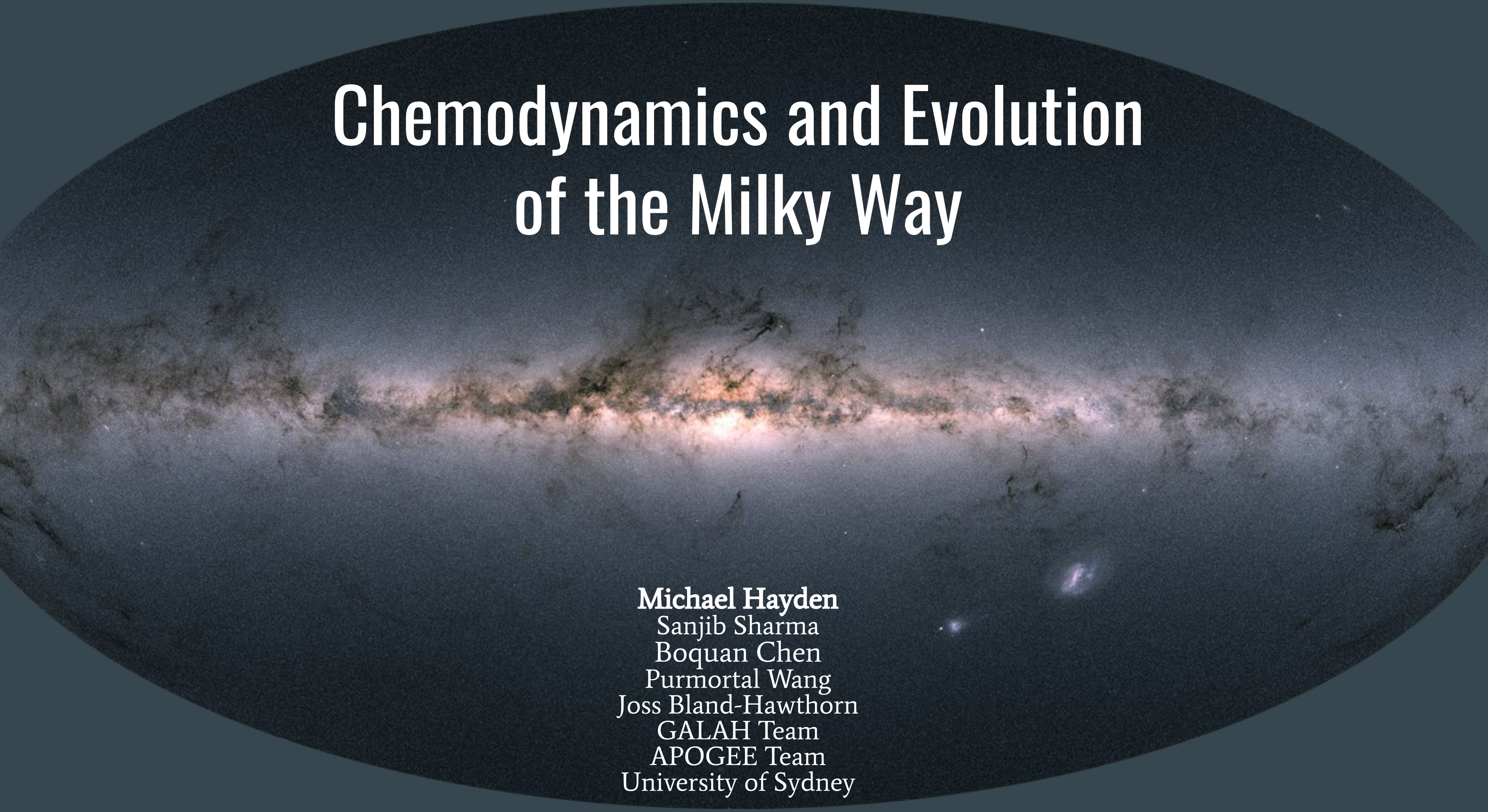
Chemodynamics and Evolution of the Milky Way



Michael Hayden
Sanjib Sharma
Boquan Chen
Purmortal Wang
Joss Bland-Hawthorn
GALAH Team
APOGEE Team
University of Sydney

The Milky Way: A Laboratory for Understanding Galaxy Formation

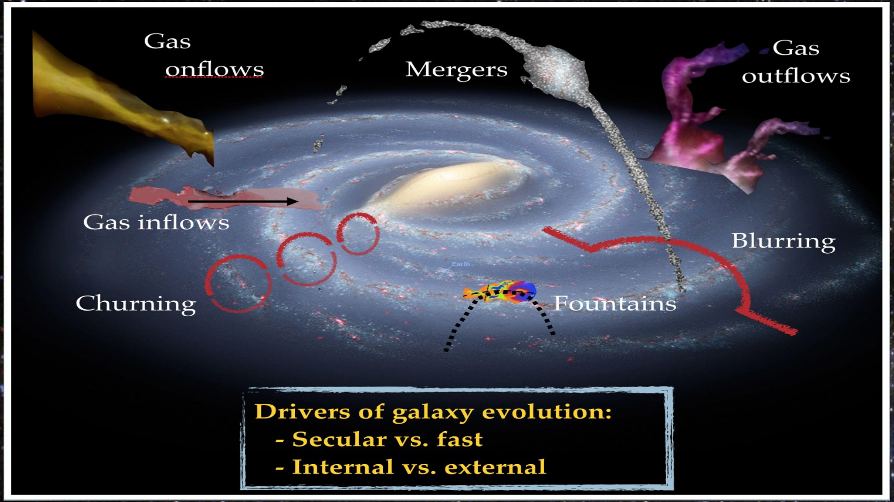


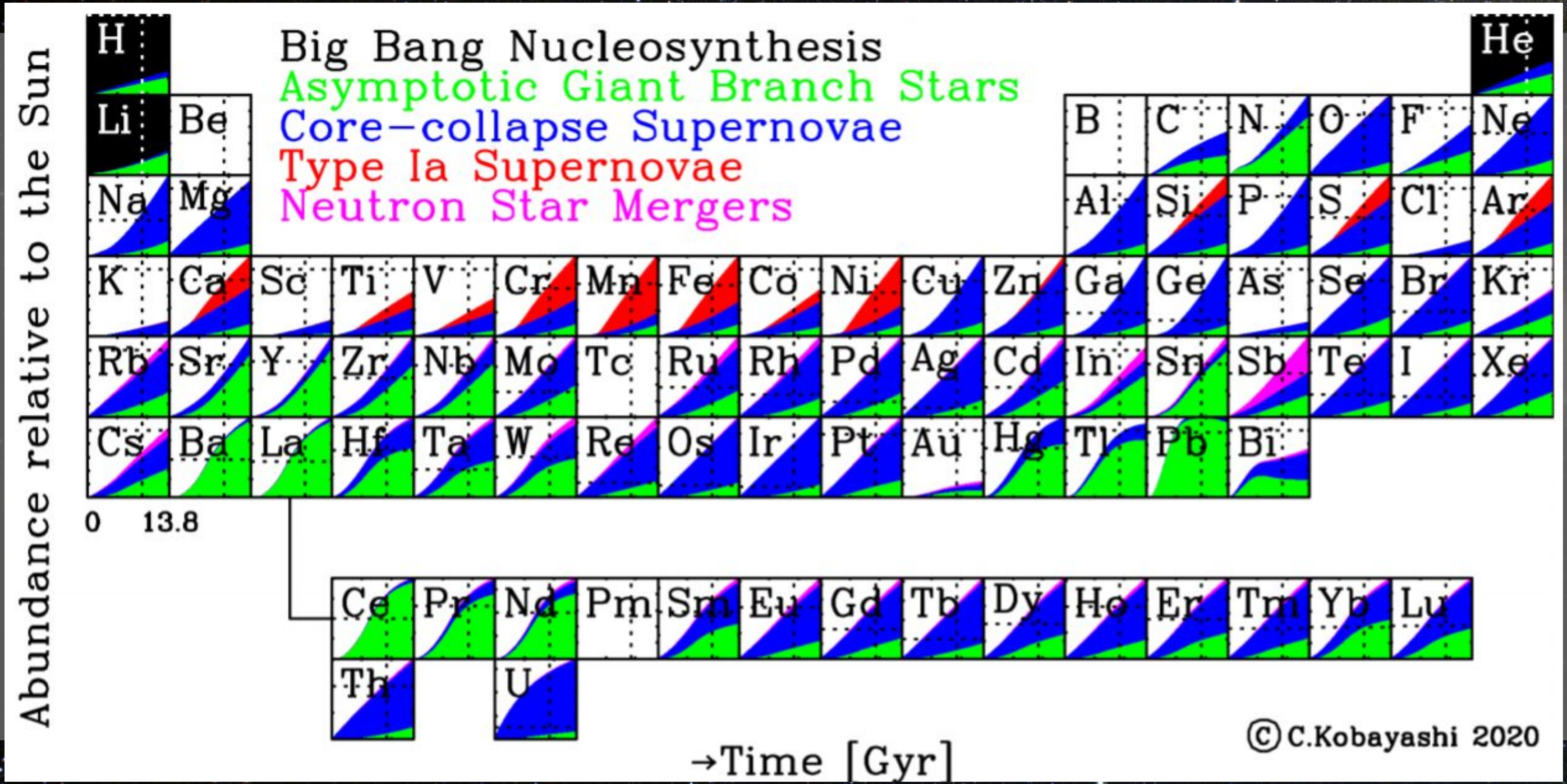
Image: Alejandra Recio-Blanco

- For distant galaxies we can only get gross properties as individual stars are difficult to resolve
- Milky Way stars are nearby: get phase space (x,v), [Fe/H], age, mass ***distributions***
- With this we can test galaxy formation theories with higher detail and better constraints than unresolved populations
- Galactic Archaeology is undergoing a revolution: massive spectroscopic surveys (abundances)+*Gaia* (astrometry) → map the entire chemodynamic structure of the Galaxy

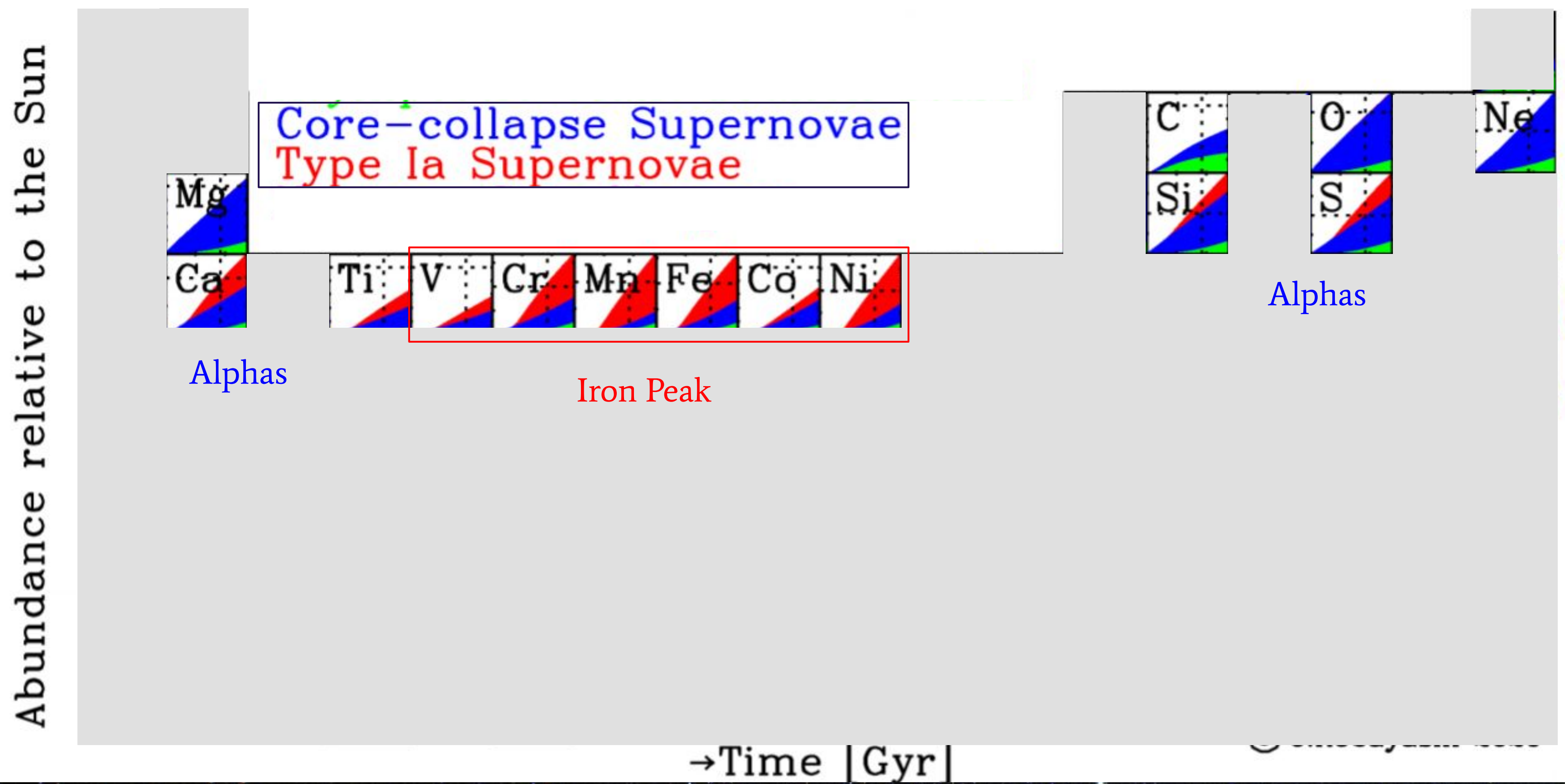
Overview

- Elemental Production Sites, Chemistry of the Solar Neighborhood
- How Stars Move About the Galaxy: Radial Mixing
- Mapping the Galaxy from the Bulge to the Edge of the Disk
- Chemical Evolution Modeling
- The Milky Way in Context: Simulations, Datacubes, GECKOS

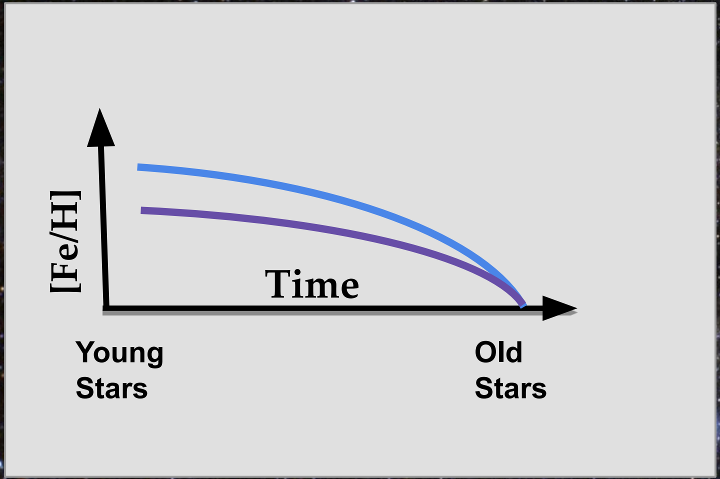
Where Do the Elements Come From?



Alpha and Iron Peak



Simple Scenario: What Happens If Star Formation Is Rapid/Slow?



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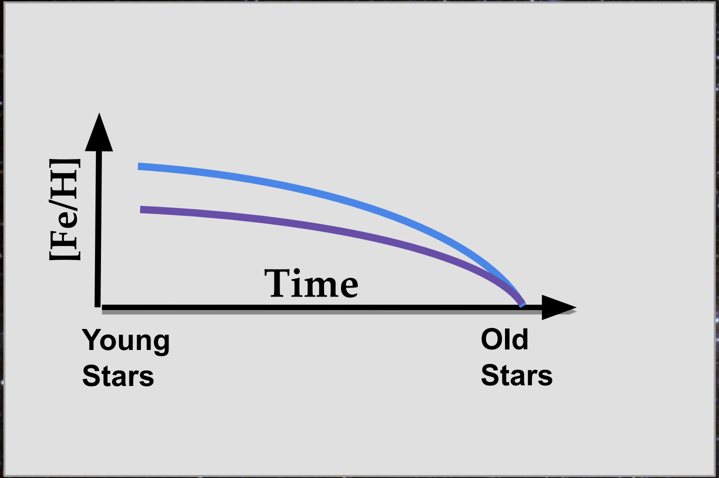
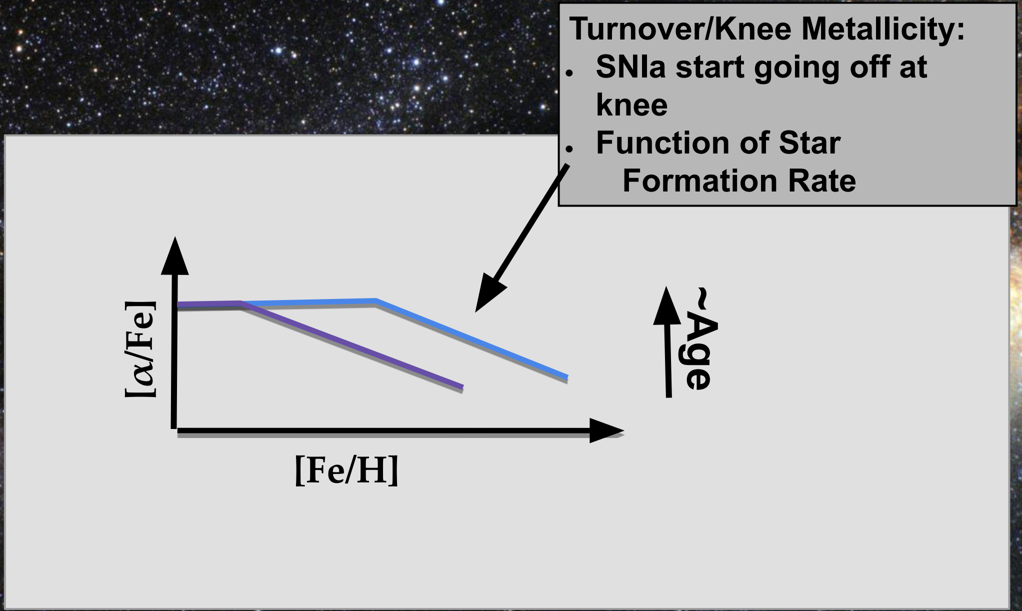
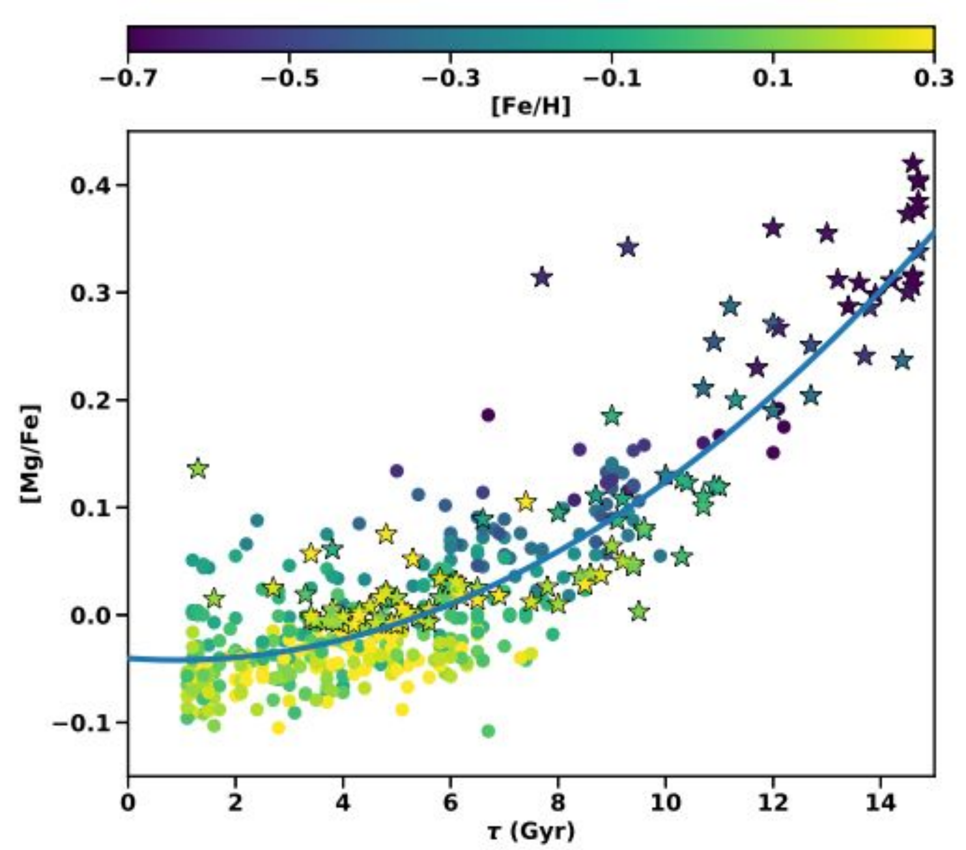




The Solar Neighborhood

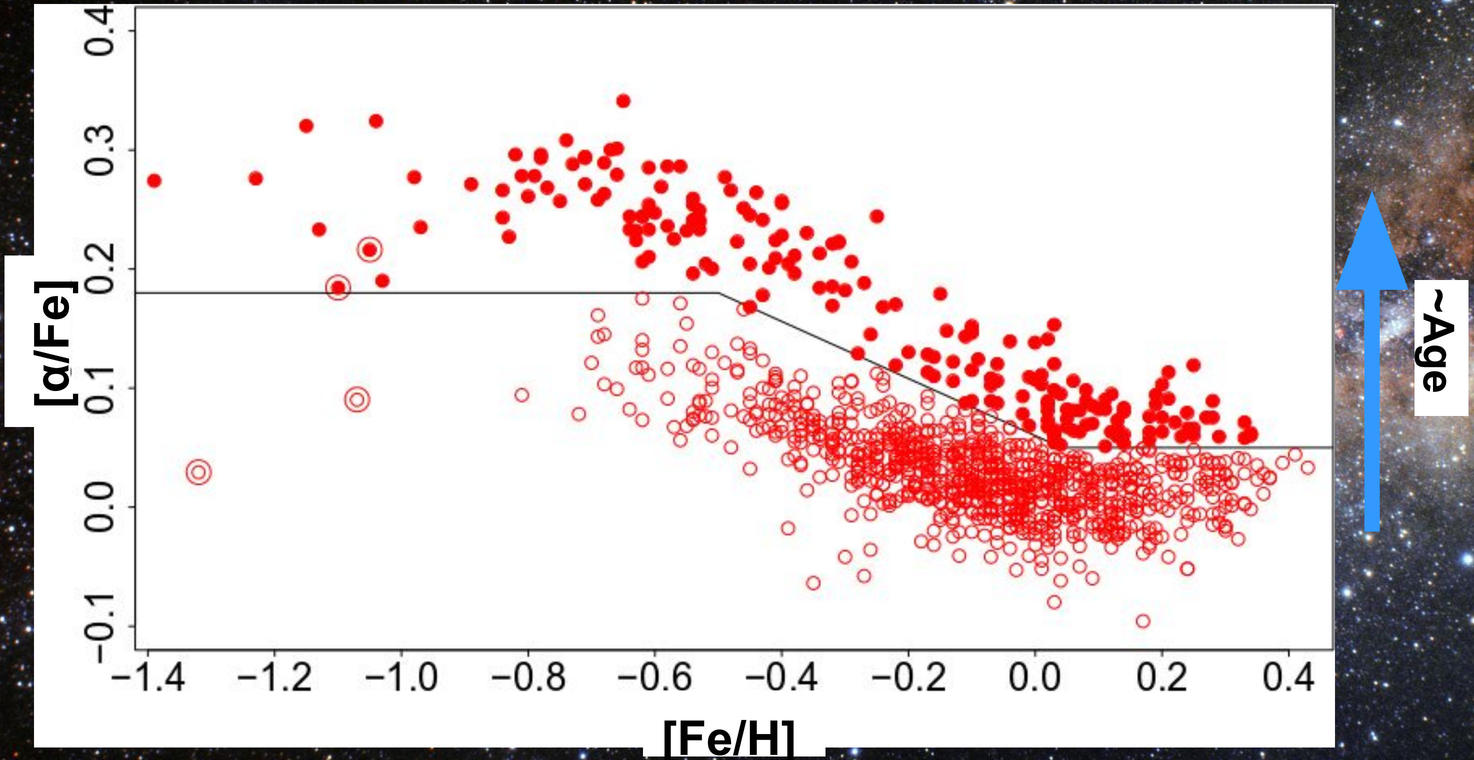
Take stars within 100 pc of the Sun, what do we see?

Ages from Abundances



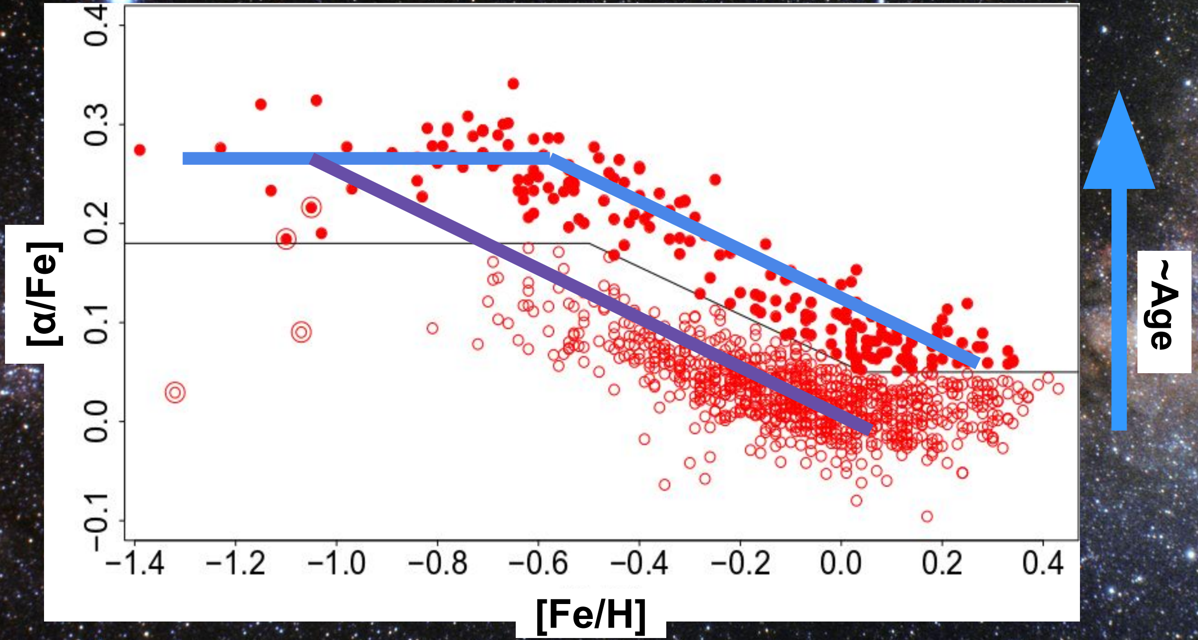
Hayden+ 2017

The Solar Neighborhood



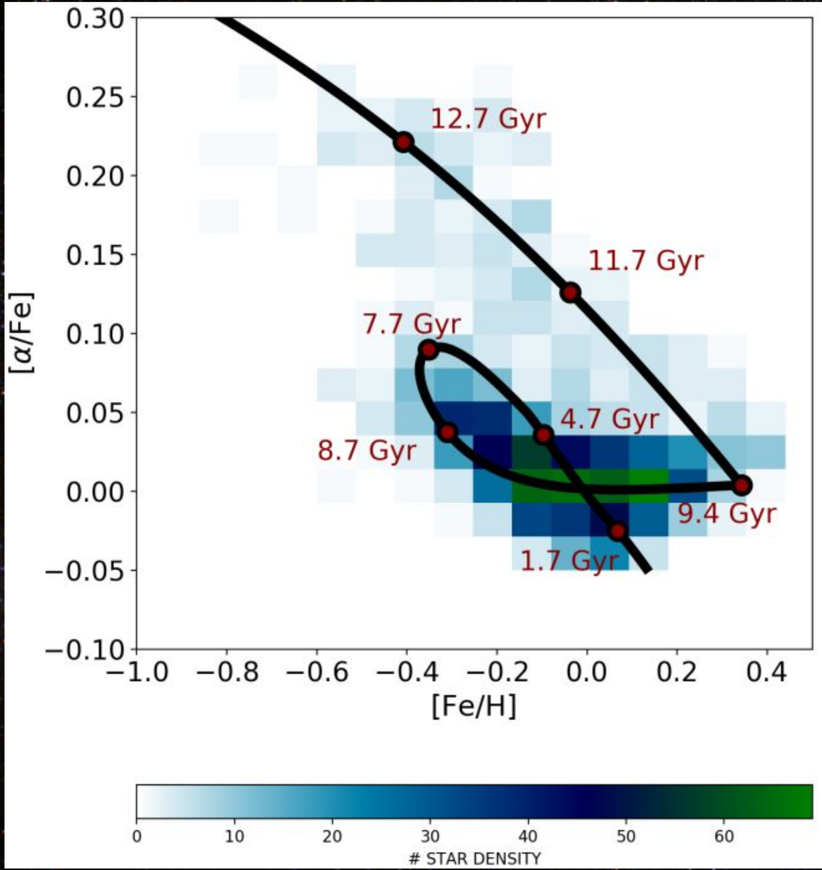
Adibekyan+2012, Haywood+ 2013

The Solar Neighborhood



Adibekyan+2012, Haywood+ 2013

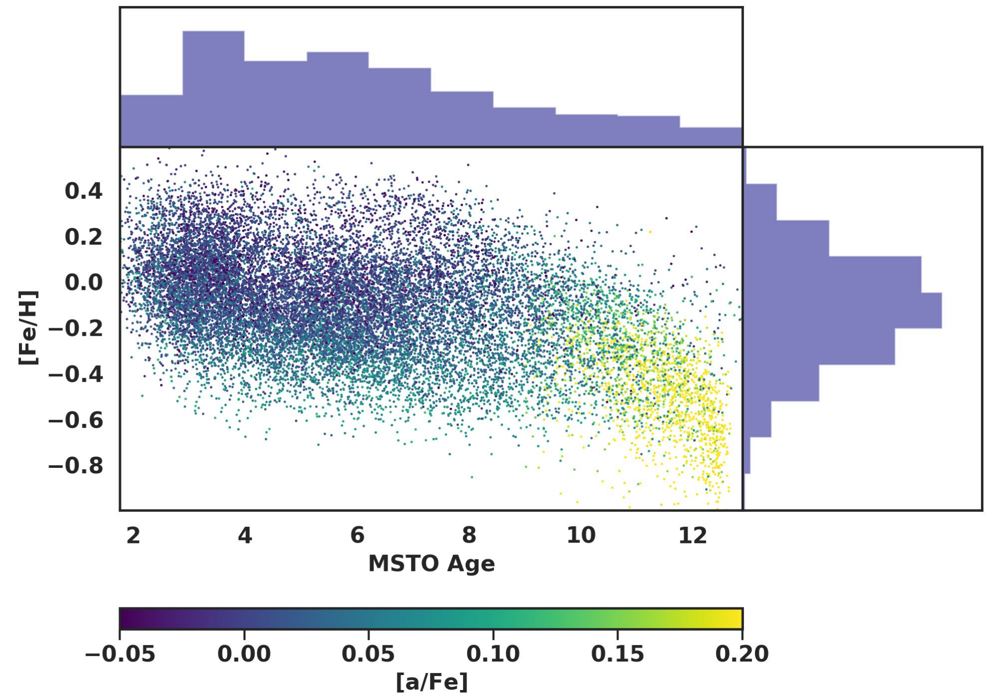
The Solar Neighborhood- Hmmm



Spitoni+2019

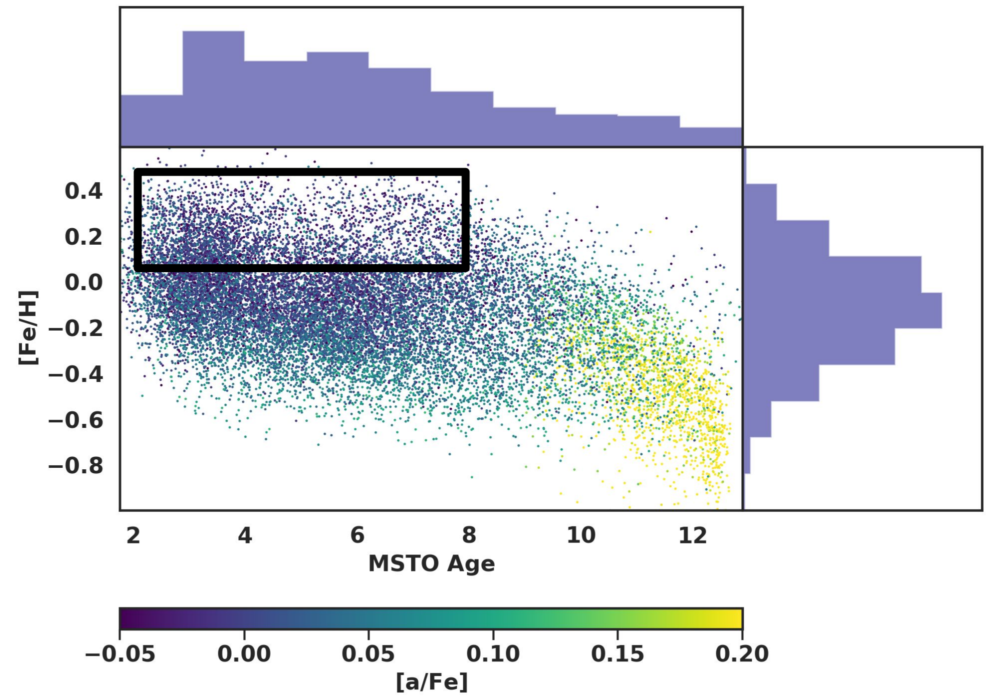
- Two-infall model: major accretion event resets chemical evolution
- Explains both the high and low alpha disk
- Potential issue: very specific age-metallicity relation, metal-rich stars can only be old!

