The Equilibrium Model of Disk Galaxy Metallicity Gradients

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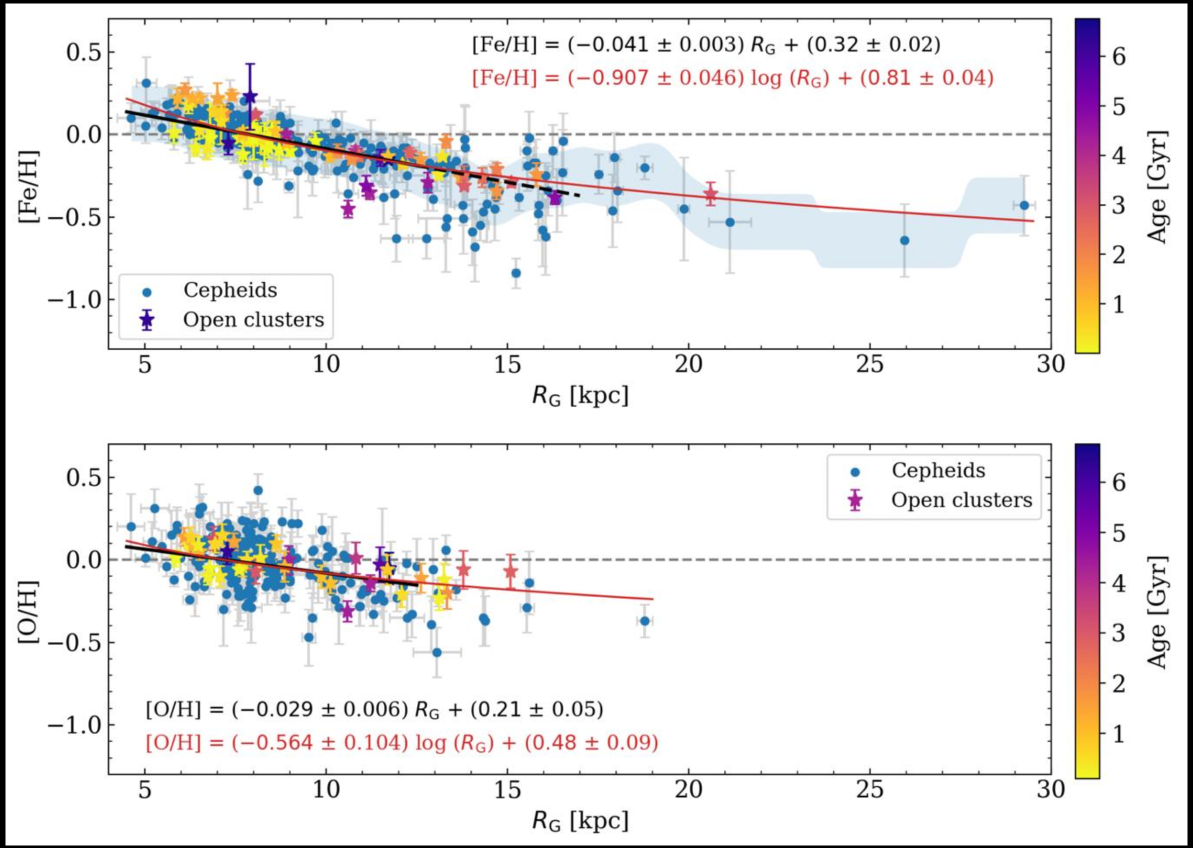
Age-Independent Metallicities in the Disk

Da Silva et al. (2023)

- No clear relationship w/age for Cepheids & Open Clusters



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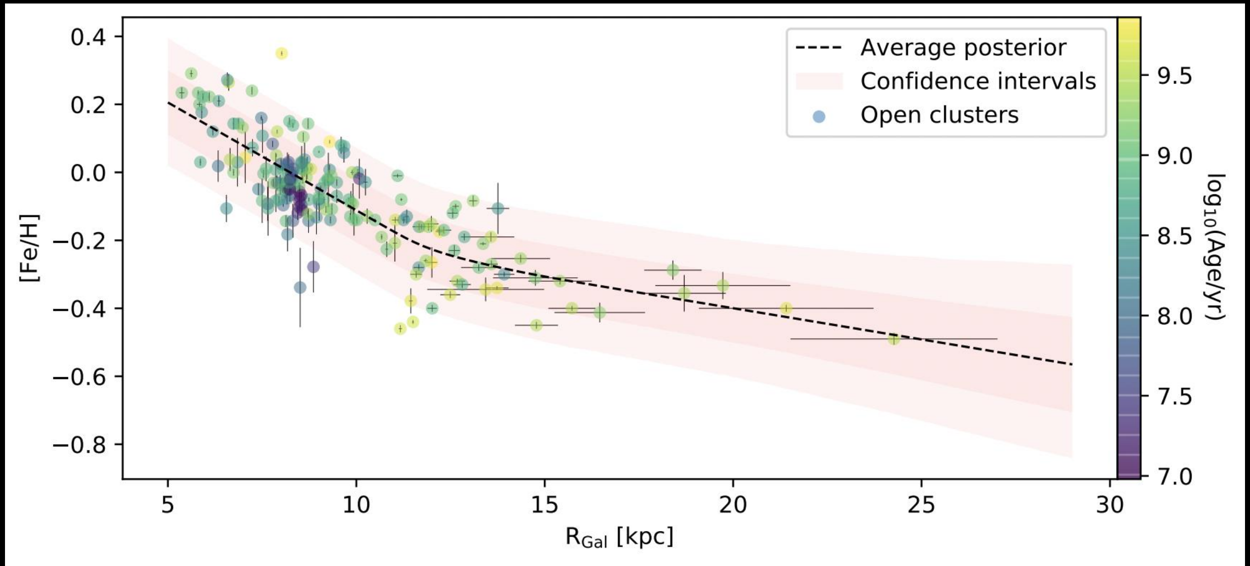
- Open clusters: minimal age relation



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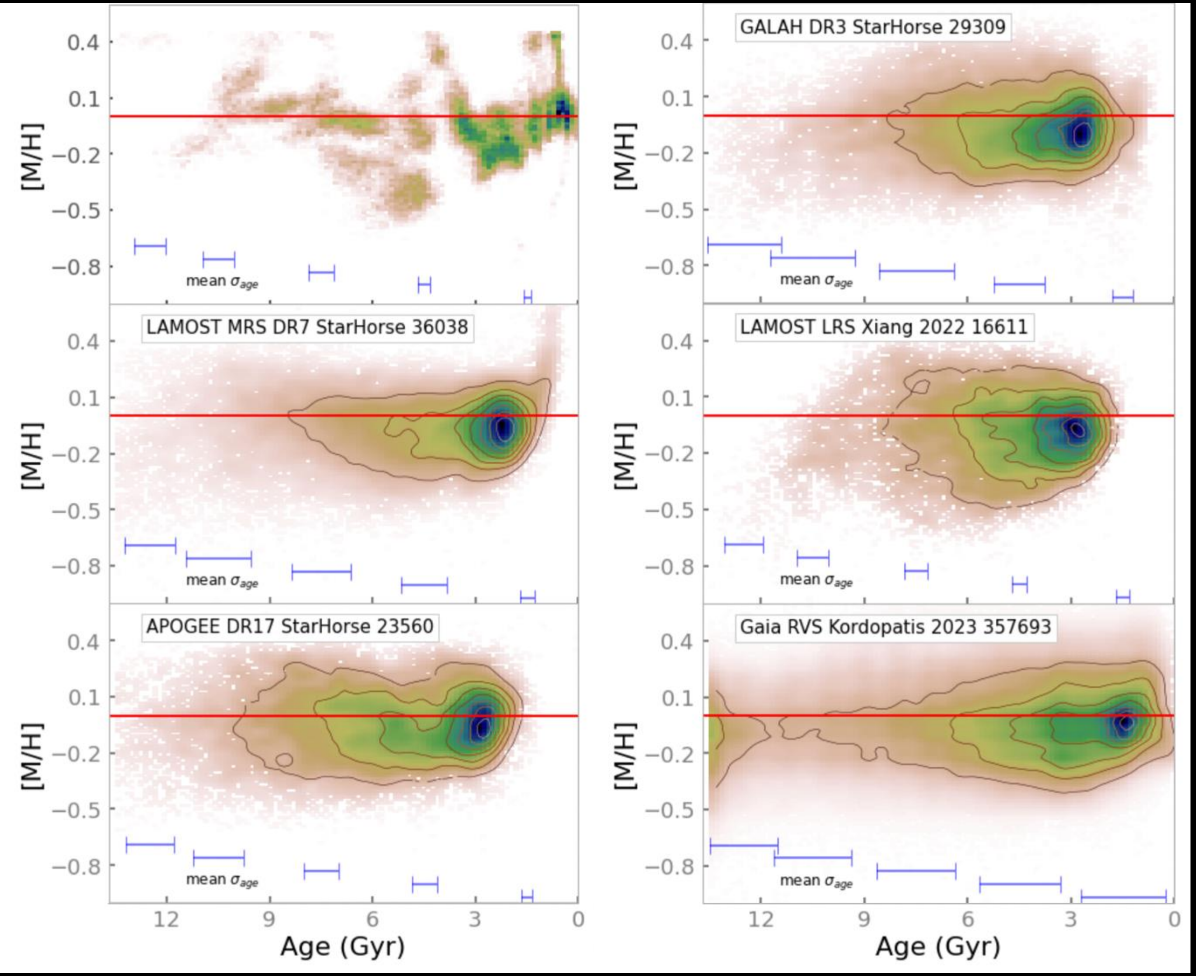
Gallart et al. (2024)

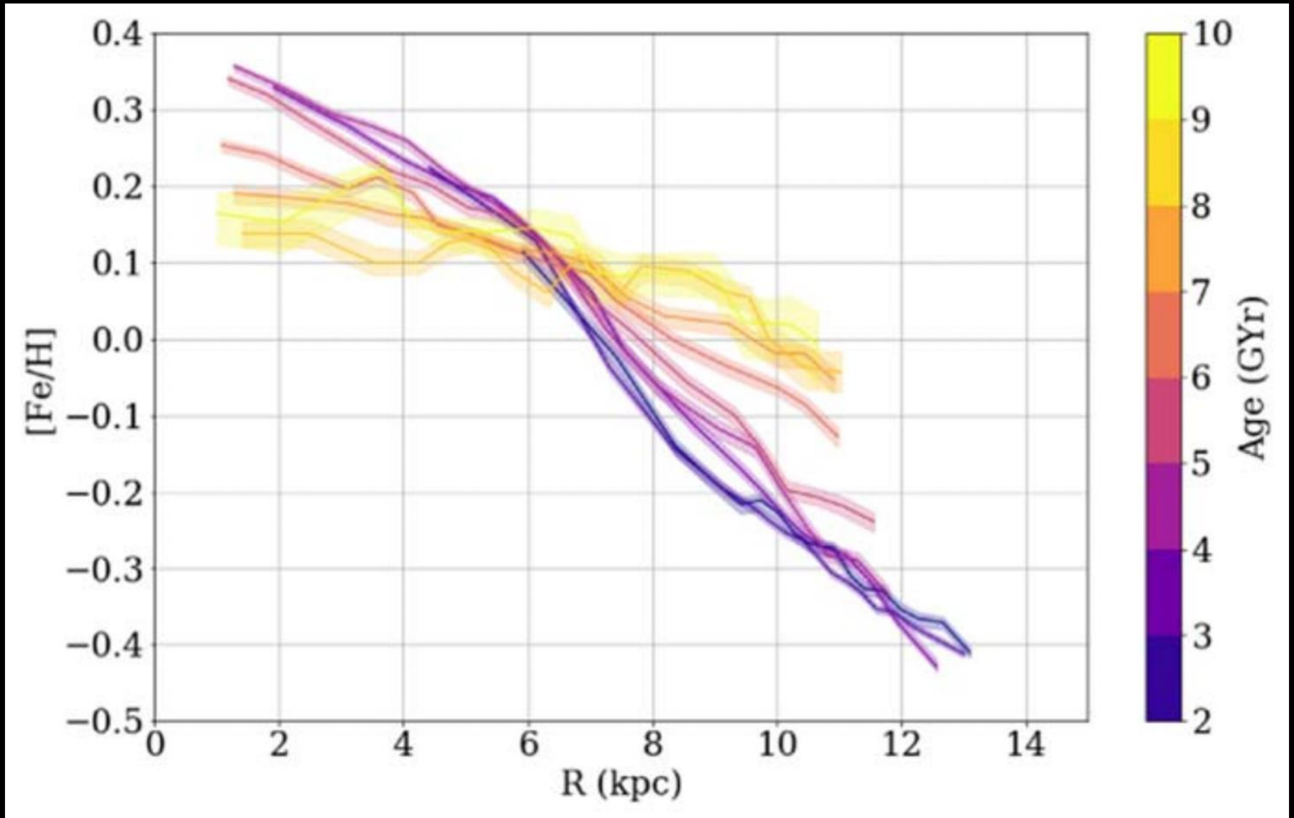
- Multiple surveys indicate flat age-metallicity relation in solar annulus



Ages from Neural Networks

Imig et al. (2023)

- Minimal evolution up to ~7 Gyr
- DistMass catalog (APOGEE) (Stone-Martinez et al. 2023)



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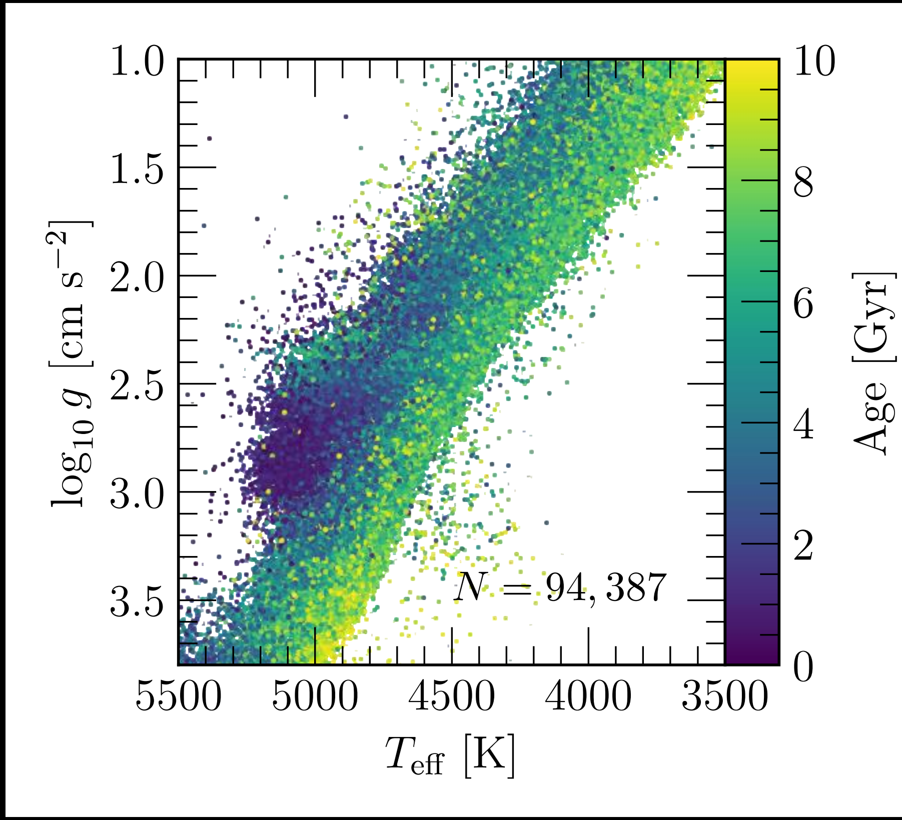
Red giants with AstroNN Value added catalog

