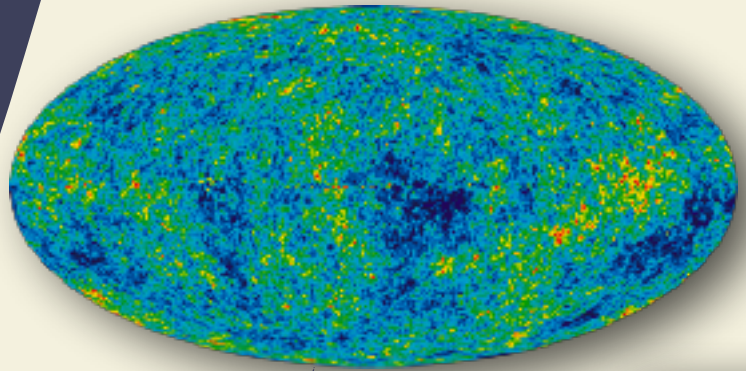
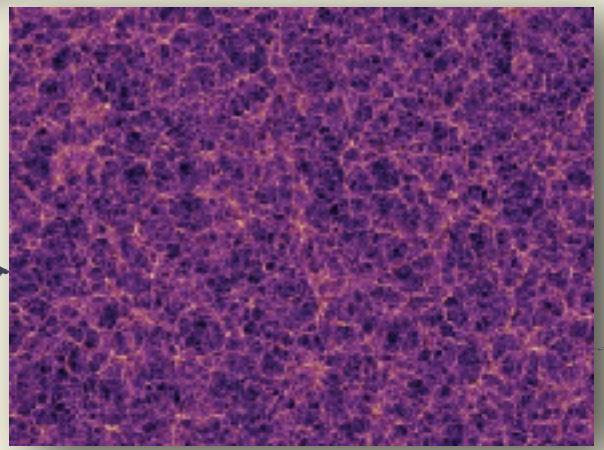
EXPLORING CHEMICAL INHOMOGENEITIES IN GALAXIES ACROSS COSMIC TIME

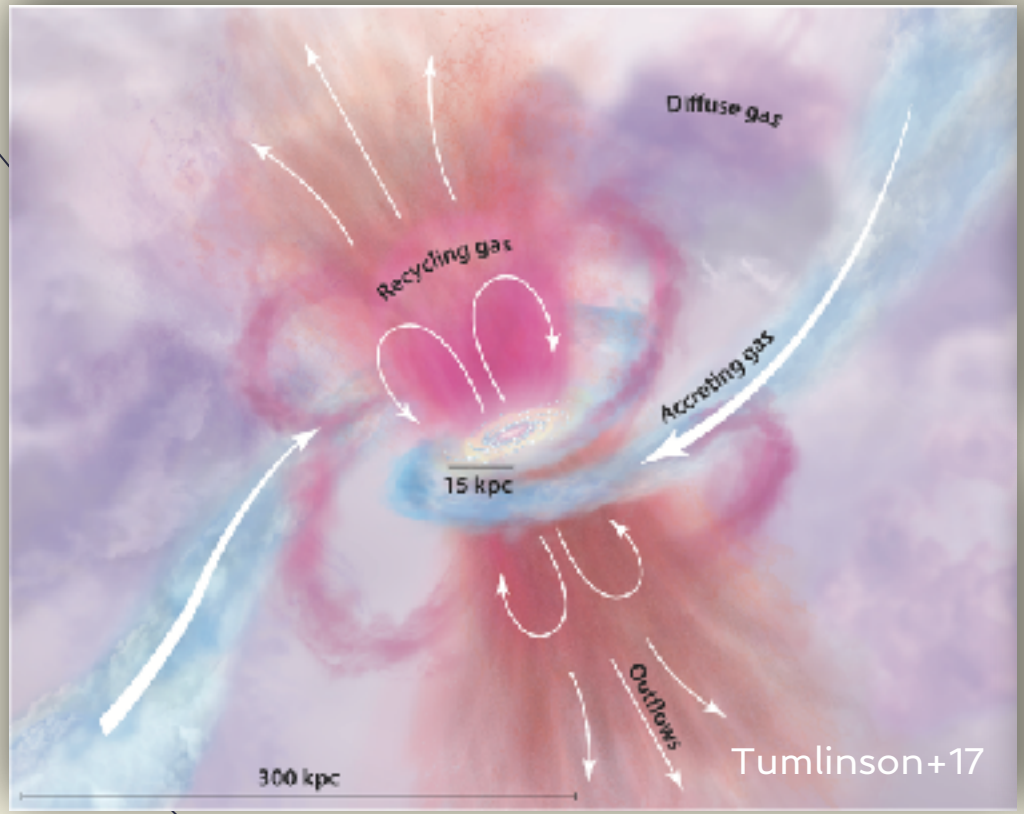
Benjamin Metha (he/him) | November 12, 2024