Age-Metallicity Relation: Oops!



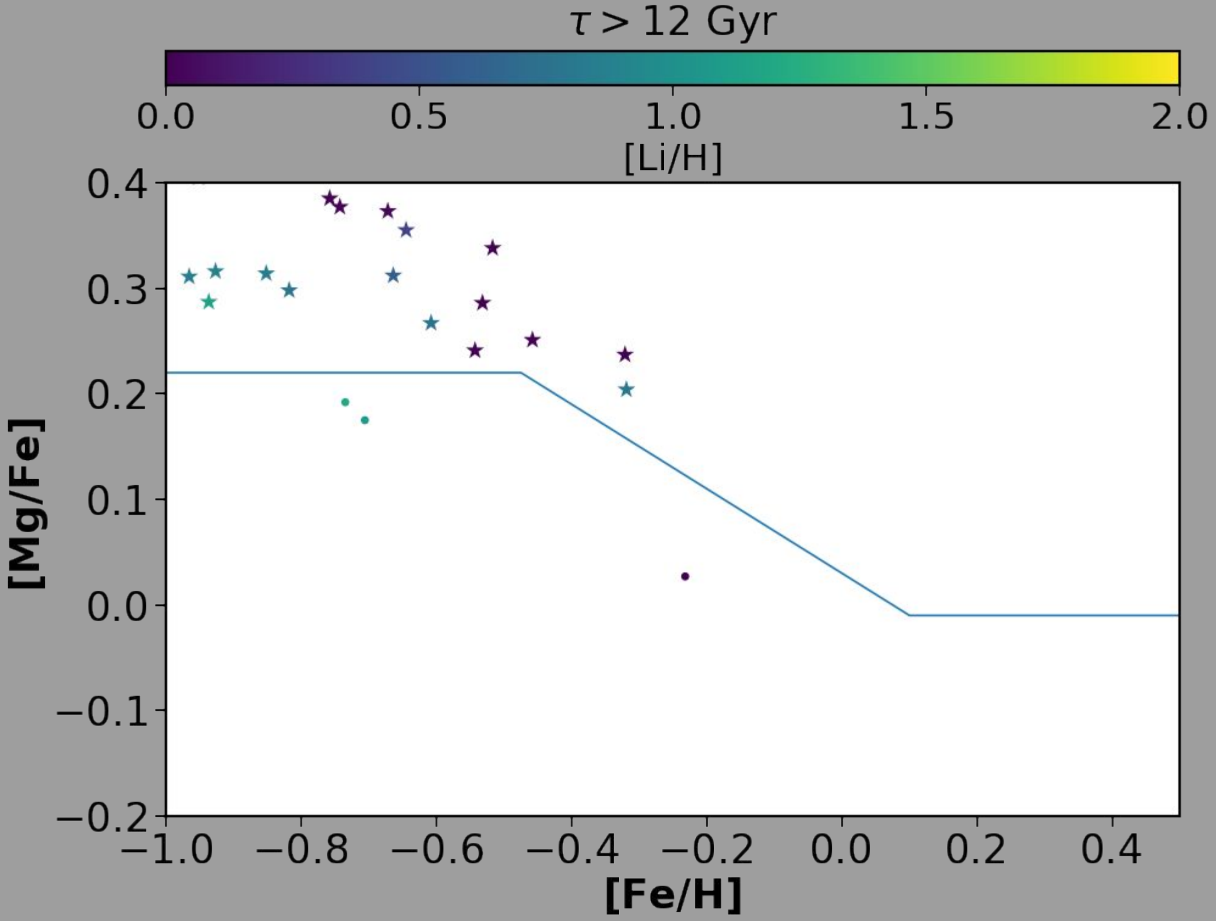
Hayden+ 2022

Age-Metallicity Relation: Oops!



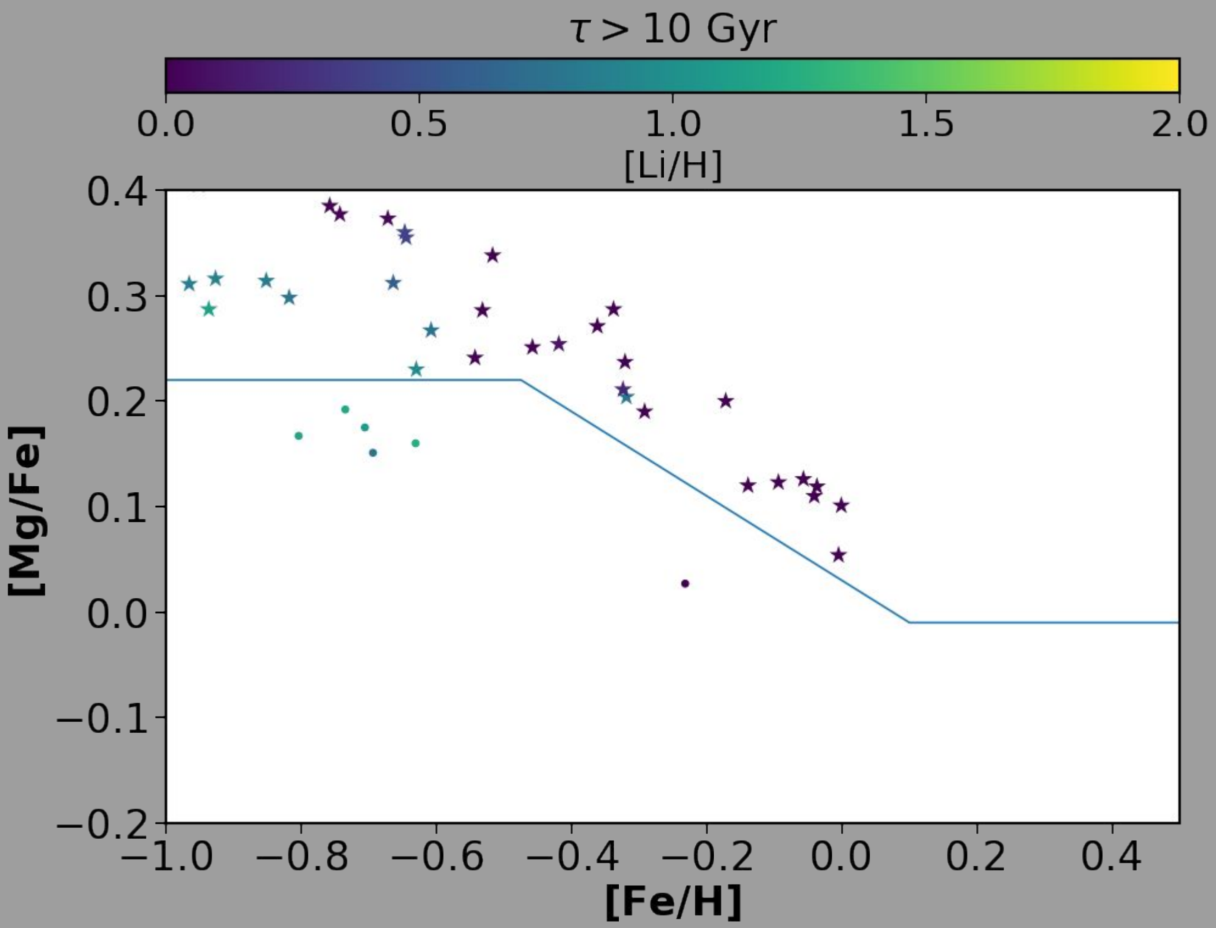
Hayden+ 2022

Adding Ages to the Mix



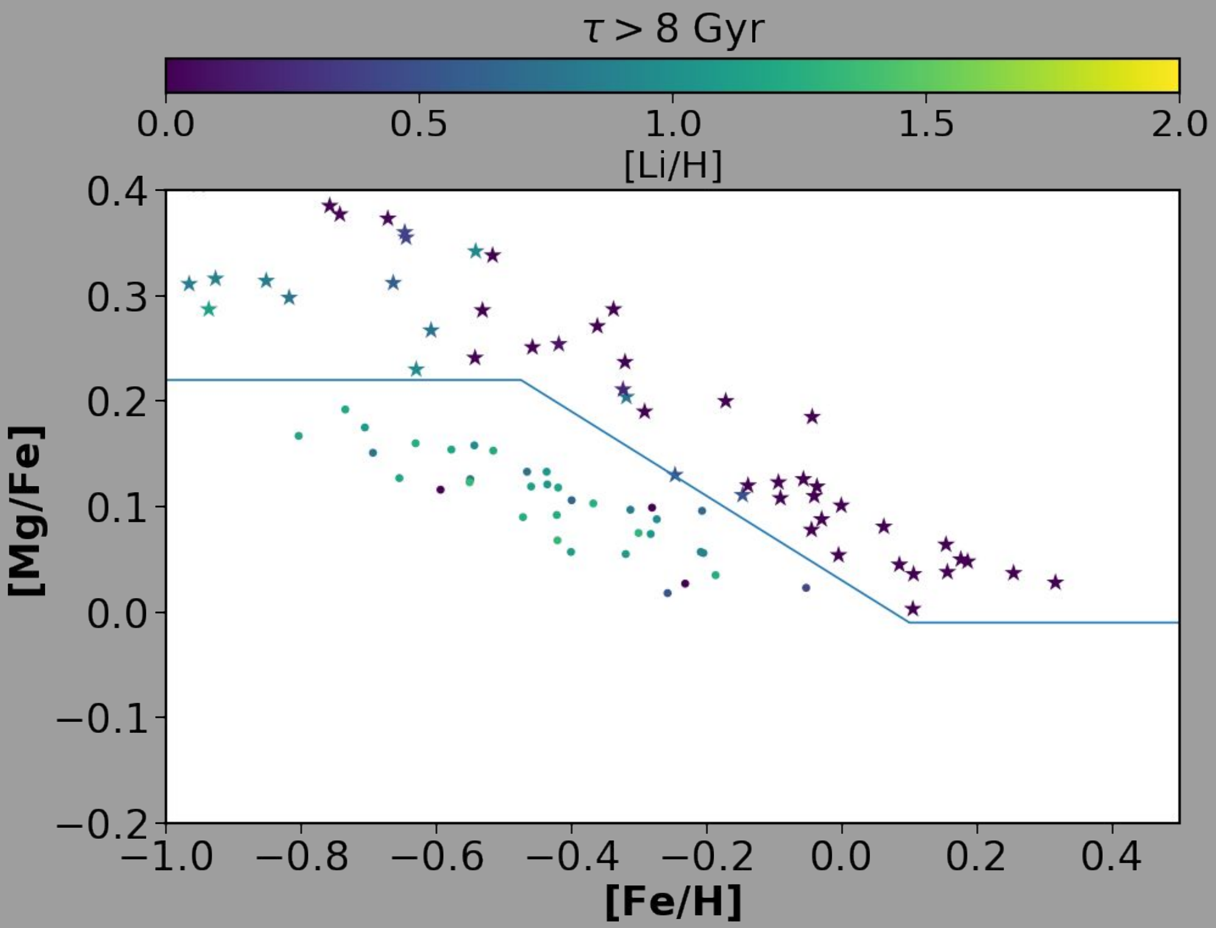
Hayden+2017

Adding Ages to the Mix



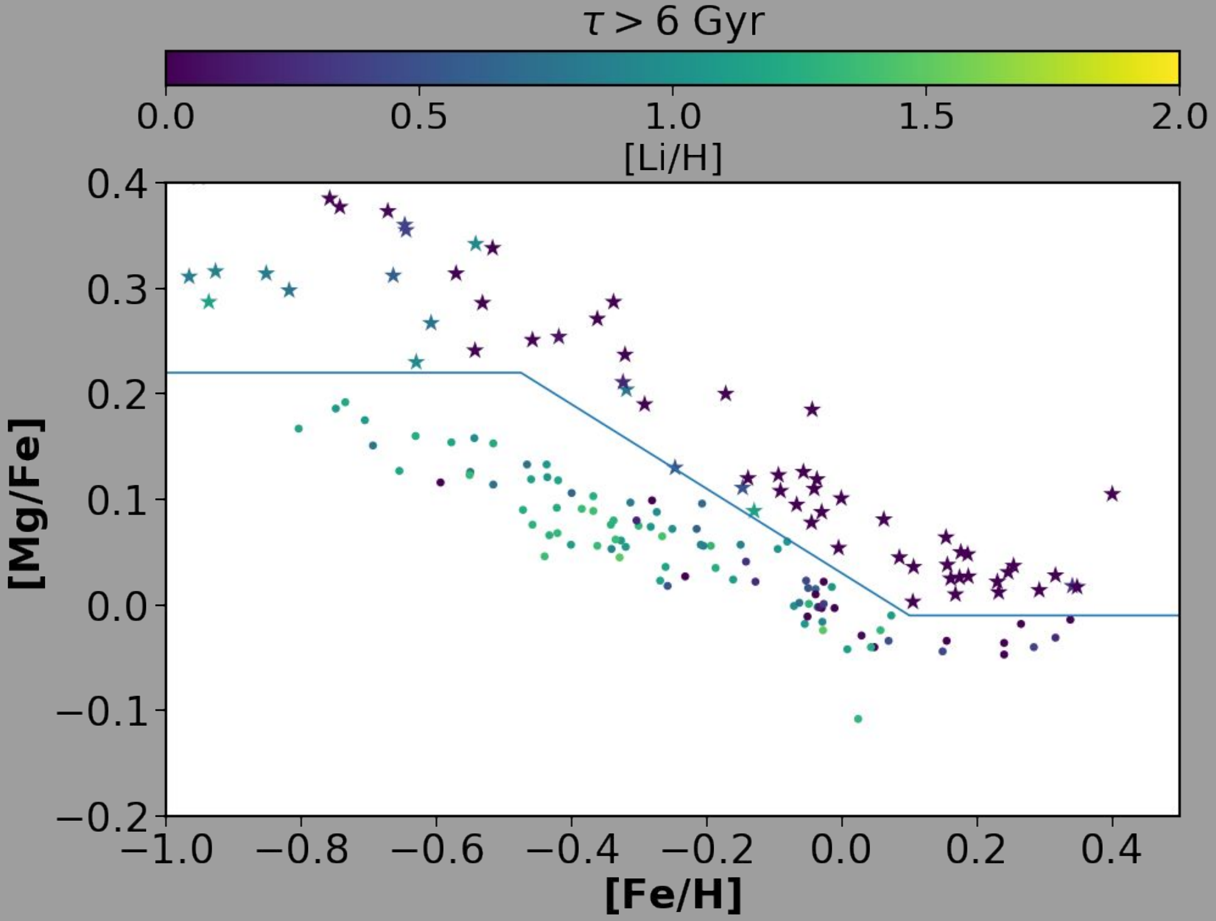
Hayden+2017

Adding Ages to the Mix



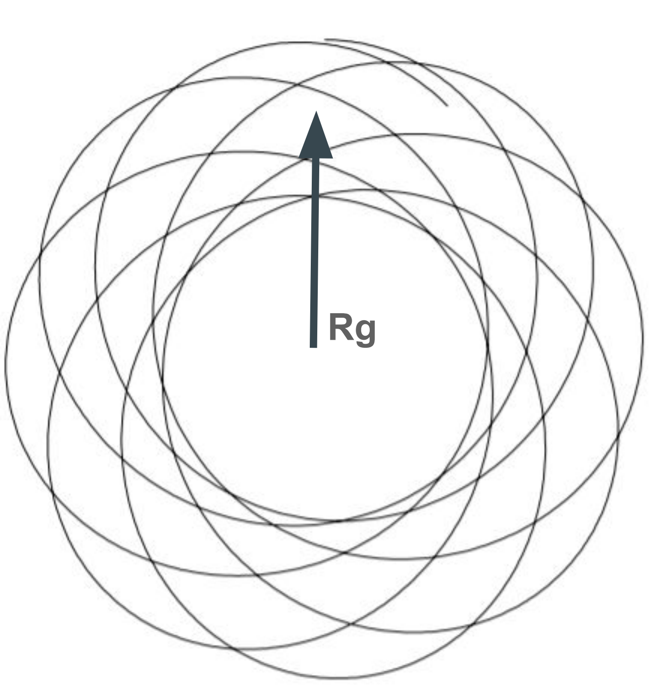
Hayden+2017

Adding Ages to the Mix



Hayden+2017

Radial Mixing

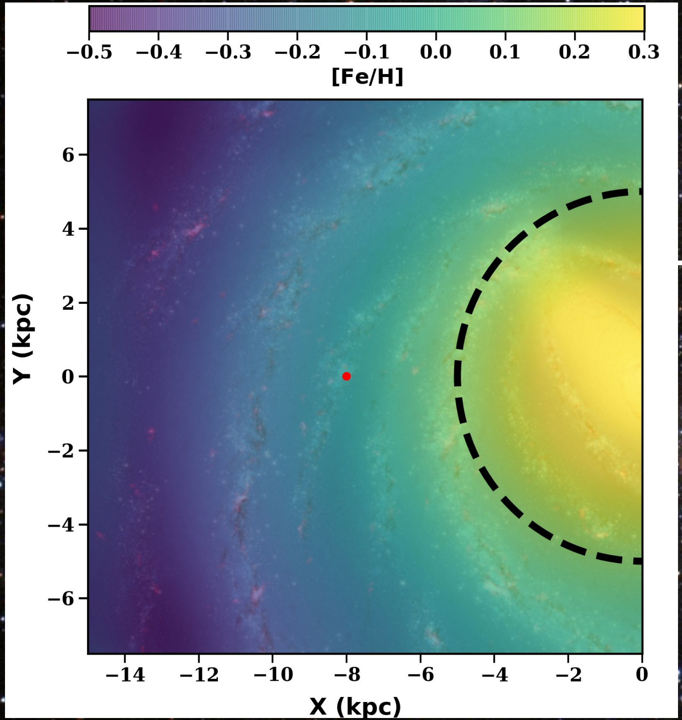


Radial Mixing: **Stars Move!!!**

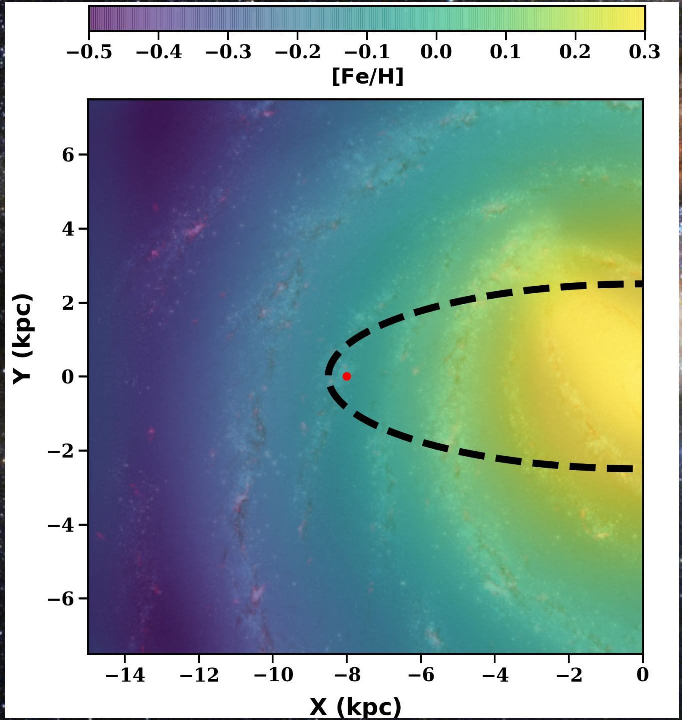
Blurring: stellar orbits heated with time, eccentricity +, angular momentum conserved (non-axisymmetric structures, GMC, satellites)

Migration: Angular momentum exchange with non-axisymmetric time dependent perturbations (*transient* spiral arms), eccentricity conserved

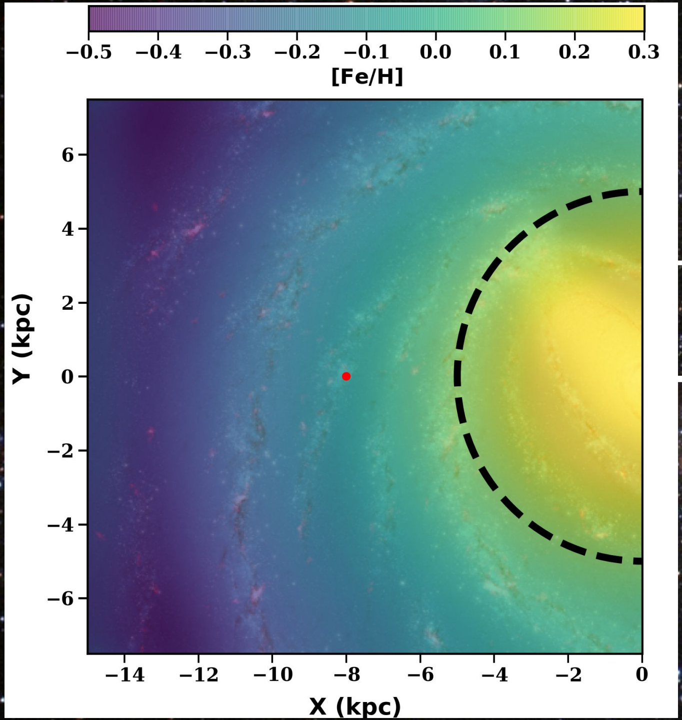
Blurring



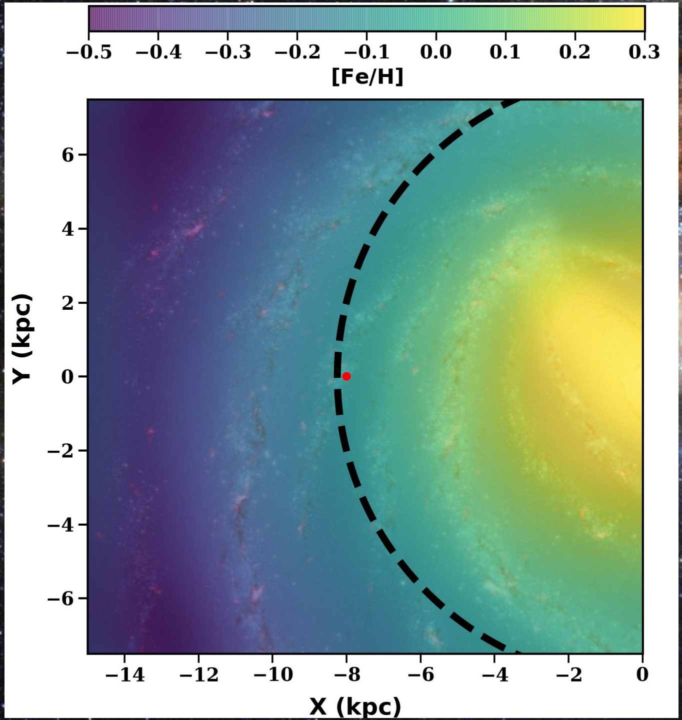
+ GMC, Merger, etc.



