Deciphering the Primordial Milky Way: Insights from Galactic Chemical Evolution Modeling

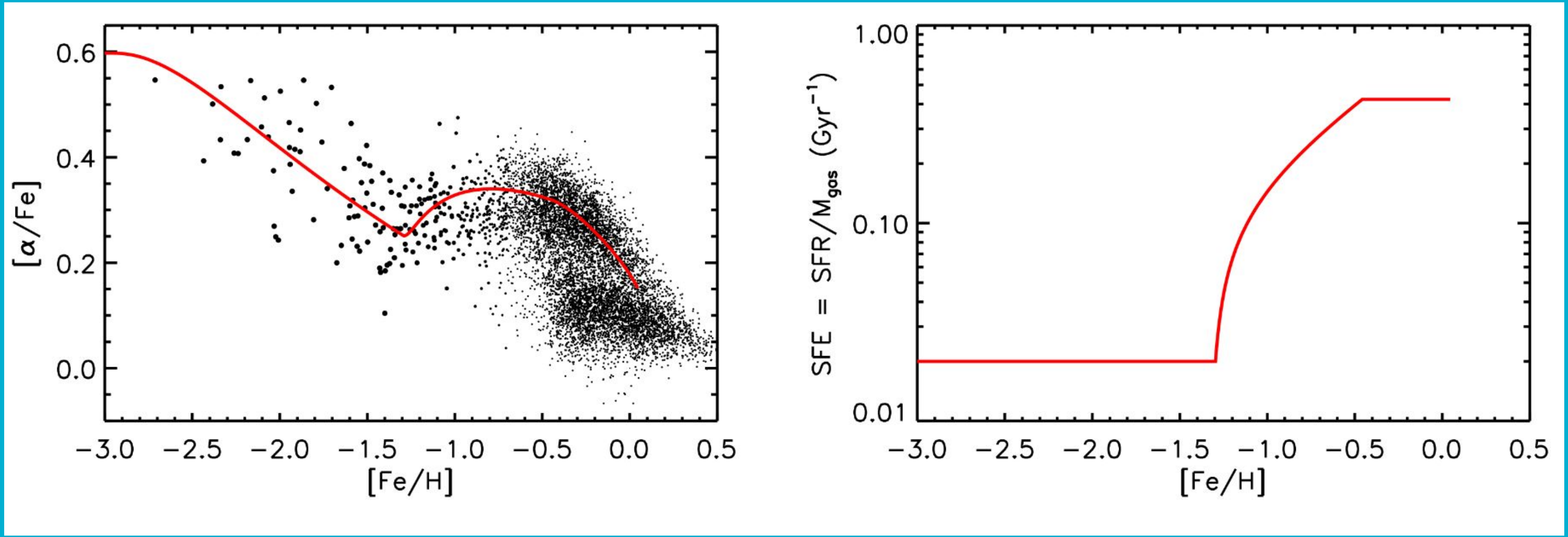
Boquan Chen (Australian National University/ Astro 3D)
Collaborators: Yuan-Sen Ting, Michael Hayden, Matt Orkney

The Milky Way Assembly Tale, Bologna, Italy May 27-31, 2024

Outline

1. **Observed chemical trend** in the Milky Way as its disk formed
2. An **introduction** to galactic chemical evolution models
3. **Set-up** for replicating the chemical evolution of the proto-Milky Way
4. **Results** from galactic chemical evolution models
5. **Discussion** in light of previous works and future **follow-up**

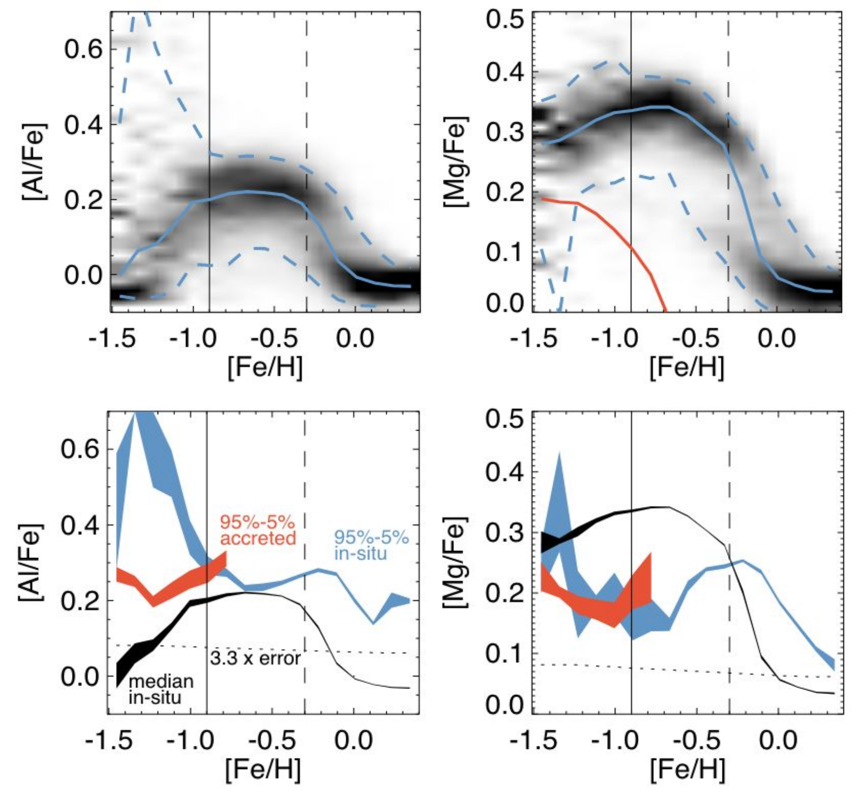
Observed chemical trend of the proto-Milky Way



Conroy et al. (2022)

An unexpected increase in [α/Fe] was observed among in-situ stars from H3 survey.

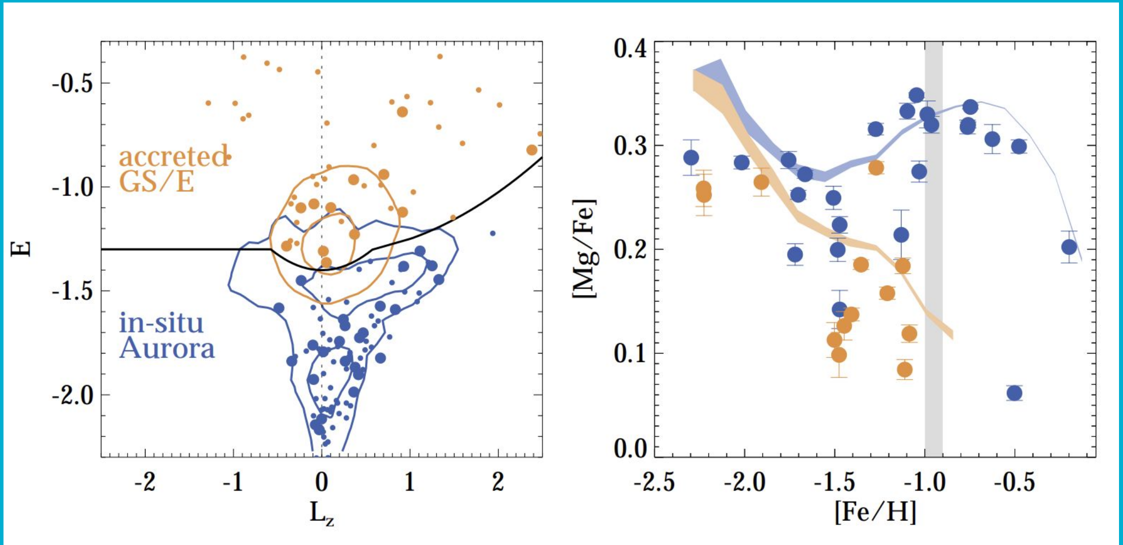
Observed chemical trend of the proto-Milky Way



A similar increase in [α/Fe] can be seen among chemo-dynamically selected in-situ stars from APOGEE survey.

