Universiteit Leiden

Sterrewacht Leiden

Tracing multi-scale structure formation in galaxies with metals

Uppsala Astronomy Seminar

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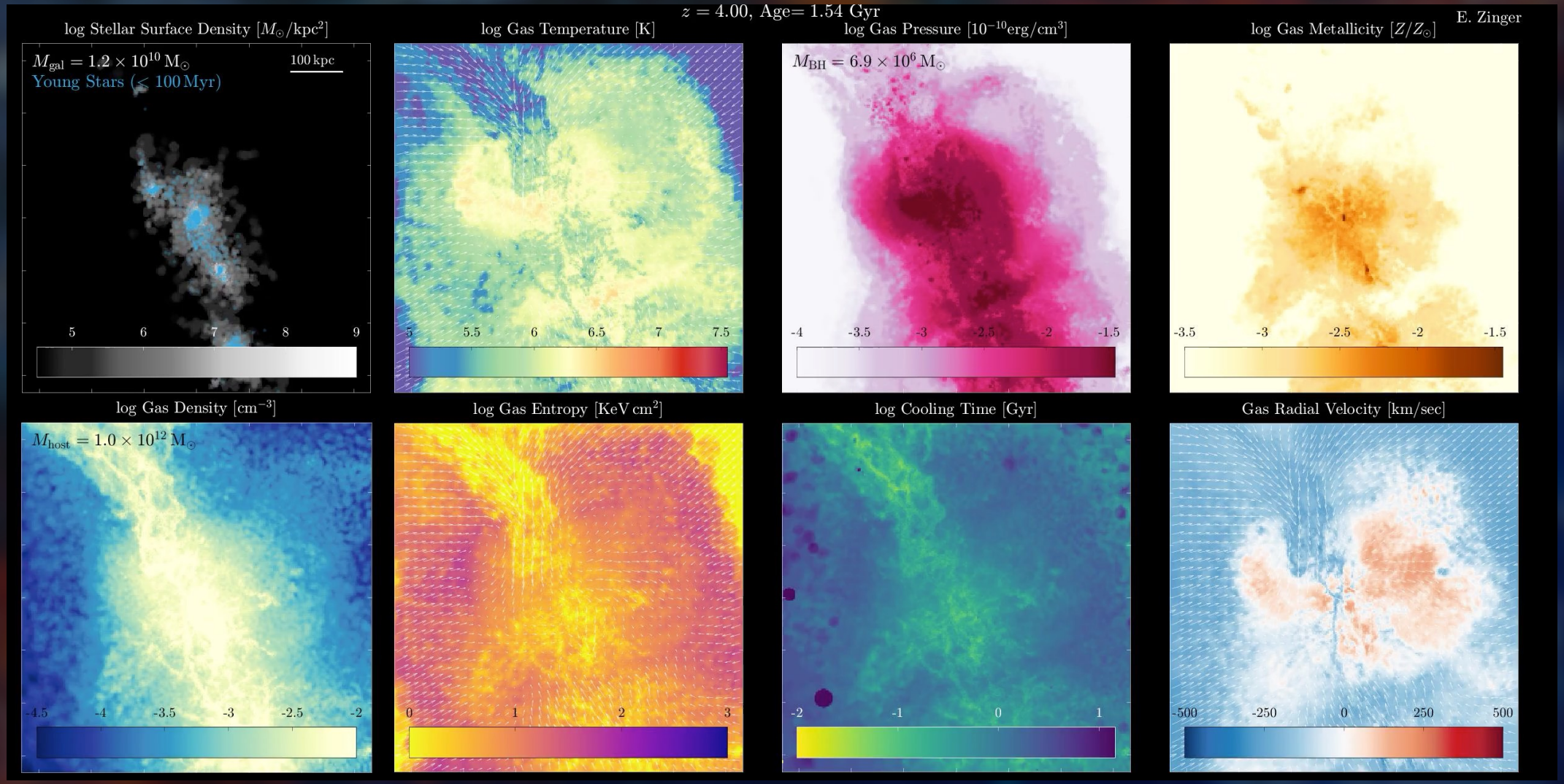
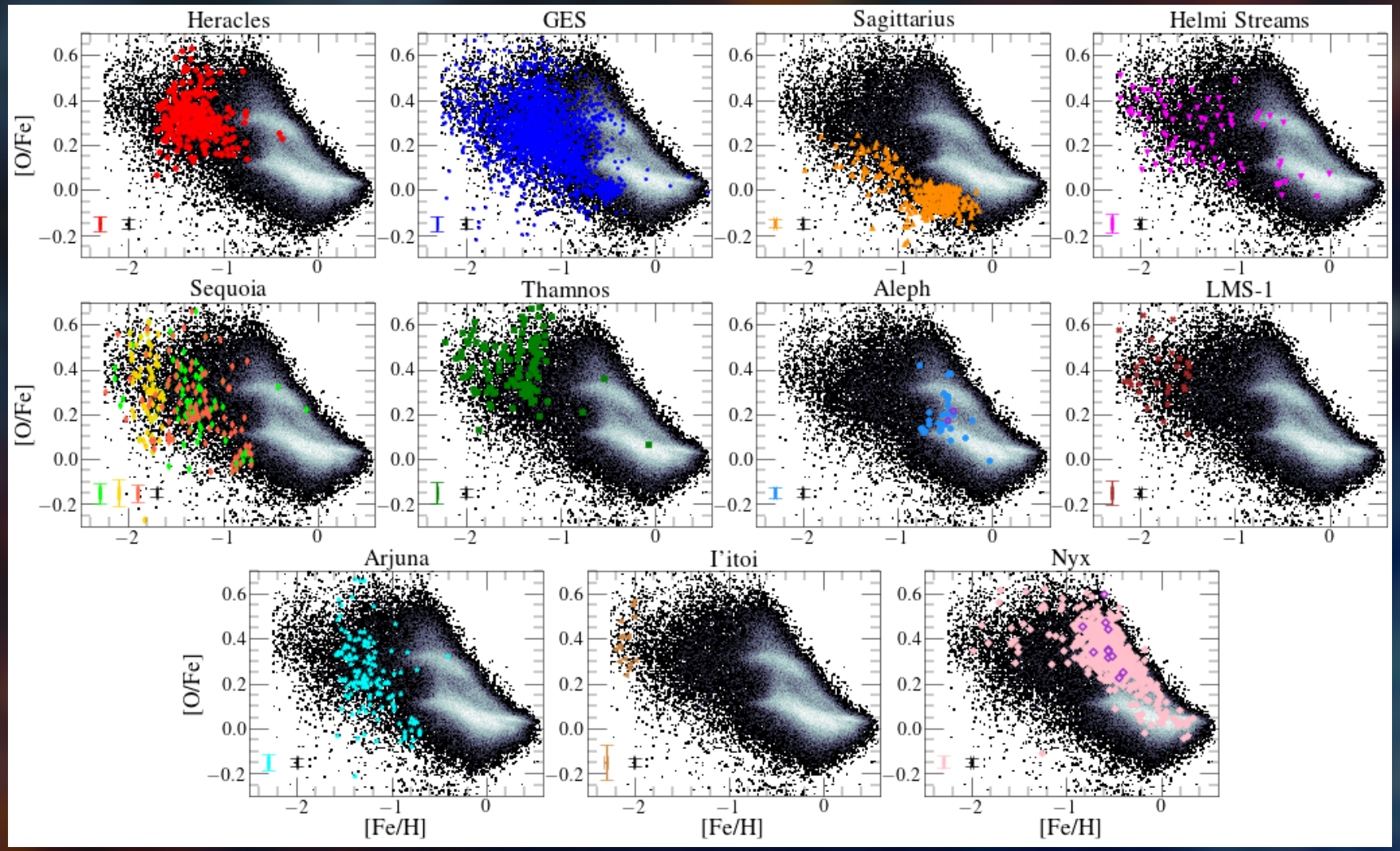
Credits: Wendy Nungarrayi Brown / Yanjirlpirri Jukurrpa (Seven Sisters Dreaming)

Metals as tracers of galaxy evolution



IllustrisTNG Project

Metals as tracers of Milky Way assembly



Horta et al. 2022, Belokurov & Kravtsov 2022

Star formation and galaxy evolution are well studied in Milky Way-like galaxies at Solar metallicity.

But… most galaxies in the Universe are smaller and have less metals as compared to the Milky Way.

Key Questions

How do stars form at zero and low metallicity?

What is the initial mass function (IMF) at low metallicities?

What is the metal content of low metallicity galaxies?

Once produced, how are metals transported all around galaxies?

Multi-scale structure formation

pc scales

kpc scales

Low metallicity star formation

Large-scale metal distribution

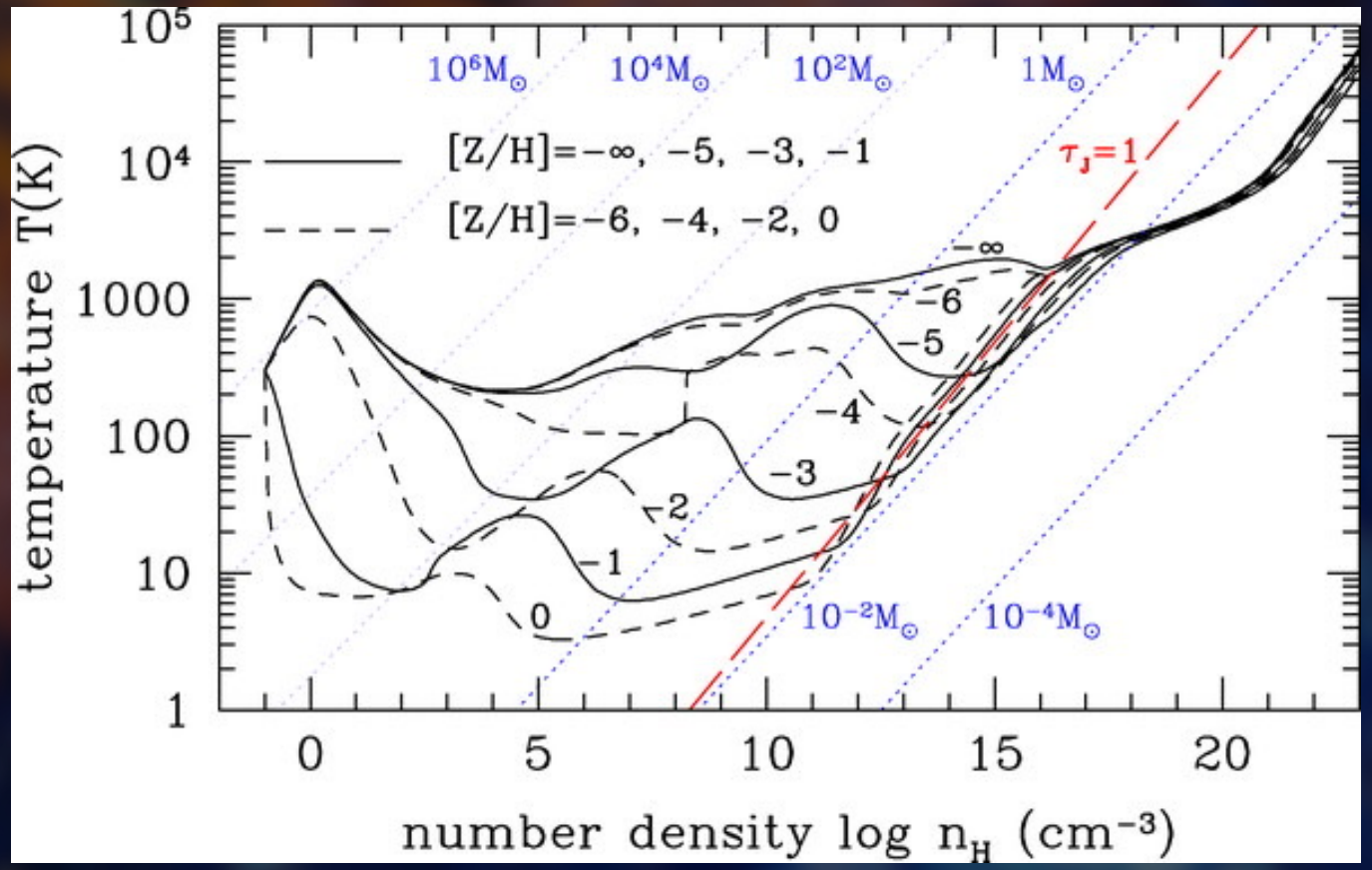
First/metal-poor galaxies

Low metallicity star formation

Interstellar medium (ISM) metallicity significantly impacts star formation, the initial mass function (IMF), and subsequent metal production.

