Implications of The Old, Metal-Rich Milky Way

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The Old, Metal-Rich Milky Way

- Most stars in the central regions of the Milky Way are old, certainly formed prior to redshift unity, 8Gyr ago – bulge/bar, inner thick disk, thin disk
- A large fraction of these old stars are chemically enriched, above [Fe/H] ~ –0.5
- A significant fraction of these old stars are very metal-rich, around solar, of order the yield for standard stellar IMF and nucleosynthesis/ejecta
- This suggests quenching of early star formation due to gas exhaustion, with some gas inflow but not much outflow

Implications of The Old, Metal-Rich Milky Way

- Stars in inner regions formed in deep enough potential well to retain enriched gas and cycle through many generations of stars, despite stellar feedback, and evolve rapidly towards the yield
- Bulge/bar plausibly formed from gravitationally unstable, massive inner stellar disk, itself formed within a deep potential well
- Last significant merger ~ 10Gyr ago formed the thick disk and both brought in new gas and drove in situ disk gas inwards (cf Wyse 2001; Brook et al 2004; Belokurov et al 2018; Helmi et al 2018; Haywood et al 2018; Gallart et al 2018; Grand et al 2020….)

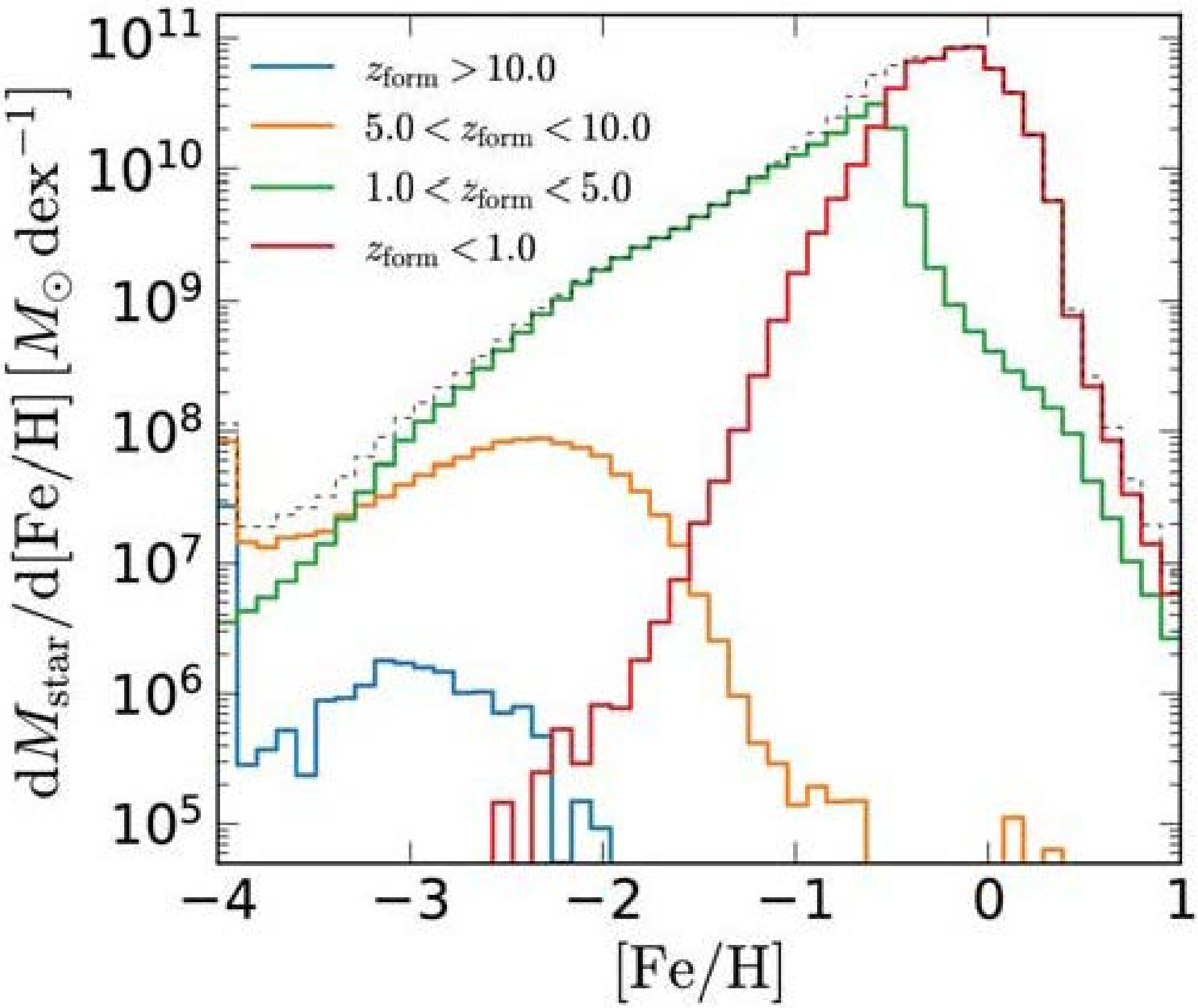
Implications of The Old, Metal-Rich Milky Way

- High star-formation rate at epoch of formation of inner disk/thick disk/bulge within deep enough potential well to allow self-enrichment (see also Conroy et al 2022; Snaith et al 2022)
  - Conservative estimate ~ 2 x $10^{10} M_\odot$ stellar mass with [Fe/H] > -0.5 and age > 8Gyr
  - Most (~75%) of the old stars in the Galaxy are at least this metal-rich
- Expect to observe fairly luminous, chemically evolved, centrally concentrated proto-galaxies at high redshift (10Gyr → z ~ 2; 12Gyr → z ~ 4)

More Implications of The Old, Metal-Rich Milky Way

- ΛCDM simulations of Milky Way analogues, with early star formation in low-mass systems and stellar feedback quenching star formation, produce mainly metal-poor old stars (e.g. El-Badry et al 2018), do not create a dominant old, metal-rich stellar population
- Plausibly reflects truncation of chemical enrichment due to inability of early-forming substructure to retain gas
- Another aspect of `tensions' between predictions of ΛCDM on galactic scales and observations, again could be indicative of too much power on small scales

Predictions from ΛCDM
Zoom-in Simulations Milky Way analog



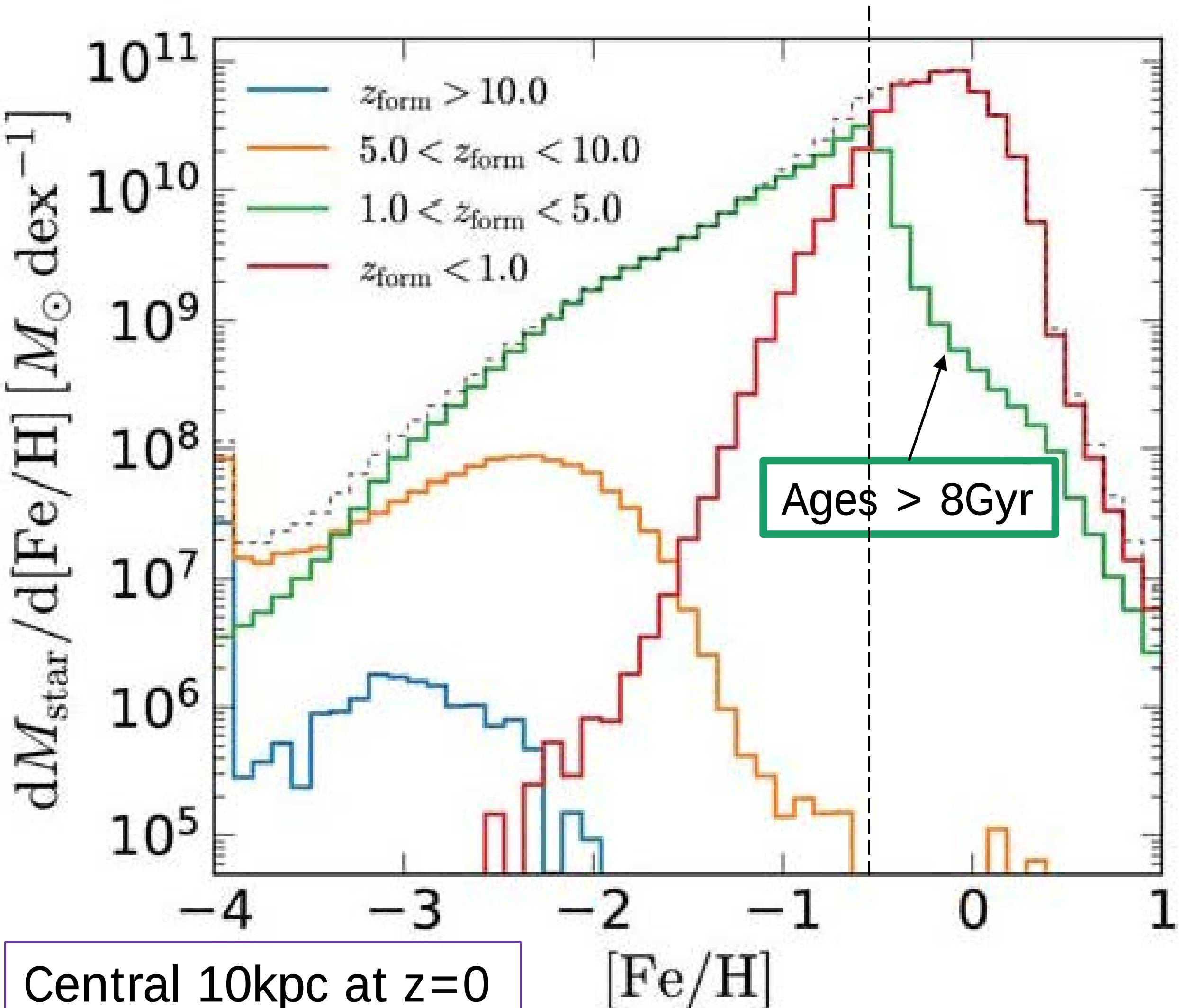
El-Badry et al 2018

FIRE-2 hydrodynamic simulations

Central 10kpc at z=0

Model m12i, ‘normal’, somewhat quiescent merger history, last significant merger z ~ 0.7

Predictions from ΛCDM
Zoom-in Simulations Milky Way analog



El-Badry et al 2018

- Most stars that formed before redshift unity, ages older than 8Gyr, have [Fe/H] < −0.5
- Steep decline in distribution function for [Fe/H] > −0.5

Central 10kpc at z=0

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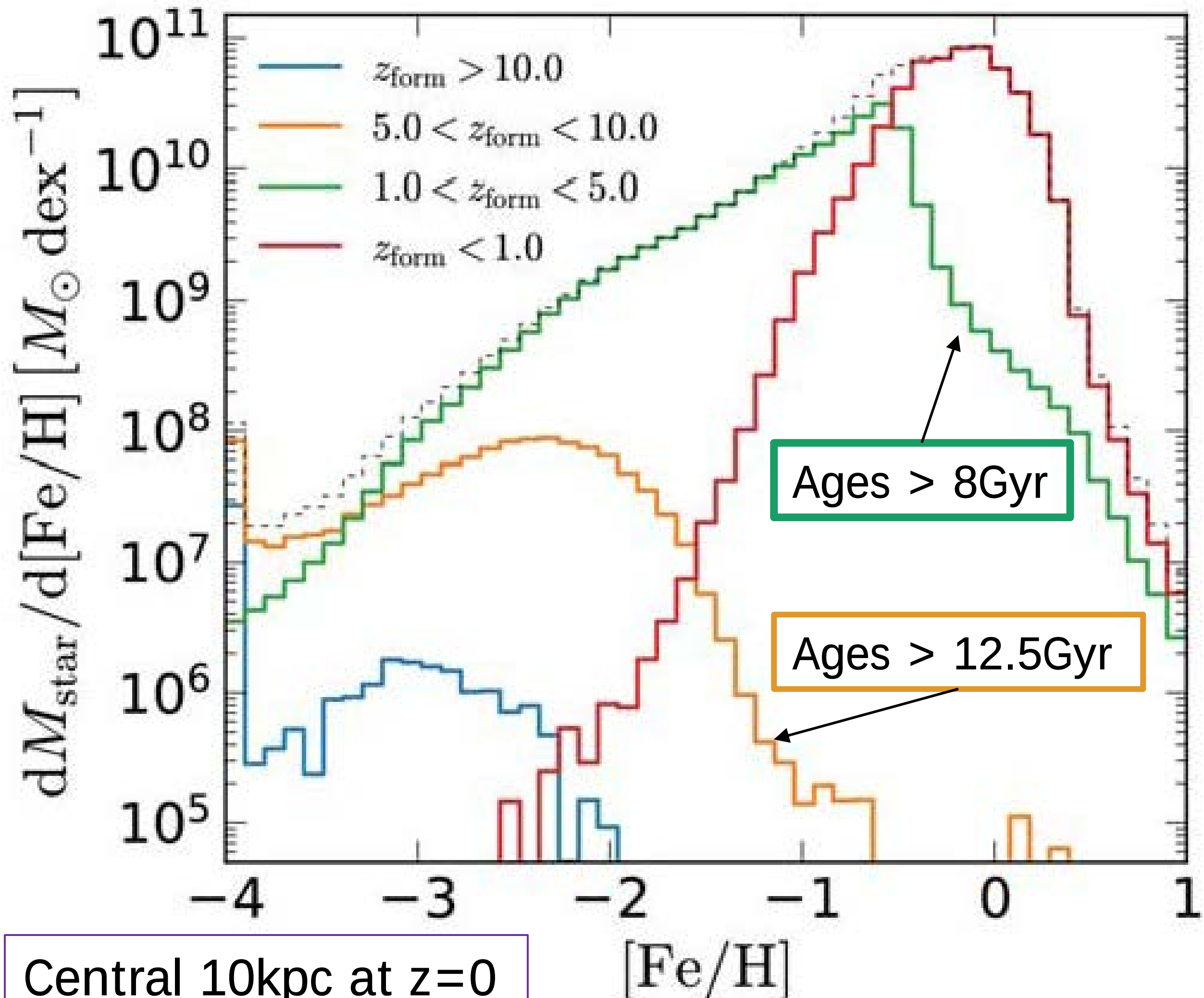
Predictions from ΛCDM
Zoom-in Simulations Milky Way analog