Belokurov and Kravtsov (2022)

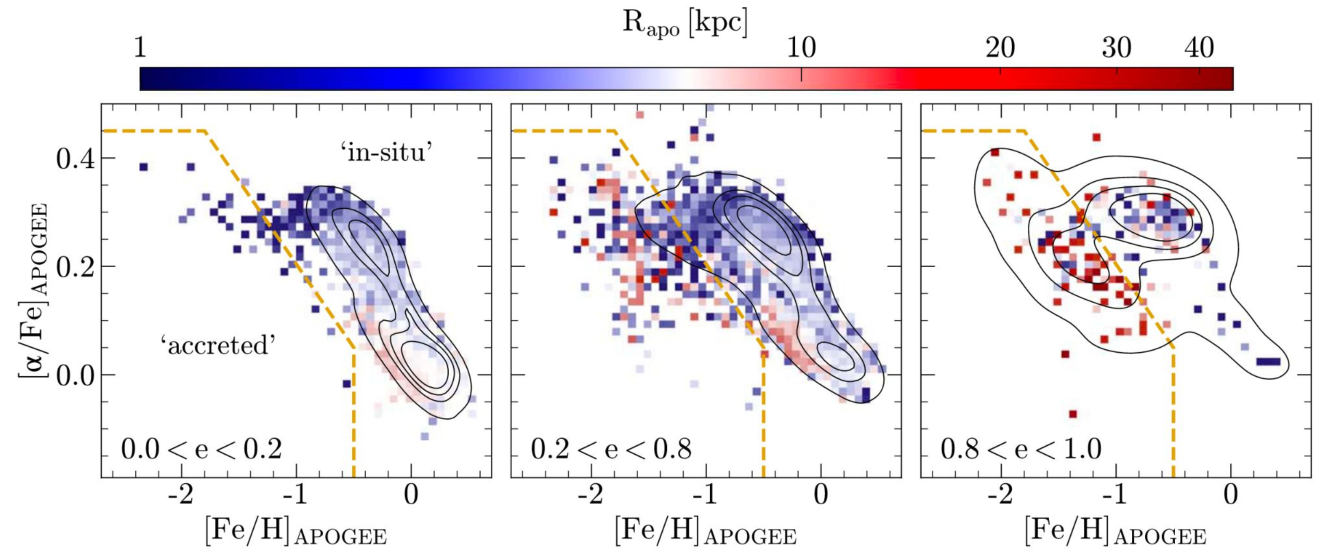
Observed chemical trend of the proto-Milky Way



Belokurov and Kravtsov (2023)

The same increase in [α/Fe] can also be seen among in-situ globular clusters from APOGEE survey.

Observed chemical trend of the proto-Milky Way



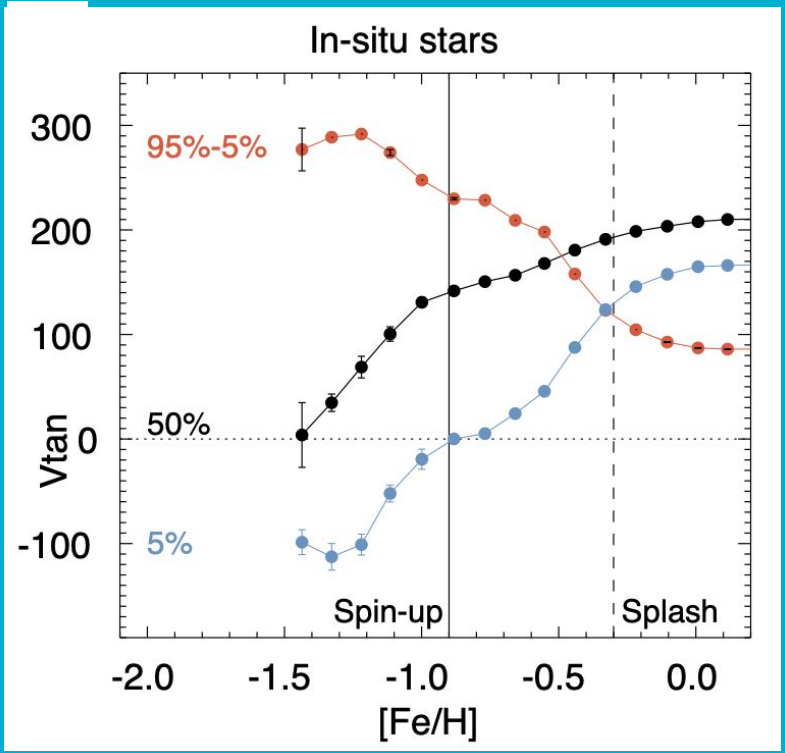
Rix et al. (2022)

Bright stars observed by Gaia are selected based on their metallicities from BP/RP spectra, which revealed the [α/Fe]-rise down to low eccentricity (e<0.2).

What do we learn from observations?

1. Conroy et al. (2022): A massive increase in star formation activity could have produced the additional α-elements needed for the [α/Fe]-rise.

What do we learn from observations?



Belokurov and Kravtsov (2022) found that the Galactocentric tangential velocities of stars rapidly increase (“spinning up”) after [Fe/H] = -1.3.

Simulations suggest that the formation of a hot gaseous halo can change the gas accretion mode, which leads to a stable rotating disk.

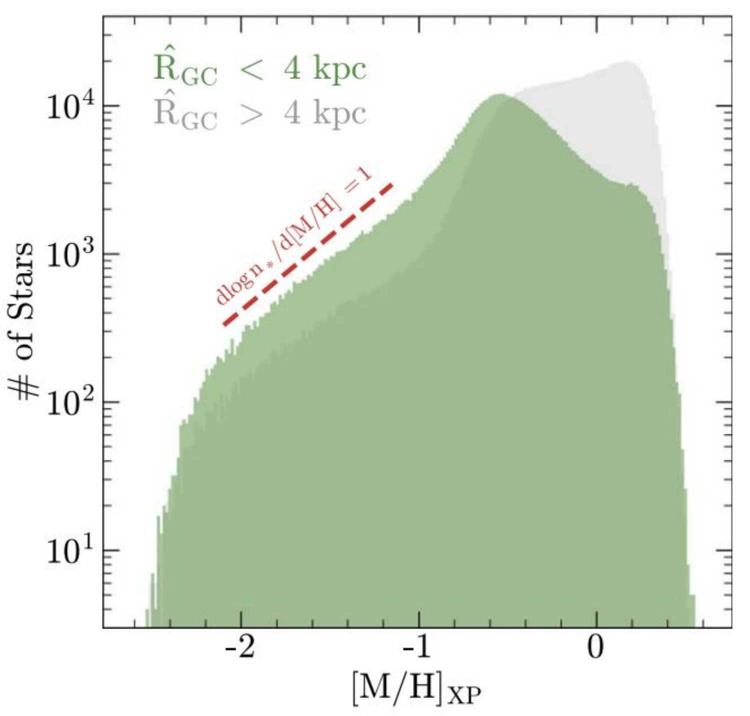
What do we learn from observations?

1. Conroy et al. (2022): Conroy et al. (2022): A massive increase in star formation activity could have produced the additional α-elements needed for the [α/Fe]-rise.
2. Belokurov and Kravtsov (2022): A change in gas accretion mode leads to a different star formation regime (from bursty to steady) which is reflected in the velocities of stars.

What do we learn from observations?

1. Conroy et al. (2022): Conroy et al. (2022): A massive increase in star formation activity could have produced the additional α-elements needed for the [α/Fe]-rise.
2. Belokurov and Kravtsov (2022): A change in gas accretion mode leads to a different star formation regime (from bursty to steady) which is reflected in the velocities of stars.
3. Belokurov and Kravtsov (2023): More globular clusters formed before the disk formed.

What do we learn from observations?