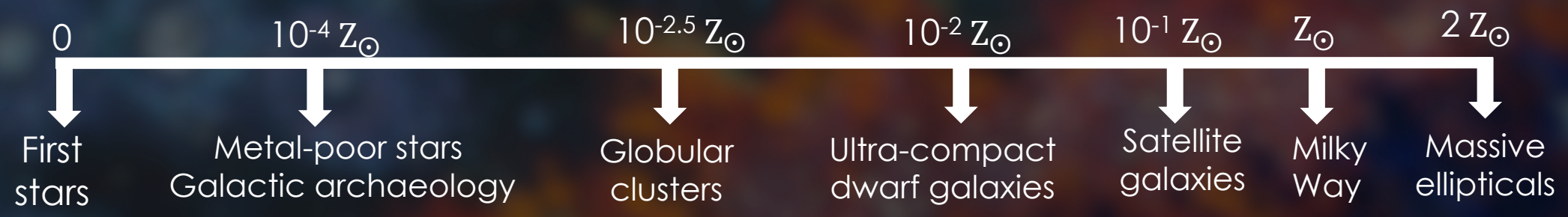
Star formation and the IMF in zero and low metallicity ISM remain largely unexplored.

This limits our understanding of the first and metal-poor stars, first galaxies and metal enrichment in the early Universe.



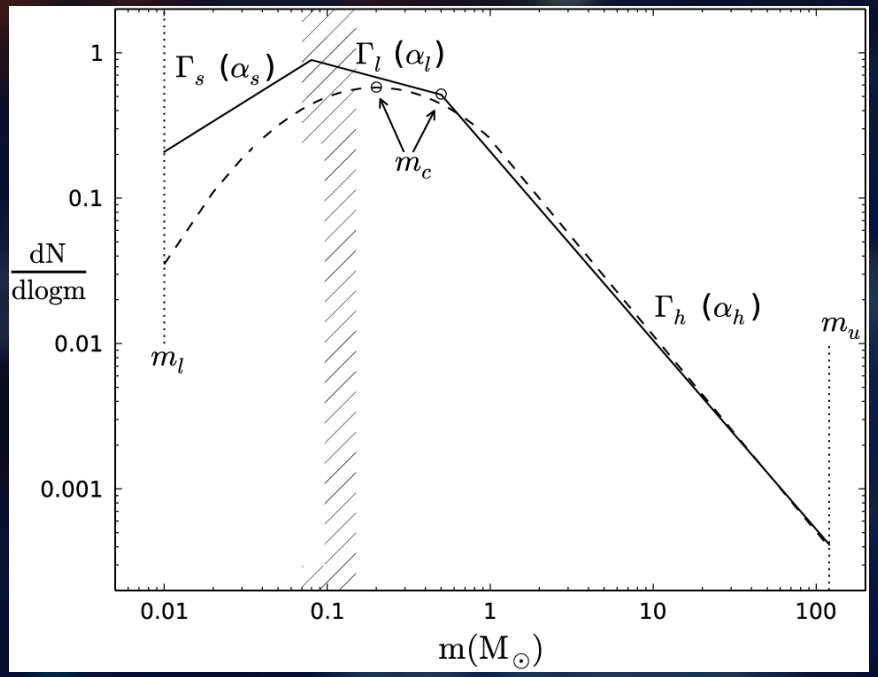
Omukai et al. 2005

Variations in the IMF with metallicity



Variations in the IMF with metallicity

0	$10^{-4}\ Z_\odot$	$10^{-2.5}\ Z_\odot$	$10^{-2}\ Z_\odot$	$10^{-1}\ Z_\odot$	$Z_\odot$	$2\ Z_\odot$
First stars	Metal-poor stars Galactic archaeology	Globular clusters	Ultra-compact dwarf galaxies	Satellite galaxies	Milky Way	Massive ellipticals



Hopkins 2018

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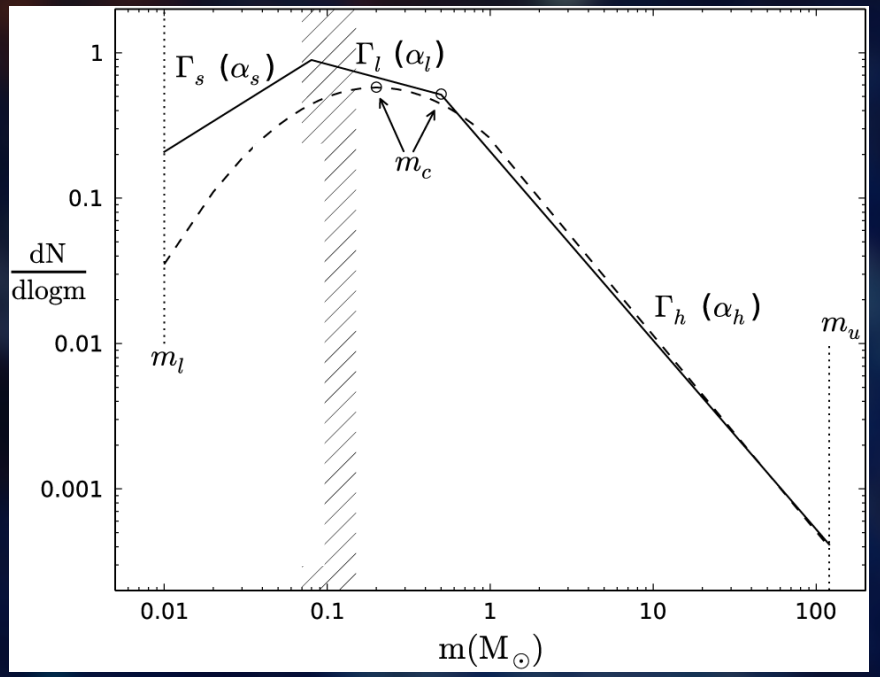


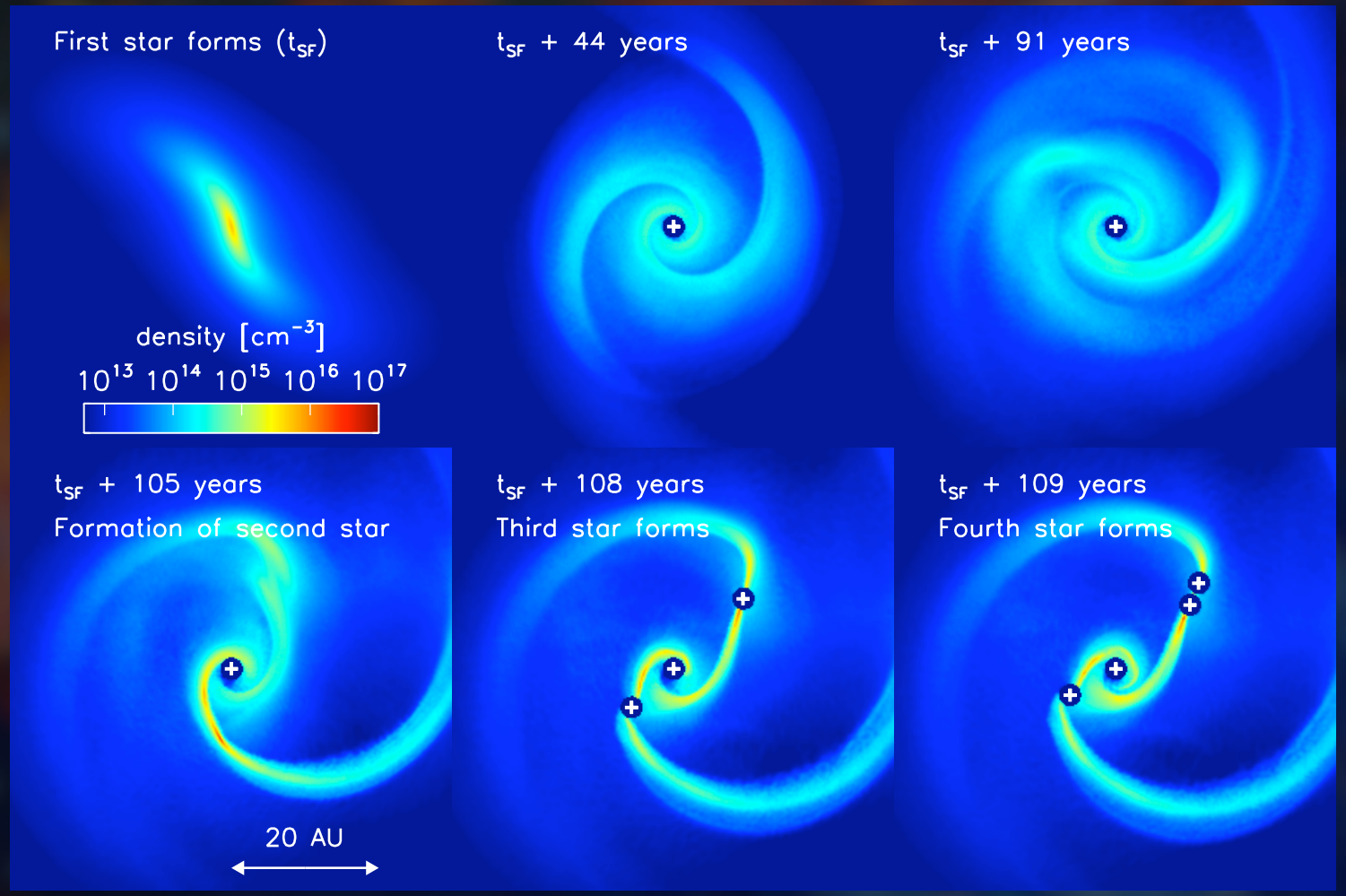
Hopkins 2018

First stars – historical context

Clark et al. 2011

Earliest simulations of the formation of first stars found them to be isolated and as massive as 100 – 200 $M_\odot$ (Bromm et al. 2000, 2002, Abel et al. 2002).

Development in numerical techniques led to the discovery of ubiquitous fragmentation in collapsing first molecular clouds down to 0.5 $M_\odot$ (Clark et al. 2011, Greif 2012).