- Convolutional Neural Network
- APOGEE DR17



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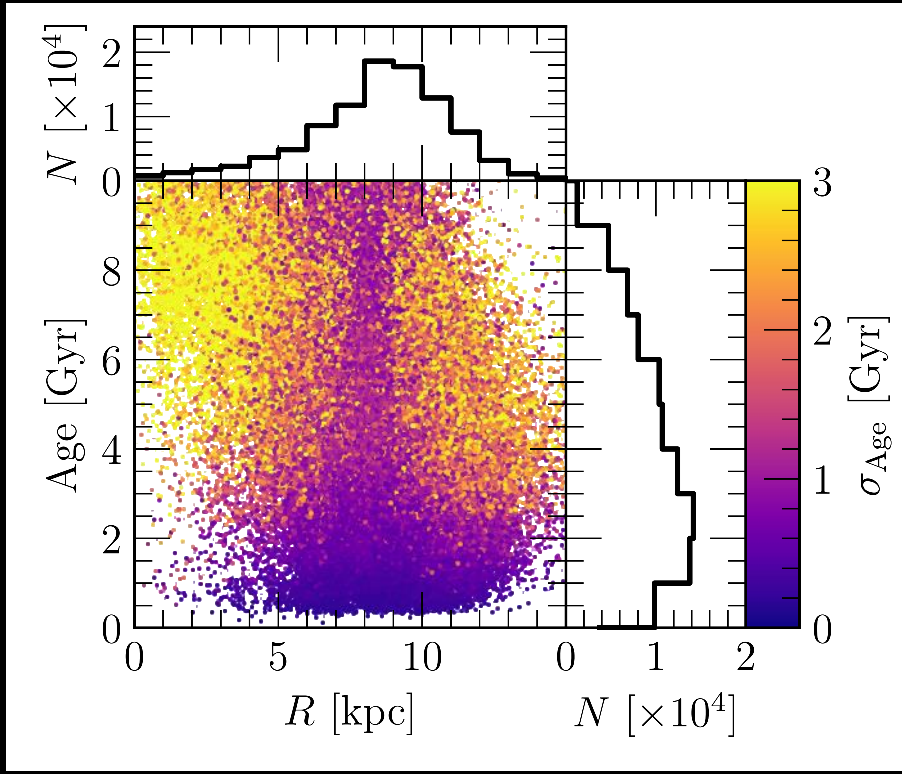

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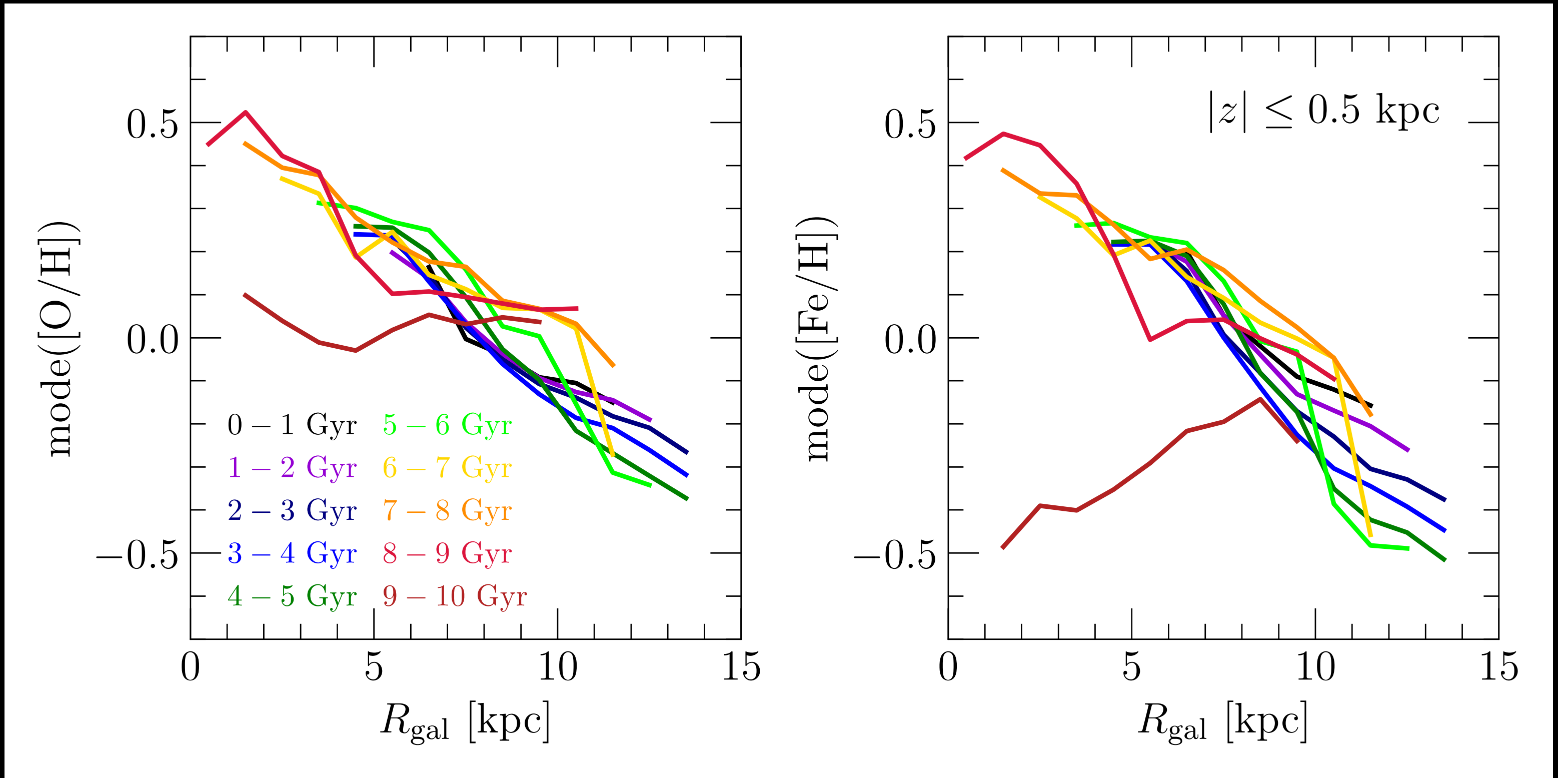
- Similar Results



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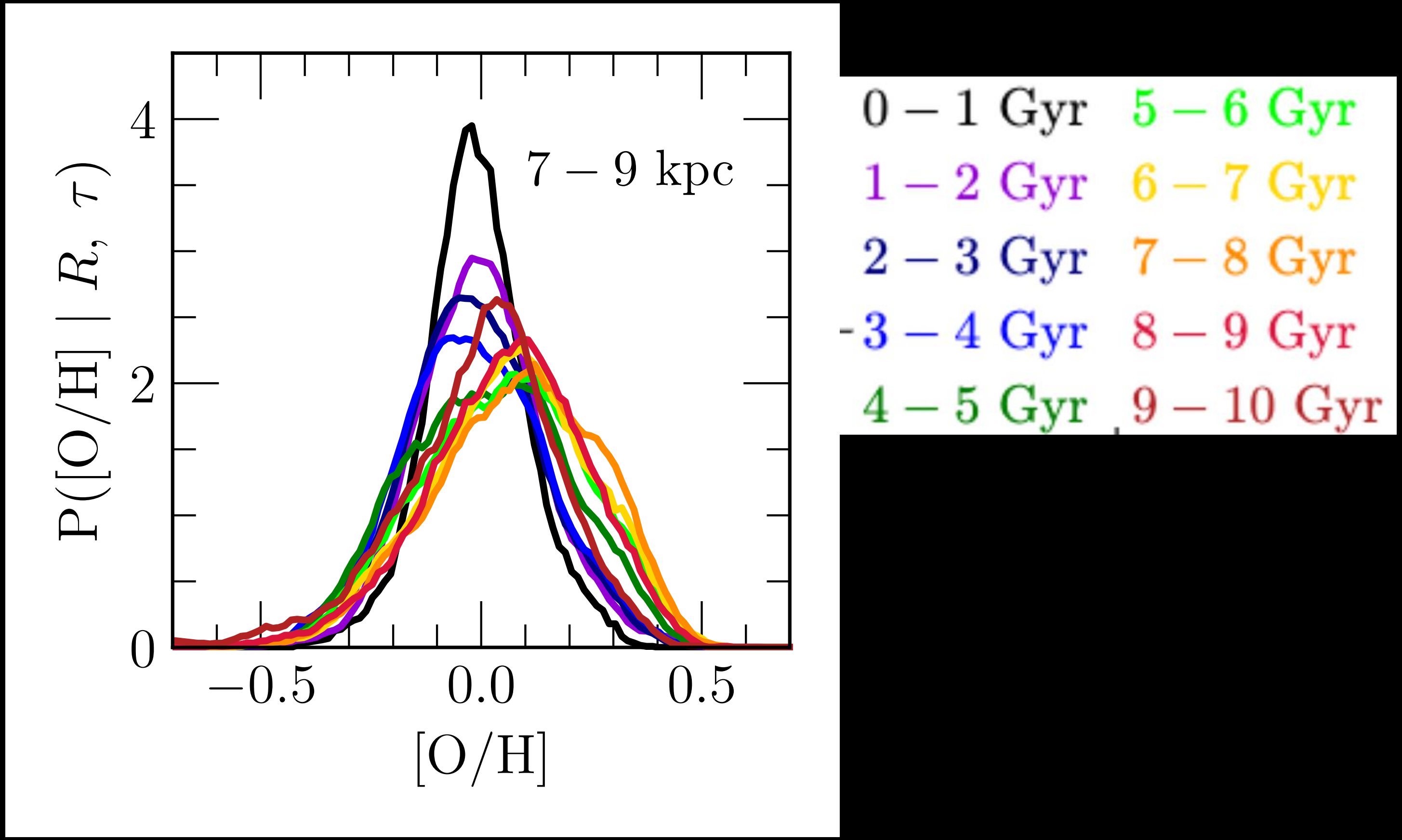
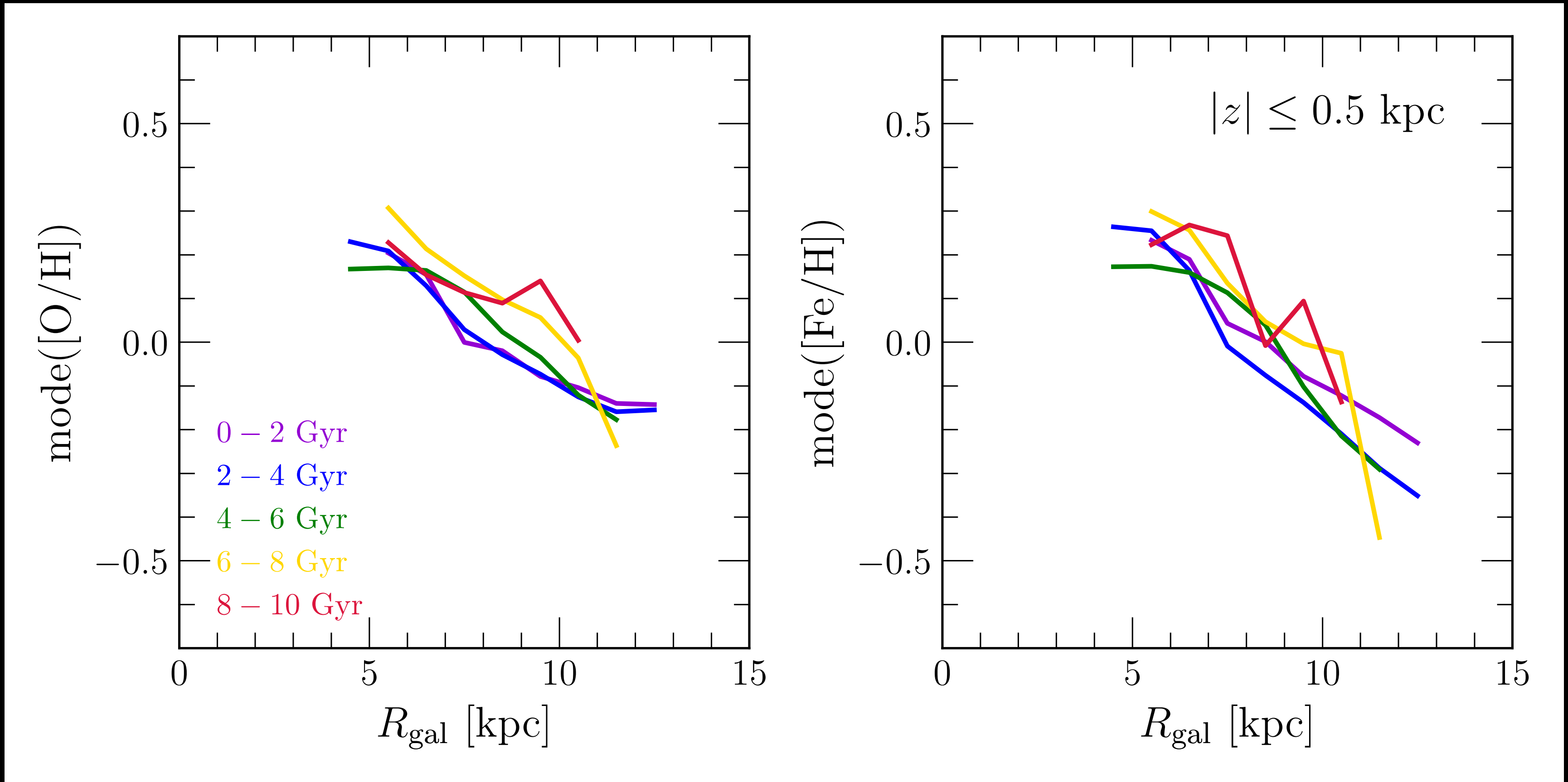


