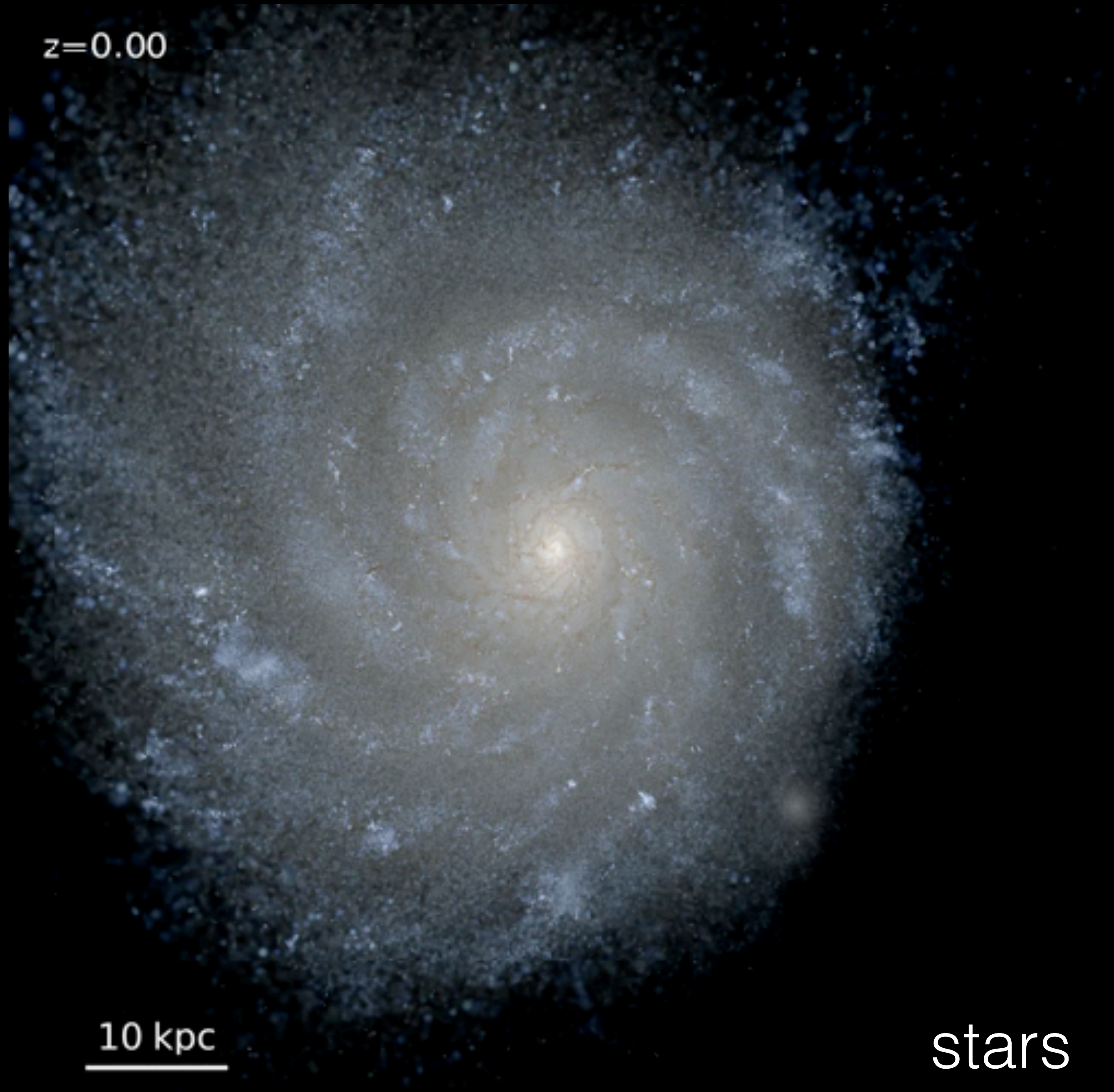
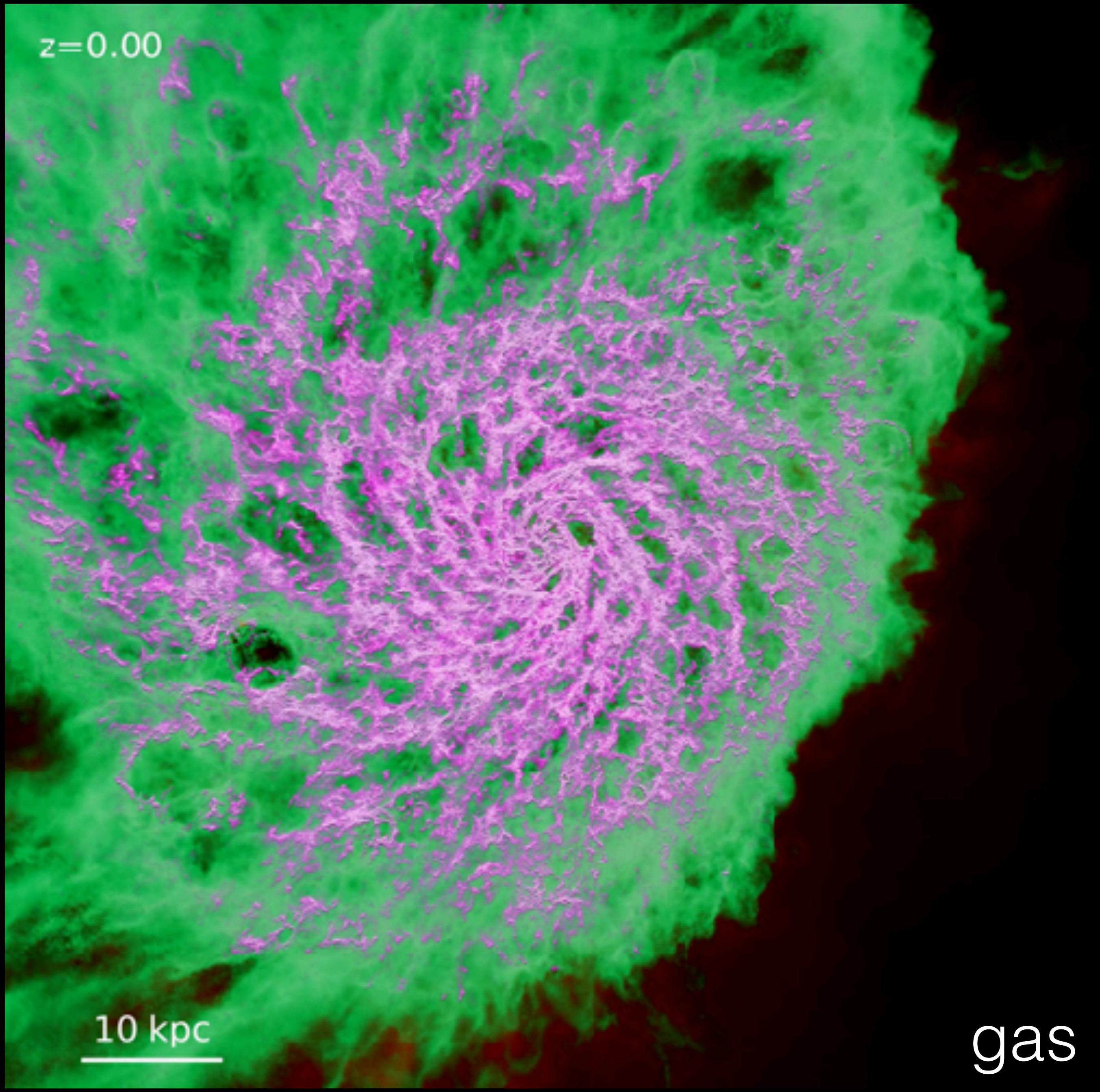
evolution of metallicity gradients in Milky Way-mass disk galaxies