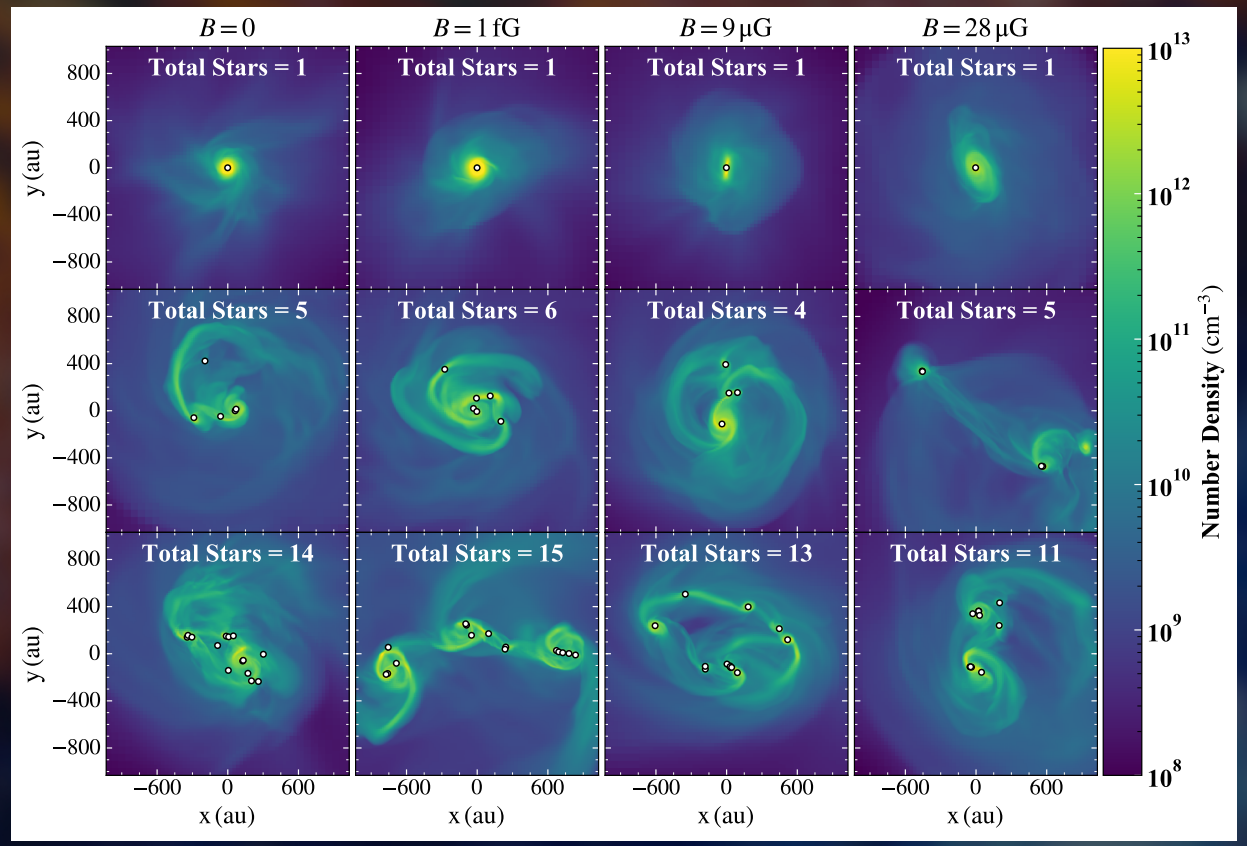
No first stars have ever been observed.

Simulating formation of the first stars

Chemo-magnetohydrodynamic (chemo-MHD) simulations of the formation of the first stars using FLASH.

Large statistics required to overcome stochasticity due to turbulence.

Statistically study the importance of turbulence and magnetic fields on the IMF of the first stars.

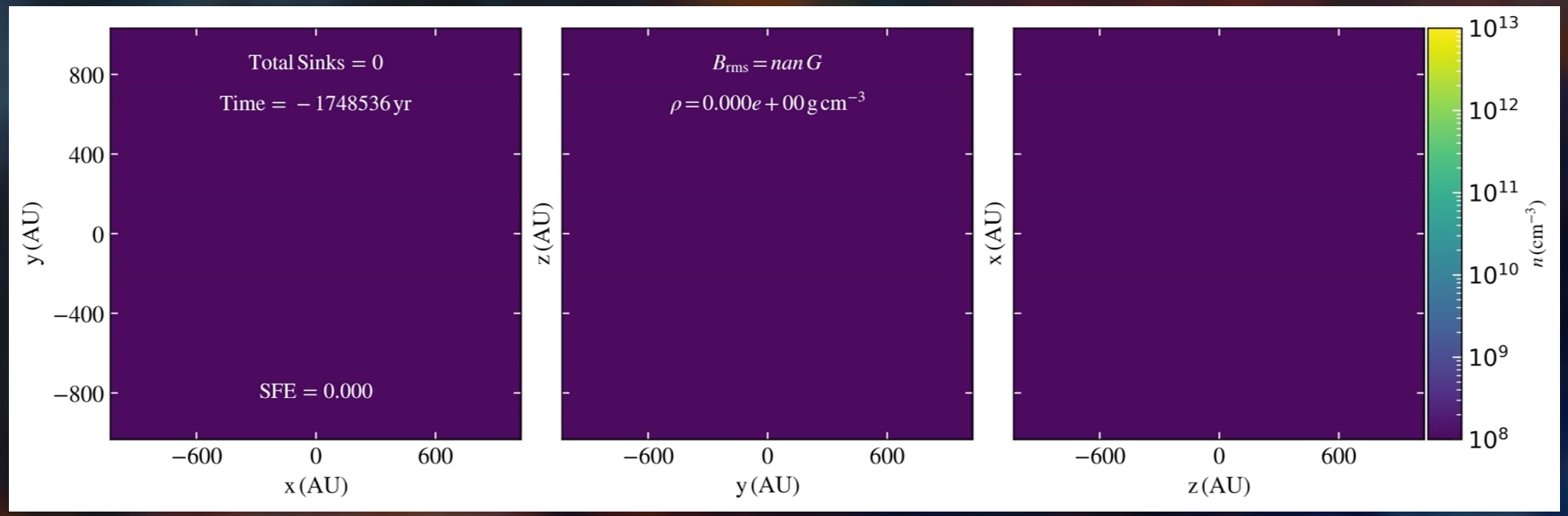


Sharda et al. 2020b

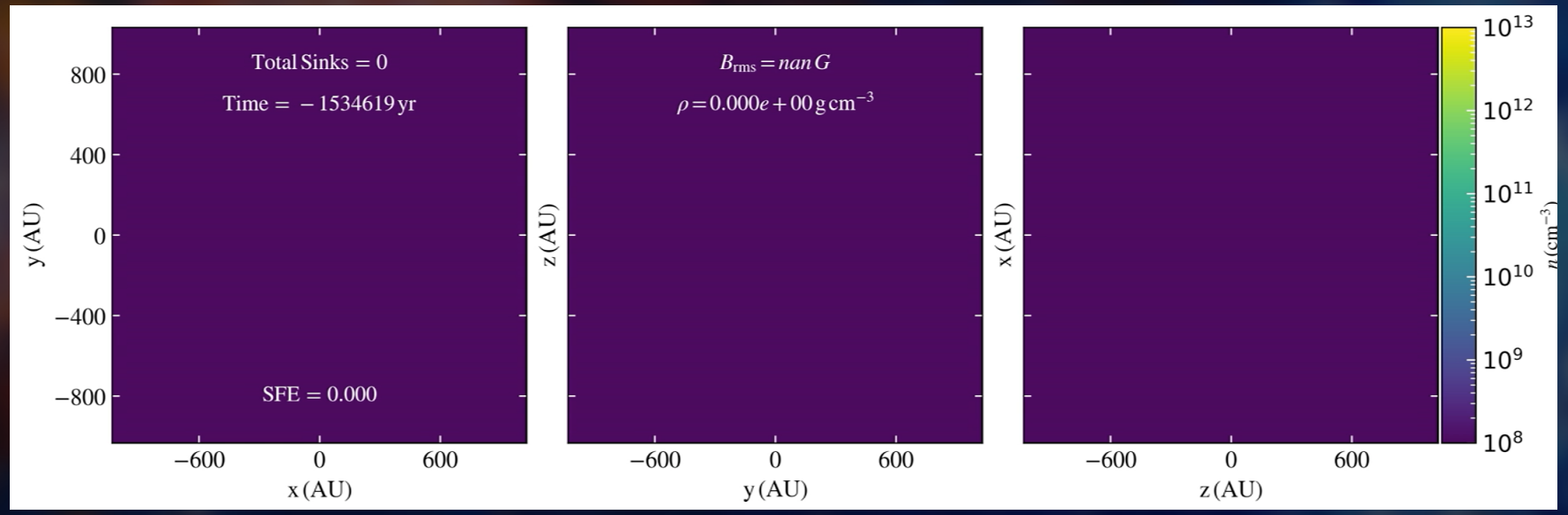
Impact of magnetic fields

Sharda et al. 2020b

Chemo-HD

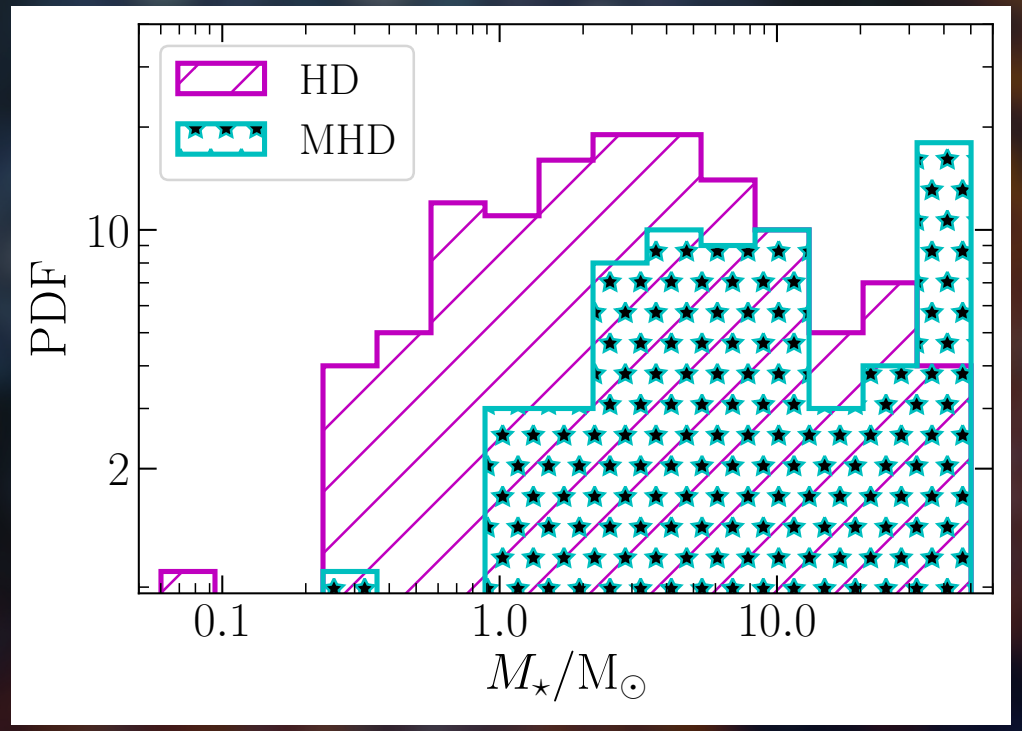


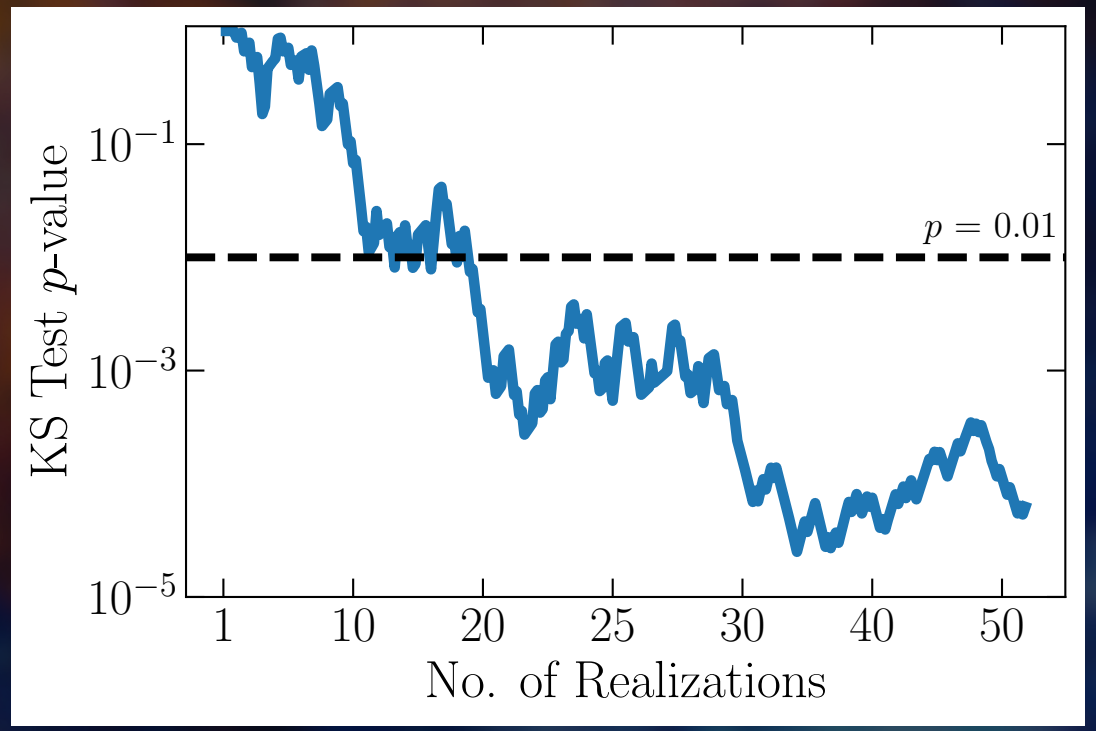
Chemo-MHD



IMF of the first stars

Sharda et al. 2020b, 2021a





Magnetic fields significantly change the mass distribution of first stars by suppressing fragmentation and formation of low mass first stars.