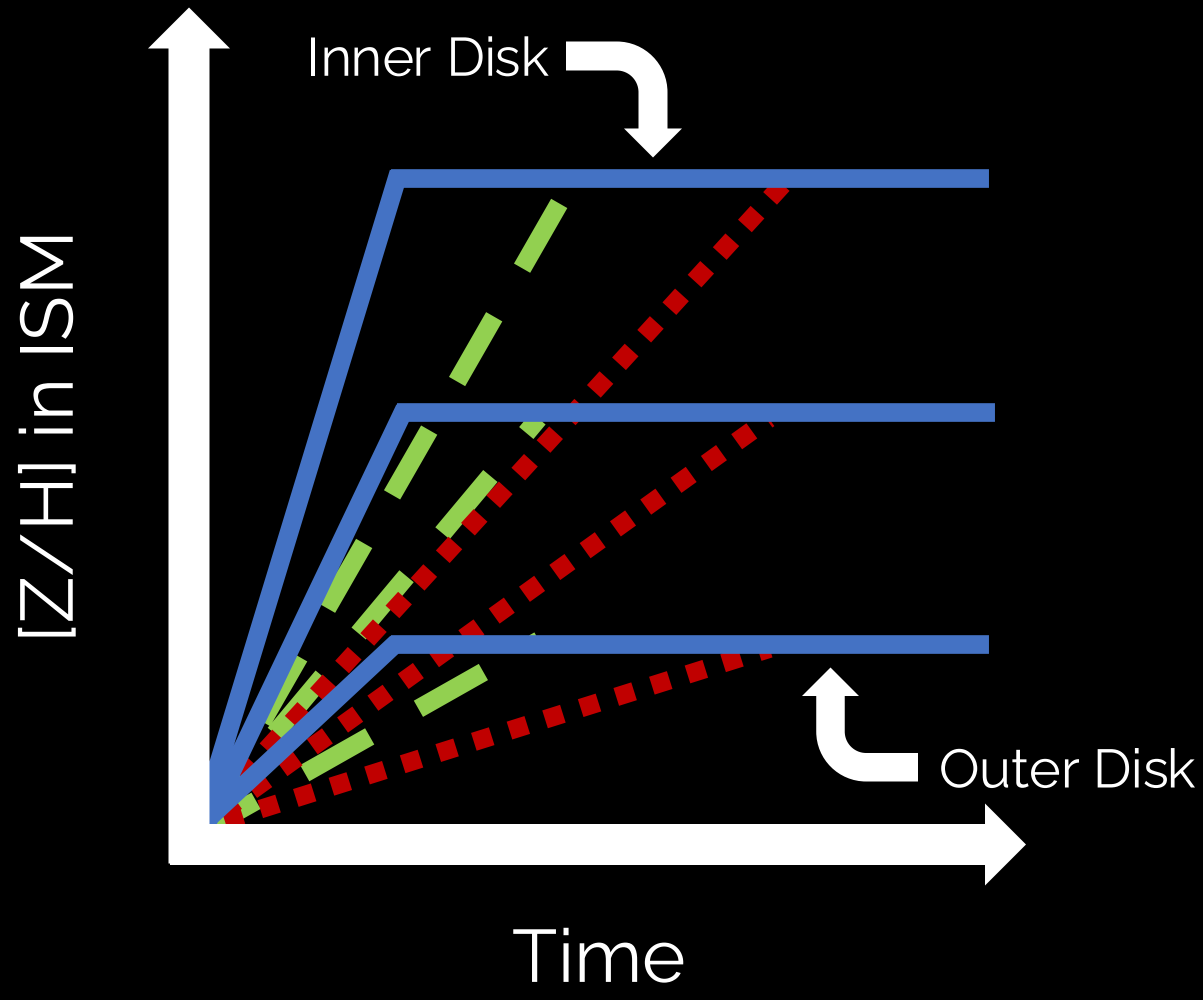
Leung et al. (2023) Age Catalog

Similar targets as AstroNN but narrow range of surface gravities

- Variational encoder-decoder vs. Bayesian CNN
- Demonstrate algorithm is insensitive to alpha and Fe abundances



Can we explain this type of behavior?



Yes!

"Equilibrium Model" refers to this generic class

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

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

Galactic Chemical Evolution parameters allow control over timescale

Equilibrium Chemical Abundances

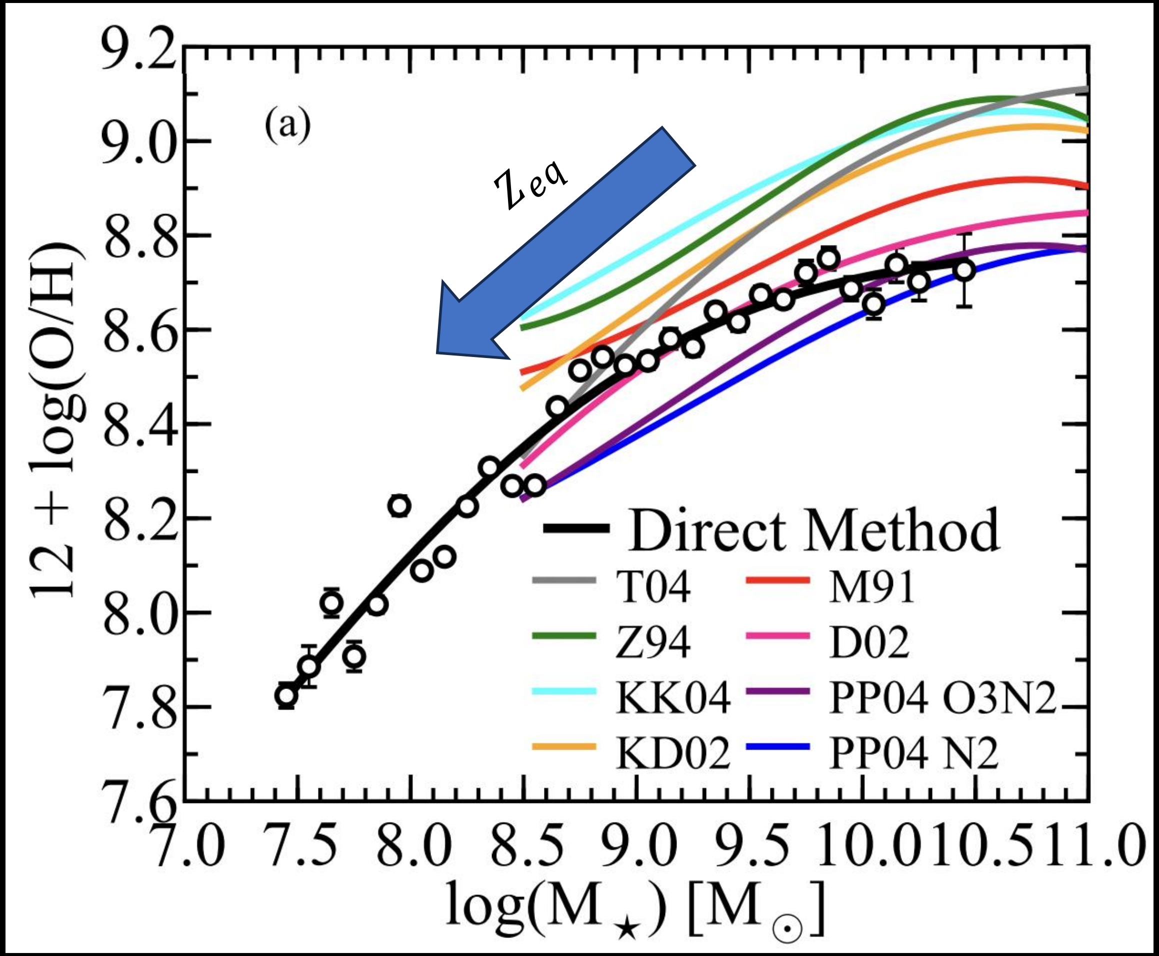
Date back to Larson (1972)

- $M_z \,/\, M_H \approx \dot{M}_Z \,/\, \dot{M}_H$

Mass-metallicity relation

- Finlator & Davé (2008), Peeples & Shankar (2011), Lilly et al. (2013)

Equilibrium model makes similar argument *within* MW disk



Andrews & Martini (2013), Fig. 10

Equilibrium Chemical Abundances

In one-zone chemical evolution models:

- Weinberg et al. (2017)

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

Population-avg. yield of alpha elements

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

Efficiency Parameter

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

Outflow mass loading factor

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

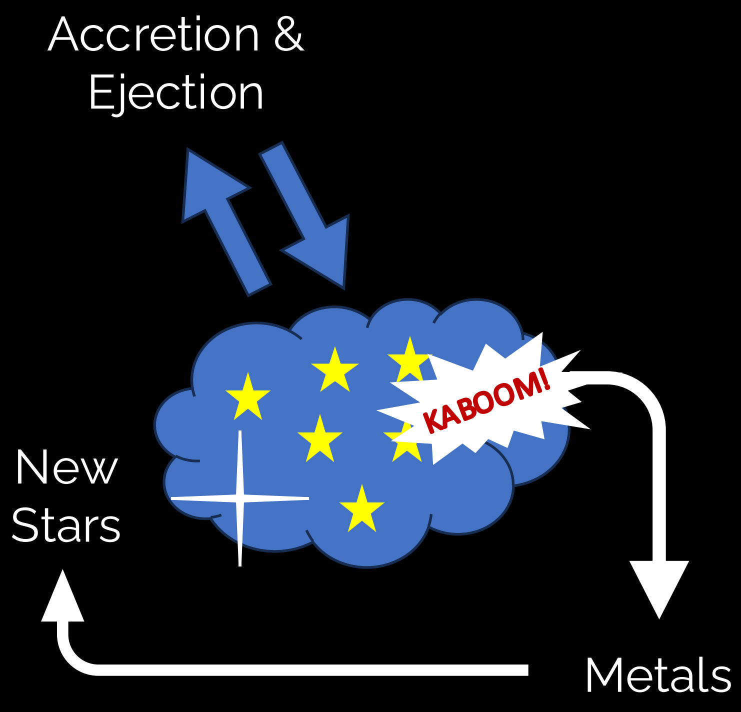
Star Formation History timescale

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

Galactic Chemical Evolution Models

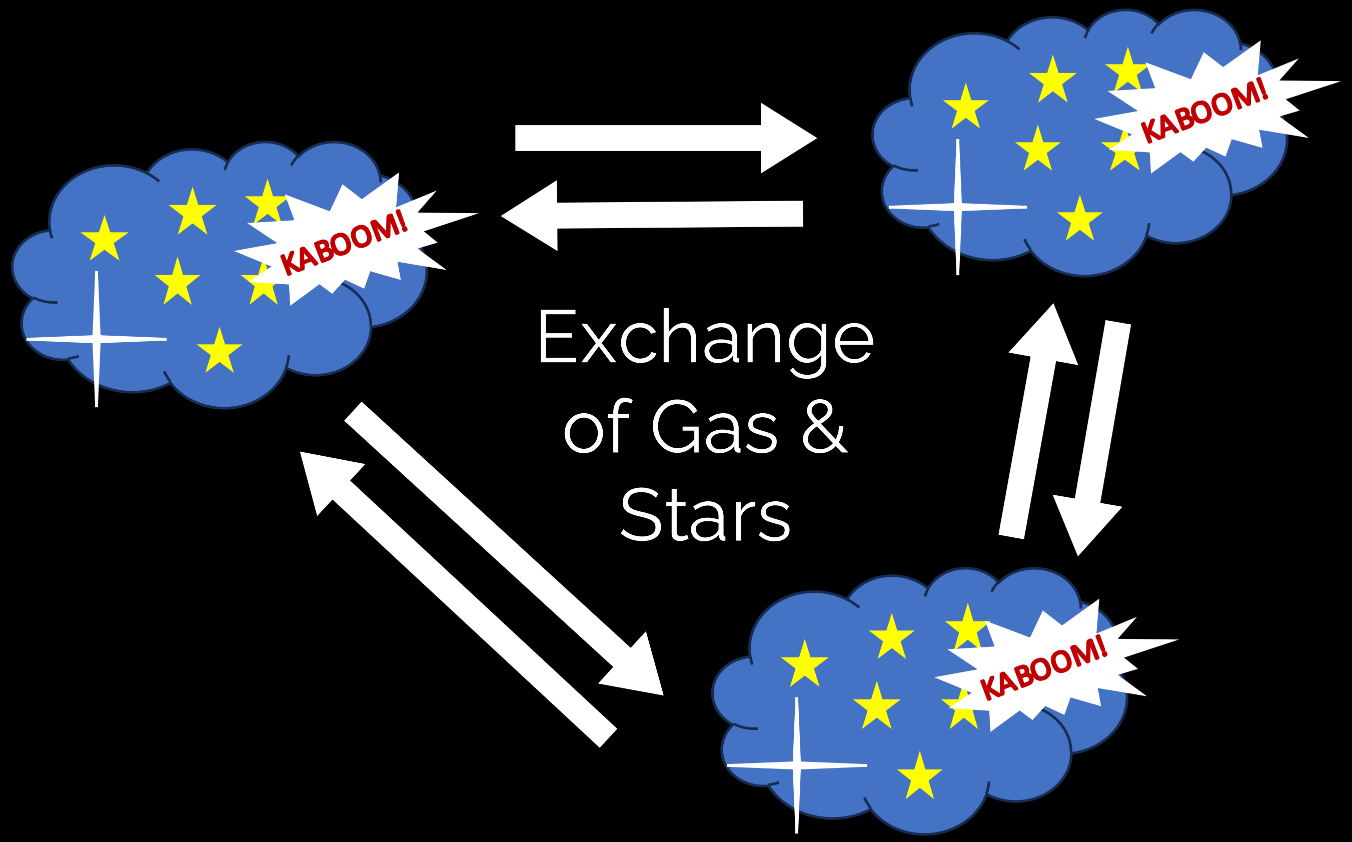
One-Zone

One chemically homogeneous gas cloud



Multi-Zone

Multiple clouds



The Milky Way: Each Zone is a Ring

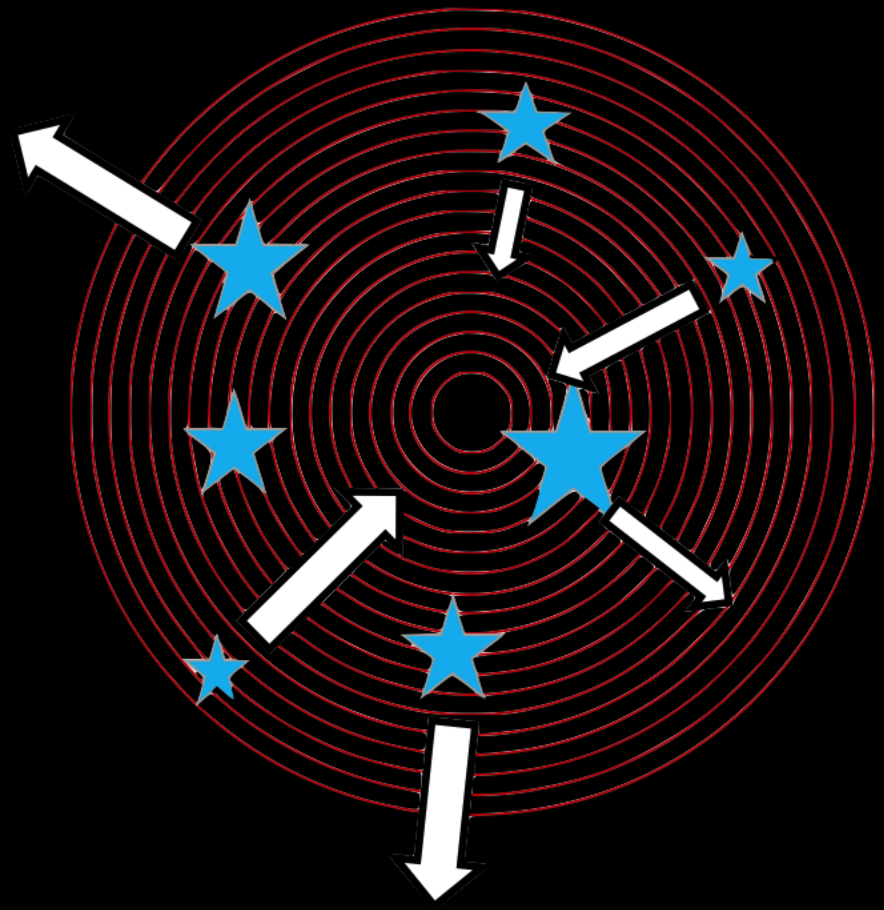
200 zones from R = 0 – 20 kpc

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

Stars move between them in a manner that mimics simulations

- h277 (N-body shop; Christensen+12)