stars



gas

UC DAVIS
UNIVERSITY OF CALIFORNIA

Andrew Wetzel

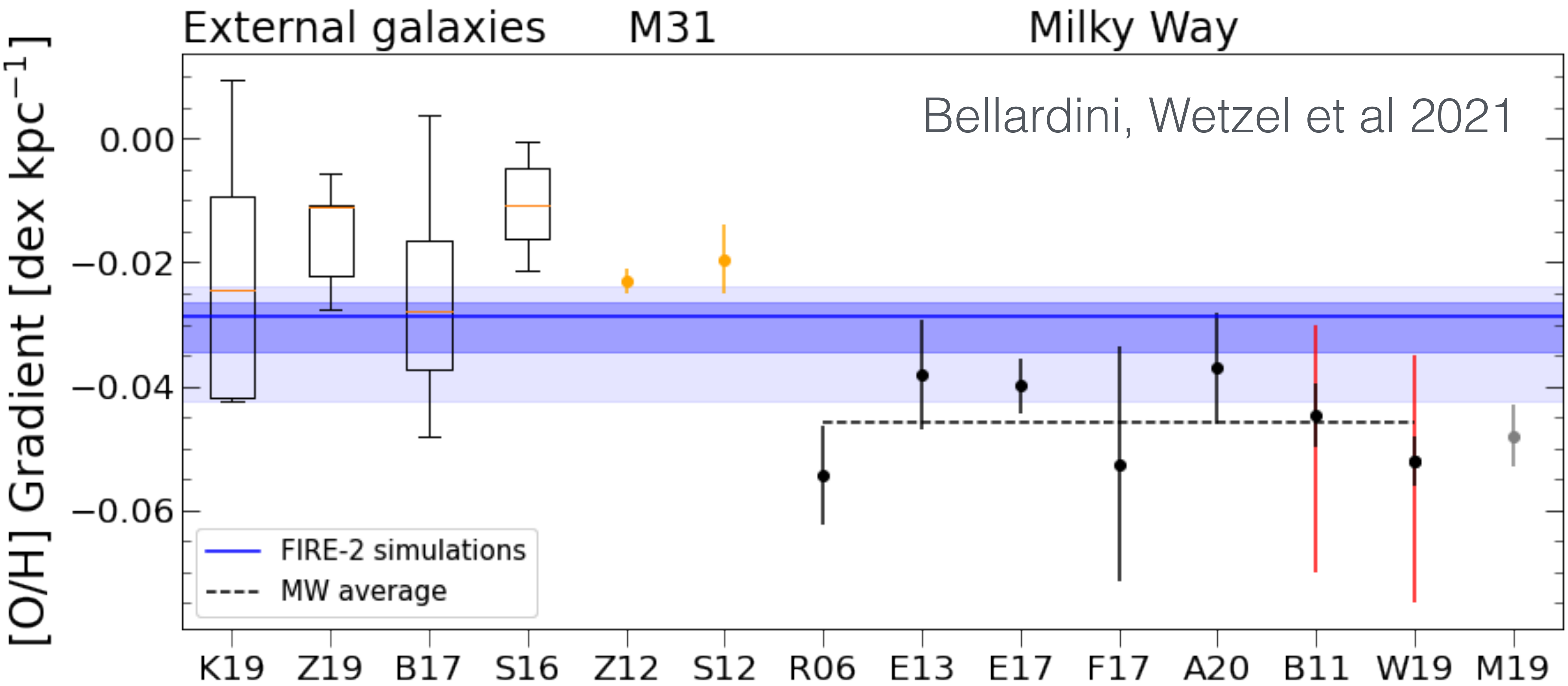
FIRE
Feedback In Realistic Environments

SPATIAL VARIATIONS OF ELEMENTAL ABUNDANCES ACROSS COSMIC TIME

Bellardini et al 2021, arxiv:2102.06220
Bellardini et al 2022, arxiv:2203.03653
Graf et al 2024, arxiv:2402.15614
Graf et al in prep

Russell Graf, undergraduate student @ UC Davis

Matt Bellardini, recent PhD student @ UC Davis



the Milky Way and most nearby disk galaxies have **negative** radial gradients in metallicity for gas and for (young) stars

‘choose your own adventure’ story
as a Milky Way-mass disk galaxy
evolves, what *typically* happens to the
metallicity radial gradient of its ISM?

1. becomes shallower (flatter) over time
2. stays about the same over time
3. becomes steeper over time

evolution of ISM metallicity radial gradients contested prediction of galaxy formation models (including cosmological simulations)

typically get shallower (flatter) over time

Minchev et al 2018, Vincenzo & Kobayashi 2018, Agertz et al 2021, Hemler et al 2021, Buck et al 2023, Ratcliffe et al 2023, Prantzos et al 2023

typically get steeper over time

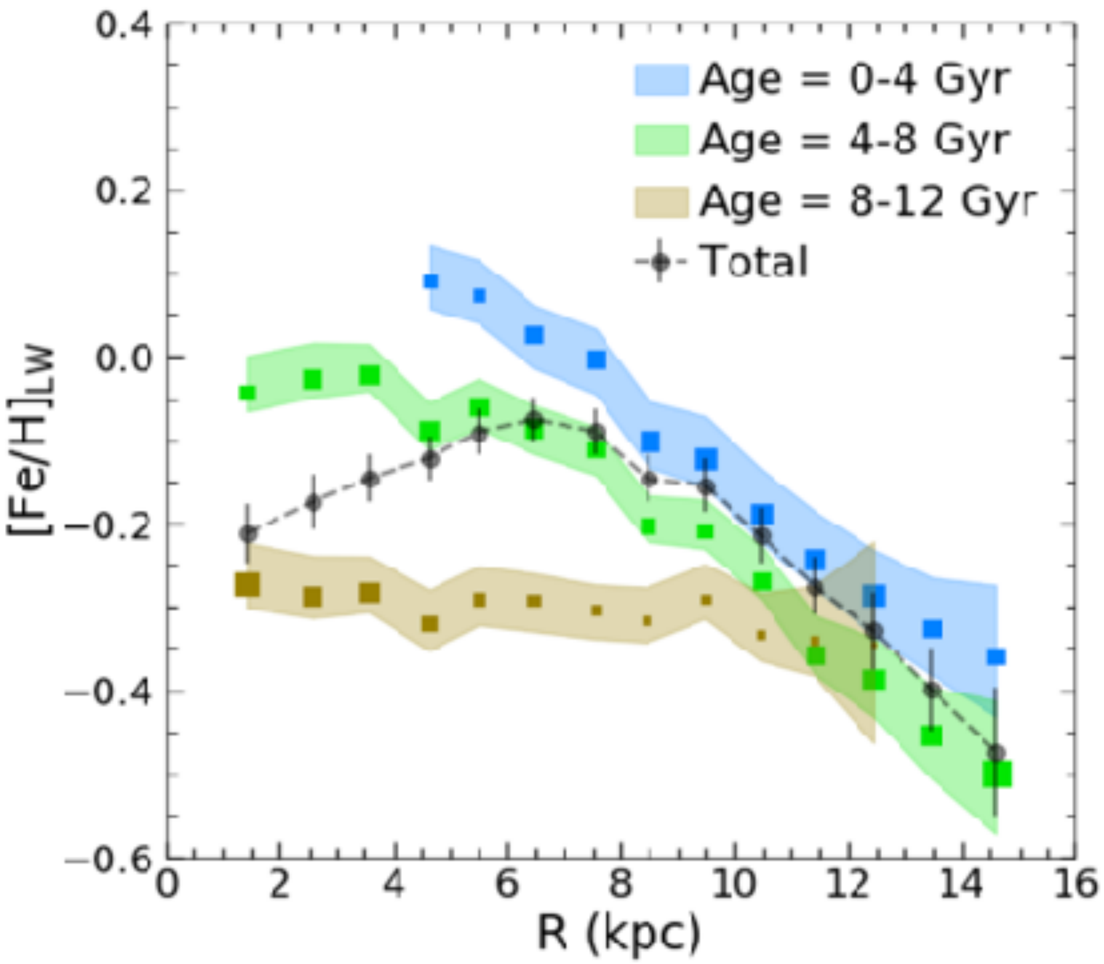
Chiappini et al 2001, Ma et al 2017, Vincenzo & Kobayashi 2020, Sharda et al 2021, Khoperskov et al 2023

