The Milky Way as a Case Study of Galactic Chemical Evolution

James W. Johnson
PhD Candidate
The Ohio State University
AAS 241
January 11, 2023

What is the assembly history of the Milky Way?

What do we know?

Local age-metallicity relation not monotonic

- Migrated stars from inner galaxy

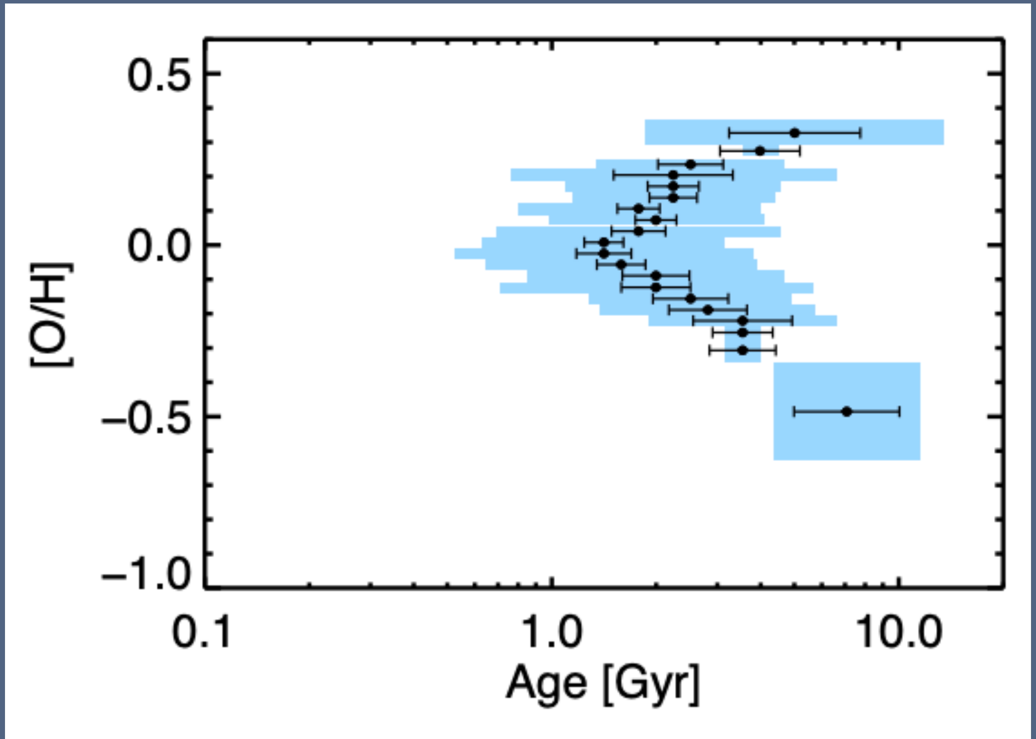


Fig. 3, Feuillet et al. (2018), MNRAS, 477, 2326

What is the assembly history of the Milky Way?

What do we know?

Local age-metallicity relation not monotonic

- Migrated stars from inner galaxy

Local age-[α/Fe] relation monotonic

- Limits burstiness of recent star formation?

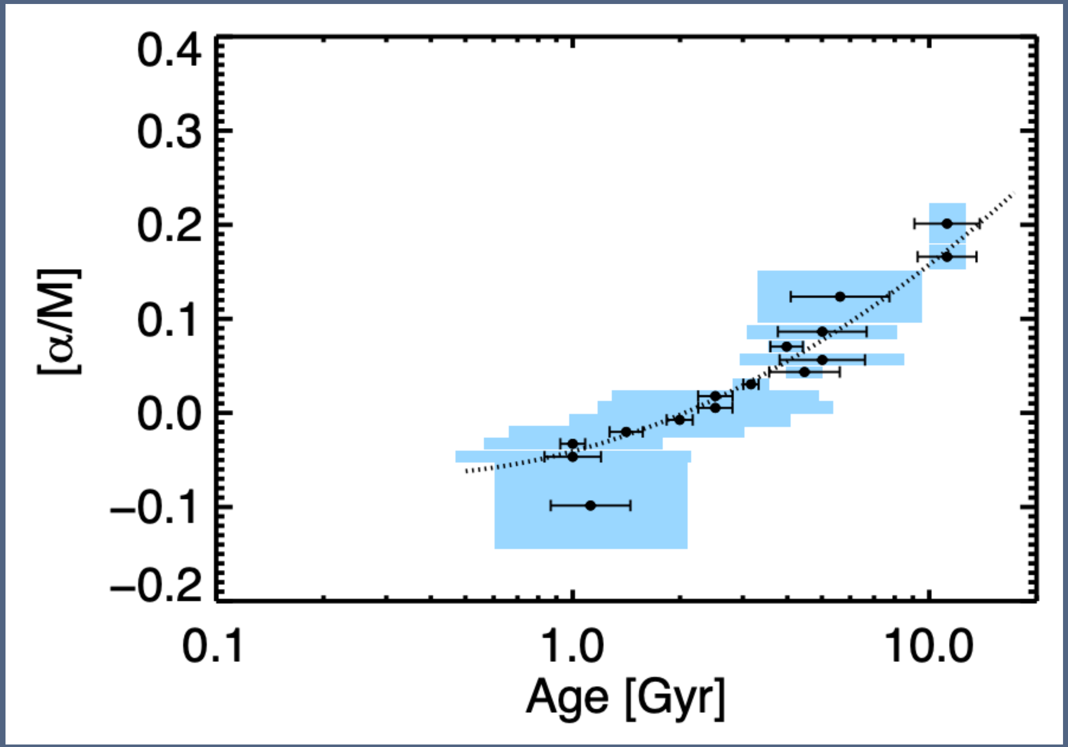


Fig. 3, Feuillet et al. (2018), MNRAS, 477, 2326

What is the assembly history of the Milky Way?

What do we know?

Local age-metallicity relation not monotonic

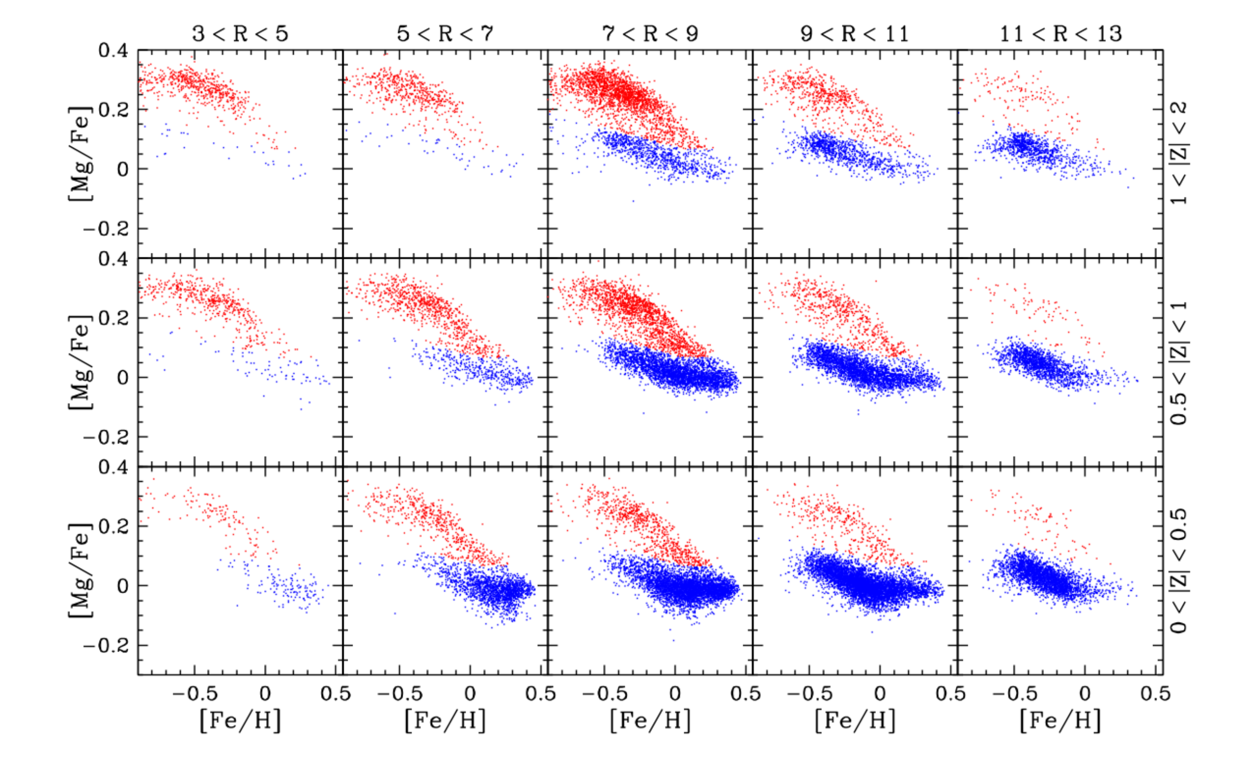
- Migrated stars from inner galaxy

Local age-[α/Fe] relation monotonic

- Limits burstiness of recent star formation?

[α/Fe]-[Fe/H] bimodality

- Origin debated



Weinberg et al. (2022), ApJS, 260, 32

What is the assembly history of the Milky Way?

What do we know?

Local age-metallicity relation not monotonic

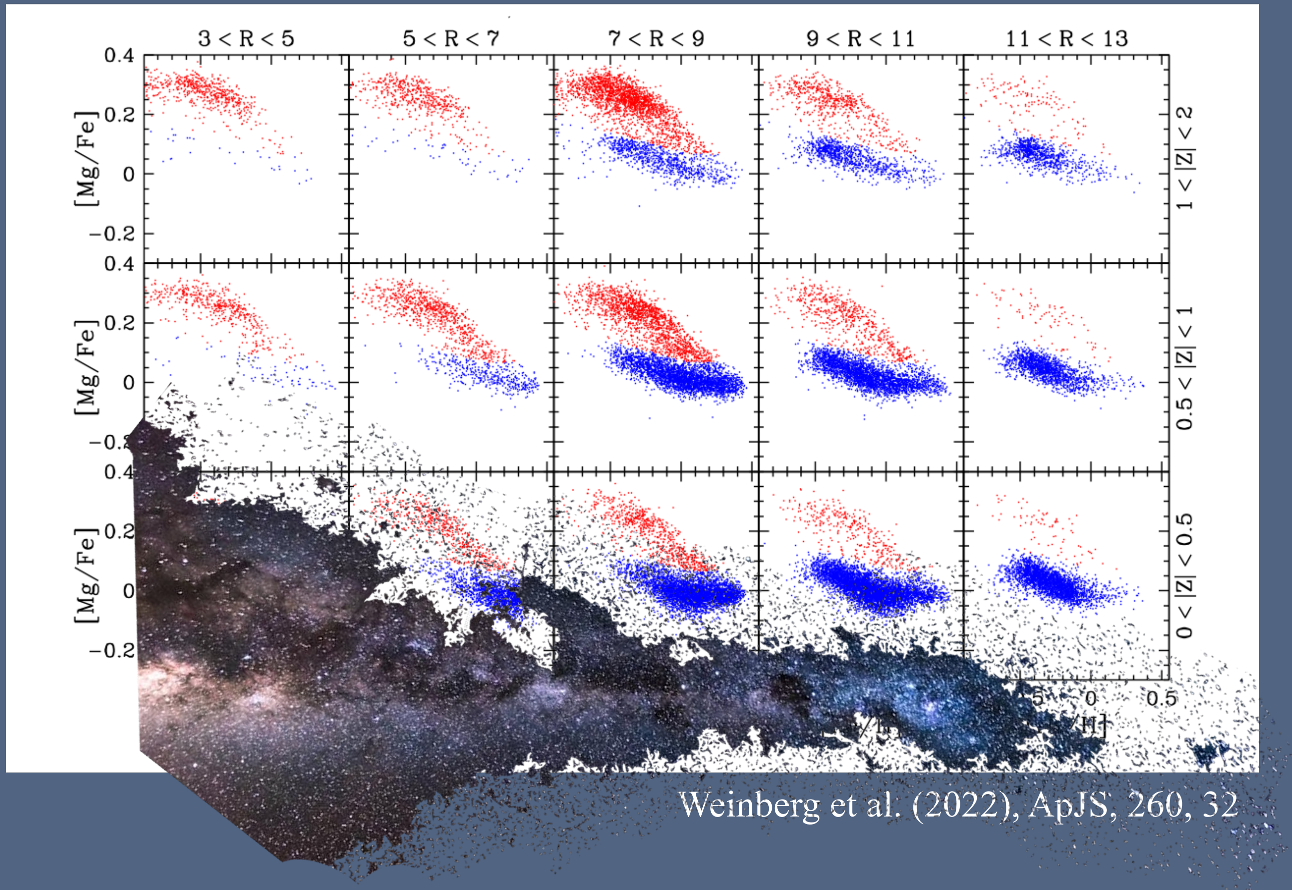
- Migrated stars from inner galaxy

Local age-[α/Fe] relation monotonic

- Limits burstiness of recent star formation?

[α/Fe]-[Fe/H] bimodality

- Origin debated



Weinberg et al. (2022), ApJS, 260, 32

What is the assembly history of the Milky Way?

What do we know?

