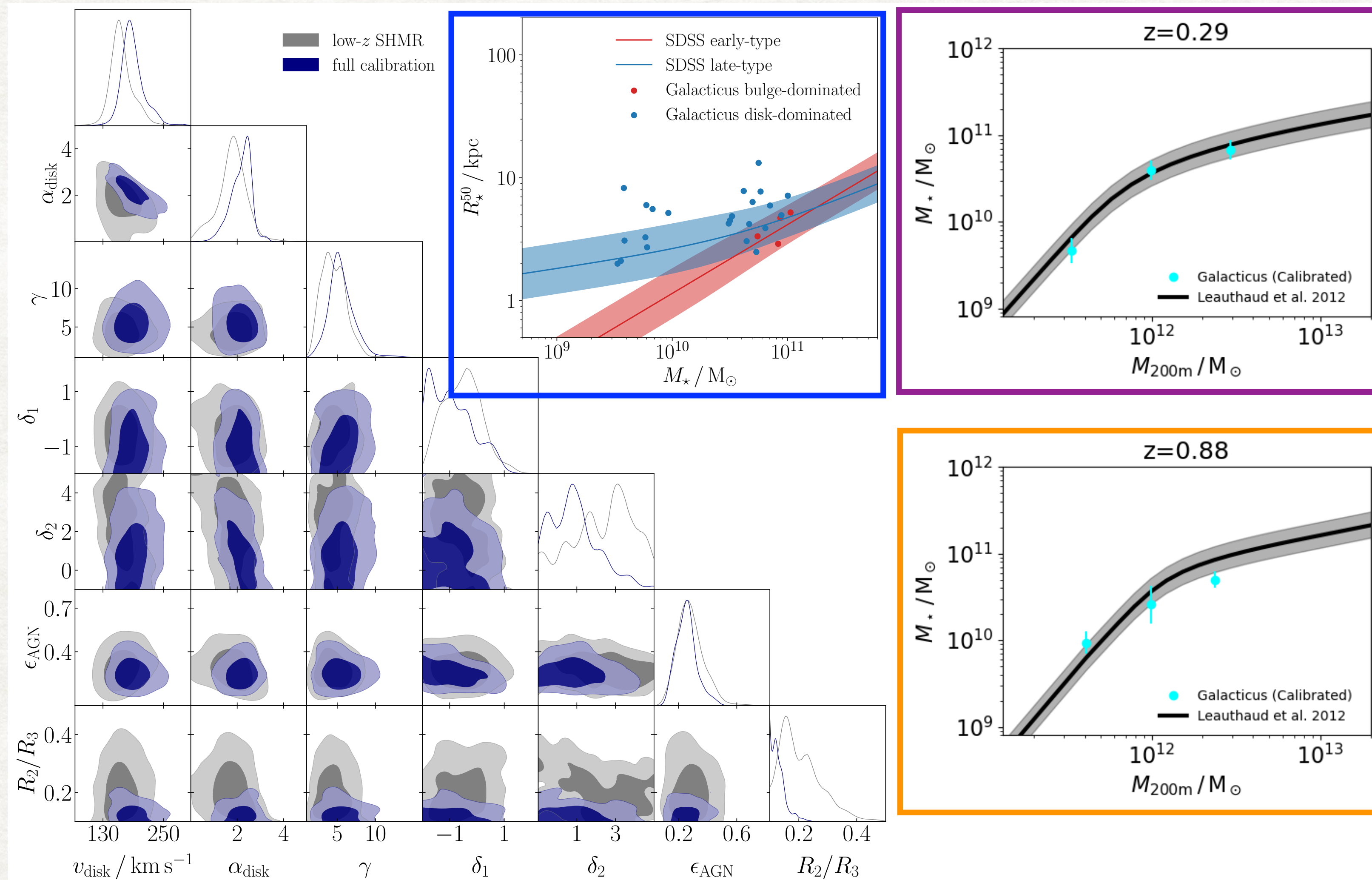
FITTING TO ADDITIONAL DATASETS

low-redshift

stellar mass - size relation

low-redshift

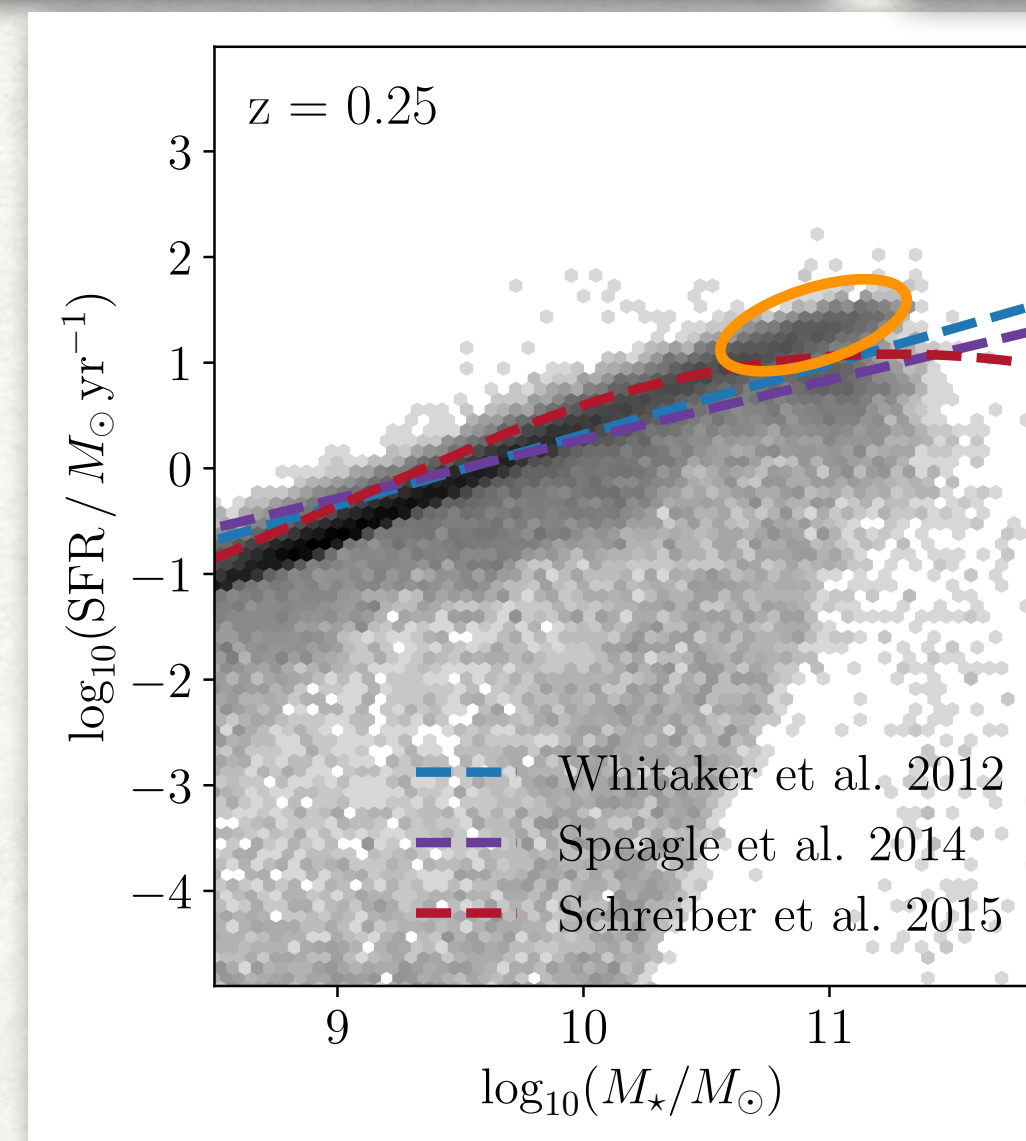
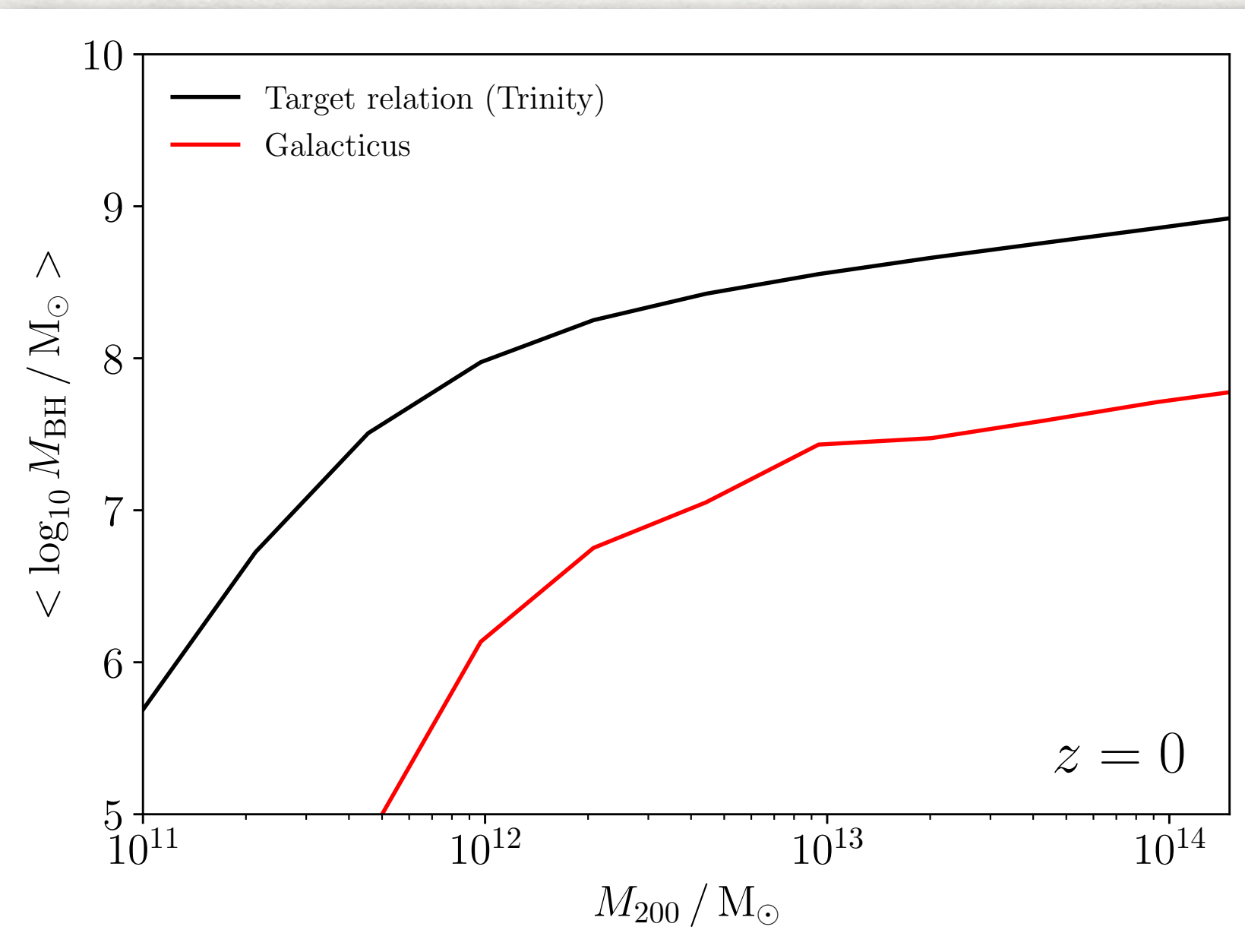
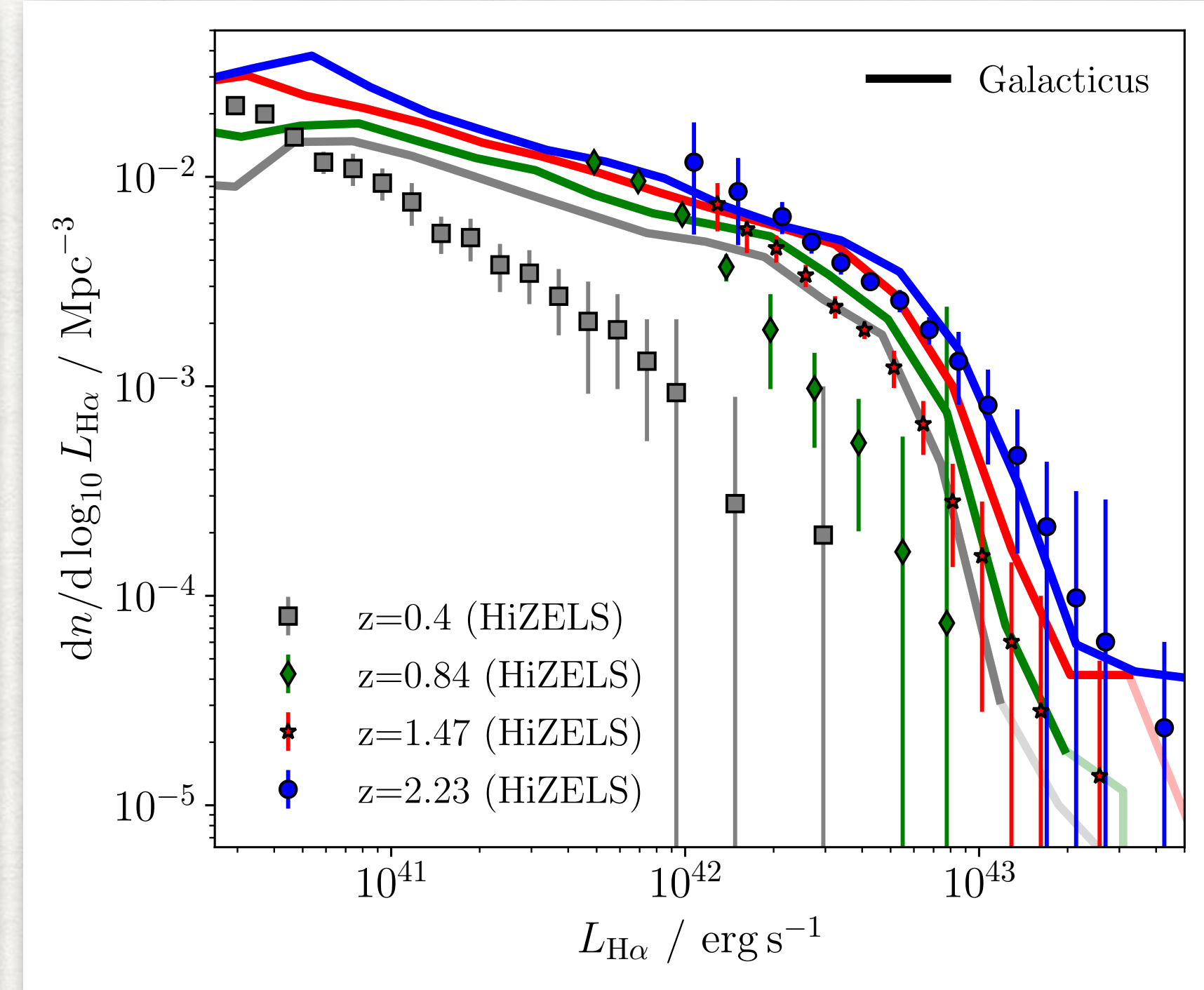
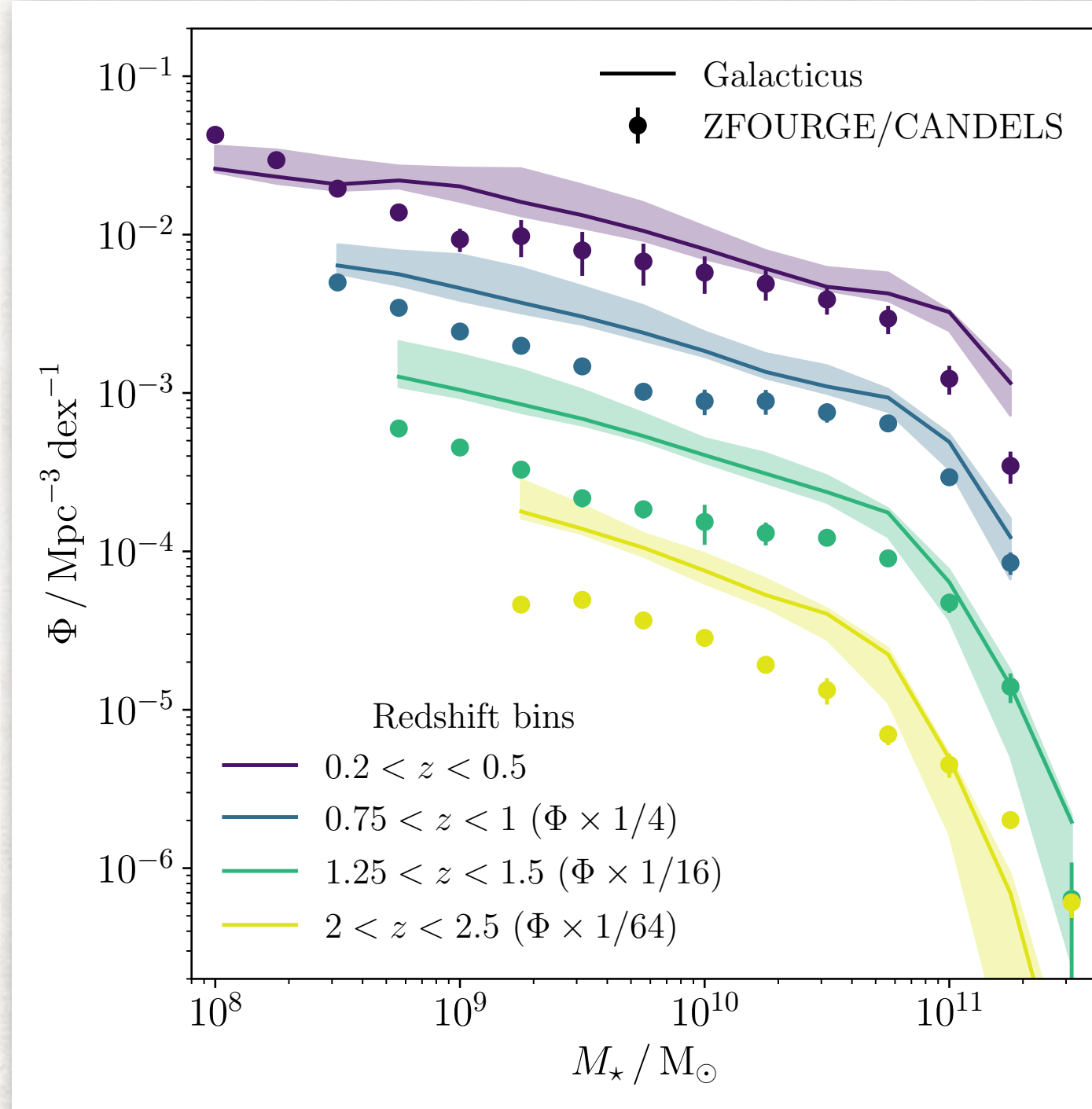
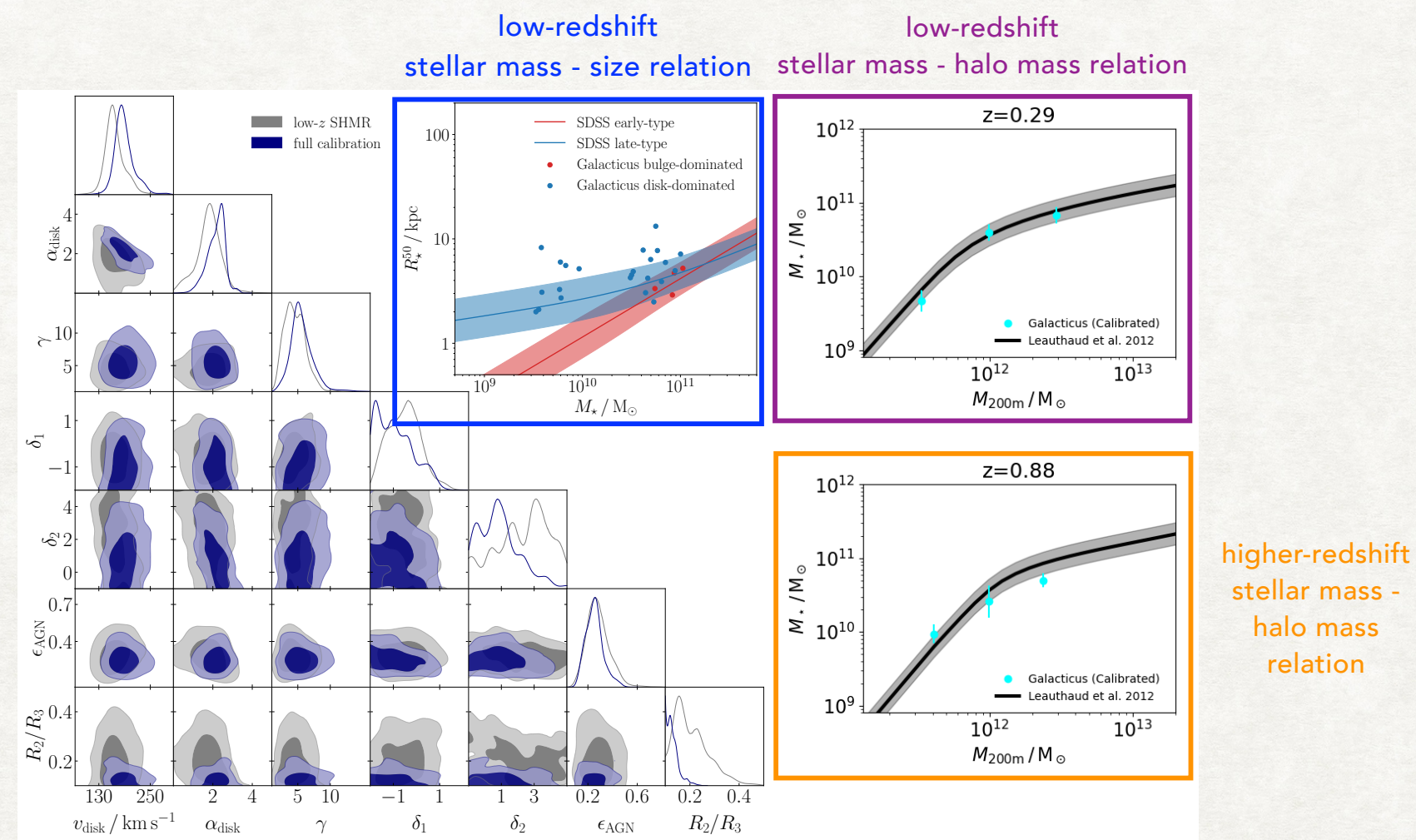
stellar mass - halo mass relation



higher-redshift
stellar mass -
halo mass
relation

THE CALIBRATED MODEL

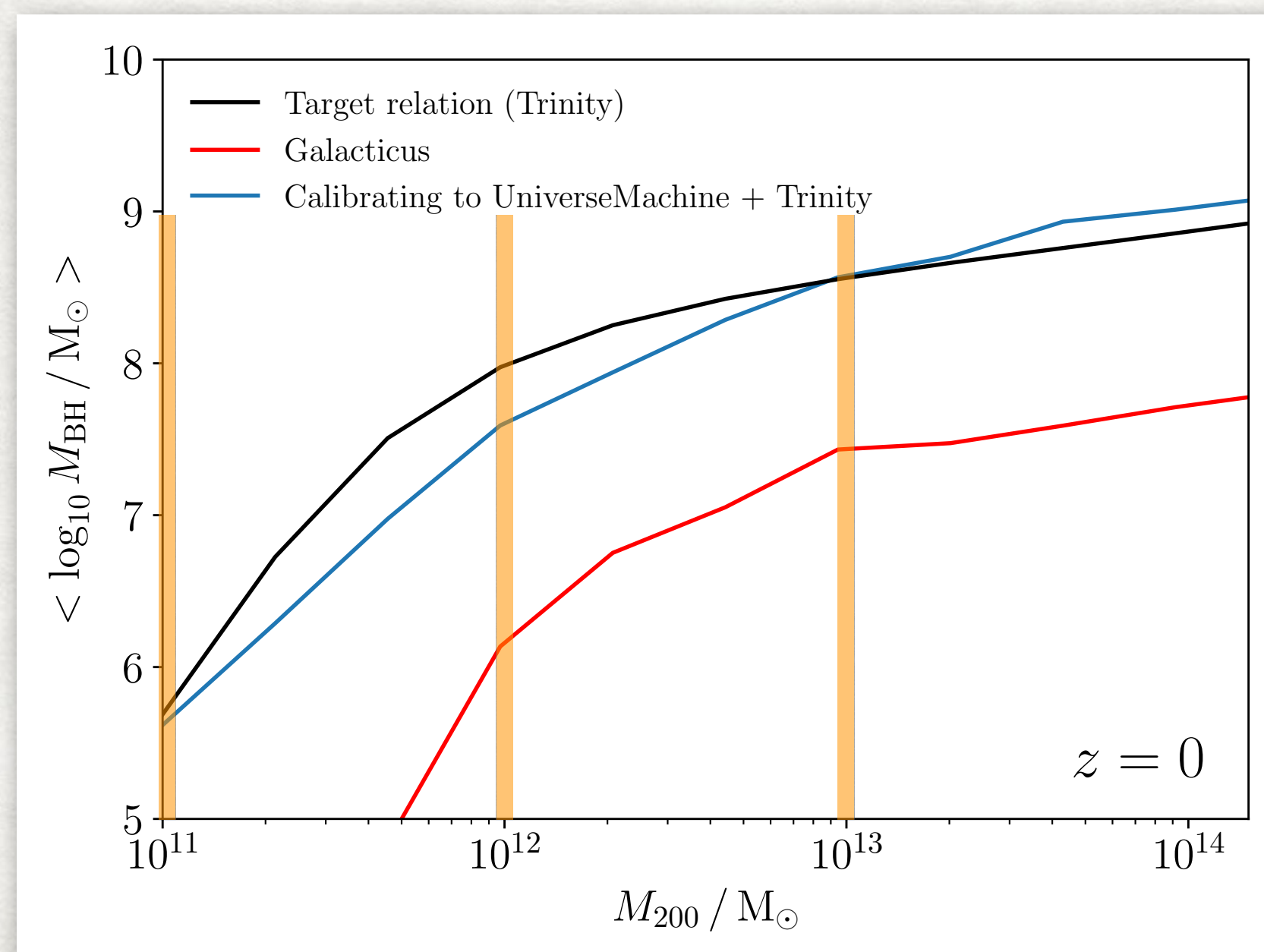
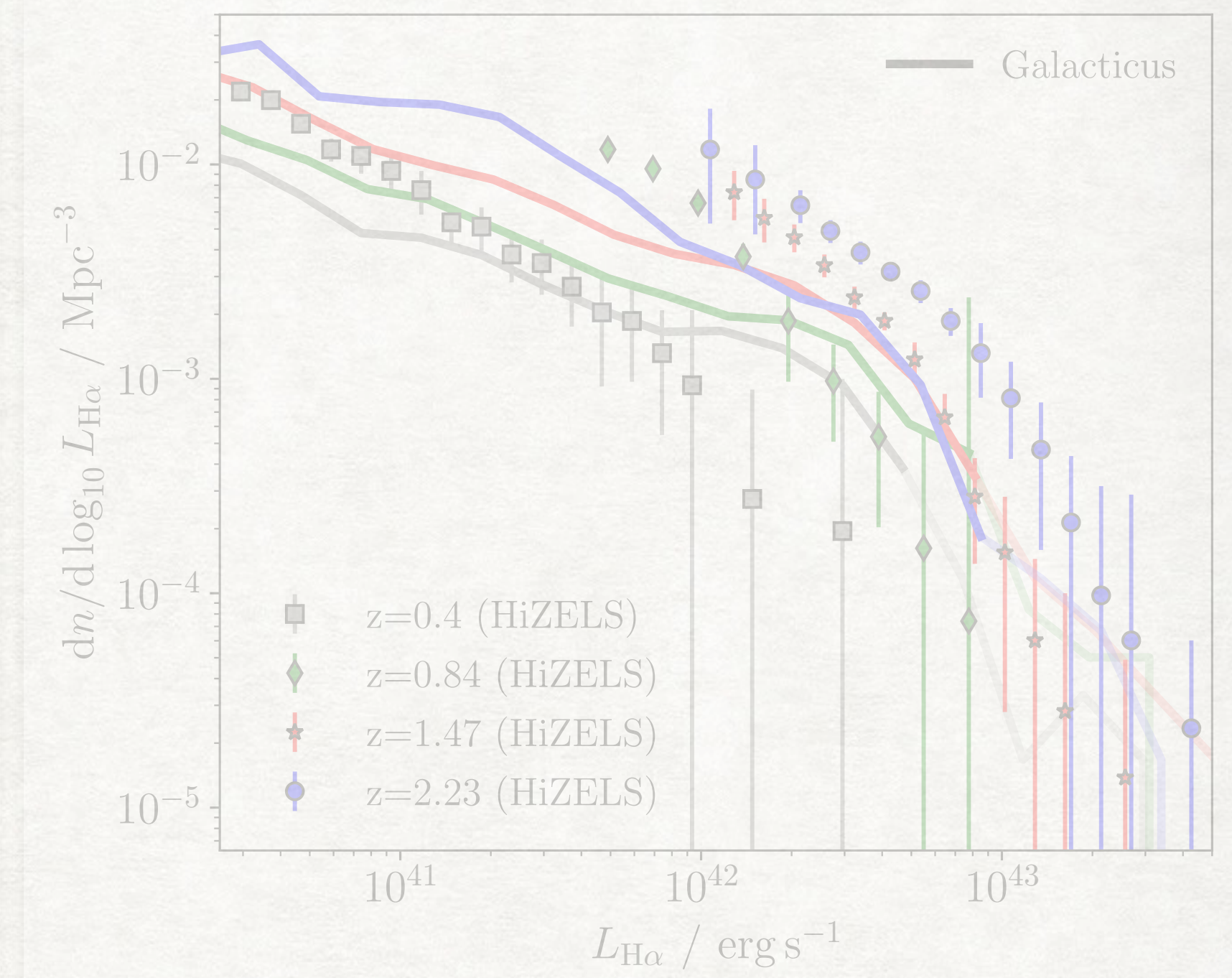
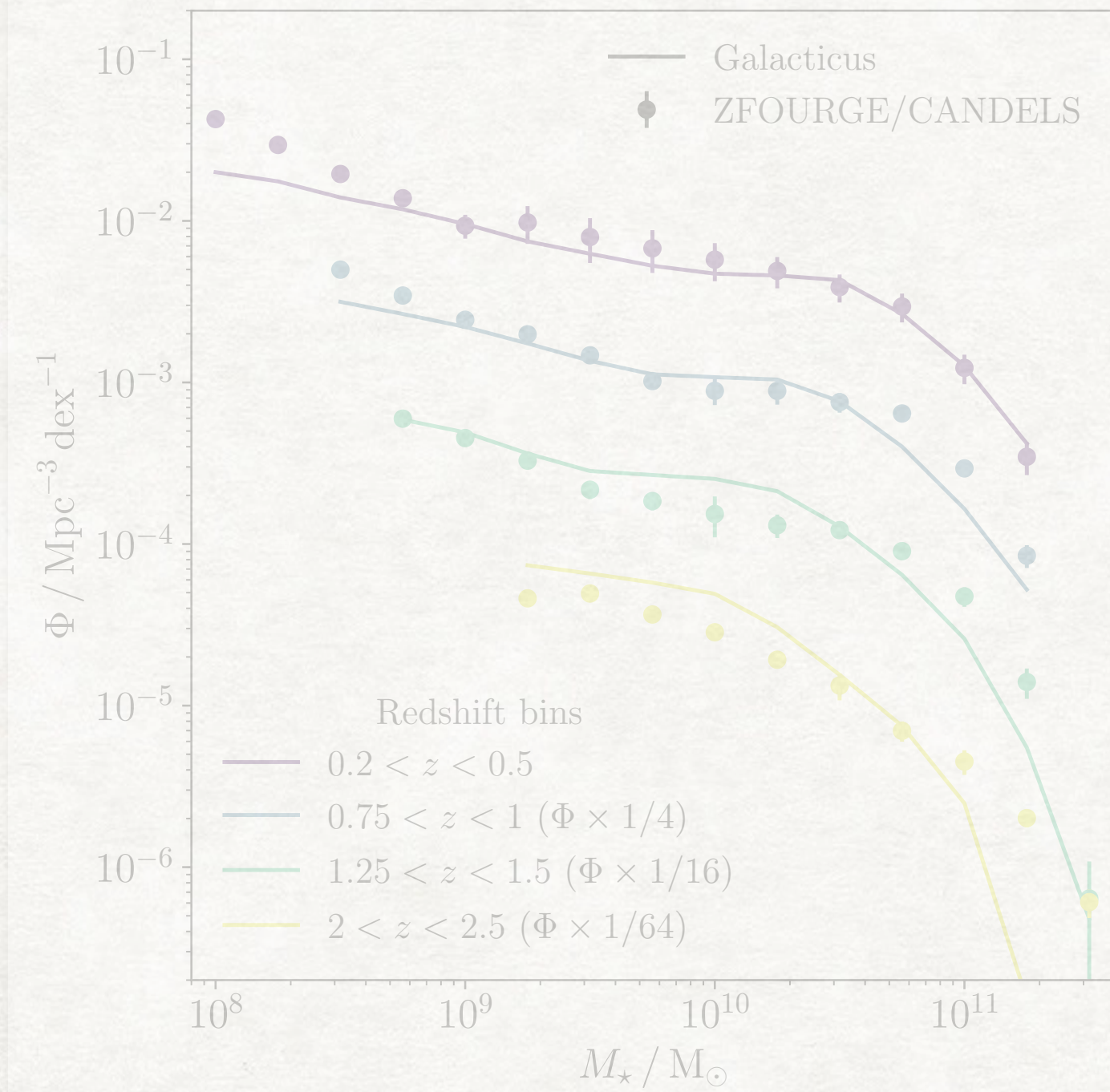
FITTING TO ADDITIONAL DATASETS



- H α is primary emission line in Roman GRS for $1 < z < 2$
- Reasonable distribution of H α luminosities at $z \sim 2$
- But too many highly star forming galaxies at $z \sim 0.4$

FURTHER IMPROVEMENTS

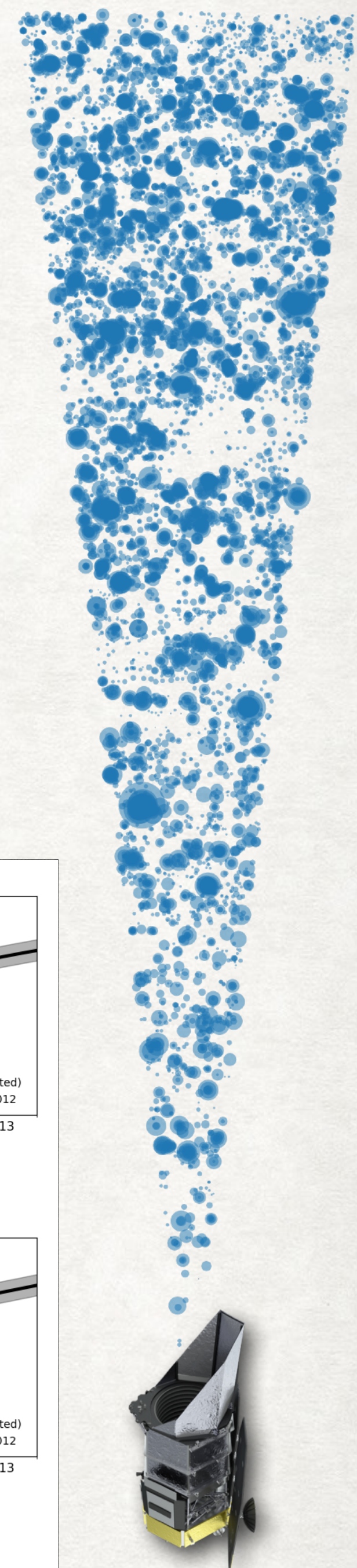
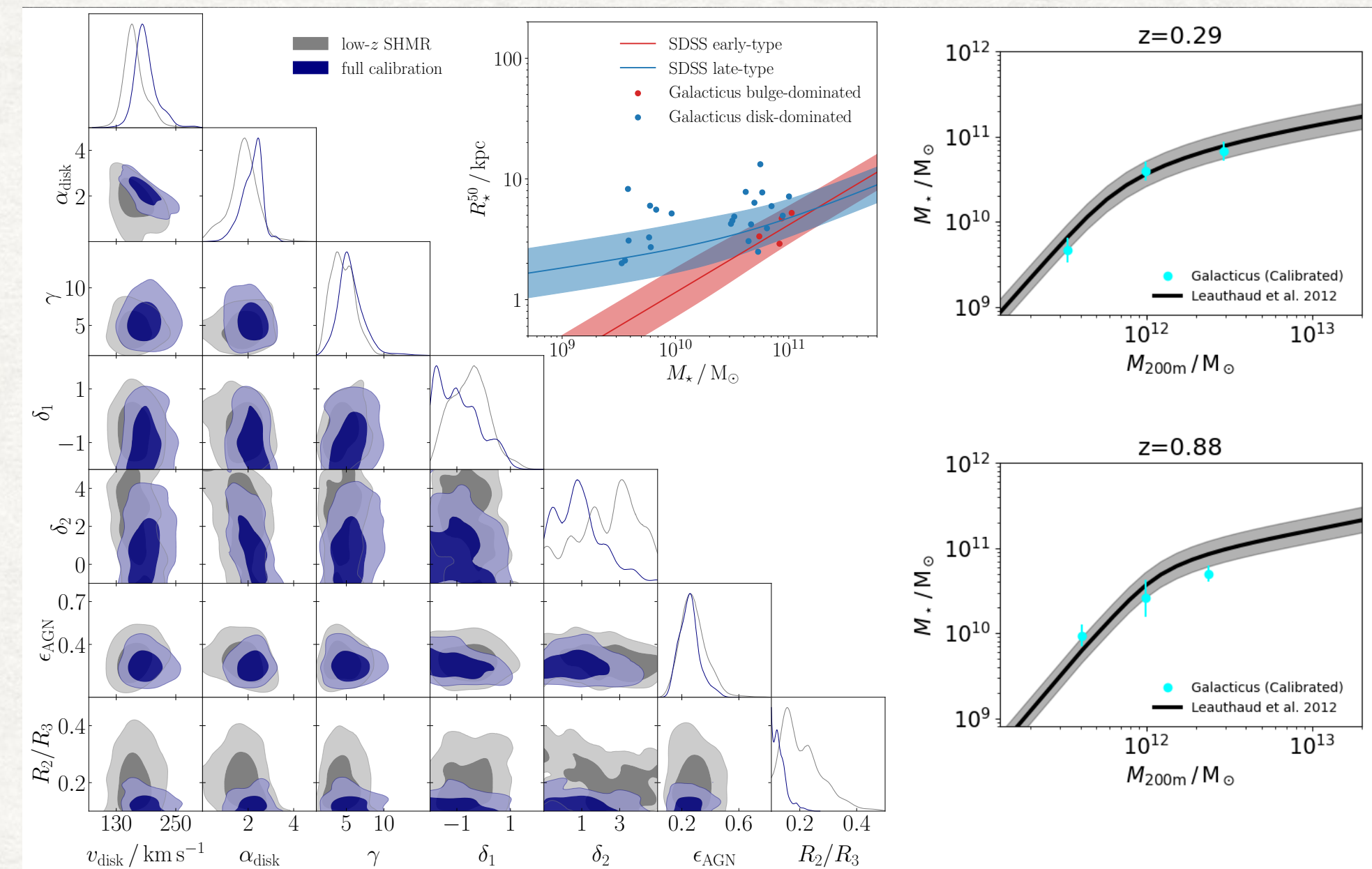
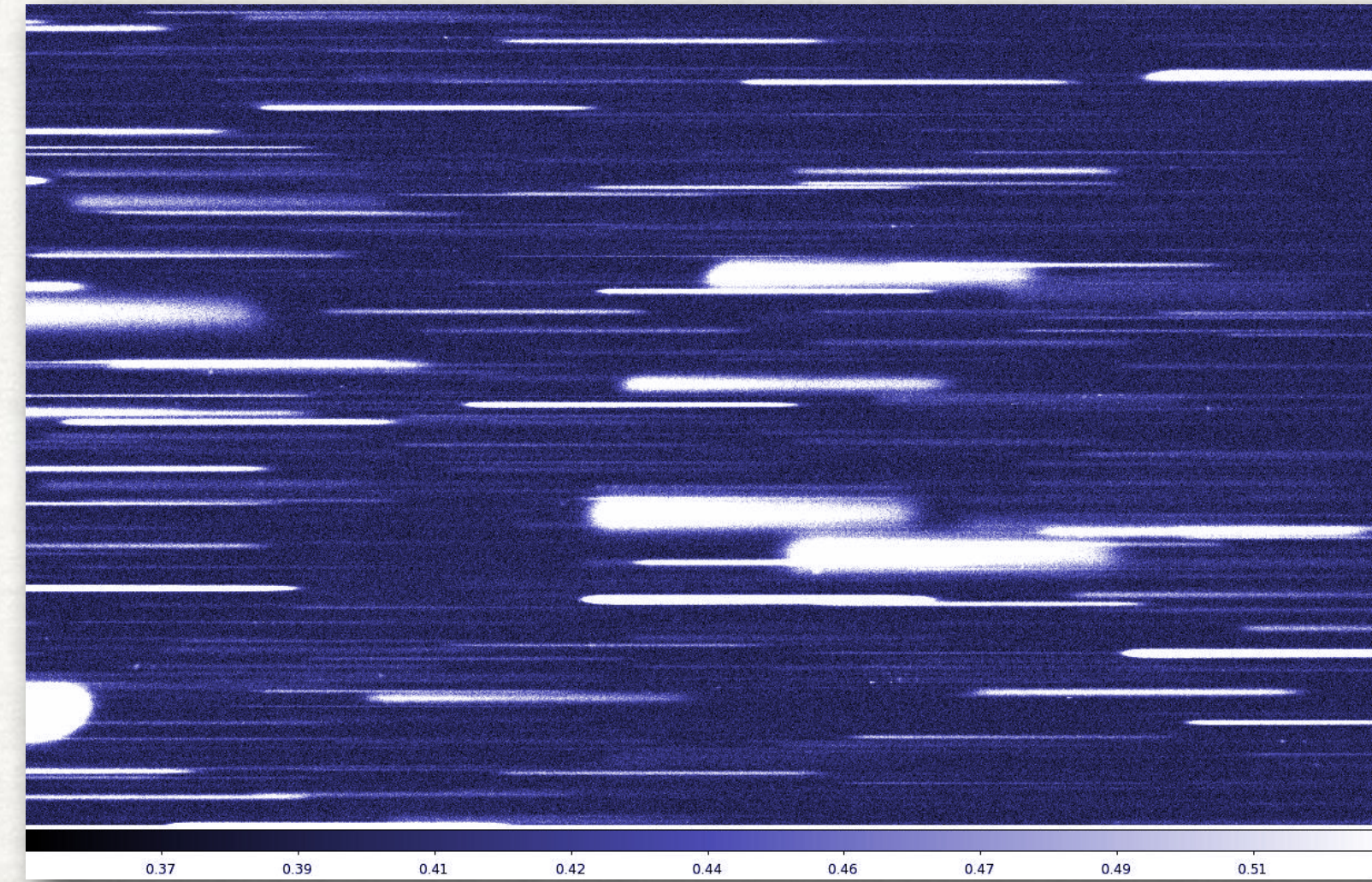
- Fit to Trinity black hole mass - halo mass relation ($M_{200} = [10^{11}, 10^{12}, 10^{13}] M_{\odot}$ at $z = [0, 1, 2]$)



- Now slightly under-predicting the high-z $H\alpha$ luminosity function
- Can improve the match somewhat by playing with dust models
- Would be nice to directly include SFRs in the calibration data - is there a good way to do this?