Variations in the IMF with metallicity

0	$10^{-4}\ Z_\odot$	$10^{-2.5}\ Z_\odot$	$10^{-2}\ Z_\odot$	$10^{-1}\ Z_\odot$	$Z_\odot$	$2\ Z_\odot$
First stars	Metal-poor stars Galactic archaeology	Globular clusters	Ultra-compact dwarf galaxies	Satellite galaxies	Milky Way	Massive ellipticals

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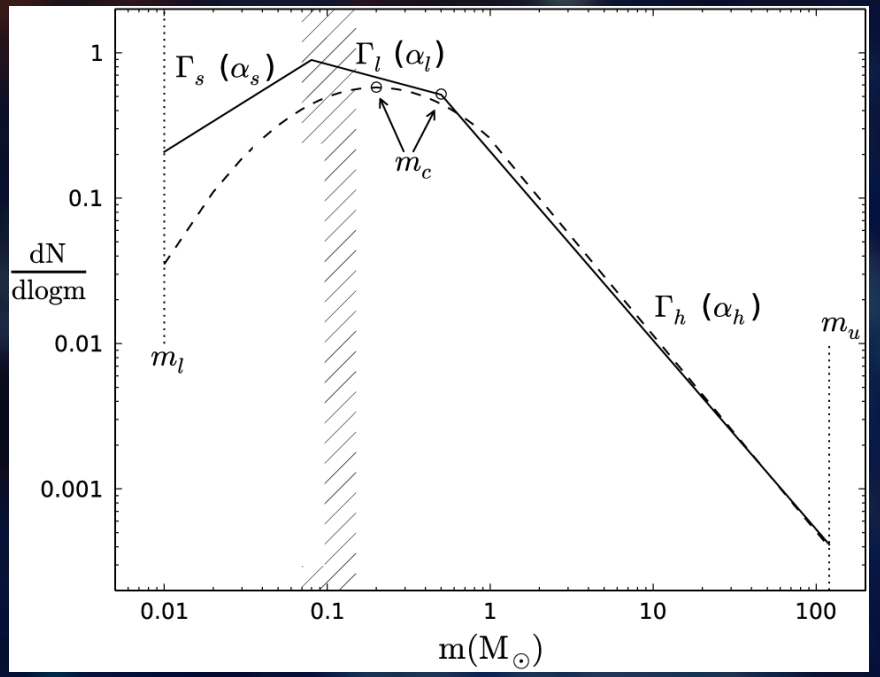
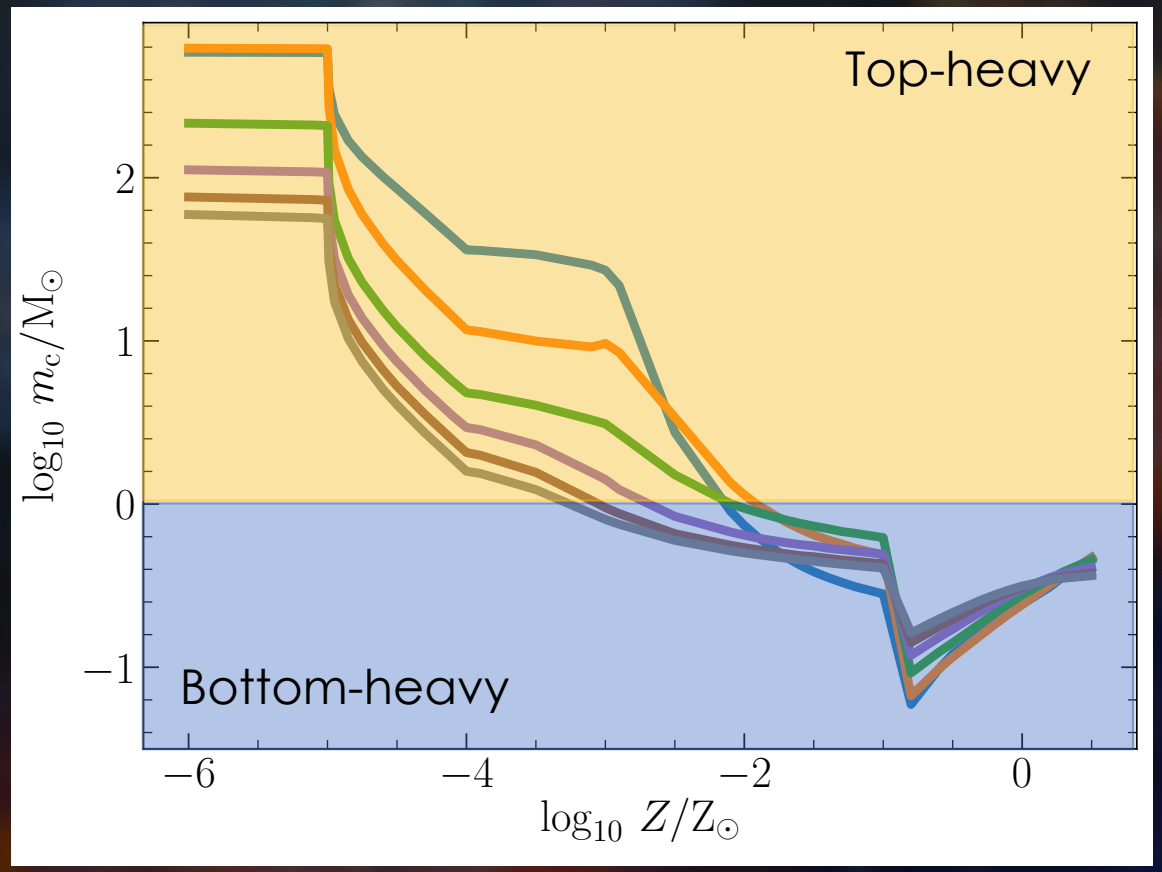


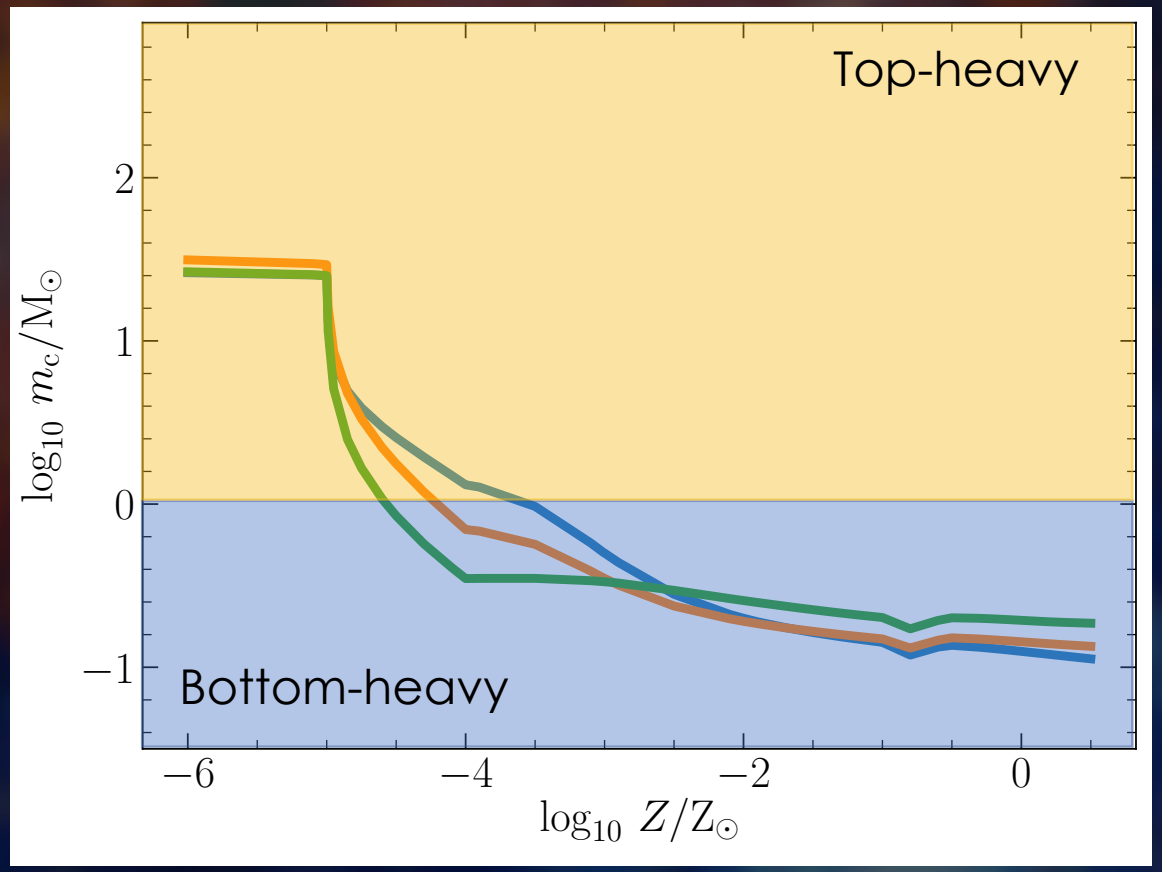
Hopkins 2018

When did the IMF become bottom-heavy?

Low pressure environments



High pressure environments



The IMF became bottom-heavy between $10^{-4} - 10^{-2}\ Z_\odot$ in Milky Way-type galaxies.
The IMF is sensitive to C and O abundances at low metallicities.

Sharda & Krumholz 2022; Sharda, Amarsi et al. 2023

Large-scale metal distribution

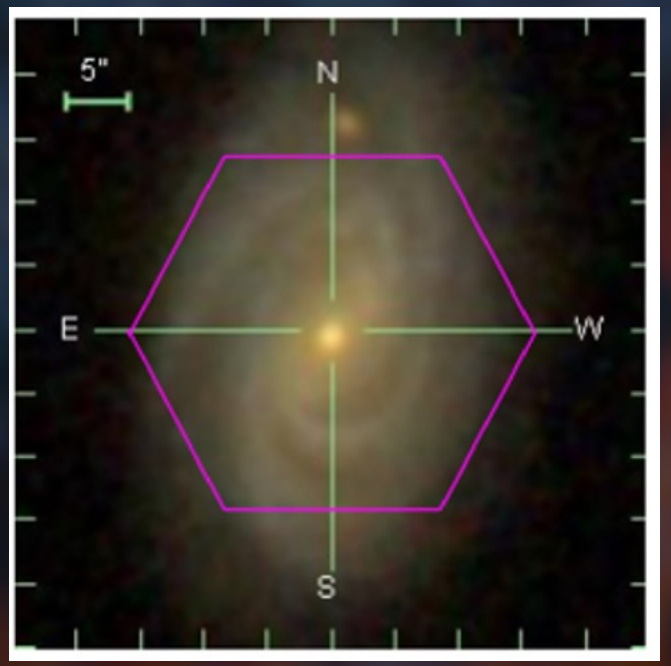
The mass distribution of massive stars directly sets the metal yield of galaxies.