~no or mixed evolution, or depends on feedback model

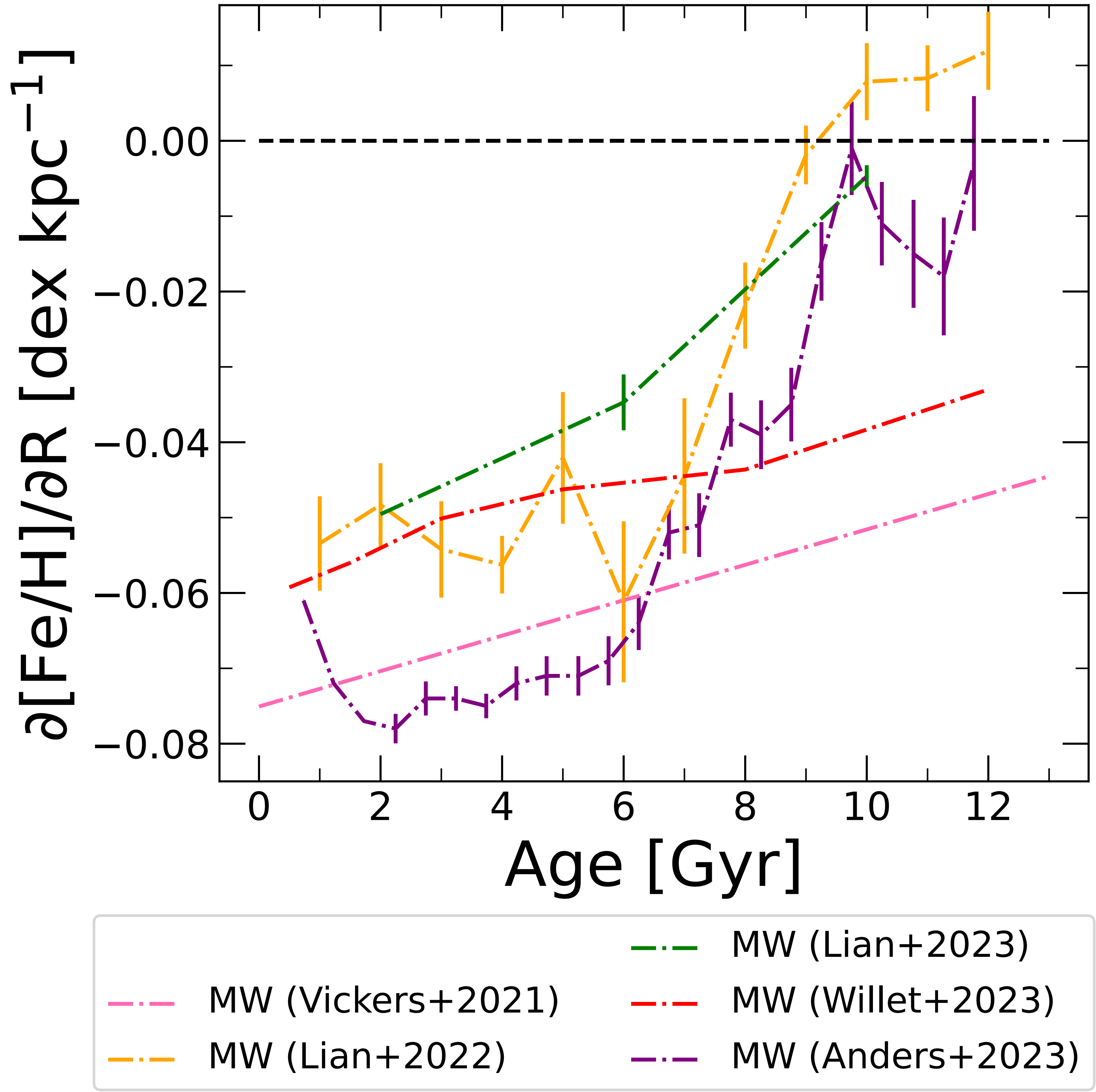
Pilkington et al 2012, Gibson et al 2013, Lu et al 2022, Tissera et al 2022

MW today: older stars have **shallower** radial gradients in metallicity

Lian et al 2023



Graf, Wetzel et al 2024



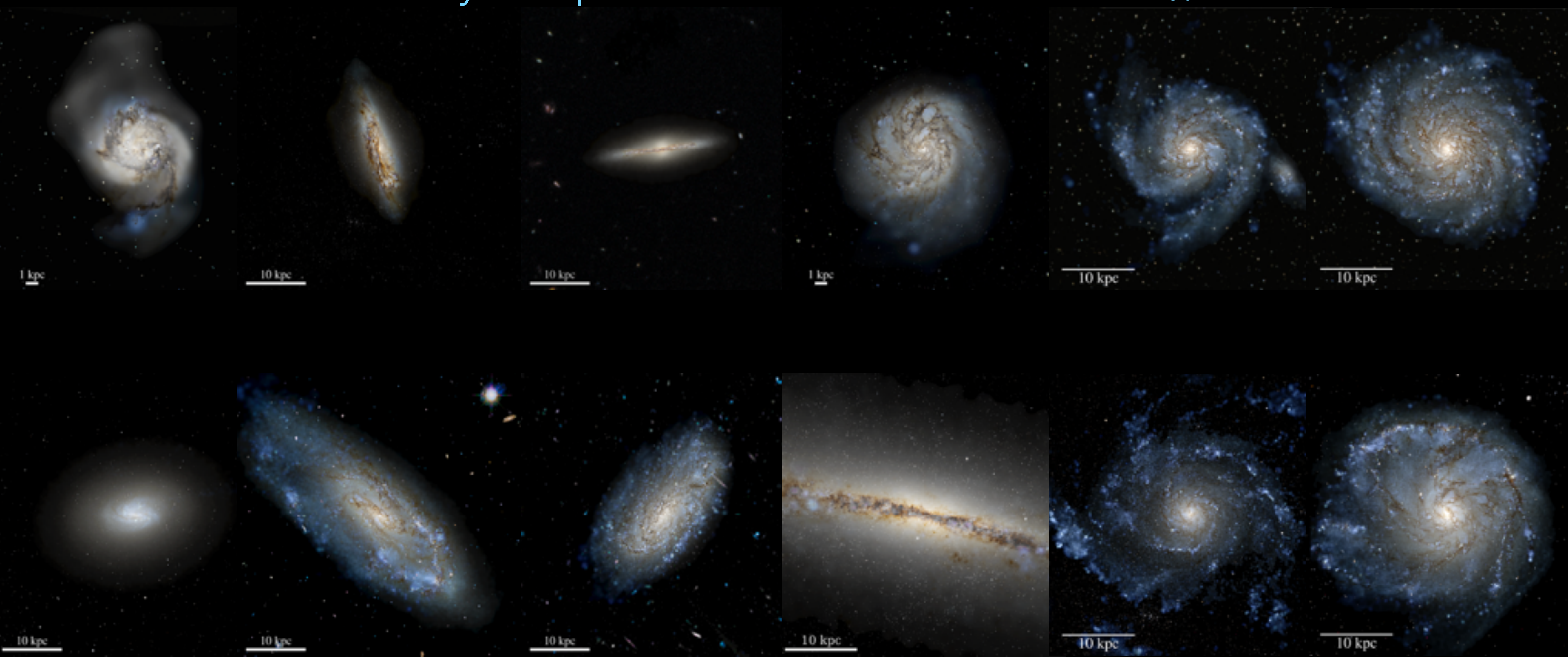
FIRE-2
Feedback In Realistic Environments

simulation suite of MW/M31-mass galaxies

Latte suite: 8 isolated MW-mass systems

ELVIS suite: 3 Local Group-like pairs (6 halos)

baryonic particle mass: 3500 - 7100 M_{sun}



FIRE-2 model for gas + star formation

Feedback In Realistic Environments

Hopkins, Wetzel et al 2018

goal: model multi-phase (dense) ISM in a cosmological setting

high resolution

- mass resolution: 3500 - 7100 M_{sun}
- spatial resolution
  gas: 1 pc (min)
  stars: 4 pc

gas cooling down to 10 K (via atoms, molecules, and metals)

star formation in self-gravitating gas (n_{SF} > 1000 atoms / cm^3)