In this low-metallicity limit, Equation (2) is simply $\dot{M}_Z = y_Z \dot{M}_*$, and for a metallicity-independent yield, its time integral implies $M_Z = y_Z M_*$ and thus $Z = y_Z M_* / M_g$. The log-slope of the MDF is

$$\frac{d\log n_*}{d[\mathrm{M/H}]} = \frac{d\log M_*}{d\log Z} = \frac{Z}{M_*} \cdot \frac{\dot{M}_*}{\dot{Z}} = \frac{y_Z}{\dot{Z}\tau_*}, \qquad (3)$$

where the last equality introduces the star formation efficiency (SFE) timescale $\tau_* \equiv M_g / \dot{M}_*$. Using

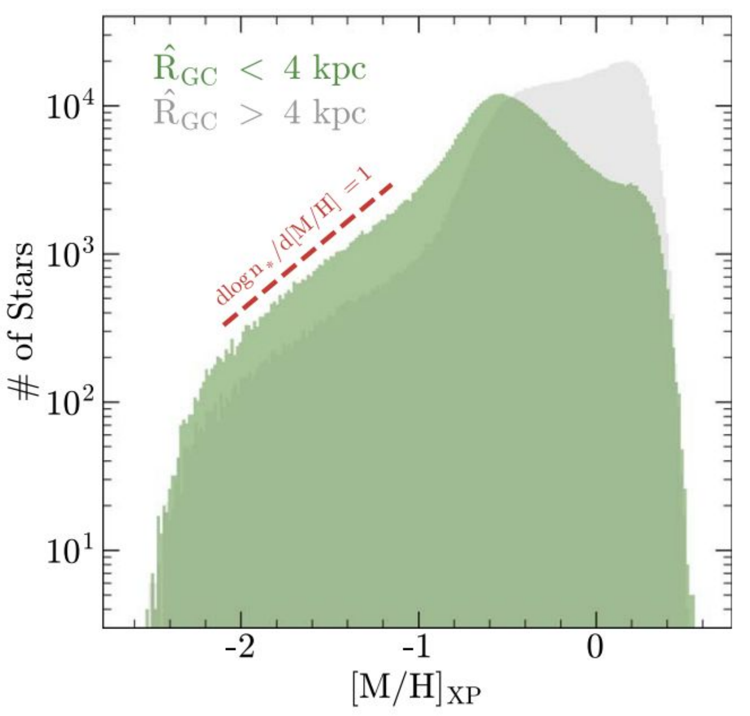
$$\dot{Z} = \frac{d}{dt}(M_Z / M_g) = y_Z \frac{\dot{M}_*}{M_g} - y_Z \frac{M_* \dot{M}_g}{M_g^2} \qquad (4)$$

gives the end result:

$$\frac{d\log n_*}{d[\mathrm{M/H}]} = \left(\frac{\dot{Z}\tau_*}{y_Z}\right)^{-1} = \left[1 - \left(\frac{M_*}{M_g}\right)\left(\frac{\tau_* \dot{M}_g}{M_g}\right)\right]^{-1}. \qquad (5)$$

Rix et al. (2022)

What do we learn from observations?

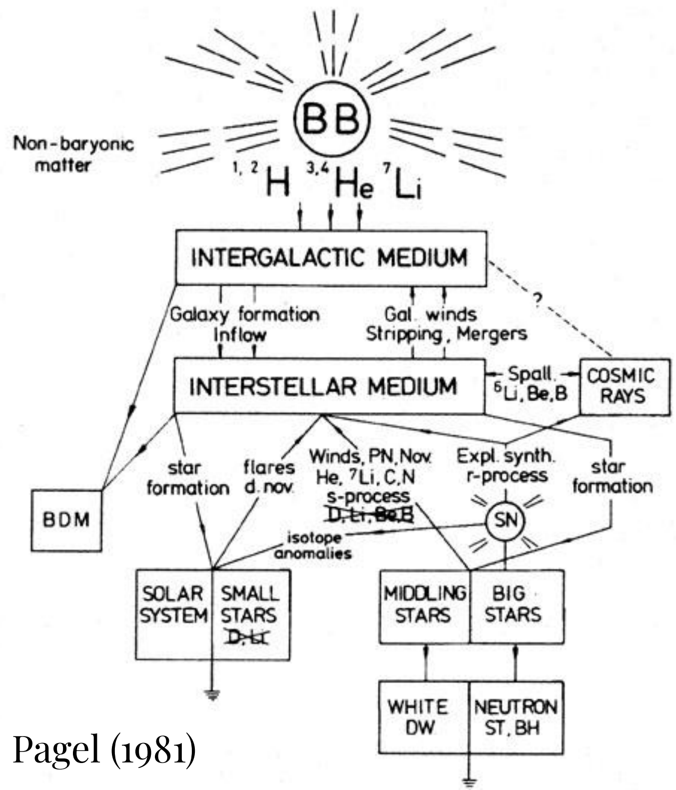


Based on analytic assumptions, the slope of the metal-poor metallicity distribution suggests that the inflow rate during the proto-Galaxy phase could have been very low.

What do we learn from observations?

1. Conroy et al. (2022): A massive increase in star formation activity could have produced the additional α-elements needed for the [α/Fe]-rise.
2. Belokurov and Kravtsov (2022): A change in gas accretion mode leads to a different star formation regime which is reflected in the velocities of stars.
3. Belokurov and Kravtsov (2023): More globular clusters formed before the disk formed.
4. Rix et al. (2022): The proto-Milky Way likely had little inflow and functioned as a closed box model in terms of chemical evolution.

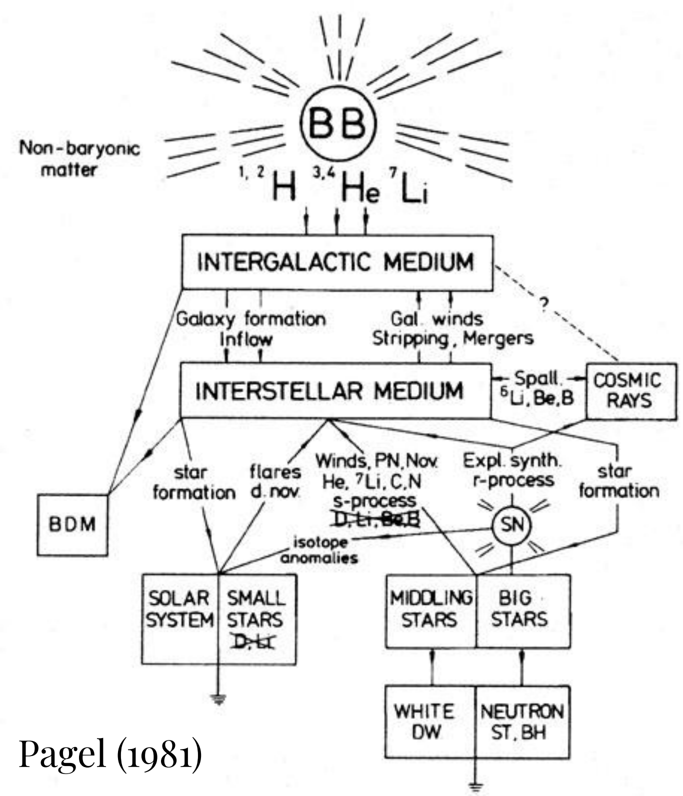
Introduction to galactic chemical evolution



Pagel (1981)

Ingredients: Intergalactic medium, interstellar medium, stars, nucleosynthesis yields, gas flow and feedback

Introduction to galactic chemical evolution

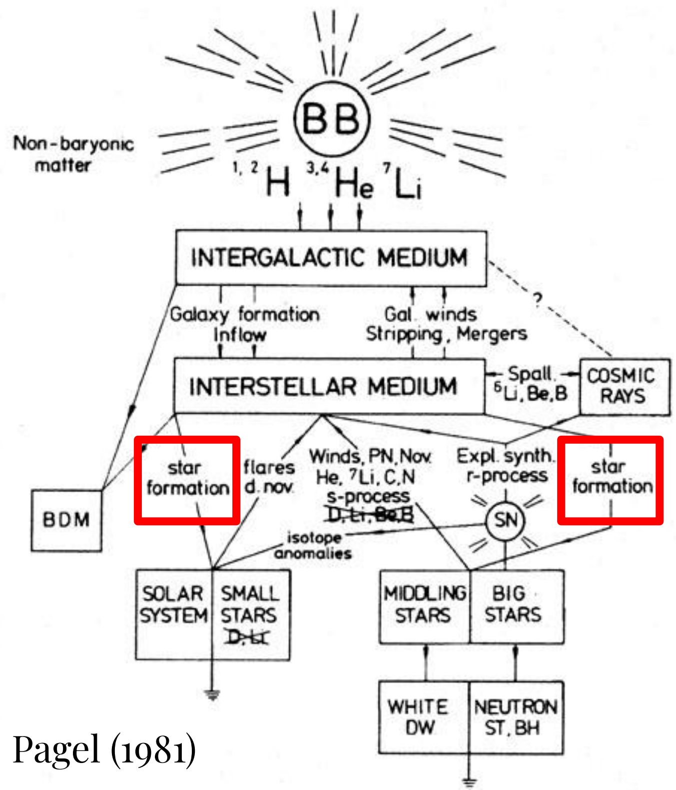


Pagel (1981)

Ingredients: Intergalactic medium, interstellar medium, stars, nucleosynthesis yields, gas flow and feedback

There are many ways to handle things in these models.