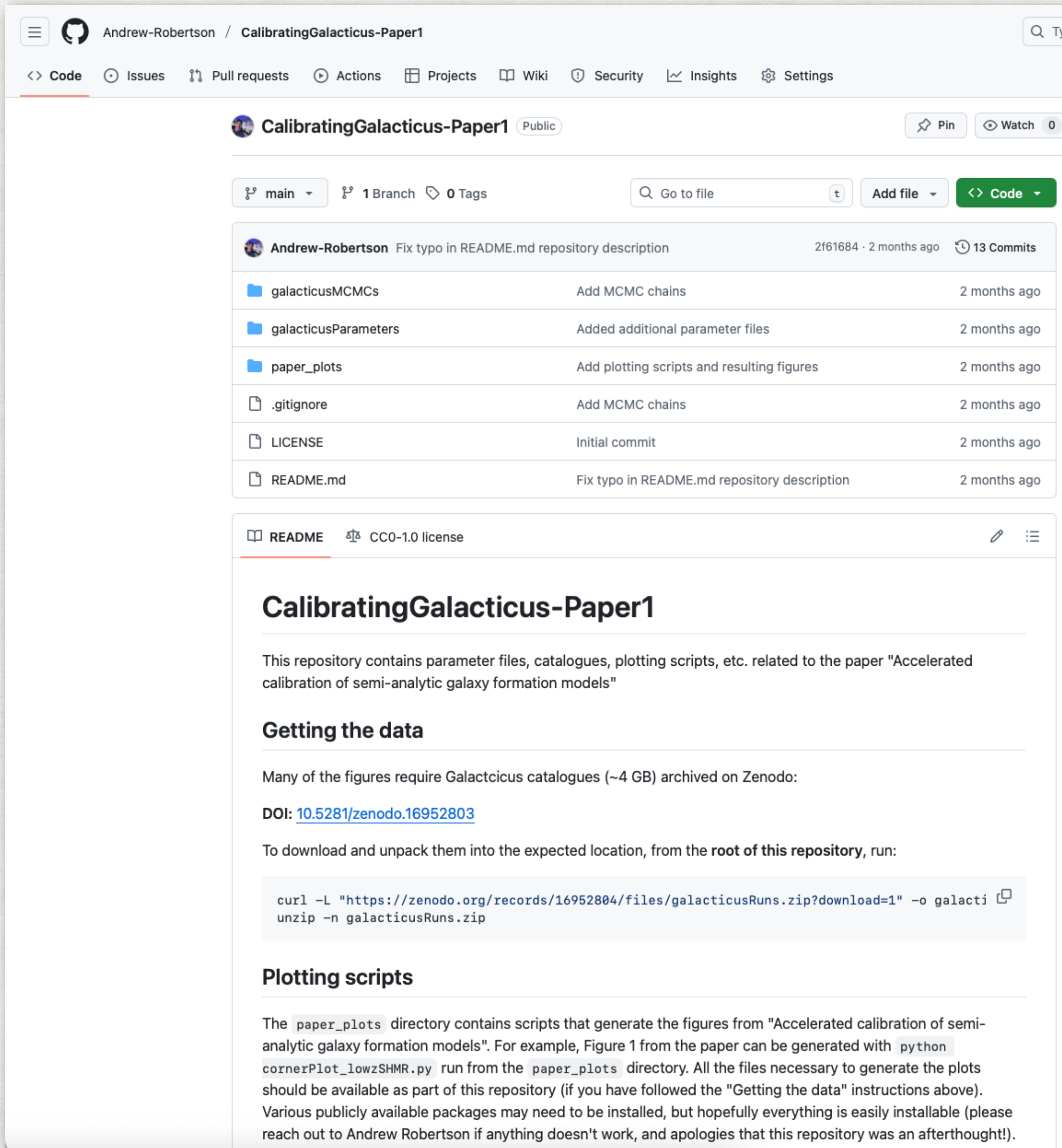
CONCLUSIONS

- Roman is due to launch in under a year!
- Galaxy clustering with grism spectroscopy brings new challenges
- Addressing them requires the ability to test strategies on realistic mock data
- Using a small number of simulated galaxies we can assess (to some extent) how well a model performs
- Using this, we have found an improved calibration of the Galacticus semi-analytic model
- Further improvements hopefully coming soon!



MODEL IS AVAILABLE

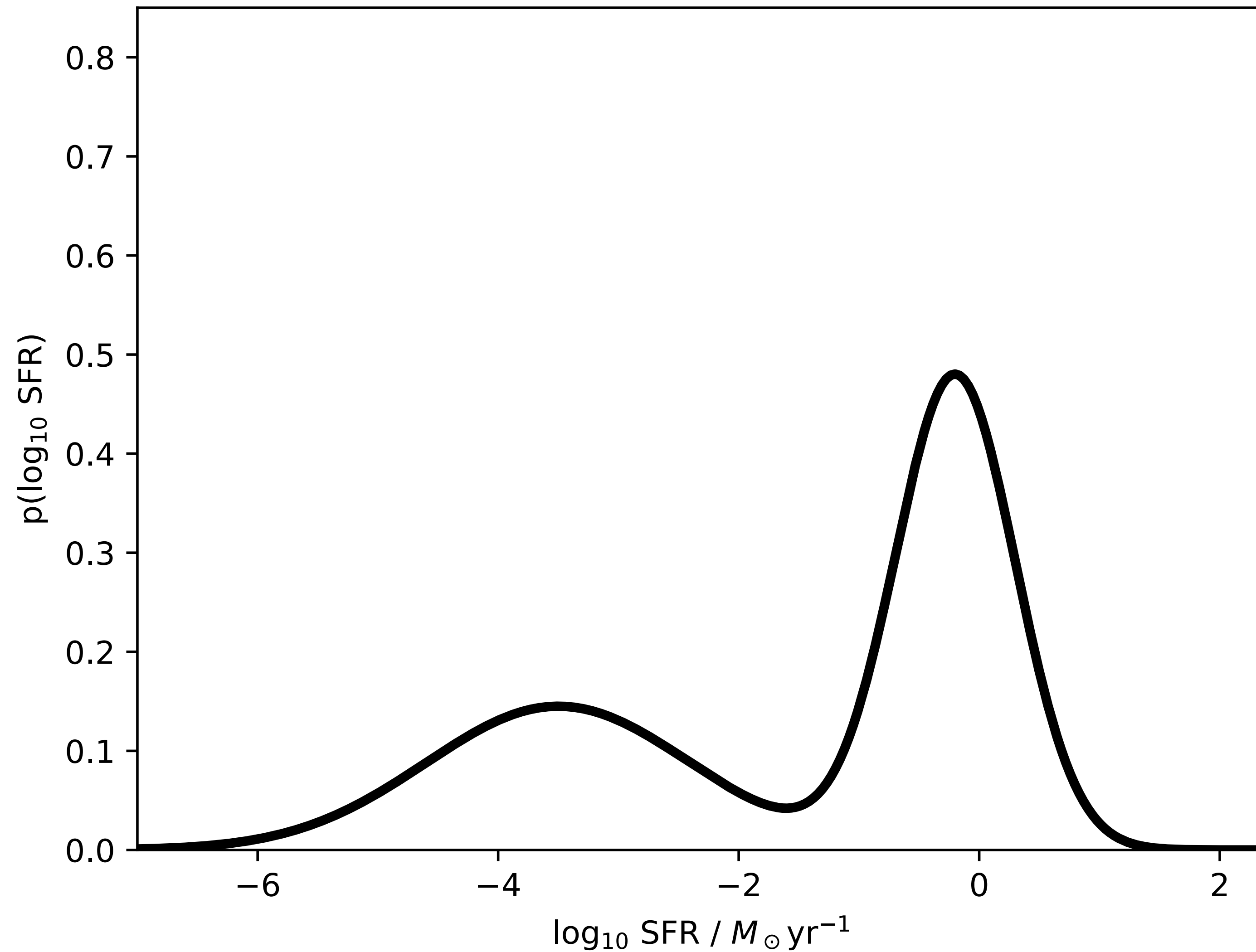
- Galacticus parameter files
- Example galaxy catalogues
- Currently running the model on the UNIT N-body simulations to generate simulated lightcones (for Roman imaging+grism mocks)



The screenshot shows the GitHub interface for the repository 'CalibratingGalacticus-Paper1' by Andrew-Robertson. The repository is public and has 13 commits. The file list includes folders for 'galacticusMCMCs', 'galacticusParameters', and 'paper_plots', along with files like '.gitignore', 'LICENSE', and 'README.md'. The README section is expanded, showing the title 'CalibratingGalacticus-Paper1' and a description: 'This repository contains parameter files, catalogues, plotting scripts, etc. related to the paper "Accelerated calibration of semi-analytic galaxy formation models"'. Under the heading 'Getting the data', it provides a Zenodo DOI link (10.5281/zenodo.16952803) and instructions to download and unzip a zip file. A terminal command is provided: `curl -L "https://zenodo.org/records/16952804/files/galacticusRuns.zip?download=1" -o galacti` followed by `unzip -n galacticusRuns.zip`. The 'Plotting scripts' section explains that the 'paper_plots' directory contains scripts for generating figures from the models, with an example of using 'python cornerPlot_lowzSHMR.py'.

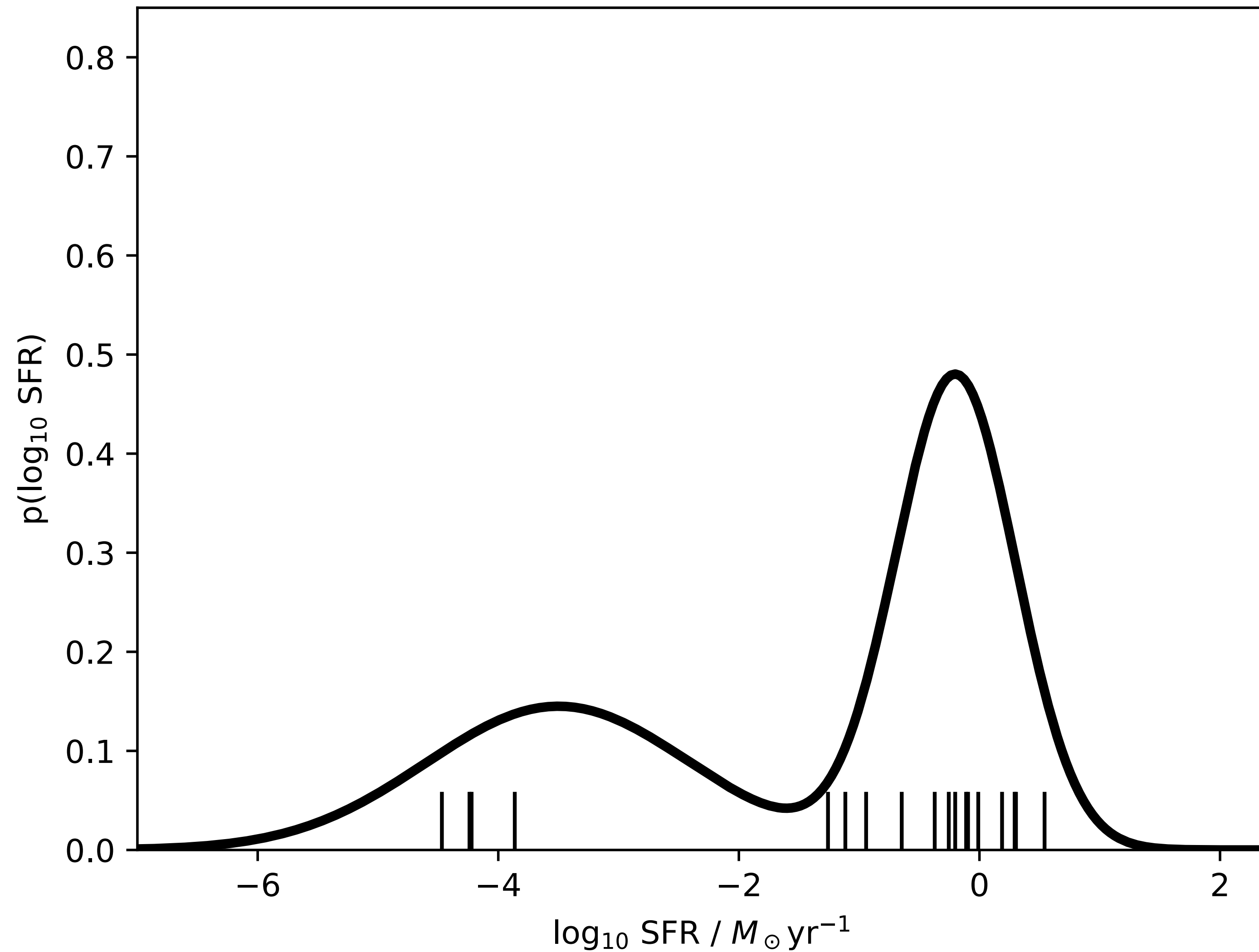


CAN WE PUSH THE METHOD FURTHER?



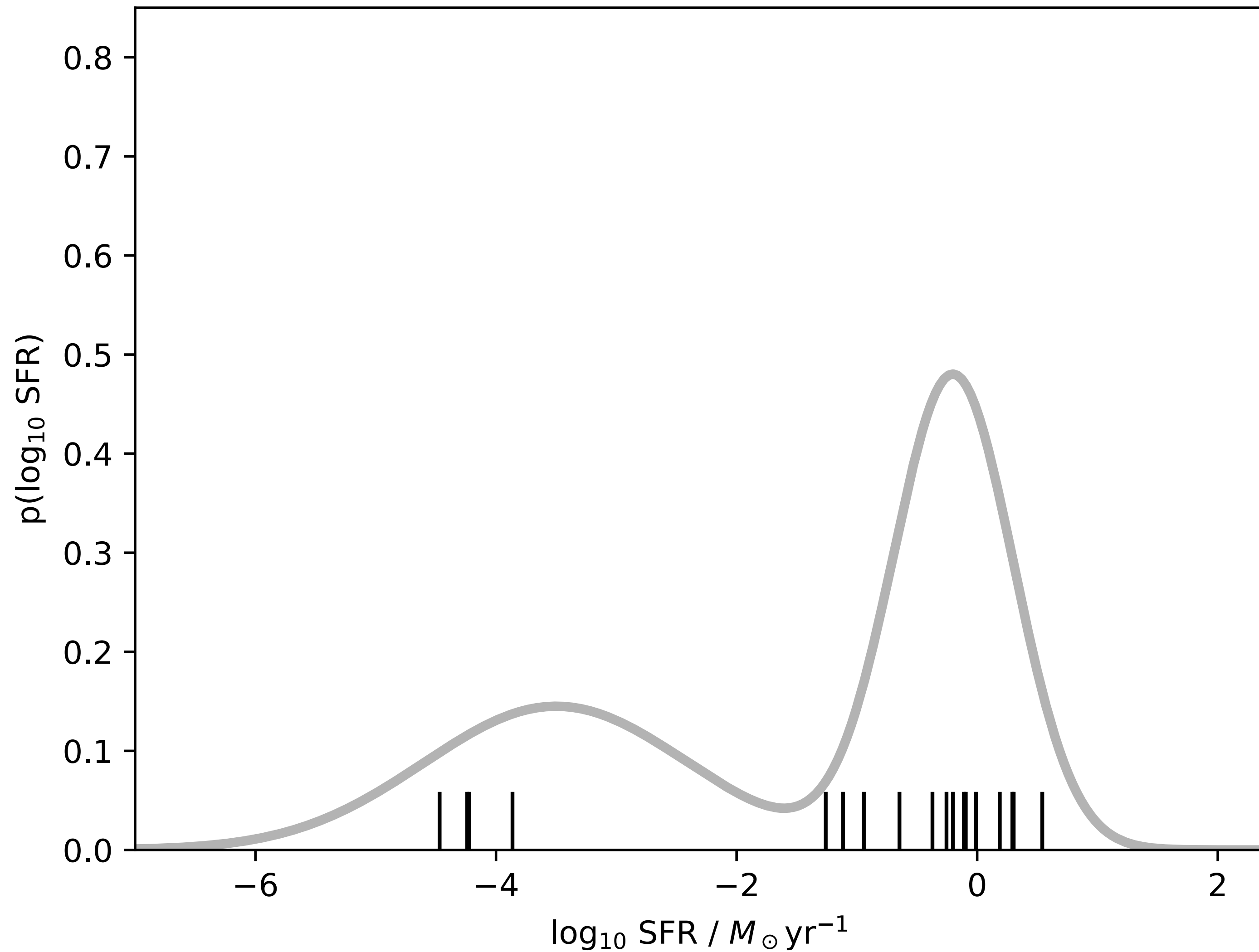
- What if we wanted to calibrate the model to match some observationally-inferred distribution of star formation rates?

CAN WE PUSH THE METHOD FURTHER?



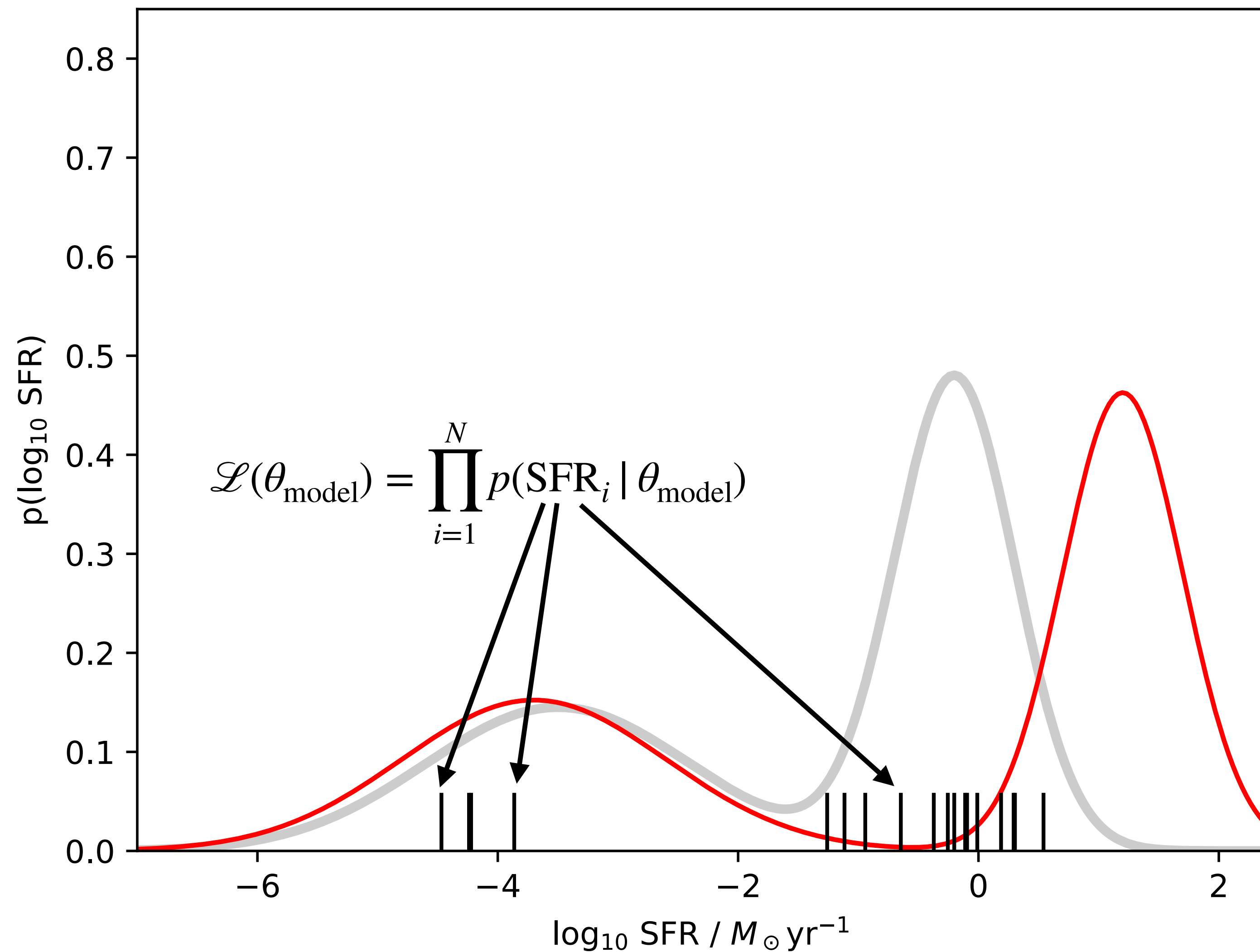
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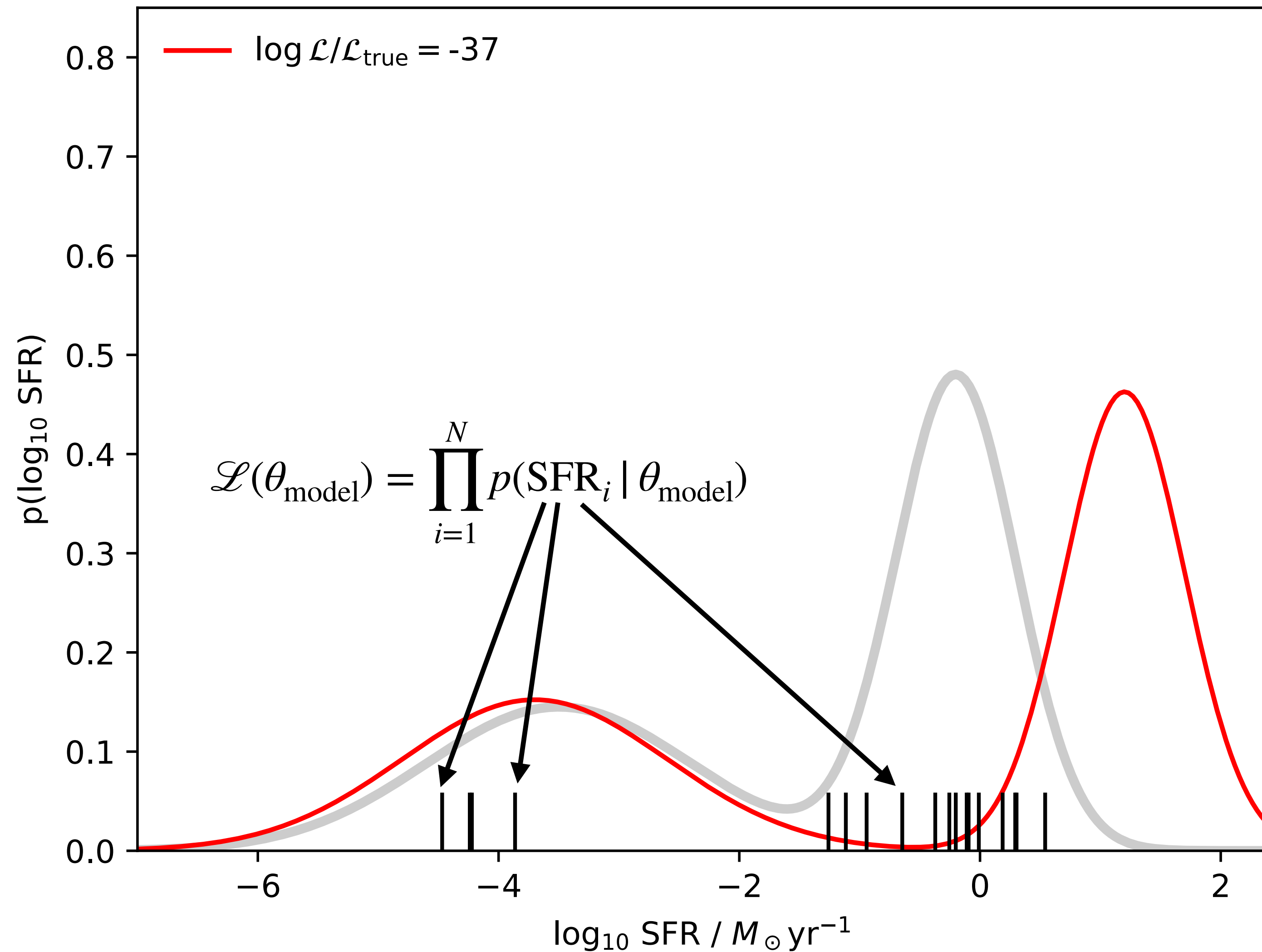
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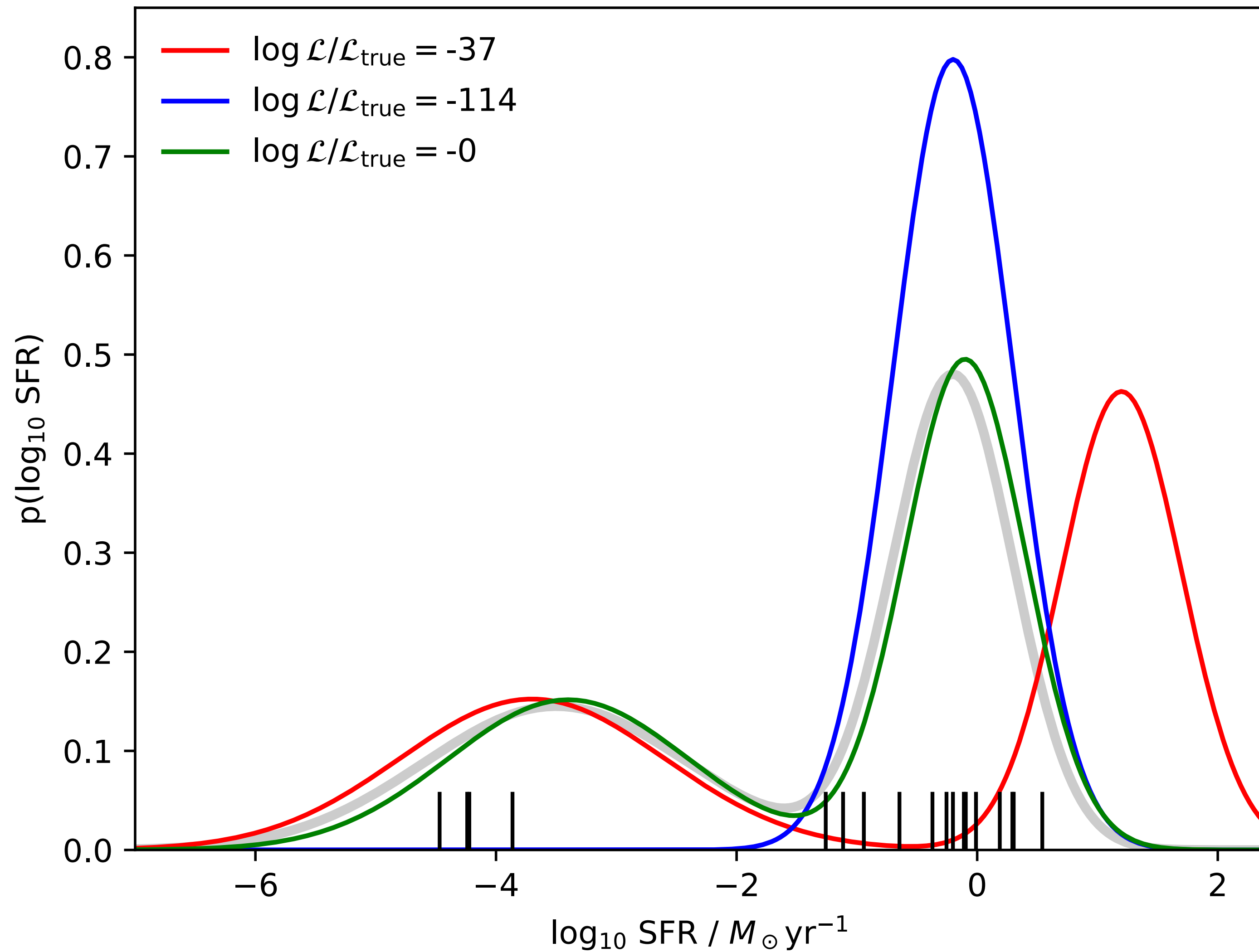
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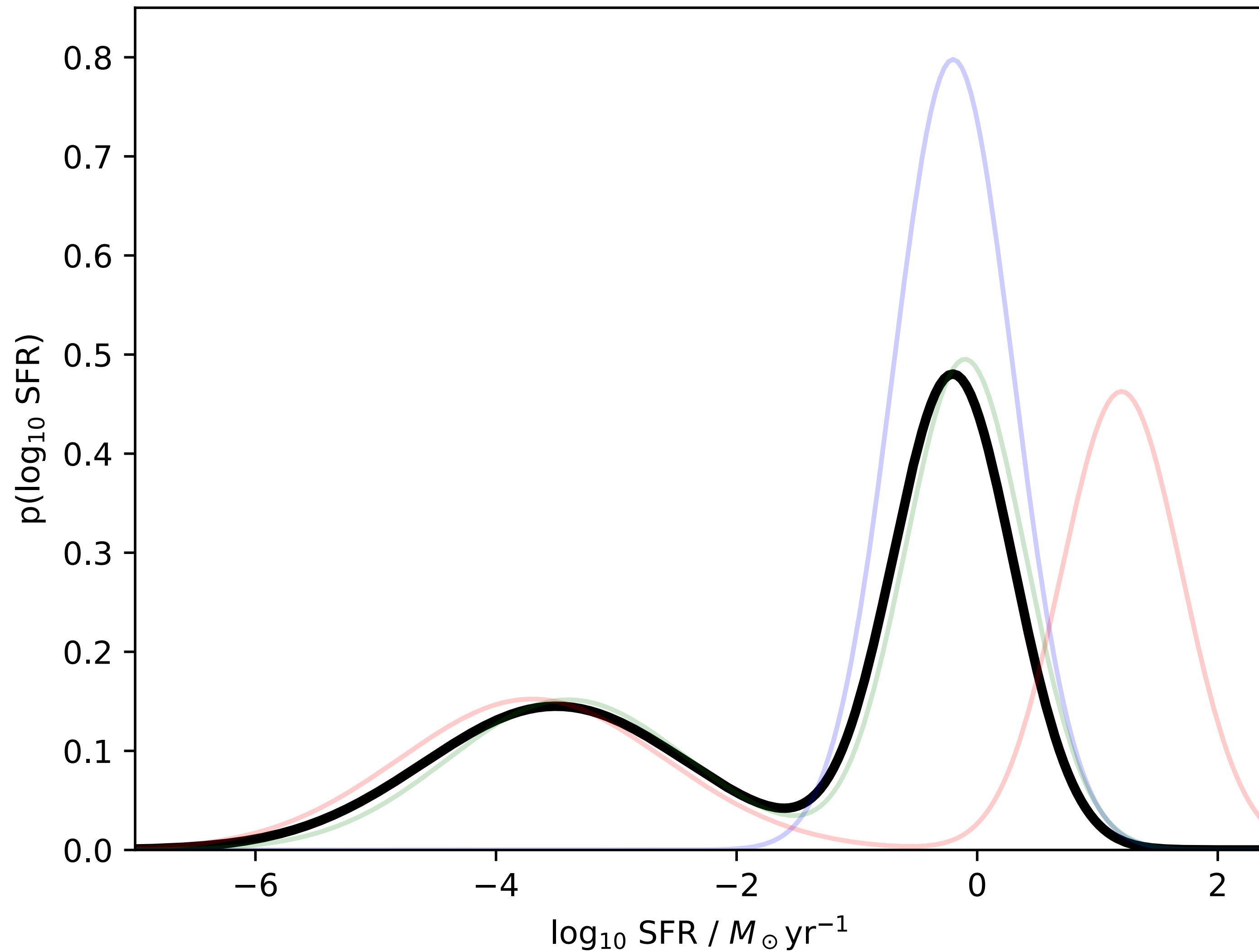
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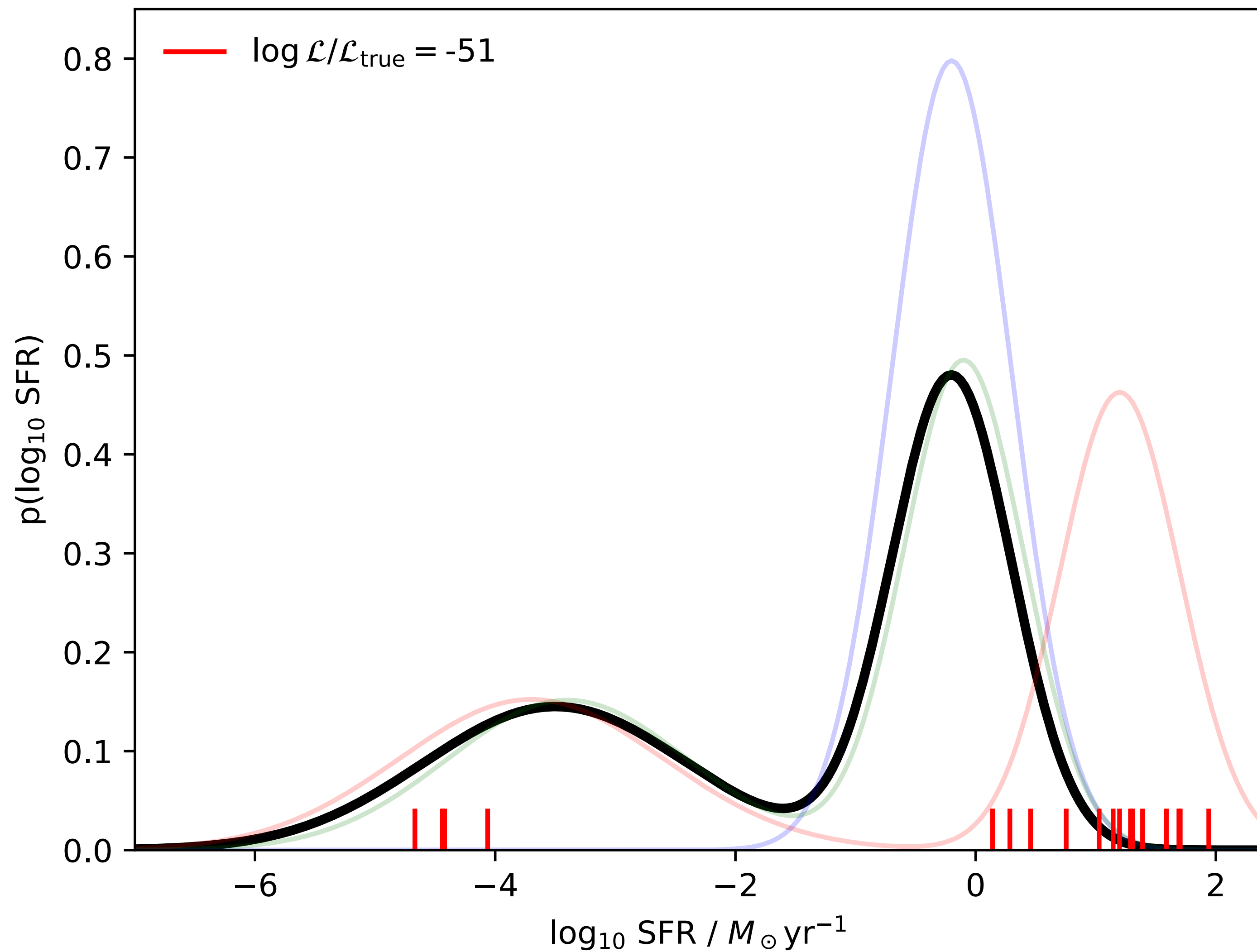
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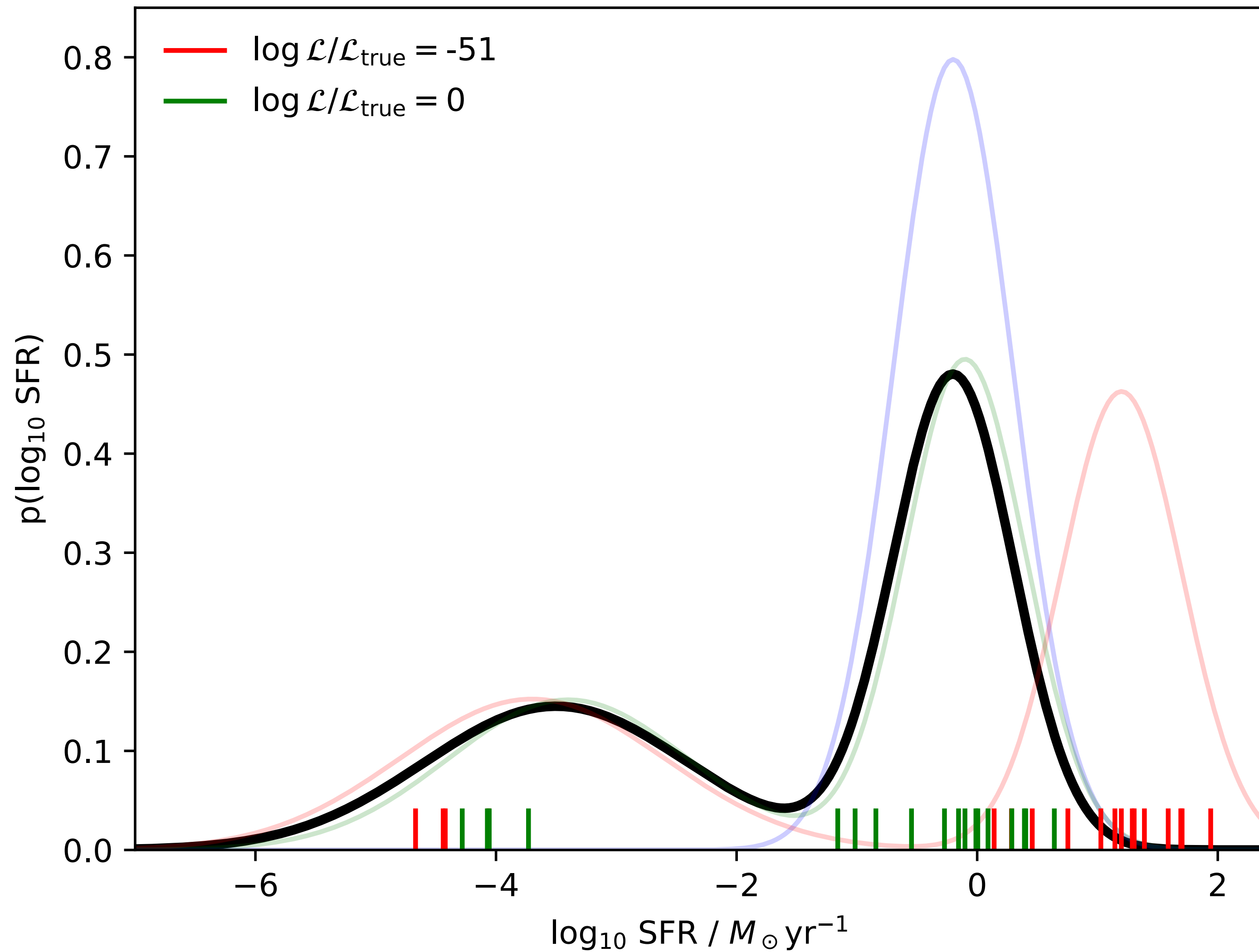
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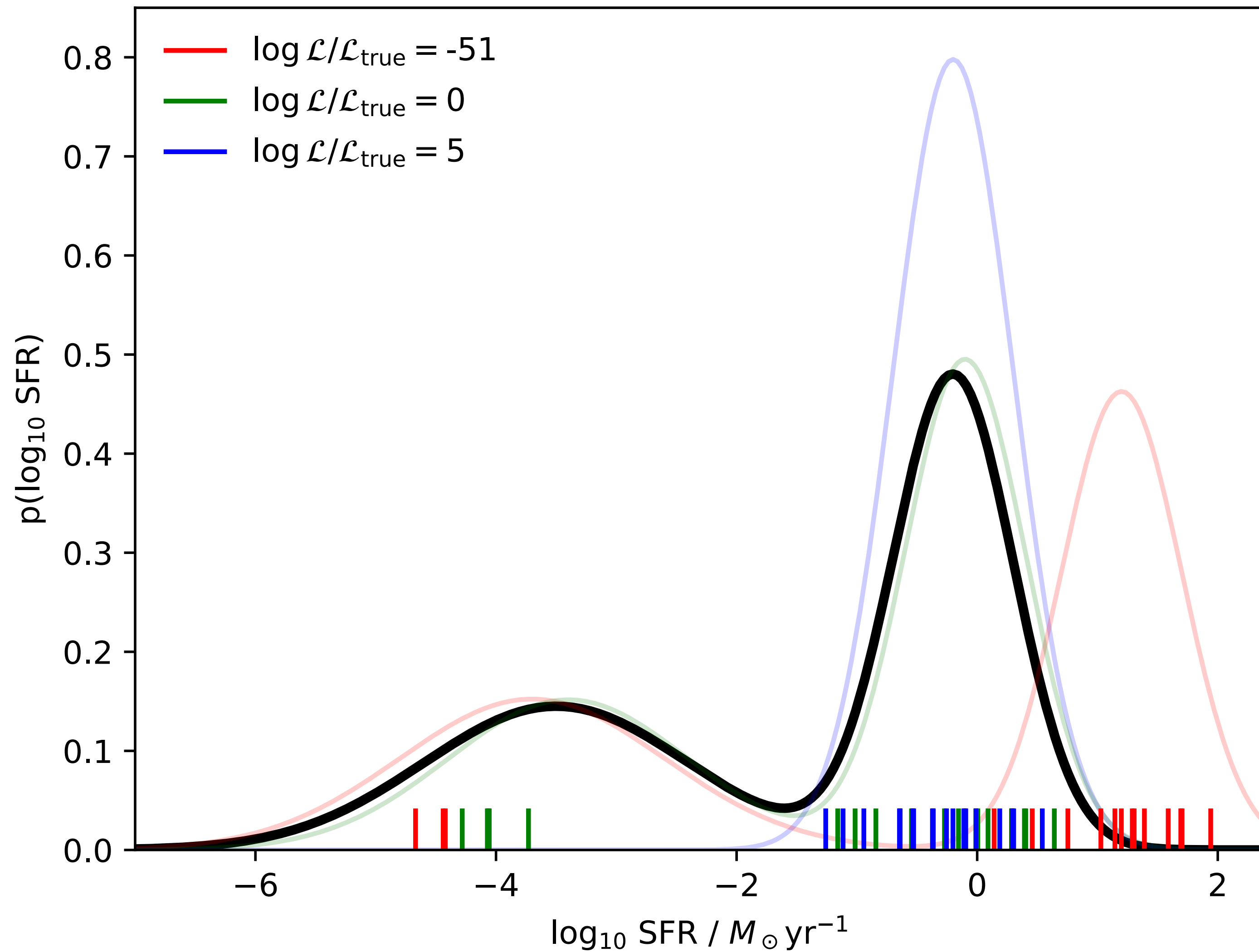
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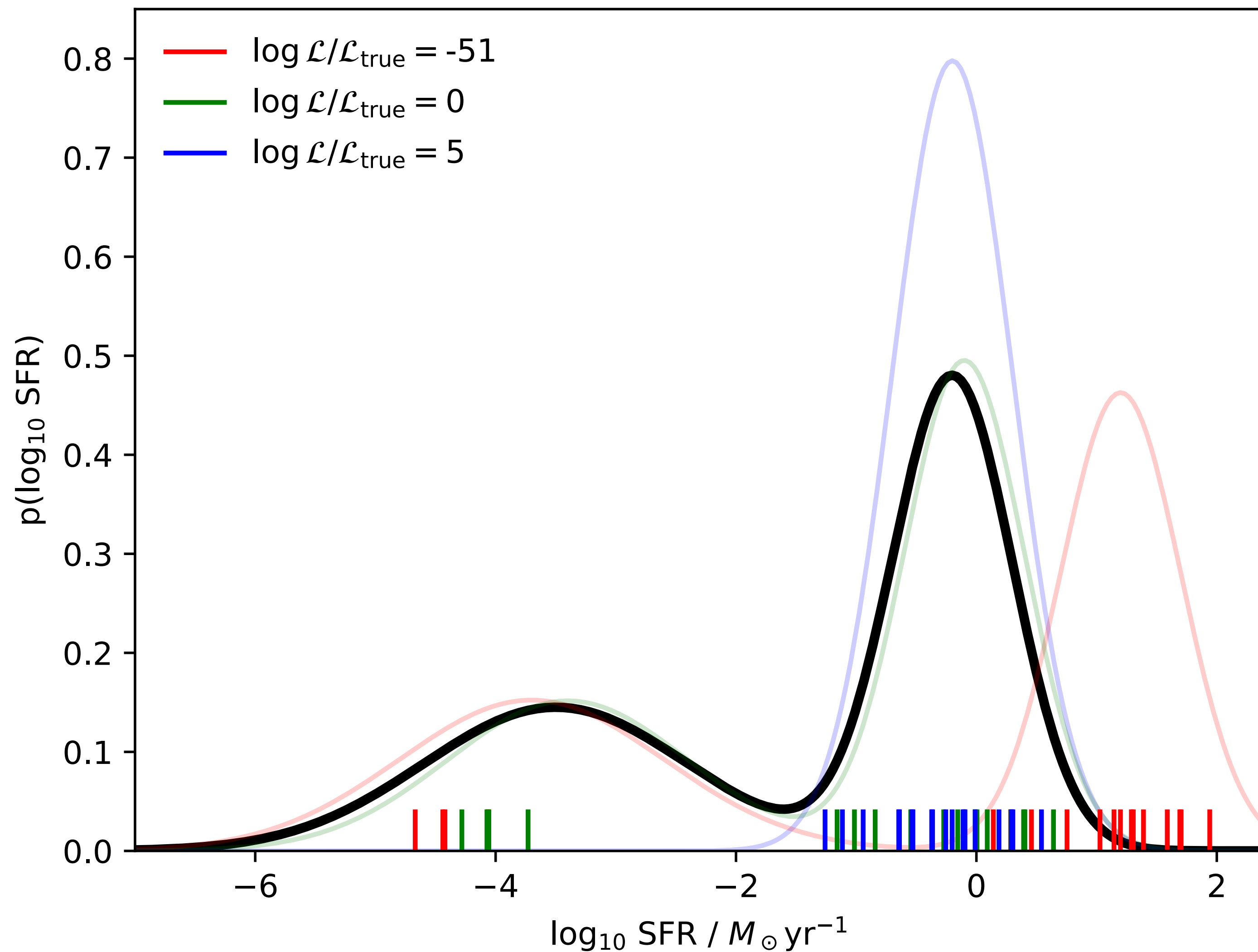
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CAN WE PUSH THE METHOD FURTHER?