Metal distribution on large scales provides important clues on stellar assembly and galaxy evolution.

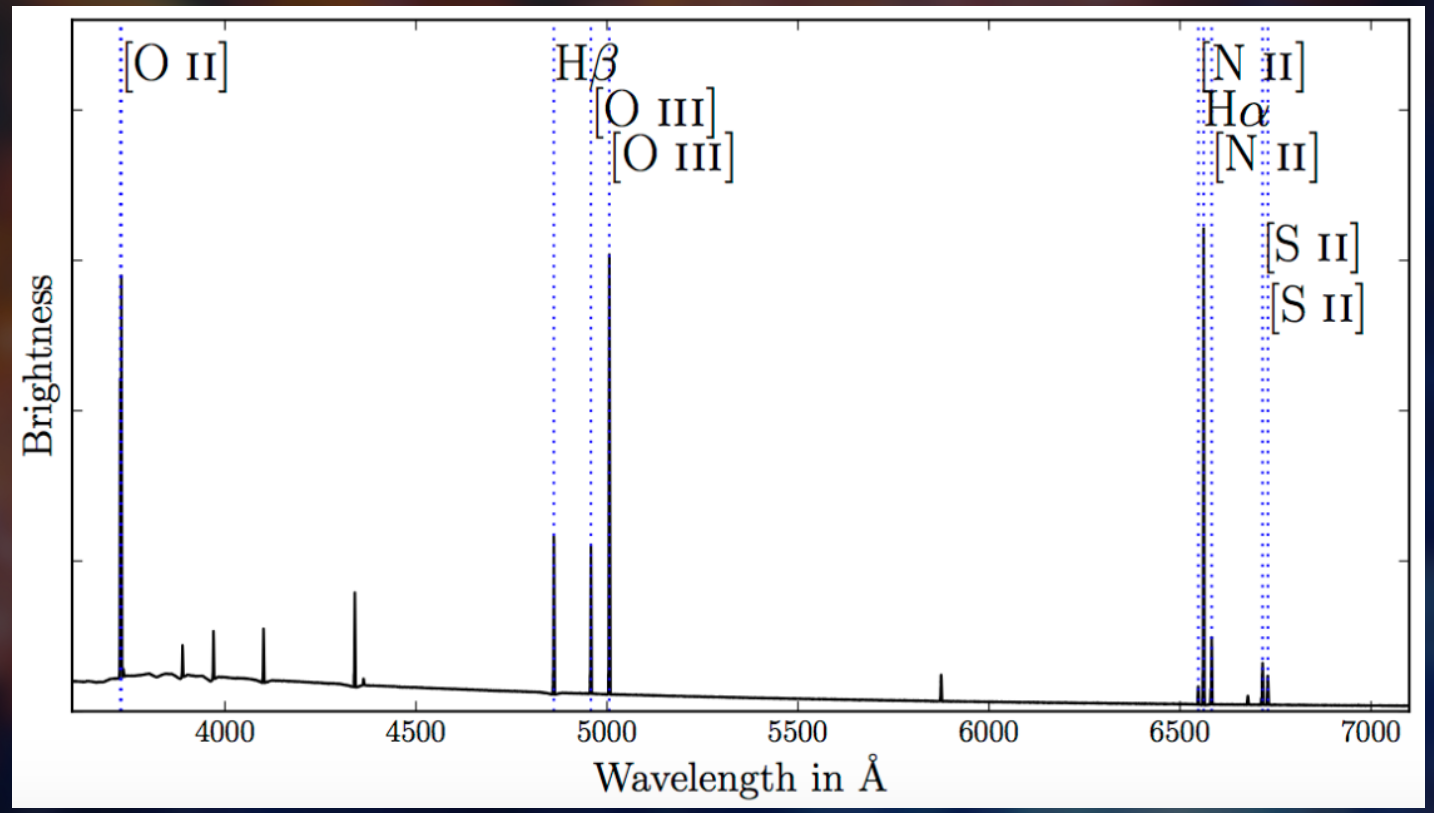
Connecting small-scale metal enrichment to large-scale metal distribution remains a challenging problem for simulations.

Naab & Ostriker 2017, Kewley et al. 2019

Measuring gas-phase metallicity

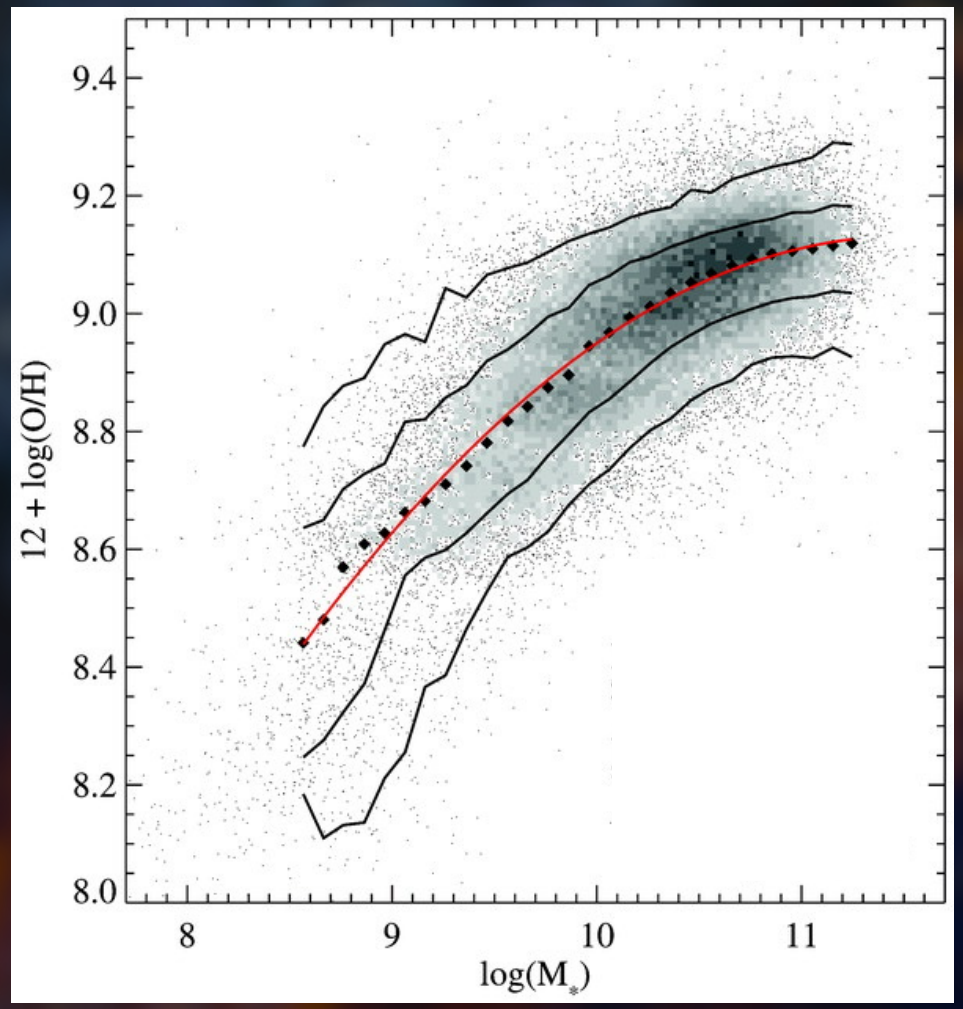


Law et al. 2016



Credits: MOSFIRE Team

Mass-metallicity relation (MZR)



Tremonti et al. 2004

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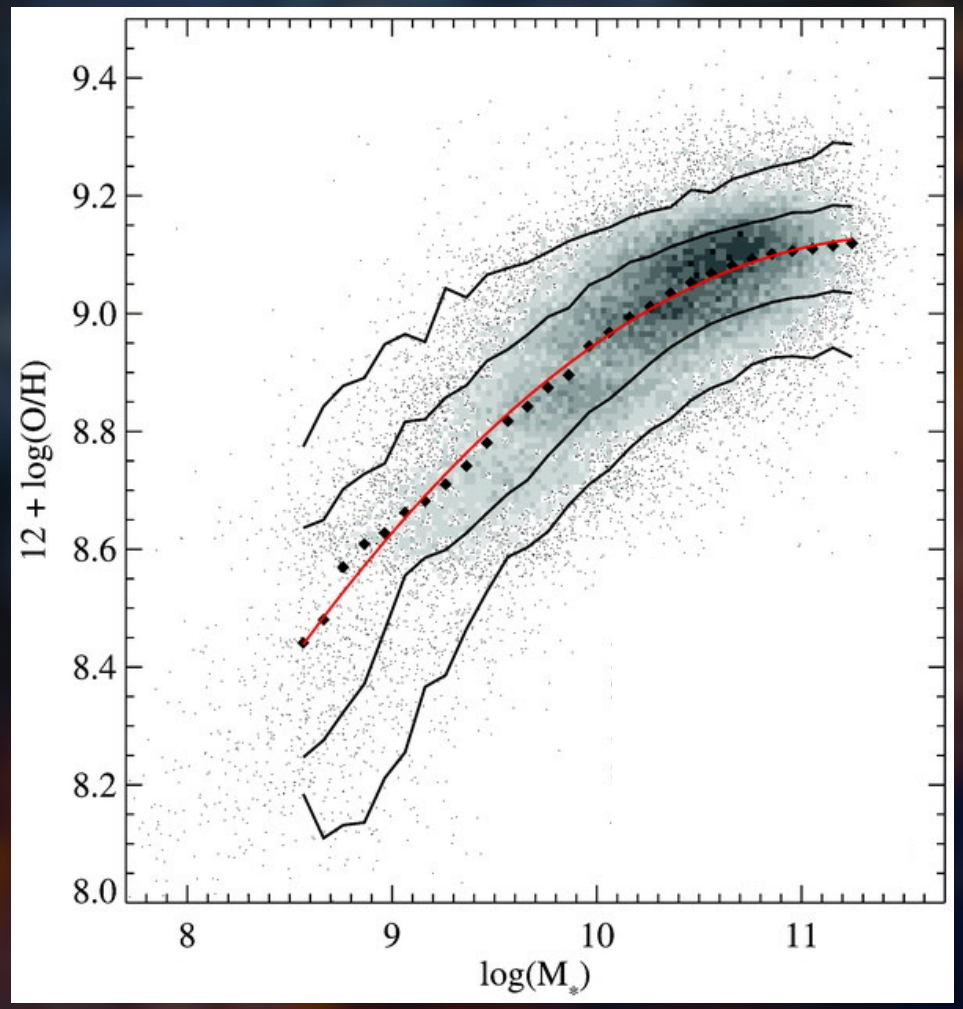
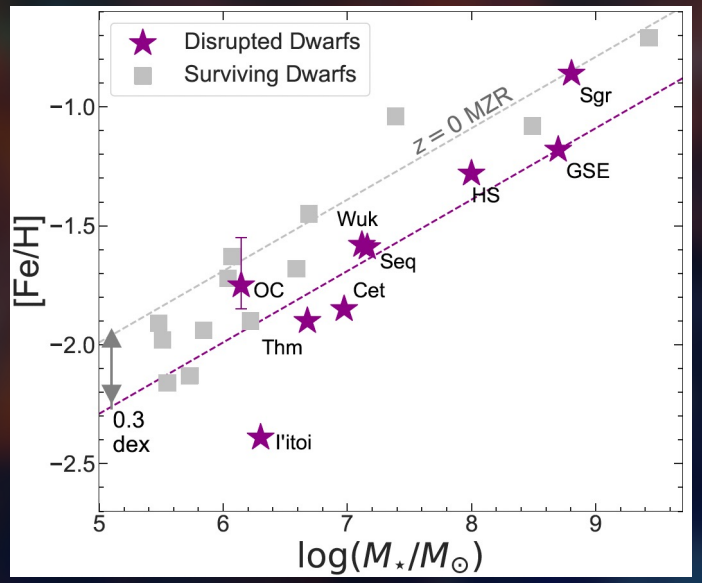