Introduction to galactic chemical evolution

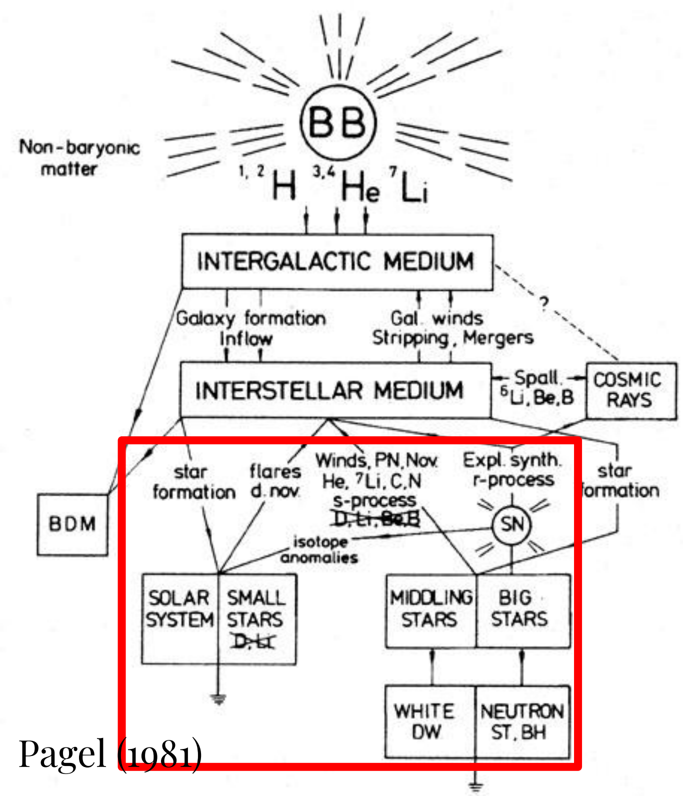


Pagel (1981)

Star formation:

1. Pre-prescribed star formation history
2. Kennicutt-Schmidt law: star formation density is based on gas surface density
3. Multi-phase ISM: updated K-S law based on molecular gas from Leroy et al. (2008) and Bigiel et al. (2008)

Introduction to galactic chemical evolution

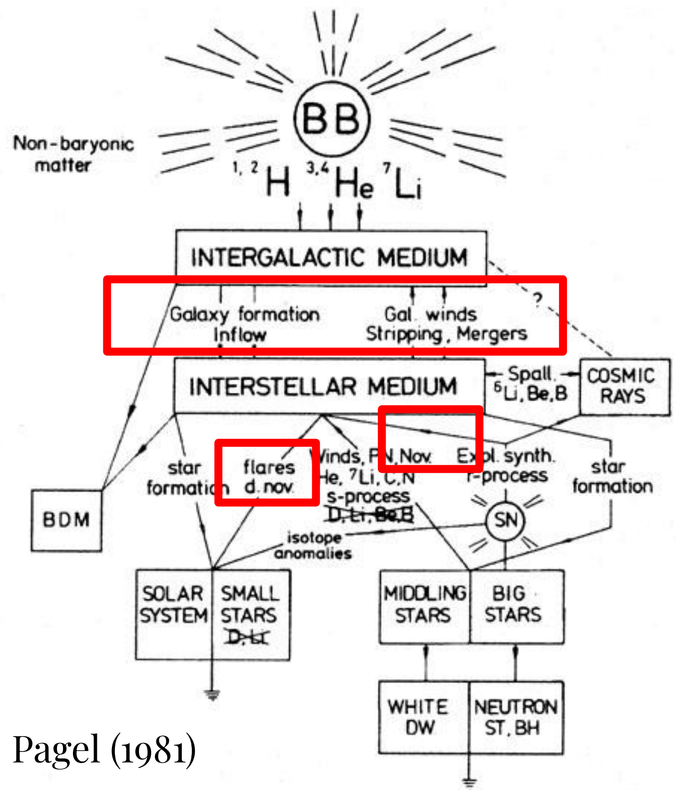


Pagel (1981)

Nucleosynthesis:

1. Nucleosynthesis yields weighted by the initial mass function for stars
2. Synthetic yields to represent nucleosynthesis channels dominating different stellar mass ranges
3. Adopt nucleosynthesis tables (elements or isotopes) sorted by progenitor mass and metallicities.

Introduction to galactic chemical evolution



Pagel (1981)

Gas recycling:

1. Instantaneous recycling of yields
2. Delayed recycling with warm ISM

Inflow:

1. Analytic functions that dictate inflow rate over time and space
2. Inflow functions from cosmological simulations (e.g. to fuel inside-out growth)

Set-up of chemical evolution model

- Initialise the model with **cold and warm ISM** with Big Bang nucleosynthesis composition
- **Inflow** enters the model by joining the warm ISM exponentially over time
- Star formation rate based on the available cold ISM by **KS-law**
- **Stellar lifetimes** determined by PARSEC-1.2S isochrone
- Star formation/ AGB/ supernovae **heat** cold ISM into warm ISM
- Warm ISM **cools** into cold ISM exponentially over time
- **Nucleosynthesis yields** for AGB and CCSN which varies by progenitor mass and metallicities from Nomoto et al. (2013) and Type Ia supernova from Iwamoto et al. (1999)
- **One Gyr of proto-Milky Way** and then the disk forms
- **Inflow rate and star formation efficiency** are allowed to freely change when the disk forms, while **high-[α/Fe]** inflow becomes available

Set-up of chemical evolution model

- Initialise the model with **cold and warm ISM** with Big Bang nucleosynthesis composition
- **Inflow** enters the model by joining the warm ISM exponentially over time
- Star formation rate based on the available cold ISM by **KS-law**
- **Stellar lifetimes** determined by PARSEC-1.2S isochrone
- Star formation/ AGB/ supernovae **heat** cold ISM into warm ISM
- Warm ISM **cools** into cold ISM exponentially over time
- **Nucleosynthesis yields** for AGB and CCSN which varies by progenitor mass and metallicities from Nomoto et al. (2013) and Type Ia supernova from Iwamoto et al. (1999)
- **One Gyr of proto-Milky Way** and then the disk forms
- **Inflow rate and star formation efficiency** are allowed to freely change when the disk forms, while **high-[α/Fe]** inflow becomes available

Set-up of chemical evolution model

- Initialise the model with **cold and warm ISM** with Big Bang nucleosynthesis composition
- **Inflow** enters the model by joining the warm ISM exponentially over time
- Star formation rate based on the available cold ISM by **KS-law**
- **Stellar lifetimes** determined by PARSEC-1.2S isochrone
- Star formation/ AGB/ supernovae **heat** cold ISM into warm ISM
- Warm ISM **cools** into cold ISM exponentially over time
- **Nucleosynthesis yields** for AGB and CCSN which varies by progenitor mass and metallicities from Nomoto et al. (2013) and Type Ia supernova from Iwamoto et al. (1999)
- **One Gyr of proto-Milky Way** and then the disk forms
- **Inflow rate and star formation efficiency** are allowed to freely change when the disk forms, while **high-[α/Fe]** inflow becomes available