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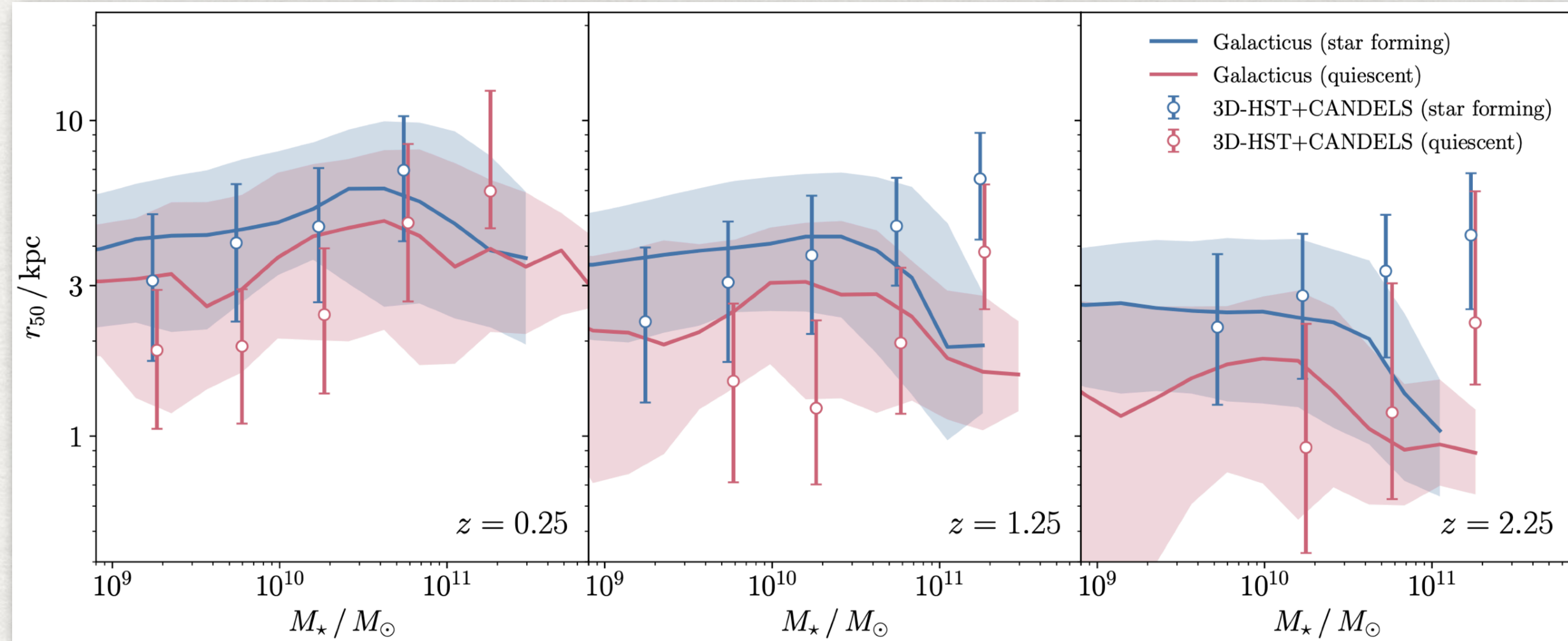
CAN WE PUSH THE METHOD FURTHER?



- What if we wanted to calibrate the model to match some observationally-inferred distribution of star formation rates?
- What statistic do you define, or procedure do you use, that will capture the fact that the green SFRs look like a credible draw from the black distribution, whereas the blue do not?

**BACKUP SLIDES
(GALACTICUS)**

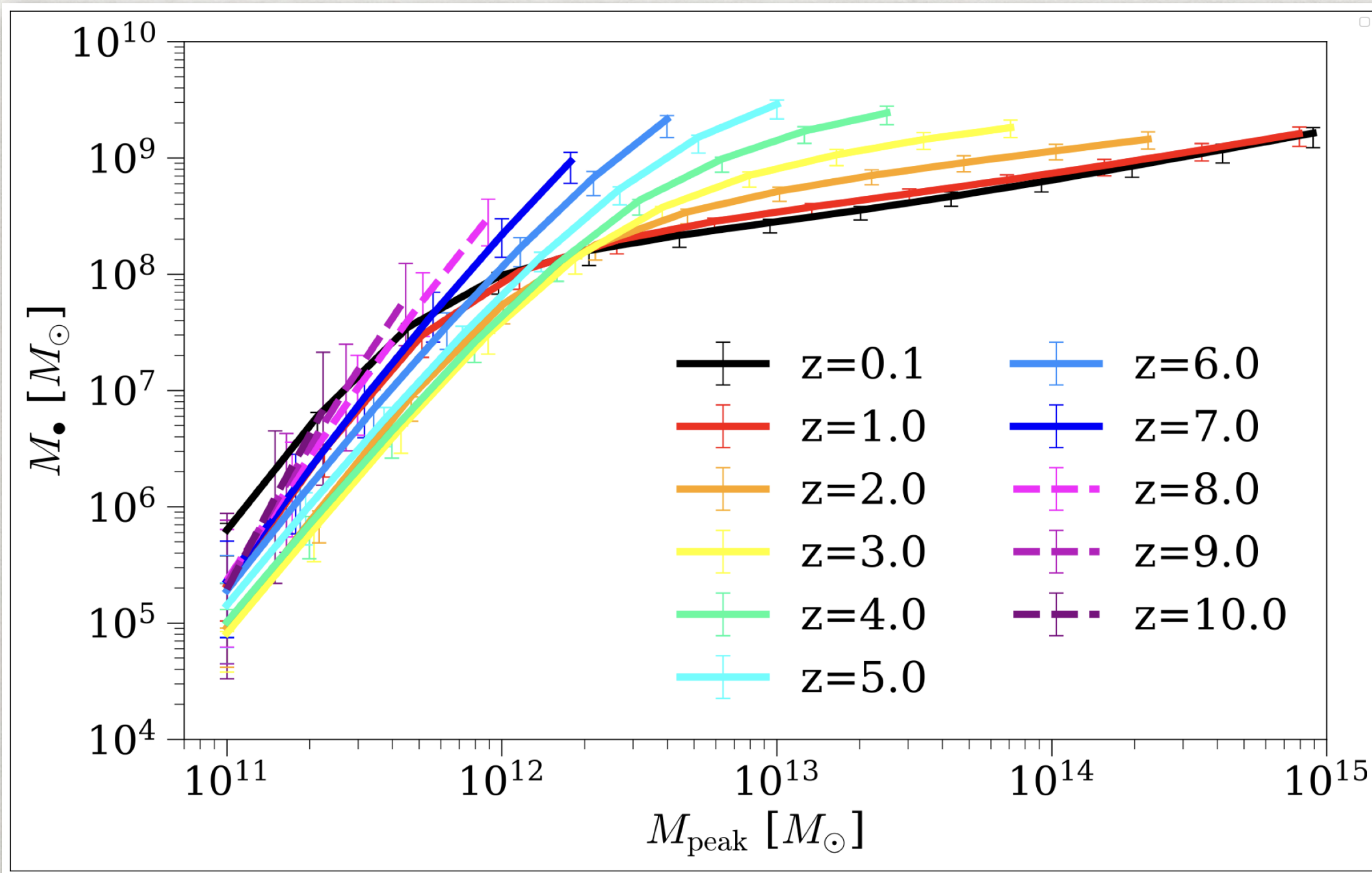
GALAXY SIZES



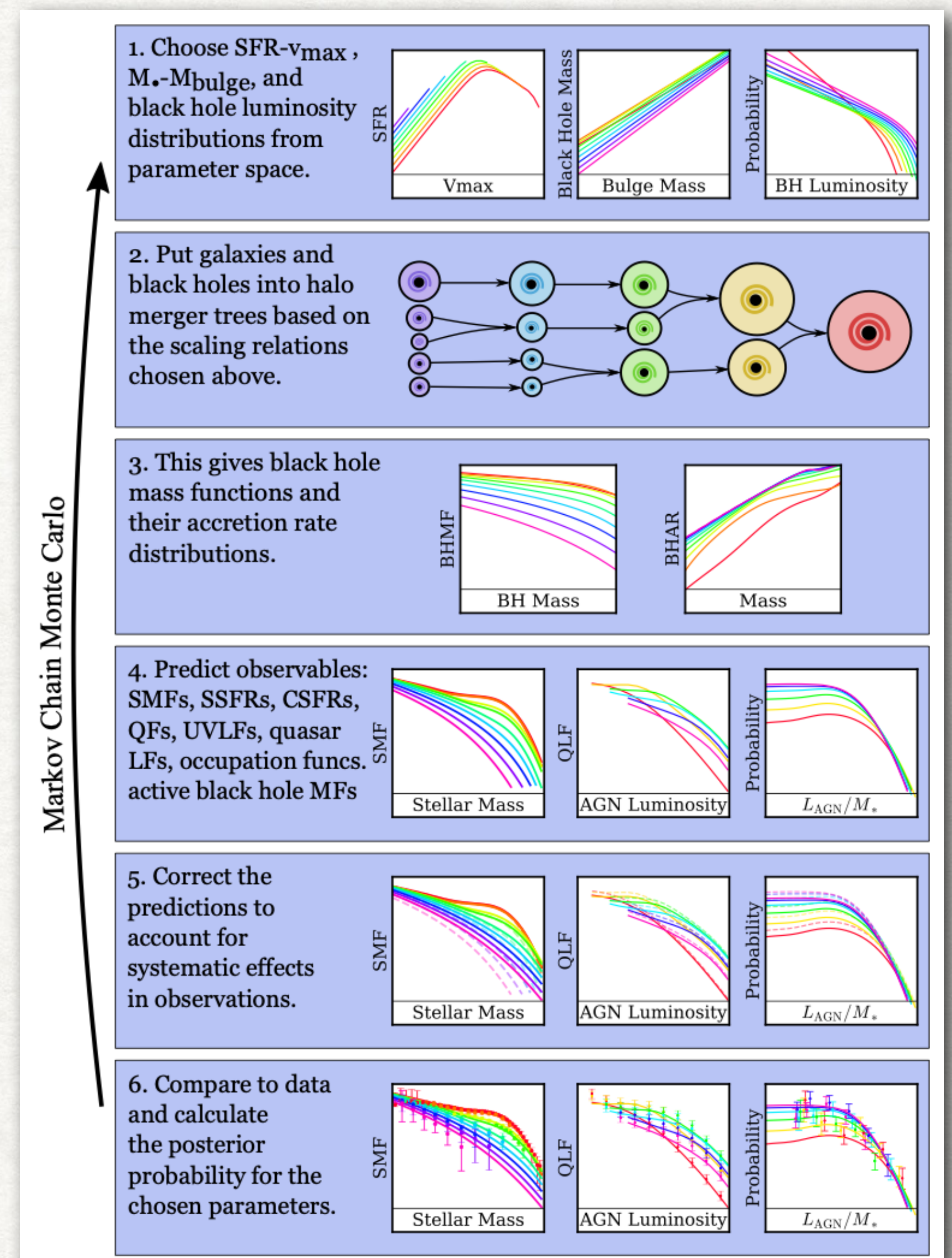
- Evolution of galaxy size with redshift is pretty good
- But the dependence of size on stellar mass is too weak (and our galaxies even get smaller at the very high-mass end!)

SUPERMASSIVE BLACK HOLES

Trinity, Zhang+ 2023

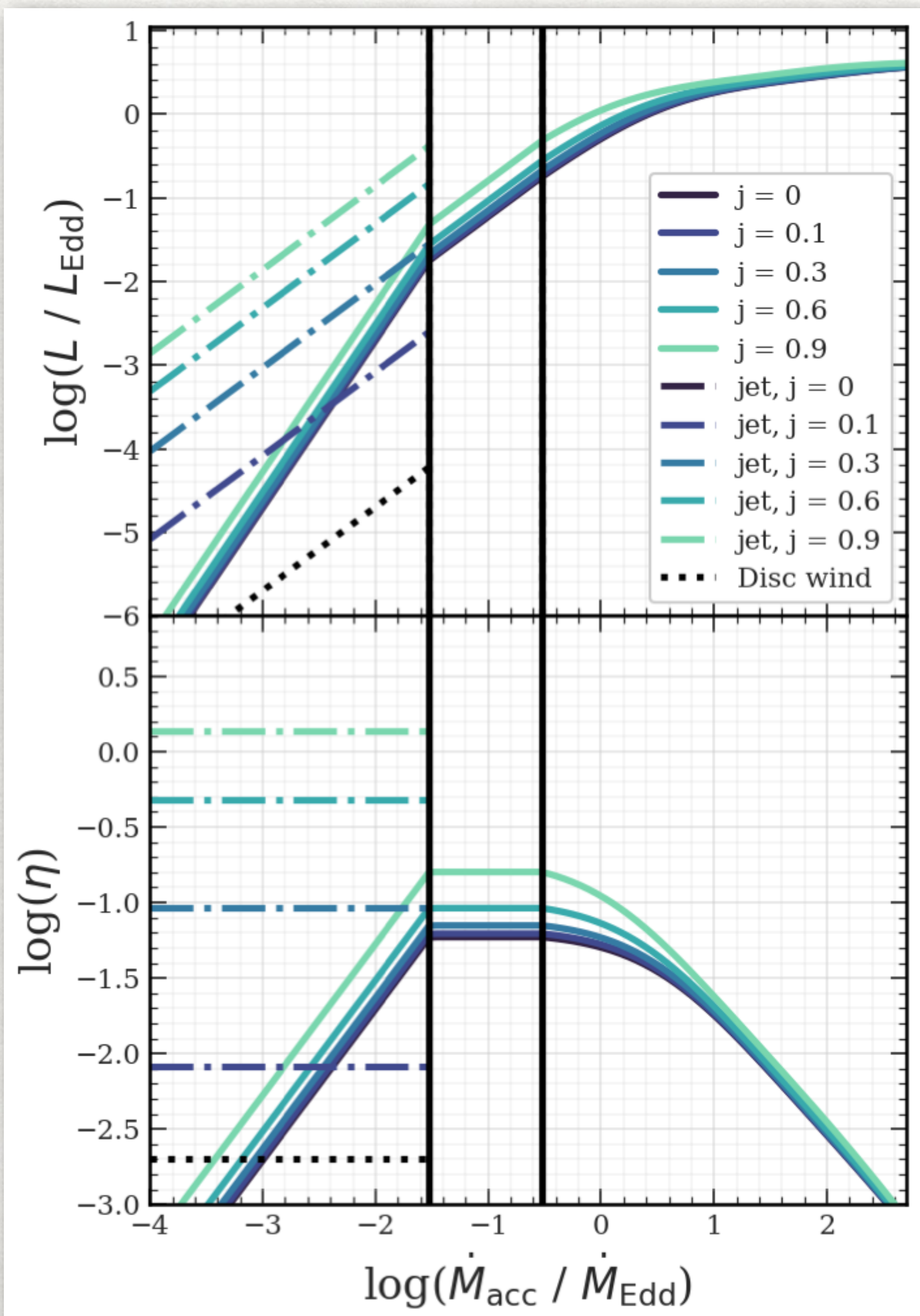


- Inferred relationship between halo mass and black hole mass

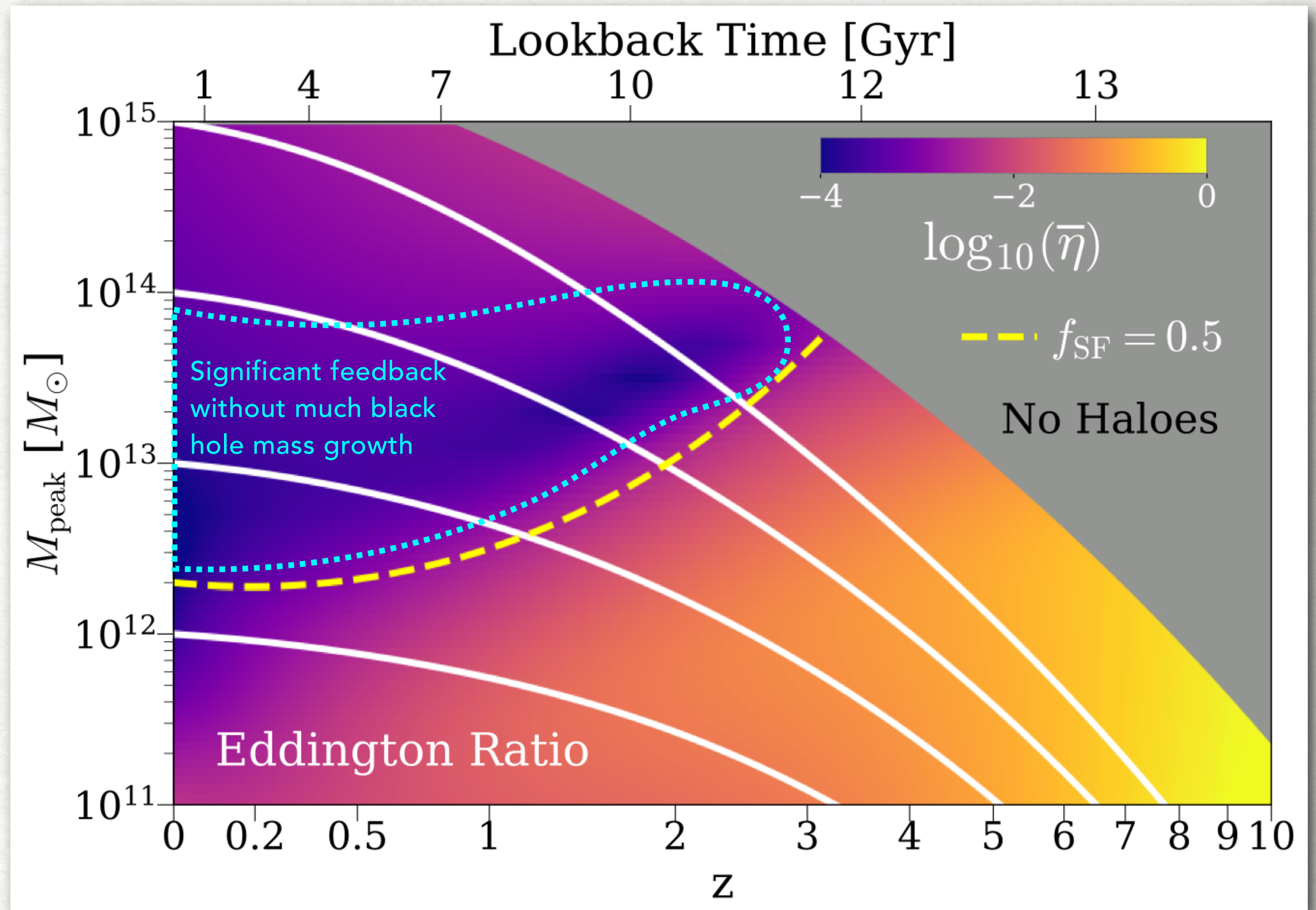


BLACK HOLE FEEDBACK IS COMPLICATED!

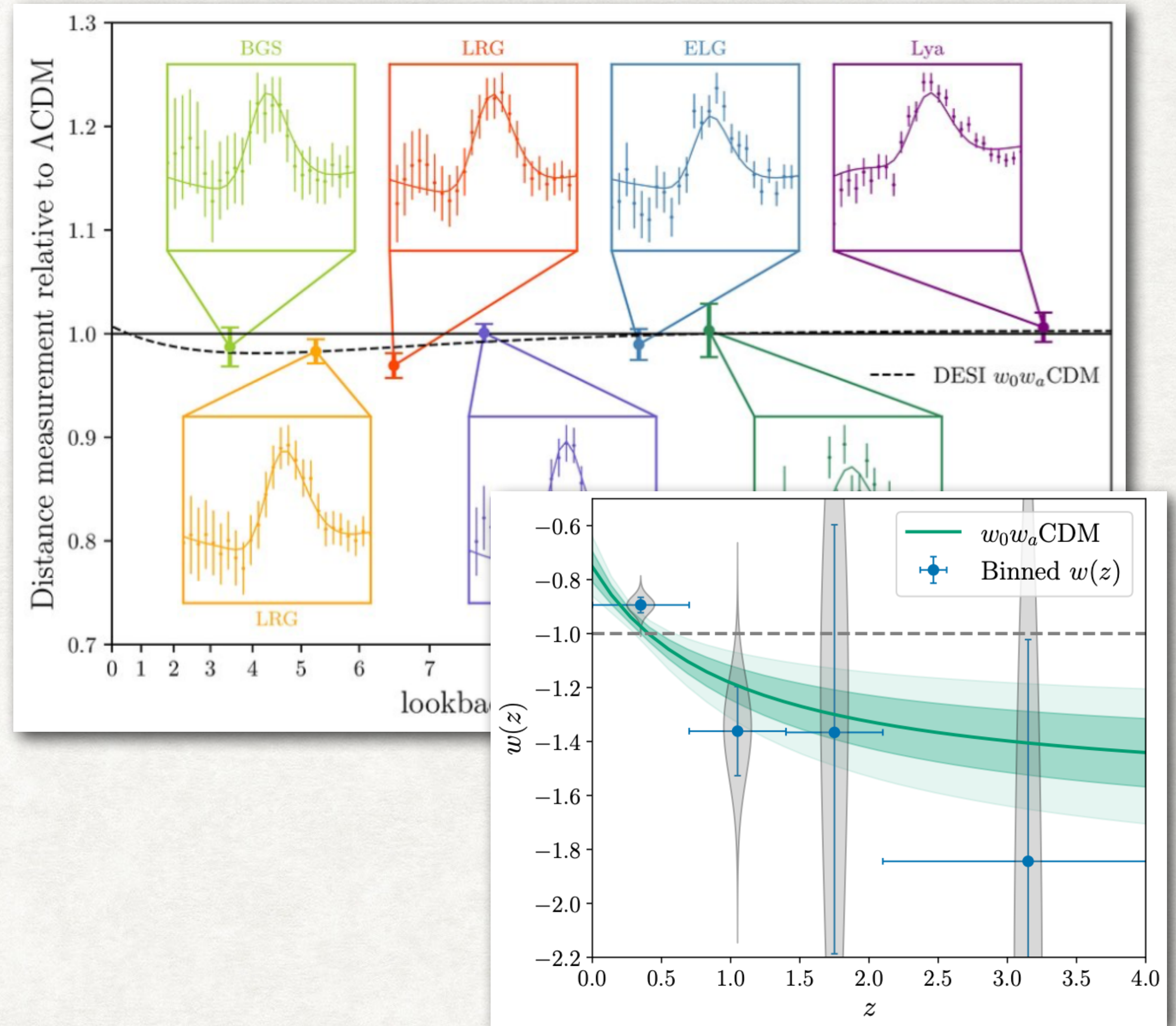
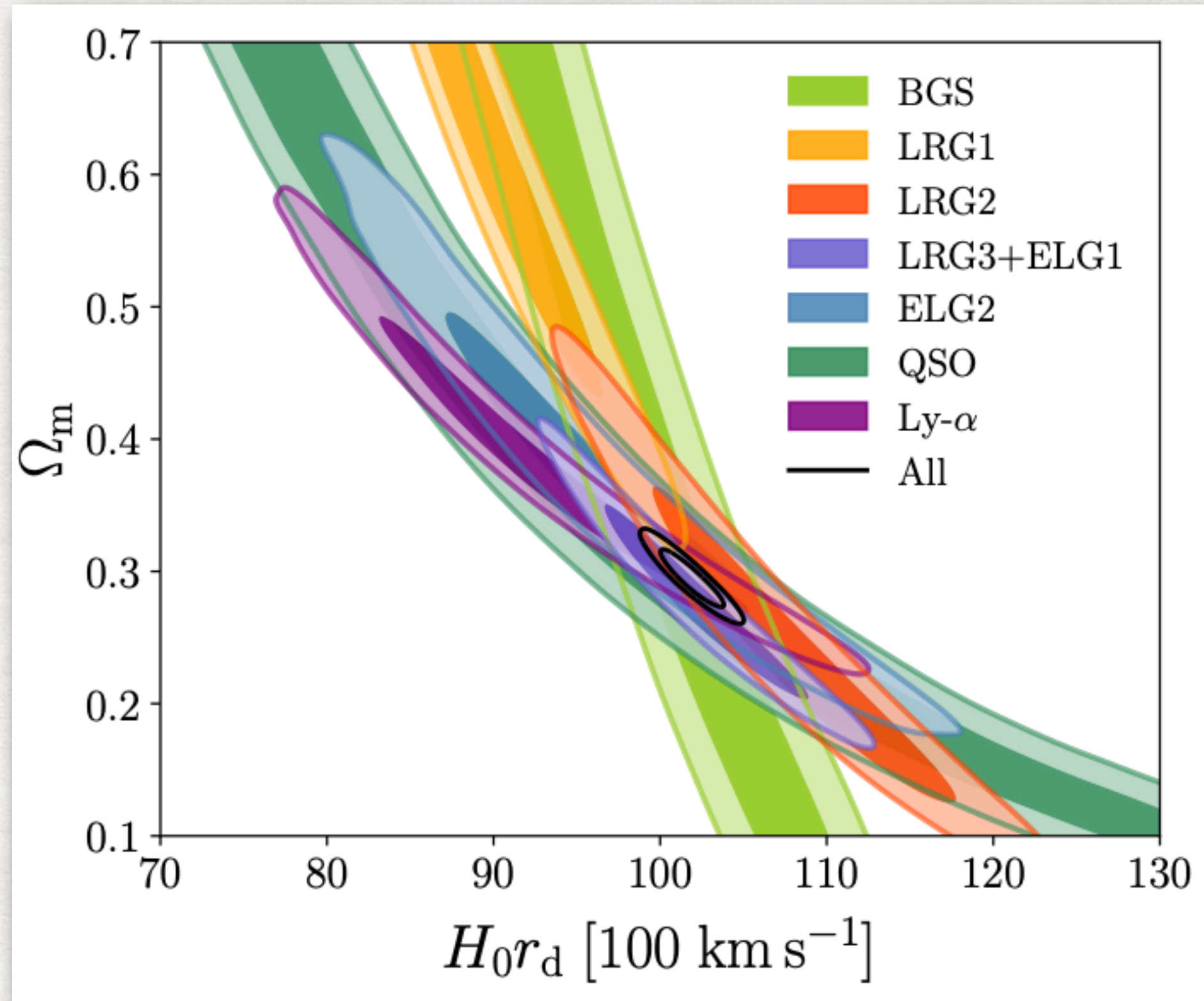
Rennehan+ 2023



Trinity, Zhang+ 2023

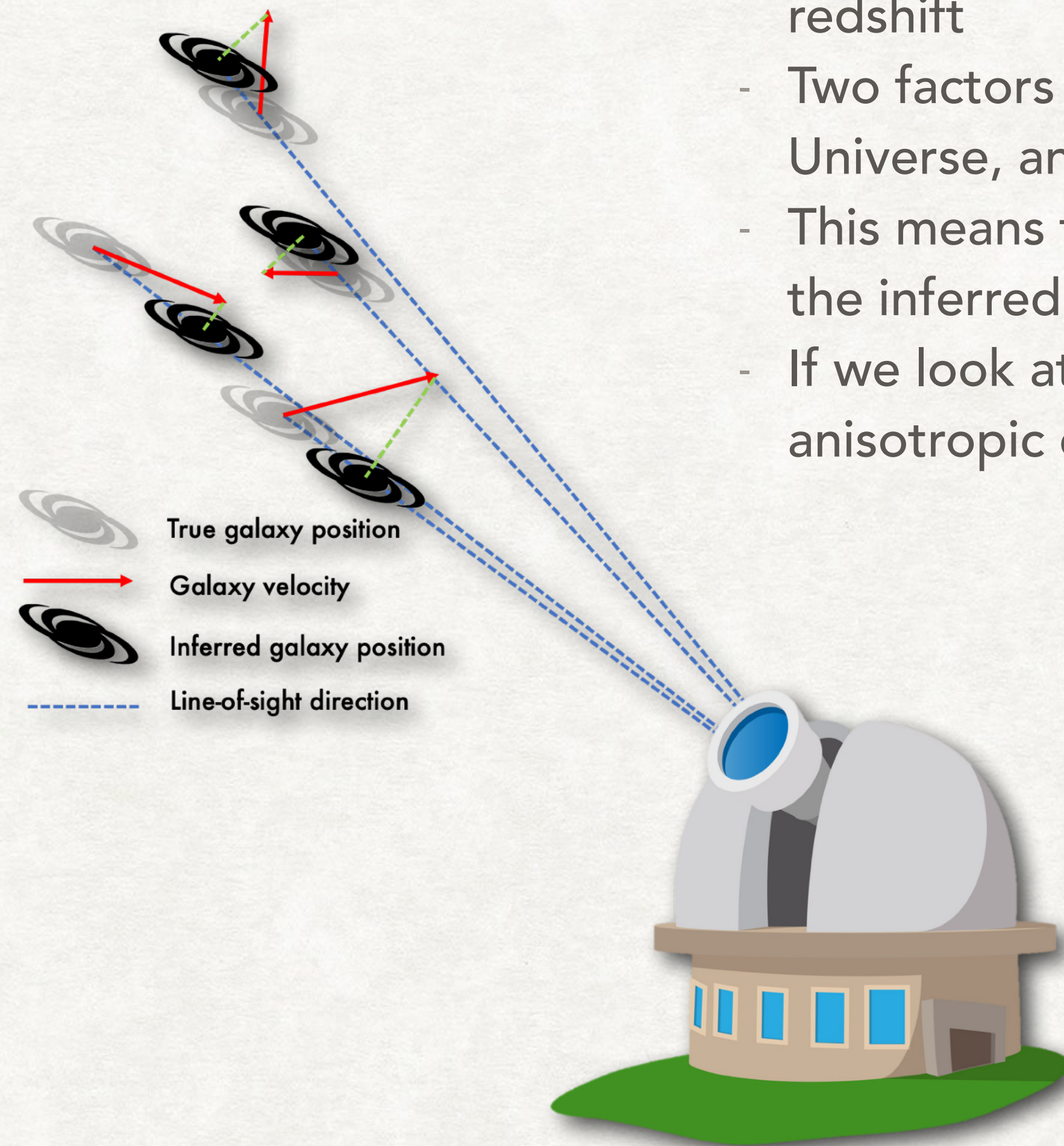


DESI STUFF



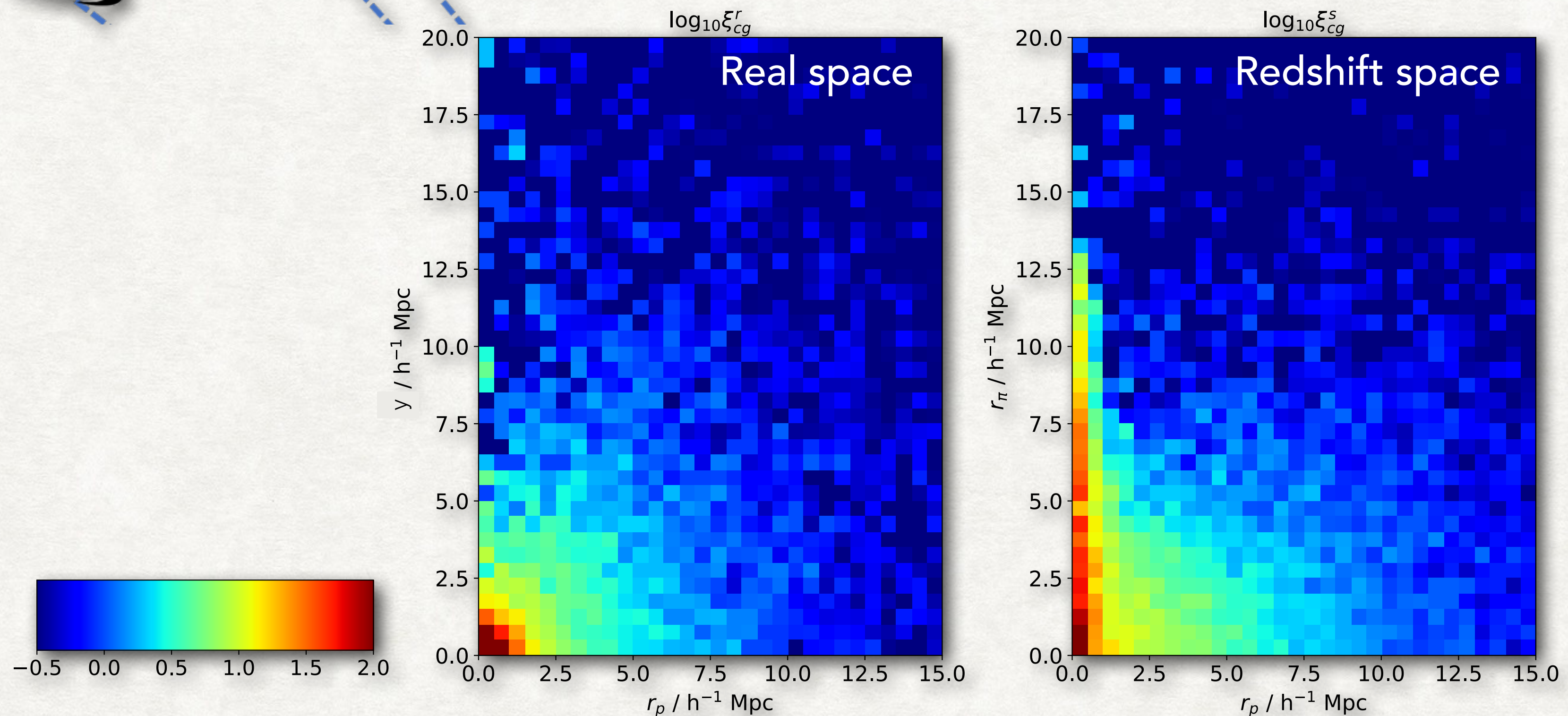
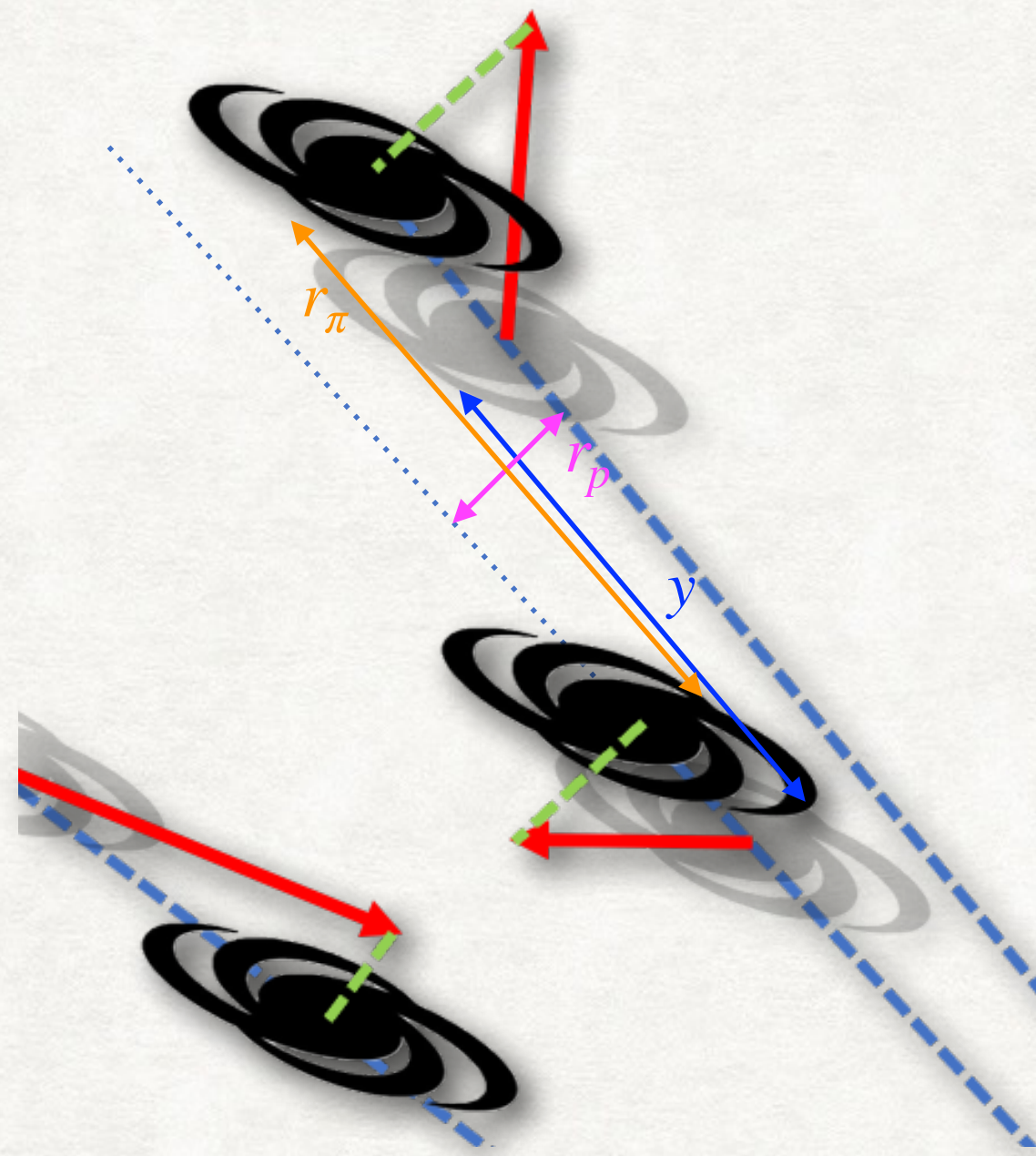
REDSHIFT SPACE DISTORTIONS

- In a galaxy redshift survey, the position of each galaxy is described by its angular position on the sky and its redshift
- Two factors contribute to redshifts: the expansion of the Universe, and the "peculiar velocities" of galaxies
- This means that the peculiar velocities of galaxies affect the inferred positions of galaxies from a redshift survey
- If we look at the clustering of galaxies, it becomes anisotropic due to these "redshift space distortions"



THE CORRELATION FUNCTION

- The relative number of galaxy pairs with a particular separation, compared with the number expected if galaxies were randomly distributed
- Observationally, we measure this in "redshift space"
- Below you can see how this differs from the true ("real space") clustering

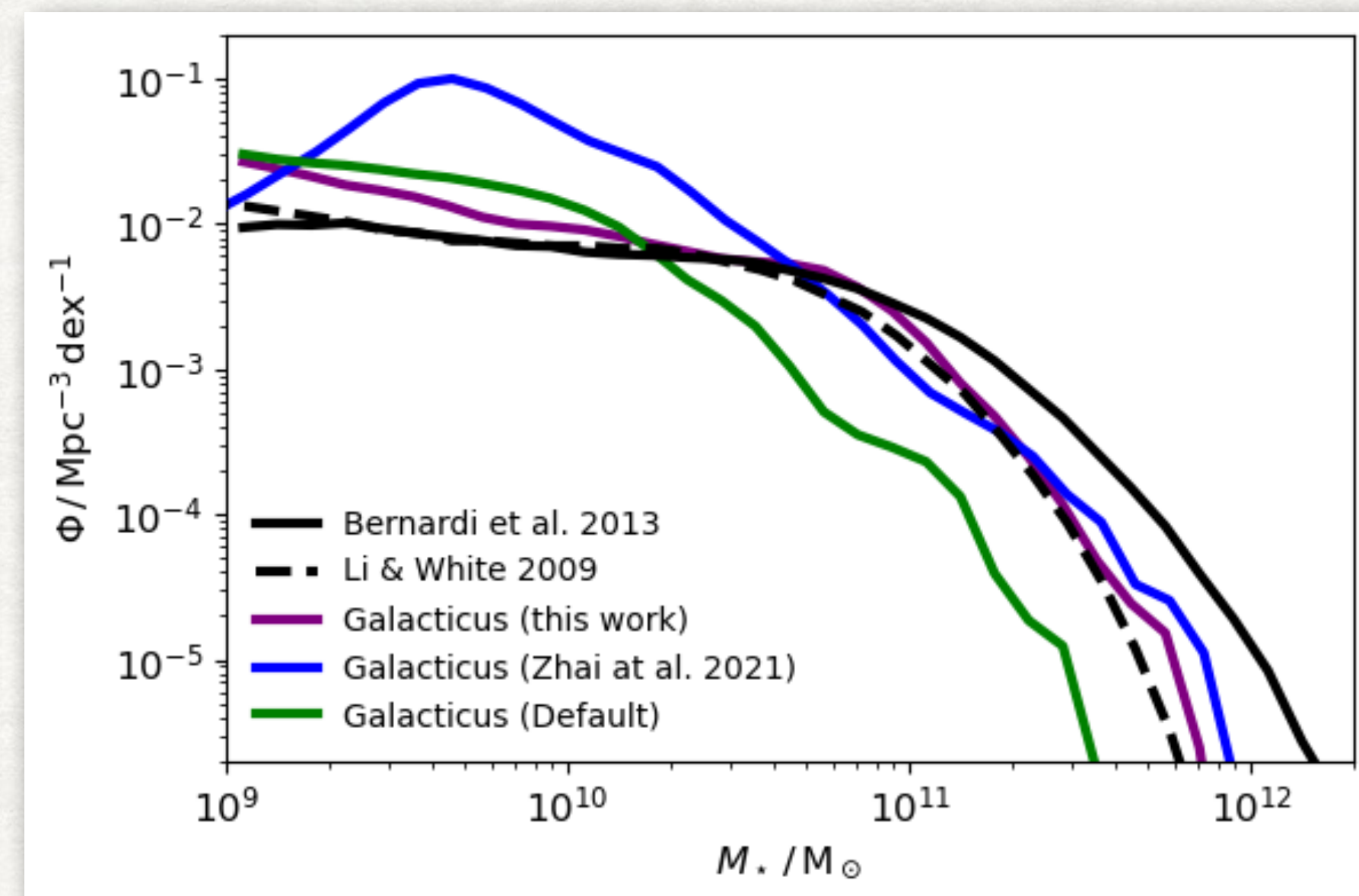
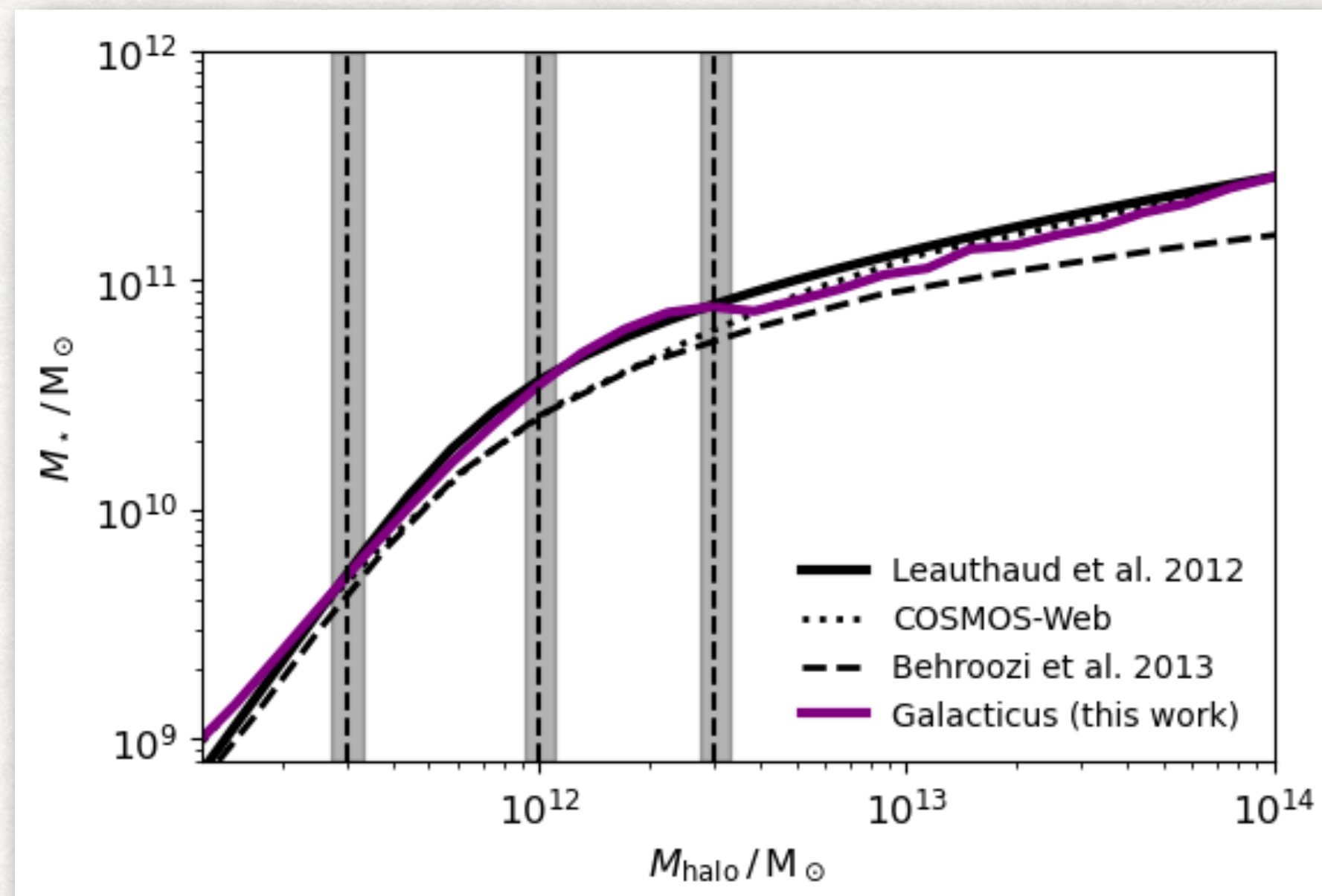


DEMONSTRATION OF HOW THE METHOD WORKS

Here, we fit to the Leauthaud Mstar-Mhalo relation in three halo mass bins.

