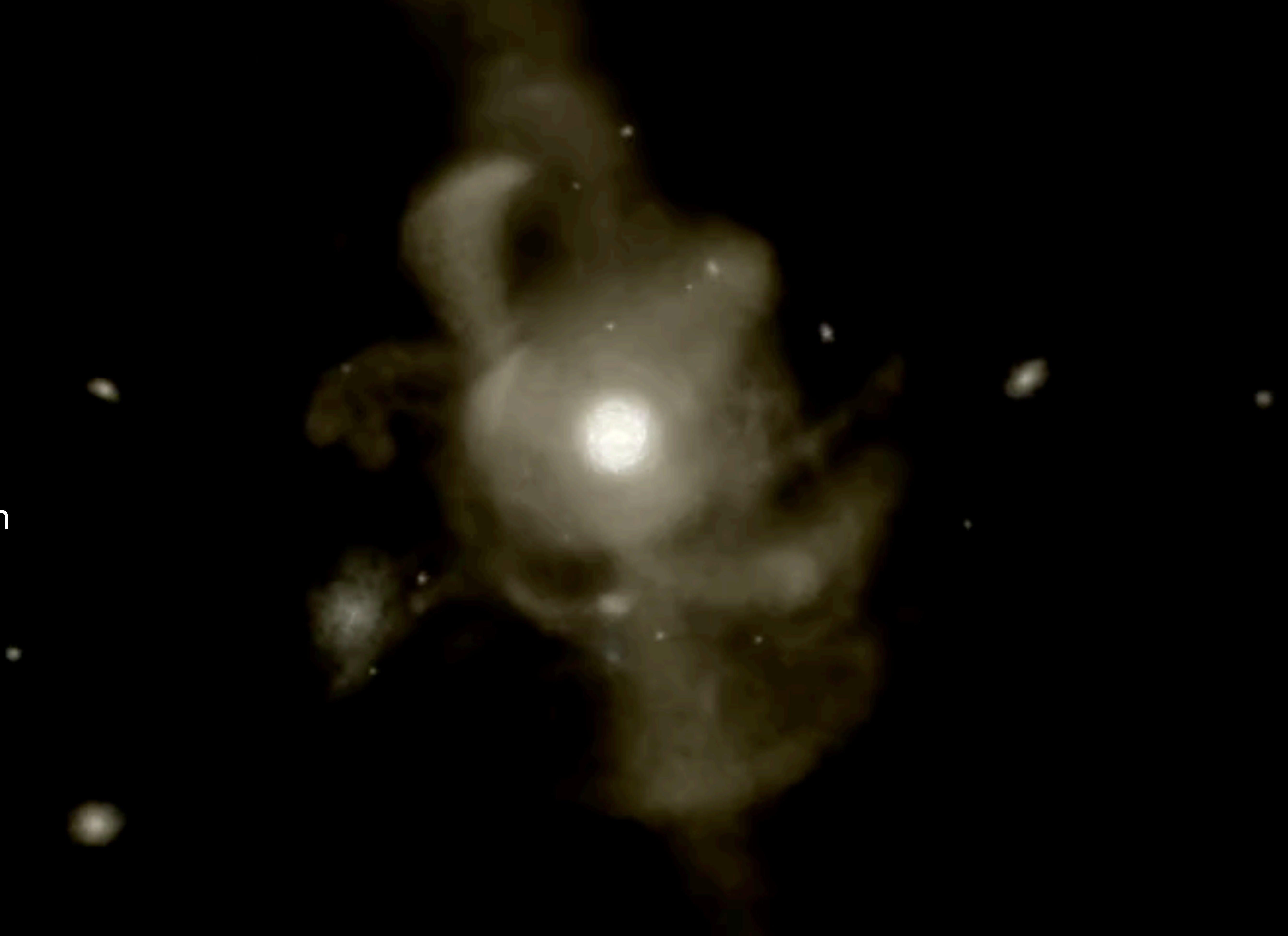
Formation of Milky Way-like galaxies in cosmological context

Facts, Fiction and Future Challenges



Tobias Buck
Leibniz-Institut für Astrophysik Potsdam

Christoph Pfrommer,
Aura Obreja,
Melissa Ness,
Lucy Lu,
Ivan Minchev,
Andrea Macciò,
Aaron Dutton,
Hans-Walter Rix,
Rüdiger Pakmor,
Robert Grand,
Volker Springel,
et al.

American Museum of Natural History Astro colloquium, 1st of March 2022
somewhere in cyber space
tbuck@aip.de

THE STRUCTURE OF THE NEXT ~40 MINUTES:

- Some selective (personally biased) observational **Facts** about the Milky Way
- Simulated **Fiction** about Milky-Way's formation history
- **Future Challenges**: How to build better models?

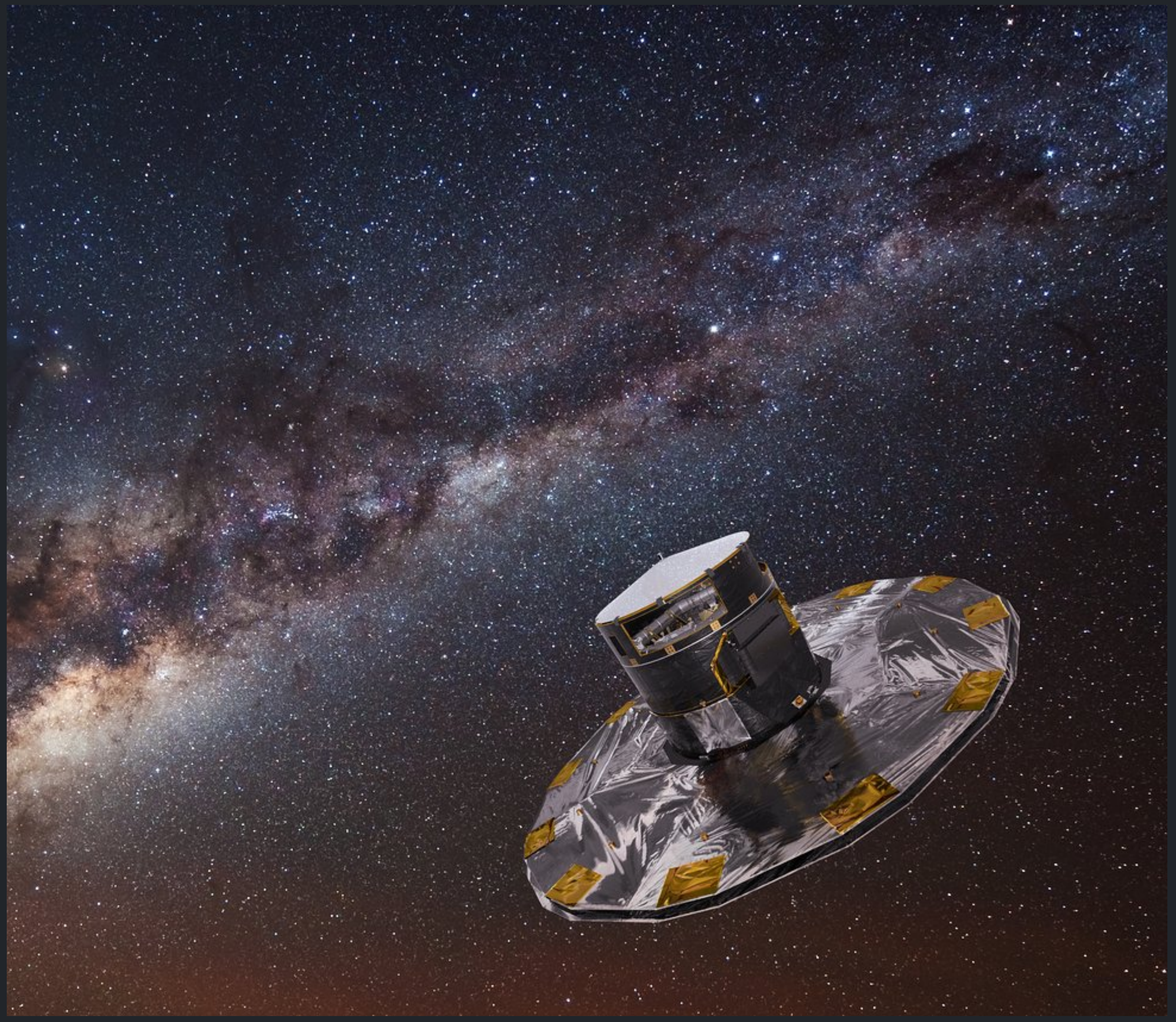
THE STRUCTURE OF THE NEXT ~40 MINUTES:

- Observational Facts about the Milky Way: Buder, Yuxi, Eilers, Sestito? chemical bimodality…, Obreja 2022
- Simulated **Fiction** about Milky-Way's formation history: all my own work… NIHAO-UHD and results, Buck+2019 SF threshold, Buck+2020 impact of CRs, Buck+2021 new elements
- **Future Challenges**: How to build better models? statistical model of density structures, AI for simulations, junior group

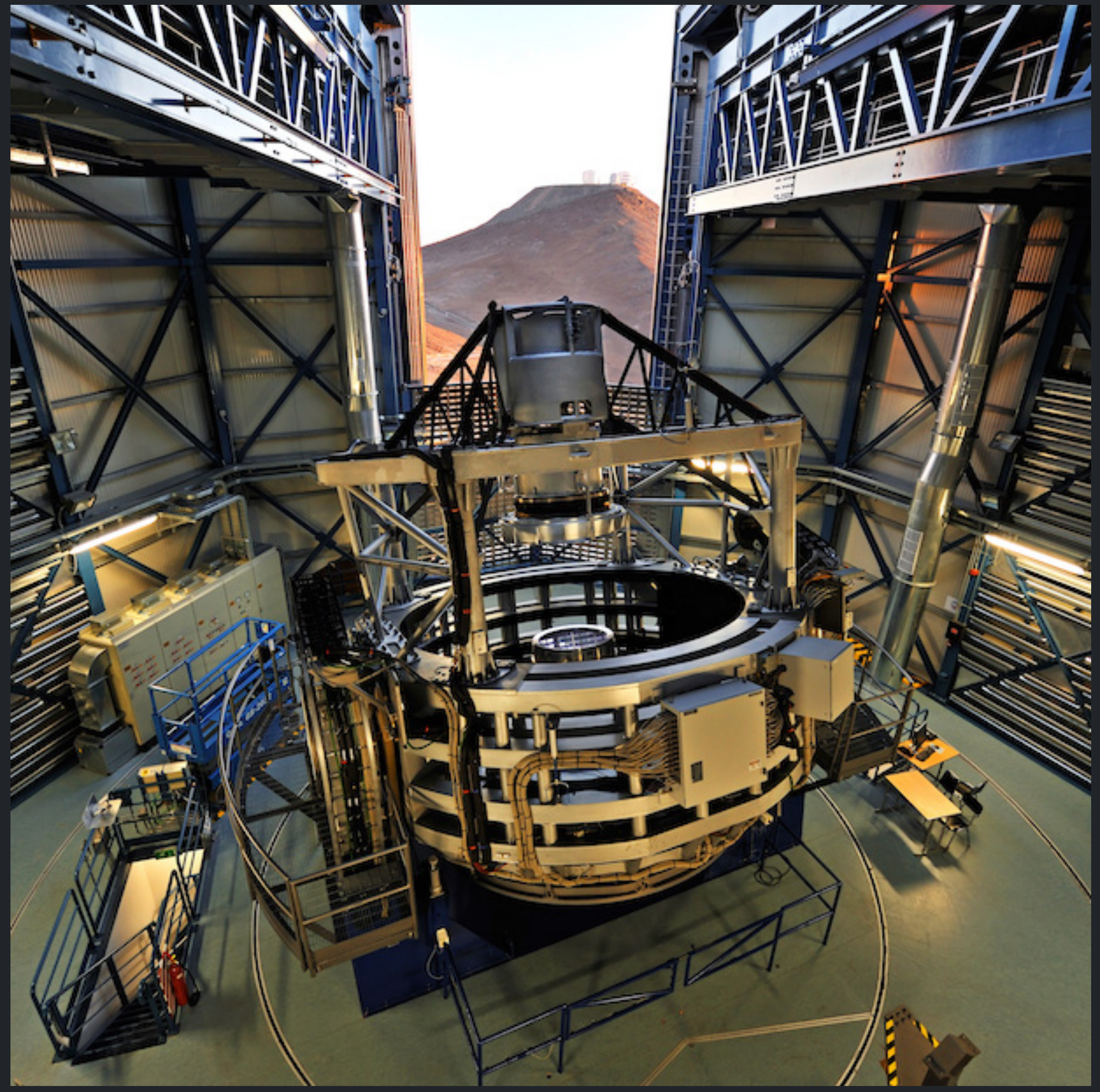
OBSERVATIONAL FACTS


the stellar disc
the bulge
Gaia
~150 000 lyr
~10 000 lyr
~15 000 lyr
d~200 000 lyr
dwarf galaxy population
~1 000 000 lyr