GALAXY EVOLUTION: WHAT WE KNOW



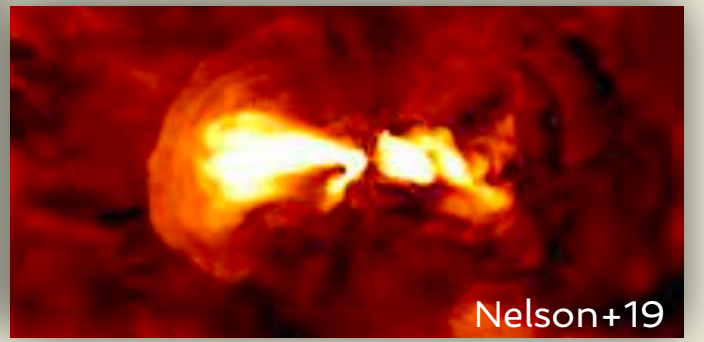


WHAT WE DON'T: GAS PHYSICS



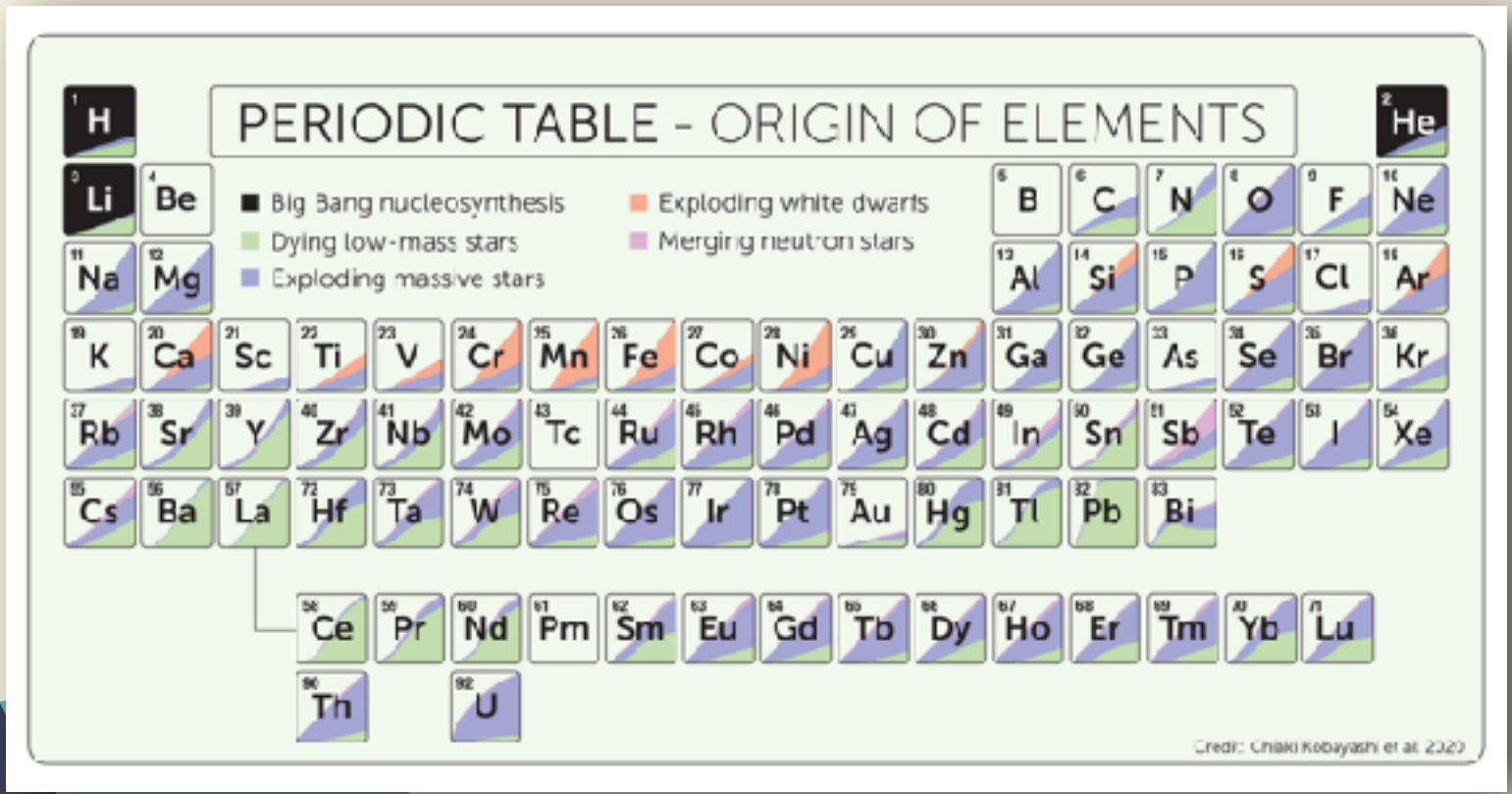
Inflows/outflows

Mergers

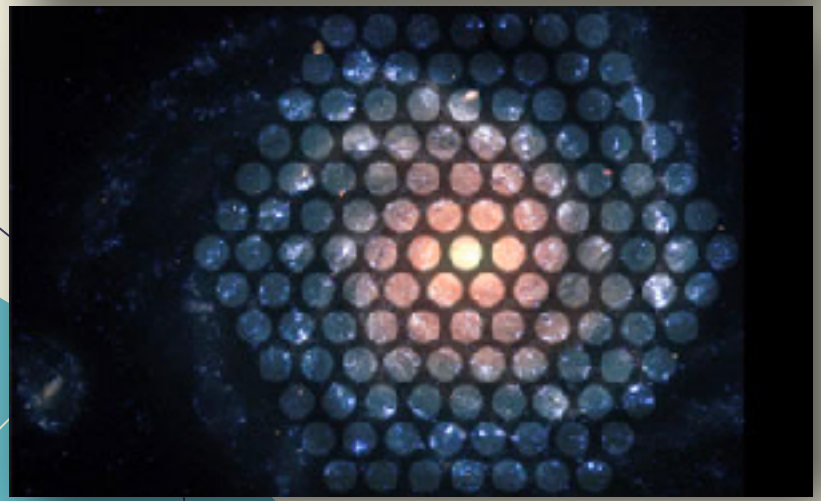


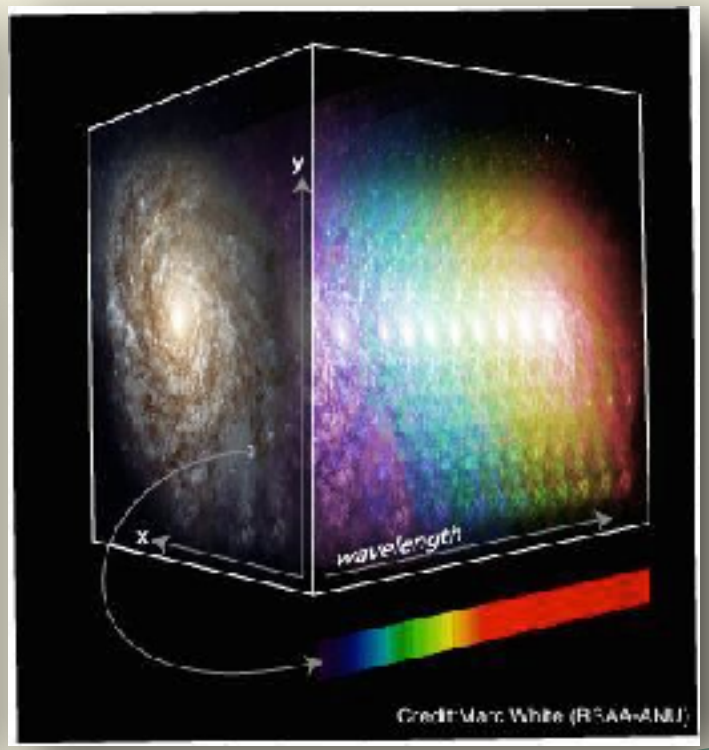
Feedback/Turbulence

TRACING GAS PHYSICS WITH METALS

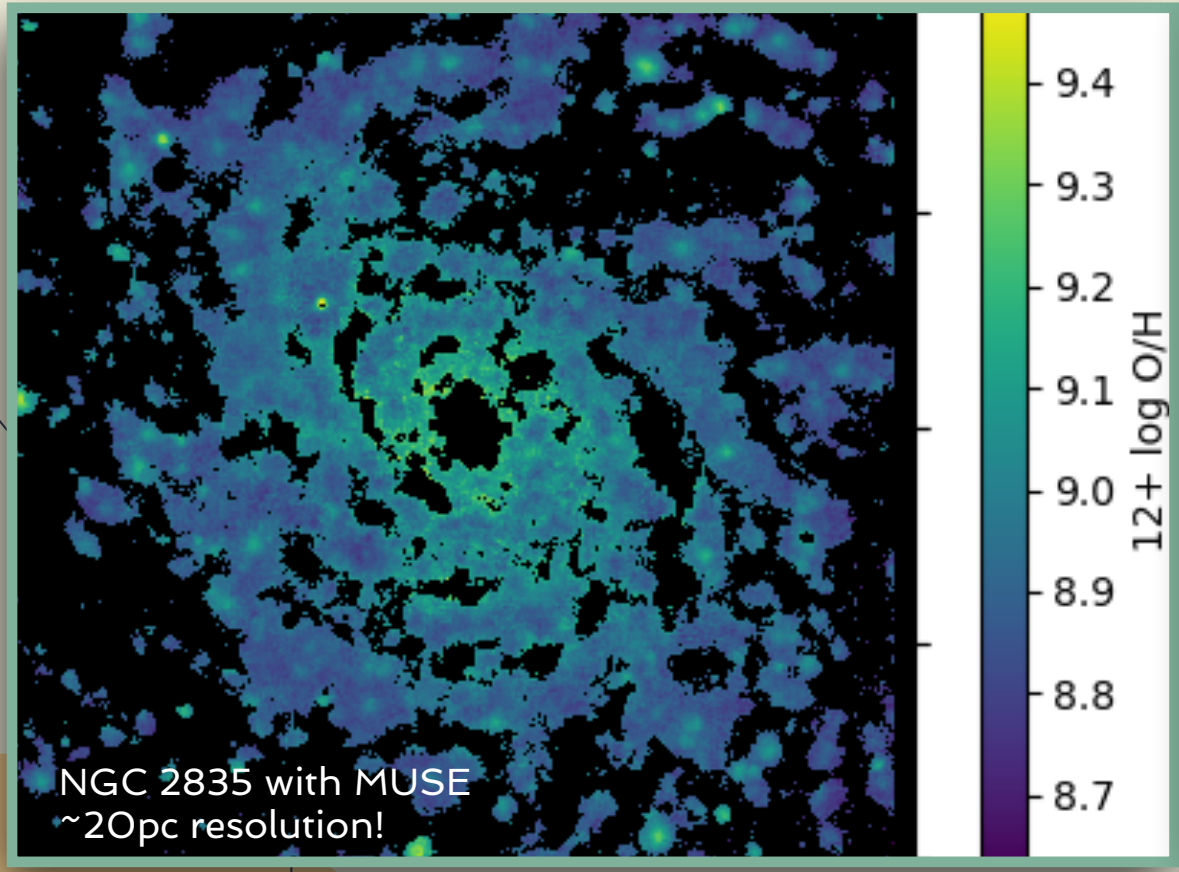


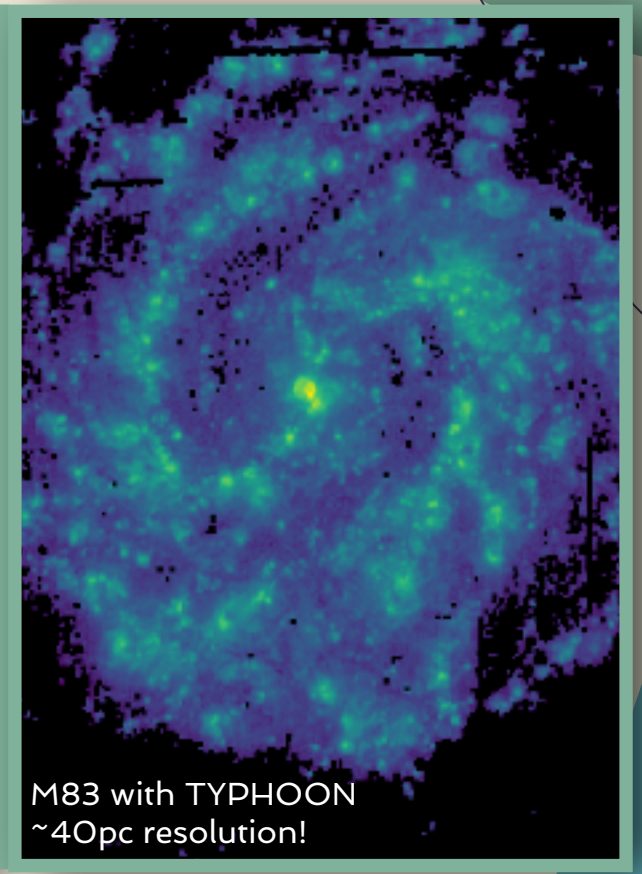
RESOLVING METALLICITY VARIATIONS





MODERN DATA LOOKS AMAZING





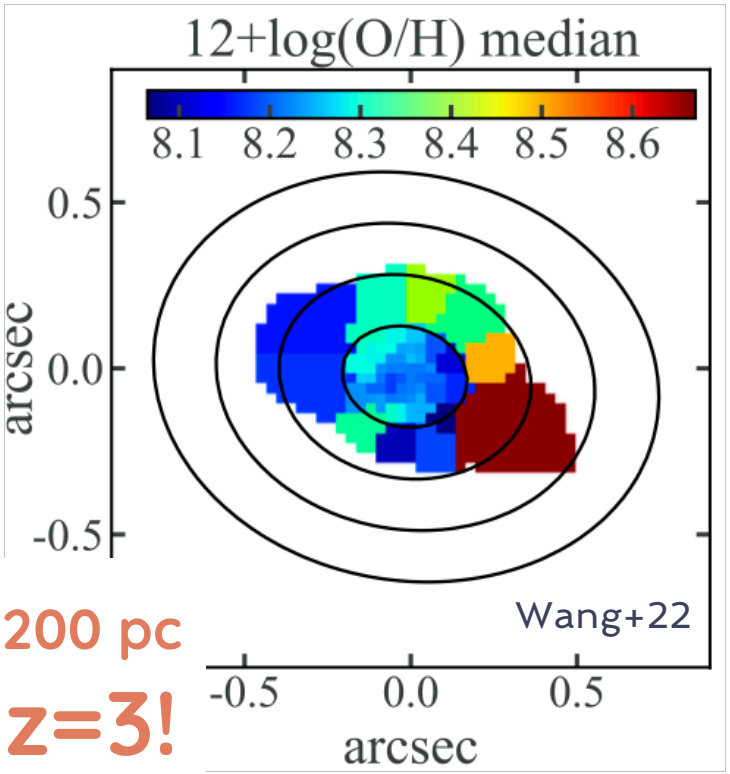
JWST DATA IS INCREDIBLE

JWST SENSITIVITY

NIRISS can do resolved spectroscopy on very faint targets

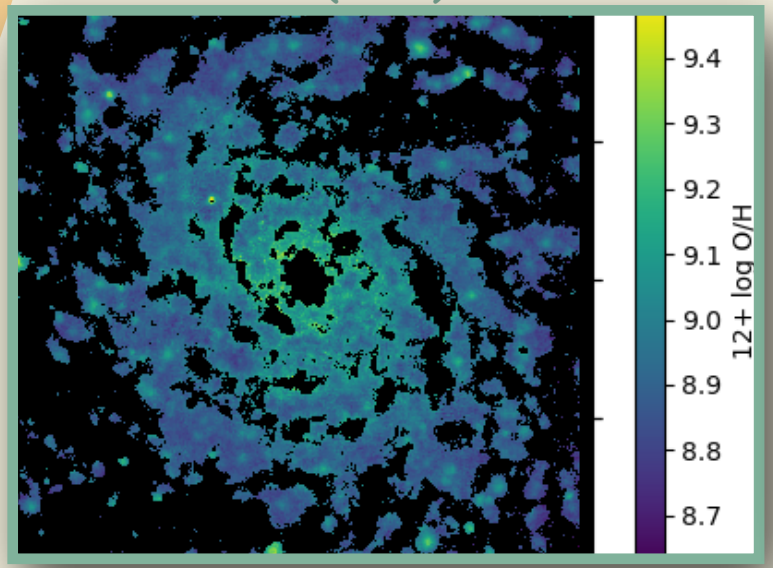
GRAVITATIONAL LENSING

Magnification improves resolution and sensitivity.

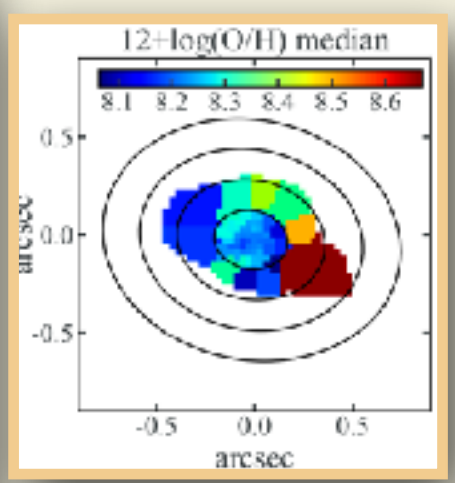


GOAL: CONNECT THEORY & OBSERVATIONS

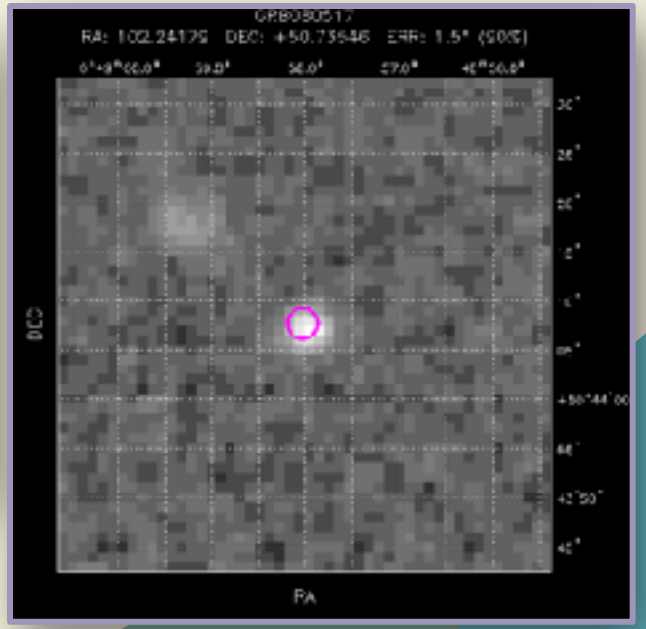
With high resolution data (z ~ 0)



With mid-resolution data ($z \lesssim 2$)



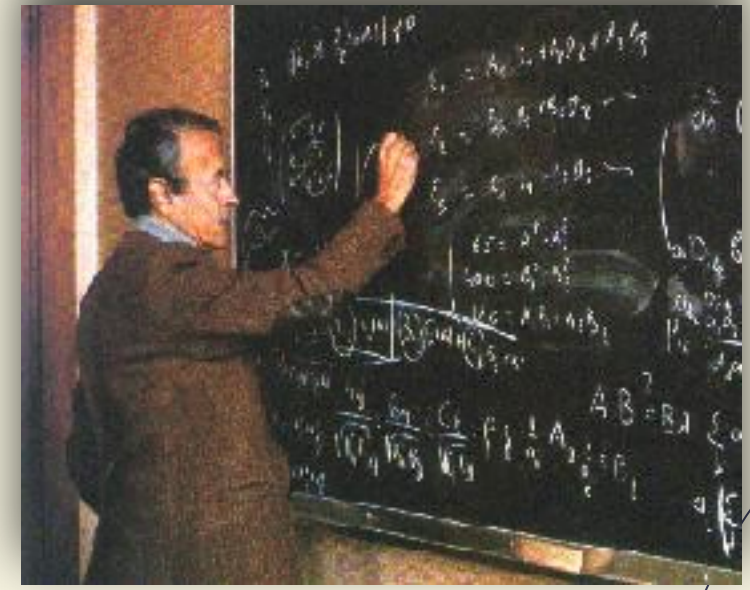
With unresolved data ($z \gtrsim 2$)



PART 1:
GEOSTATISTICS
(resolution $\lesssim$ 200pc)

WHAT IS GEOSTATISTICS?

"GEOSTATISTICS IS THE STUDY OF A RANDOM PROCESS THAT VARIES OVER A SPATIAL DOMAIN IN A PREDICTABLE WAY"



Georges Matheron. Image credit:

Centre de Geosciences

HIERARCHICAL MODELLING

Observation error:
known from telescope properties

$$Z_{obs}(x) = Z_{true}(x) + \epsilon(x)$$

$$Z_{true}(x) = \mu(x) + \eta(x)$$

Process mean:
accounts for the metallicity gradient

Random fluctuations:
spatially-correlated deviations

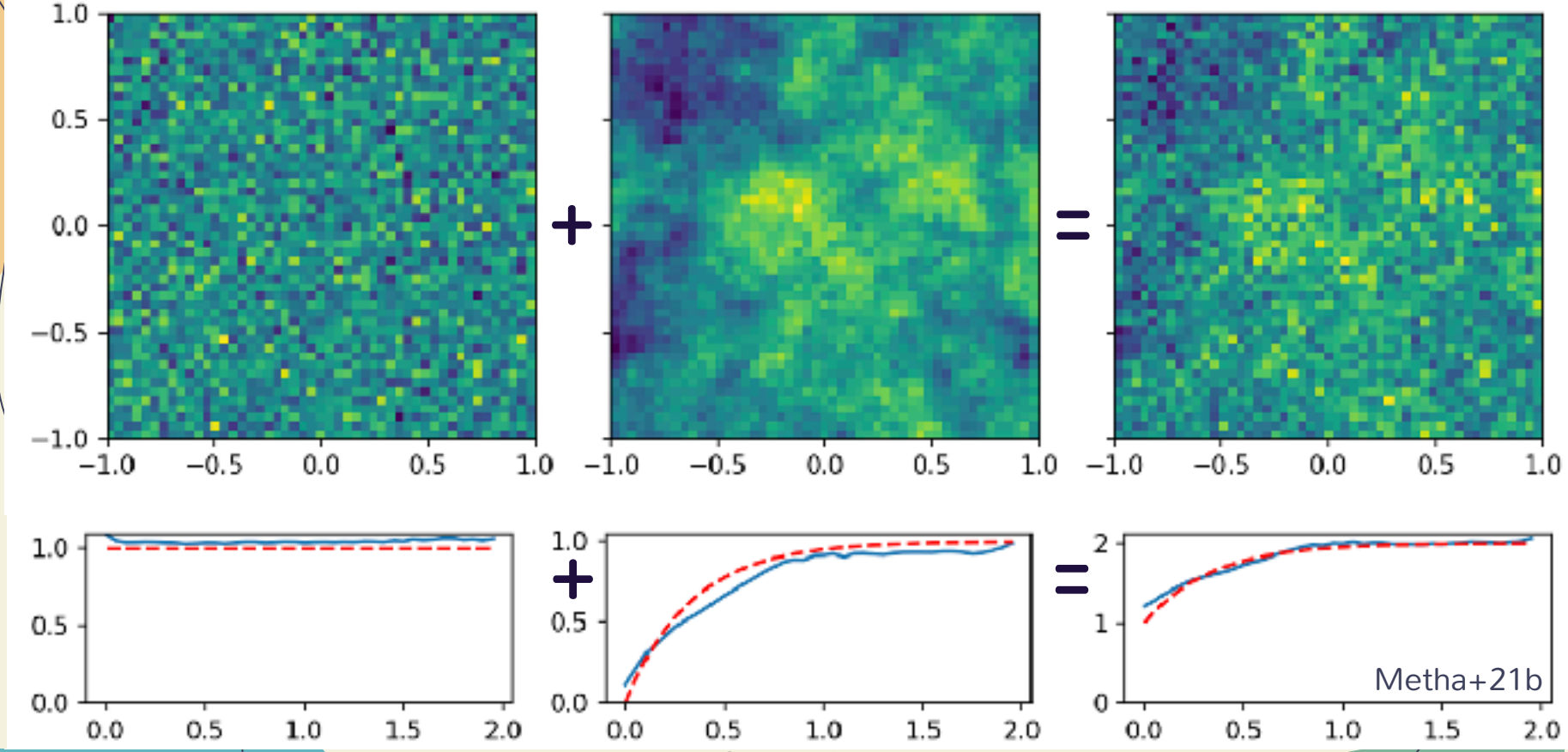
IF WE CAN MODEL $\epsilon(x)$, $\mu(x)$, AND $\eta(x)$, THEN WE CAN MODEL THE GALAXY!

SEPARATING SMALL FEATURES FROM NOISE

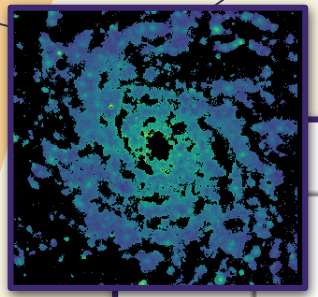
A **semivariogram** shows how the **variance between data points** depends on their **distance**.

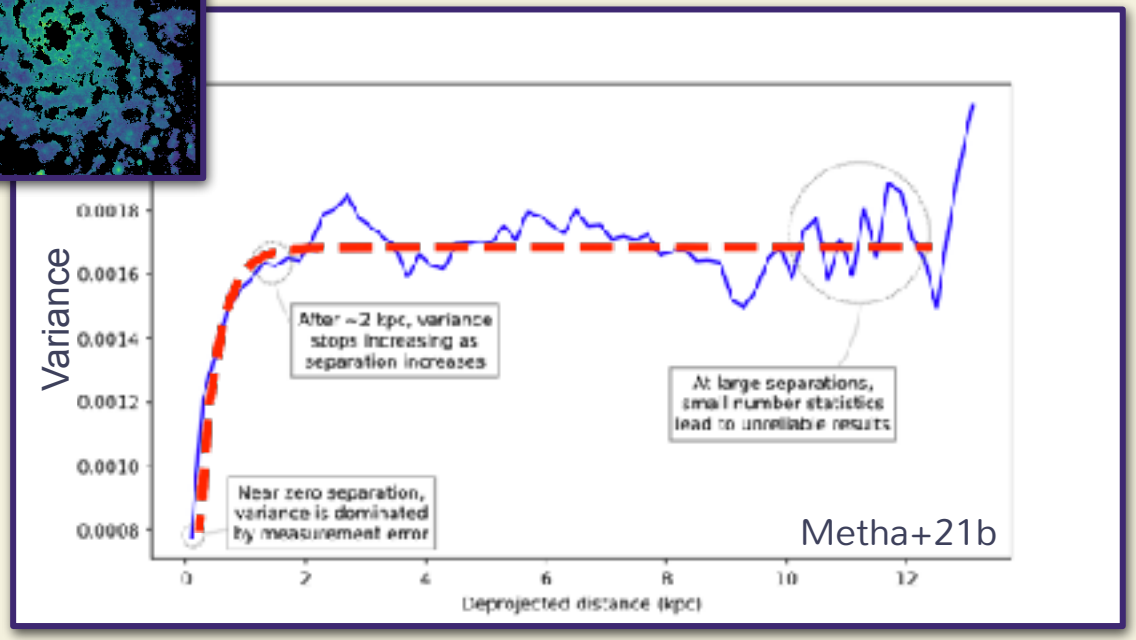
This lets us distinguish **spatially correlated** and **uncorrelated** sources of scatter around **the mean trend**.

