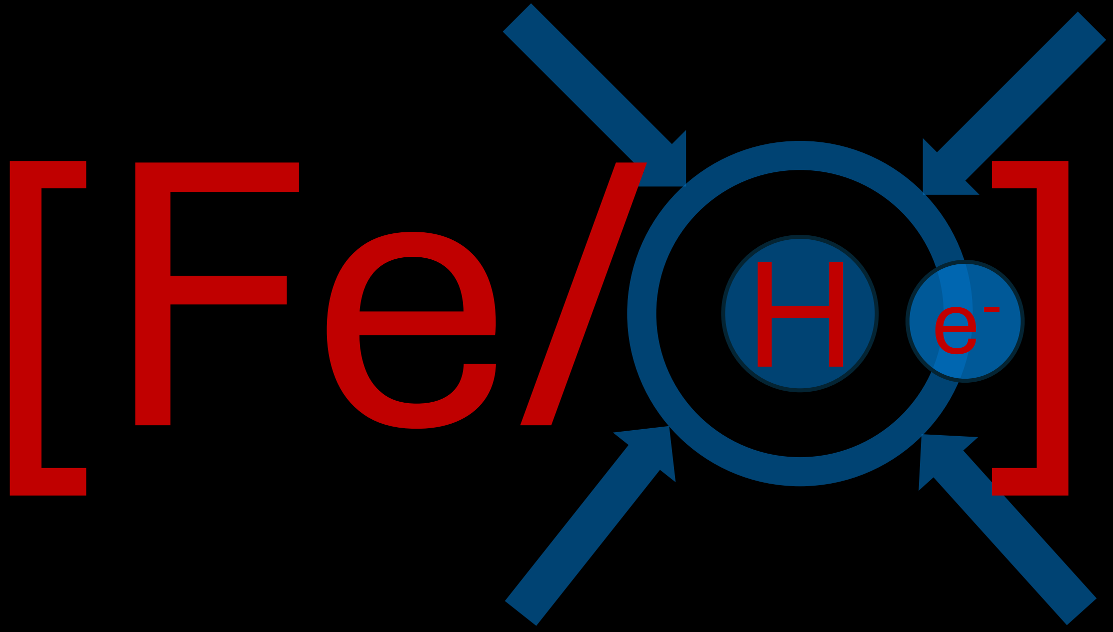
Why Galactic Chemical Evolution is Actually About Hydrogen



James W. Johnson

Galactic Metal Cycles

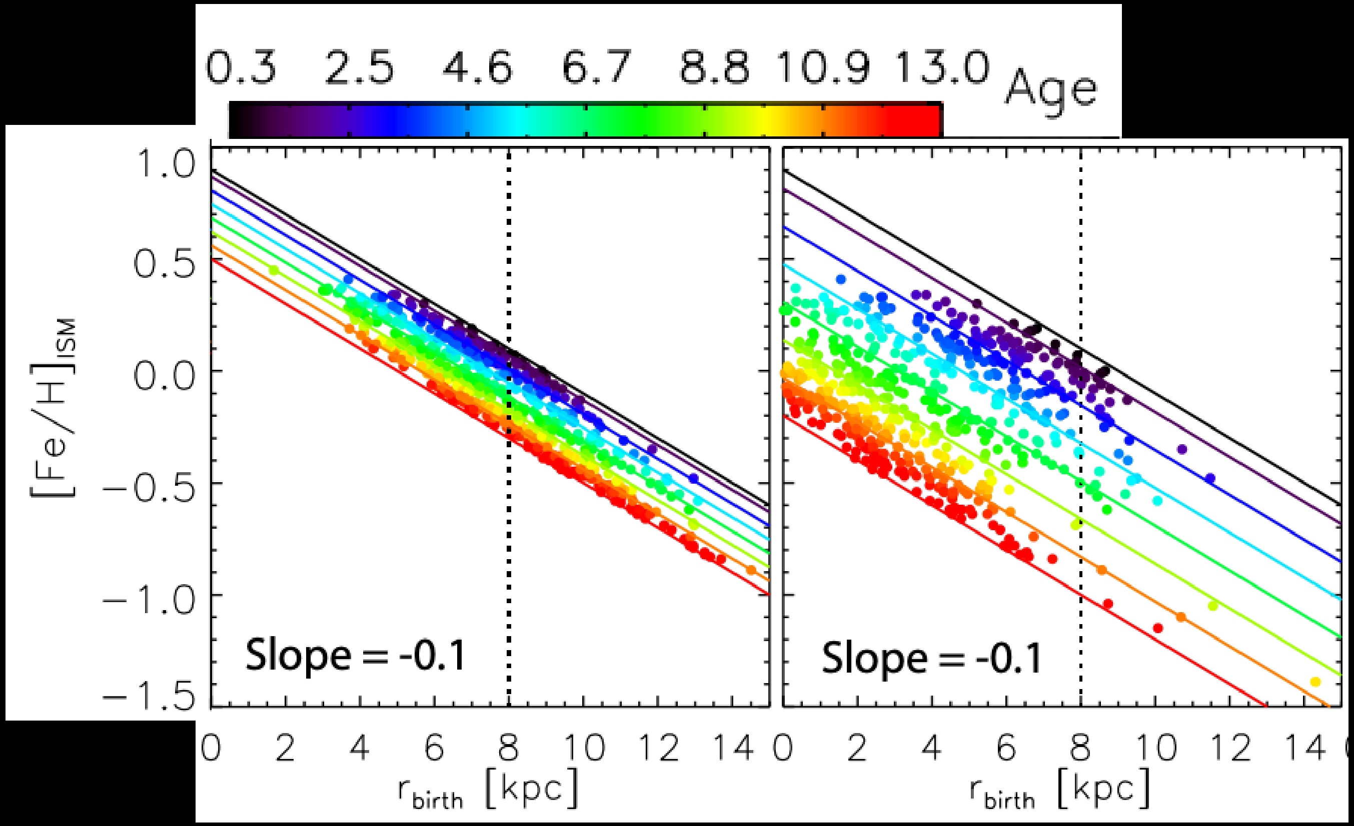
Kylemore Abbey

May 12, 2026

CARNEGIE SCIENCE

A Conundrum

Models



Minchev et al. (2018), MNRAS, 481, 1645

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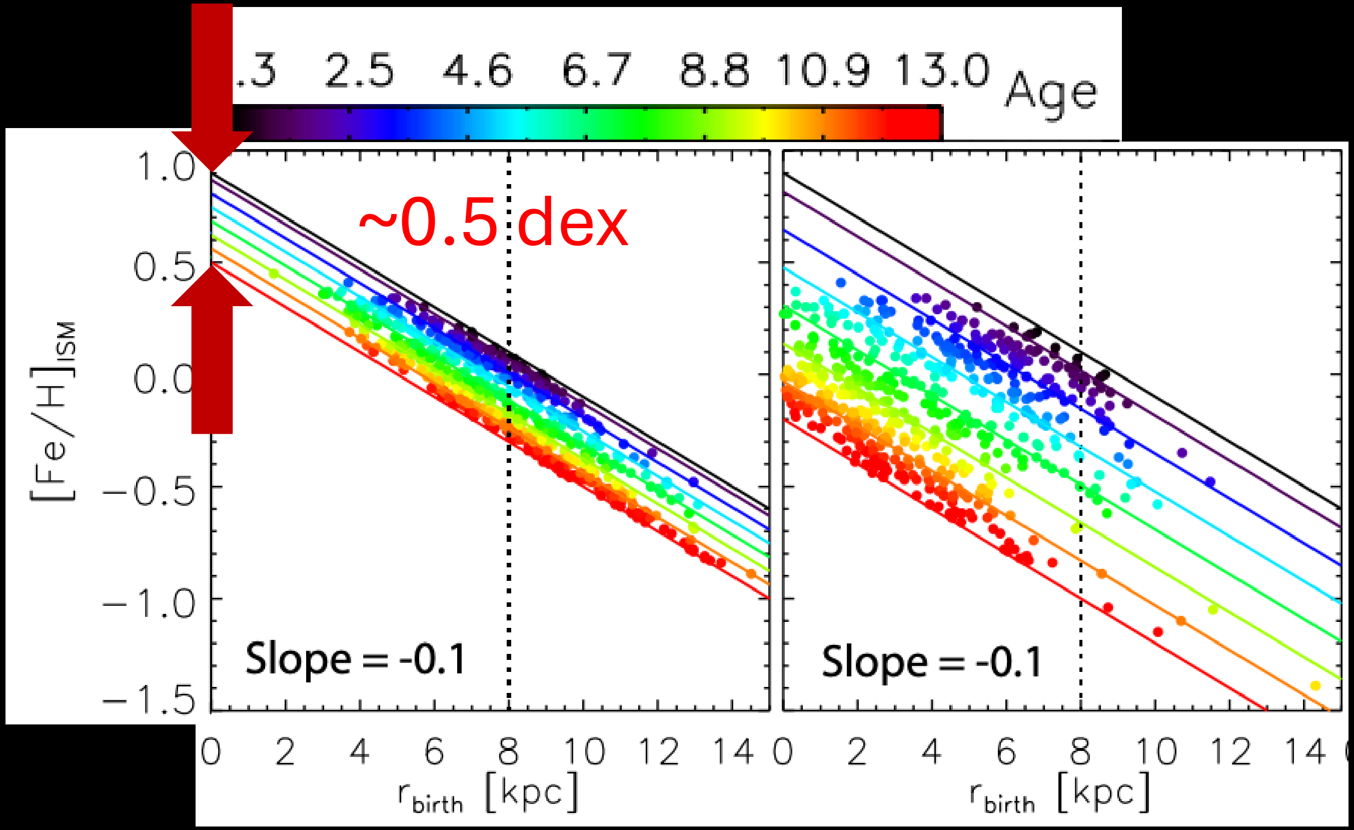

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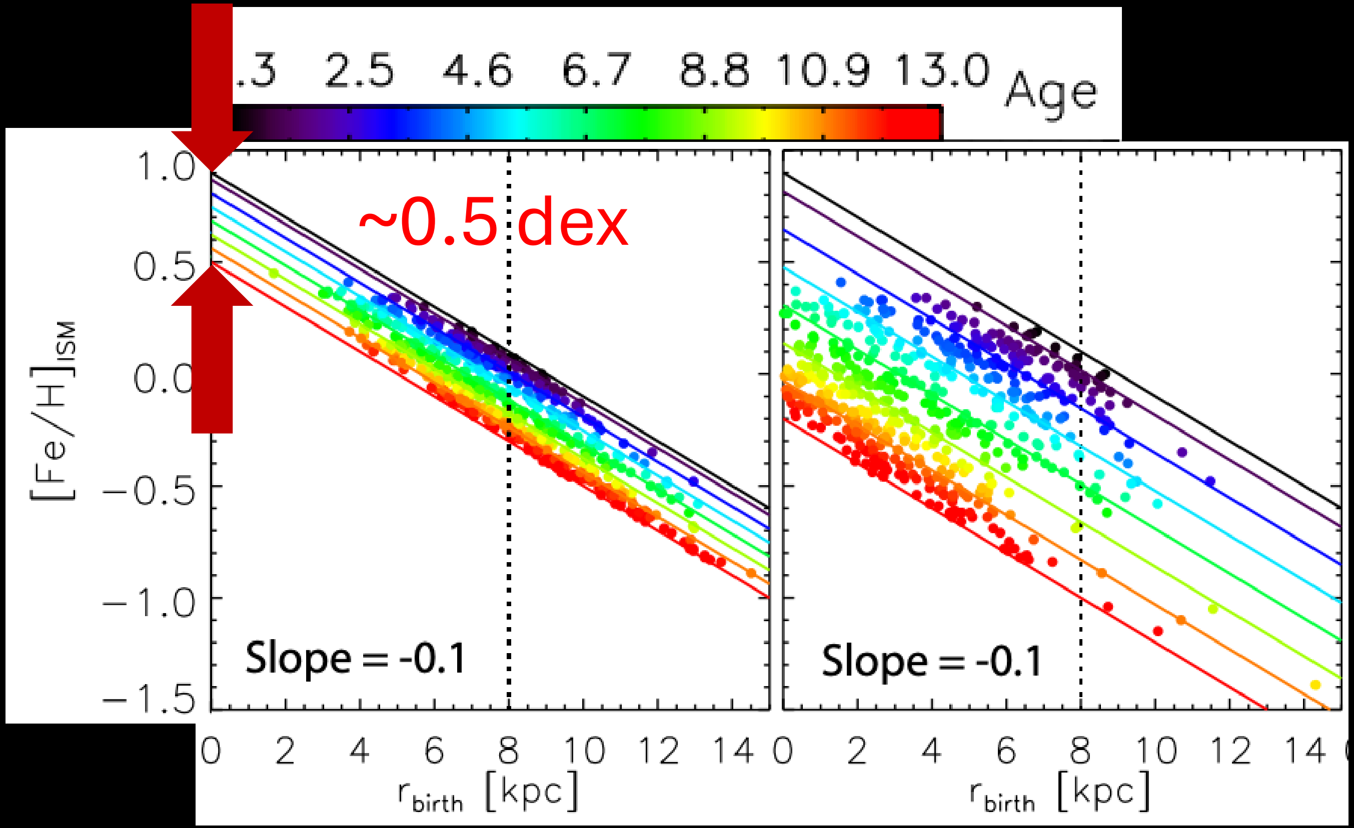
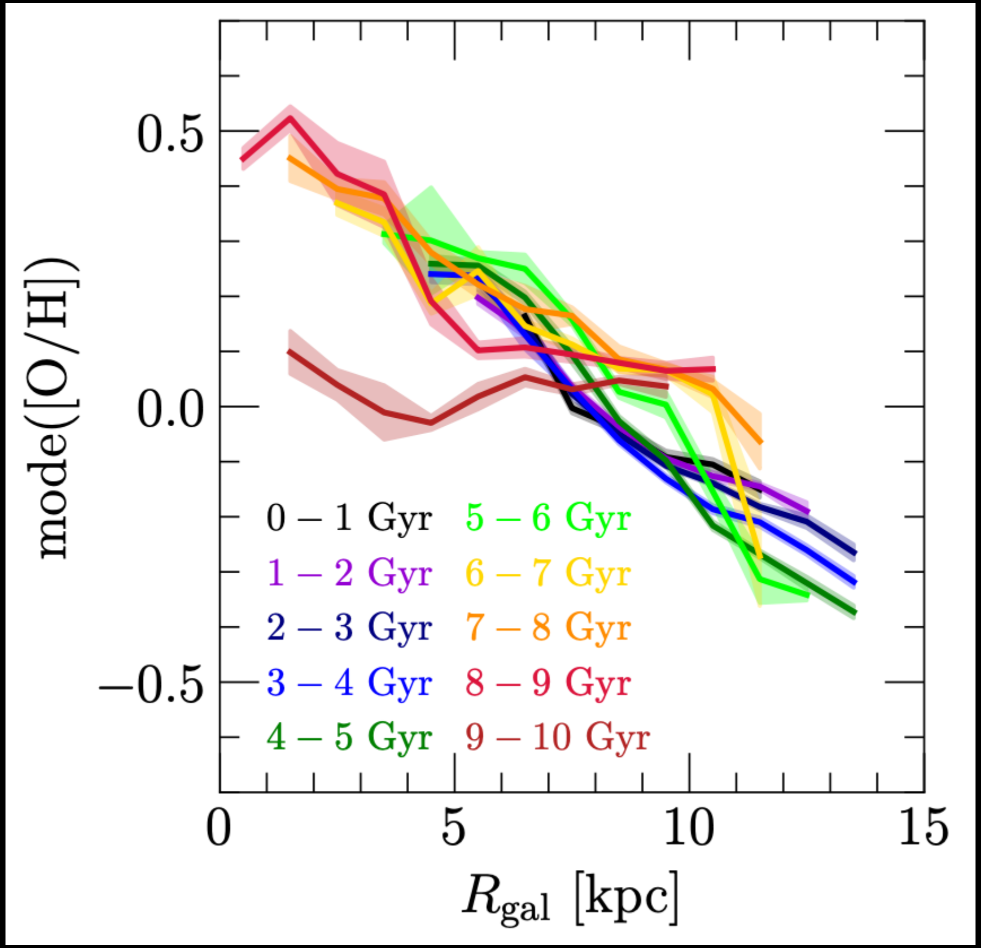