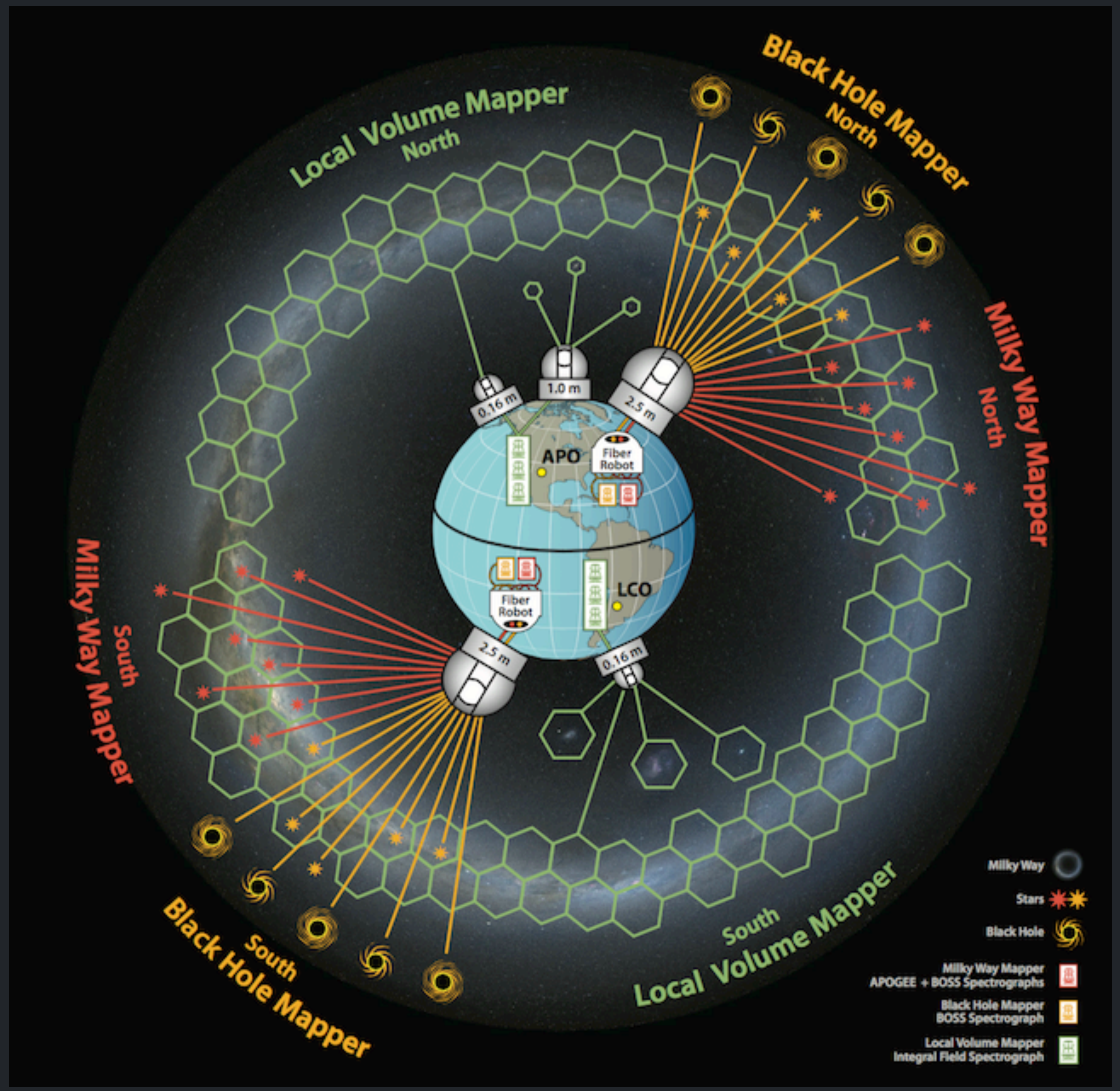
MILKY WAY SURVEYS



Gaia



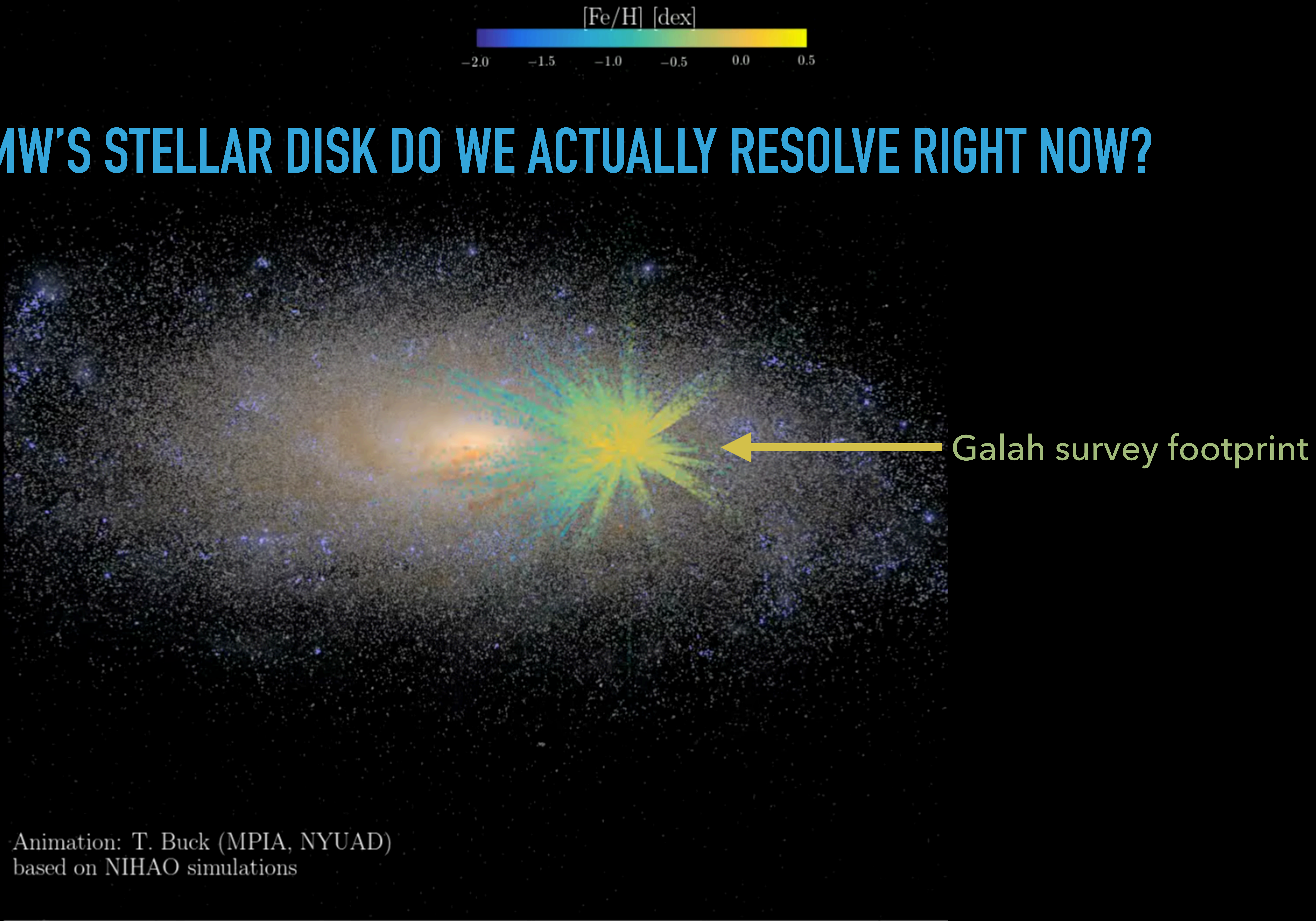
4MOST



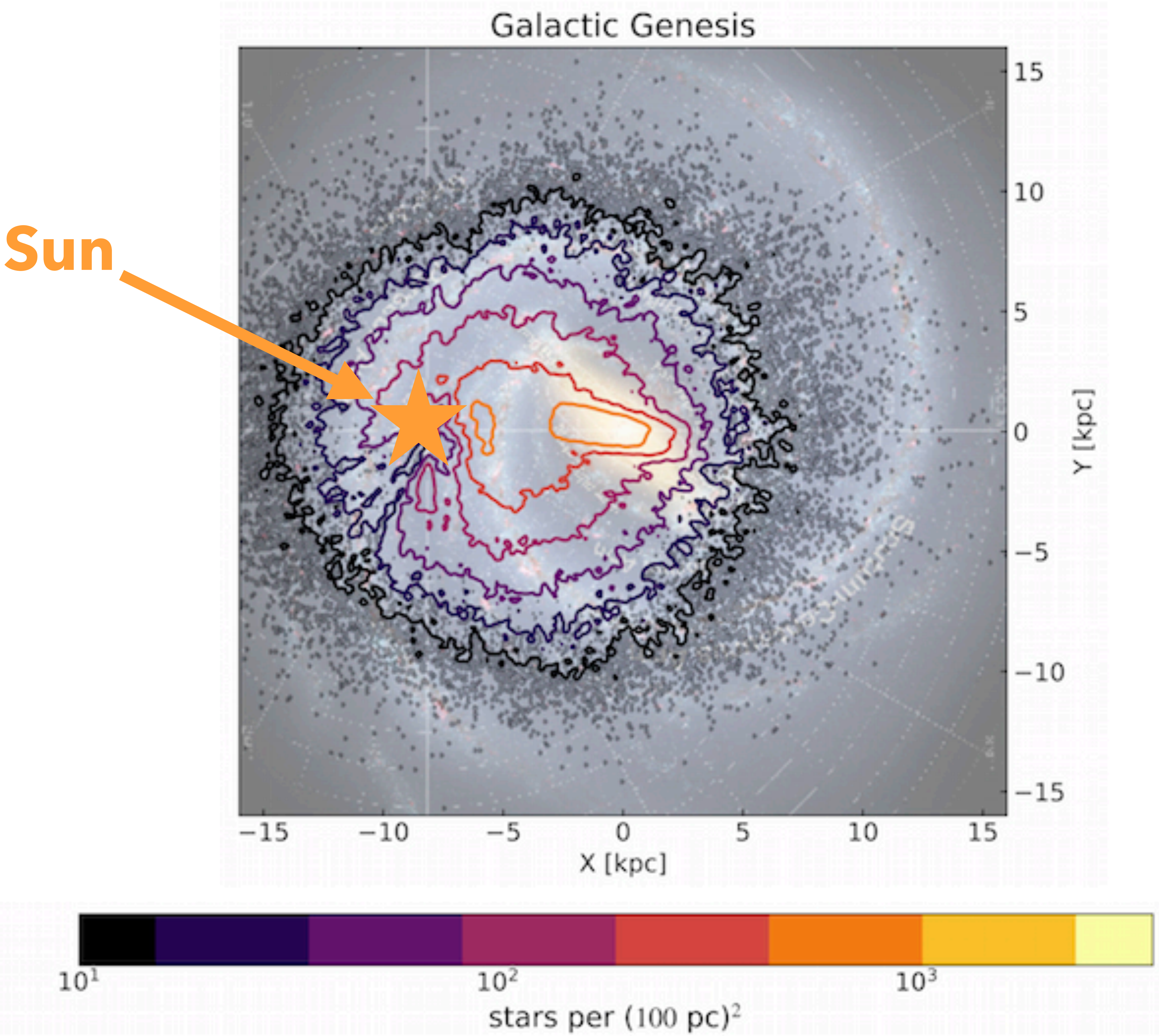
SDSS-V

MAIN DATA PRODUCT: ~10^7 STELLAR SPECTRA

HOW MUCH OF MW'S STELLAR DISK DO WE ACTUALLY RESOLVE RIGHT NOW?

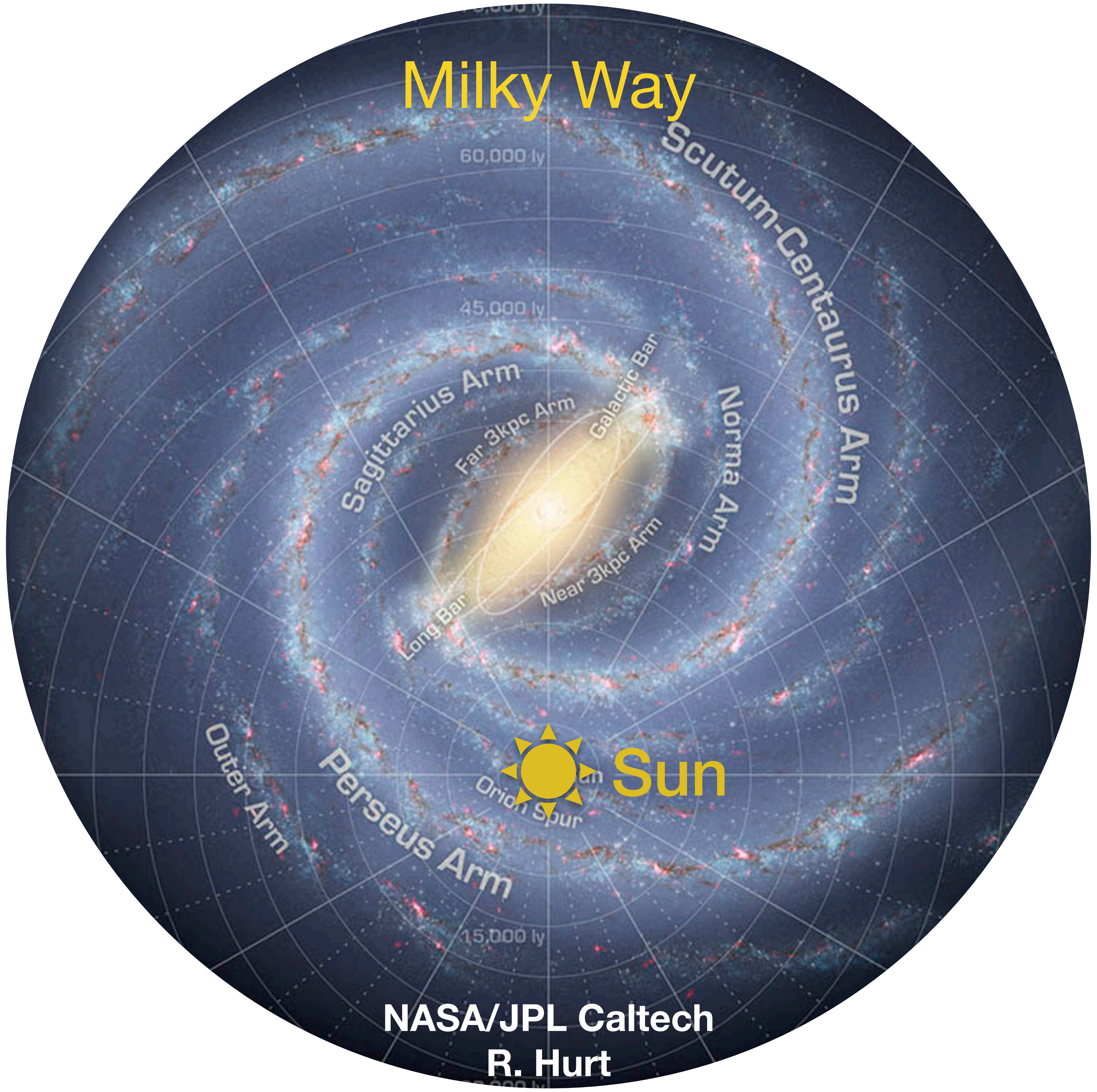


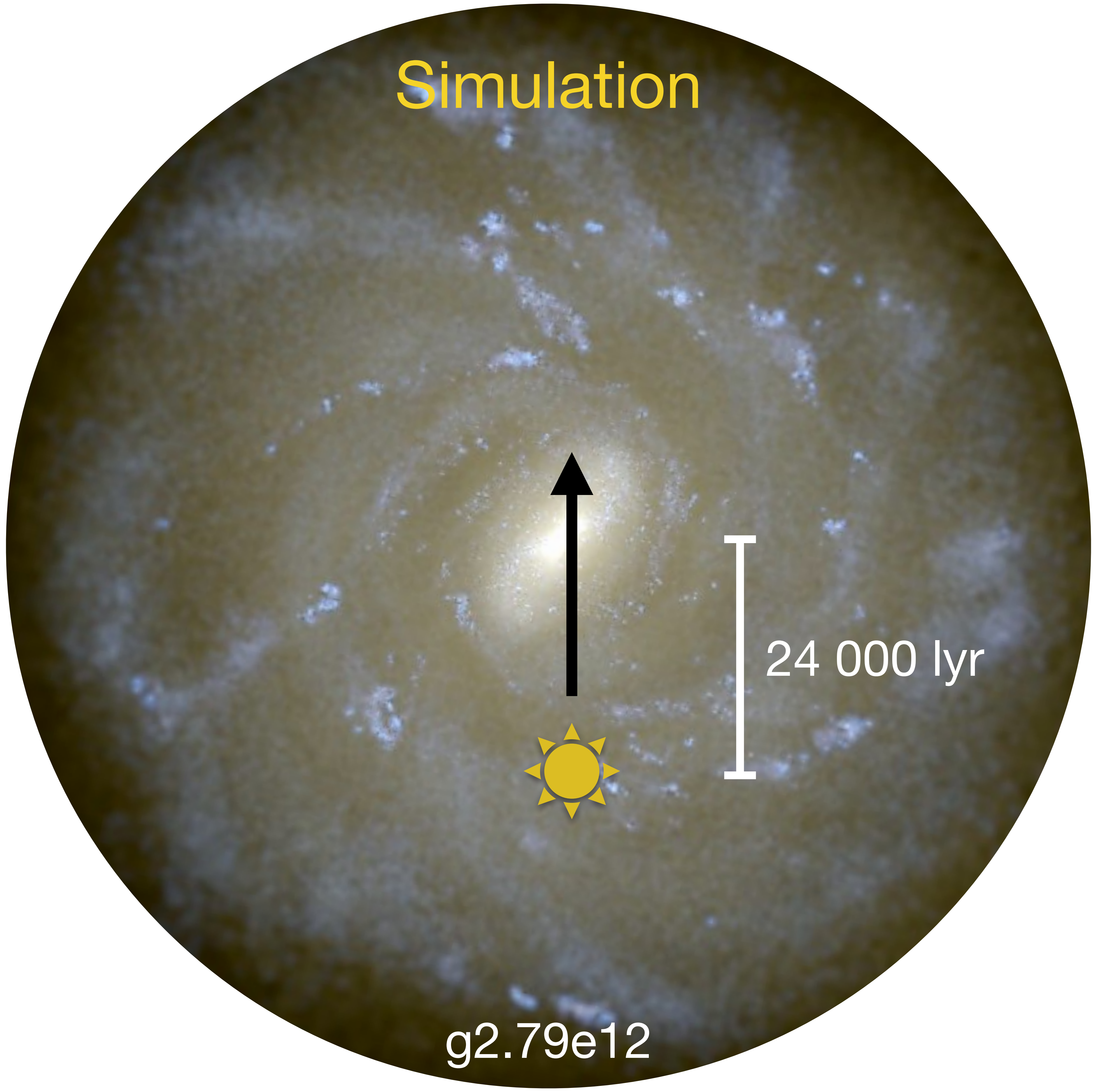
MILKY WAY AS A RESOLVED MODEL GALAXY:



- Milky Way's formation history is encoded in its structure
- Stellar properties like age and chemical composition correlate with stellar orbits
- Stellar orbits in turn are set by global properties like gravitational potential (dark matter, gas and stars), size and shape
- Need to understand Milky Way in cosmological context

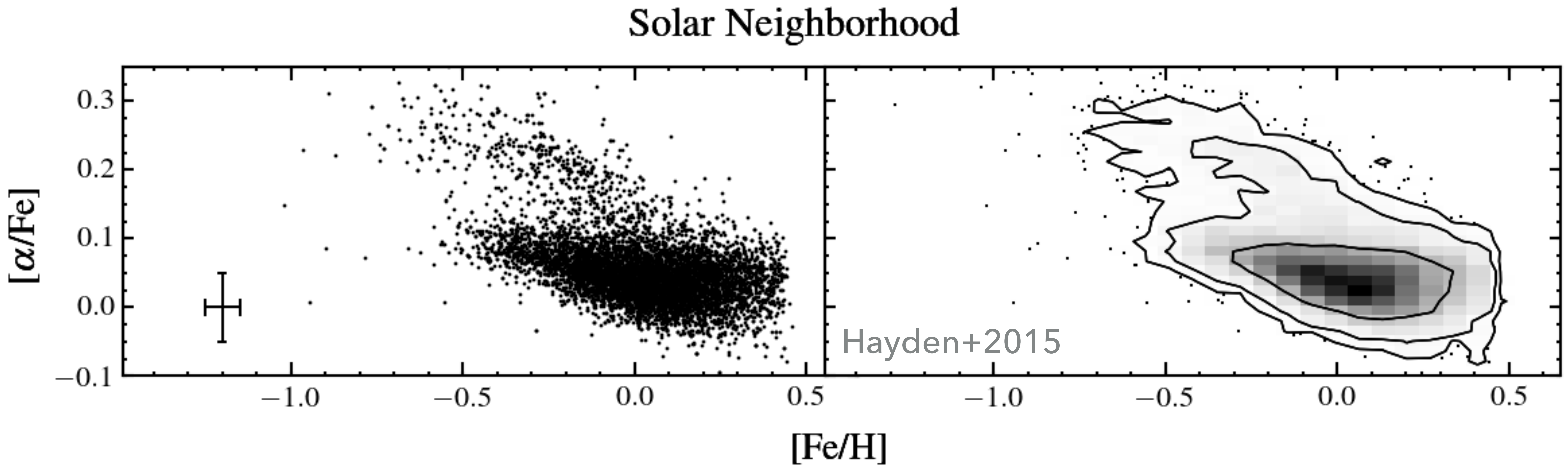
MW BULGE: MORPHOLOGY AND KINEMATICS – ONGOING DISCUSSIONS

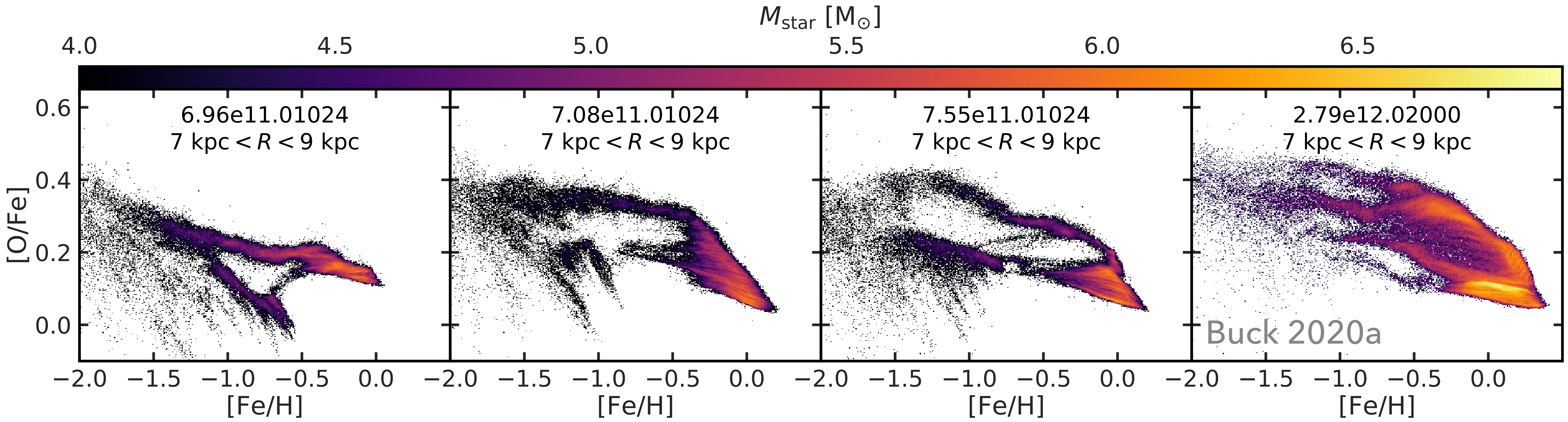




Buck+2018a, Buck+2019b, Hilmi,Minchev,Buck+2020

MILKY WAY'S AGE-ABUNDANCE STRUCTURE FROM STELLAR SPECTRA

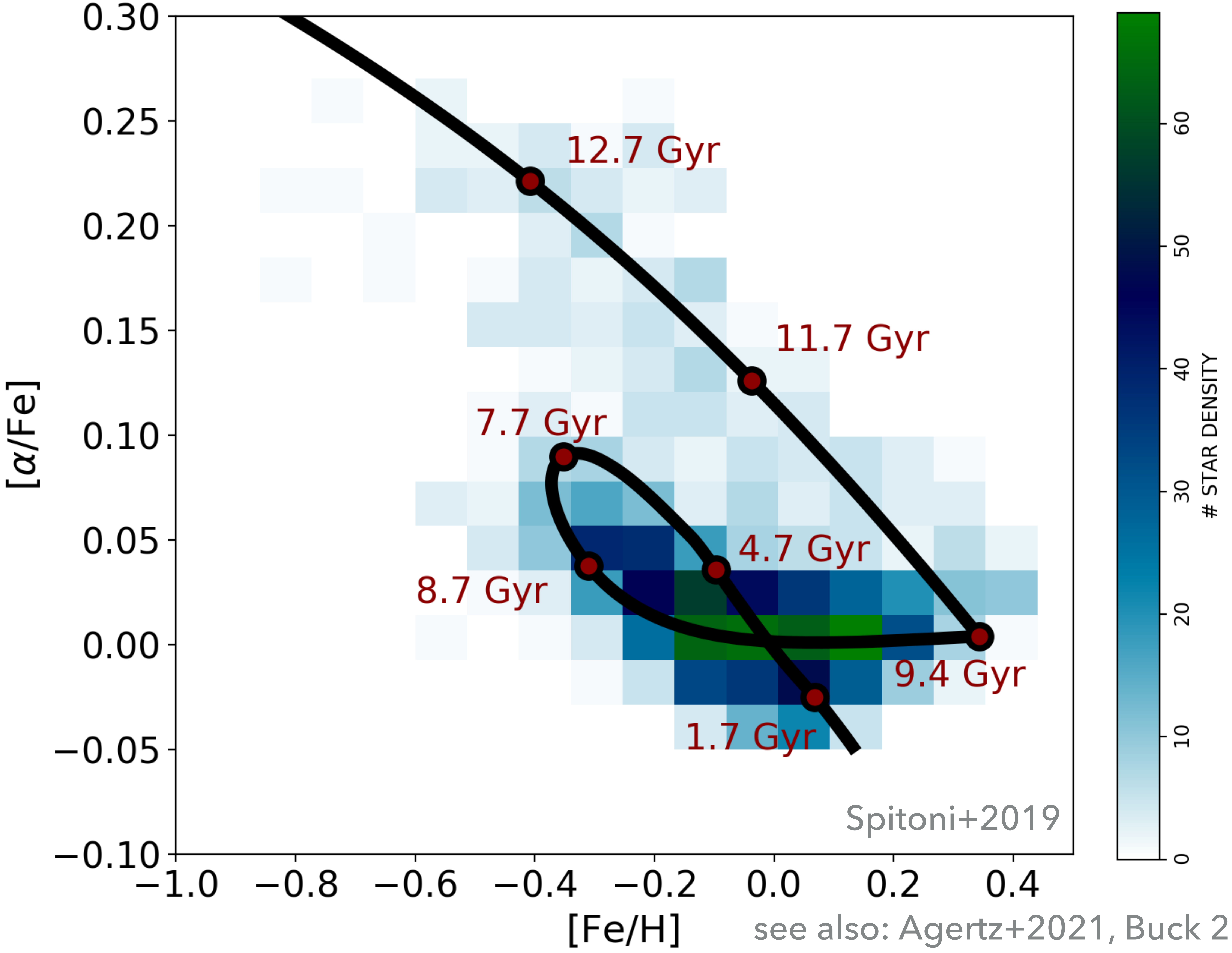




MILKY WAY'S AGE-ABUNDANCE STRUCTURE FROM STELLAR SPECTRA

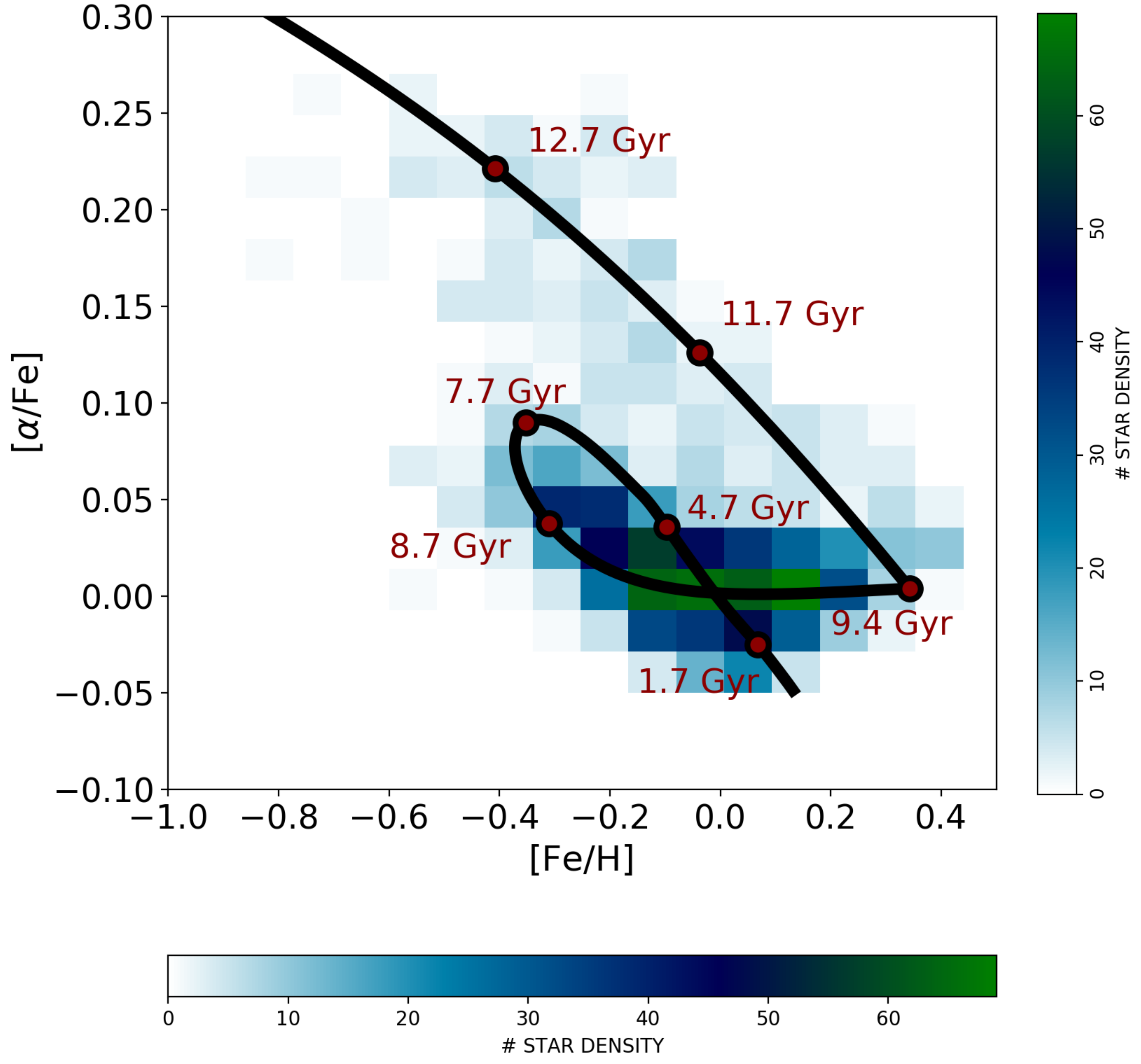
see also: Nidever et al. 2014, Hayden et al. 2015, Martig et al. 2016, Ness et al. 2016,2019, Bensby et al. 2017 Mackereth et al. 2019, Bovy et al. 2019,