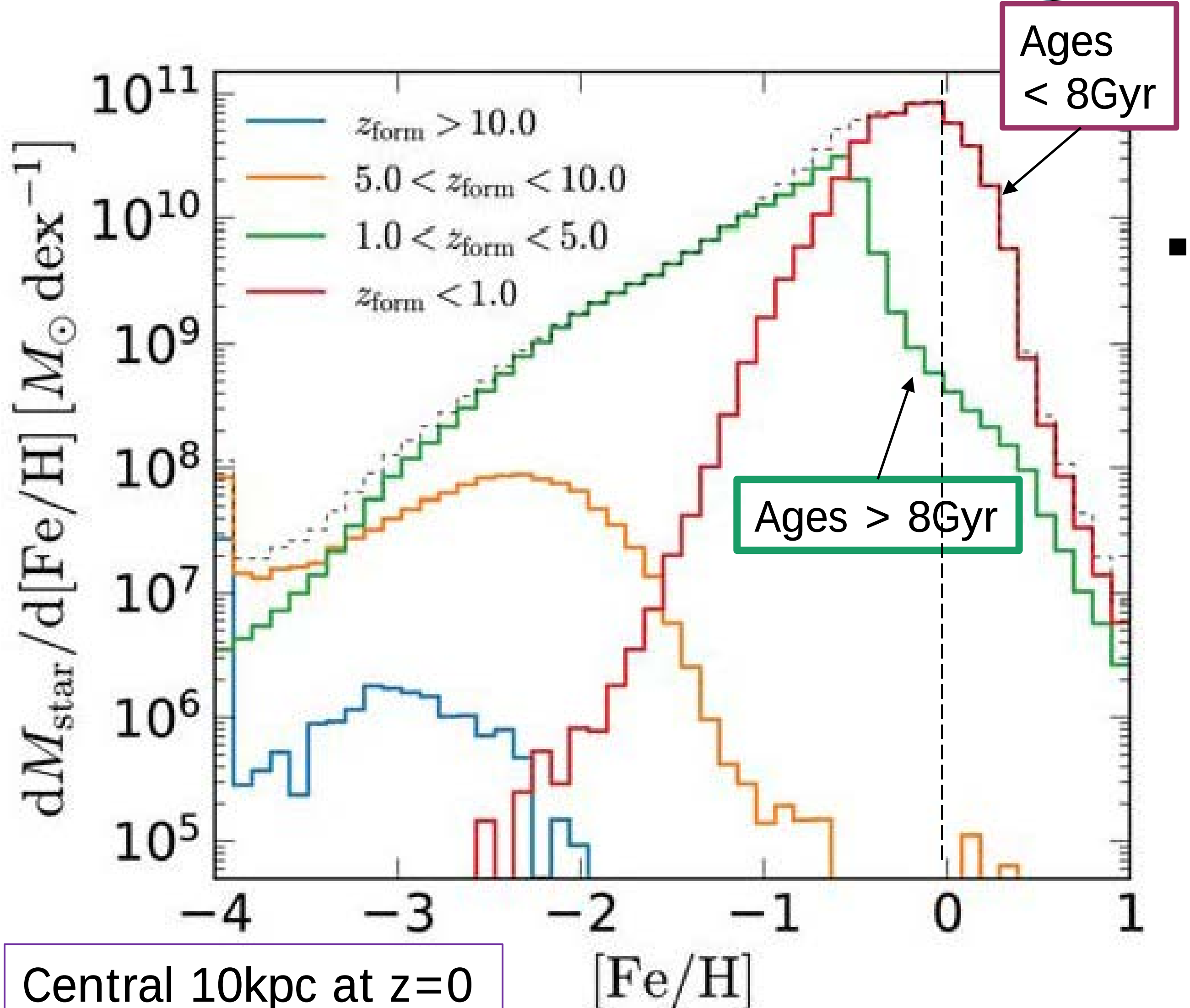
El-Badry et al 2018

- Negligible population of stars age ~12Gyr above [Fe/H] ~ -1 dex

Central 10kpc at z=0

Model m12i, 'normal', somewhat quiescent merger history, last significant merger z ~ 0.7

Predictions from ΛCDM
Zoom-in Simulations Milky Way analog



El-Badry et al 2018

- Most solar iron abundance stars form after redshift unity, ages younger than 8Gyr

Central 10kpc at z=0

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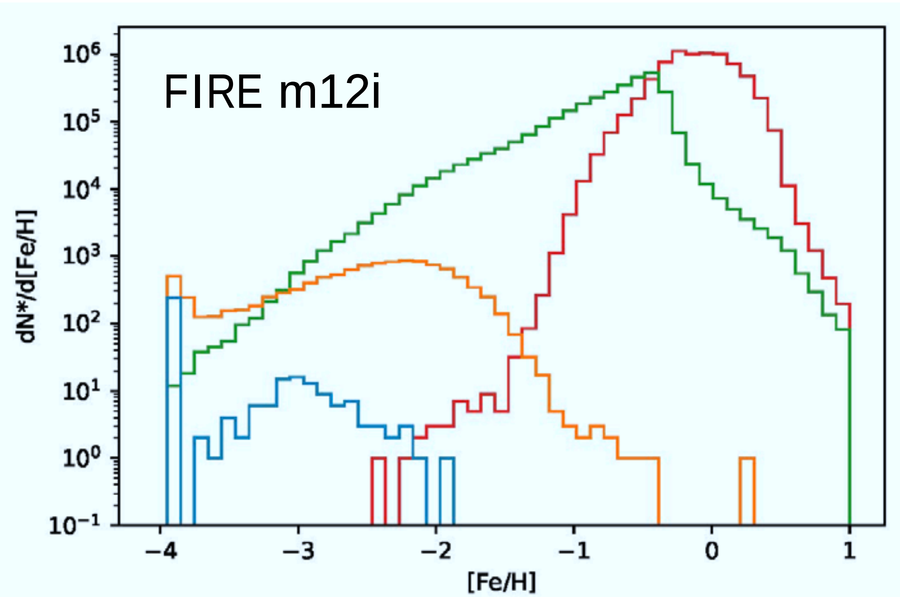
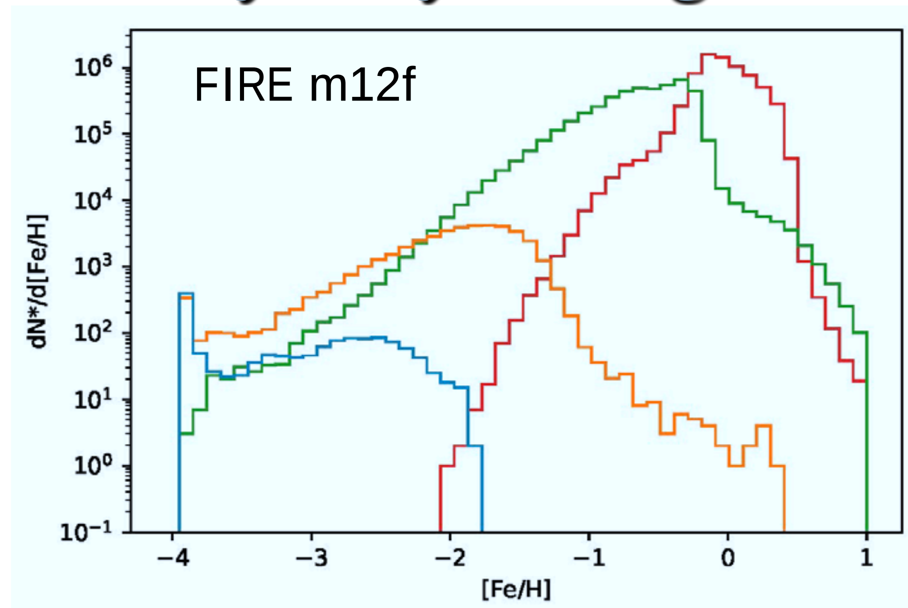
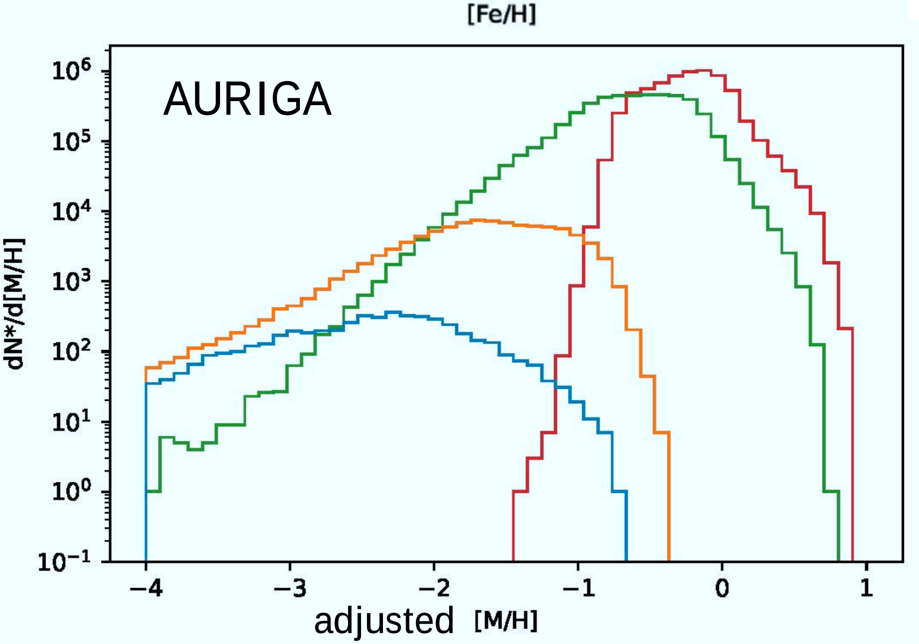
Predictions from ΛCDM
Zoom-in Simulations Milky Way analogs

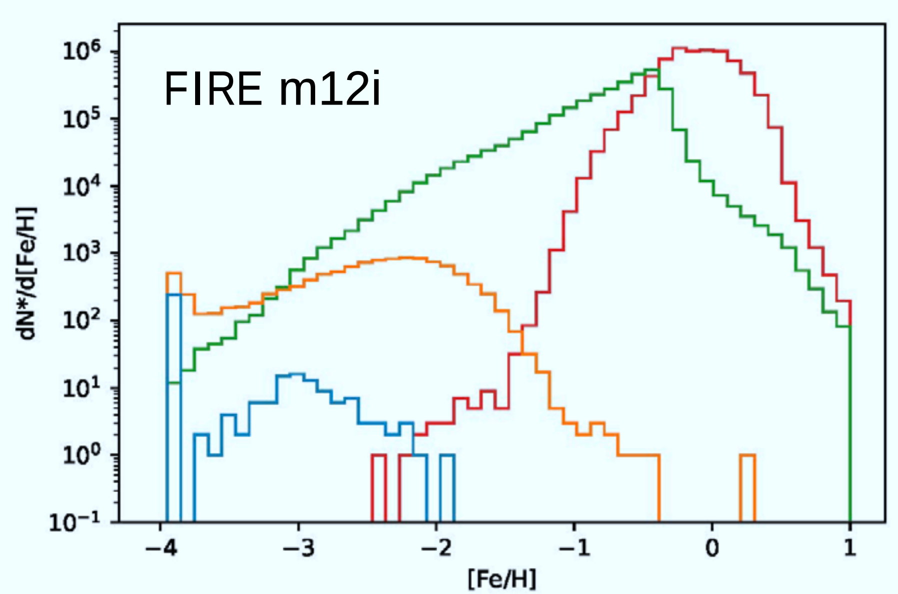


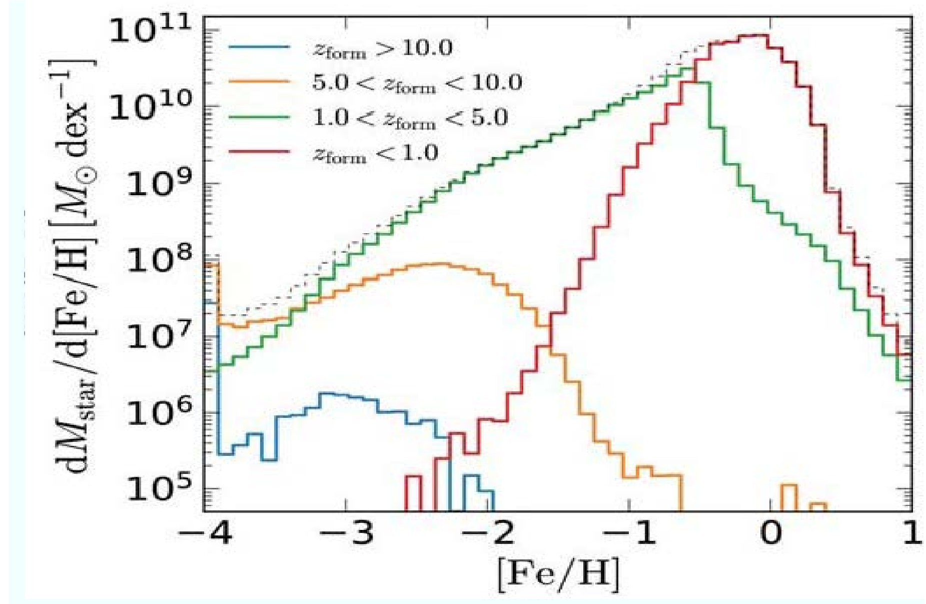


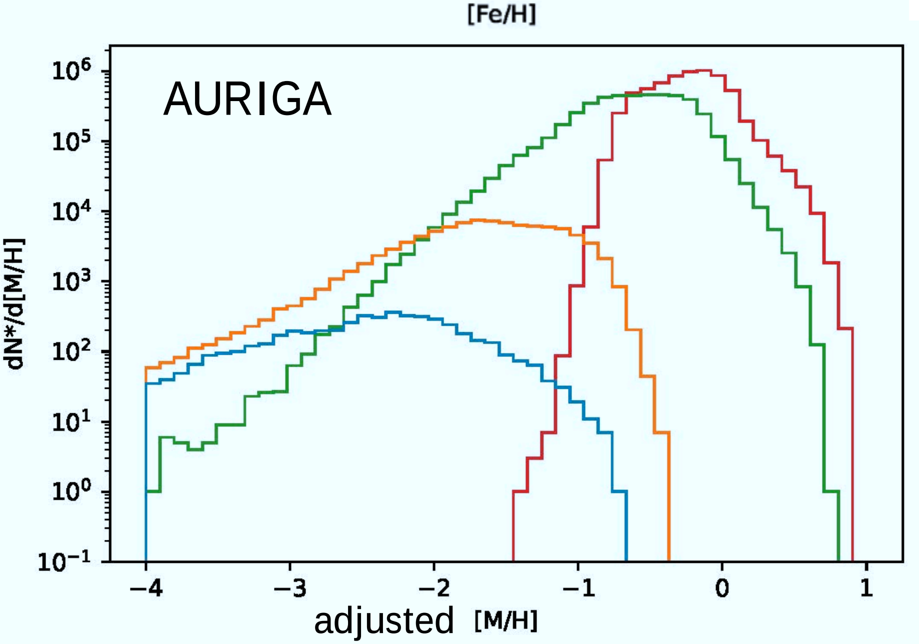


- Two different merger histories within same simulation suite (FIRE-2, Hopkins et al 2018)
  - m12f forms dominant core early
- Two different simulation suites
  - AURIGA (Grand et al 2017)
- Similar predictions