A WORKED EXAMPLE



SEMIVARIOGRAMS REVEAL SUBSTRUCTURE





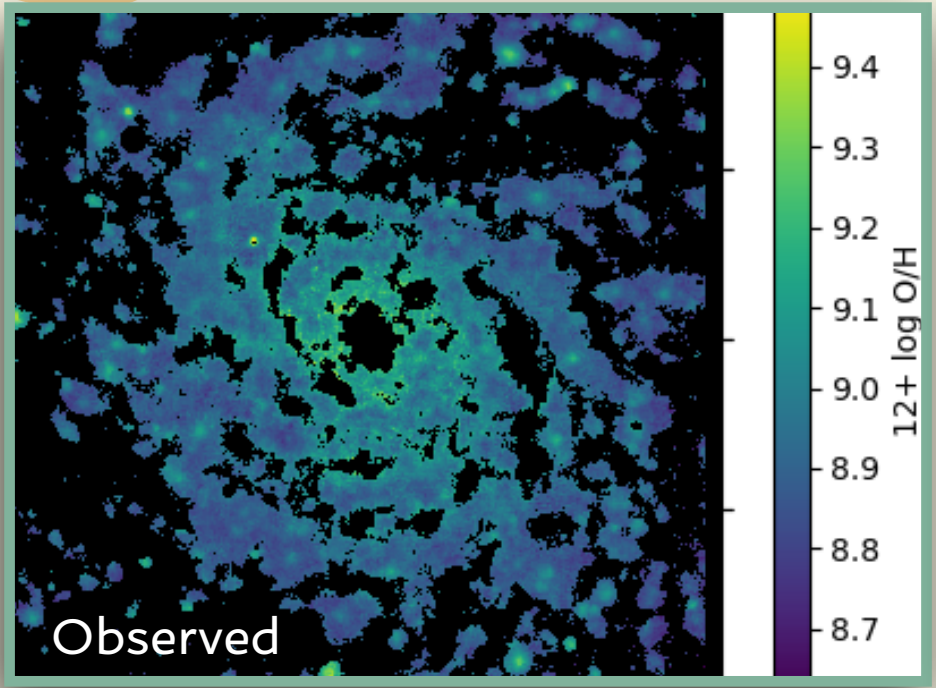
WORKS ON BAD DATA

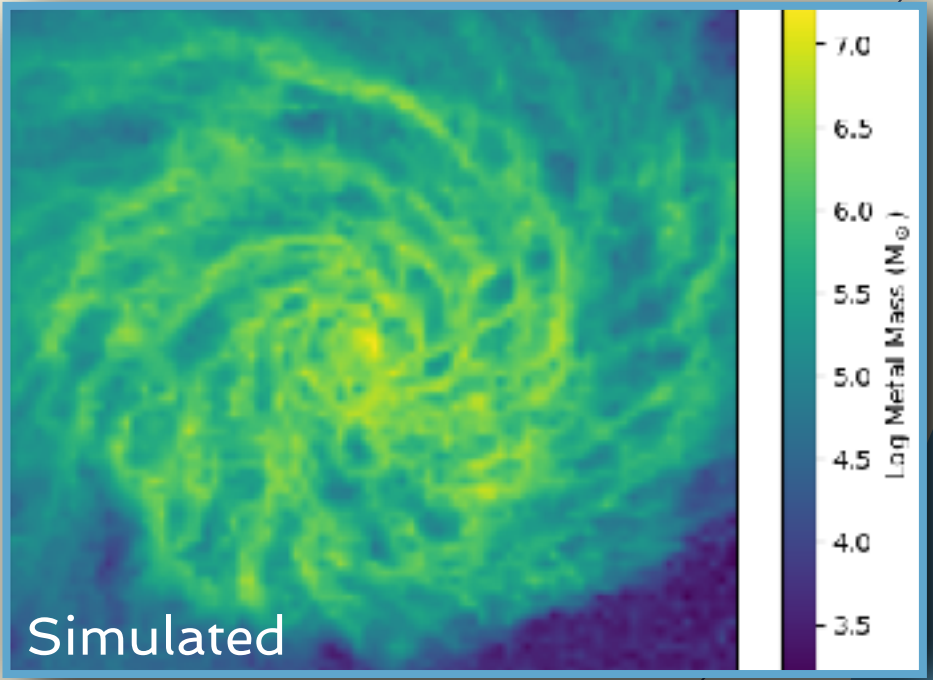
Naturally separates structures from uncorrelated noise.

HIGHLY INFORMATIVE

Shows covariance structure, like a power spectrum.

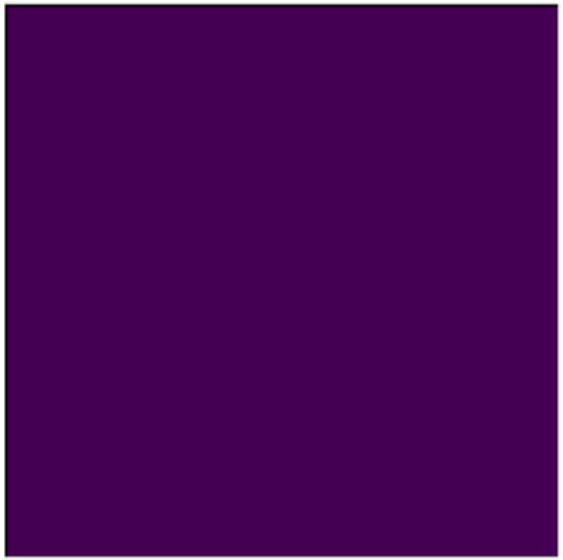
GEOSTATISTICS IN ACTION



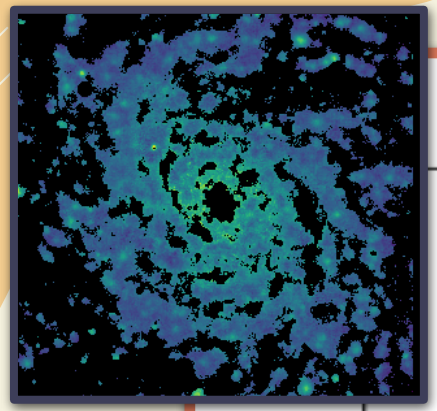


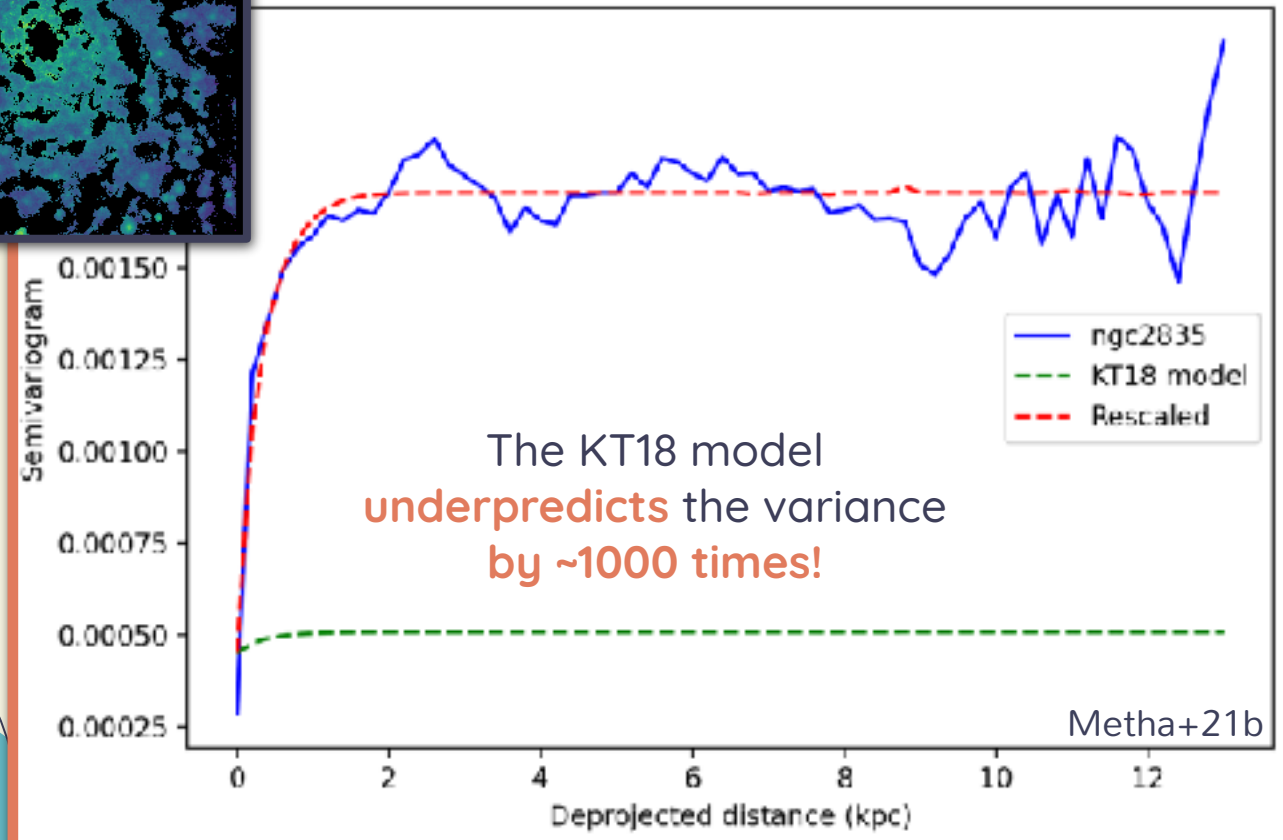
TESTING AN ANALYTICAL MODEL

- Stochastic partial differential equations
- Assumptions:
  - Constant, uniform star formation
  - **Linear diffusion**
  - No stellar winds
- Predictions:
  - Spatial correlation of metallicity

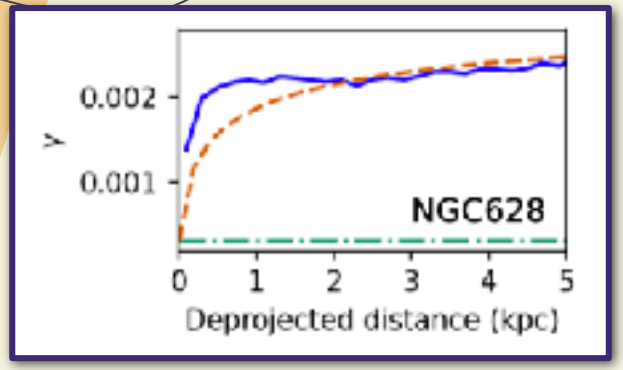


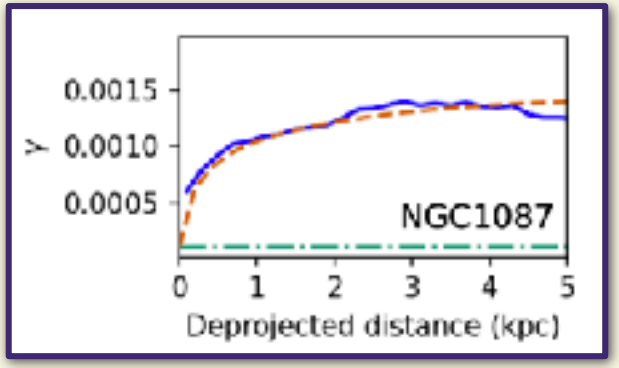
Krumholz+Ting18

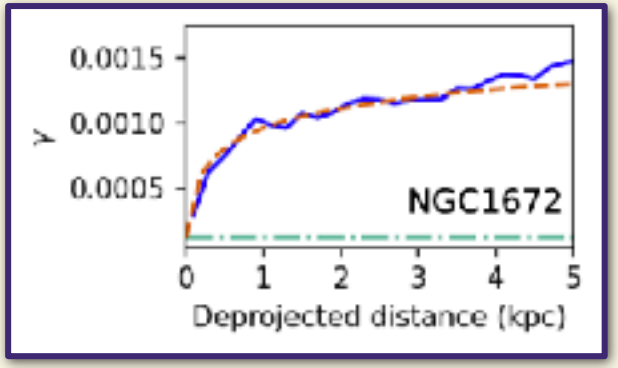


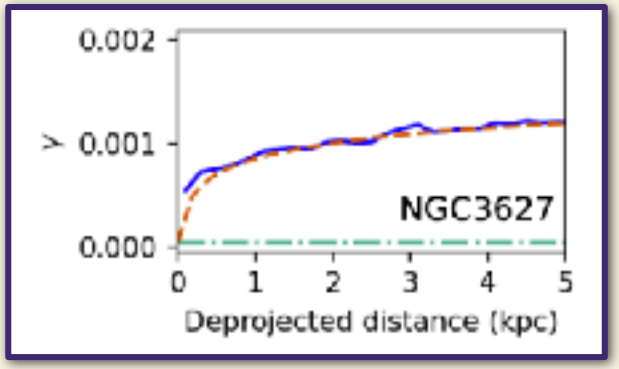

Semivariogram
0.00150
0.00125
0.00100
0.00075
0.00050
0.00025
0
2
4
6
8
10
12
Deprojected distance (kpc)
ngc2835
KT18 model
Rescaled
The KT18 model
underpredicts the variance
by ~1000 times!
Metha+21b