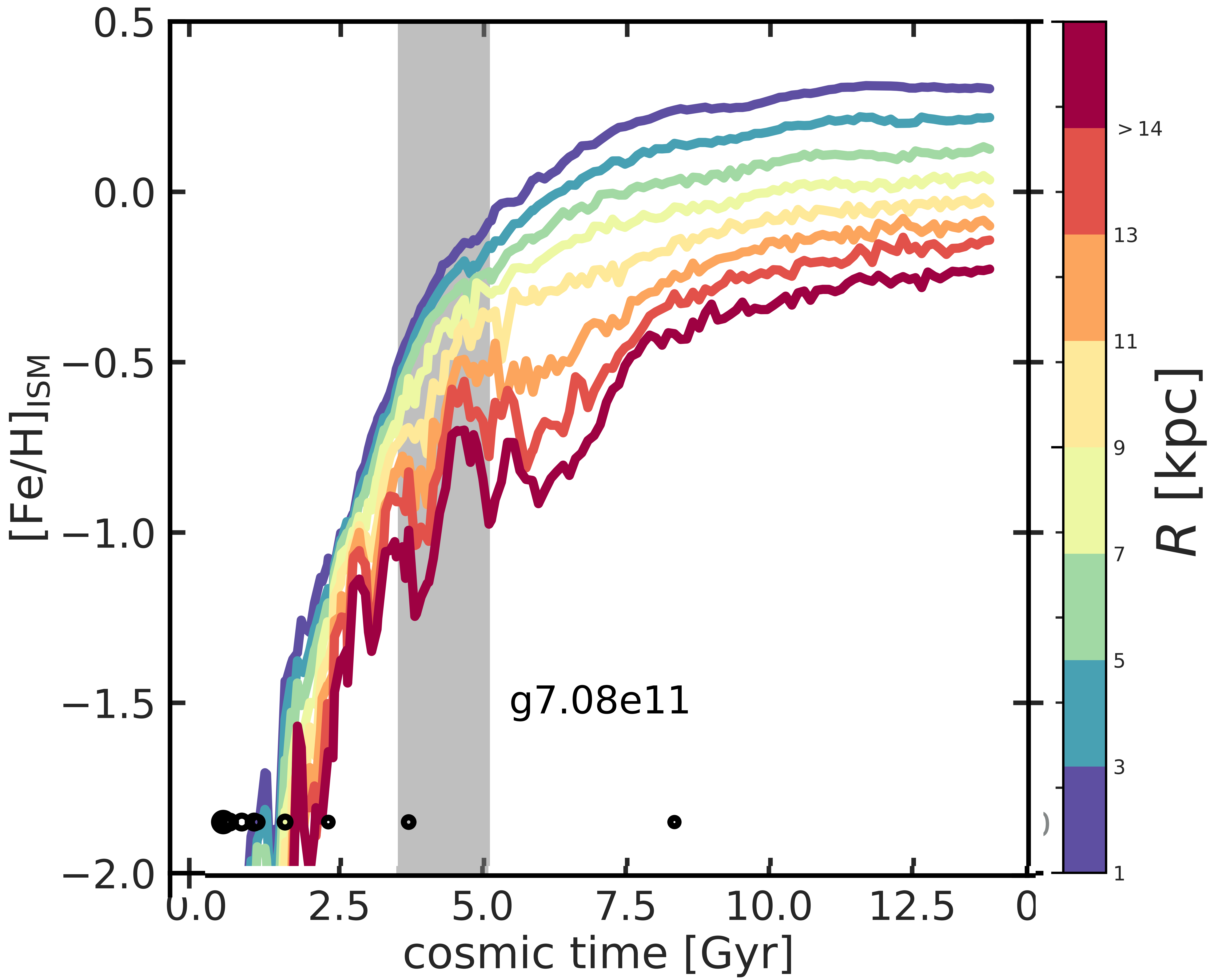
MILKY WAY'S AGE-ABUNDANCE STRUCTURE FROM STELLAR SPECTRA



see also: Agertz+2021, Buck 2020 for simulation results

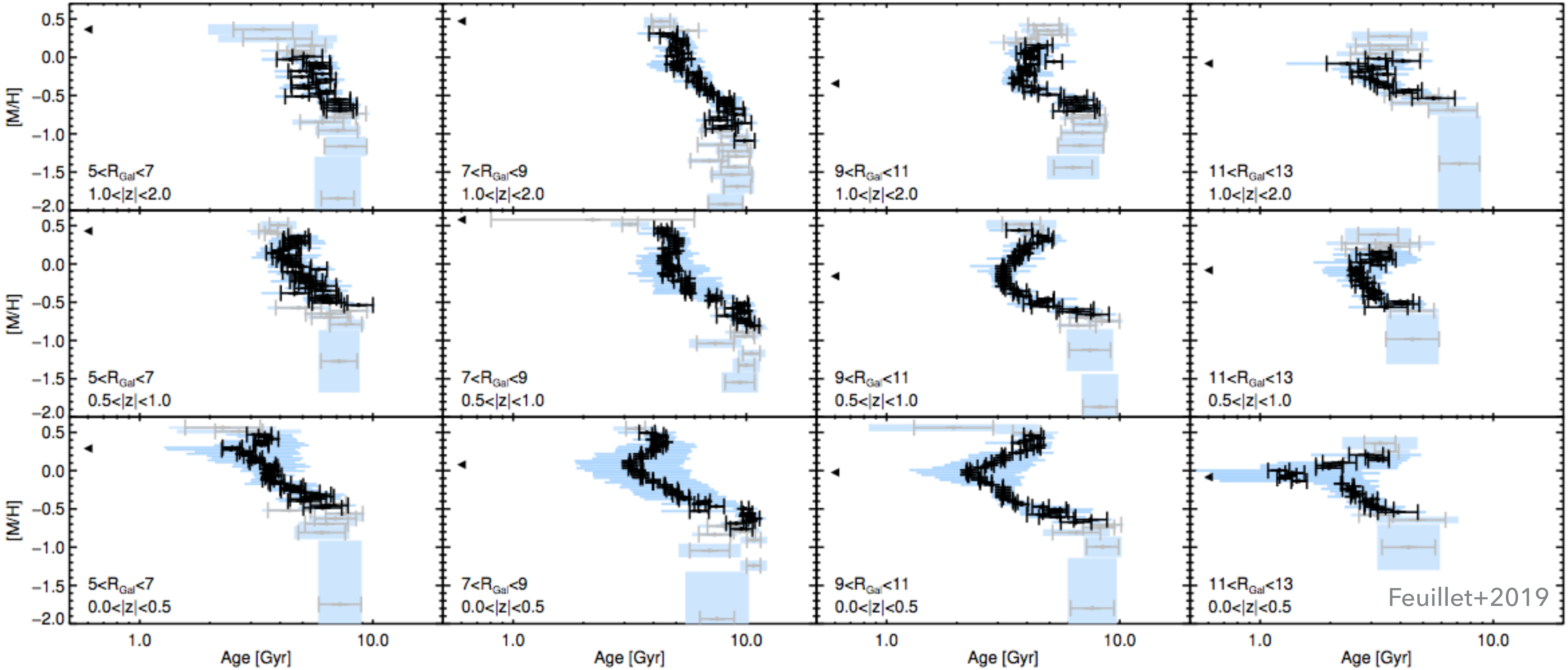
TURNING POINTS IN THE AGE–METALLICITY RELATION





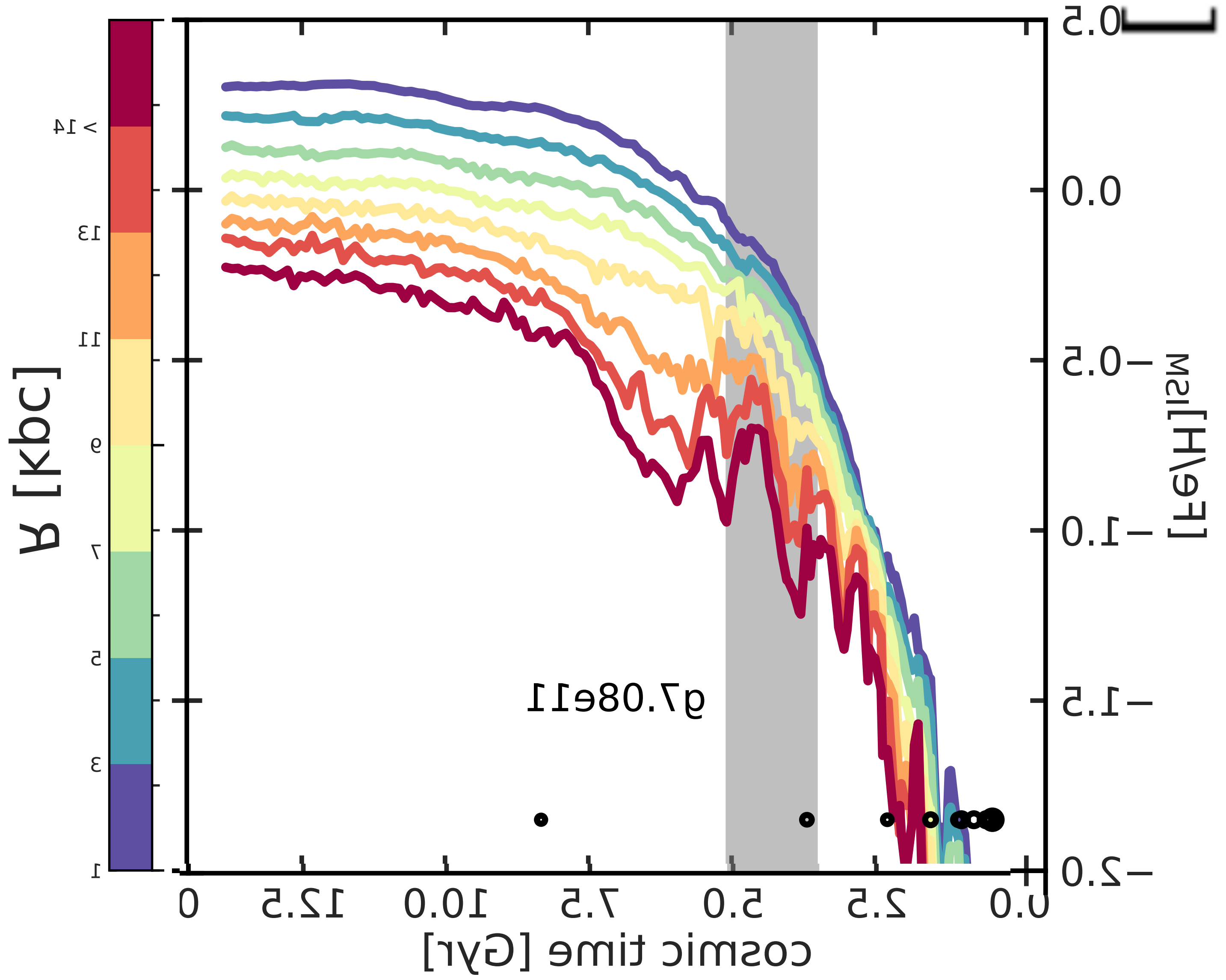
see also: Yuxi+2021

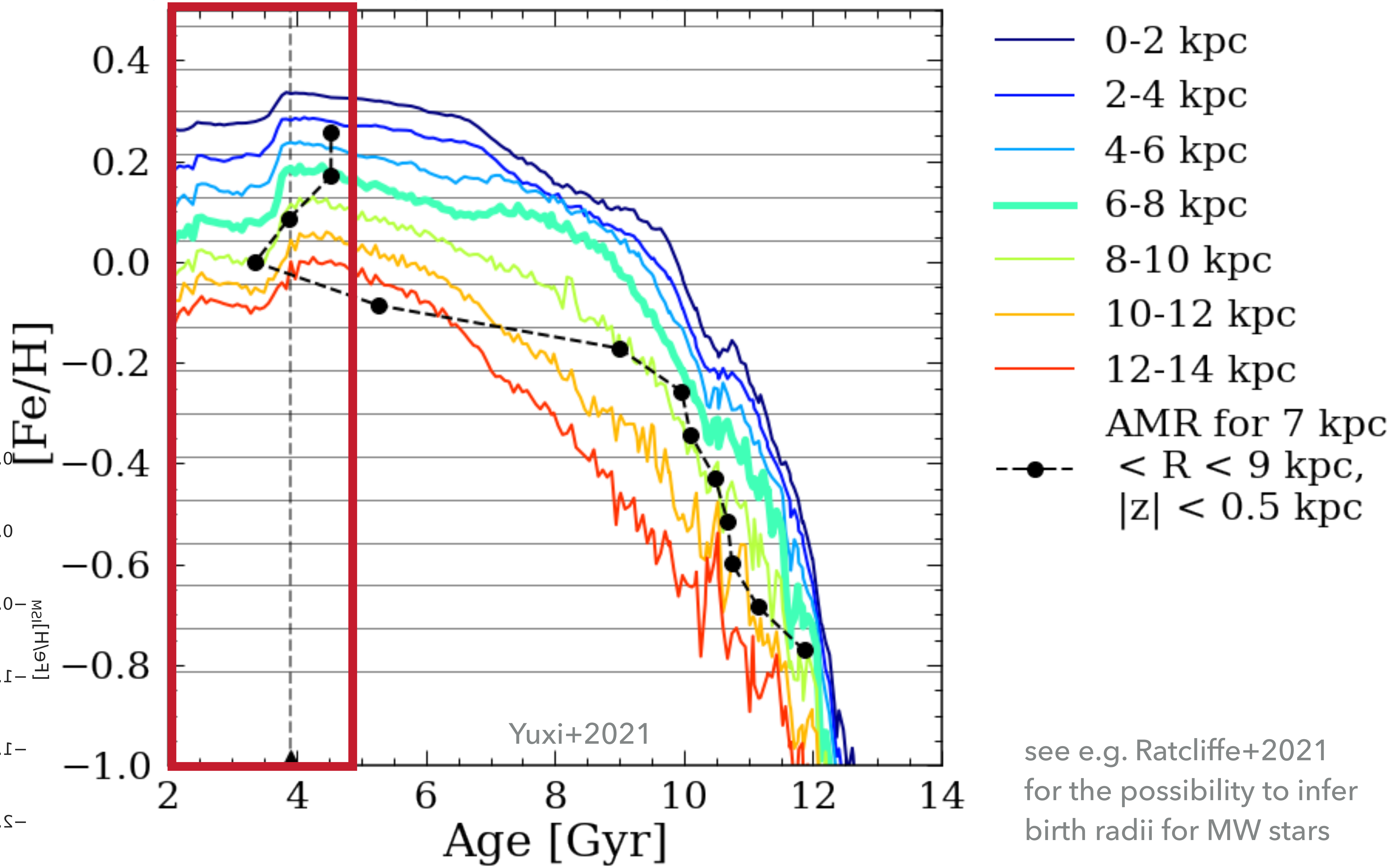
TURNING POINTS IN THE AGE–METALLICITY RELATION



see also: Yuxi+2021

TURNING POINTS IN THE AGE-METALLICITY RELATION

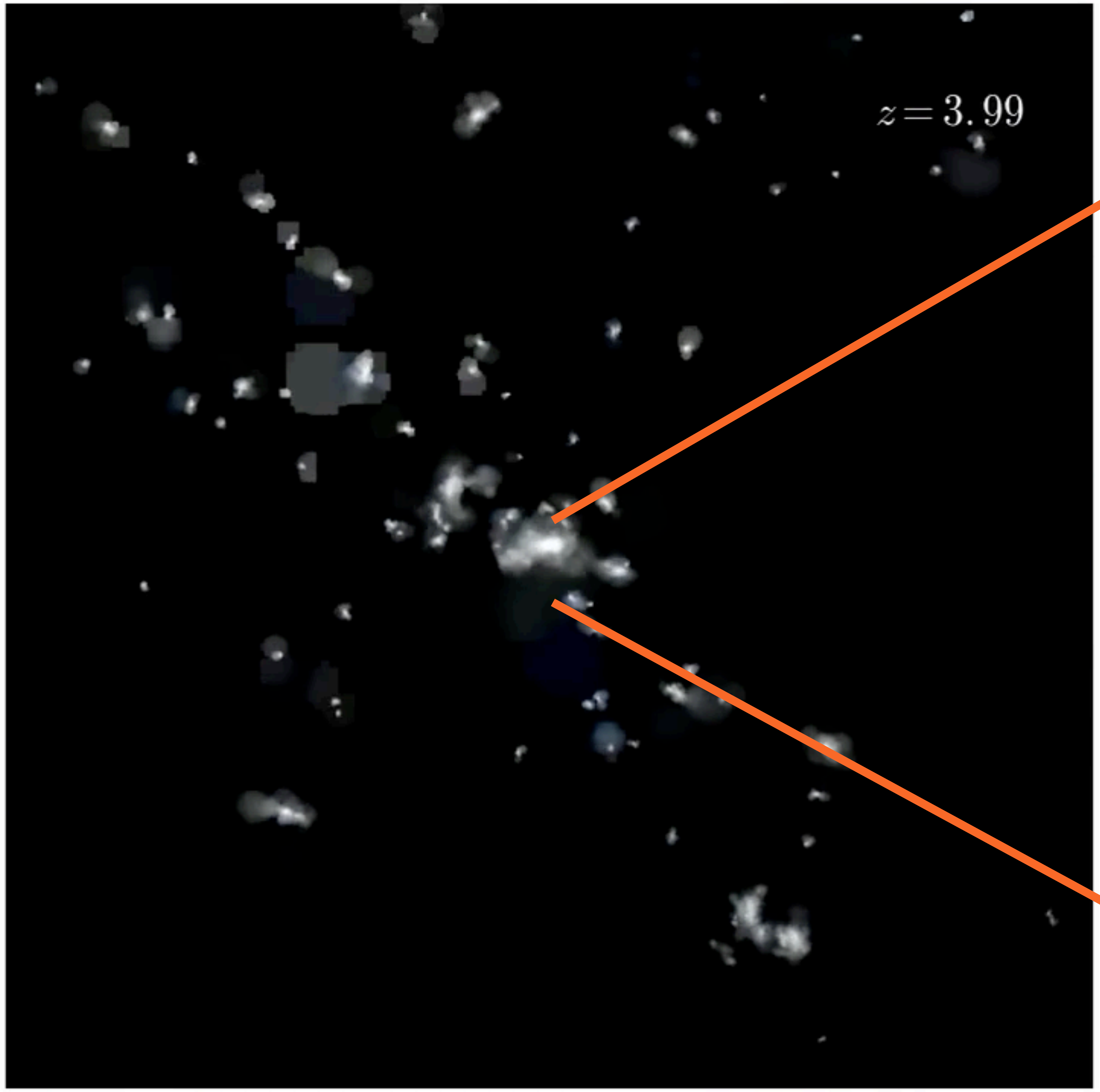




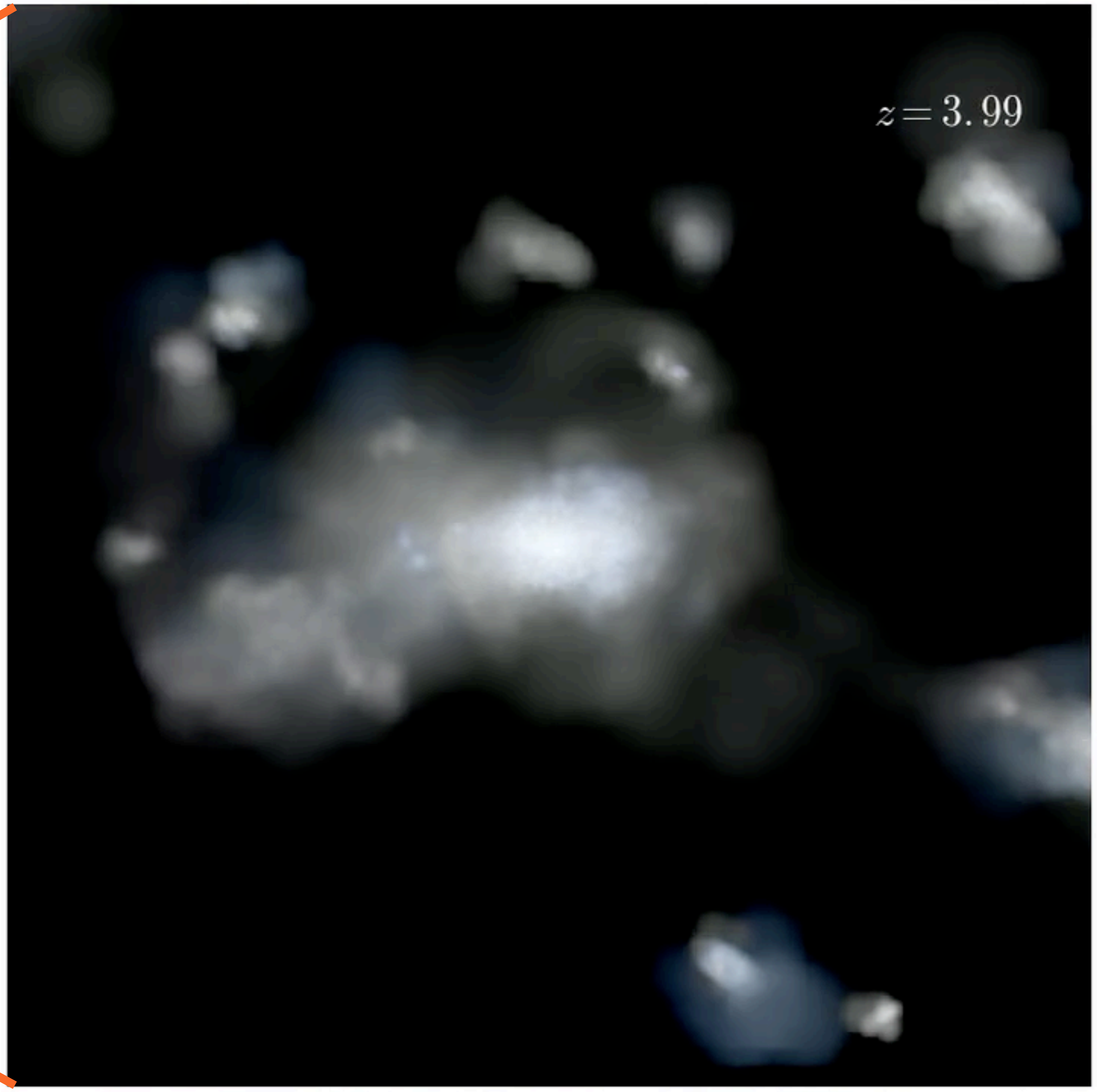
see e.g. Ratcliffe+2021 for the possibility to infer birth radii for MW stars