FIRE-2
Feedback In Realistic Environments

model for stellar evolution + feedback

Hopkins, Wetzel et al 2018

goals

- forward model (as much as possible)
- directly model single stellar populations
- explicitly model 3 feedback channels

supernovae

- core-collapse (prompt)
- type Ia (delayed)

stellar radiation

- radiation pressure
- photoionization heating (HII regions)
- photoelectric heating (via dust)

stellar winds

- massive O & B stars (prompt)
- AGB stars (delayed)


stellar scale

galaxy scale

FIRE-2 model for elemental abundances

Feedback In Realistic Environments

Hopkins, Wetzel et al 2018

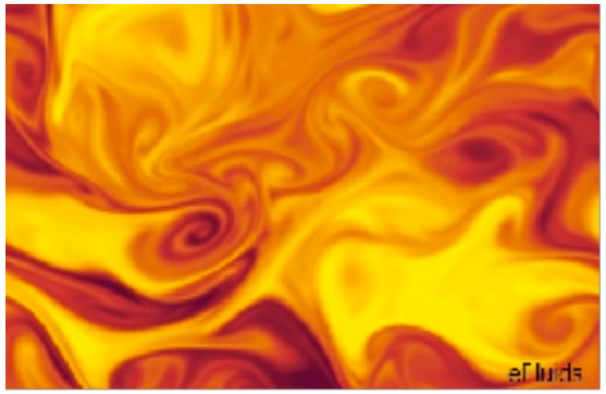
self-consistent generation of 11 abundances:
H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe

stellar nucleosynthesis (generation of metals) via:

- core-collapse supernovae
- white-dwarf (type Ia) supernovae
- stellar winds (dominated by O, B, & AGB stars)