Predictions from ΛCDM
Zoom-in Simulations Milky Way analogs







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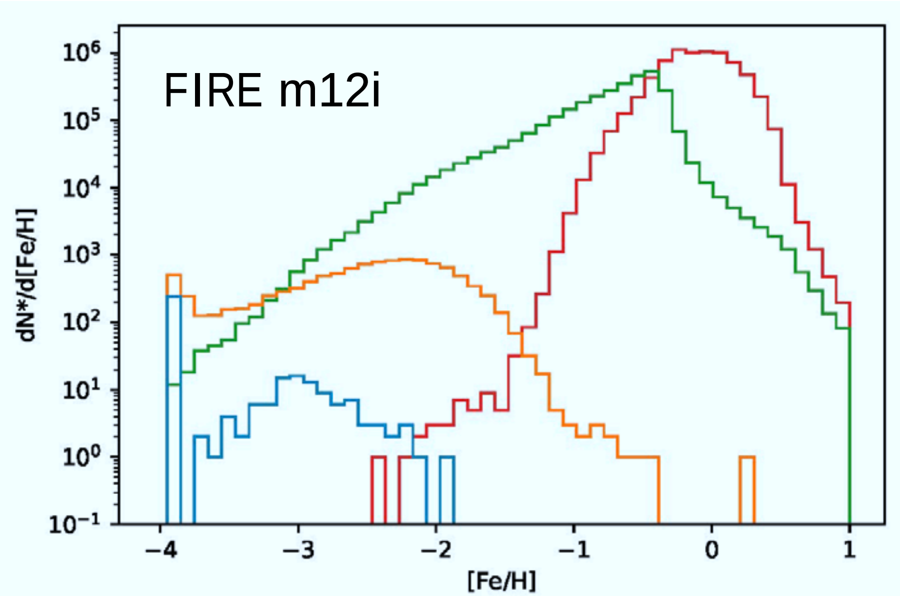
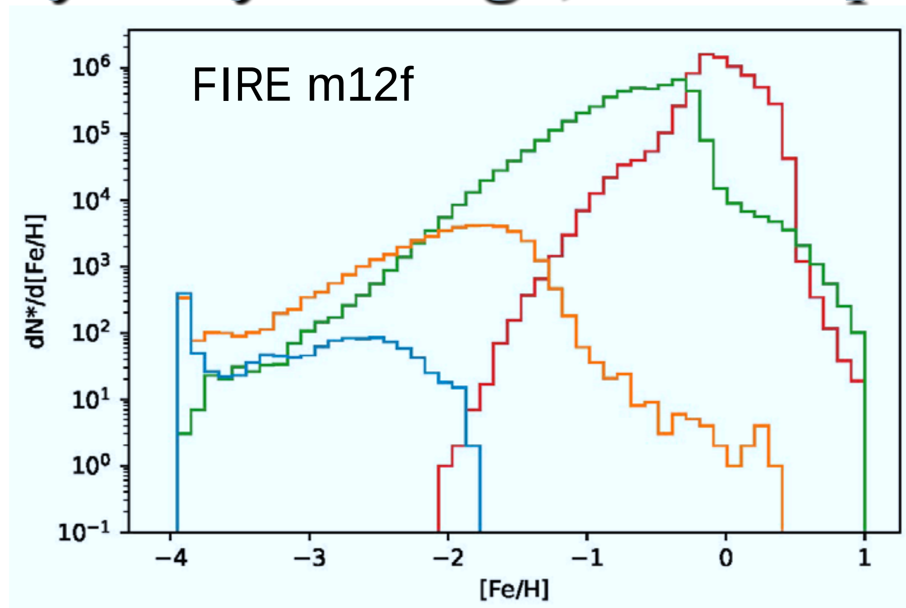
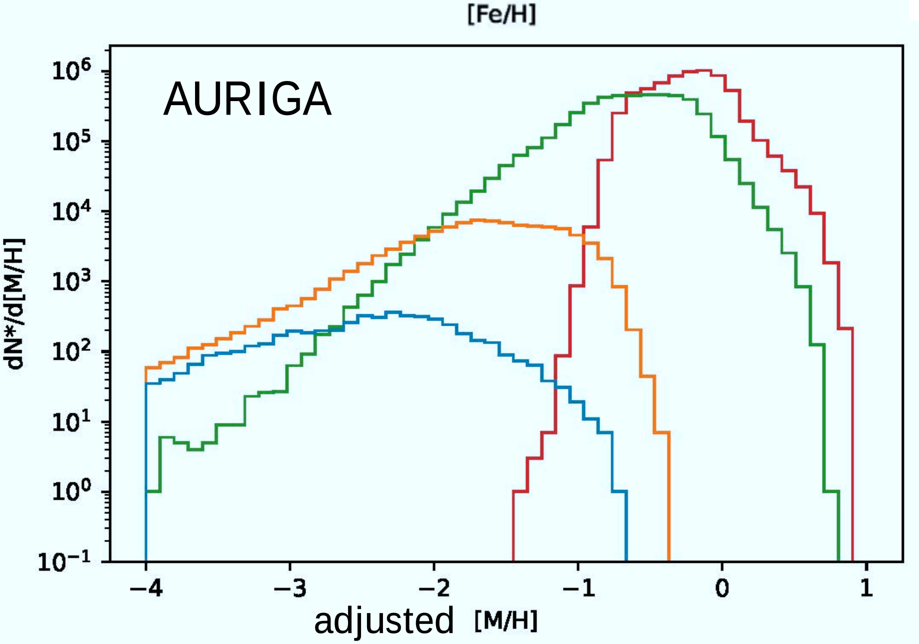
Predictions from ΛCDM
Zoom-in Simulations Milky Way analogs, r < 10kpc







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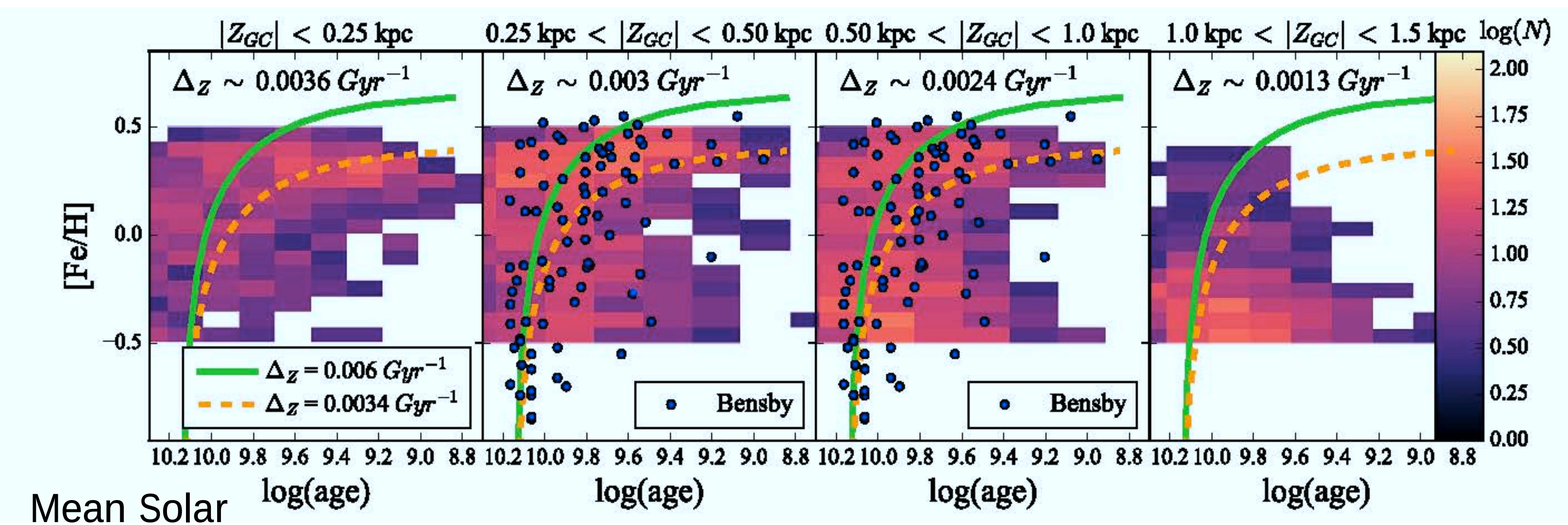
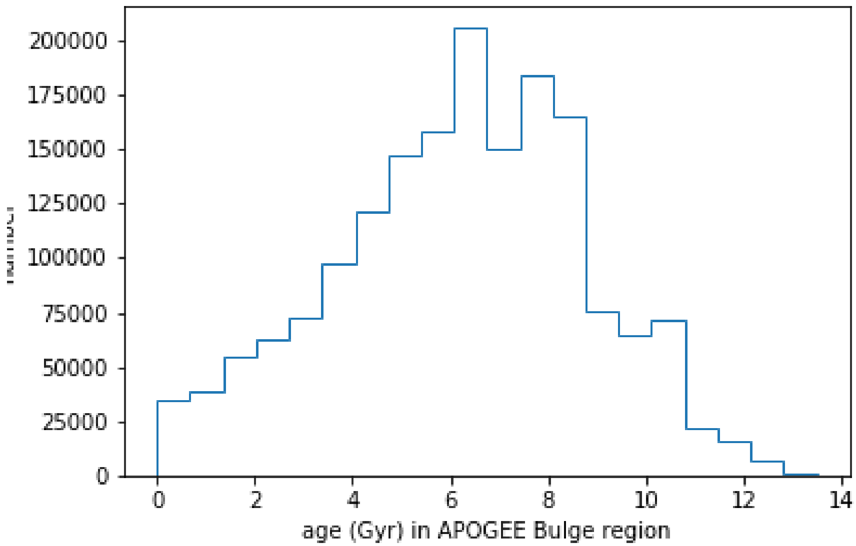
Old, metal-rich stars in the Milky Way Bulge/Bar

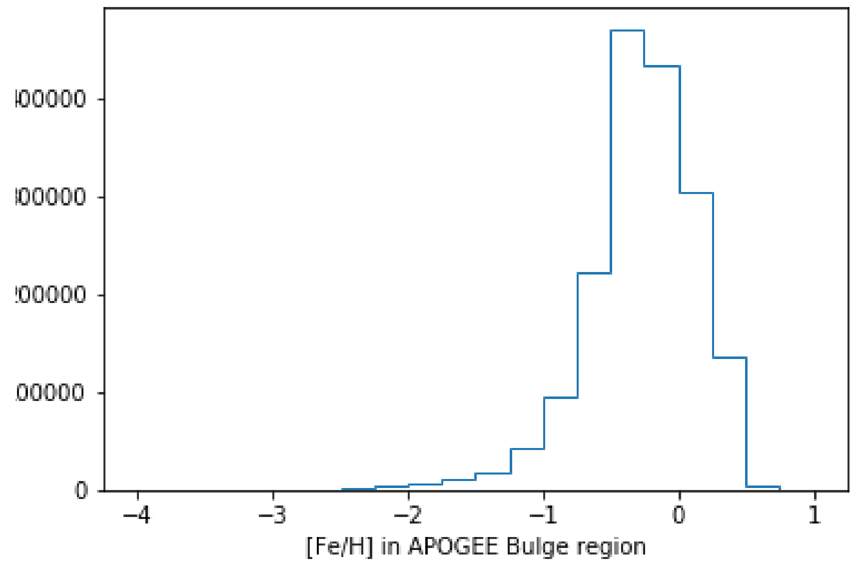
- APOGEE spectra contain both age (C/N ratio) and metallicity (elemental abundances) information
- Training set with isochrone-based ages used to determine age-metallicity data for ~6000 metal-rich ([Fe/H] > −0.5) low-gravity giants in the inner Galaxy, R < 3.5kpc (Hasselquist et al 2020): many metal-rich, old stars, ages > 10Gyr



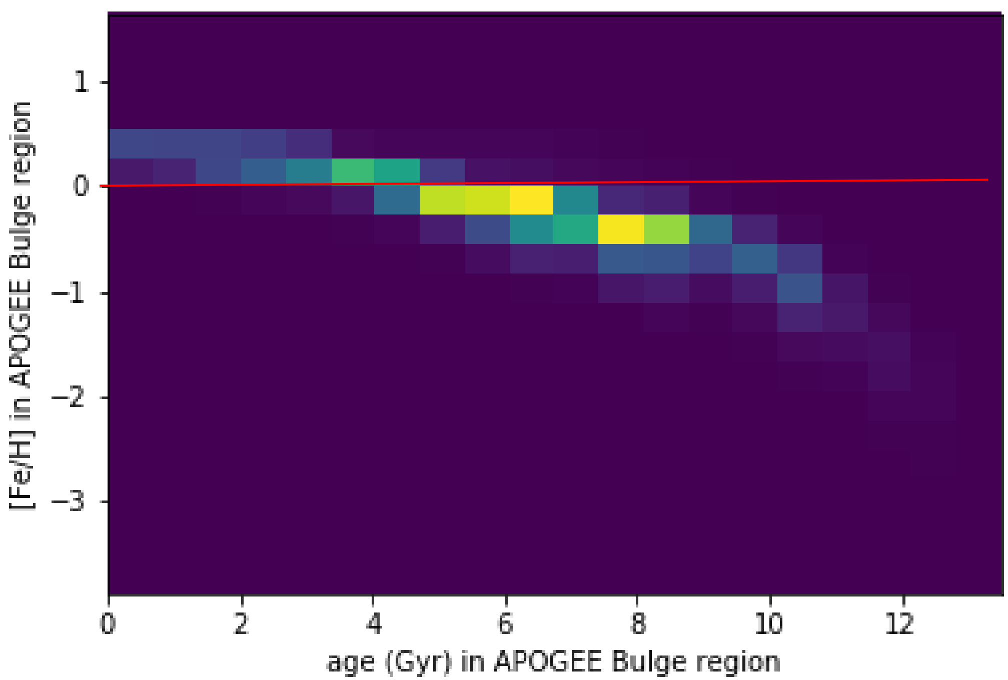
Mean Solar iron at age 8.7Gyr 7.7Gyr 7.2Gyr