MOVIE TIME: COSMOLOGICAL FORMATION SCENARIO FOR THE MW

Satellite population properties: see Buck+2015,2016 and Buck+2019b

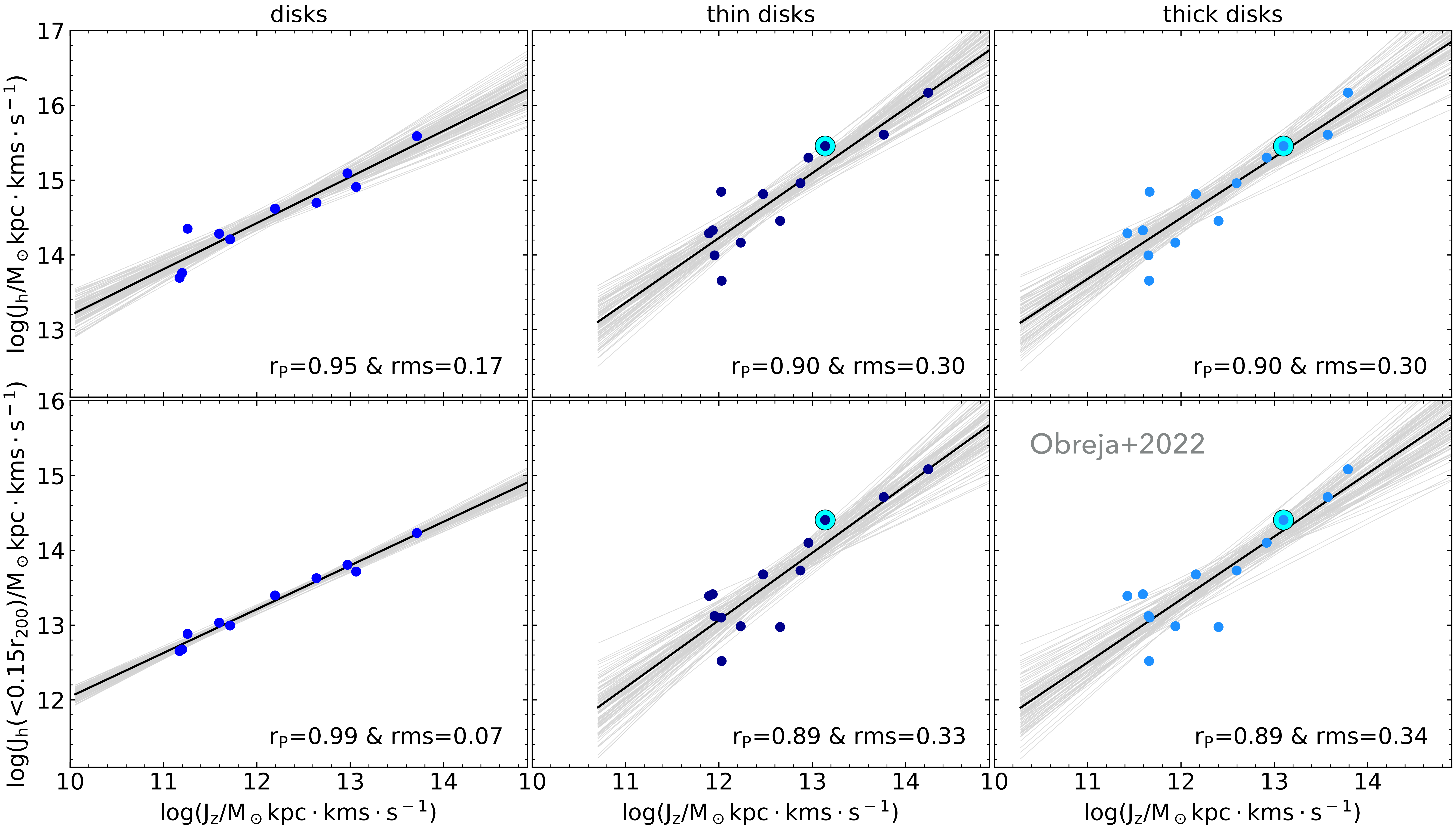


Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations



Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

MW'S DARK MATTER HALO SPIN



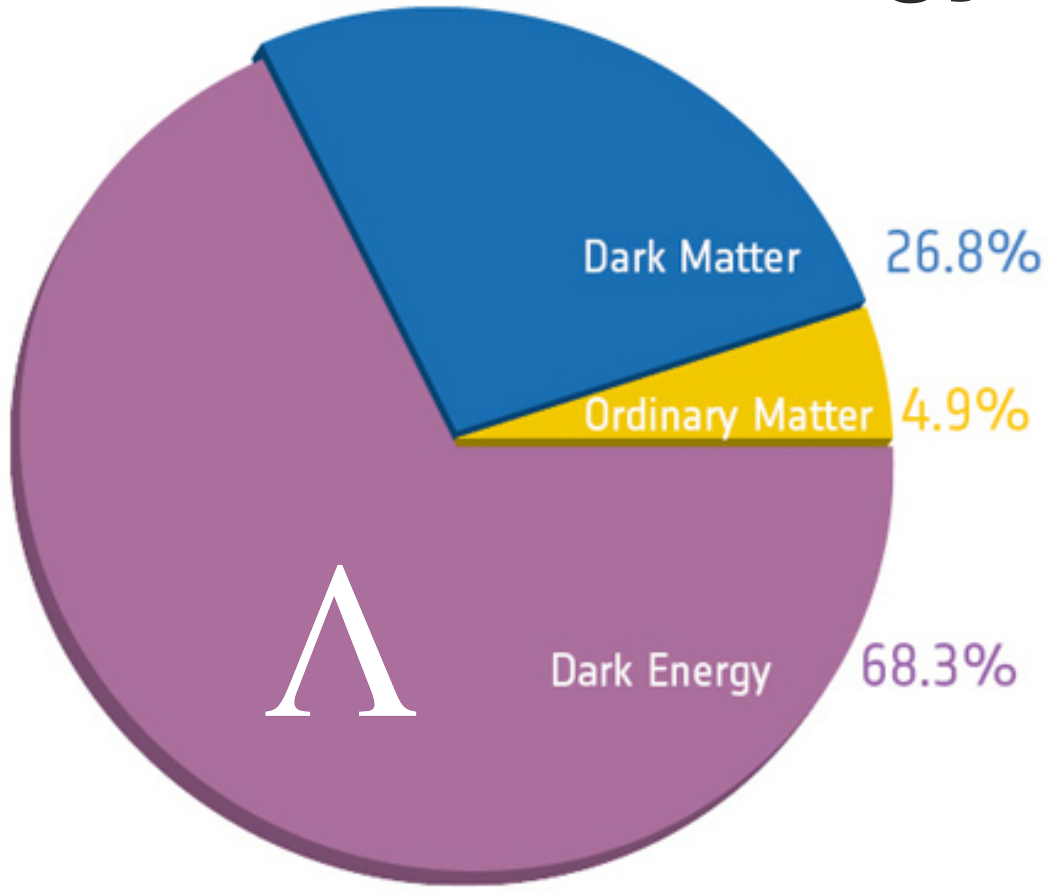
see also: Obreja+2018 for GMM method

FICTION

AKA. SIMULATIONS

A GALAXY FORMATION MODEL IN A NUTSHELL

ΛCDM Cosmology

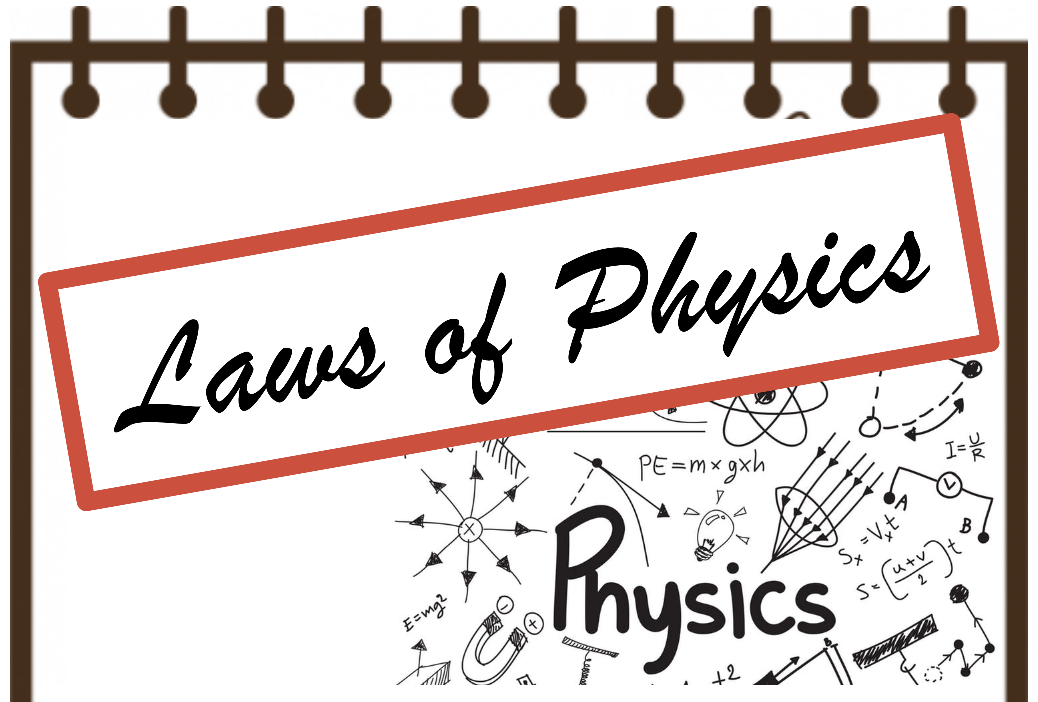


Cold dark matter = GeV mass elementary particle

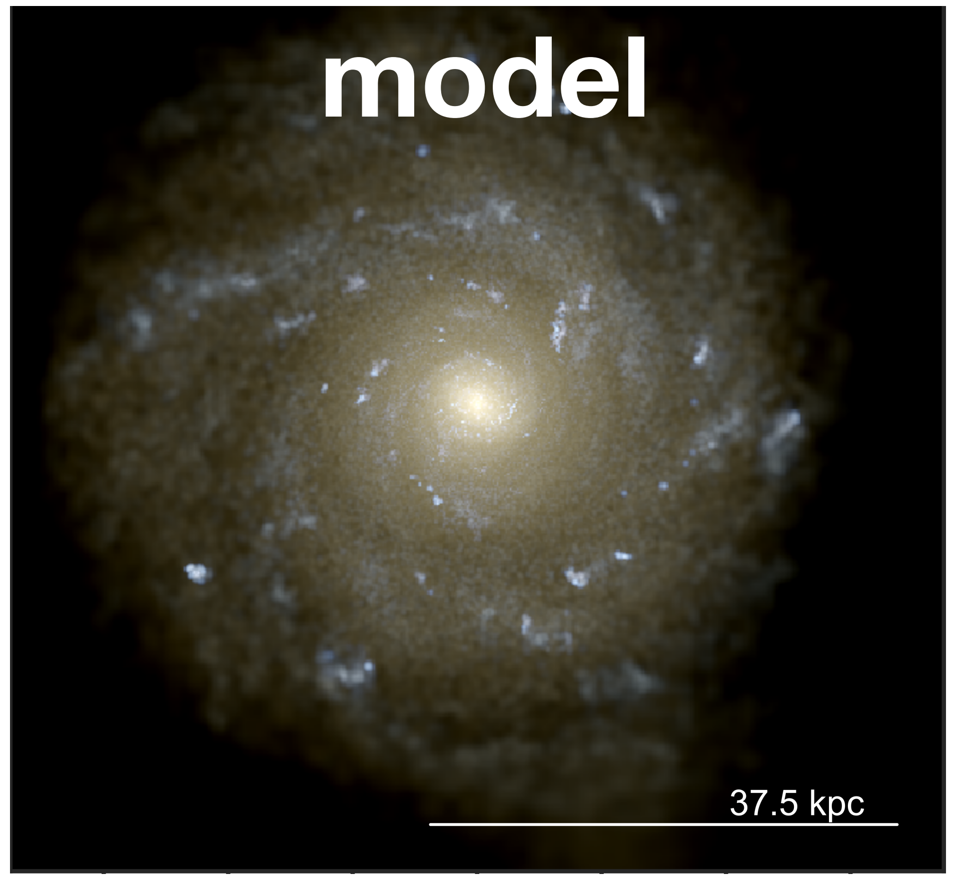
Ordinary matter = baryons

Dark energy, Λ = ???