Local age-metallicity relation not monotonic

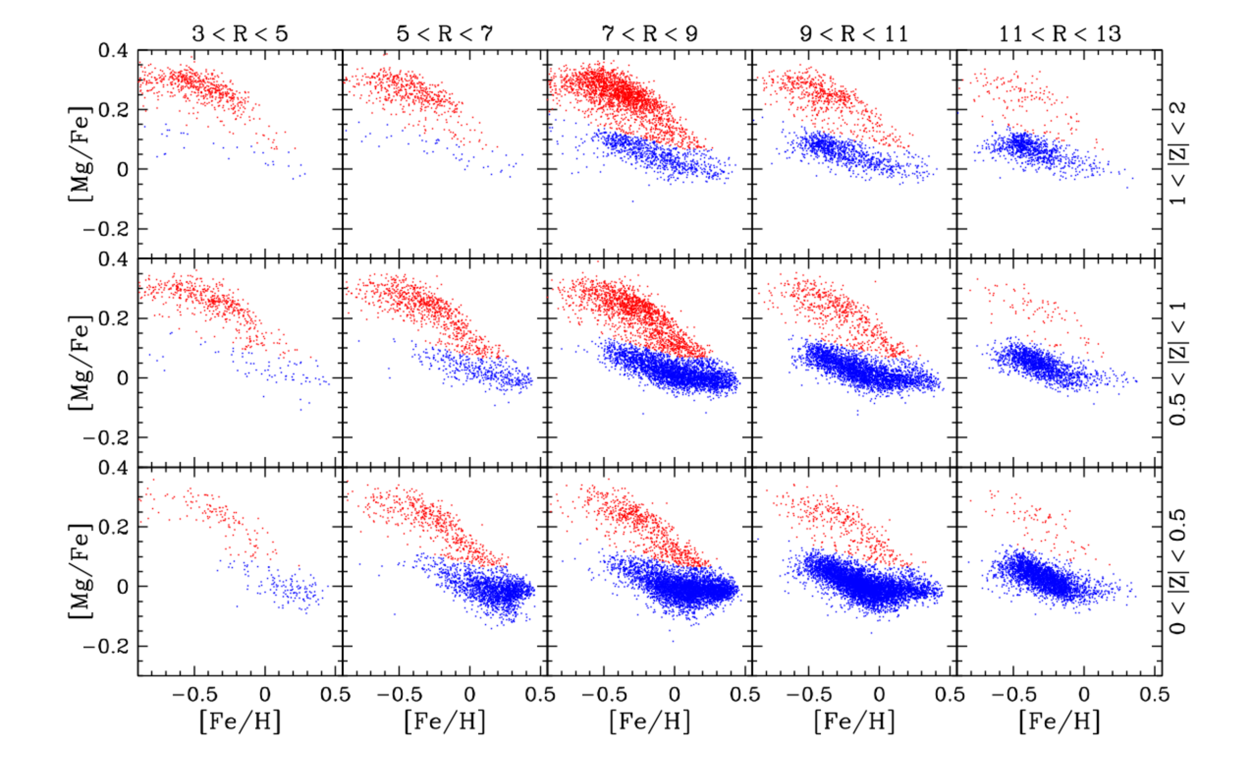
- Migrated stars from inner galaxy

Local age-[α/Fe] relation monotonic

- Limits burstiness of recent star formation?

[α/Fe]-[Fe/H] bimodality

- Origin debated



Weinberg et al. (2022), ApJS, 260, 32

Galactic Chemical Evolution

Evolutionary History

Chemical Content

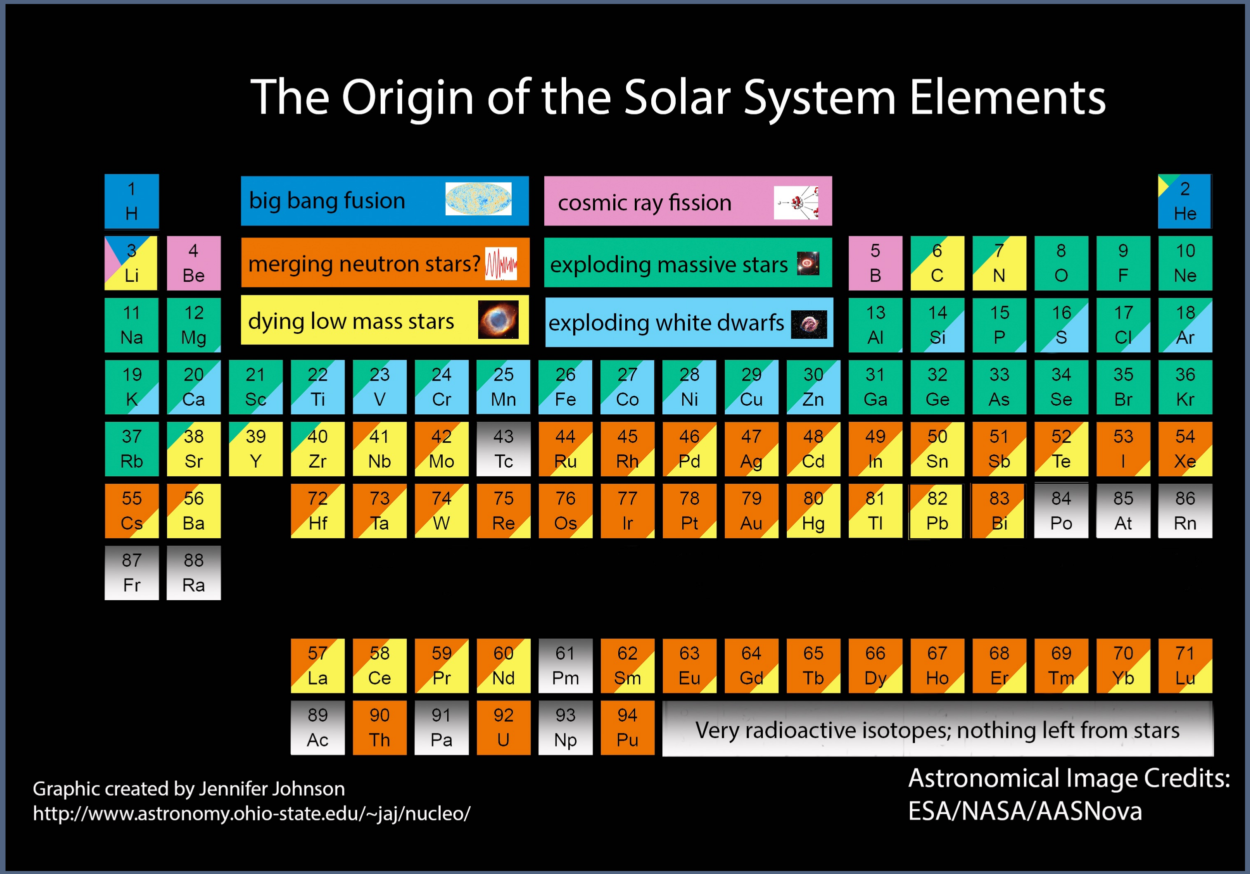


Fig. 3, Johnson (2019), Science, 363, 474

One-Zone Models

Assume instantaneous mixing

Take yields from stellar evolution models

Apply timestep algorithm

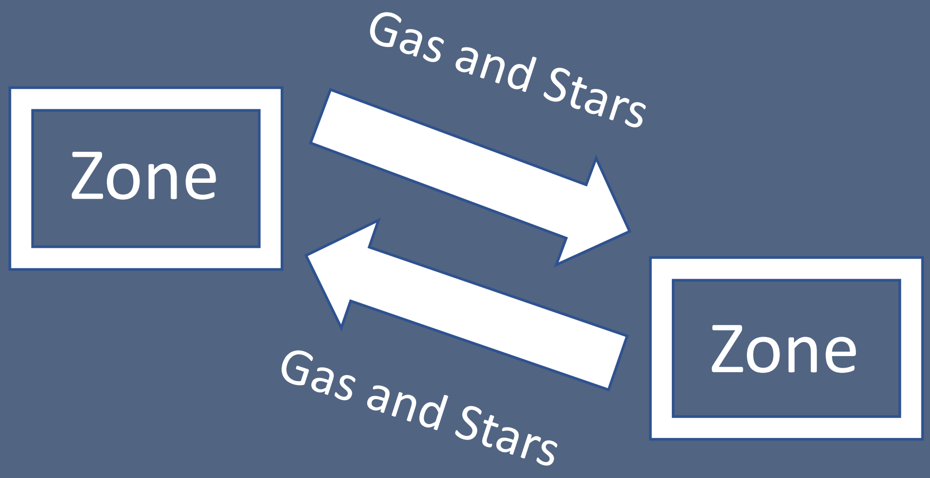
$$\text{Enrichment Rate} = \overbrace{\text{Stars} + \text{Supernovae}}^{\text{Sources}} - \overbrace{\text{Outflows} - \text{Star Formation}}^{\text{Sinks}}$$

Multi-Zone Models

~~Assume instantaneous mixing~~

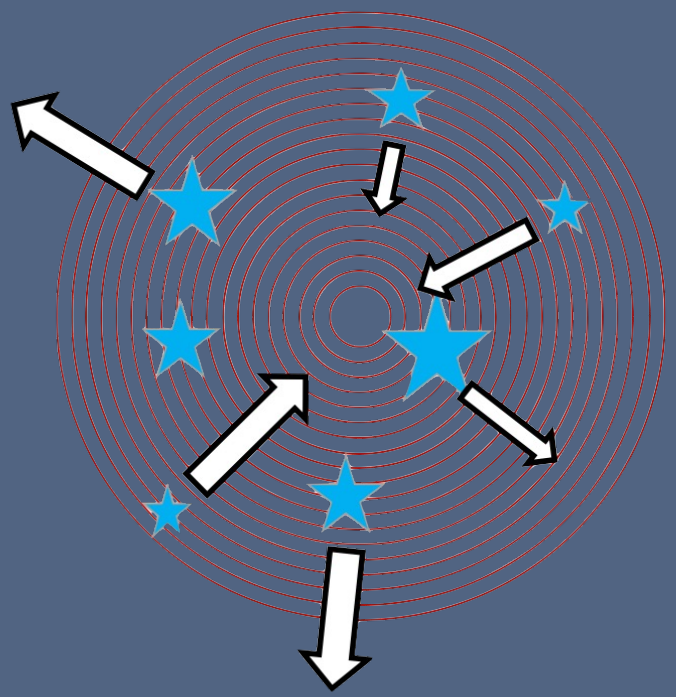
Take yields from stellar evolution models

Apply timestep algorithm



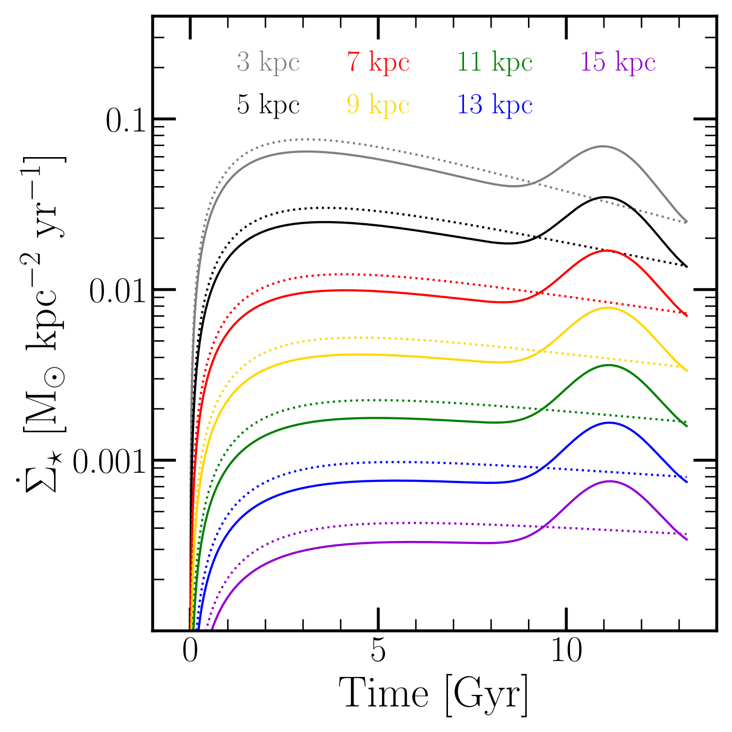
$$\text{Enrichment Rate} = \overbrace{\text{Stars} + \text{Supernovae}}^{\text{Sources}} - \overbrace{\text{Outflows} - \text{Star Formation}}^{\text{Sinks}}$$

The Milky Way: A Concentric Ring Model



Similar to
- Schönrich & Binney (2009)
- Minchev, Chiappini & Martig (2013, 2014)

Simulation-based stellar migration



Versatile Integrator for Chemical Evolution

vice 1.3.0

```
pip install vice
```

VICE

Details of disk models are input

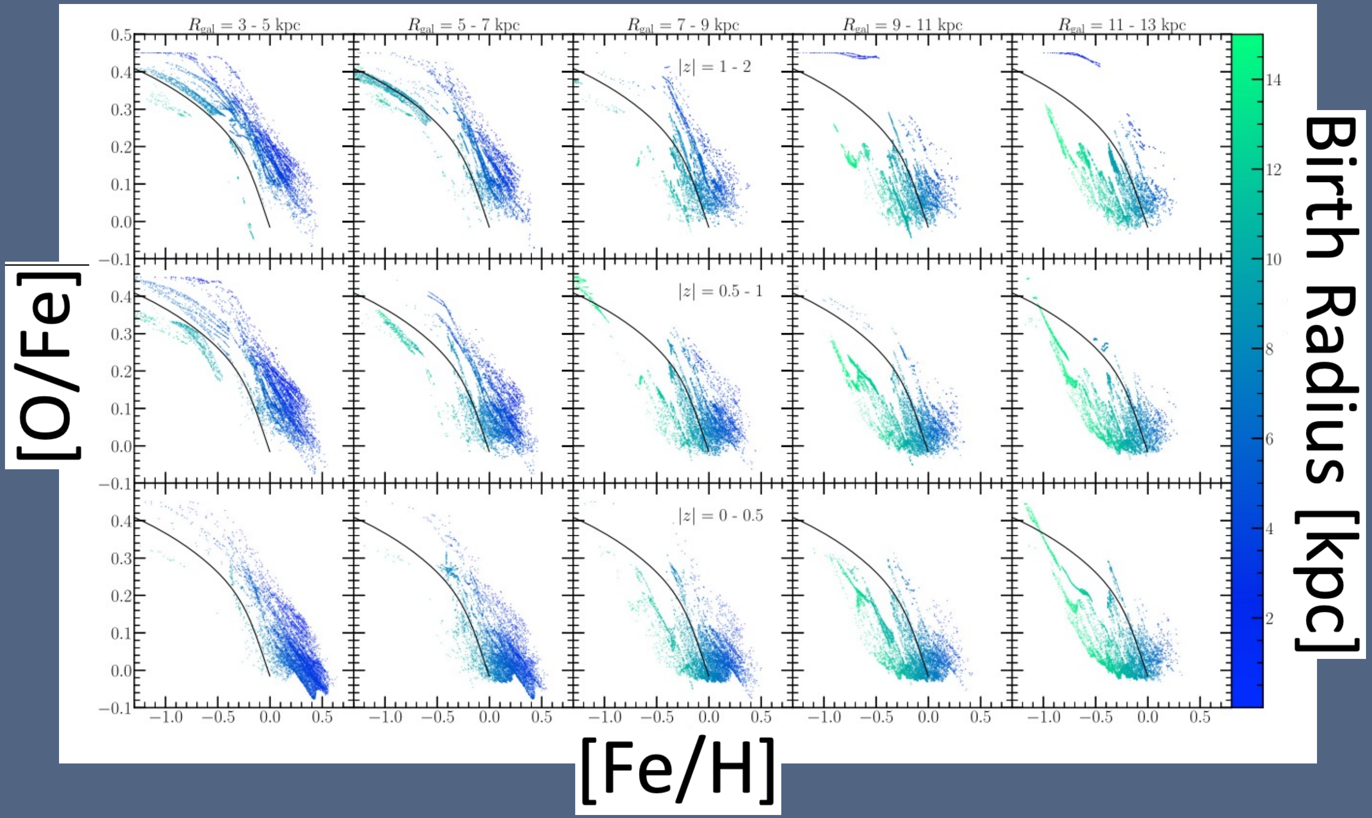
- SFH, IMF, yields
- Annular zones, migration