Simulated age-metallicity relations for bulge region





FIRE
m12i



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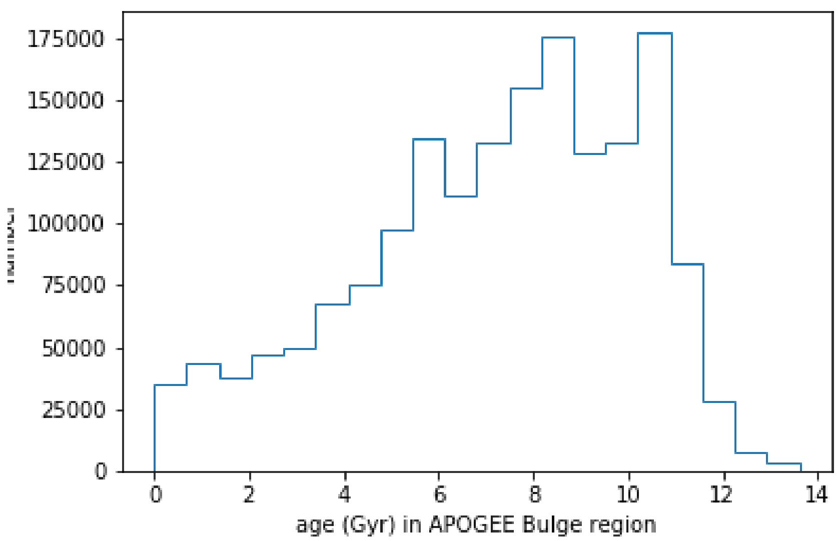
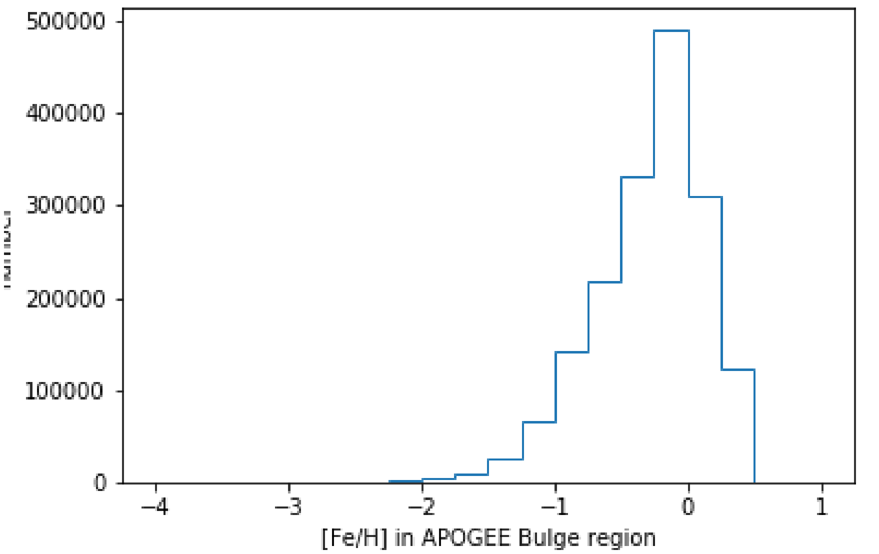
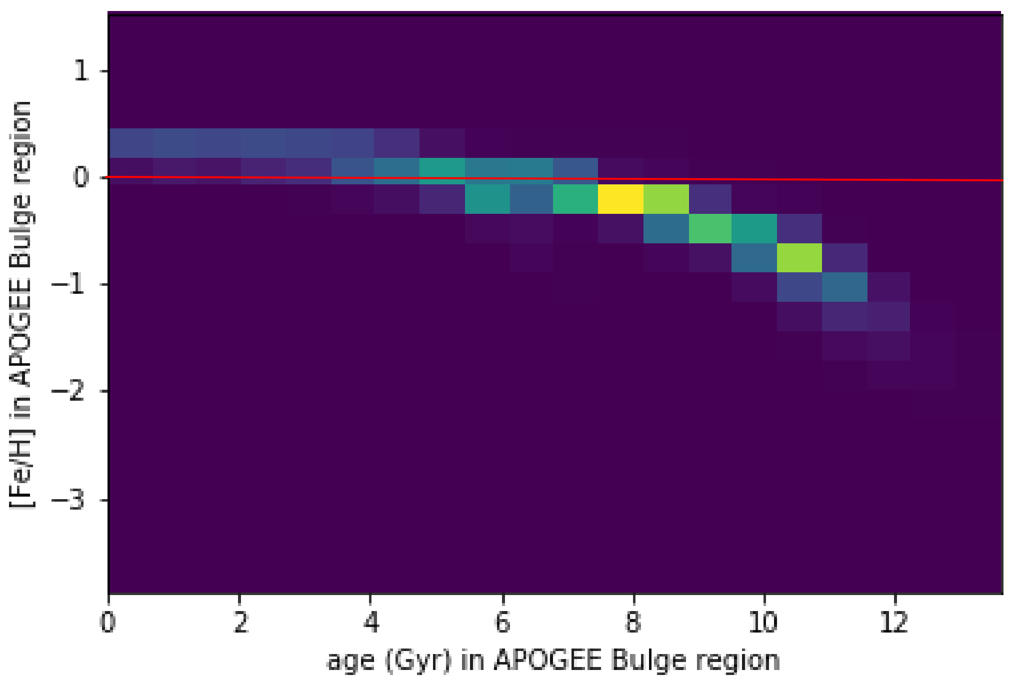




FIRE
m12f



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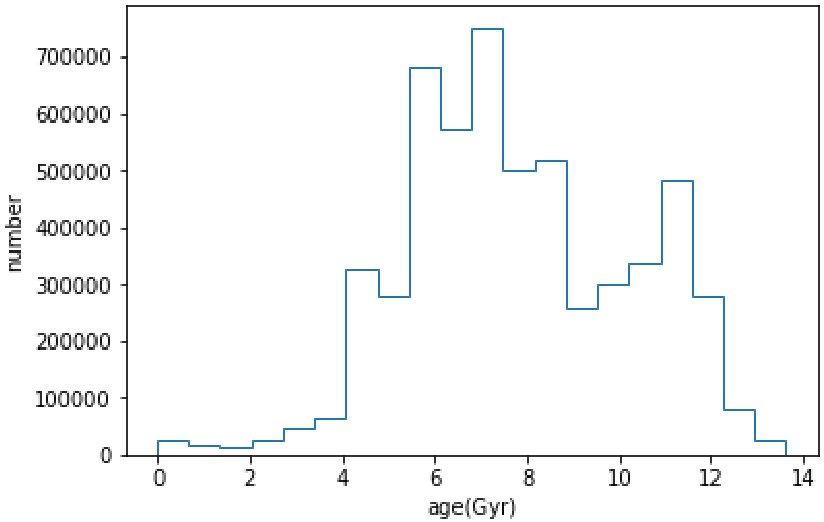
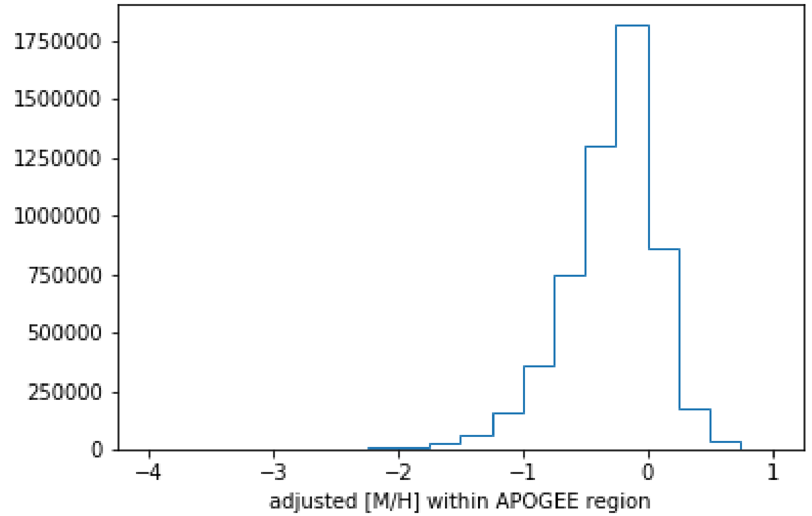
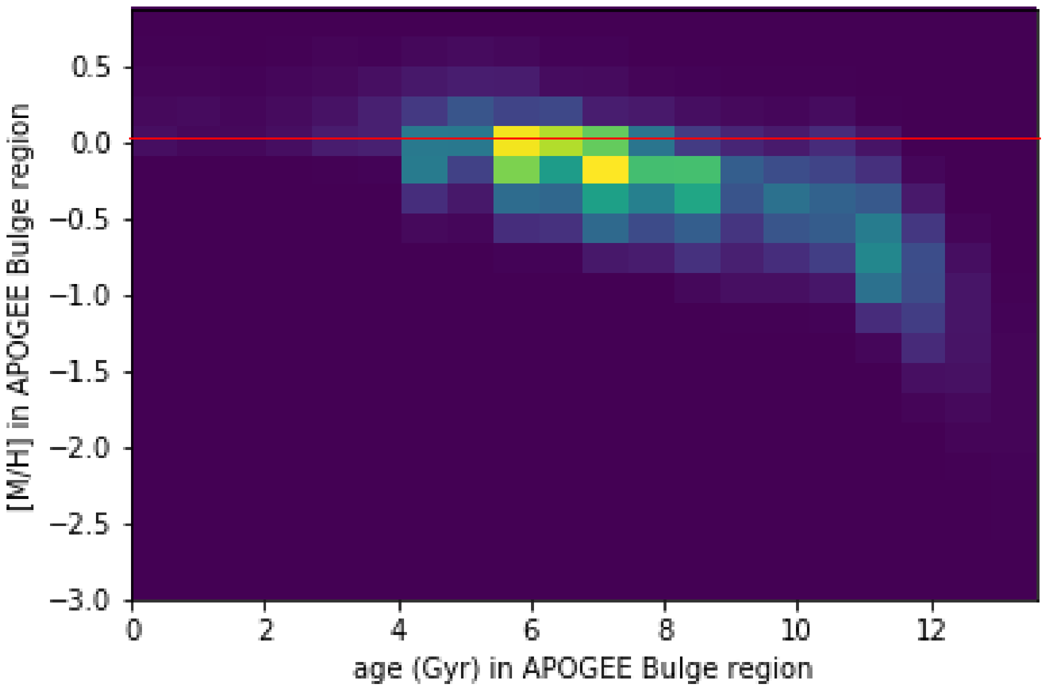