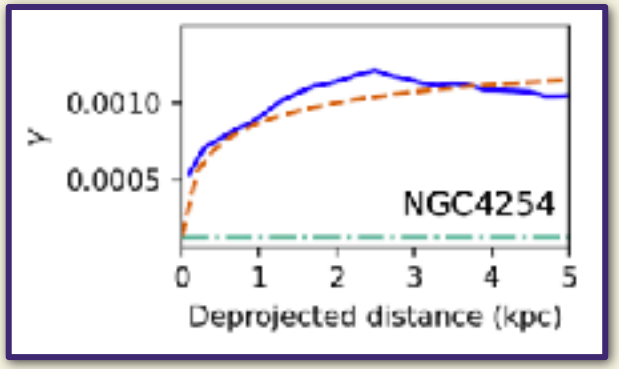
FOR 6 OTHER GALAXIES

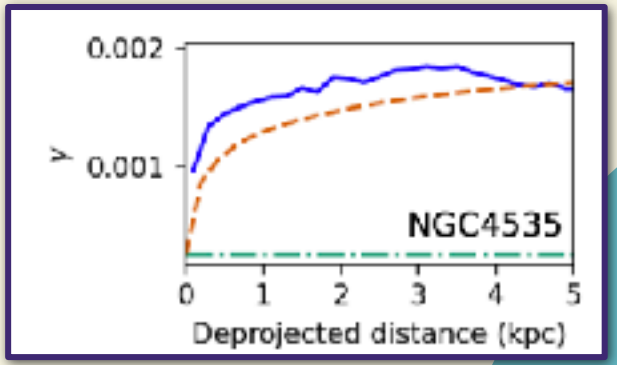








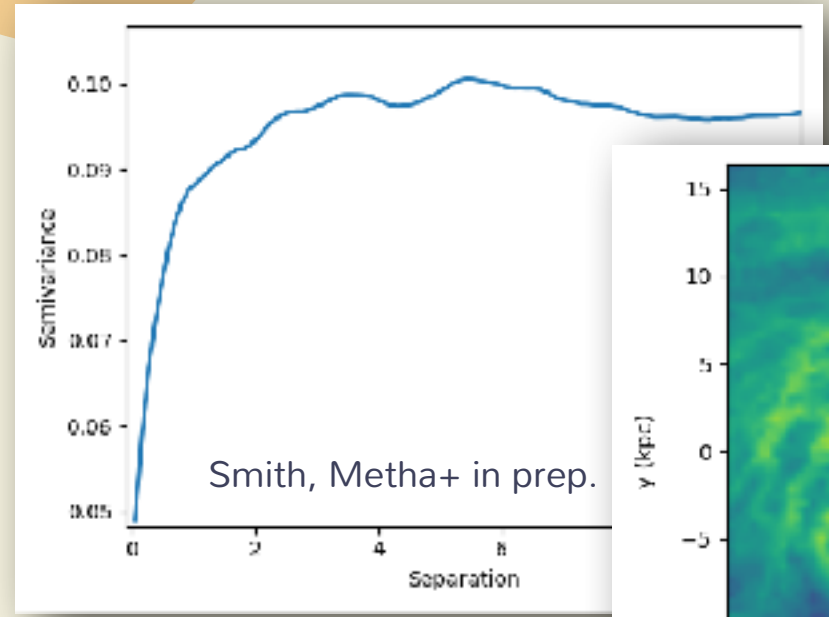




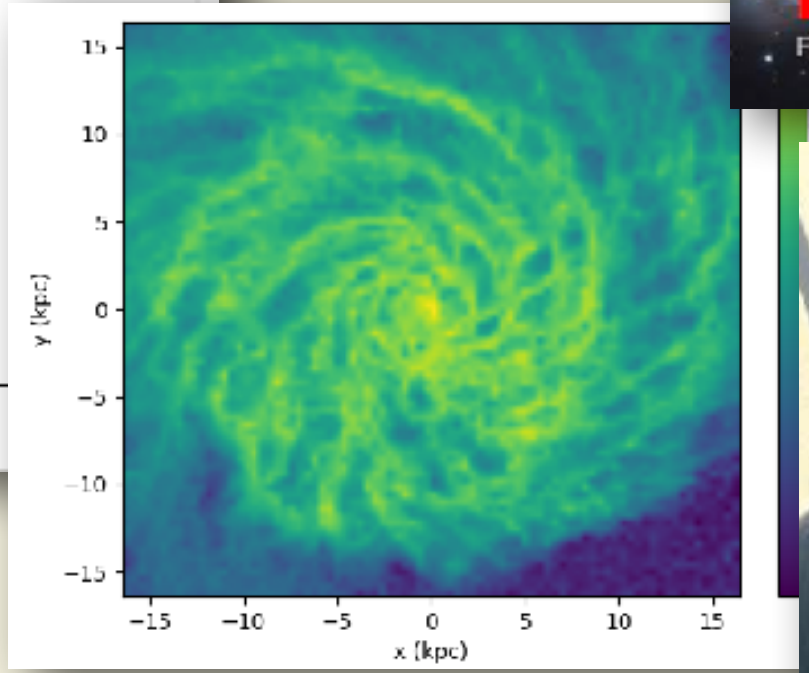
Empirical Semivariogram
KT18 model
Rescaled KT18 model

GALAXIES AREN'T VERY WELL MIXED!

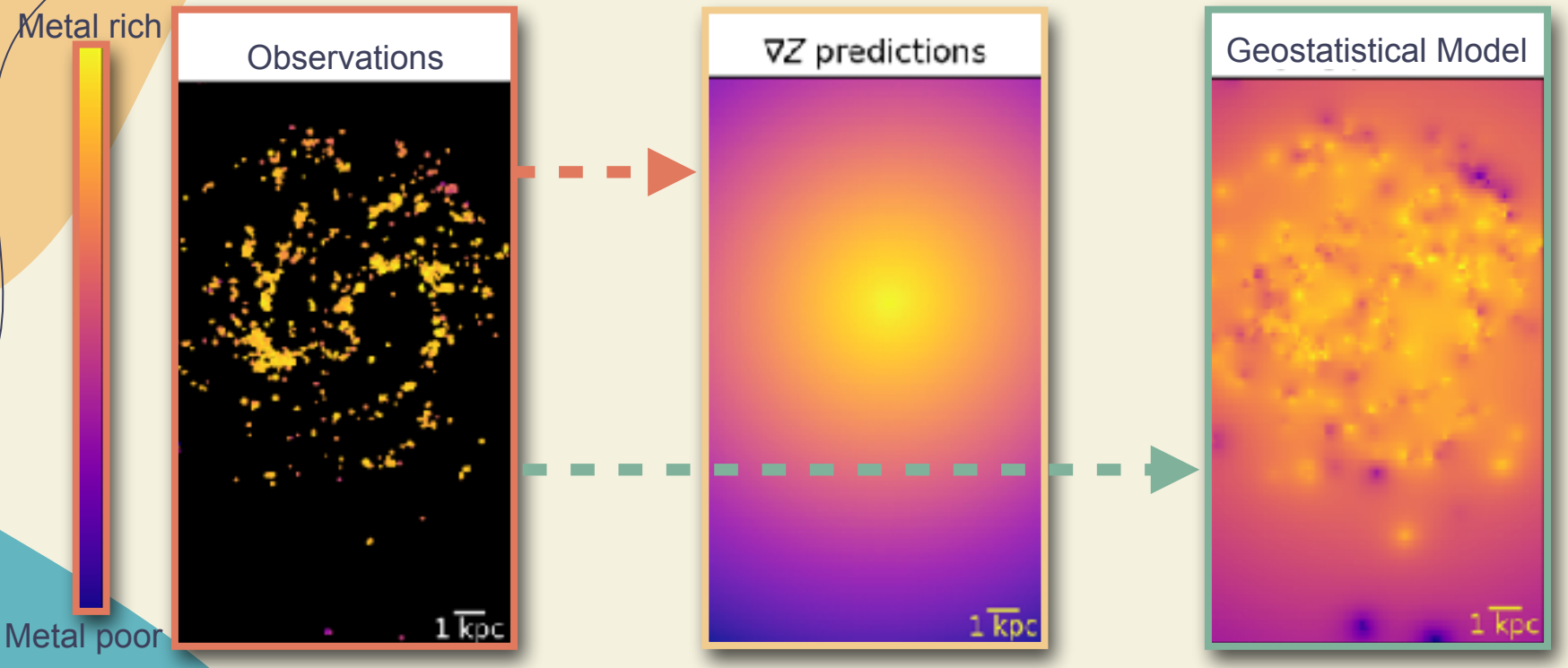
TESTING MORE DETAILED MODELS



Smith, Metha+ in prep.

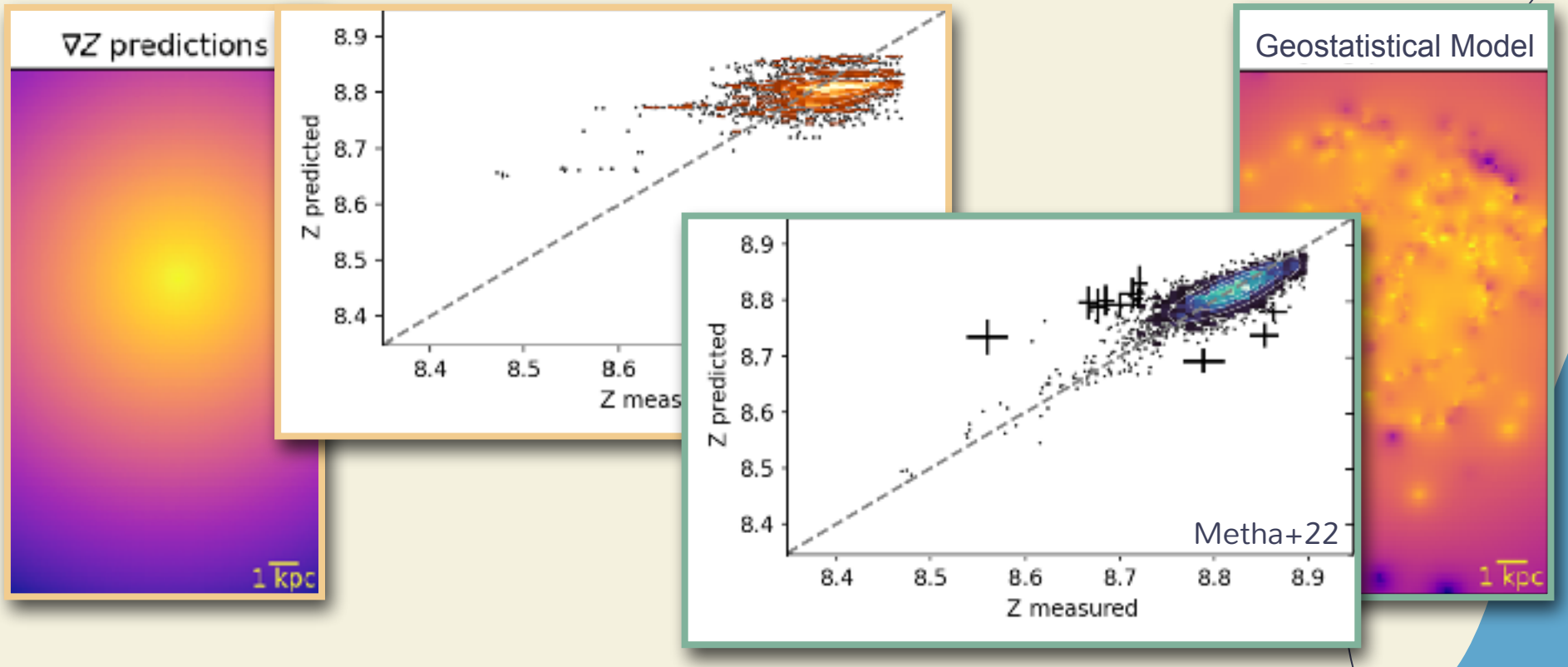


GEOSTATISTIC MODELS → MORE DETAILS



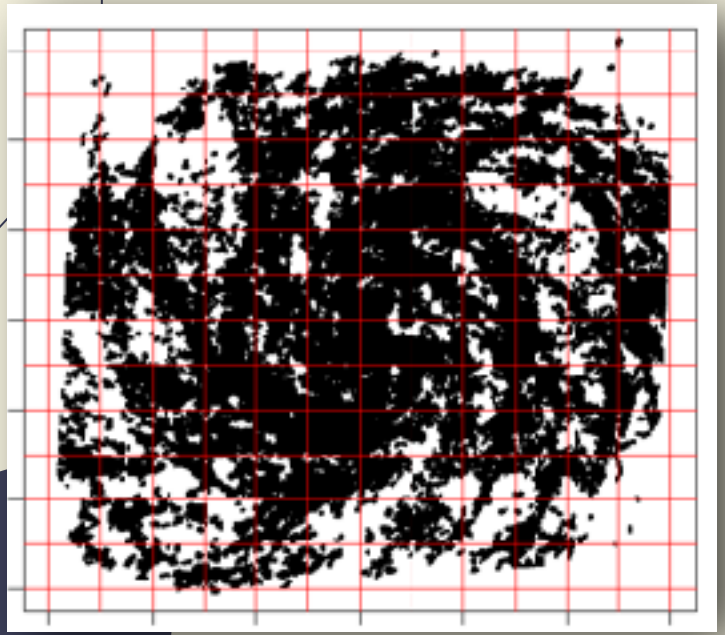
Metha+22

GEOSTATISTIC MODELS → BETTER PREDICTIONS

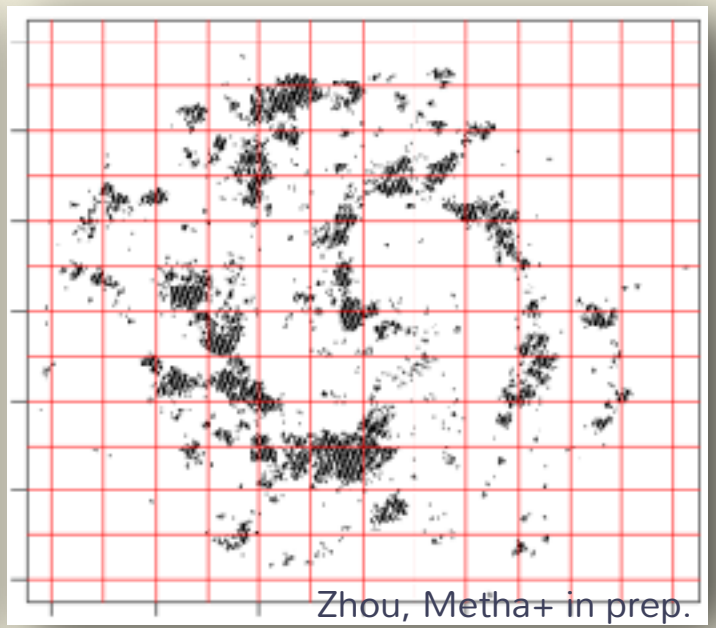


Combining data with different resolutions

Σ_{mol}

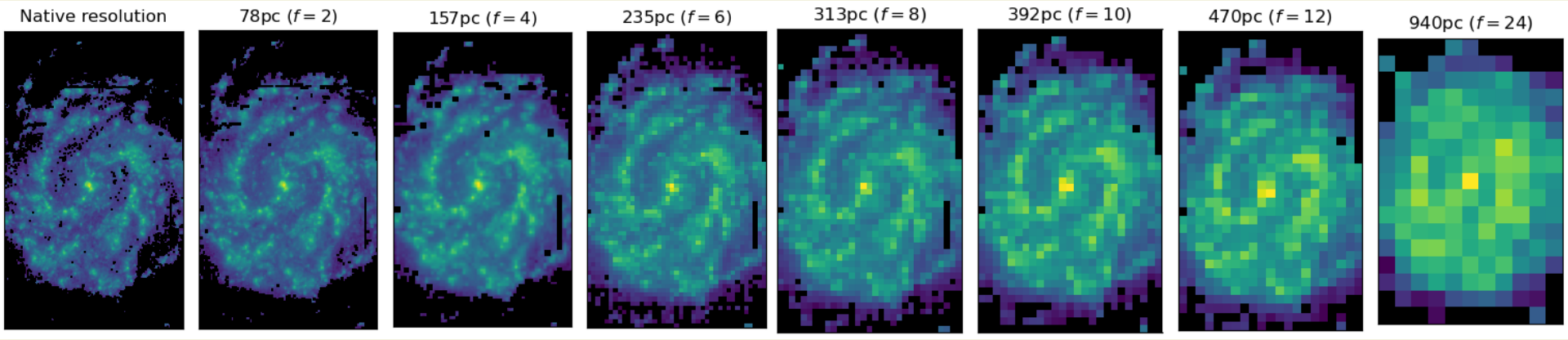


Z



Zhou, Metha+ in prep.