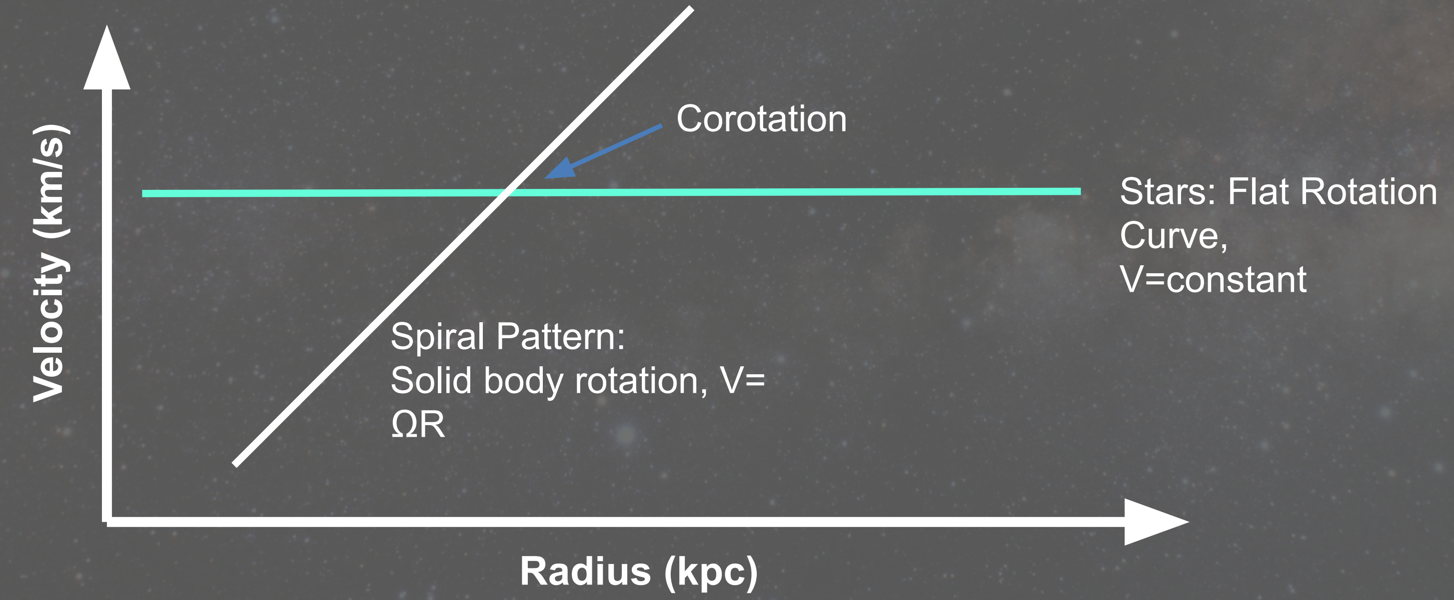
Churning



+ Transient Spiral Arm



Migration: Transient Spirals



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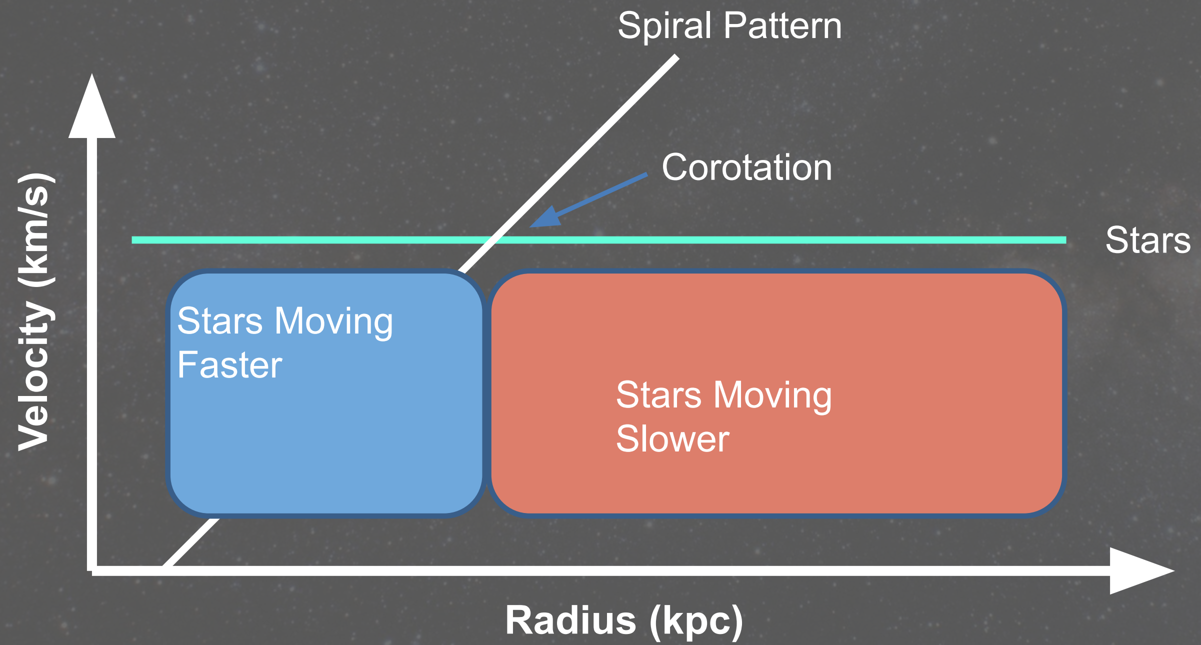
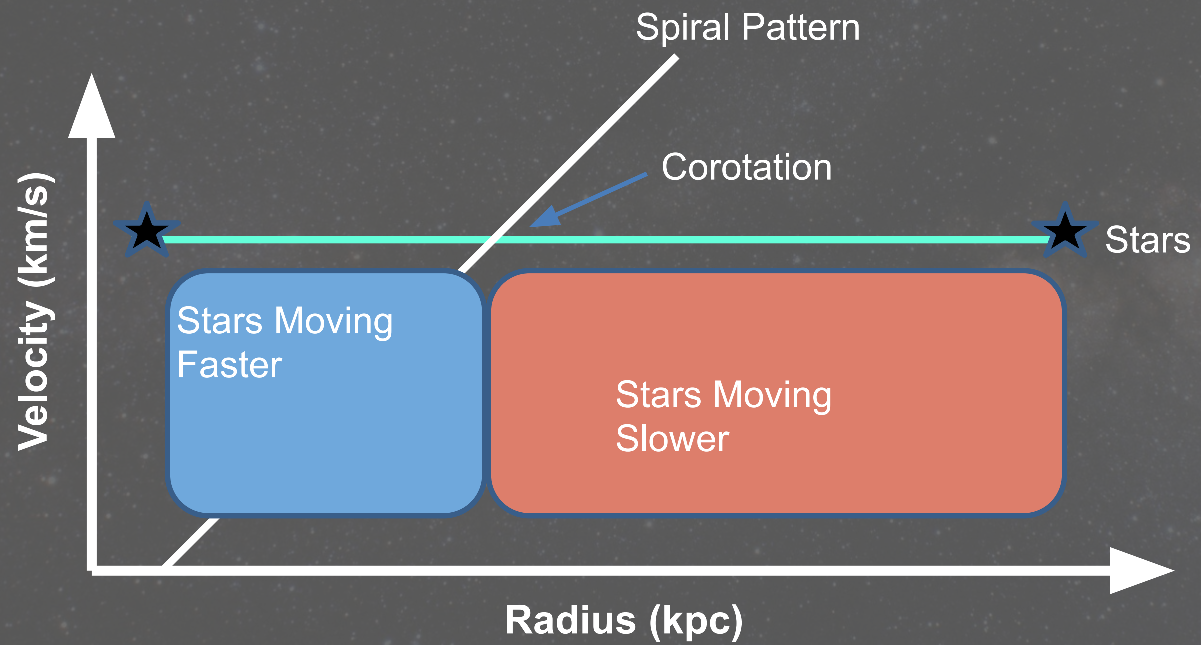
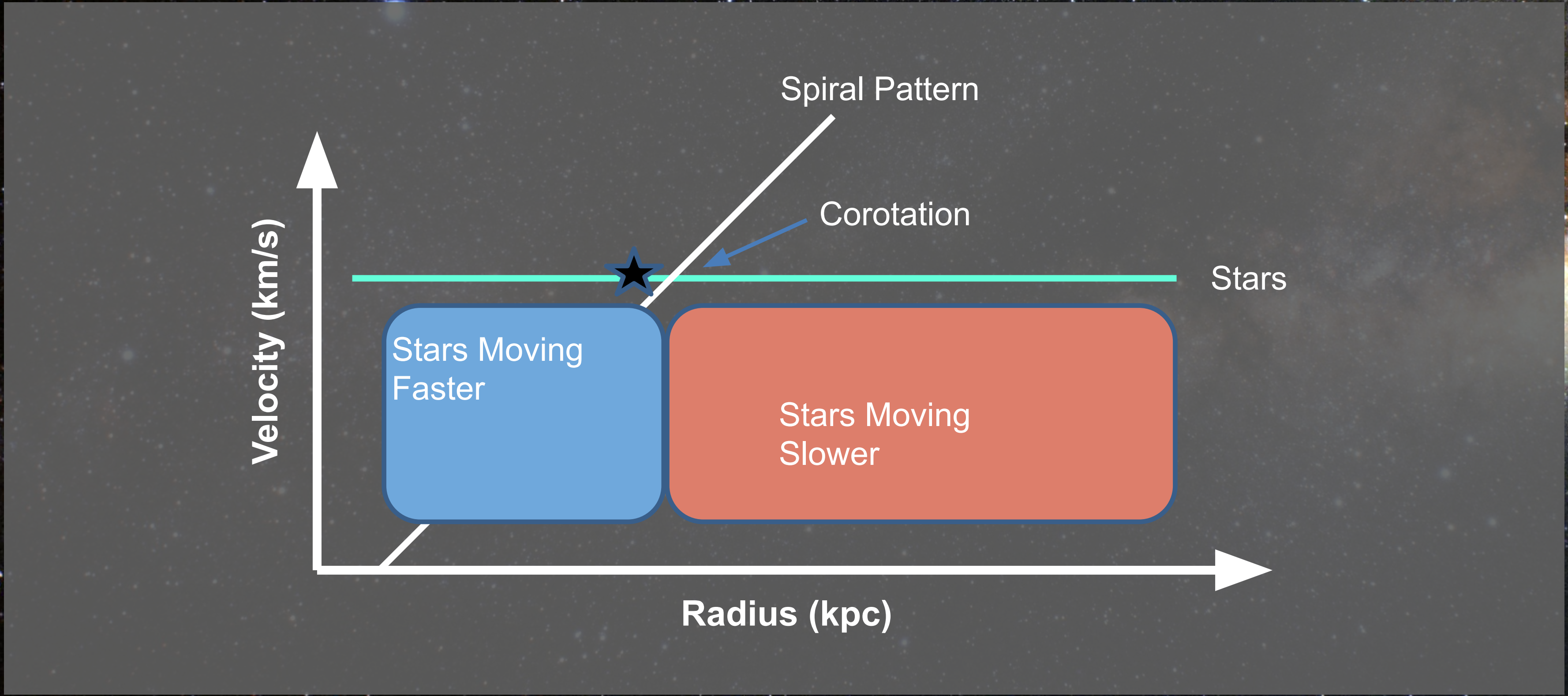


Migration: Transient Spirals



Migration: Transient Spirals



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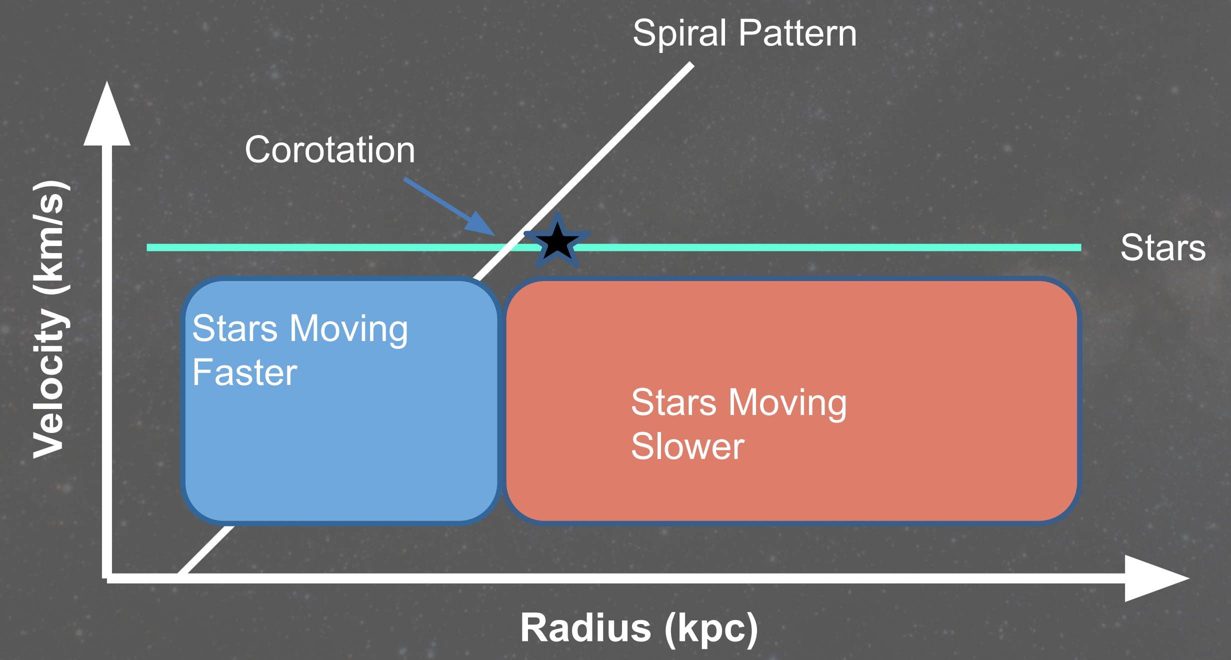
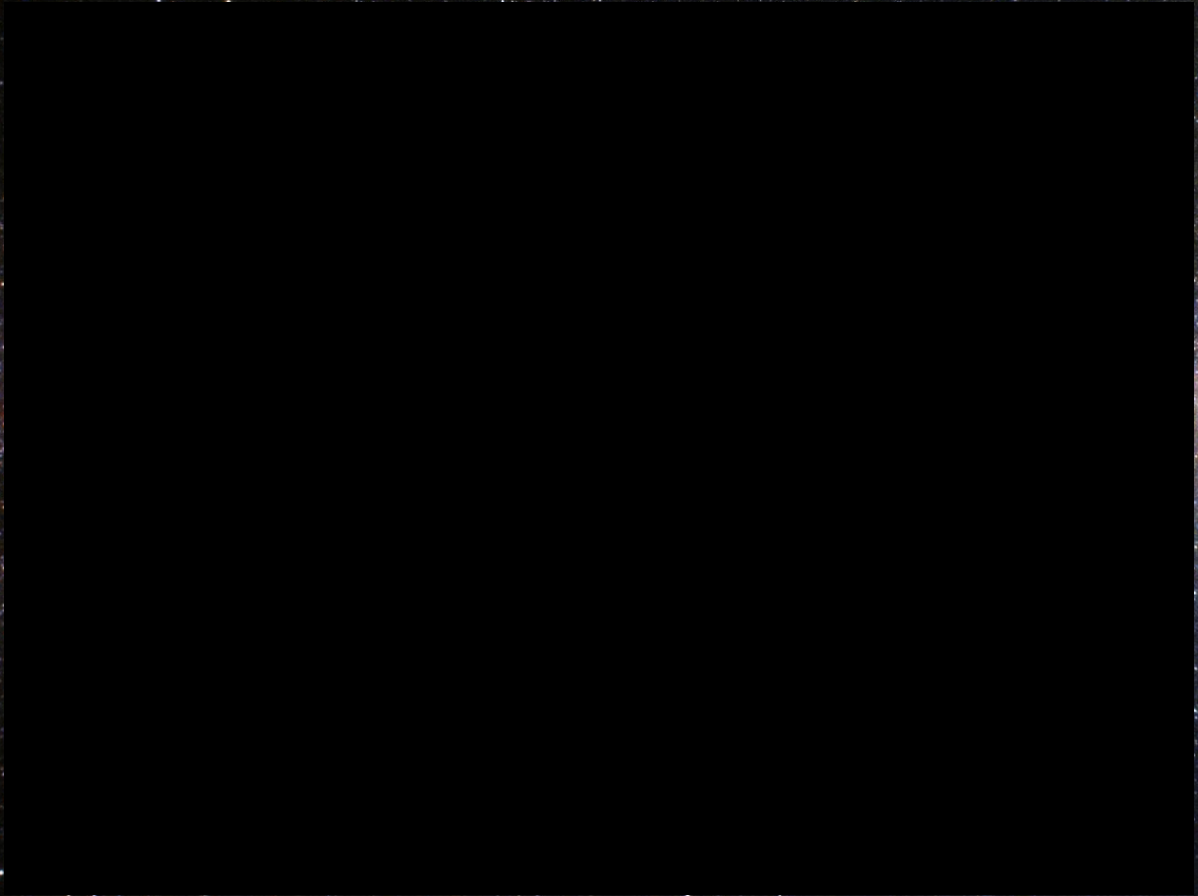


How Migration Works

Credit:
Neige Frankel

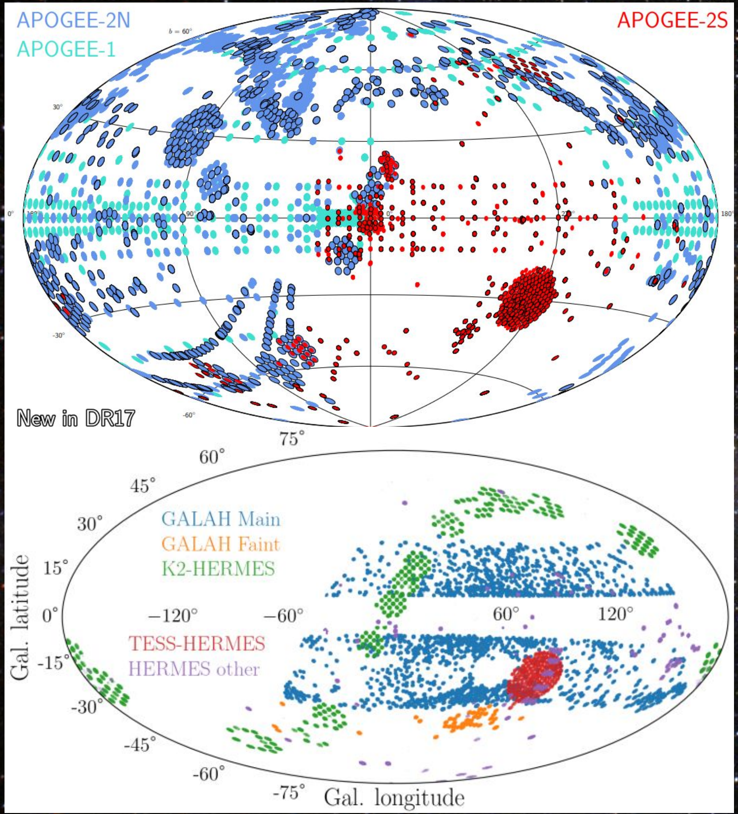
Migration Efficiency

Credit:
Neige Frankel



Large Scale Surveys

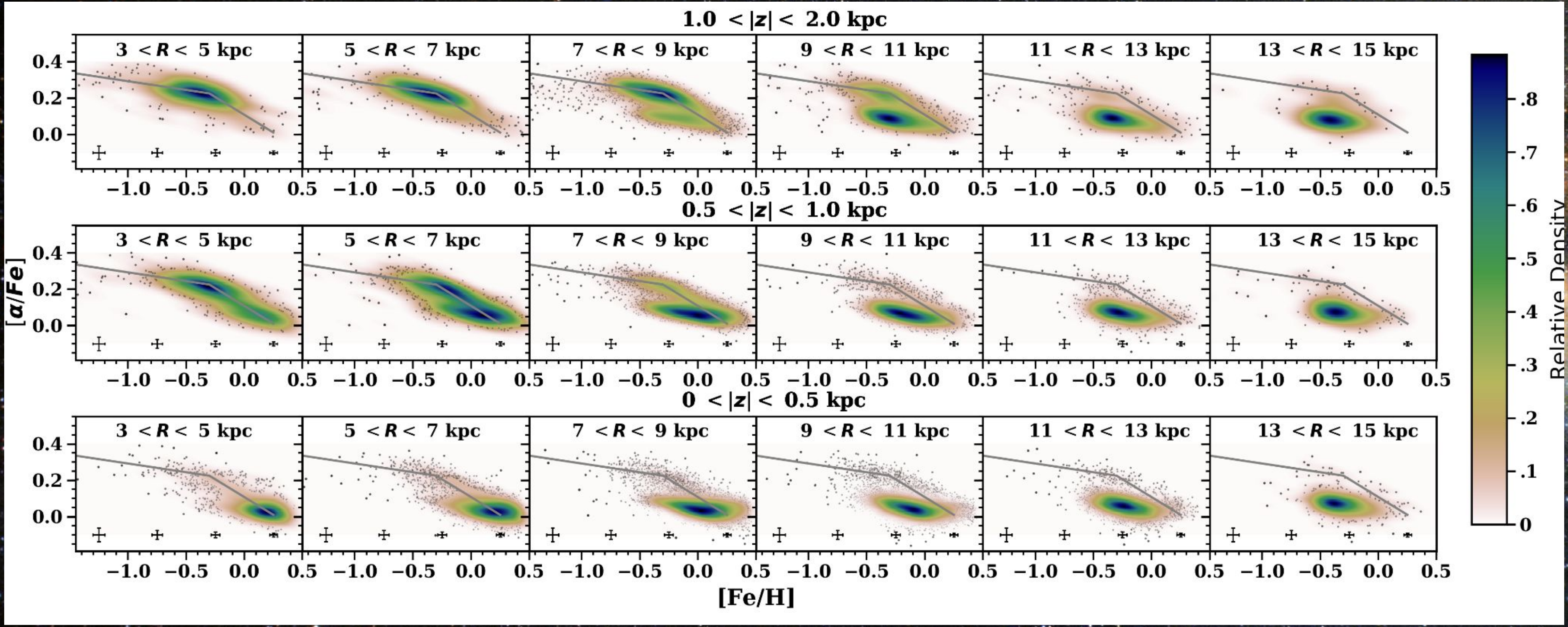
SDSS DR17



GALAH DR3

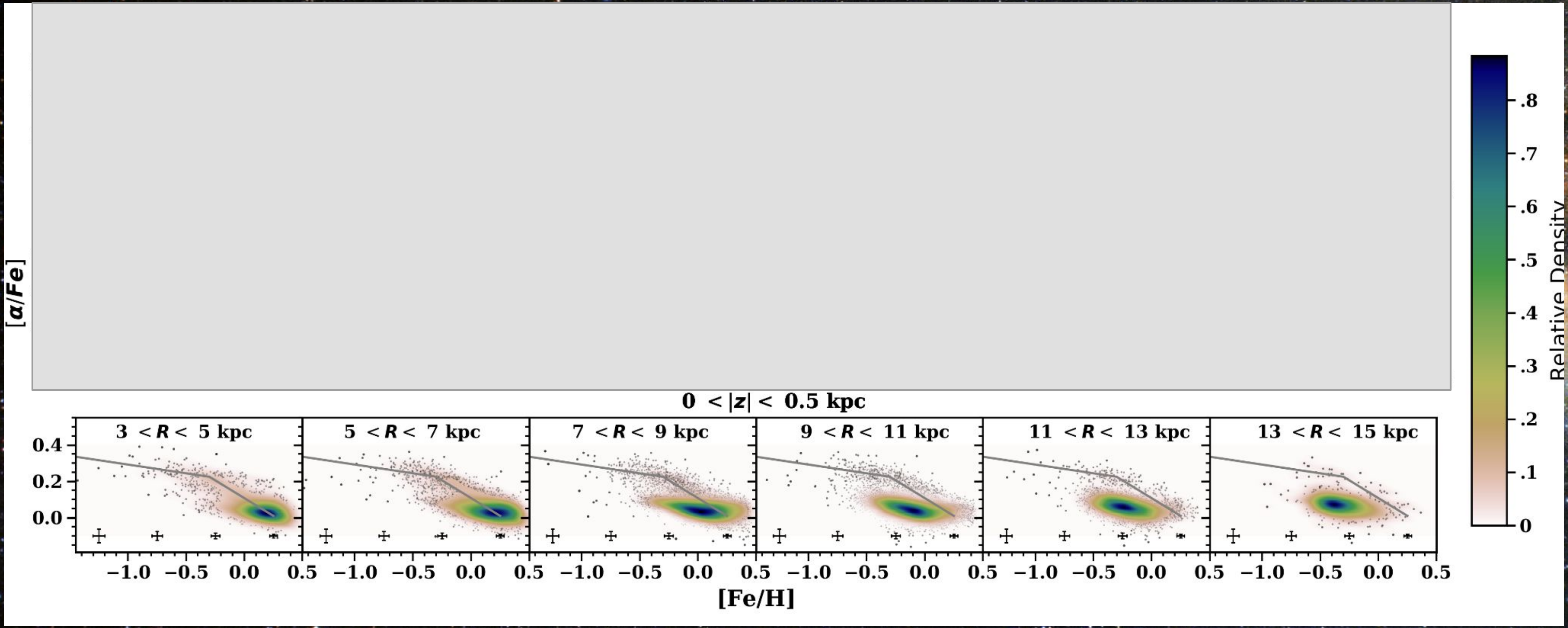
- Several Ongoing Spectroscopic Surveys of the Entire Sky: APOGEE, GALAH, LAMOST
- Millions of Stellar Spectra, Dozens of Abundances
- Future: 4MOST, WEAVE, DESI, SDSS5: Nearly 100 million high quality stellar spectra!

Milky Way Disk: Chemical Map



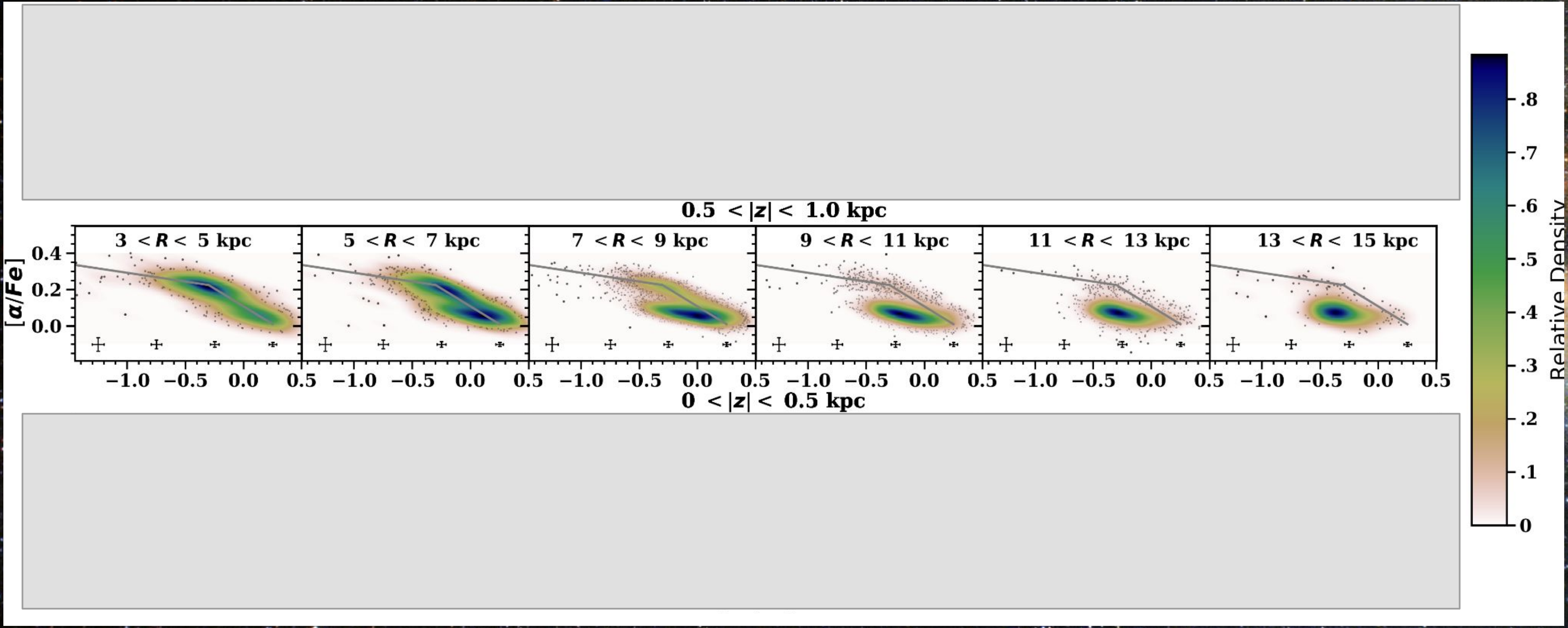
Hayden+2015

Milky Way Disk: Chemical Map



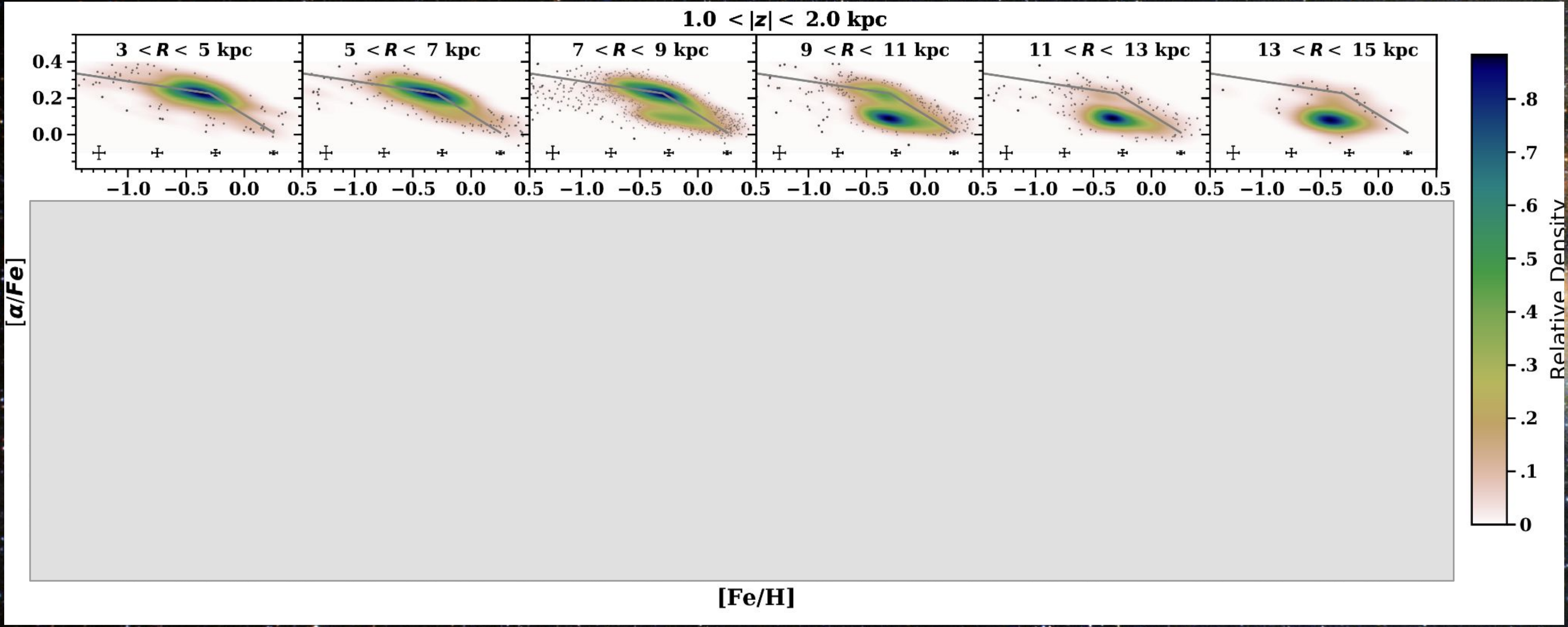
Hayden+2015

Milky Way Disk: Chemical Map



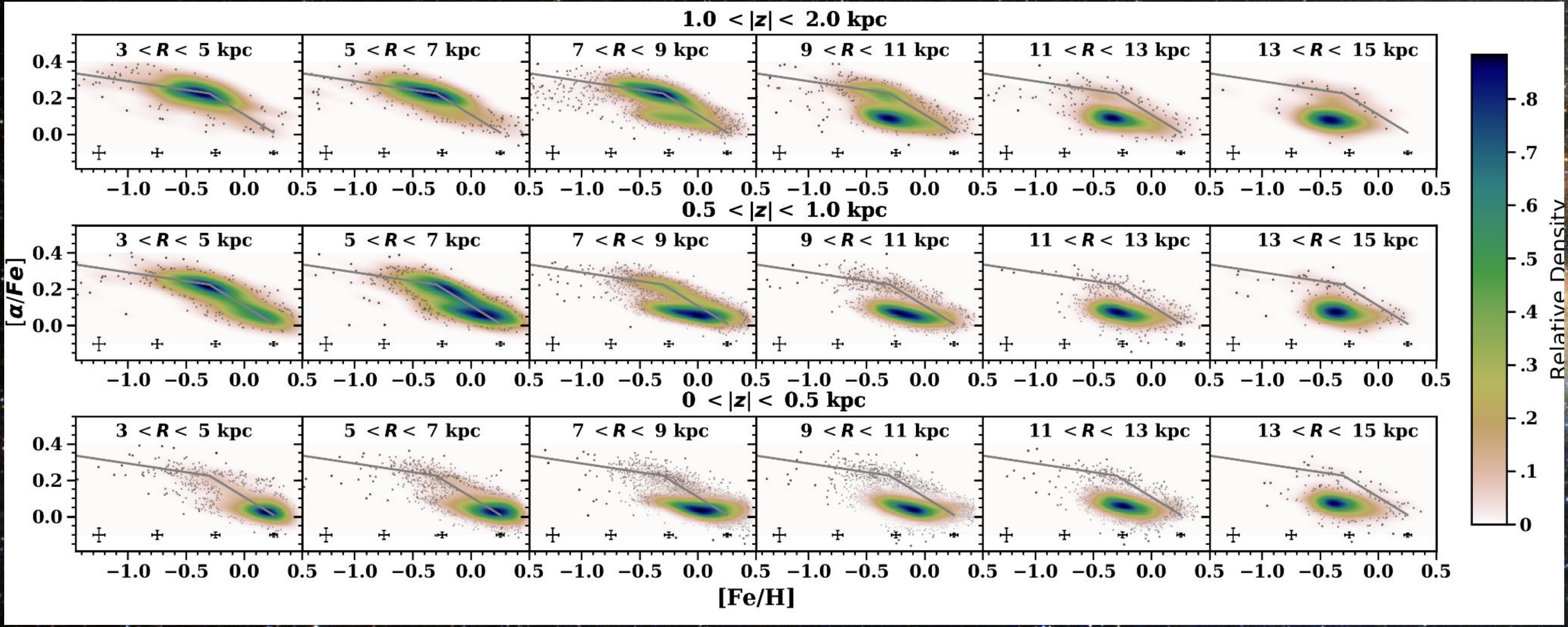
Hayden+2015

Milky Way Disk: Chemical Map



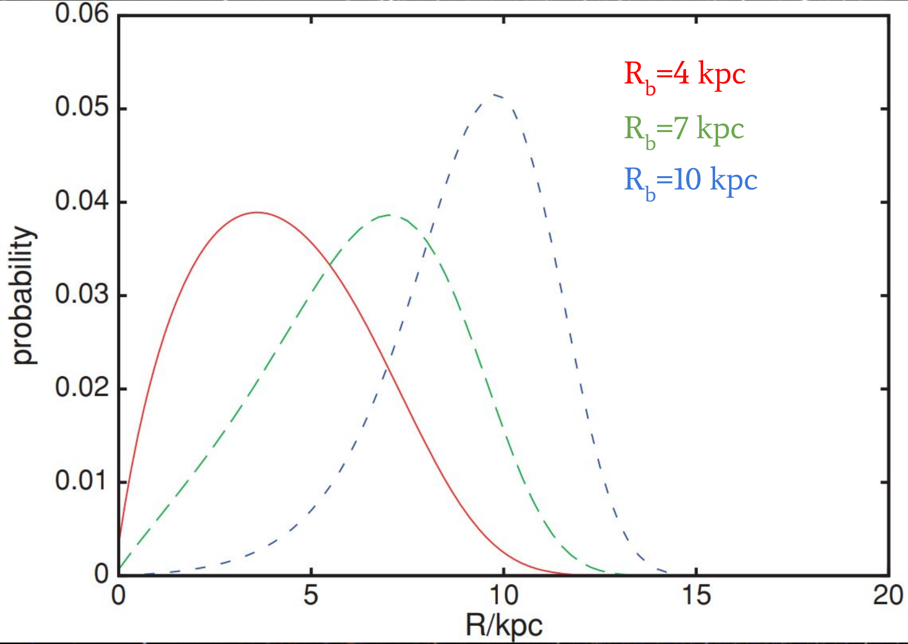
Hayden+2015

Milky Way Disk: Chemical Map



Hayden+2015

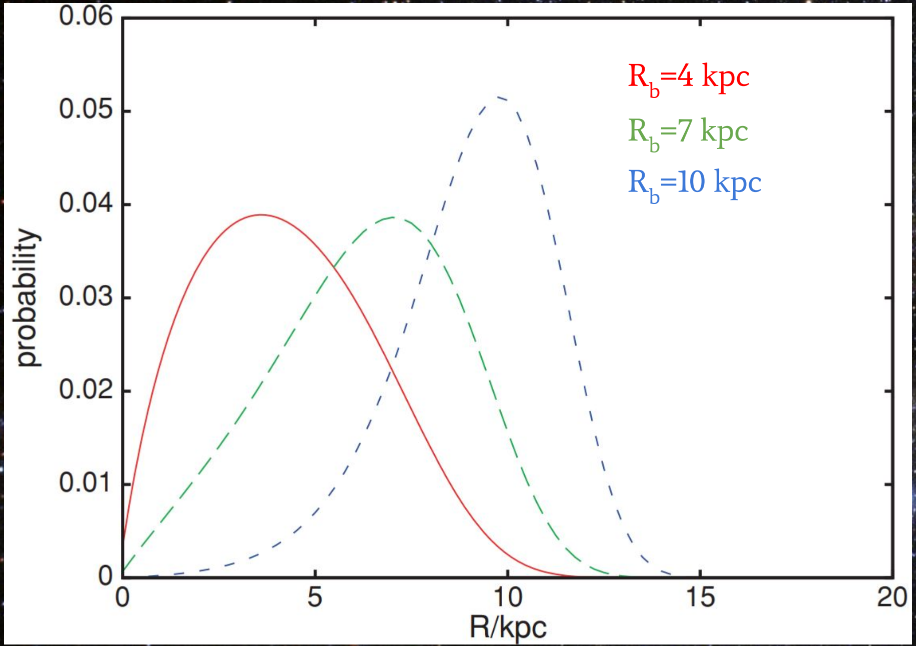
Radial Mixing: Stars Move!