Data



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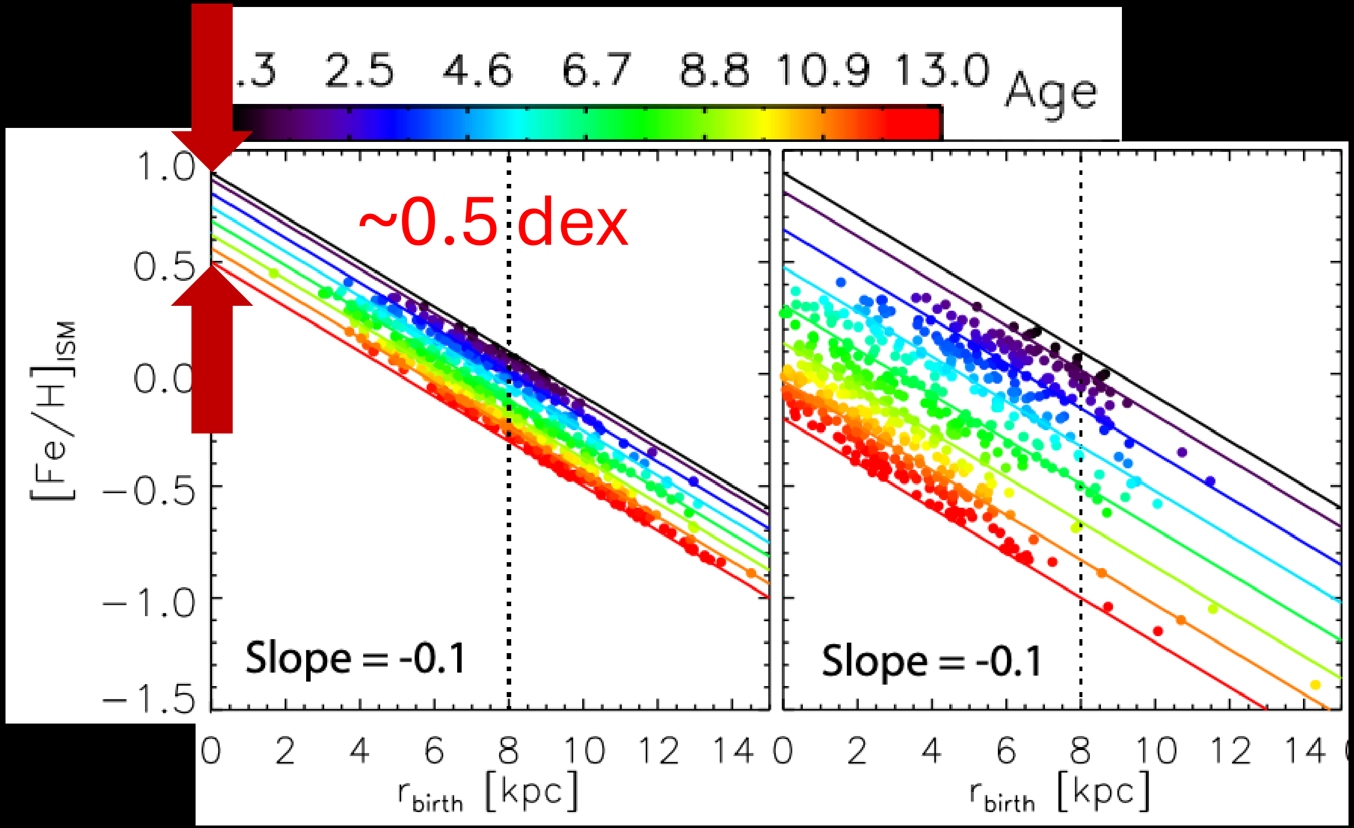

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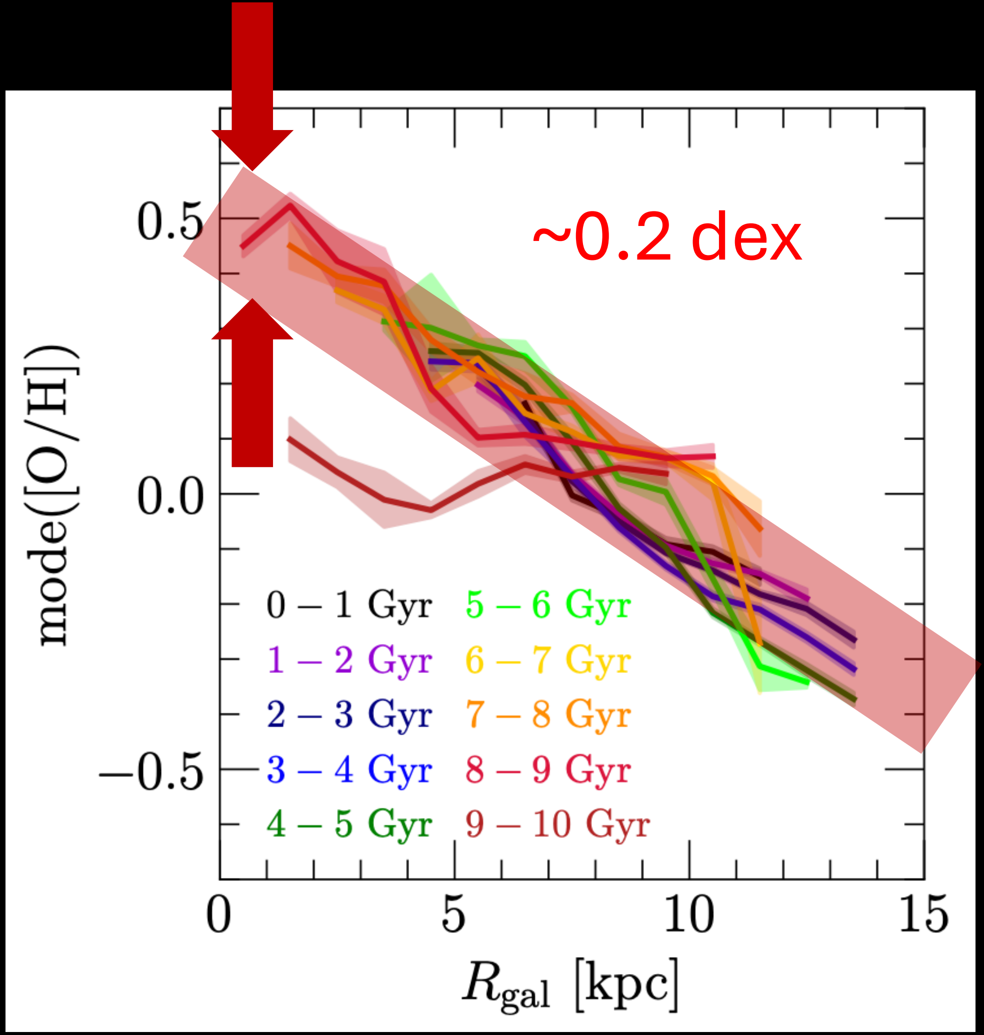

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A History Lesson: “Closed-Box” Models

First GCE models:

- No accretion
- Some gas at $t = 0$
- Initially metal-free

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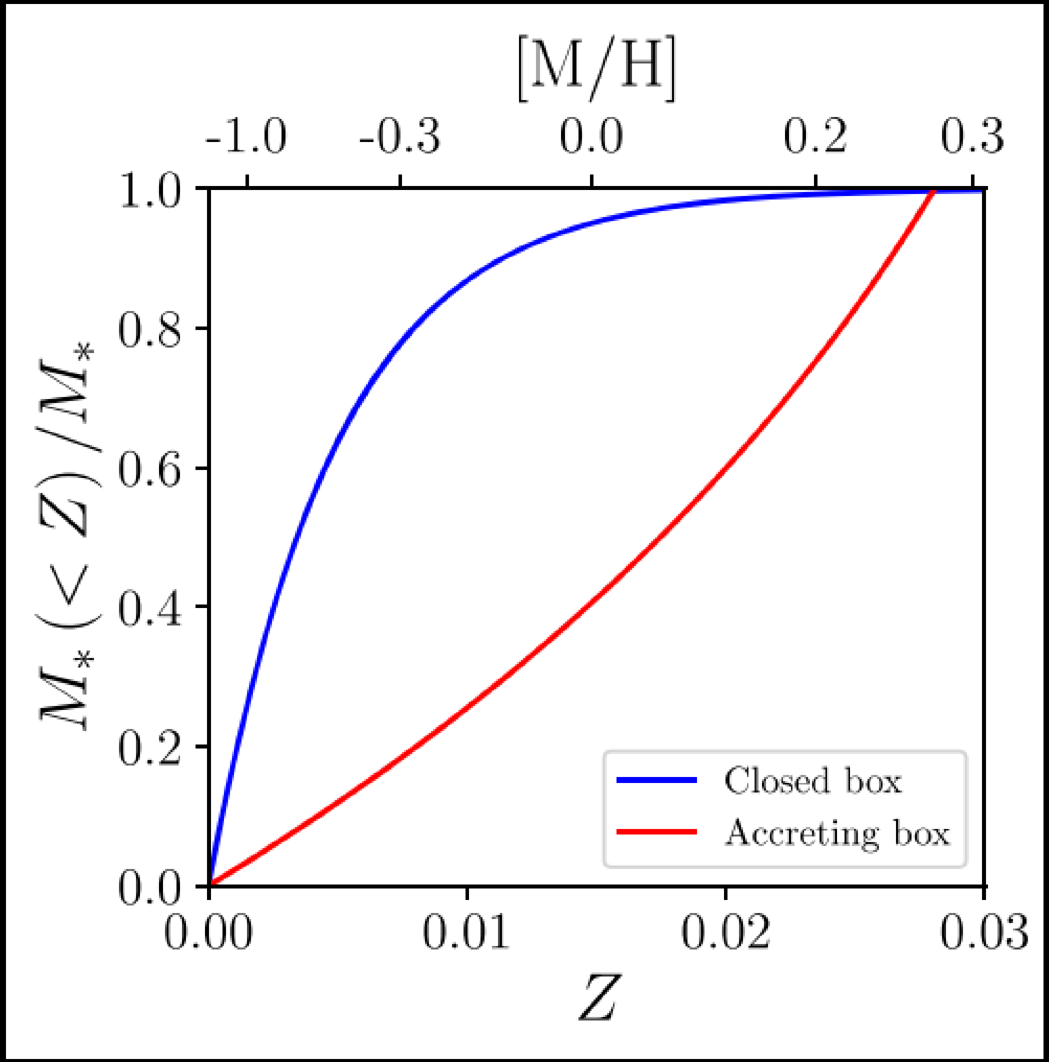

Greener et al. (2021), MNRAS, 502, 95

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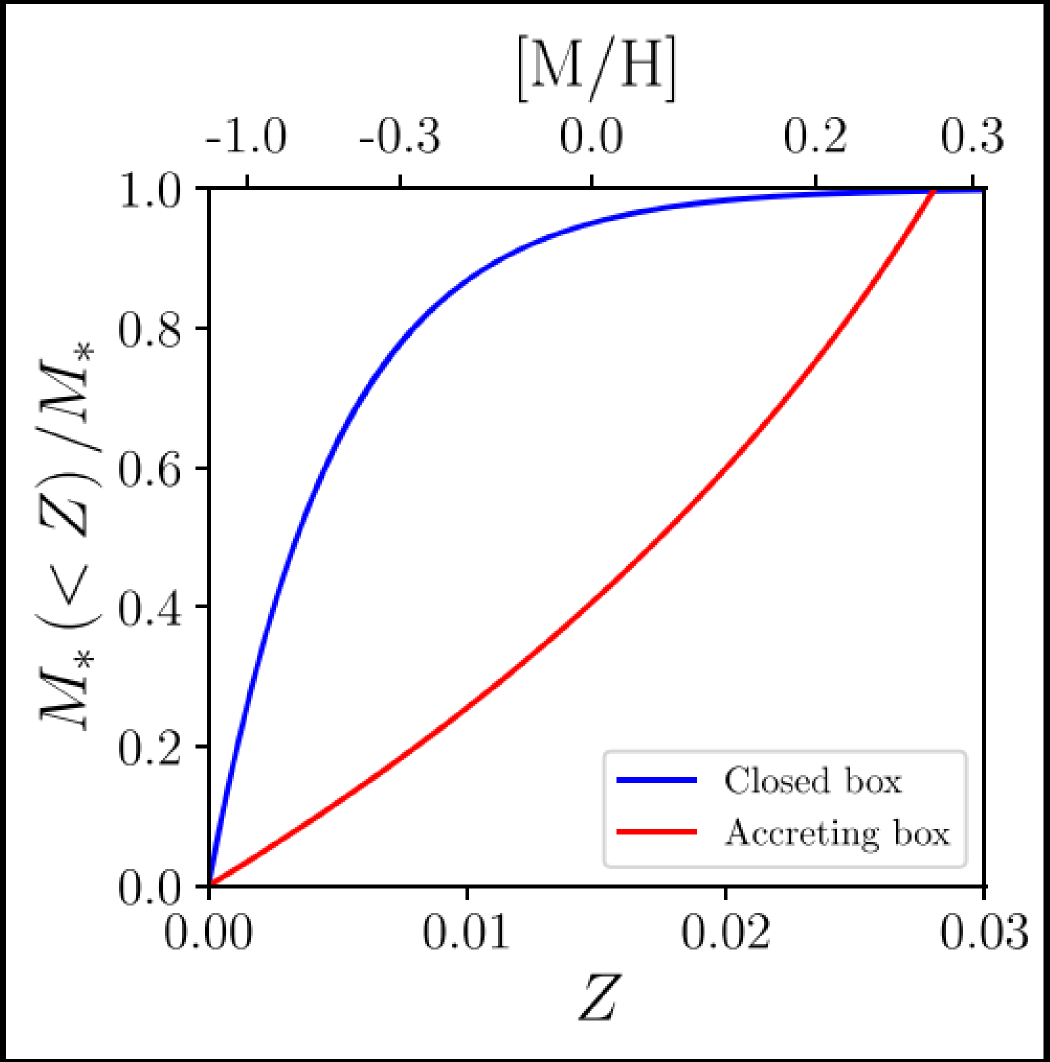
- "G-dwarf problem" (Tinsley 1980 review)