All documentation available at

https://vice-astro.readthedocs.io

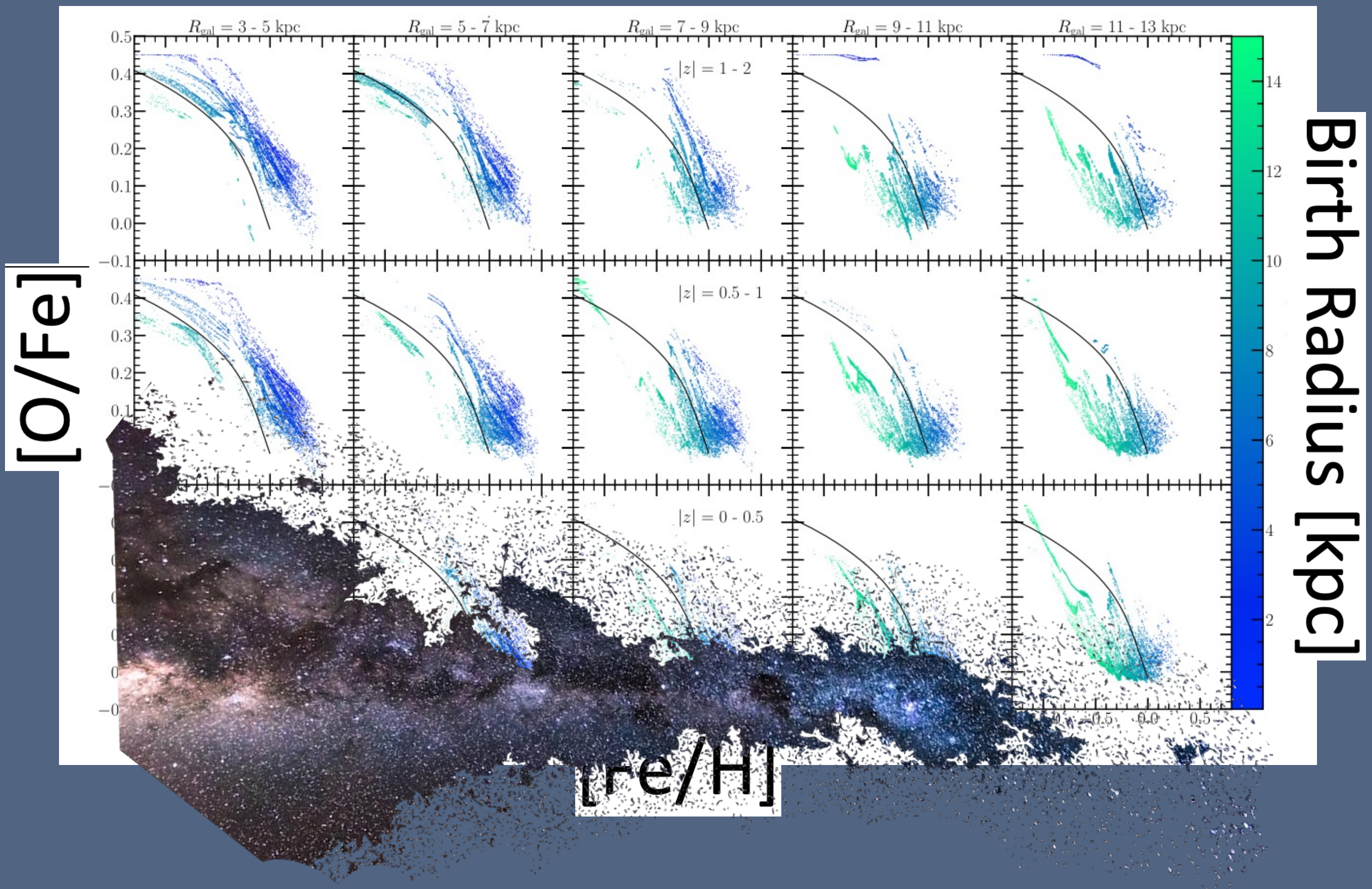
The [α/Fe] Bimodality

Fig. 7, Johnson et al. (2022), MNRAS, 508, 4484



The [α/Fe] Bimodality

Fig. 7, Johnson et al. (2022), MNRAS, 508, 4484



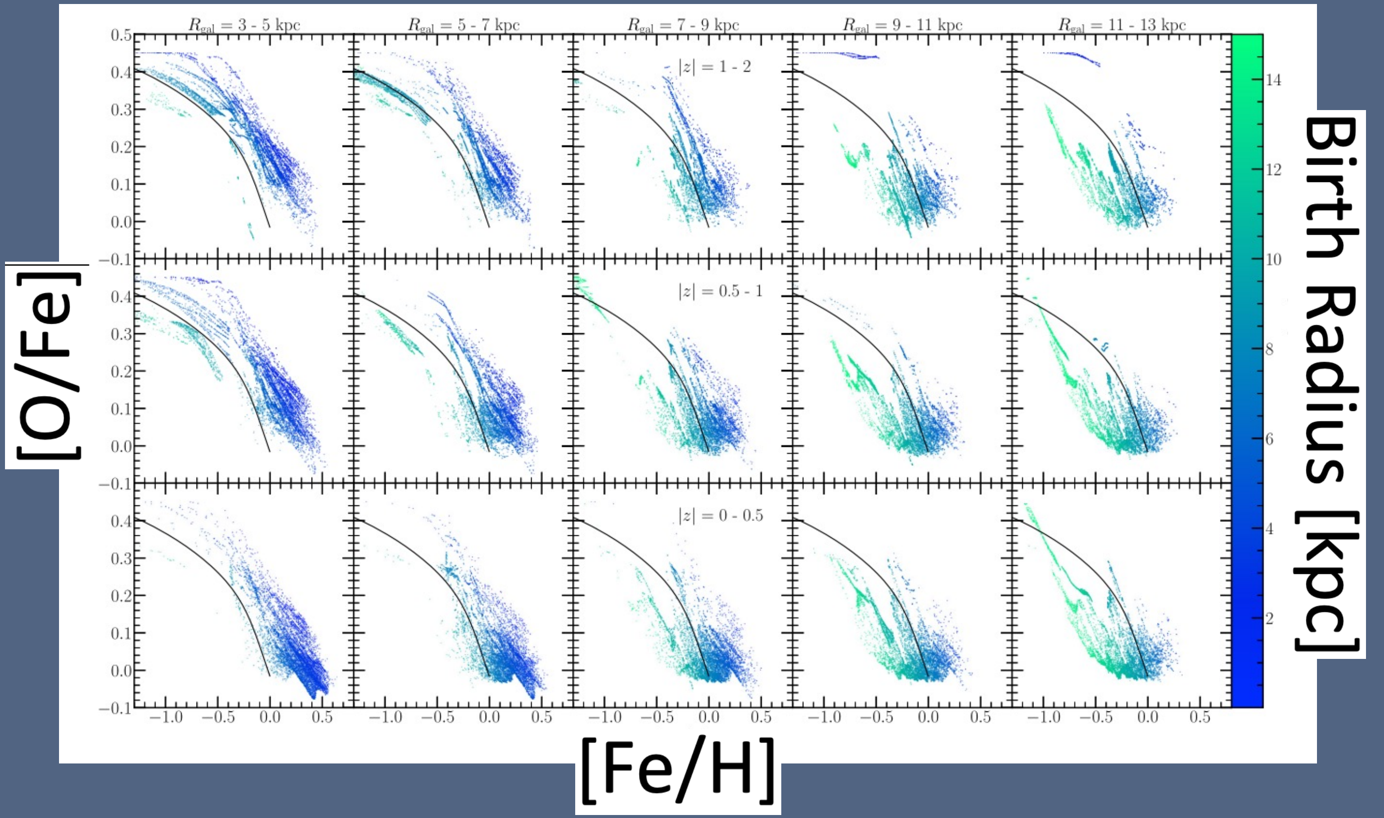
The [α/Fe] Bimodality

Success: spatial dependence

Failure: bimodality itself (both SFHs)

- Descent from high [α/Fe] too slow?
- SFR too high at mid [α/Fe]?

Fig. 7, Johnson et al. (2022), MNRAS, 508, 4484



The [α/Fe] Bimodality

Success: spatial dependence

Failure: bimodality itself (both SFHs)

- Descent from high [α/Fe] too slow?
- SFR too high at mid [α/Fe]?

Future work: "two-infall" model

Liam Dubay (Ohio State)

Combinations of SFHs and SN Ia DTDs that reproduce bimodality

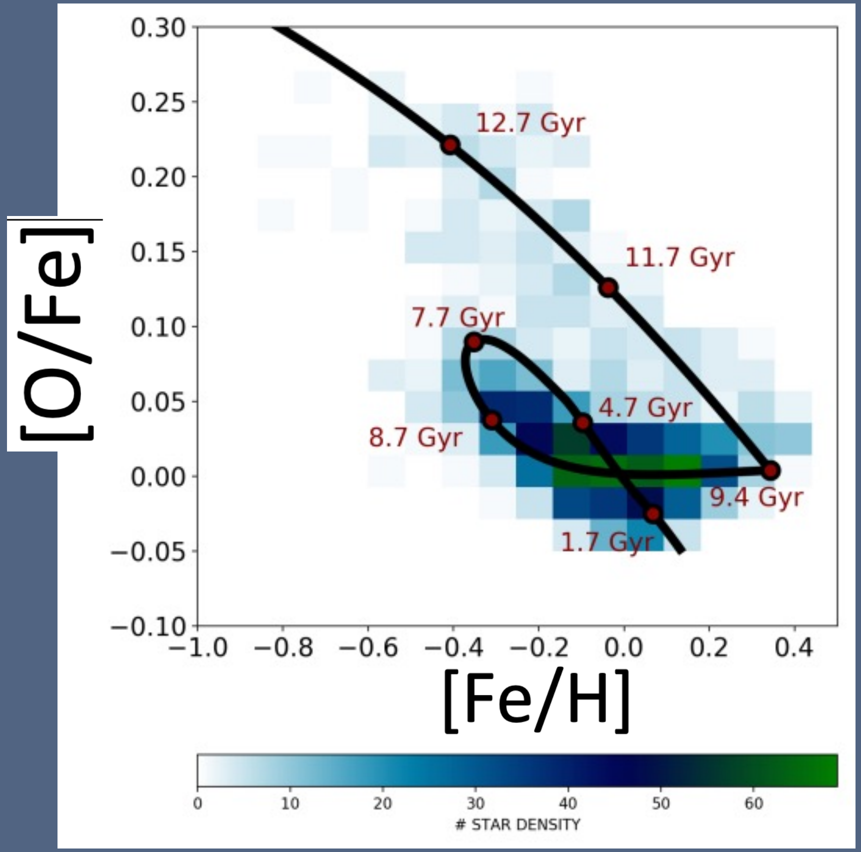
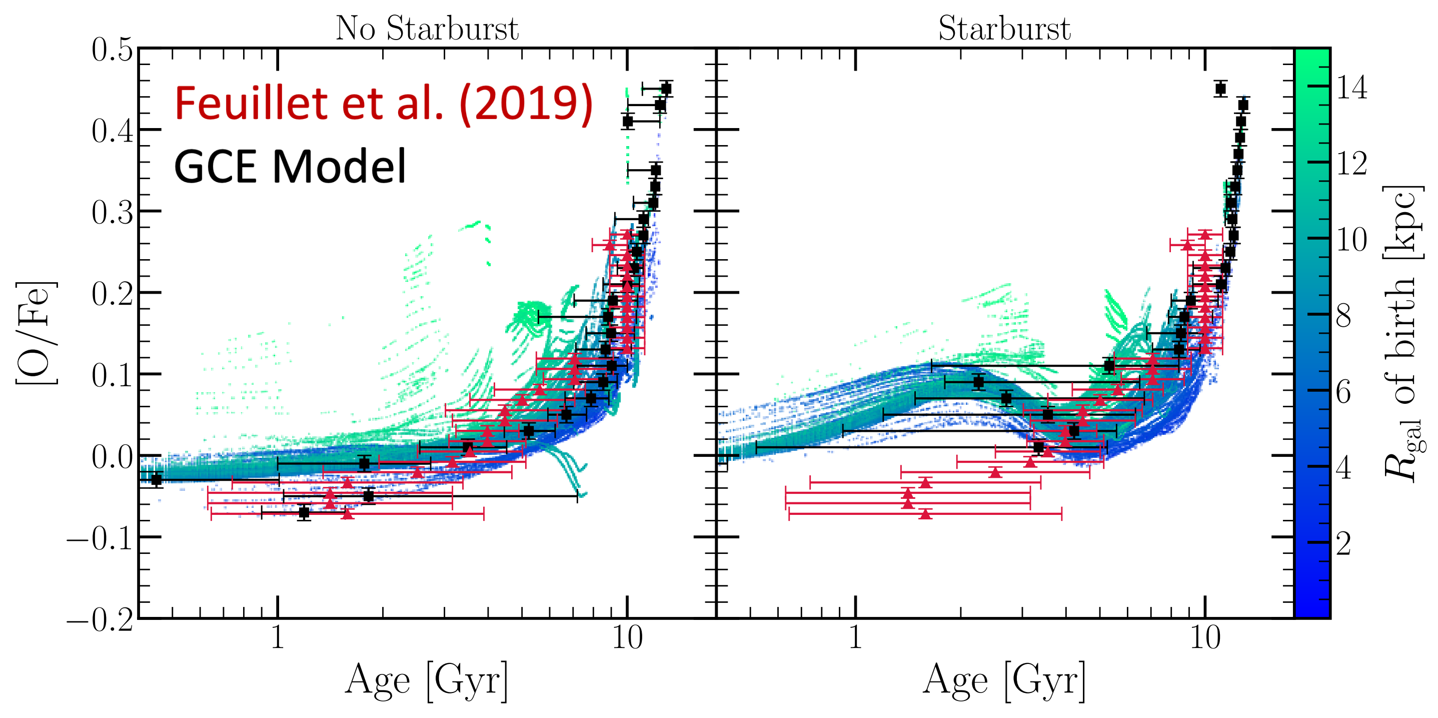


