Inflows, Outflows, and Radial Flows

The Puppet Masters of Chemical Evolution in the Milky Way

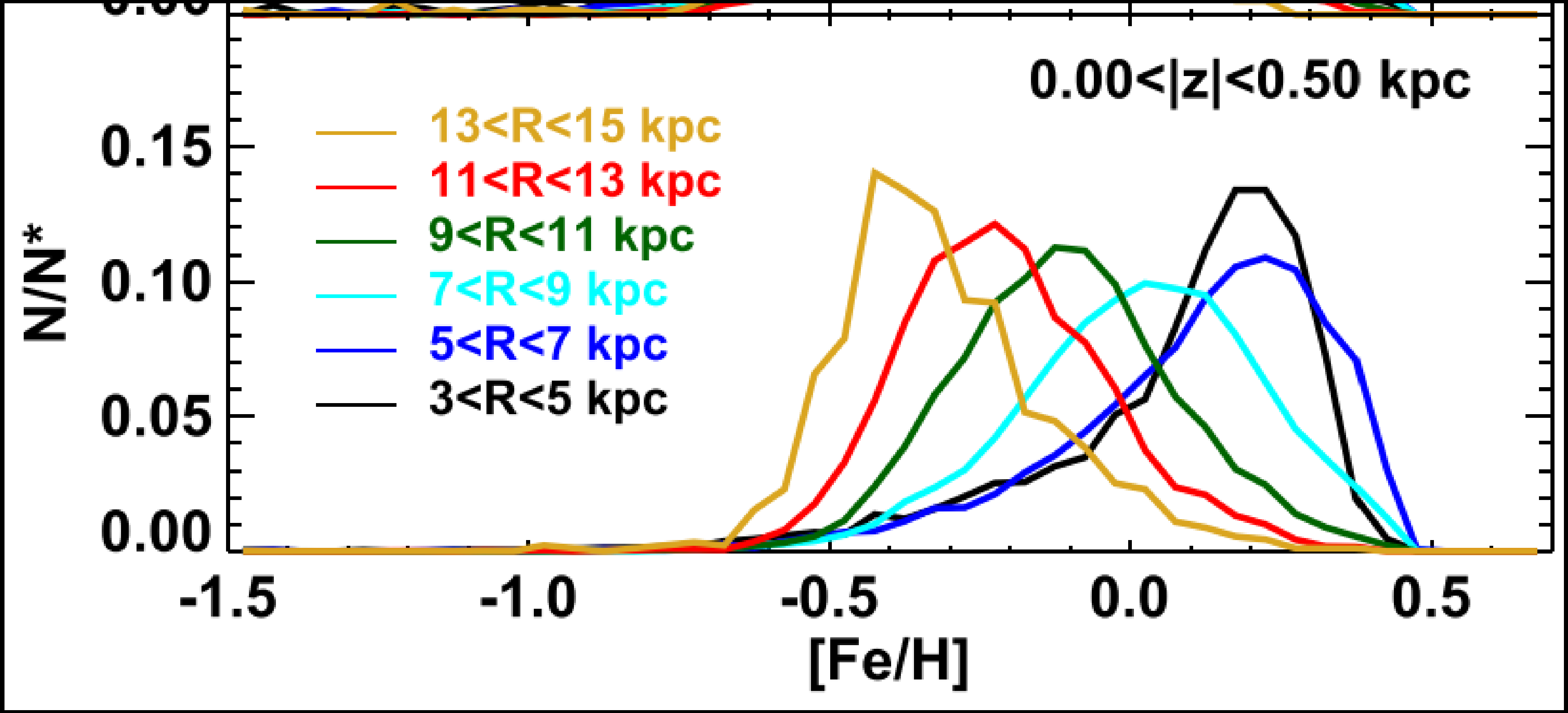
James W. Johnson | Carnegie Observatories

Astrophysics Seminar – University of California, Davis

May 1, 2025

Radial Metallicity Gradient

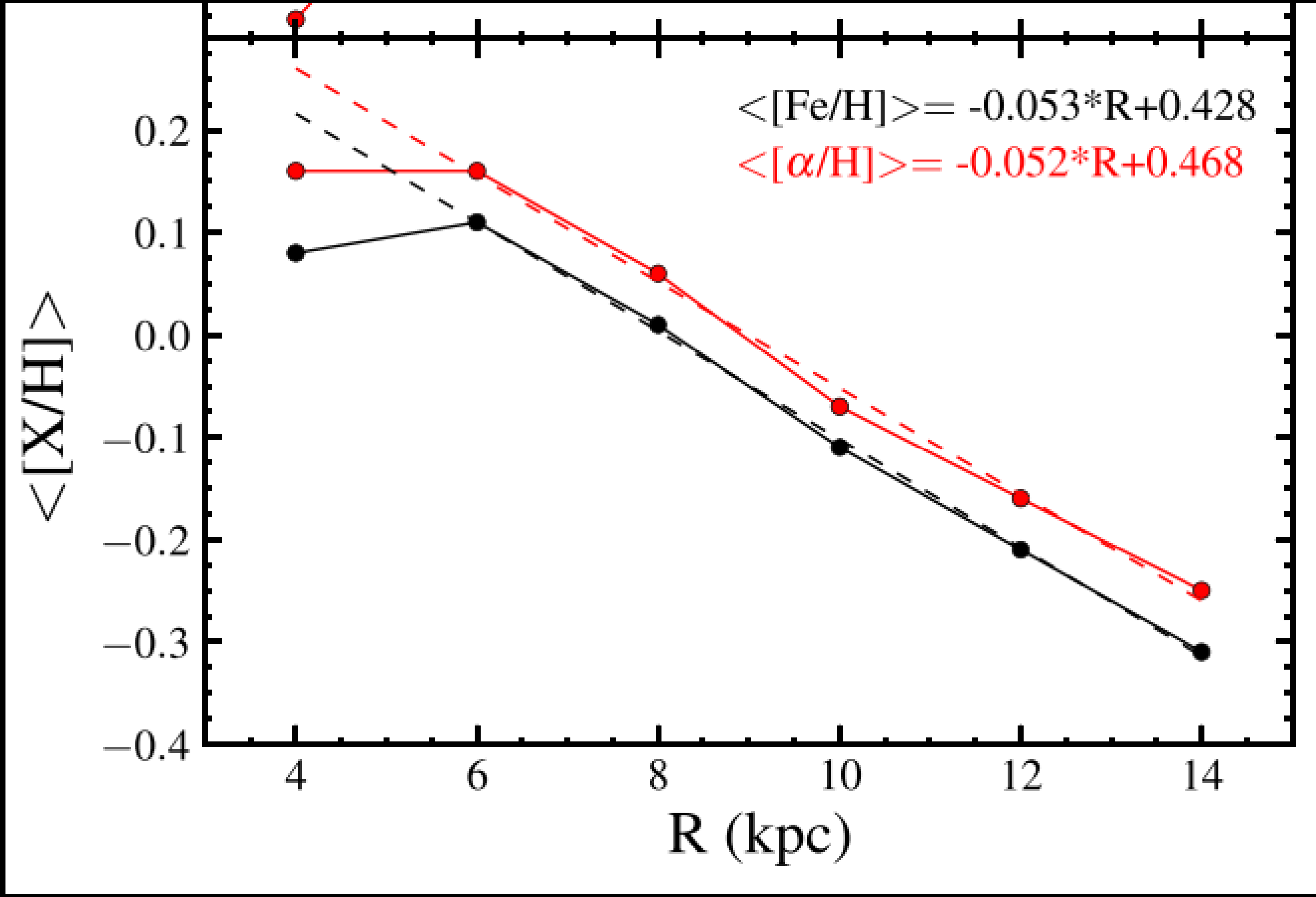
Bulk decline in stellar population and ISM metallicities toward outer disk



Hayden et al. (2015), Figure 5

Radial Metallicity Gradient

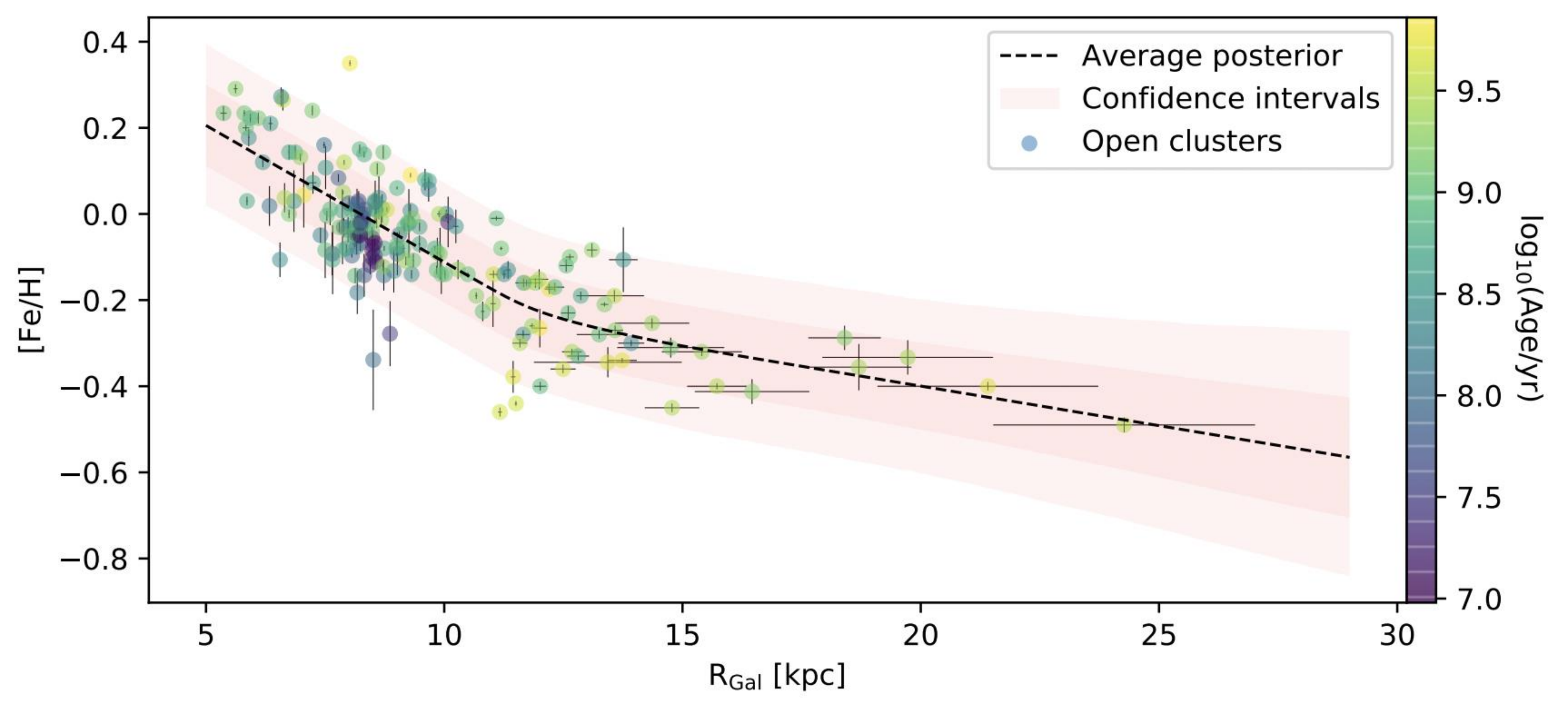
Slope of order -0.05 dex/kpc, some variation



Hayden et al. (2015), Figure 5

Age-Resolved Chemistry

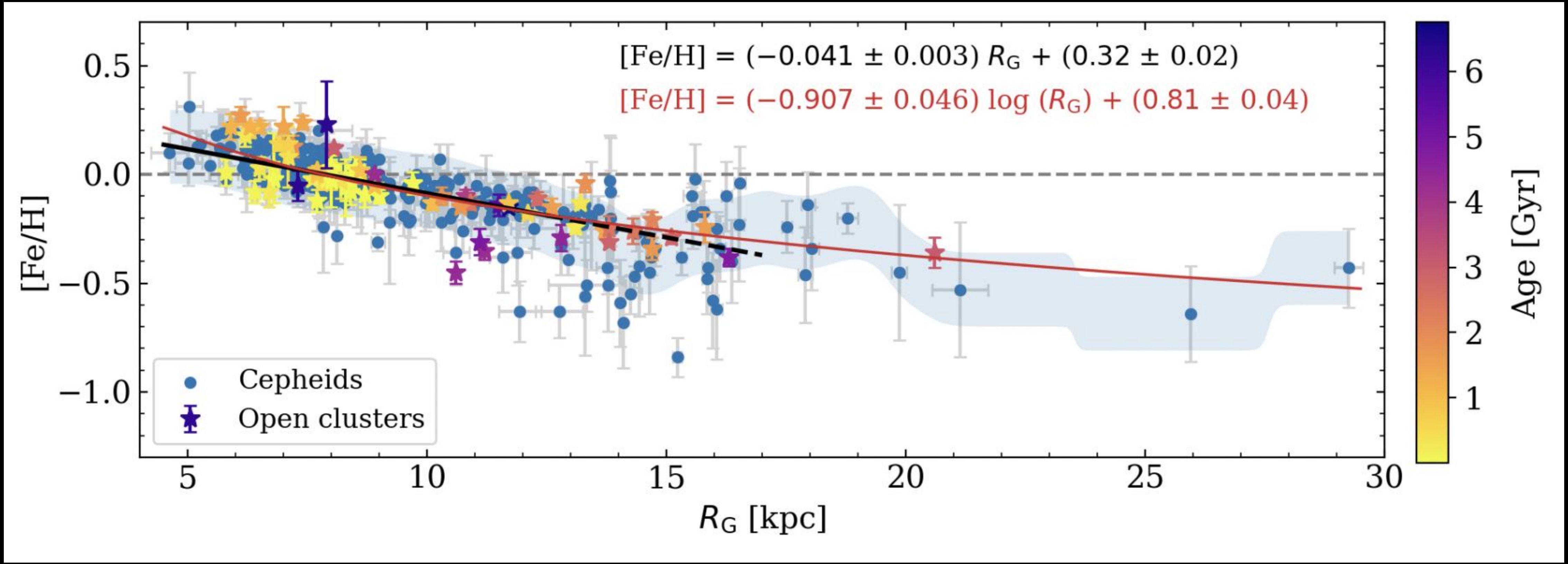
Open Clusters – no clear trend with age



Spina et al. (2022), Figure 2

Age-Resolved Chemistry

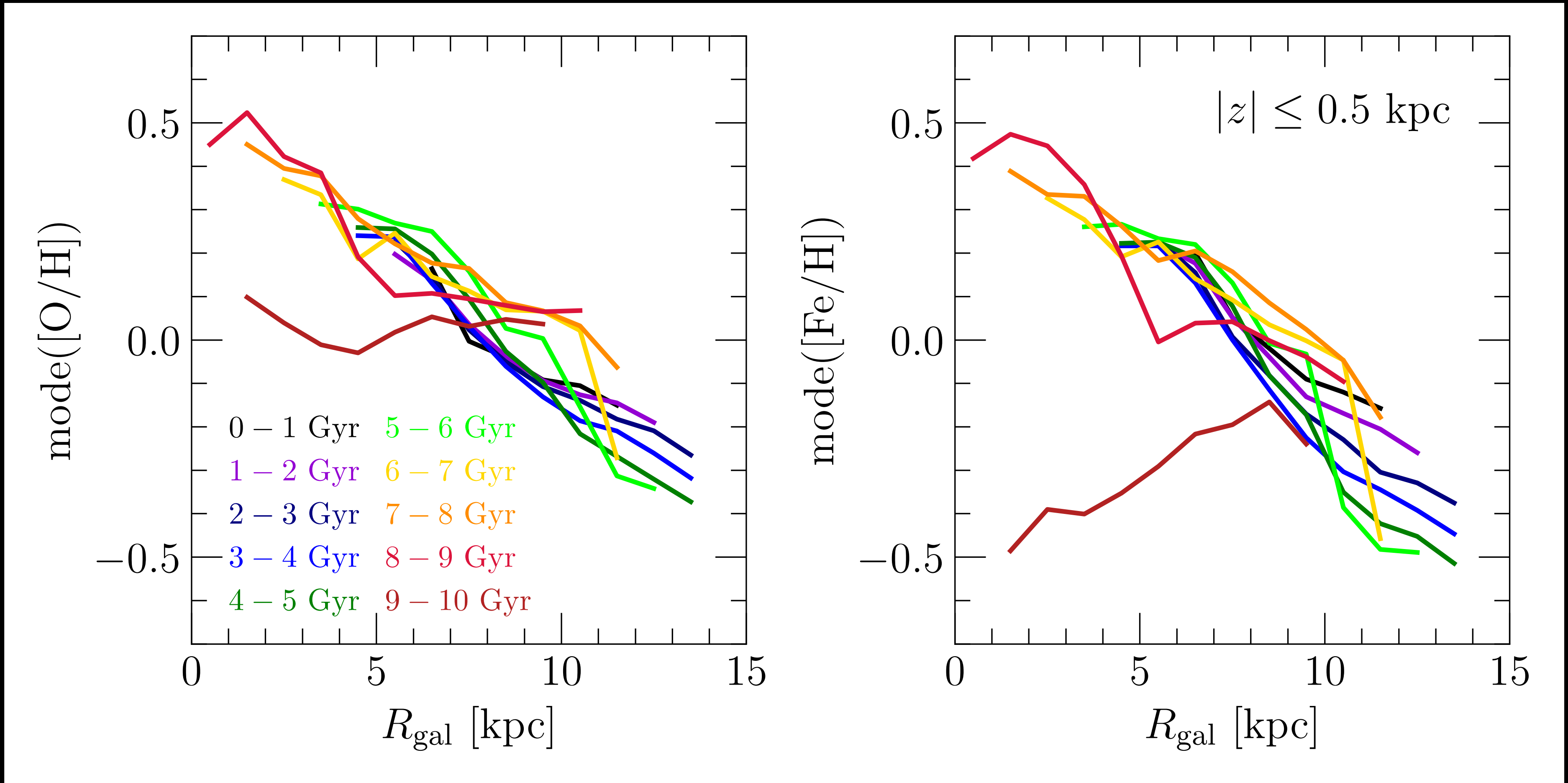
Open Clusters & Classical Cepheids – still no clear trend with age



Da Silva et al. (2023), Figure 2

Age-Resolved Chemistry

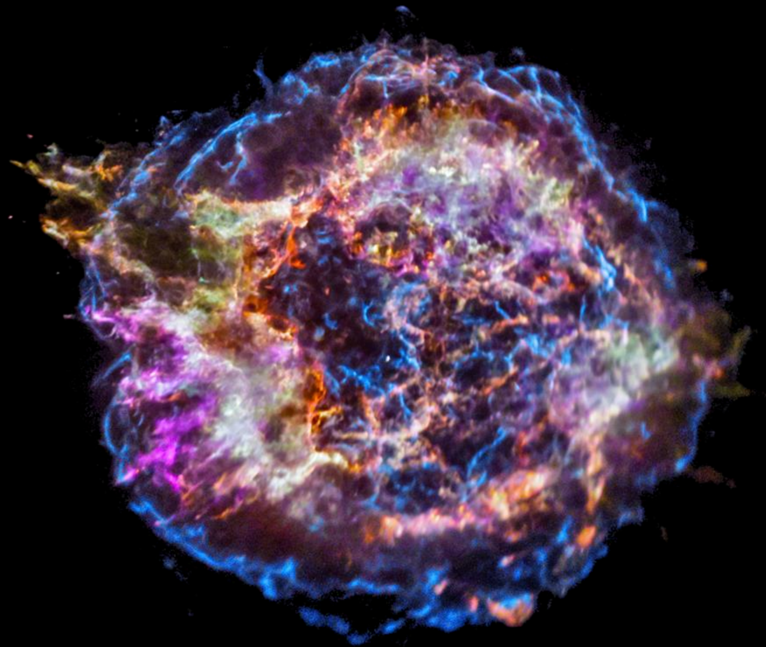
Neural Networks with Asteroseismology of Red Giants in APOGEE