model sub-grid turbulent mixing of each abundance in gas

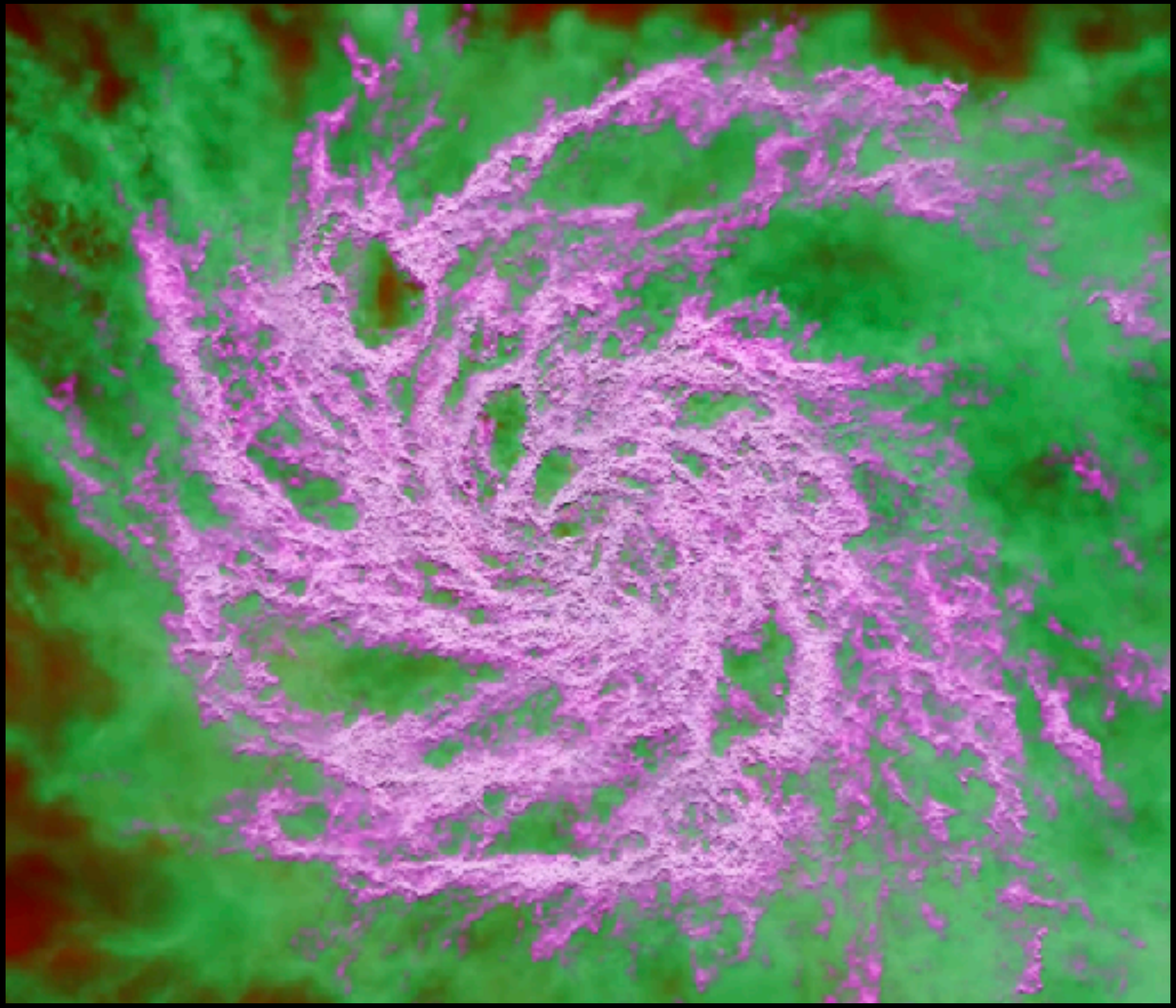
Escala, Wetzel et al 2017



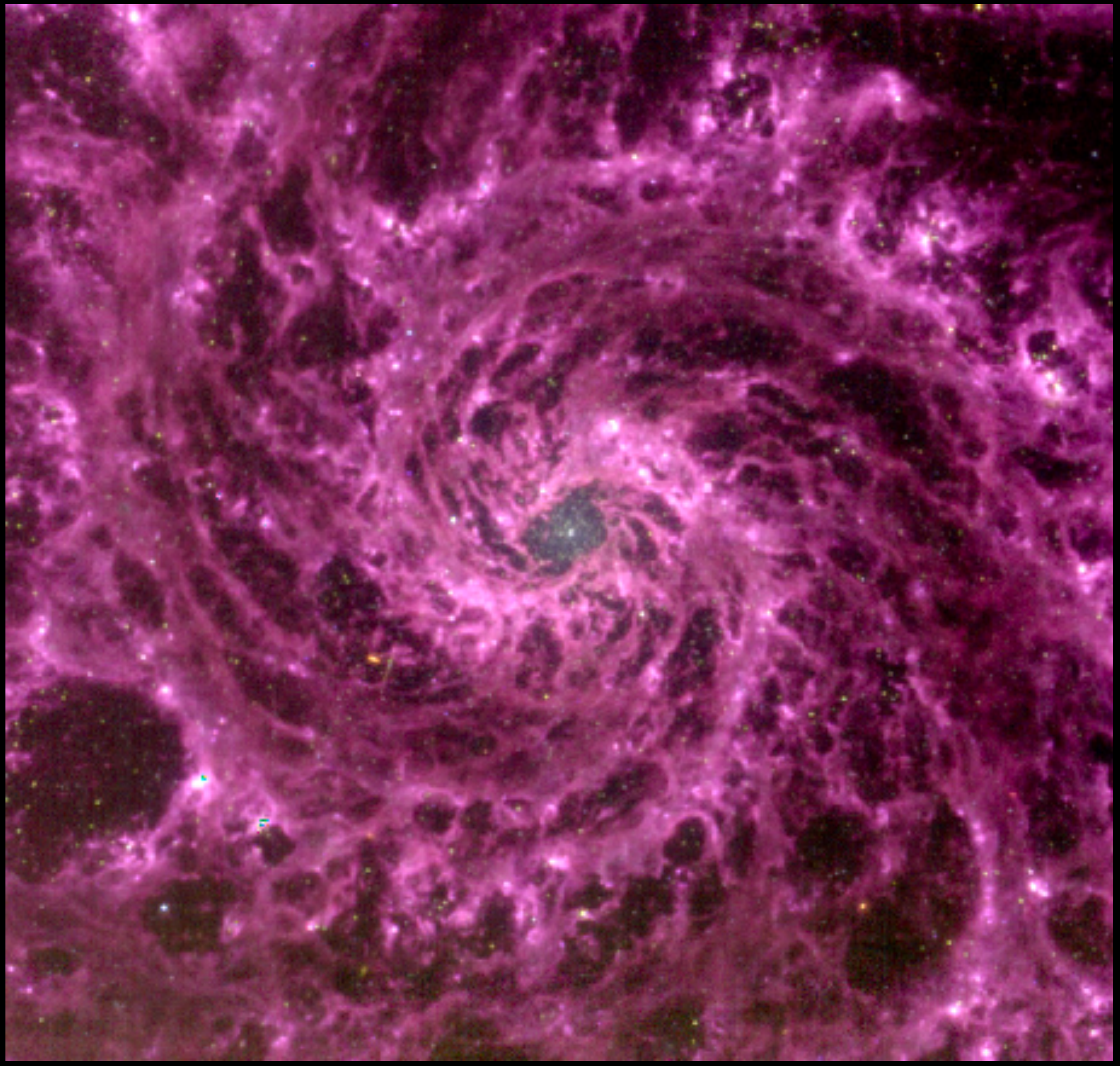
FIRE simulations model dense multi-phase ISM with emergent GMCs, HII regions, spiral arms, etc

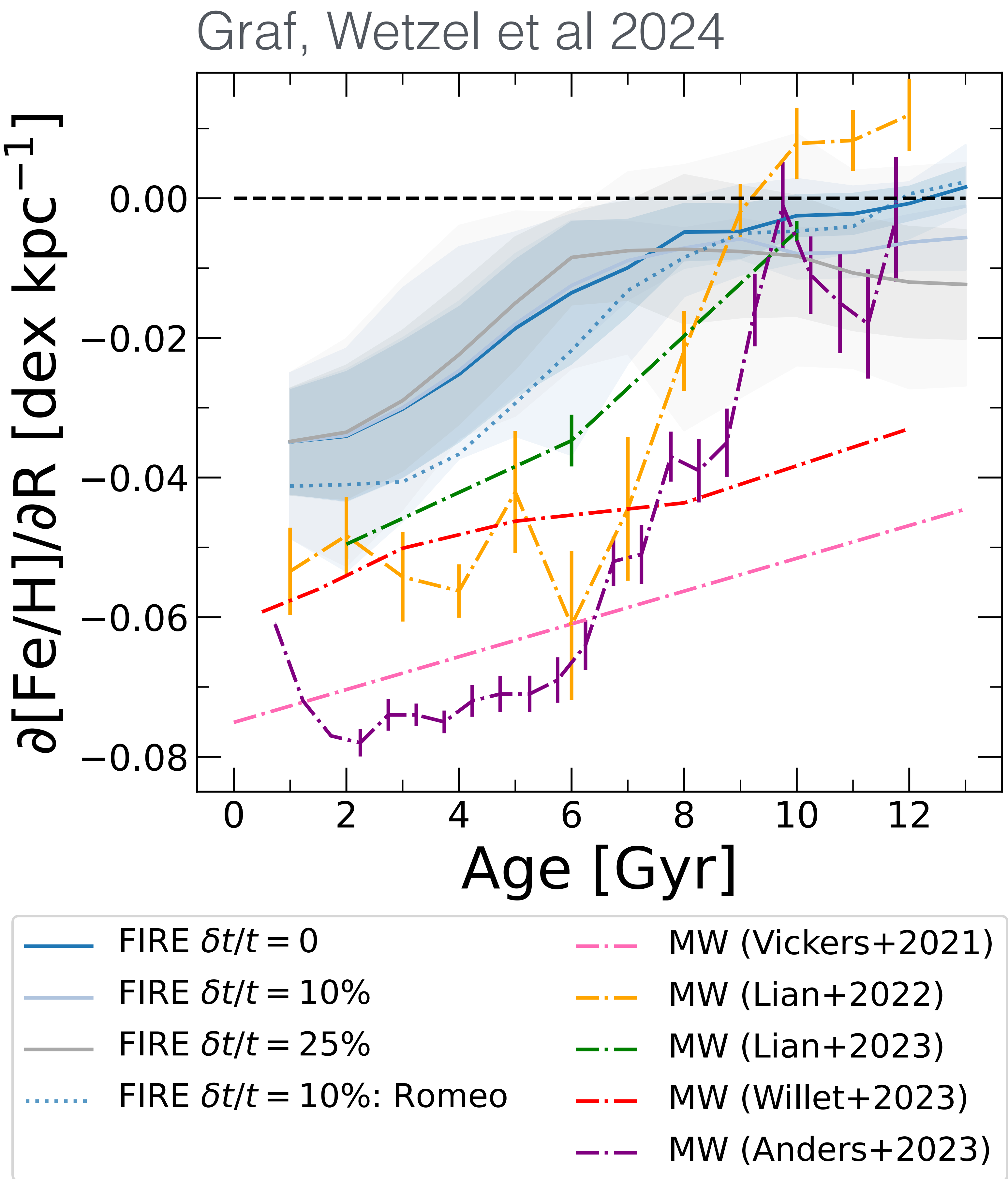
(Benincasa et al 2020, Guszejnov et al 2020, Ansar et al 2023)

FIRE-2 (m12c)