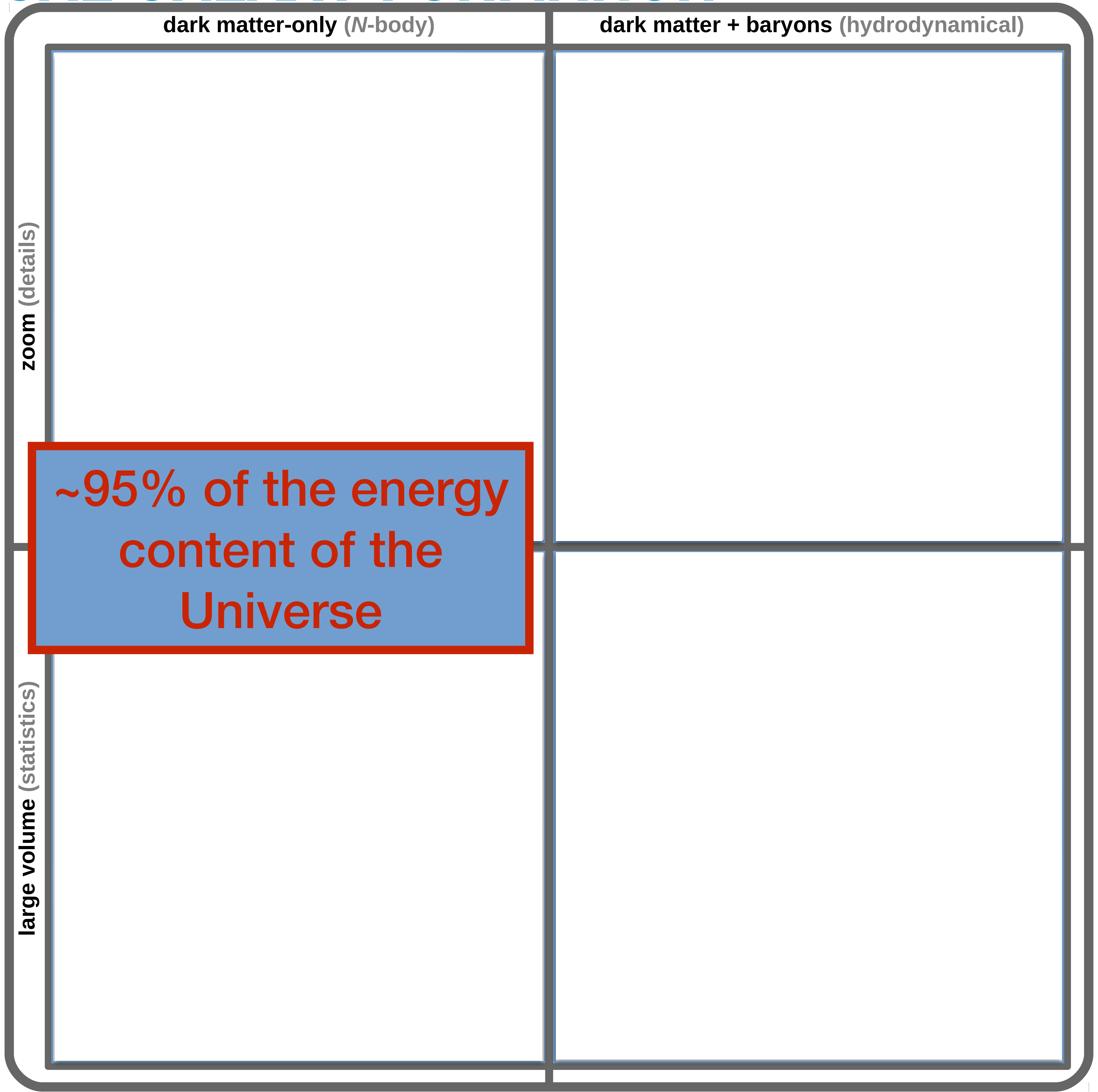
Computer



- General Relativity
- Gas Physics
- Stellar Physics
- Radiation Physics

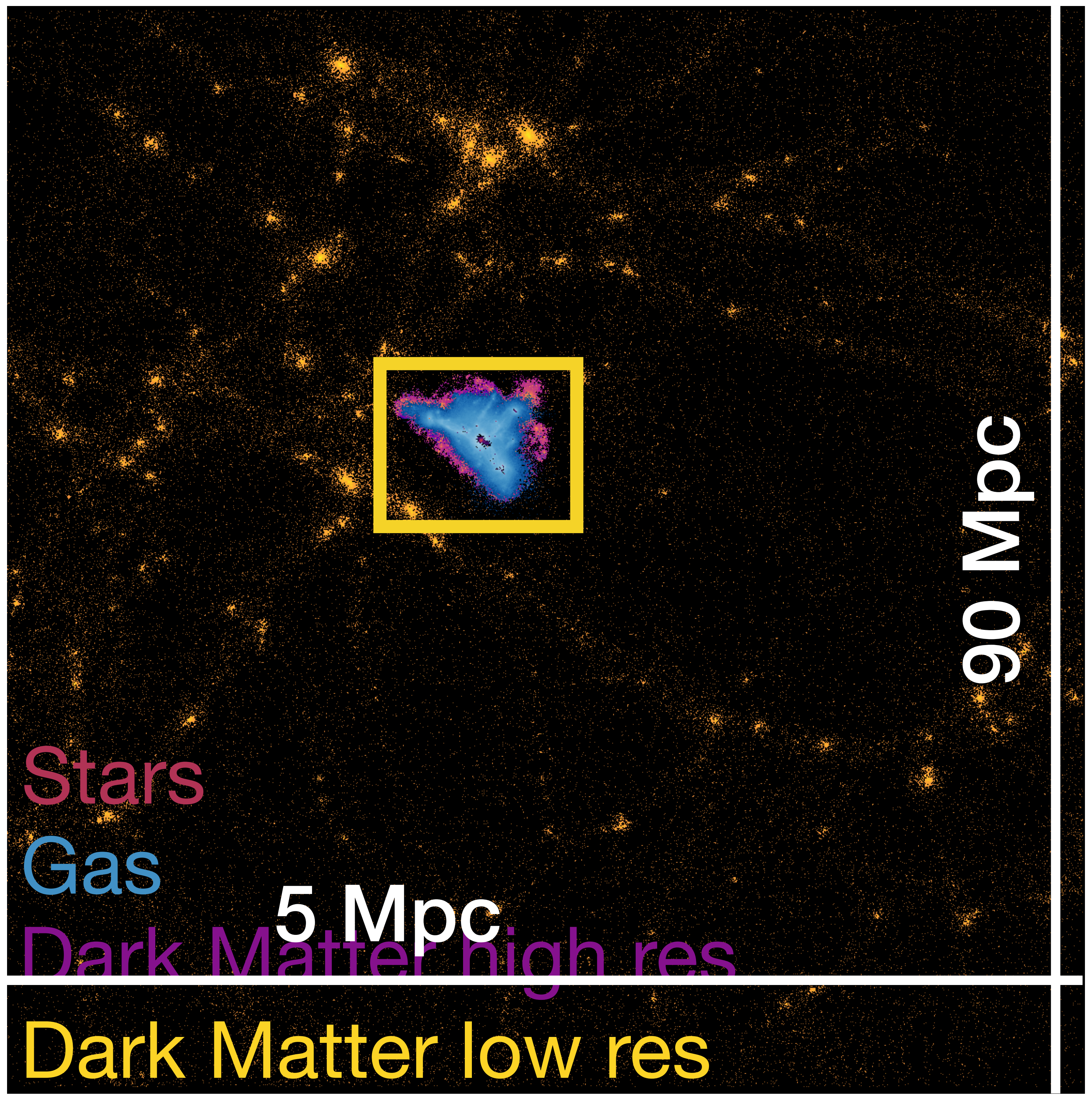


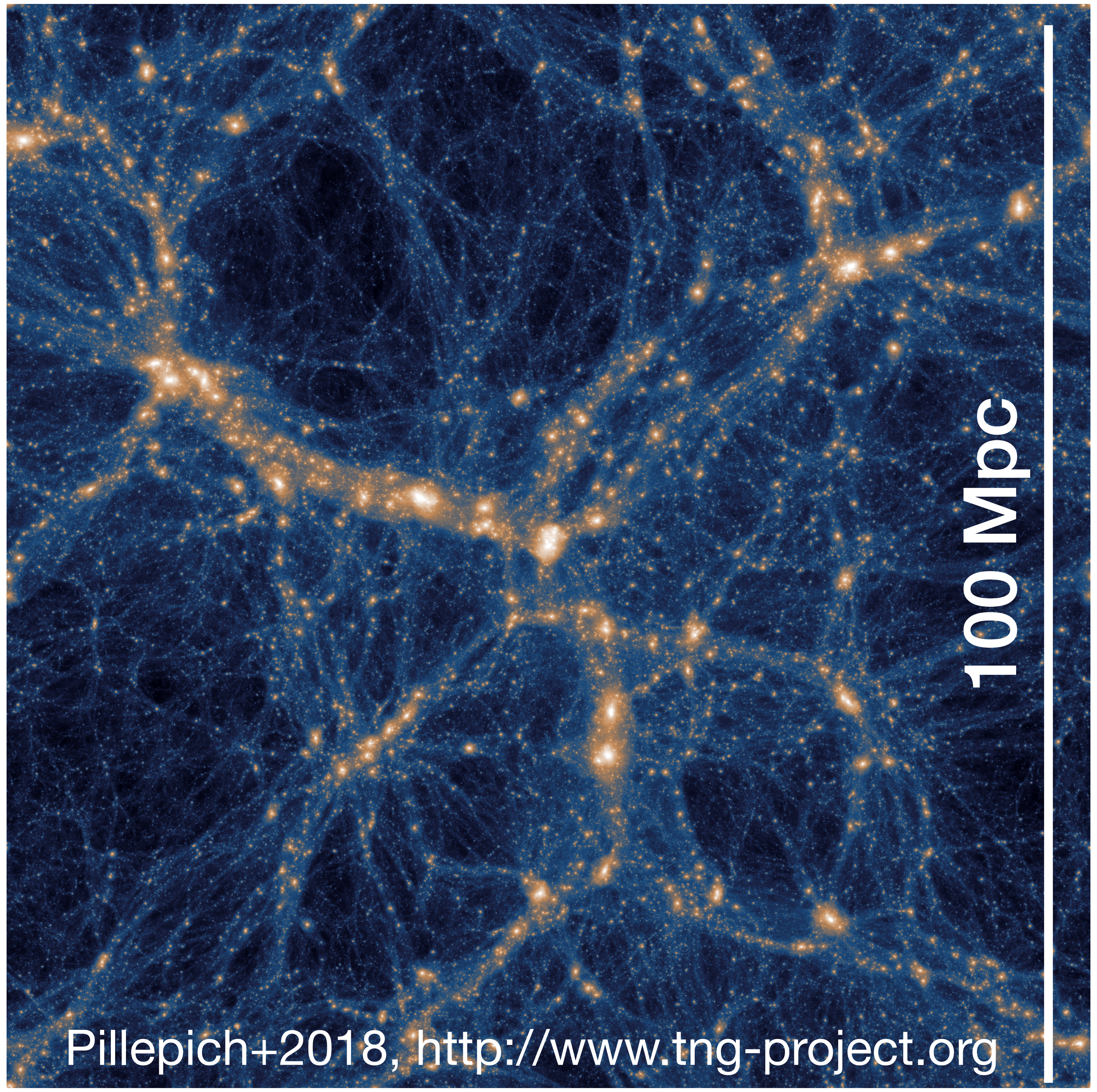
BASICS OF NUMERICAL GALAXY FORMATION



Vogelsberger+2019

ZOOM SIMS VS. VOLUME SIMS





- zoom-in, „single object“ sim
- mass resolution: stars ~$10^4\,M_\odot$

- Large scale uniform box
- mass resolution: stars ~$10^6\,M_\odot$

SIMULATED ASTROPHYSICAL PROCESSES

gas cooling	inter-stellar medium	star formation	stellar feedback	super-massive black holes	active galactic nuclei	magnetic fields	radiation fields	cosmic rays
atomic/ molecular/ metals/ tabulated/ network	effective equation of state/ multi-phase	initial stellar mass function/ probabilistic sampling/ enrichment	kinetic/ thermal/ variety of sources from stars, supernovae	numerical seeding/ growth by accretion prescription/ merging	kinetic/ thermal/ radiative/ quasar mode/ radio mode	ideal MHD/ cleaning schemes/ constrained transport	ray tracing/ Monte Carlo/ moment-based	production/ heating/ anisotropic diffusion/ streaming

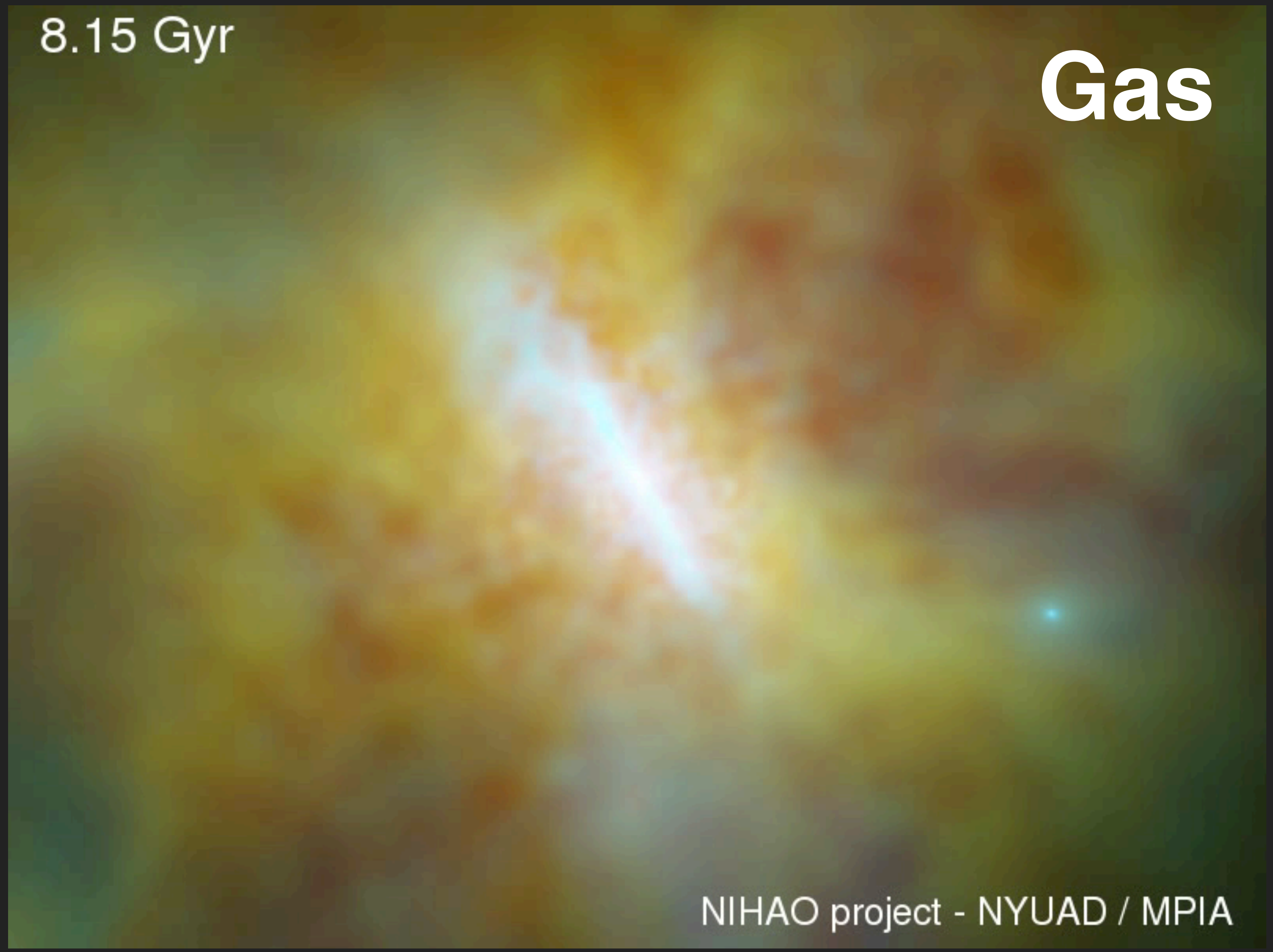
most important astrophysical processes

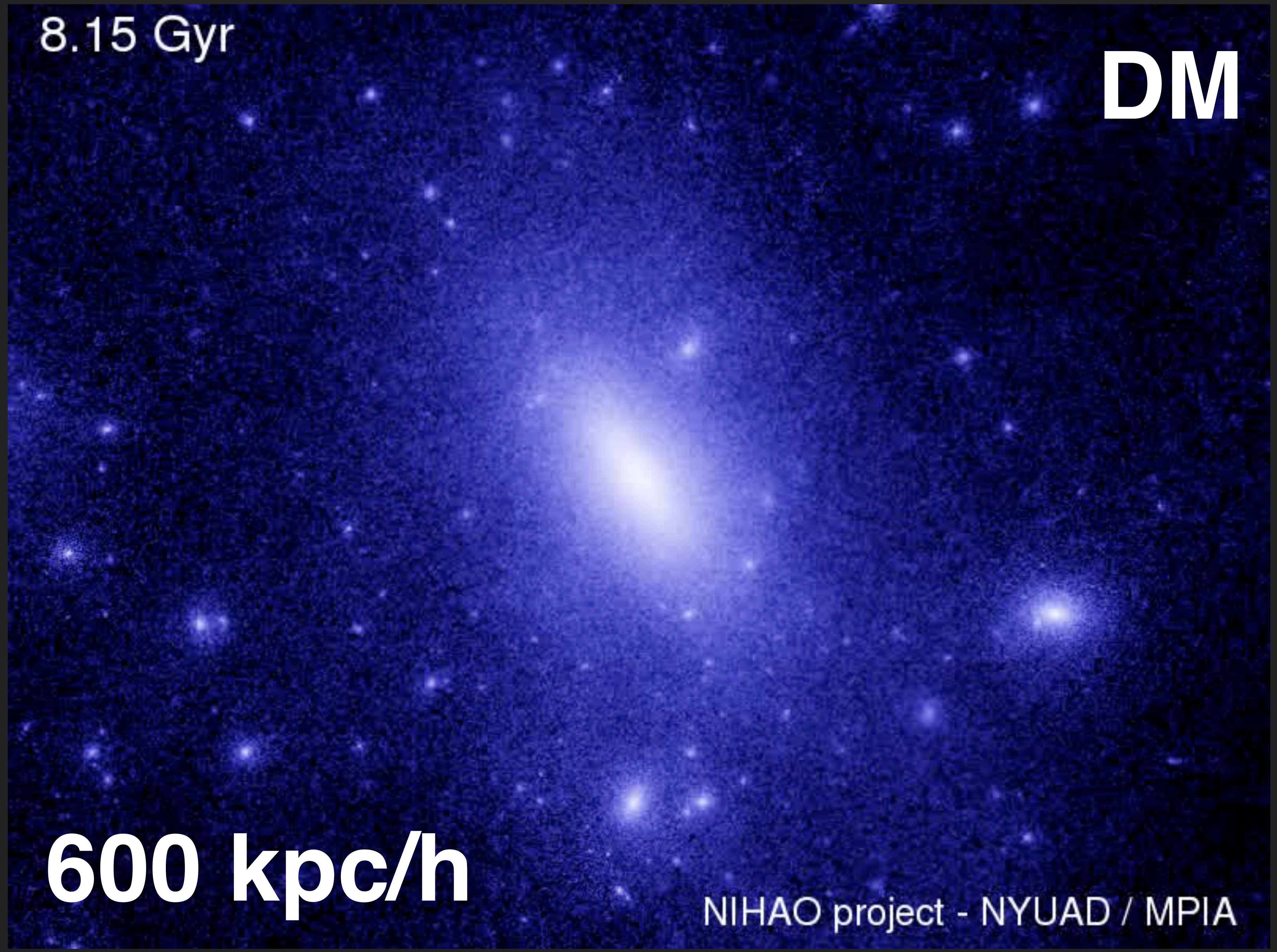
Vogelsberger+2020

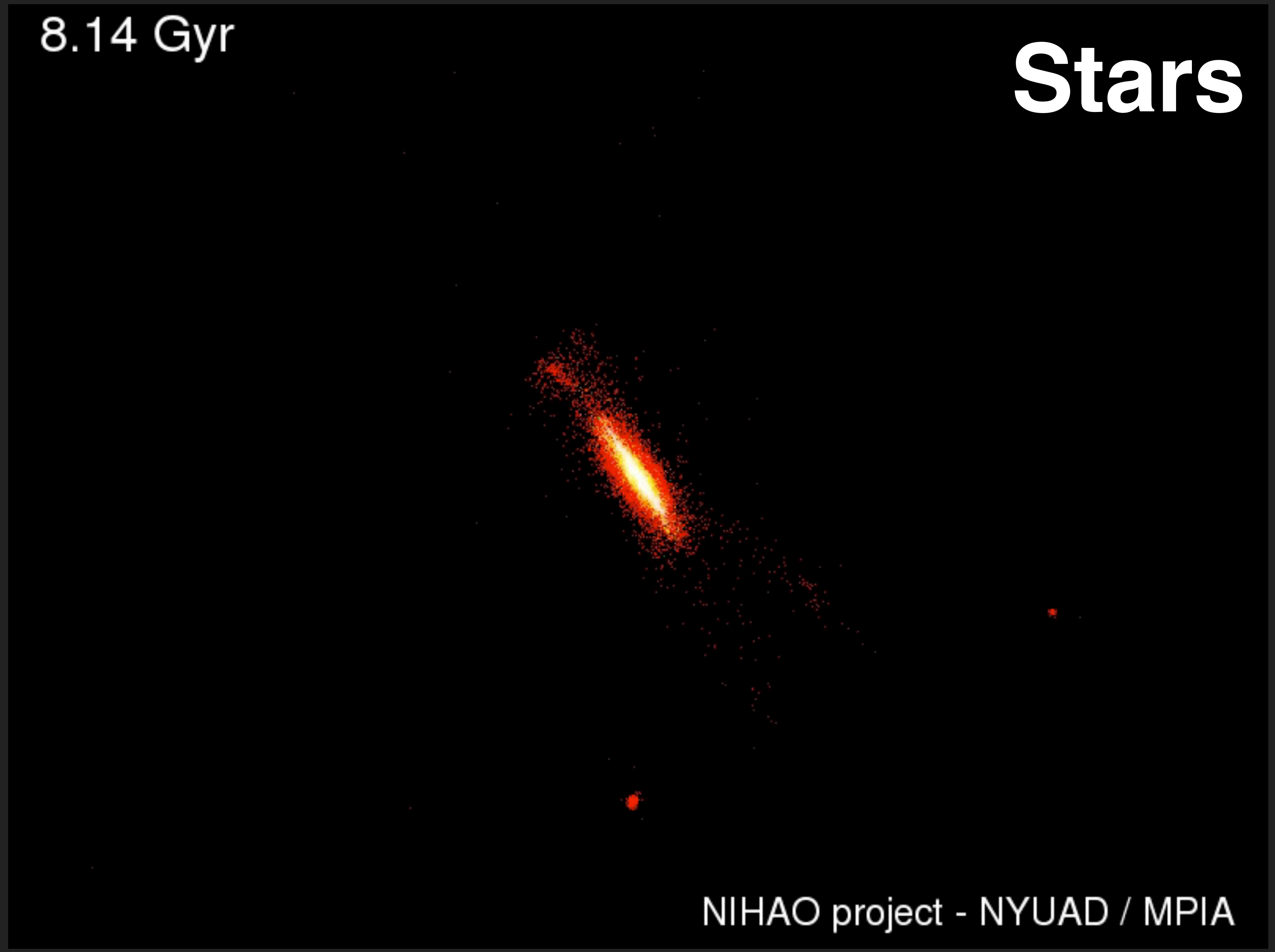
- At the same time: bridging 10^6 orders of magnitude in spatial scale from sizes of stars to entire galaxies and beyond

MOST MECHANISM PUT IN BY HAND IN A PARAMETRISED WAY.