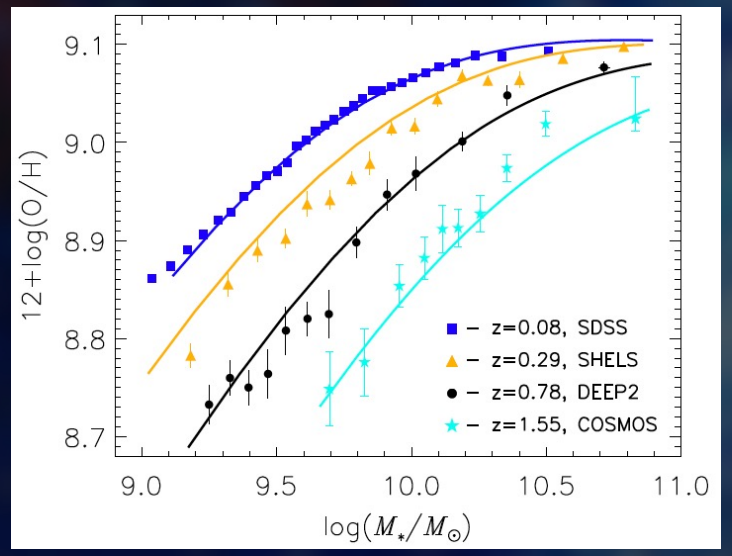
Tremonti et al. 2004

low masses

high redshifts



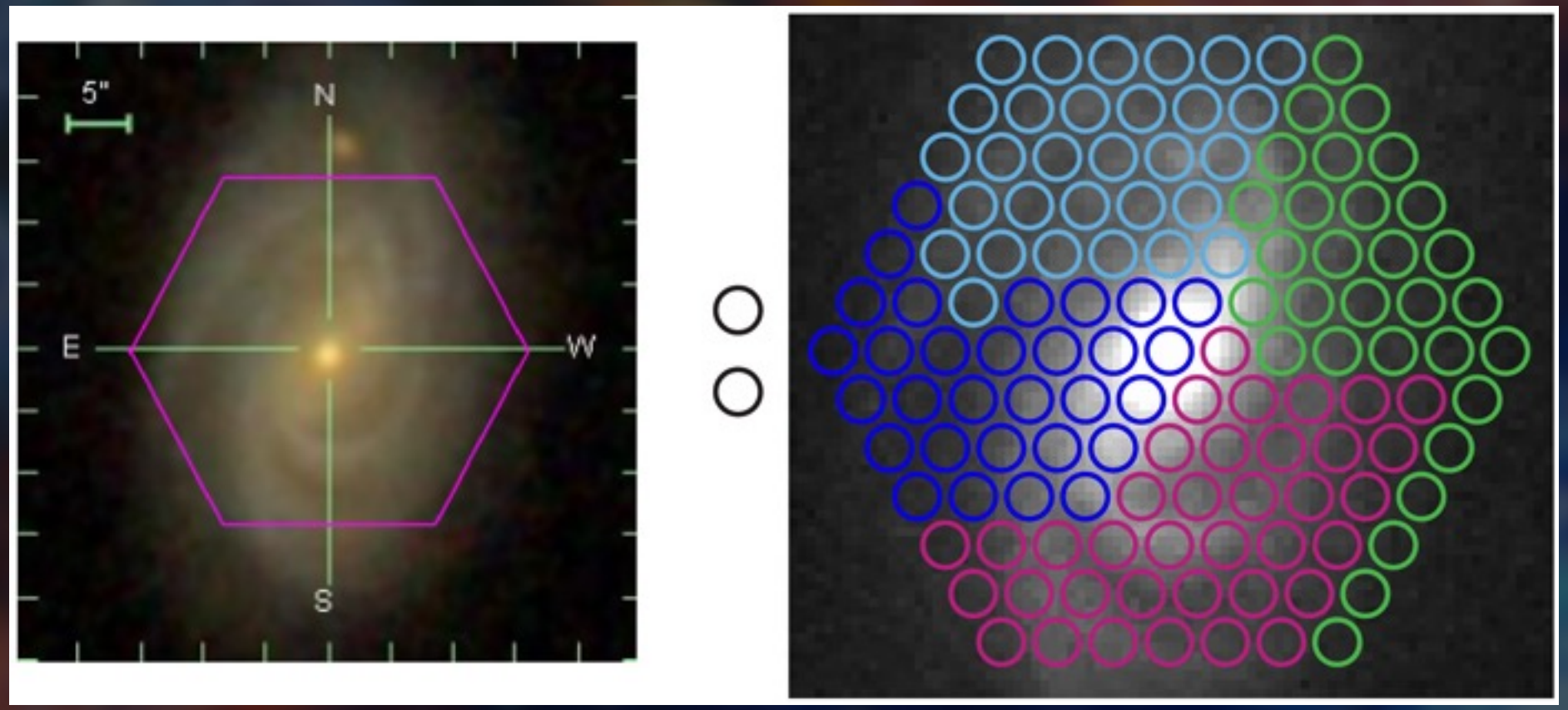
Naidu et al. 2022



Zahid et al. 2014

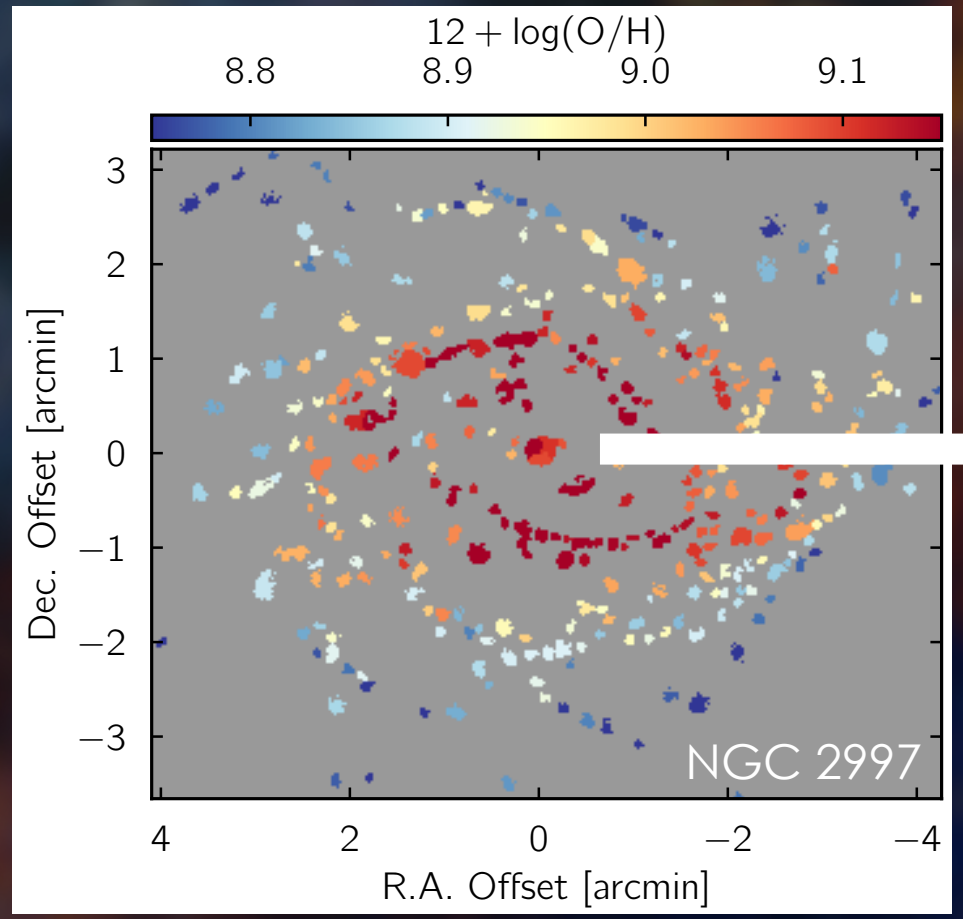
Integral Field Unit Spectroscopy

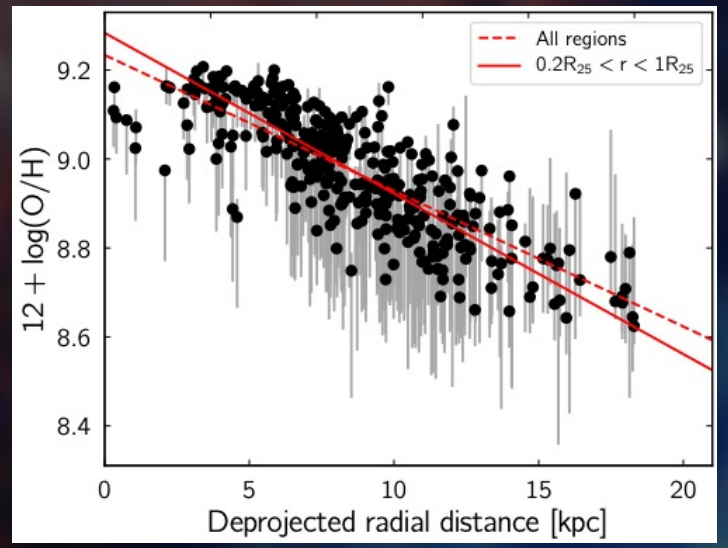
Law et al. 2016



Thanks to IFU Spectroscopy, we can now measure metallicities in spatially-resolved regions in thousands of galaxies.

Metal distribution in galaxies

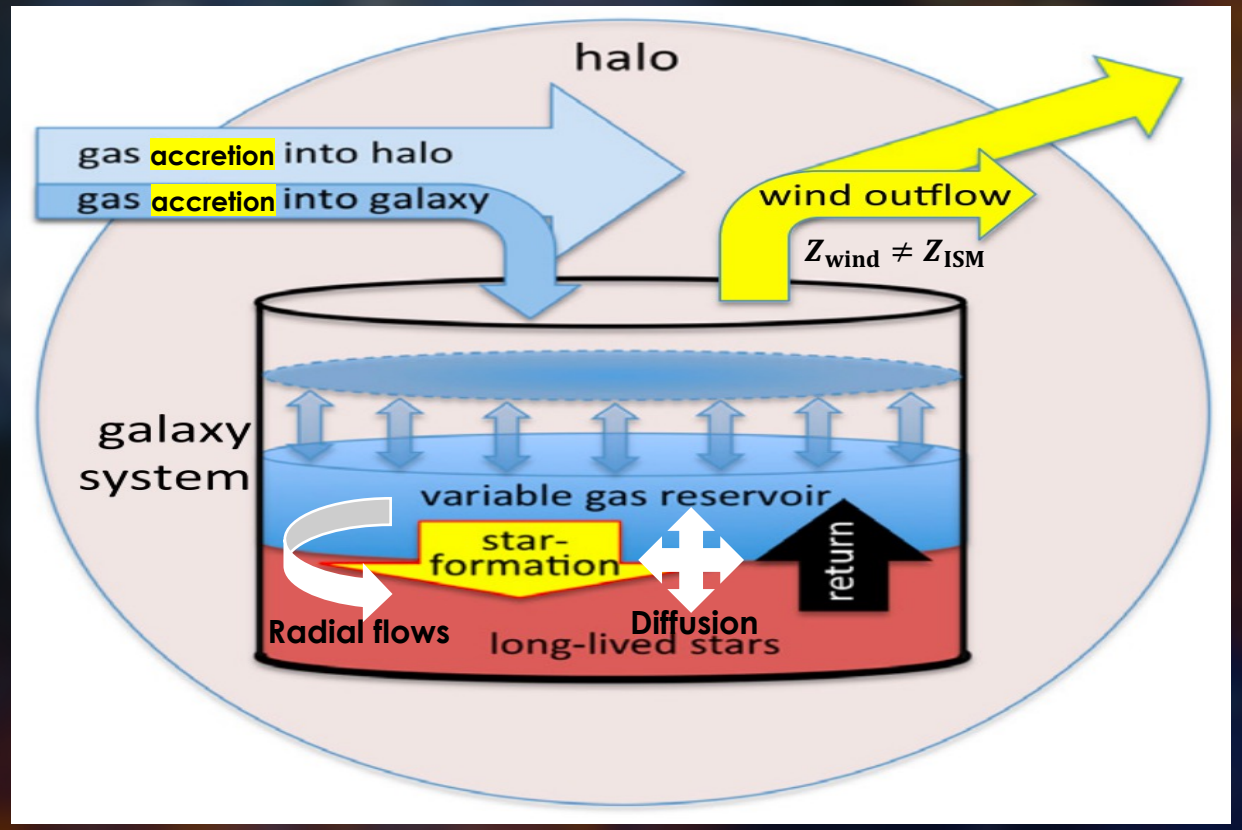




Slope = metallicity gradient

Ho et al. 2018

New model for metallicity gradients



Sharda et al. 2021b

Includes major modes of metal transport.