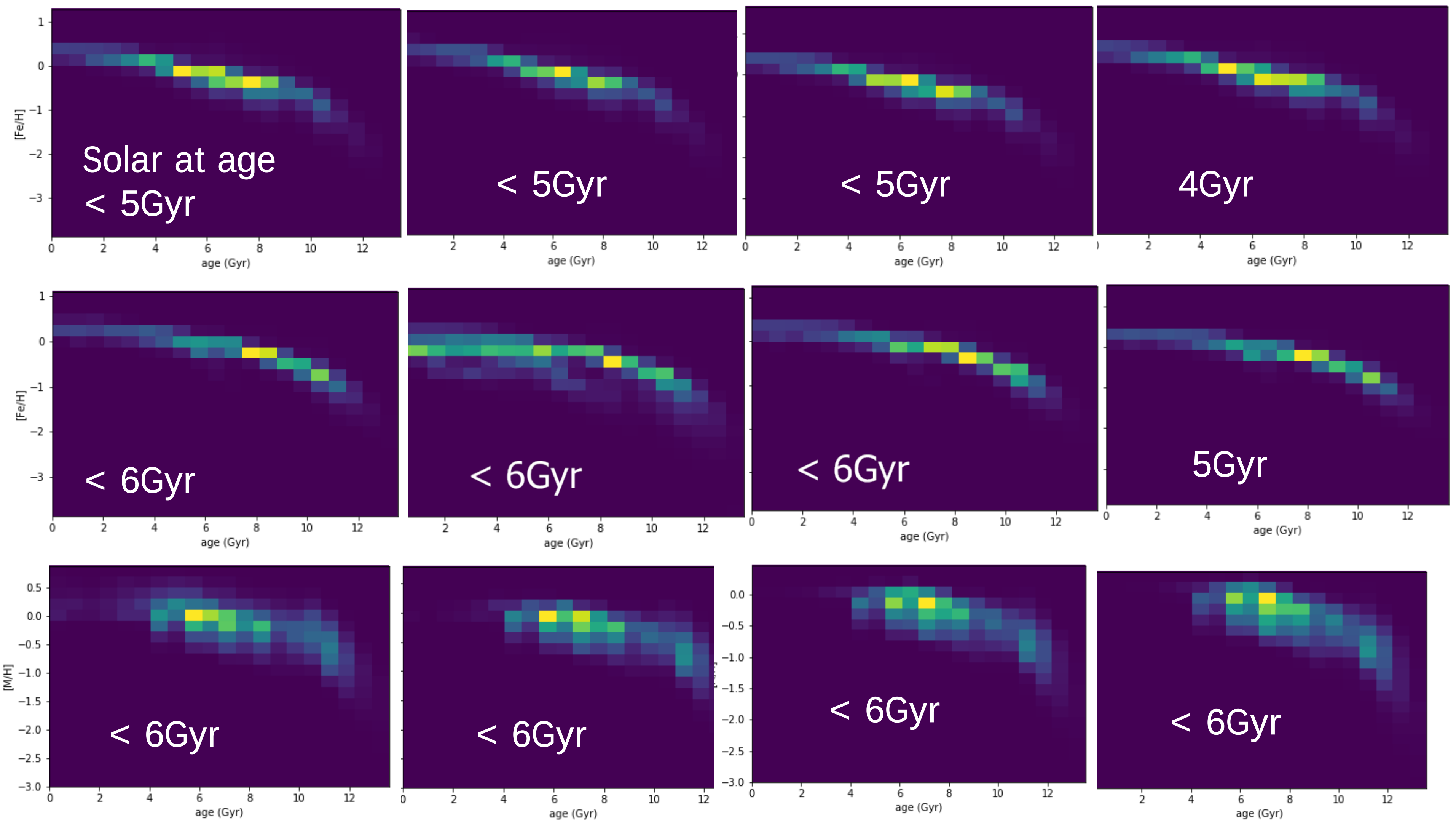


AURIGA



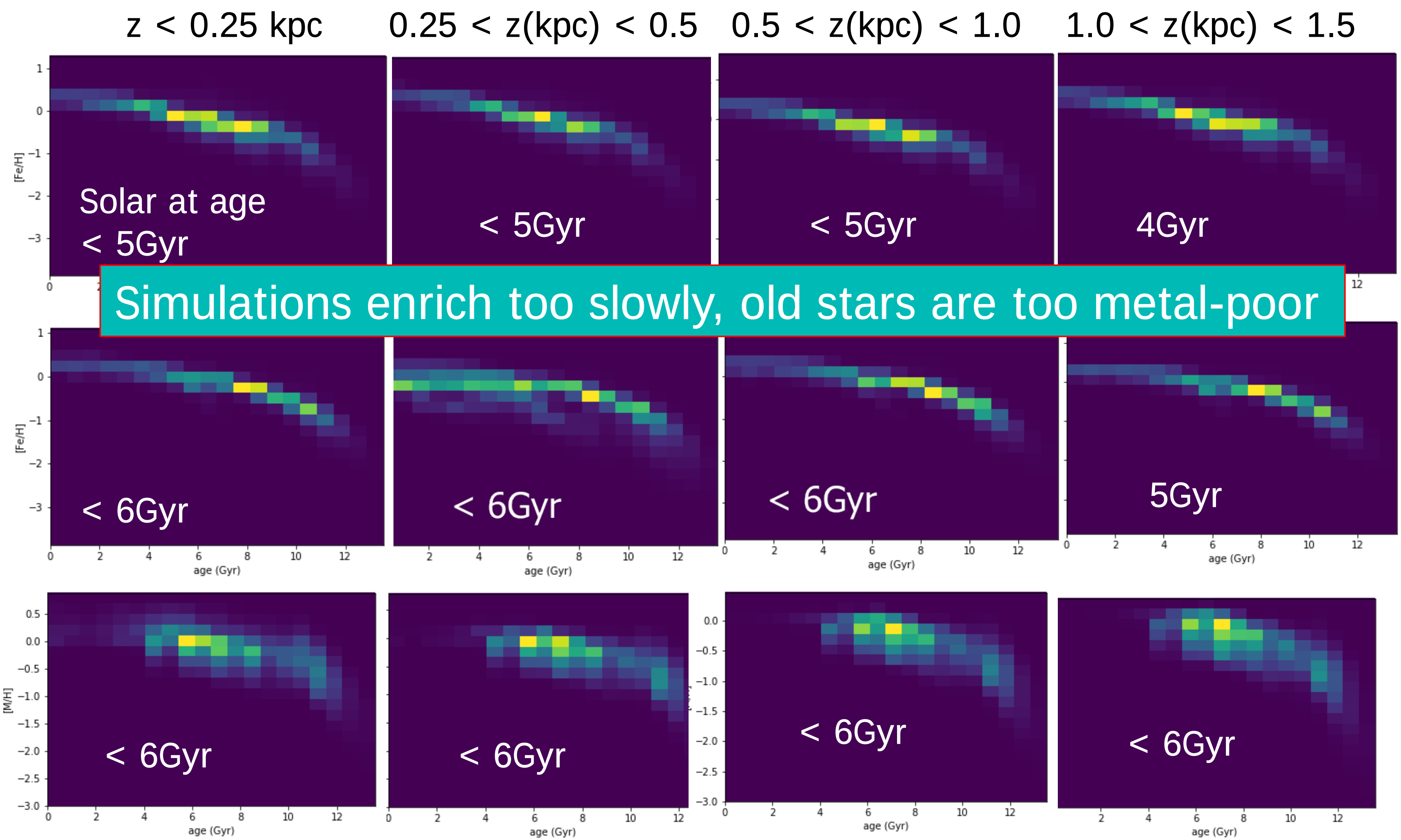
Simulated age-metallicity relations for bulge region

z < 0.25 kpc | 0.25 < z(kpc) < 0.5 | 0.5 < z(kpc) < 1.0 | 1.0 < z(kpc) < 1.5



Top row: FIRE m12i Middle row: FIRE m12f Bottom row: AURIGA

Simulated age-metallicity relations for bulge region



Top row: FIRE m12i Middle row: FIRE m12f Bottom row: AURIGA

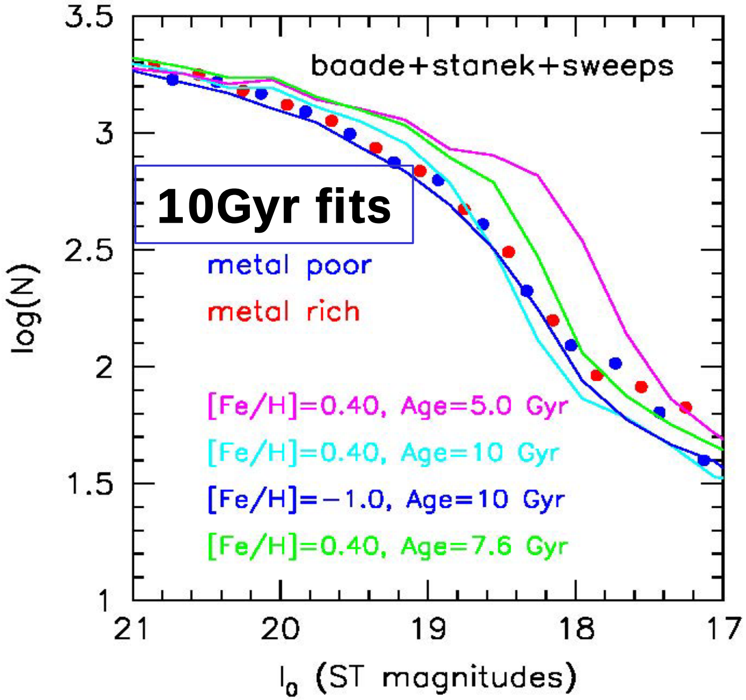
Implications of The Old, Metal-Rich Milky Way

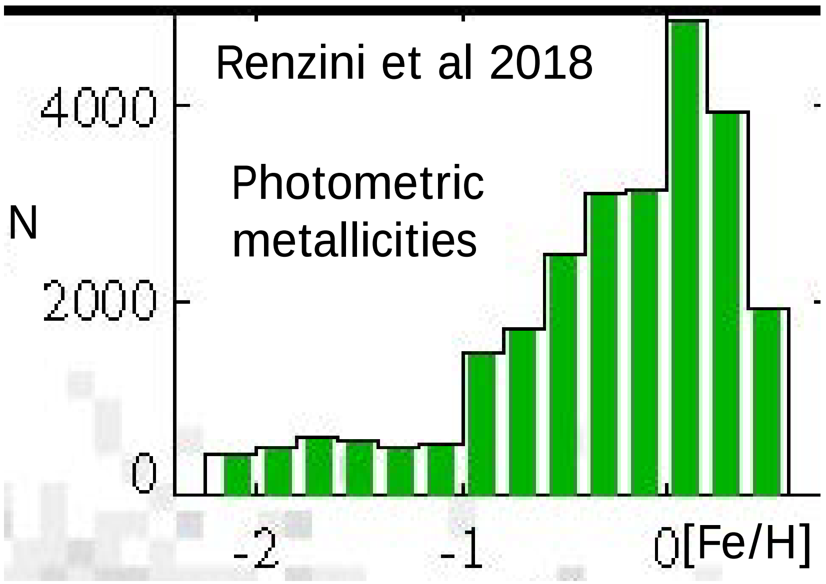
- Assuming Milky Way typical, expect to observe fairly luminous, chemically evolved, centrally concentrated proto-galaxies at high redshift (10Gyr → $z \sim 2$; 12Gyr → $z \sim 4$) -- JWST
- ΛCDM simulations of Milky Way analogues, with early star formation in low-mass systems and stellar feedback quenching star formation do not create a dominant old, metal-rich stellar population
- Plausibly reflects truncation of chemical enrichment due to inability of early-forming substructure to retain gas
- Another aspect of `tensions' between predictions of ΛCDM on galactic scales and observations, possibly indicative of too much power on small scales

Old, metal-rich stars in the Milky Way

The bulge/bar:

- Several CMD-based analyses have all bulge stars older than 8 Gyr, with population of blue stragglers (descendants?)
  - Optical HST data (Clarkson et al 2011; Renzini et al 2018)
  - IR + spectroscopic metallicity distribution (Surot et al 2019)



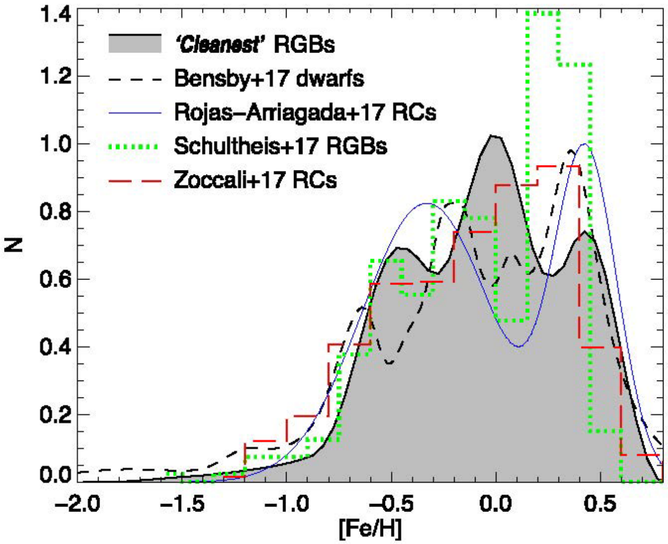


Foreground disk removed using proper motions cf Kuijken & Rich 2002

Old, metal-rich stars in the Milky Way

The bulge/bar:

- Others find that for stars above solar metallicity, only ~ 60% are older than 8Gyr and between -0.5 dex and solar metallicity, ~80% are older than 8Gyr (no BSS)
  - Bensby et al 17: micro-lensed dwarfs (but see Joyce et al 22)
- Bournard et al 2018: same HST dataset as Renzini et al, different analysis approach (fits to synthetic CMDs created by linear combinations of Simple Stellar Pops)



Good agreement that most of the stellar mass has metallicity above -0.5 dex, and about half of the mass is above solar

Old, metal-rich stars in the Milky Way

The bulge/bar:

- Chemodynamic analysis fitting star counts and kinematics with adopted (spectroscopic) metallicity distribution and 10Gyr age finds stellar mass of bulge/bar ~ 2 x $10^{10} M_{\odot}$ (Portail et al 2017; cf Zoccali et al 2017)

➔ Conservative consensus of published analyses: More than 50% (~70%) of stellar mass, ~ 1.4 x $10^{10} M_{\odot}$, is older than 8 Gyr and more metal-rich than [Fe/H] = −0.5

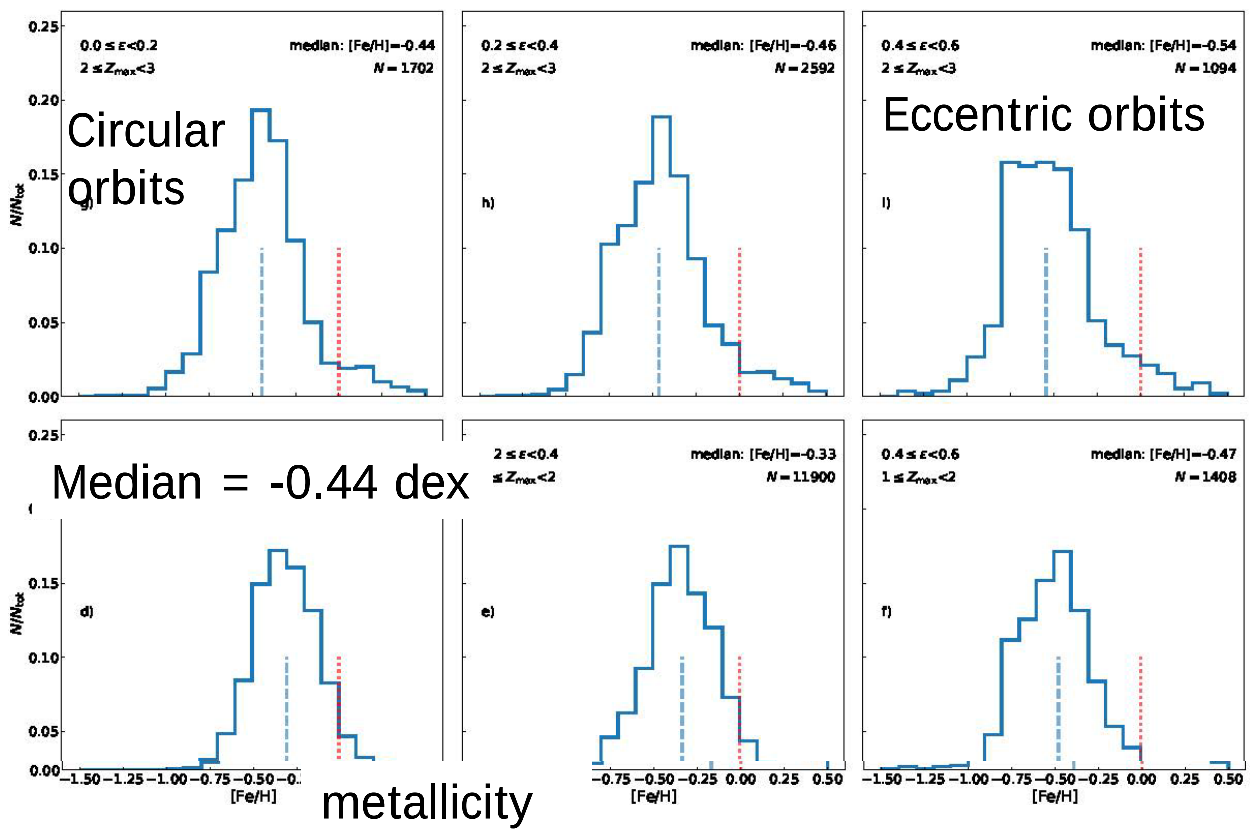
- Includes ~ 30% of bulge/bar mass being above solar metallicity and older than 8 Gyr

Old, metal-rich stars in the Milky Way

- **The thick disk:** stellar mass ~ 1/5 that of thin disk, ~ 6 x $10^9 M_\odot$, older than 8 Gyr (some BSS) with mean [Fe/H] > −0.5 ➔ ~3 x $10^9 M_\odot$ above -0.5 dex
  - Little evidence for radial metallicity gradient (Hayden et al ’15; Steinmetz et al 2019)