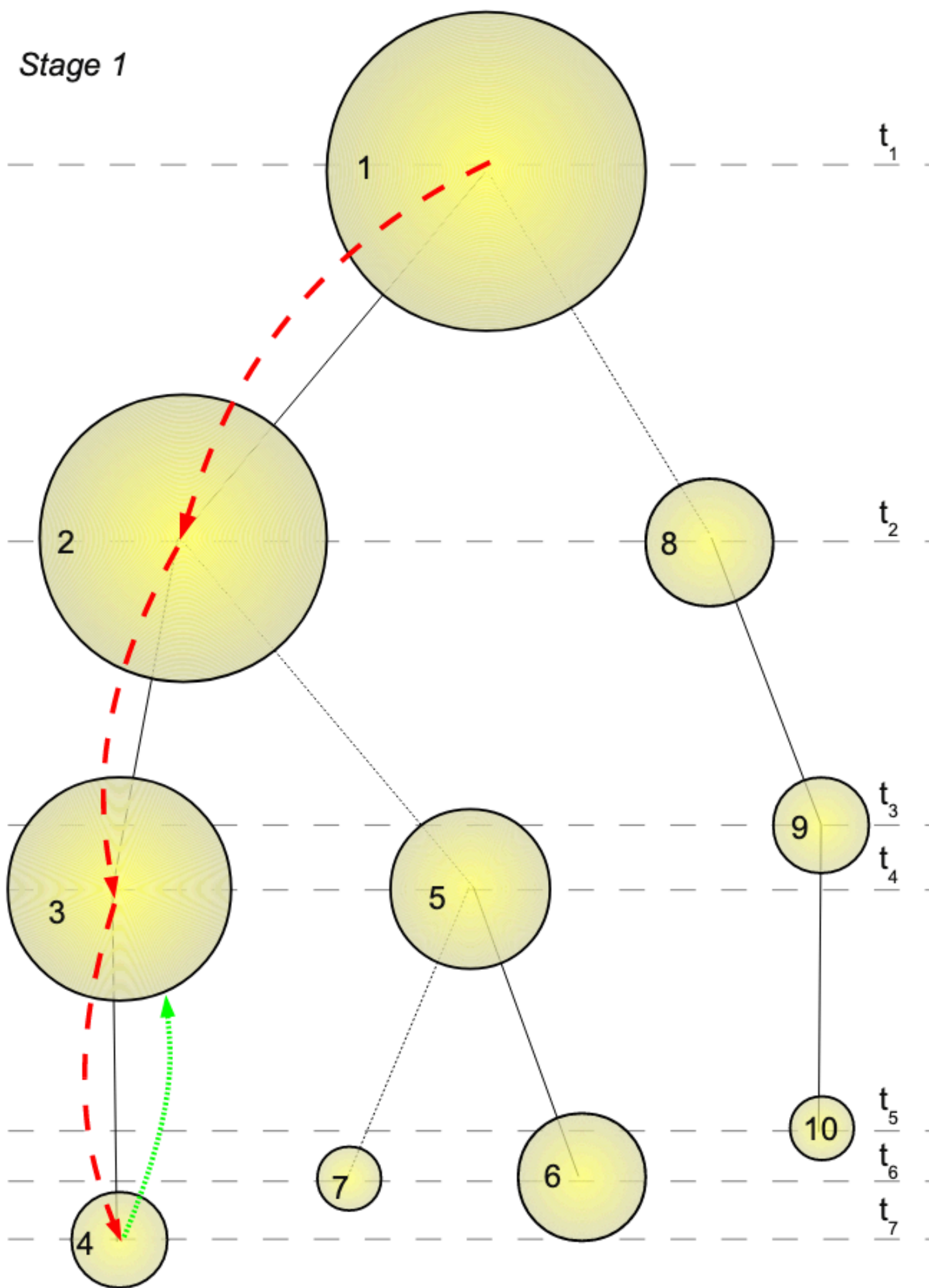
The best fitting model does well “between” bins, but also does reasonably well when extrapolated outside of the halo mass range calibrated to.

And matching the stellar mass - halo mass relation (and its scatter) means that we do a good job of matching to the stellar mass function (as expected).

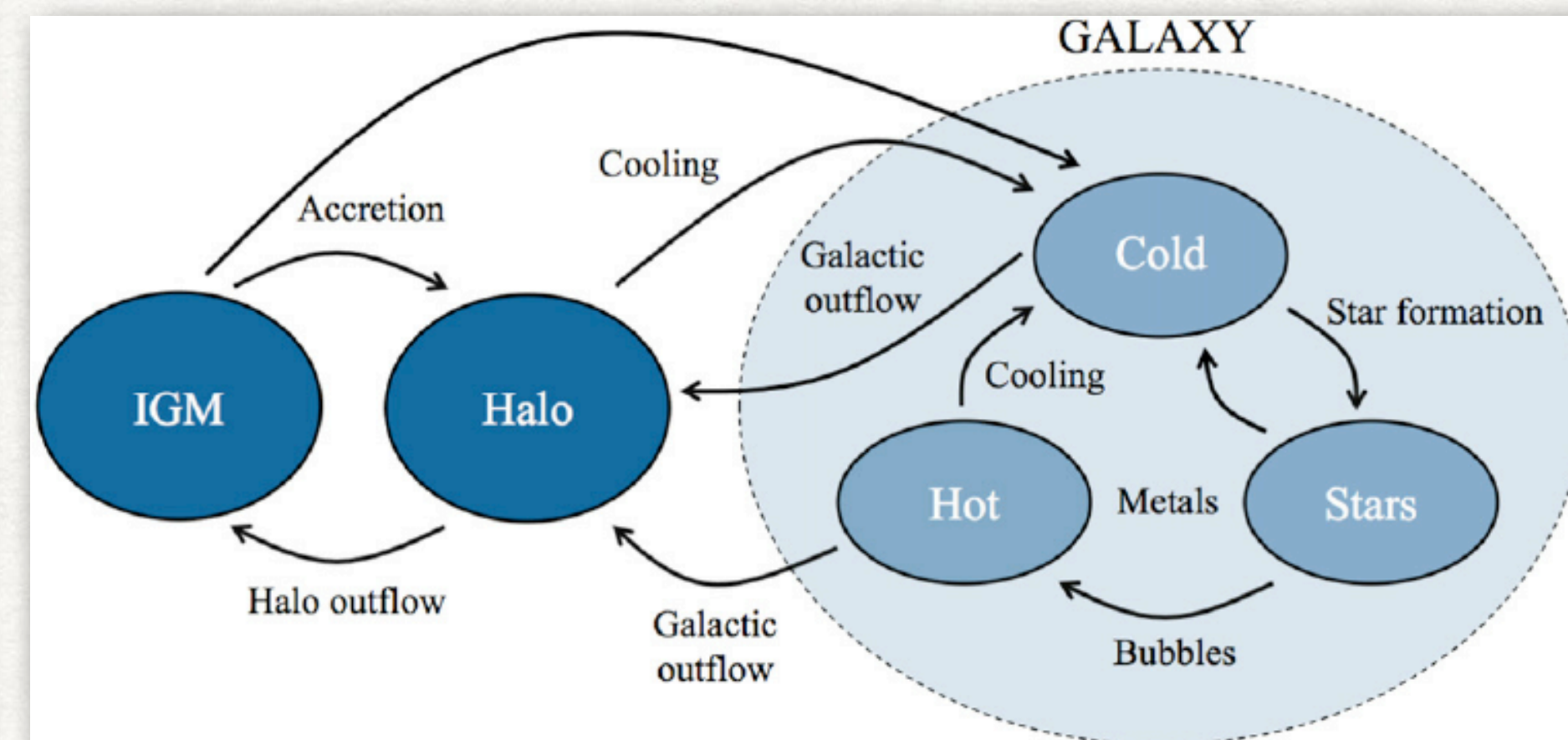


SEMI-ANALYTIC GALAXY FORMATION

Using Galacticus, a code written by Andrew Benson at Carnegie



- Take DM-only merger tree from a simulation.
- Tie gas accretion to DM accretion.
- Have a set of differential equations describing how baryonic mass "flows" between different components of a "galaxy".
- Also treat mergers in some way (i.e. some fraction of disk stars might end up in a bulge)



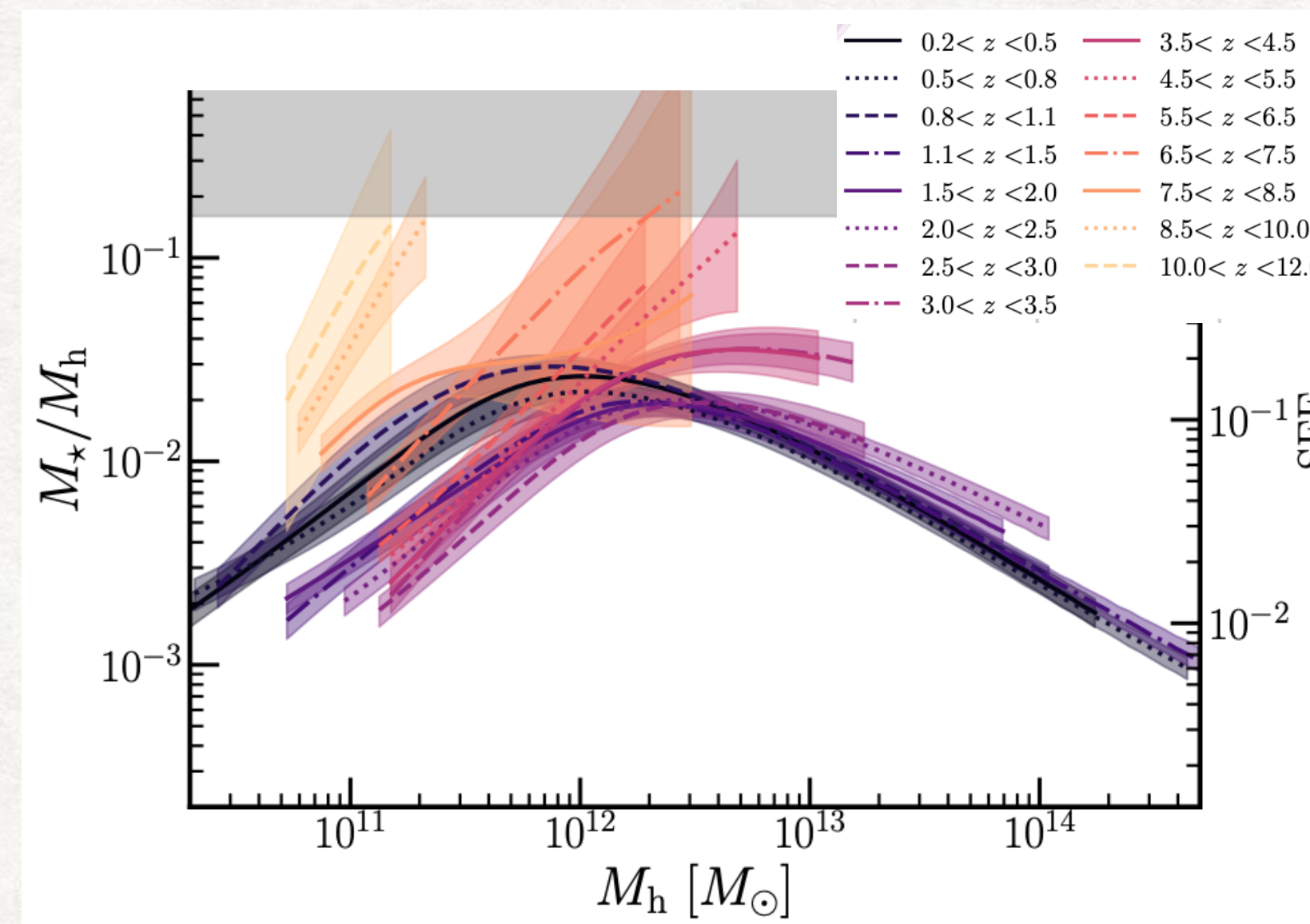
- Galaxy described by quantities such as: M_{disk}^* , M_{bulge}^* , $M_{\text{disk}}^{\text{gas}}$, R_{disk}^* , $Z_{\text{disk}}^{\text{gas}}$, etc.

ONGOING WORK

- Adding in a model for emission line production (see Sachi Weerasooriya's poster)
- Running the calibrated model on the UNIT simulation to generate galaxies on a lightcone
- Using newly-calibrated Galacticus model in the Galaxy Redshift Survey PIT Grism Simulations (see Ashley Ross's talk on Thursday)

WHAT NEXT?

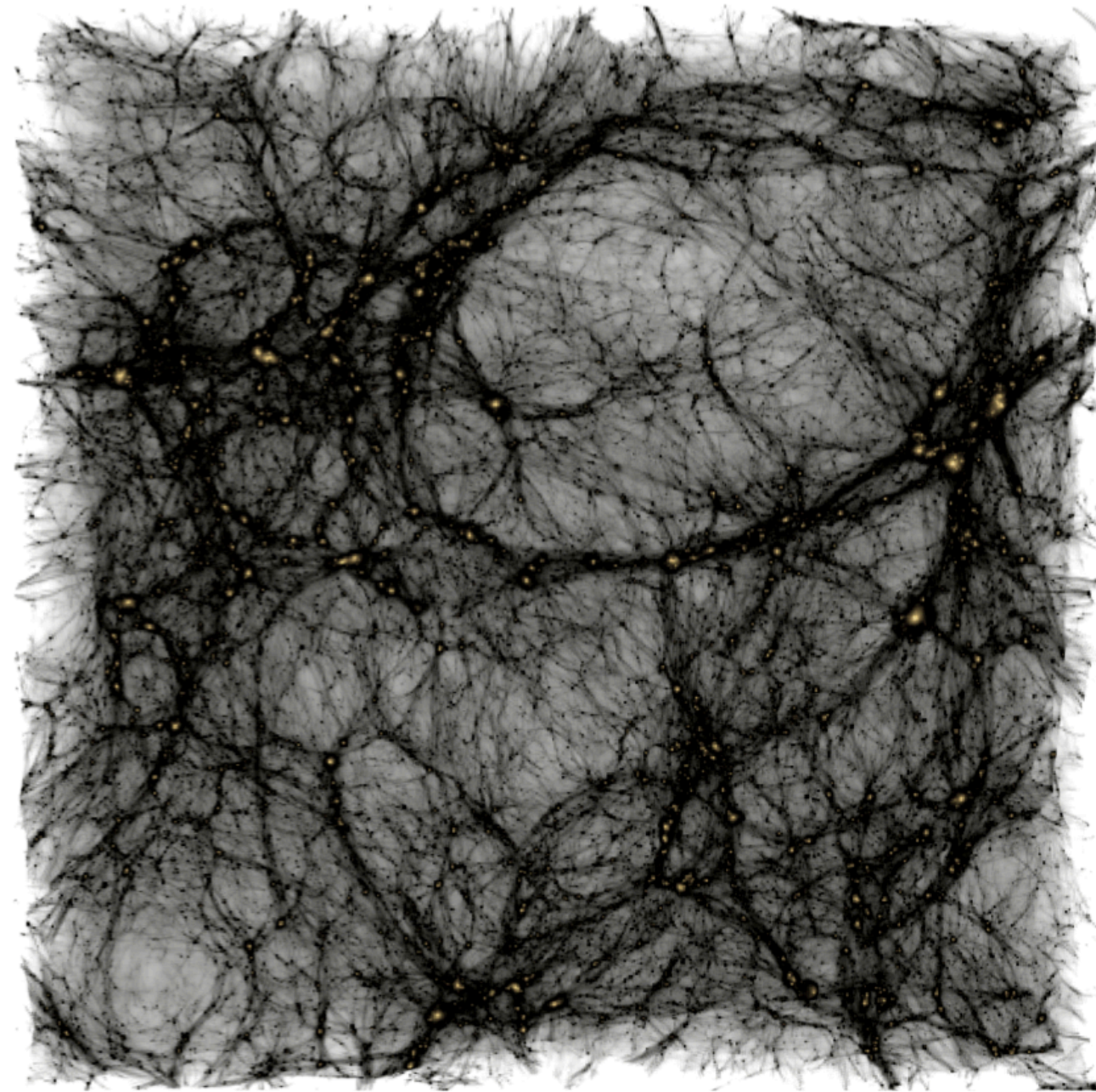
- Explore alternative feedback/star formation/etc. prescriptions that may allow for a better match to observations across a range of redshifts
- Calibrate to higher-redshift data
- Additional calibration data / model diagnostics (galaxy metallicities, black hole masses, etc.)
- Use alternatives to MCMC, such as particle swarm optimization (we primarily care about finding a good model, rather than posteriors on Galacticus model parameters)



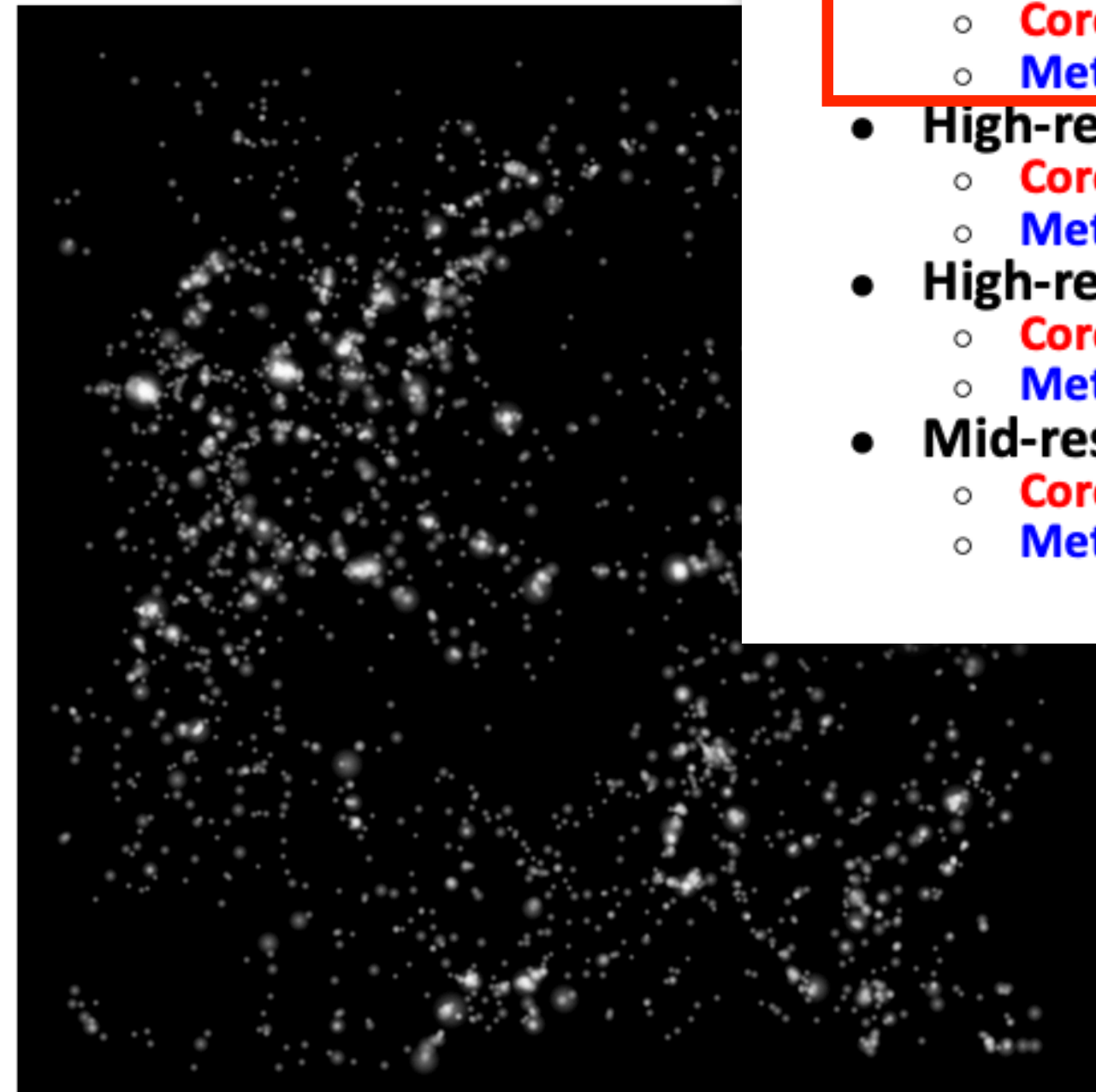
Shuntov et al. 2025
(COSMOS-Web)



Wechsler &
Tinker 2018



galaxy-halo
connection



Approaches to modeling the galaxy-halo connection

← physical models		empirical models →		
Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models
Simulate halos & gas; Star formation & feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

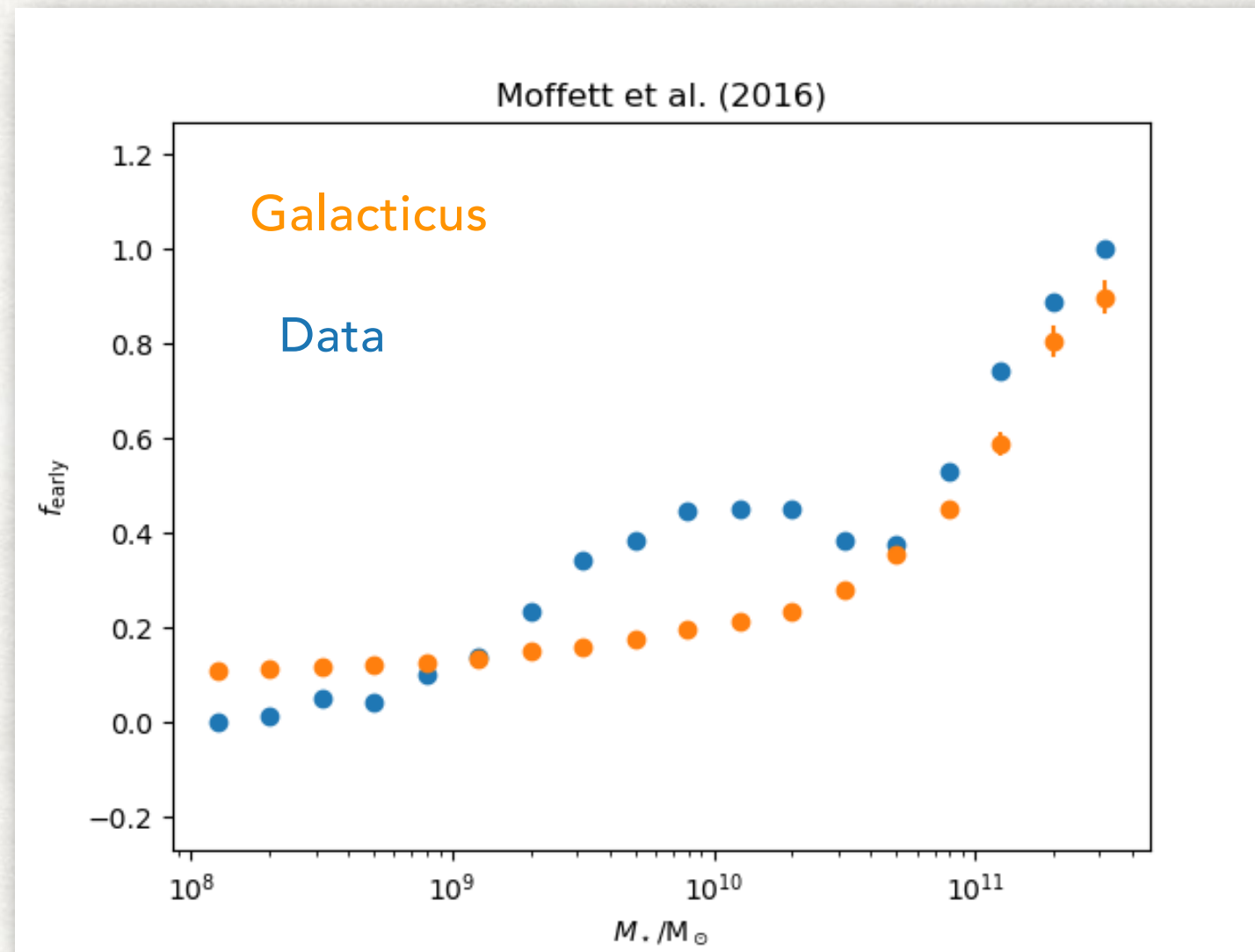


Diversity of galaxy mocks for diverse applications

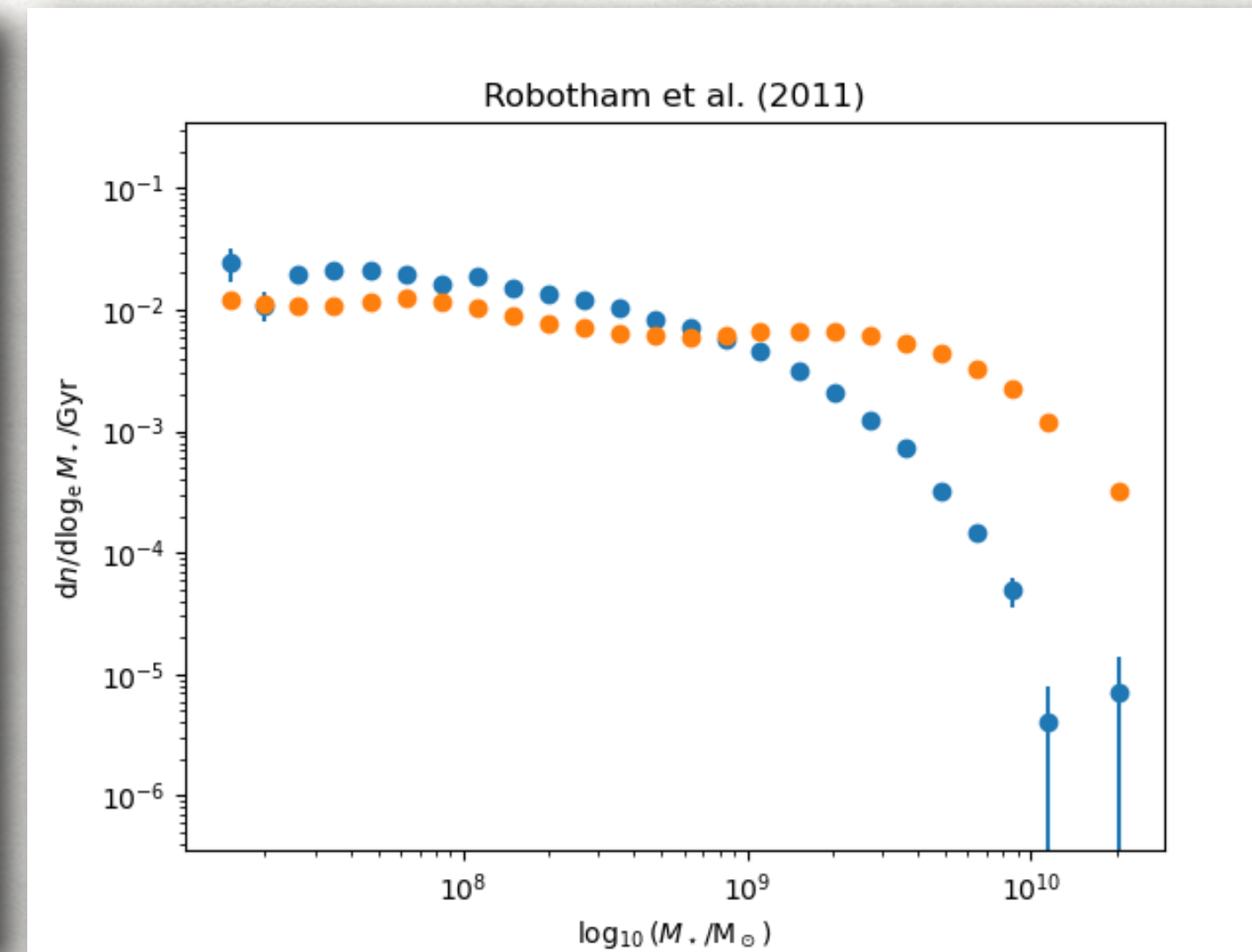
- **High-res small-volume lightcone (Andrew Benson)**
 - **Core application:** input to GRISM simulation
 - **Method:** Galacticus + N-body substructure merger trees
- **High-res Roman-volume lightcone (Andrew Hearin)**
 - **Core application:** systematics testing on full Roman survey volume
 - **Method:** Diffsky and UniverseMachine + N-body substructure merger trees
- **High-res suite of Roman-volume lightcones (Andrew Hearin)**
 - **Core application:** testing sample variance for cosmological observables
 - **Method:** Diffsky + N-body substructure merger trees
- **Mid-res suite of Roman-volume lightcones (Risa Wechsler)**
 - **Core application:** covariance estimation for key statistics
 - **Method:** Diffsky + N-body halos + synthetic merger trees