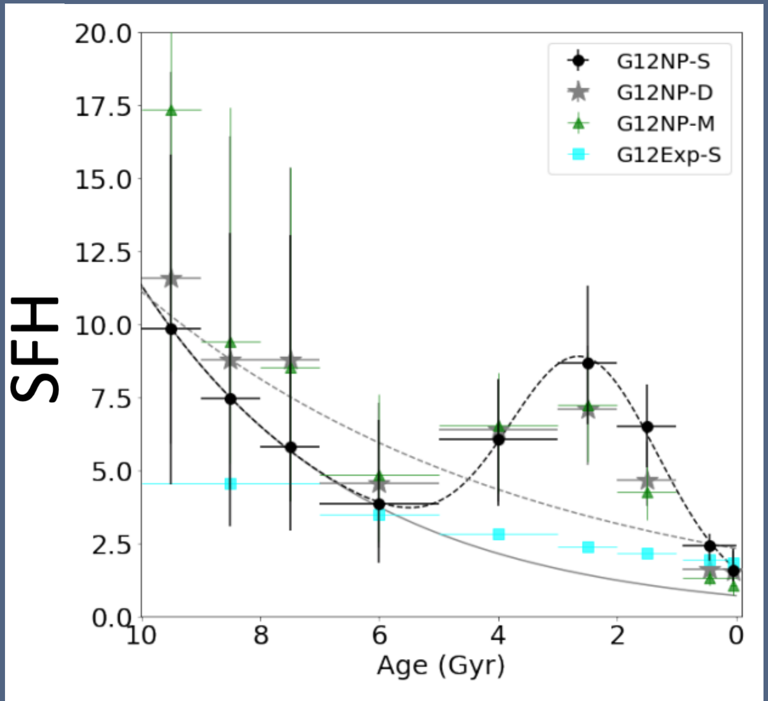
Fig. 2, Spitoni et al. (2019), A&A, 623, 60

Age-[O/Fe]: The Impact of the SFH

Recent burst increases [O/Fe] of young stars

- Not seen in the data





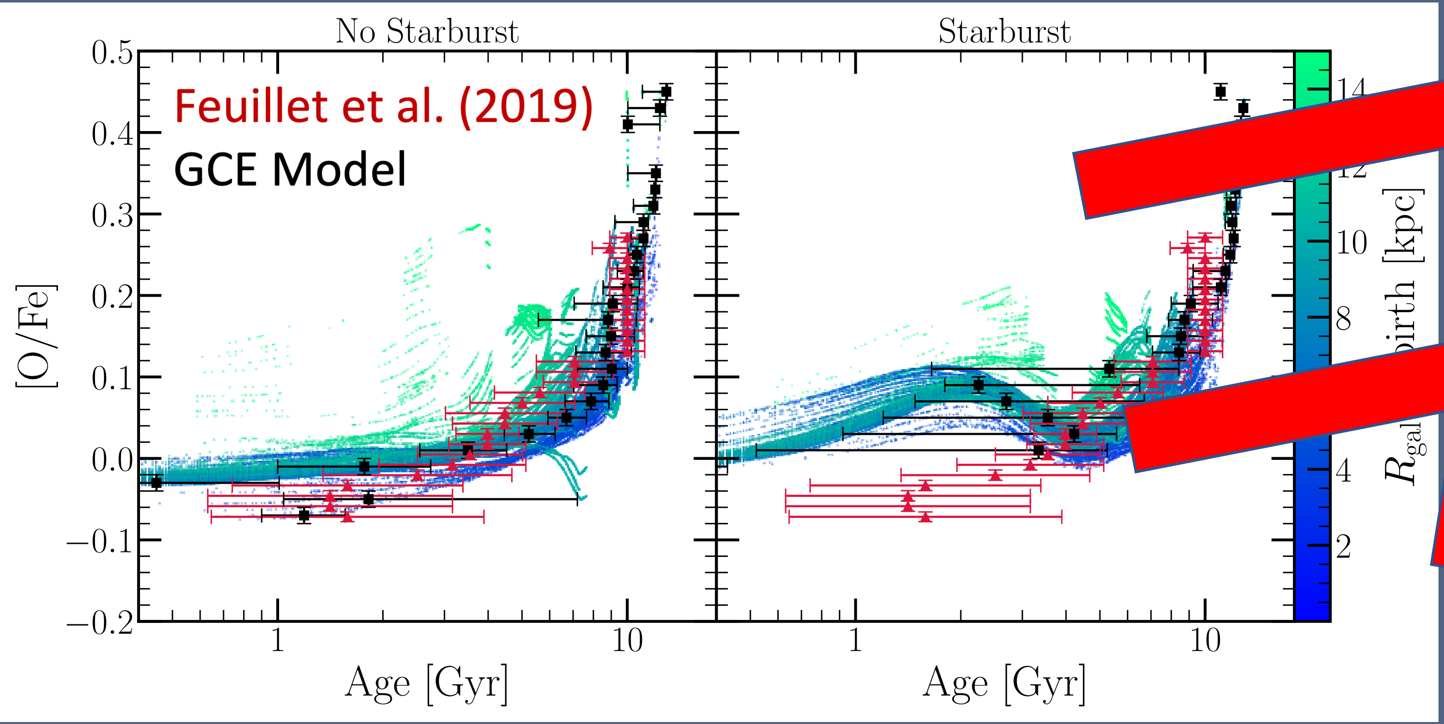
Mor et al. (2019):

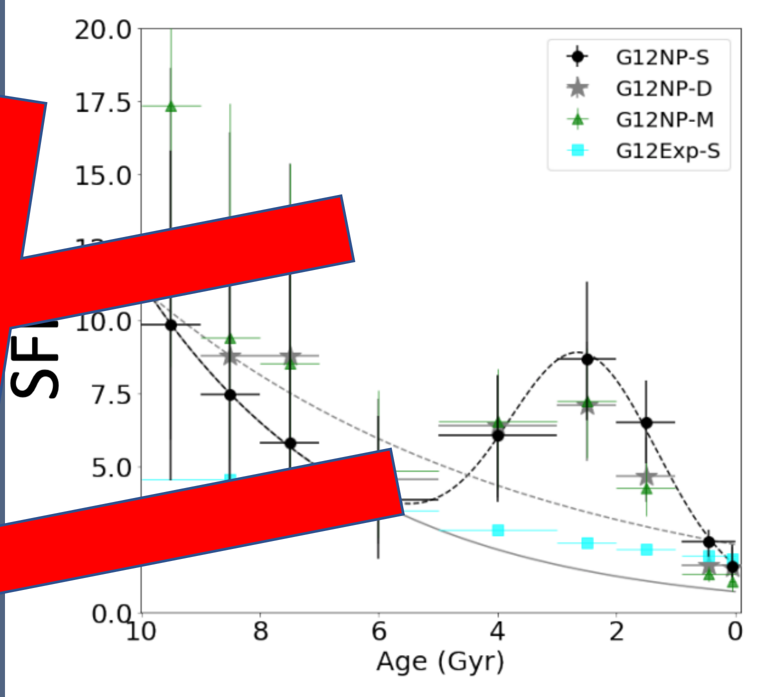
- Evidence for starburst in Gaia

Age-[O/Fe]: The Impact of the SFH

Recent burst increases [O/Fe] of young stars

- Not seen in the data





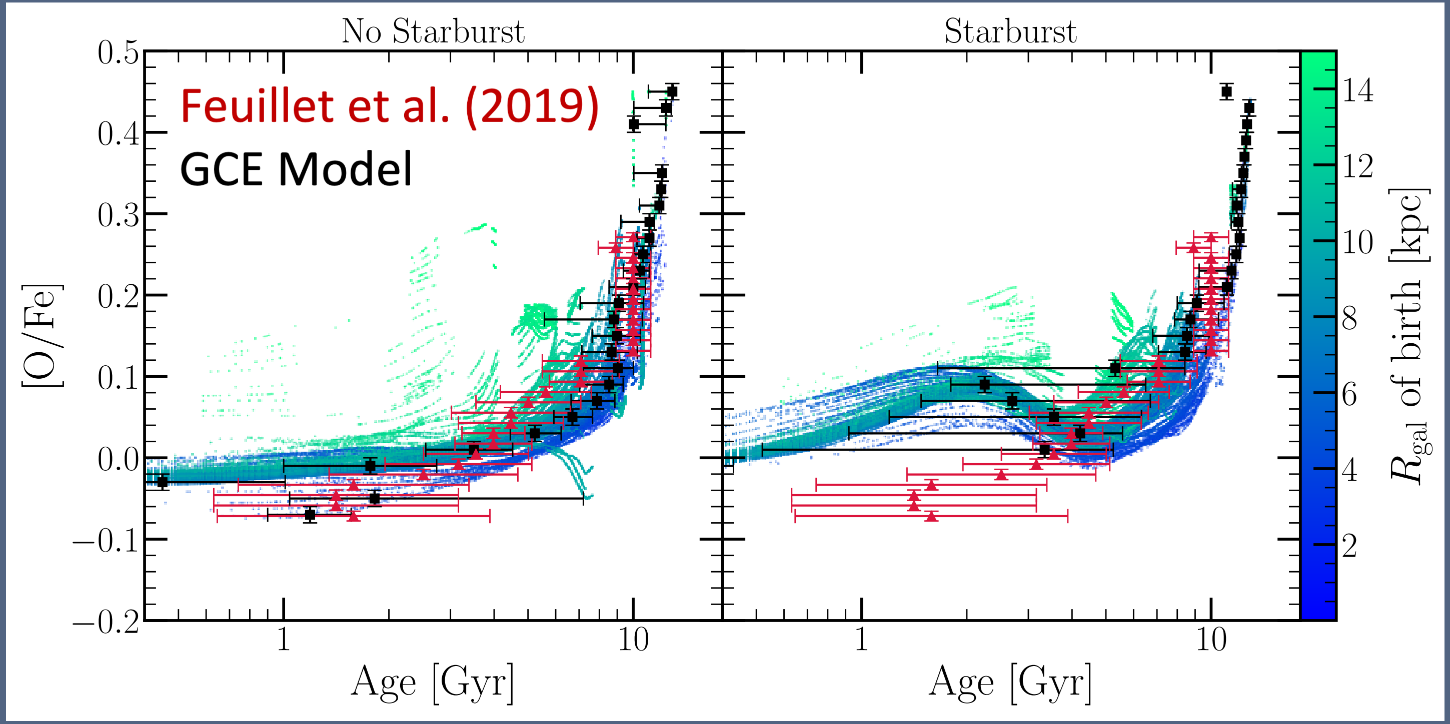
Mor et al. (2019):