Set-up of chemical evolution model

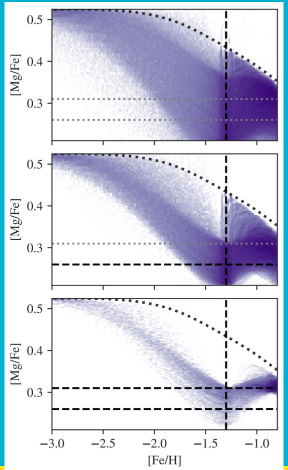
- Initialise the model with **cold and warm ISM** with Big Bang nucleosynthesis composition
- **Inflow** enters the model by joining the warm ISM exponentially over time
- Star formation rate based on the available cold ISM by **KS-law**
- **Stellar lifetimes** determined by PARSEC-1.2S isochrone
- Star formation/ AGB/ supernovae **heat** cold ISM into warm ISM
- Warm ISM **cools** into cold ISM exponentially over time
- **Nucleosynthesis yields** for AGB and CCSN which varies by progenitor mass and metallicities from Nomoto et al. (2013) and Type Ia supernova from Iwamoto et al. (1999)
- **One Gyr of proto-Milky Way** and then the disk forms
- **Inflow rate and star formation efficiency** are allowed to freely change when the disk forms, while **high-[α/Fe]** inflow becomes available

Set-up of chemical evolution model

- Initialise the model with **cold and warm ISM** with Big Bang nucleosynthesis composition
- **Inflow** enters the model by joining the warm ISM exponentially over time
- Star formation rate based on the available cold ISM by **KS-law**
- **Stellar lifetimes** determined by PARSEC-1.2S isochrone
- Star formation/ AGB/ supernovae **heat** cold ISM into warm ISM
- Warm ISM **cools** into cold ISM exponentially over time
- **Nucleosynthesis yields** for AGB and CCSN which varies by progenitor mass and metallicities from Nomoto et al. (2013) and Type Ia supernova from Iwamoto et al. (1999)
- **One Gyr of proto-Milky Way** and then the disk forms
- **Inflow rate and star formation efficiency** are allowed to freely change when the disk forms, while **high-[α/Fe]** inflow becomes available

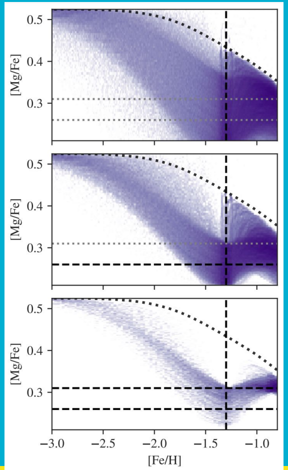
Results from chemical evolution model

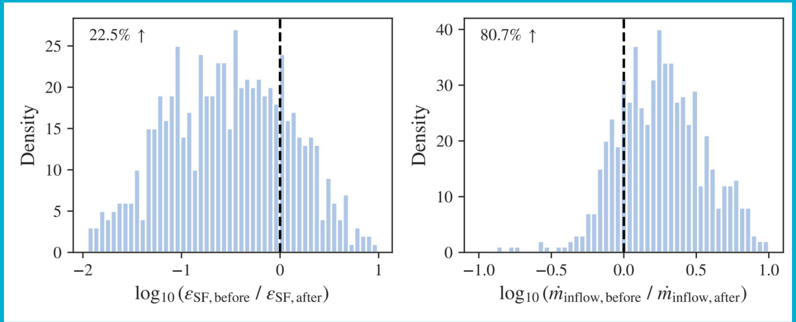
1. Select the models that replicate the [α/Fe]-rise



Results from chemical evolution model

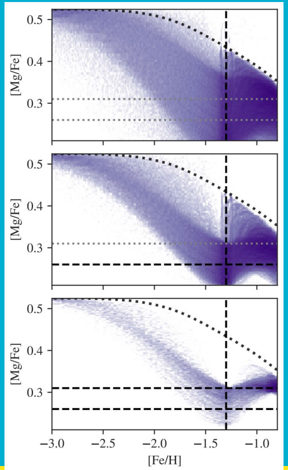
1. Select the models that replicate the [α/Fe]-rise
2. Check the inflow rate and SFEs before and after the [α/Fe]-rise for these models

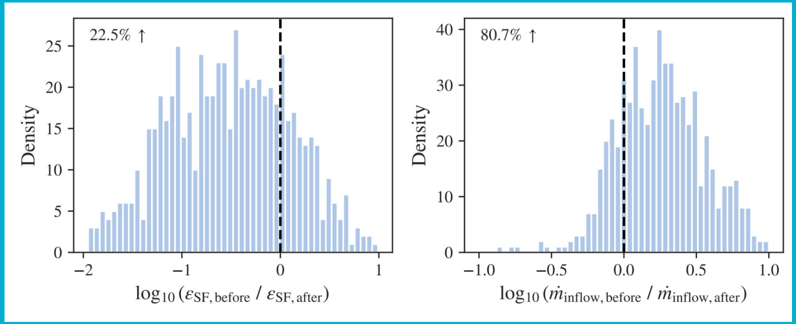


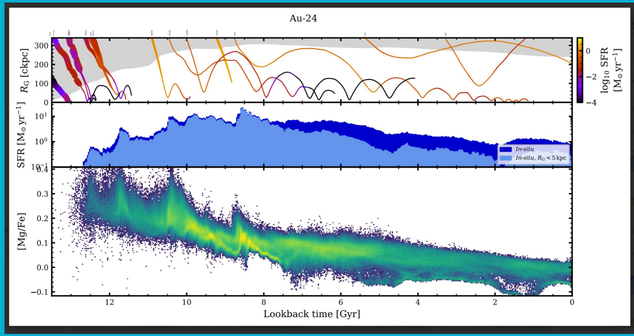


Results from chemical evolution model

1. Select the models that replicate the [α/Fe]-rise
2. Check the inflow rate and SFEs before and after the [α/Fe]-rise for these models
3. Find counterparts in simulations