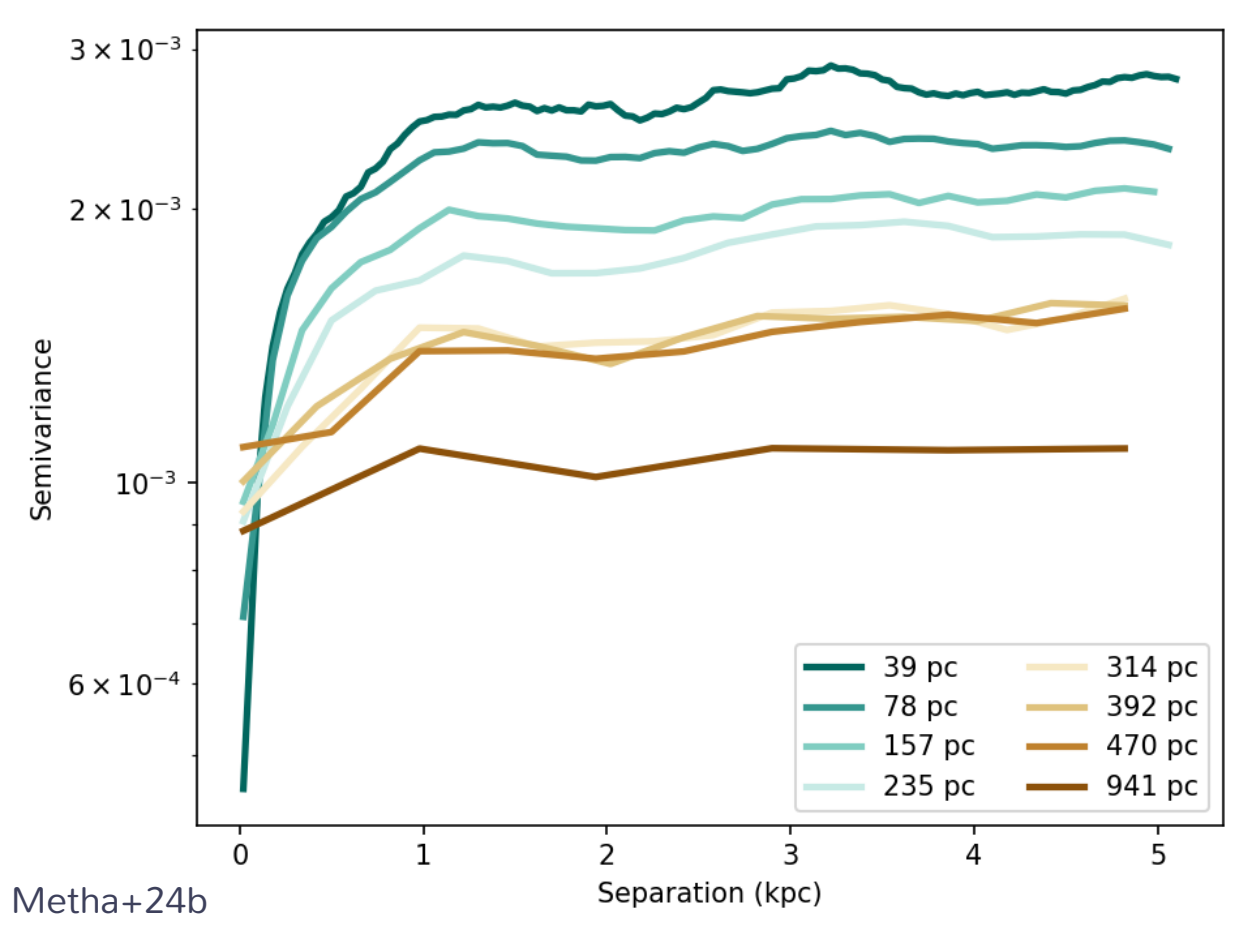
RESOLUTION LIMITS



MUSE quality

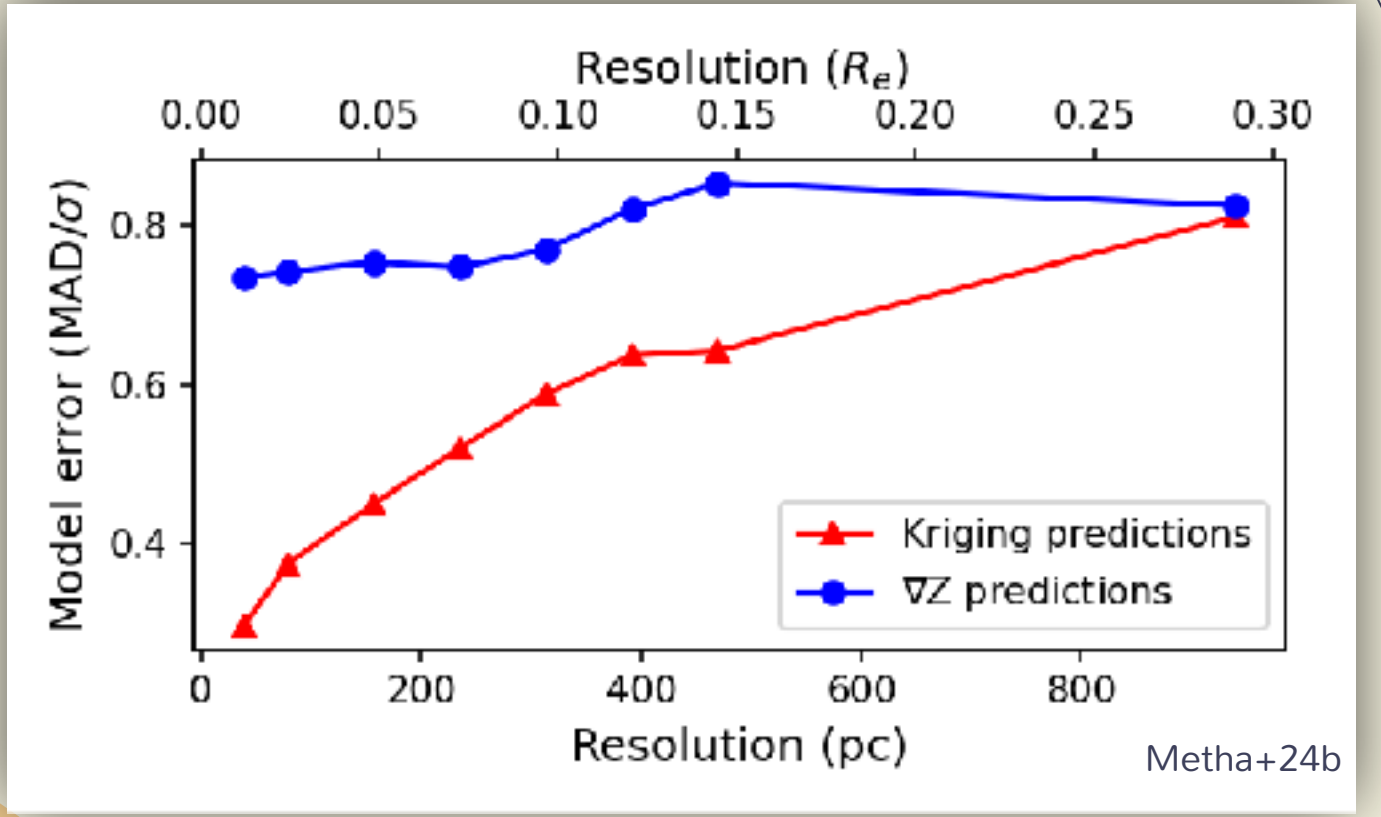
CALIFA/SAMI/
MANGA quality

RESOLUTION LIMITS



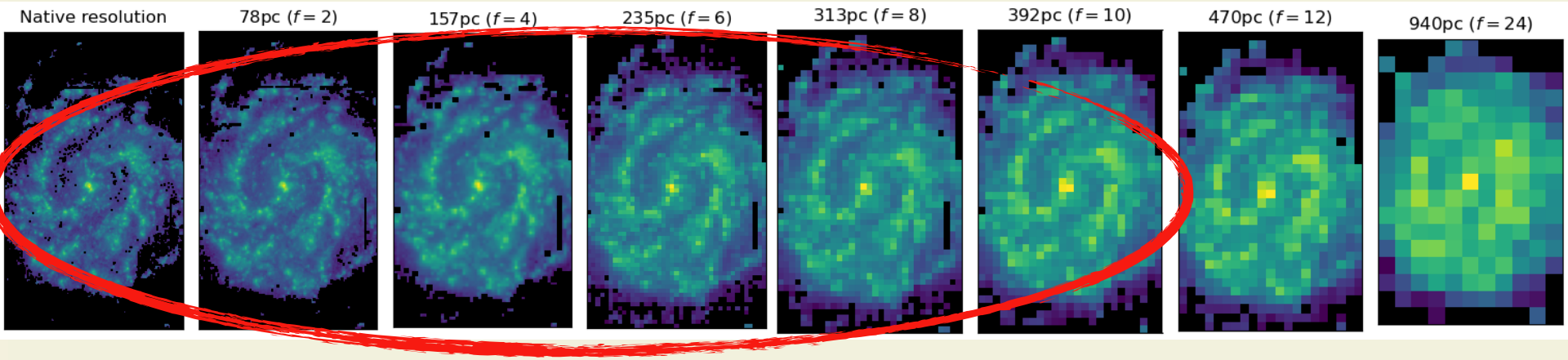
Metha+24b

PREDICTION ACCURACY vs RESOLUTION



Metha+24b

RESOLUTION LIMITS

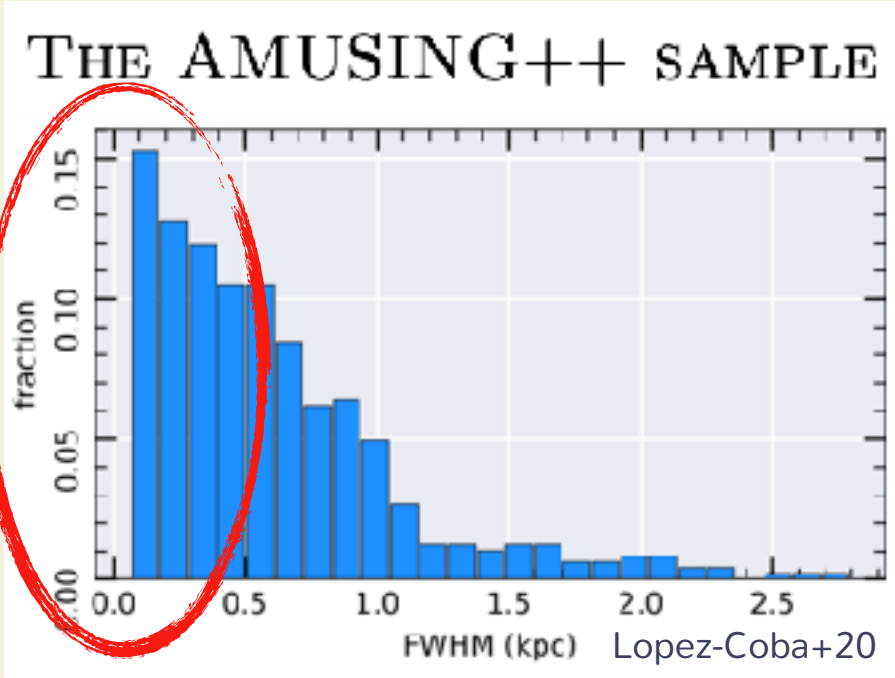


Consistent correlation scales

MUSE quality

CALIFA/SAMI/
MANGA quality

A DATA OPPORTUNITY

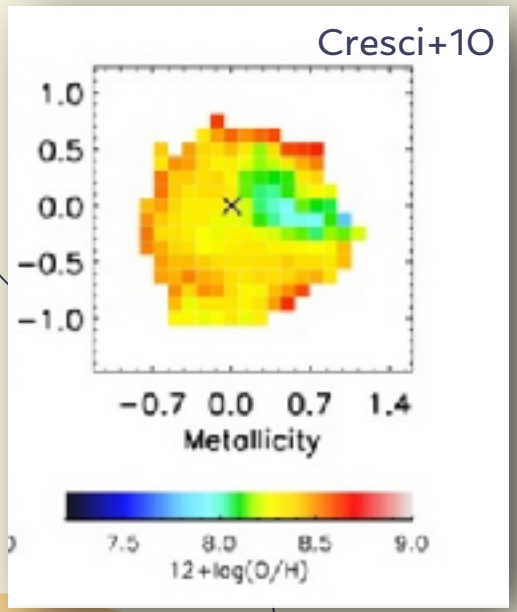


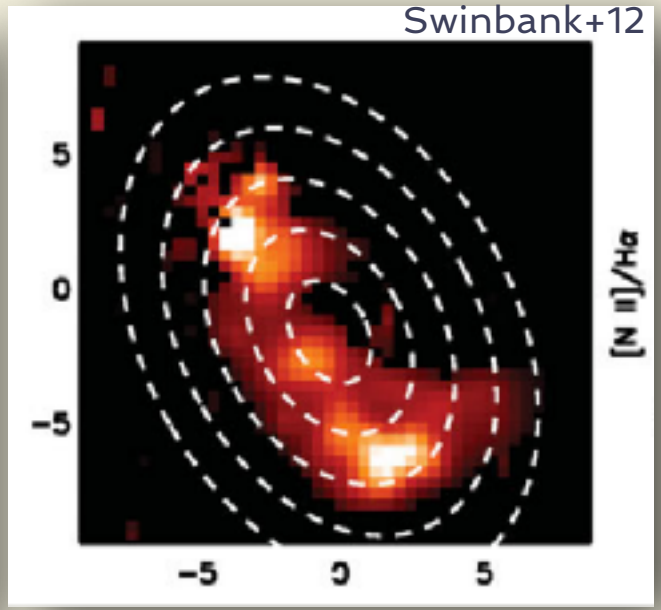
635 GALAXIES

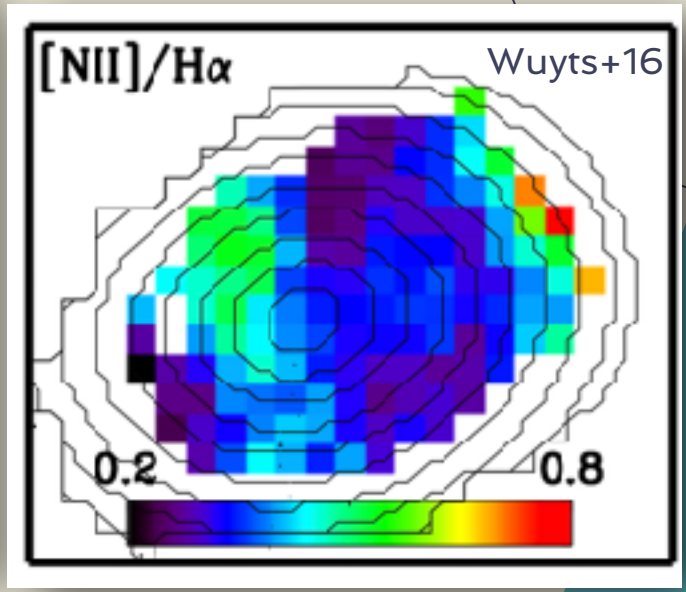
Enough to decide if metal mixing depends on other galaxy properties (M, SFR, AGN...)

PART 2:
LENSTRONOMY
(100pc-1kpc)