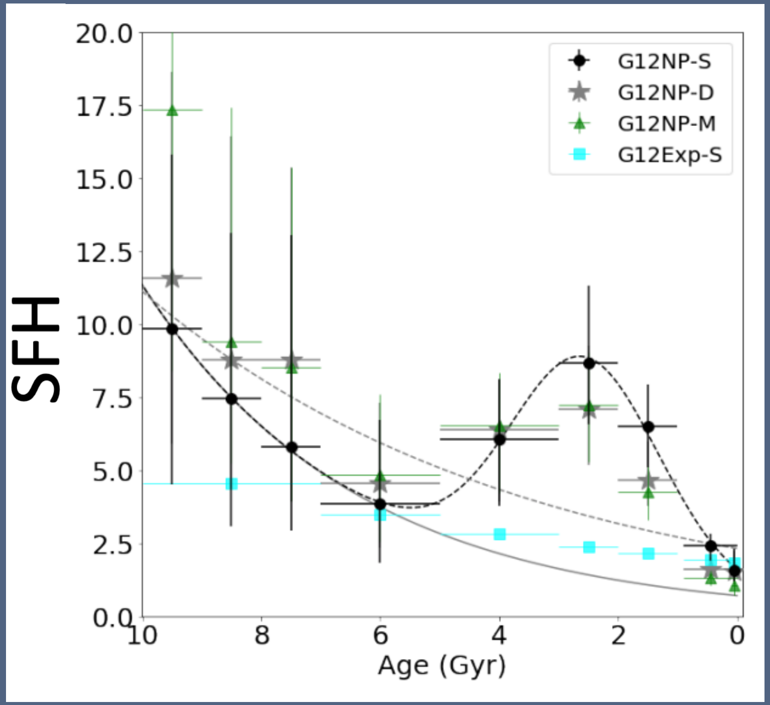
- Evidence for starburst in Gaia

Age-[O/Fe]: The Impact of the SFH

Recent burst increases [O/Fe] of young stars

- Not seen in the data

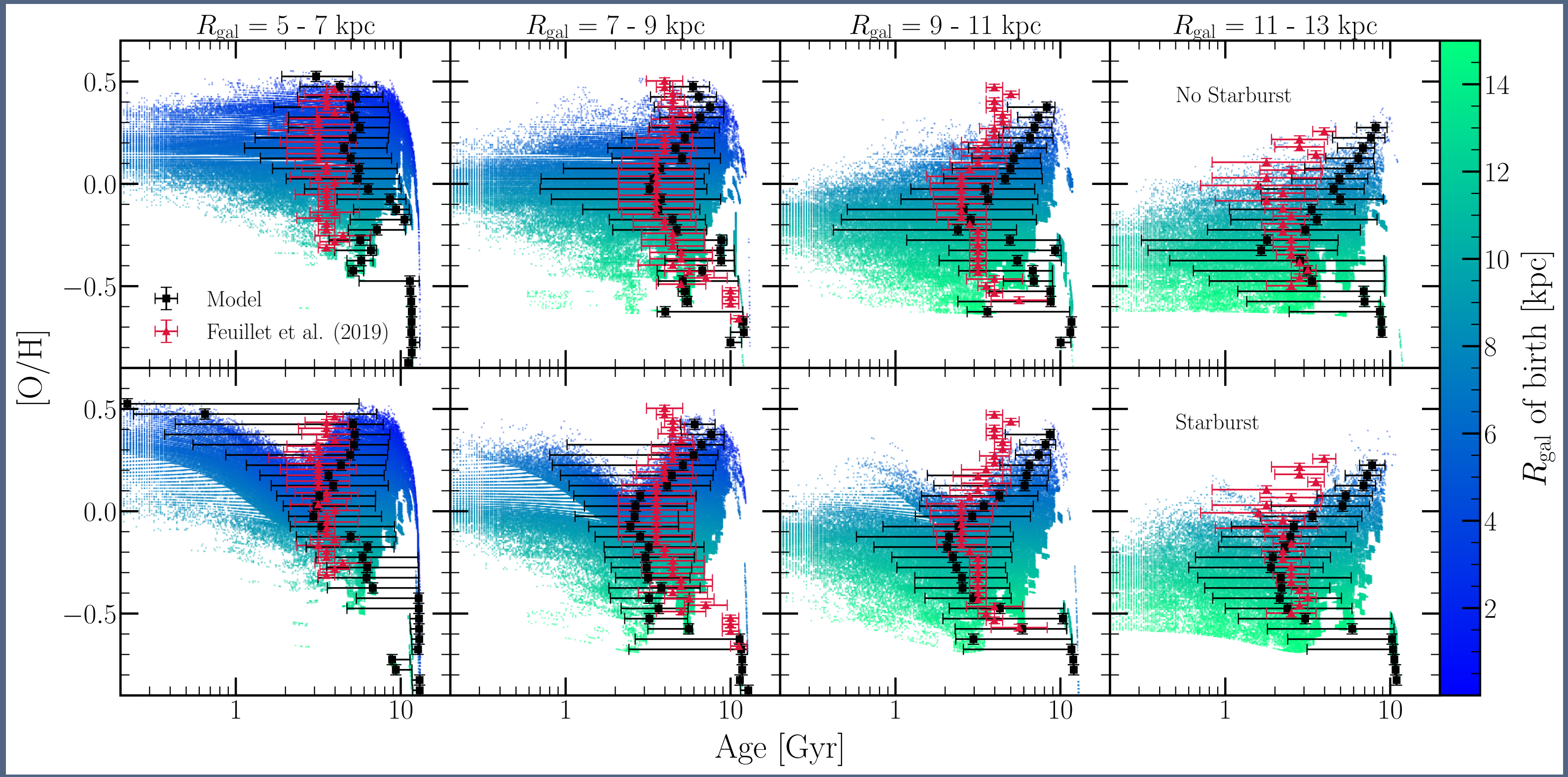




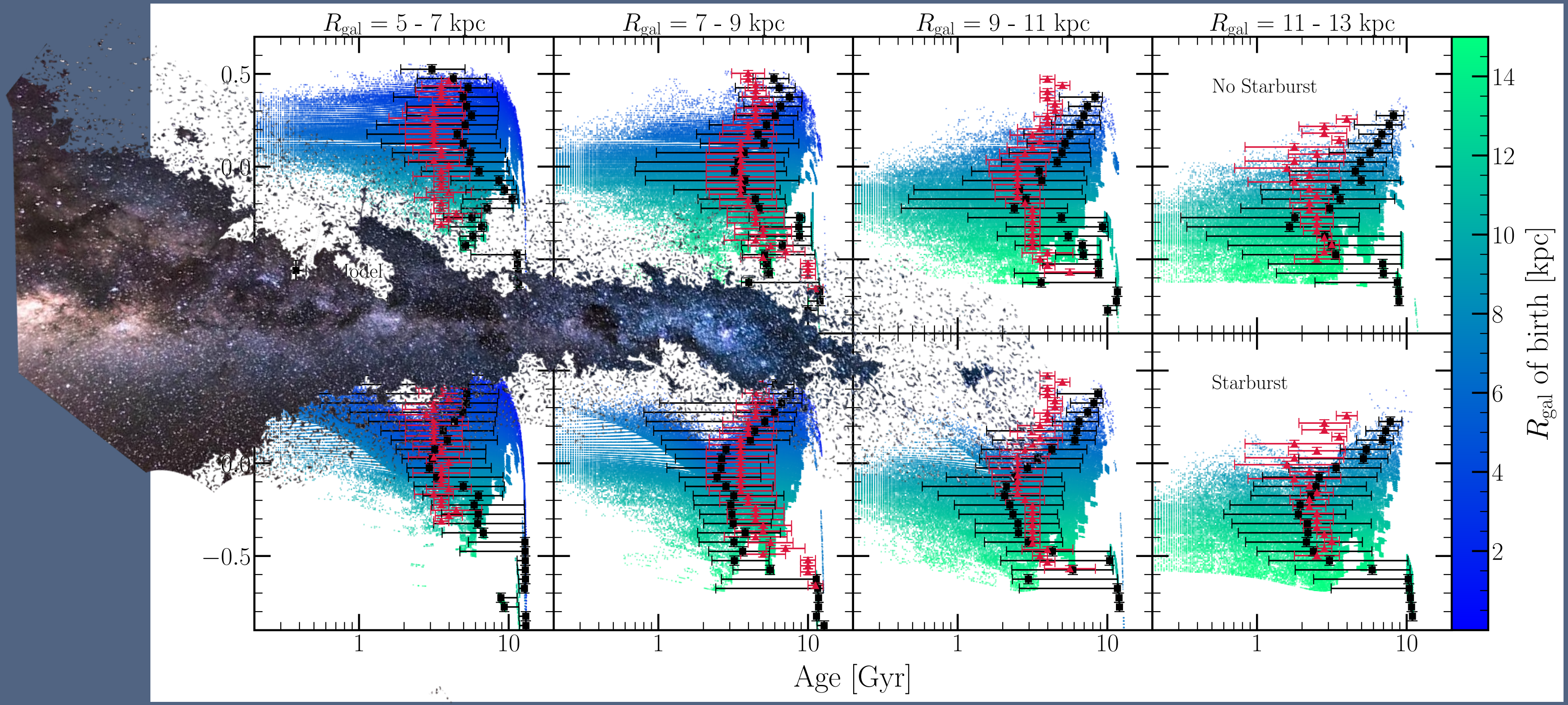
Mor et al. (2019):