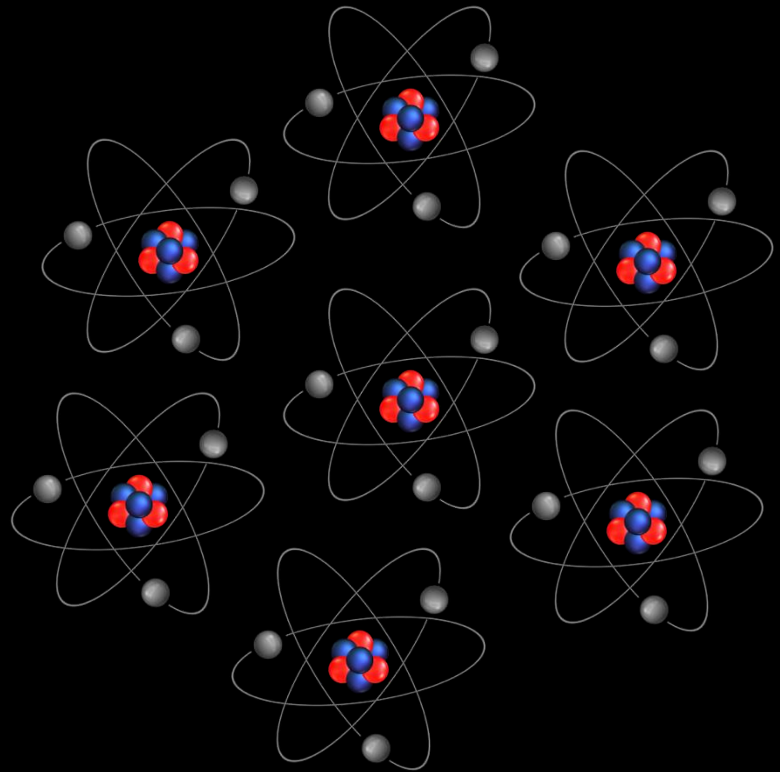


Johnson et al. (2024), Figure 4 (arxiv:2410.13256)

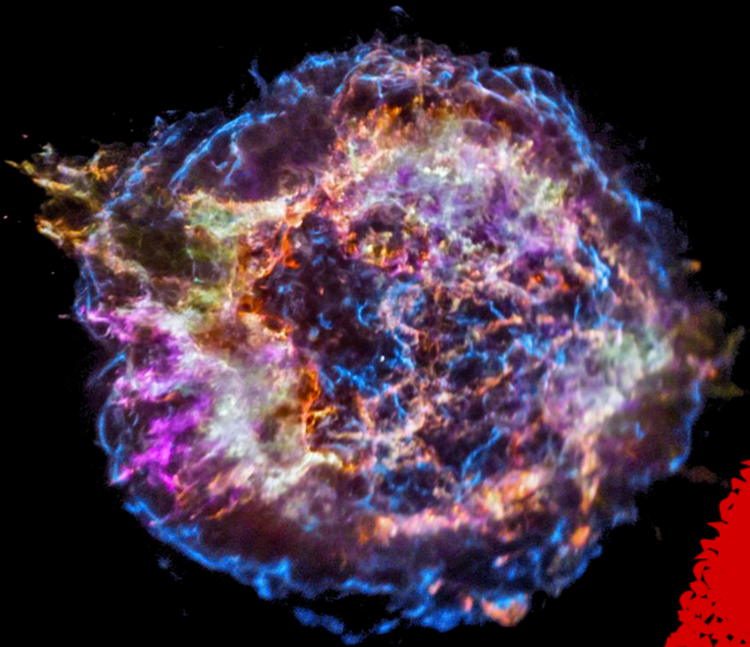
Star Formation & Supernovae

Metallicity Increases





Star Formation Supernovae



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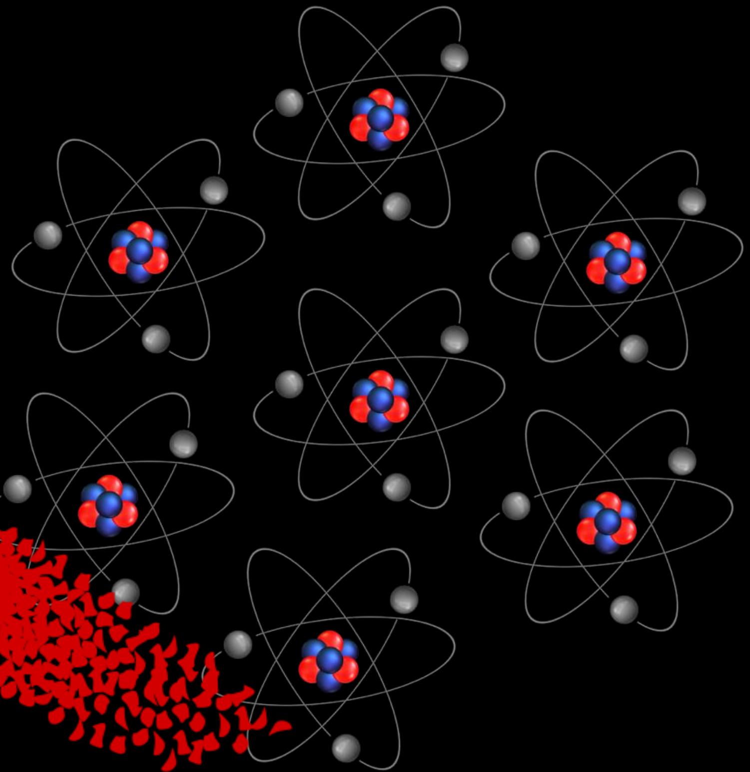
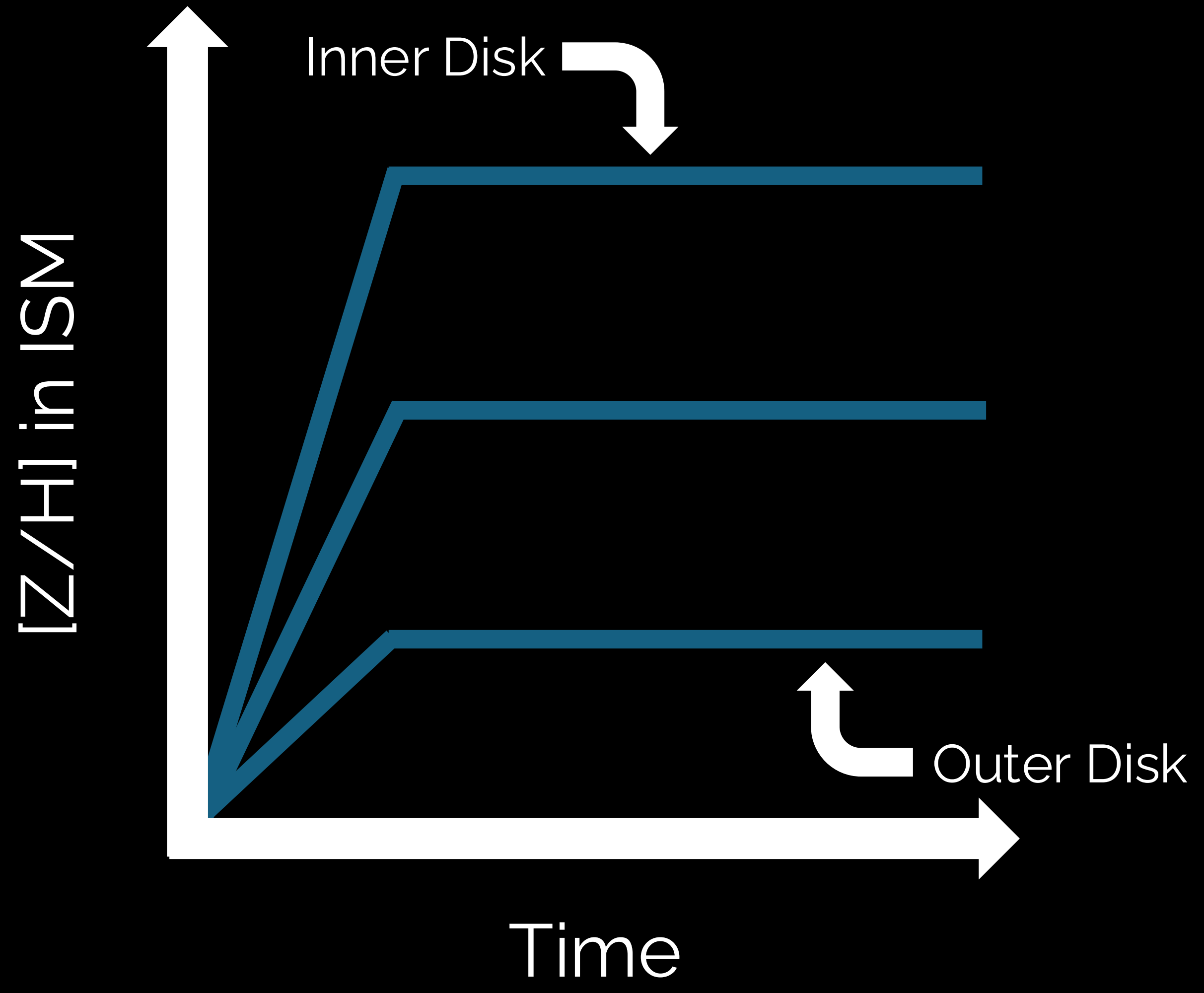


Equilibrium Scenario



$$\dot{Z} = 0 \text{ at } Z = Z_{eq}$$

$$Z_{eq} \propto e^{-R} \Longrightarrow [\mathrm{Z/H}] \propto -R$$

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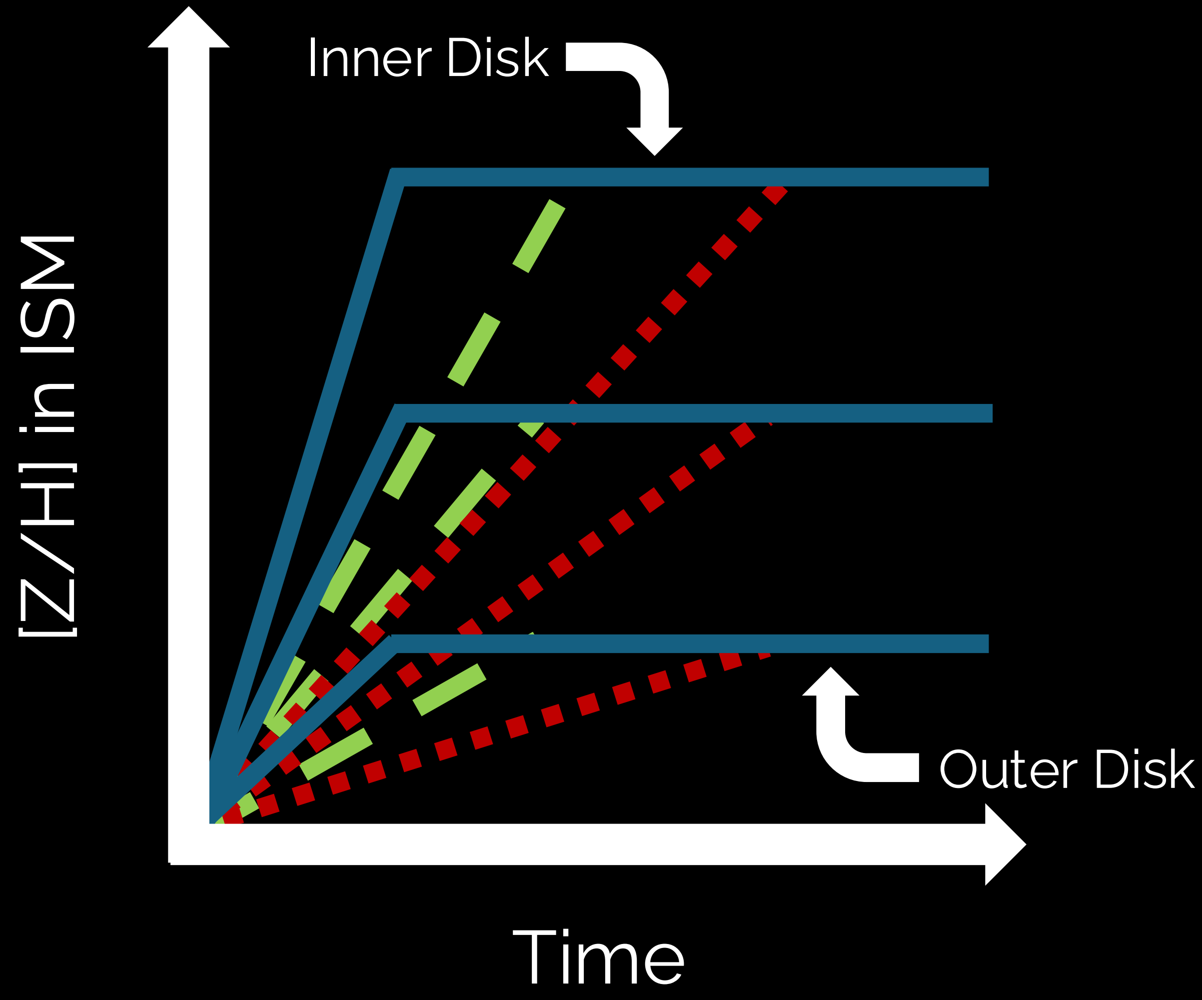

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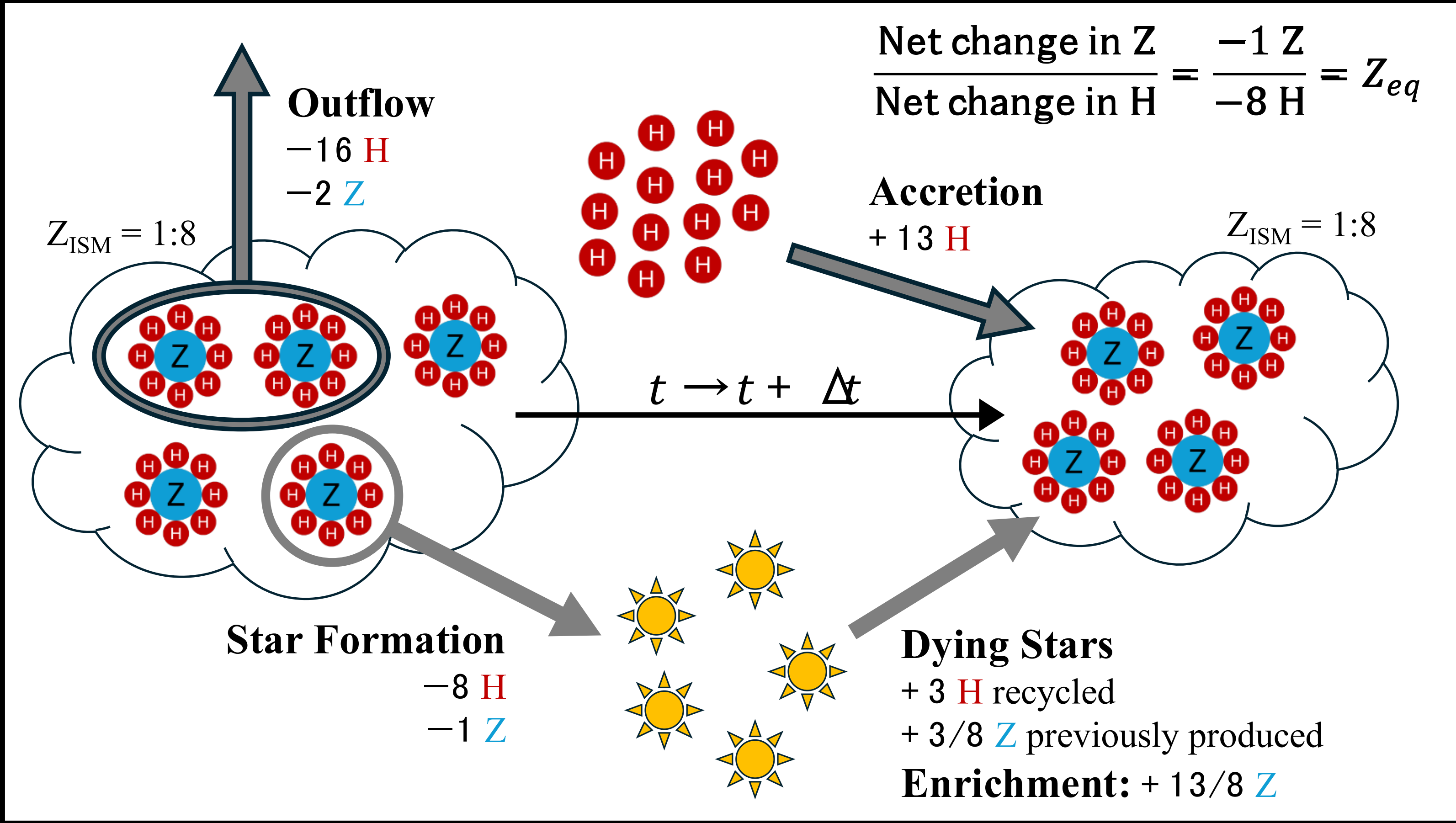
Galactic Chemical Evolution parameters allow control over equilibration timescale

What does chemical equilibrium look like?

Evolutionary processes balance, ISM mixture minimally affected

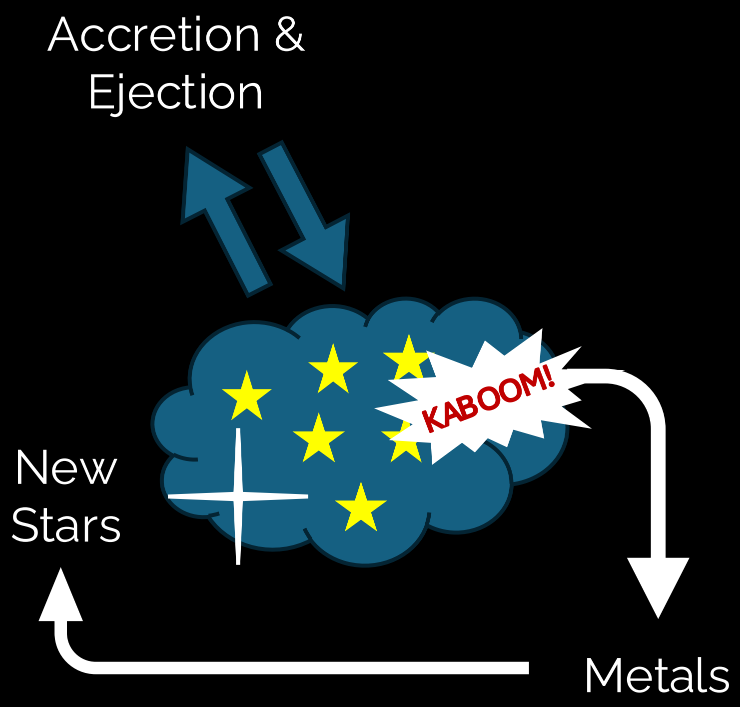


Johnson et al. (2024), Figure 1 (arxiv:2410.13256)