OTHER PROPERTIES

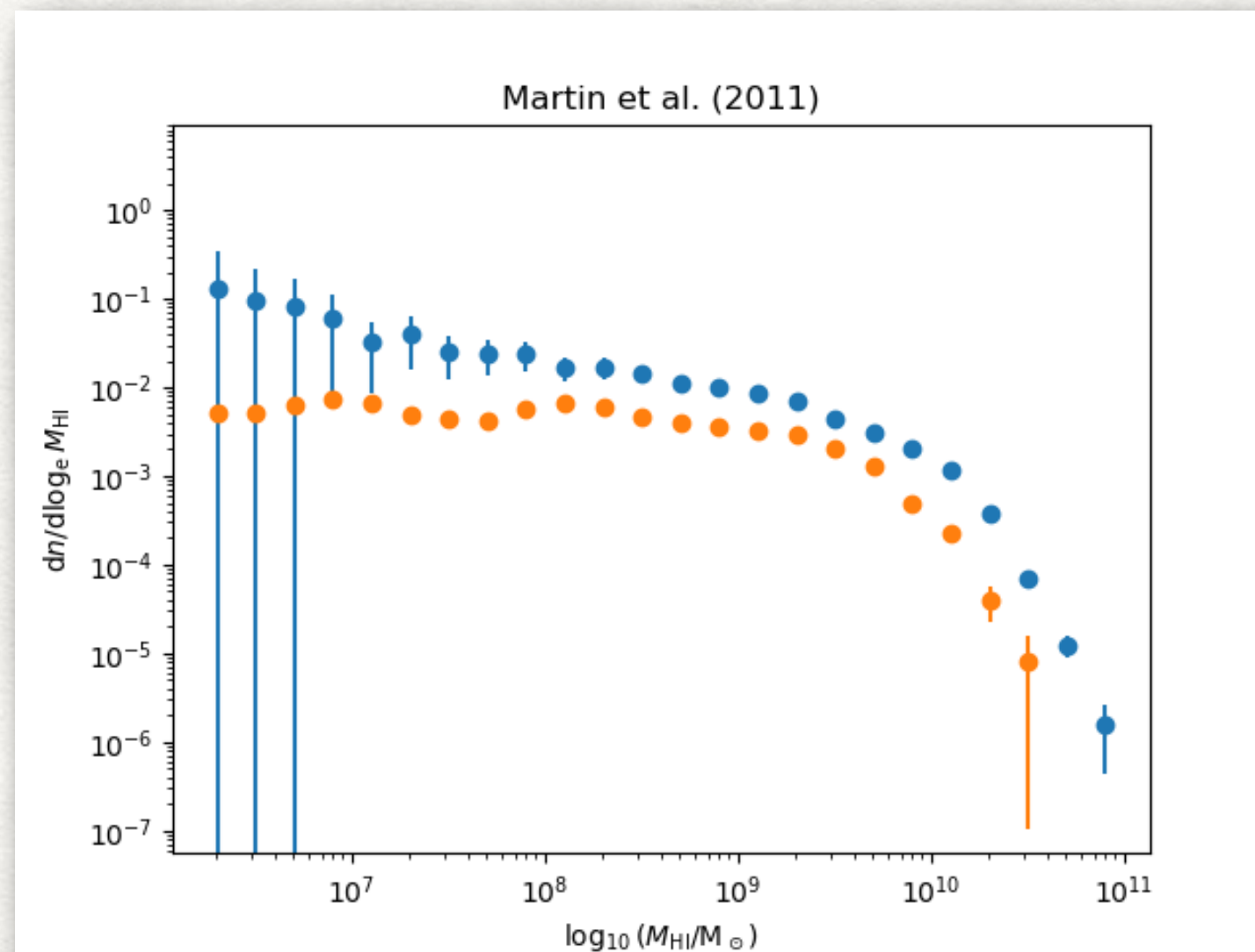
Morphological-type fraction



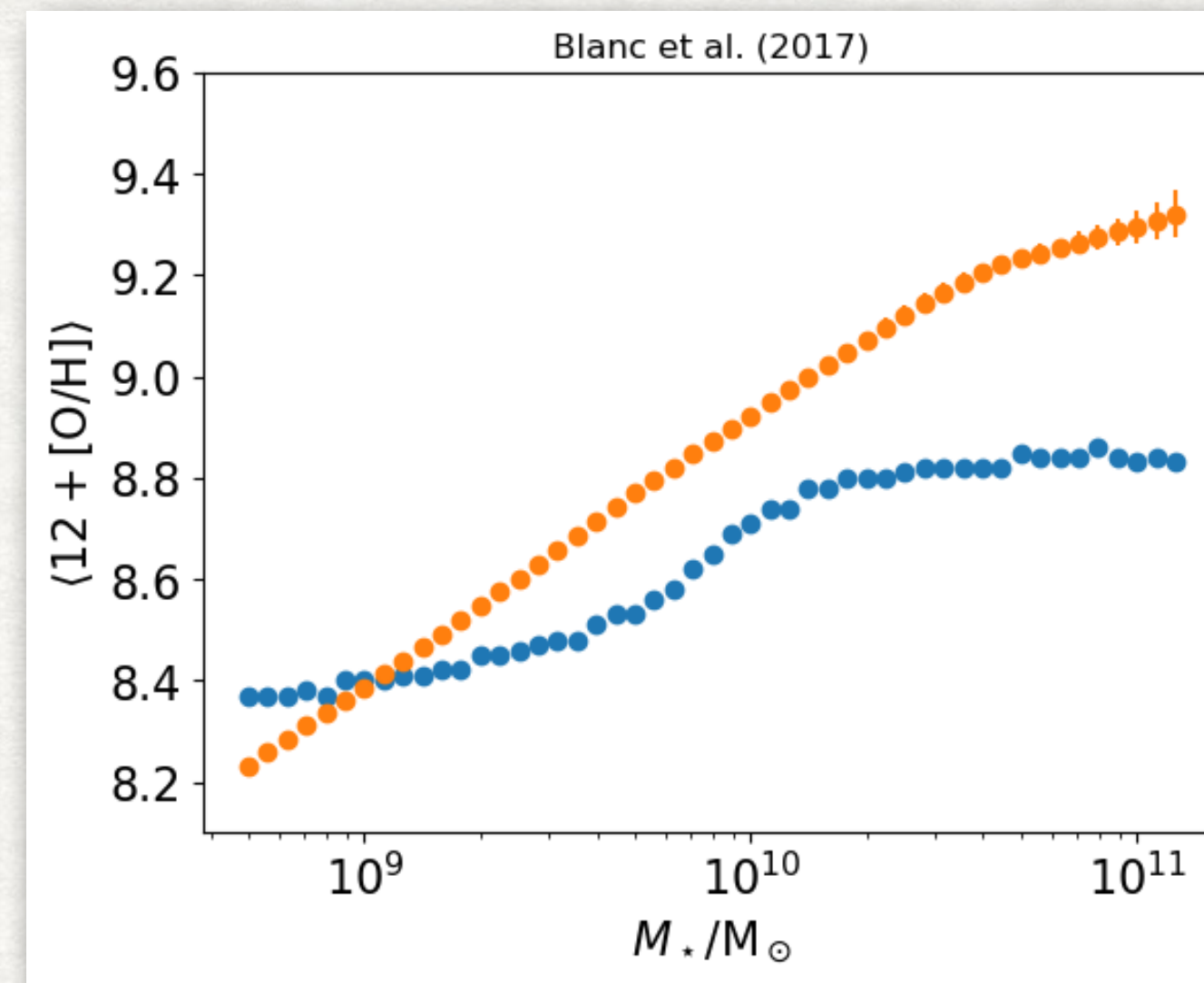
Star formation rate



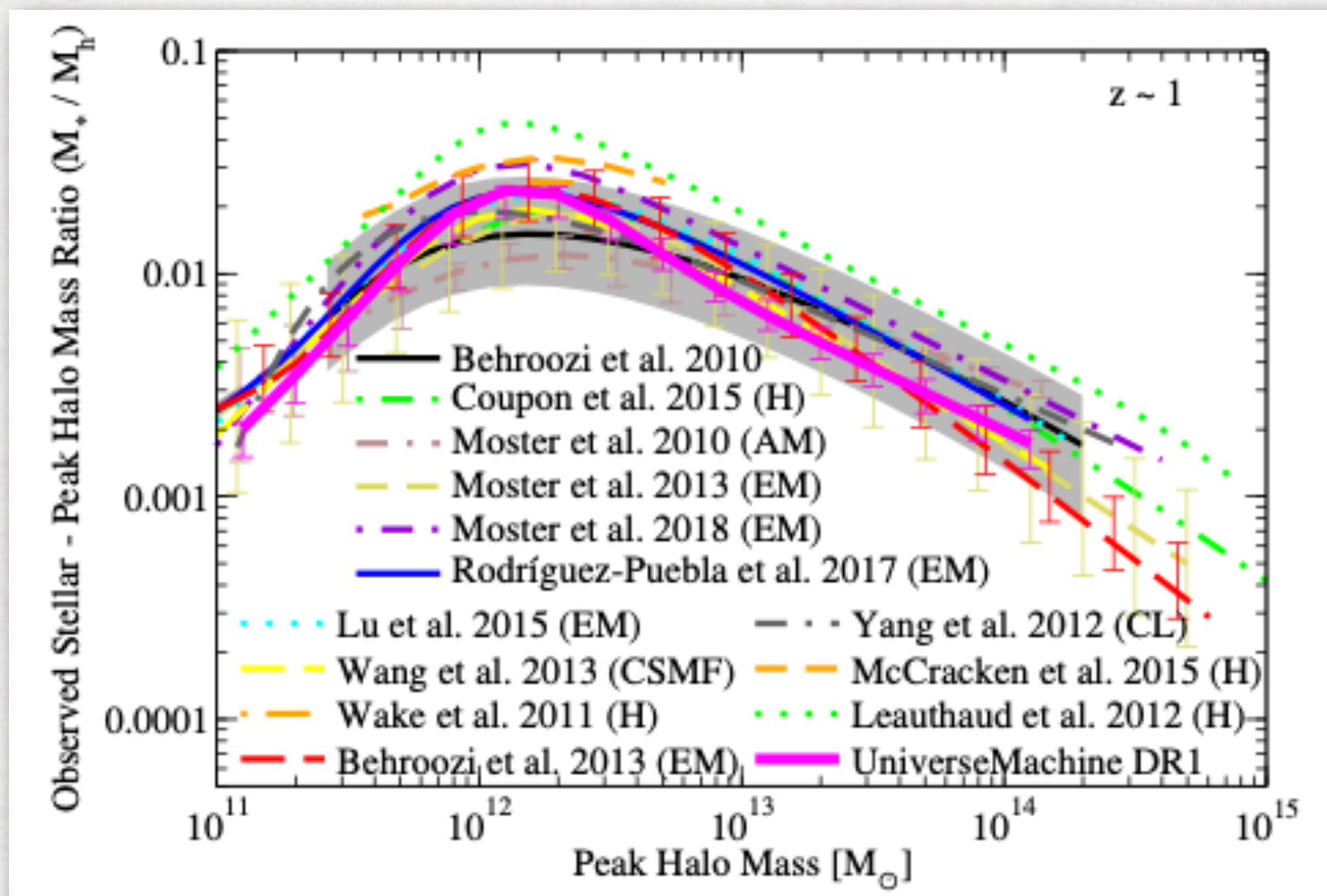
Atomic Hydrogen mass function



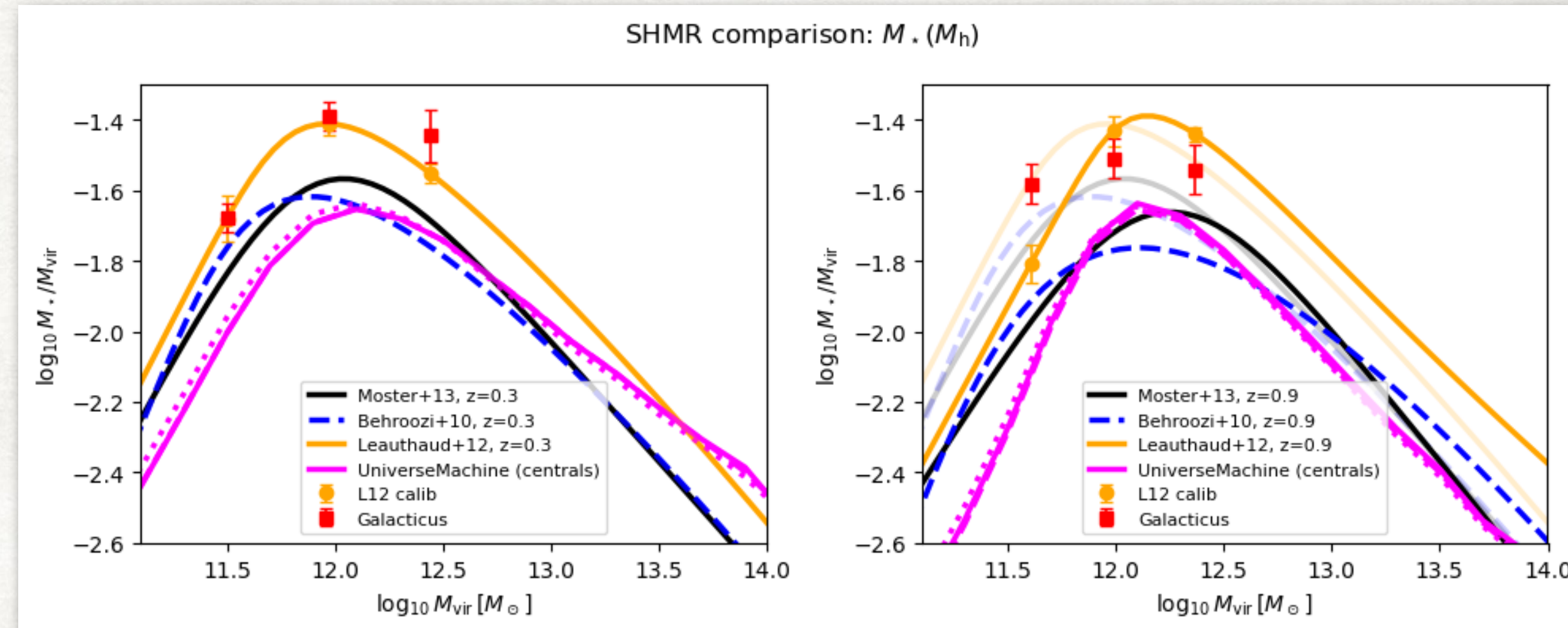
mass-metallicity relation



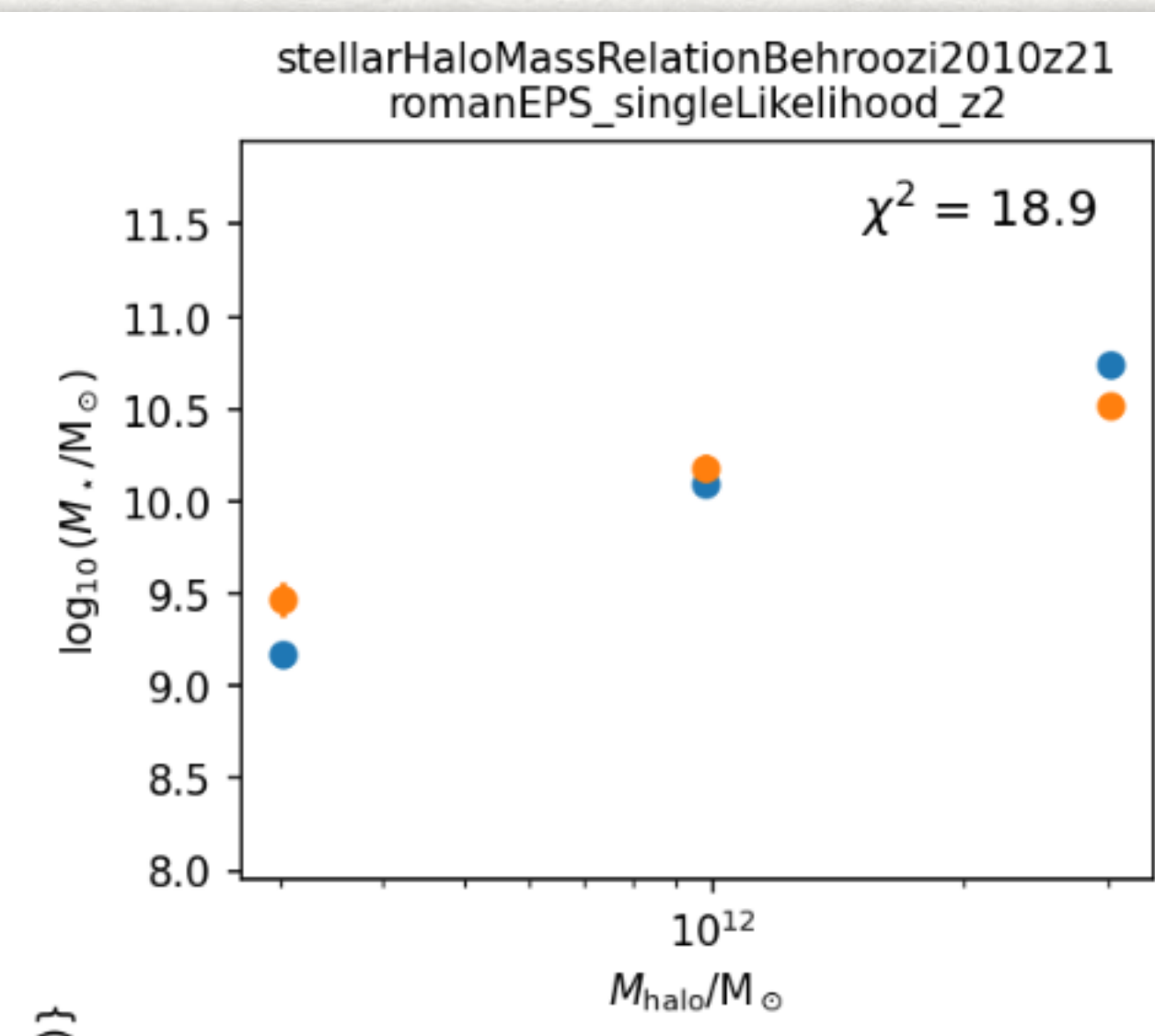
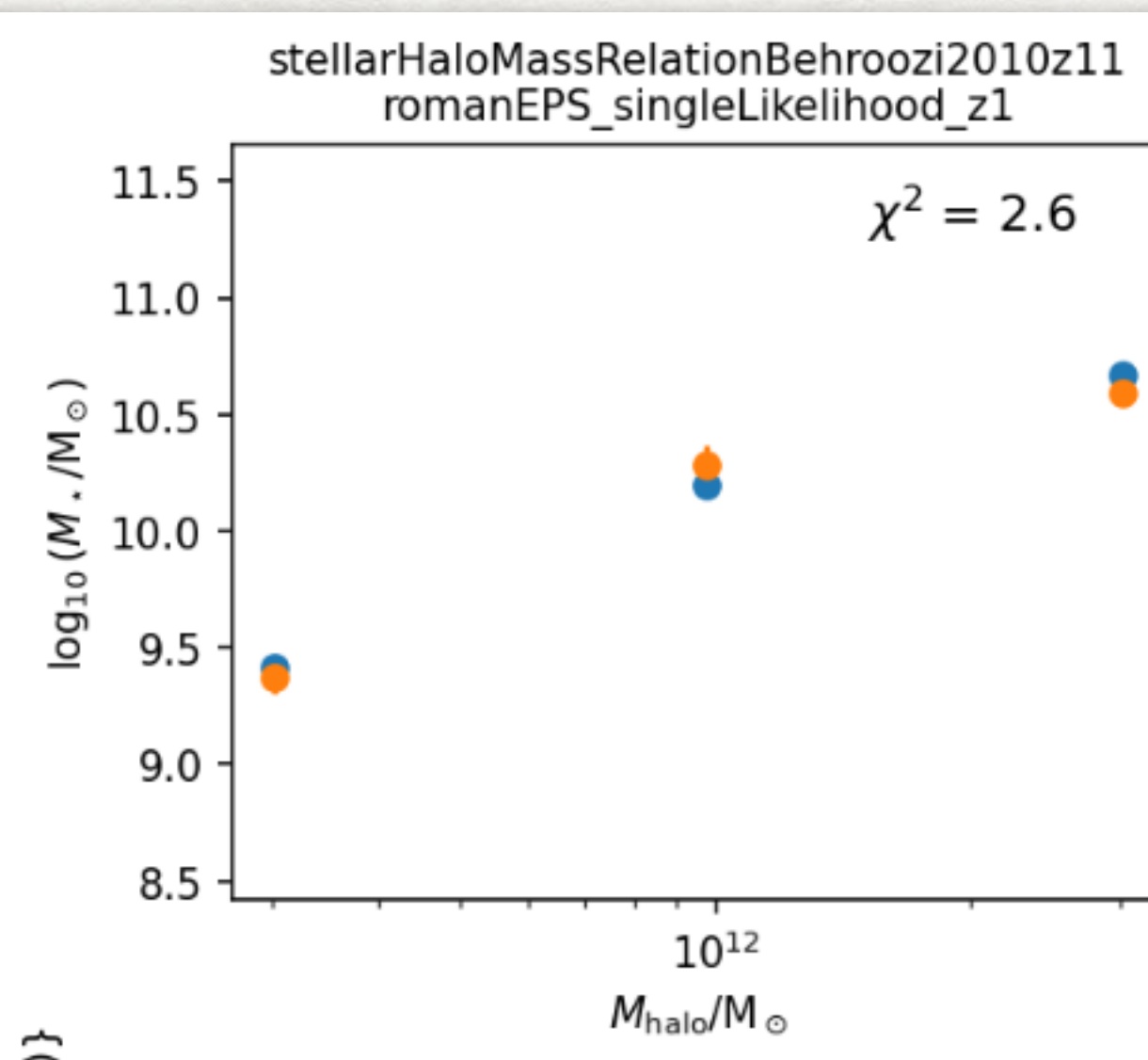
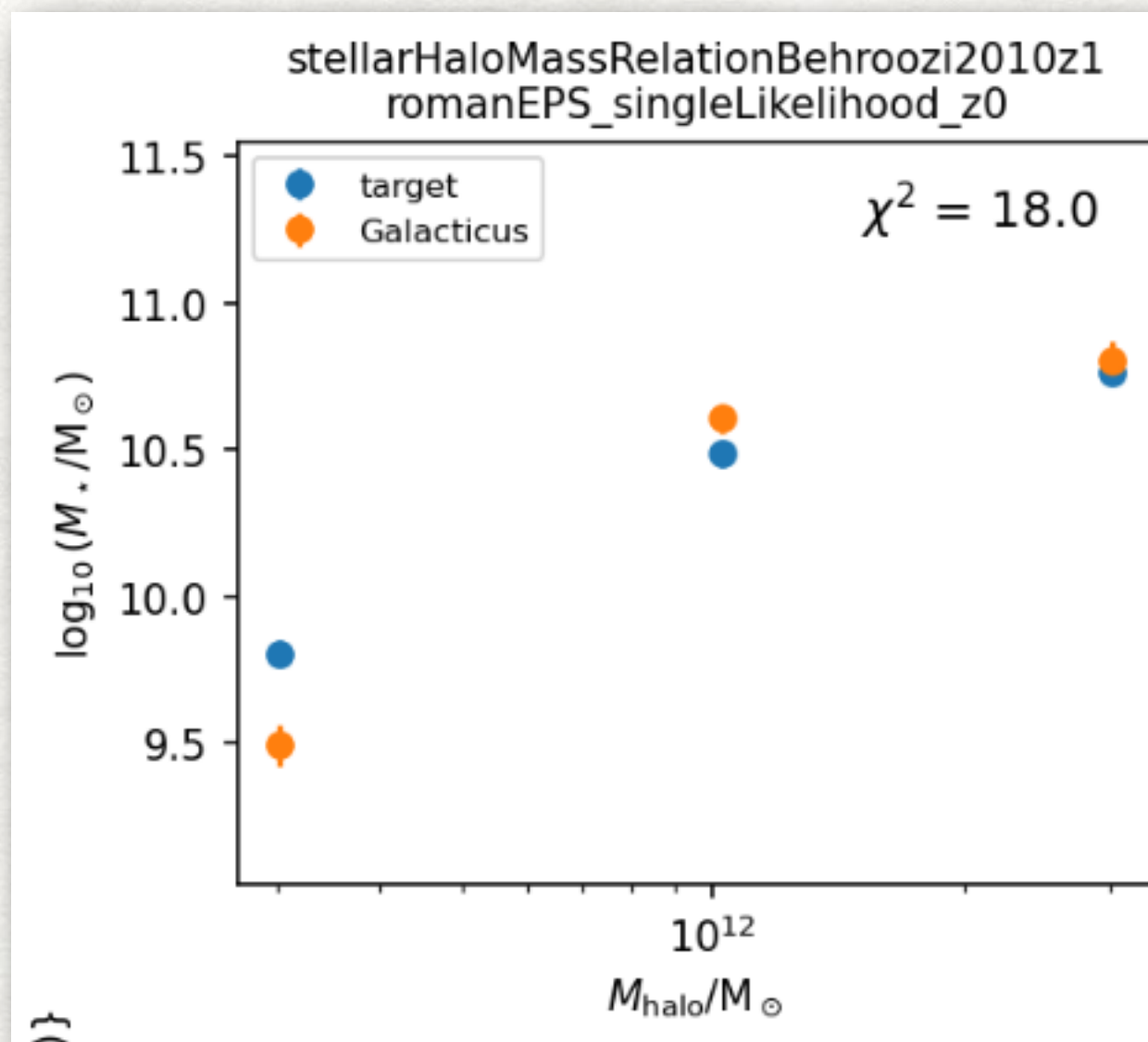
USING UPDATED SHMR RELATIONS



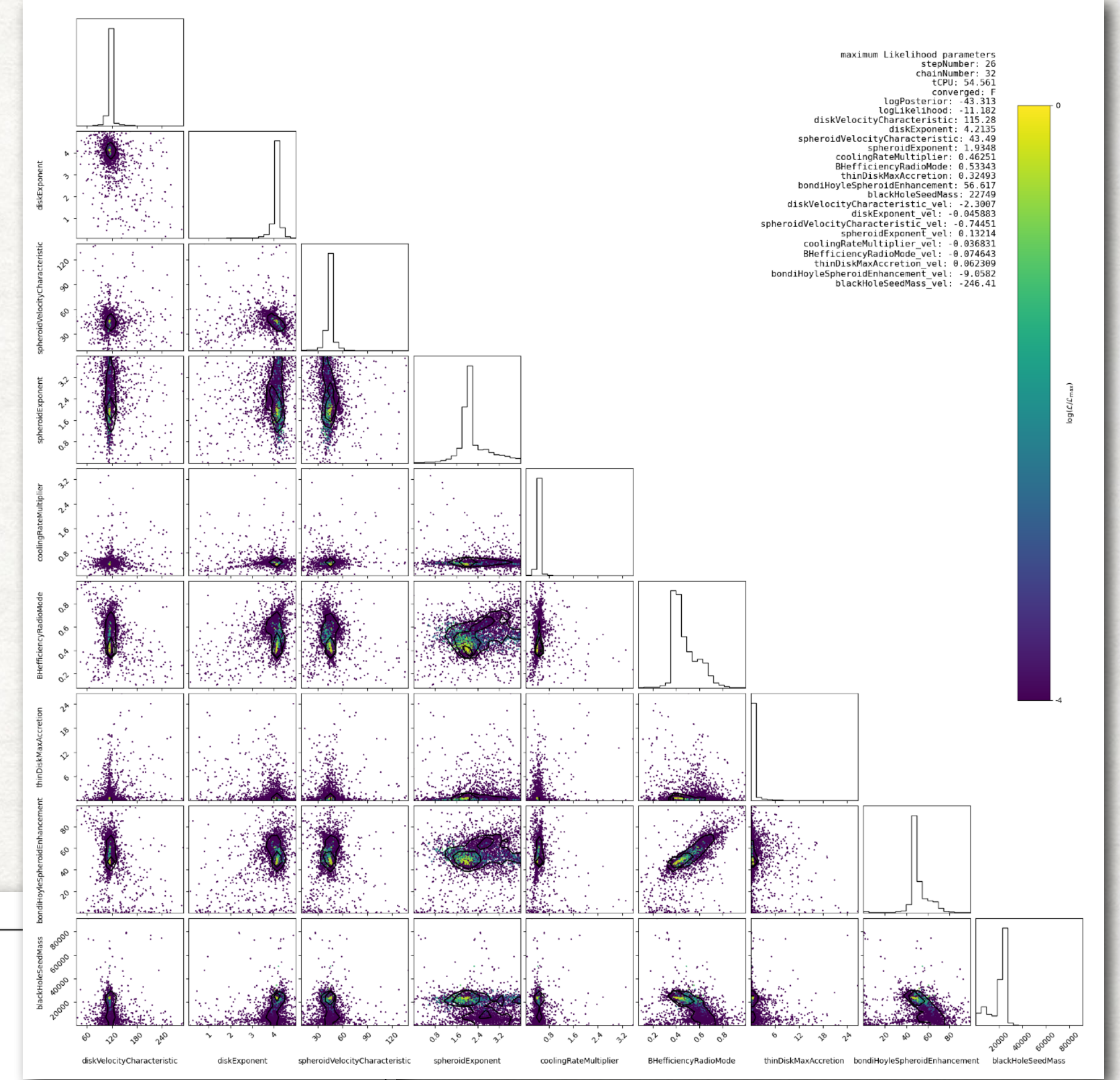
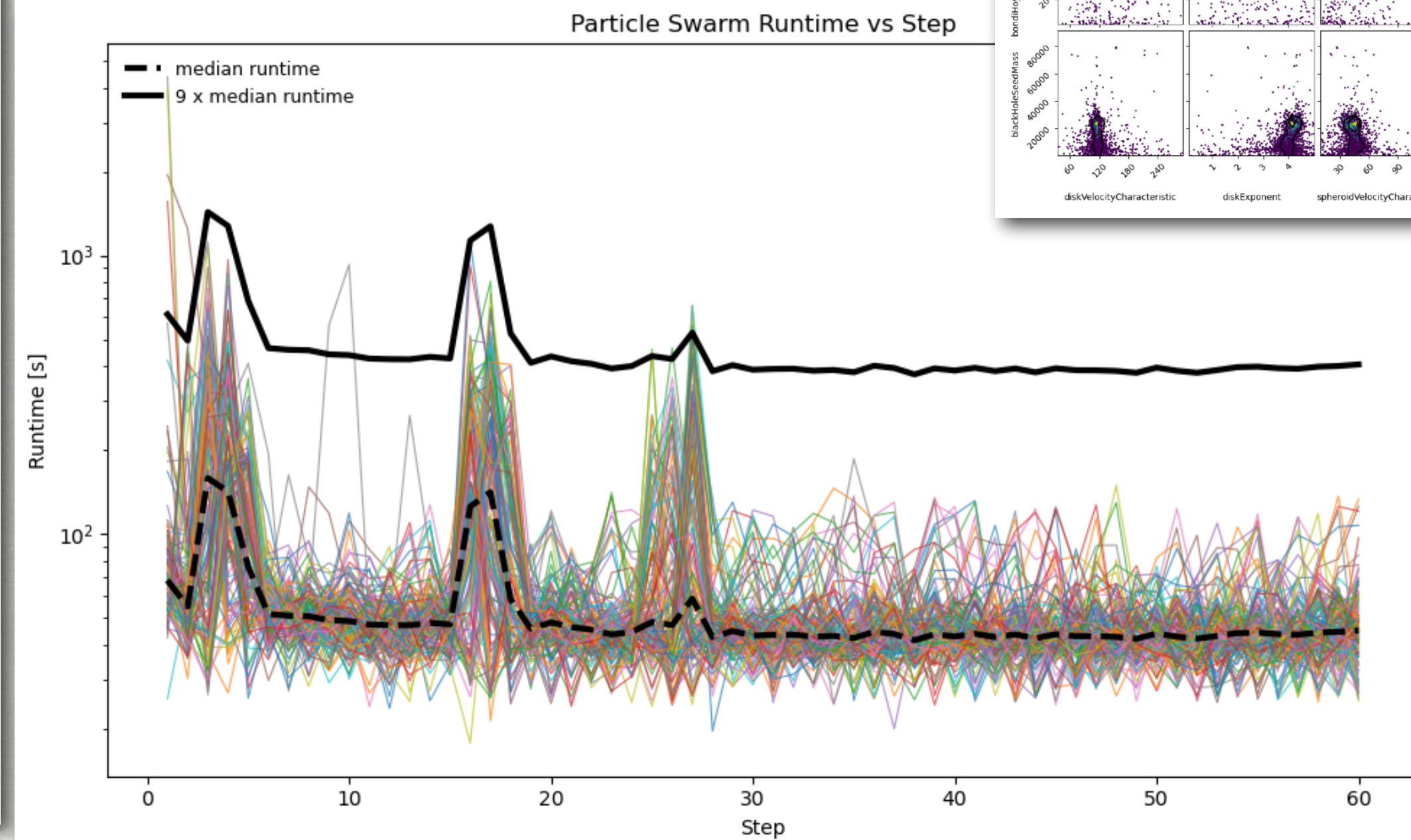
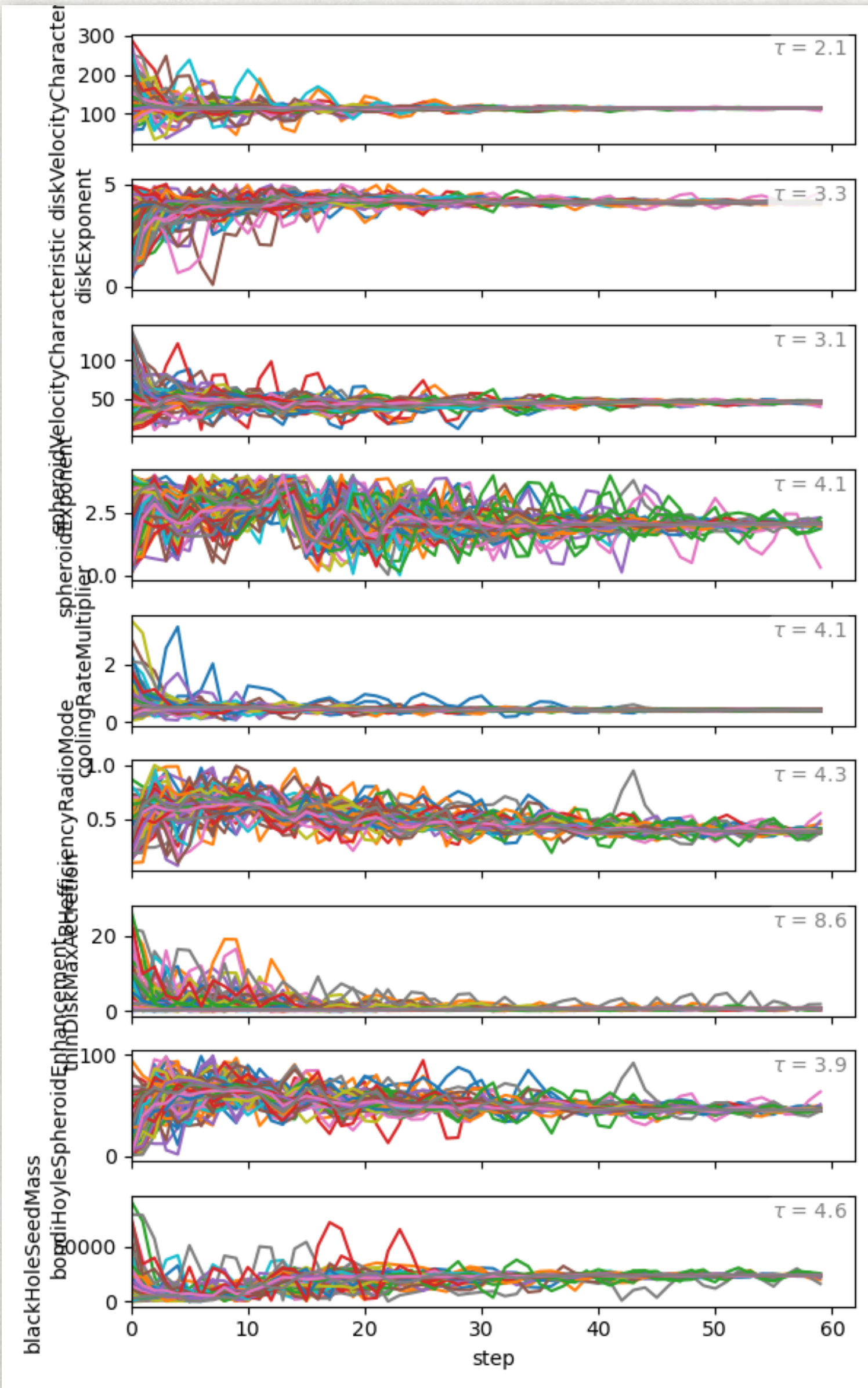
Reasonable amount of variation between different inferred SHMRs. With the Leauthaud 2012 relation something of an outlier.



Switching to a different SHMR (in this case Behroozi 2010) does not change the picture that the evolution of the steepness of the inferred SHMR with redshift cannot be reproduced by Galacticus (with all the model choices, free parameters, etc. that I am using).



HAVE SWITCHED FROM MCMC TO PARTICLE SWARM OPTIMISATION



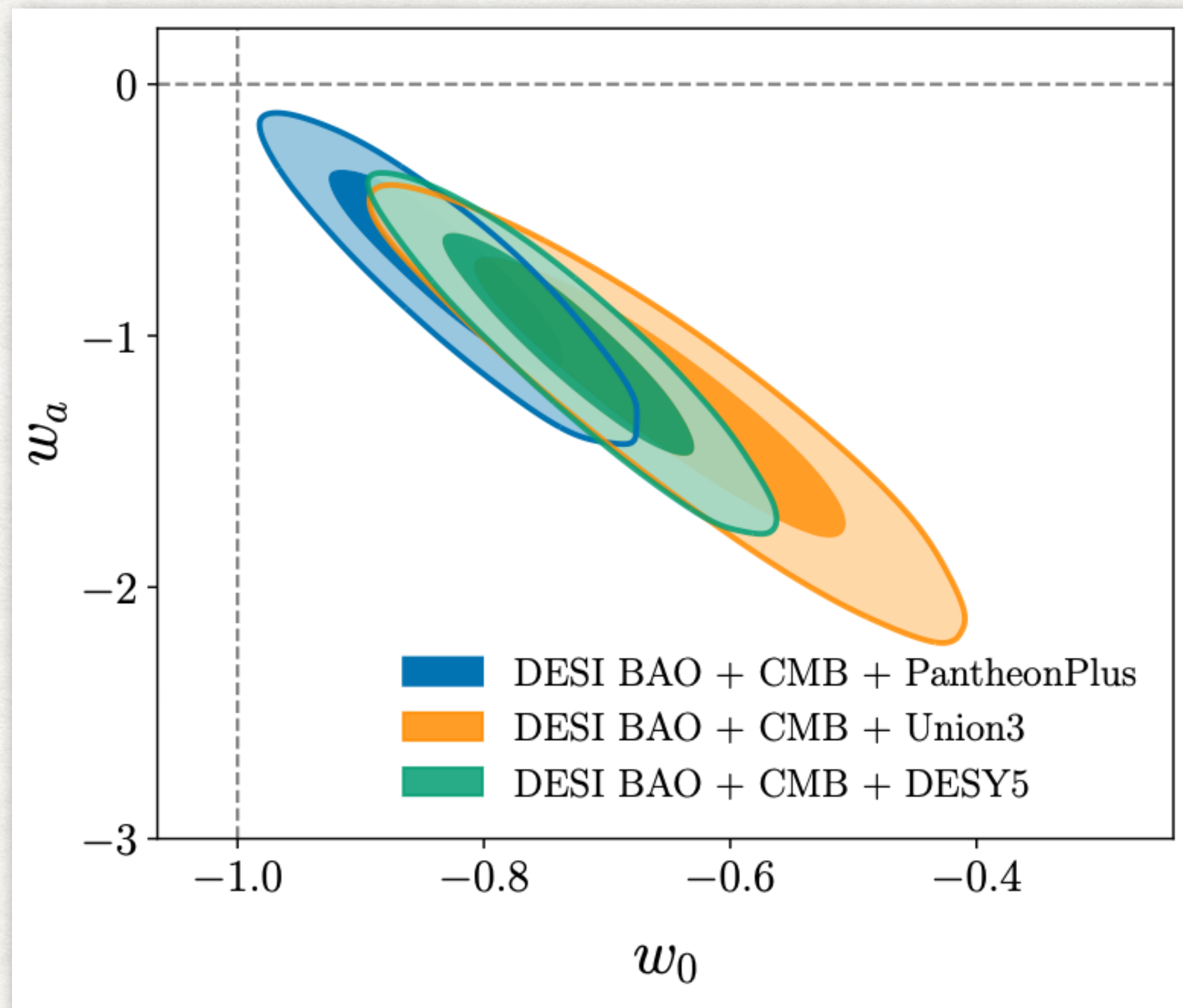
Wide variation of likelihood evaluation times means it is worth thinking about how your parallelise

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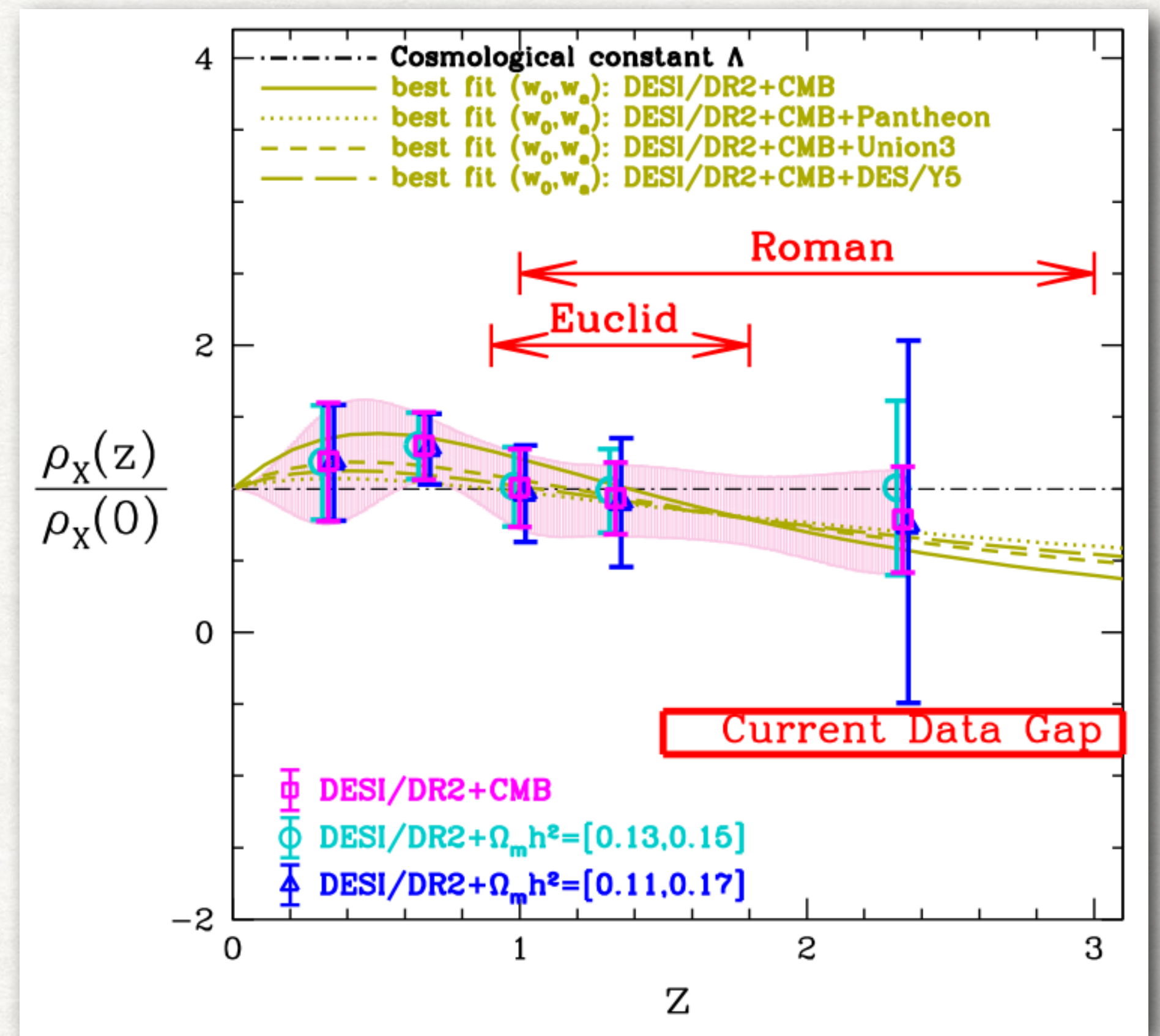
WHAT MIGHT WE LEARN?

Roman will probe this same physics at higher redshift.

Hints from DESI that dark energy is not simply a cosmological constant



DESI Collaboration 2024

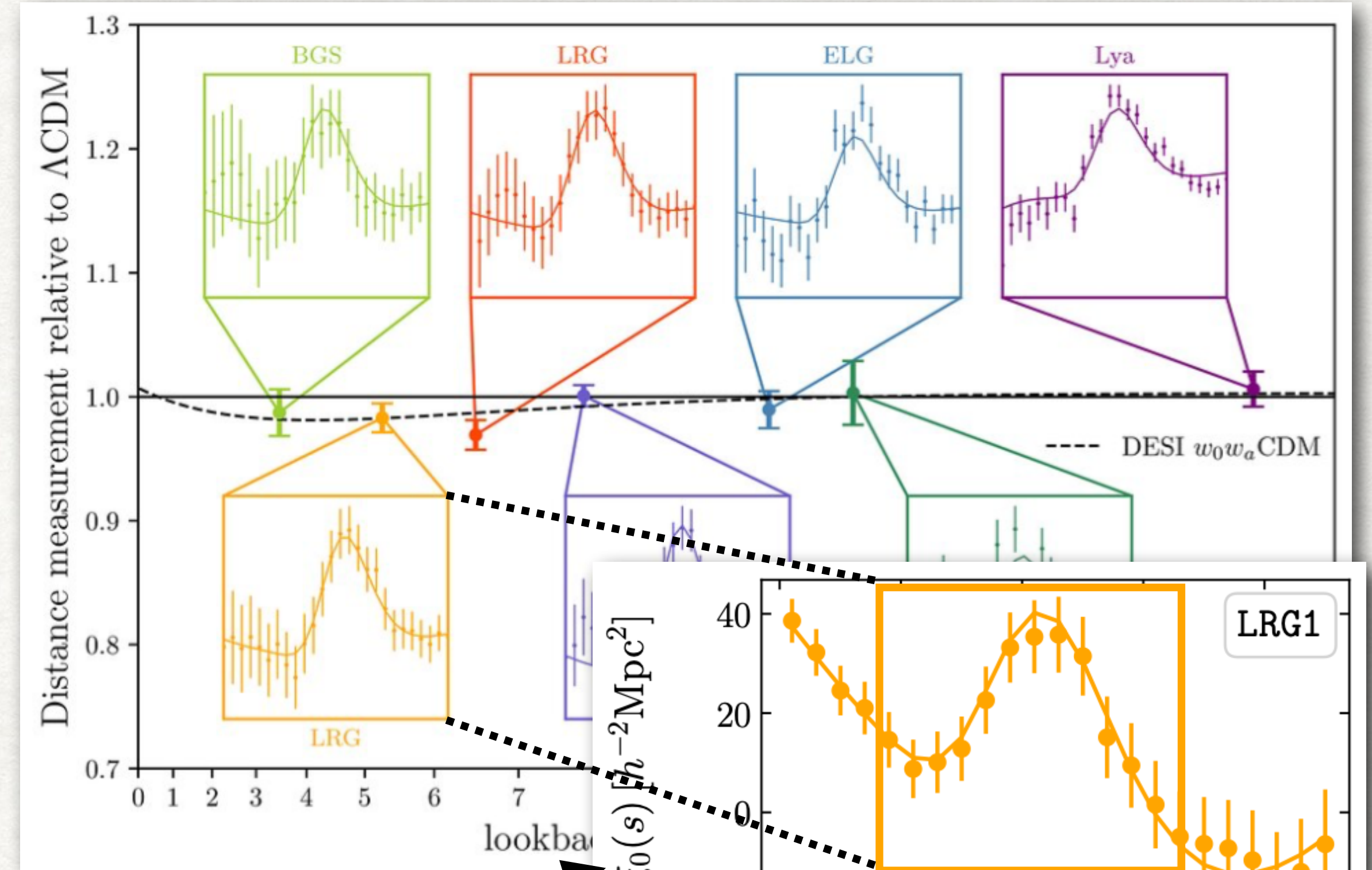
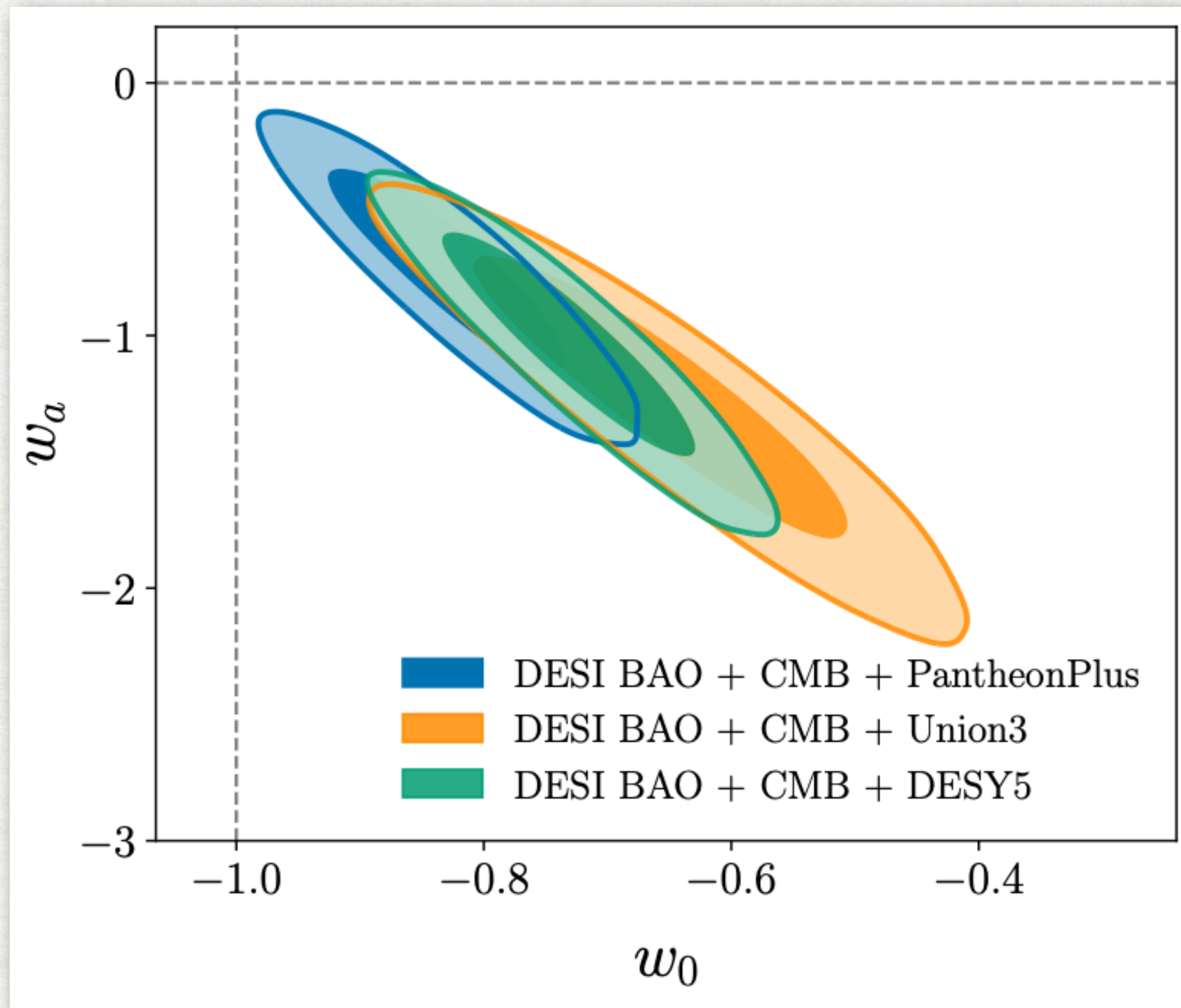


Wang & Freese 2025

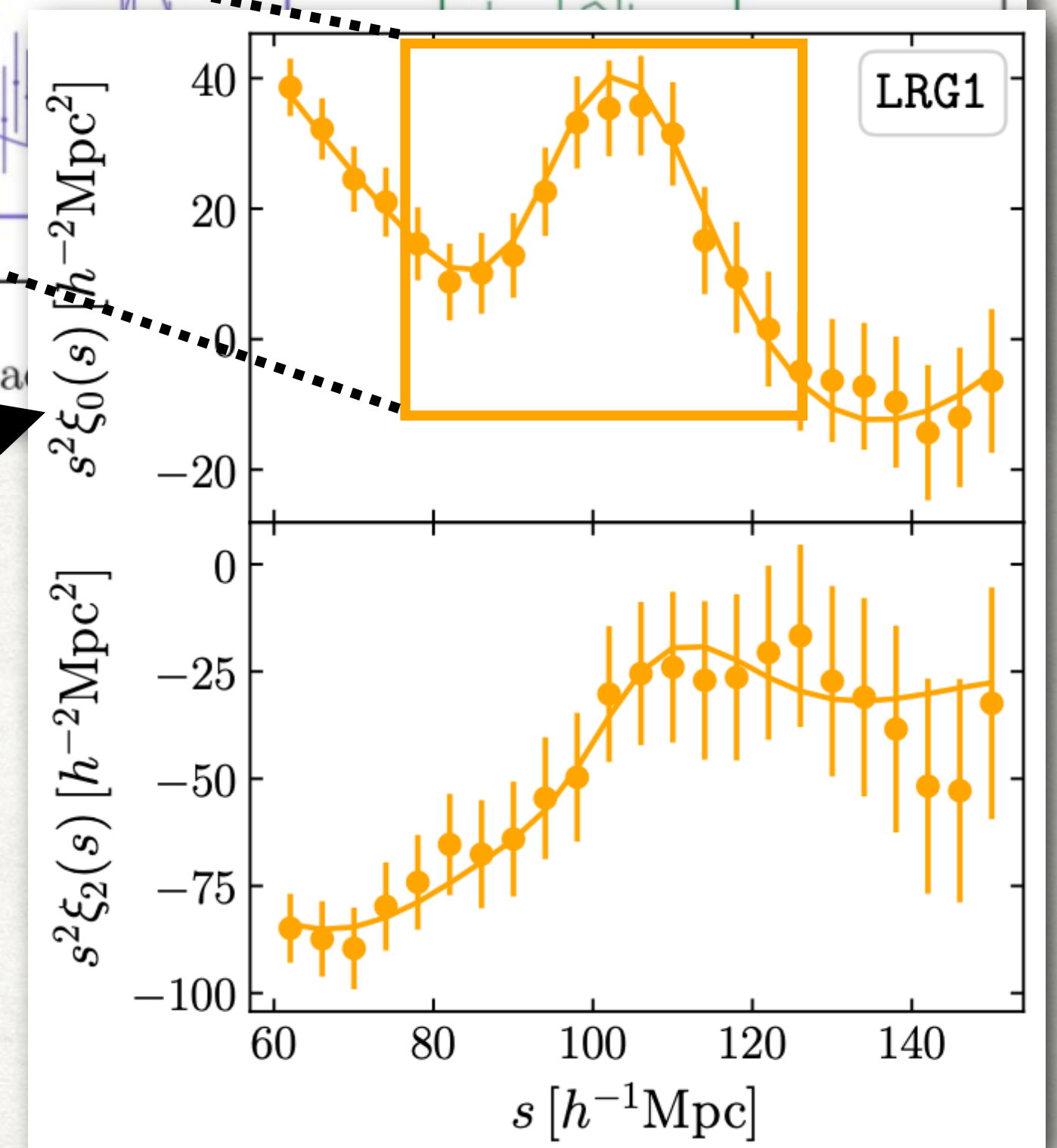
Useful for distinguishing between physics and systematics, and (if it is new physics) for distinguishing between different explanations.

HOW DO WE LEARN IT?