- Evidence for starburst in Gaia

Age-[O/H]: The Impact of the SFH

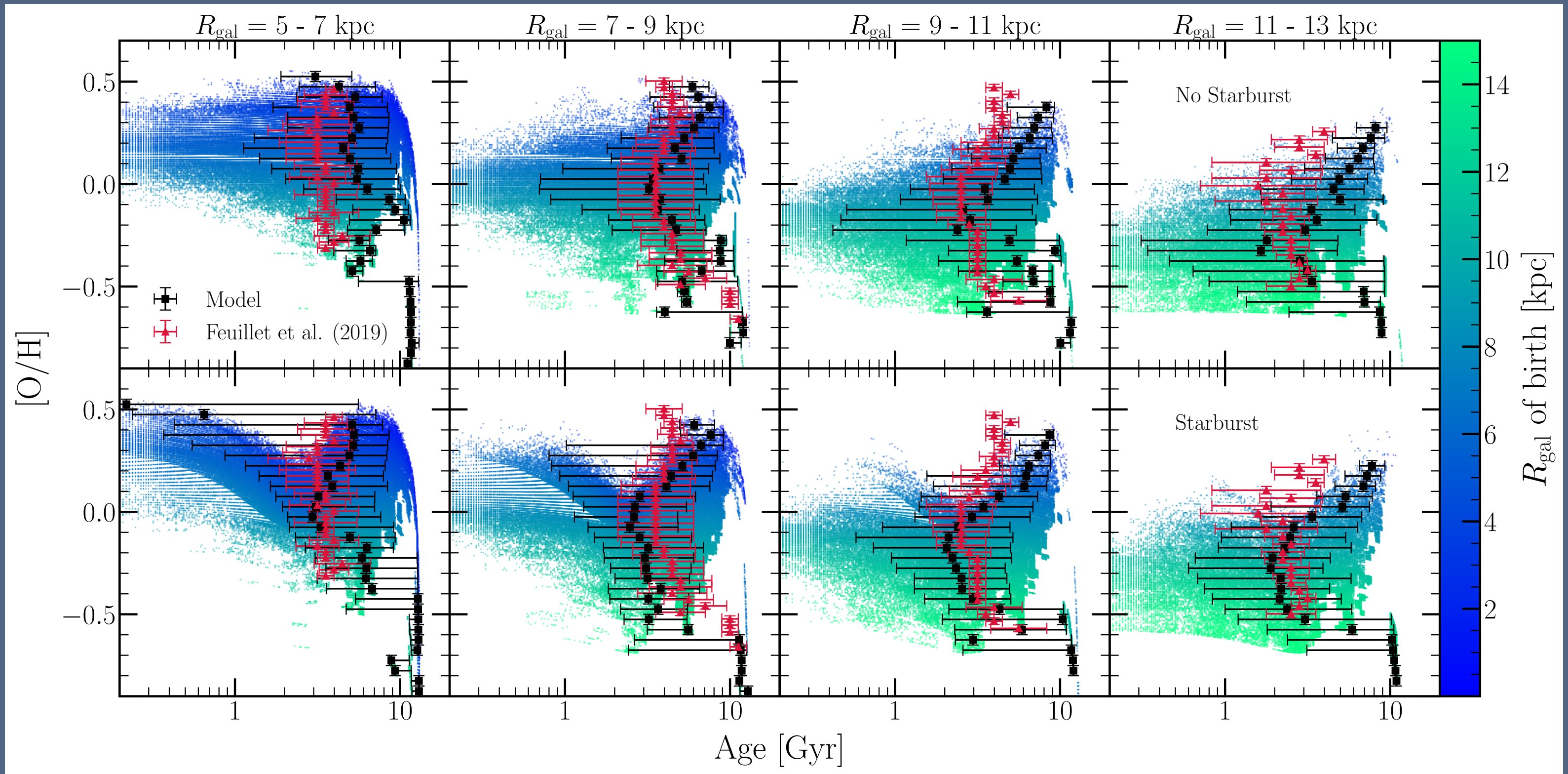


Age-[O/H]: The Impact of the SFH



Age-[O/H]: The Impact of the SFH

Support interpretation that old metal-rich stars migrated from inner Galaxy

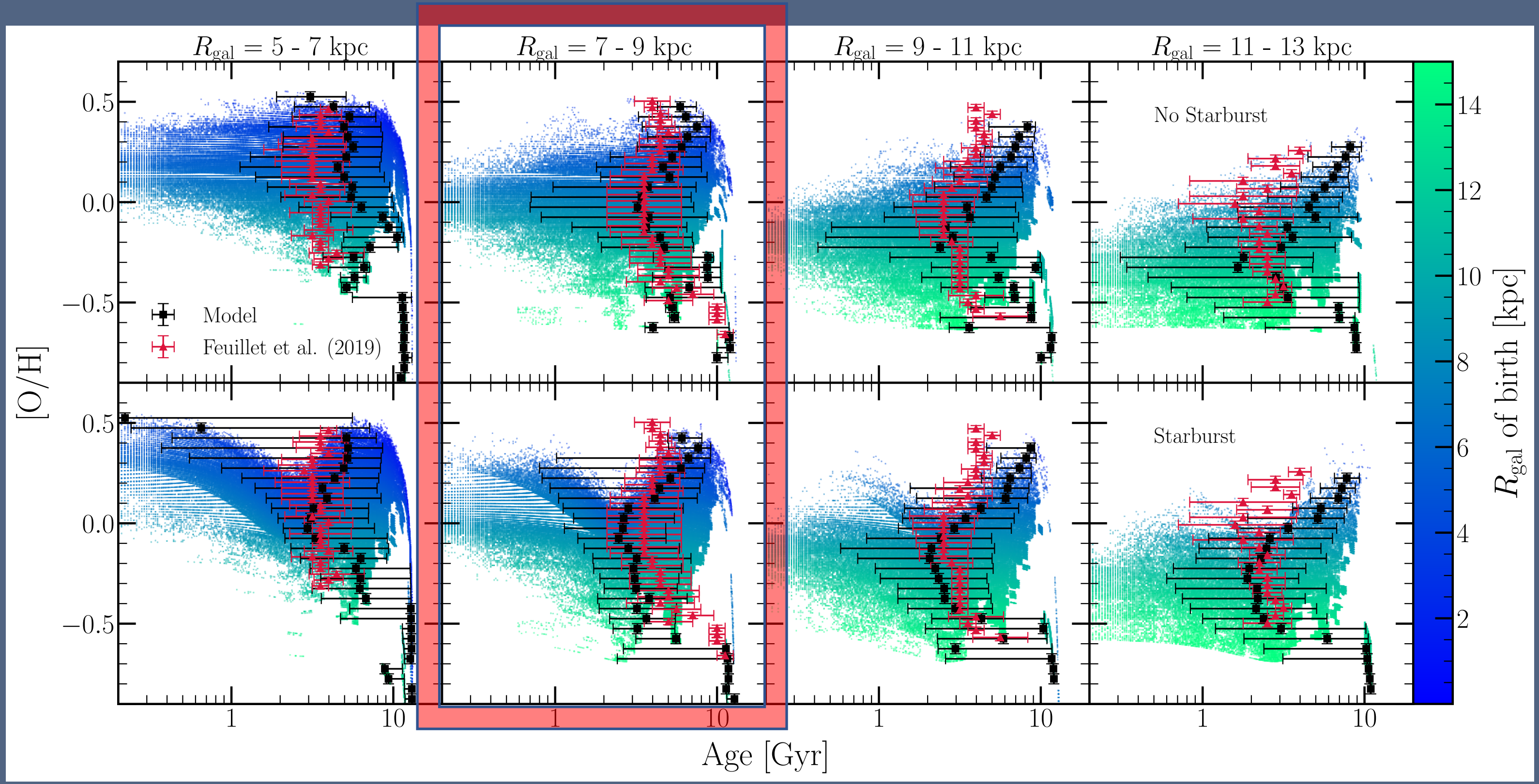


Age-[O/H]: The Impact of the SFH

Support interpretation that old metal-rich stars migrated from inner Galaxy

Solar annulus

- Both models reasonable



Age-[O/H]: The Impact of the SFH

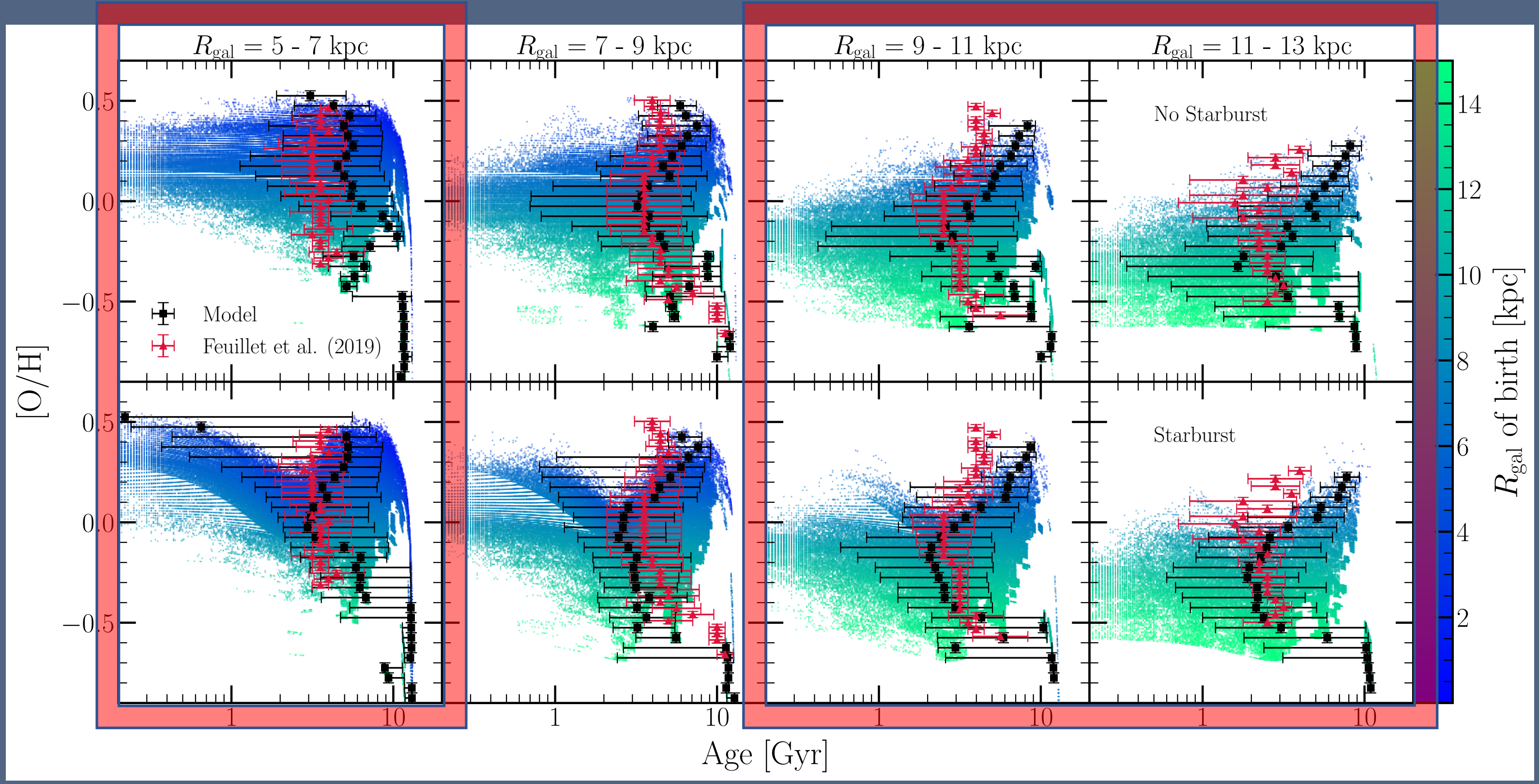
Support interpretation that old metal-rich stars migrated from inner Galaxy

Solar annulus

- Both models reasonable

Other Galactic regions

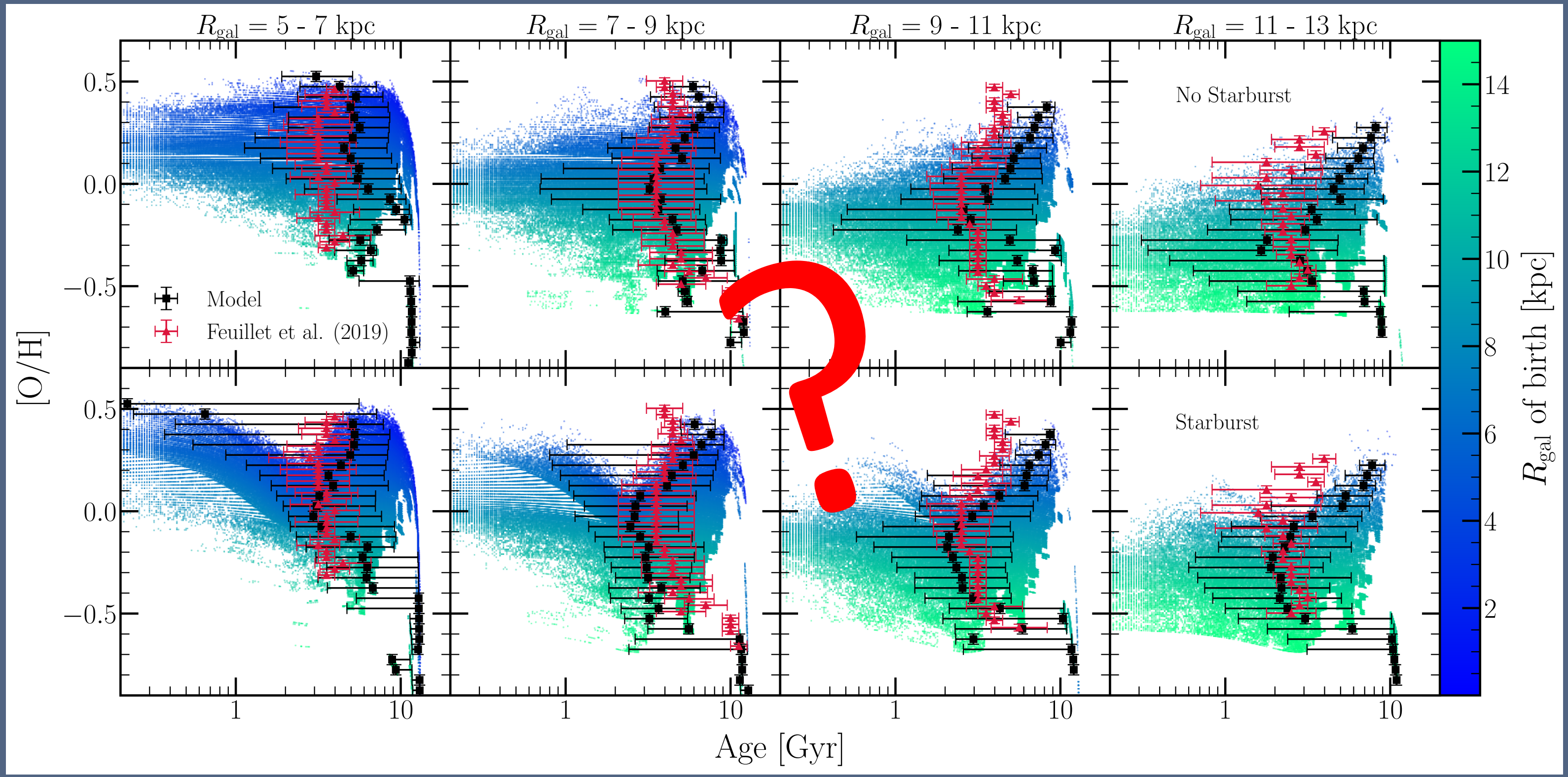
- No-burst model overpredicts ages
- Burst model better reproduces trend's shape



Age-[O/H]: The Impact of the SFH

Ambiguous results

- Episodic SFH potentially more accurate



What are the Relative Yields of Different Elements?

Key parameter in chemical evolution models

Establish trends in abundance ratios in our disk models

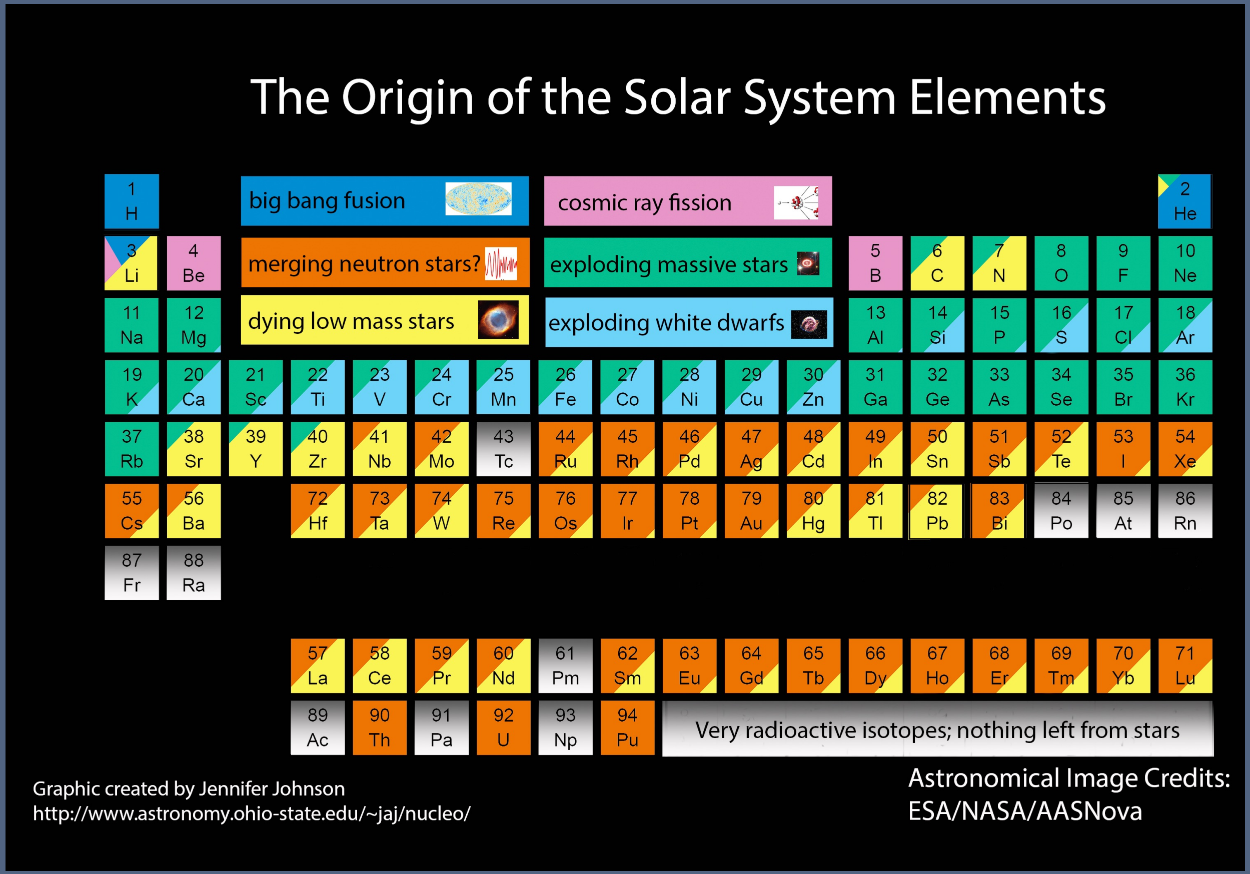


Fig. 3, Johnson (2019), Science, 363, 474

What are the Relative Yields of Different Elements?