Johnson et al. (2021) – detailed description of the model



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 (Ryan Cooke+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
```

Four Comparison Cases

Outflow parameterizations

- $\eta = 0$
- $\eta = 0.4$
- $\eta \propto e^R$ (x2 normalizations)
  $\eta_\odot \approx 2$ and $\eta_\odot \approx 0.7$

3 models take $y_O = Z_{O,\odot}$

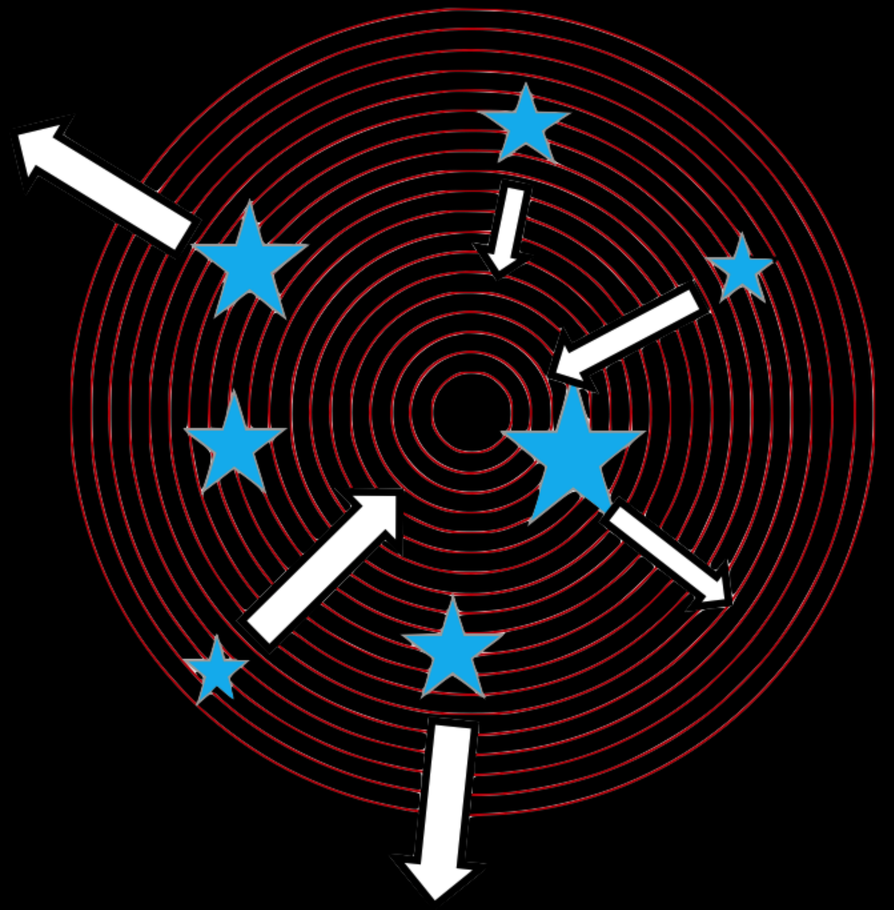
- Consistent w/Sukhbold et al. (2016)

1 model takes $y_O = 3Z_{O,\odot}$

- Consistent w/Chieffi & Limongi (2013)

35%/65% of Fe from CCSNe/SNe Ia

Models closely approximate radial gradients in ISM [O/H] and stellar age



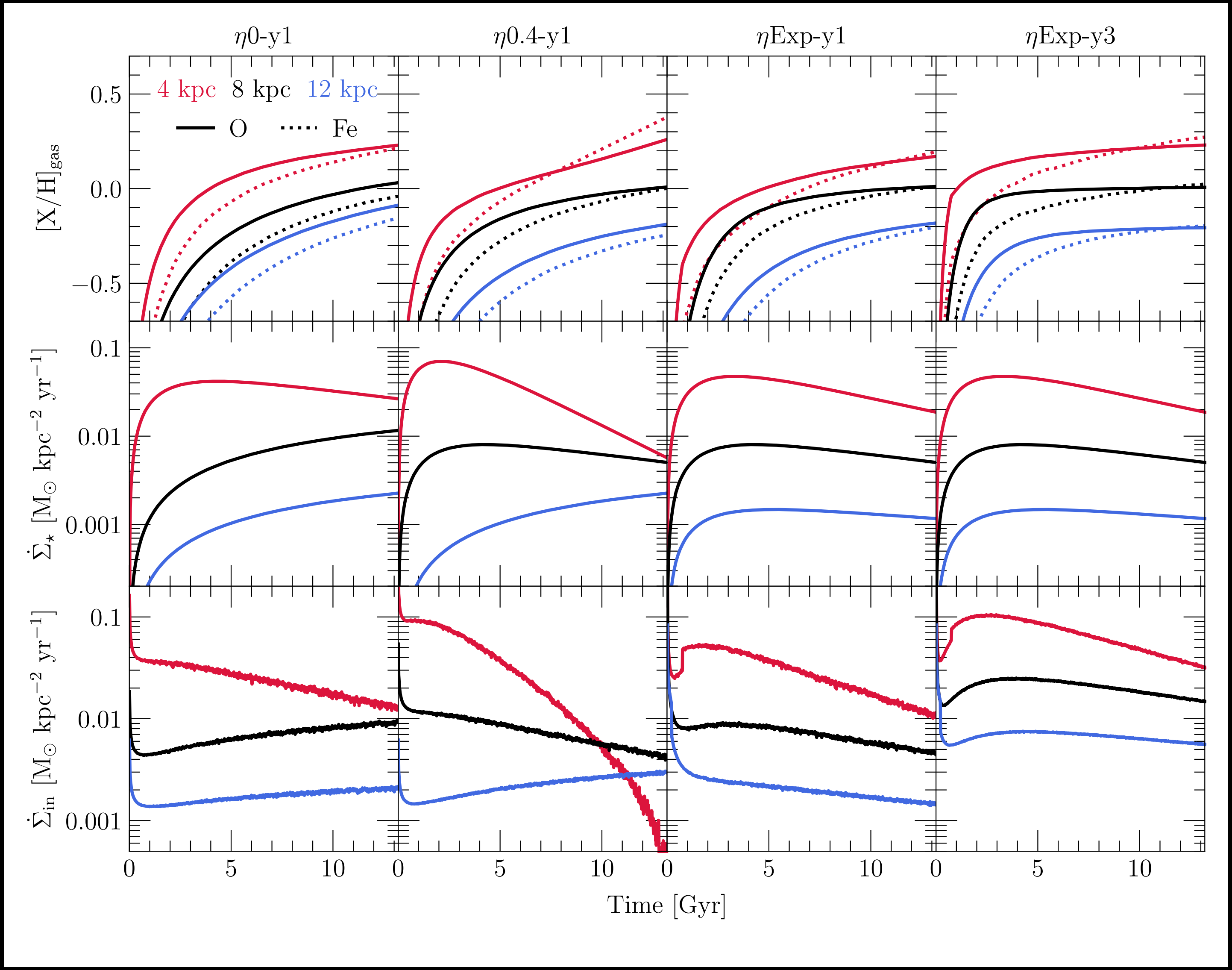
Predicted Evolutionary Histories

Slightly different SFHs between each model, each within inside-out paradigm

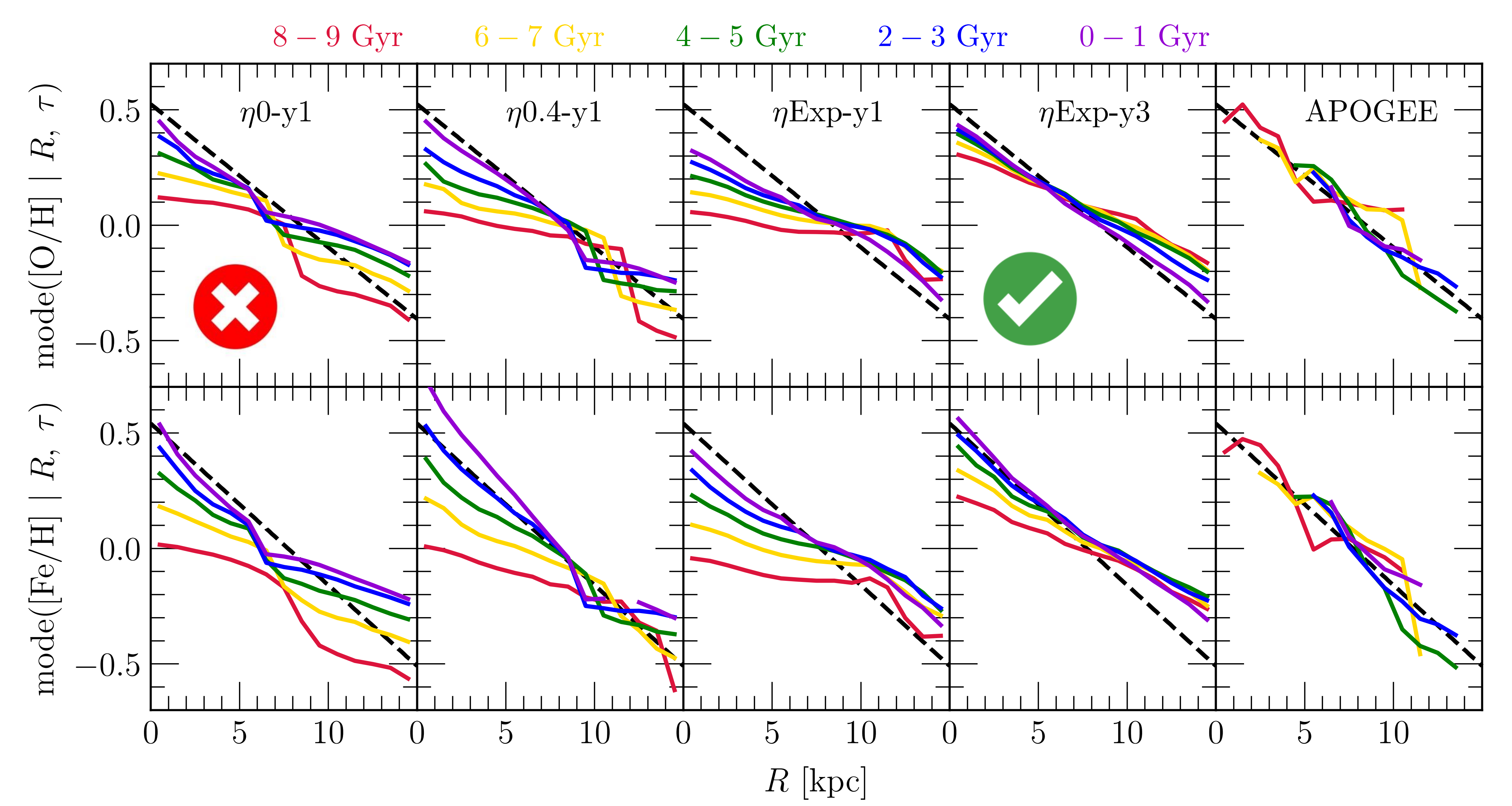
Each model reaches present-day abundances on different timescales

Smooth SFH ⇒ no alpha bimodality

- Future work: eq. + earlyburst

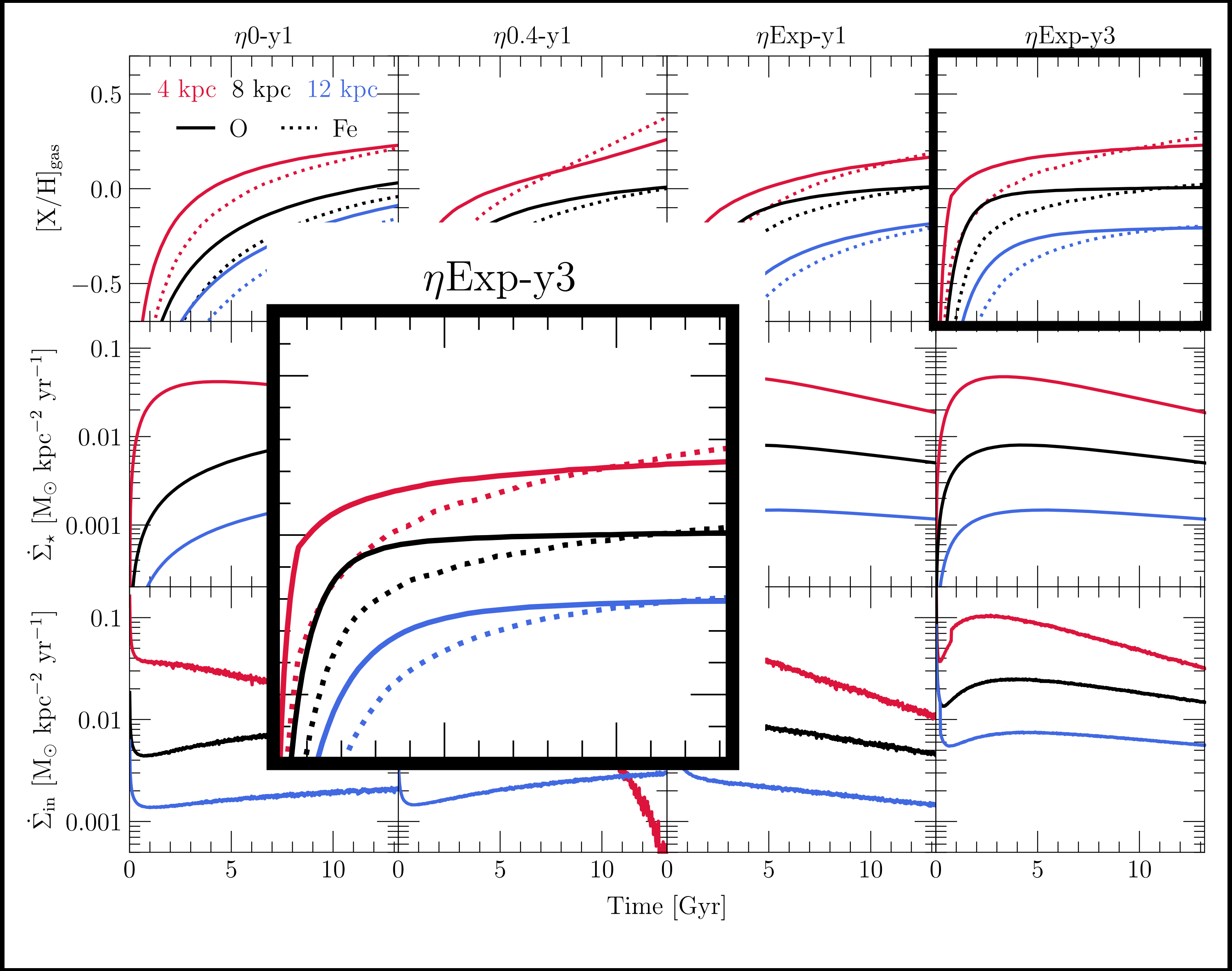


Which one looks the most like APOGEE?

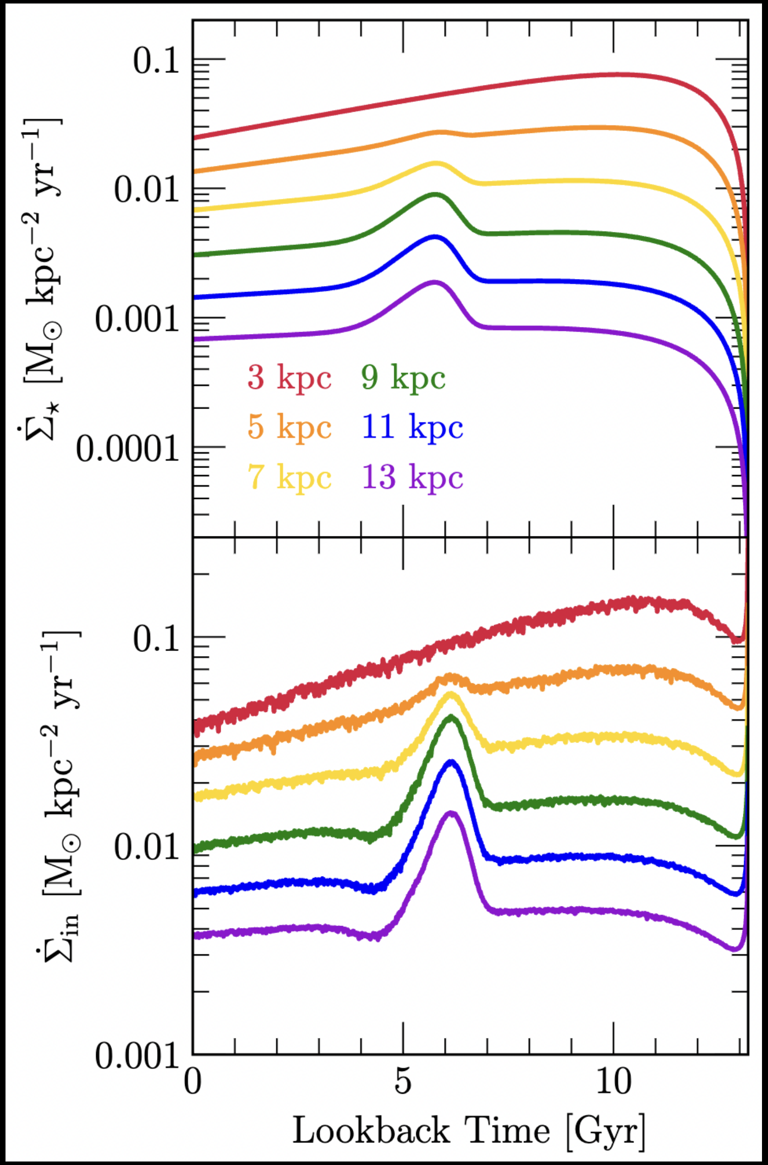


Which one looks the most like APOGEE?

Best performing model predicts this equilibrium scenario



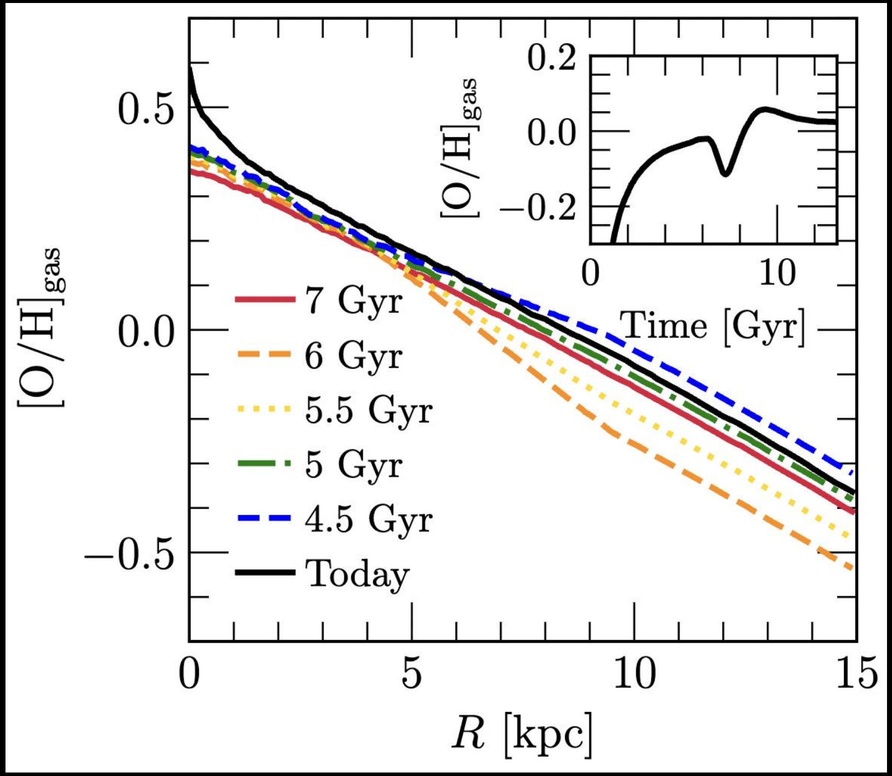
Major Mergers: Perturbations from Equilibrium



Accretion event ~6 Gyr ago

Dilution followed by re-enrichment

- Relaxes on ~Gyr timescales