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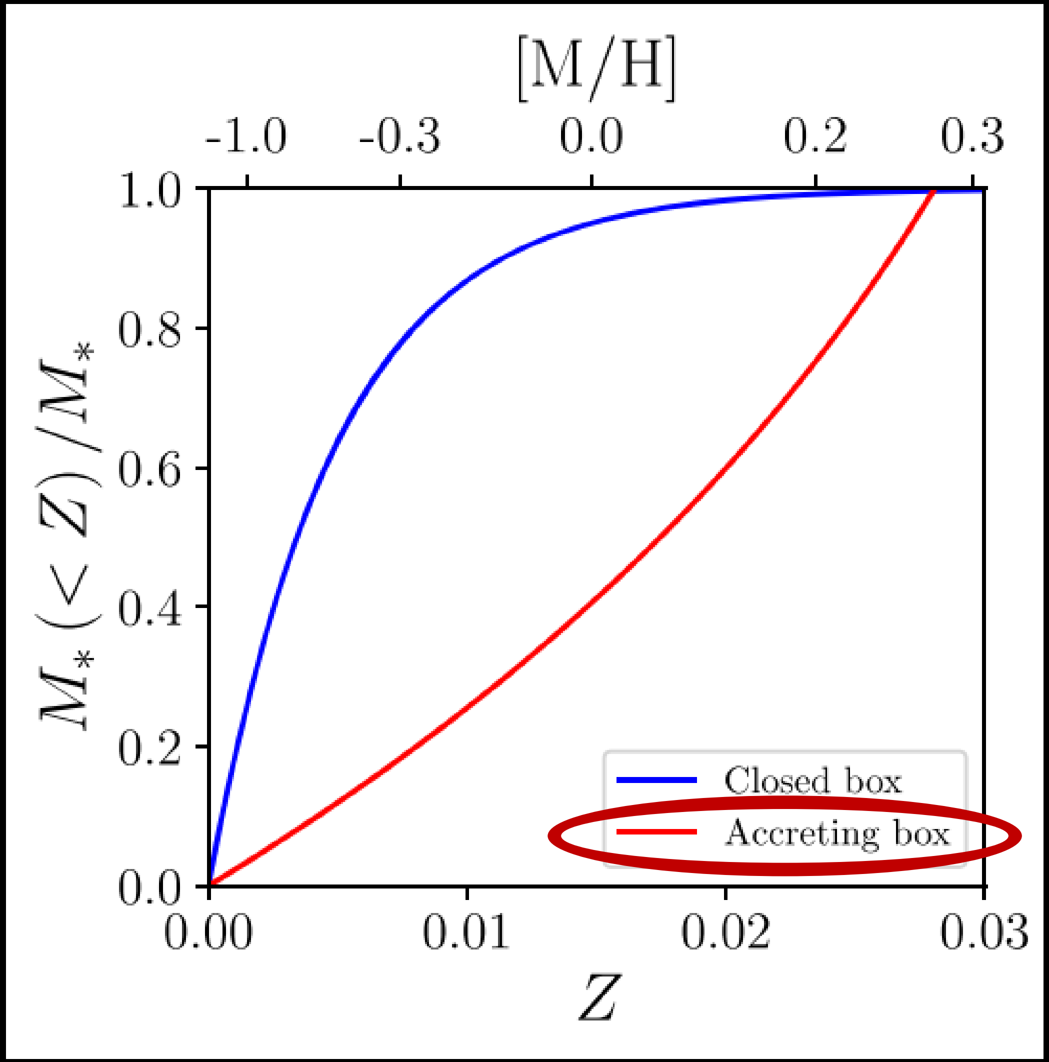

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A History Lesson: The Effect of Accretion

Ensures an ongoing supply of fresh H

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“yield”: mass of metals released per mass of stars formed

“recycling”: stellar envelopes return to ISM; ~40% of mass across IMF

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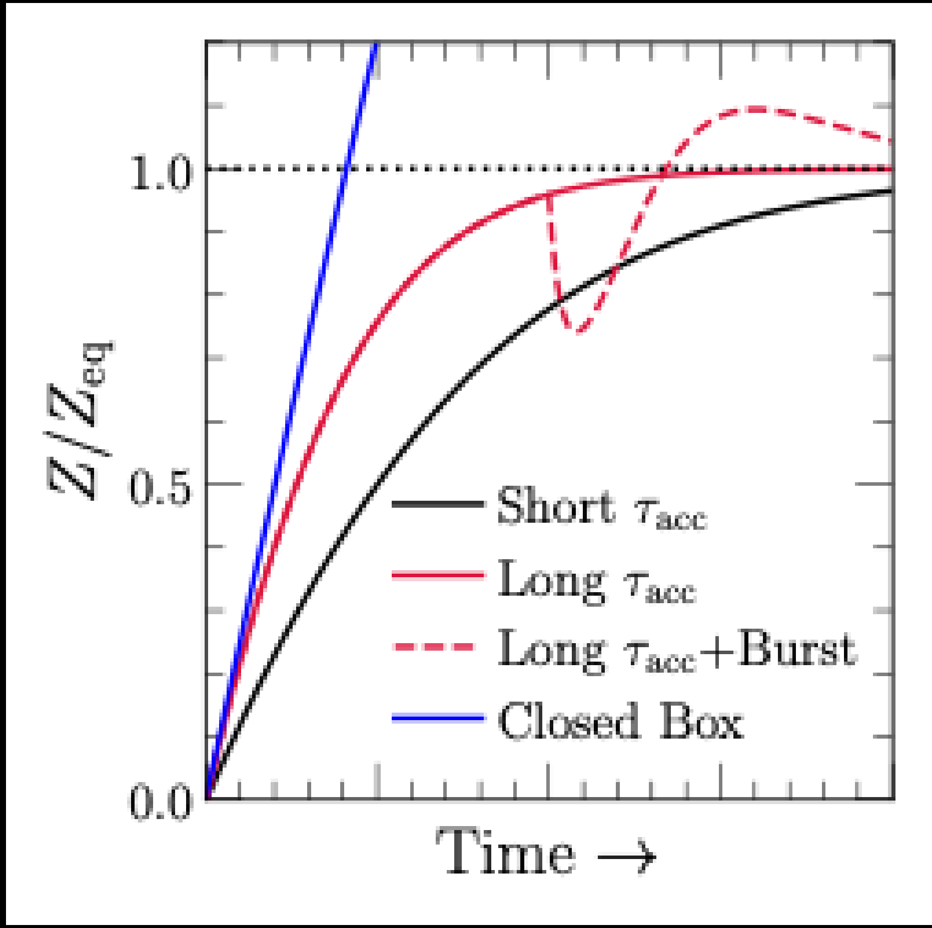

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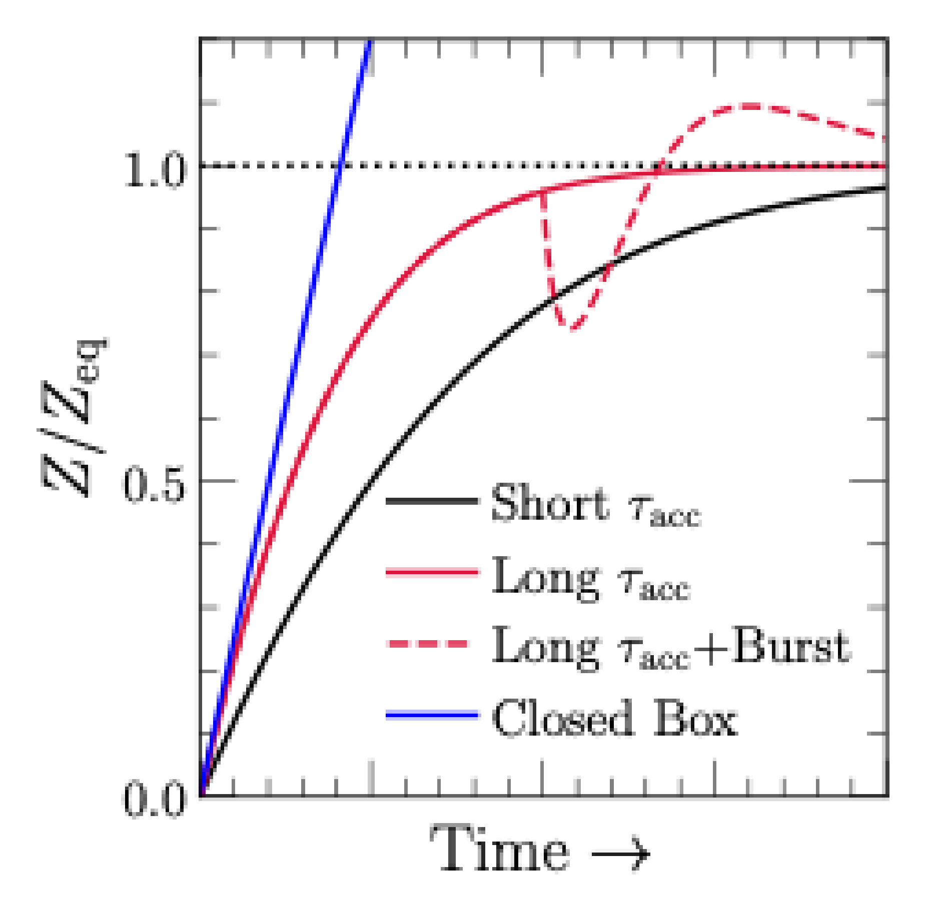
Closed box: $Z_{eq} \to \infty$

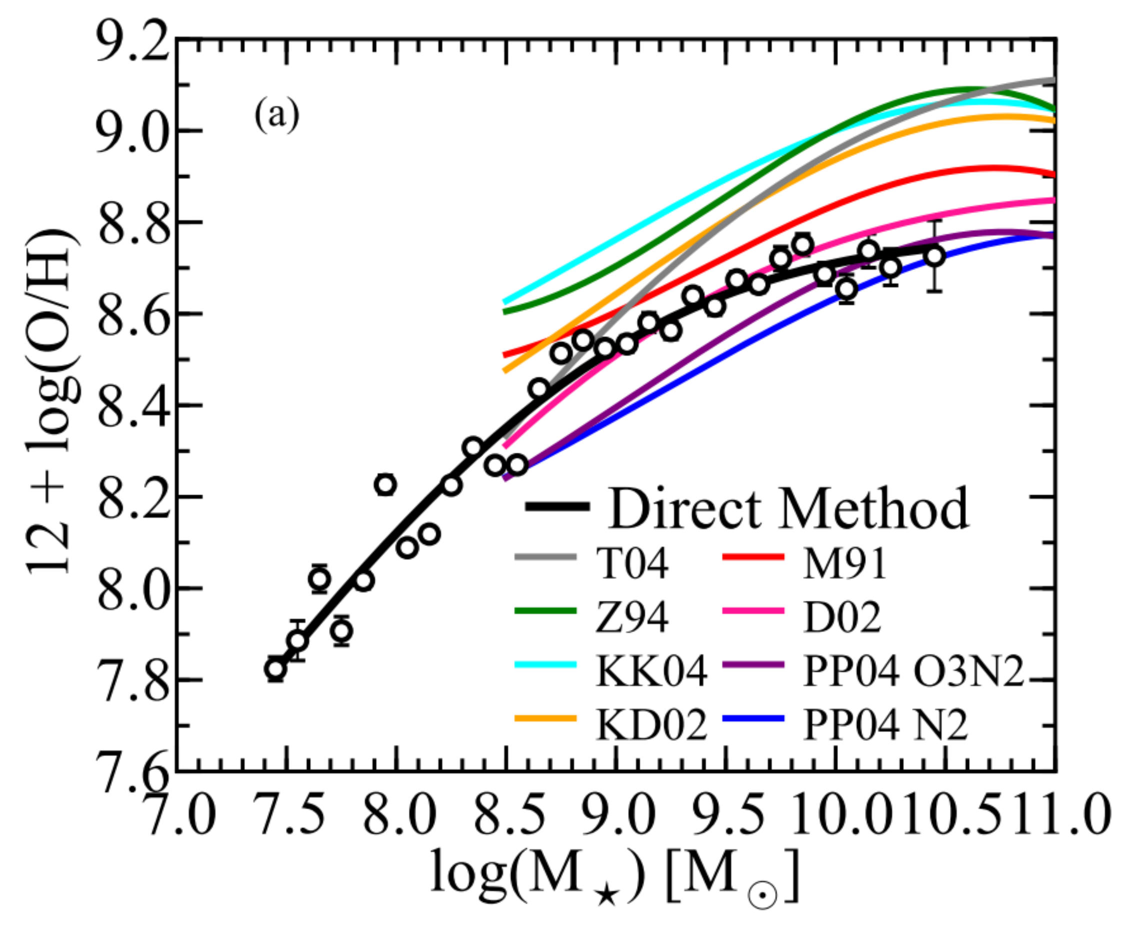
- Eventually all H fuses
- Observationally: $Z_{ISM} \sim Z_{\star}$



A History Lesson: The Effect of Outflows

Mass-metallicity relation for galaxies

- Finlator & Davé (2008)
- Peeples & Shankar (2011)
- Sanchez-Menguiano et al. (2024)



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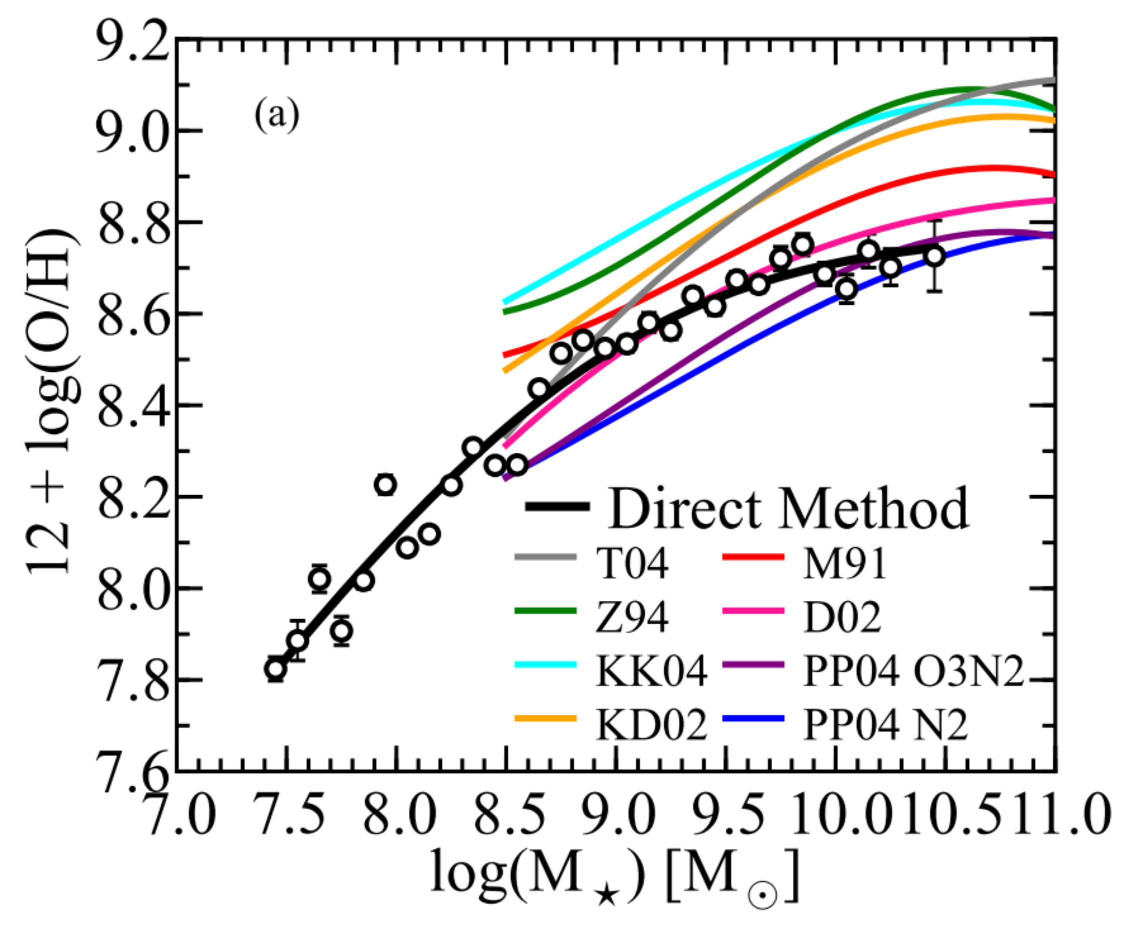