Key parameter in chemical evolution models

Establish trends in abundance ratios in our disk models

Poorly Understood

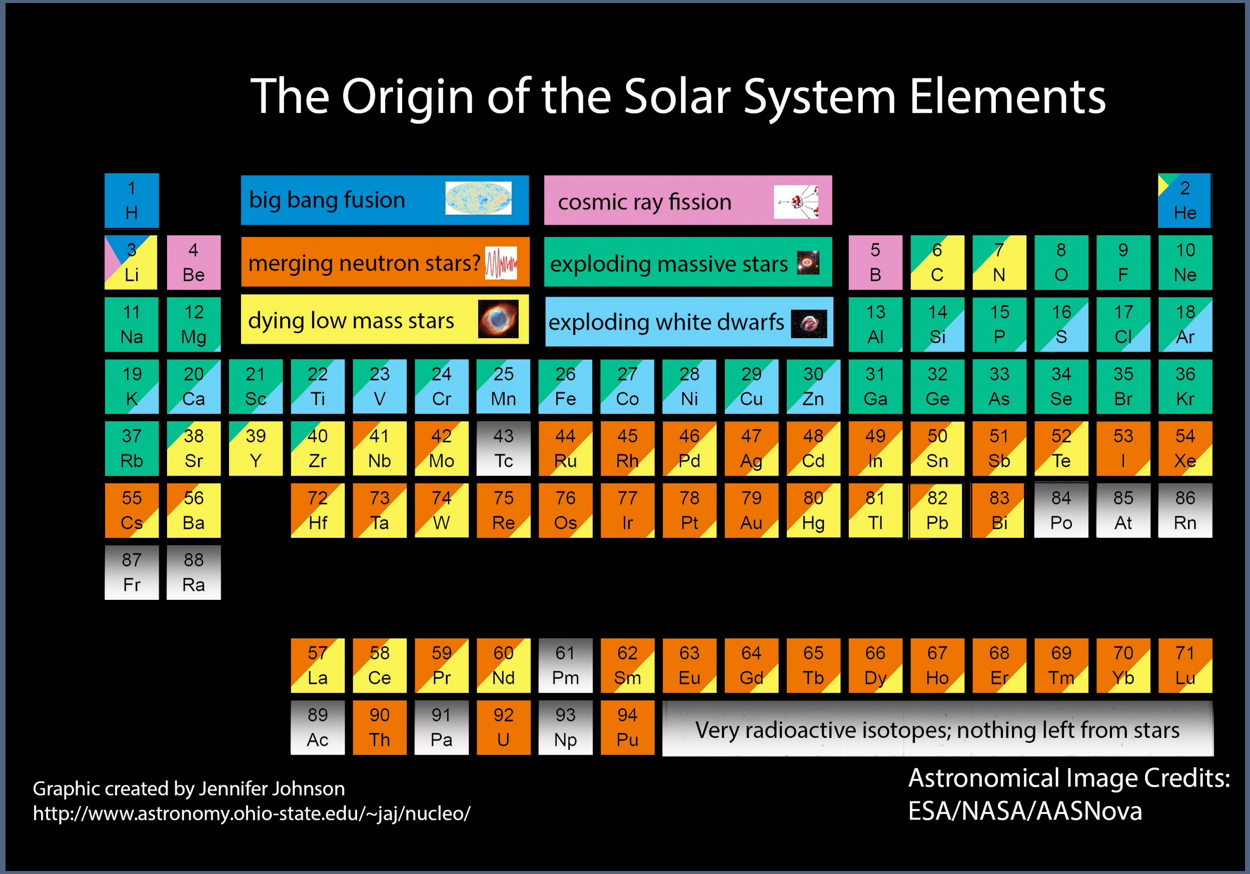


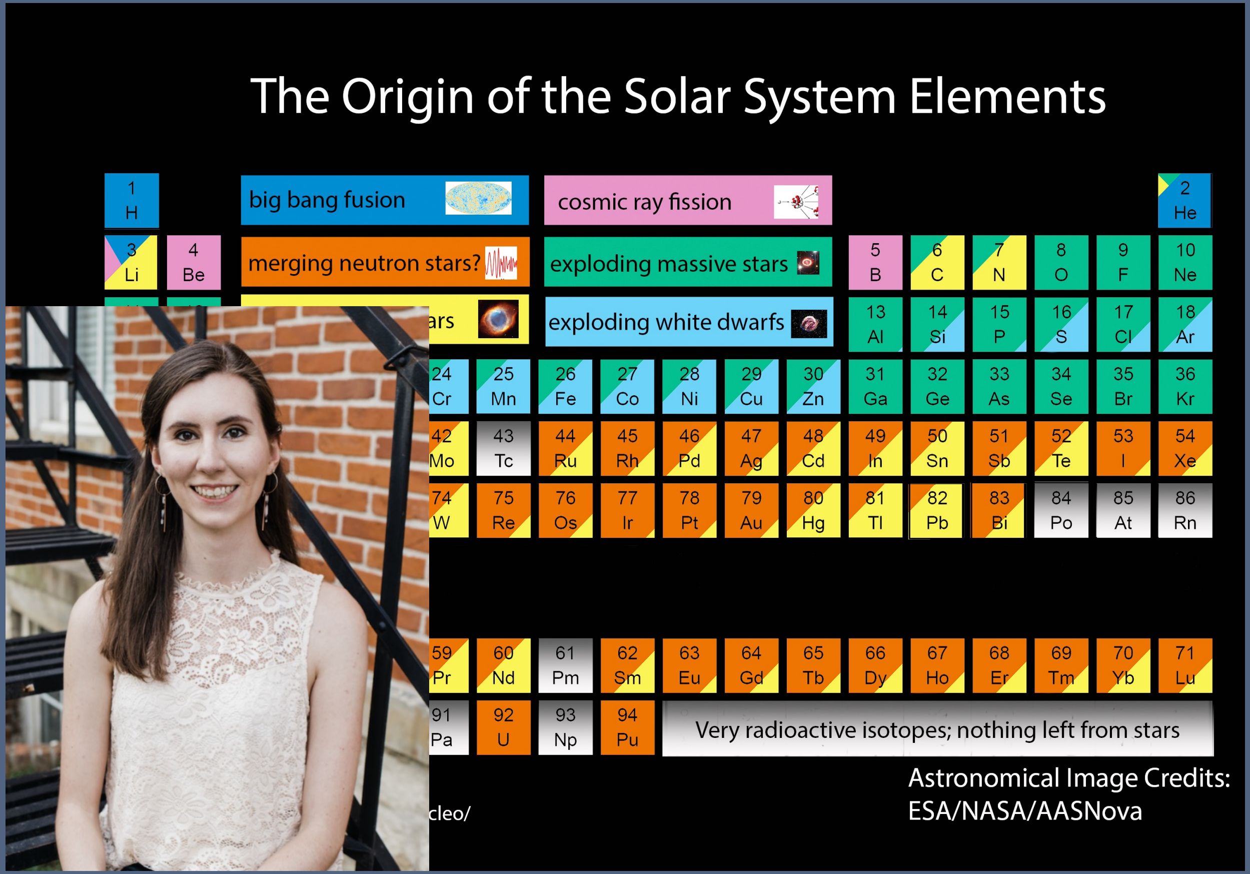
Fig. 3, Johnson (2019), Science, 363, 474

What are the Relative Yields of Different Elements?

Key parameter in chemical evolution models

Establish trends in abundance ratios in our disk models

Poorly Understood



Emily Griffith
(CU Boulder)

Fig. 3, Johnson (2019), Science, 363, 474

What are the Relative Yields of Different Elements?

Nitrogen: theoretically difficult

- Third dredge-up
- Hot bottom burning
- Mixing

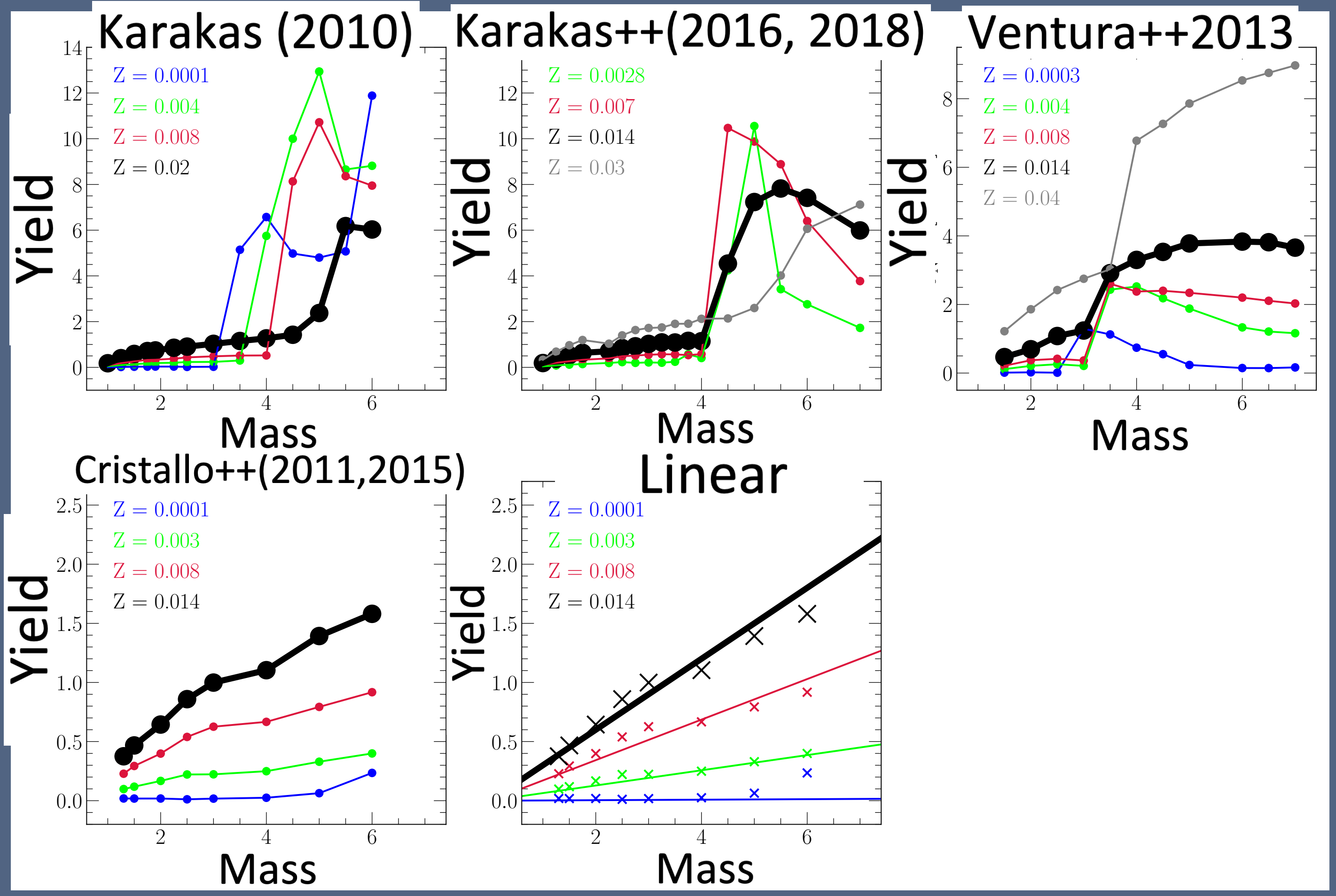


Fig. 3, Johnson et al. (2022), arxiv:2202.04666

What are the Relative Yields of Different Elements?

Nitrogen: theoretically difficult

- Third dredge-up
- Hot bottom burning
- Mixing

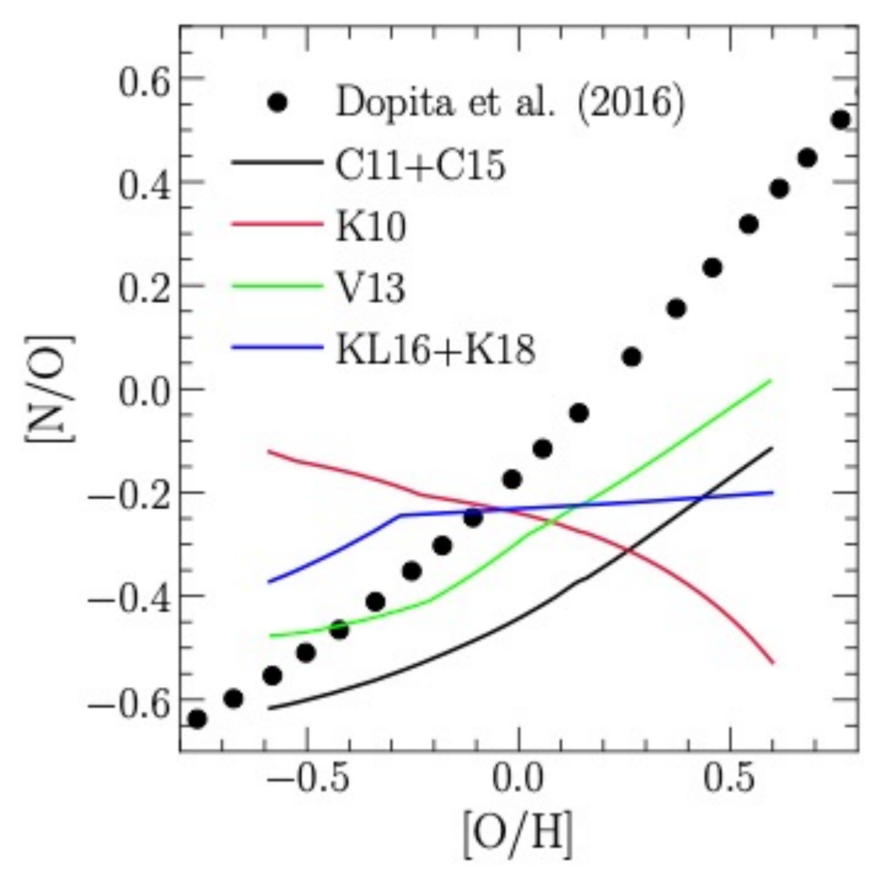


Fig. 6a, Johnson et al. (2022), arxiv:2202.04666

Different trends of [N/O] with [O/H]

- Z-dep of yield

What are the Relative Yields of Different Elements?