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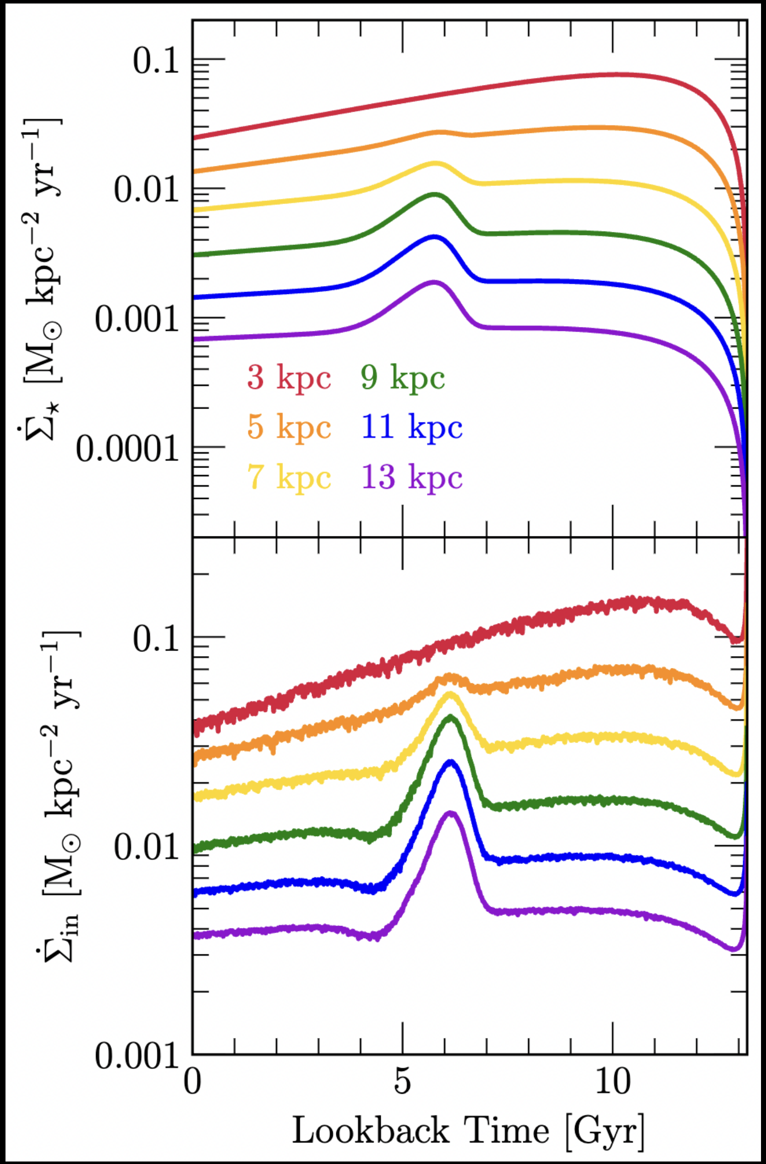

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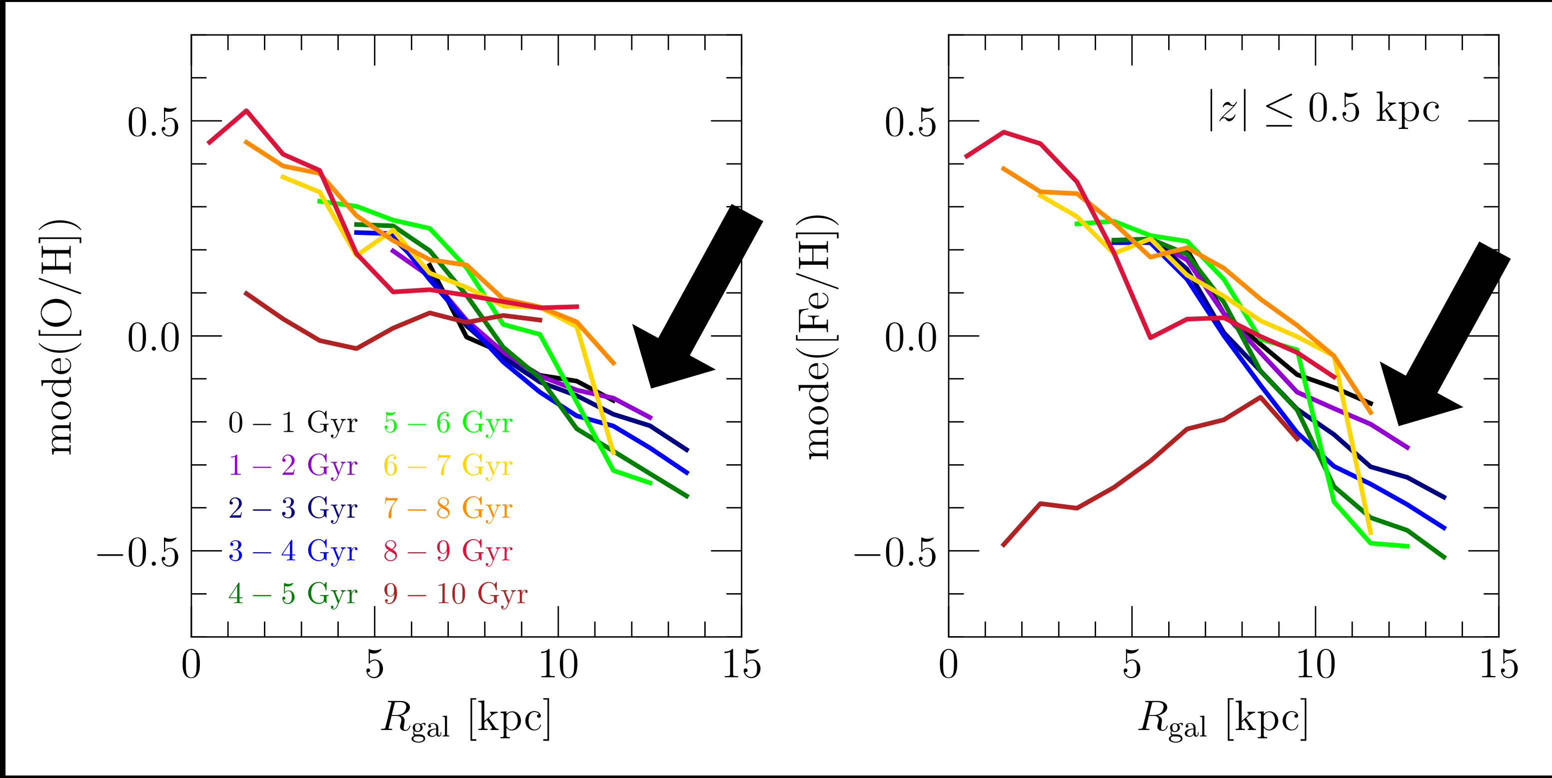
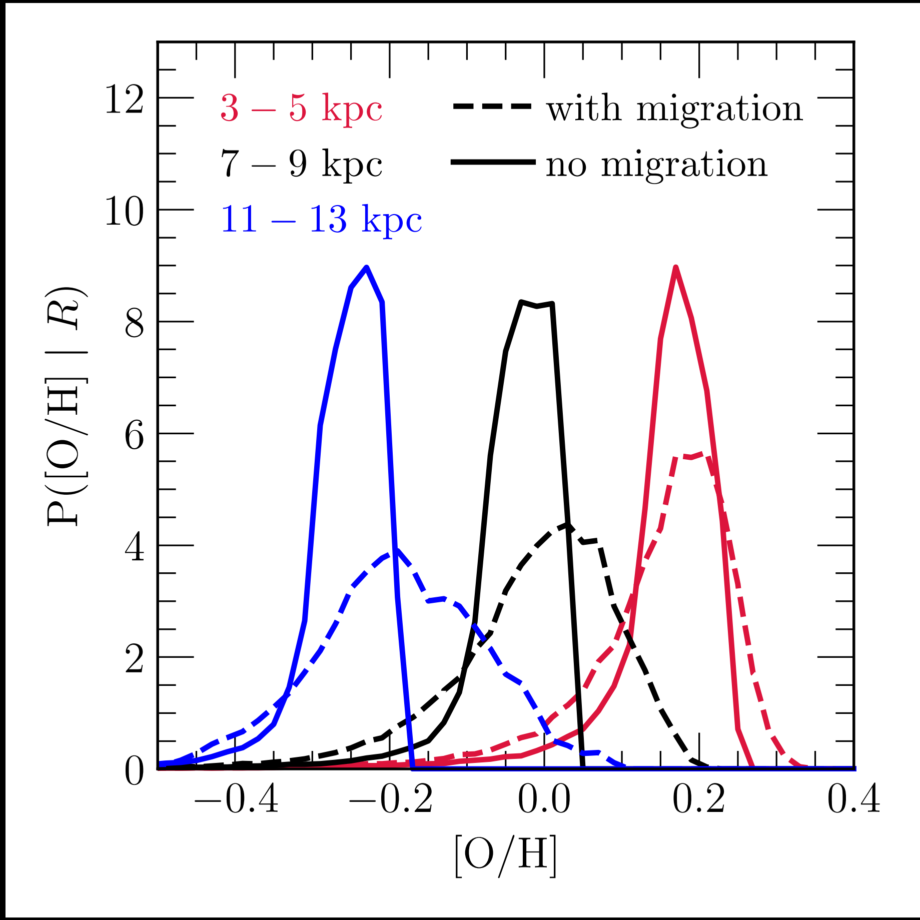
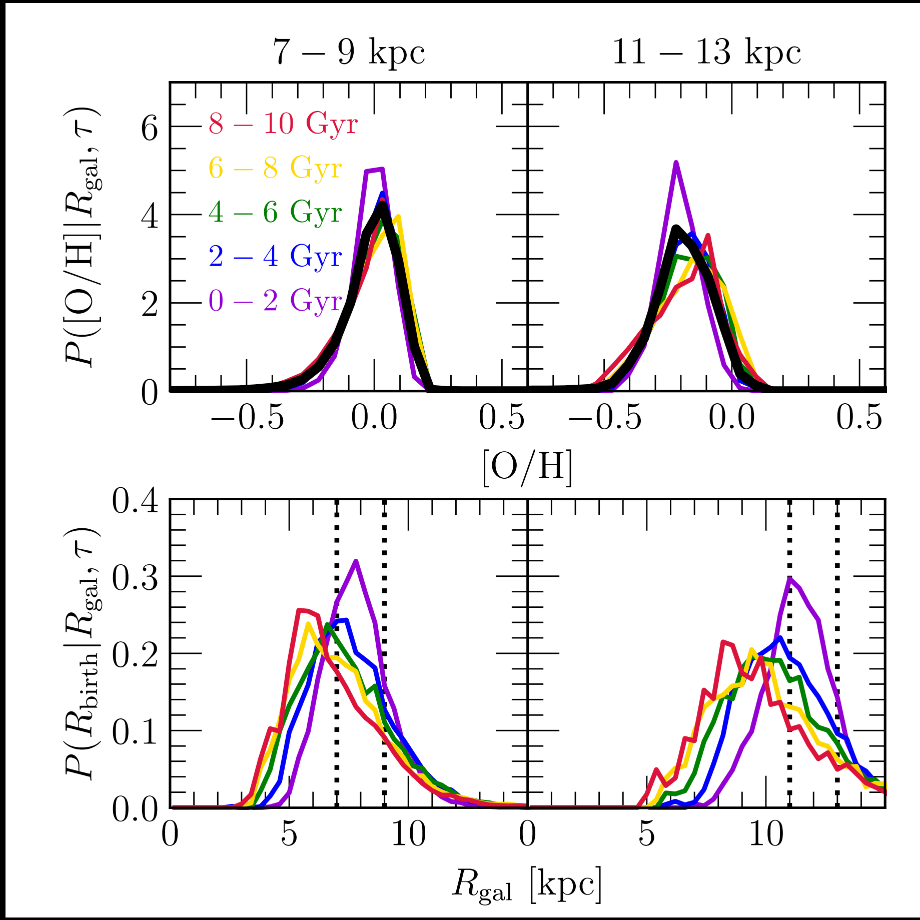


Effect of Radial Migration of Stars

Position of metallicity distribution peak preserved



Metallicity gradient too shallow to produce strong shifts



What is happening in the ISM that makes it reach an equilibrium state?

Main Driver of Equilibrium Variations

Ratio of star formation per unit infall

- Reaches ~constant value near $Z_{\alpha,eq}$

$$Z_{\alpha,eq} = \frac{y_\alpha}{1+\eta-r-\frac{\tau_\star}{\tau_{sfh}}} \rightarrow y_\alpha \frac{\dot{\Sigma}_\star}{\dot{\Sigma}_{in}}$$

$\dot{\Sigma}_Z$

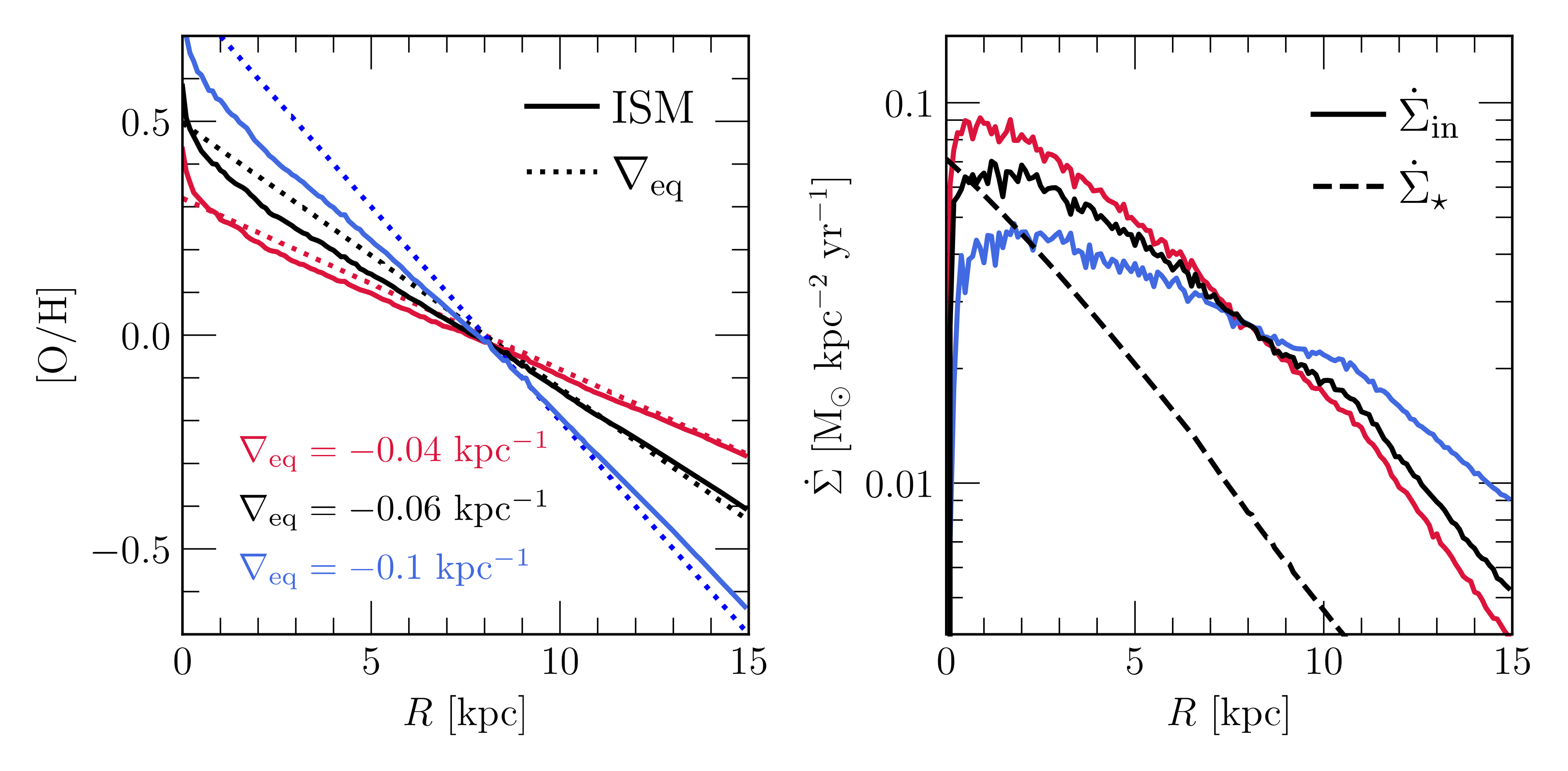
$\dot{\Sigma}_H$

$$\nabla[Z/H] \rightarrow \frac{1}{\ln 10}\left(\frac{\partial \ln \dot{\Sigma}_\star}{\partial R} - \frac{\partial \ln \dot{\Sigma}_{in}}{\partial R}\right)$$

Metal rich gas lost to outflow replaced with metal-poor accretion

Main Driver of Equilibrium Variations

$\eta \propto e^{R/R_\eta} \Rightarrow R_\eta$ controls slope of equilibrium gradient



How fast is the approach to equilibrium?

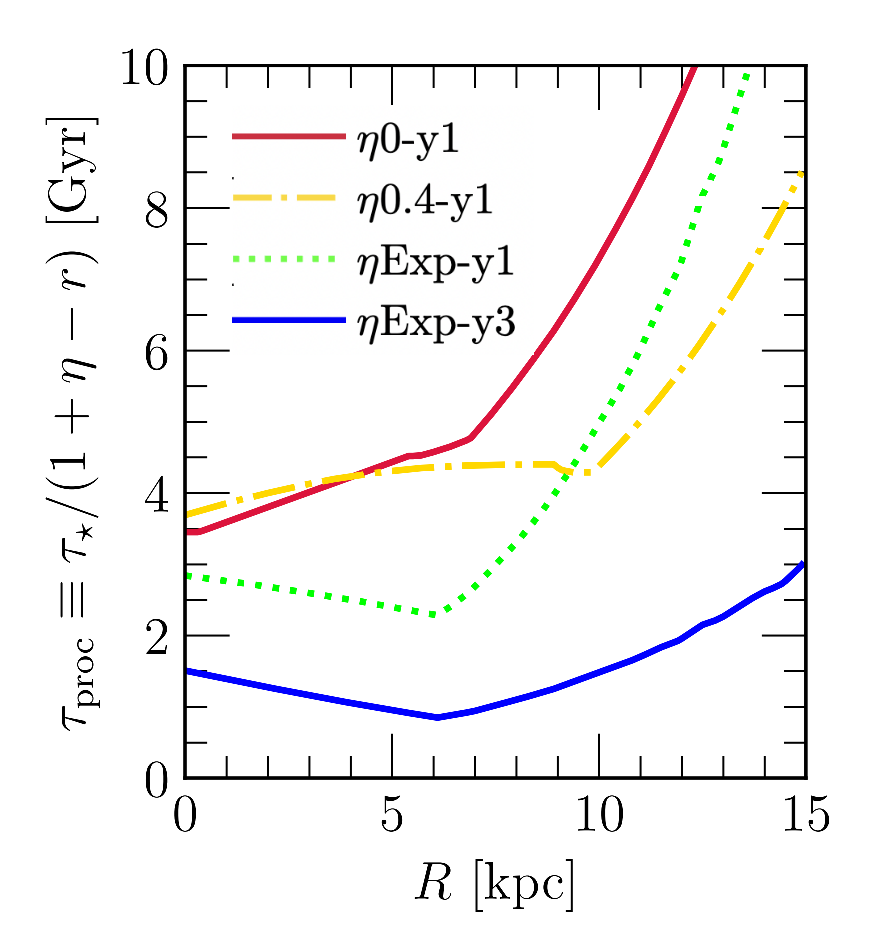
"Processing" timescale: How long a fluid element remains present in the ISM

$$\tau_{proc} \equiv \frac{\tau_\star}{1 + \eta - r}$$