Schoenrich+Binney 2009

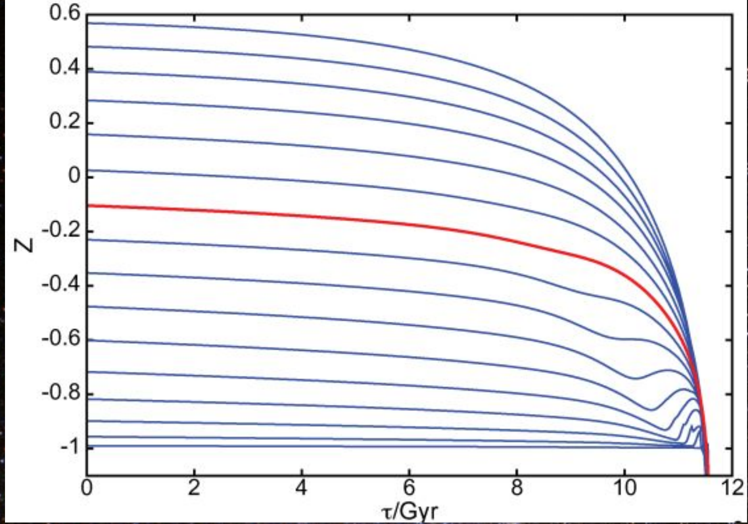
- Idea: Maybe stars move from their birth place!

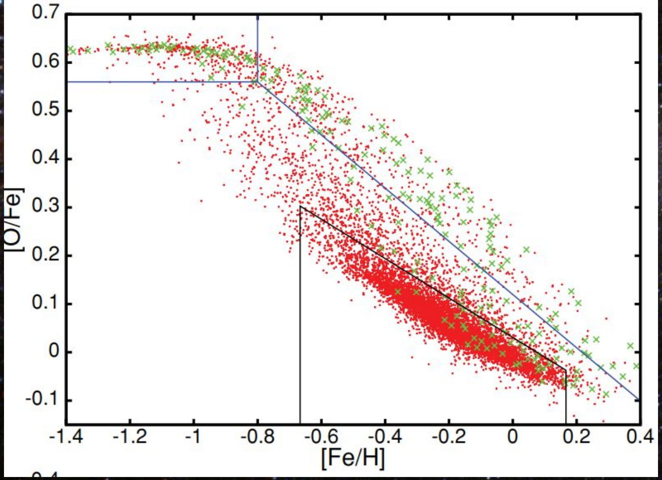
Radial Mixing: Stars Move!



Schoenrich+Binney 2009

- ISM at different radii in the disk have a set, steady evolution
- We mix stars after they are born
- Two sequences: one inner disk, one outer disk→stars born in different places

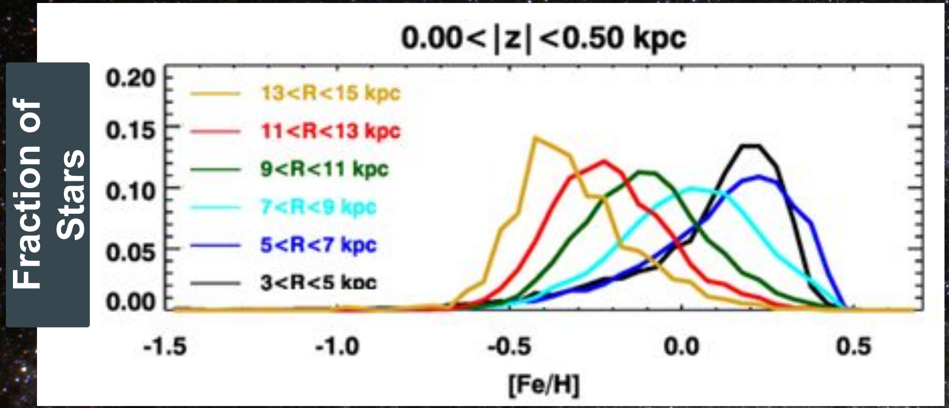


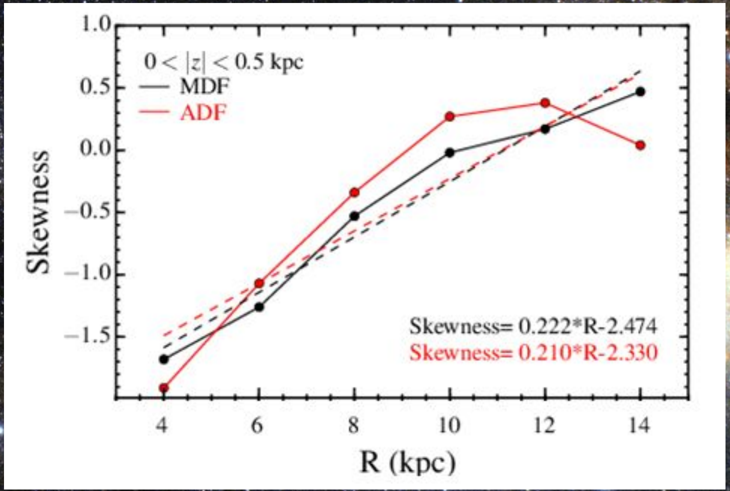


Schoenrich+Binney 2009

- Different radii in the disk have their own evolution
- Stars move around after they are born

Metallicity Distribution: Higher Order Moments

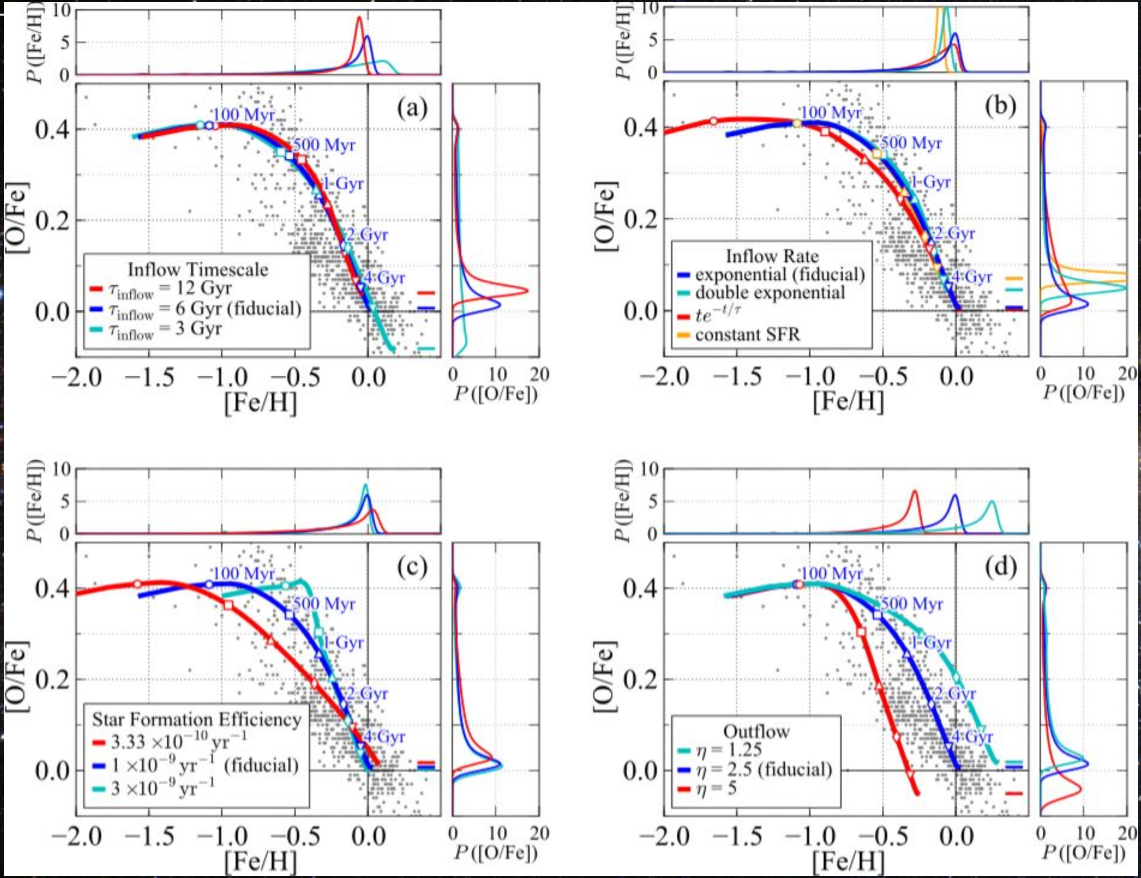




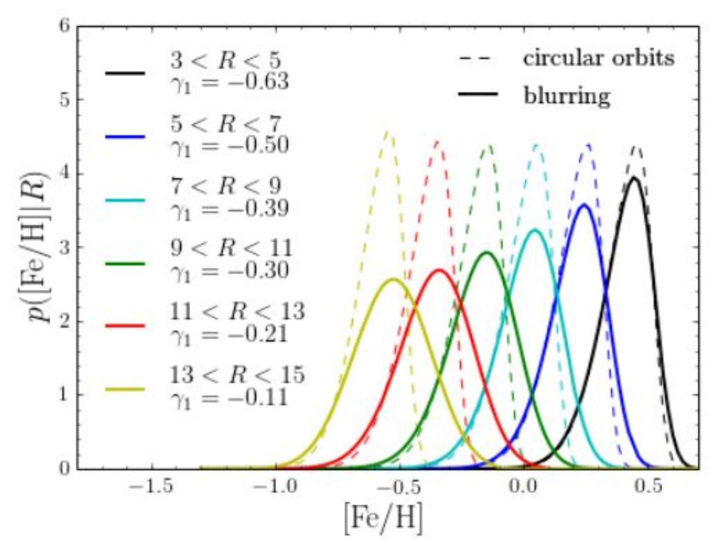
Hayden+ 2015

Positively Skewed MDFs?

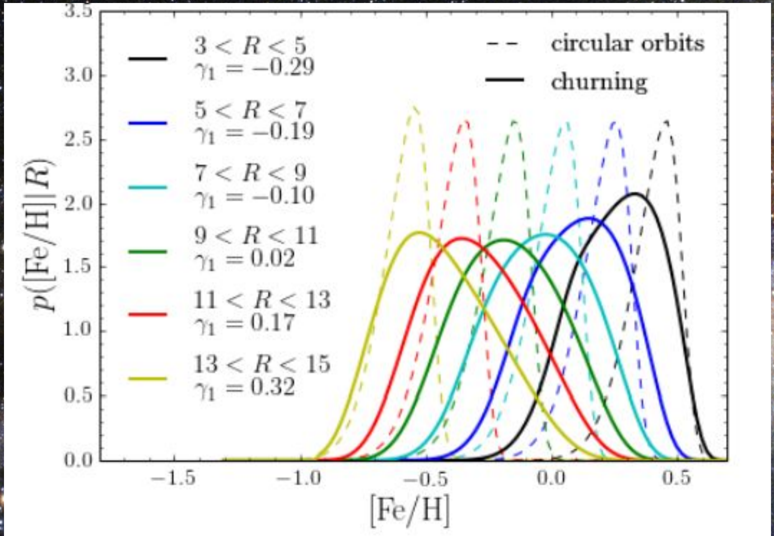
Andrews+2016



Toy Model: Migration Needed



Blurring

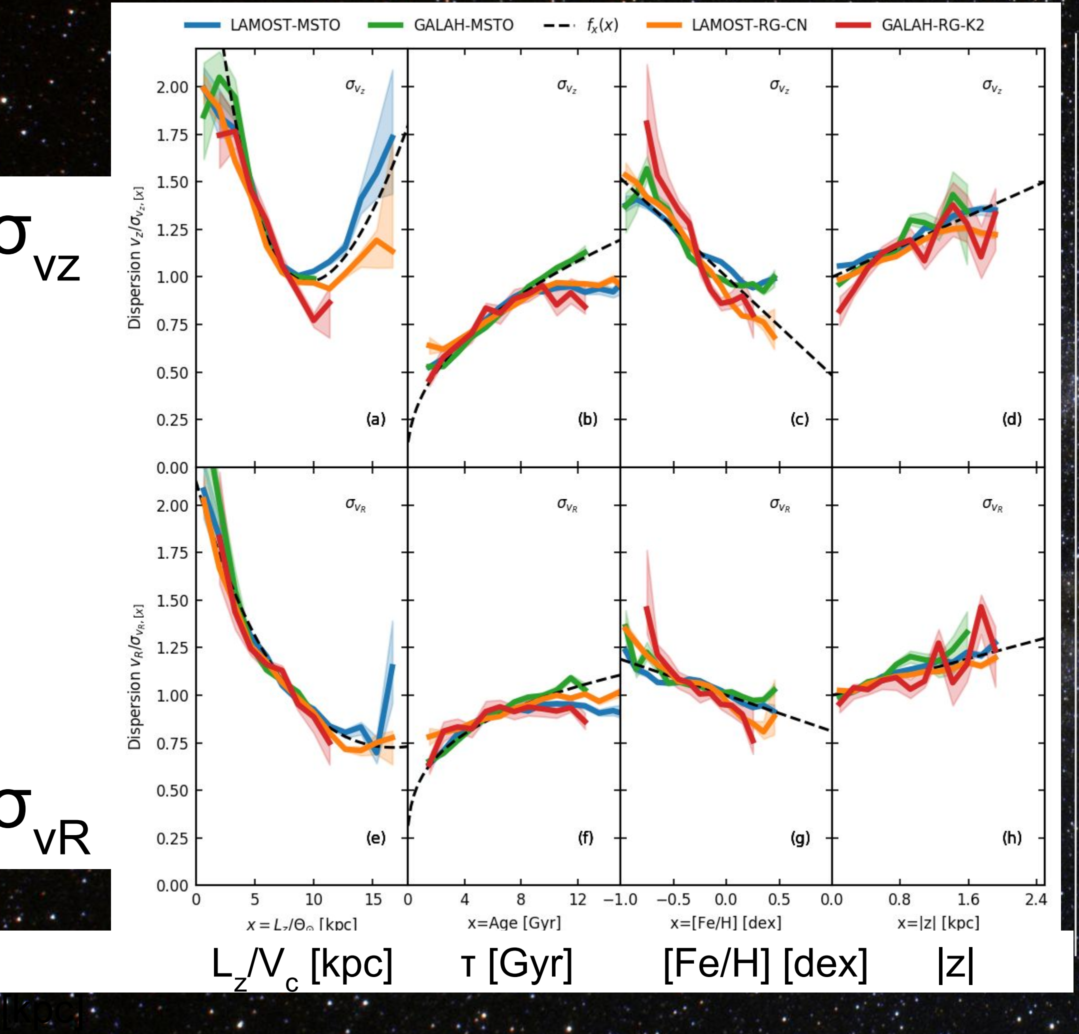


Migration

Hayden 2015

Fundamental Relations for Velocity Dispersion

- $\sigma_v(\tau, L_z, [\mathrm{Fe/H}], |z|) = \sigma_{v0}\ f_\tau\ \ f_{Lz}\ \ f_{[\mathrm{Fe/H}]}\ \ f_z$
  - Dispersion depends on Age, Angular Momentum, [Fe/H], and |z|
  - How to visualize this multivariable problem?
  - We plot, dispersion of $v\,/\,(\sigma_{v0}\, f_{Lz}\ \ f_{[\mathrm{Fe/H}]}\ \ f_z) \rightarrow\ f_\tau$
    - *Divide out the dependence of other variables*



- Different **spectroscopic surveys** agree.
- Different **stellar types** agree.
  - MSTO seismic
  - RG with C/N
  - Giants with astero-seismology
- **Old and young all on same line: no separate thick disk**

What We Want to Answer

Boquan (Erwin) Chen (ANU)

arXiv:2204.11413

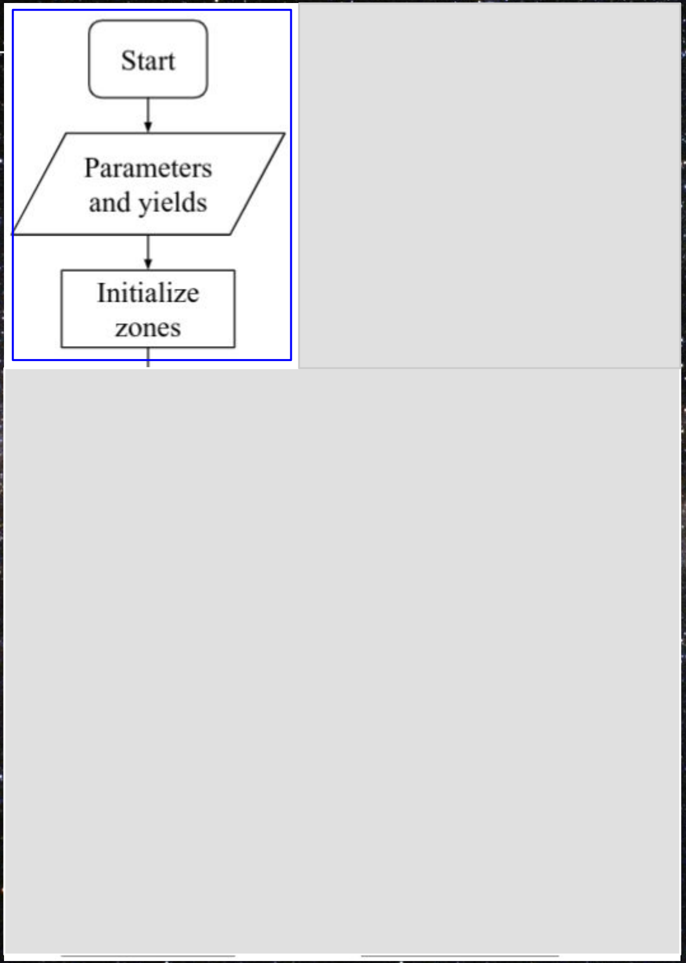
- Want to explain the detailed chemical abundances of the Galaxy
- How the abundances vary with position in the disk
- Identify Likely Formation Pathway for Thick/high-α disk
- Build upon pioneering work from Schoenrich & Binney 2009

Model Ingredients

- Multiple Radial Zones: Need to track abundances /w position!
- Two Phase ISM: Cold+Warm
- Gas: Accretion, cooling, radial flow→ try and maintain exponential gas disk
- Star Formation+Stellar Evolution
- Supernovae Yields+Delay Time Distributions
- AGB Yields
- Radial Mixing of Stars and Gas: Both blurring+migration
- 30 Myr Time Step: Maximum Age of SNII Progenitor
- Smooth Gas Accretion History: No Mergers!

Model Ingredients

Chen,Hayden+2022



Model Ingredients

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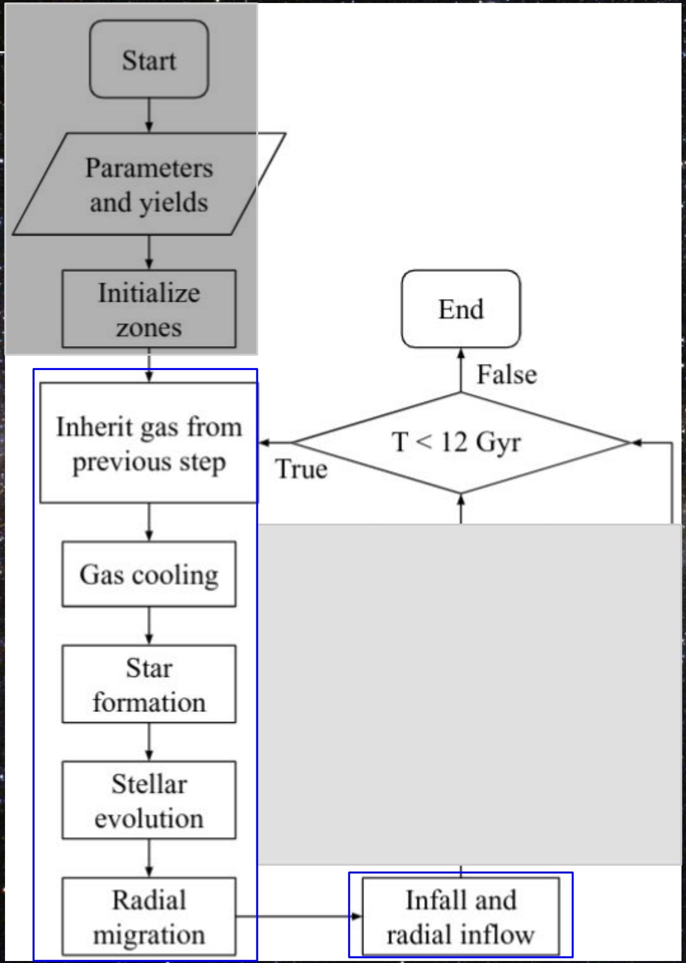

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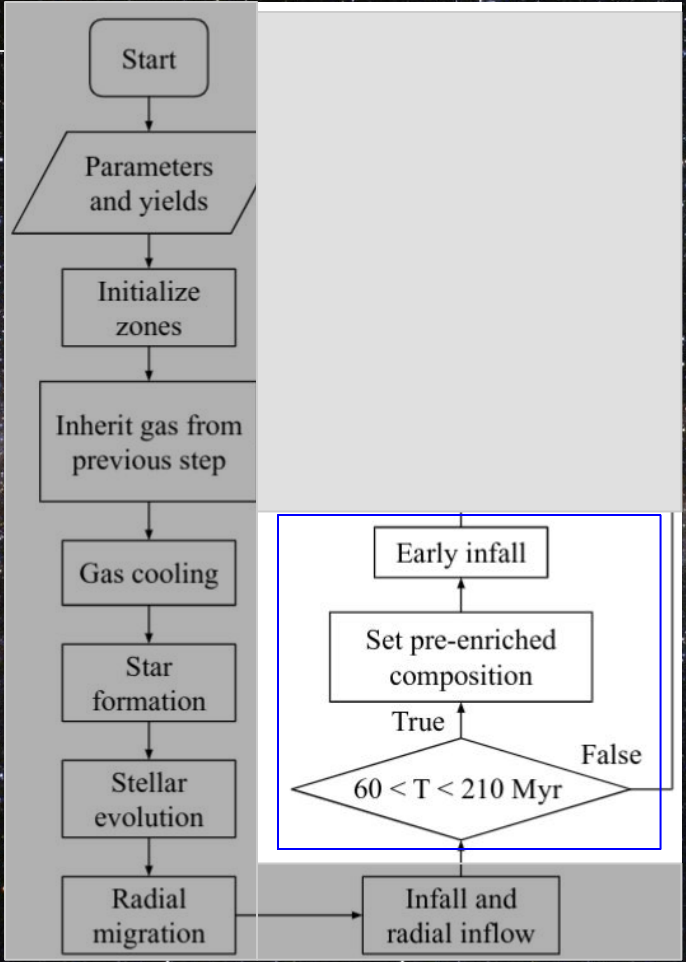

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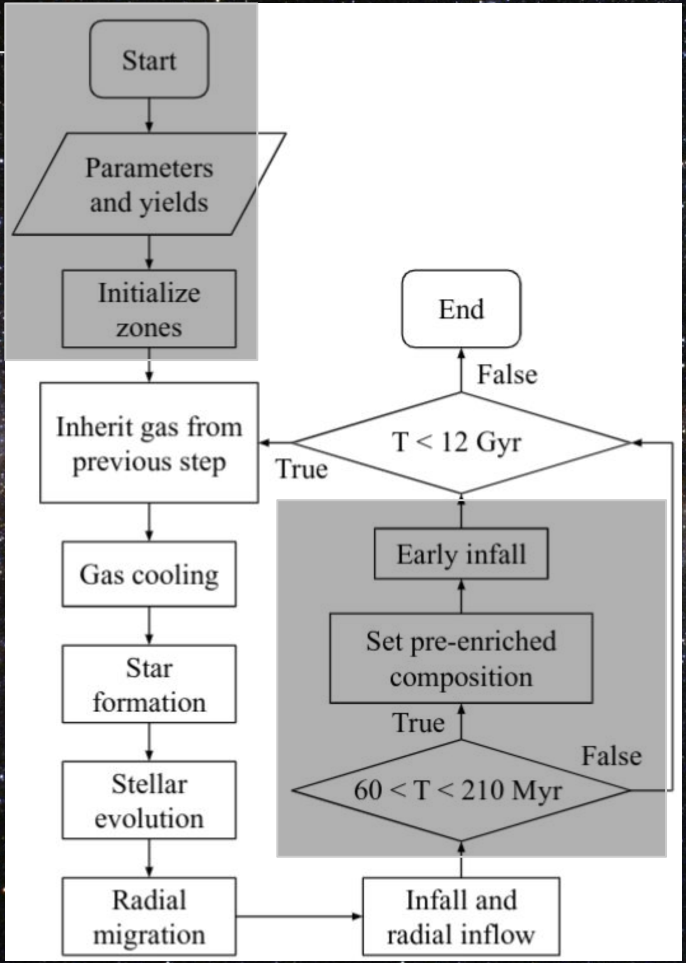
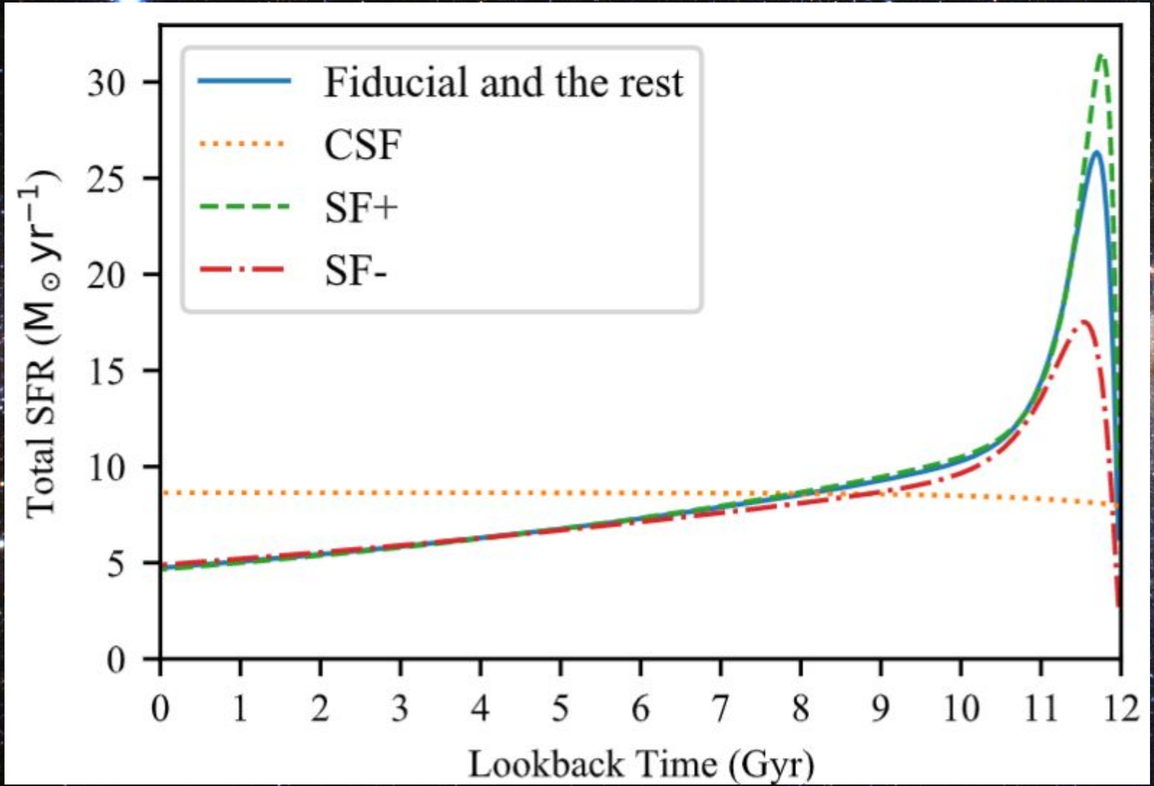
Chen,Hayden+2022