$2 < z_{max}$(kpc) < 3

$1 < z_{max}$(kpc) < 2



Old, metal-rich stars in the Milky Way

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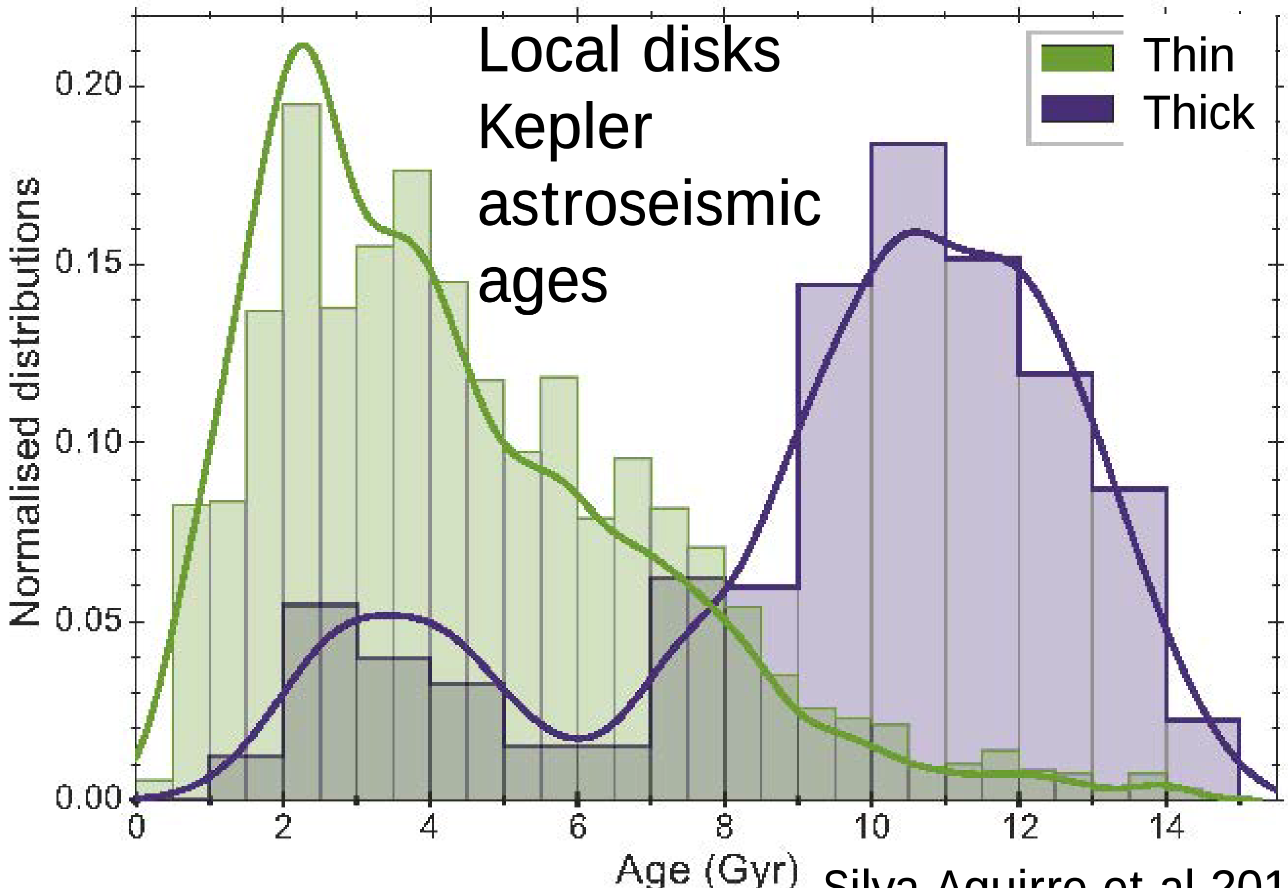
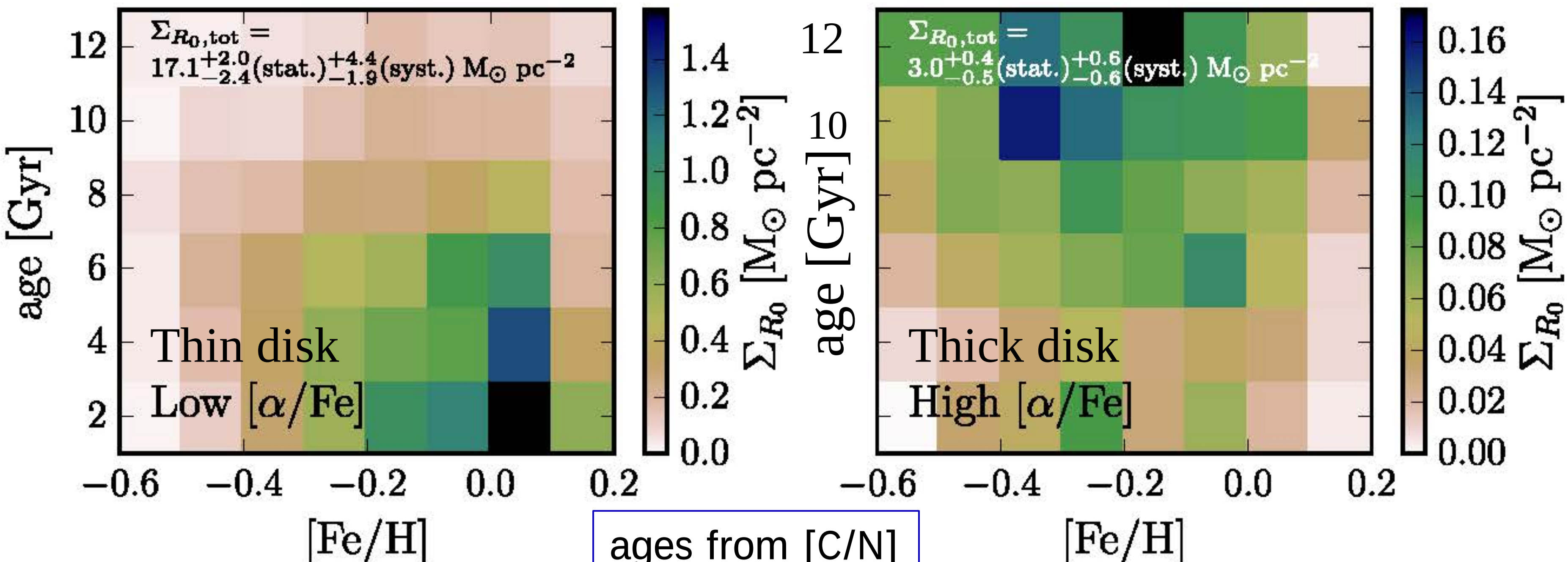


Silva Aguirre et al 2018

Old, metal-rich stars in the Milky Way

- **The thick disk:** stellar mass ~ 1/5 that of thin disk, ~ 6 x $10^9 M_\odot$, older than 8 Gyr (some BSS) with mean [Fe/H] > −0.5 ➔ ~ 4 x $10^9 M_\odot$, older than 8 Gyr and above -0.5 dex

Mackereth et al 2017

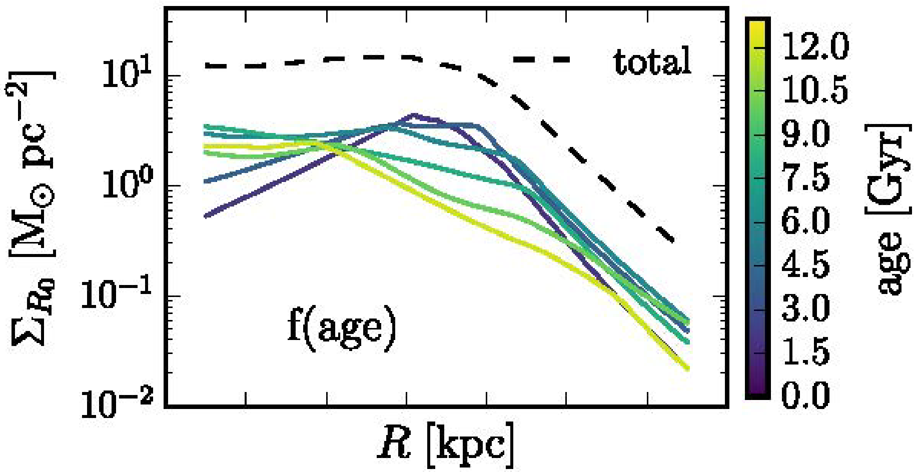


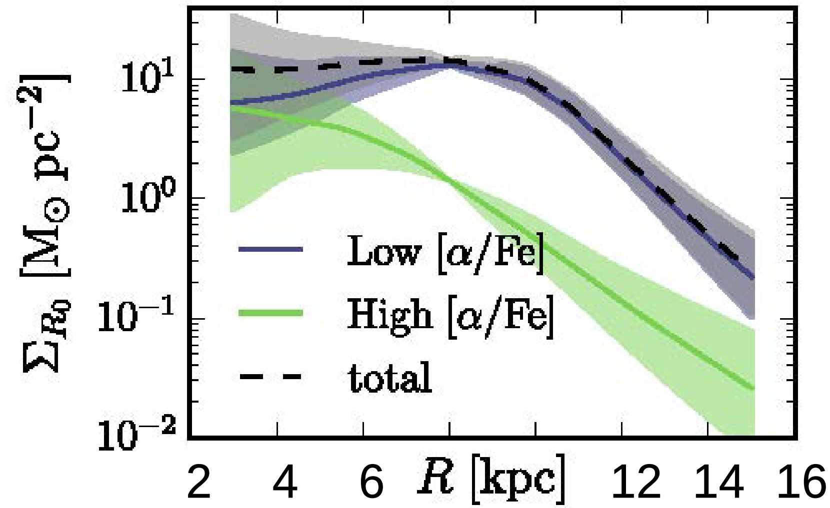
ages from [C/N]

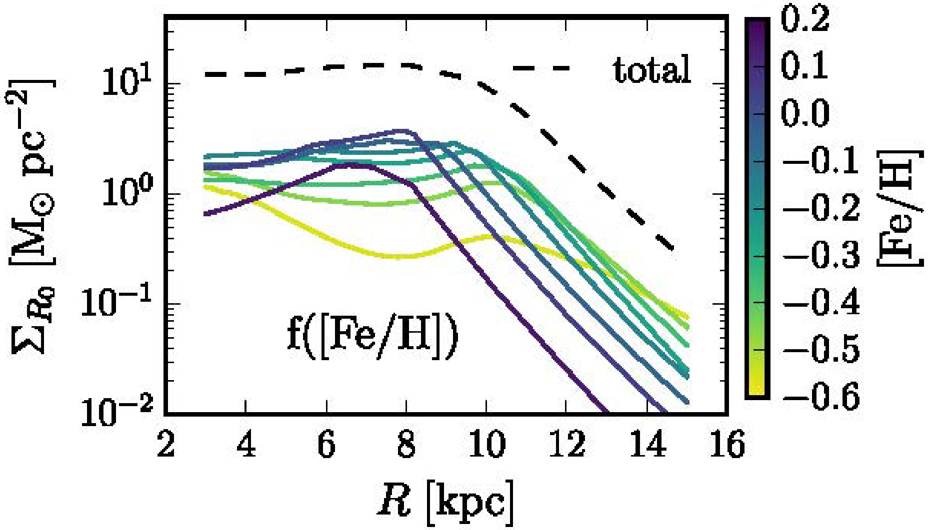
Note even in local thin disk, peak iron abundance for stars older than 8Gyr is around solar

Old, metal-rich stars in the Milky Way

- **Inner thin disk**: old and metal-rich (Mackereth et al 2017, 2019)



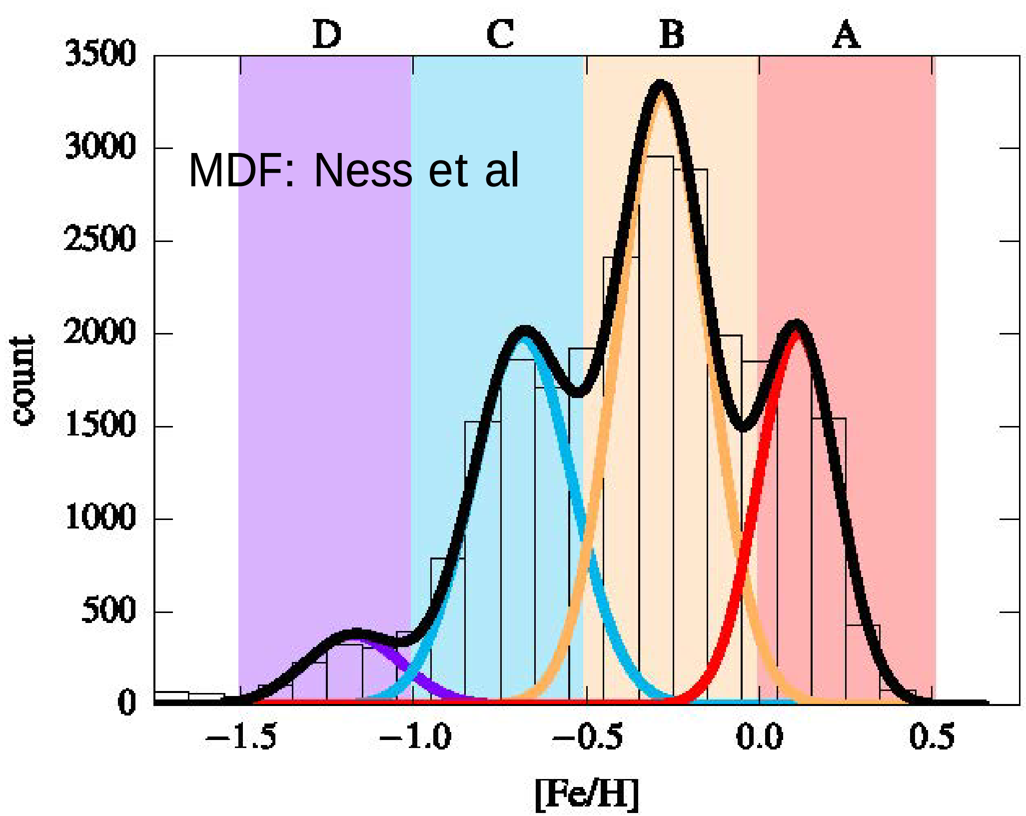




Thick and thin disks contribute approx. equally to surface density in inner disk, where old, (> 8Gyr) metal-rich (above solar) stars dominate

Old, metal-rich stars in the Milky Way

- **Inner thin disk**: mass within 5kpc (half-length of bar) ~ $10^{10} M_{\odot}$ (Portail et al 2017a)
  - Chemodynamic modelling (Portail et al 2017b), assuming age 10Gyr:



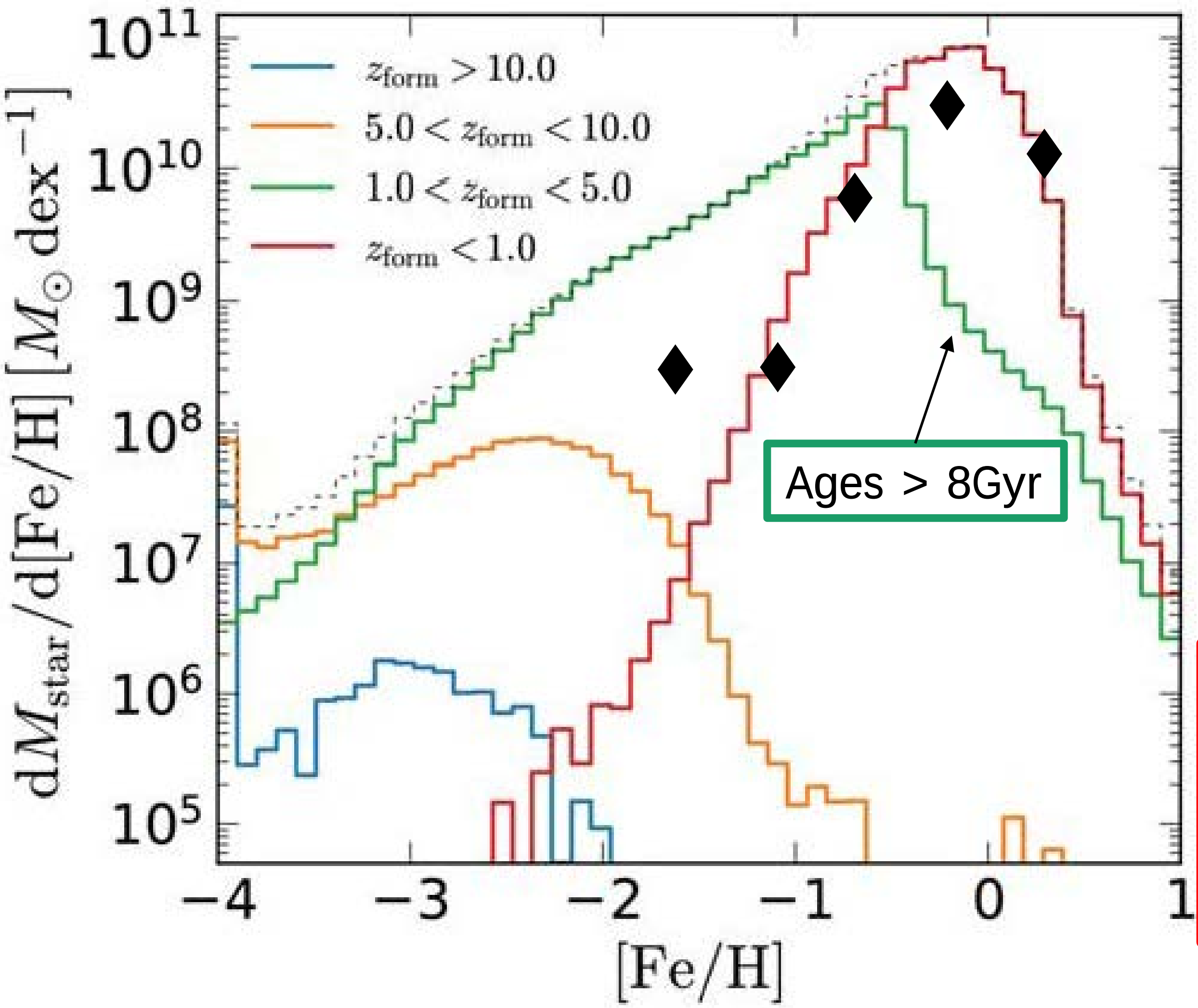
~40% of stars in A, 50% in B, 15% in C on disk orbits

Conservatively, one quarter of inner disk is older than 8Gyr, and above -0.5 dex

Old, metal-poor stars in the Milky Way

- ~ 50% of thick disk below -0.5 dex, ~ $3 \times 10^9 M_\odot$
  - Dominates the `metal-poor' old stars
- stellar halo: vast majority of stars have metallicity below -1 dex, older than 8Gyr
  - Both accreted (e.g. Belokurov et al 2018) and in situ (Rix et al 2022)
  - around 1% of total MW stellar mass, or ~ $5 \times 10^8 M_\odot$
- Metal-poor thin disk, extends to below -1 locally, but hard to quantify stellar mass (or age) especially in inner regions of the Galaxy (Conroy et al 2022)

Predictions from ΛCDM
Zoom-in Simulations Milky Way analog



El-Badry et al 2018

FIRE hydrodynamic simulations

Central 10kpc at z=0

♦ Observations, inner regions Milky Way Galaxy, stars with ages > 8Gyr

Model m12i, 'normal', somewhat quiescent merger history, final minor merger z ~ 0.7

Conclusions

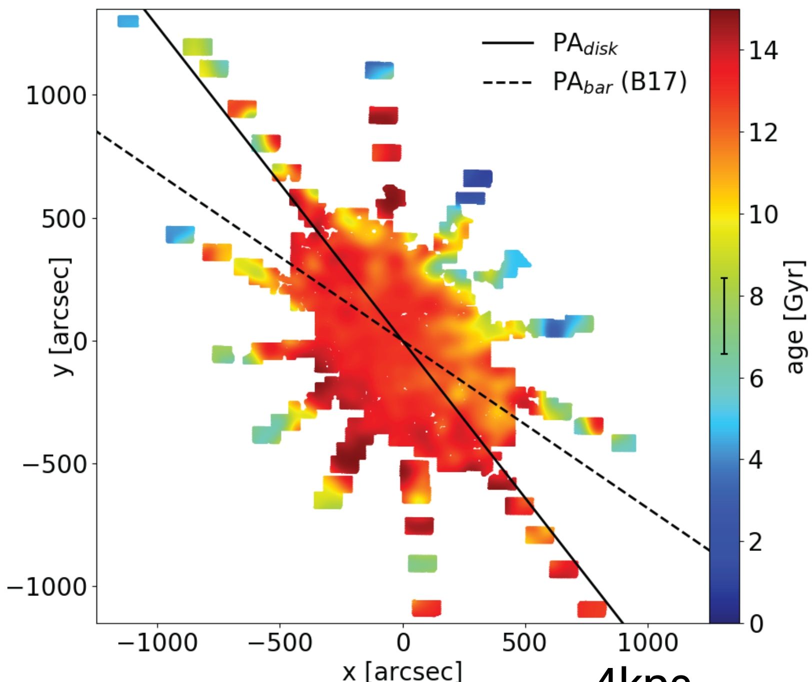
- Most stars in the Milky Way that formed prior to redshift unity have metallicity above -0.5 dex
  - MWG: ~80% above -0.5 dex, ~30% above solar
  - Unlike predicted distribution for MWG analog in ΛCMD simulation (FIRE)
- Centrally concentrated – bulge/bar/inner disk
- Likely formed in deep potential well, due to massive substructure, that could sustain high star-formation rate and rapid chemical enrichment to completion
  - Inside-out quenching at early times (cf Tachella et al 2015), due to exhaustion of gas – supply driven by merging(?)

Old Metal-Rich Stars in M31

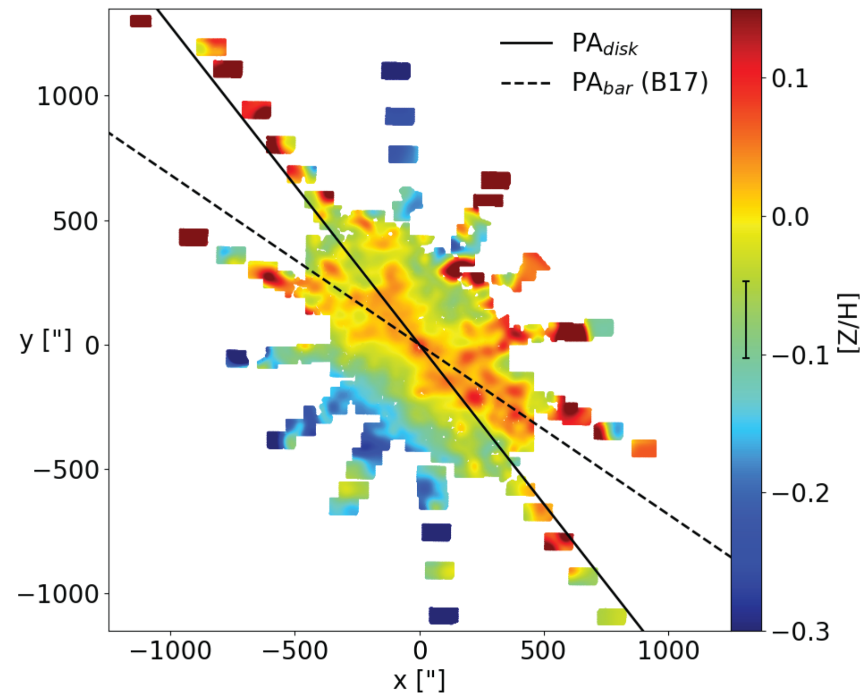
- PHAT team analysed HST data for evolved stars in fields covering 2 < R < 20kpc and found 'most stars are metal rich and most metal rich stars are older than 8Gyr' (Williams et al 2017)
  - ~1/3 of stellar mass within 5kpc of the center is older than 8Gyr and has metallicity above -0.4dex
- Consistent result using deeper data, down to old main sequence turn-off, for outer disk at R > 20kpc (Bernard et al 2015): [Fe/H] = -0.4 dex, 10Gyr ago
- Halo of M31 dominated by old, metal-rich population, > -0.6 dex (e.g. Ibata et al 2014)

Old Metal-Rich Stars in M31

- Stellar populations in inner disk and bulge analysed through IFU spectroscopic data (Saglia et al 2018),
- Dominated by stars older than 10Gyr and around solar metallicity (Lick indices)