Lower Z_{eq}

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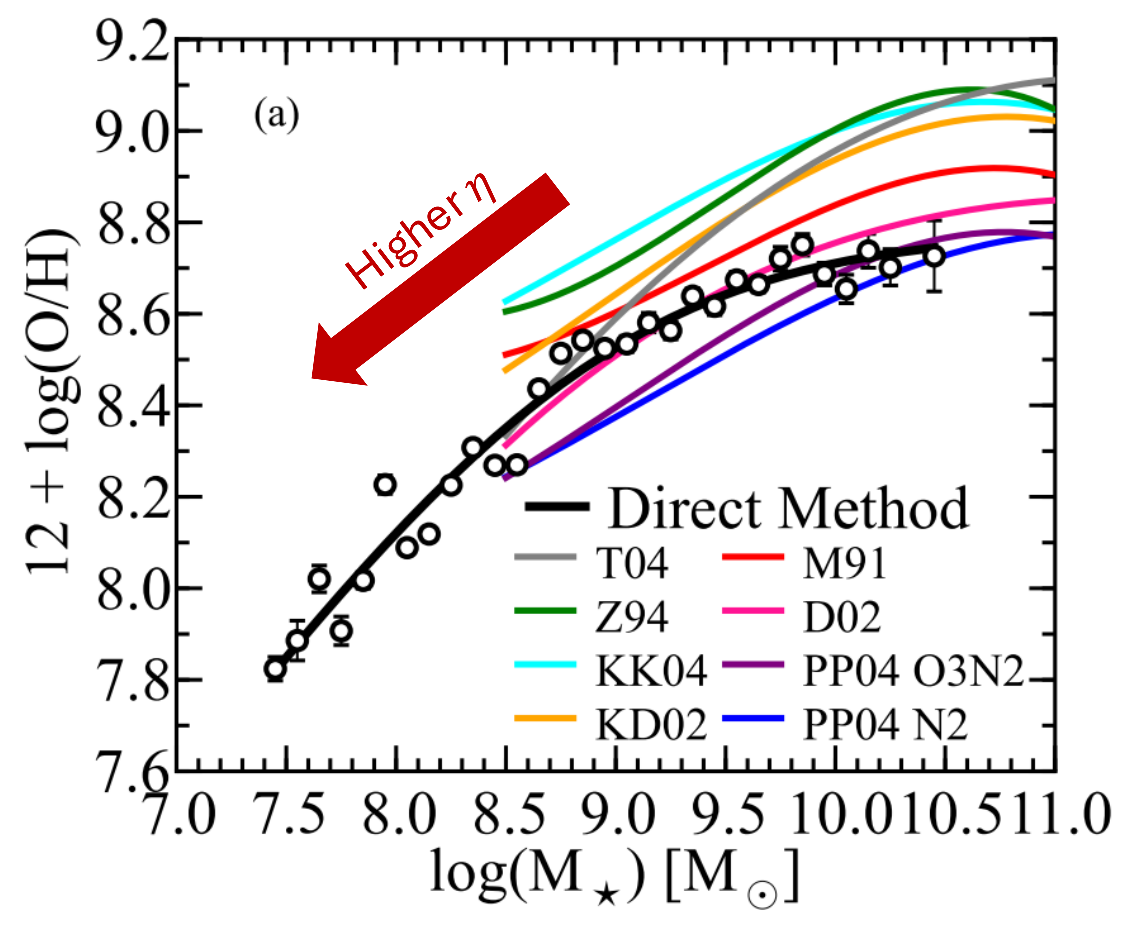

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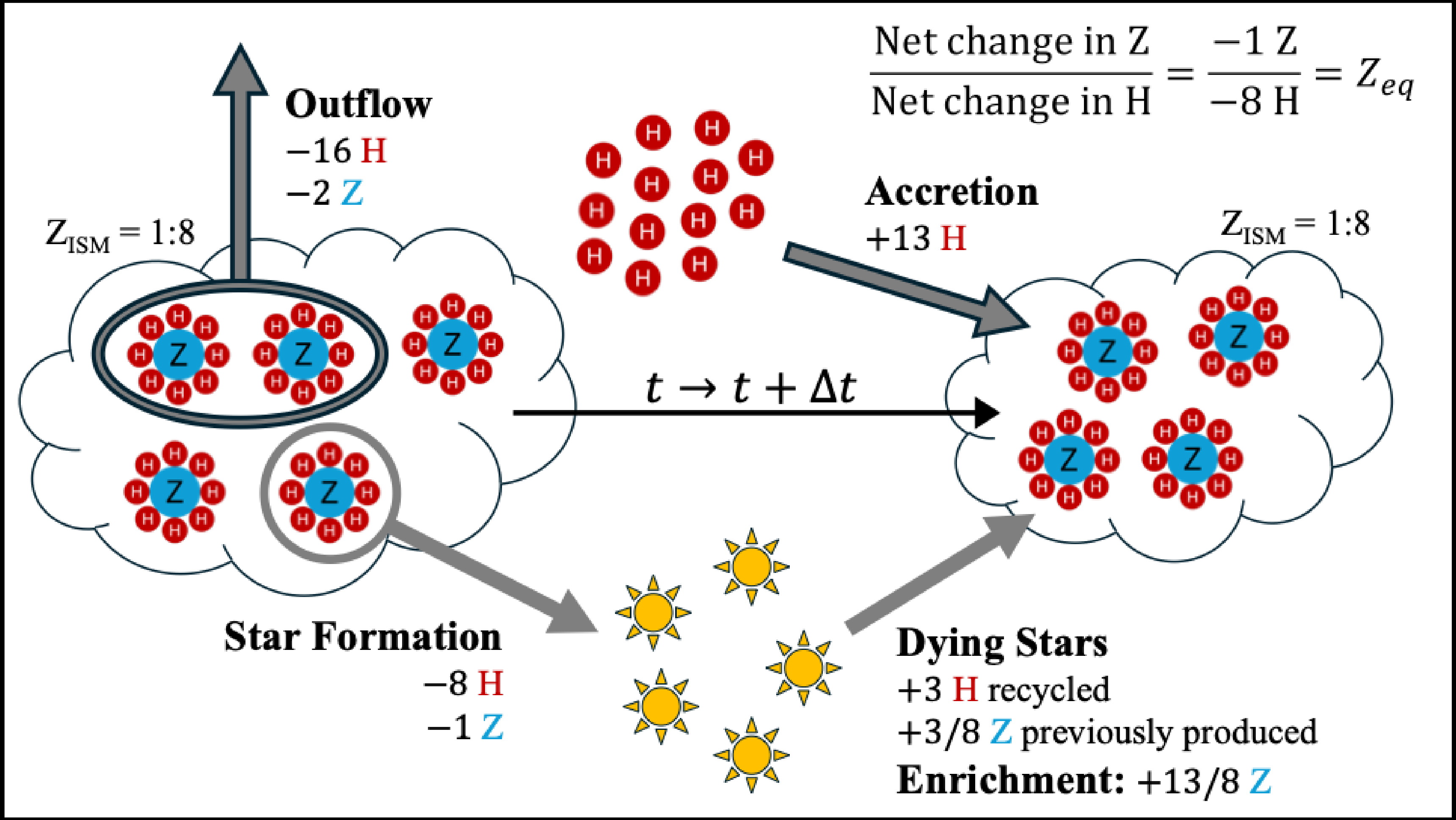
Visualizing Chemical Equilibrium

The ISM evolves in many ways, but metal-hydrogen mixture is unaffected

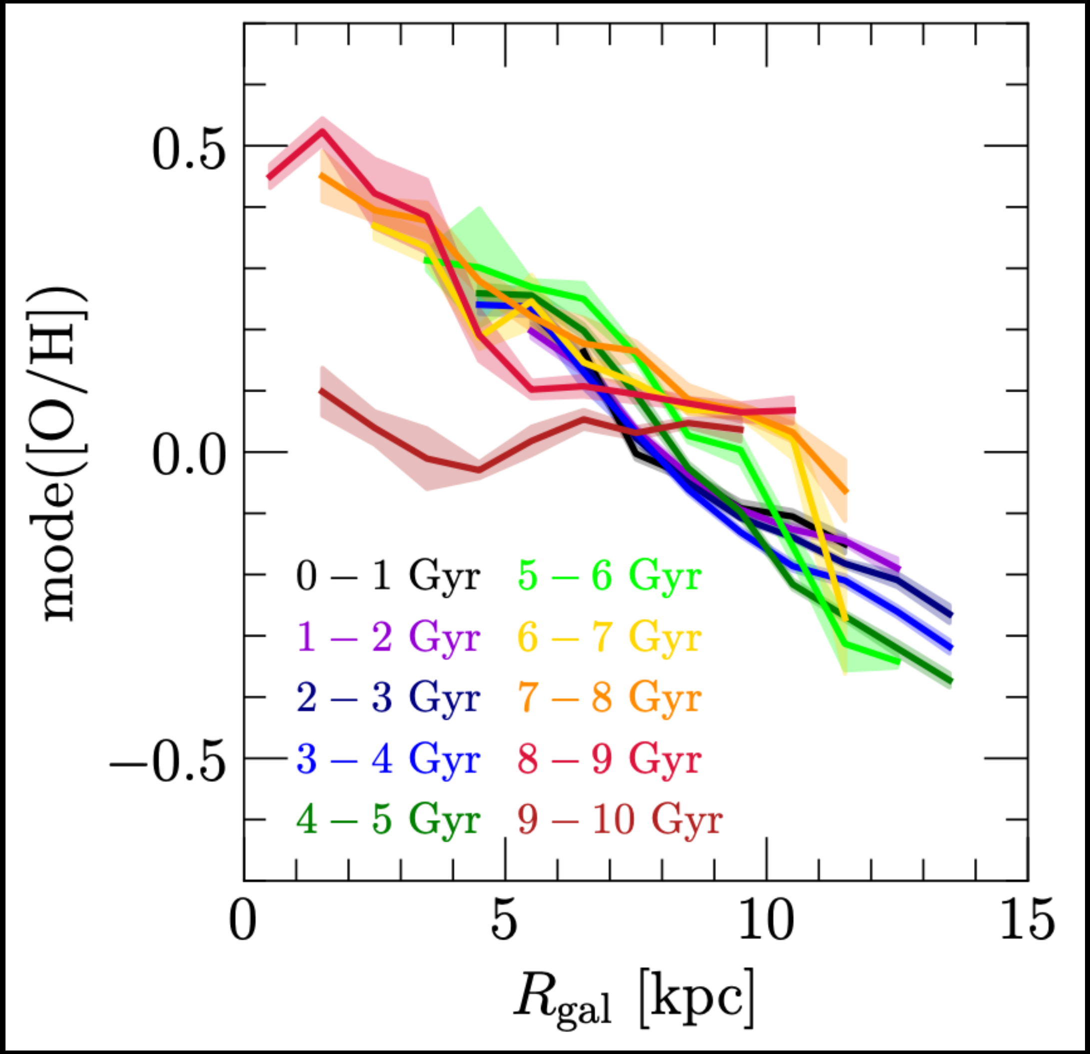


Johnson et al. (2025), ApJ, 988, 8

An Apparent Equilibrium in the Milky Way

Shockingly little variation in metallicity with population age

- Appears to exist across the Galaxy
- Reached ~9 Gyr ago in this sample (APOGEE red giants)



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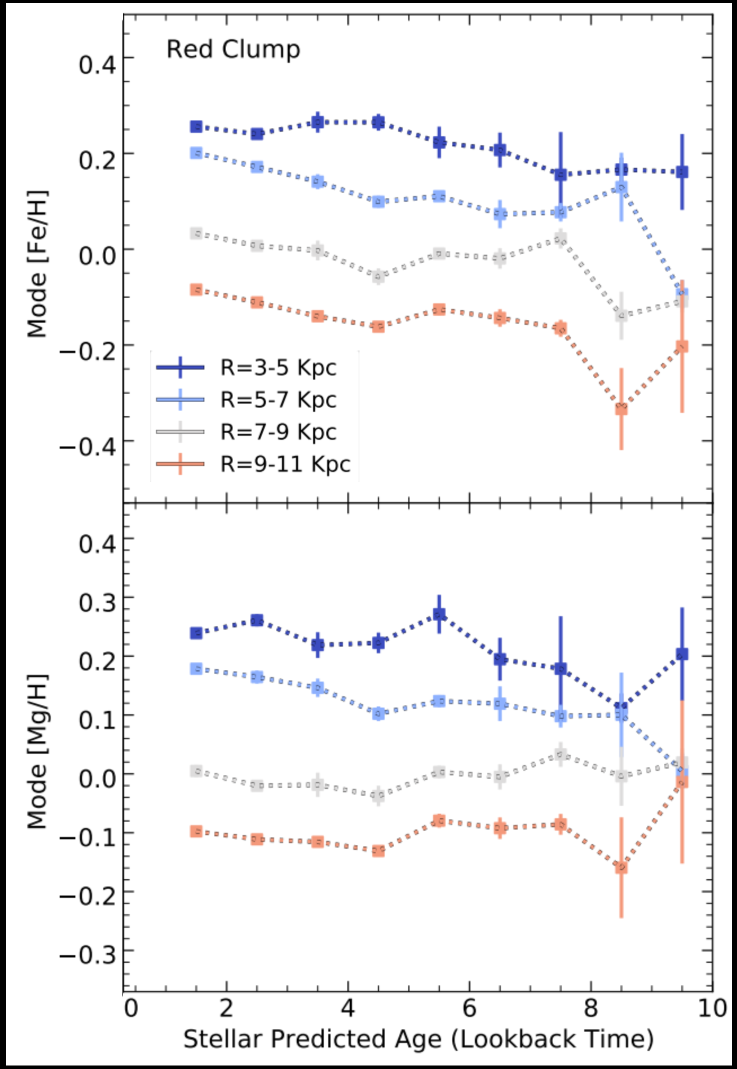

Jack Roberts
(Ohio State)

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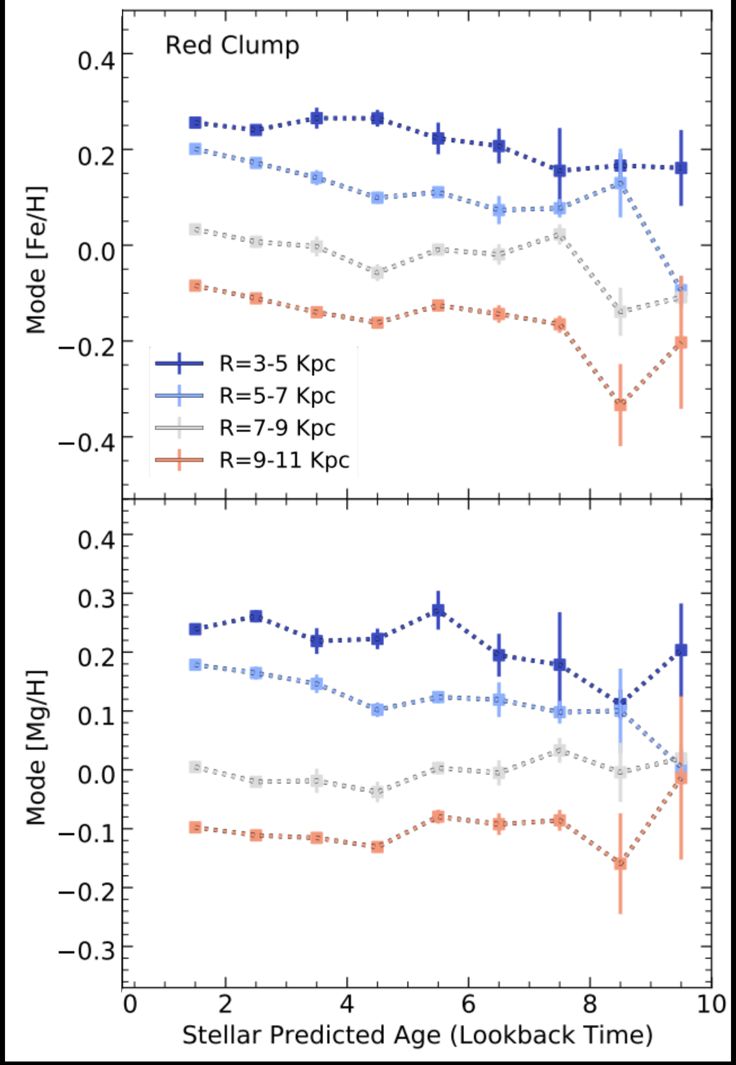
- Magrini et al. (2022)
- Willett et al. (2023)
- Gallart et al. (2024)