Galactic Chemical Evolution Models

One-Zone

One chemically homogeneous
gas cloud



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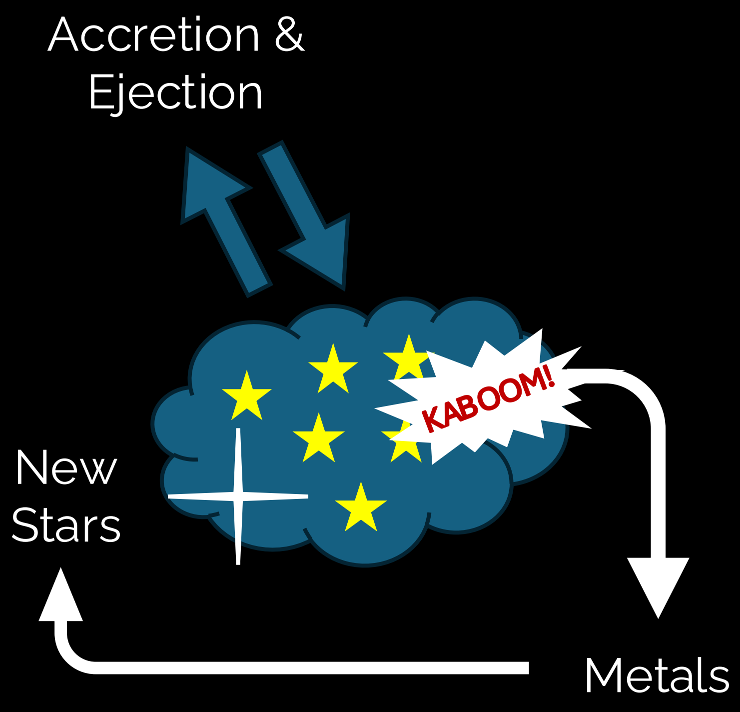
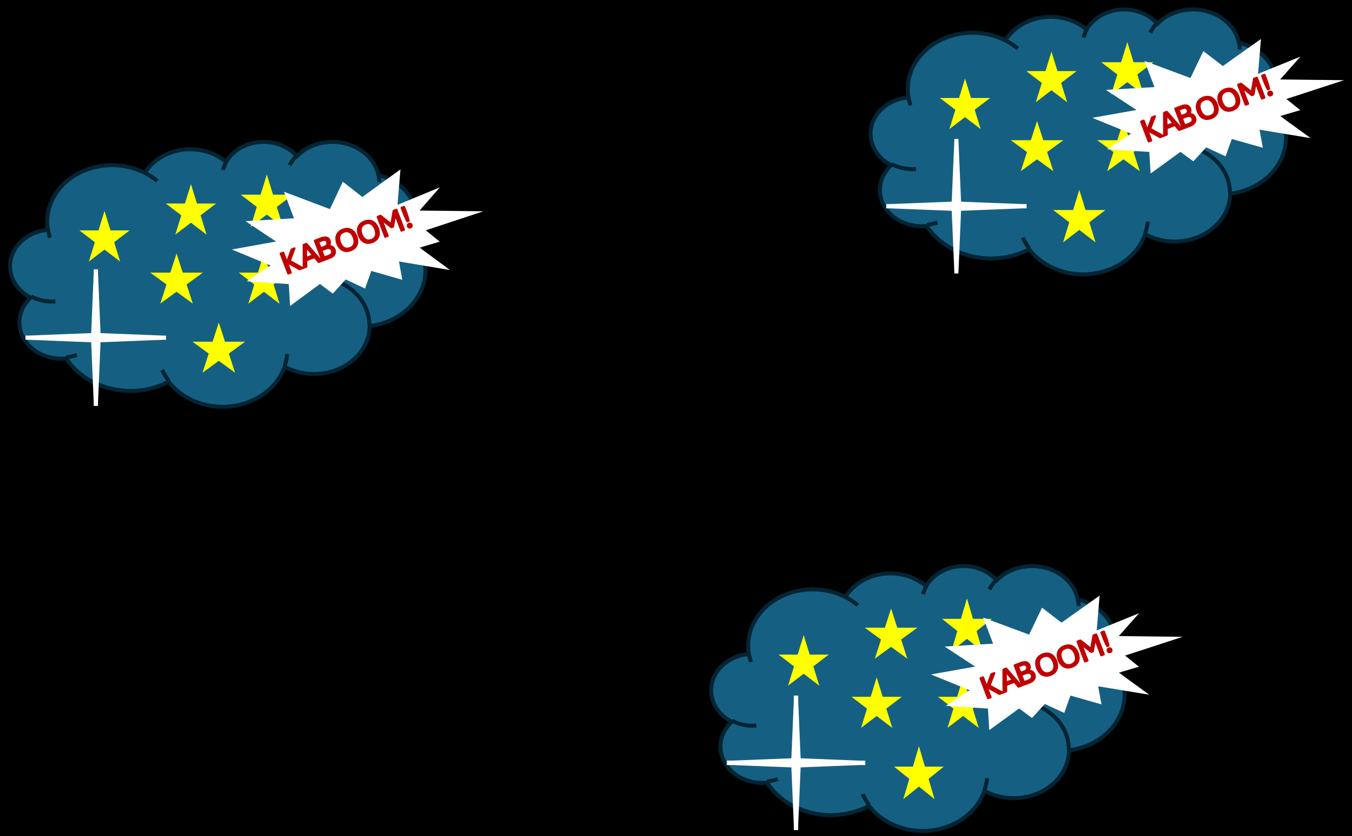


Multi-Zone

Multiple clouds



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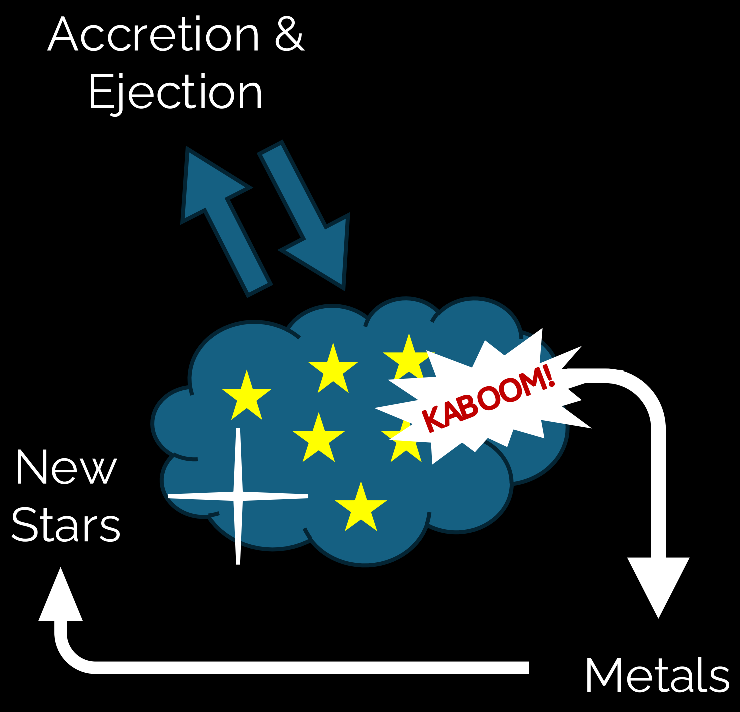

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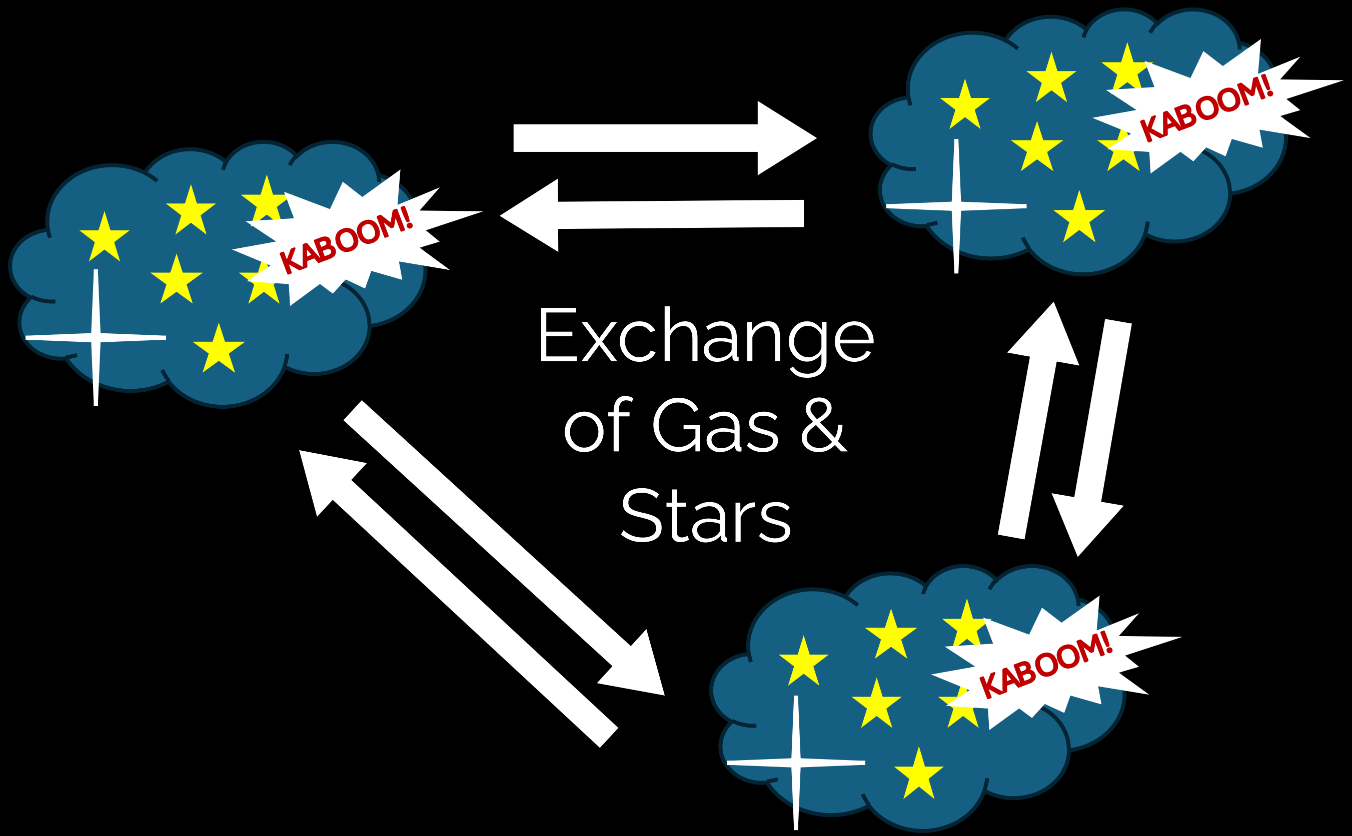


The Milky Way: Each Zone is a Ring

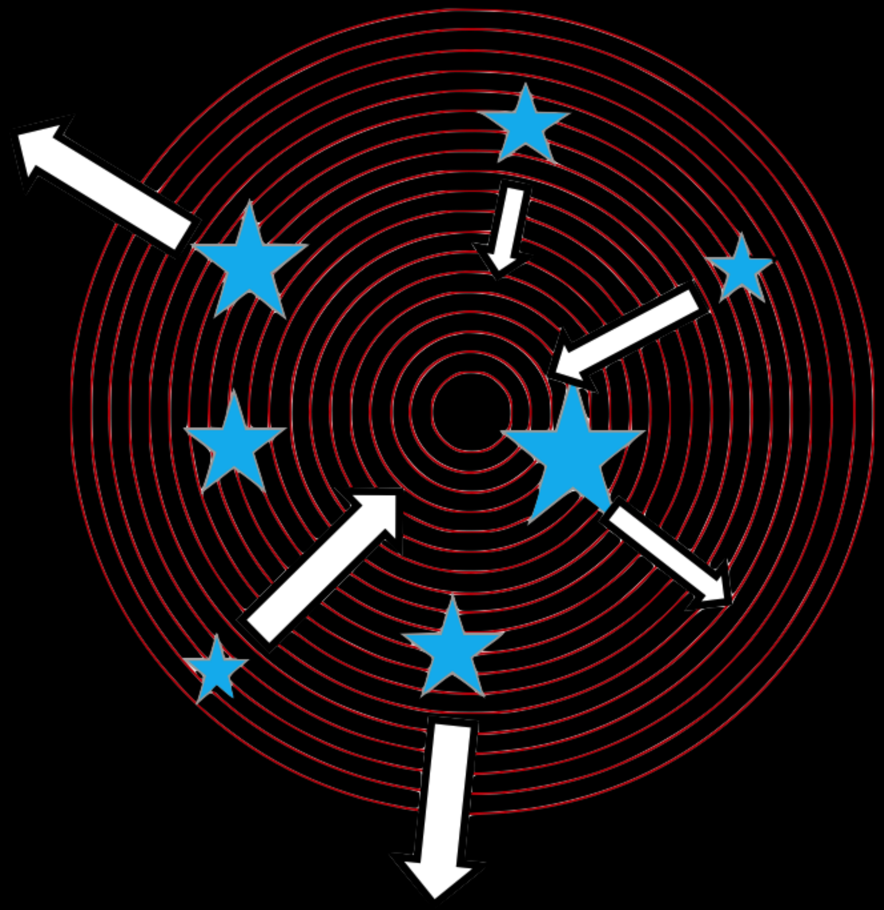
200 zones from R = 0 – 20 kpc

- Schönrich & Binney (2009)
- Minchev et al. (2013, 2014)

Stars move between them in a manner that mimics simulations

- h277 (N-body shop; Christensen et al. 2012)

Johnson et al. (2021, 2023, 2024) – detailed descriptions of the model



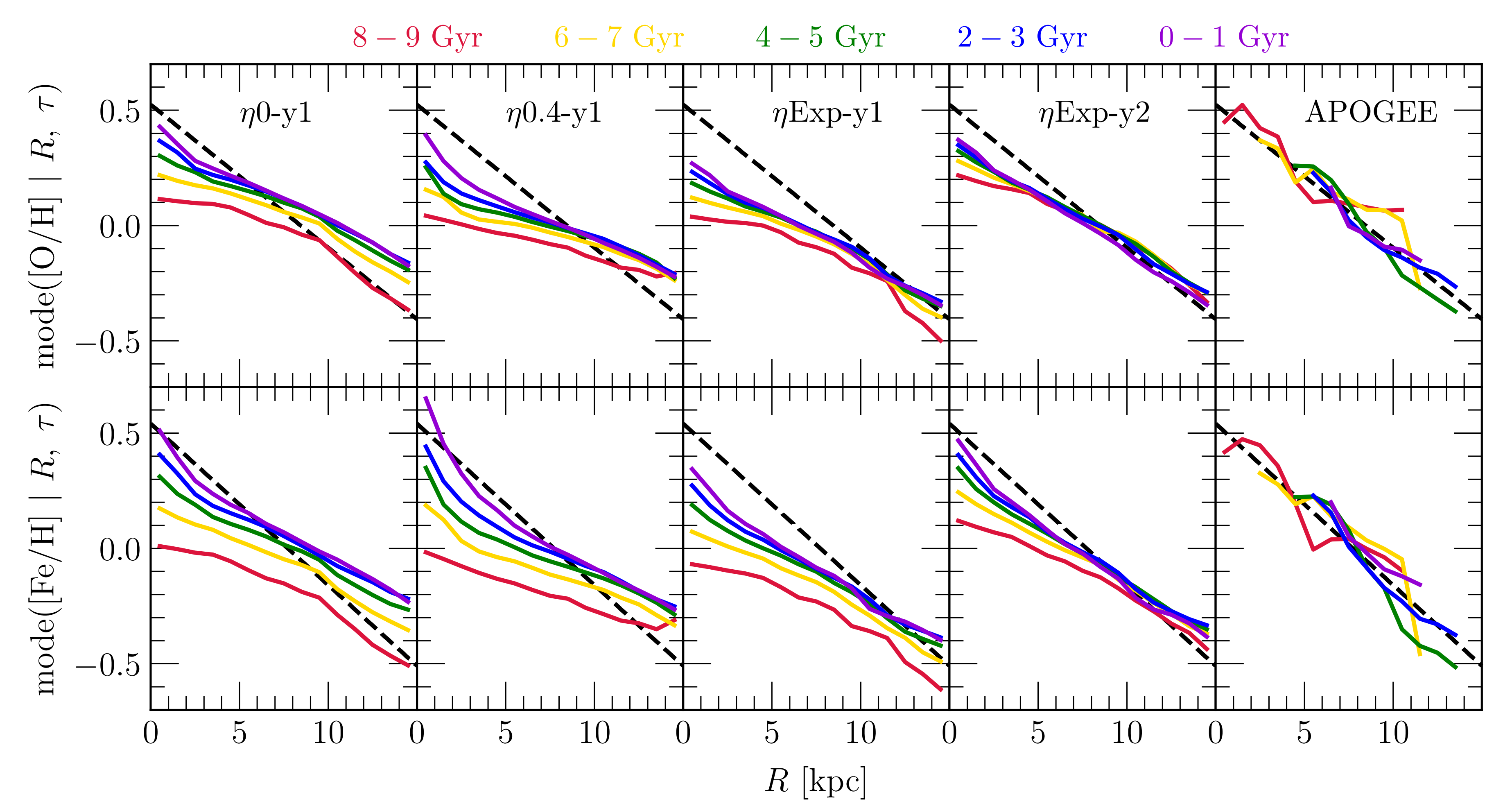
Radially-Dependent Ejection of ISM

Mass loading of outflows traces local gravitational potential, otherwise ad hoc

$$\eta \equiv \dot{\Sigma}_{out} \,/\, \dot{\Sigma}_{\star}$$

Left-to-right:

- $\eta = 0$ everywhere
- $\eta = 0.4$ everywhere
- $\eta \propto e^{R}$
- $\eta \propto e^{R}$ with 2x the yields and outflows
- Data



Johnson et al. (2024), Figure 4 (arxiv:2410.13256)

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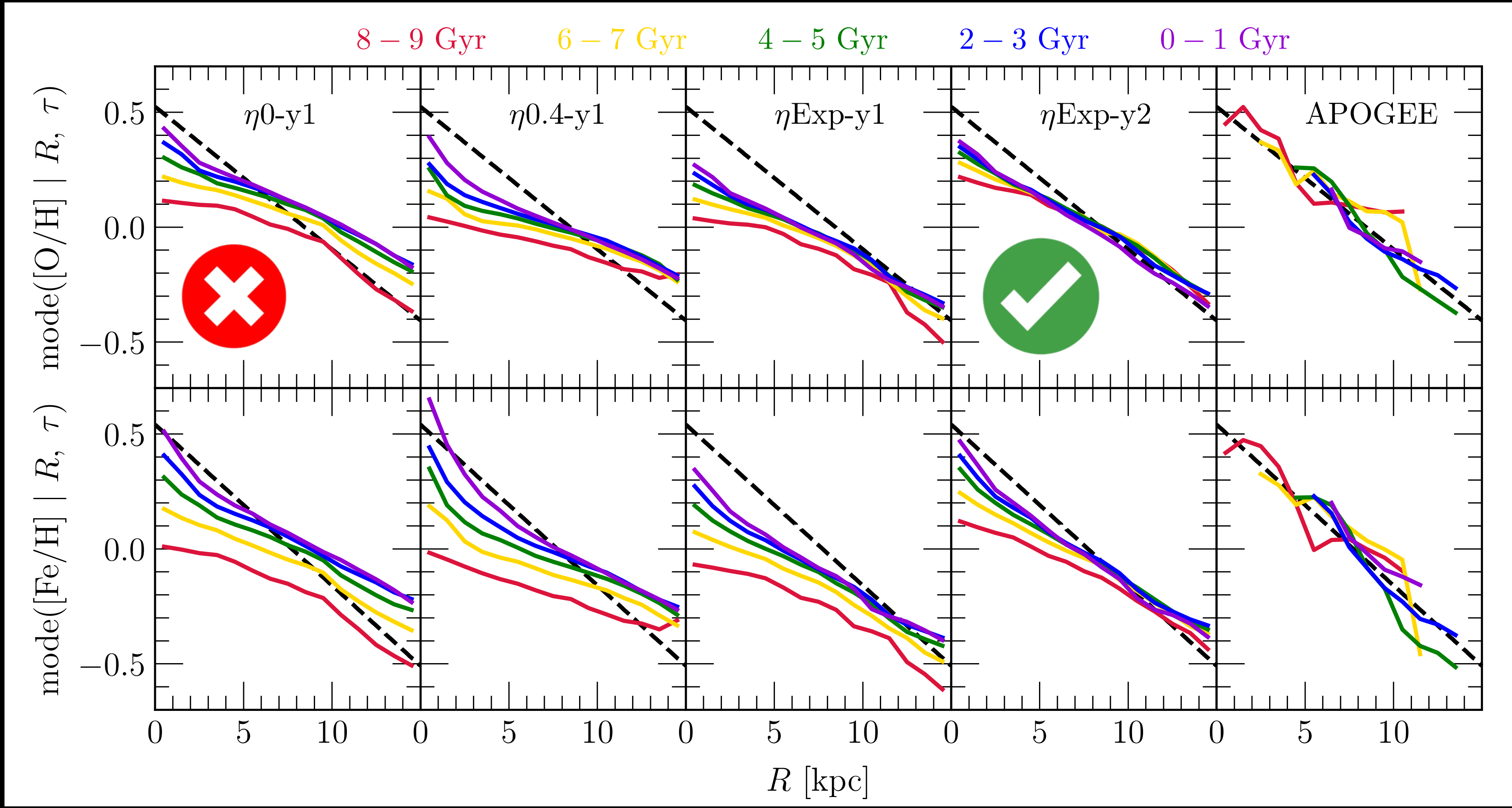


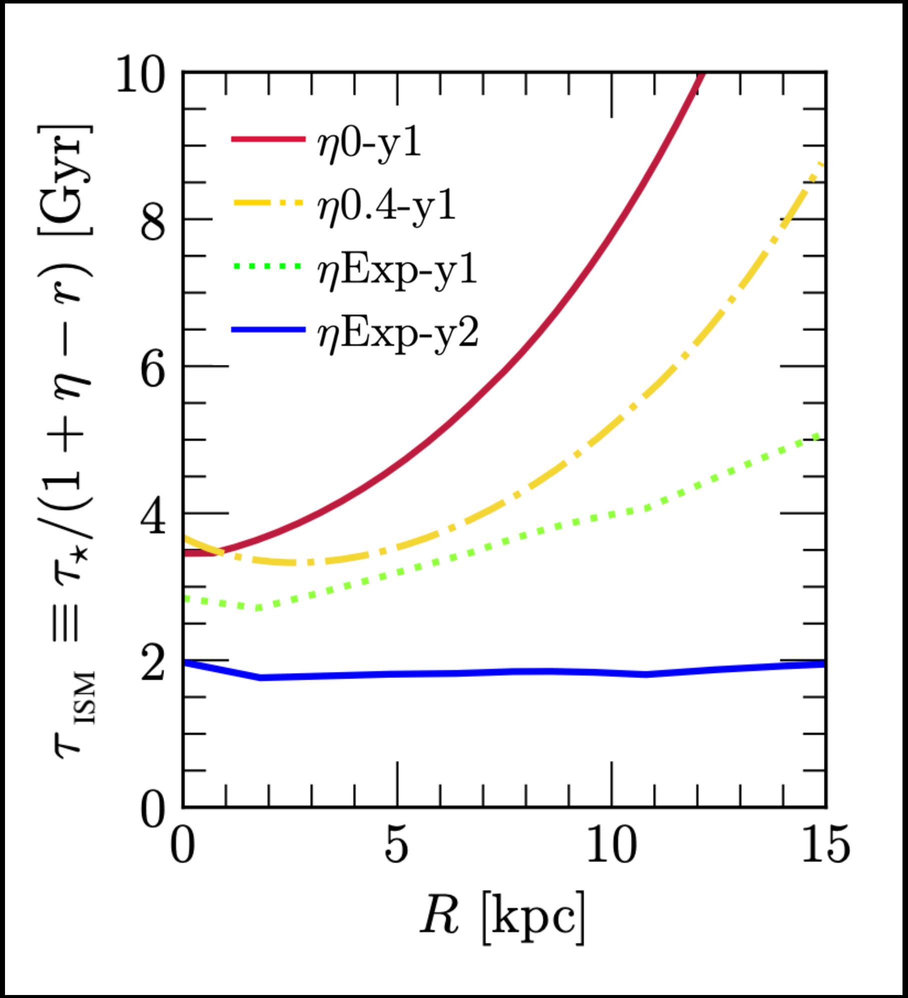
Johnson et al. (2024), Figure 4 (arxiv:2410.13256)

Why Do Outflows Work?