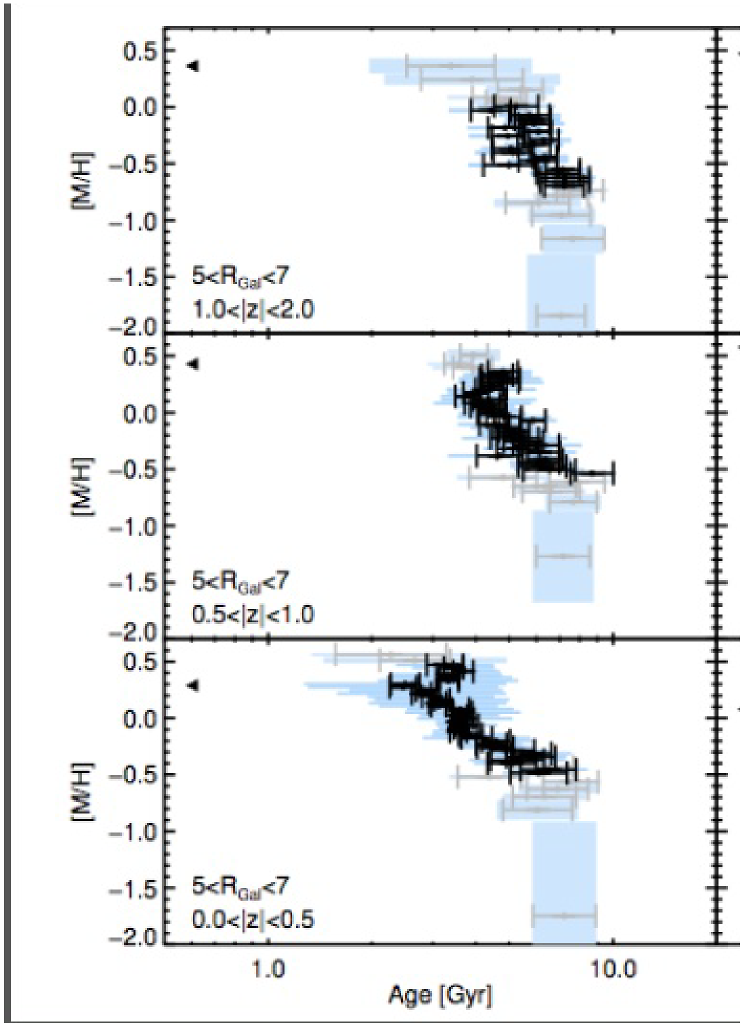


4kpc

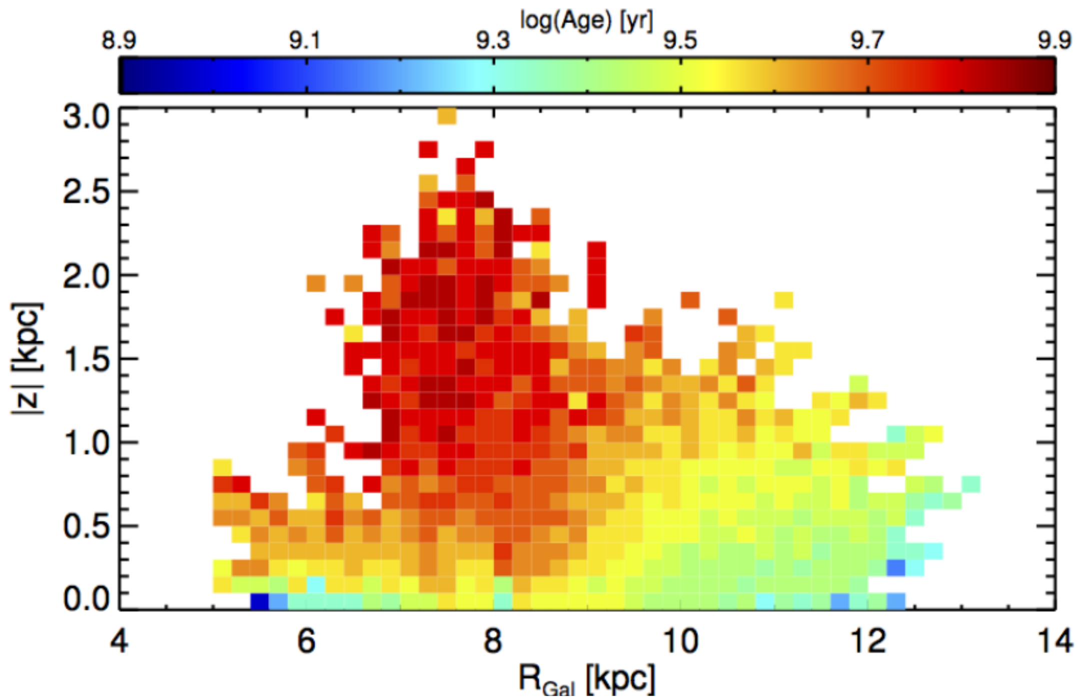


Old, metal-rich stars in the Milky Way

- **Inner thin disk**: metal-rich, above -0.5 dex, age-metallicity trend



Feuillet et al 2019



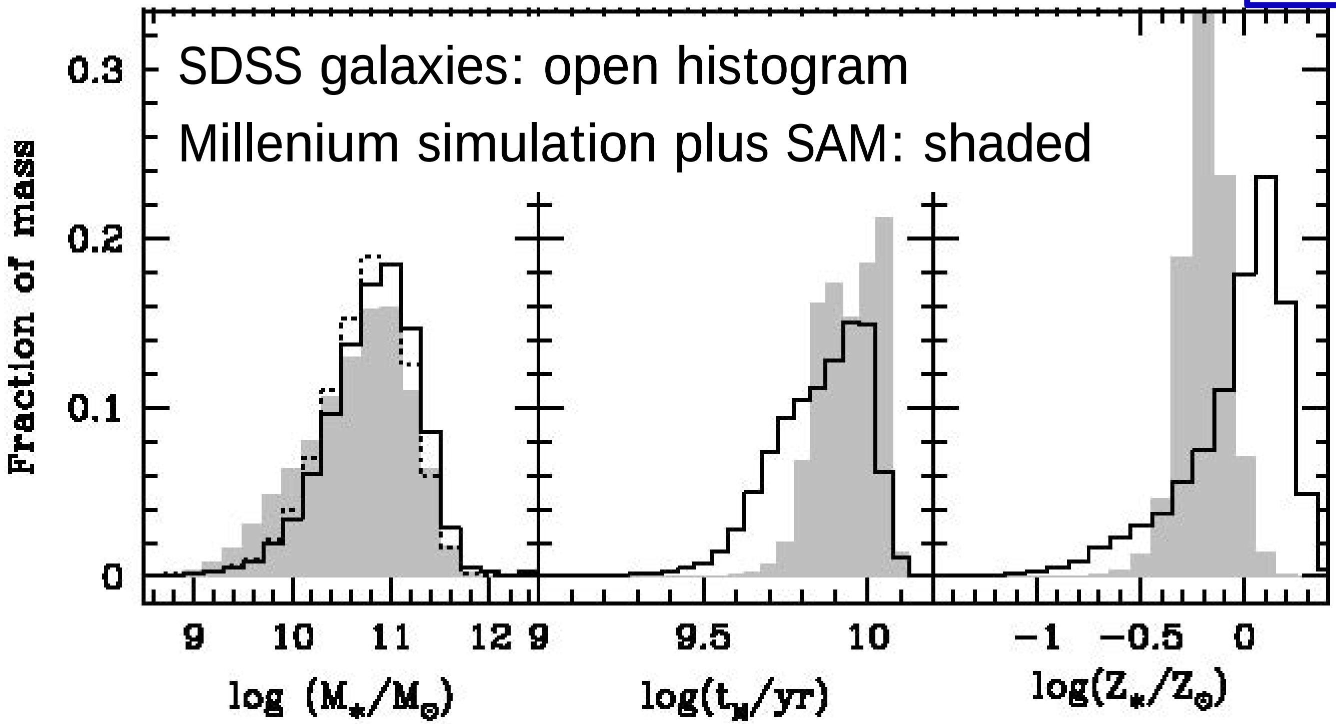
Old inner-disk stars are more metal-rich than -0.5 dex. Isochrone-based ages (younger?)

Predictions from ΛCDM

- Early cosmological simulations could make predictions for the metallicity and age distributions of entire galaxies only
  - Lacked resolution for more detailed study
- Predict most stars are too old and too metal-poor

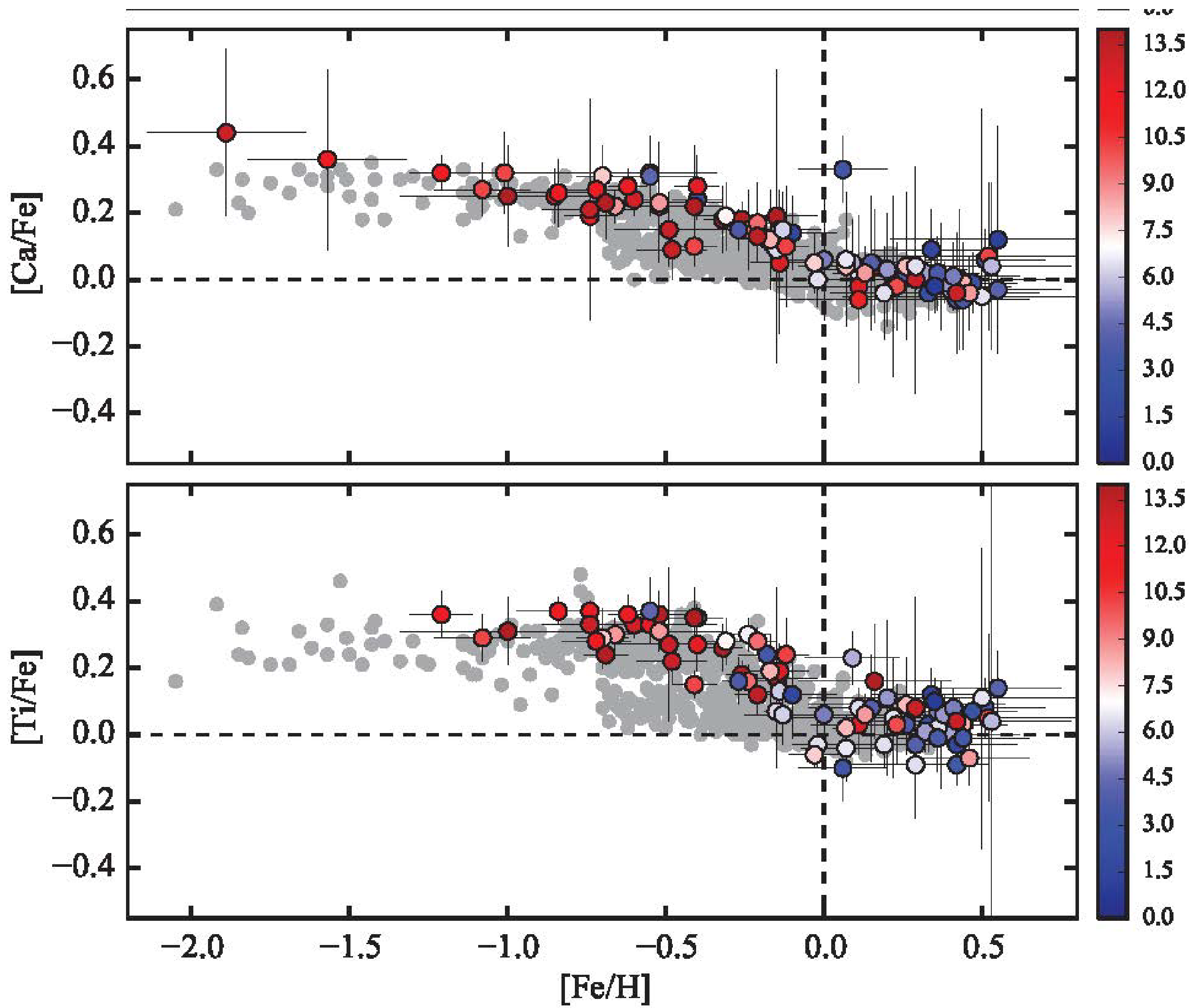
➔ Stellar feedback needed to prevent too much early star formation in small-scale structure

Gallazzi et al 2008

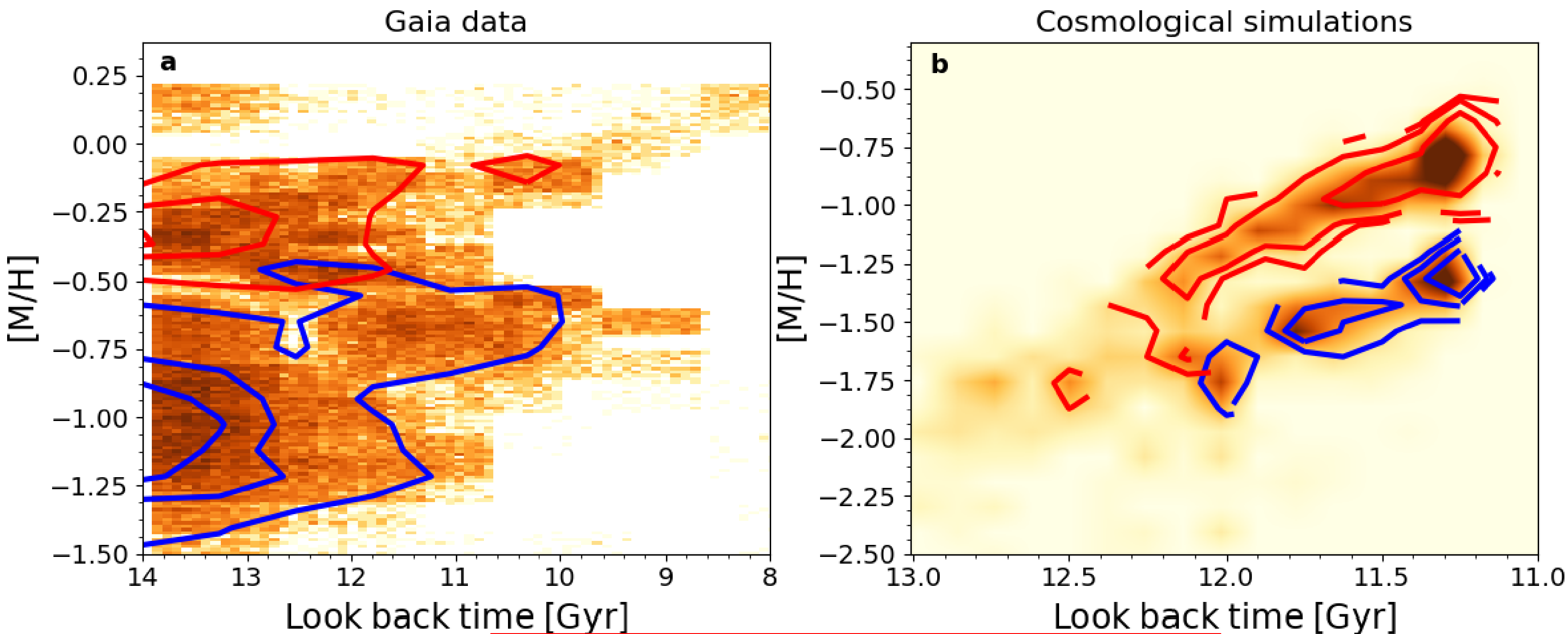


Bensby et al 2017

Coloured points:
Microlensed dwarfs in bulge



Gallart et al 2018



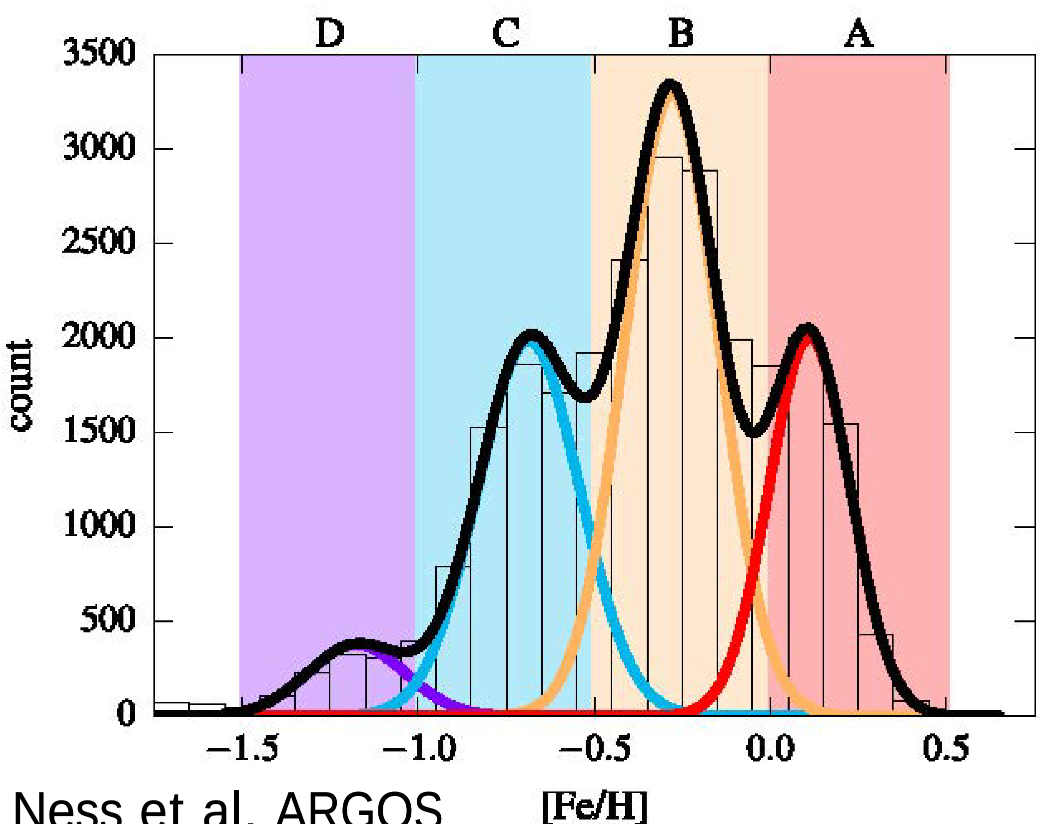
Notice different metallicity scales

Left panel: Kinematically selected ‘halo’ stars

Right panel: age-metallicity trends for stellar particles from simulation (MAGICC) of a Milky Way analogue, main progenitor (red) and last significant merger (blue)

Old, metal-rich stars in the Milky Way

- The bulge/bar: From CMD, more than 80%, stellar mass ~ $10^{10} M_\odot$, is older than 8 Gyr and more metal-rich than [Fe/H] = −0.5



Ness et al, ARGOS

Chemodynamic modelling of inner 5kpc, assuming age 10Gyr: ~50% of stars in A, 30% in B, 10% in C on bar orbits (Portail et al 2017b)

Conclusions

- Most stars in the Milky Way (and M31) that formed prior to redshift unity have metallicity above -0.5 dex
  - MWG: 80% above -0.5 dex, ~30% above solar
  - Unlike predicted distribution for MWG analogues in ΛCMD simulations
- Centrally concentrated – bulge/bar/inner disk/thick disk
- Likely formed in deep potential well, due to massive substructure, that could sustain high star-formation rate and rapid chemical enrichment
  - Another aspect of the small-scale tensions between ΛCMD and observations?

  → Too much small-scale power

Predictions from ΛCDM

- Early cosmological simulations could make predictions for the metallicity and age distributions of entire galaxies only
  - Lacked resolution for more detailed study
- Predict most stars are old and metal-poor, metallicity distribution poor match to observations

Gallazzi et al 2008