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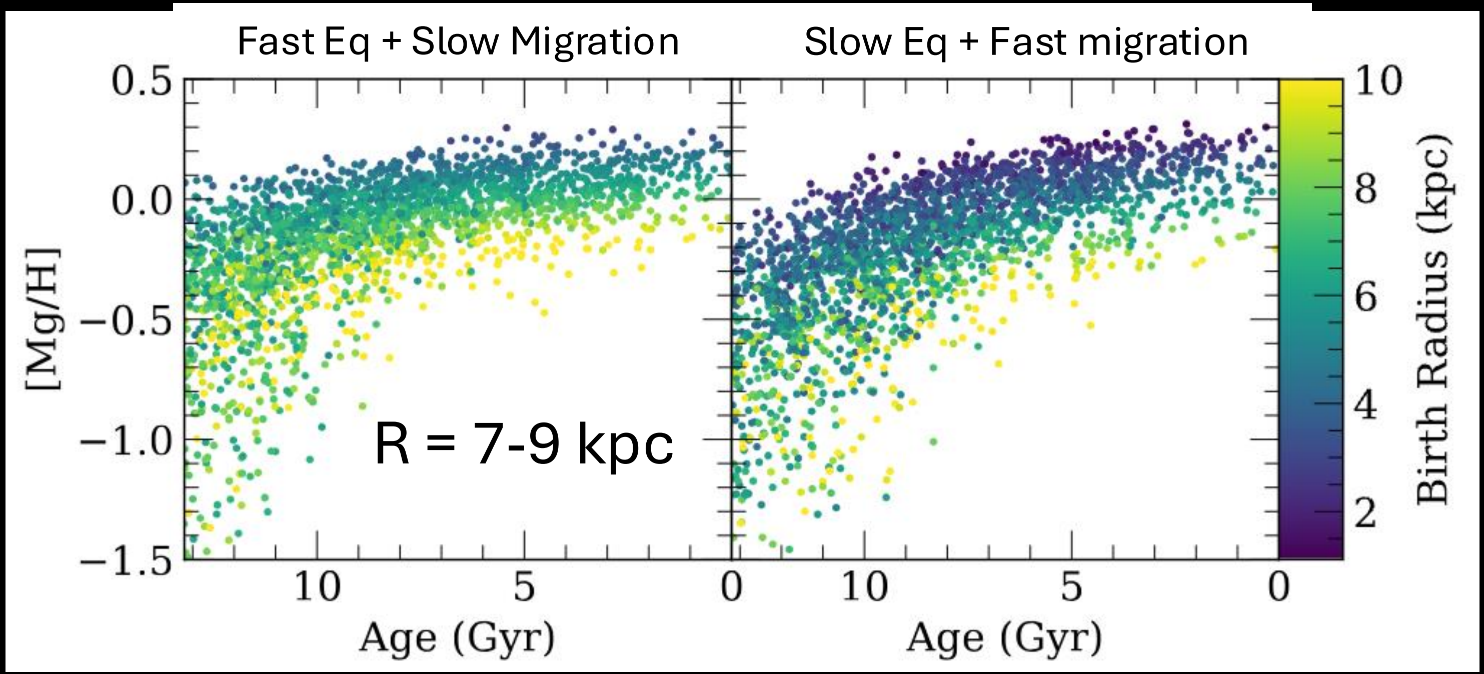
Alternatively: Fast Radial Migration

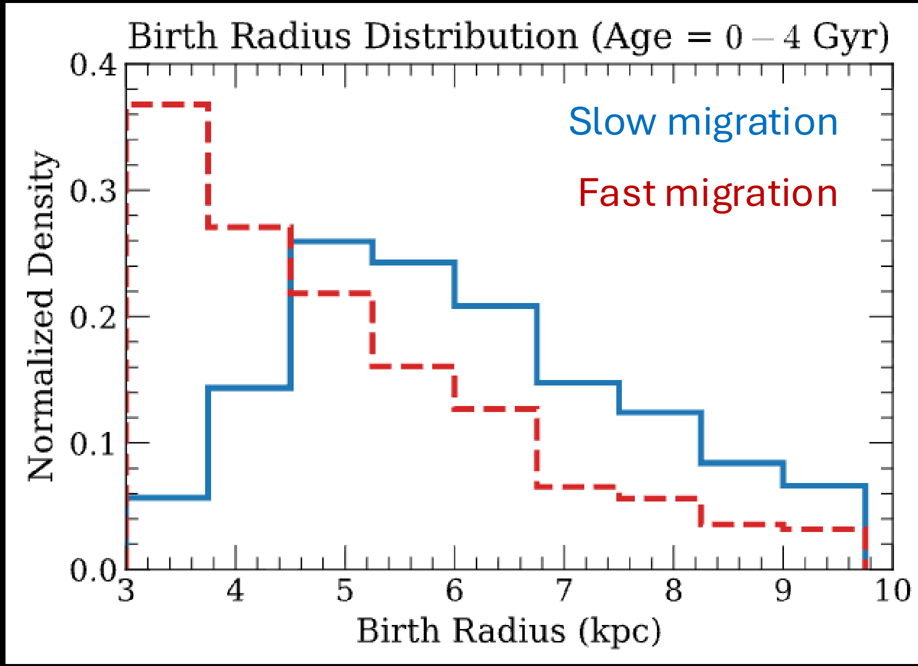
Local stars no longer reflect local enrichment history

- Roškar et al. (2008)
- Loebman et al. (2011)

Christopher Giudice

(San Francisco State)





Chemical Equilibrium from Radial Gas Flows?

New coefficient describing rate relative to SFR:

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Chemical Equilibrium from Radial Gas Flows?

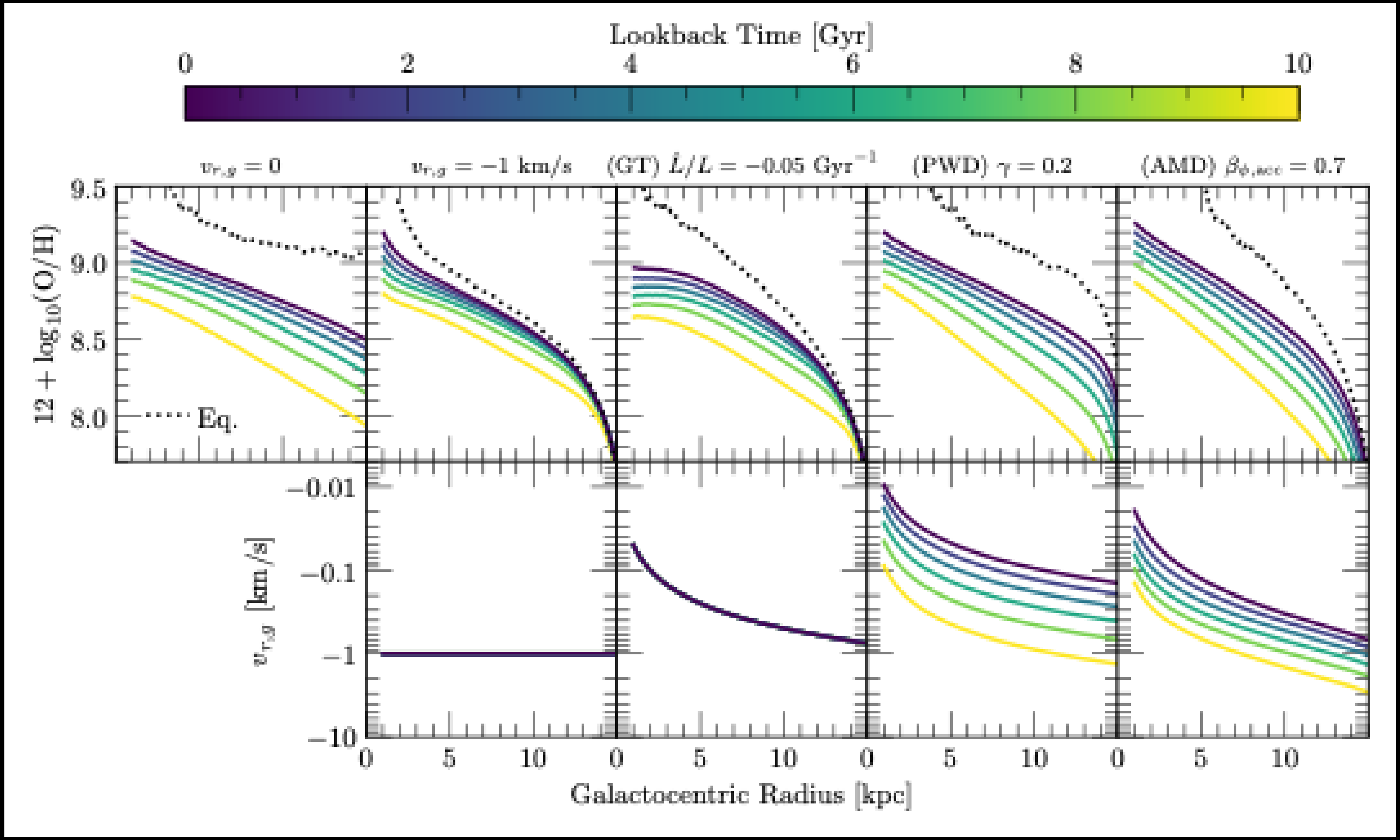
New coefficient describing rate relative to SFR:

$$Z \to Z_{eq} = \frac{y}{1 + \eta - \mu_Z - r}$$

$\eta > 0 \Rightarrow \dot{M}_{out} > 0$ (removing mass)

$\mu > 0$ when $\dot{\Sigma}_{flow} > 0$ (adding mass)

Four Radial Flow Prescriptions



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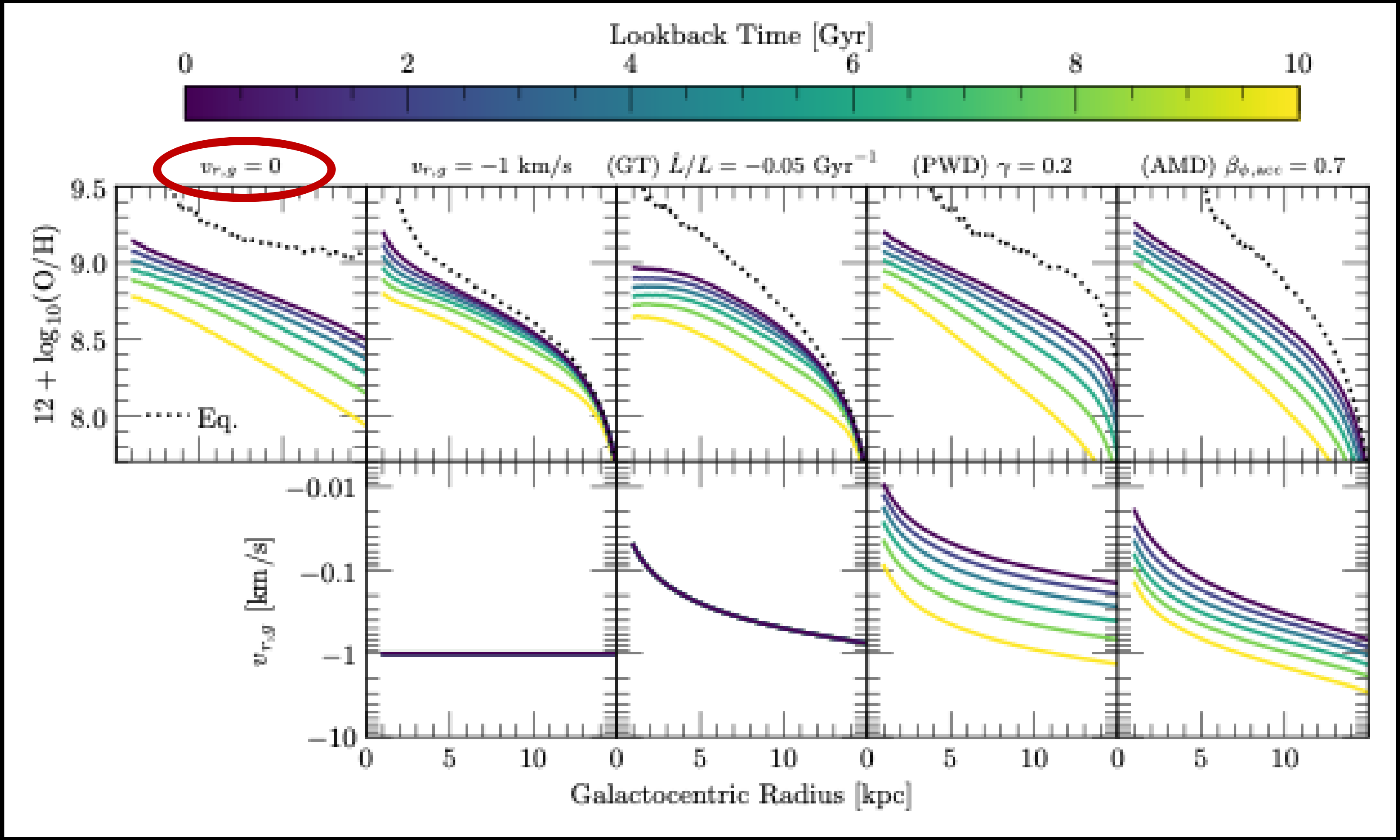

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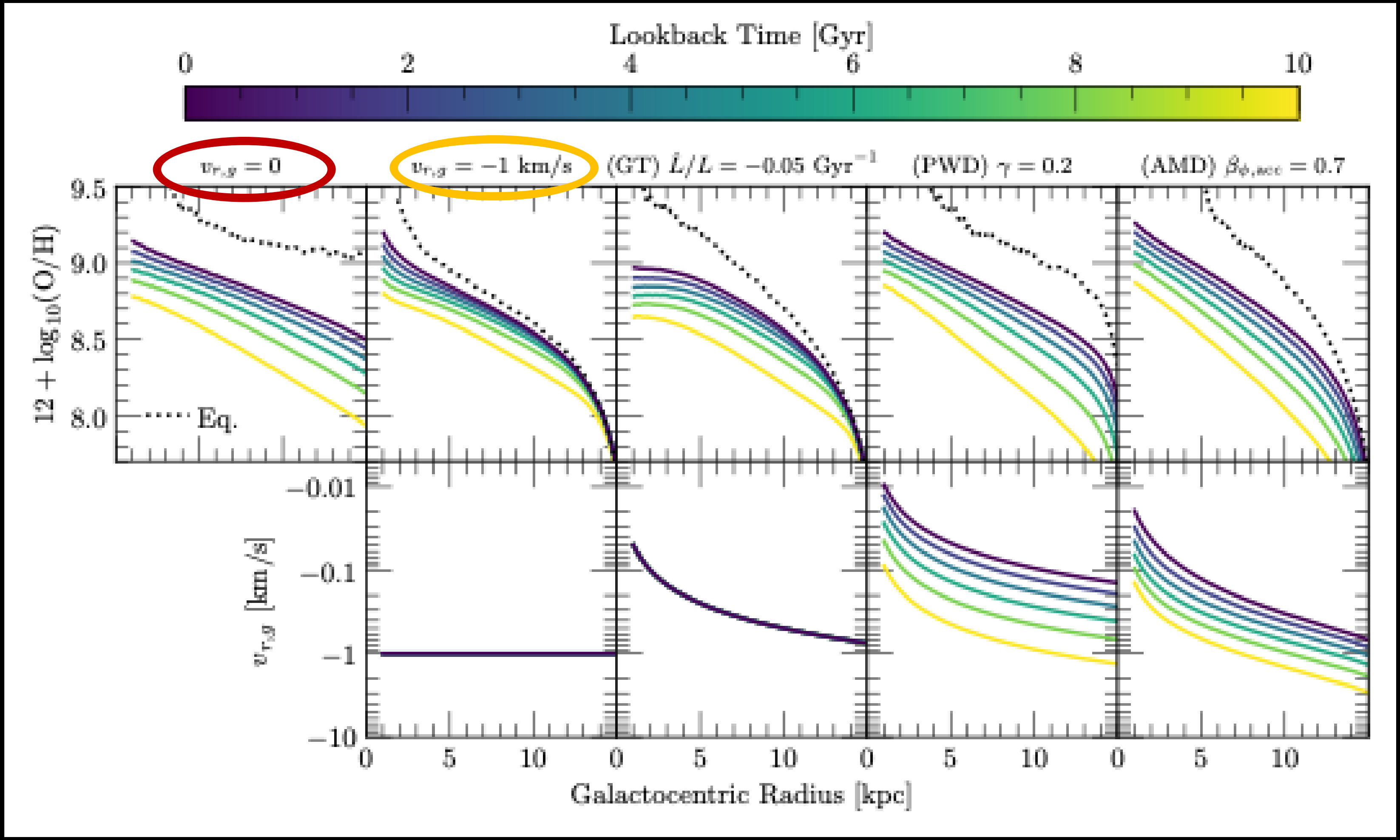