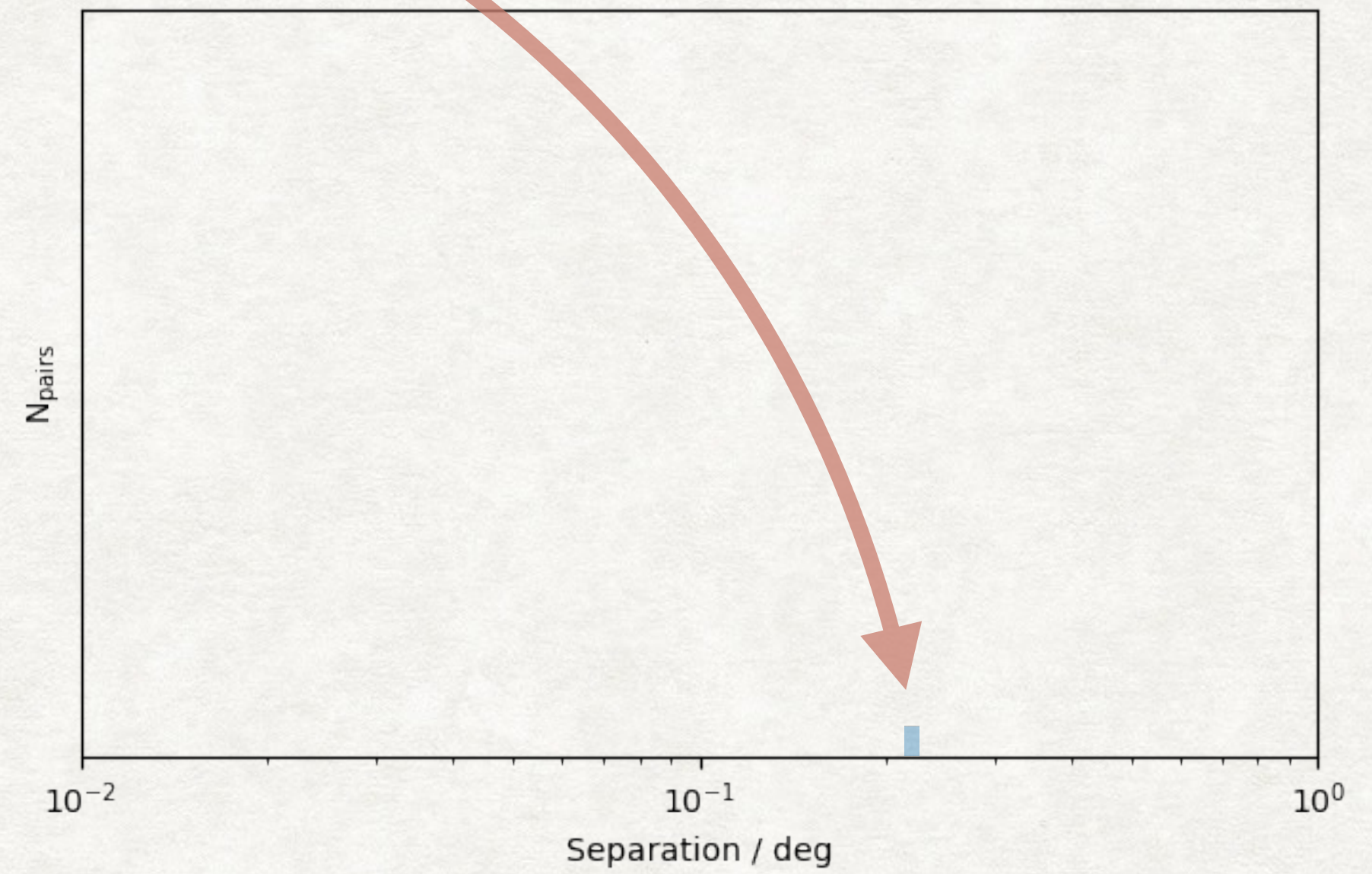
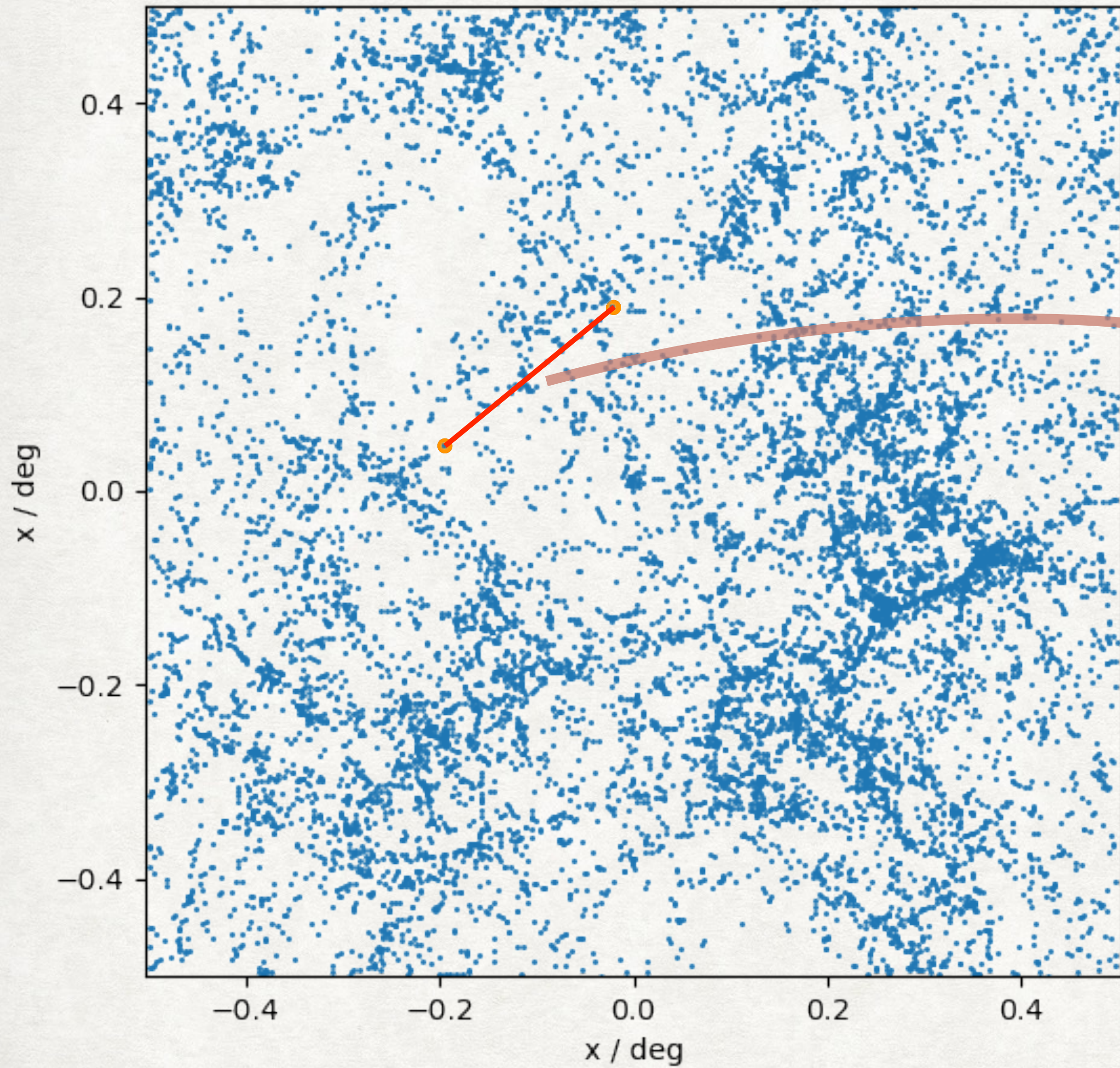
Hints from DESI that dark energy is not simply a cosmological constant



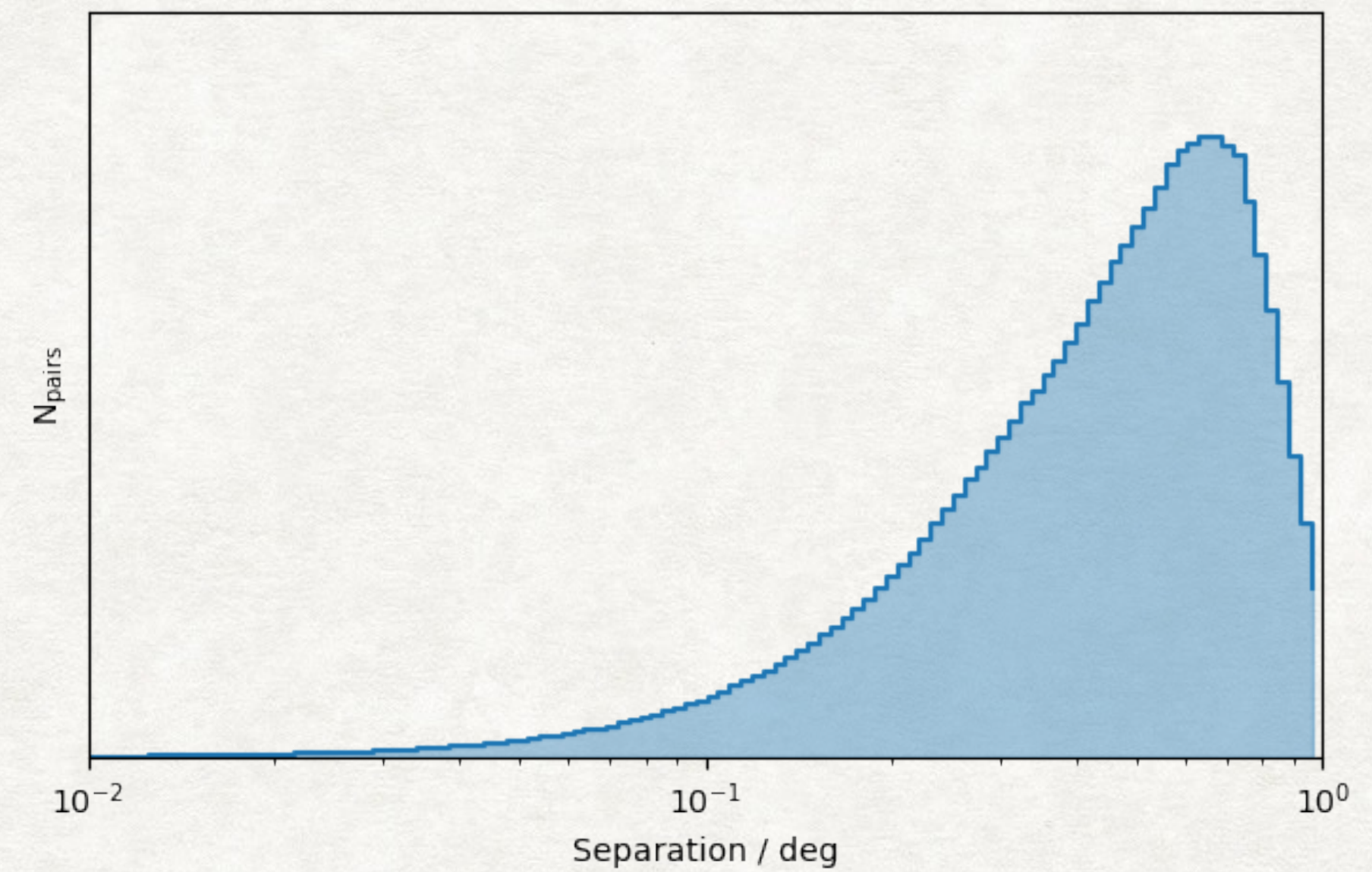
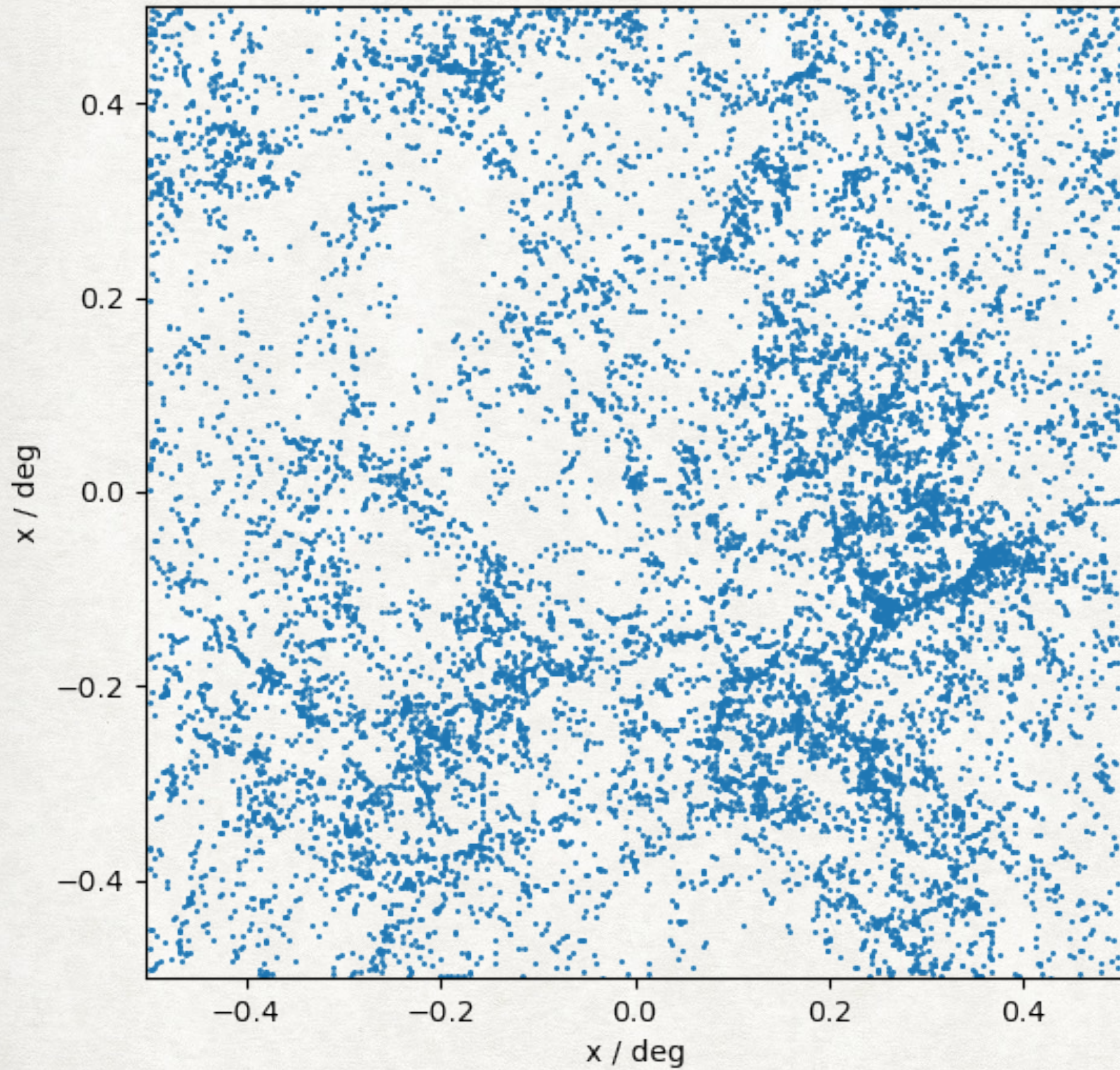
2pt correlation function. More on that later...



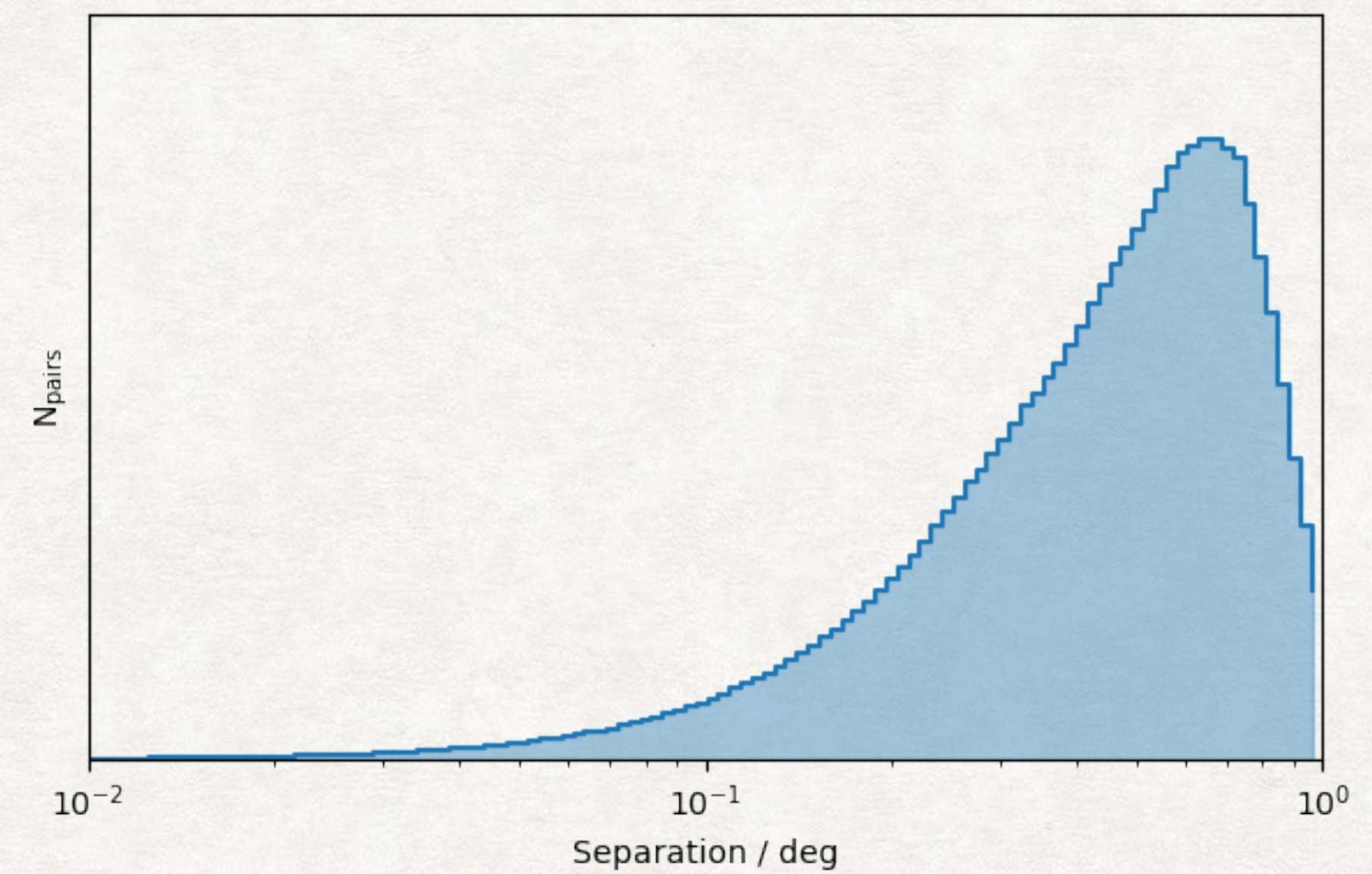
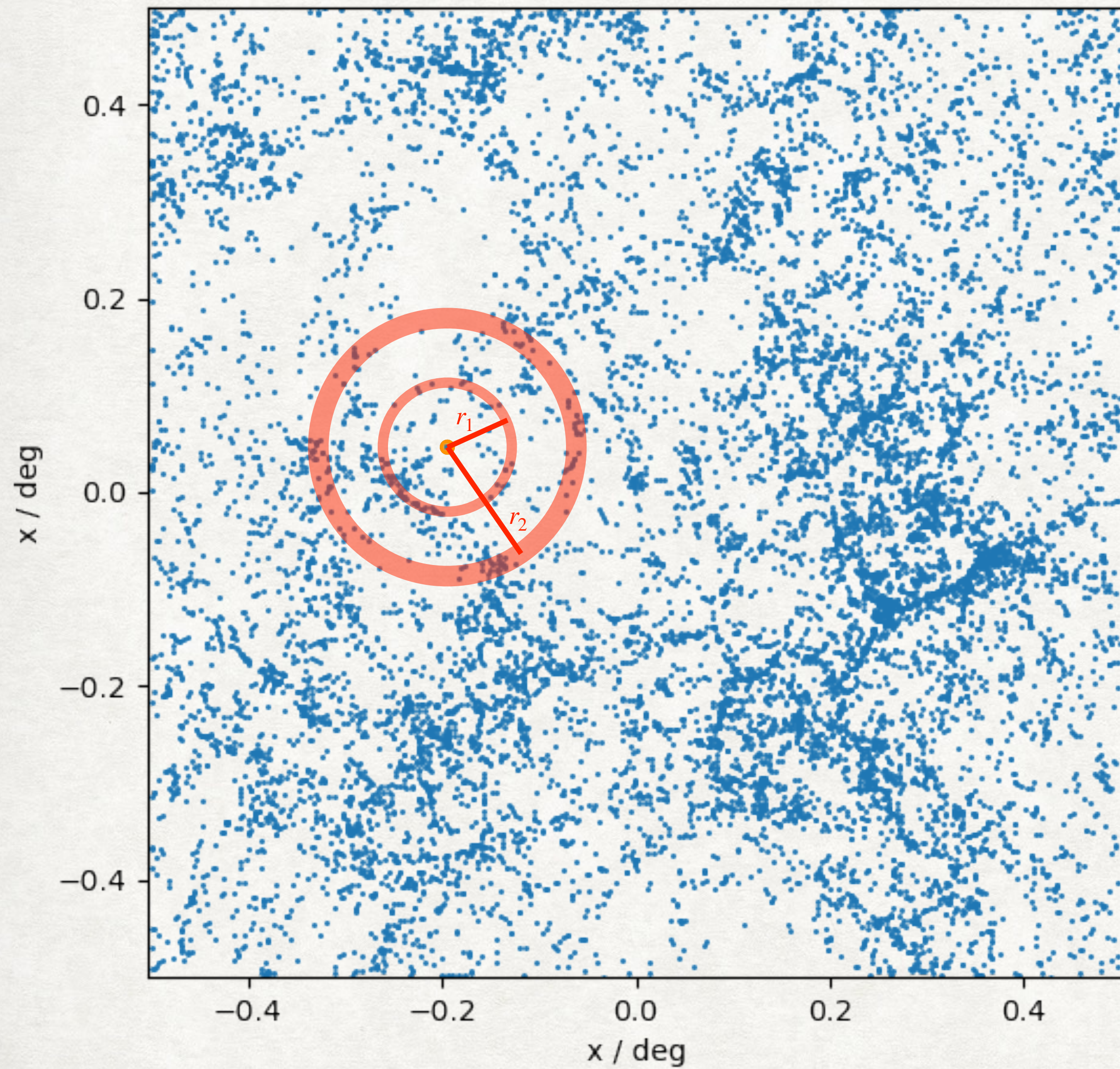
HOW DO WE MEASURE A GALAXY CORRELATION FUNCTION?



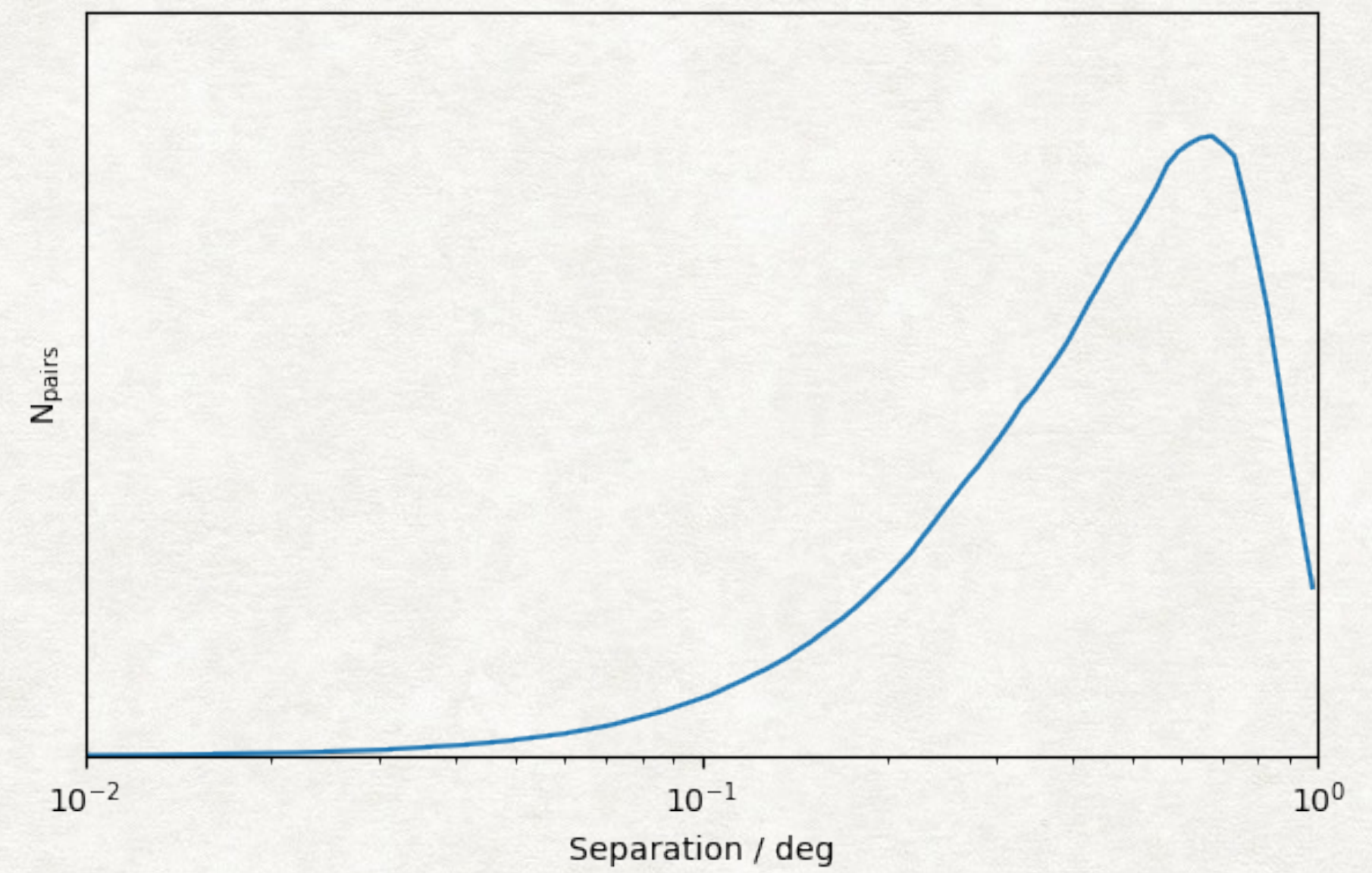
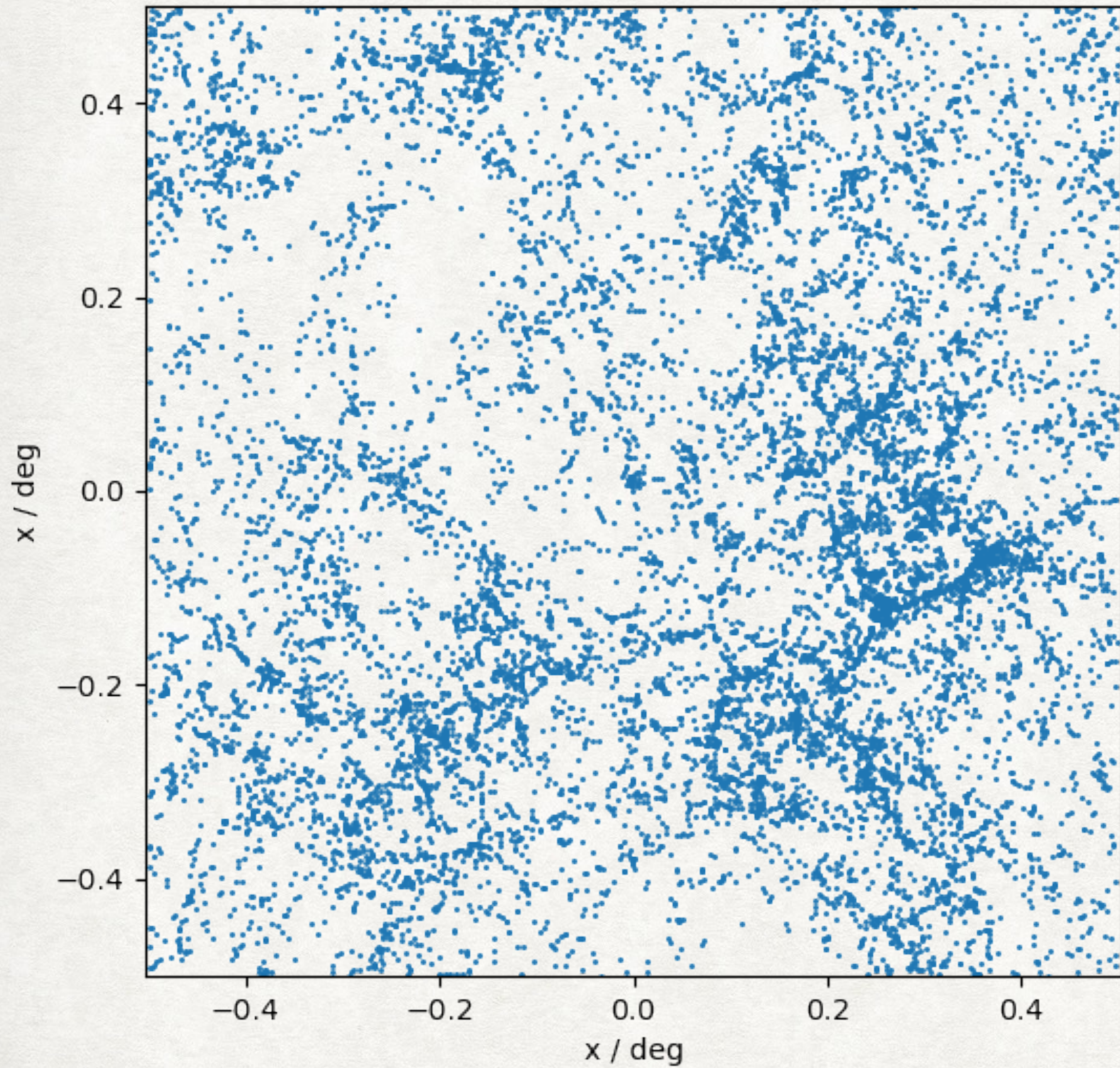
HOW DO WE MEASURE A GALAXY CORRELATION FUNCTION?



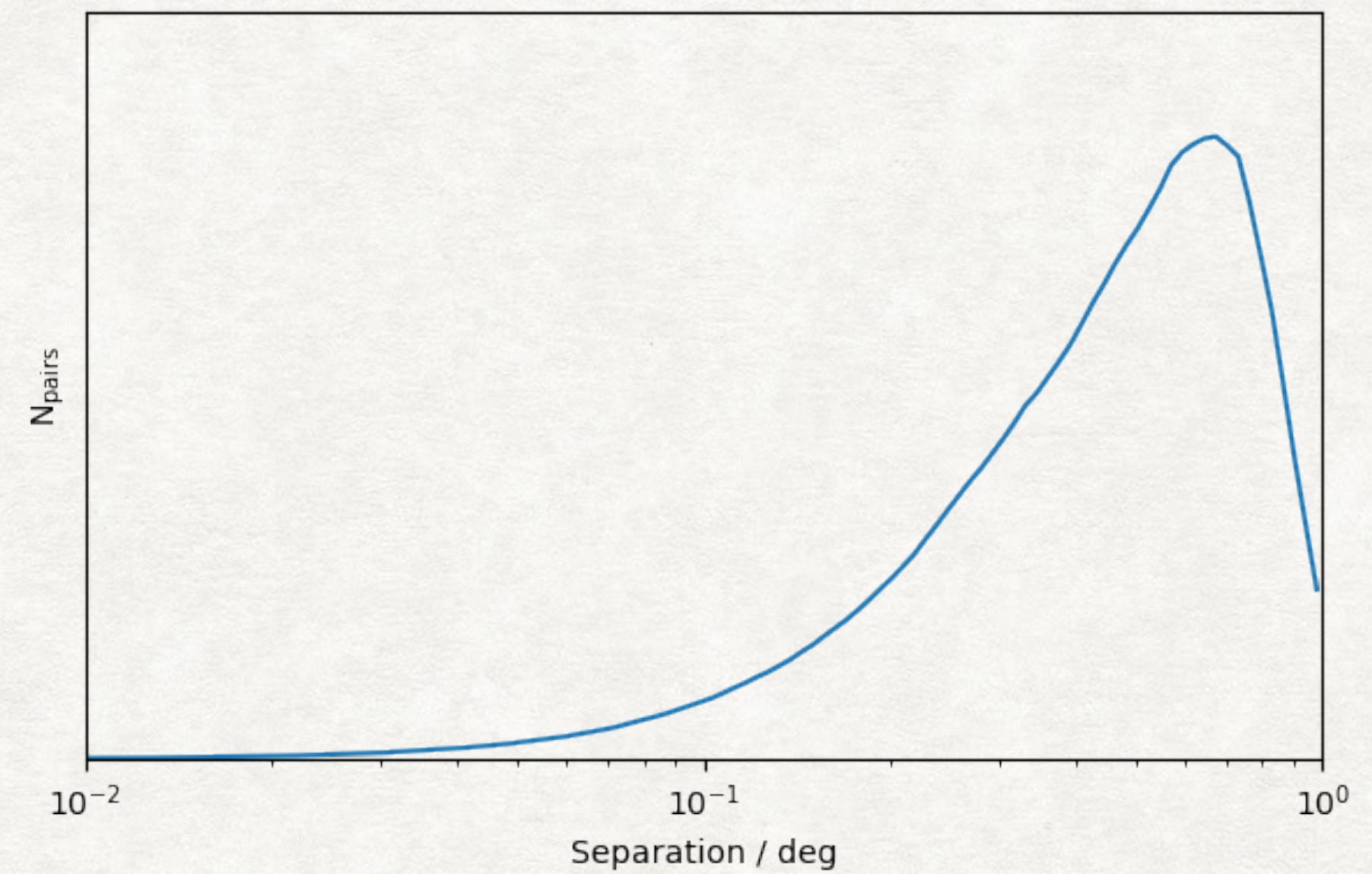
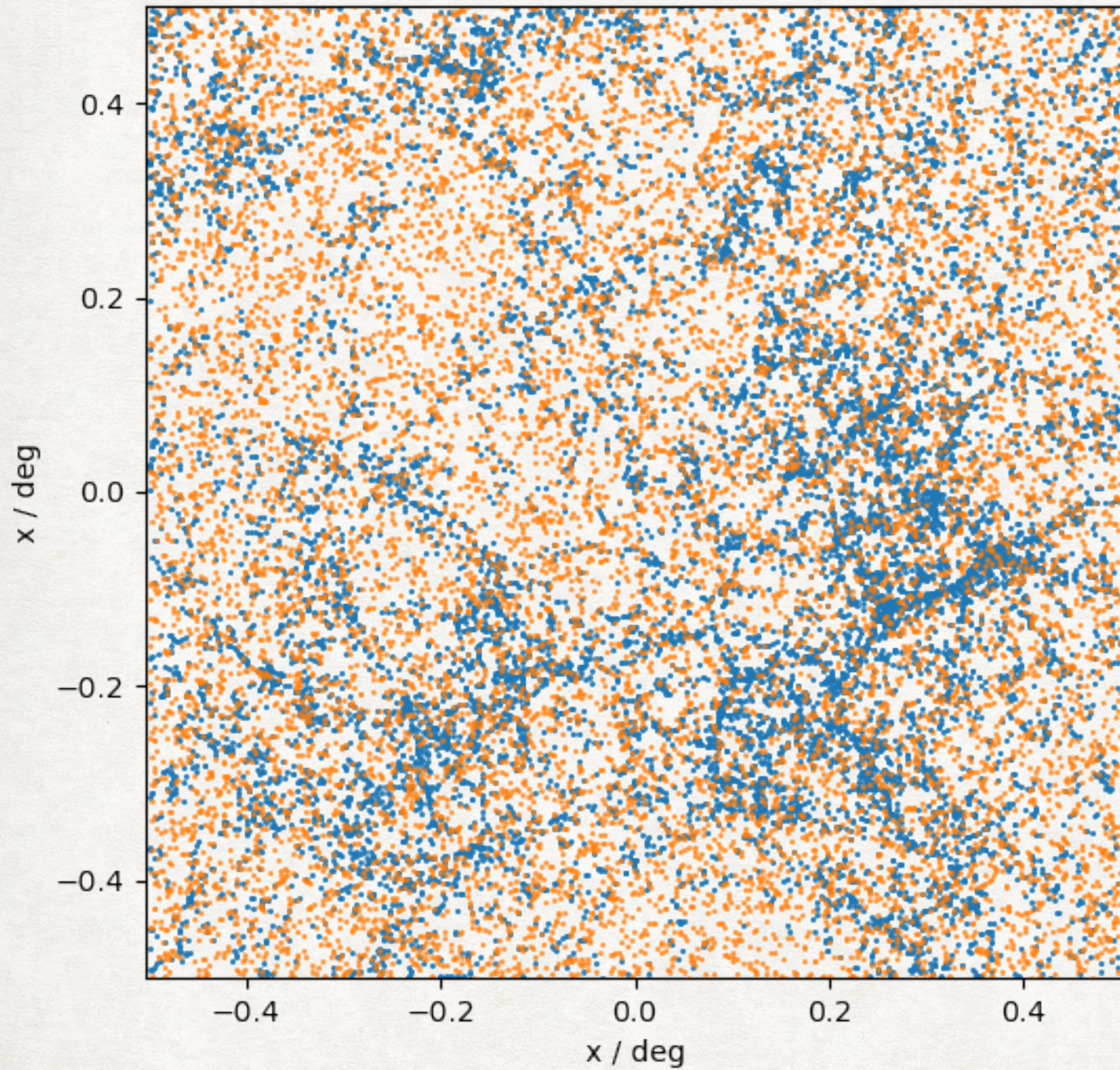
HOW DO WE MEASURE A GALAXY CORRELATION FUNCTION?