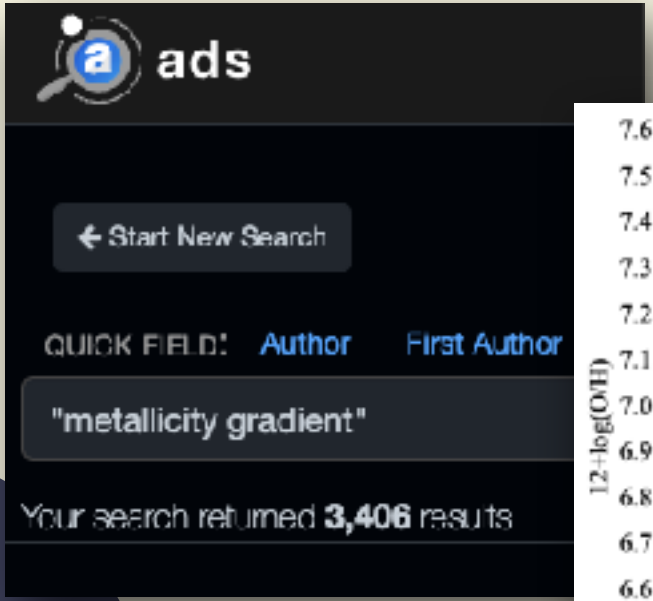
GOAL: MODEL DATA LIKE THIS

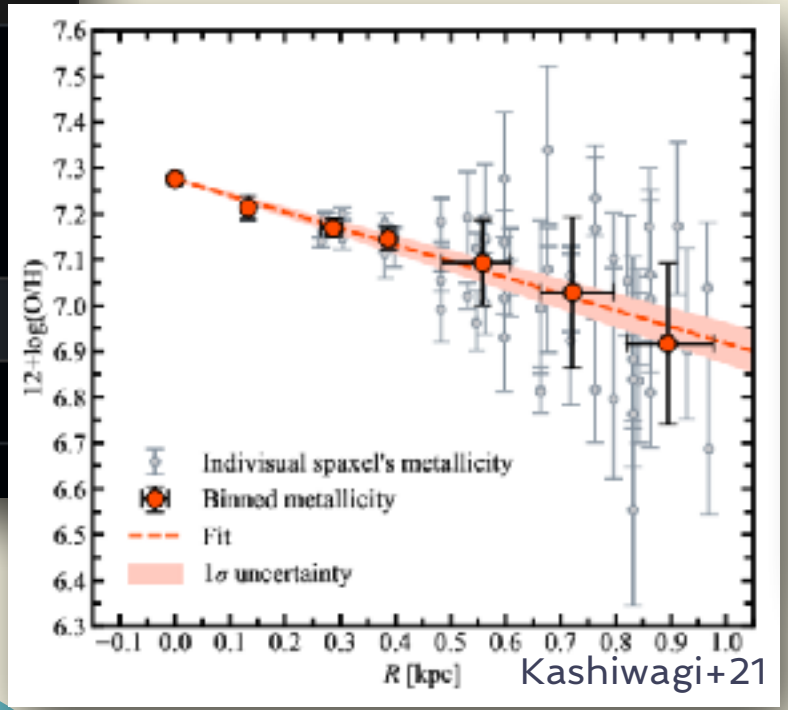




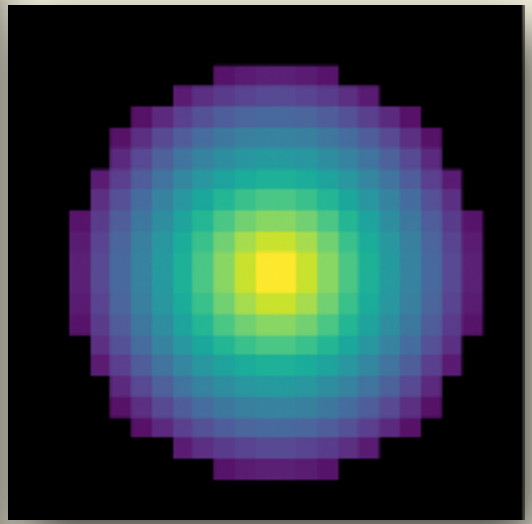


THE STANDARD APPROACH

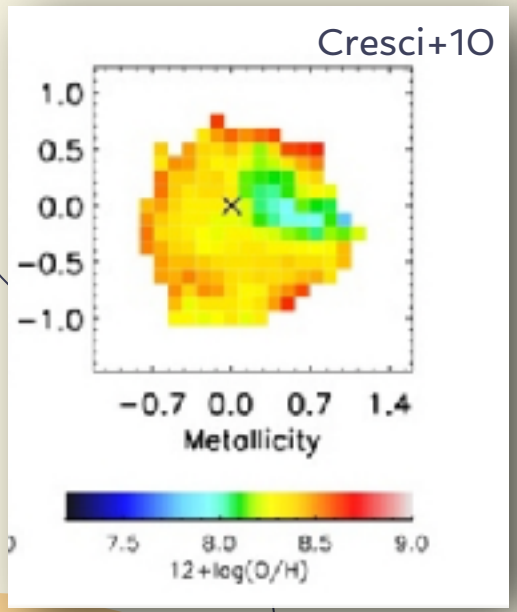


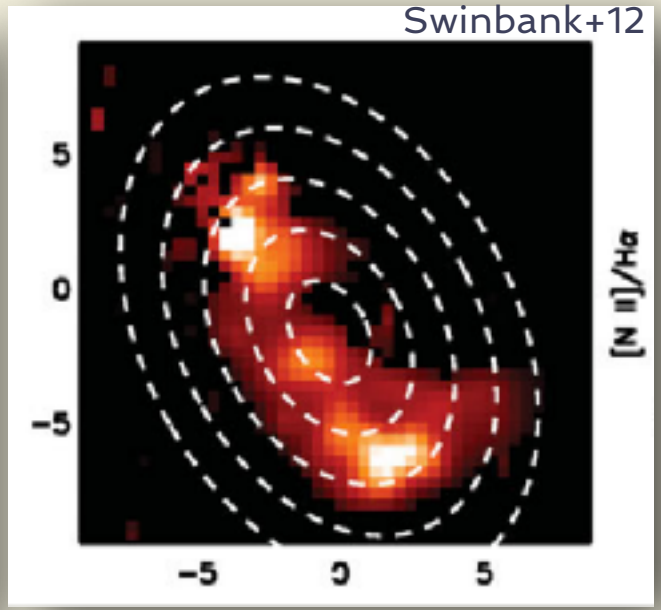


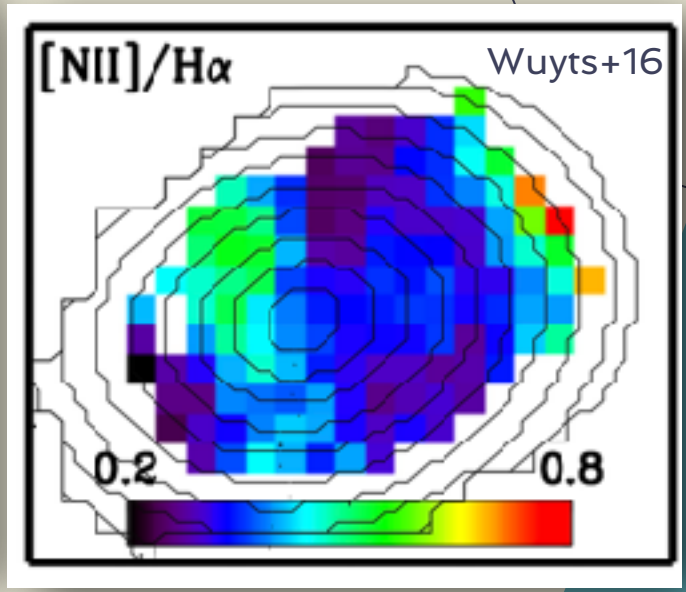
Kashiwagi+21



OUR DATA ISN'T LIKE THAT







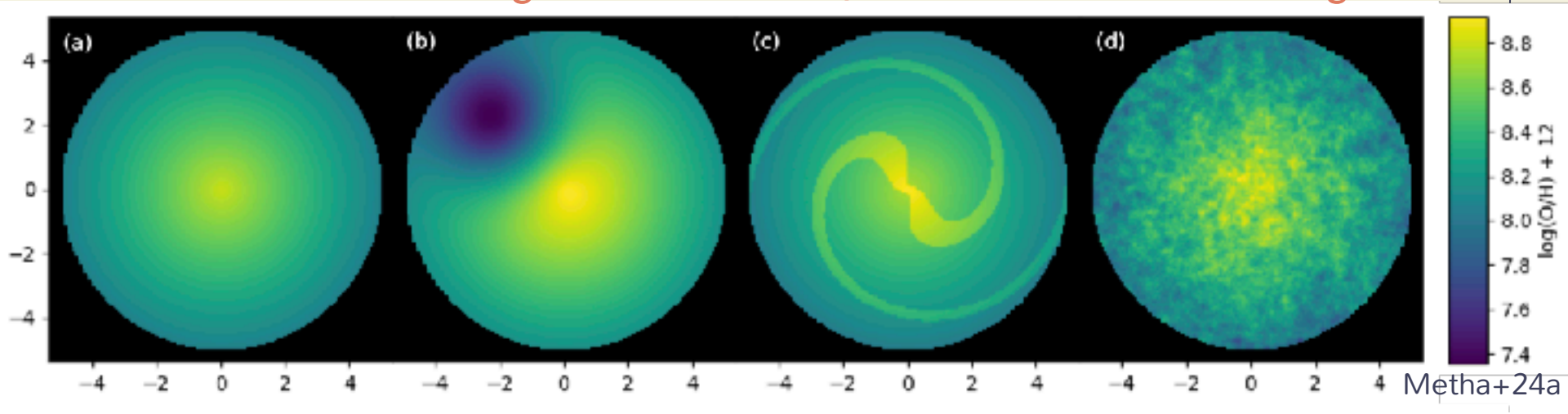
METALLICITY GRADIENTS CAN'T DISTINGUISH

Smooth profiles

Merger signatures

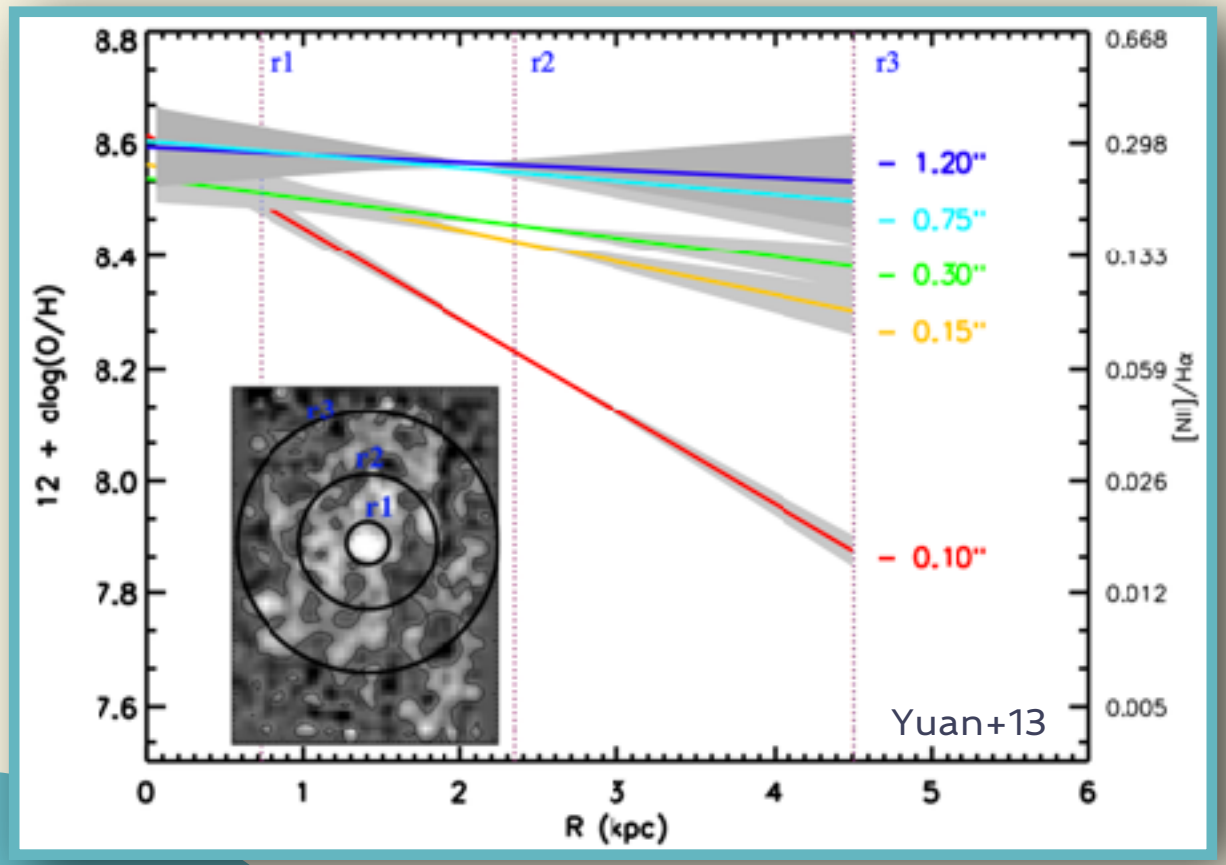
Enrichment in spiral arms

Inefficient mixing



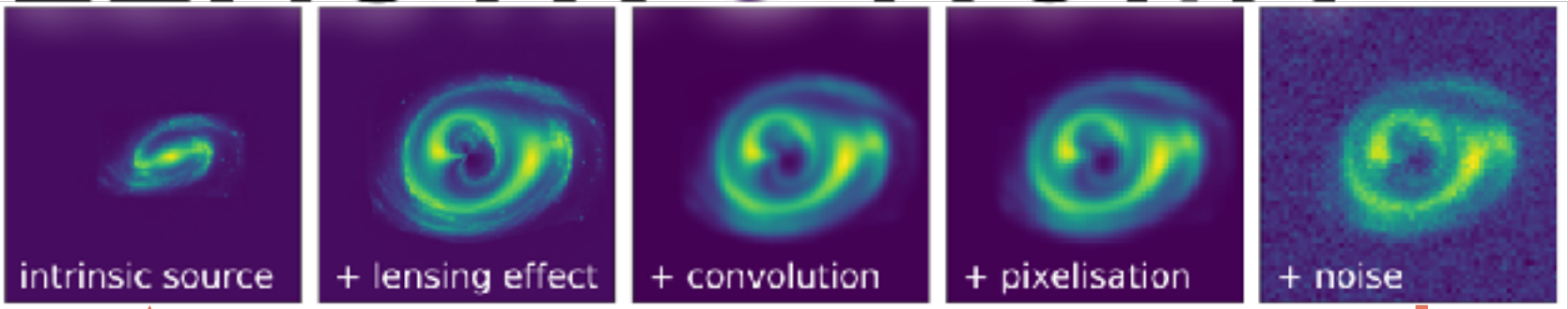
Metha+24a

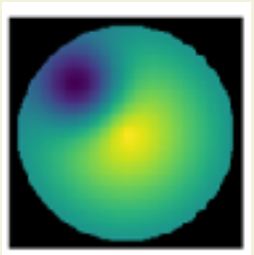
POINT SPREAD SMEARING FLATTENS GRADIENTS



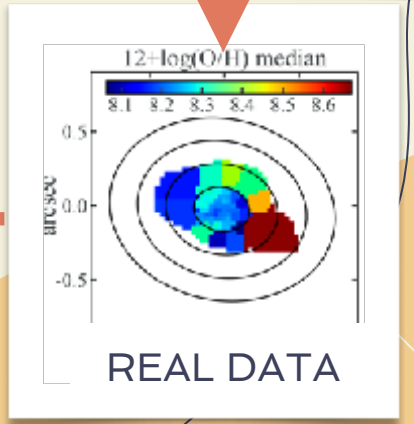
METALLICITY MODELLING IN:

LENSTRONOMY



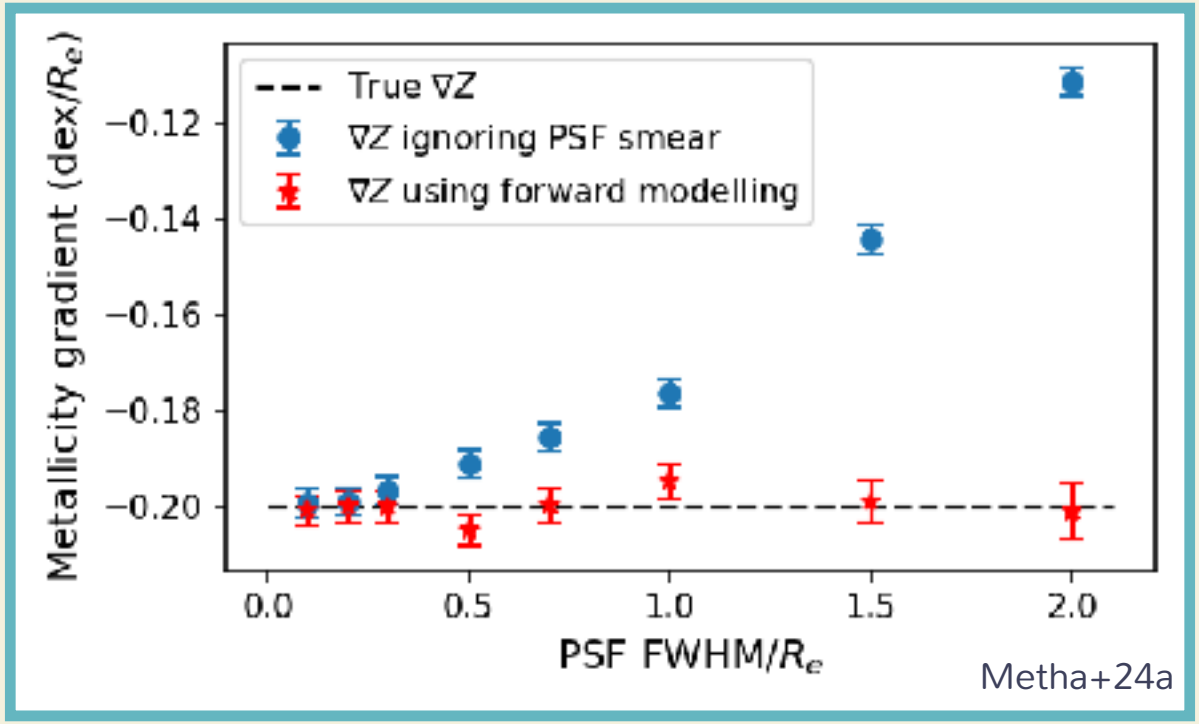


MODELS WITH
2D STRUCTURE

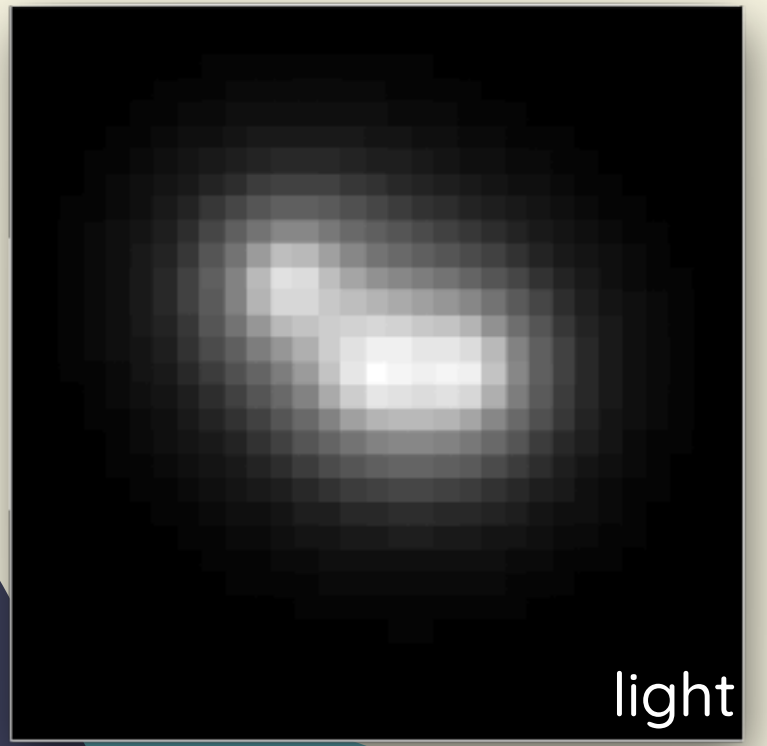


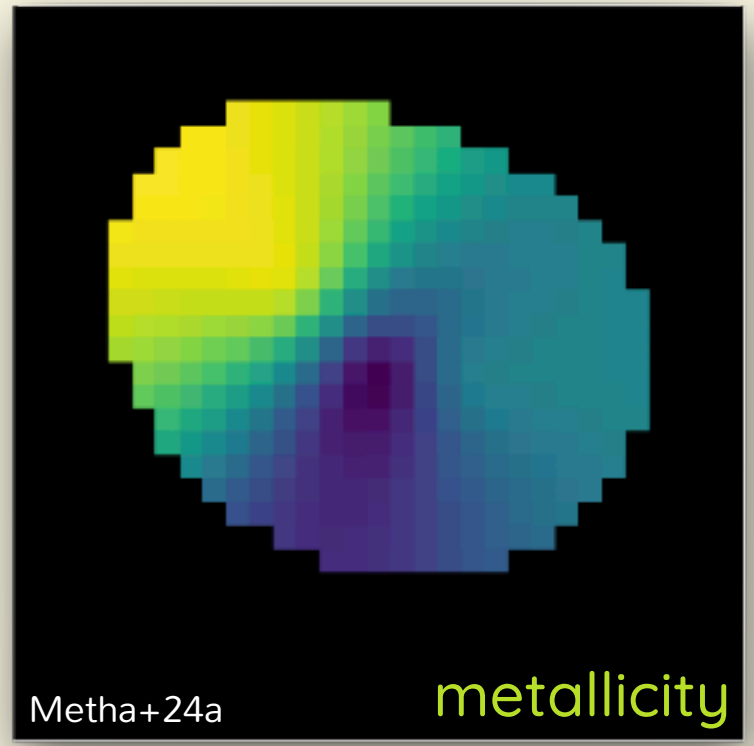
REAL DATA

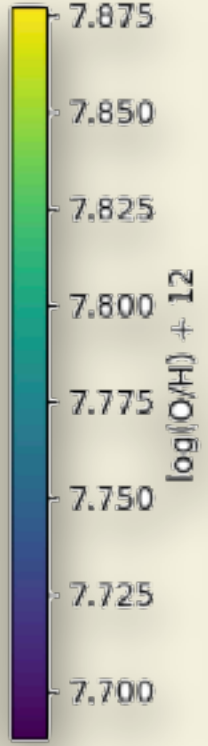
CORRECTIONS FOR PSF SMEAR



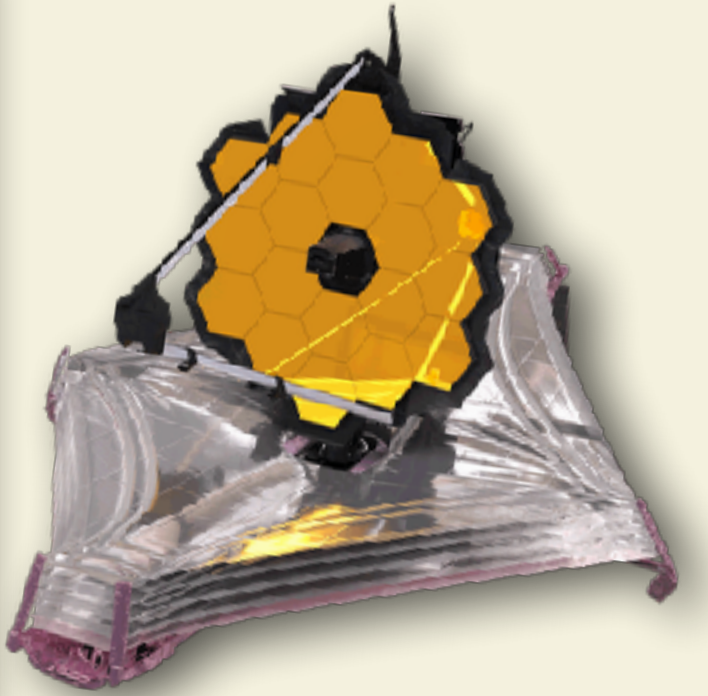
FITTING MORE FLEXIBLE MODELS







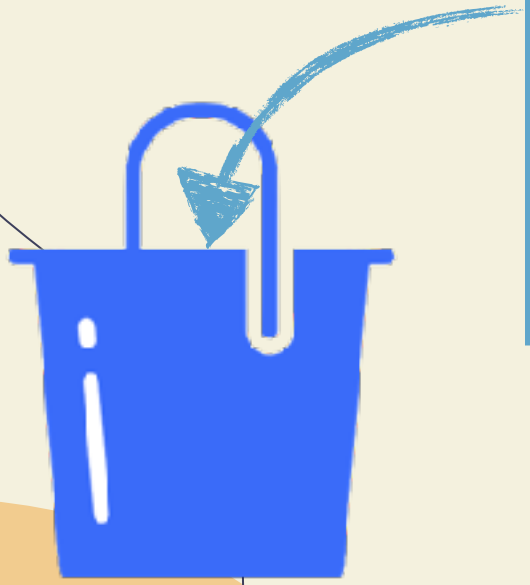
ONGOING COLLABORATIONS

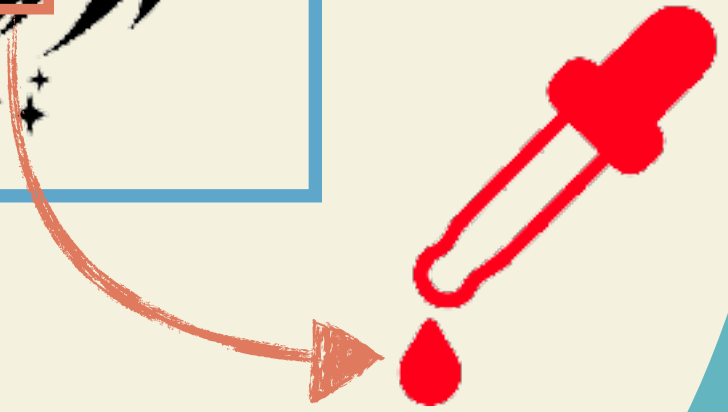


PART 3: THE Z_{abs}-Z_{emiss} RELATION

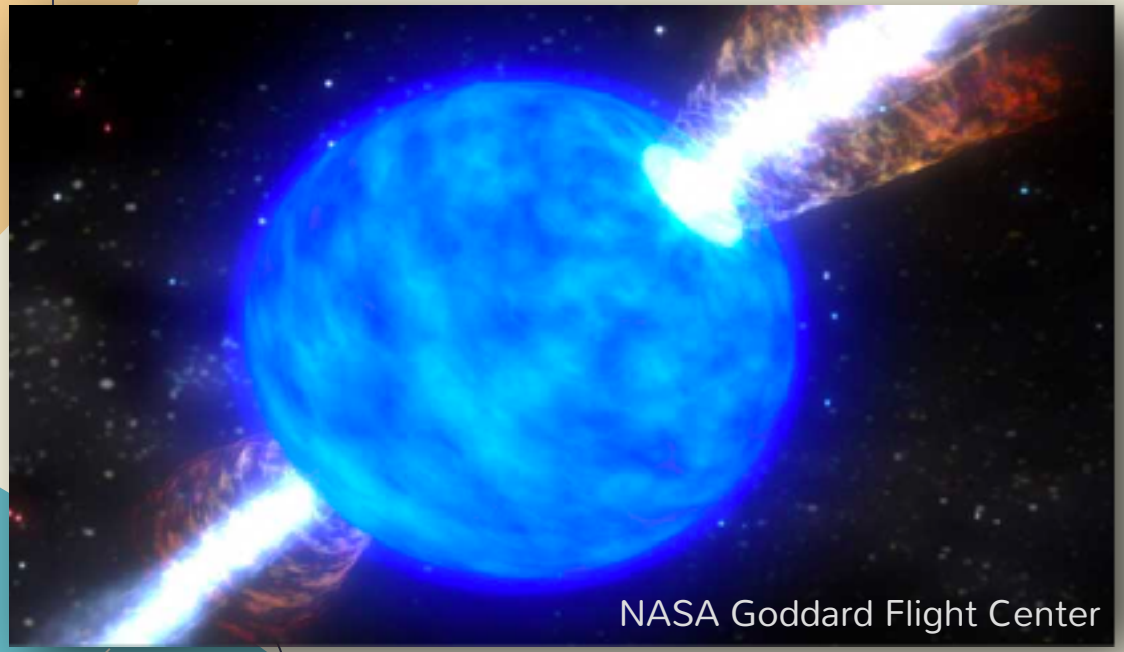
(unresolved sources)

HOW CAN THIS BE DONE?





INTRODUCING GAMMA RAY BURSTS



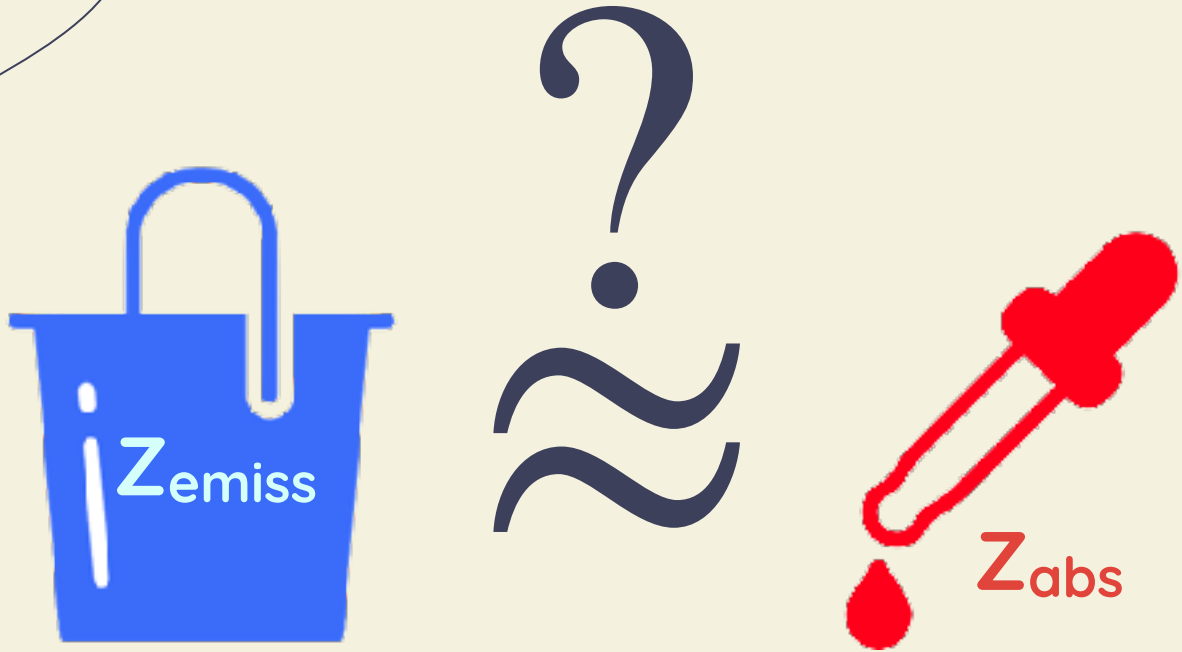
BRIGHT

Outshine their host galaxies by a factor of 1 million.

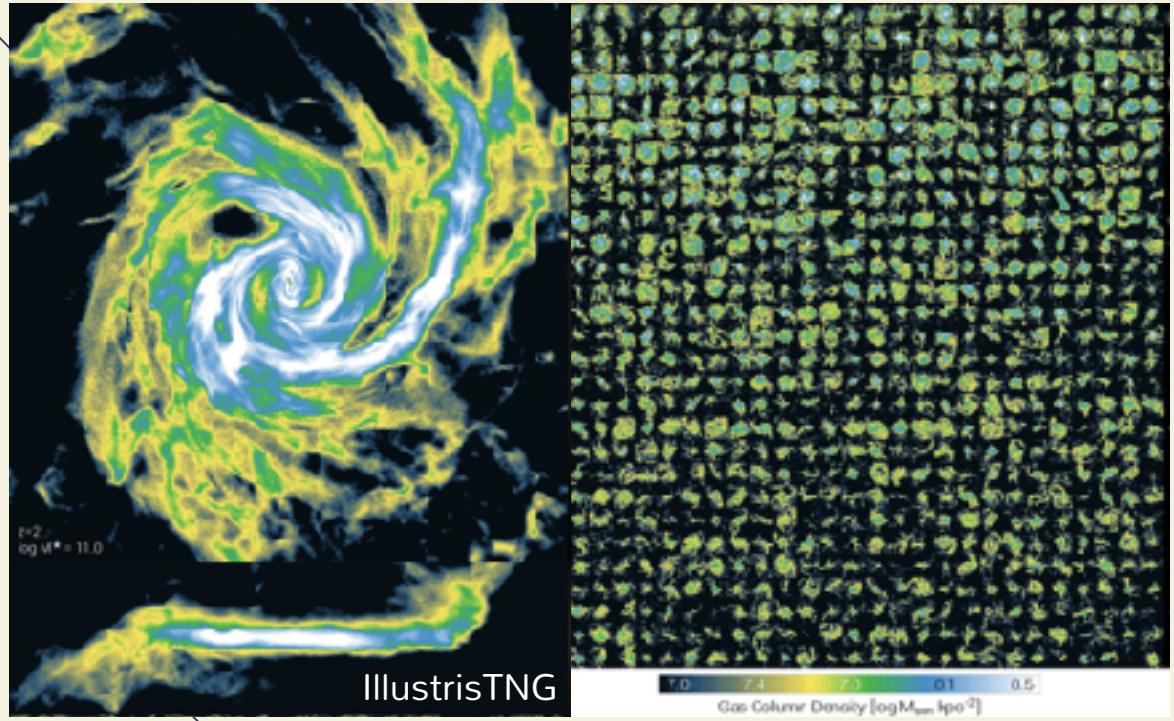
LOW METALLICITY

Necessary for high mass and rapid rotation at time of collapse.