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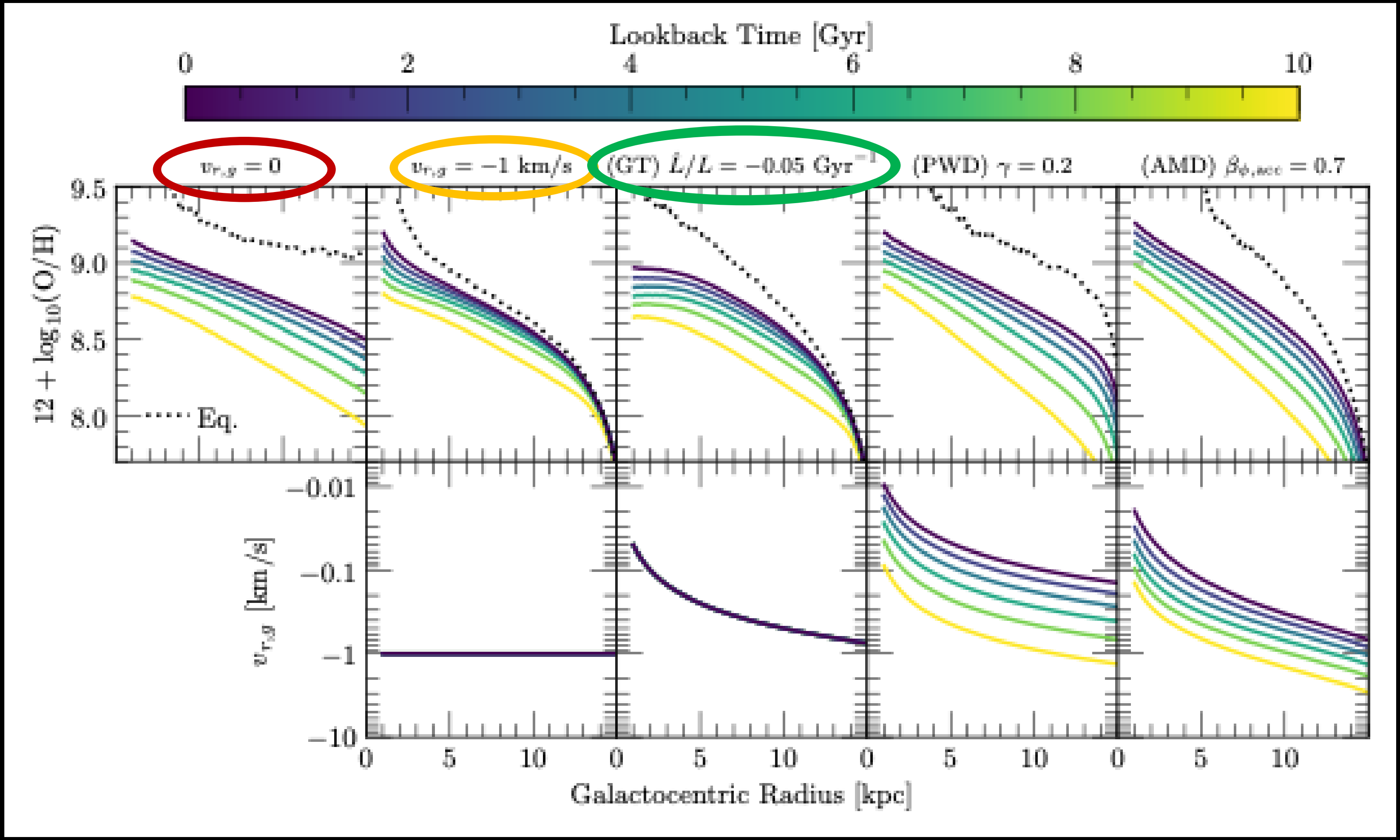
Global Torque: constant angular momentum loss



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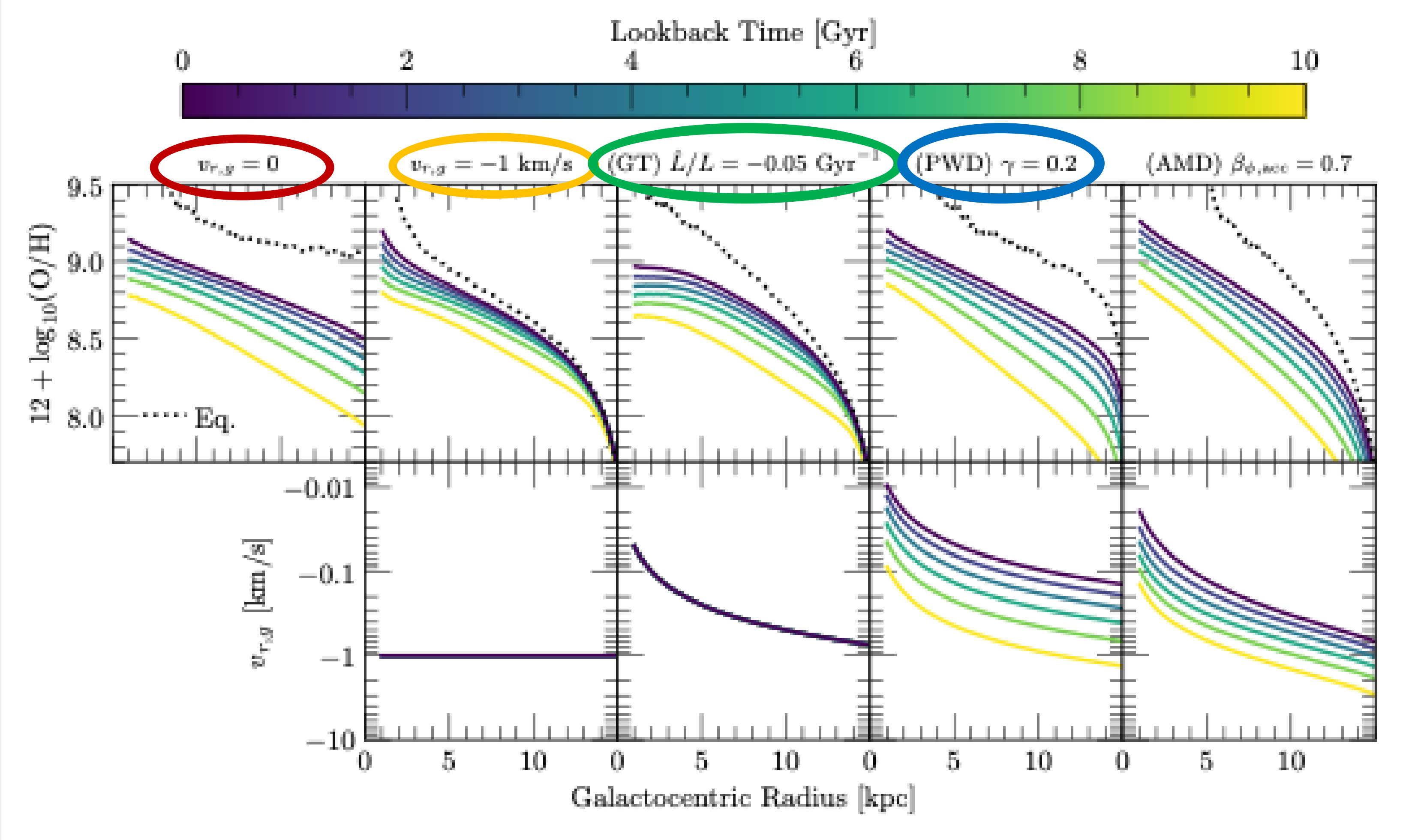

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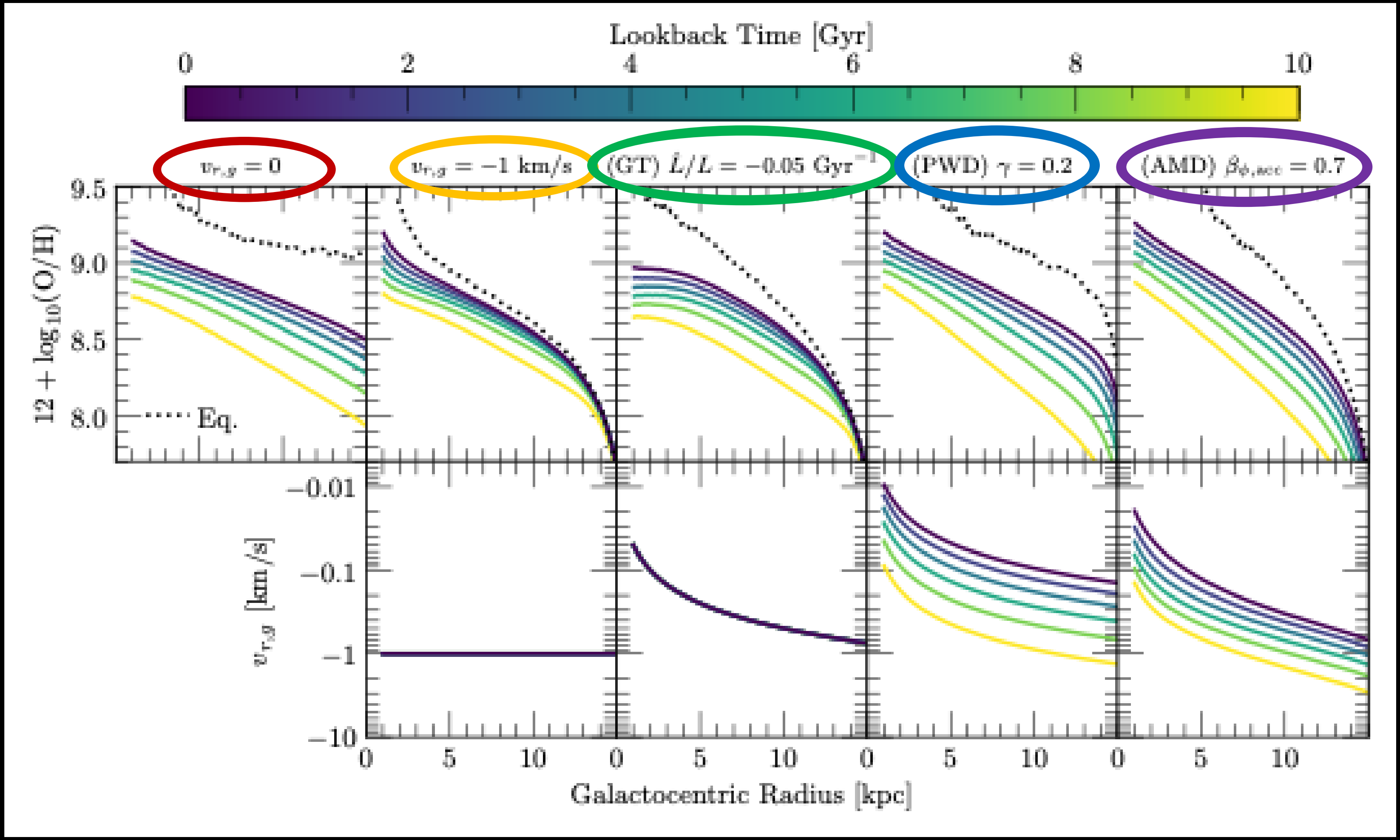
Angular Momentum Dilution: $L_{z,acc} < L_{z,ISM}$



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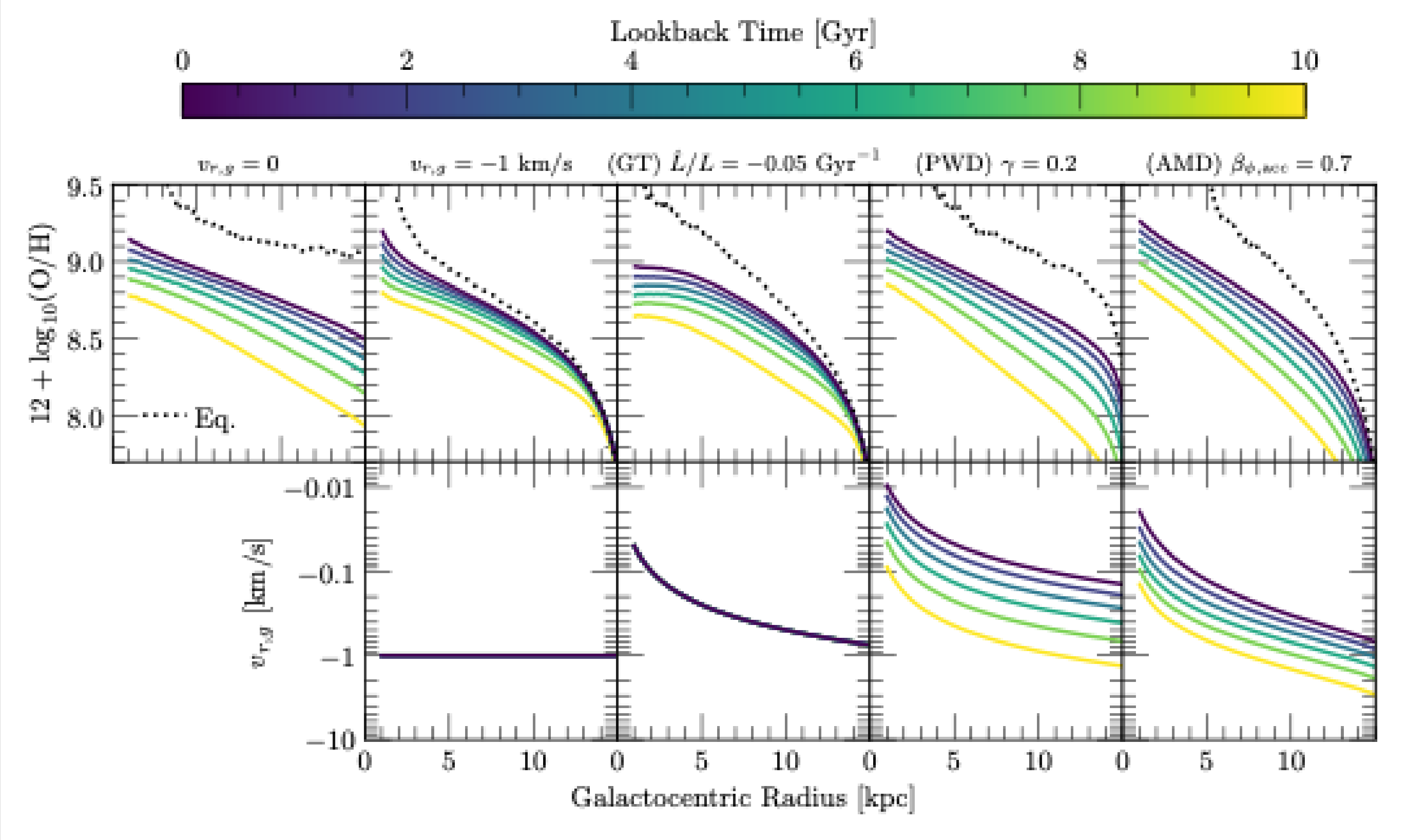