Lower the average time one baryon spends in one region of the ISM

$$\tau_{ISM} = \frac{\Sigma_g}{\dot{\Sigma}_\star + \dot{\Sigma}_{out} - \dot{\Sigma}_r}$$

$$Z_{ISM} \approx Z_{eq}(1 - e^{-t/\tau_{ISM}})$$

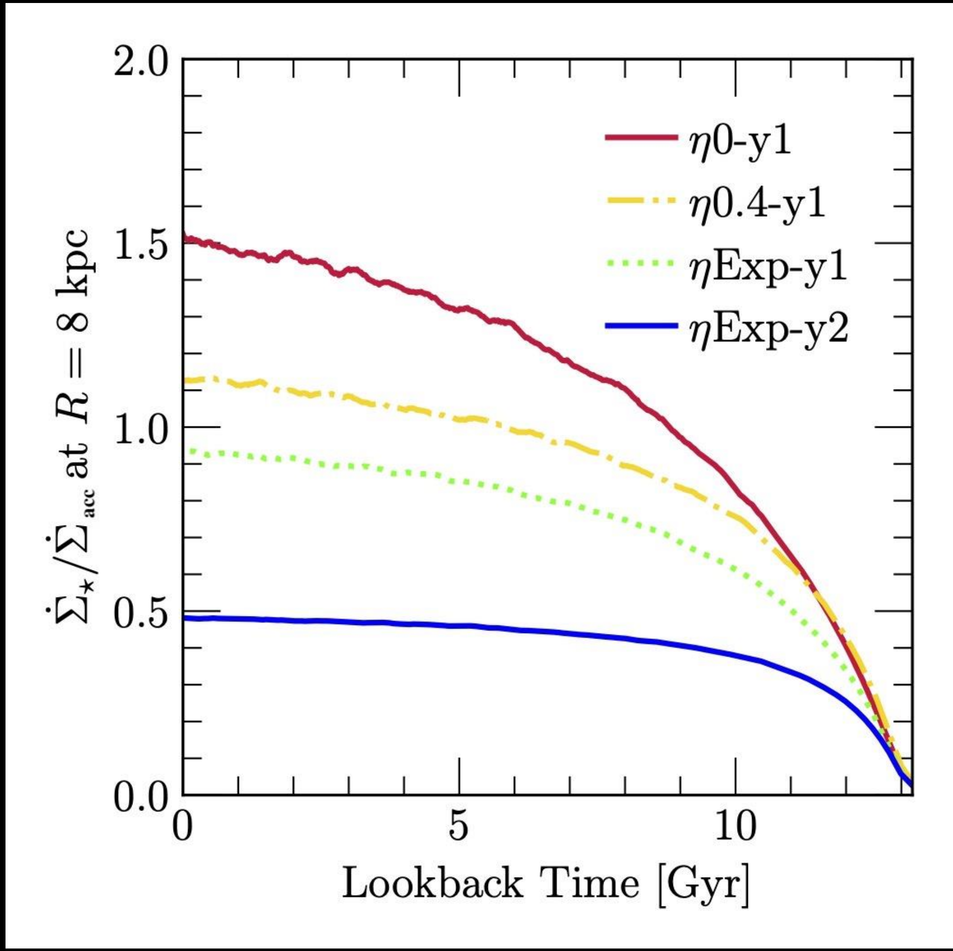


Johnson et al. (2024), Figure 10 (arxiv:2410.13256)

Why Do Outflows Work?

Lower the average time one baryon spends in one region of the ISM

$$\frac{\dot{\Sigma}_\star}{\dot{\Sigma}_{acc}} \to \text{Constant}$$



Johnson et al. (2024), Figure 11 (arxiv:2410.13256)

Why Do Outflows Work?

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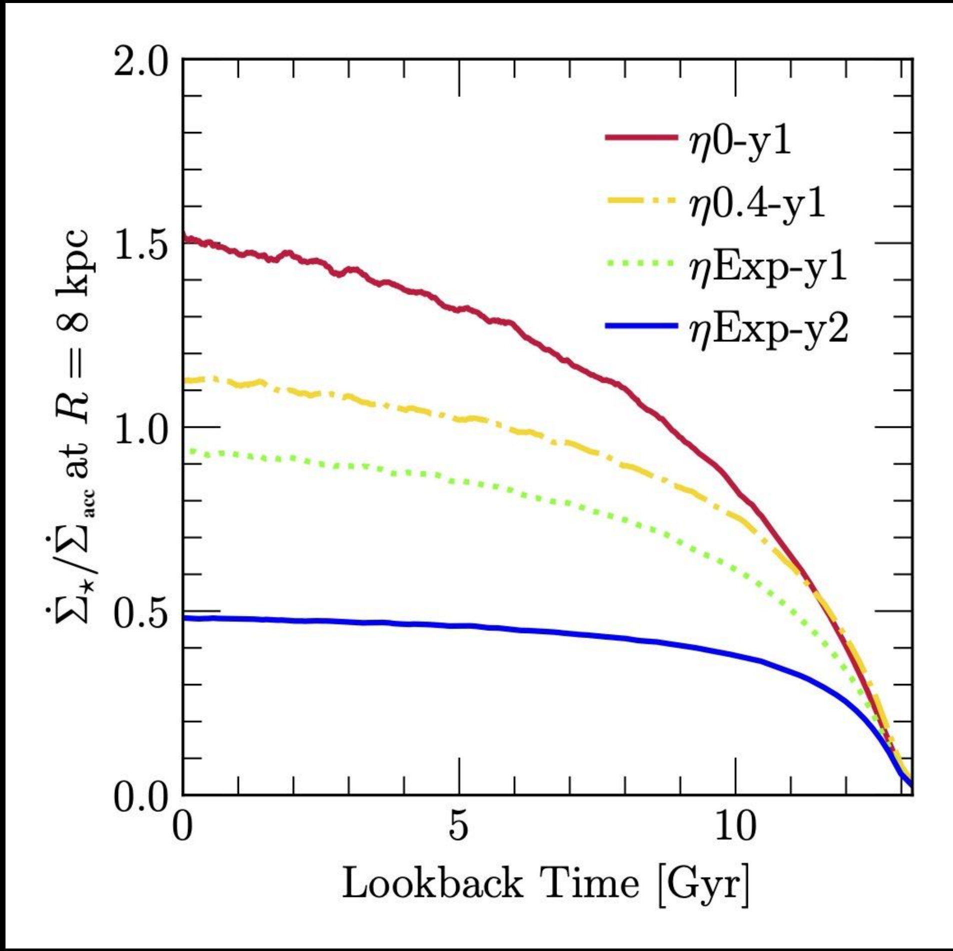
$$\frac{\dot{\Sigma}_\star}{\dot{\Sigma}_{acc}} \rightarrow \text{Constant}$$

$\dot{\Sigma}_Z$

$\dot{\Sigma}_H$



Johnson et al. (2024), Figure 11 (arxiv:2410.13256)

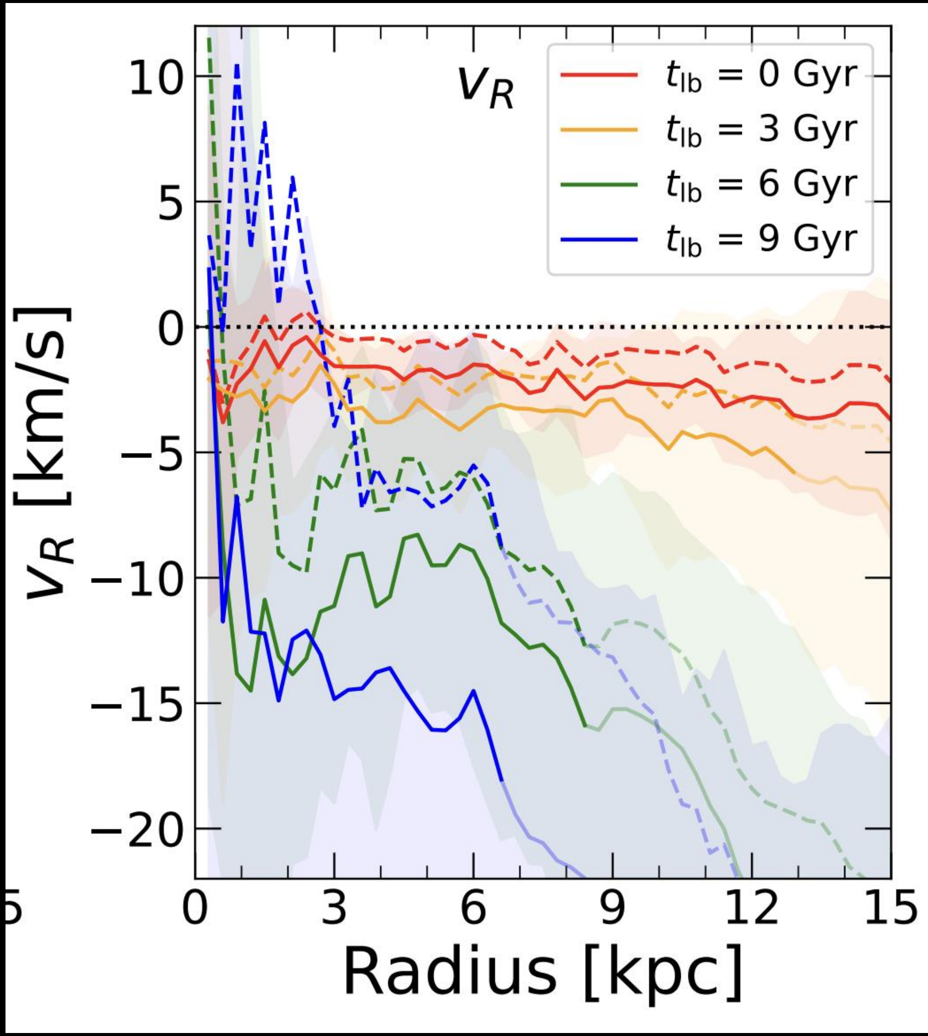
Outflows: Only One Possible Origin

Potential alternative: radial gas flows

- Predicted by galaxy formation models
- Arise in simulations
- Thought to be directed inward
- Only weak observational constraints
  - < 5-ish km/s at $z \sim 0$ (Di Teodoro & Peek 2021)

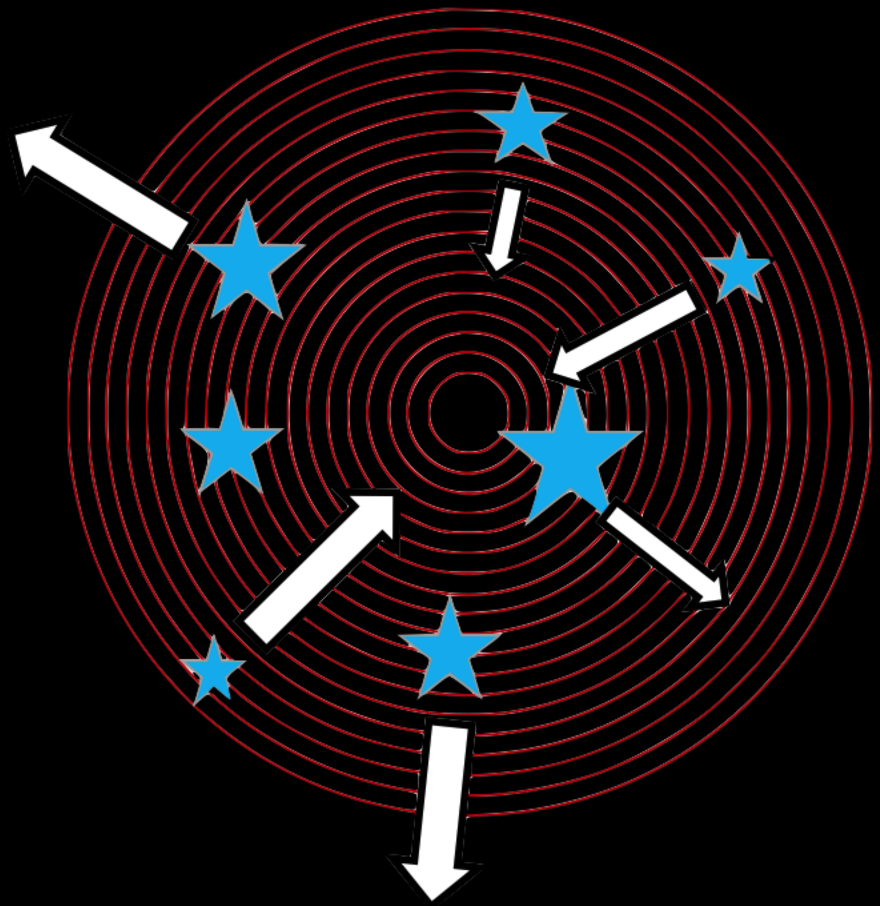
Switch from $\eta = 0$ to $v_r < 0$

- Future work: combining the two



Graf et al. (2024), Figure 7 (arxiv:2410.21377)

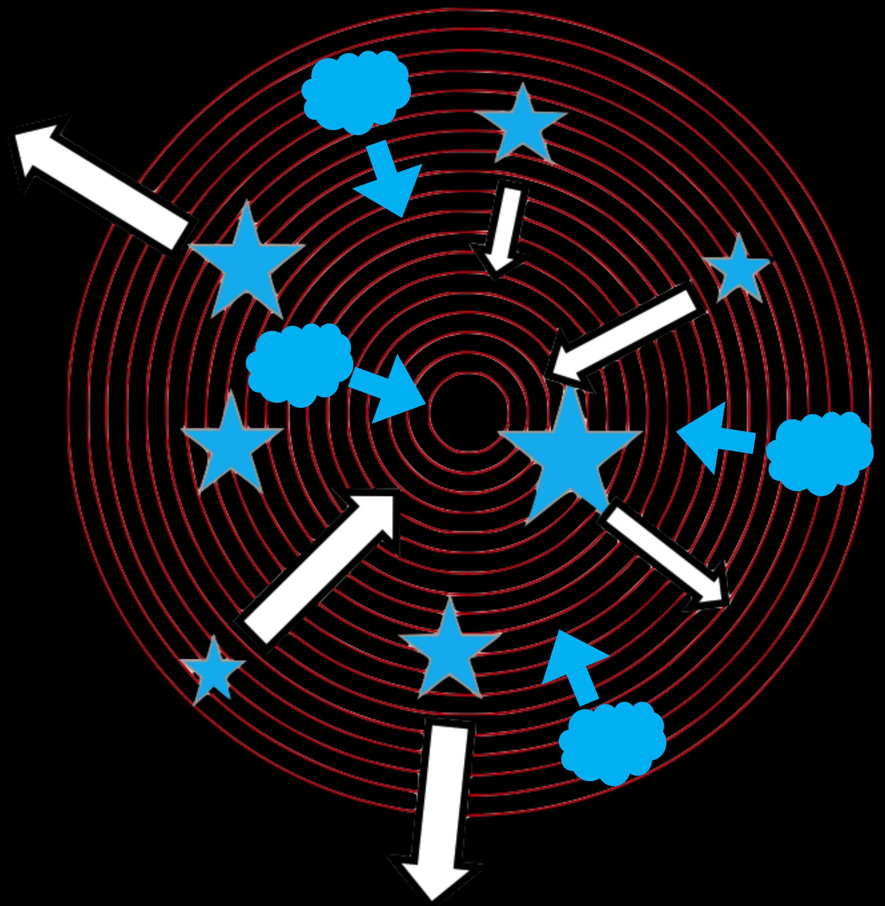
Radial Gas Flows



Exchange gas between neighboring zones at each timestep

JW Johnson et al., in prep.

Radial Gas Flows



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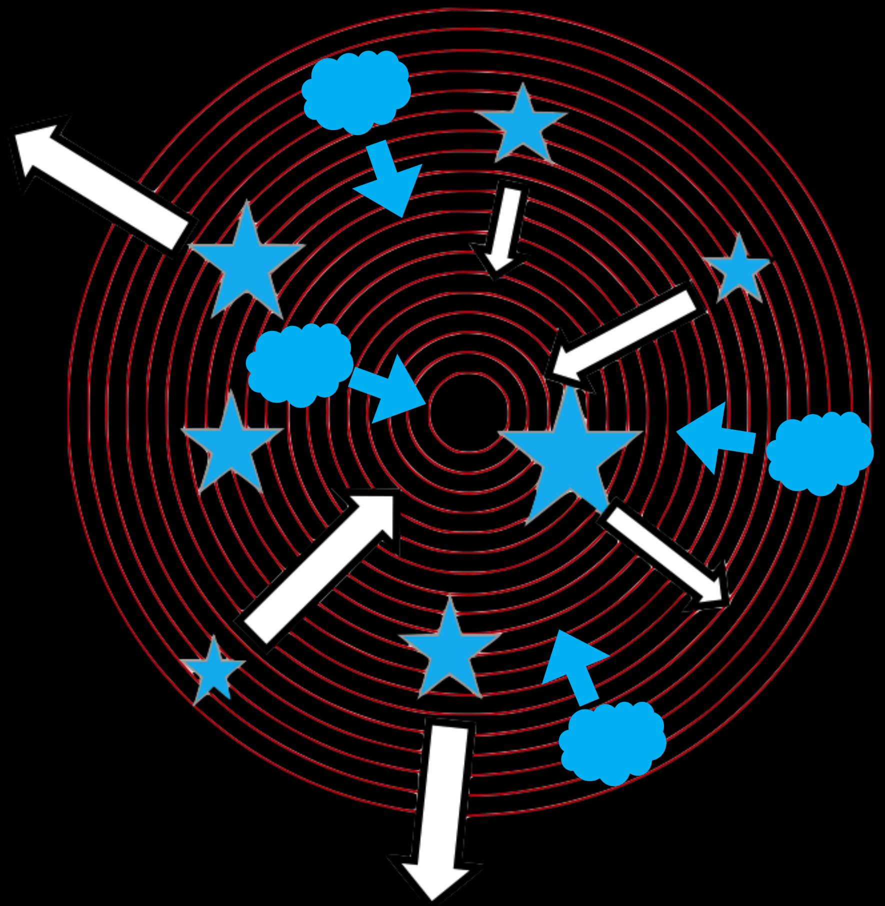

Exchange gas between neighboring zones at each timestep

This work: analytic solutions to ∇_{ISM}

JW Johnson et al., in prep.