GRBs LOCALLY SAMPLE THE ISM


Zemiss
?
≈
Zabs

PREDICTIONS USING IllustrisTNG



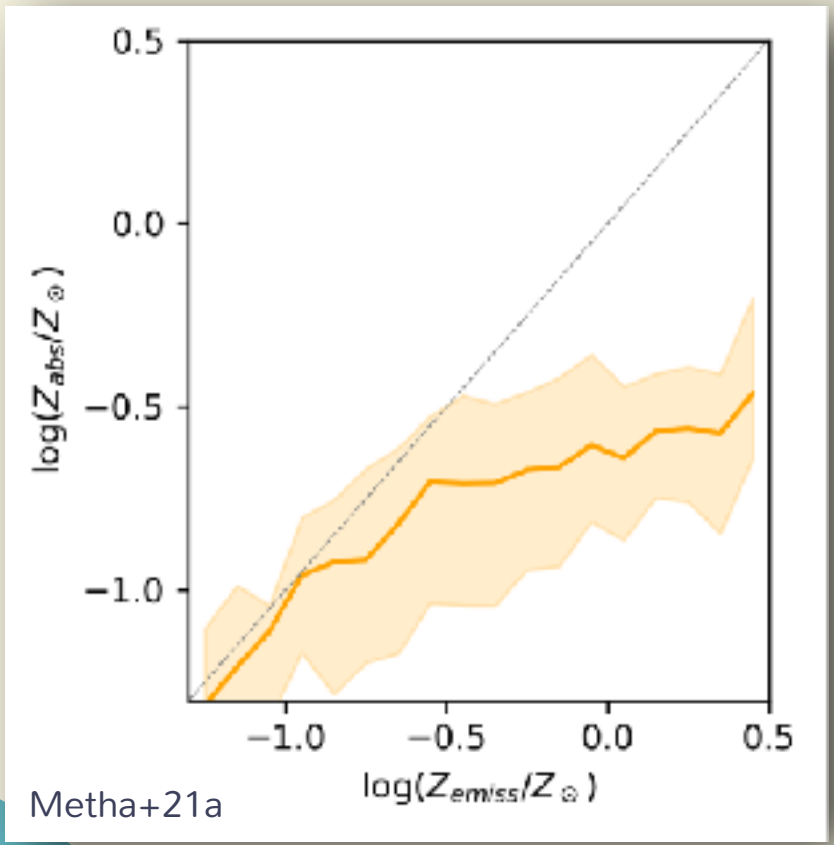
LARGE + HIGH RESOLUTION

10^{10} gas particles in a 100 Mpc^3 volume. Millions of galaxies!

DETAILED PHYSICS

Includes star formation + evolution, metal enrichment, feedback, and more!

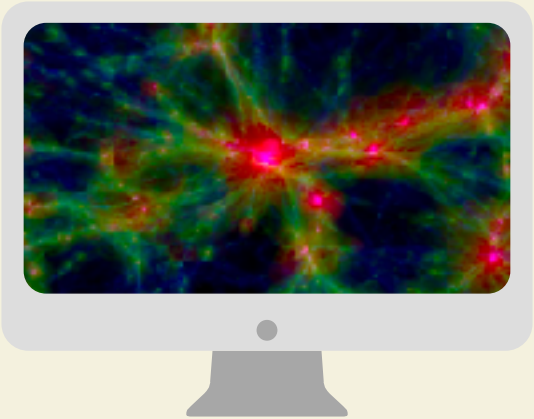
Z_{abs} AND Z_{emiss} DON'T AGREE



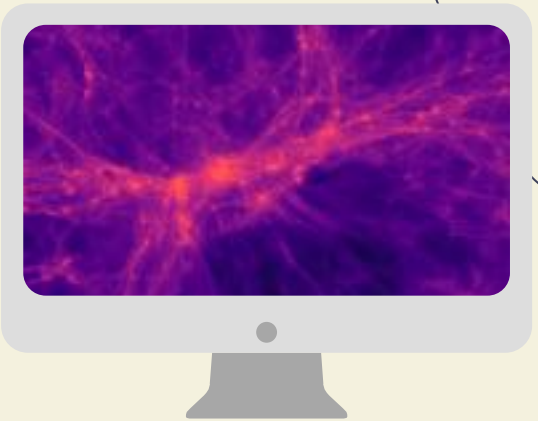
Metha+21a

TRY 3 DIFFERENT SIMULATIONS

ILLUSTRIS

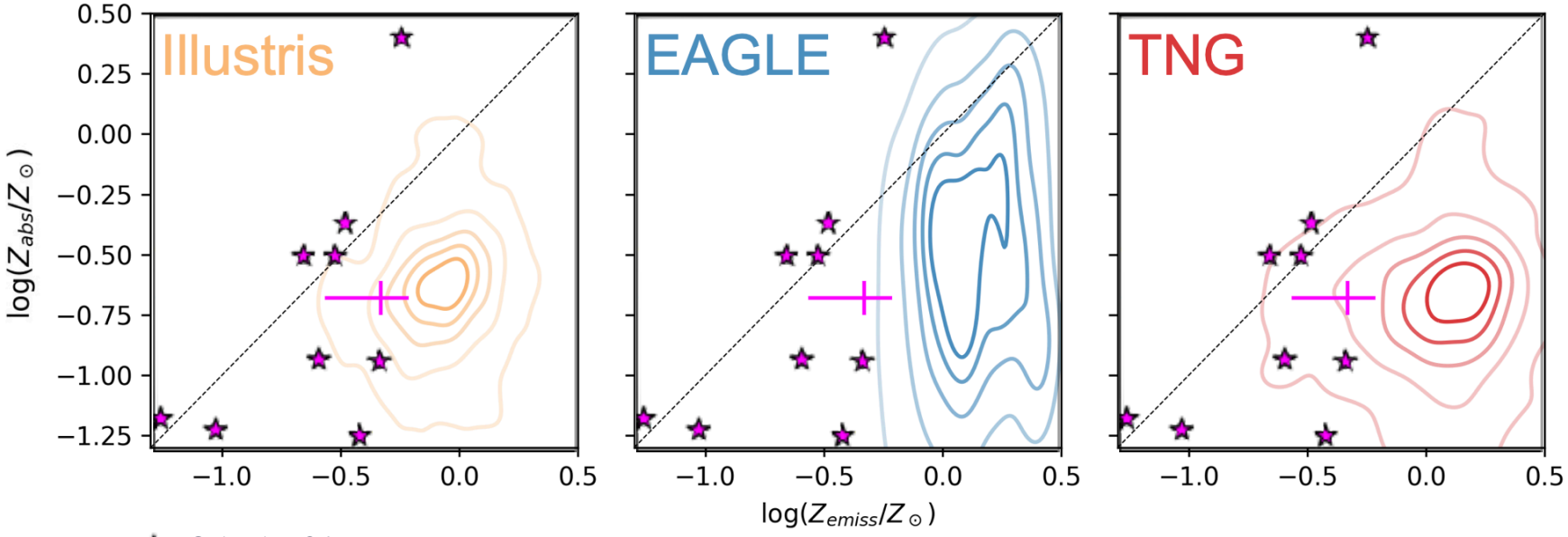


EAGLE



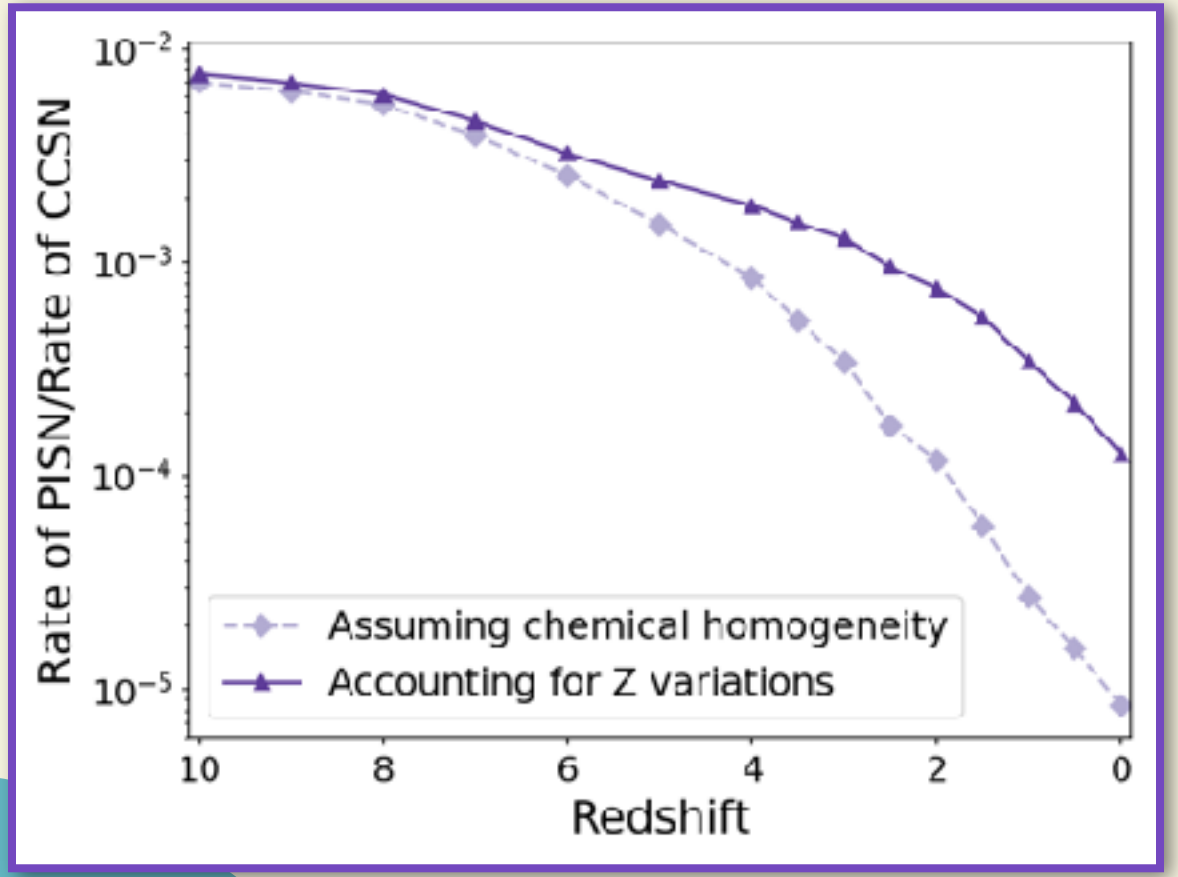
ILLUSTRIS TNG

GET 3 DIFFERENT RELATIONS



Metha+23a

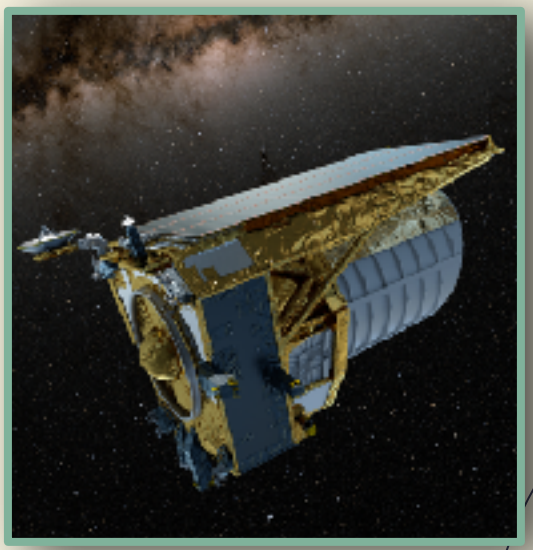
IMPLICATIONS FOR METAL-POOR EVENTS



HOW MANY PISNe CAN WE SEE?

HYPER SUPRIME CAM

0.03

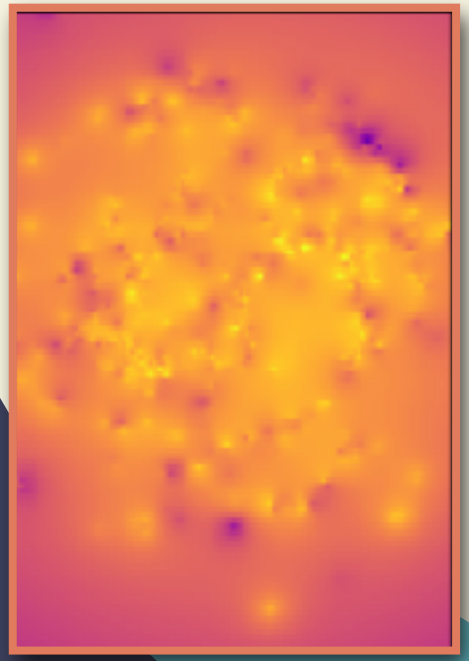


EUCLID DEEP SURVEY

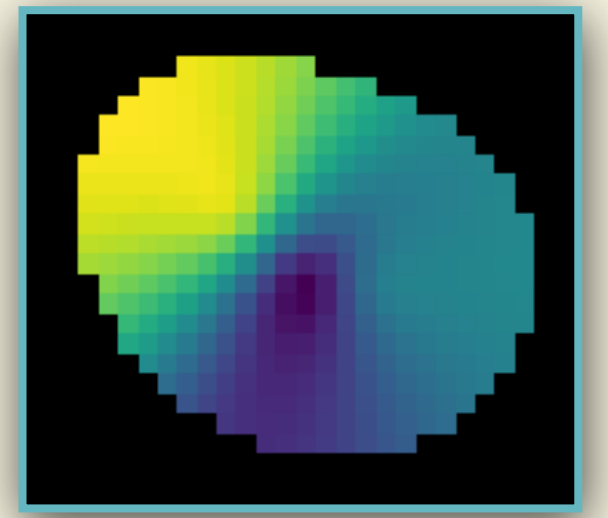
83! (Only 7 if galaxies are considered uniform)

SUMMARY

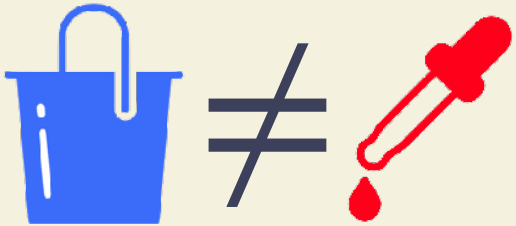
Geostatistical methods are ideal for modern and upcoming high-res data



Lenstronomy's new module can correct for PSF smear and fit new models to JWST data



GRBs let us detect metal inhomogeneities in unresolved sources



THANKS!

DO YOU HAVE ANY QUESTIONS?

methab@student.unimelb.edu.au

WAIT, ISN'T THIS A POWER SPECTRUM?

A "Rosetta Stone" for Studies of Spatial Variation in Astrophysical Data: Power Spectra, Semivariograms, and Structure Functions

Benjamin Metha [1, 2] and Sabrina Berger [1, 2, 3, *]

[1] *University of Melbourne, 1 Tin Alley, Parkville 3050 Victoria, Australia*
[2] *Australian Research Council Centre of Excellence for All-Sky Astrophysics in 3-Dimensions, Australia*
[3] *Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia*

ABSTRACT

From the turbulent interstellar medium to the cosmic web, astronomers in many different fields have needed to make sense of spatial data describing our Universe, spanning centimetre to Gigaparsec scales. Through different historical choices for mathematical conventions, many different subfields of spatial data analysis have evolved their own language for analysing structures and quantifying correlation in spatial data. Because of this history, terminology from a myriad of different fields is used, often to describe two data products that are mathematically identical. In this Note, we define and describe the differences and similarities between the power spectrum, the two-point correlation function, the covariance function, the semivariogram, and the structure functions, in an effort to unify the languages used to study spatial correlation. We also highlight under which conditions these data products are useful and describe how the results found using one method can be translated to those found using another, allowing for easier comparison between different subfields' native methods. We hope for this document to be a "Rosetta Stone" for translating between different statistical approaches, allowing results to be shared between researchers from different backgrounds, facilitating more cross-disciplinary approaches to data analysis.