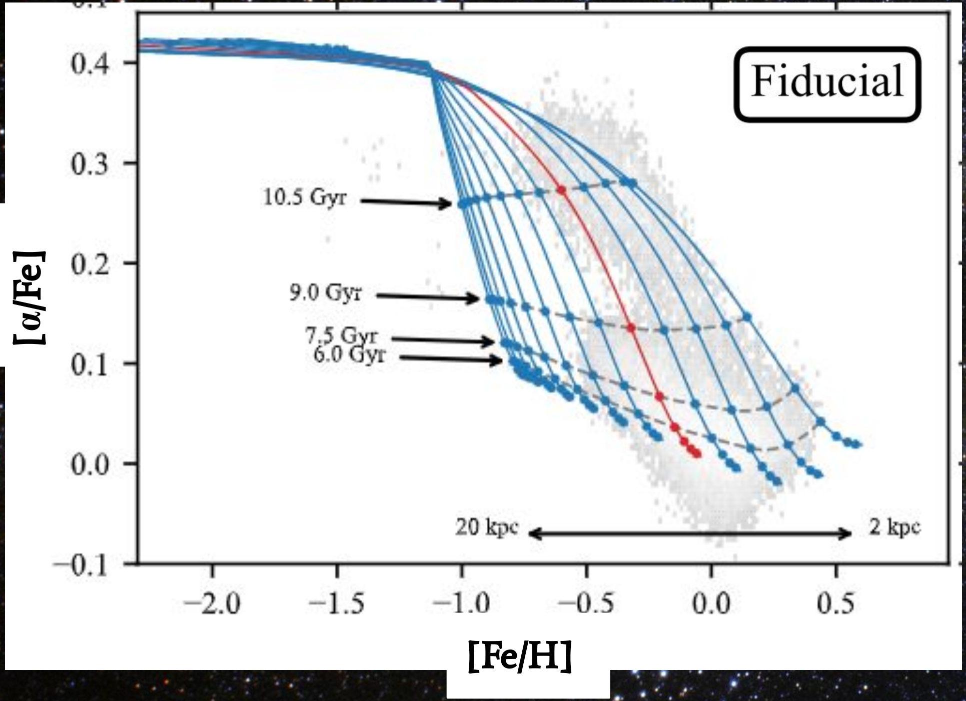


SFR/SFH



Chen, Hayden+2022

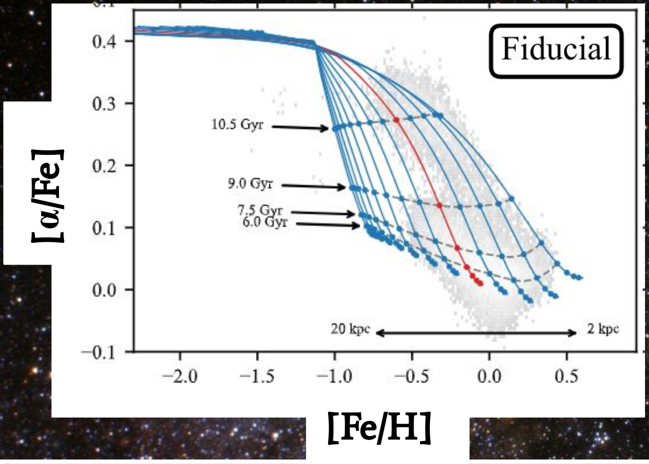
The Model

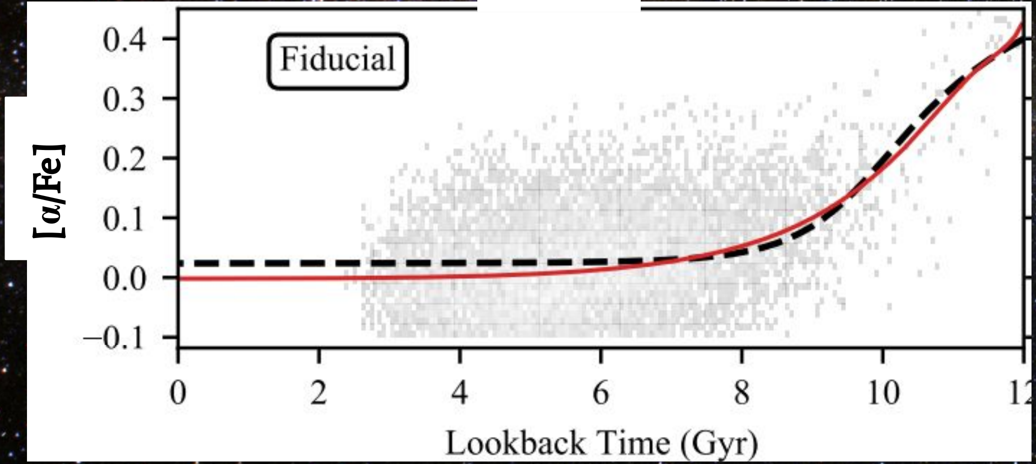


Chen,Hayden+2022

- Solar neighborhood data in greyscale
- Strong radial gradient→ inner Galaxy metal rich, outer galaxy metal poor
- Rapid chemical enrichment early on, slow enrichment later
- Most high alpha stars born in inner Galaxy

The Model

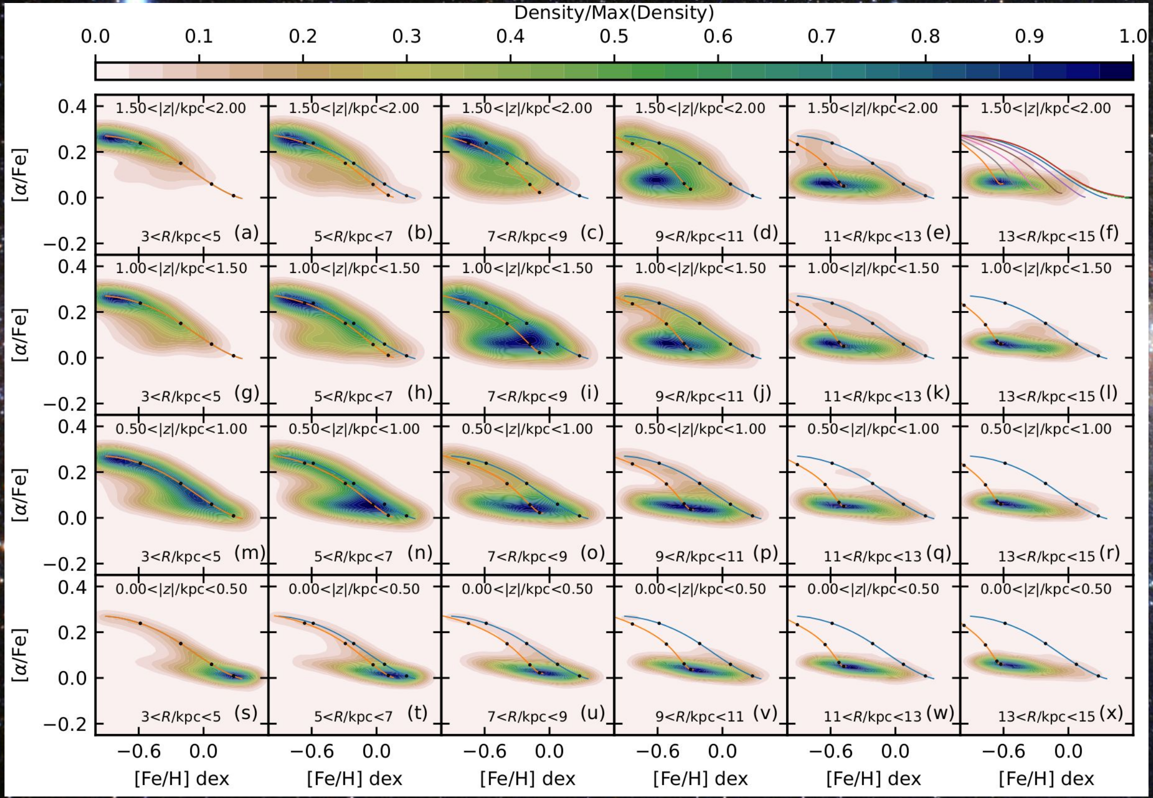




Chen,Hayden+2022

- Solar neighborhood data in greyscale
- Strong radial gradient→ inner Galaxy metal rich, outer galaxy metal poor
- Rapid chemical enrichment early on, slow enrichment later
- Evolution of α with time matches data

Model: Chemical Map of the Disk

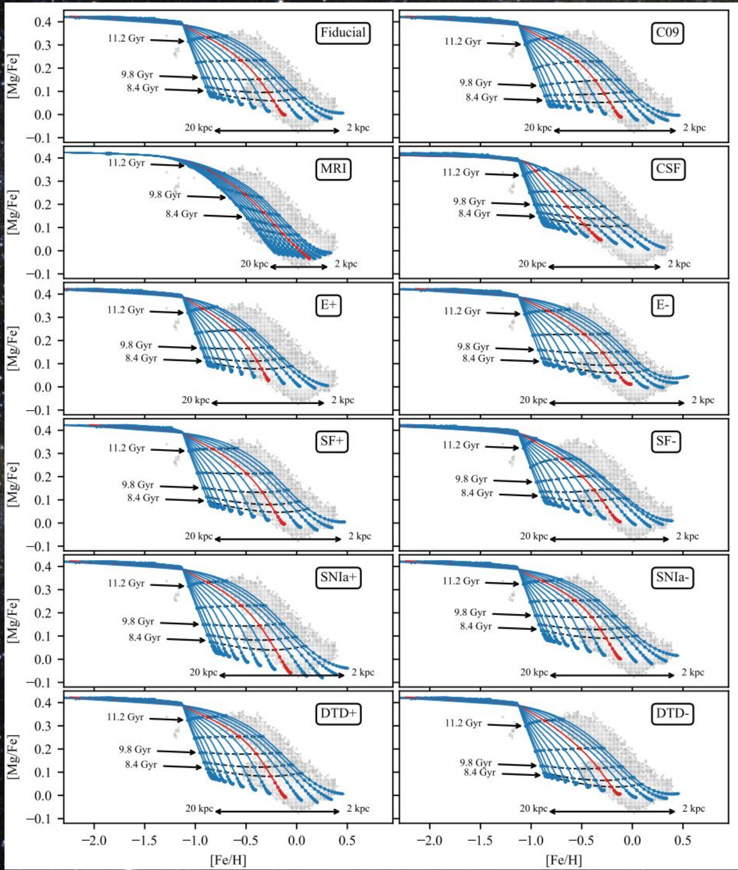


Chen,Hayden+2022

Model Parameters

Table 1. Parameters of the standard model.

Parameter	Meaning	Value
R_d	Scalelength of cold gas	3.5 kpc
C	Star formation efficiency constant	2.2×10^{-10}
N	Power in star formation law	1.4
$M_{0,\mathrm{cold}}$	Initial cold gas mass	$7 \times 10^{9} M_{\odot}$
$M_{0,\mathrm{warm}}$	Initial warm gas mass	$1 \times 10^{9} M_{\odot}$
ΔM_{warm}	Early infall mass per step onto warm gas	$2.5 \times 10^{8} M_{\odot}$
M_1	Short timescale infall mass	$1 \times 10^{10} M_{\odot}$
M_2	Long timescale infall mass	$1 \times 10^{11} M_{\odot}$
b_1	Timescale for M_1	150 Myr
b_2	Timescale for M_2	1.4 Gyr
$t_{\mathrm{min,SNeIa}}$	Minimum time delay before first SNe Ia	150 Myr
$t_{\mathrm{scale,SNeIa}}$	Timescale for decay of SNe Ia	1.5 Gyr
t_{cool}	Cooling timescale of warm gas	1.2 Gyr
f_{direct}	Fraction of ejecta directly into cold gas	0.01
f_{eject}	Fraction of ejecta lost	0.3-0.04
$Z_{M_{\odot}}$	Metallicity of the Sun	0.0156
Z_{IGM}	Metallicity of the IGM	$10^{-0.8} Z_{M_{\odot}}$
f_{IGM}	The fraction of gas directly deposited from IGM	0.25
%SNeIa	Fraction of white dwarfs from stars within $(3.2, 8.5)M_{\odot}$ that turn into SNe Ia	0.05
%HNe	Fraction of CCSN that explode as hypernovae	0.5
%MRSN	Fraction of CCSN that explode as magneto-rotational supernovae	0.0025
v_0	Rotational velocity of the Milky Way from Sanders & Binney (2015)	220 km/s
σ_{L_0}	Churning amplitude from Sanders & Binney (2015)	1150 kpc km/s
t_{max}	Maximum age of the Milky Way	12 Gyr



Chemical Evolution Summary

- Developed a detailed chemical evolution model that takes into account many physical processes including radial mixing
- First chemical evolution model that closely matches the entire chemical distribution of stars in the Galaxy
- Able to reproduce the high-α disk and bimodal distribution of stars in solar neighborhood with no mergers required!
- Implies that this might be natural evolution of disk galaxies, rather than rare event
- Lots more things to look at: s-process abundances, more gas processes, etc!

The Milky Way in Context

- MW is only a single galaxy: can't constrain all of galaxy evolution with one data point!
- Build data cubes of our chemical evolution model to directly compare to external observations
- GECKOS: large ESO Program to look at edge on galaxies, directly compare to MW+Apply Chemodynmical Models

How Common is the Milky Way?

The origin of diverse α-element abundances in galaxy discs

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ABSTRACT

Spectroscopic surveys of the Galaxy reveal that its disc stars exhibit a spread in [α/Fe] at fixed [Fe/H], manifest at some locations as a bimodality. The origin of these diverse, and possibly distinct, stellar populations in the Galactic disc is not well understood. We examine the Fe and α-element evolution of 133 Milky Way-like galaxies from the EAGLE simulation, to investigate the origin and diversity of their [α/Fe]-[Fe/H] distributions. We find that bimodal [α/Fe] distributions arise in galaxies whose gas accretion histories exhibit episodes of significant infall at both early and late times, with the former fostering more intense star formation than the latter. The shorter characteristic consumption timescale of gas accreted in the earlier episode suppresses its enrichment with iron synthesised by Type Ia SNe, resulting in the formation of a high-[α/Fe] sequence. We find that bimodality in [α/Fe] similar to that seen in the Galaxy is rare, appearing in approximately 5 percent of galaxies in our sample. We posit that this is a consequence of an early gas accretion episode requiring the mass accretion history of a galaxy's dark matter halo to exhibit a phase of atypically-rapid growth at early epochs. The scarcity of EAGLE galaxies exhibiting distinct sequences in the [α/Fe]-[Fe/H] plane may therefore indicate that the Milky Way's elemental abundance patterns, and its accretion history, are not representative of the broader population of $\sim L^\star$ disc galaxies.

For external galaxies...

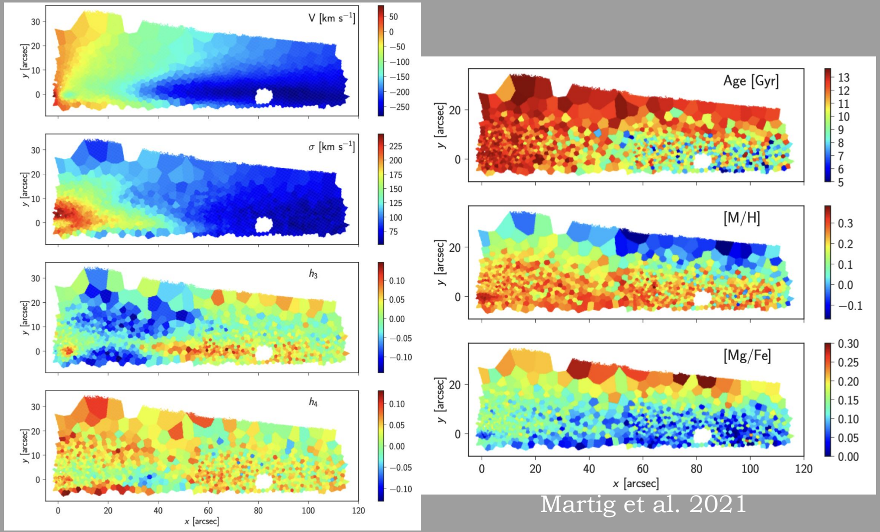
Integrated spectrum

↓ PPXF+MILES, etc

Kinematics (v, v_sig, h3, h4)

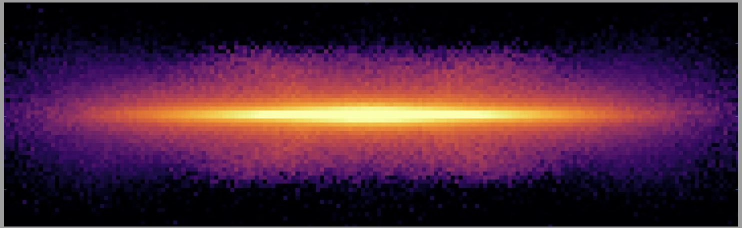
↓ PPXF+MILES

Chemical composition



Martig et al. 2021

For MW datacubes...



↑ Instrument properties

Integrated spectrum

↑ MILES SSP

Particles (mass, age, [Fe/H], [α/Fe], V_los)

↑ Spatial binning

MW view externally

↑ Distance, inclination

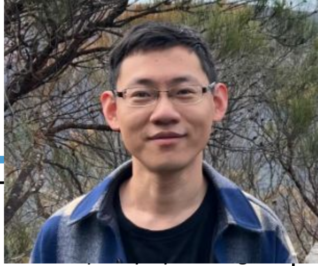
MW analytical model (~10e8 particles)

↑ Galaxia

Age, [Fe/H], [α/Fe], LOSVD distributions

The Milky Way in Context: Building an IFS Data Cube of the Galaxy

Purmortal (Zixian) Wang (zwan0382@uni.sydney.edu.au), Michael Hayden, Sanjib Sharma, Jesse van de Sande, Joss Bland-Hawthorn
Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW, 2006



Synopsis

In this work, we present a novel approach to generating the mock IFS data cube of use of the SSP spectral libraries and E-Galaxia. This tool is flexible about adjustable the galaxy distance, inclination, spatial and spectral resolution, instrument properties (SAMI/Hector, MUSE, etc) and observation properties (seeing, SNR, etc.)

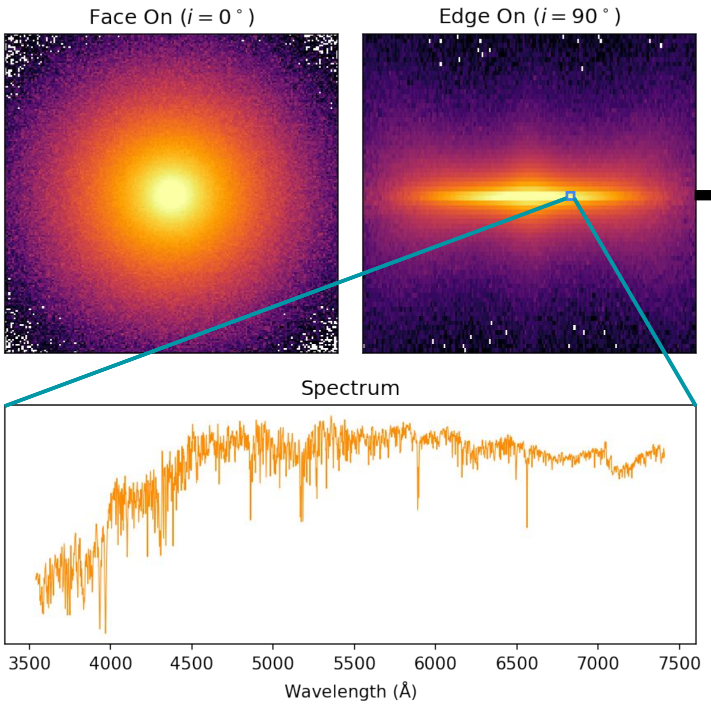


Figure 1: Top: Flux distributions of two generated Milky Way data cubes at wavelength $\lambda = 5500$ Å. The galaxy is firstly placed at 50Mpc from the observer, then rotated by different angles. No extinction/seeing is added on these data cubes. Bottom: Spectrum of one spatial pixel (marked on the top-right panel) generated by using MILES models.

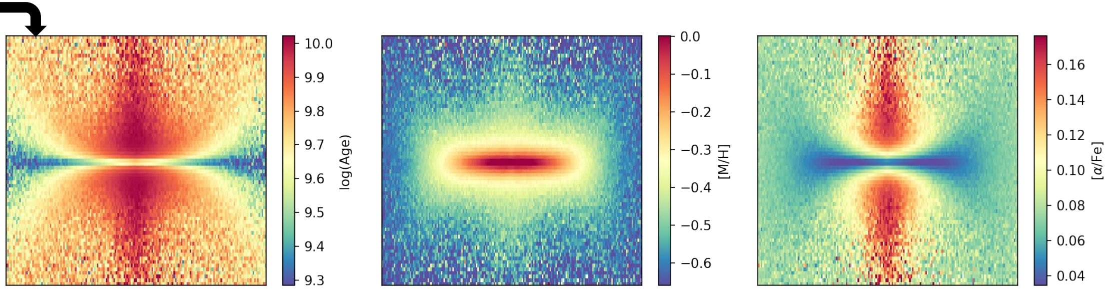


Figure 2: The age, metallicity and $[\alpha/\text{Fe}]$ distributions of the generated Milky Way data cube in the top-right panel of Figure 1. For each spatial pixel, the (age, metallicity, $[\alpha/\text{Fe}]$) values are mass-weighted averages from the MILES SSP model grids, where the mass is dependent on the particles lying in the pixel.

Ingredients

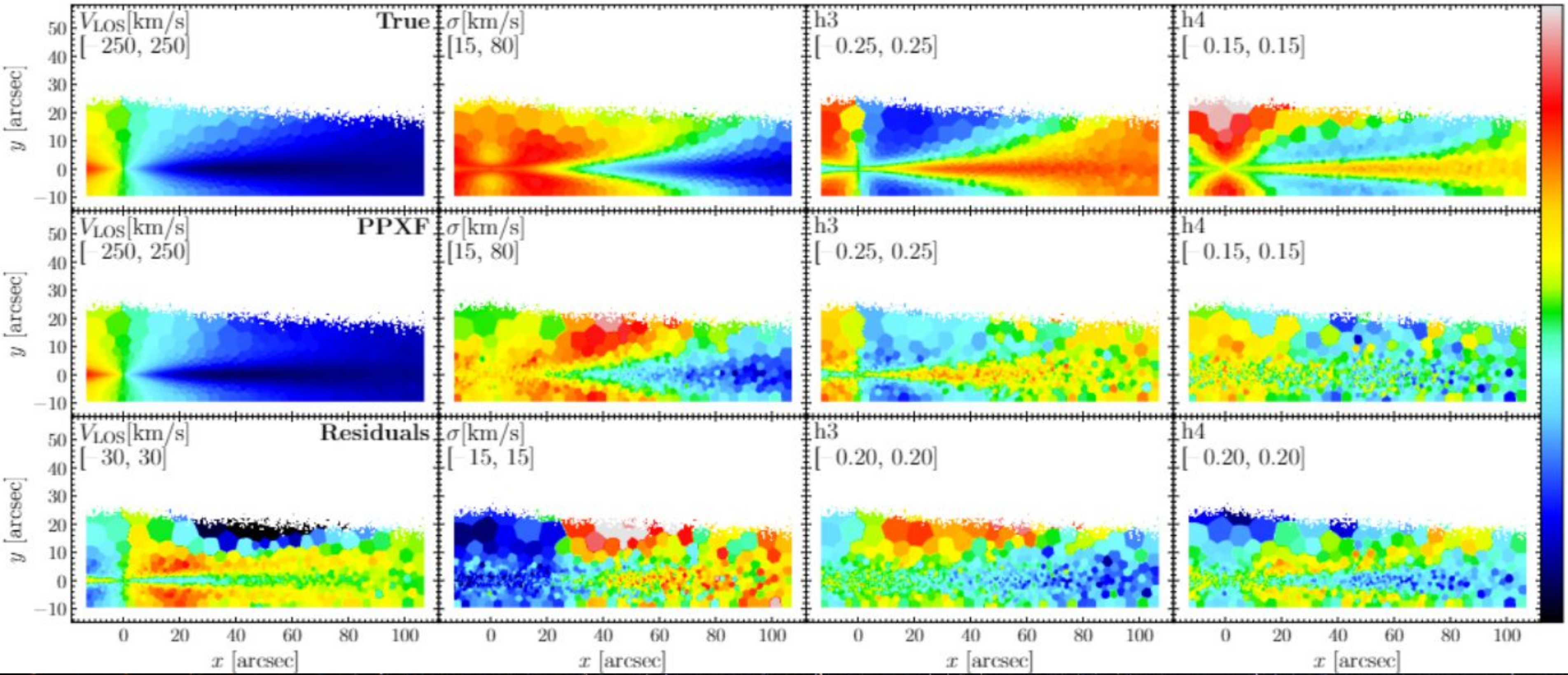
- E-Galaxia (Sharma et al. in prep 2022)
- Milky Way model (Sharma et al. 2020)
- SSP spectra libraries (MILES, PEGASE-HR, etc.)
- pPXF (Cappellari 2017)
- Data-cube properties
- Instrument properties

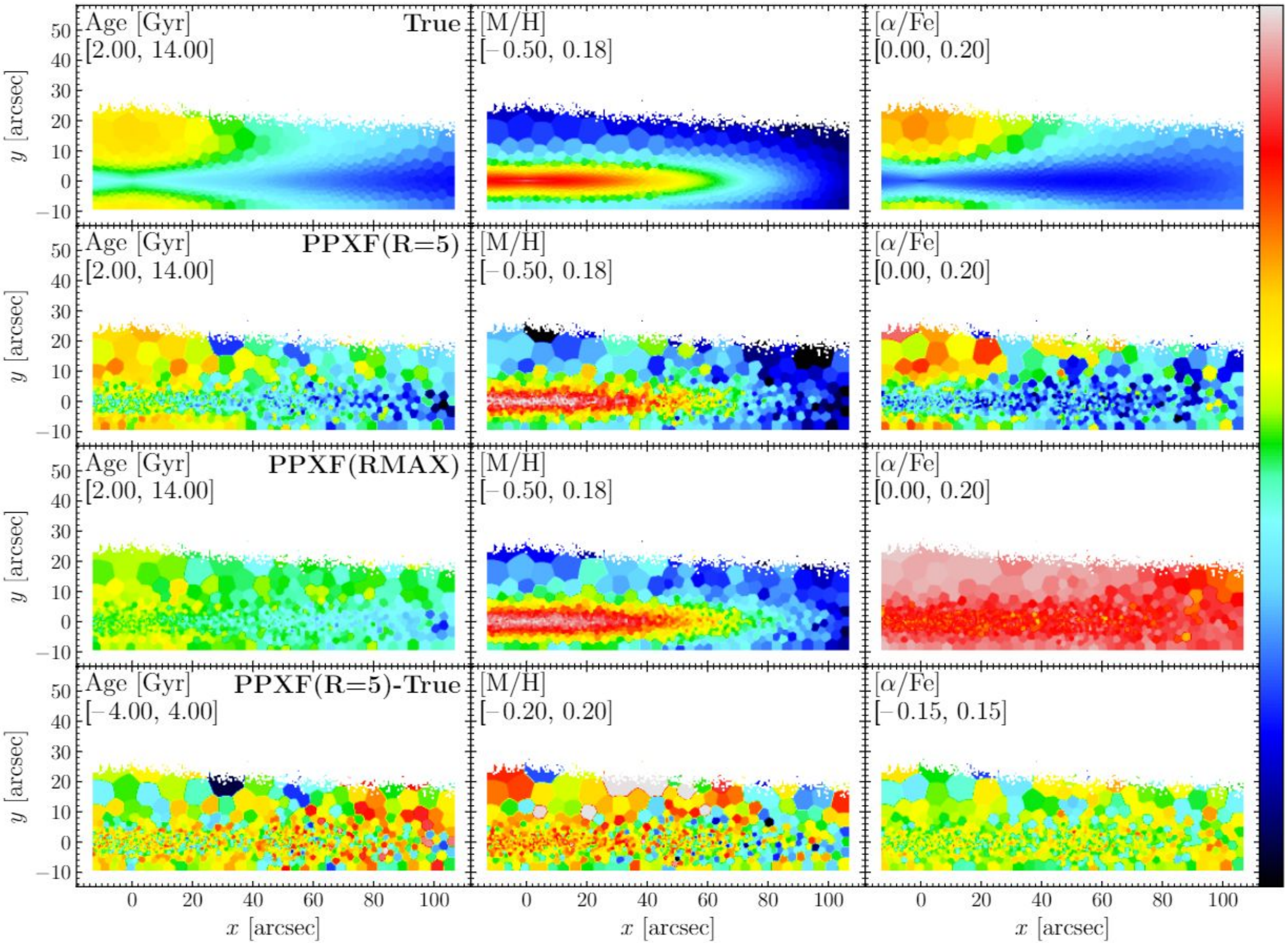
Applications

Direct chemo-dynamical structure comparison between external galaxies and the Milky Way on:

- Velocity dispersion profiles
- Radial and vertical age gradients
- Mass fraction of the $[\alpha/\text{Fe}]$-rich versus $[\alpha/\text{Fe}]$-poor populations

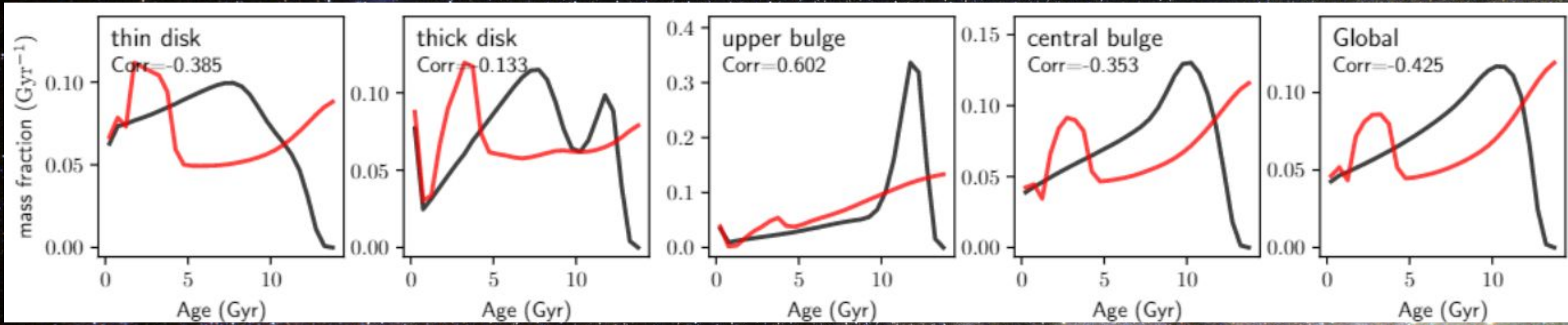
Velocities: Pretty Good!