Various Radial Flow Scenarios

$$v_r = -R\left[\frac{\dot{v}_{\phi,g}}{v_{\phi,g}} + \frac{\dot{\Sigma}_{acc}}{\Sigma_g}\left(1 - \beta_{\phi,acc}\right) - \frac{\dot{L}_{dyn}}{L}\right]$$

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Potential Well Deepening

Circular velocity grows due to growth of disk & halo

$$\frac{\dot{v}_{\phi,g}}{v_{\phi,g}} = -\gamma\frac{\partial \ln M_\star}{\partial t}$$

$$\gamma = 0.2$$

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Angular Momentum Dilution

Accreting material has low angular momentum relative to the ISM

$$\beta_{\phi,acc} \equiv \frac{v_{\phi,acc}}{v_{\phi,g}}$$

$$\beta_{\phi,acc} = 0.7$$

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$$\beta_{\phi,acc} \equiv \frac{v_{\phi,acc}}{v_{\phi,g}}$$

$$\beta_{\phi,acc} = 0.7$$

Constant

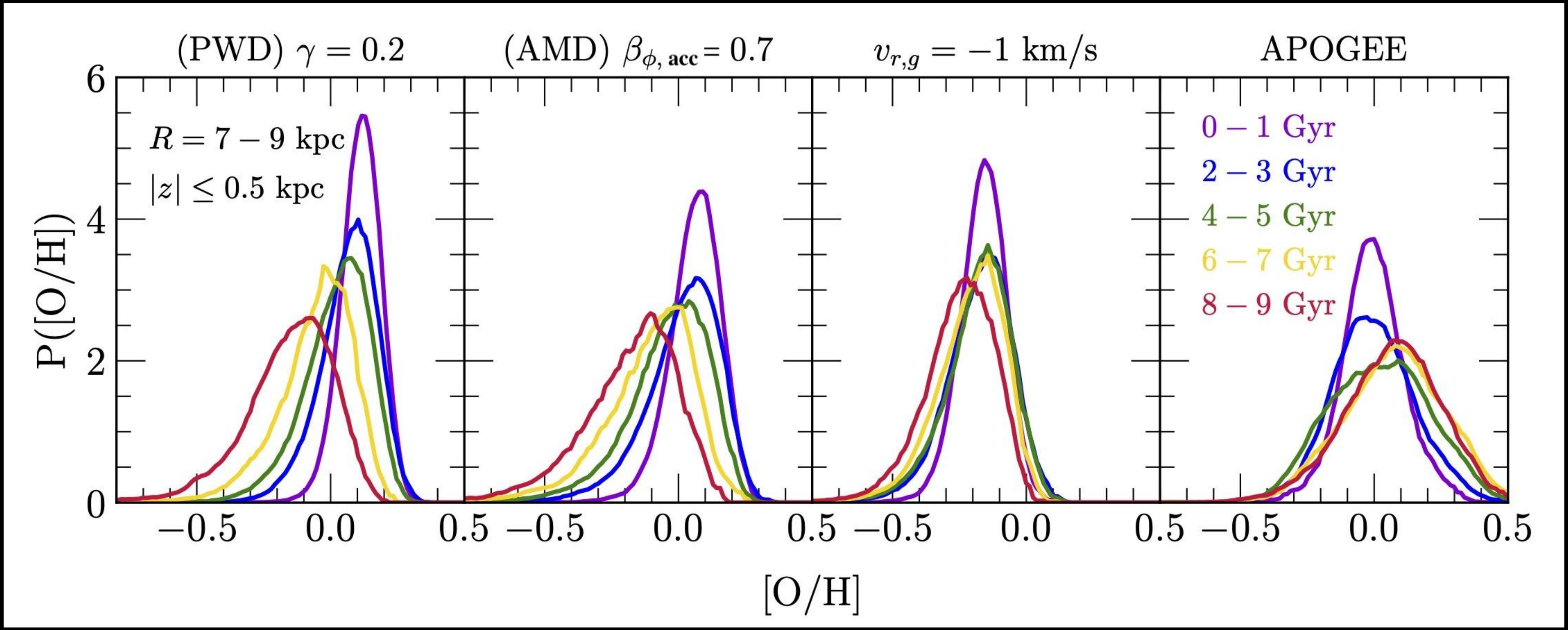
Useful for interpretation but ad hoc

$$\frac{\dot{L}_{dyn}}{L} \sim -\frac{1}{R}$$

$$v_r \approx -1 \text{ km/s}$$

Chemical Equilibrium with Radial Gas Flows

Constant velocity compatible, PWD & AMD incompatible



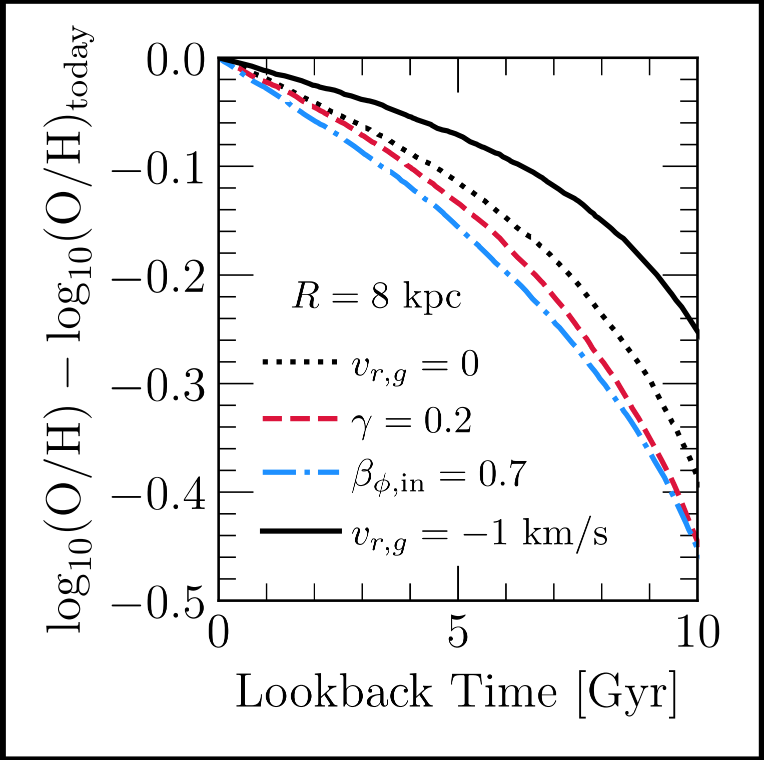
JW Johnson et al., in prep.

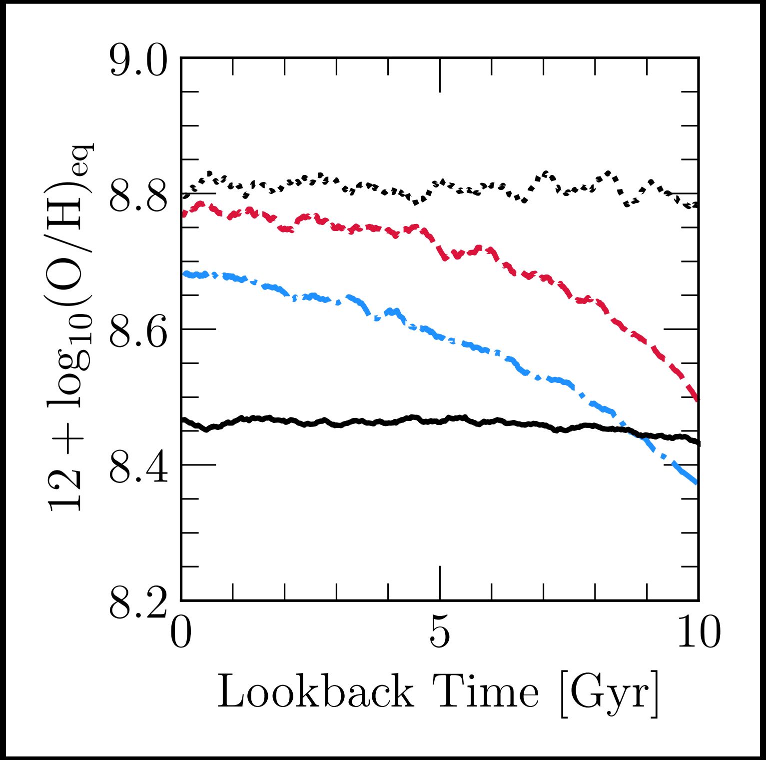
Requirements for Equilibrium Scenario

PWD & AMD → *sources* of gas as opposed to *sinks*

Exacerbate the problems with time-evolving metal abundances

Velocities evolve with time ⇒ $Z_{\alpha,eq}$ evolves with time



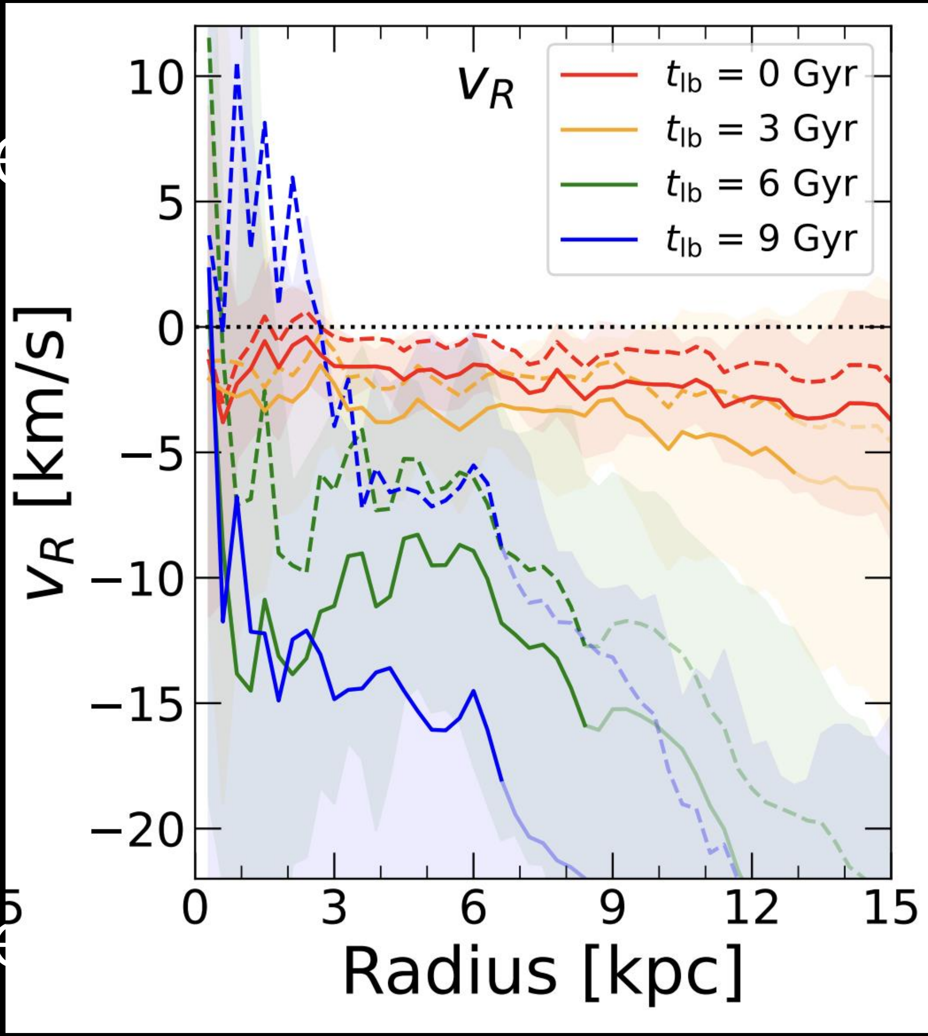


JW Johnson et al., in prep.

Requirements for Equilibrium Scenario

Relatively flat velocity profile

- Source versus sink
- $\frac{\partial \ln v_r}{\partial R} \ll \frac{-\partial \ln \Sigma_g}{\partial R}$



Nearly constant in time

- $Z_{\alpha,eq}$ can't be a moving targe

Graf et al. (2024), Figure 7 (arxiv:2410.21377)

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Nearly constant in time

- $Z_{\alpha,eq}$ can't be a moving target

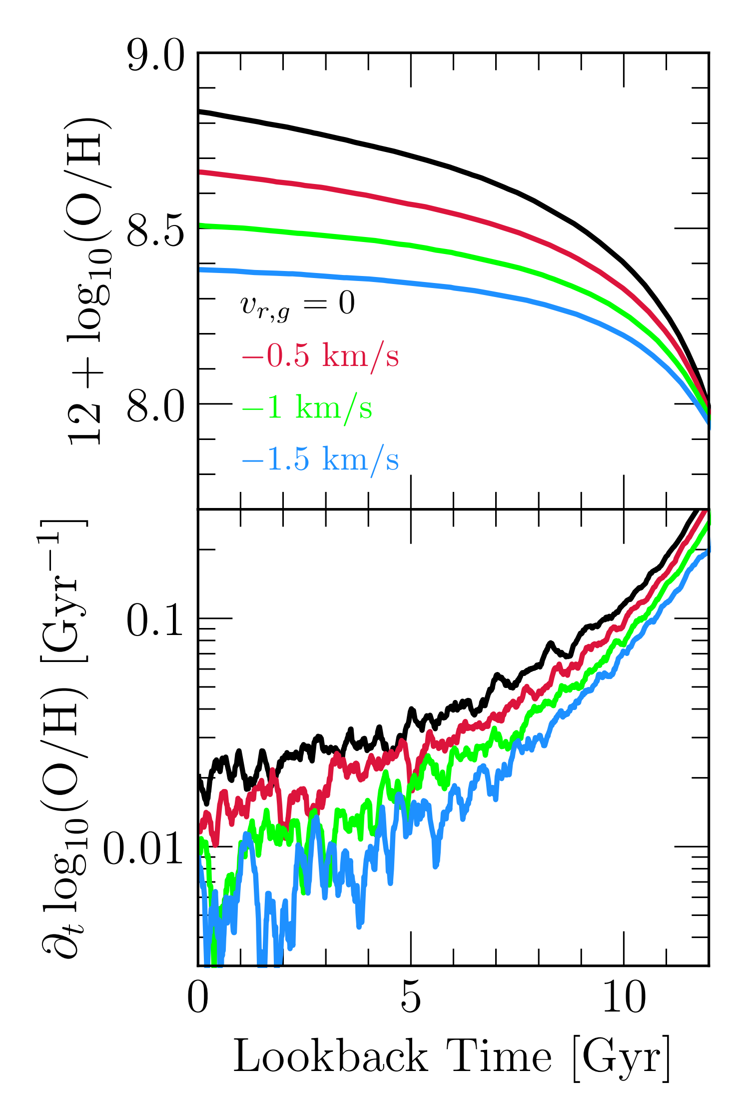
$$Z_\alpha(R) \rightarrow Z_{\alpha,eq}(R)$$

$$Z_{\alpha,eq} \sim e^{-R}$$

Inward Flows are Strongly Diluting

Local ISM material lost to flow, replaced by more metal-poor gas from larger radii

With other parameters held fixed, a ~1 km/s radial gas flow removes ***half*** of the O from the solar neighborhood



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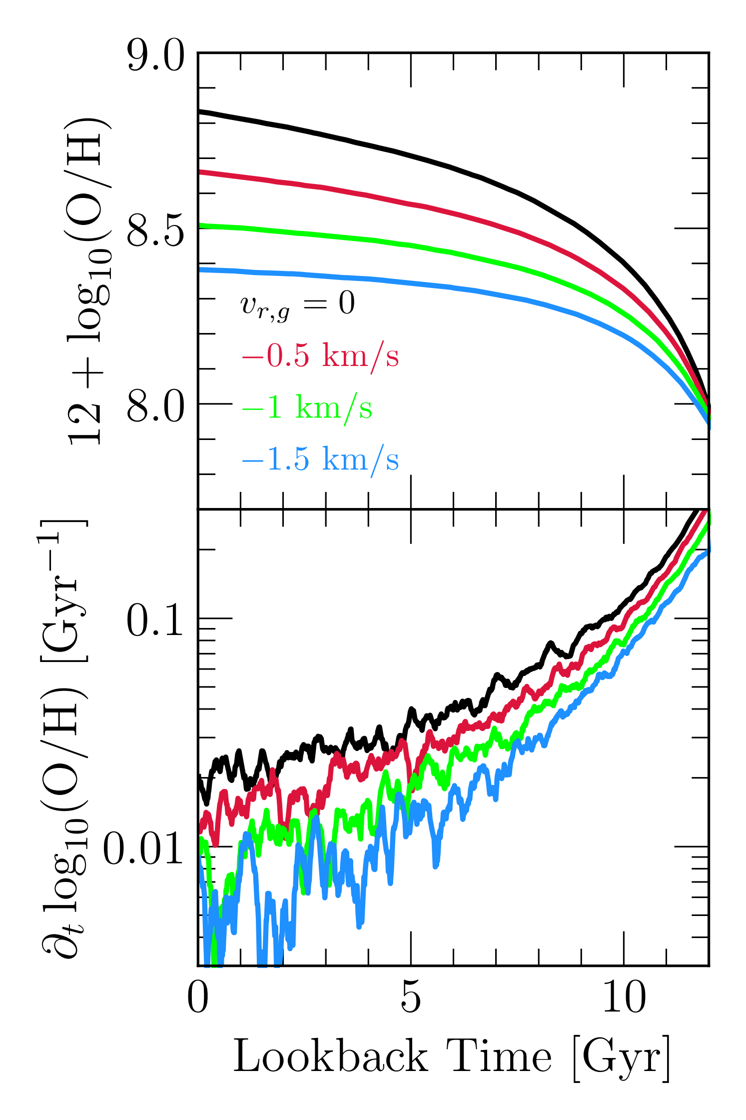
Order of Magnitude:

- 1 km/s ≈ 1 kpc/Gyr
- Flow traverses the entire disk within the age of the Universe



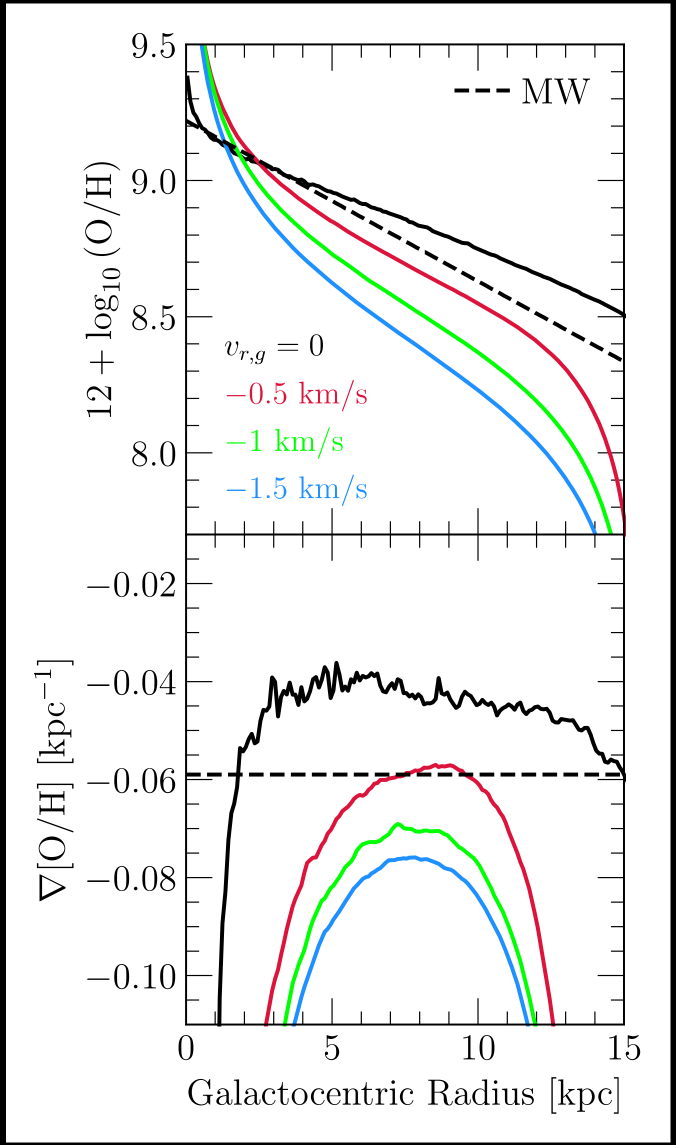
JW Johnson et al., in prep.