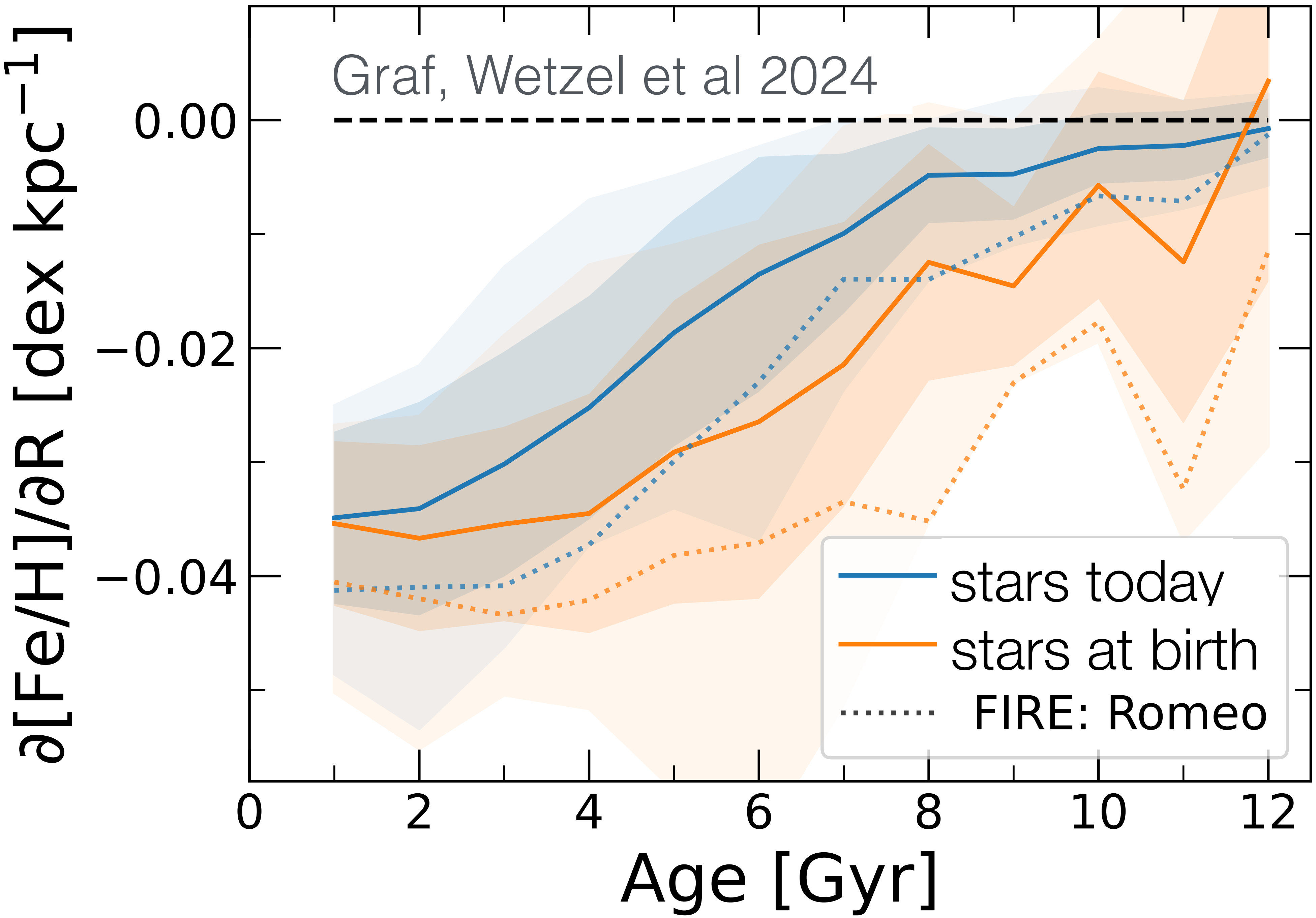


PHANGS (M74)





- archeological histories of FIRE-2 simulations qualitatively **match** MW's stellar metallicity gradient v age
- MW is steeper than FIRE-2 at most ages
  (MW is unusually steep, possibly because it formed early?)

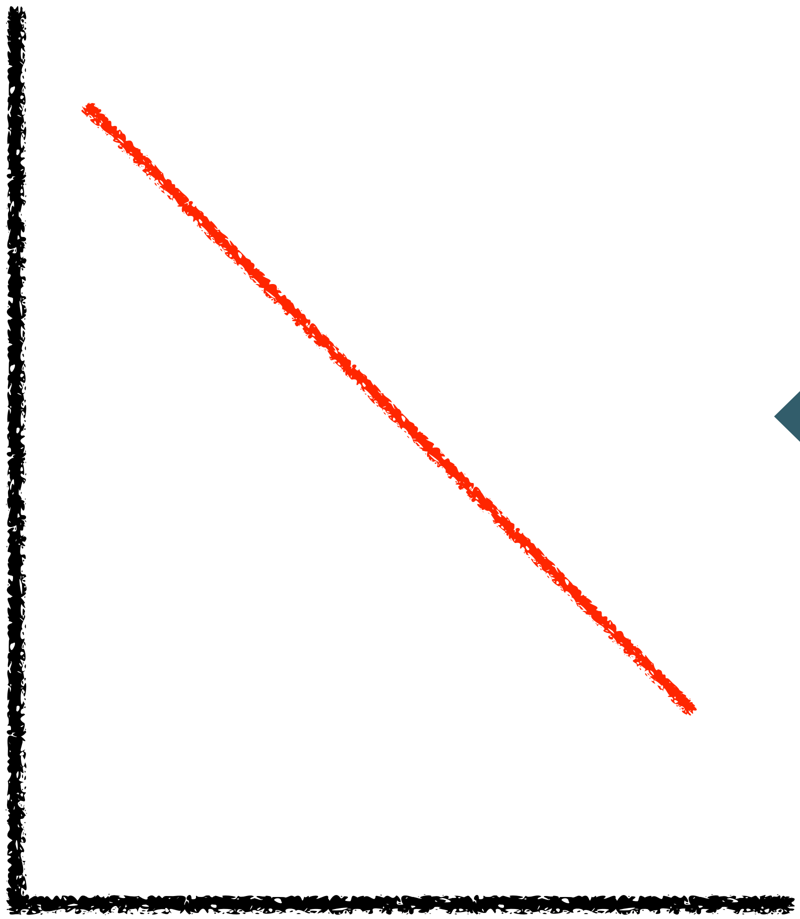


radial redistribution of stars after birth only moderately shallows the radial gradient, as measured today

radial gradient in star-forming ISM became steeper over time

why do disk galaxies form negative radial gradients in metallicity?

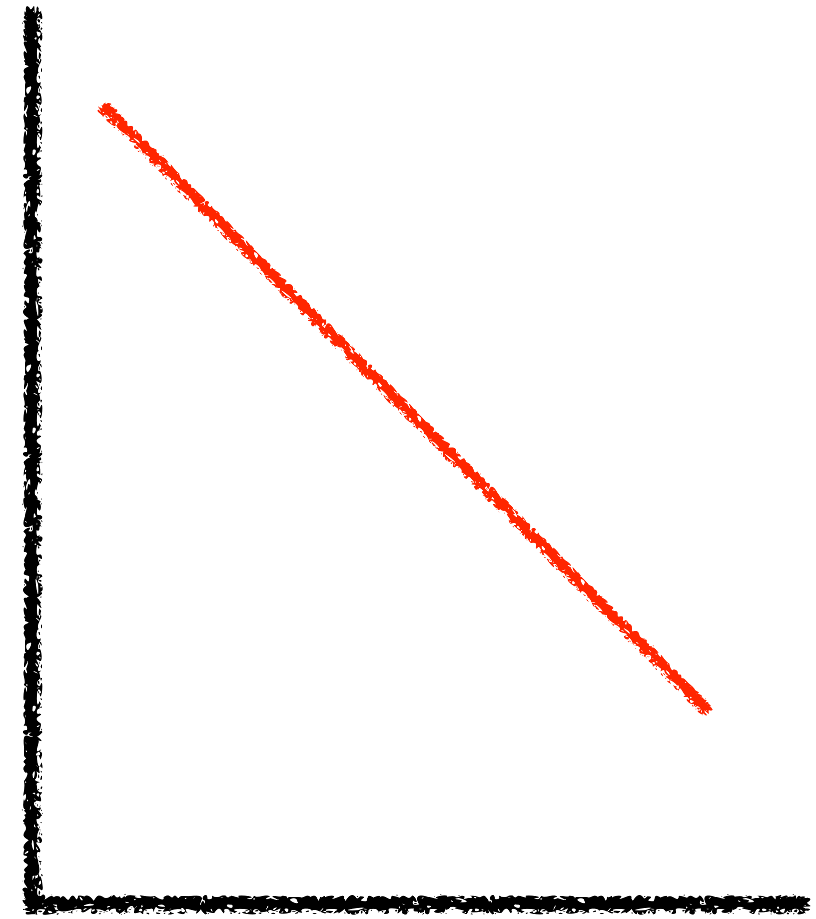
[Z/H]