In a one-zone model w/smooth SFH:

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

Inefficient star formation and/or weaker outflows ⇒ reach equilibrium later



$\eta \propto e^R$: Tracing disk surface density?

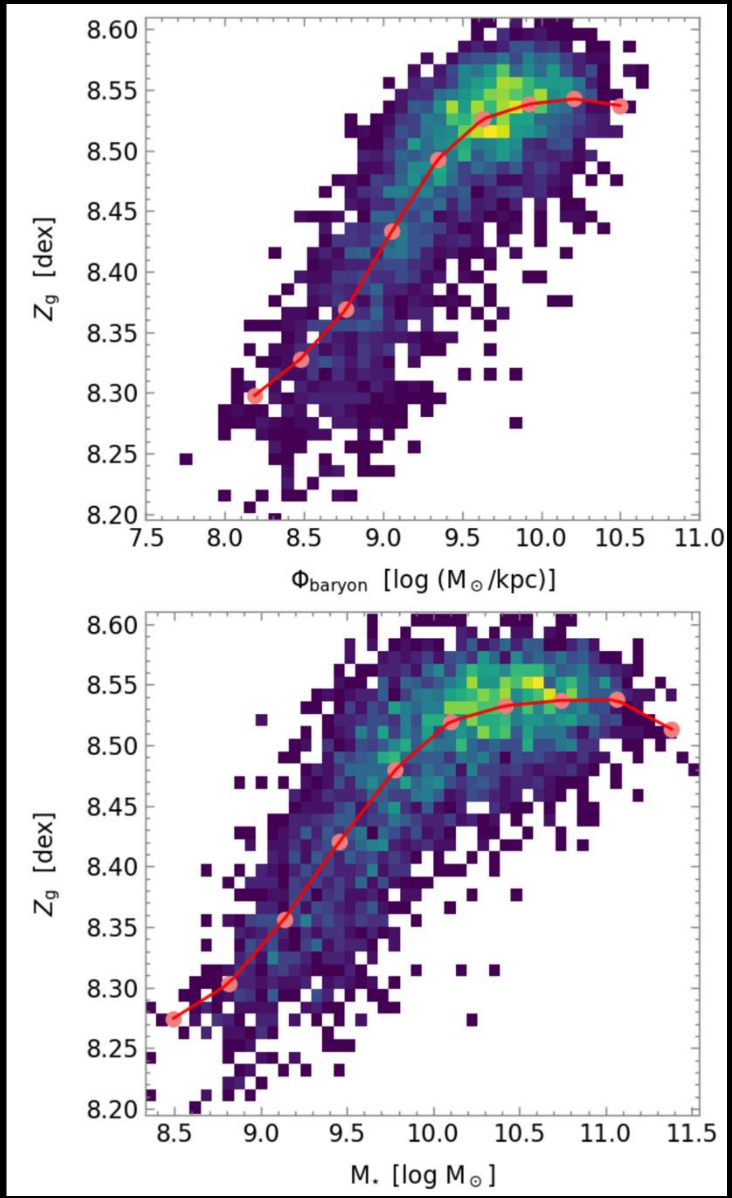
MZR: $\Phi_{bary} - Z_{ISM}$ tighter than $M_\star - Z_{ISM}$

- Sánchez-Menguiano et al. (2024a,b)

Within the disk: $\nabla Z_{eq} \propto \nabla \Phi_{bary}$

Inside-out growth *indirect* cause of metallicity gradients

- Inside-out ⇒ exp. disk
  $\Rightarrow \nabla\Phi_{bary} < 0 \Rightarrow \nabla Z < 0$



Outflows: Only One Possible Origin

What we can say relatively concretely:

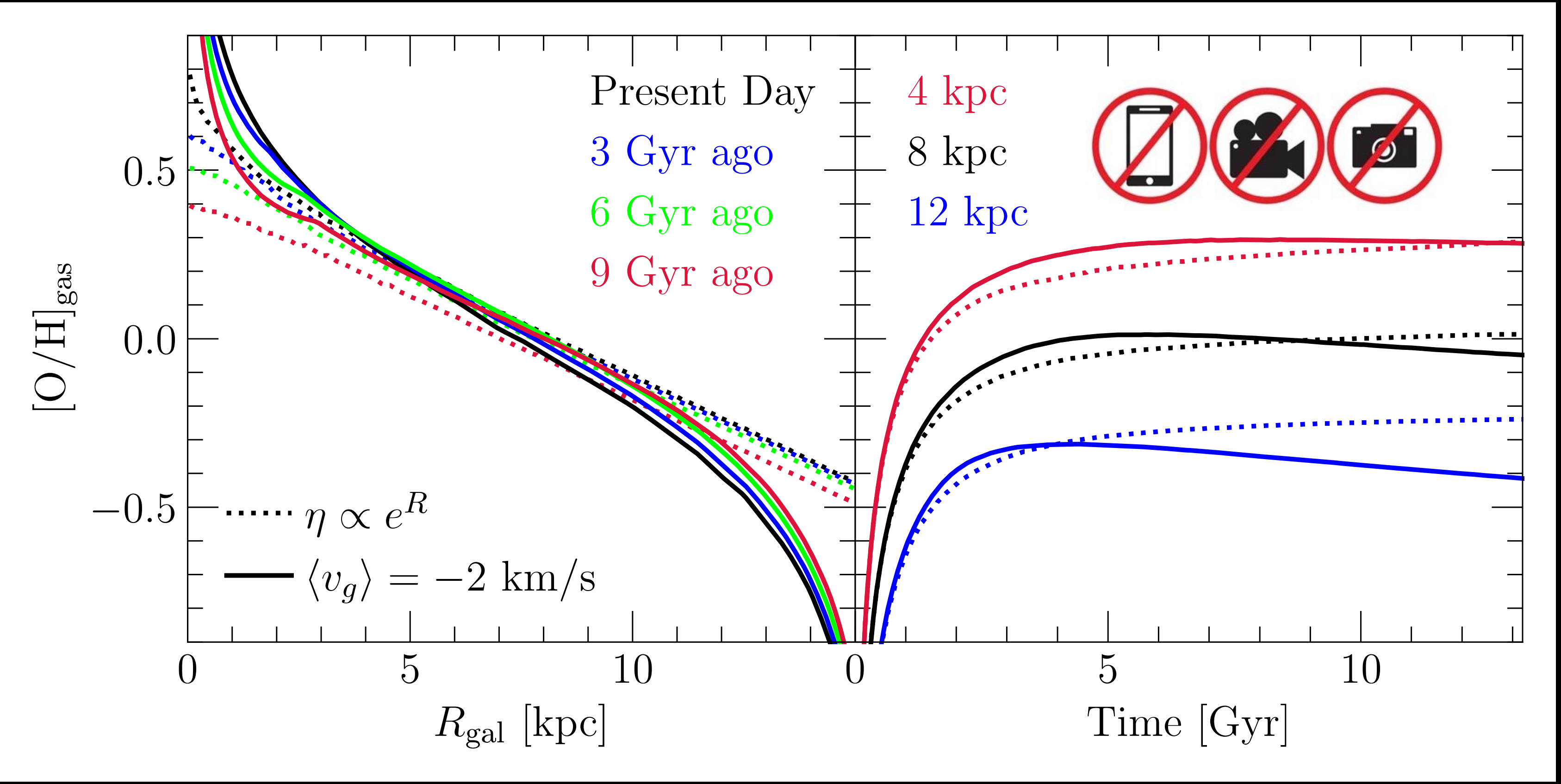
- Some process removing metal-rich gas from star forming region with $A_{proc} \equiv -\dot{\Sigma}_{proc} \,/\, \dot{\Sigma}_{\star} \propto e^{R}$
  - Shape of the gradient
- A_{proc} must be ~steady on ~10 Gyr timescales
  - Age-independence of the metallicity gradient normalization

Future Work: Radial gas flows

Preliminary Model with Radial Gas Flows

Removing outflow and inserting v_g = const. ⇒ equilibrium behavior

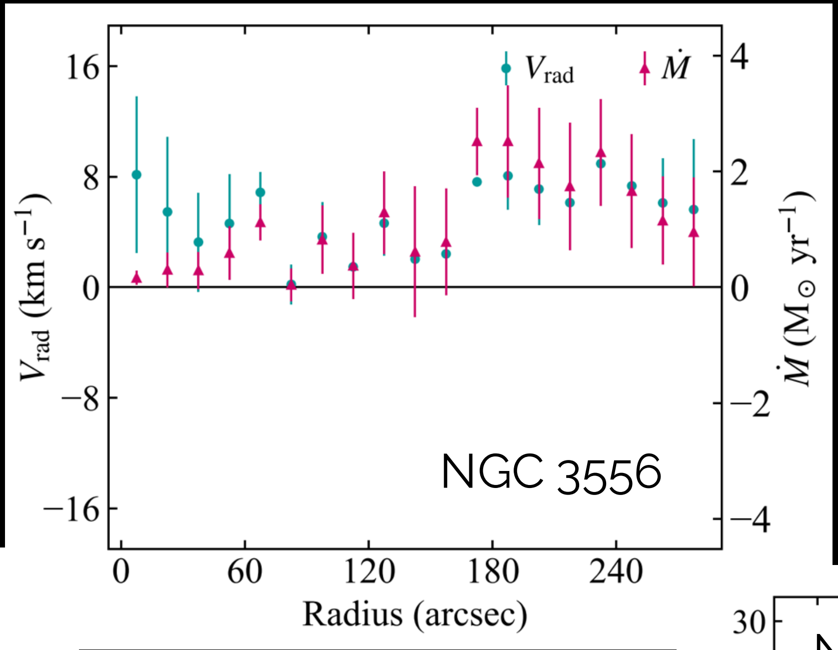
$y - \eta$ degeneracy becomes $y - v_g$ degeneracy

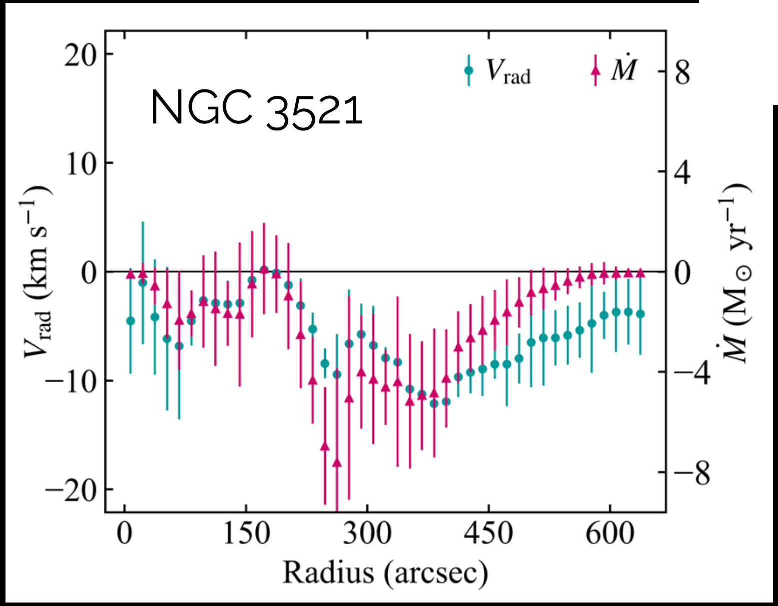


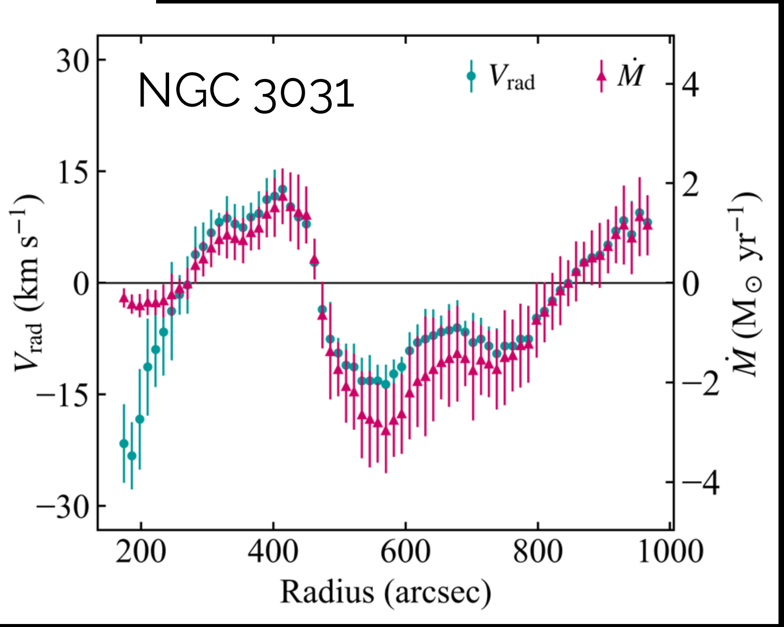
Is $v_g \neq$ constant realistic?

Di Teodoro & Peek (2021)

- Measured radial velocities in 54 nearby spirals with HI 21 cm line