Includes differential enrichment of outflows.

Can be applied to a wide-range of galaxies, both in the local and high-z Universe.

Model parameters independently constrained by galaxy evolution theory.

Mass-metallicity gradient relation (MZGR)

MZGR is the scaling of metallicity gradients with galaxy mass.

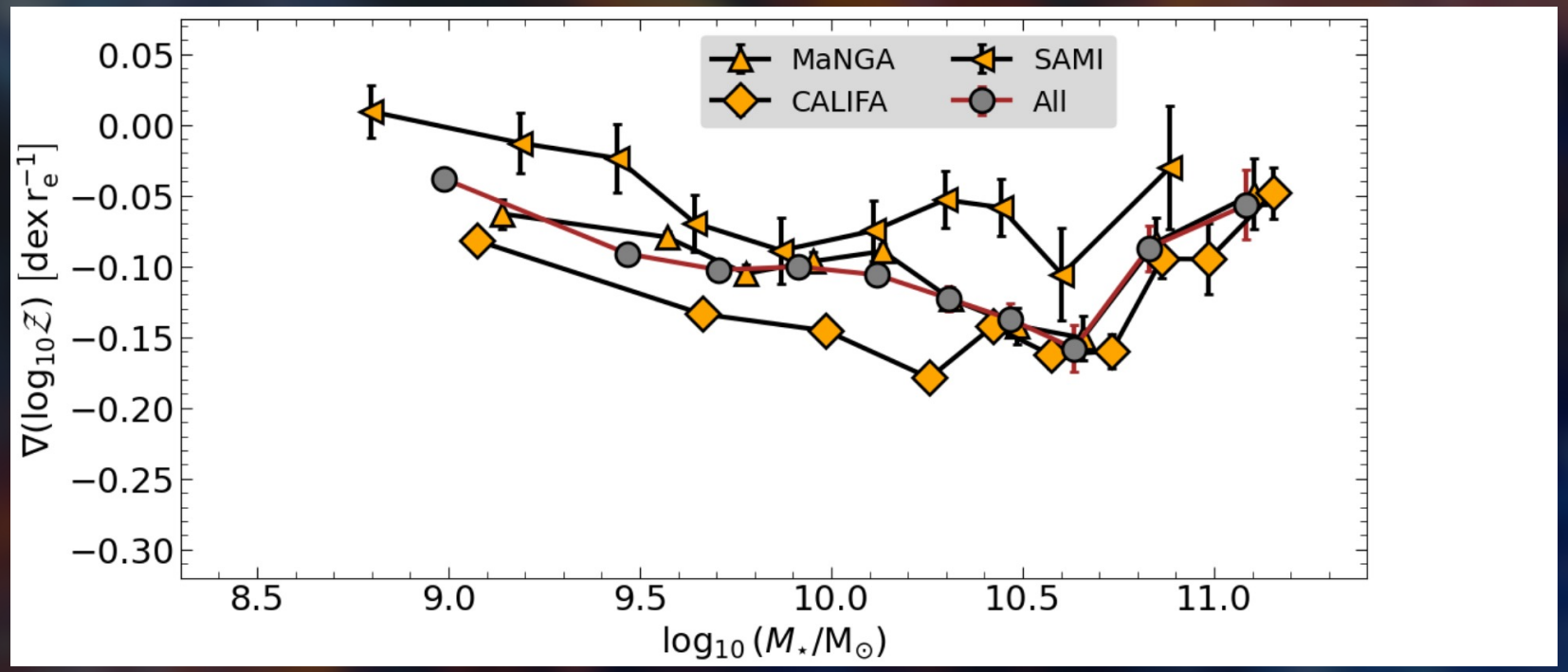
The local MZGR has recently been produced from different IFU galaxy surveys.

The origin of the local MZGR is not well understood.

Sánchez et al. 2014, Sánchez-Menguiano et al. 2016,
Belfiore et al. 2017, Poetrodjojo et al. 2019, 2021, Mingozzi et al. 2020

Mass-metallicity gradient relation (MZGR)

Sharda et al. 2021c

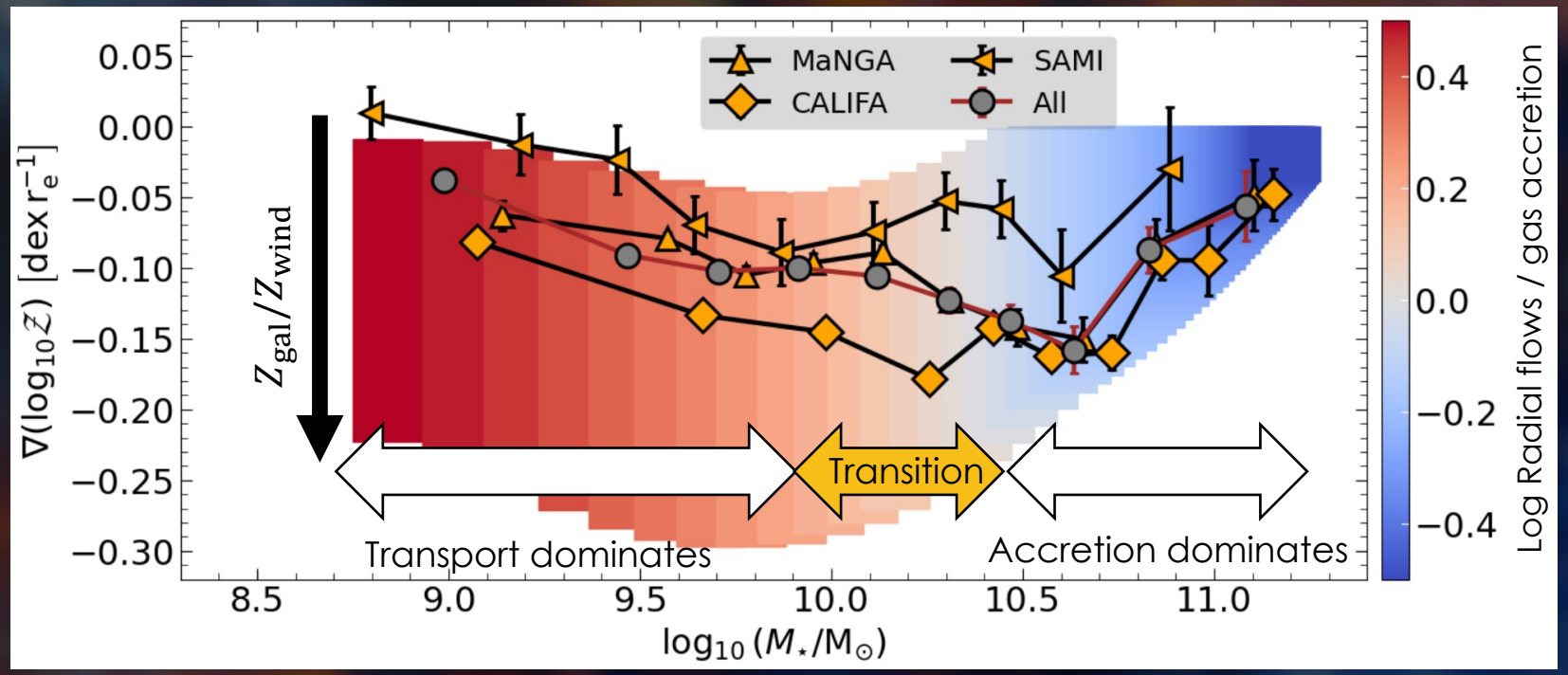


MZGR steepens from low to intermediate masses, and then flattens again.

The curvature in the MZGR is robust against systematics due to metallicity calibrations.

Mass-metallicity gradient relation (MZGR)

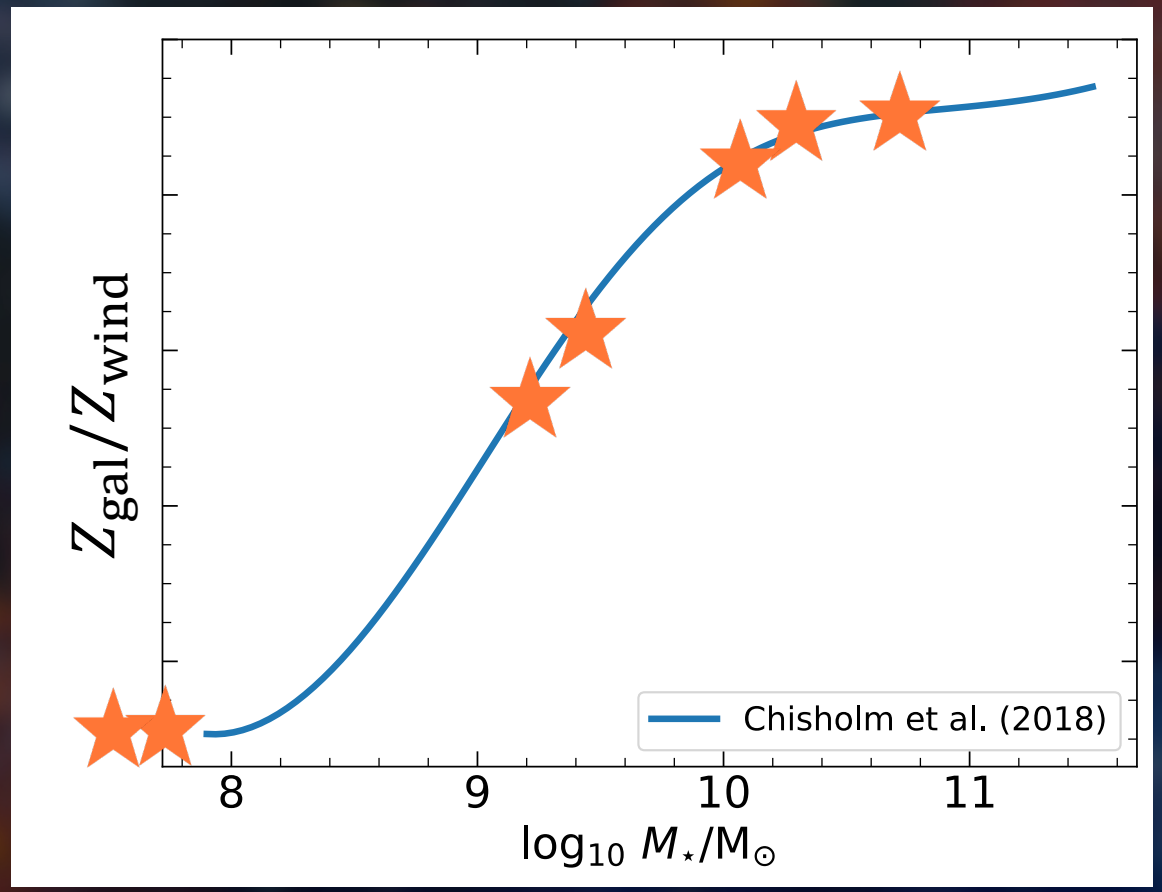
Sharda et al. 2021c



Galaxies transition from being transport-dominated to being accretion-dominated at the location where the MZGR shows a curvature.