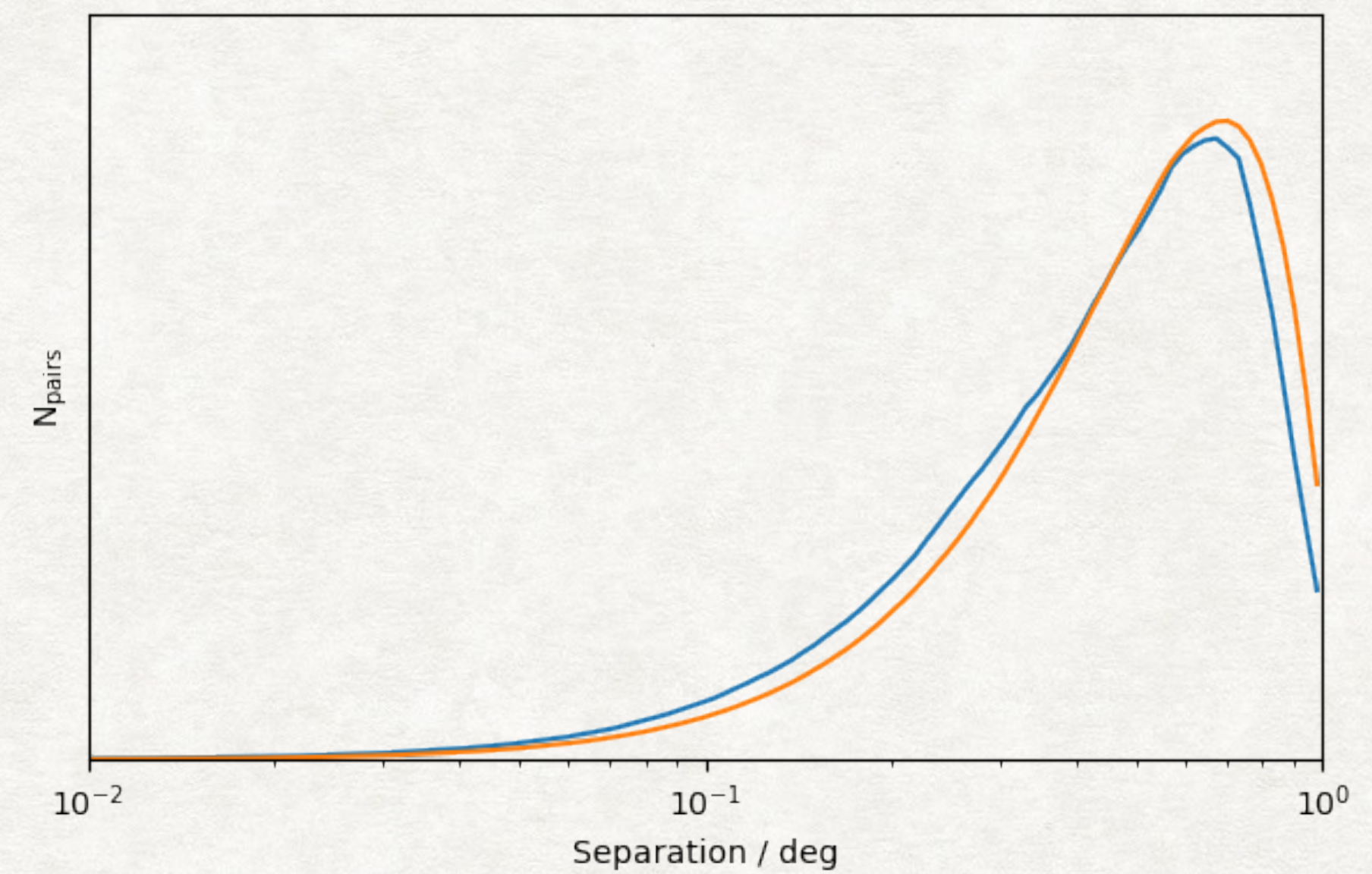
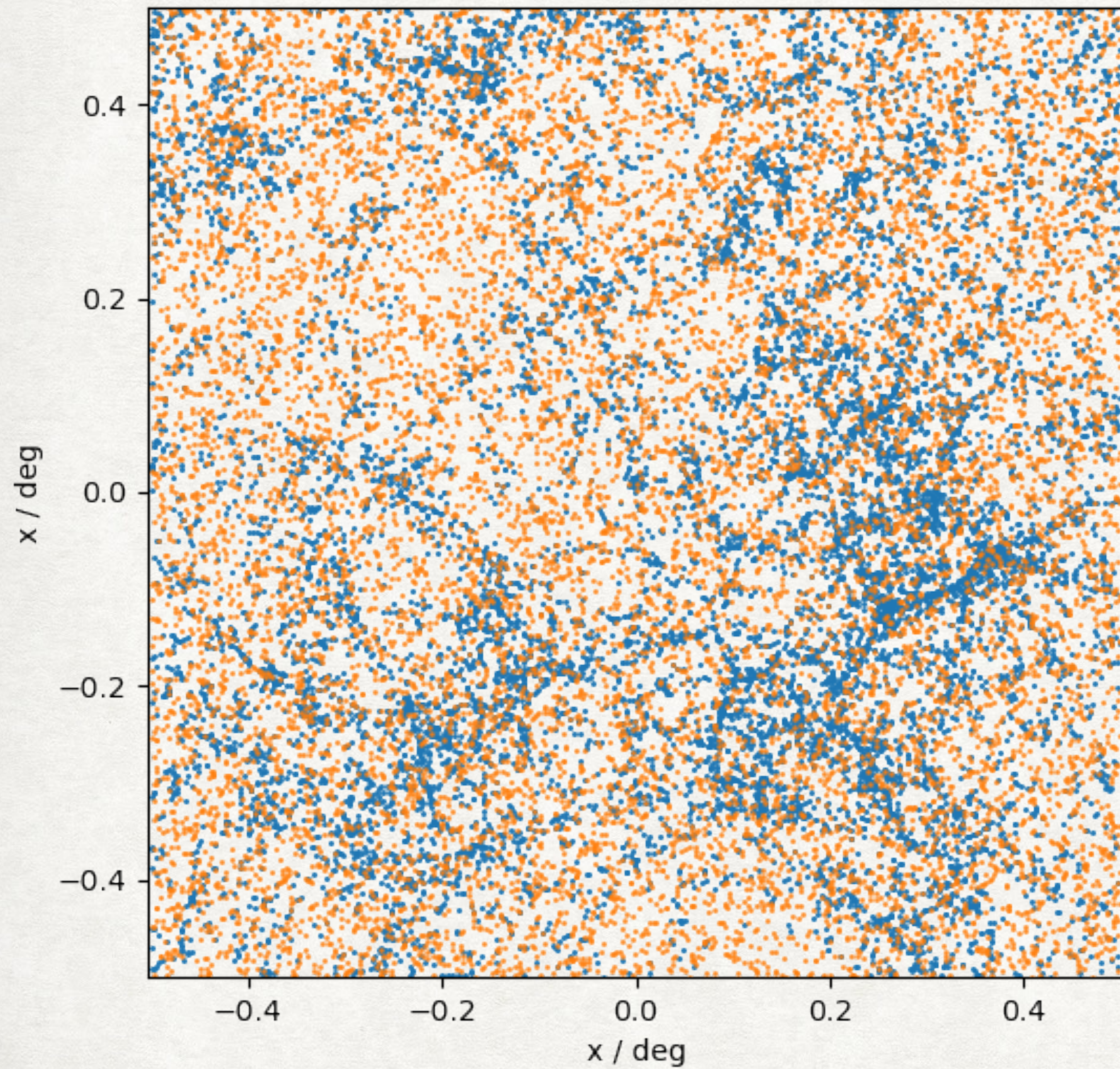
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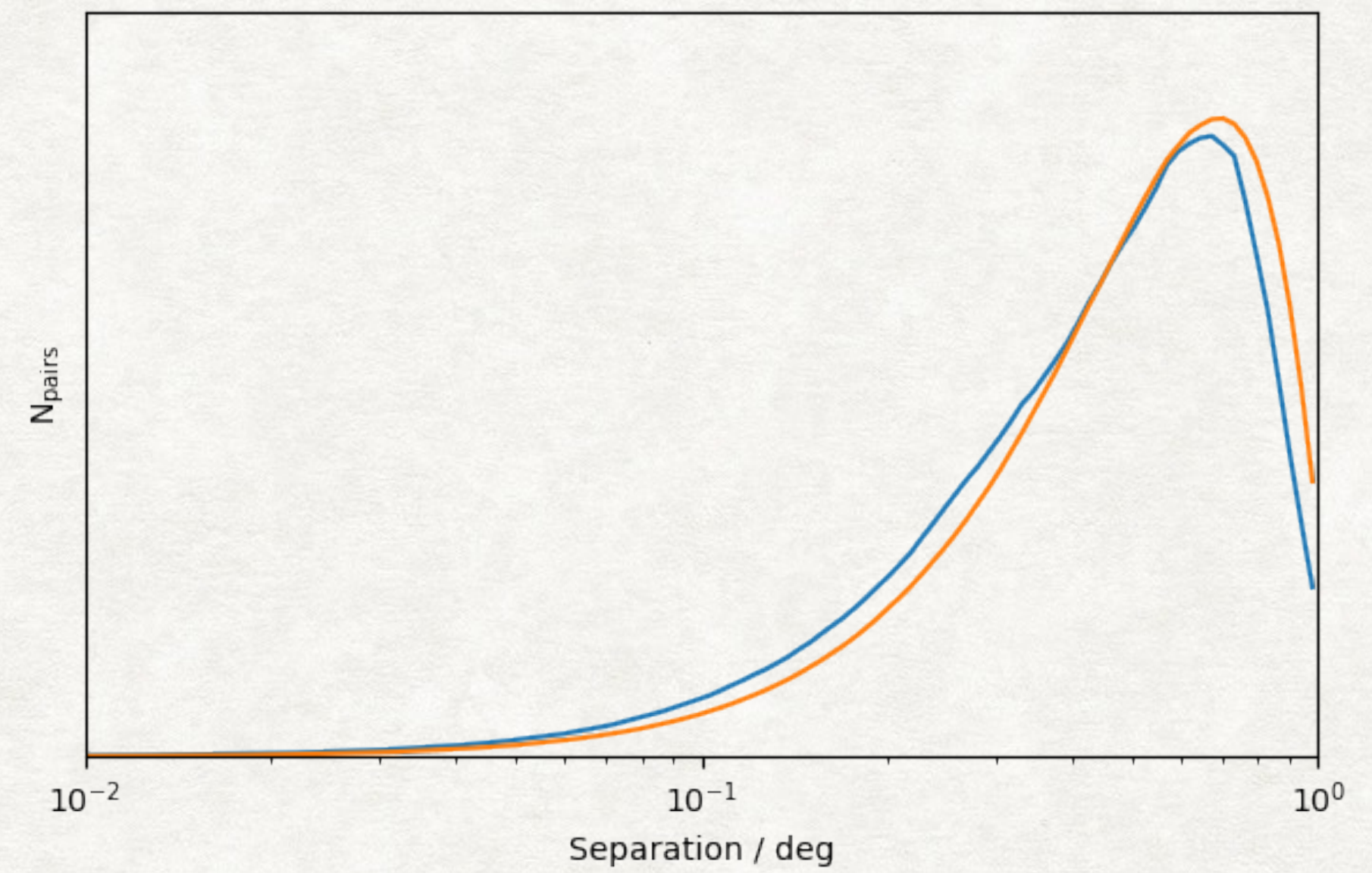
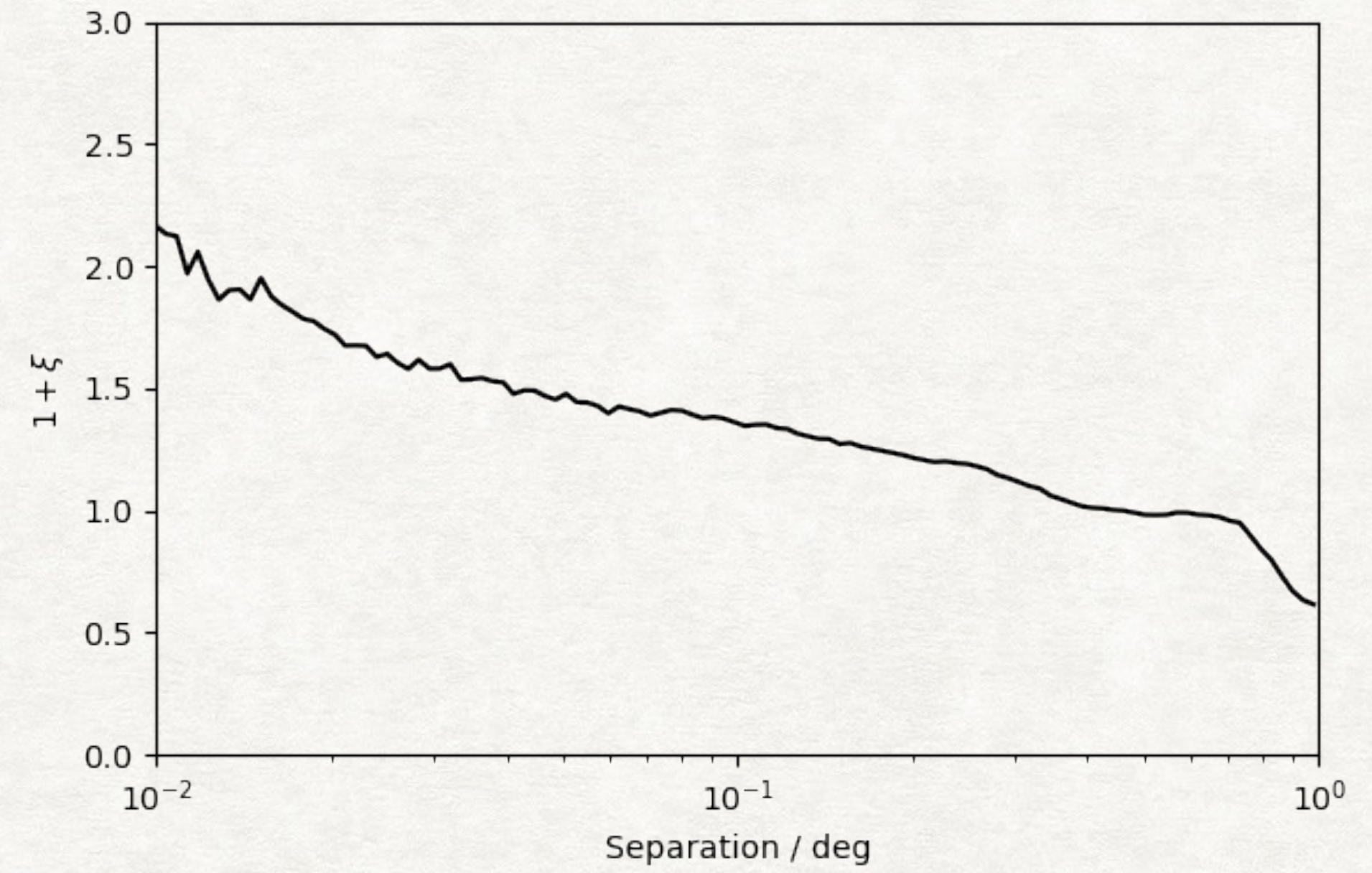
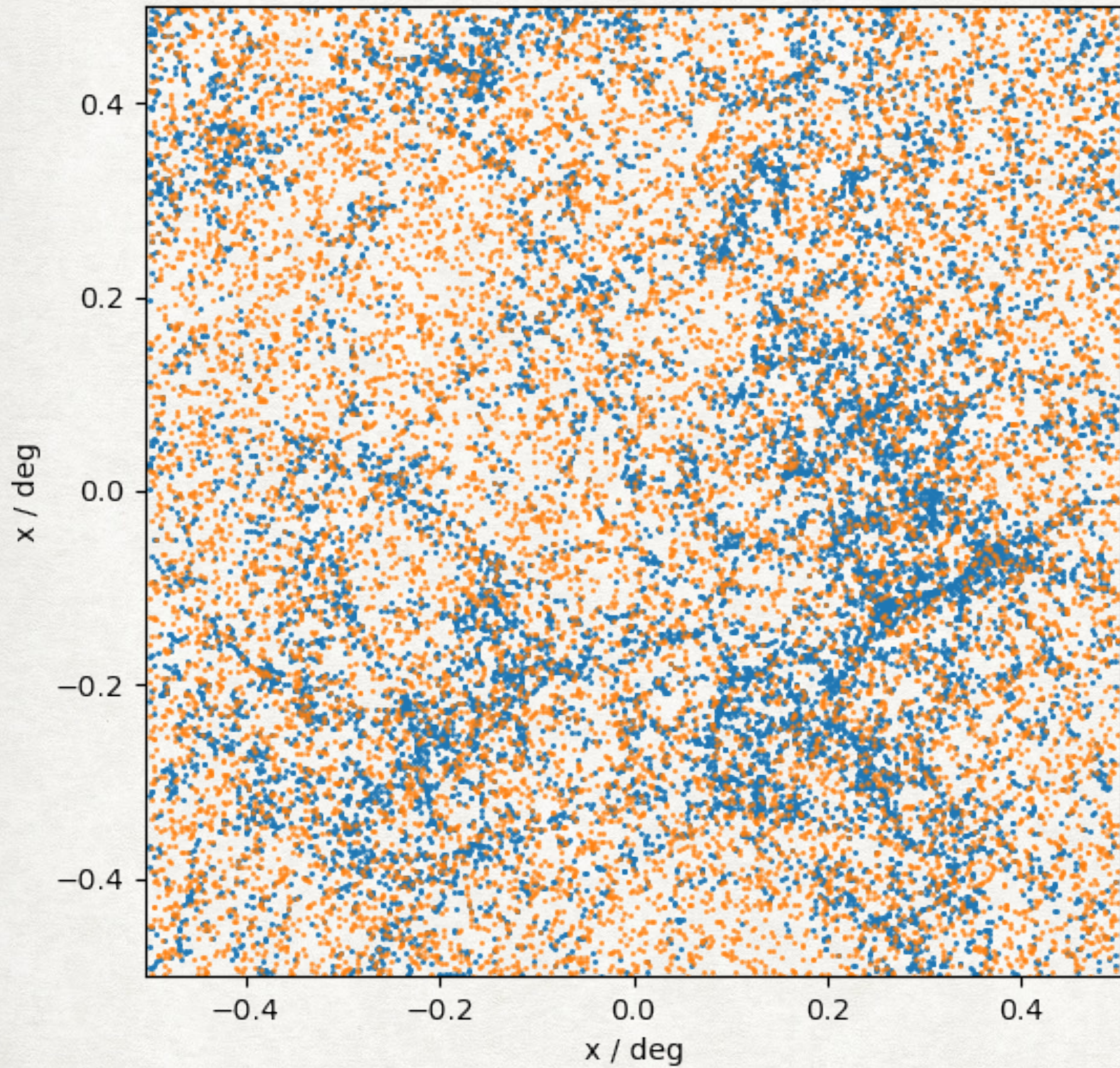
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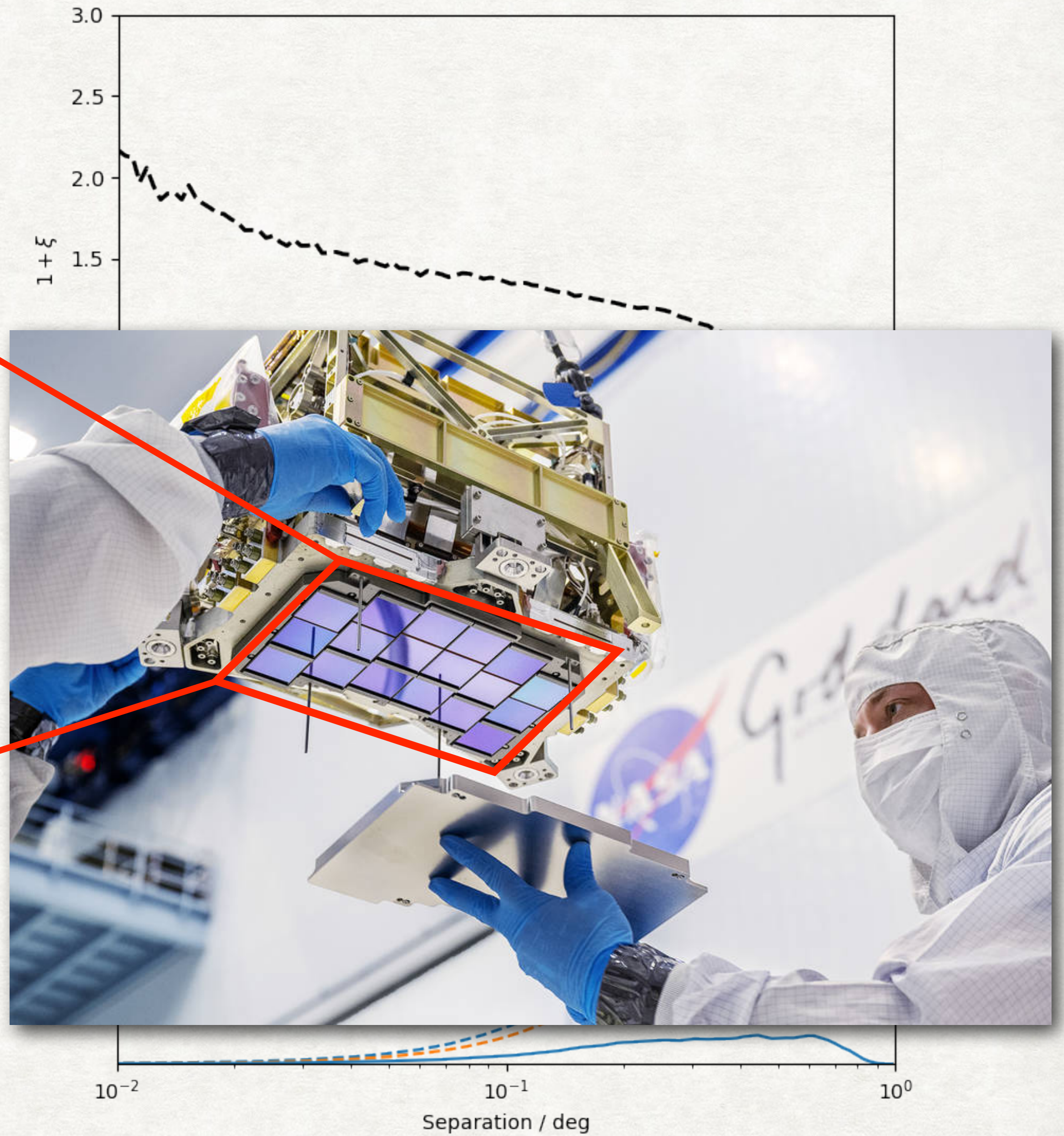
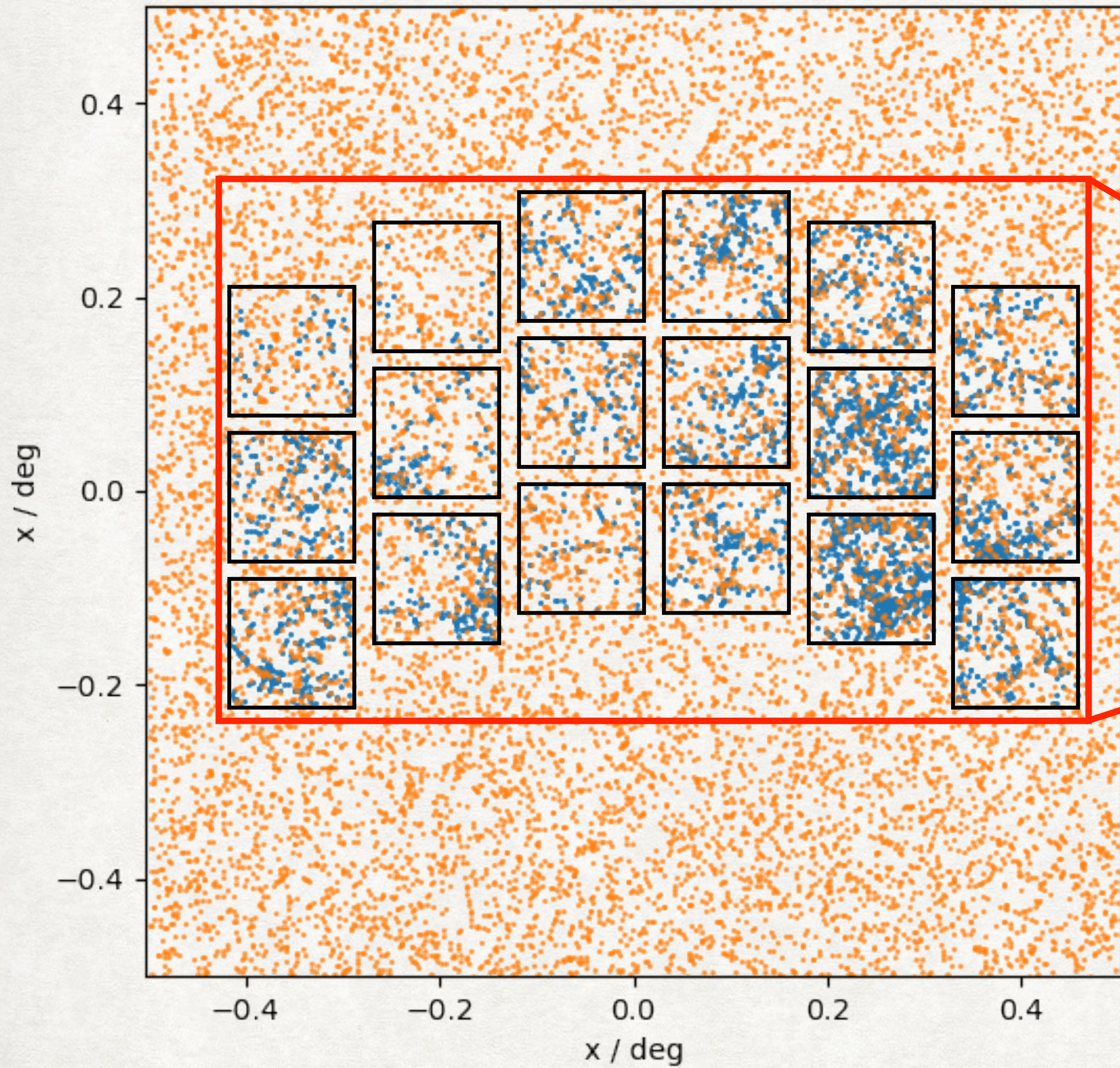
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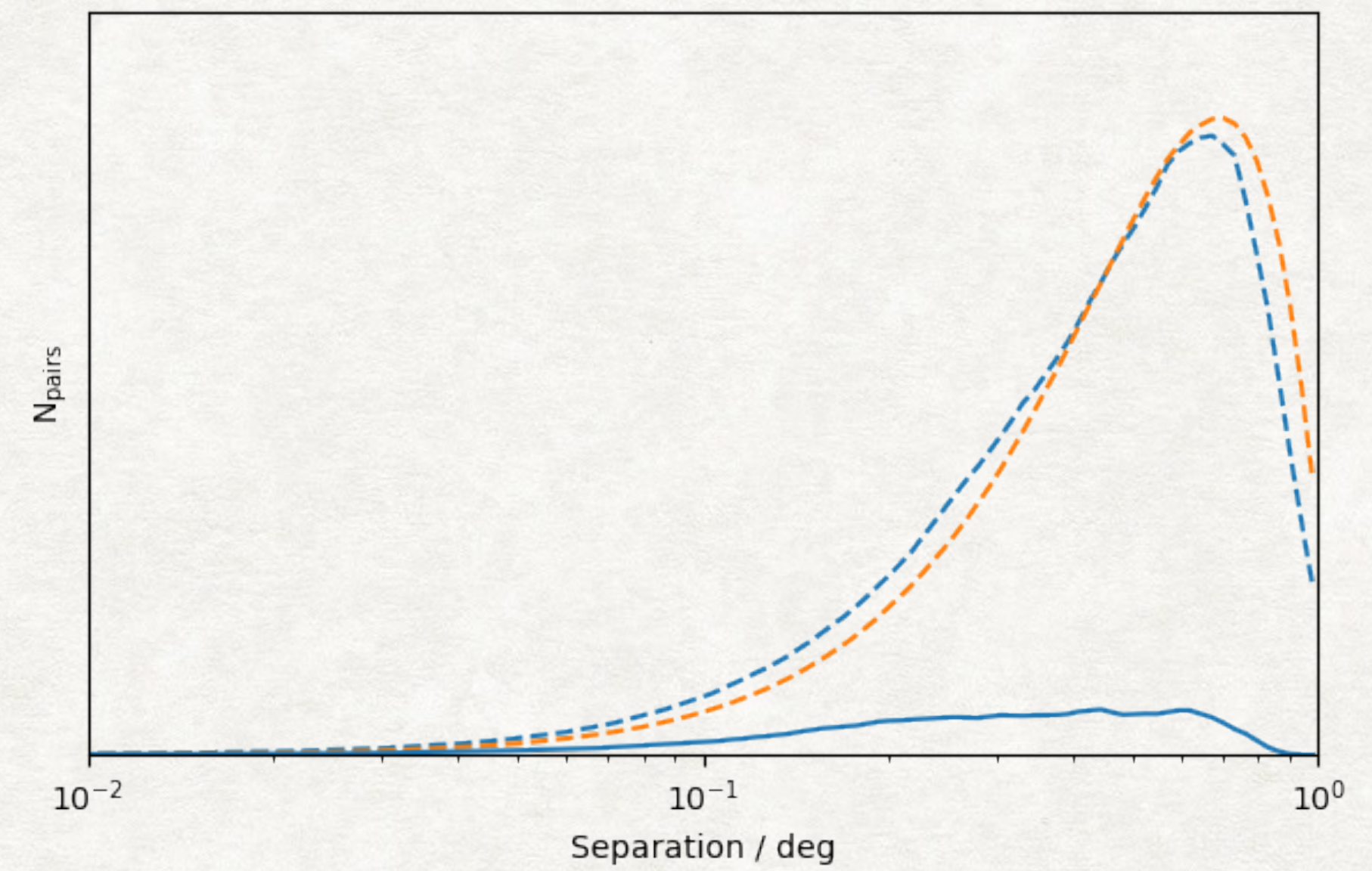
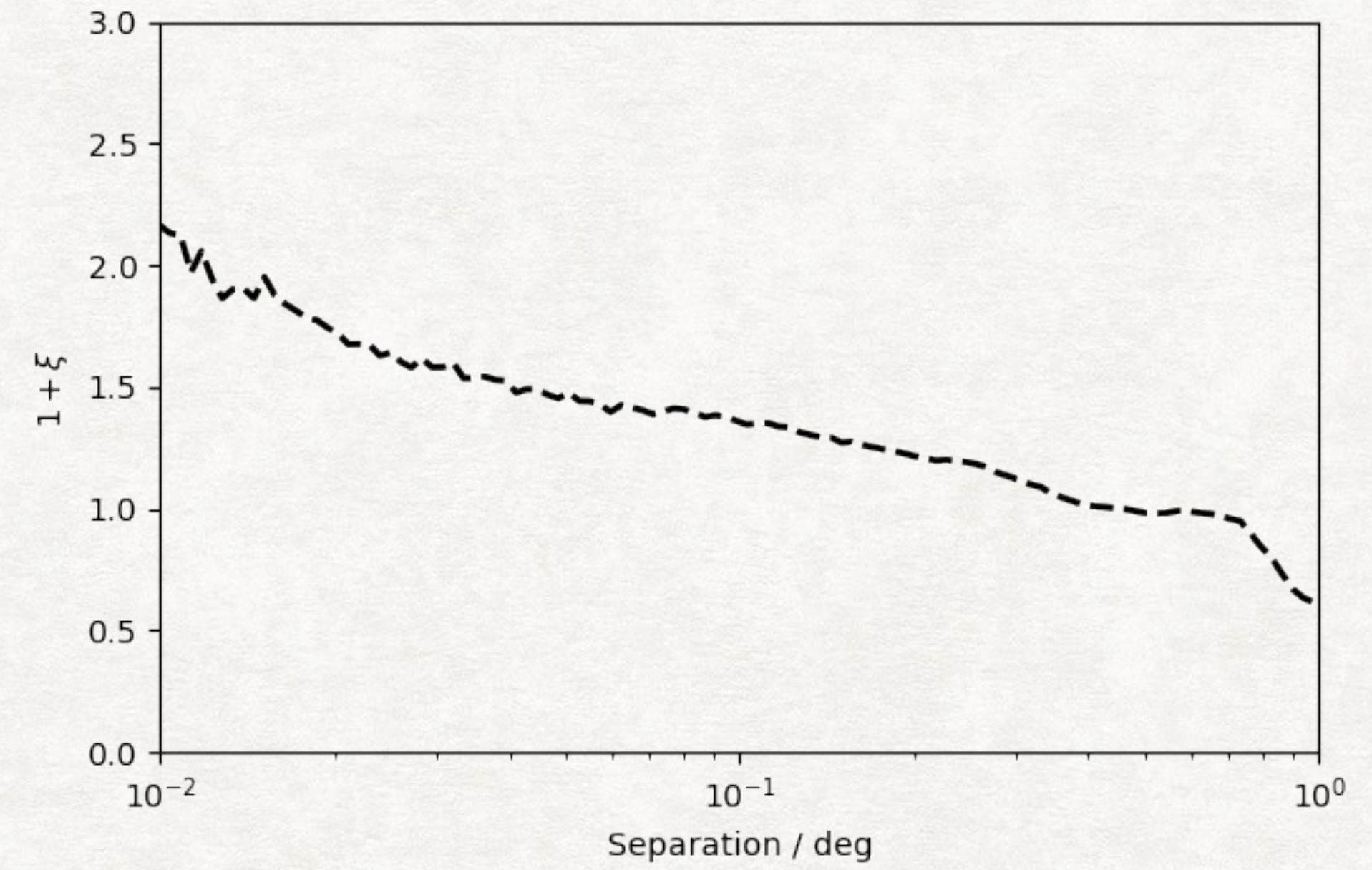
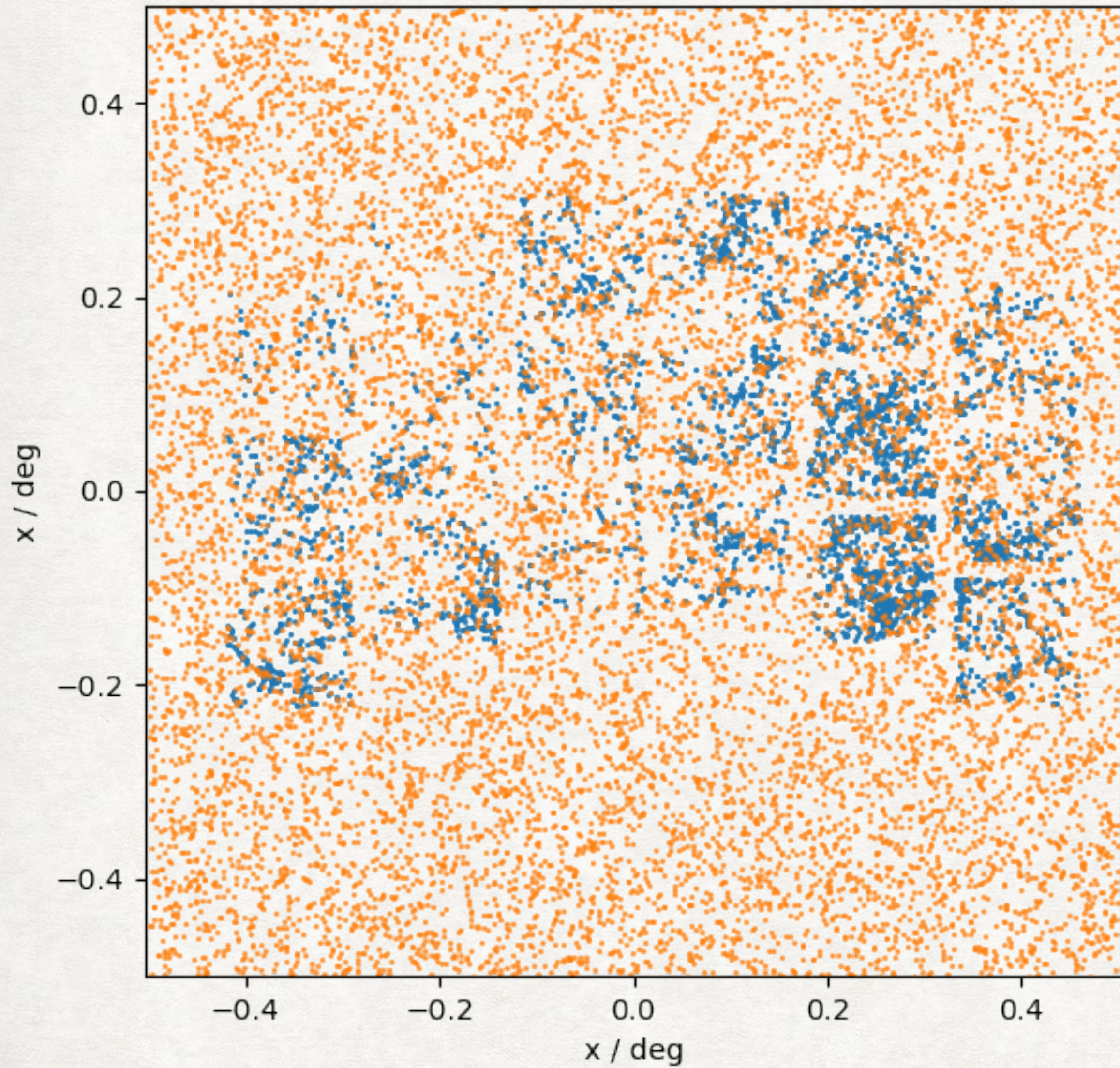
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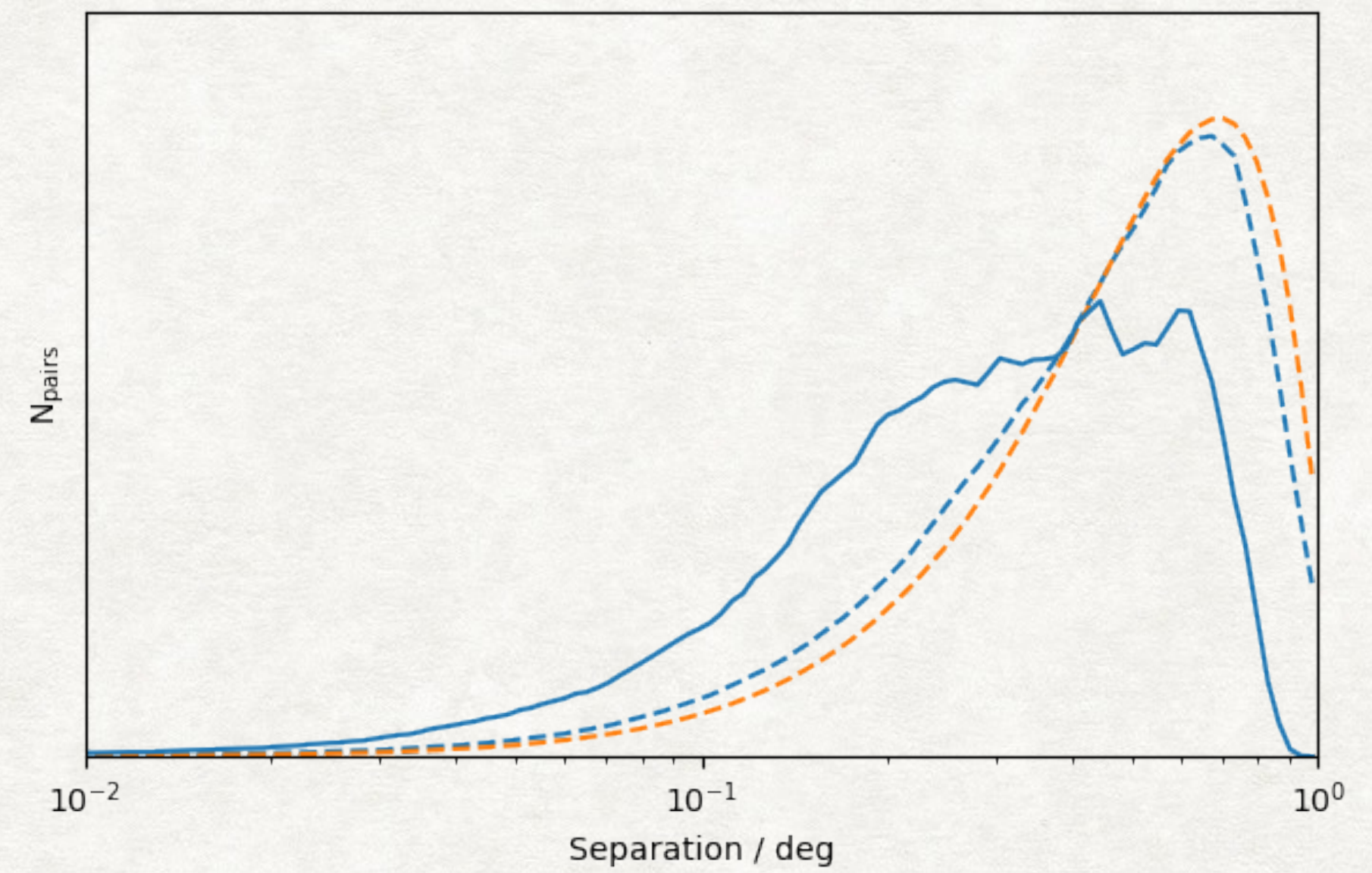
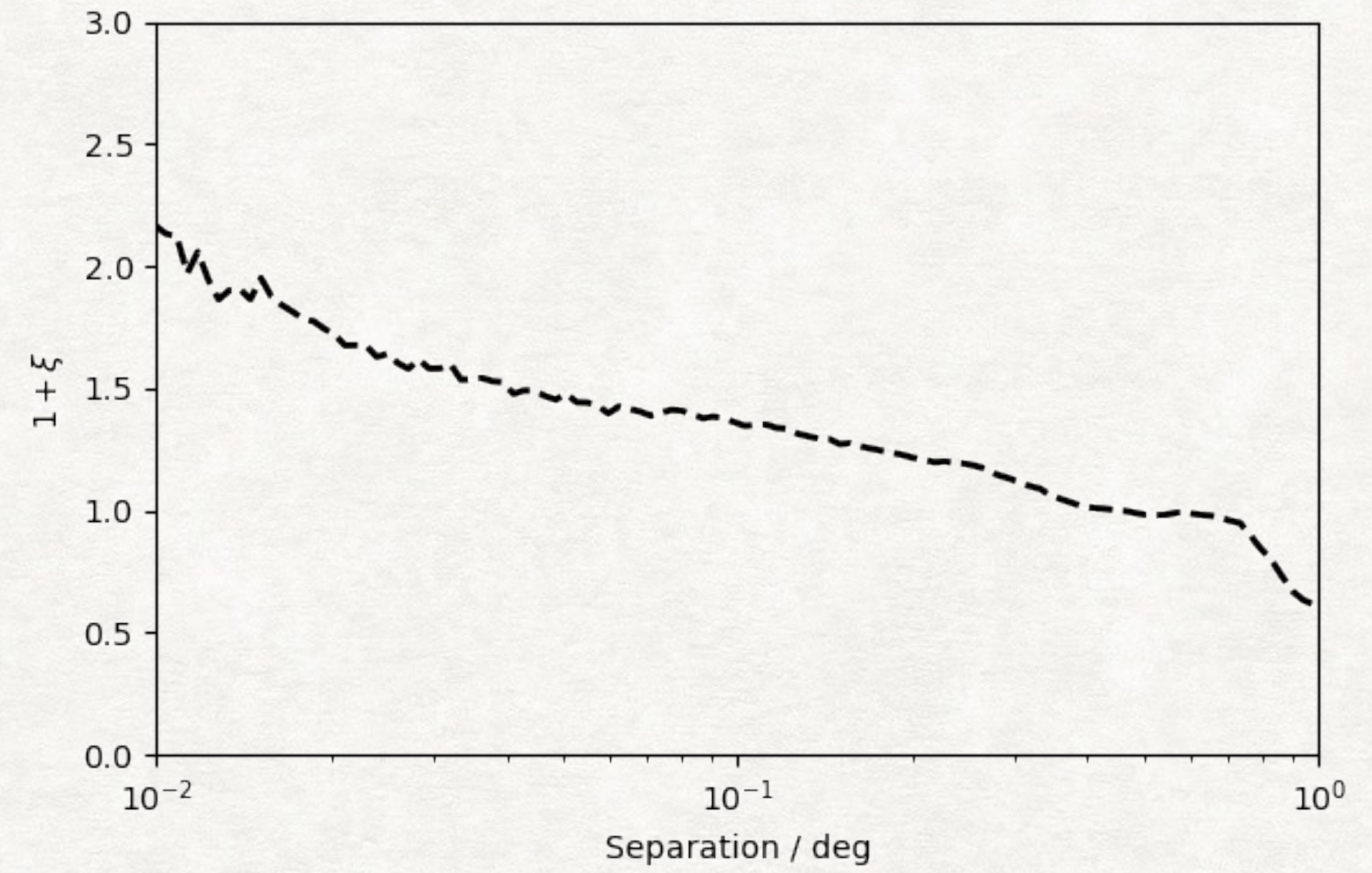
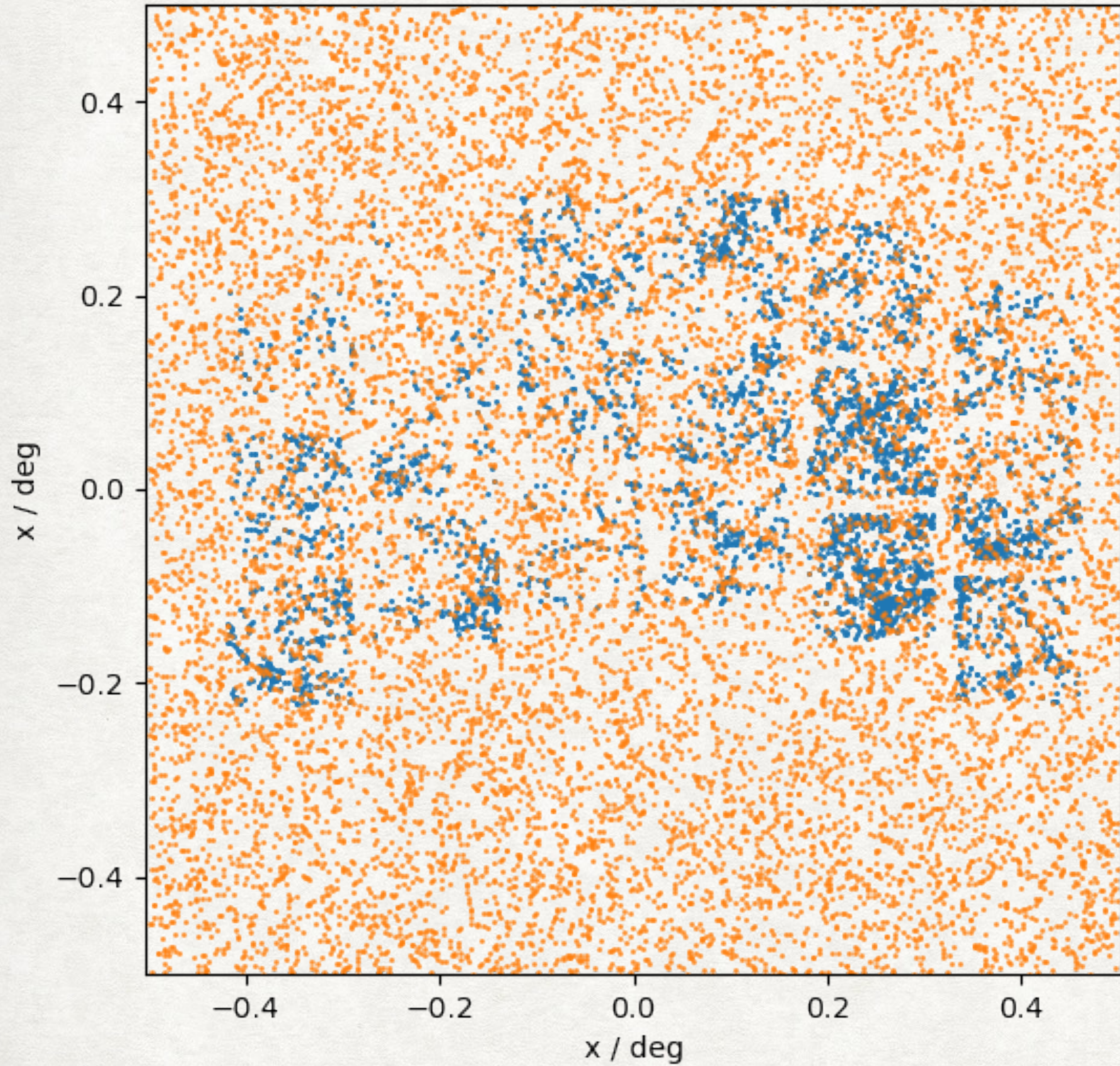
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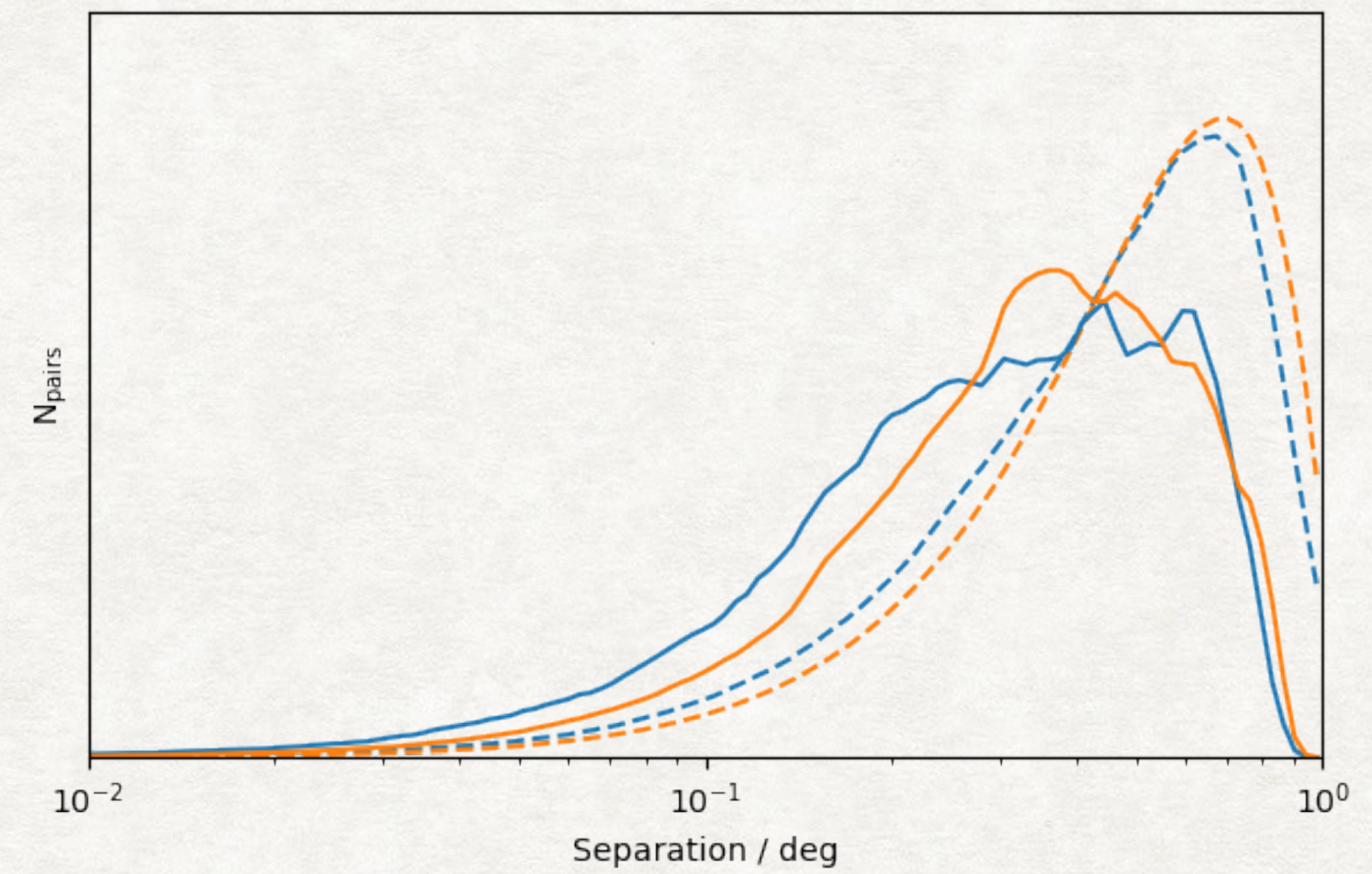