Normalization of [N/O]-[O/H] relation set by strength of yields and outflows

Slope of relationship requires $y_N \propto Z$

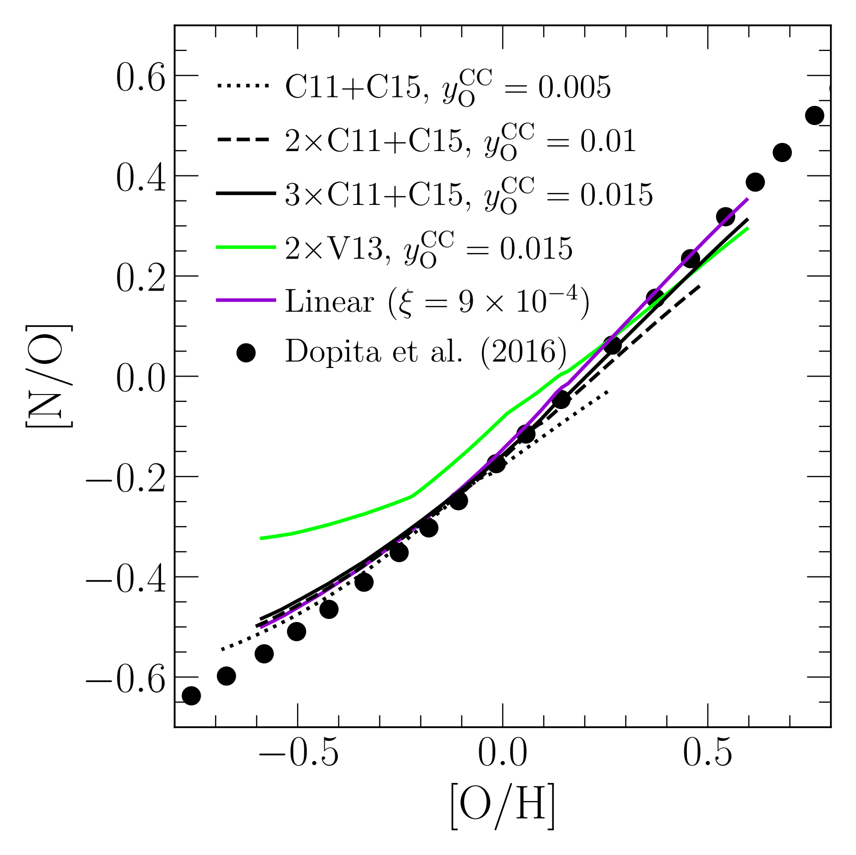


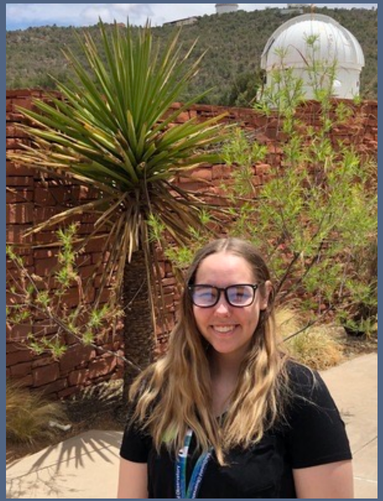
Fig. 6b, Johnson et al. (2022), arxiv:2202.04666

What are the Relative Yields of Different Elements?

Variability in SFR source of scatter

Daniel Boyea – Carbon

(Ohio State Undergraduate)



Miqaela Weller – Helium

(Ohio State)

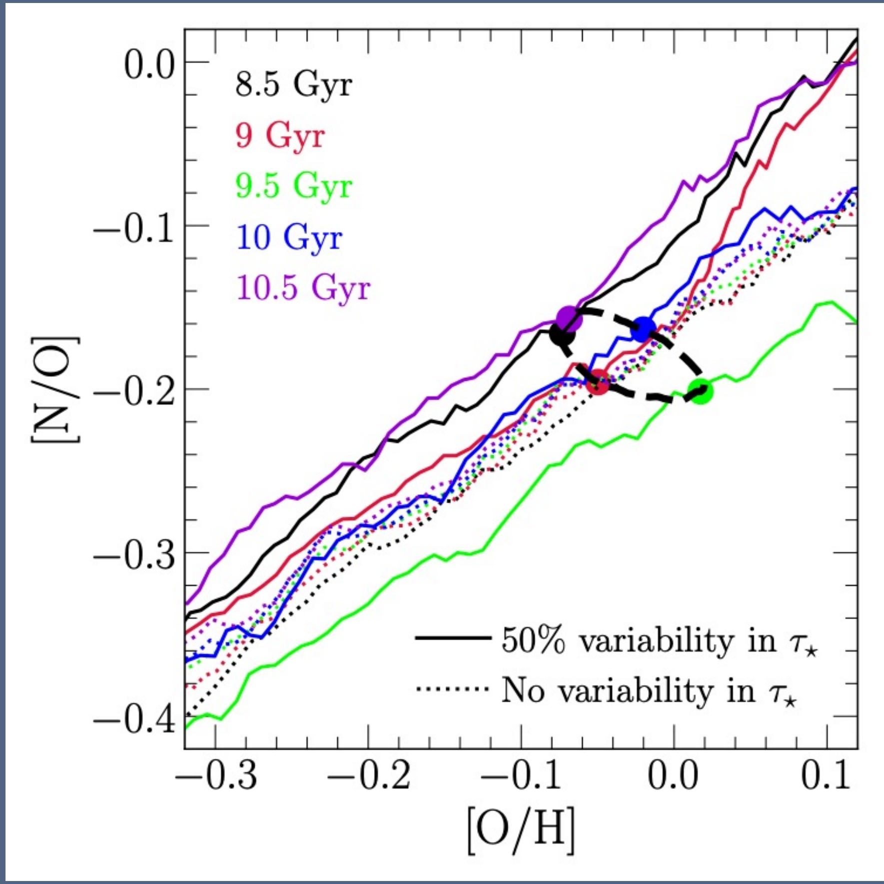


Fig. 6b, Johnson et al. (2022), arxiv:2202.04666

The Normalization of Stellar Yields

Come chat if you're interested!

Degenerate with how much gas a galaxy has exchanged with its surroundings

Primordially produced elements

- Cooke et al. (2022): helium isotopes
- Weinberg (2017): deuterium

Ryan Cooke
(Durham)

David Weinberg
(Ohio State)

Disrupted Dwarf Galaxies in the Stellar Halo

Come chat if you’re interested!

Novel method of fitting one-zone models to data

Proof of concept application to *Gaia*-Sausage Enceladus and Wukong/LMS-1

H3

Charlie Conroy
(Harvard)

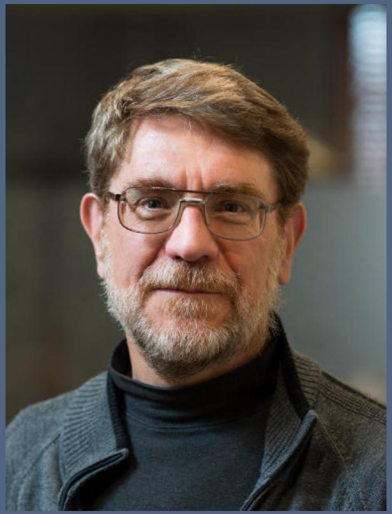
Metallicity-Dependent Type Ia Supernova Rates

Come chat if you're interested!

Combined

- Mass-metallicity relation
- Mass-SFH relation from semi-analytic model
- SN Ia delay-time distribution
- Prefactor computed from metallicity

Recent measurements suggest $N_{Ia} \propto 1/\sqrt{Z}$



Chris Kochanek
(Ohio State)

Kris Stanek
(Ohio State)

Key Takeaways

Come get an OSU Astronomy sticker!

Recent SFH of the Milky Way

- Ambiguous results comparing to age-[O/Fe] and age-[O/H] relations

[α/Fe] bimodality

- Combination of inside-out galaxy growth with radial migration is unsuccessful

GCE models can be used to constrain elemental yields

- Nitrogen: should increase ~linearly above some metallicity independent minimum

If you're also interested in dwarf galaxies, SN rates, or getting started with VICE, let's chat!

What is the Normalization of Elemental Yields?

Difficulty: strong degeneracy with strength of outflows

- Primary source and sink terms

$$\dot{M}_x = \sum_i Y_x - Z_x(\dot{M}_\star + \dot{M}_{out}) + \dot{M}_{return} + Z_{x,in}\dot{M}_{in}$$

$$\dot{M}_g = \dot{M}_{in} + \dot{M}_{return} - \dot{M}_\star - \dot{M}_{out}$$

Fit mock sample drawn from one-zone GCE model with yields, outflows as free parameters

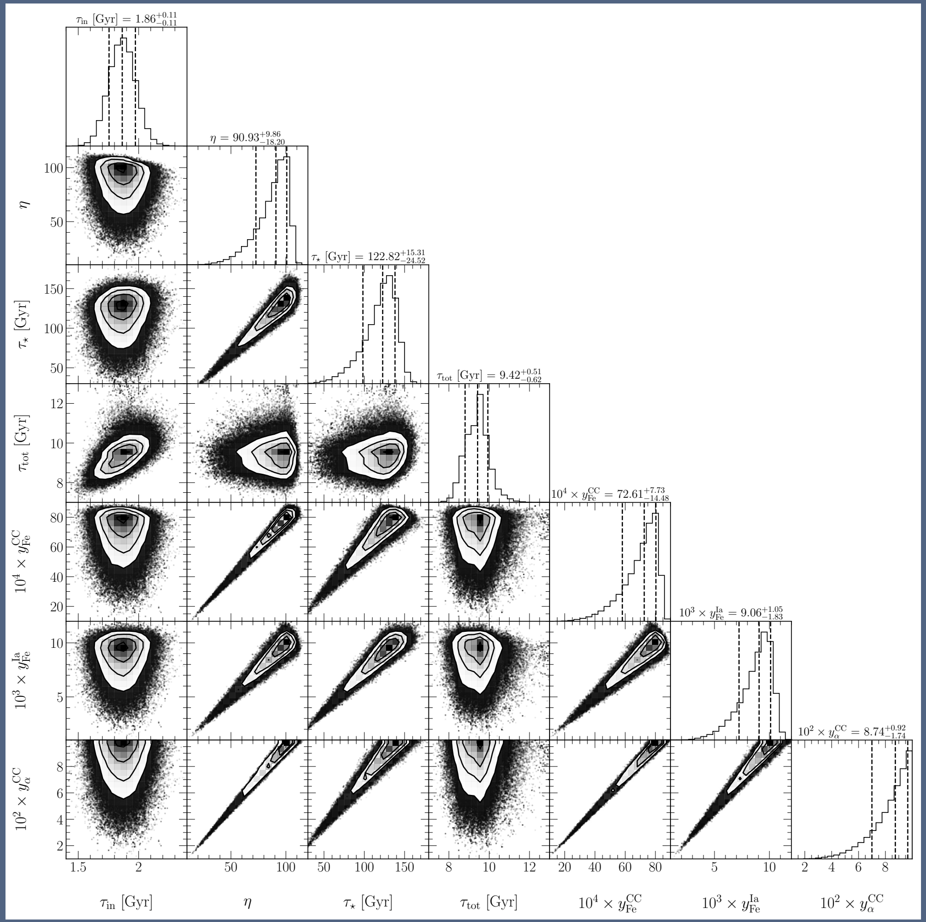


Fig. B1, Johnson et al. (2022), arxiv:2210.01816

VICE on Slack

SCAN ME

What are the Relative Yields of Different Elements?

[N/O]-[O/H] relation ~universal across galactic environments

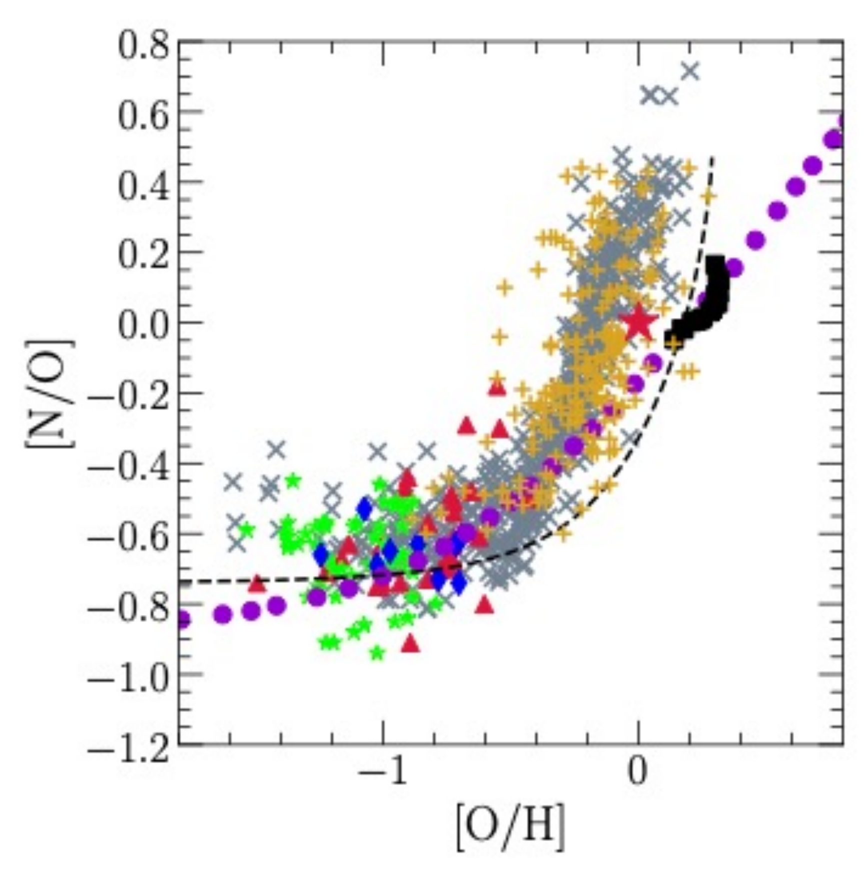


Fig. 1, Johnson et al. (2022), arxiv:2202.04666