radius

⟷

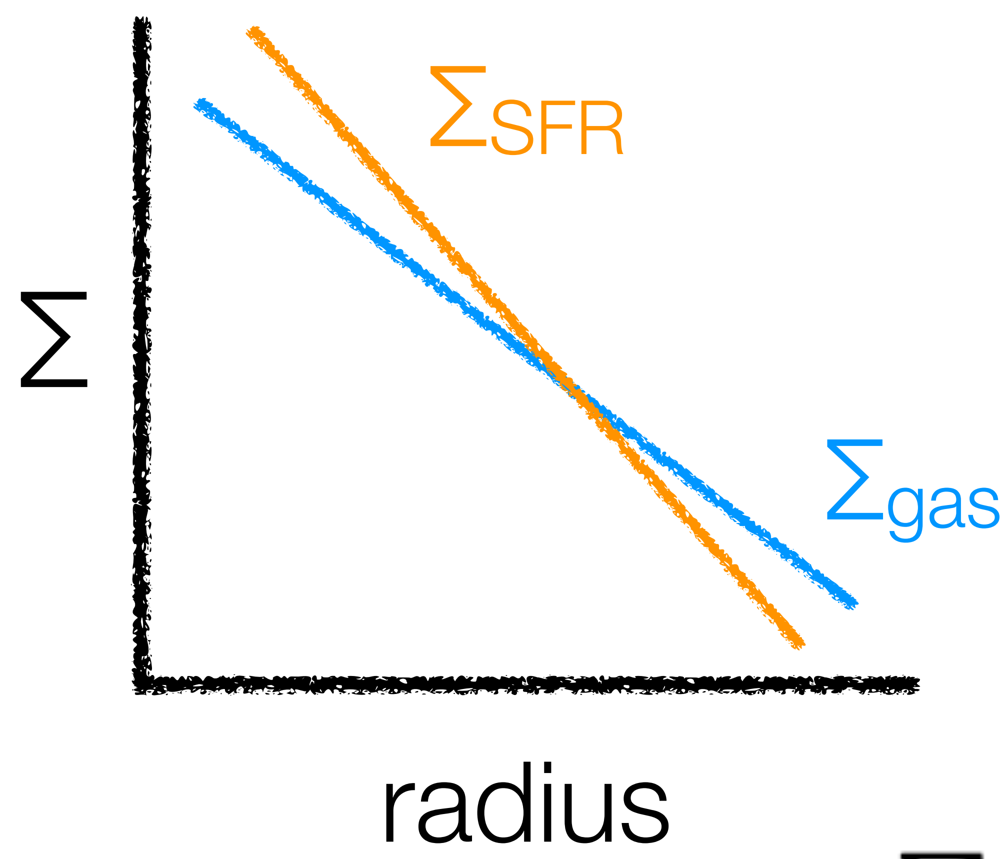
$\Sigma_{star}/\Sigma_{gas}$



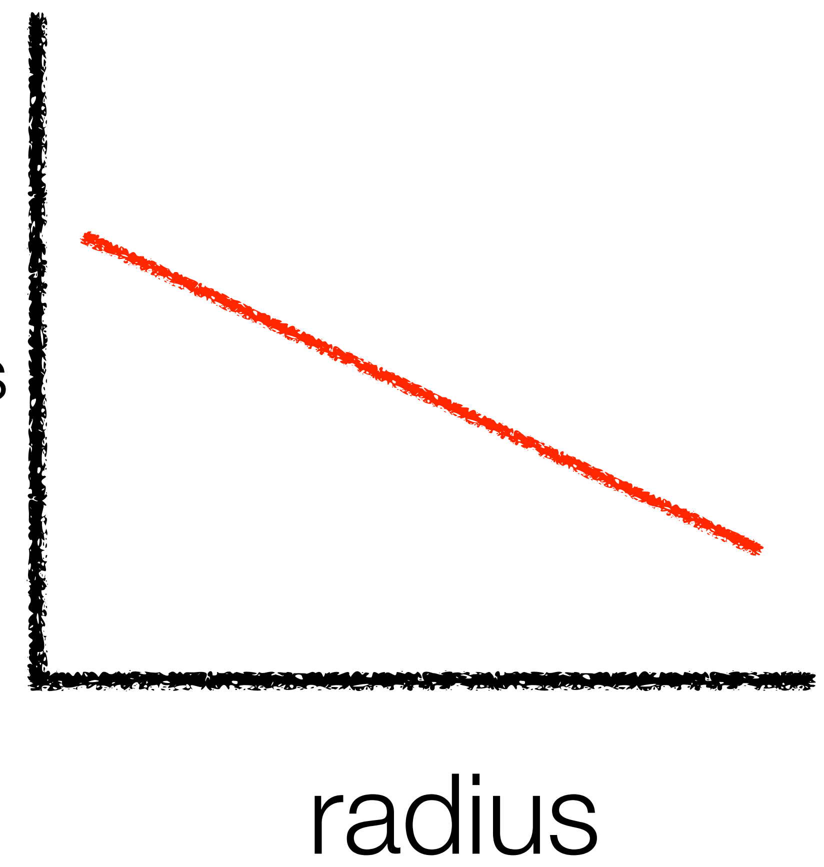
radius

$$[Z/H](R) \propto \log[\Sigma_{star,young}(R) / \Sigma_{gas}(R)]$$

why do disk galaxies form negative radial gradients in metallicity?