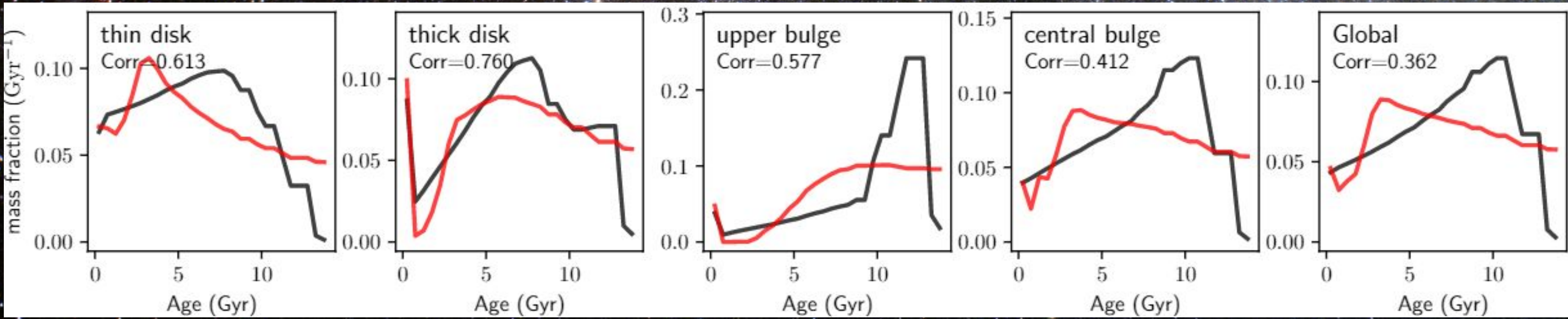

Age [Gyr]
[2.00, 14.00]
True
[M/H]
[−0.50, 0.18]
[α/Fe]
[0.00, 0.20]
PPXF(R=5)
PPXF(RMAX)
PPXF(R=5)-True
[−4.00, 4.00]
[−0.20, 0.20]
[−0.15, 0.15]
y [arcsec]
x [arcsec]

SFR: Not So Good

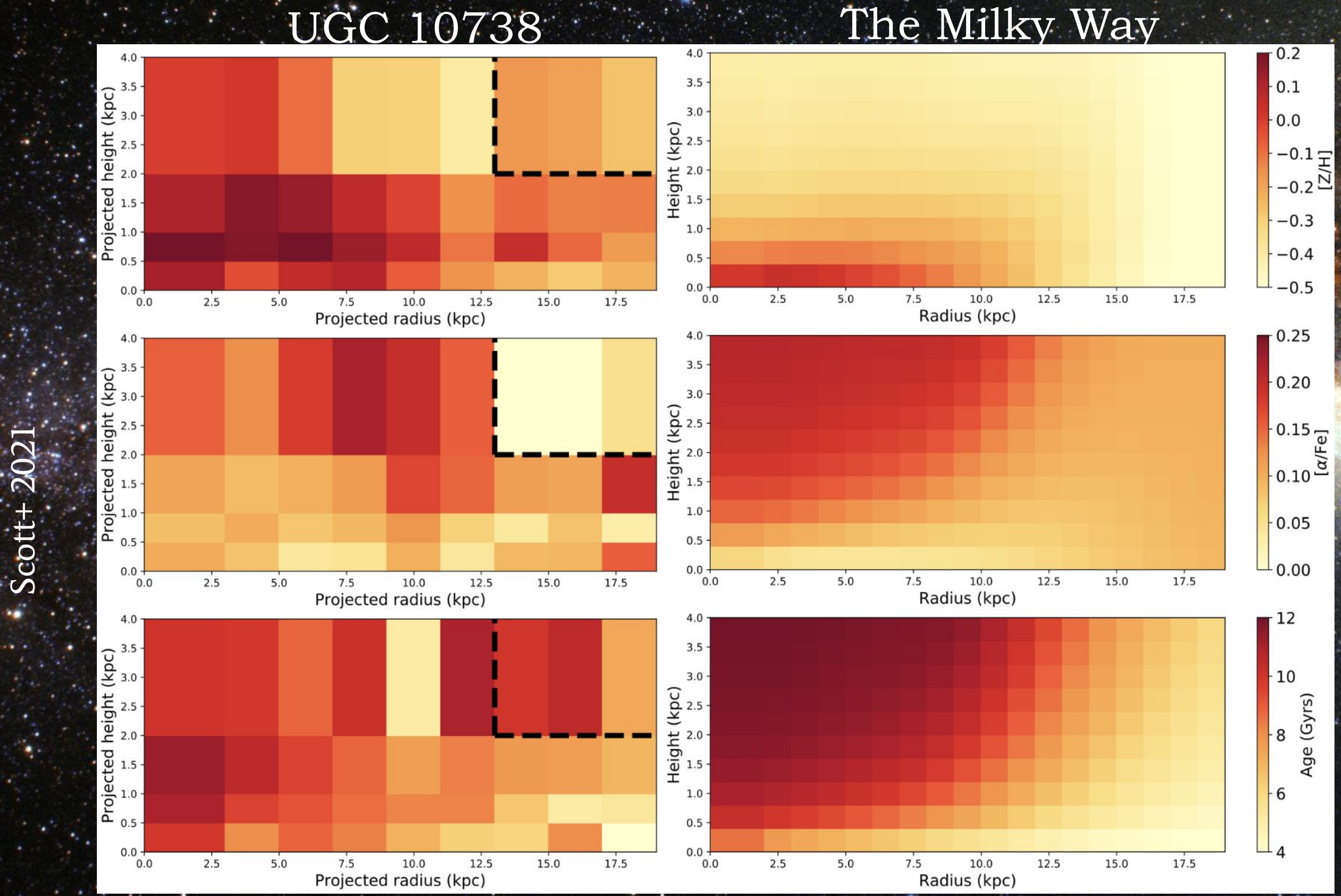
MILES



PEGASE



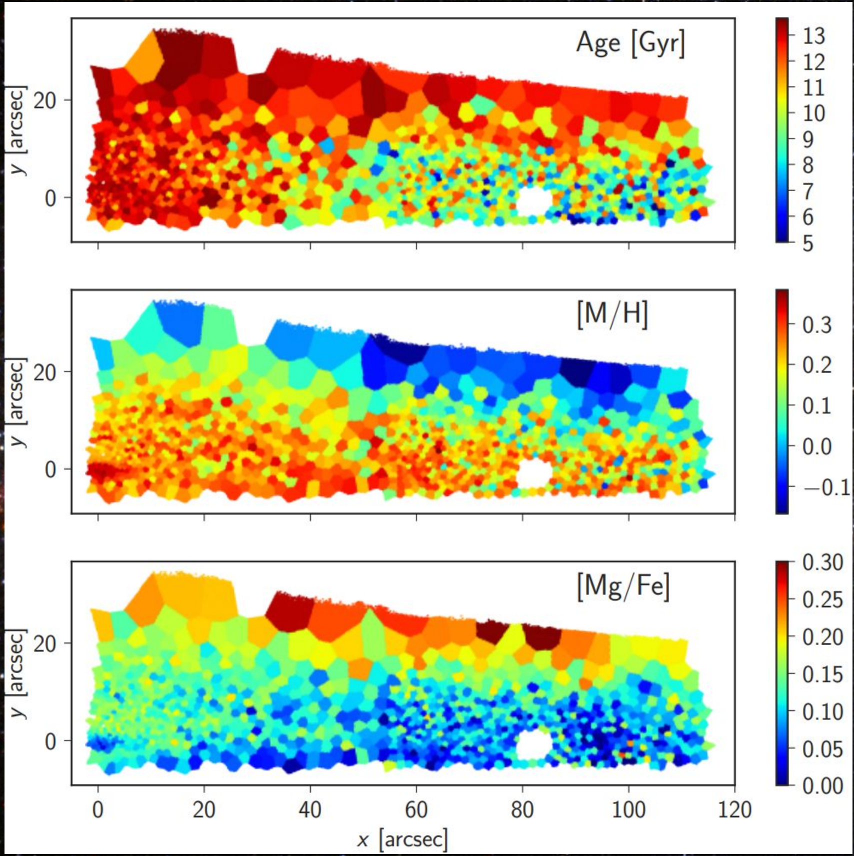
The Milky Way in Context



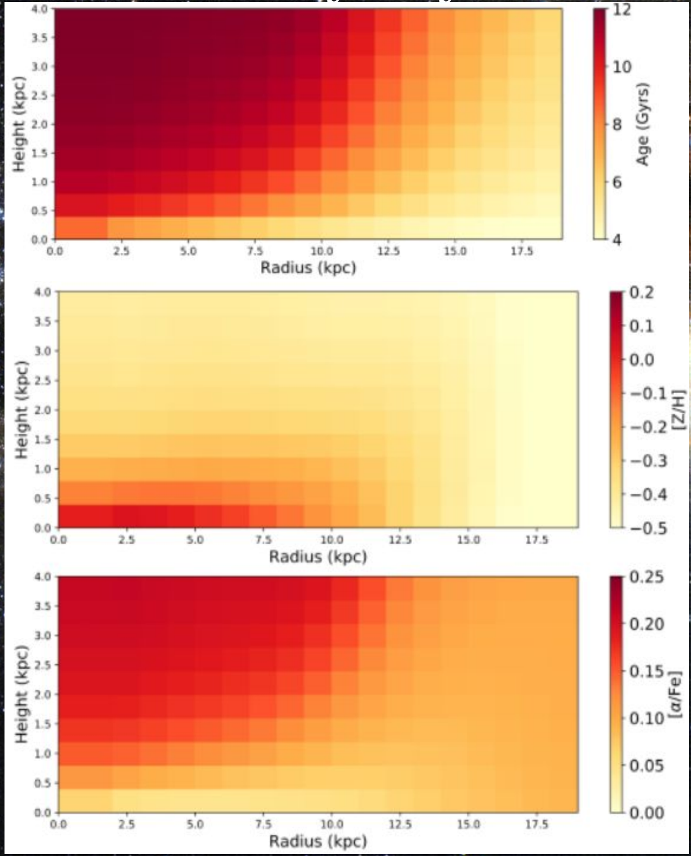
The Milky Way in Context

Martig+ 2021

NGC 5746

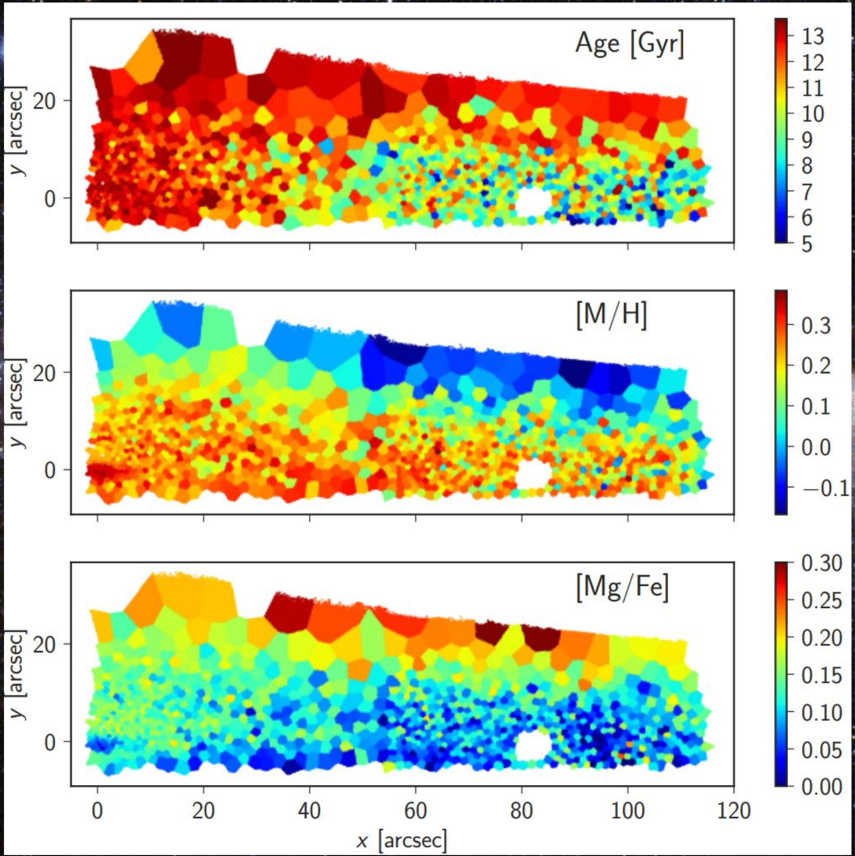


The Milky Way



The Milky Way in Context

NGC 5746



Martig+ 2021

An ESO VLT/MUSE Large Program

Turning galaxy evolution on its side with deep observations of edge-on galaxies

What is GECKOS?

Generalising **E**dge-on galaxies and their **C**hemical bimodalities, **K**inematics, and **O**utflows out to **S**olar environments

- 317 hours of VLT/MUSE in various seeing conditions
- 35 edge-on galaxies at D < 70 Mpc
- Better than 200pc spatial resolution out to solar environments
- S/N = 40 at surface brightness 23.5 mag/arcsec^2

Who is GECKOS?

PI: Jesse van de Sande

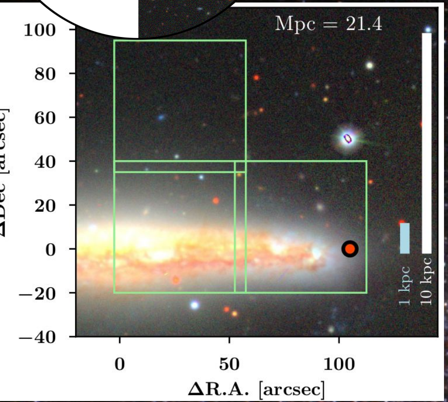
Deanne Fisher

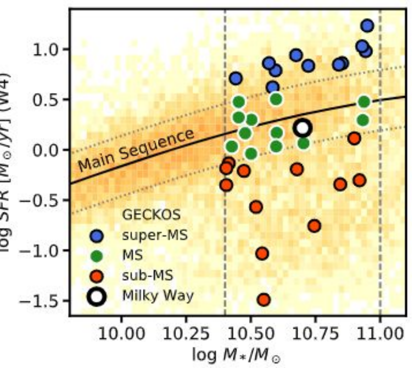
Amelia Fraser-McKelvie

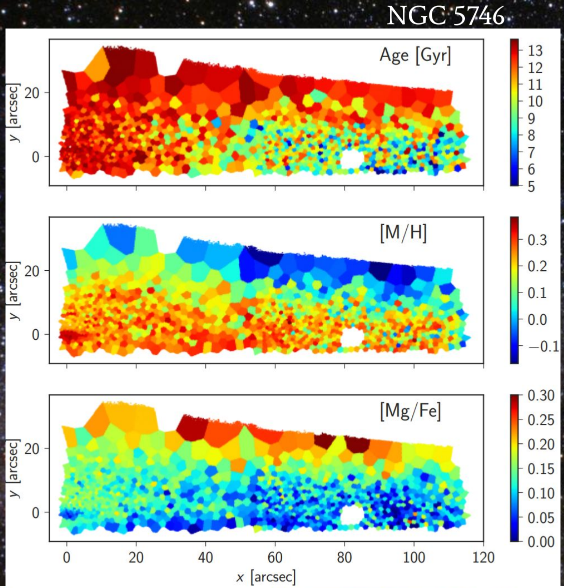
Marie Martig

Michael Hayden

Team: Adriano Poci, Alberto Bolatto, Andrew Wetzel, Barbara Catinella, Barbara Ciraulo, Claudia Lagos, Emily Wisnioski, Eric Emsellem, Fabian Walter, Francesca Fragkoudi, Francesca Pinna, Glenn van de Ven, Ivan Minchev, Jesús Falcón-Barroso, Jo Ciuca, Joss Bland-Hawthorn, Kate Harborne, Ken Freeman, Ling Zhu, Luca Cortese, Ortwin Gerhard, Payel Das, Purmortal (Zixian) Wang, Richard McDermid, Ryan Leaman, Sanjib Sharma, Sarah Martel, Scott Croom, Sven Buder, Tobias Buck, and Trevor Mendel geckos



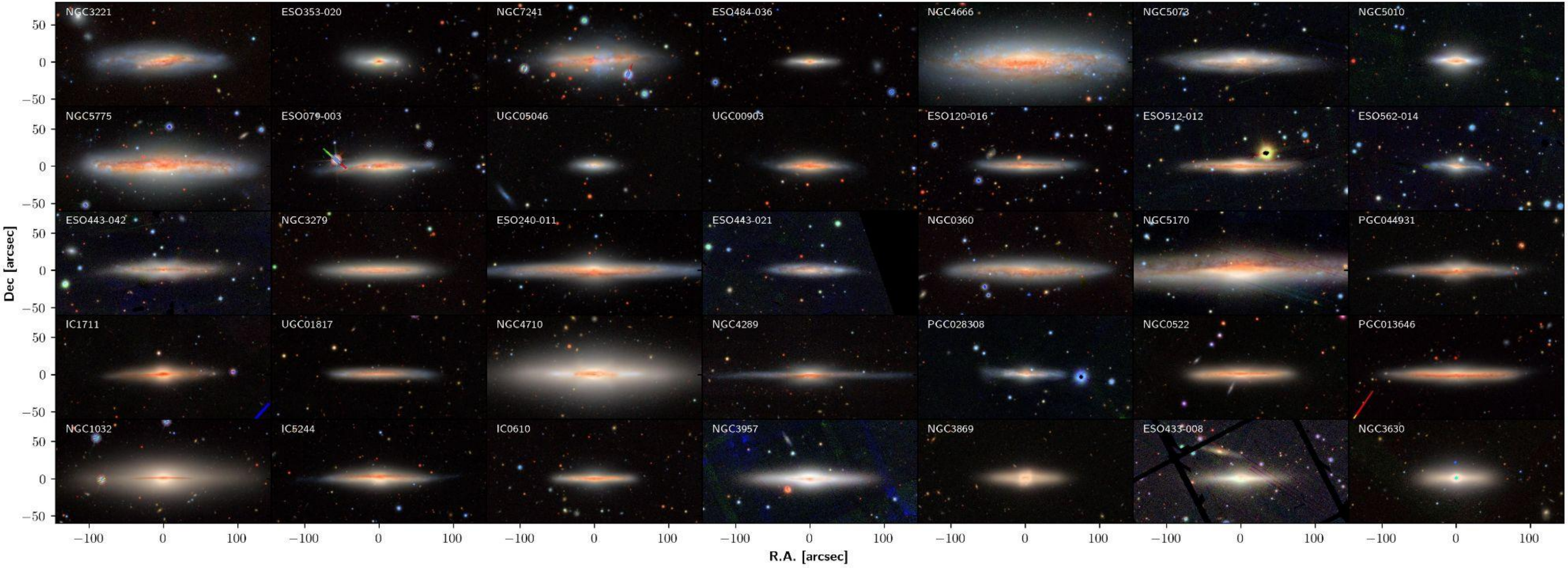




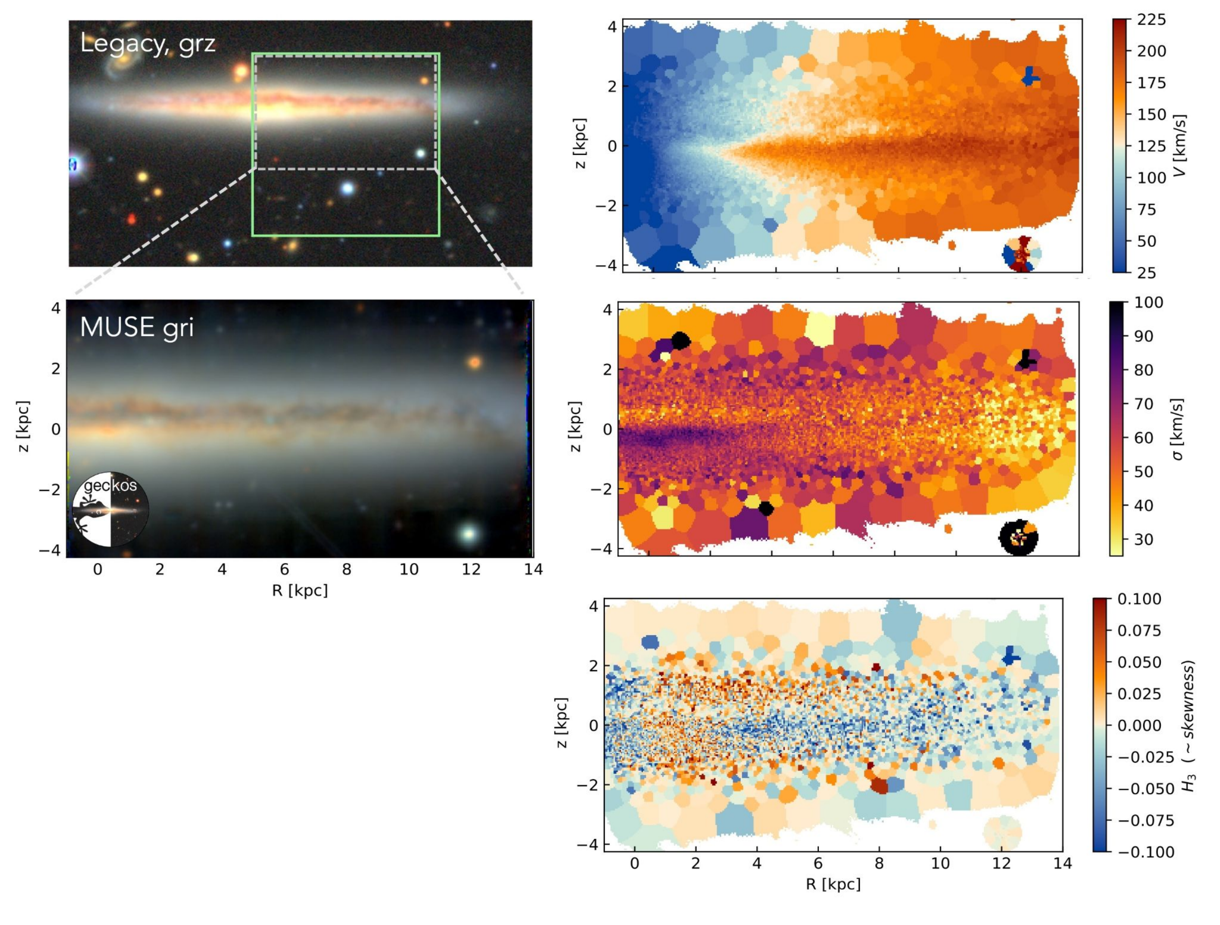
Martig+2022

- Observe 35 edge-on galaxies to very high S/N out to large Re (~3Re)
- Range of star formation rate+histories: What drives disk galaxy evolution?
- Measure stellar populations of disks, identify accreted structures, measure outflows
- Apply detailed chemical modeling from MW to these external systems

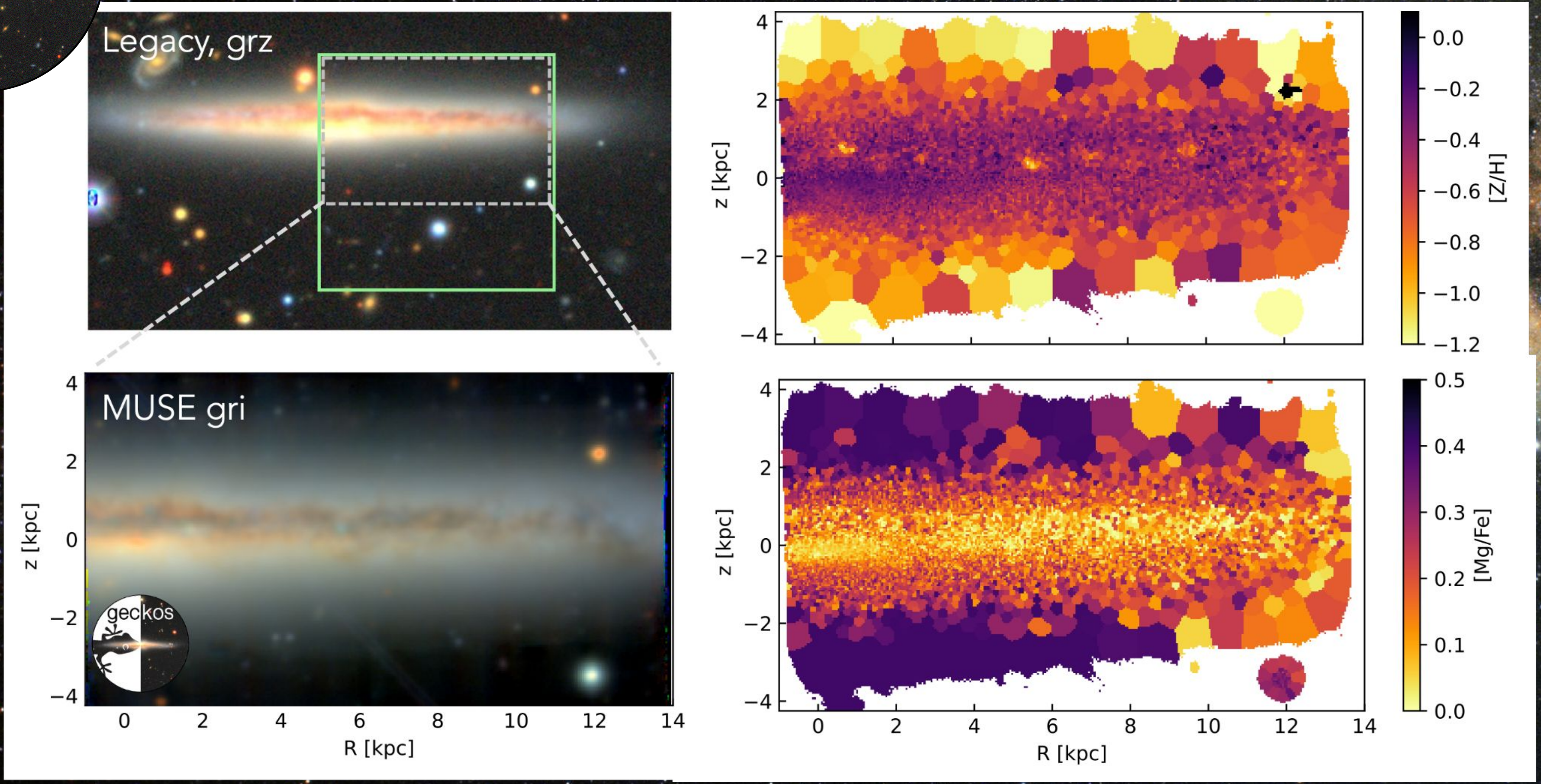

geckos


NGC3221
ESO353-020
NGC7241
ESO484-036
NGC4666
NGC5073
NGC5010
NGC5775
ESO079-003
UGC05046
UGC00903
ESO120-016
ESO512-012
ESO562-014
ESO443-042
NGC3279
ESO240-011
ESO443-021
NGC0360
NGC5170
PGC044931
IC1711
UGC01817
NGC4710
NGC4289
PGC028308
NGC0522
PGC013646
NGC1032
IC5244
IC0610
NGC3957
NGC3869
ESO433-008
NGC3630
50
0
−50
−100
100
Dec [arcsec]
R.A. [arcsec]

First Finished Galaxy: ESO 120-016



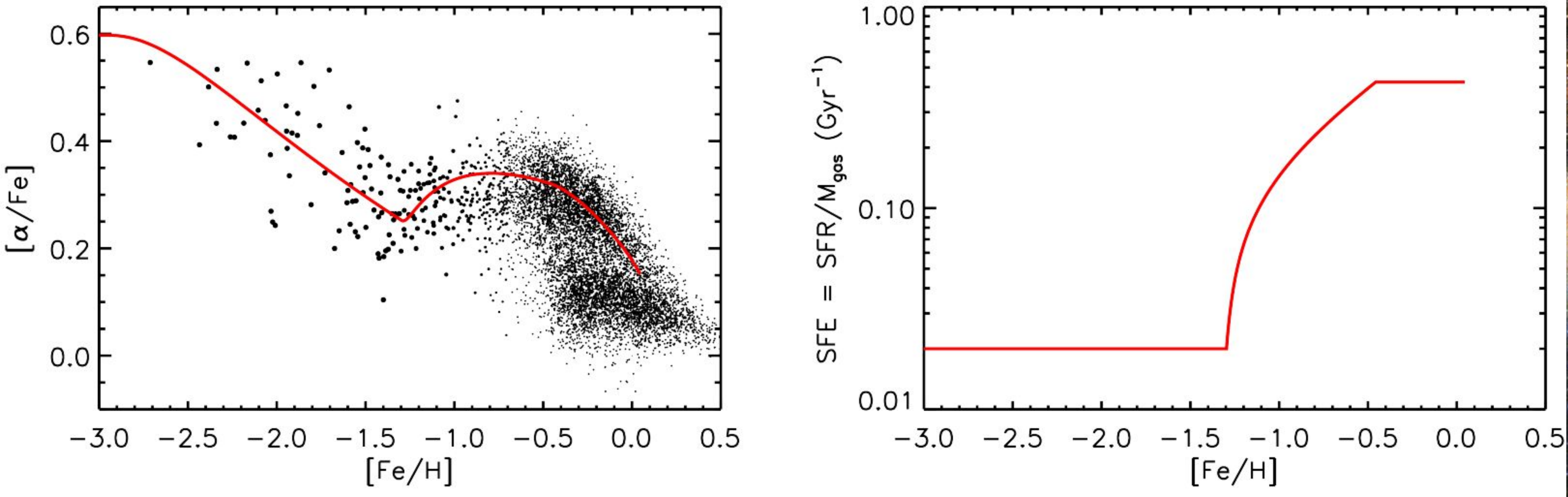
First Finished Galaxy: ESO 120-016



Conclusions

- Made the first complete chemical map of the Galaxy
  - Strong variation of abundances /w position
  - High-Alpha stars centrally concentrated, dominate in thick disk
  - Outer disk: flared young populations, similar metallicity to high alpha pops
- Radial mixing is important (and really annoying!)
- Developed the first chemical evolution model to reproduce nearly all observables (chemical maps, MDF skewness, etc)
  - No Major Merger Needed →bimodal chemical disks potentially common
  - Lots of Room to Explore: neutron capture abundances, galactic fountains, non-axis symmetric structure (bar, spiral arm) → azimuthal variation
- Using the Milky Way as a Testbed for Galaxy Evolution:
  - Building MW Datacubes for a range of distances, inclinations, stellar libraries, instruments
  - GECKOS: ESO MUSE Program to Obtain High Quality Observations for Detailed Comparisons