cosmological zoom-in hydro simulations of a Milky Way analogue

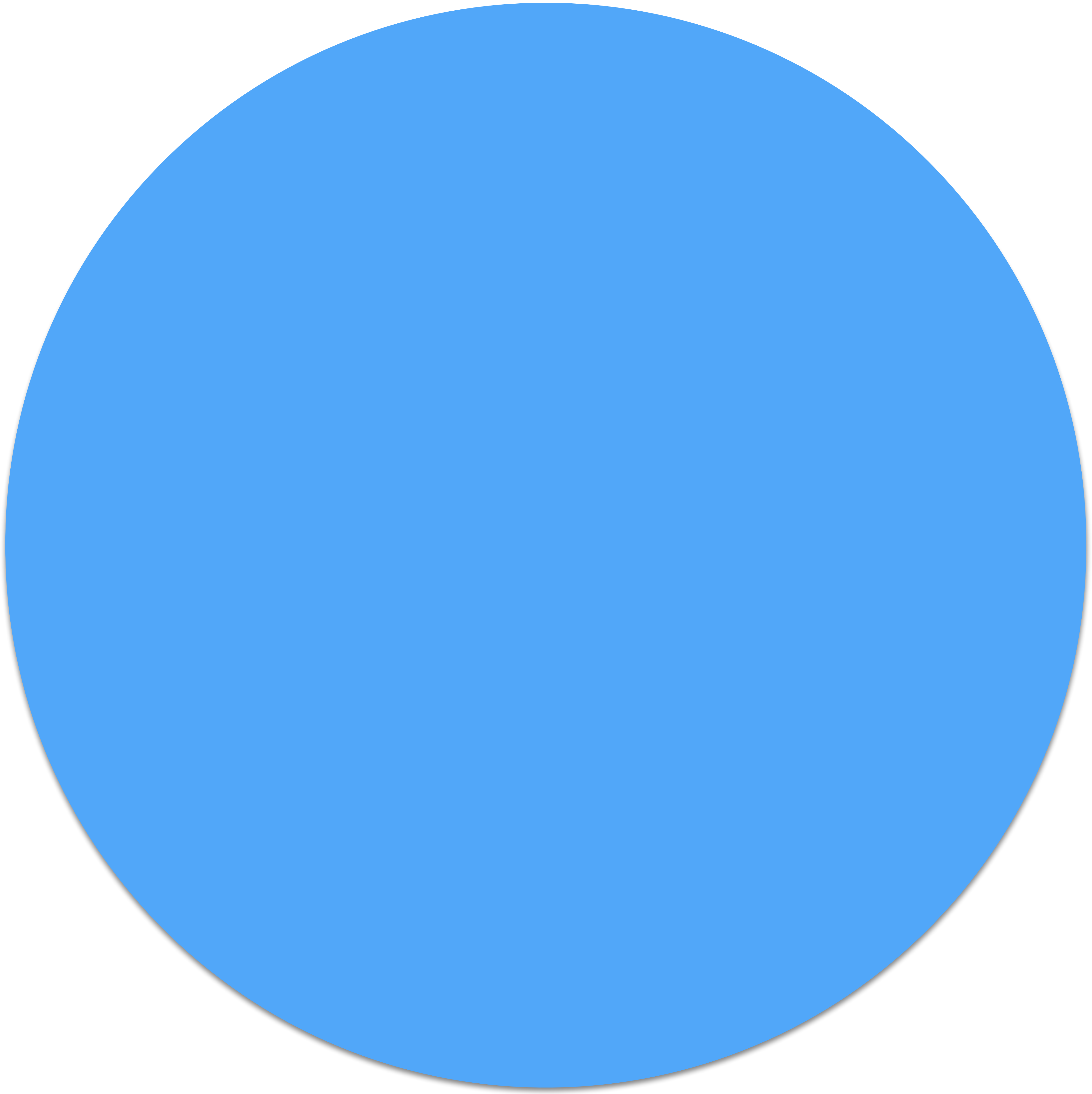




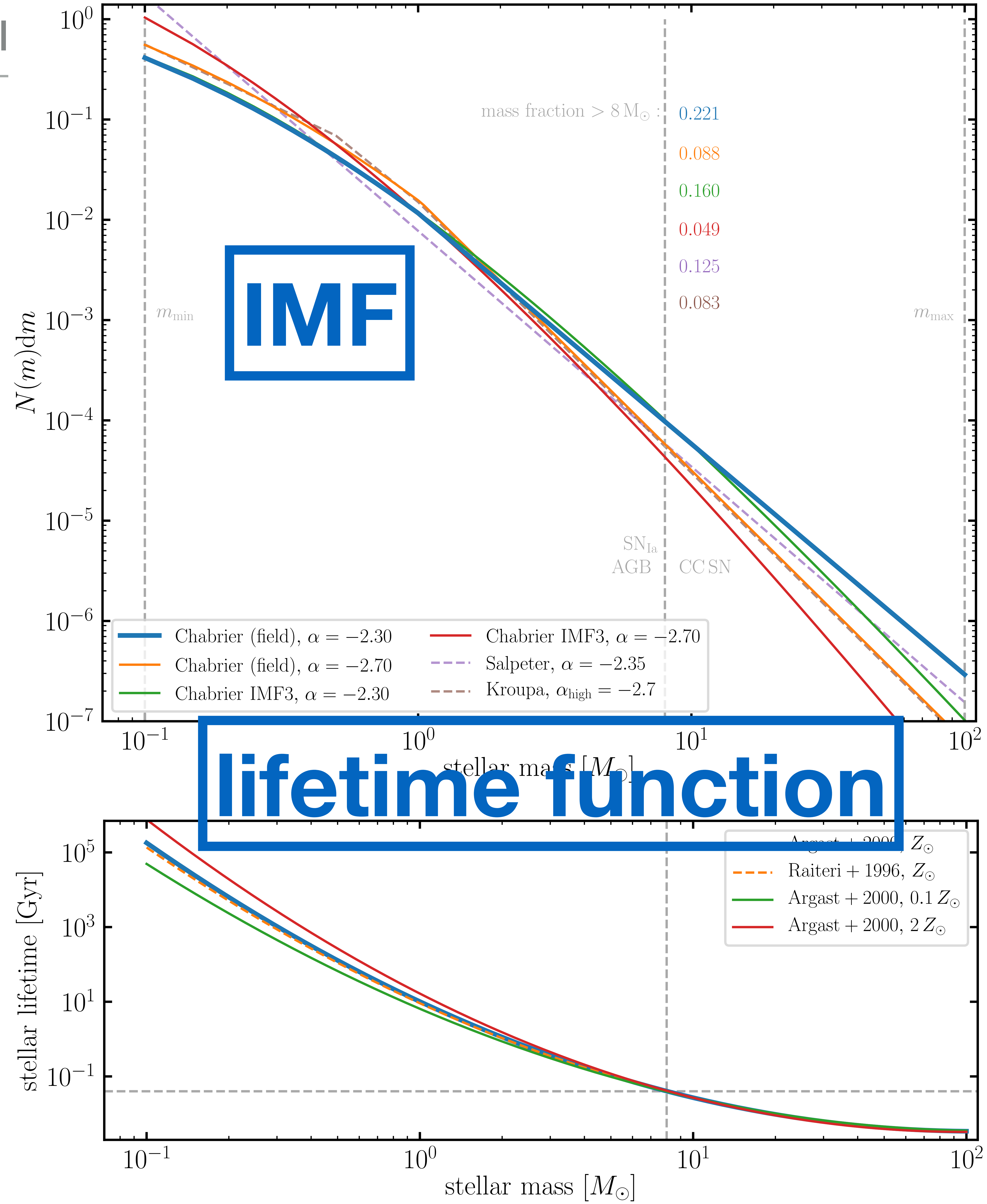



NIHAO-UHD
BUCK ET AL. 2020

STAR PARTICLES IN COSMOLOGICAL SIMULATIONS



SIMPLE STELLAR POPULATION



Simple stellar population model

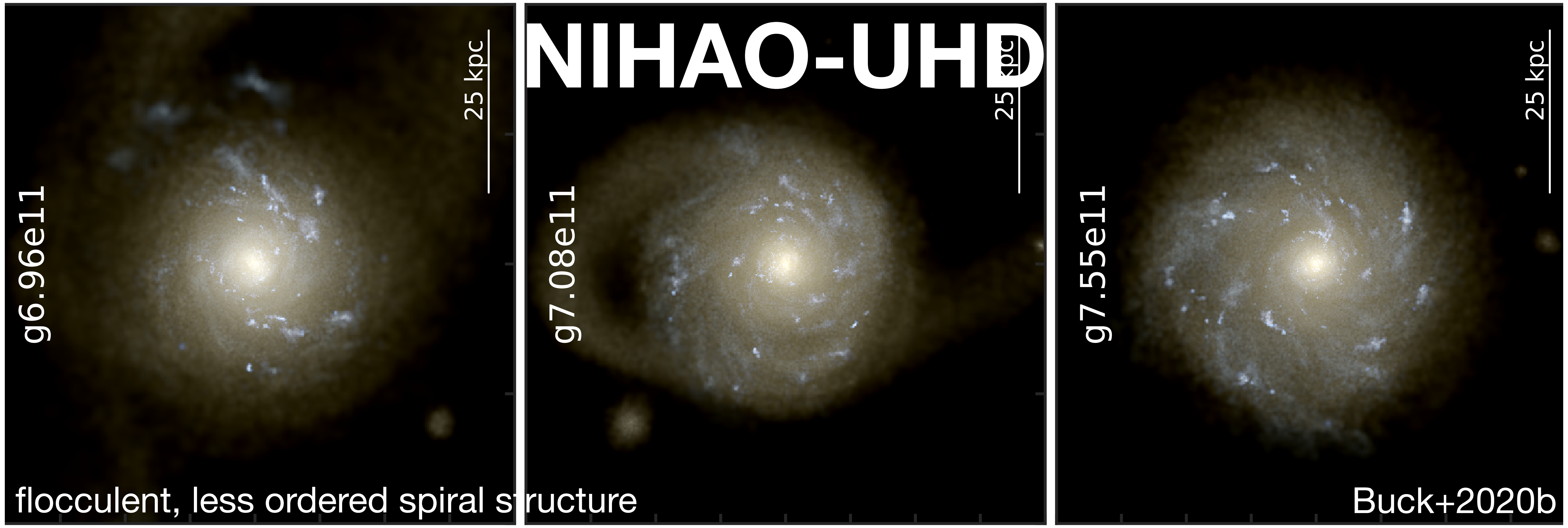
assume stellar evolution models to calculate time evolution of the SSP
i.e. massloss and stellar remnant masses

massive stars dying
low mass stars dying

DIFFERENCE IN CHEMICAL ABUNDANCES DUE TO MODEL UNCERTAINTIES

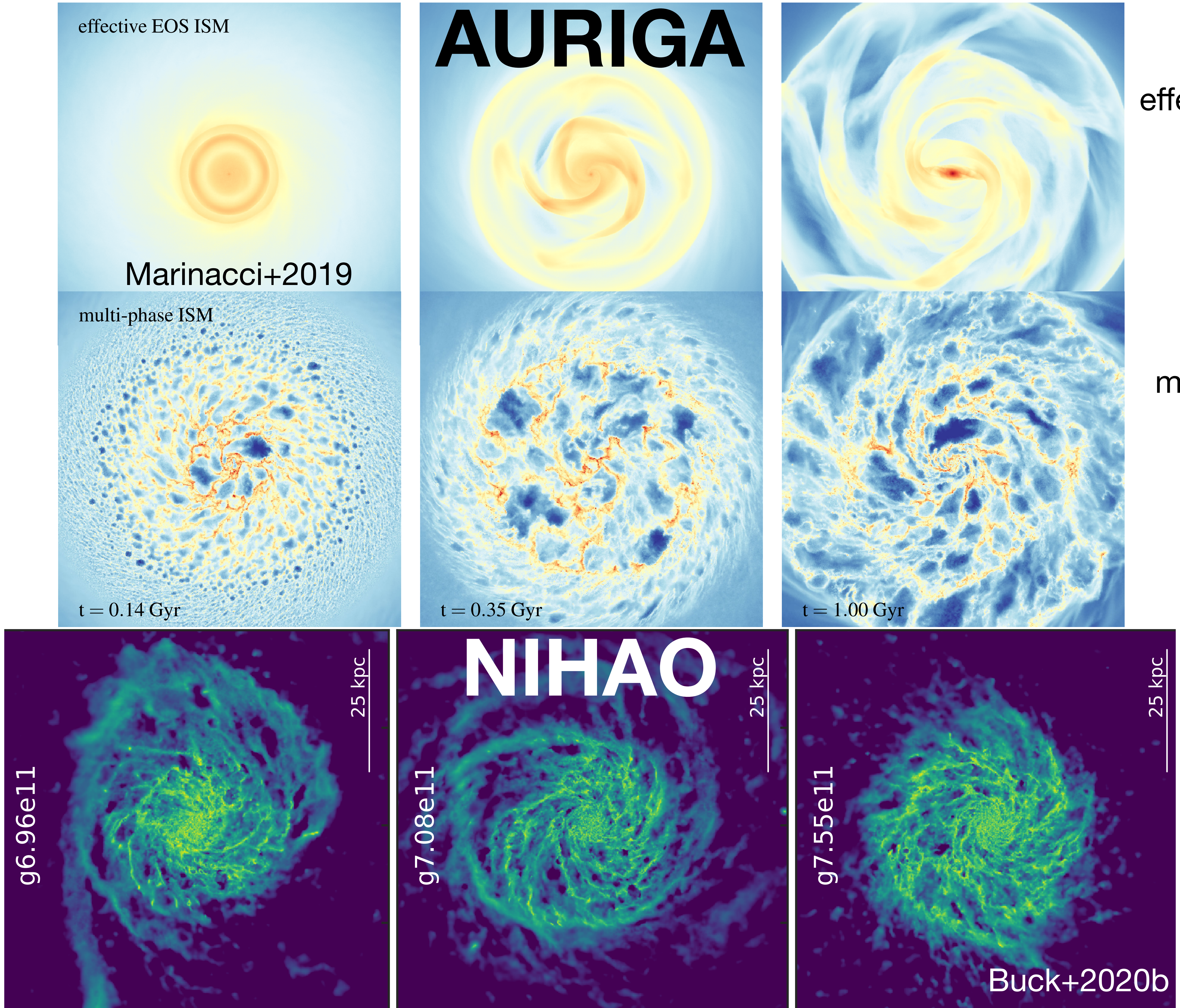
GALAXY MORPHOLOGY DEPENDS ON THE EXACT PHYSICS IMPLEMENTATION!

Arepo
moving-mesh



Gasoline2
SPH

THE IMPACT OF GAS COOLING AND HEATING PHYSICS ON GALAXY MORPHOLOGY



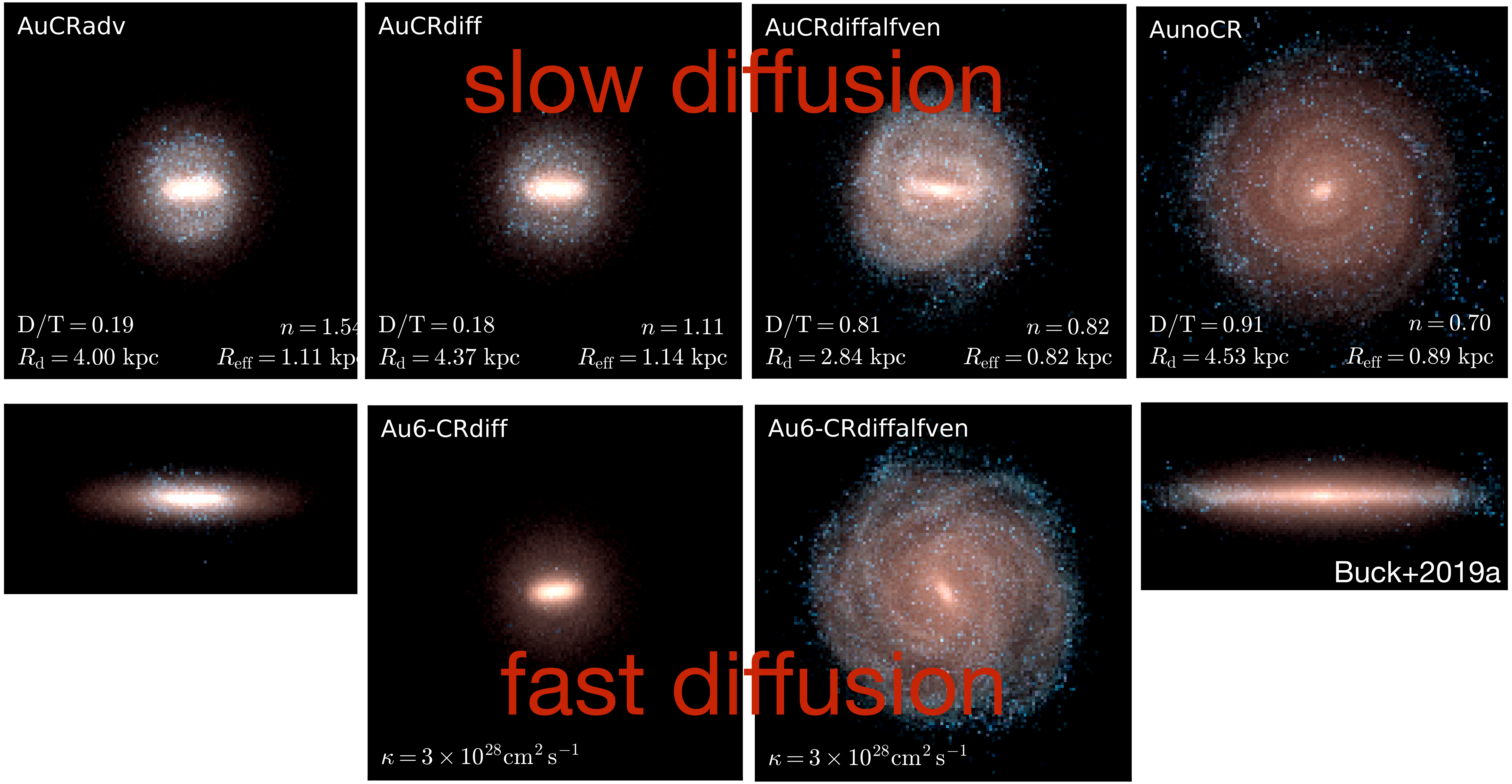
Arepo effective equation of state

Arepo multiphase ISM

Gasoline2 multiphase ISM

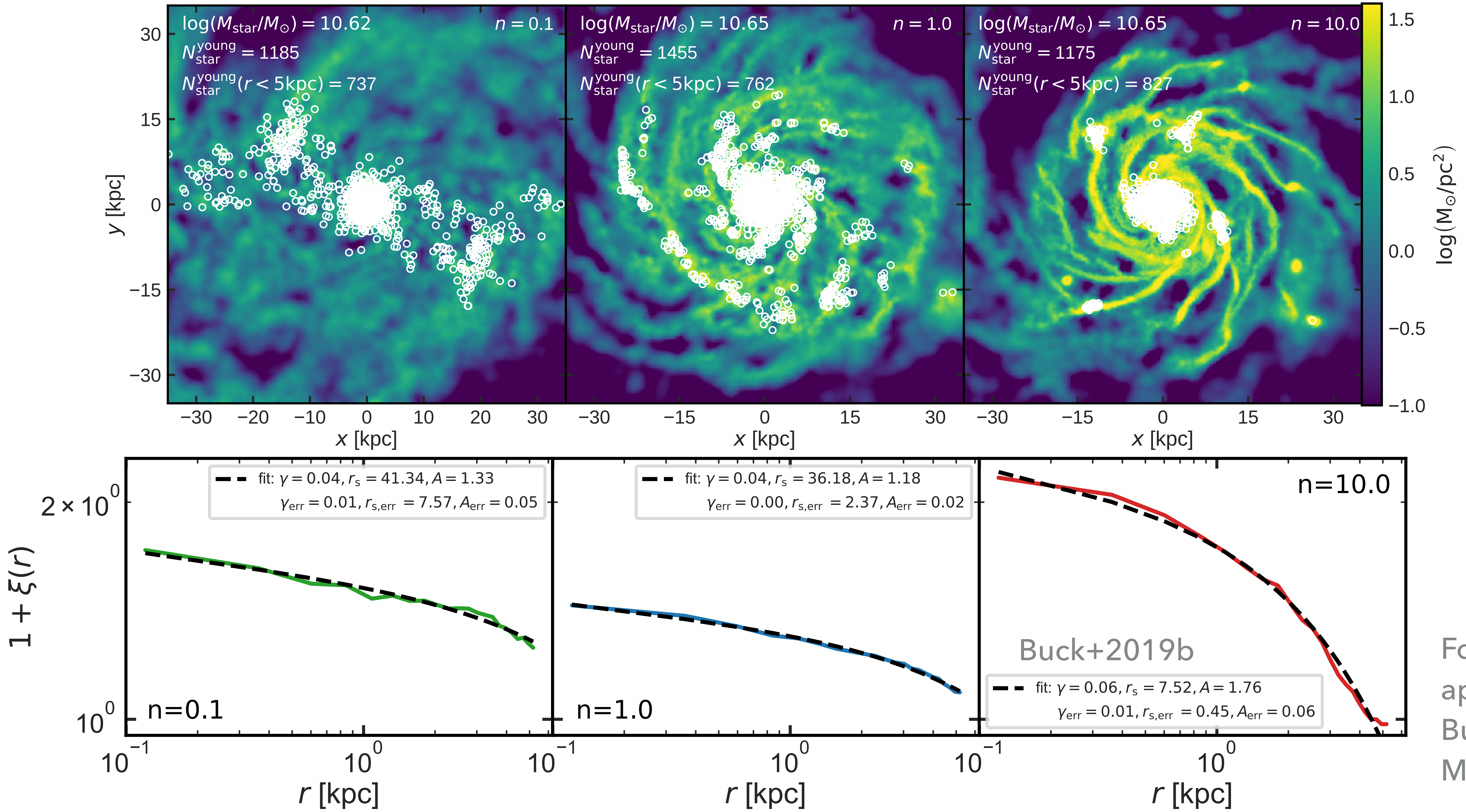
THE IMPACT OF CR PHYSICS ON GALAXY MORPHOLOGY