Low-mass ($M_* < 10^{9.5}$ $M_\odot$) galaxies preferentially lose metals in galactic winds.

Are galactic winds metal-enriched?



Sharda et al. 2021c

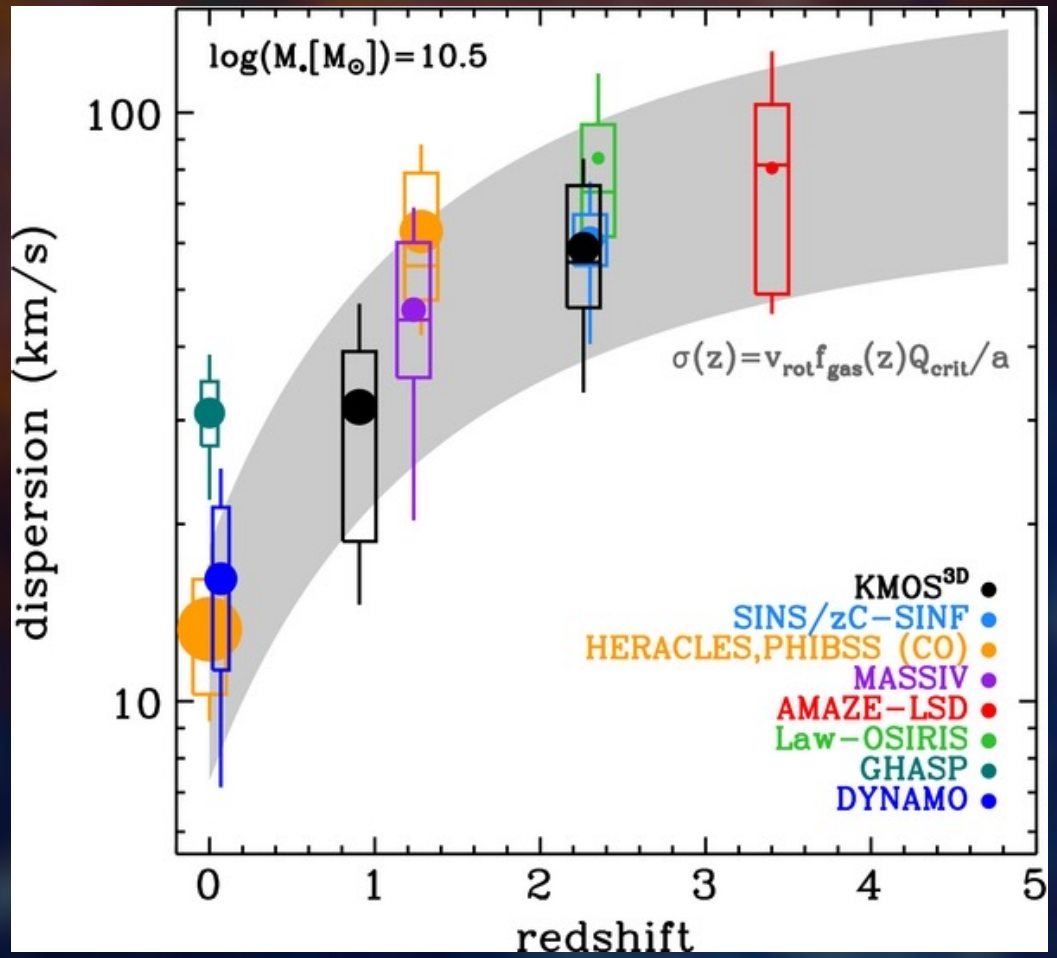
Low-mass ($M_* < 10^{9.5}$ $M_\odot$) galaxies preferentially lose metals in galactic winds.

Metallicity gradients and kinematics

In addition to galaxy mass, we can also study the dependency of metallicity gradients on gas kinematics from the model.

This is more easily done at high redshifts where galaxies show a large diversity in their gas kinematics.

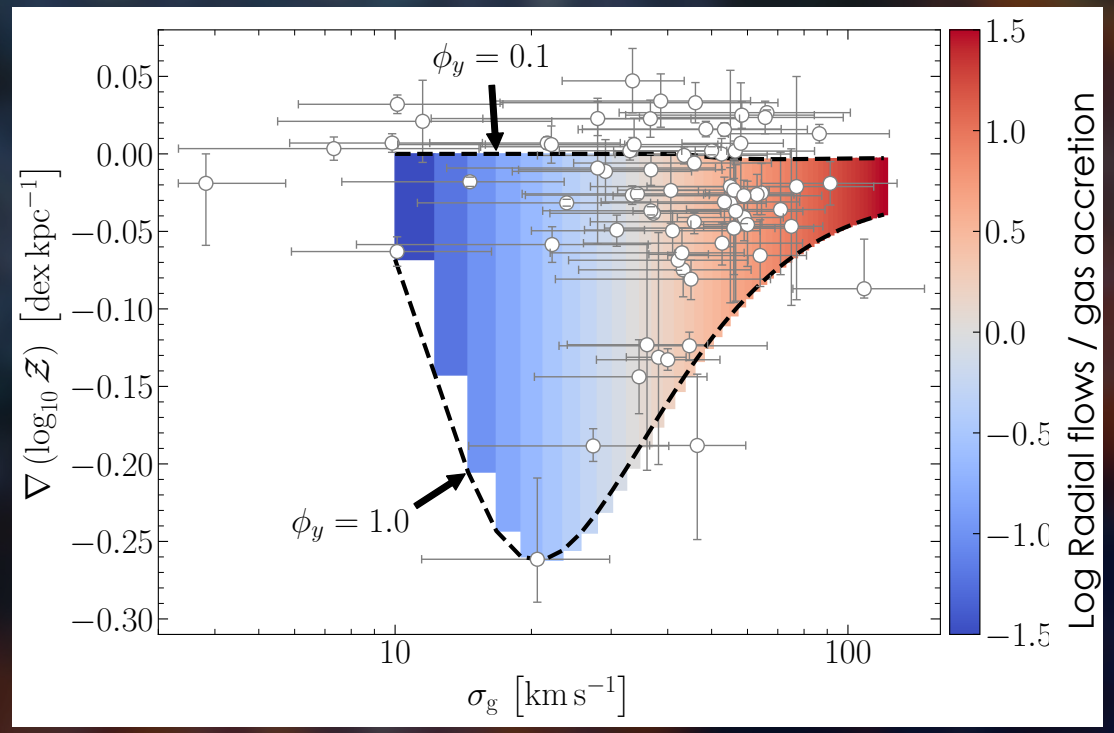
The role of gas kinematics in setting metallicity gradients remains unexplored (Queyrel et al 2012, Gillman et al 2021).

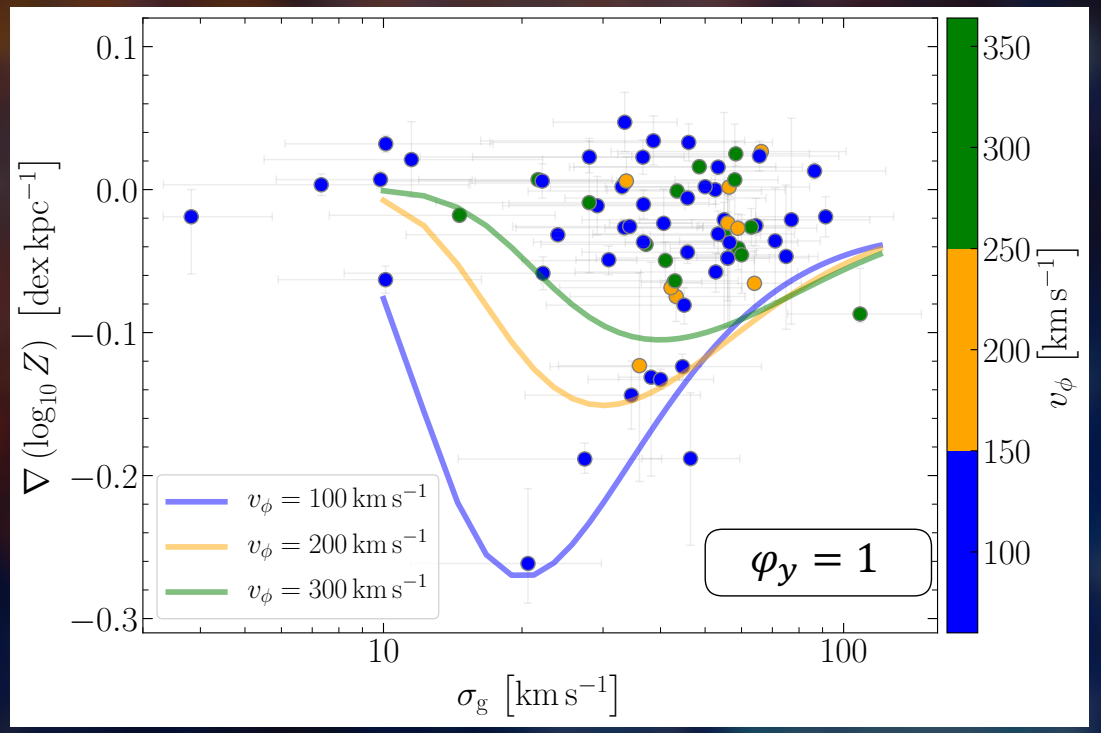


Wisnioski et al. 2015, 2019

Metallicity gradients and kinematics

Sharda et al. 2021d





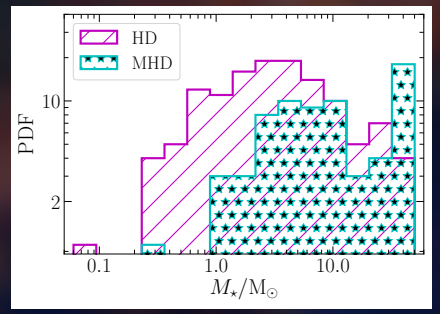
High velocity dispersion → efficient metal mixing → flat metallicity gradients.

Low velocity dispersion → efficient metal dilution → flat metallicity gradients.

Summary

Metals act as nature's Lagrangian tracers of multi-scale structure formation.

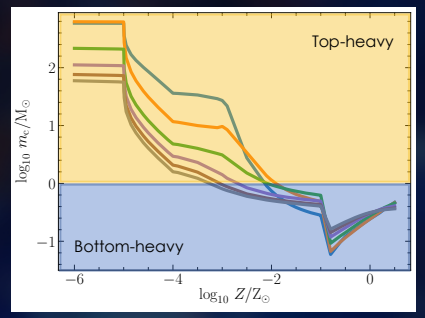
Studying the first galaxies will require understanding both small scale (1-100 pc) and large scale (1-10 kpc) metal enrichment.



Low metallicity star formation

IMF at zero metallicity is significantly shaped by physical processes such as turbulence and magnetic fields.

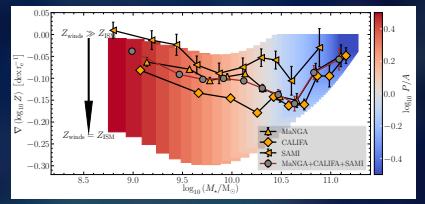
IMF at zero and ultra-low metallicities can be significantly different from the Milky Way IMF.



Large-scale metal distribution

Low-mass ($M_* < 10^{9.5}\ M_\odot$) galaxies preferentially lose metals through galactic winds.

Massive ($M_* > 10^{10.5}\ M_\odot$) galaxies and galaxies with high gas velocity dispersions show flat metal distributions regardless of the nature of their winds.



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