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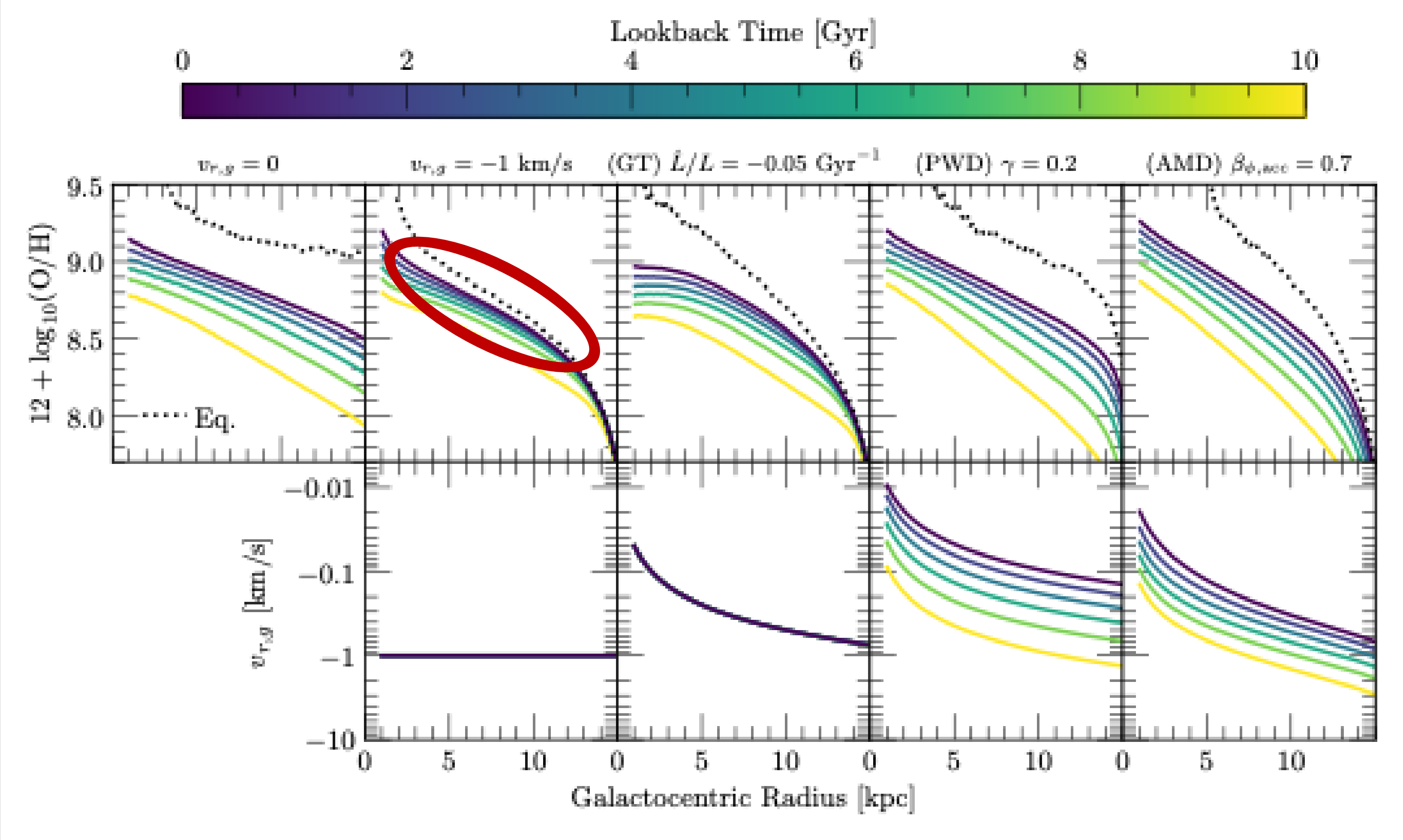
Four Radial Flow Prescriptions

Some predict $Z_{ISM} \sim Z_{eq}$



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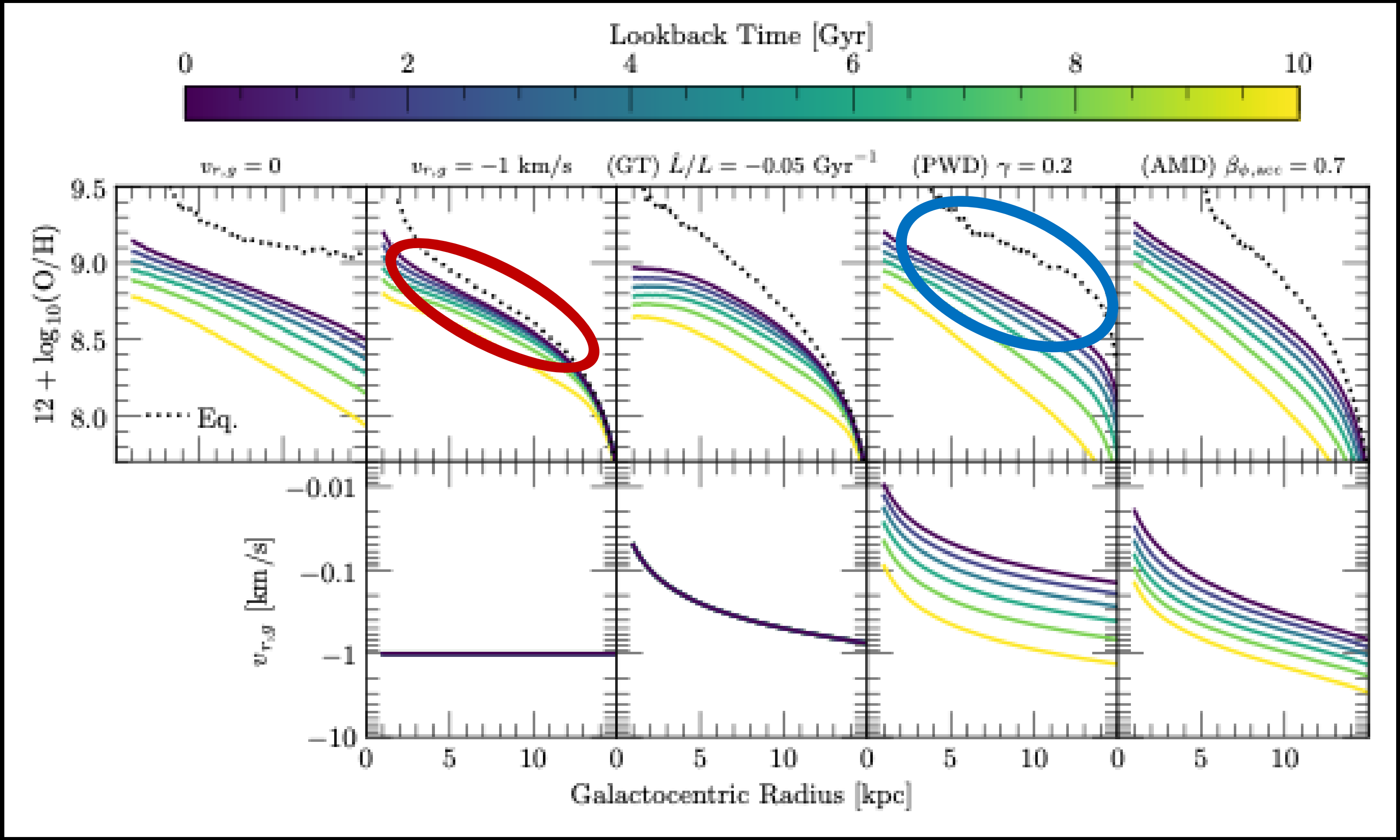

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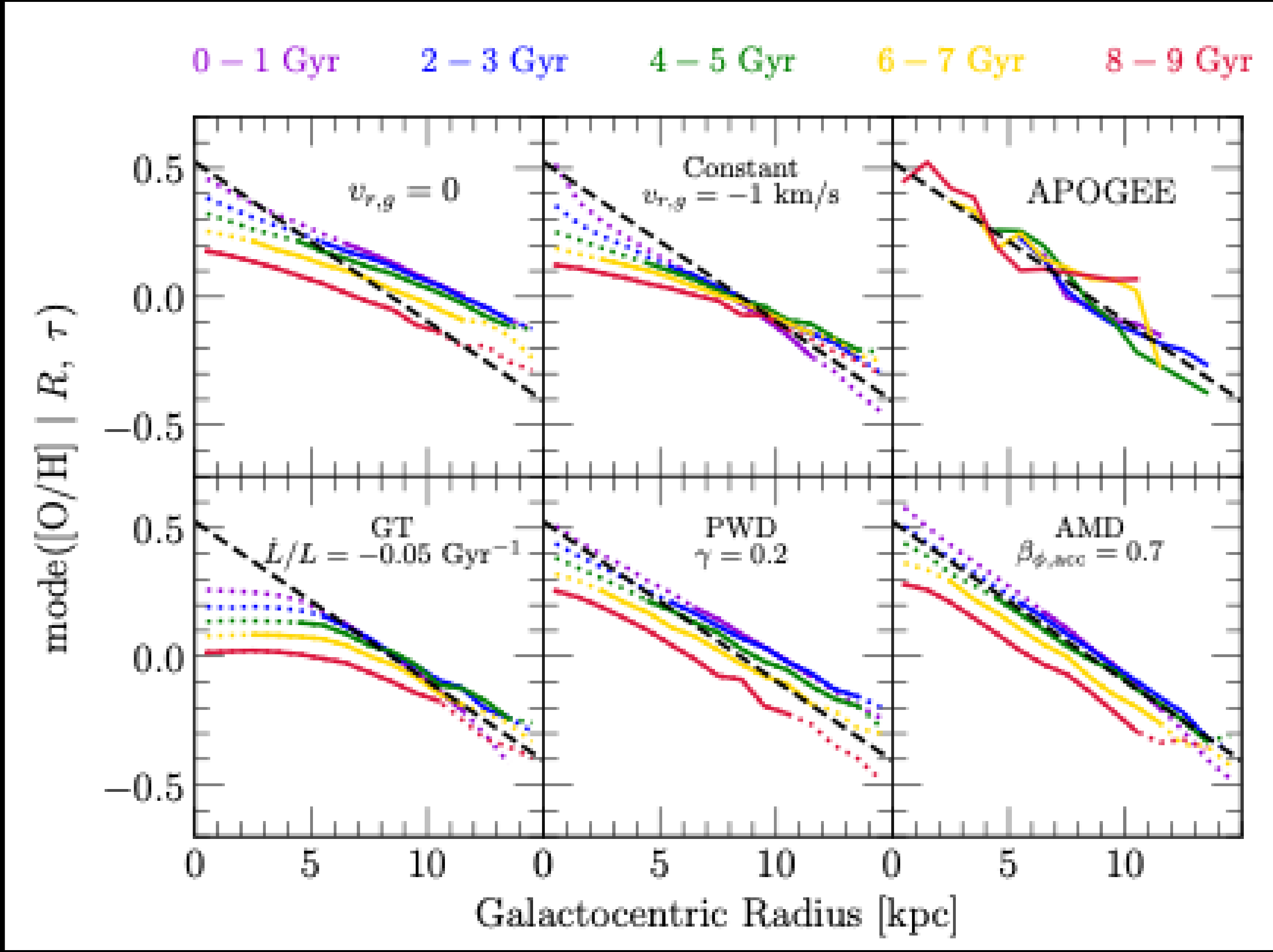
Age-Metallicity Relation with Radial Gas Flows

All models improve agreement with data by steepening gradient

Cannot wipe out age trend entirely



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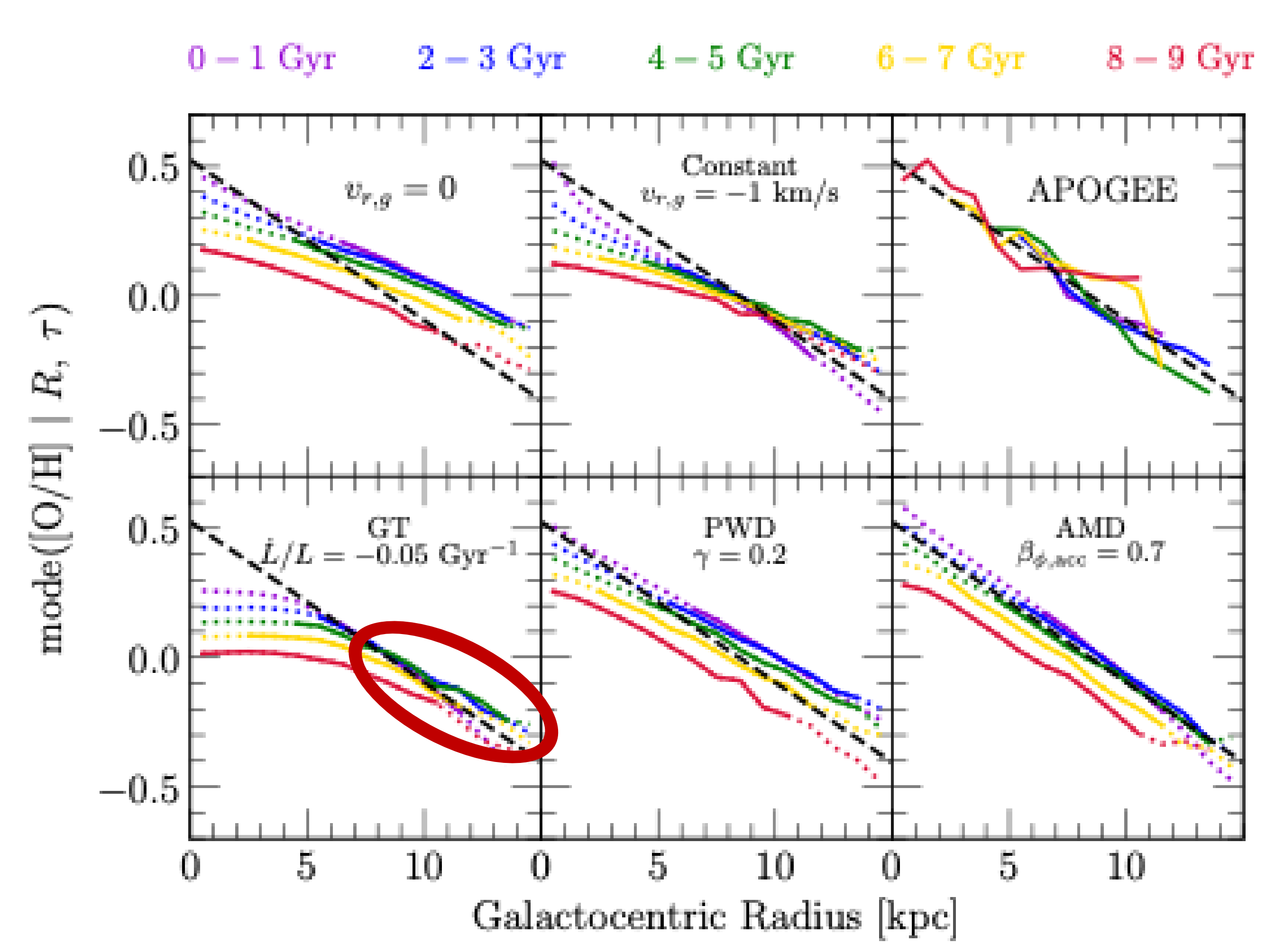