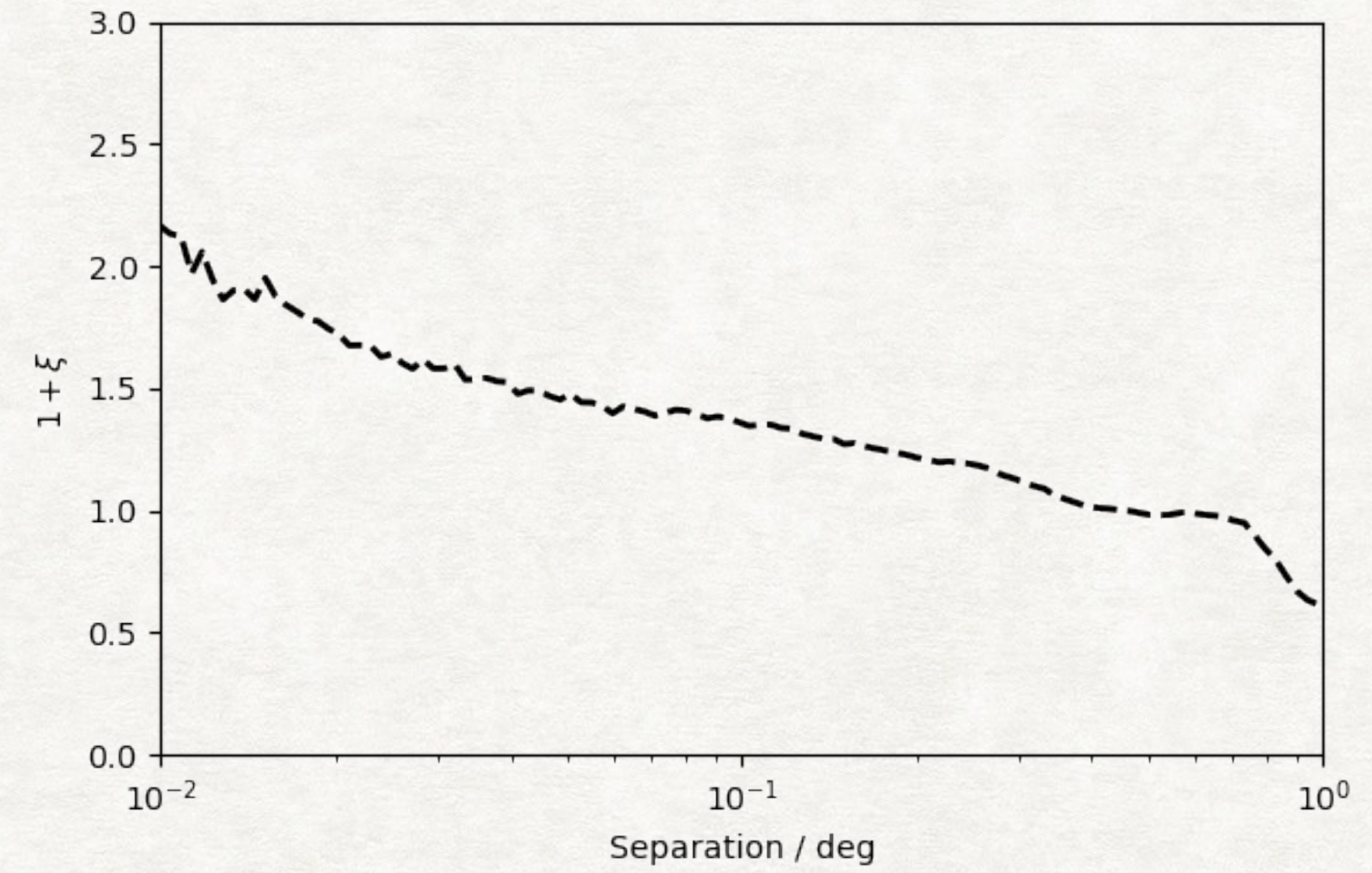
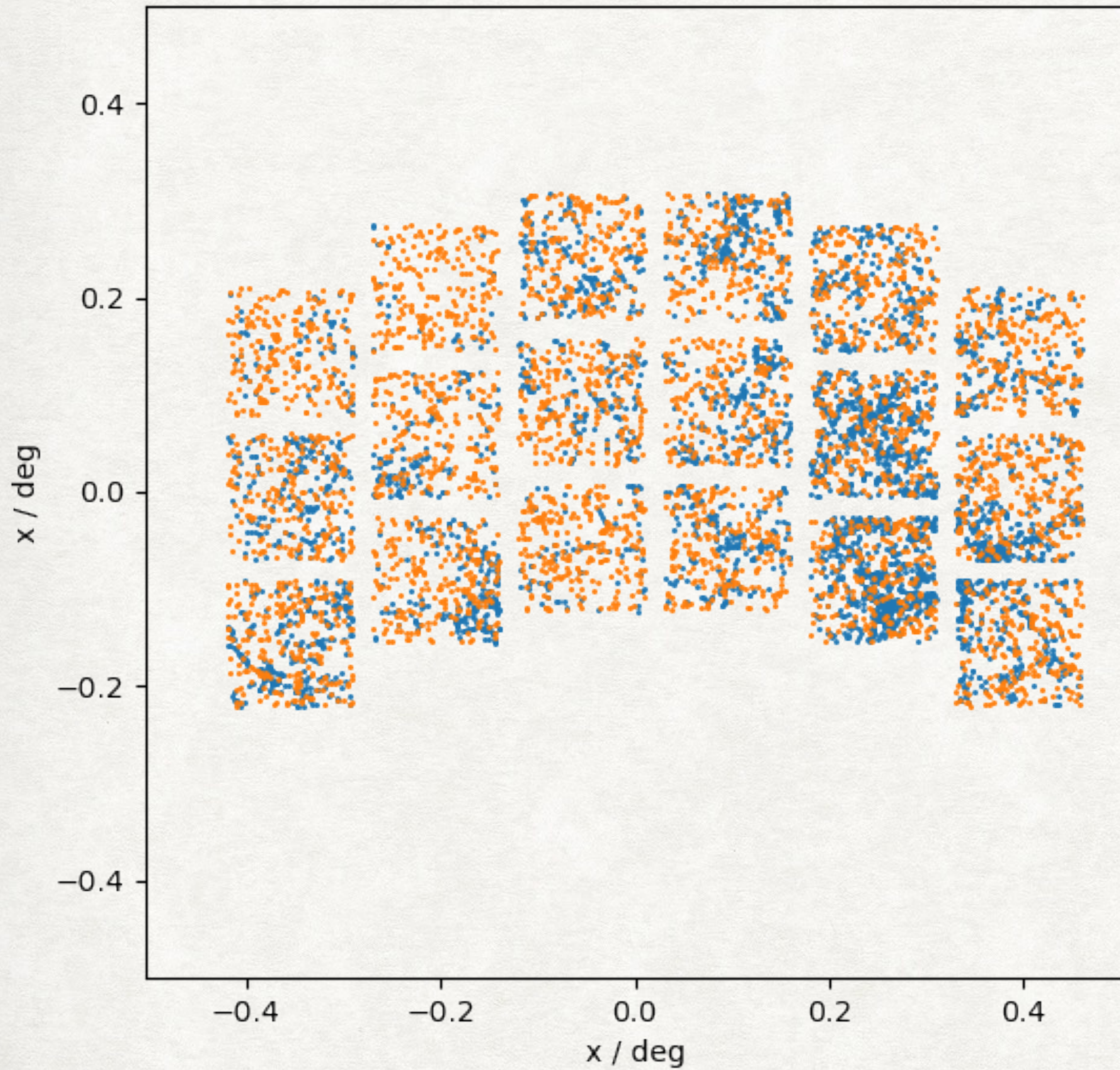
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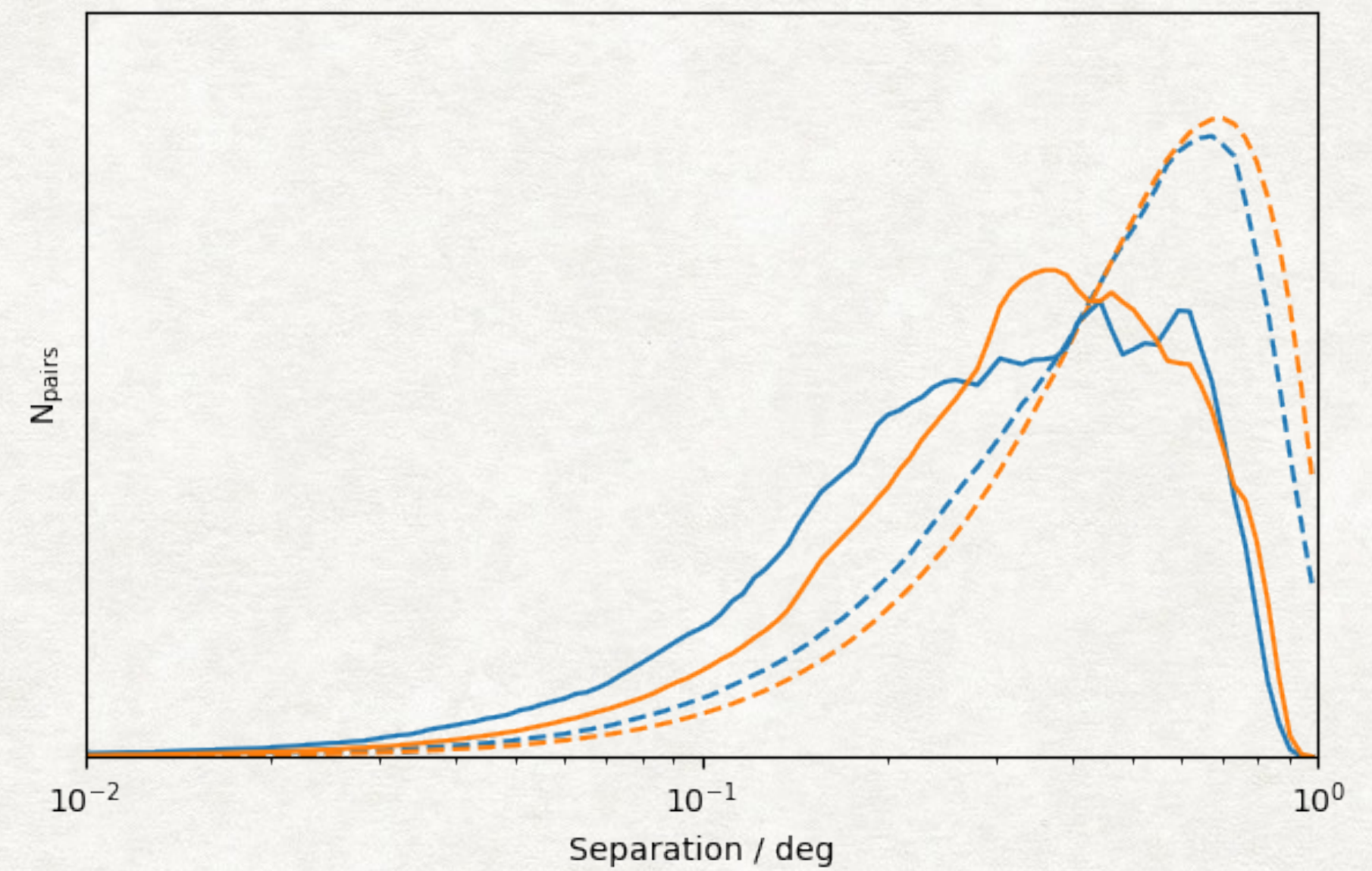
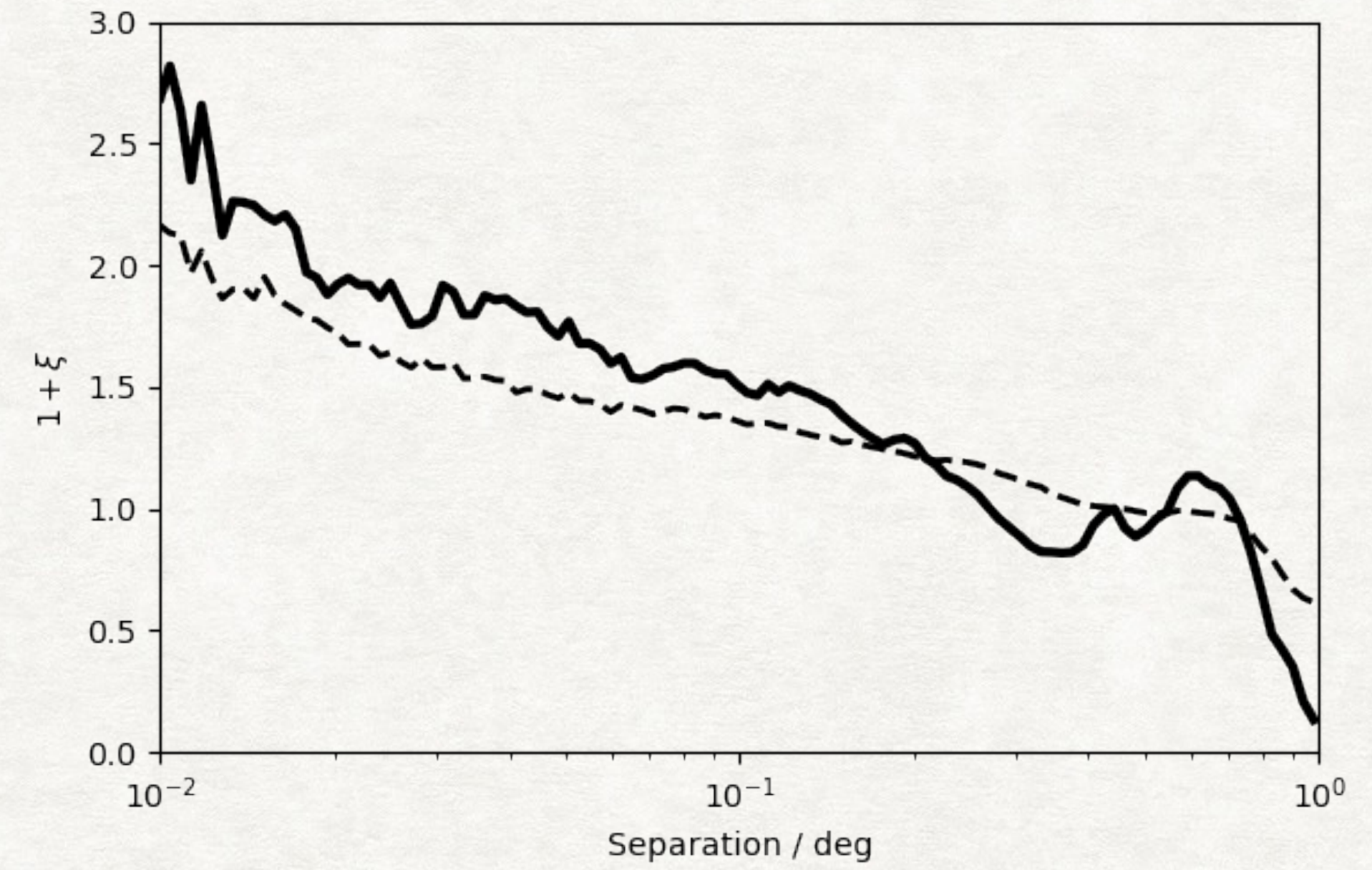
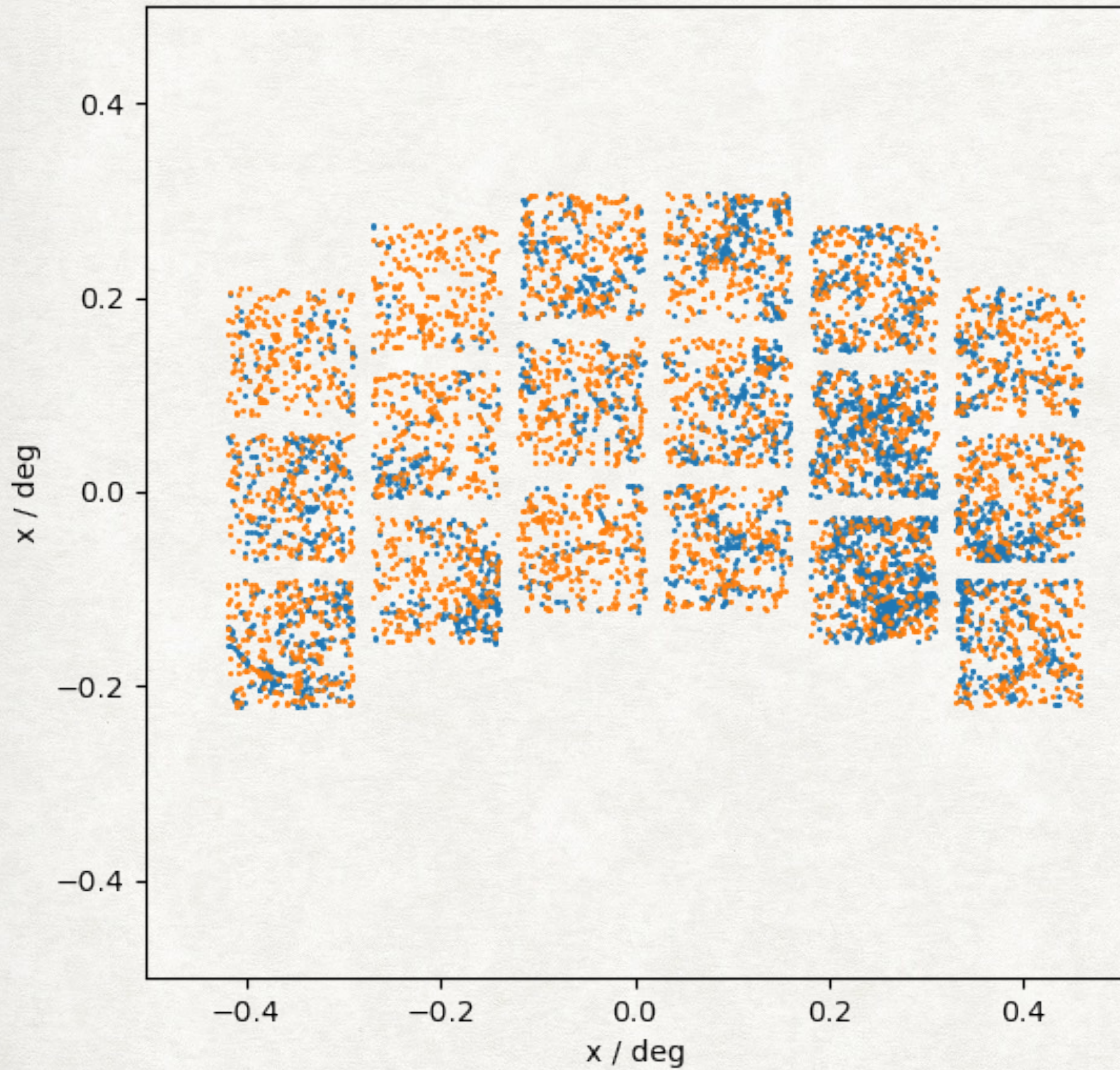
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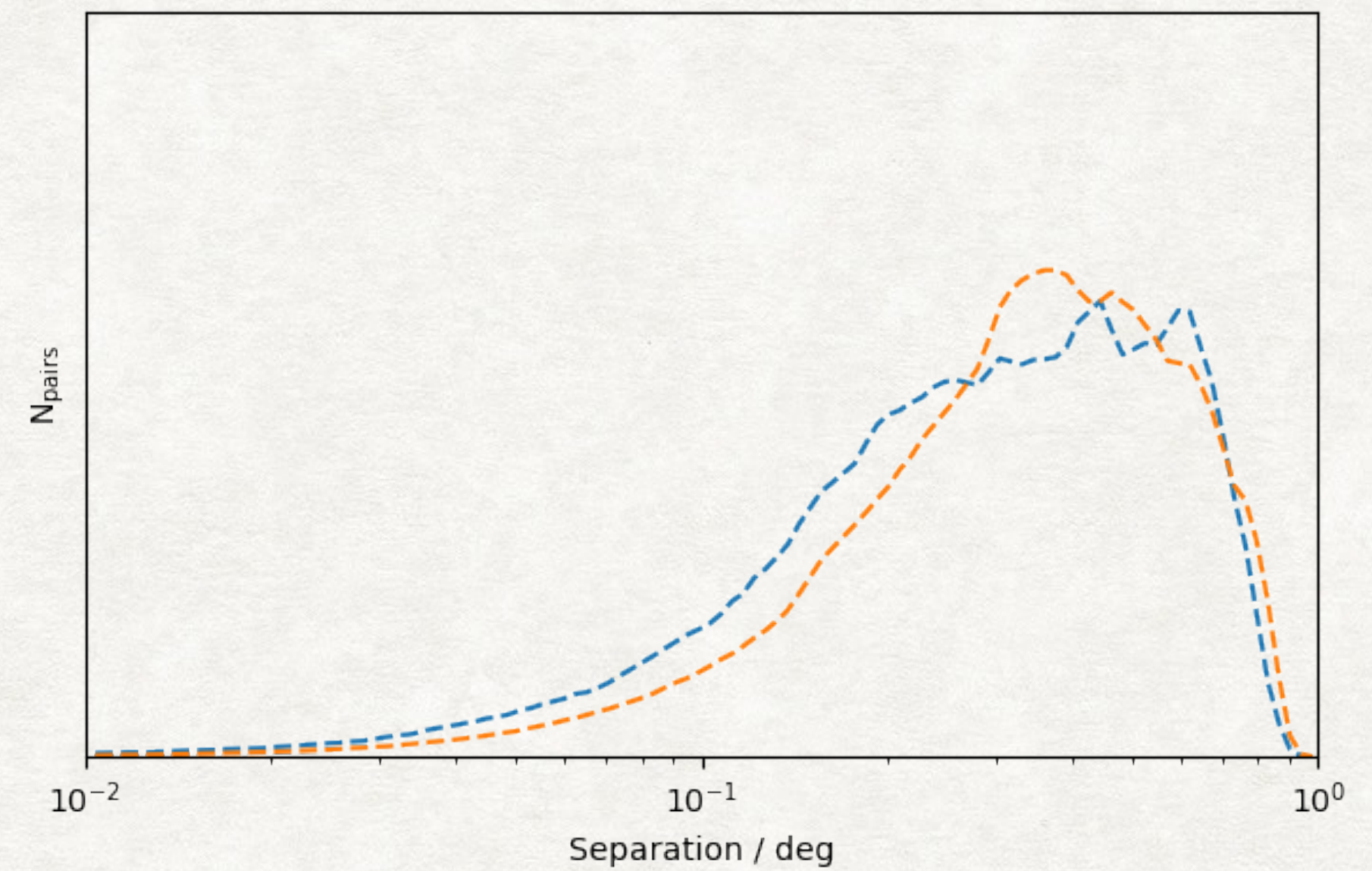
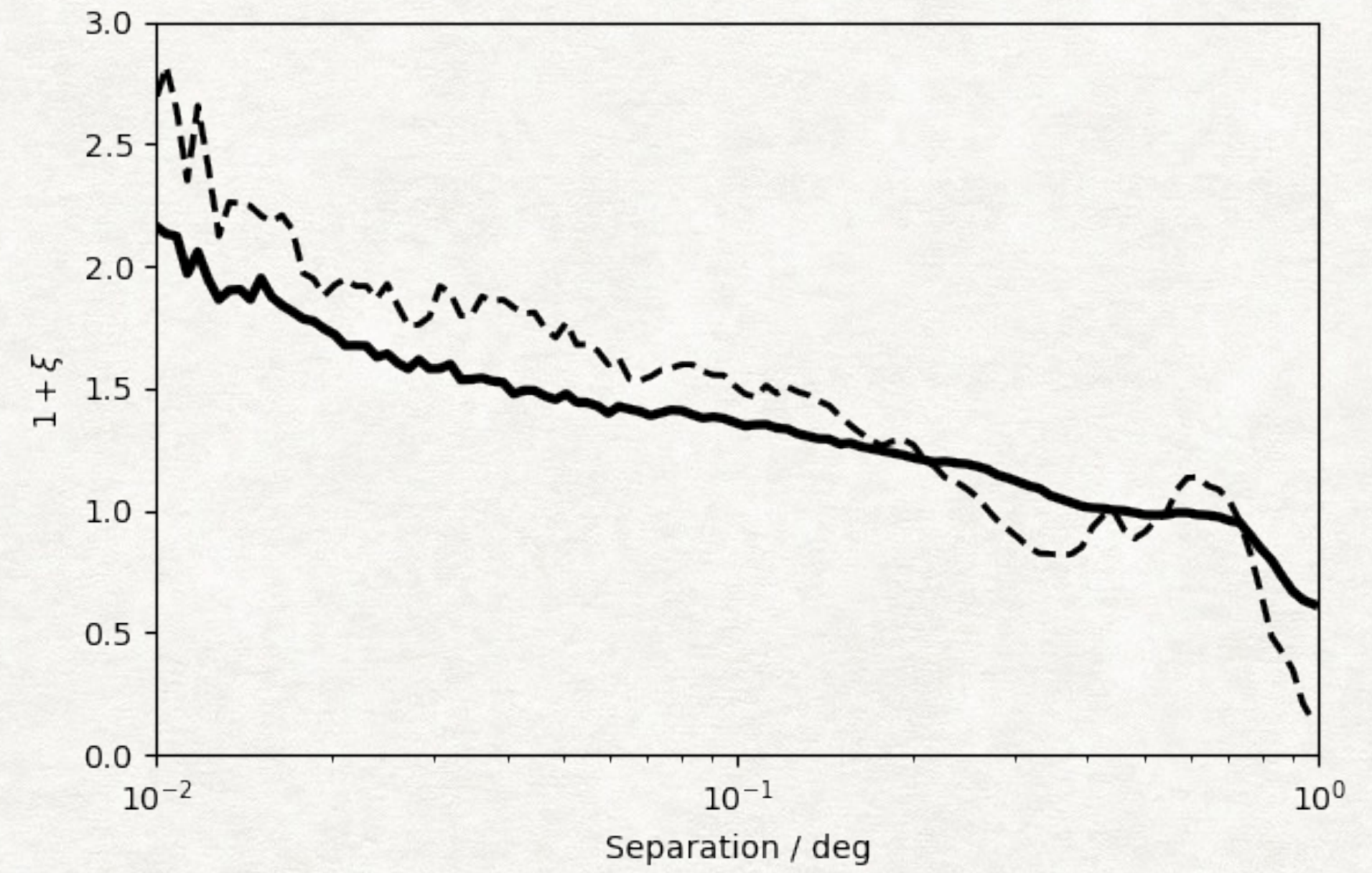
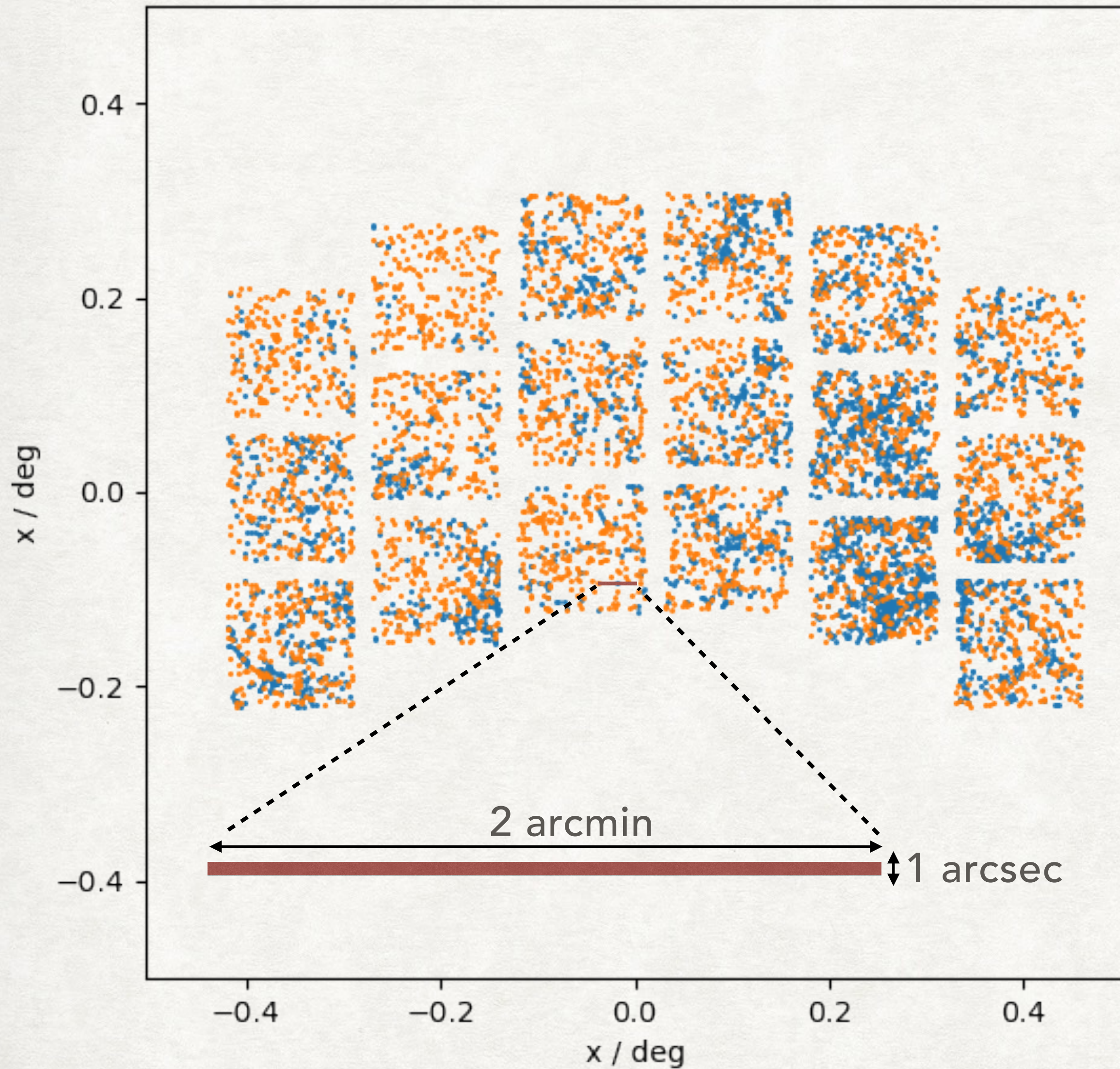
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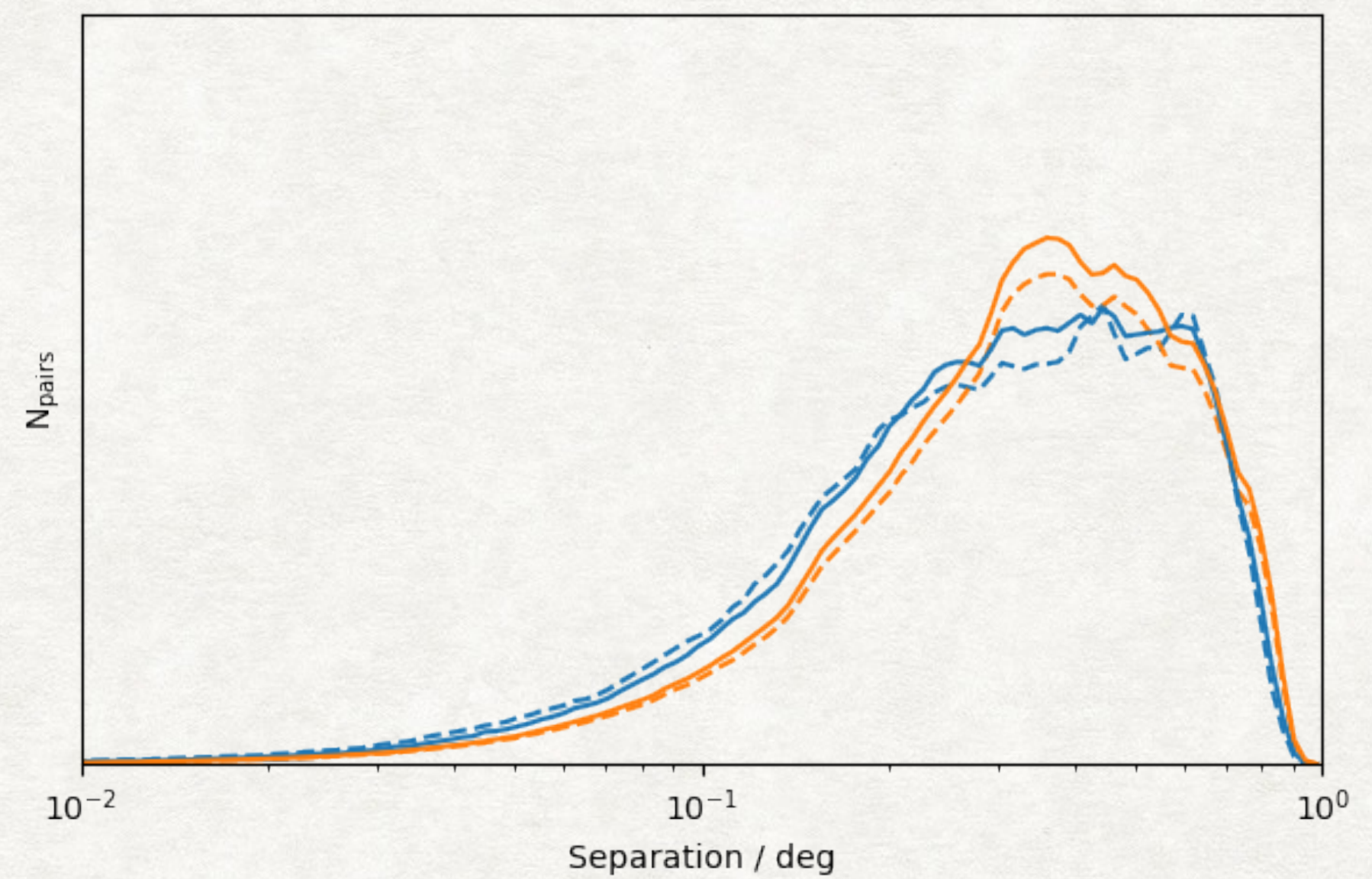
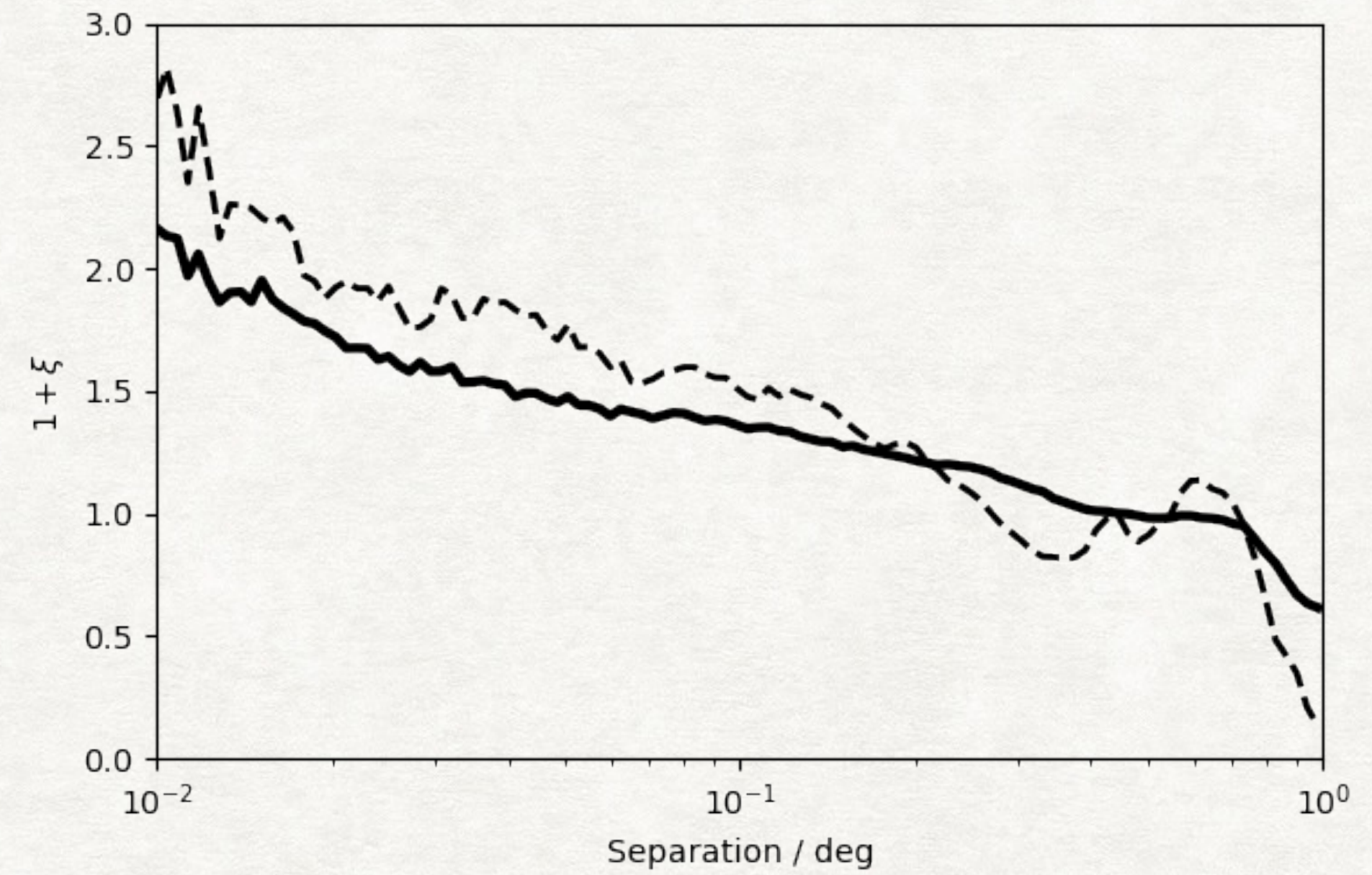
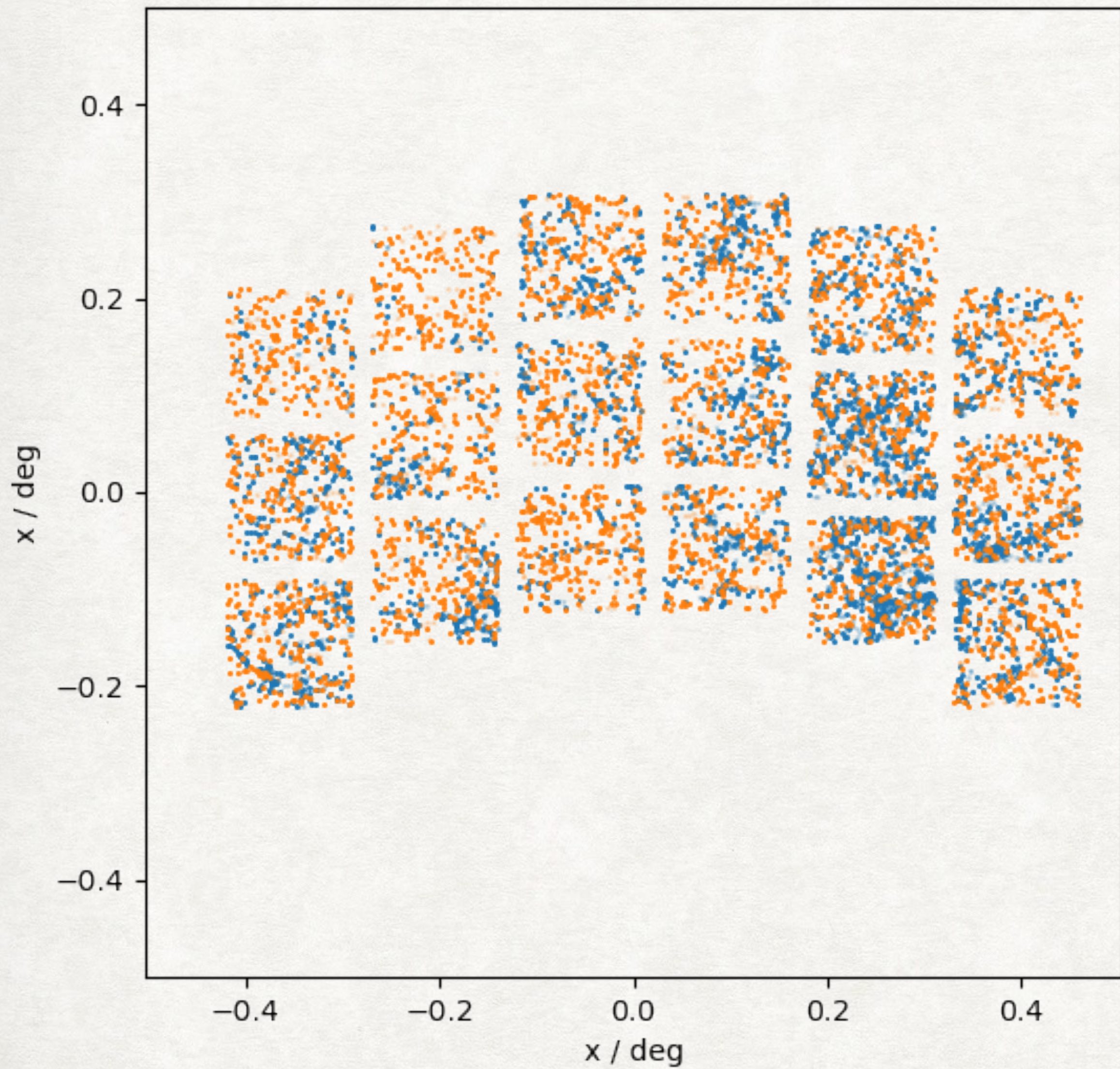
HOW DO WE MEASURE A GALAXY CORRELATION FUNCTION?



THE EFFECTS OF OVERLAPPING SPECTRA



THE EFFECTS OF OVERLAPPING SPECTRA



THE EFFECTS OF OVERLAPPING SPECTRA