Inward Flows are Strongly Diluting

Dilution seen across the entire disk

- Highly metal-rich Galactic center only within $R \approx$ few kpc

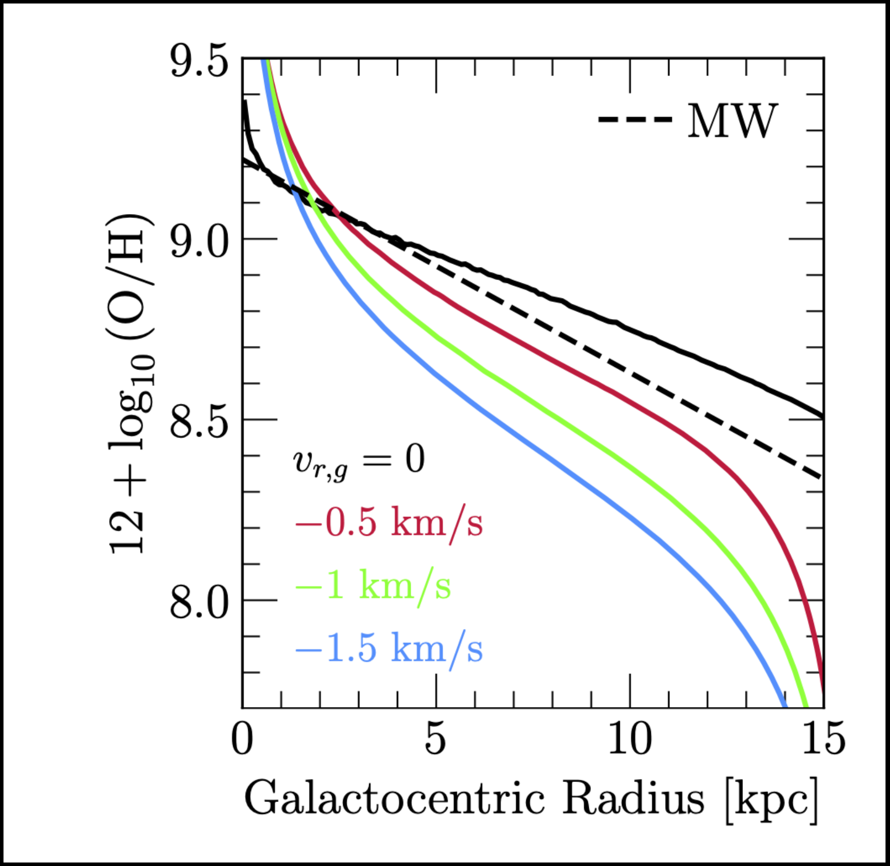
Gradient steepens with increasing flow speed

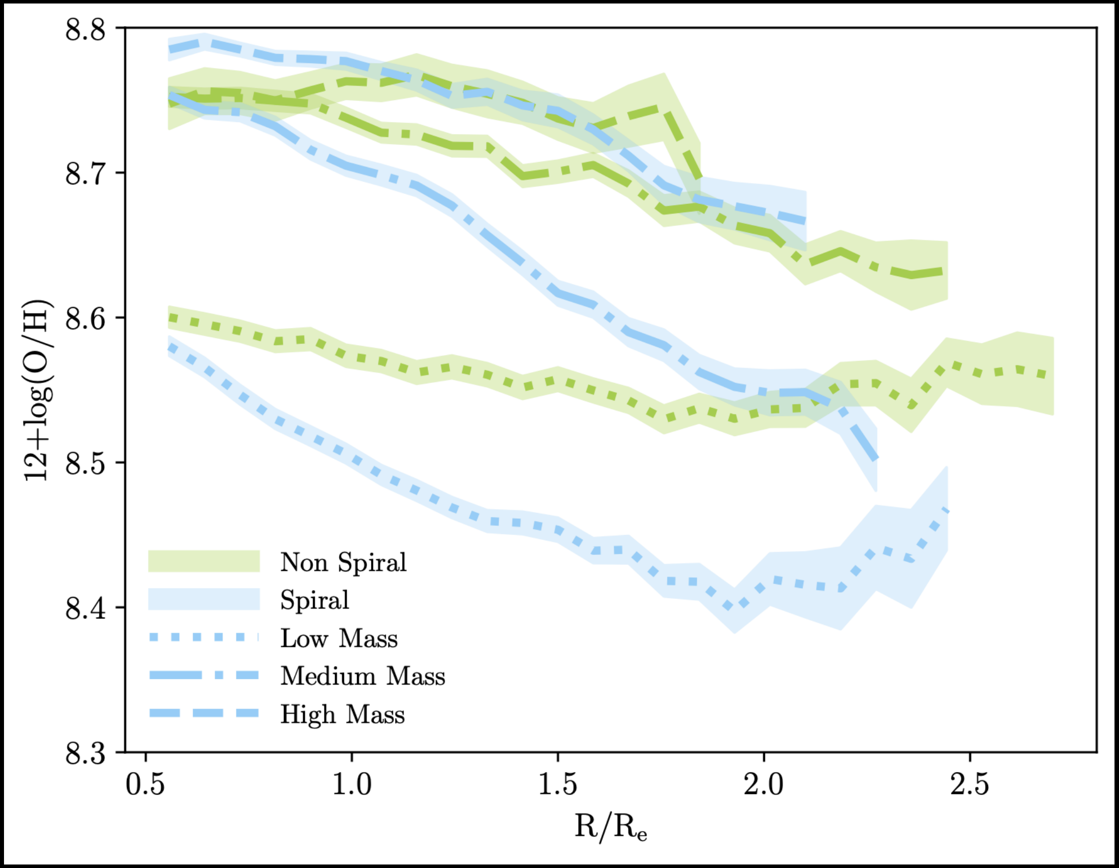


JW Johnson et al., in prep.

Association with Spiral Structure?

Recent comparisons of spirals vs. non-spirals in MaNGA indicate differences qualitatively similar to our models w/long-lived radial flows

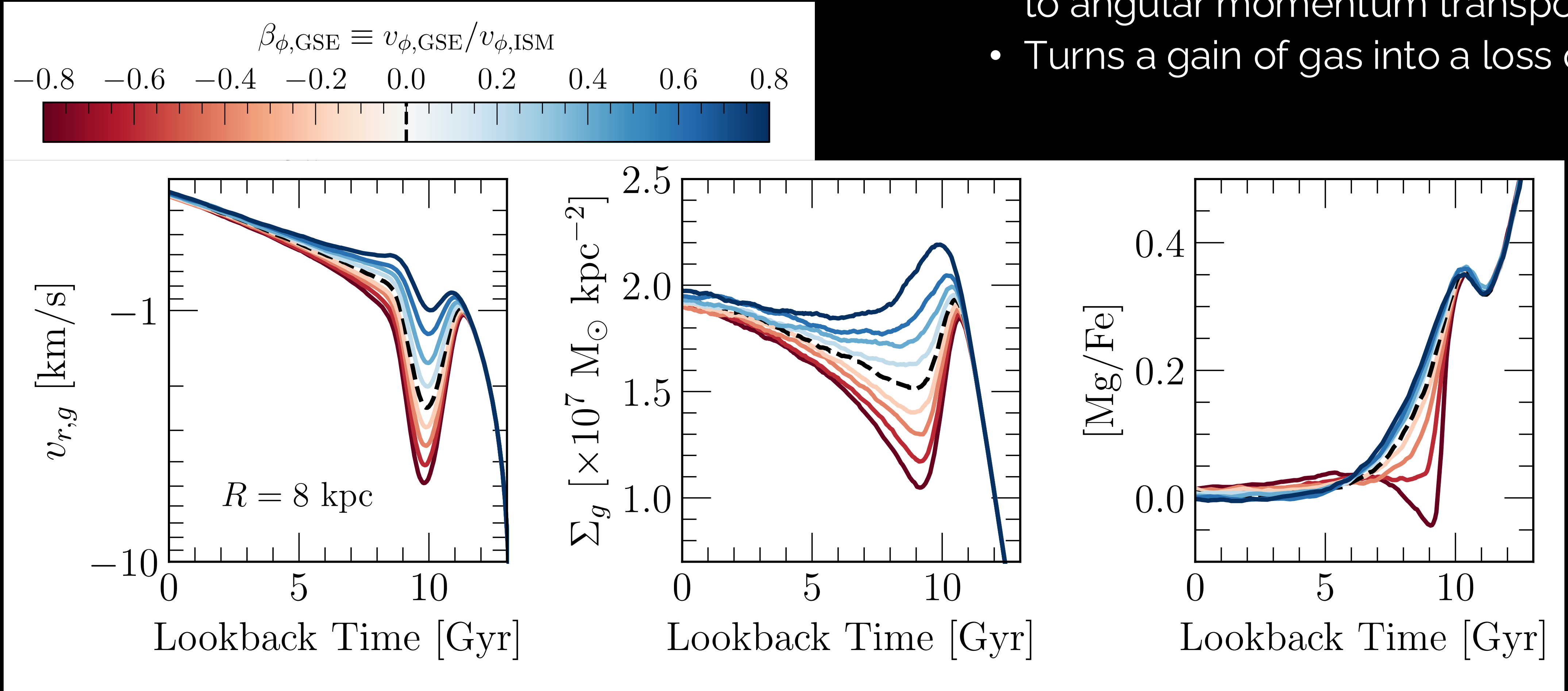




Wisz et al. (2025), Figure 9

Role in Merger Events

GSE-like events -- 3:1 mass ratio



Prograde vs. Radial vs. Retrograde

- Different radial flow velocities in ISM due to angular momentum transport
- Turns a gain of gas into a loss of gas

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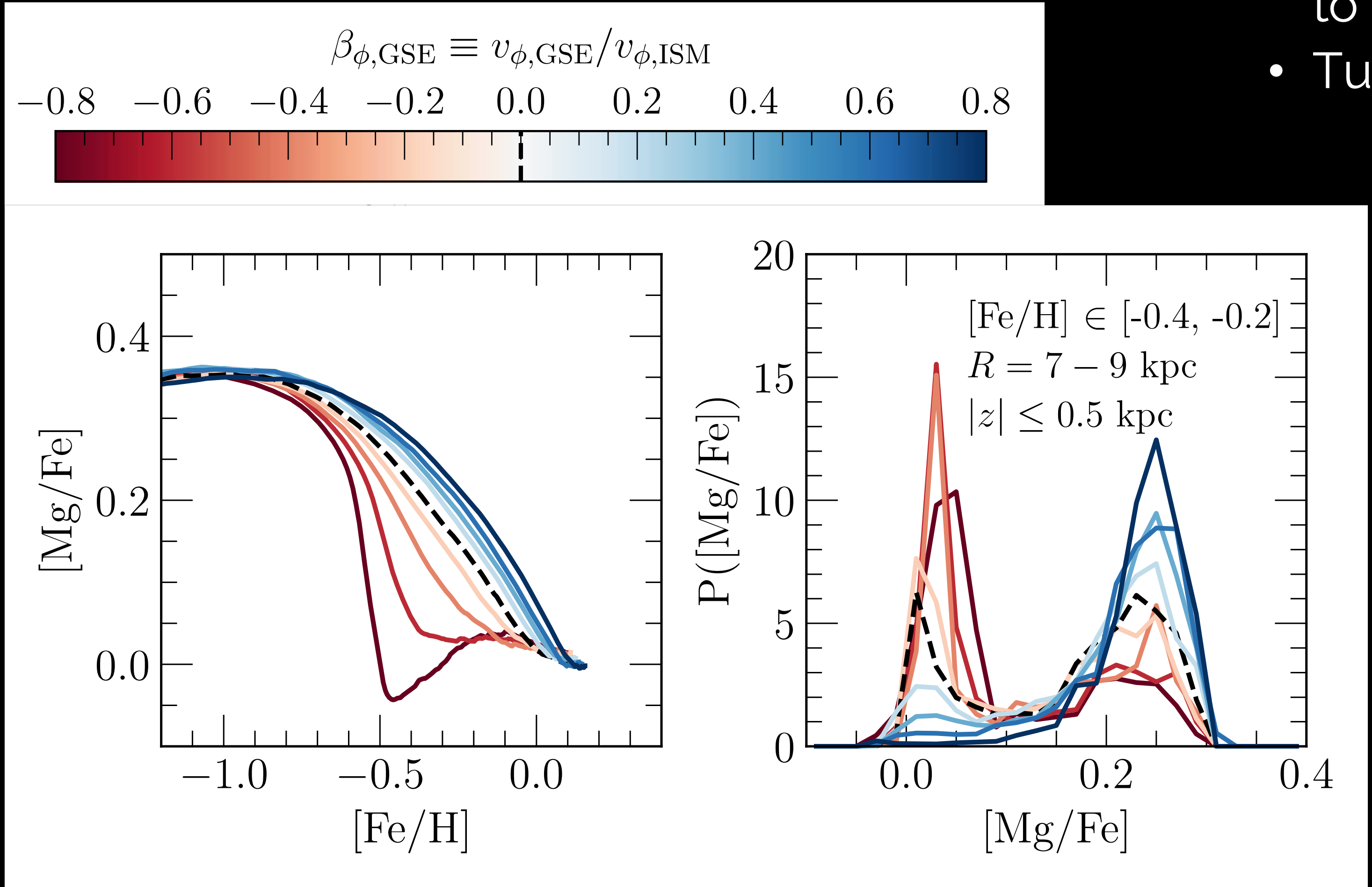

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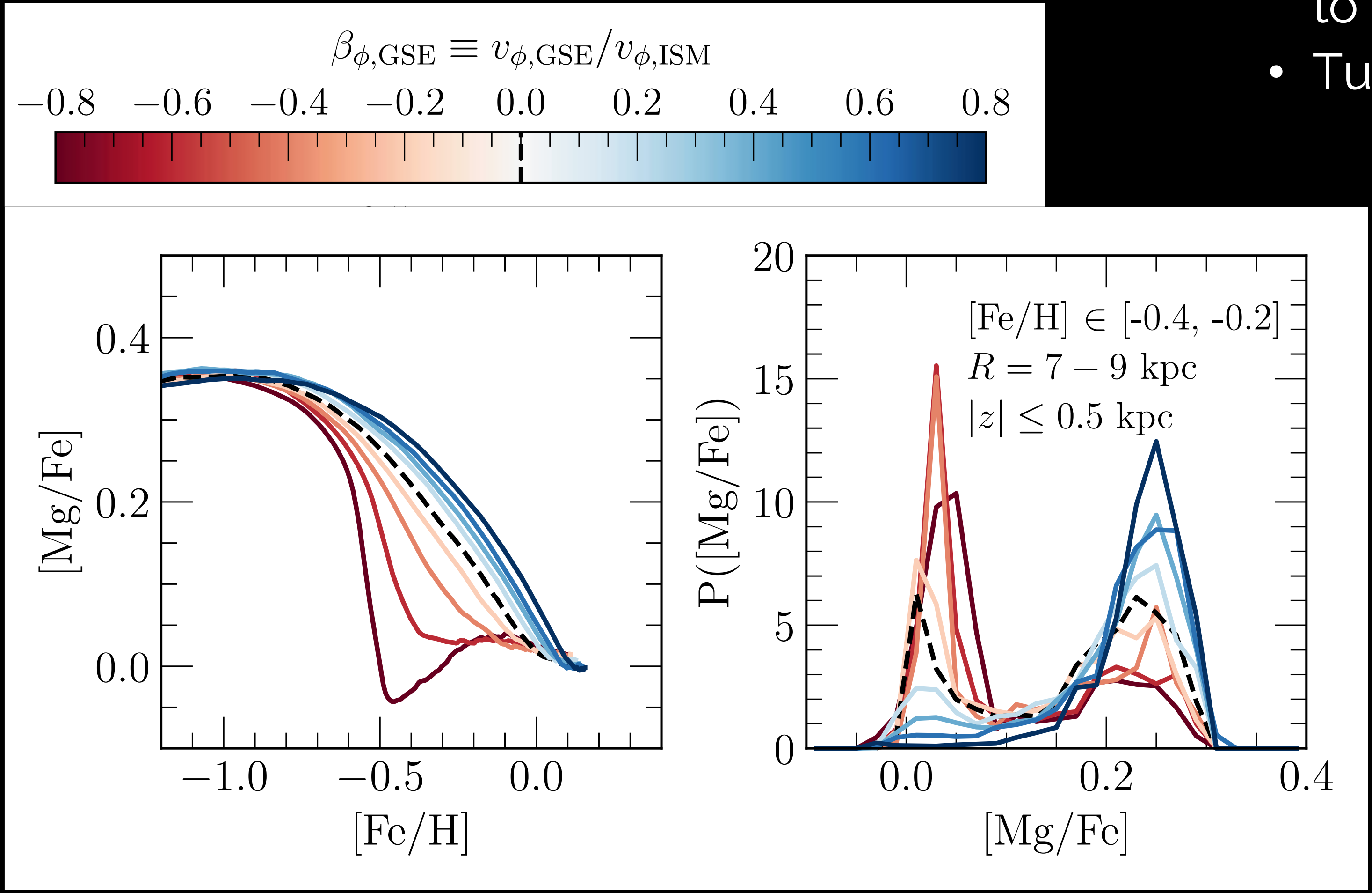


Prograde vs. Radial vs. Retrograde

- Different radial flow velocities in ISM due to angular momentum transport
- Turns a gain of gas into a loss of gas

Taking ISM dynamics into account can produce alpha bimodality in the disk

Summary

Metallicity shows little correlation with age at fixed Galactocentric radius

- Robust against measurement method and sample selection

Empirical indication of equilibrium chemical evolution; origin poorly understood

- Outflows: if $\eta \propto e^R$
- Radial Gas Flows: if $\langle v_r \rangle$ depends weakly on radius and varies little with time
- Future work: combine them

If accurate, what are the implications of equilibrium?

- Broadly, the baryon cycle is vigorous – equilibrium arises when chemical evolution is *fast*

VICE: Versatile Integrator for Chemical Evolution

Backend written in C

User-specified functional forms for:

- Stellar yields
- Accretion/star formation histories
- Migration of gas & stars

Flexible enough to handle isotopic models without doing so natively (Cooke et al. 2022)

Tutorial: python –m vice --tutorial

Docs: https://vice-astro.readthedocs.io

I'm happy to help you get started!