- A lot of variety in profiles







The Equilibrium Model

Postulates that metal abundances tend toward some steady state

- Gradient traces ratio of star formation per unit infall

Physically motivated with connection between outflow efficiency and baryonic gravitational potential as functions of radius

Reaching equilibrium early requires *fast* chemical evolution

- High stellar yields and short processing timescales
- Original motivation was to get chemical evolution to *slow down*

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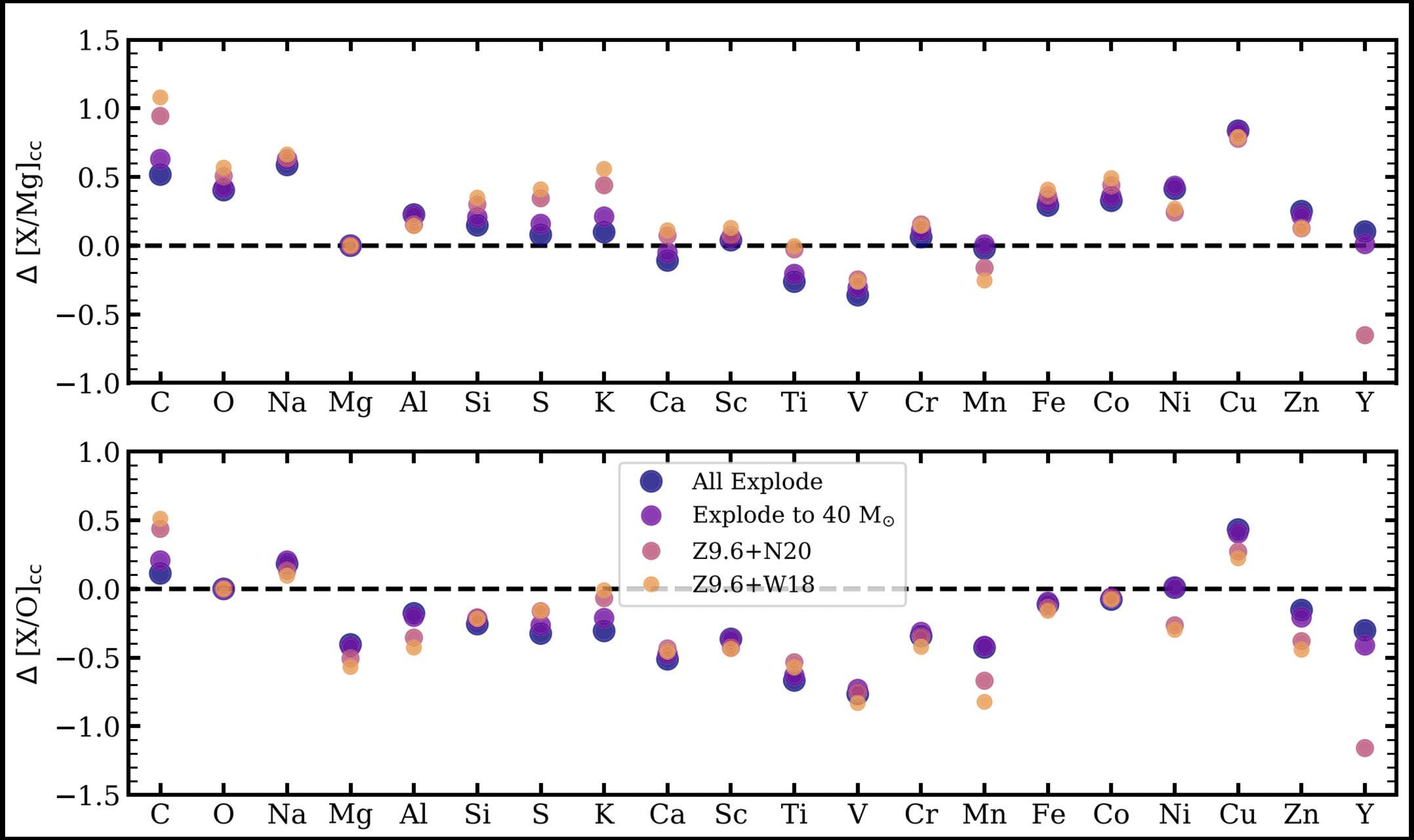
Uncertainties in Stellar Yield Predictions

Sukhbold et al. (2016) yields with forced explosion

Combine yields w/various BH formation prescriptions & none reproduce data

Reaction rates themselves uncertain (Fields et al. 2018)



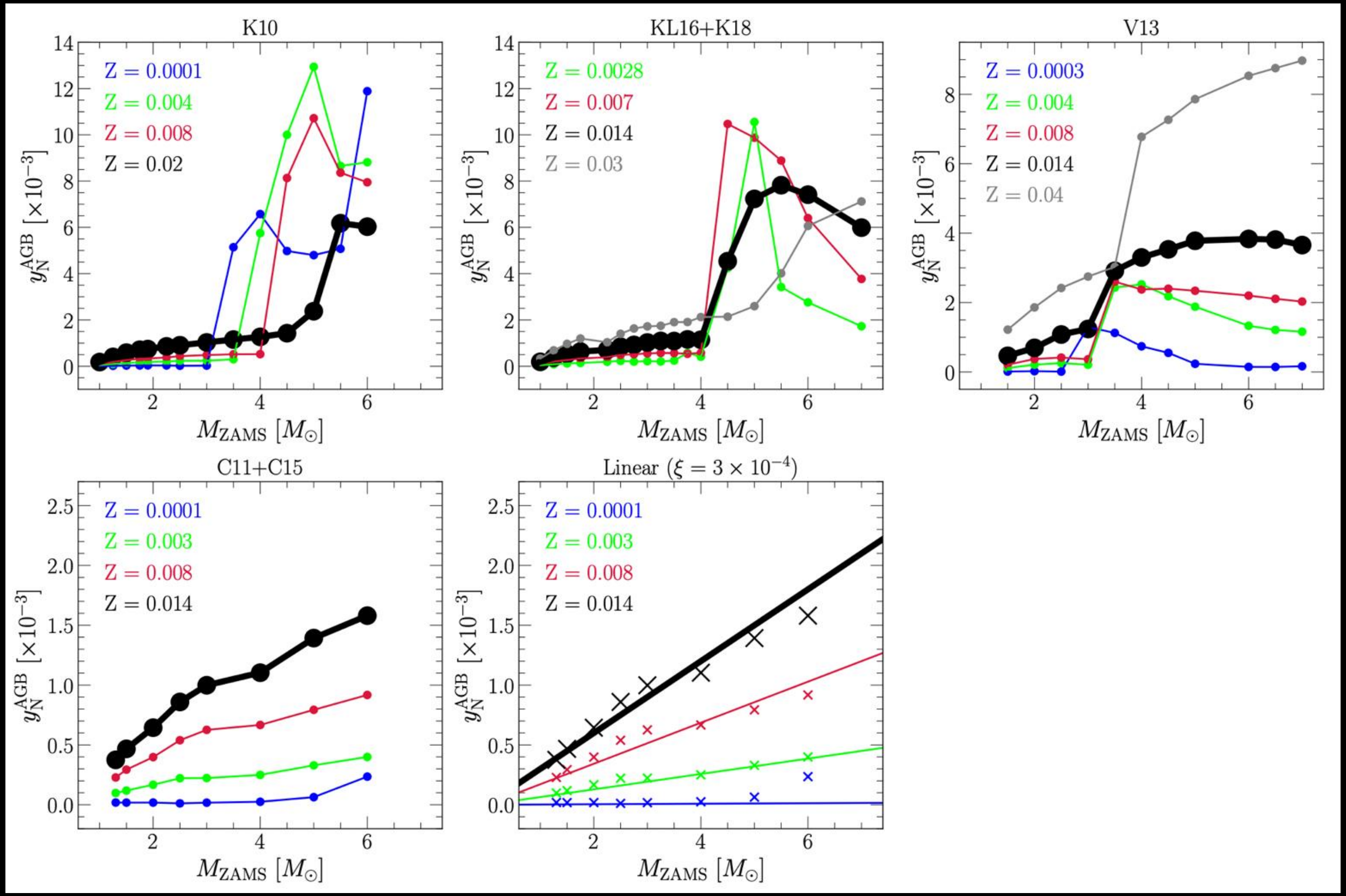
Griffith et al. (2021), Fig. 9

Uncertainties in Stellar Yield Predictions

Fundamentally different trends in N yields from AGB stars predicted by different models

Uncertain processes:

- Hot Bottom Burning
- Third Dredge Up
- Nuclear reaction rates
- Rotation & rotational mixing
- Convection
- Mass loss



Johnson et al. (2023), Fig. 3

Mathematics behind the Models

$$\dot{\Sigma}_g = \dot{\Sigma}_{in} - \dot{\Sigma}_\star - \dot{\Sigma}_{out} + \dot{\Sigma}_r$$

$$= \dot{\Sigma}_{in} - \dot{\Sigma}_\star(1 + \eta - r)$$