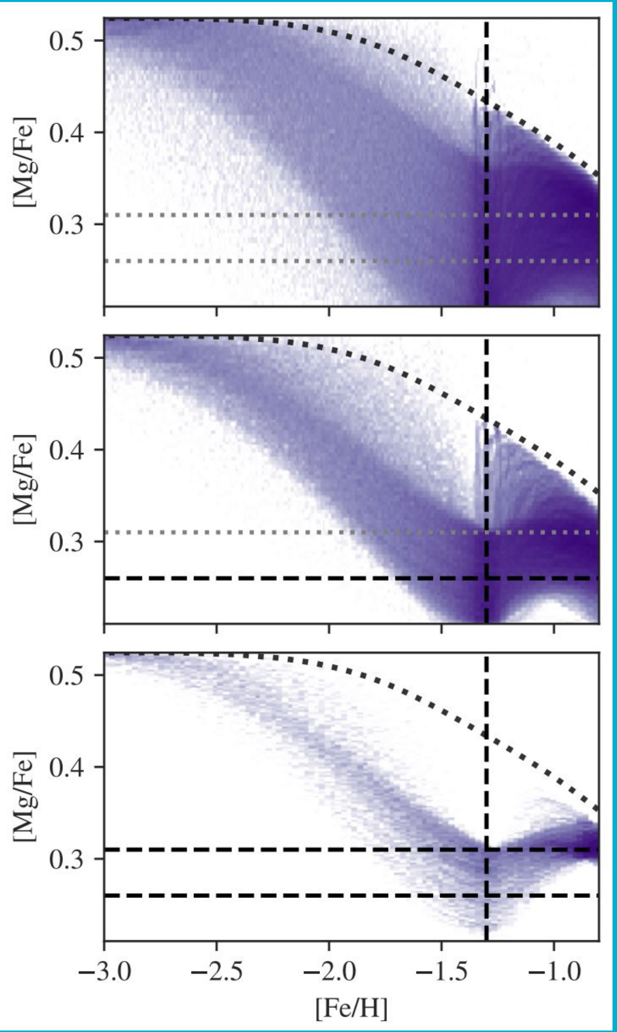


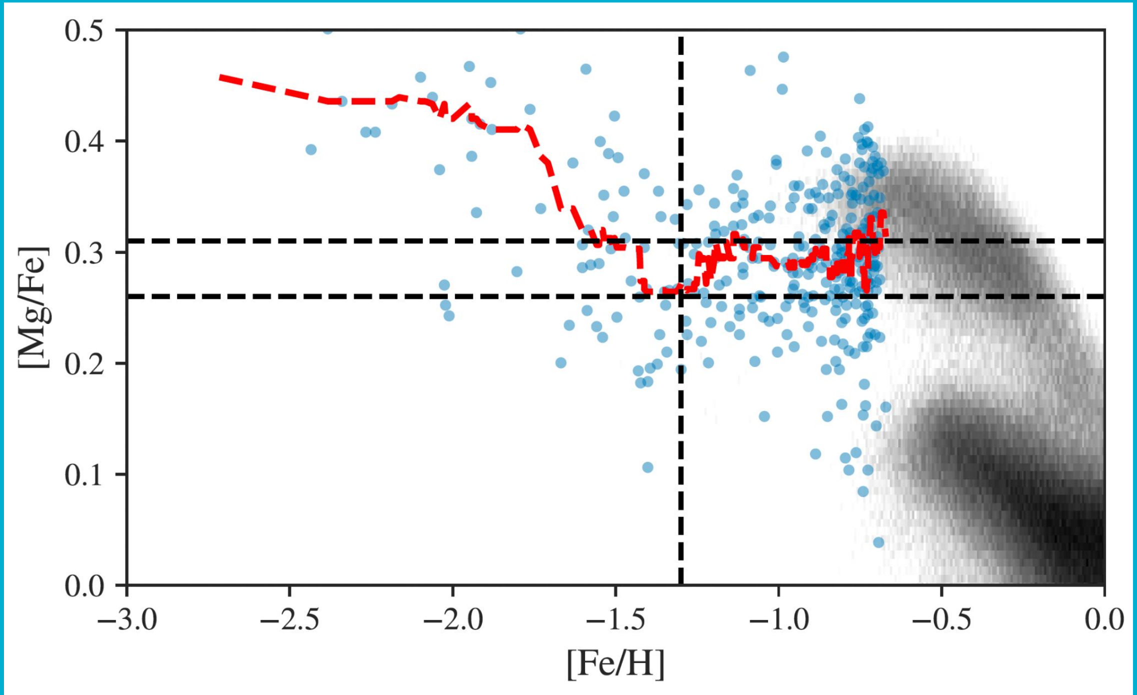




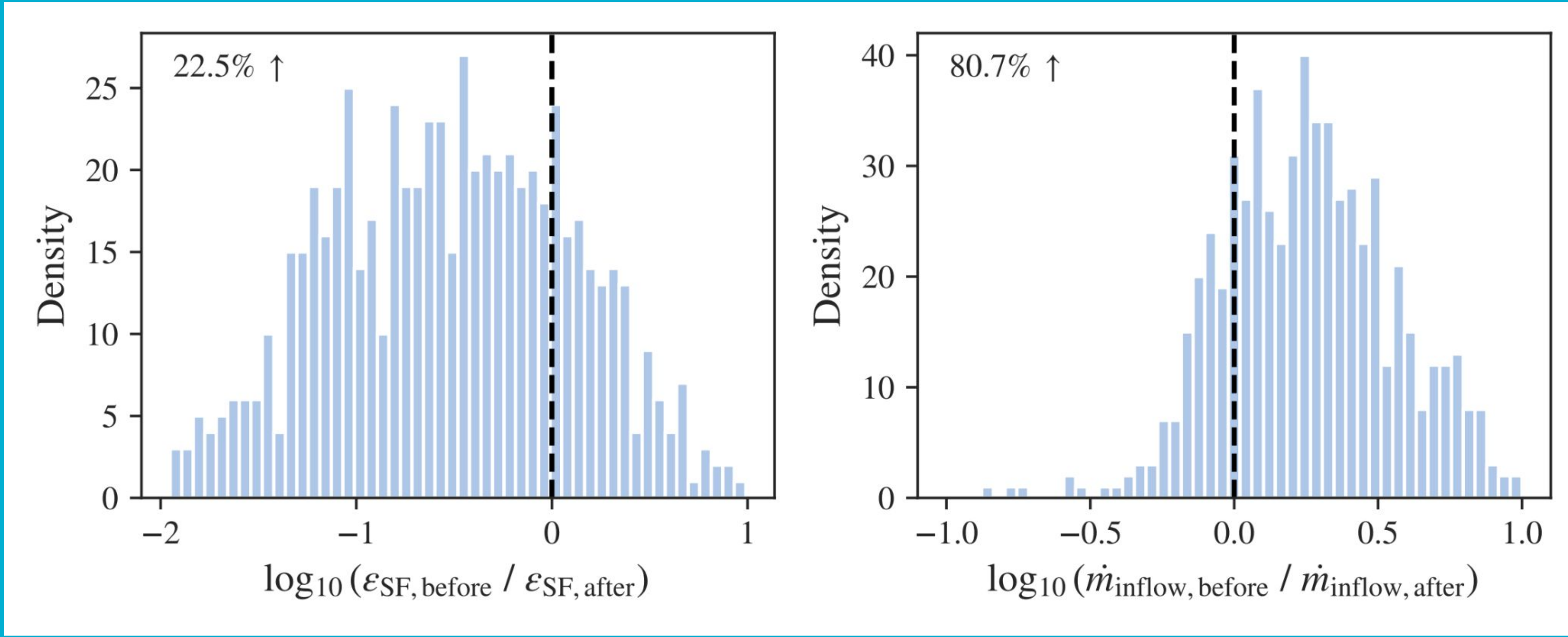
The Milky Way Assembly Tale, Bologna, Italy May 27-31, 2024