4 different models for CR transport



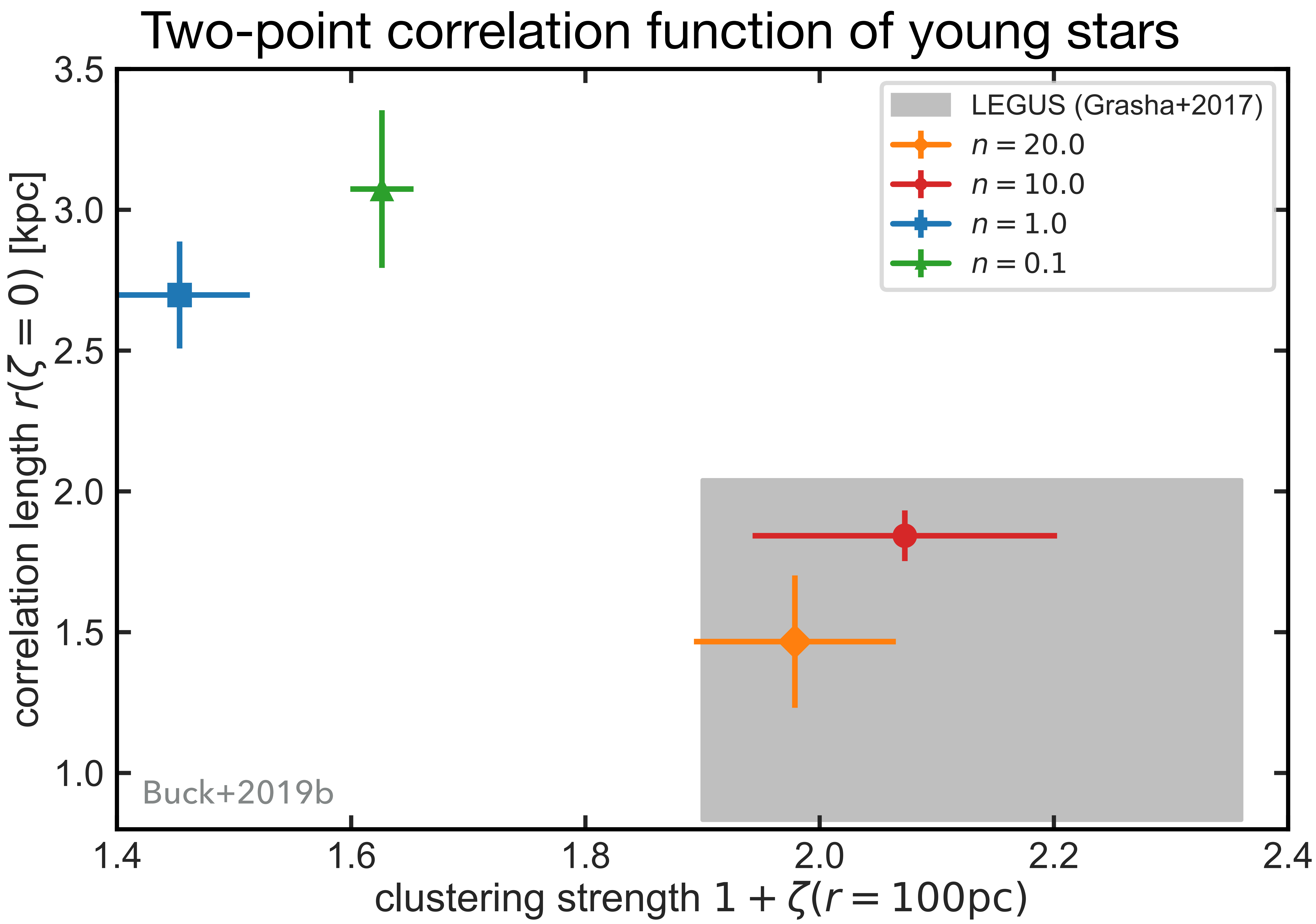
HOW TO DISTINGUISH MODELS? —> CAREFUL COMPARISON TO OBSERVATIONS!

Two-point correlation function of young stars



For a more fancy ML approach see: Buck+Wolf 2021, Macciò+2022

HOW TO DISTINGUISH MODELS? —> CAREFUL COMPARISON TO OBSERVATIONS!

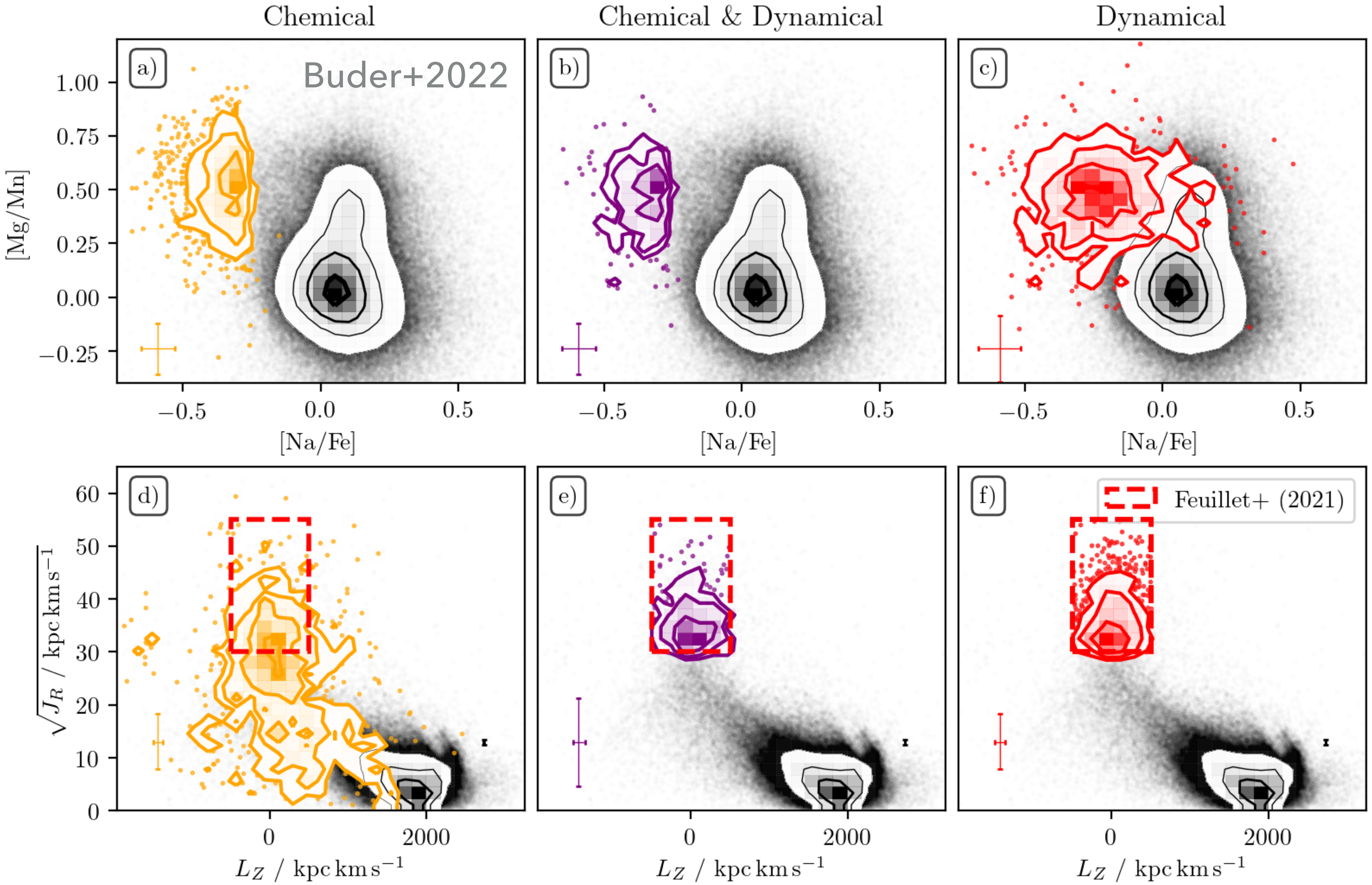


For a more fancy ML approach see: Buck+Wolf 2021, Macciò+2022

FUTURE CHALLENGES

HOW TO CONNECT PRESENT AND PAST?

FINDING ACCRETED STARS IN THE MILKY WAY



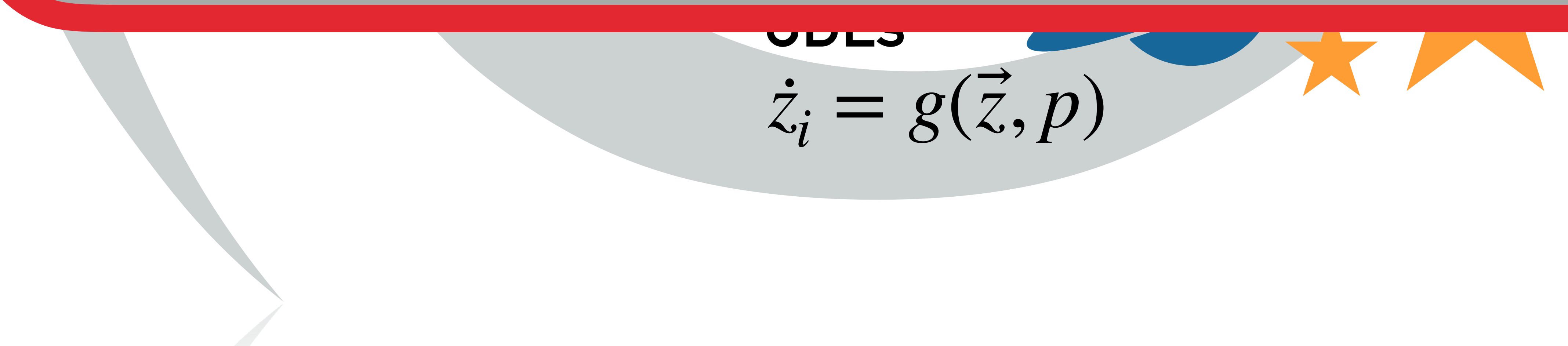
see also:
Helmi+2018,
Belokurov+2018,
and many more

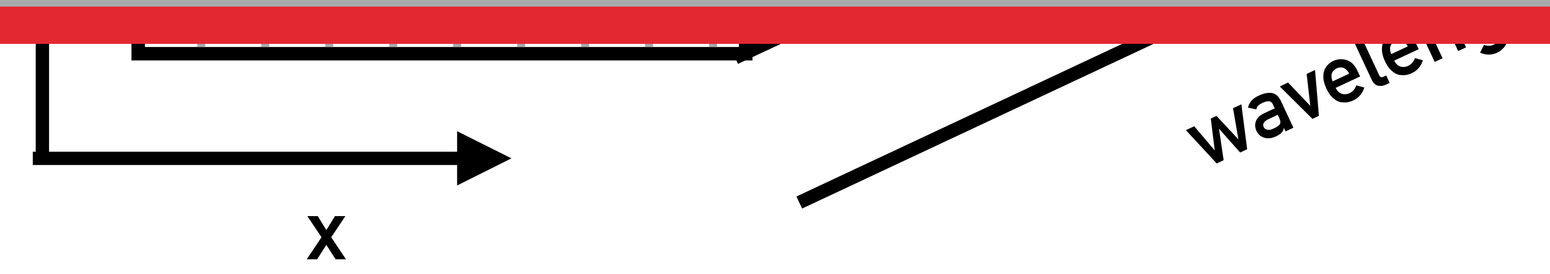
HOW TO CONNECT PRESENT AND PAST?

DERIVING BIRTH RADII FROM PRESENT-DAY ABUNDANCES

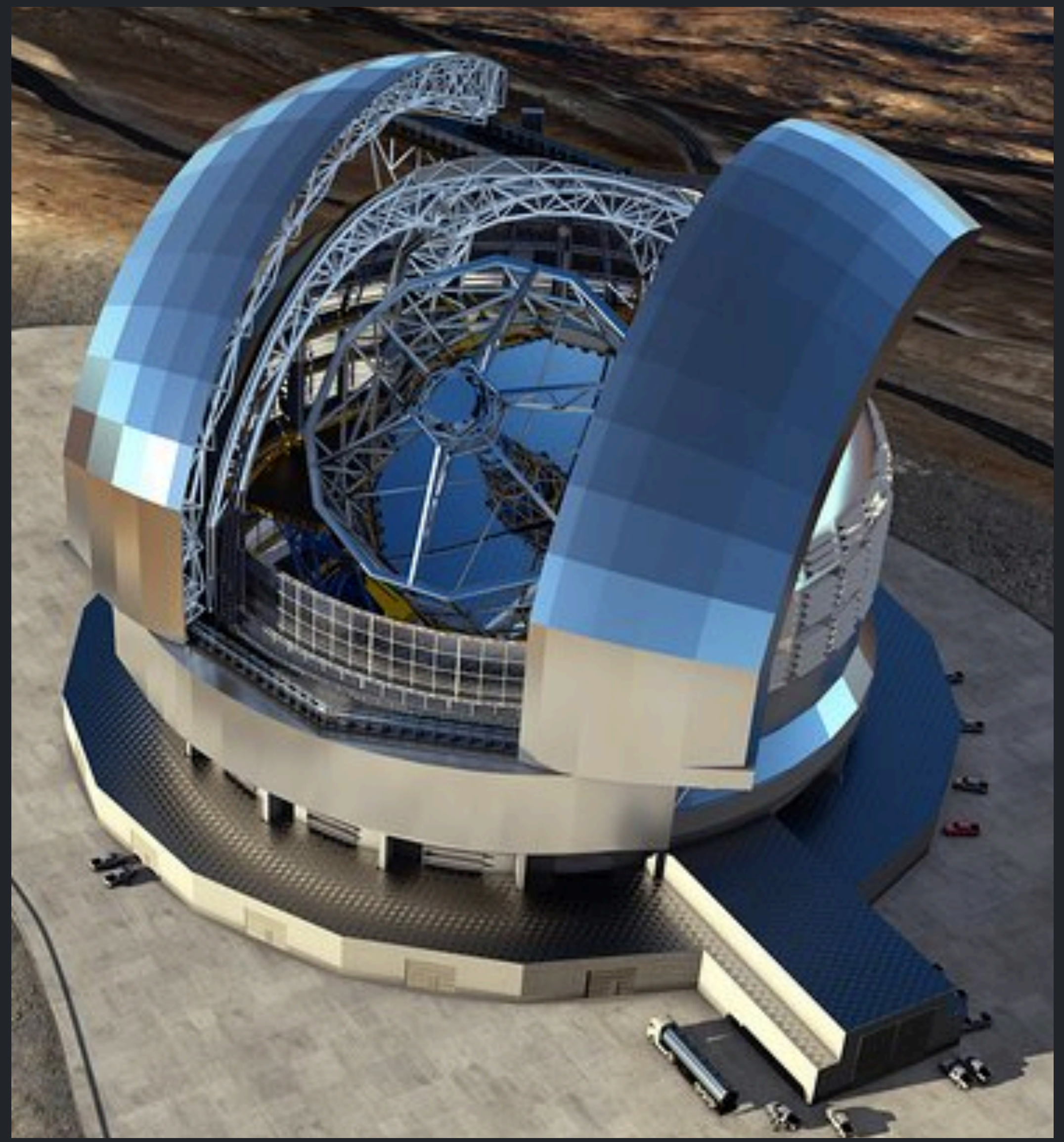
GALAXY FORMATION IS A DATA INTENSIVE, MULTI-SCALE PROBLEM

HOW CAN WE BUILT PREDICTIVE MULTI-SCALE MODELS FOR GALAXIES?

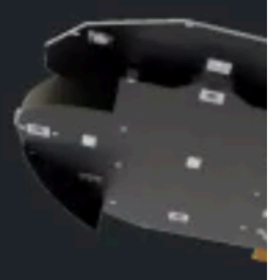




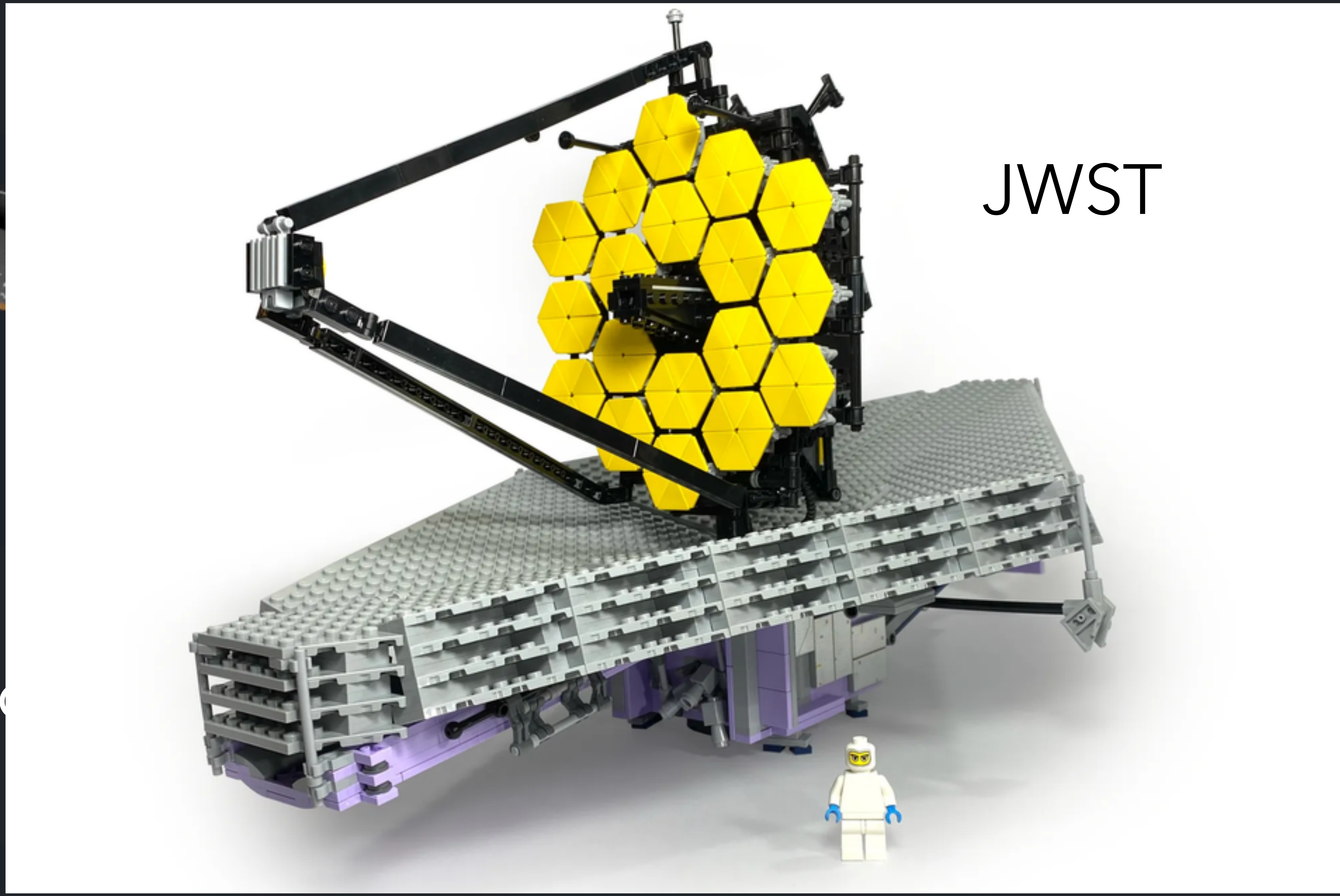
EXTRAGALACTIC SURVEYS

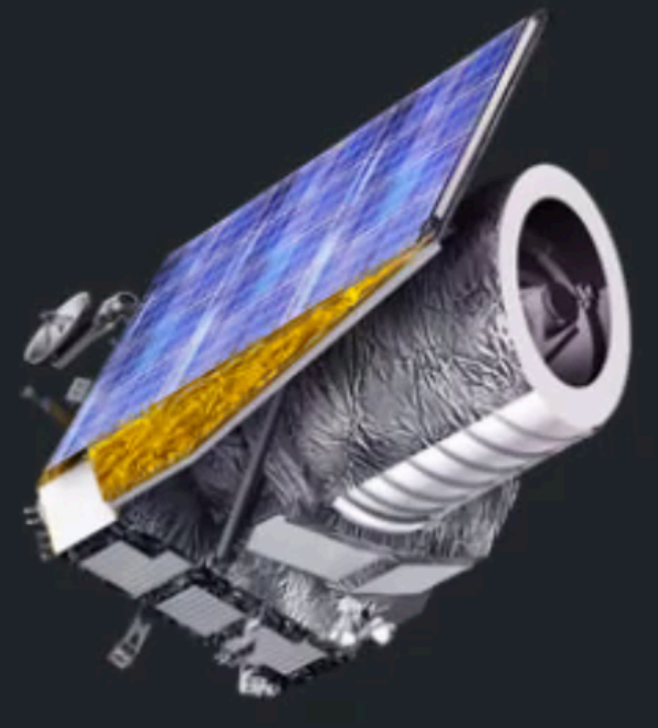


European Extremely Large Telescope



Nan
Spa





Euclid

MAIN DATA PRODUCT: ~10^6 GALAXY IMAGES

~30 TERABYTES PER NIGHT —> HOW TO PROPERLY ANALYSE ALL THE DATA?