$$\Rightarrow \dot{\Sigma}_{in} = \dot{\Sigma}_g + \dot{\Sigma}_\star(1 + \eta - r)$$

$$\Rightarrow \frac{\dot{\Sigma}_{in}}{\dot{\Sigma}_\star} = \frac{\dot{\Sigma}_g}{\dot{\Sigma}_\star} + 1 + \eta - r$$

$$\rightarrow 1 + \eta - r - \frac{\tau_\star}{\tau_{sfh}}$$

$$\dot{\Sigma}_\alpha = y_\alpha^{CC}\dot{\Sigma}_\star - Z_\alpha\dot{\Sigma}_\star(1 + \eta - r)$$

$$\dot{\Sigma}_{Fe} = y_{Fe}^{CC}\dot{\Sigma}_\star - y_{Fe}^{Ia}\left\langle\dot{\Sigma}_\star\right\rangle_{Ia} - Z_{Fe}\dot{\Sigma}_\star(1 + \eta - r)$$

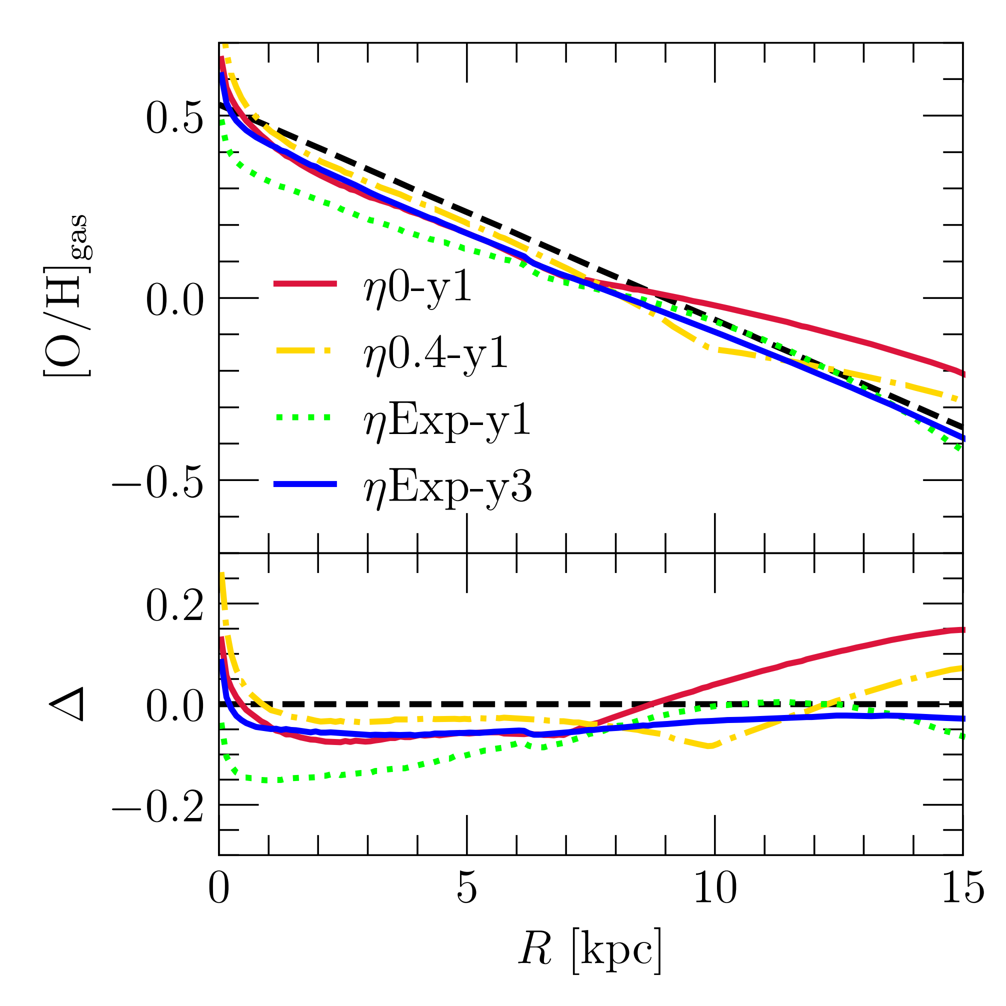
$$R_{Ia} \propto t^{-1.1}$$

Parameter Calibration

$$\dot{\Sigma}_\star \propto \left(1 - e^{-t/\tau_{rise}}\right) e^{-t/\tau_{sfh}}$$

All models tuned to approximate present-day ISM abundances

- Mendez-Delgado et al. (2022)
- Scaling of η with radius for $\eta \propto e^R$
- Scaling of τ_{rise}, τ_{sfh} for η = const.



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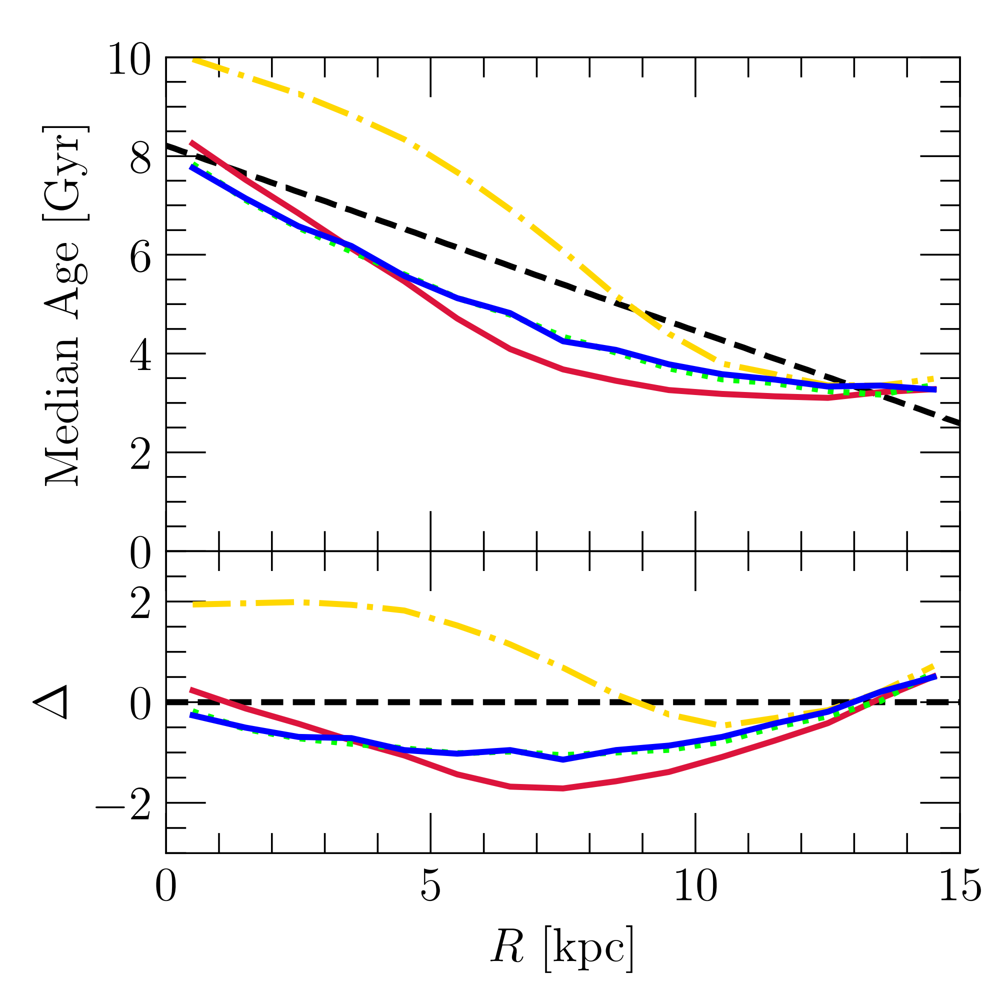
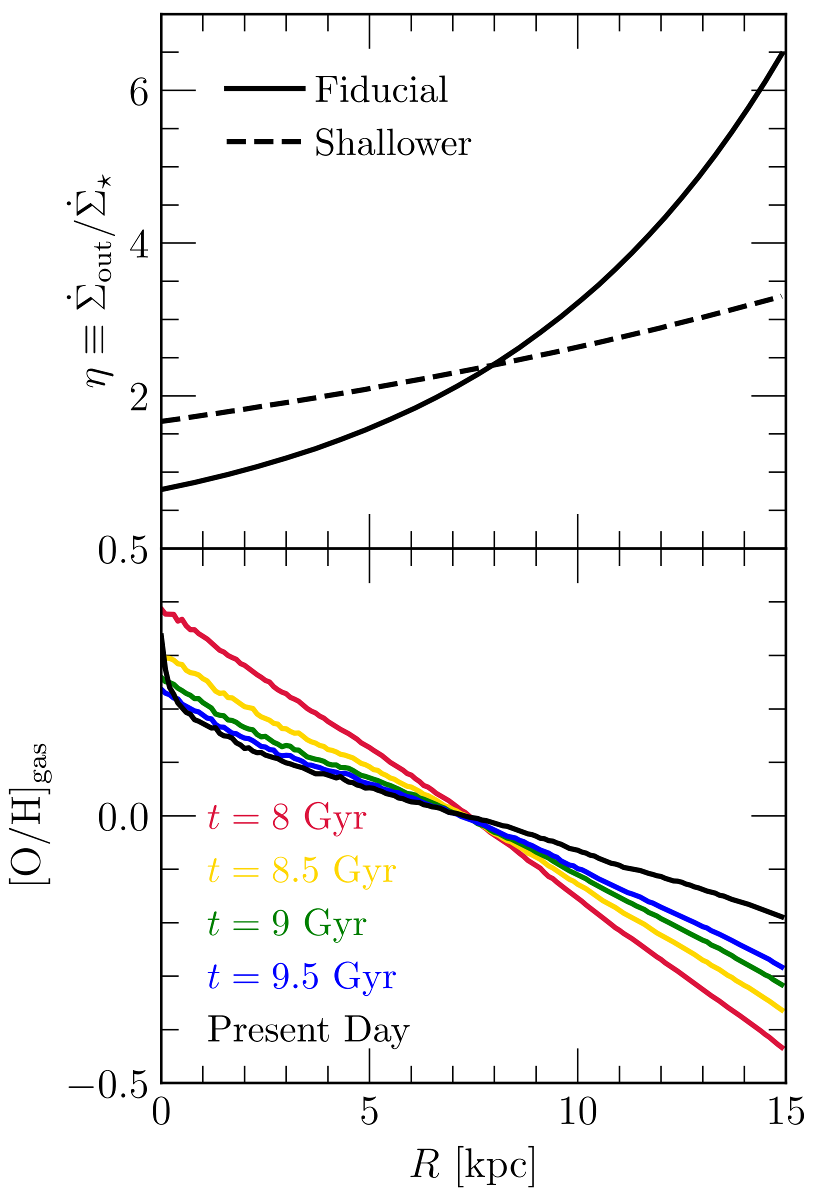
τ_{rise}, τ_{sfh} chosen to approximate age gradient for $\eta \propto e^R$

- η = const. models get close to it anyway




Fiducial
Shallower
$\eta \equiv \dot{\Sigma}_{\rm out}/\dot{\Sigma}_\star$
6
4
2
0.5
$[\rm O/H]_{gas}$
0.0
−0.5
$t = 8$ Gyr
$t = 8.5$ Gyr
$t = 9$ Gyr
$t = 9.5$ Gyr
Present Day
0
5
10
15
R [kpc]

Effect of Radial Migration of Stars

Naturally broadens the metallicity distribution with age