Select the models

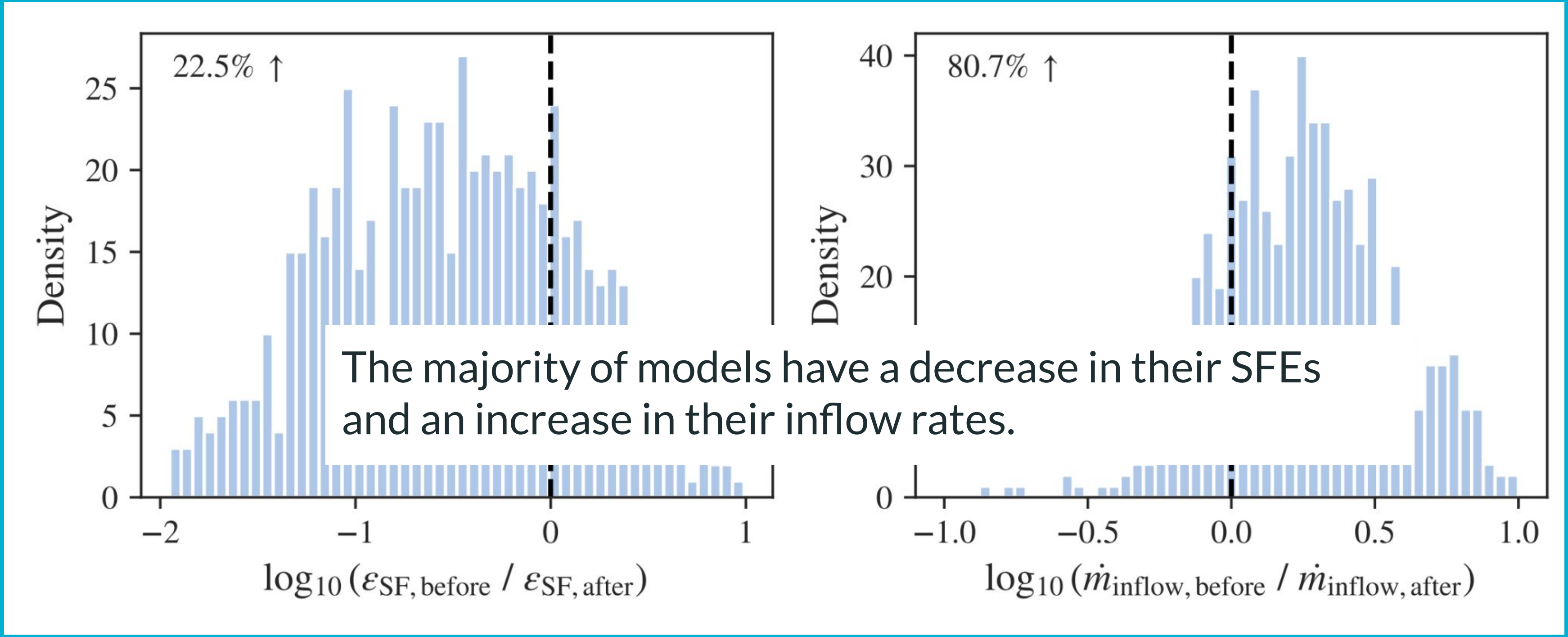




The change in parameters

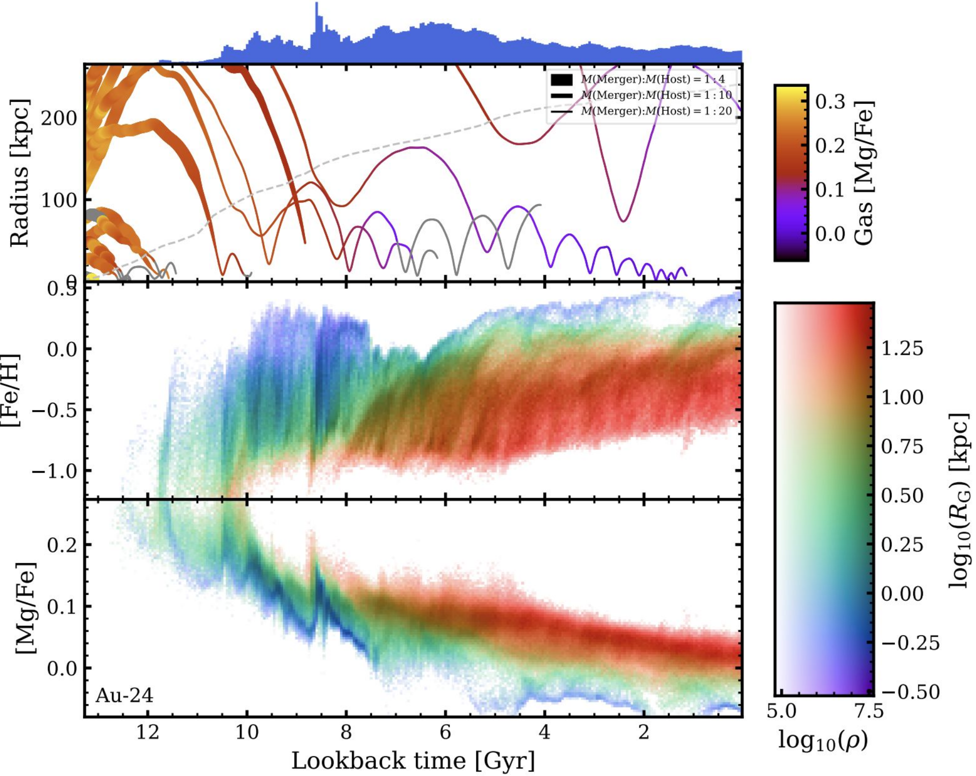


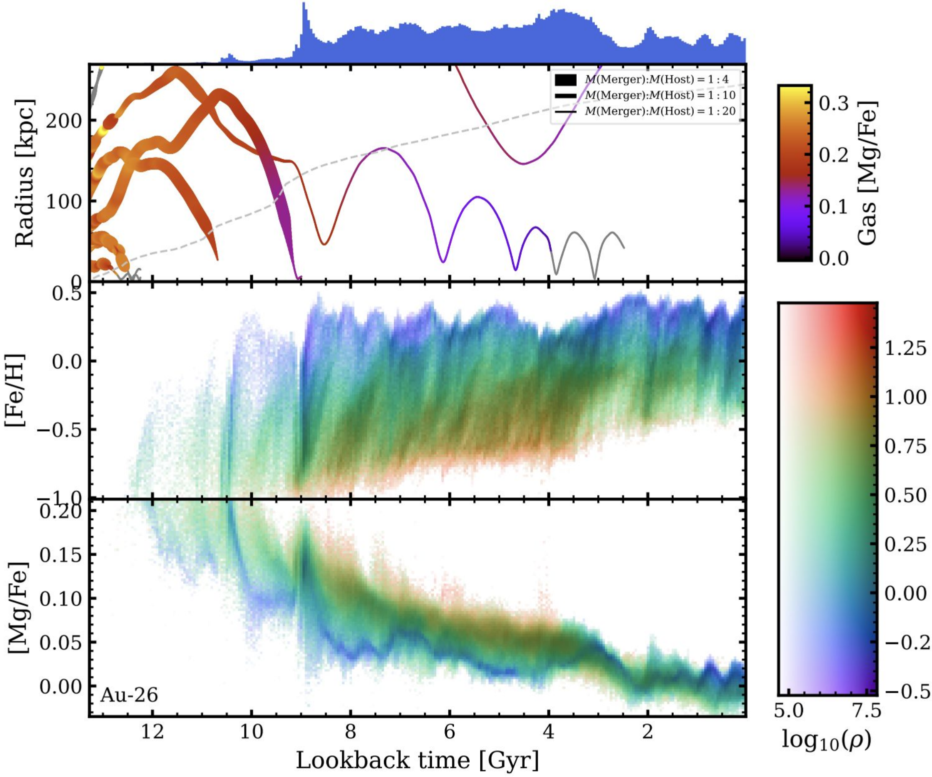
The change in parameters

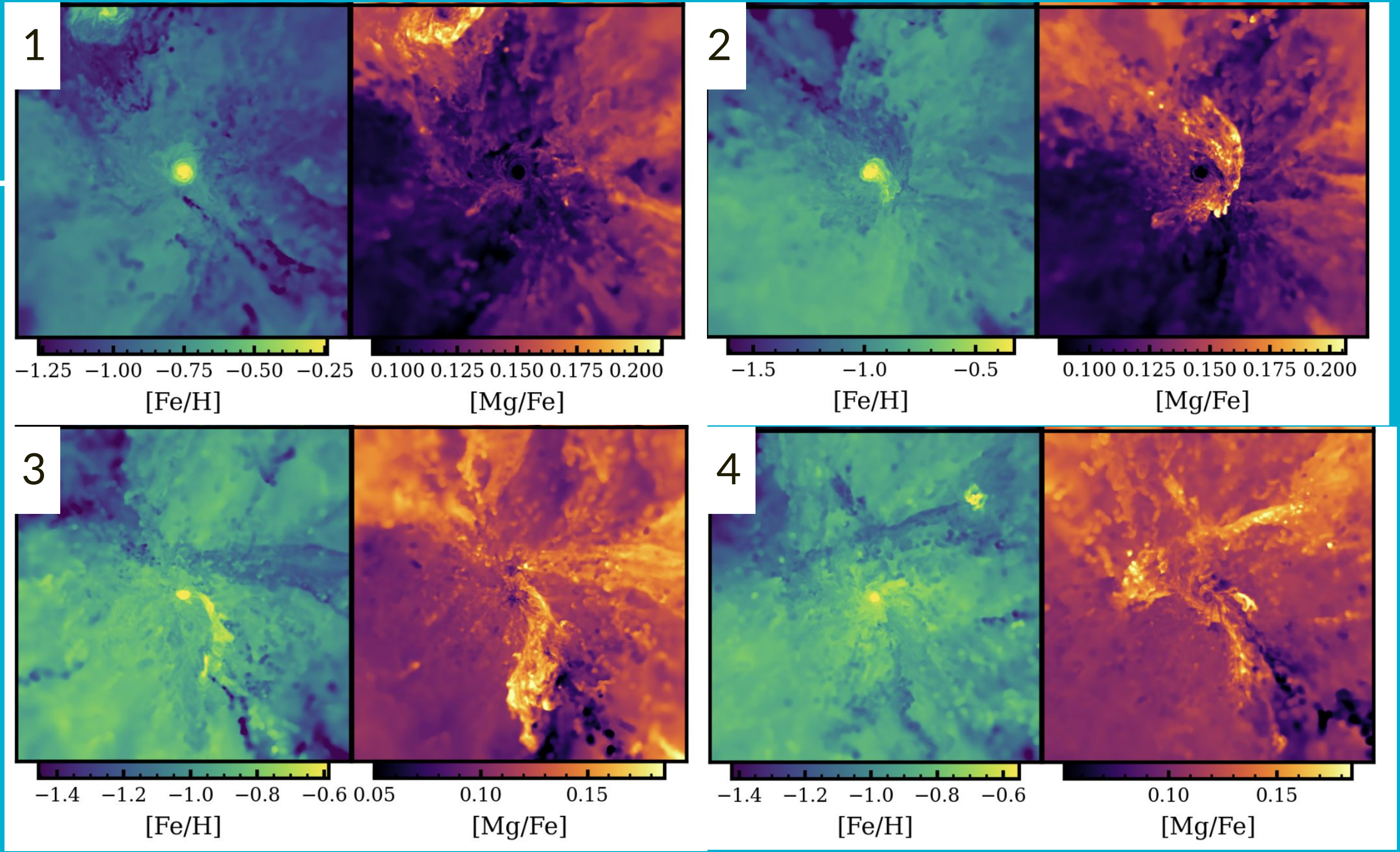


The majority of models have a decrease in their SFEs and an increase in their inflow rates.