vice 1.3.1

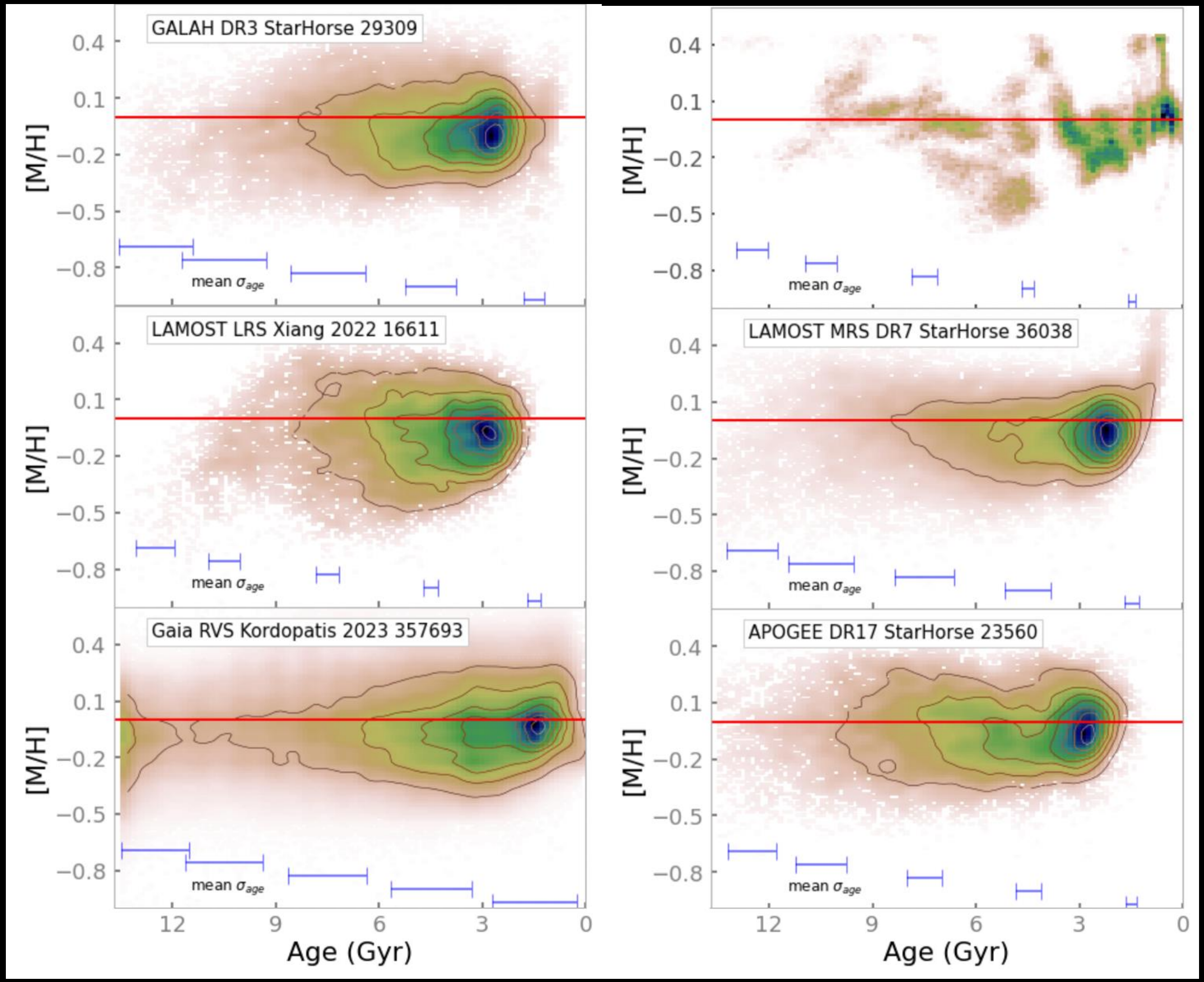
```
pip install vice
```

VICE

Age-Resolved Chemistry

Age-metallicity relation in the solar annulus

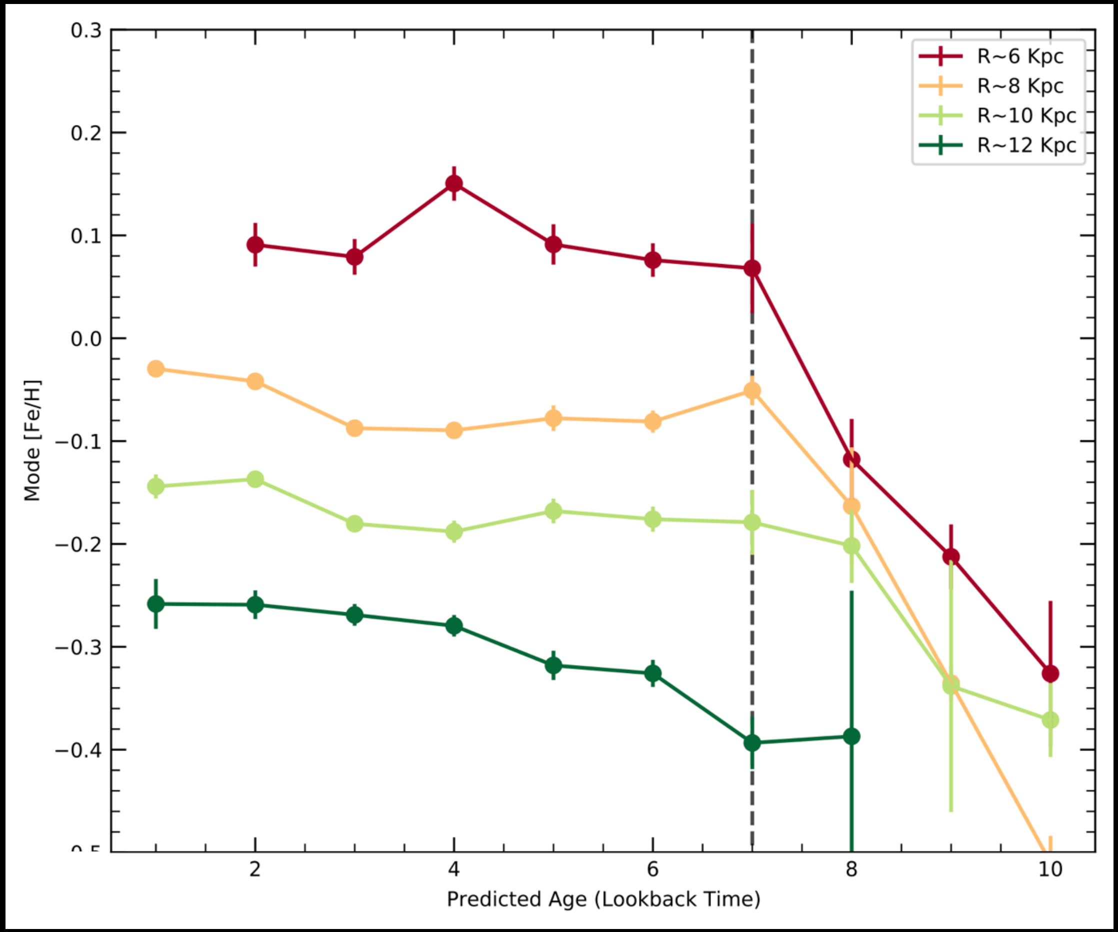
No statistically significant slope across six catalogs



Gallart et al. (2024), Figure 13

Age-Resolved Chemistry

C/N ratios – metallicity variations are within ~0.1 dex up to ages of ~7 Gyr



Jack Roberts

PhD student @ Ohio State

Chemical Equilibrium on the Whiteboard

In one-zone chemical evolution models:

- e.g., Weinberg et al. (2017)

$$Z_{\alpha,eq} = \frac{y_\alpha}{1 + \eta - r - \frac{\tau_\star}{\tau_{sfh}}}$$

Population-avg. yield from alpha process

($M_\odot$ of production per $M_\odot$ of star formation)

Efficiency Parameter

$$\tau_\star \equiv \frac{\Sigma_g}{\dot{\Sigma}_\star}$$

Outflow mass loading factor

$$\eta \equiv \frac{\dot{\Sigma}_{out}}{\dot{\Sigma}_\star}$$

Star Formation History timescale

$$\dot{\Sigma}_\star \propto e^{-t/\tau_{sfh}}$$

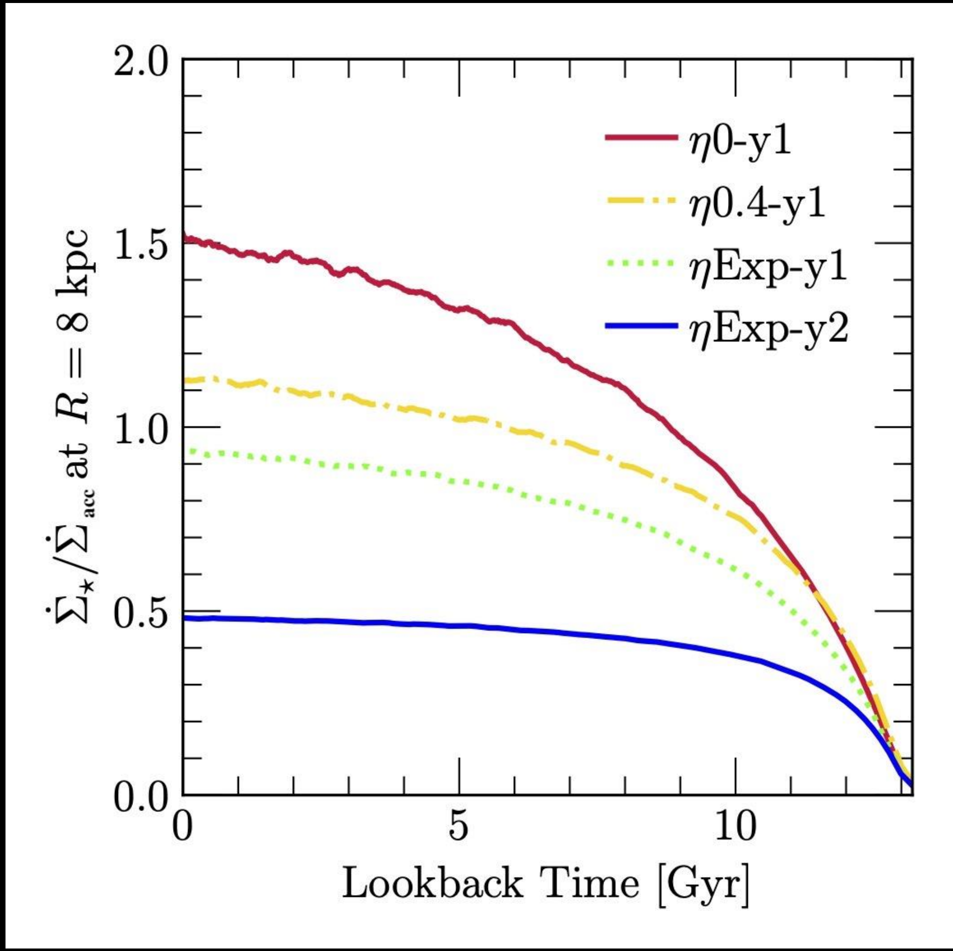
Why Do Outflows Work?

Lower the average time one baryon spends in one region of the ISM

$$Z_{\alpha,eq} = \frac{y_\alpha}{1 + \eta - r \; - \frac{\tau_\star}{\tau_{sfh}}}$$

$$\rightarrow y_\alpha \left(\frac{\dot{\Sigma}_\star}{\dot{\Sigma}_{acc}} \right)$$

$$\Rightarrow \nabla \ln Z_{\alpha,eq} \approx \nabla \ln(\dot{\Sigma}_\star \,/\, \dot{\Sigma}_{acc})$$

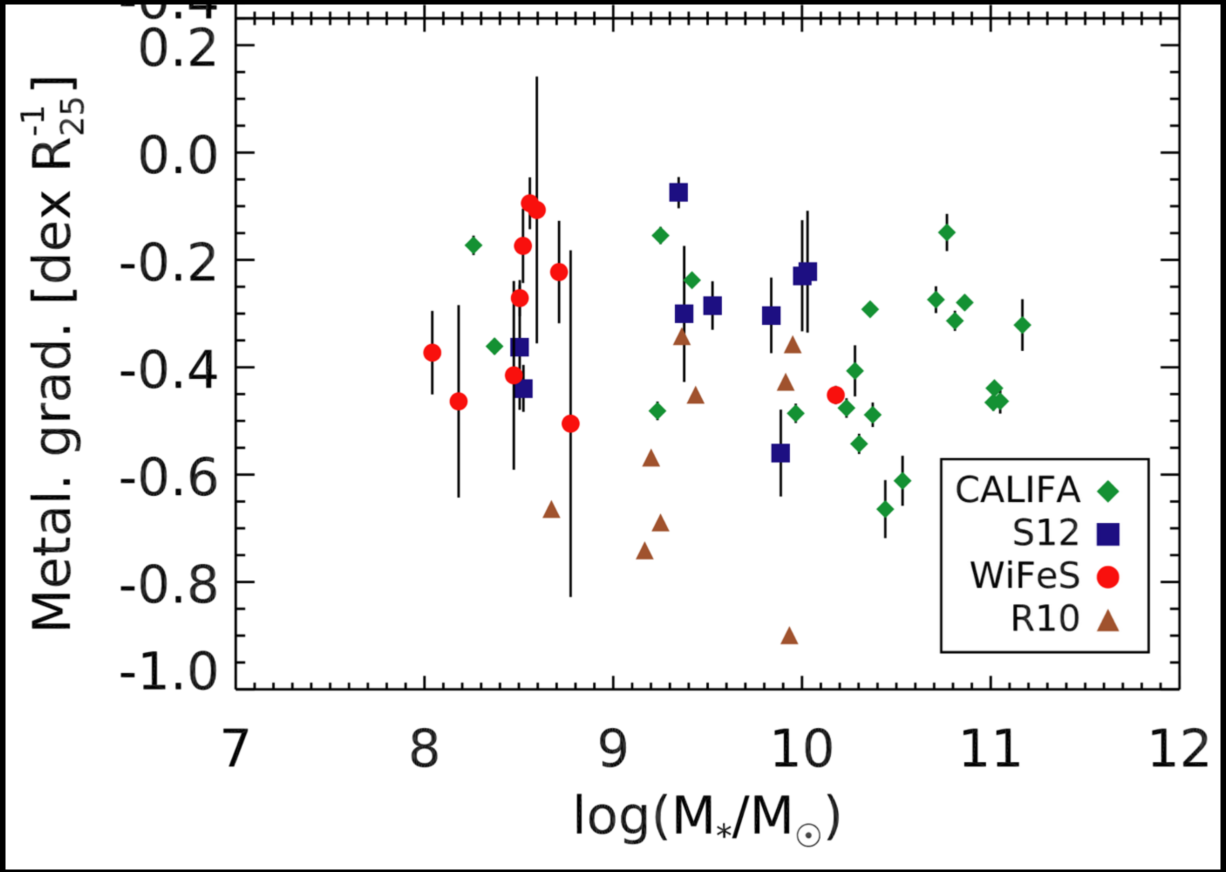


Johnson et al. (2024), Figure 11 (arxiv:2410.13256)

Apparent Universality between Galaxies

No obvious trends when scaled for size

Some arguments for a subtle trend with mass



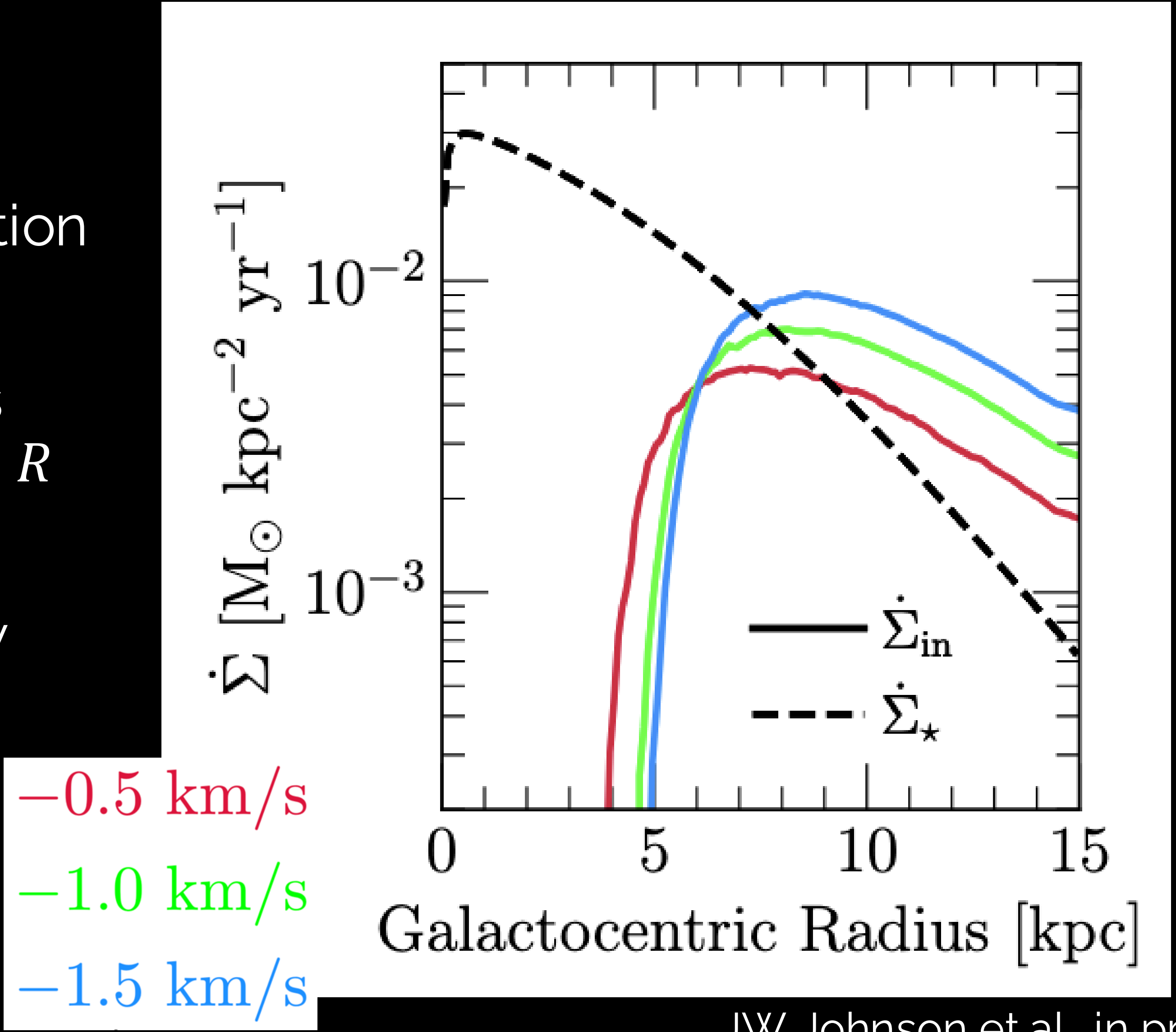
Ho et al. (2015), Figure 9

The Radial Profile of Accretion

Adjusting the radial gas flow speed in turn adjusts the radial profile of accretion

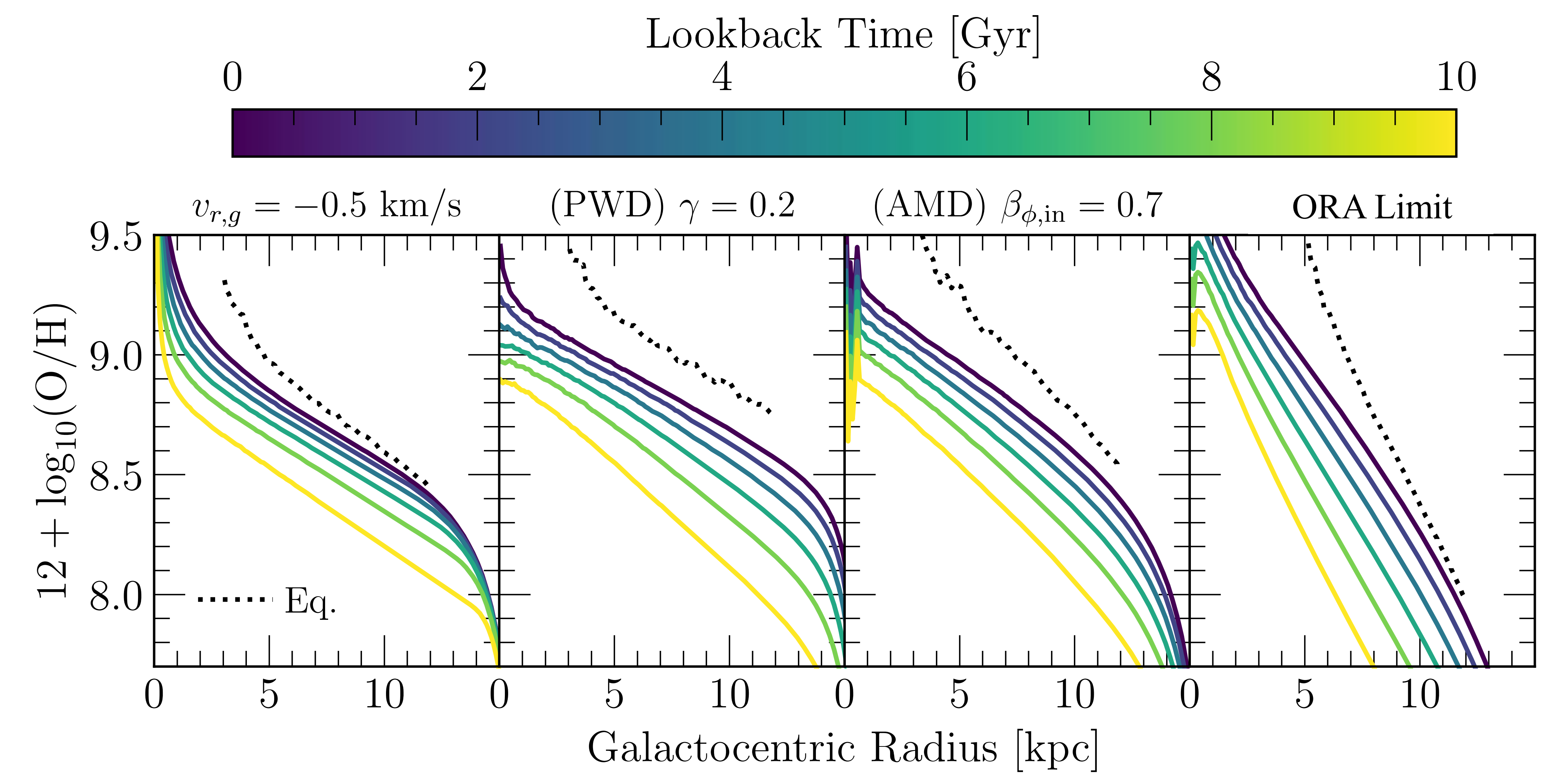
Mnemonic: Additional metal-poor gas "weighs down" the metallicity at large R

These effects arise in *every* radial flow model



JW Johnson et al., in prep.