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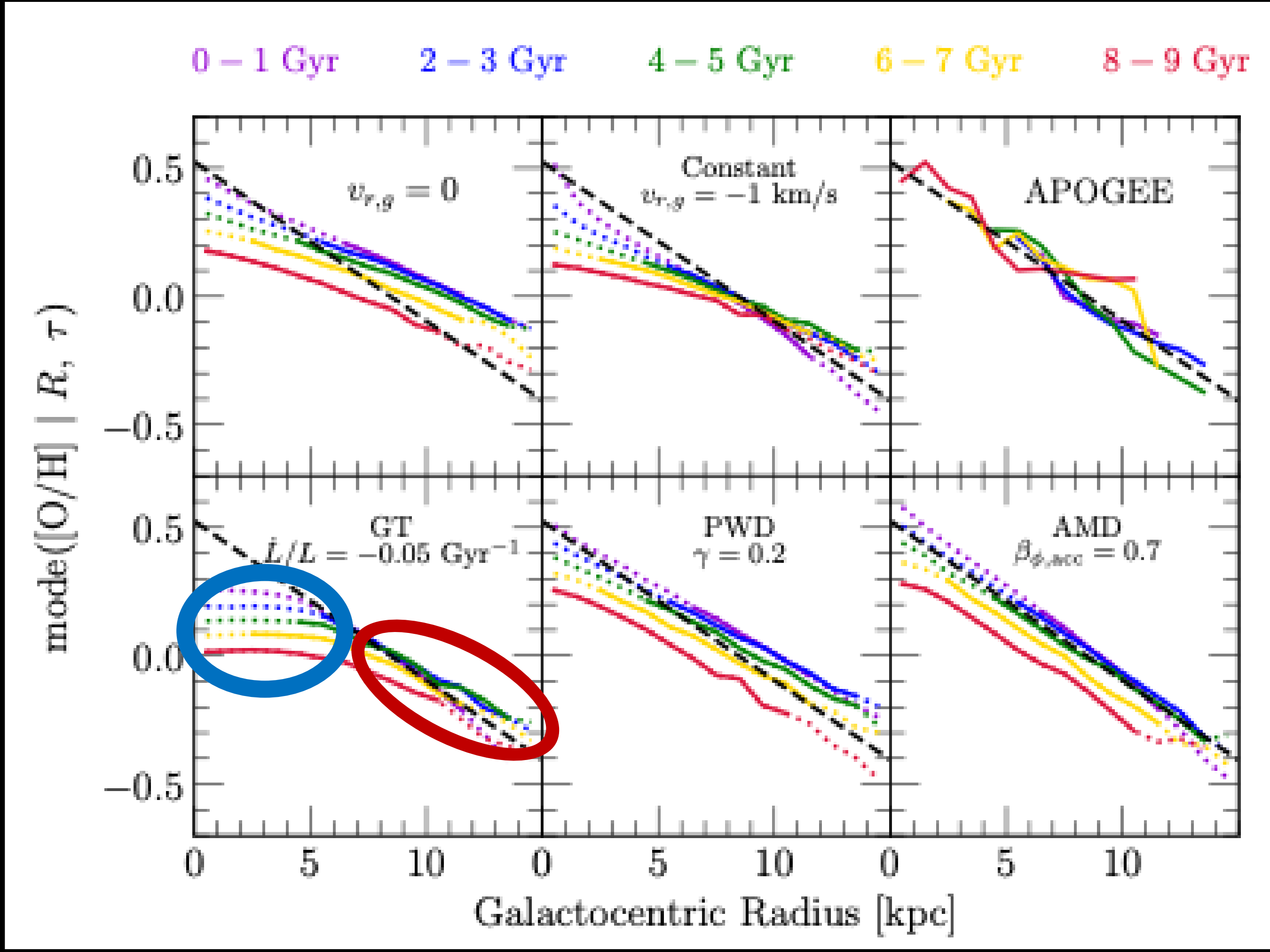
- Equilibrium region
- Disequilibrium region



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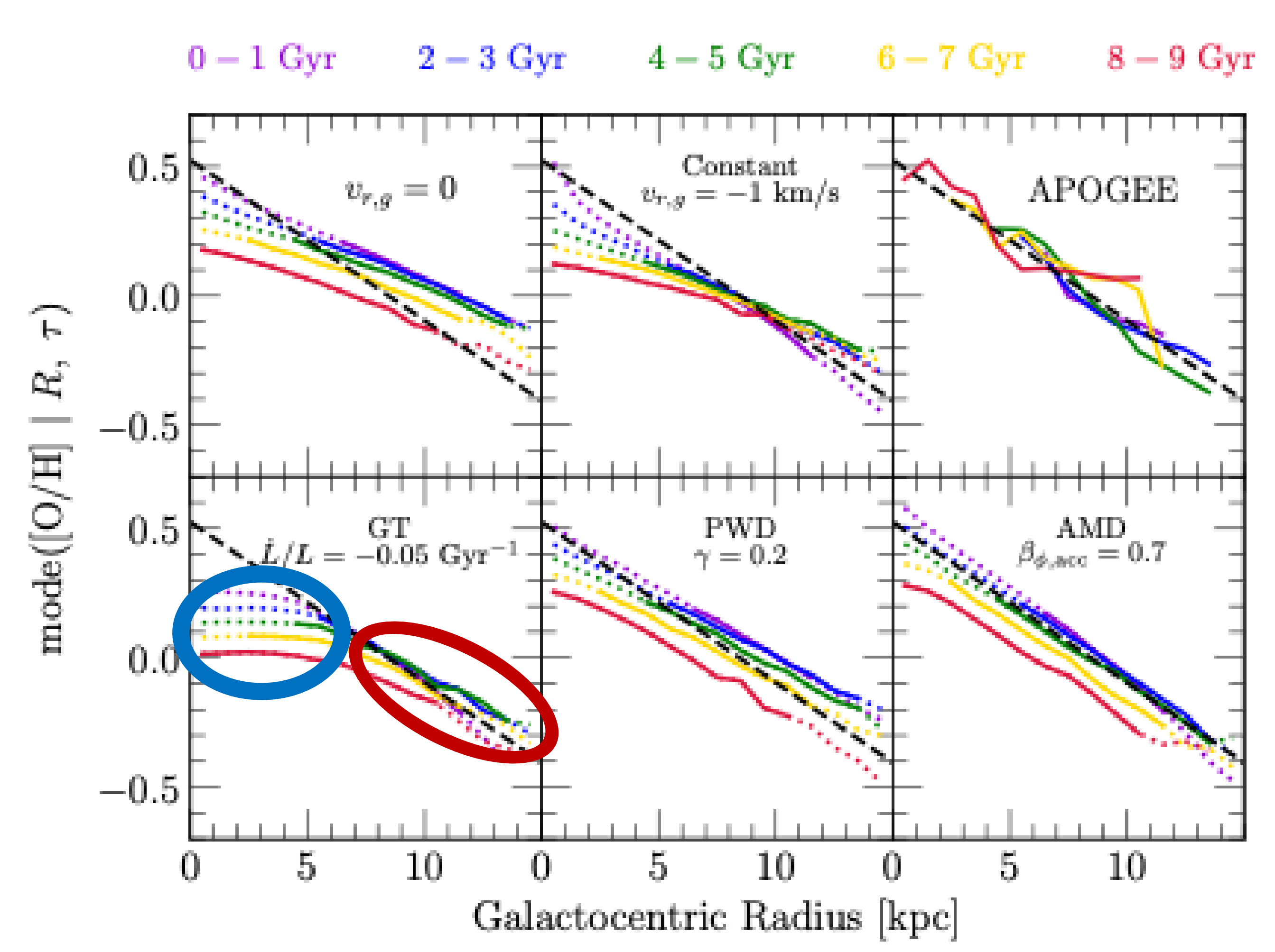
Age-Metallicity Relation with Radial Gas Flows

Mass Conservation:

$$\int_0^\infty \mu Z \dot{\Sigma}_\star R dR = 0$$

$\mu < 0 \Rightarrow$ Equilibrium

$\mu > 0 \Rightarrow$ Disequilibrium



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Hydrogen sets the Metallicity Scale

Outflows and radial flows → adjust amount of H that mixes with new metals

$$Z \to Z_{eq} = \frac{y}{1 + \eta - \mu_Z - r\ - \tau_\star/\tau_{sfh}}$$

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How many stars form?

... Per accreted baryon?

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$\dot{Z}$

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$\dot{H}$

Hydrogen sets the Metallicity Scale

Early lesson learned from GCE: galaxies are not closed boxes

Outflows & mass-metallicity relation: dwarf galaxies need more H to form the same amount of stars

If equilibrium scenario is accurate: H does not hang around in a galaxy for long before forming stars, being ejected, moving in a flow, etc.

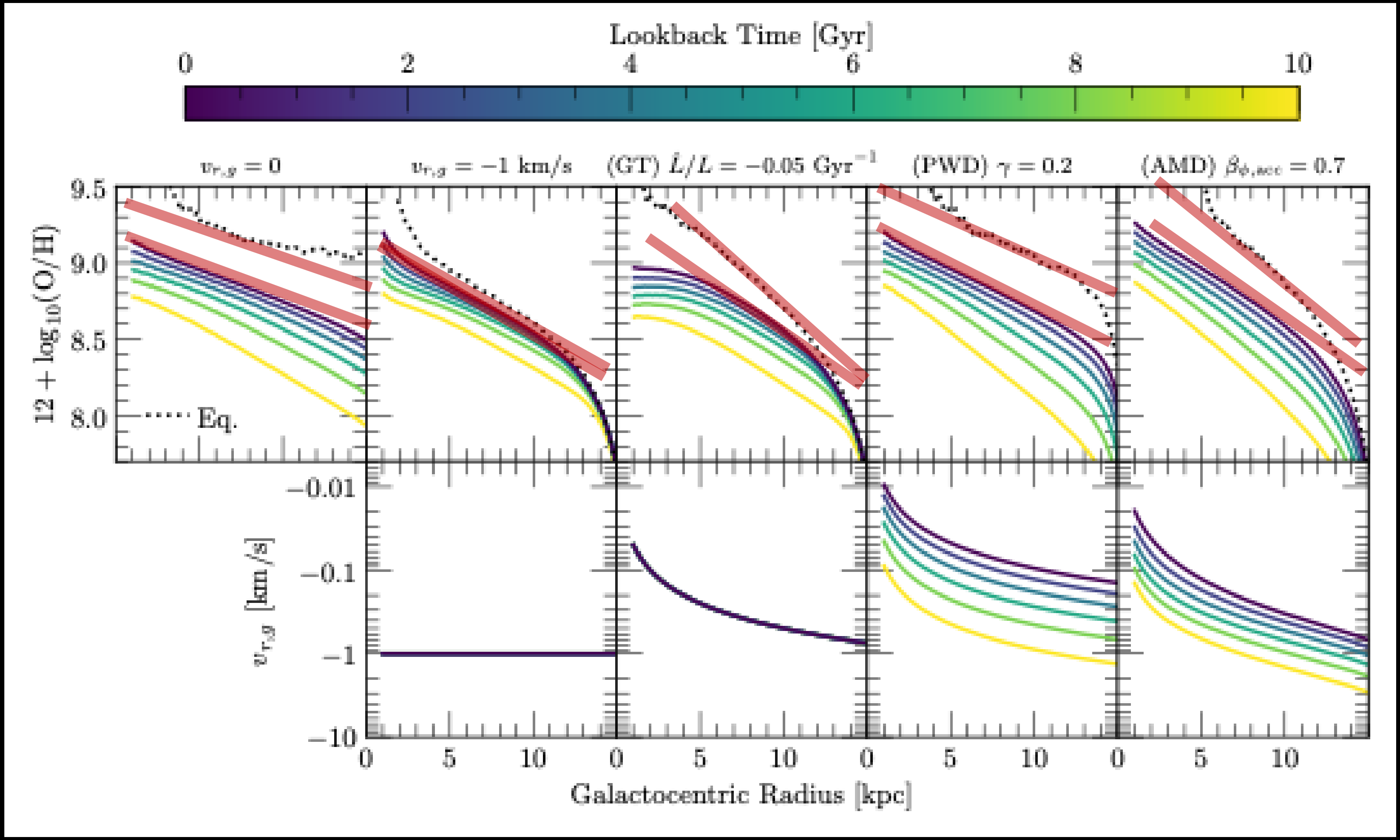
Metallicity gradients: same quantities – now R-dependence within galaxies

Gradient Evolution as an Equilibration Process

$$\frac{\partial \ln Z_{ISM}}{\partial R} \approx \frac{\partial \ln Z_{eq}}{\partial R}$$

even when

$$Z_{ISM} \ll Z_{eq}$$



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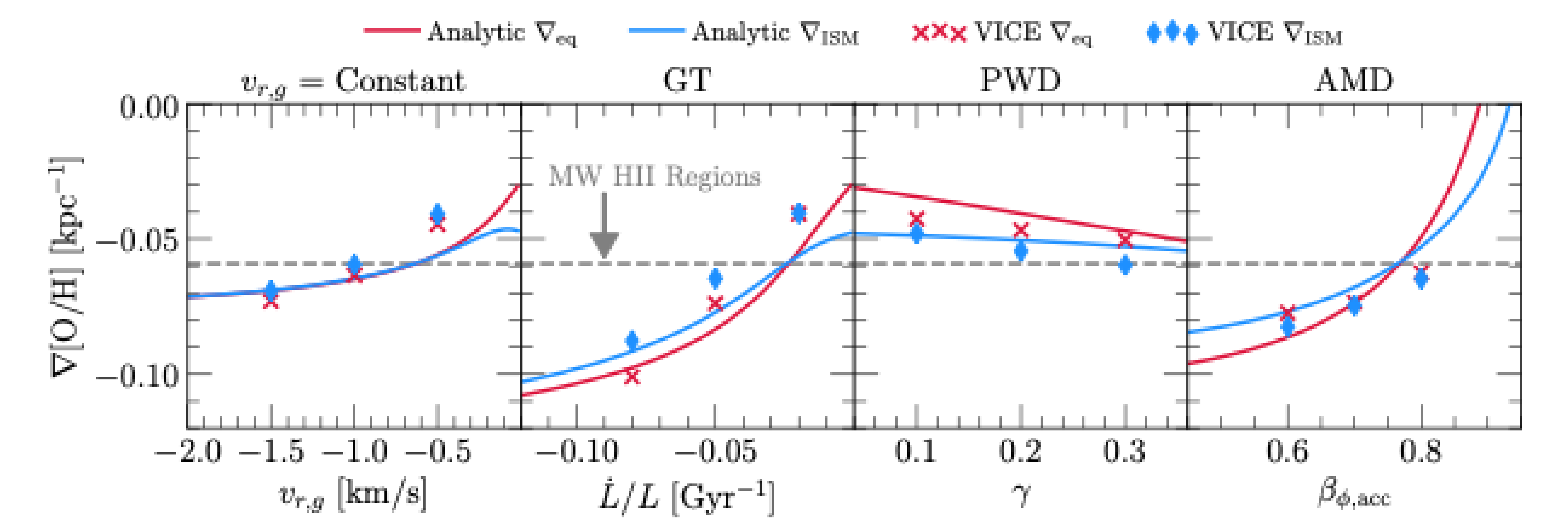
Allows Analytic Approximations of $\nabla[Z/H]$

$$\frac{\partial}{\partial R}\left[1+\eta-\mu\ -r\ -\frac{\tau_\star}{\tau_{sfh}}\right] \rightarrow\ \ldots \rightarrow\ \ldots \rightarrow \nabla \ln Z_{eq} \sim \nabla \ln Z_{ISM}$$

Folding in disequilibrium corrections, accurate to ~0.01 dex/kpc



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