HOW CAN WE BUILT PREDICTIVE MULTI-SCALE MODELS?

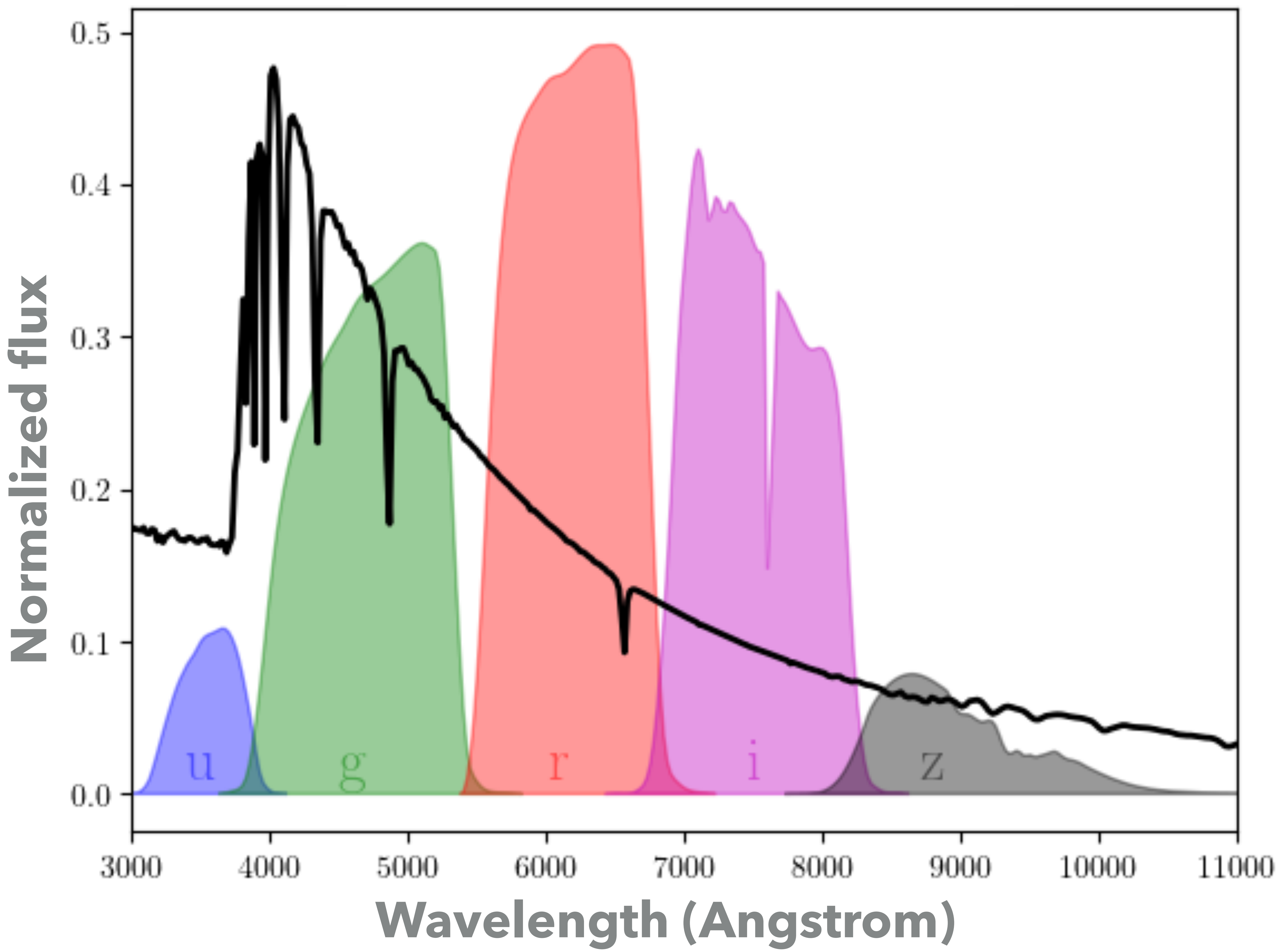
- limits for models will always be the computational power
- need smart algorithms!
- combine physical laws with the flexibility of modern machine learning!
- In August I will start a junior research group on physics informed Machine Learning!
- You have ML experience and are looking for an interdisciplinary PhD or a Postdoc position: Get in contact with me!

SUMMARY AND CONCLUSION

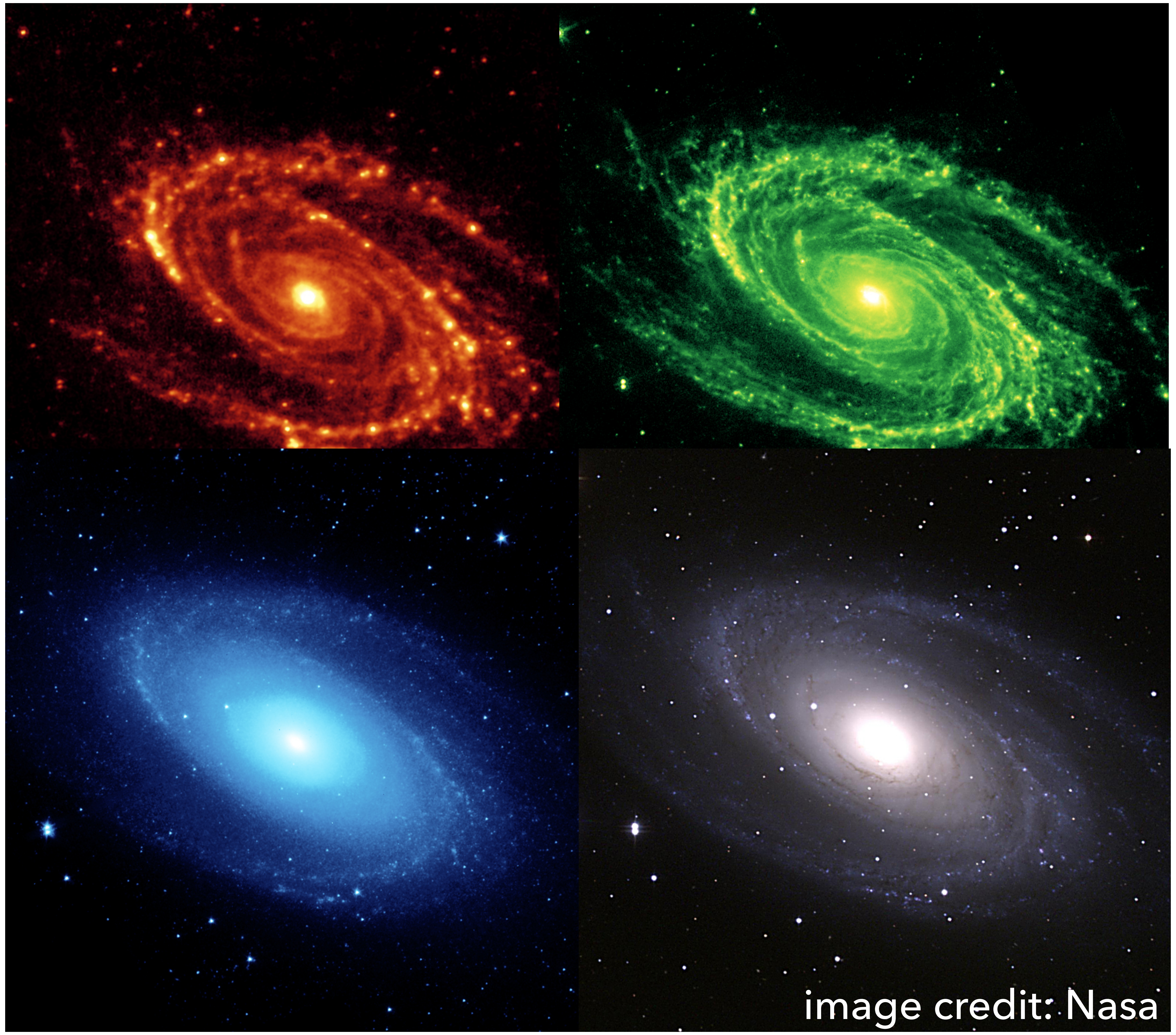
- large spectroscopic surveys in combination with state-of-the-art numerical simulations unravel MW's formation history
- simulations inform about MW's past and observations inform about numerical limitations of the models
- computational power is always a limit for the physical fidelity of our models
  - need a diversity of algorithms and implementations to cross-compare
  - need smart, innovative approaches. Data driven and AI/ML models can help

OBSERVATIONS: SPECTROSCOPY VS. PHOTOMETRY

Spectroscopy



Photometry



ESTABLISHED CORRELATIONS BETWEEN OBSERVABLES AND PHYSICAL PROPERTIES

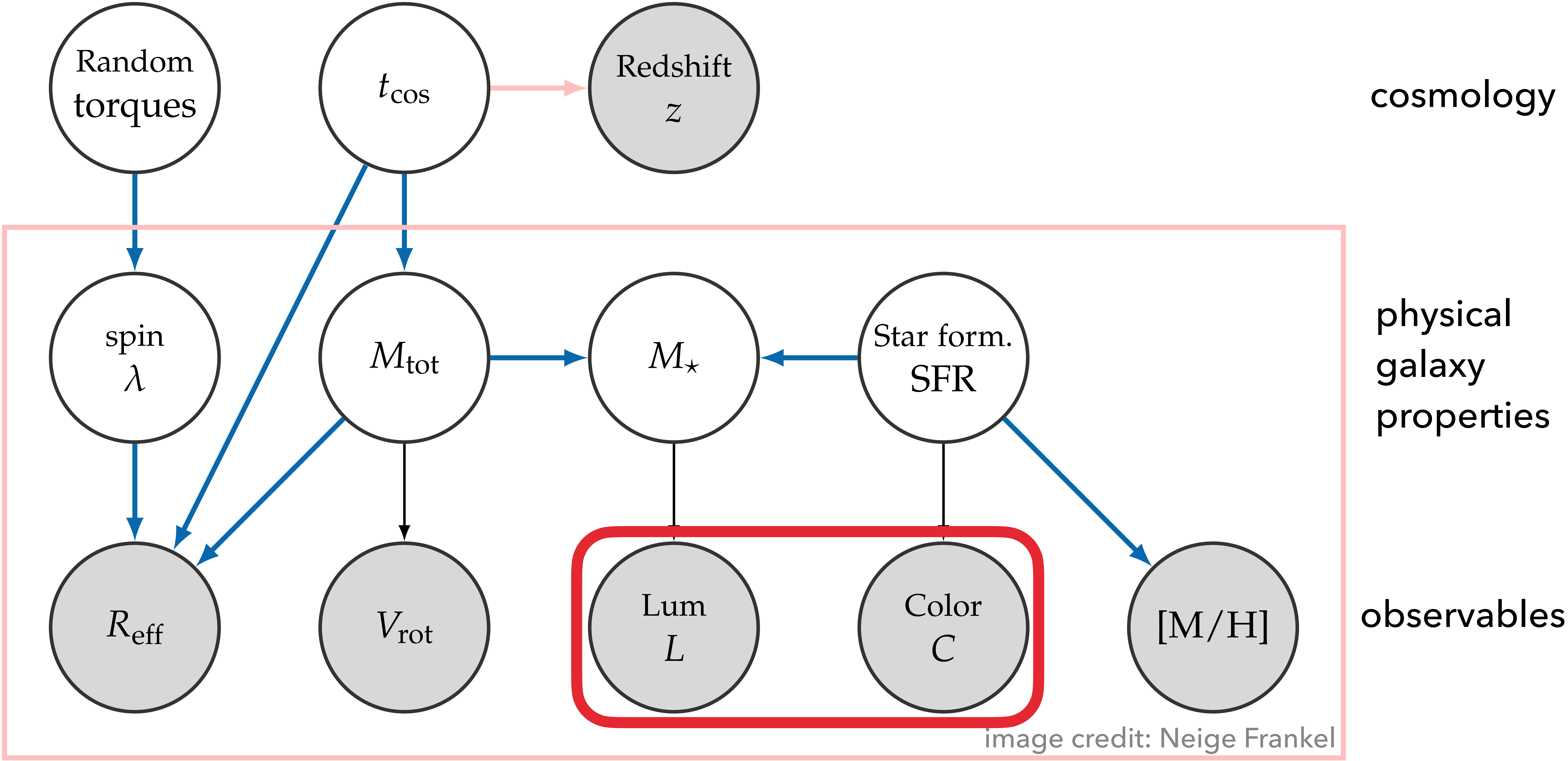
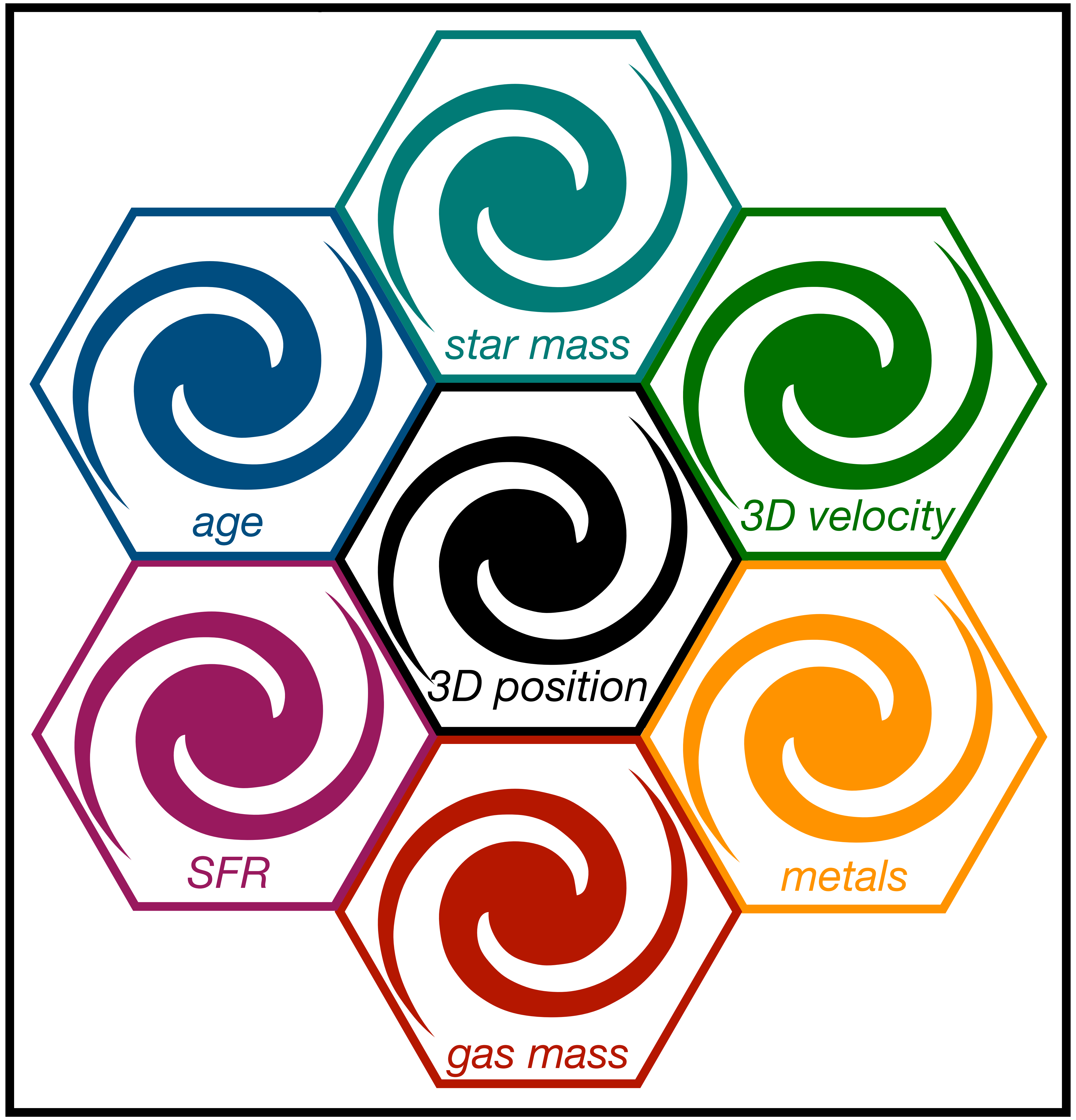


image credit: Neige Frankel

EXTRACTING GALAXY PROPERTIES FROM THOSE IMAGES?

- Can we reconstruct intrinsic galaxy properties from their images?
- Can we build a (3D) galaxy model from multi-band images?

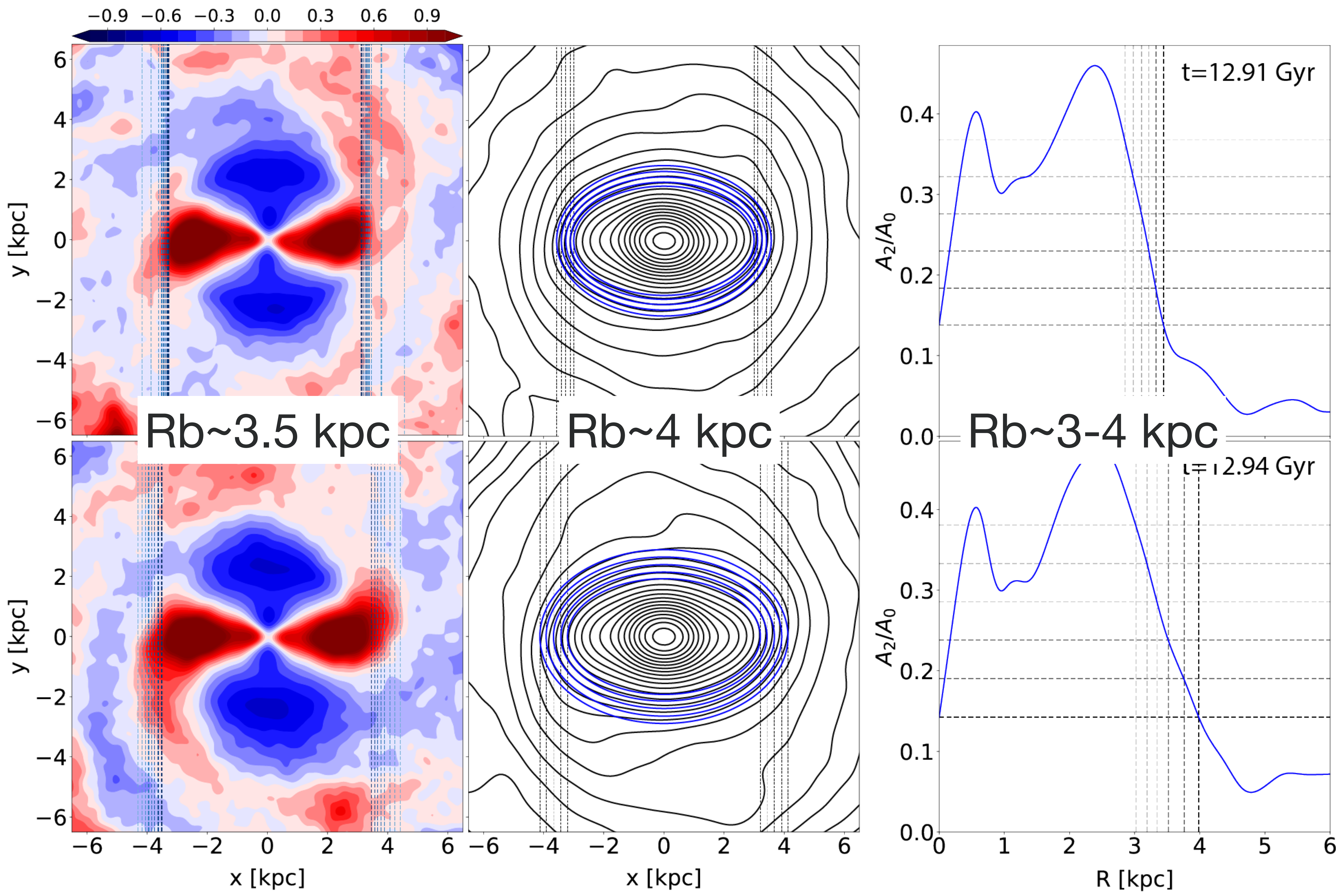
derive maps of physical parameters



THE IDEA: RECONSTRUCTING GALAXY MODELS FROM IMAGES

idea credit: Bernhard Schölkopf based on face reconstruction by Tewari+2017

How to measure the length of MW's central stellar bar?



Hilmi,Minchev,Buck+2020

QUANTIFYING MILKY WAY'S SPIRAL STRUCTURE FROM STELLAR SPECTRA

Eilers,Hogg,Rix,(incl.Buck)+2020