What's Next: Simmering Phase



Conroy+22

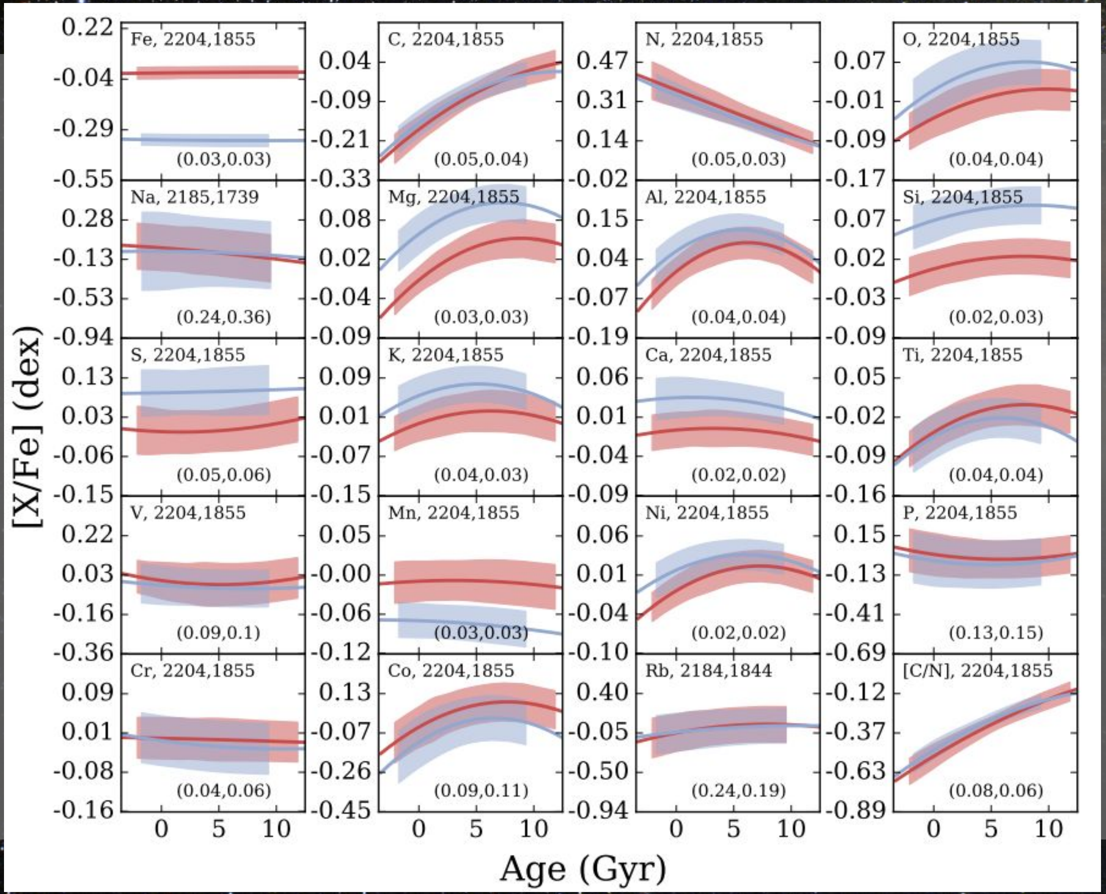
Age-Metallicity-Abundance Relations

Blue: Metal-poor

Red: Metal-rich

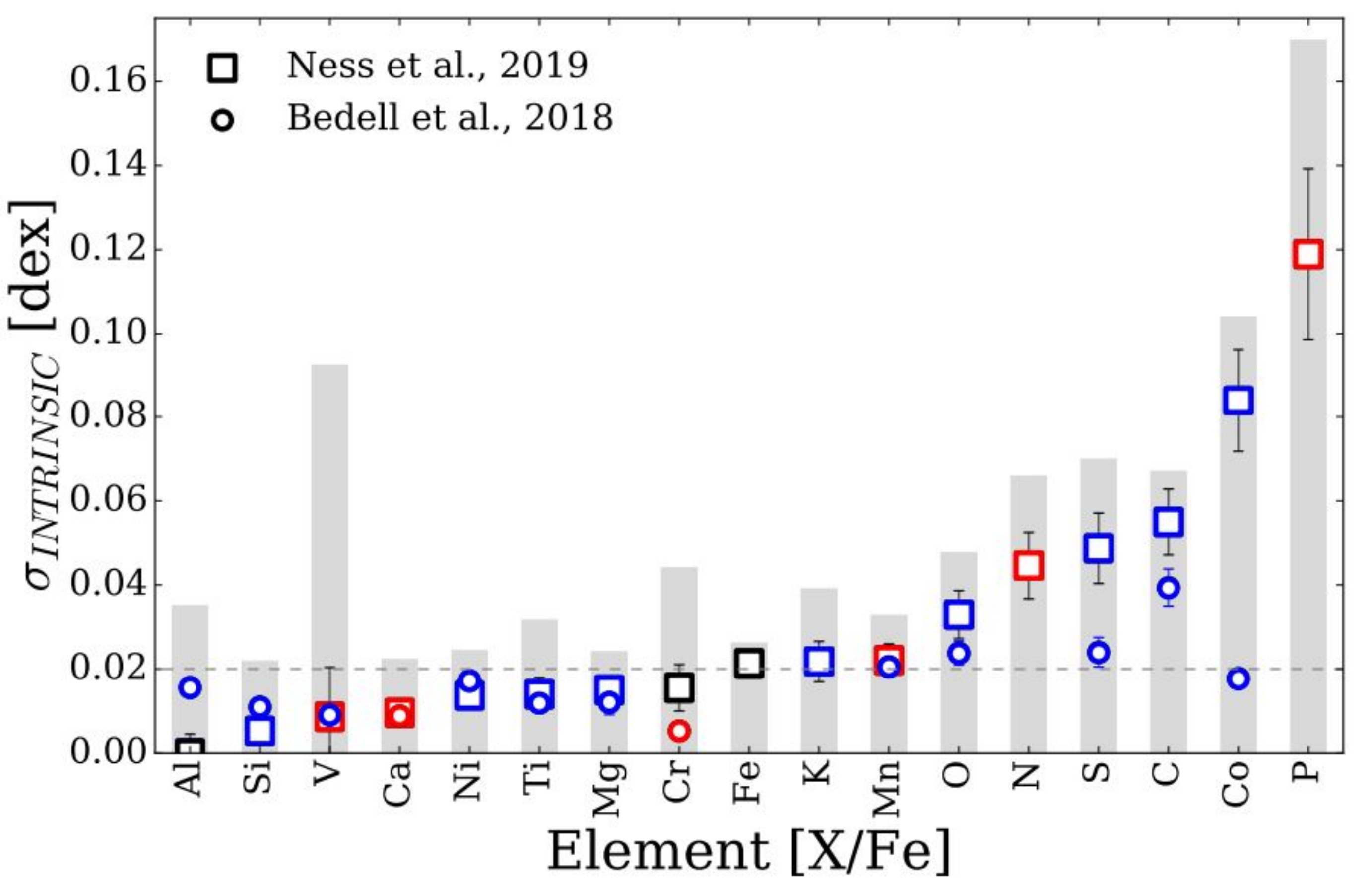
All you need is age+metallicity to estimate an abundance

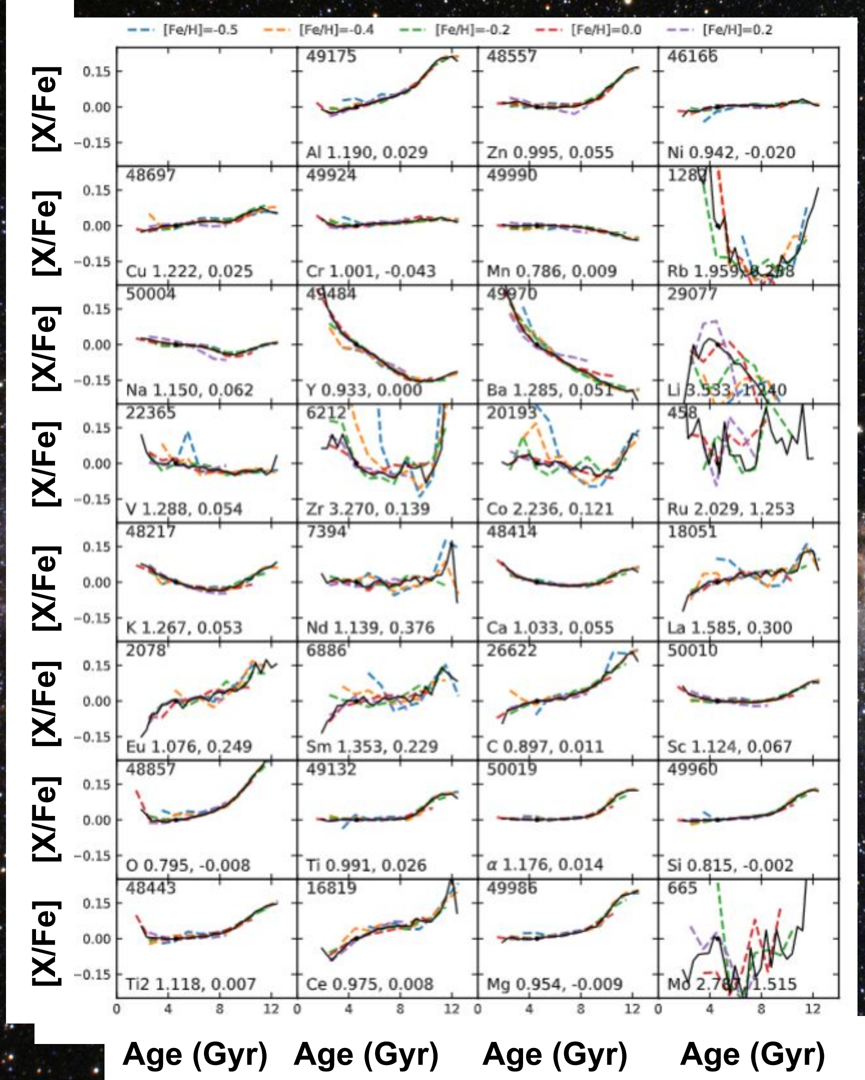
Implication: Galaxy has had almost no azimuthal metallicity variation for most of its history



Ness 2019

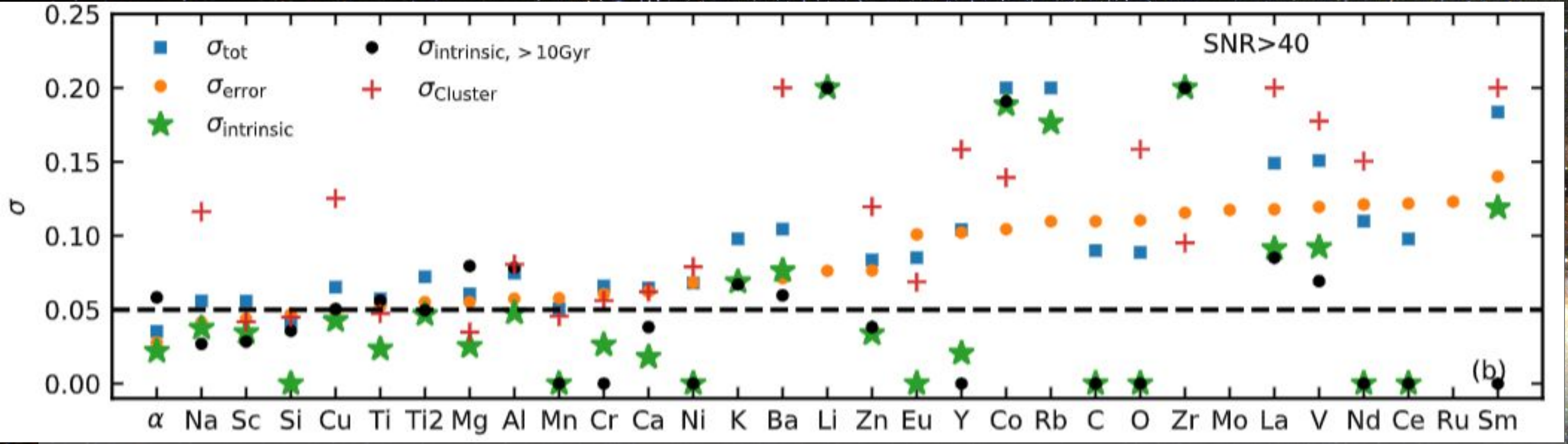
Age-Metallicity-Abundance Relations





Sharma+Hayden 2020
[Fe/H]=-0.5
[Fe/H]=-0.4
[Fe/H]=-0.2
[Fe/H]=0.0
[Fe/H]=0.2
[X/Fe]
Age (Gyr)
Al 1.190, 0.029
Zn 0.995, 0.055
Ni 0.942, -0.020
Cu 1.222, 0.025
Cr 1.001, -0.043
Mn 0.786, 0.009
Na 1.150, 0.062
Y 0.933, 0.000
Ba 1.285, 0.051
V 1.288, 0.054
Zr 3.270, 0.139
Co 2.236, 0.121
Ru 2.029, 1.253
K 1.267, 0.053
Nd 1.139, 0.376
Ca 1.033, 0.055
La 1.585, 0.300
Eu 1.076, 0.249
Sm 1.353, 0.229
C 0.897, 0.011
Sc 1.124, 0.067
O 0.795, -0.008
Ti 0.991, 0.026
α 1.176, 0.014
Si 0.815, -0.002
Ti2 1.118, 0.007
Ce 0.975, 0.008
Mg 0.954, -0.009

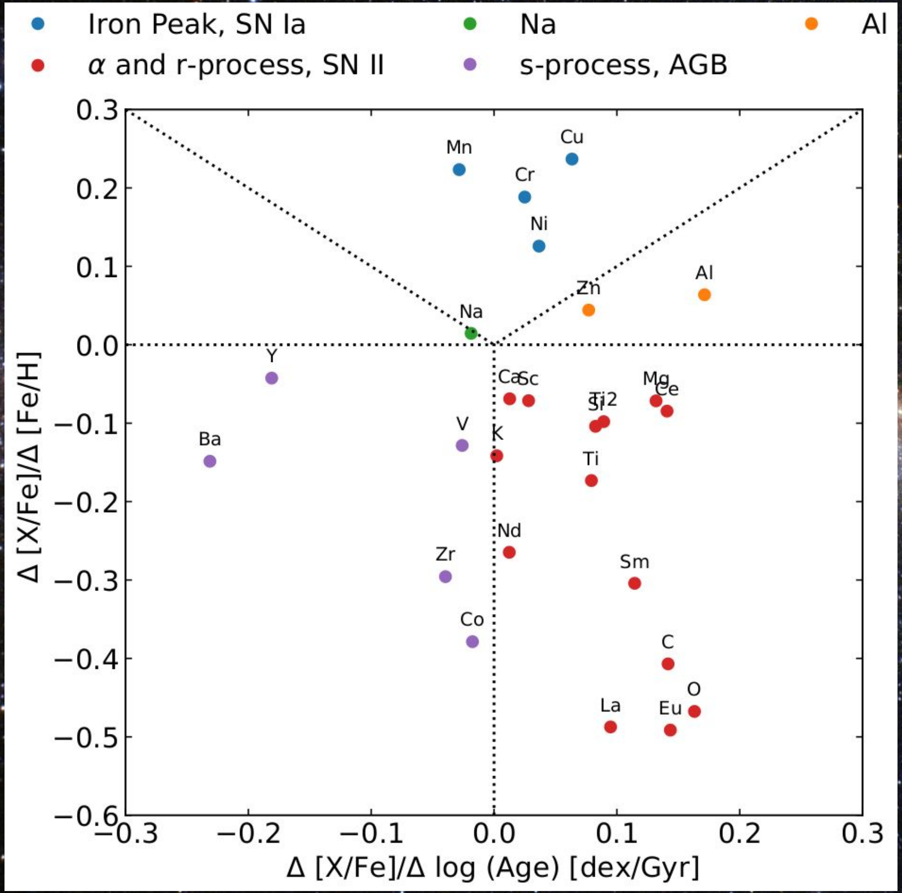
Age-Metallicity-Abundance Relations



Sharma+Hayden 2020

- Estimate abundance from age, [Fe/H]
- Compare estimated abundance to measured abundance, measure scatter
- Compare scatter to that of measurement uncertainties, determine intrinsic scatter: how well can we predict an element based on age, [Fe/H]? Low sigma→ better prediction

Age-Metallicity-Abundance Relations

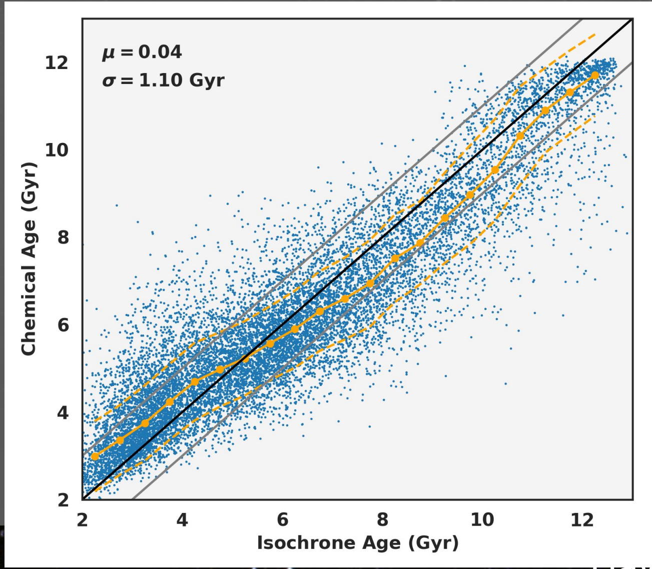


Sharma+Hayden 2020

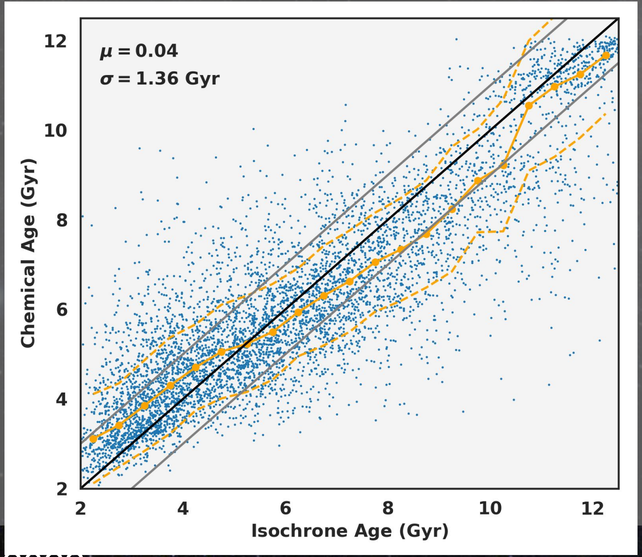
Turning This Around: Ages from Abundances

- We can estimate abundances to <0.05 dex just from age+[Fe/H] →
  We can estimate ages just from abundances + [Fe/H]

- Use XGBoost to estimate ages from 13 abundances in GALAH: [Fe/H], [Y/Fe], [Ba/Fe], [Mn/Fe], [O/Fe], [Cr/Fe], [Na/Fe], [Ca/Fe], [Ti/Fe], [Mg/Fe], [Si/Fe], [K/Fe], [Sc/Fe] with MSTO stars providing training set ages



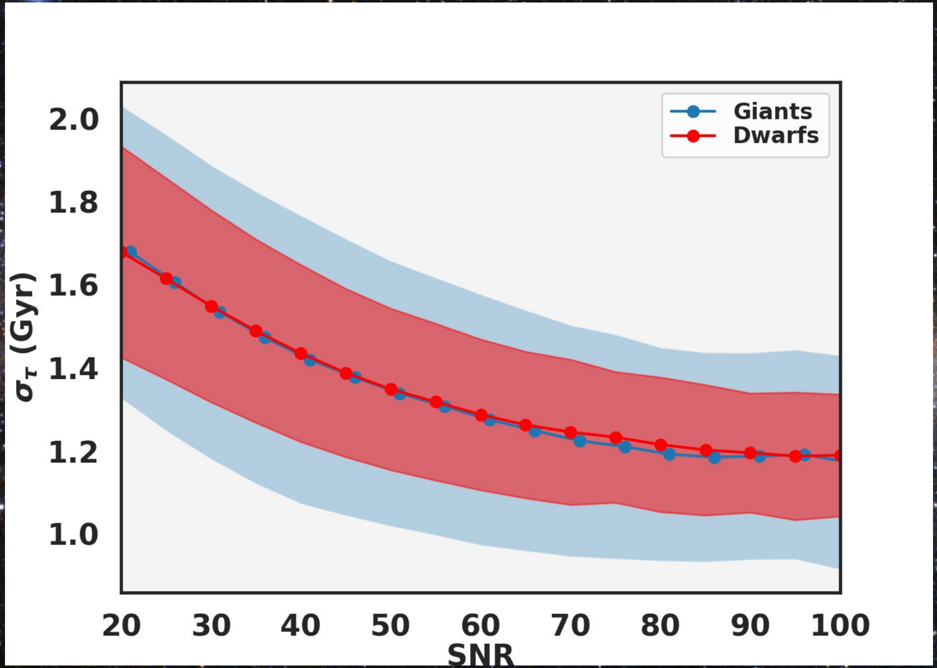
Training Set



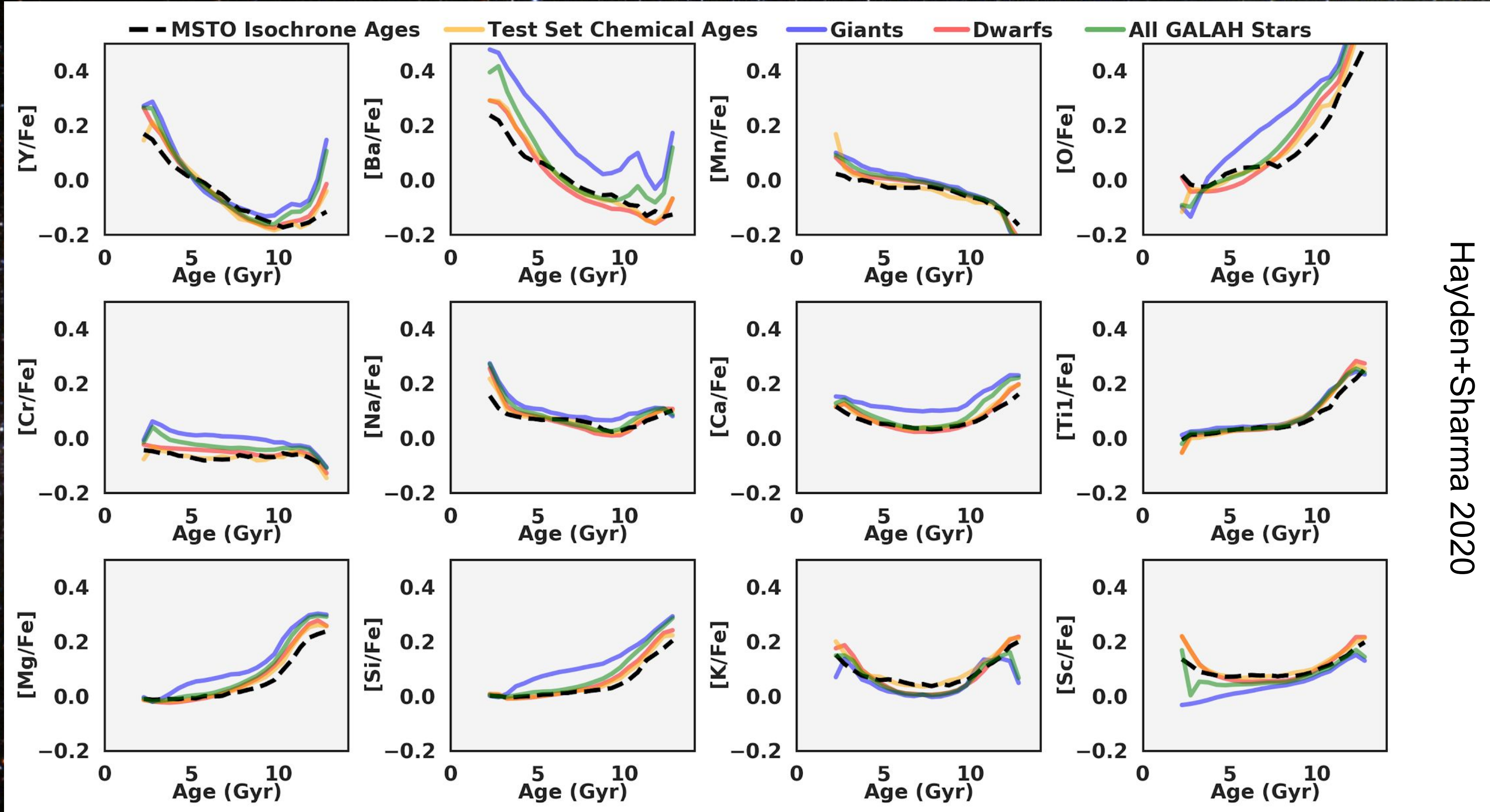
Test Set

Hayden+Sharma 2022

Uncertainties in Ages from Abundances

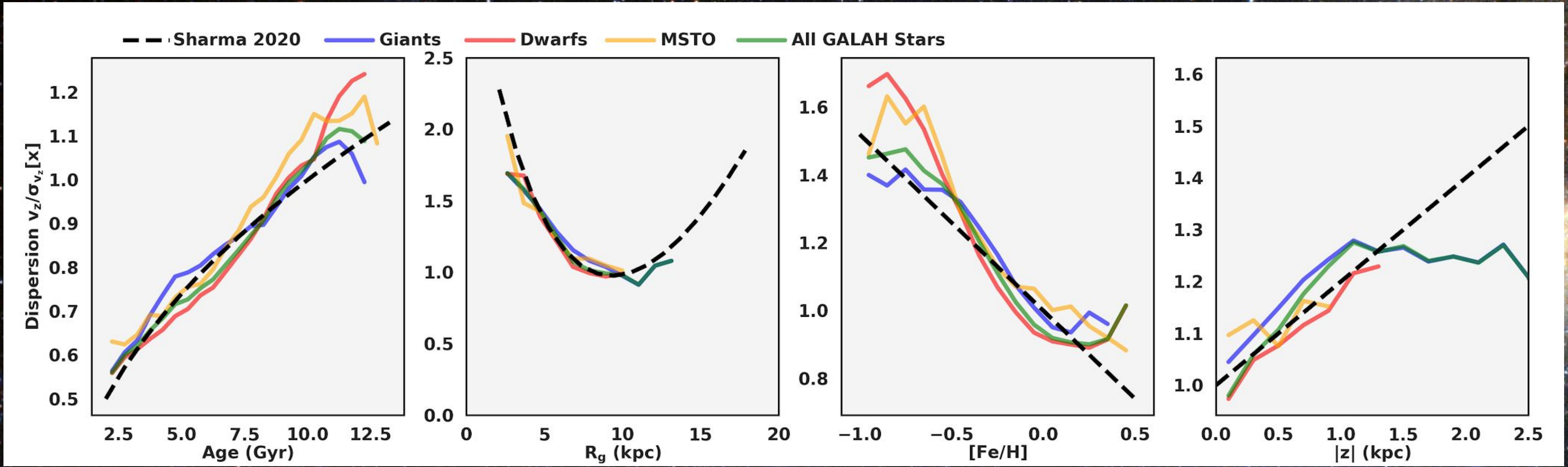


Age Abundance Trends



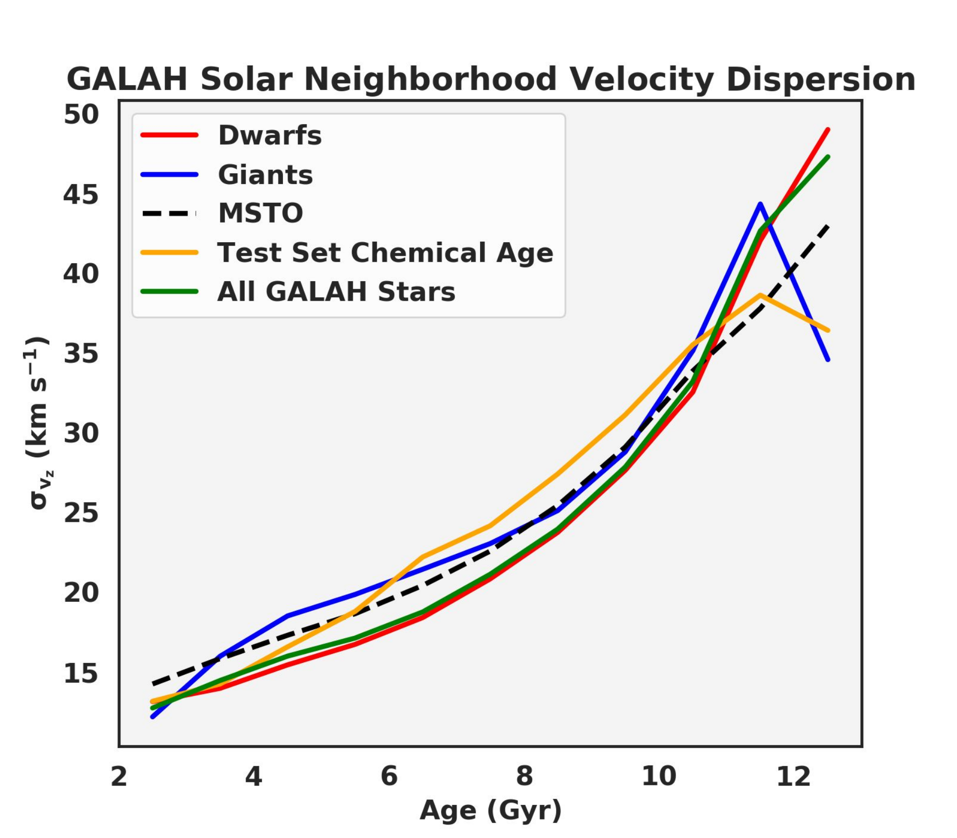
Hayden+Sharma 2020

Kinematic Studies of the Disk



Hayden+Sharma 2022

Kinematic Studies of the Disk



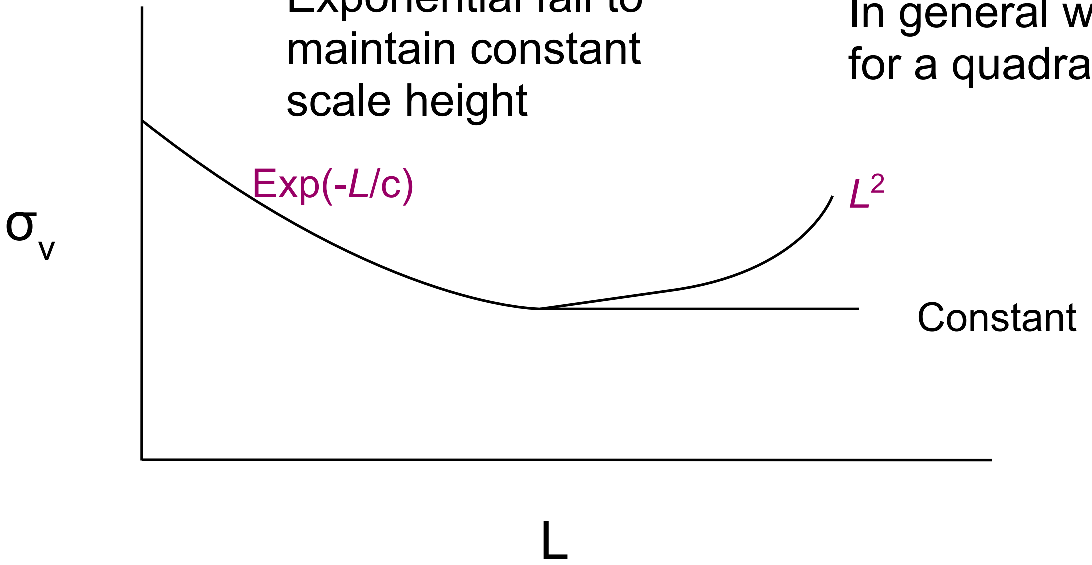
Hayden+Sharma 2022

Angular momentum L

$$f_L = a\,\mathrm{Exp}(-L/c) + b\,L^2$$

Exponential fall to maintain constant scale height

In general we allow for a quadratic rise.