Snapshots of Radial Flow Models



The Outer Rim Accretion Limit

All accretion happens at the outer edge of the disk ($\dot{\Sigma}_{in} \rightarrow 0$)

Mass transfer to fuel star formation at intermediate radii happens via the radial flow

As far out in radius as one can push the accreting matter

- Should be the steepest possible gradient in this framework

Equilibrium formalism breaks down entirely

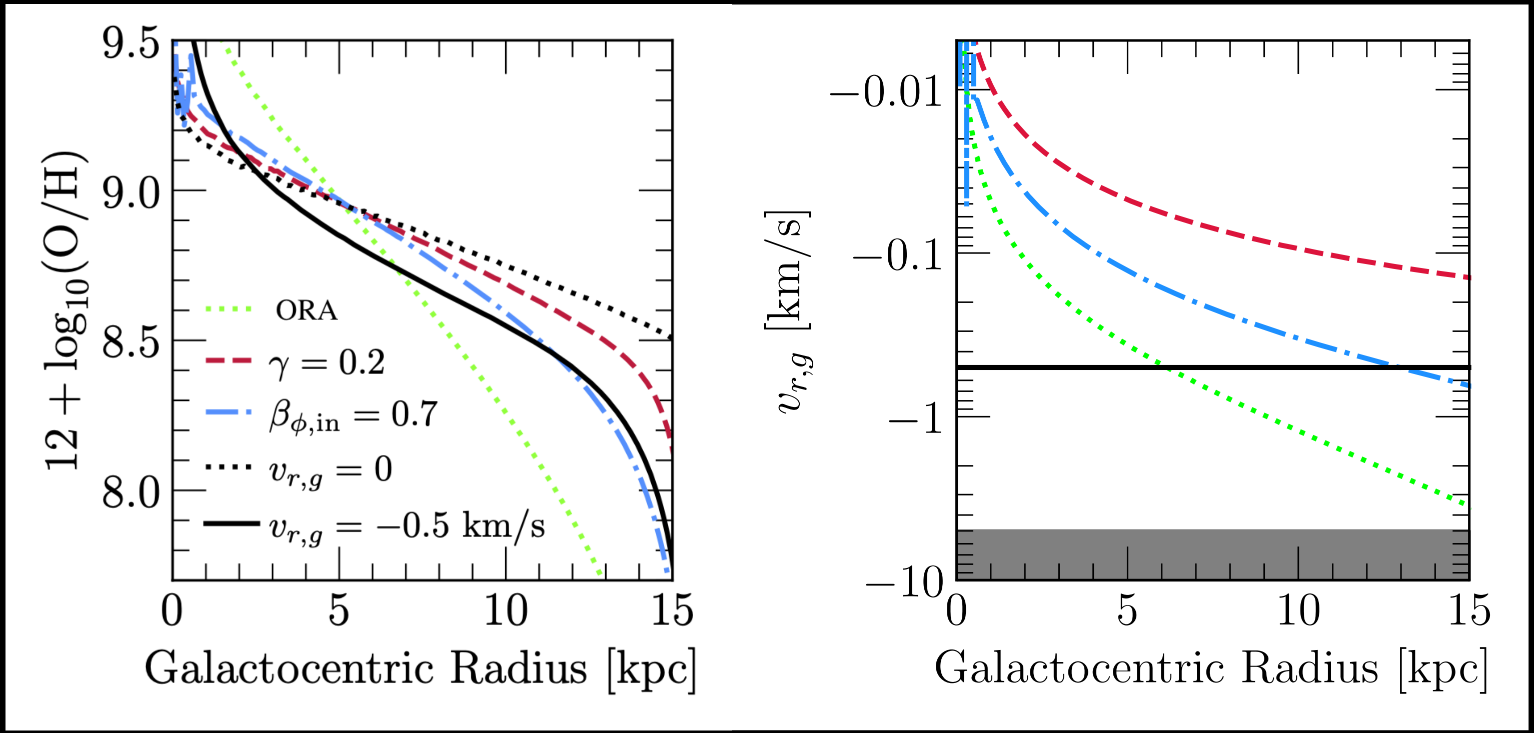
- Equilibration timescale $\rightarrow \infty$
- Local equilibrium abundance undefined

Comparing Scenarios

Free parameter in each scenario can be chosen to agree with the data

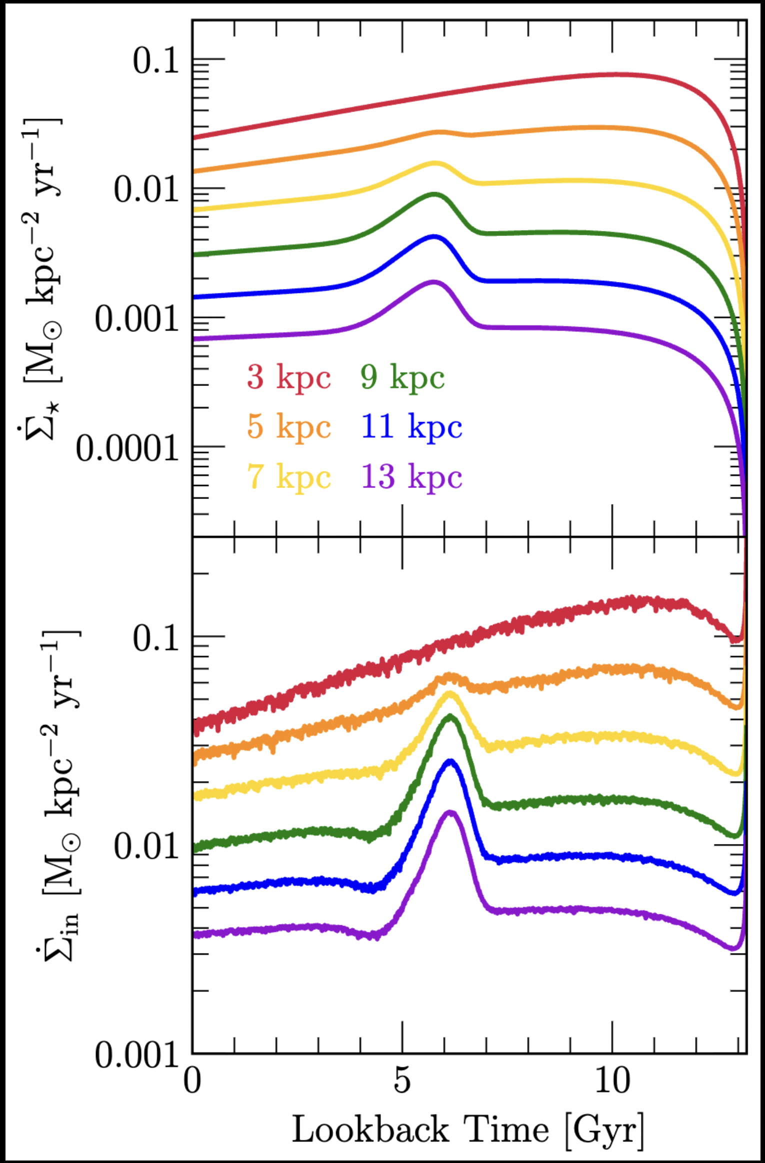
Clear relationship between metallicity profile and velocity profile

ORA limit: −0.13 dex/kpc



JW Johnson et al., in prep.

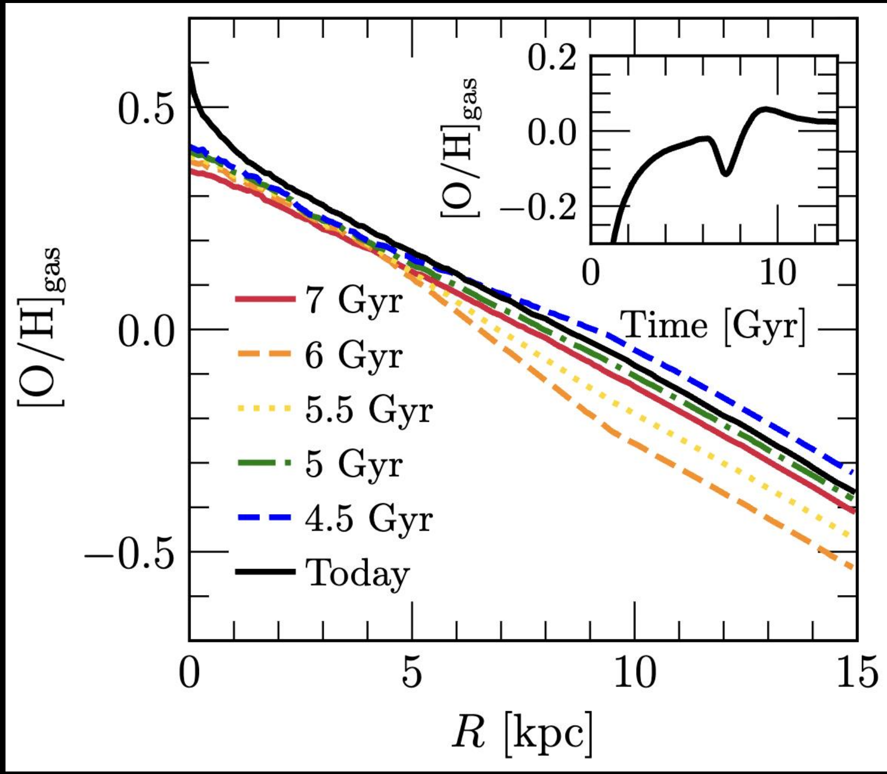
Major Mergers: Perturbations from Equilibrium



Accretion event ~6 Gyr ago (Sgr?)

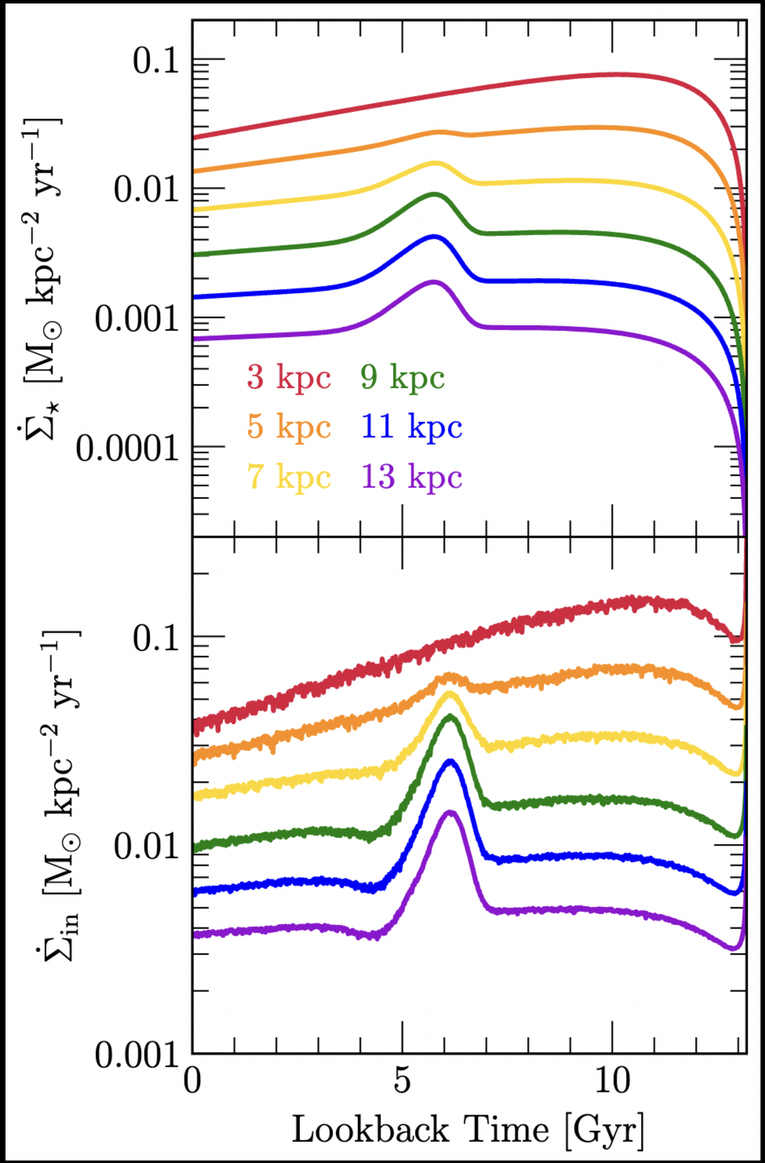
Dilution followed by re-enrichment

- Relaxes on ~Gyr timescales



Johnson et al. (2024), Figure 13 (arxiv:2410.13256)

Major Mergers: Perturbations from Equilibrium



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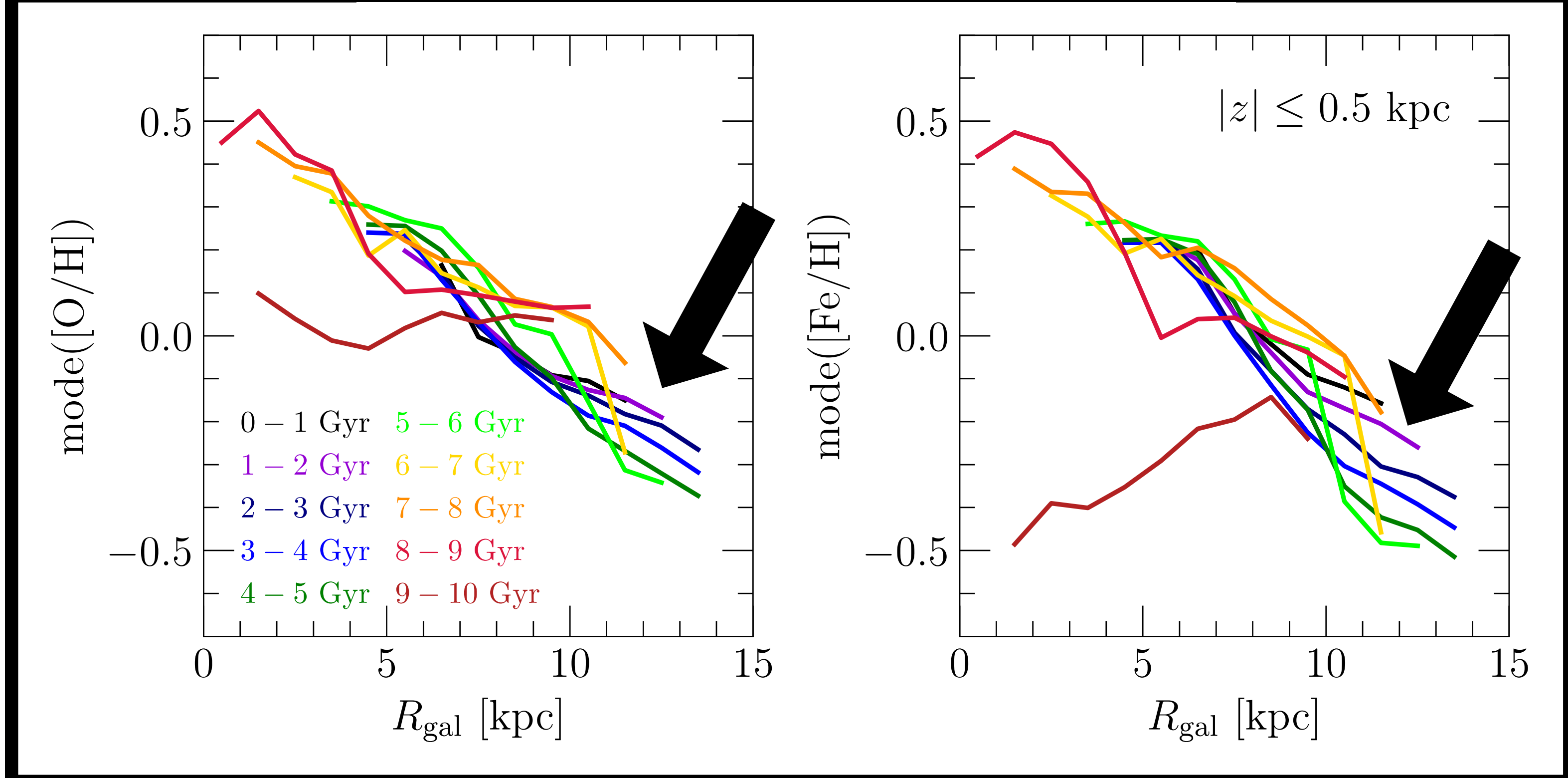

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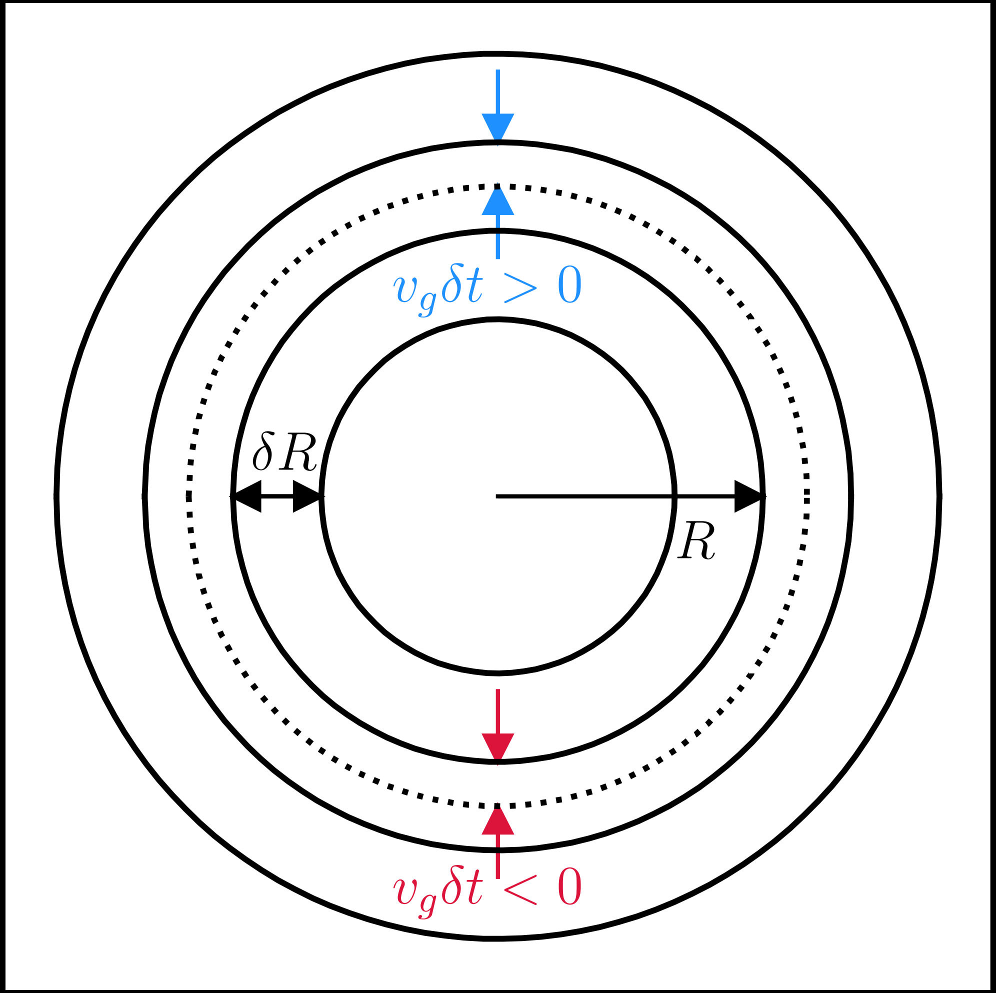
Analytic Solutions

Effect on enrichment poorly understood ⇒ can learn a lot from the whiteboard



Take this implementation and apply the limit as $\delta R, \delta t \to 0$

Taylor series with unknown coefficients:

- Gas surface density
- Radial metallicity profile
- Radial velocity distribution

First analytic solution to radial flows limited primarily by axisymmetry

- Agrees w/numerical models to within 0.005 dex/kpc

JW Johnson et al., in prep.

Executive Summary

$$\dot{\Sigma}_{g,flow} = \mu_g \dot{\Sigma}_\star \text{ where } \mu_g \equiv -\tau_\star \langle v_r \rangle \left[\frac{1}{R} + \frac{\partial \ln \Sigma_g}{\partial R} + \frac{\partial \ln\langle v_r\rangle}{\partial R}\right]$$

Mean radial velocity

$$\langle v_r \rangle = \int_{-\infty}^{\infty} v_r P(v_r|R) dr$$

Mass Profile

$$d \ln M_g = d \ln A + d \ln \Sigma_g$$

Dynamical pile-up

Executive Summary

$$\dot{\Sigma}_{x,flow} = Z_x \mu_x \dot{\Sigma}_\star \text{ where } \mu_x \equiv \mu_g - \tau_\star \langle v_r \rangle \frac{\partial \ln Z_x}{\partial R}$$

Extra dependence on local abundance by mass

All of the same processes as the gas

Flowing material has slightly different composition

Executive Summary

Direct effect of mixing goes as $\mu_x - \mu_g \rightarrow \dot{Z}_{x,mix} = -\langle v_r \rangle \frac{\partial Z_x}{\partial R}$

How quickly are different gas reservoirs being mixed?

By how much does their composition differ?

Influence on $Z_{\alpha,eq}$

$$Z_{\alpha,eq} = \frac{y_\alpha\, y_\alpha}{1 + \eta - \mu_x \frac{\tau_\star}{\tau_{sfh}} - r - \frac{\tau_\star}{\tau_{sfh}}}$$

$$\rightarrow \frac{y_\alpha}{\frac{\dot{\Sigma}_{in}}{\dot{\Sigma}_\star} + \tau_\star \langle v_r \rangle \frac{\partial \ln Z_{x,eq}}{\partial R}}$$

Exponential Cutoff

Radial variations in $\dot{\Sigma}_\star / \dot{\Sigma}_{in}$

The Flow Coefficients

Effect on metal surface density similar between models, but effect on H differs