Support from simulations






1
−1.25 −1.00 −0.75 −0.50 −0.25
[Fe/H]
0.100 0.125 0.150 0.175 0.200
[Mg/Fe]
2
−1.5 −1.0 −0.5
[Fe/H]
0.100 0.125 0.150 0.175 0.200
[Mg/Fe]
3
−1.4 −1.2 −1.0 −0.8 −0.6
[Fe/H]
0.05 0.10 0.15
[Mg/Fe]
4
−1.4 −1.2 −1.0 −0.8 −0.6
[Fe/H]
0.10 0.15
[Mg/Fe]

Discussion

1. We agree with Conroy et al. (2022) that heightened star formation activity is responsible for the rise in [α/Fe].
2. The change of inflow regime discussed by Belokurov and Kravtsov (2022) likely involved a change in the inflow rate and composition.
3. We confirm the theoretical calculation by Rix et al. (2022) that inflow was suppressed during the proto-Milky Way phase.
4. The additional inflow gas could have been brought in by another progenitor of the Milky Way as shown in simulations by Horta et al. (2024).

Implications for the Milky Way

1. The high [α/Fe] value associated with old stars in the Milky Way should not be taken for granted. Type Ia supernovae start lowering [α/Fe] very early on.
2. The large spread in [α/Fe] in the low-metallicity region could hide signatures for early mergers. There might be more than one interruptions on [α/Fe].
3. The metallicity distributions produced by our models predict a strong peak at [Fe/H] = -1.3 as a result of the increased inflow.
4. Our models show the proto-Galaxy has a stellar mass of around 10^9 solar masses, consistent with the estimates from simulations.

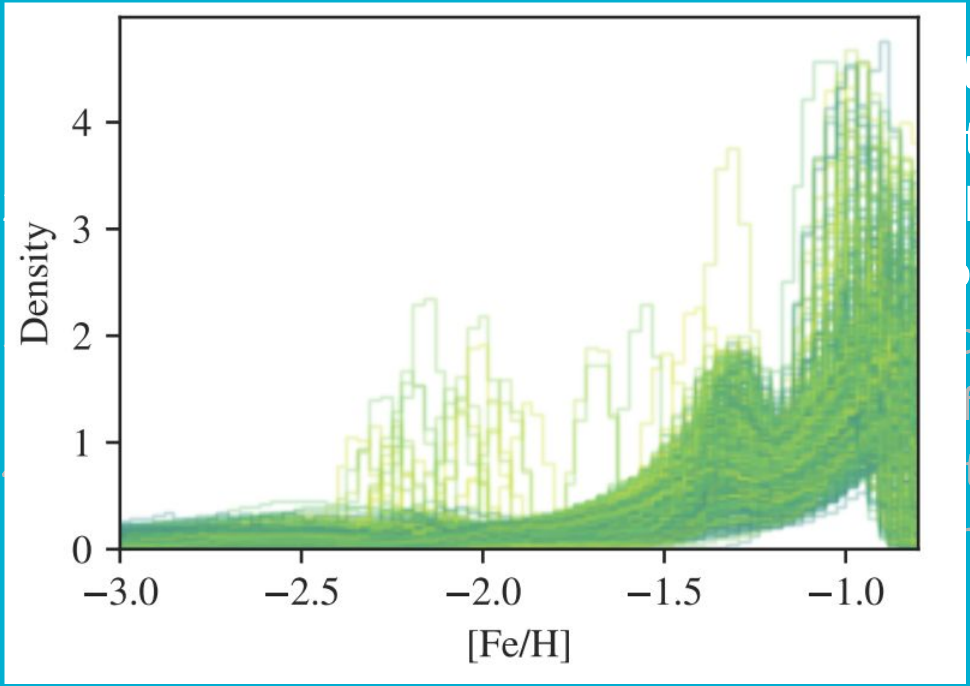
Implications for the Milky Way

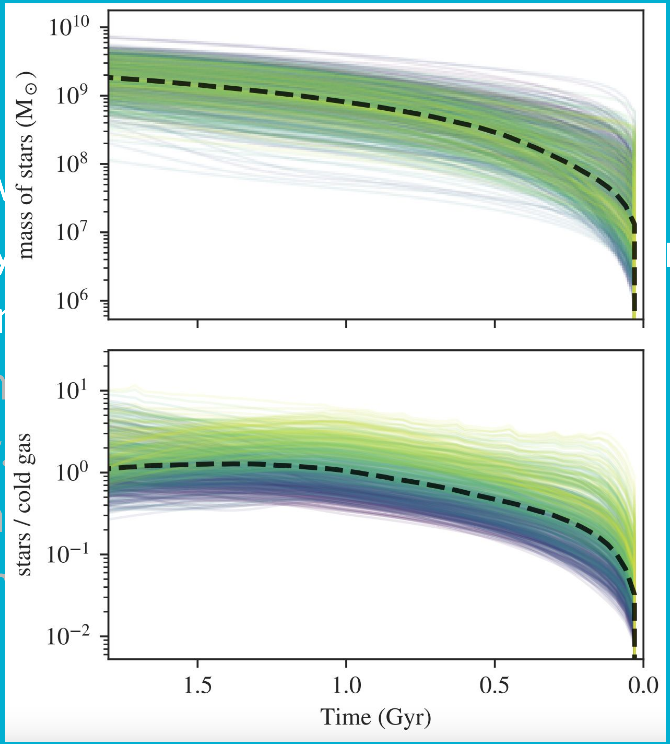
1. The high [α/Fe] value associated with old stars in the Milky Way should not be taken for granted. Type Ia supernovae start lowering [α/Fe] very early on.
2. The large spread in [α/Fe] in the low-metallicity region could hide signatures for early mergers. There might be more than one interruptions on [α/Fe].
3. The metallicity distributions produced by our models predict a strong peak at [Fe/H] = -1.3 as a result of the increased inflow.
4. Our models show the proto-Galaxy has a stellar mass of around 10^9 solar masses, consistent with the estimates from simulations.

Implications for the Milky Way

1. The high [α/Fe] value associated with old stars in the Milky Way should not be taken for granted. Type Ia supernovae start lowering [α/Fe] very early on.
2. The large spread in [α/Fe] in the low-metallicity region could hide signatures for early mergers. There might be more than one interruptions on [α/Fe].
3. The metallicity distributions produced by our models predict a strong peak at [Fe/H] = -1.3 as a result of the increased inflow.
4. Our models show the proto-Galaxy has a stellar mass of around 10^9 solar masses, consistent with the estimates from simulations.

Implications for the Milky Way





Implications for the Milky Way

1. The high [α/Fe] value associated with old stars in the Milky Way should not be taken for granted. Type Ia supernovae start lowering [α/Fe] very early on.
2. The large spread in [α/Fe] in the low-metallicity region could hide signatures for early mergers. There might be more than one interruptions on [α/Fe].
3. The metallicity distributions produced by our models predict a strong peak at [Fe/H] = -1.3 as a result of the increased inflow.
4. Our models show the proto-Galaxy has a stellar mass of around 10^9 solar masses, consistent with the estimates from simulations.

Follow-up

1. Much of the observational evidence focuses on the transitional phase as the disk formed. Can we find more direct evidence on the proto-Galaxy?
2. Simulations suggest that it is common for proto-Milky Way analogs to have more than one progenitor. Can we identify the progenitors from currently observed metal-poor stars?
3. Chemical evolution models that replicate the rise in [α/Fe] require high-[α/Fe] gas. Where is the gas coming from? ISM of the progenitor? CCSN from star formation burst?