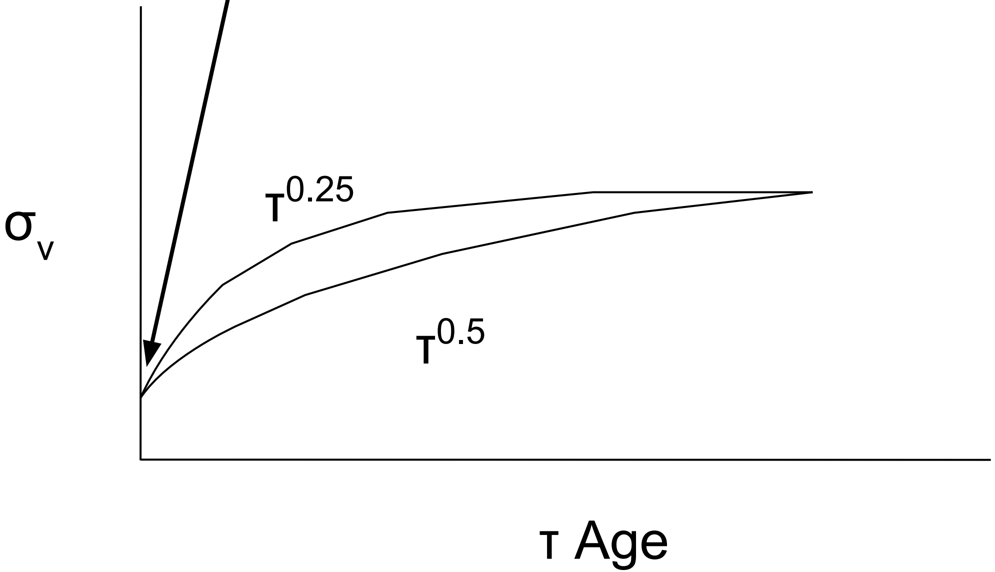
Minimum threshold set by finite ***birth dispersion***

Age τ

Power law

$$f_\tau = \left(\frac{\tau/Gyr + 0.1}{10 + 0.1}\right)^{\beta_v}$$

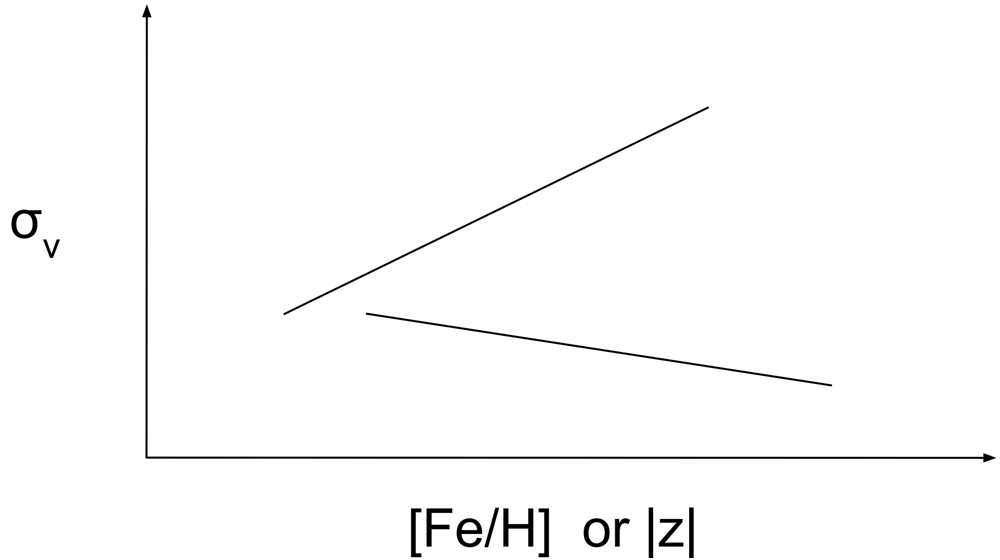
Minimum threshold set by finite ***birth dispersion***.



Metallicity [Fe/H] and *height* |z|

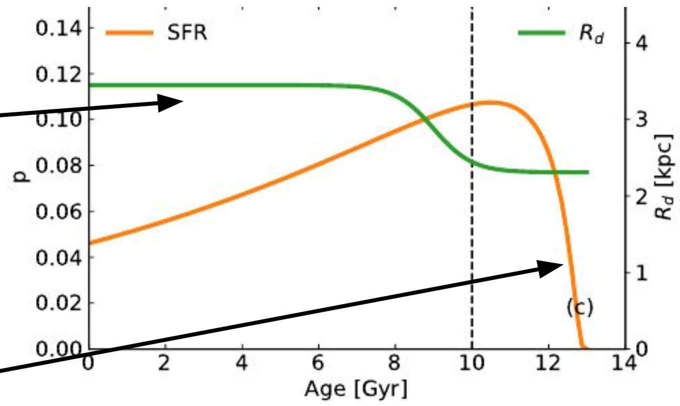
$f_{[Fe/H]} = 1 + d\,[Fe/H]$, $f_z = 1 + e\,|z|$

- Linear functions



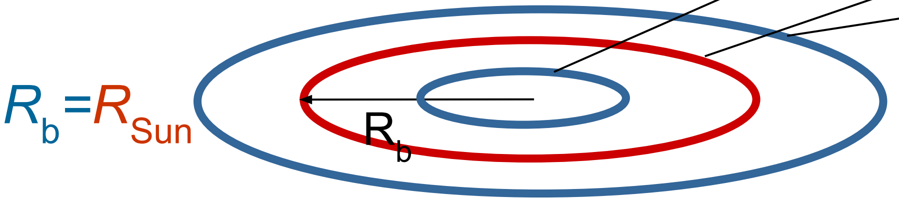
Chemical Evolution with Radial Mixing

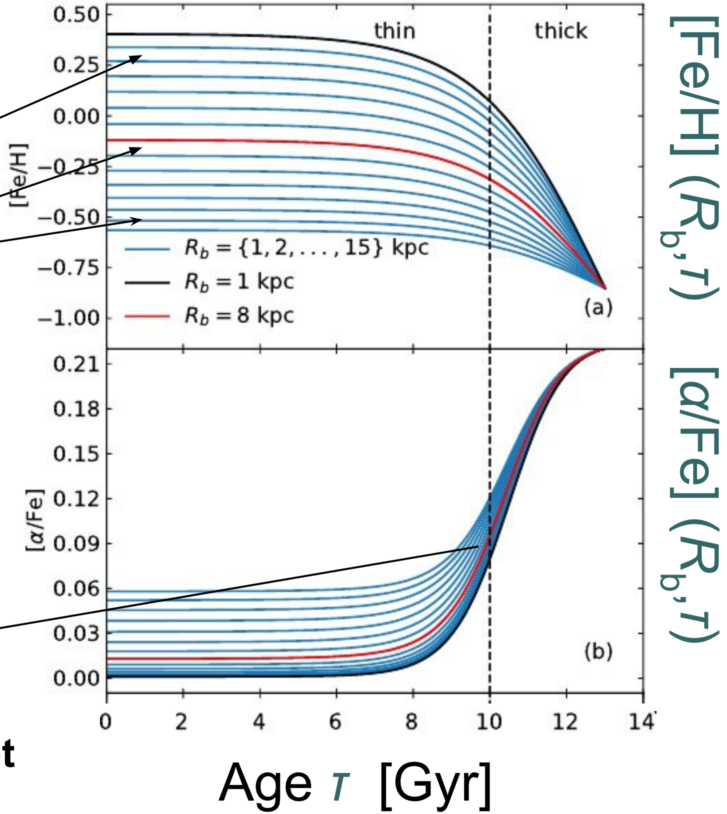
- Structure of disk:
  - $\text{Exp}(-R_b/R_d)$
  - No distinct thick disk!
- $R_d(\tau)$ Star formation history:
  - $p(\tau)$
- Chemical evolution: (empirical)
  - $[Fe/H](R_b,\tau)$
  - $[\alpha/Fe](R_b,\tau)$



Sharma+Hayden 2020b

- Chemical evolution: (empirical, motivated by obs)





Smooth Evolution → No thick disk

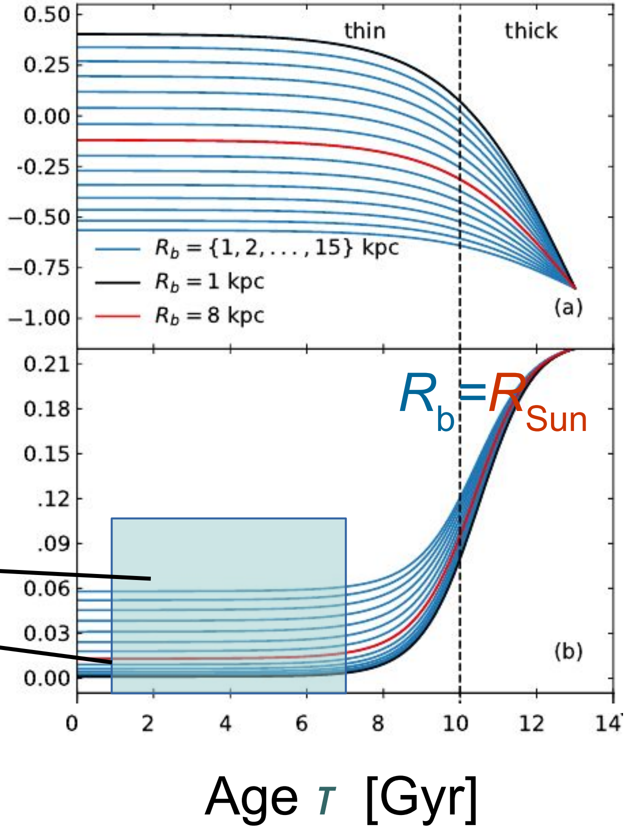
Gap Between High/Low Alpha: Caused by time delay between star formation and onset of SN-Ia.

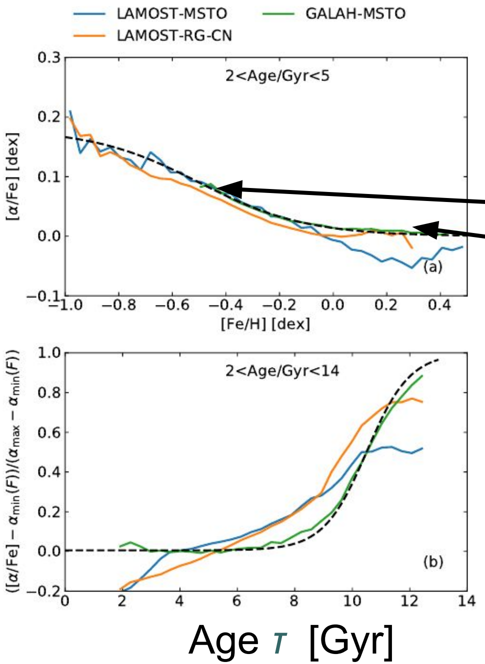
Sharma+Hayden 2020b

- Chemical evolution: (empirical)

[Fe/H] (R_b,τ)

[α/Fe] (R_b,τ)





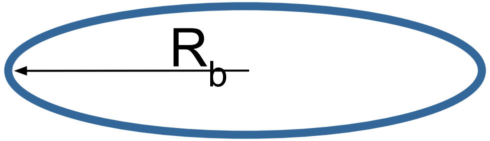
Sharma+Hayden 2020b

Birth configuration

$p(R_b,\tau)=p(\tau)\, p(R_b|\tau)$

Star formation history: $p(\tau)$

Structure of disk: $\mathrm{Exp}(-R_b/R_d)$

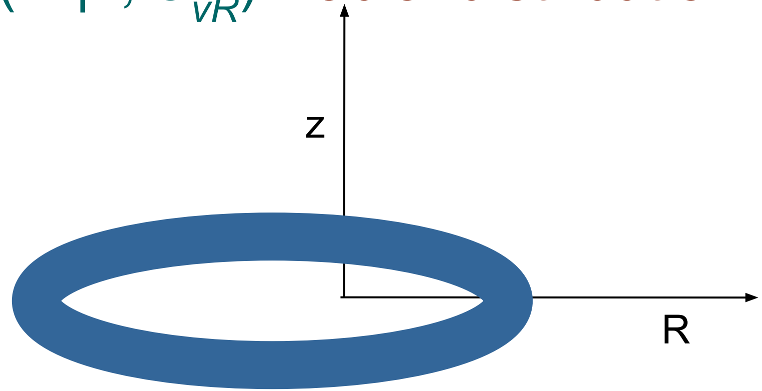


Present configuration

$p(x,v|R_b,\tau)$

$p(z|\, \sigma_{vz})$, Vertical distribution

$p(\, R|L,\, \sigma_{vR})$ Radial distribution



Birth configuration

$p(R_b,\tau)=p(\tau)\ p(R_b|\tau)$

Star formation history: $p(\tau)$

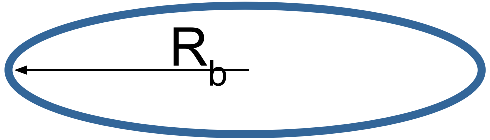
Structure of disk: $\mathrm{Exp}(-R_b/R_d)$

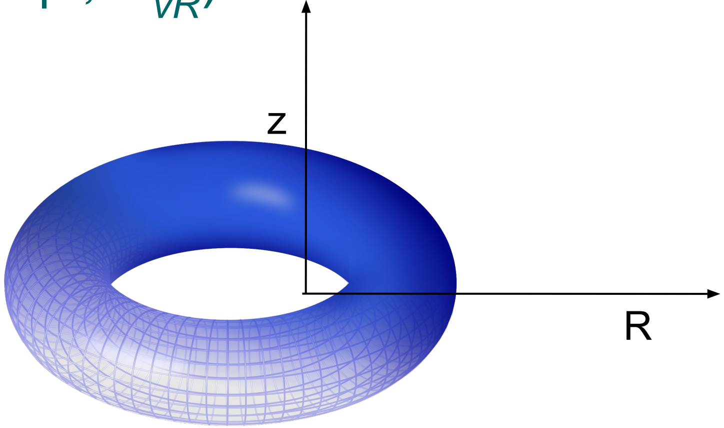
Present configuration

$p(x,v|R_b,\tau)$

$p(z|\ \sigma_{vz})$, Vertical distribution

$p(\ R|L,\ \sigma_{vR})$ Radial distribution

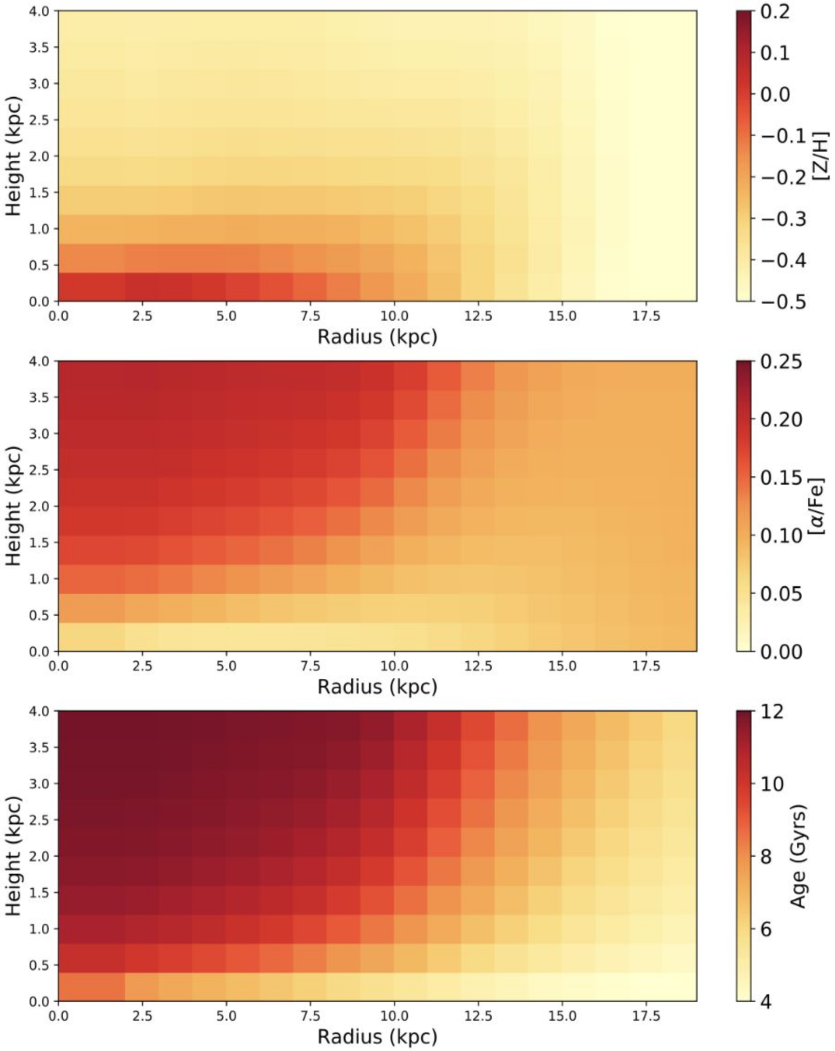




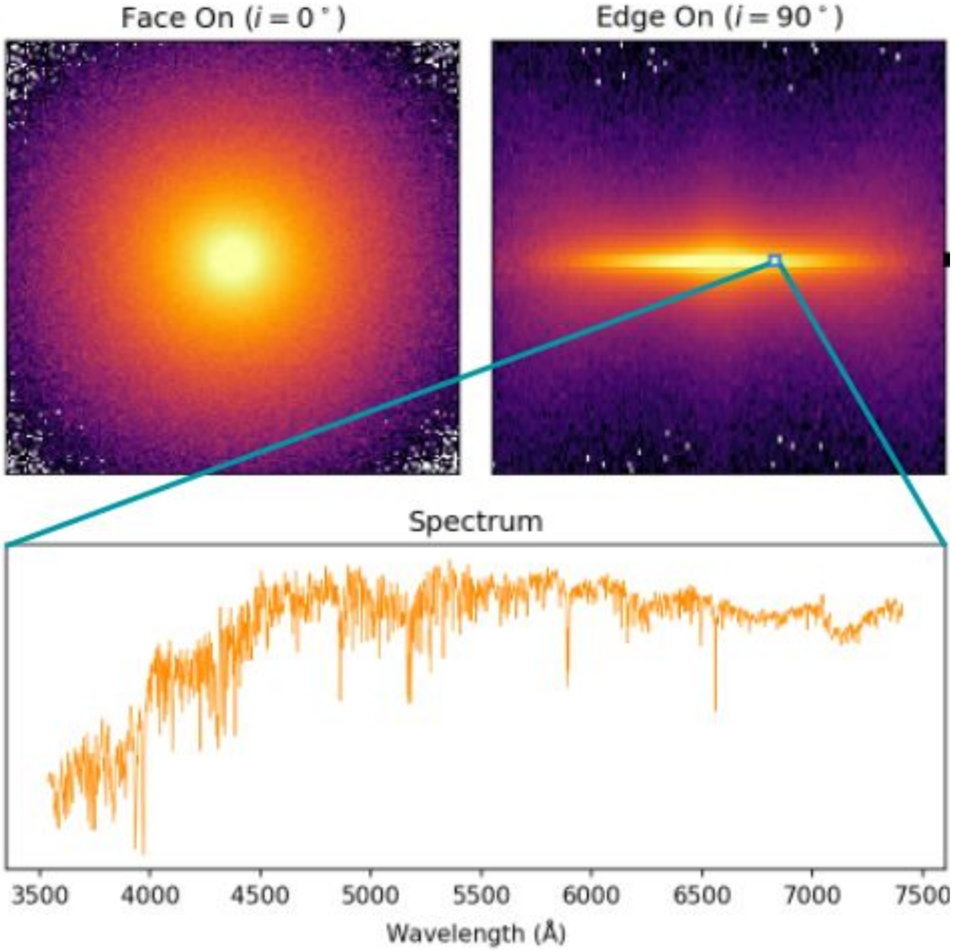
$p(\ L\ |\ R_b,\tau\ )$ Radial Migration:

Gaussian Diffusion Process, σ_{L0}= 1150 km/s kpc

$\sigma_v(\ L,\ R_b,\ \tau)$ Velocity dispersion



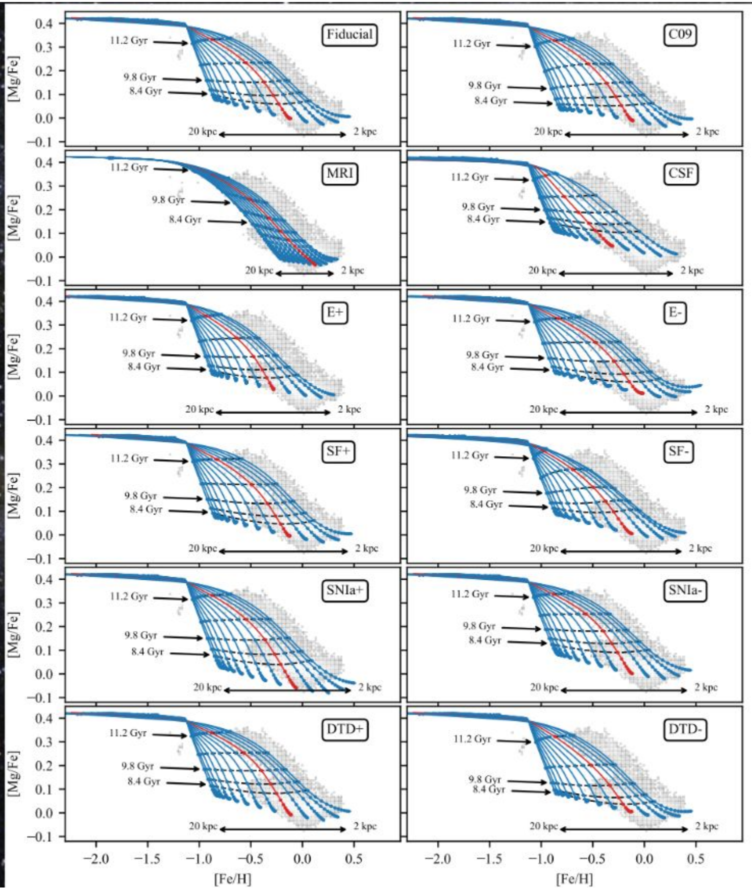
Height (kpc)
Radius (kpc)
[Z/H]
Height (kpc)
Radius (kpc)
[α/Fe]
Height (kpc)
Radius (kpc)
Age (Gyrs)



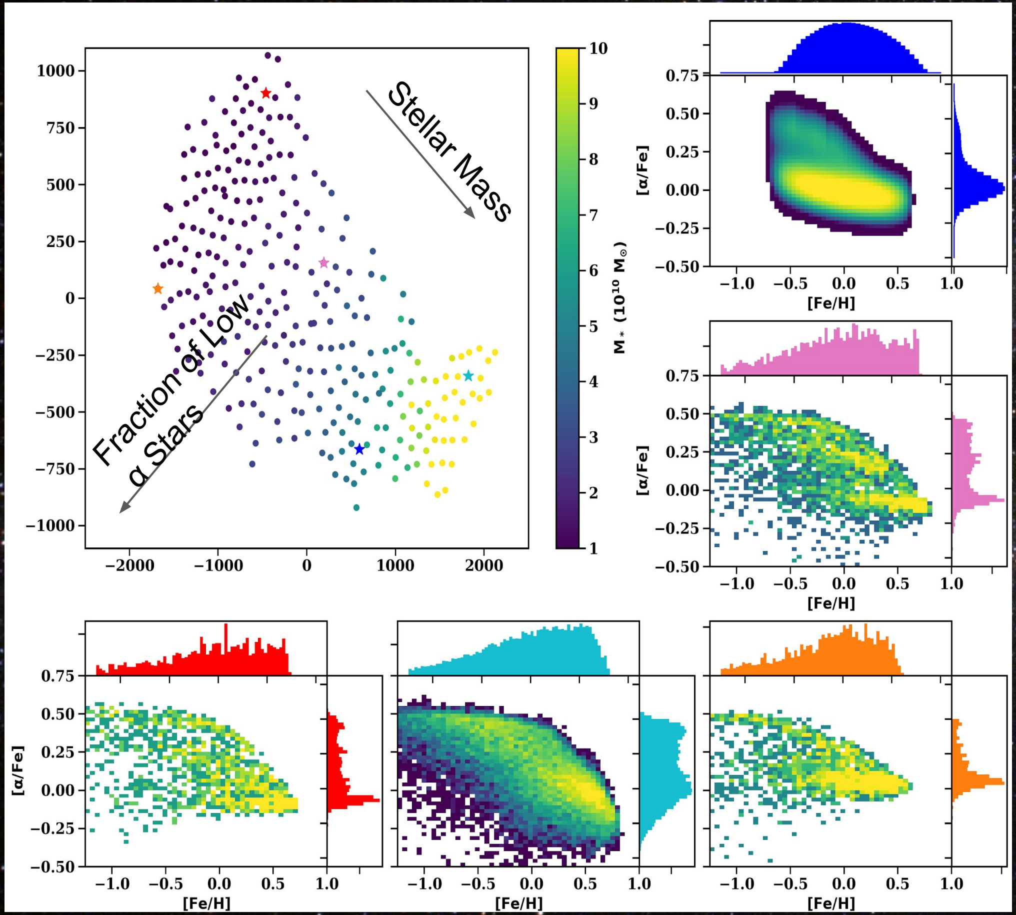
Face On ($i = 0^\circ$)
Edge On ($i = 90^\circ$)
Spectrum
3500
4000
4500
5000
5500
6000
6500
7000
7500
Wavelength (Å)

Table 1. Parameters of the standard model.

Parameter	Meaning	Value
R_d	Scalelength of cold gas	3.5 kpc
C	Star formation efficiency constant	2.2×10^{-10}
N	Power in star formation law	1.4
$M_{0,\mathrm{cold}}$	Initial cold gas mass	$7 \times 10^{9} M_{\odot}$
$M_{0,\mathrm{warm}}$	Initial warm gas mass	$1 \times 10^{9} M_{\odot}$
ΔM_{warm}	Early infall mass per step onto warm gas	$2.5 \times 10^{8} M_{\odot}$
M_1	Short timescale infall mass	$1 \times 10^{10} M_{\odot}$
M_2	Long timescale infall mass	$1 \times 10^{11} M_{\odot}$
b_1	Timescale for M_1	150 Myr
b_2	Timescale for M_2	1.4 Gyr
$t_{\mathrm{min,SNeIa}}$	Minimum time delay before first SNe Ia	150 Myr
$t_{\mathrm{scale,SNeIa}}$	Timescale for decay of SNe Ia	1.5 Gyr
t_{cool}	Cooling timescale of warm gas	1.2 Gyr
f_{direct}	Fraction of ejecta directly into cold gas	0.01
f_{eject}	Fraction of ejecta lost	0.3-0.04
$Z_{M_{\odot}}$	Metallicity of the Sun	0.0156
Z_{IGM}	Metallicity of the IGM	$10^{-0.8} Z_{M_{\odot}}$
f_{IGM}	The fraction of gas directly deposited from IGM	0.25
%SNeIa	Fraction of white dwarfs from stars within $(3.2, 8.5) M_{\odot}$ that turn into SNe Ia	0.05
%HNe	Fraction of CCSN that explode as hypernovae	0.5
%MRSN	Fraction of CCSN that explode as magneto-rotational supernovae	0.0025
v_0	Rotational velocity of the Milky Way from Sanders & Binney (2015)	220 km/s
σ_{L_0}	Churning amplitude from Sanders & Binney (2015)	1150 kpc km/s
t_{max}	Maximum age of the Milky Way	12 Gyr



Future Research: MW In Context



- MW is only a single galaxy: can't constrain all of galaxy evolution with one data point!
- Can compare detailed chemical evolution models to simulations→ identify MW analogues, look at range of formation pathways
- Goal: Use several suites of simulations (FIRE-LATTE, TNG50, EAGLE, Auriga, etc.). Determine which processes are critical to producing realistic chemical maps