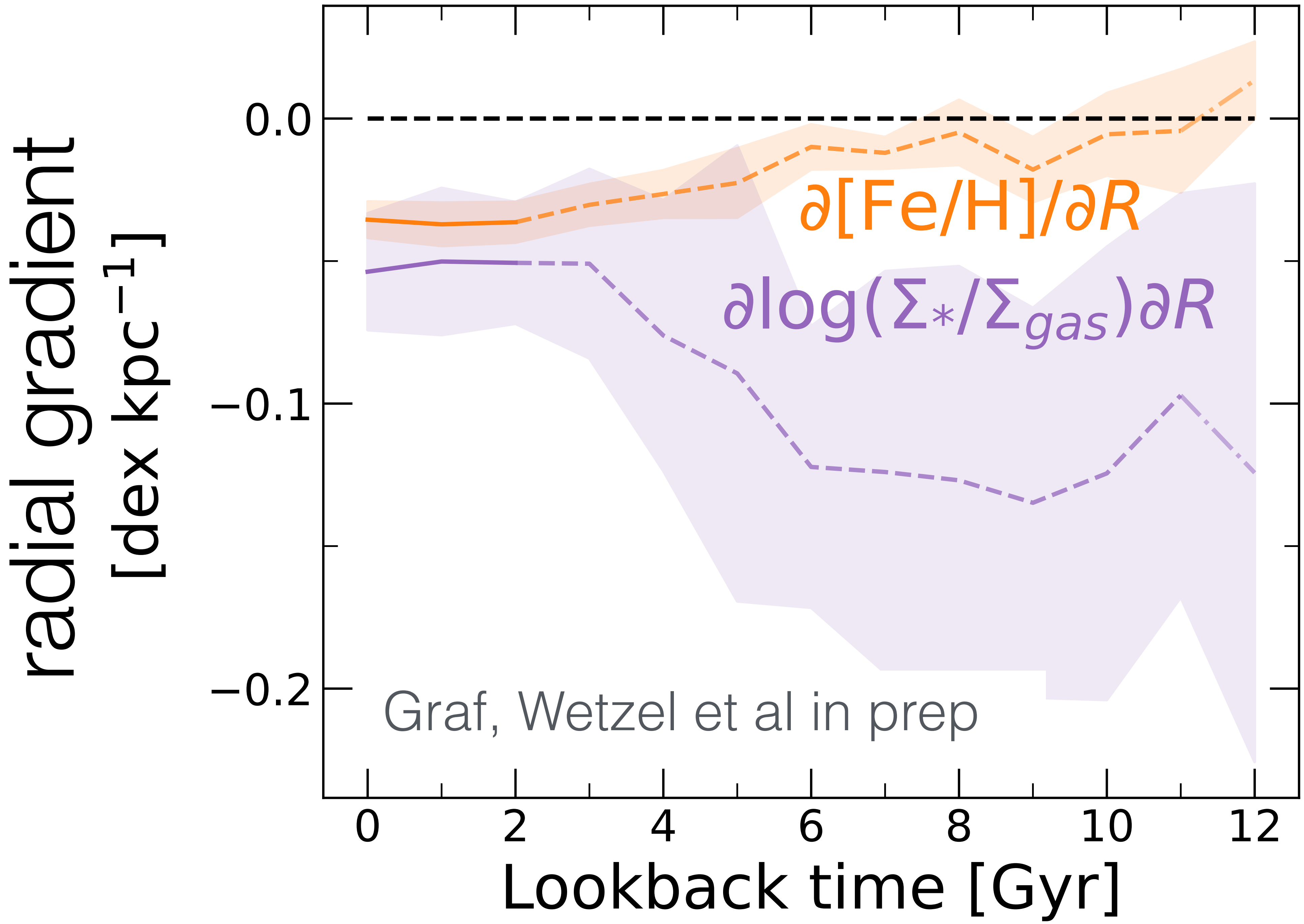


$\Sigma_{stars}/\Sigma_{gas}$



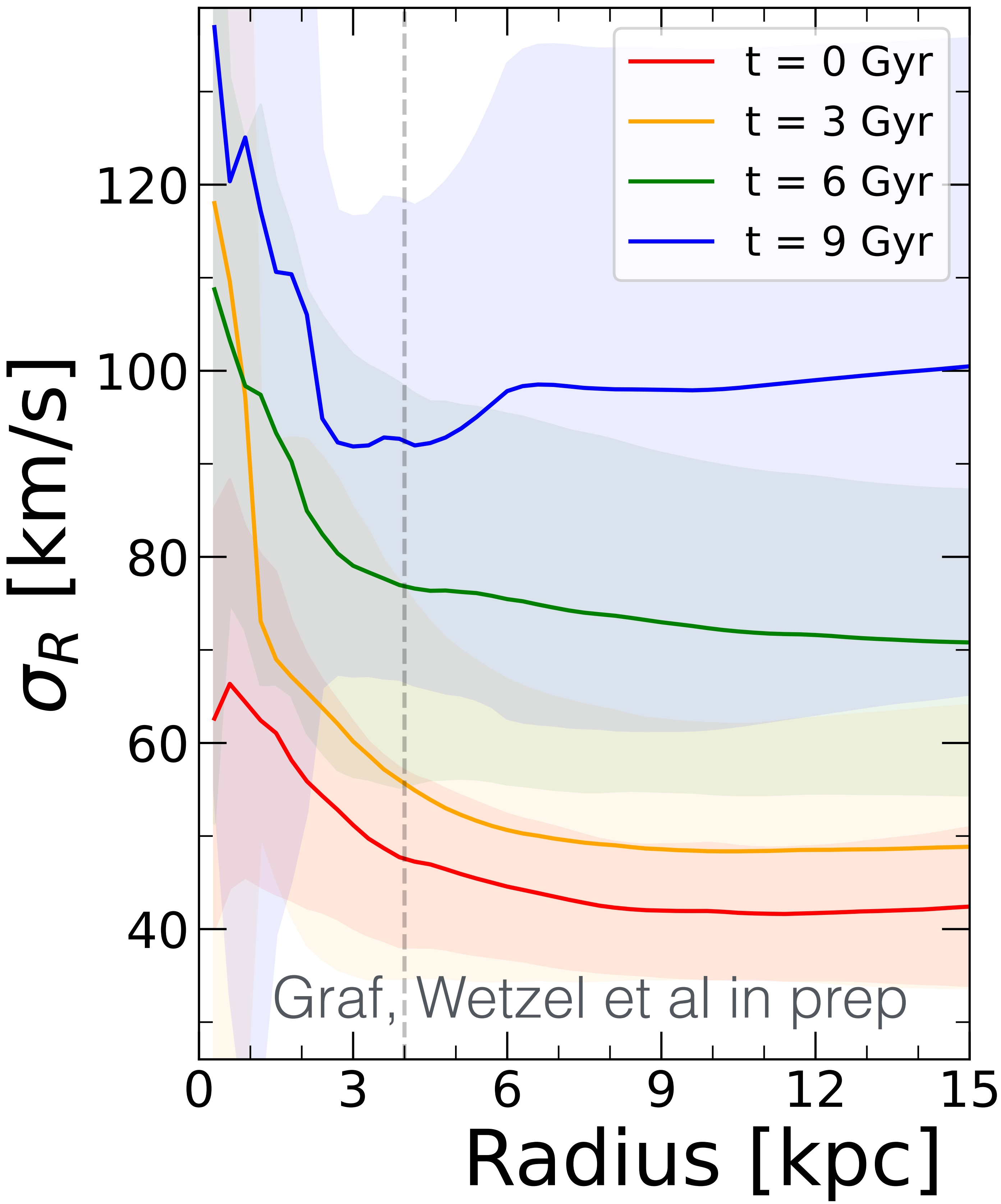
$$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{n}$$

- if $n > 1$ (K-S relation), $\Sigma_{SFR}(R) / \Sigma_{gas}(R)$ declines with radius
- negative gradient in metallicity **if** metals stay where injected
- $\Sigma_{SFR}(R) / \Sigma_{gas}(R)$ evolves (flattens) if $\Sigma_{gas}(R)$ evolves (flattens) via inside-out formation (via gas accretion)



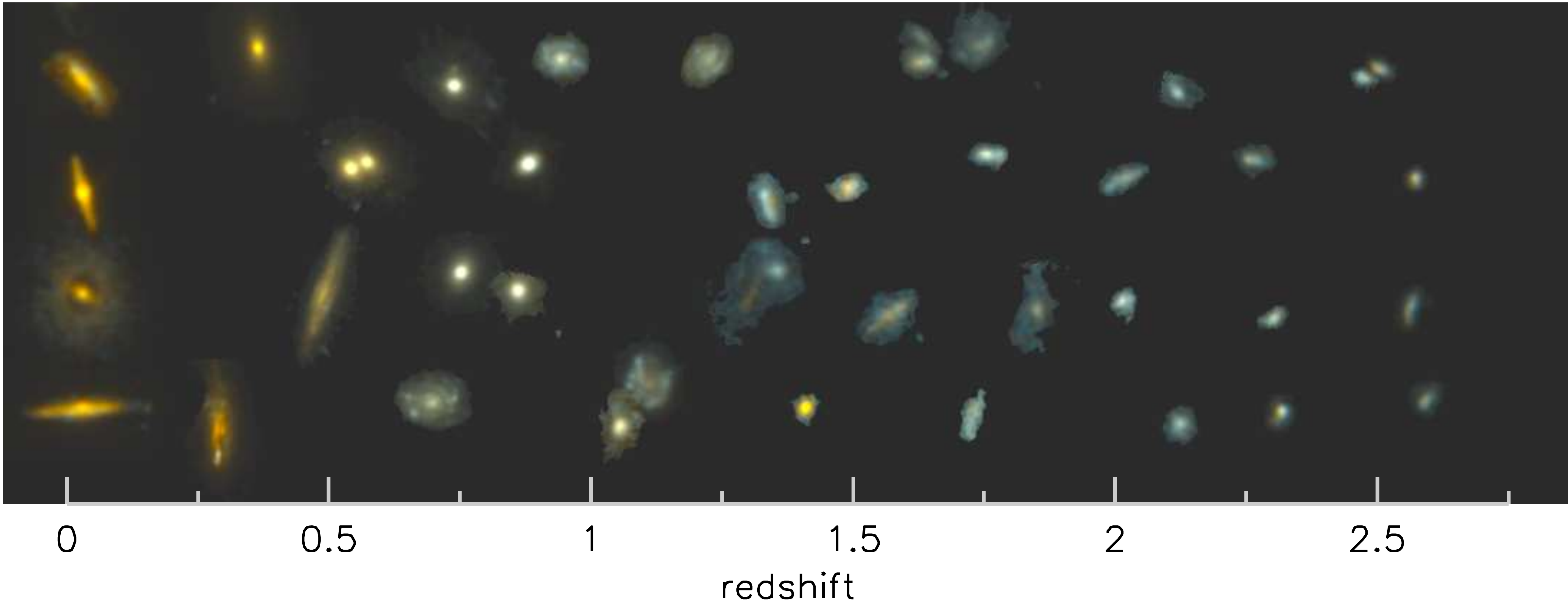
- FIRE-2 galaxies experience 'inside-out' radial evolution naively implying gradients that become shallower
- but **actual** metallicity gradient evolution is **opposite** (steepens over time)
- why? **metals do not stay where they were injected**

radial mixing in **total** ISM at different lookback times



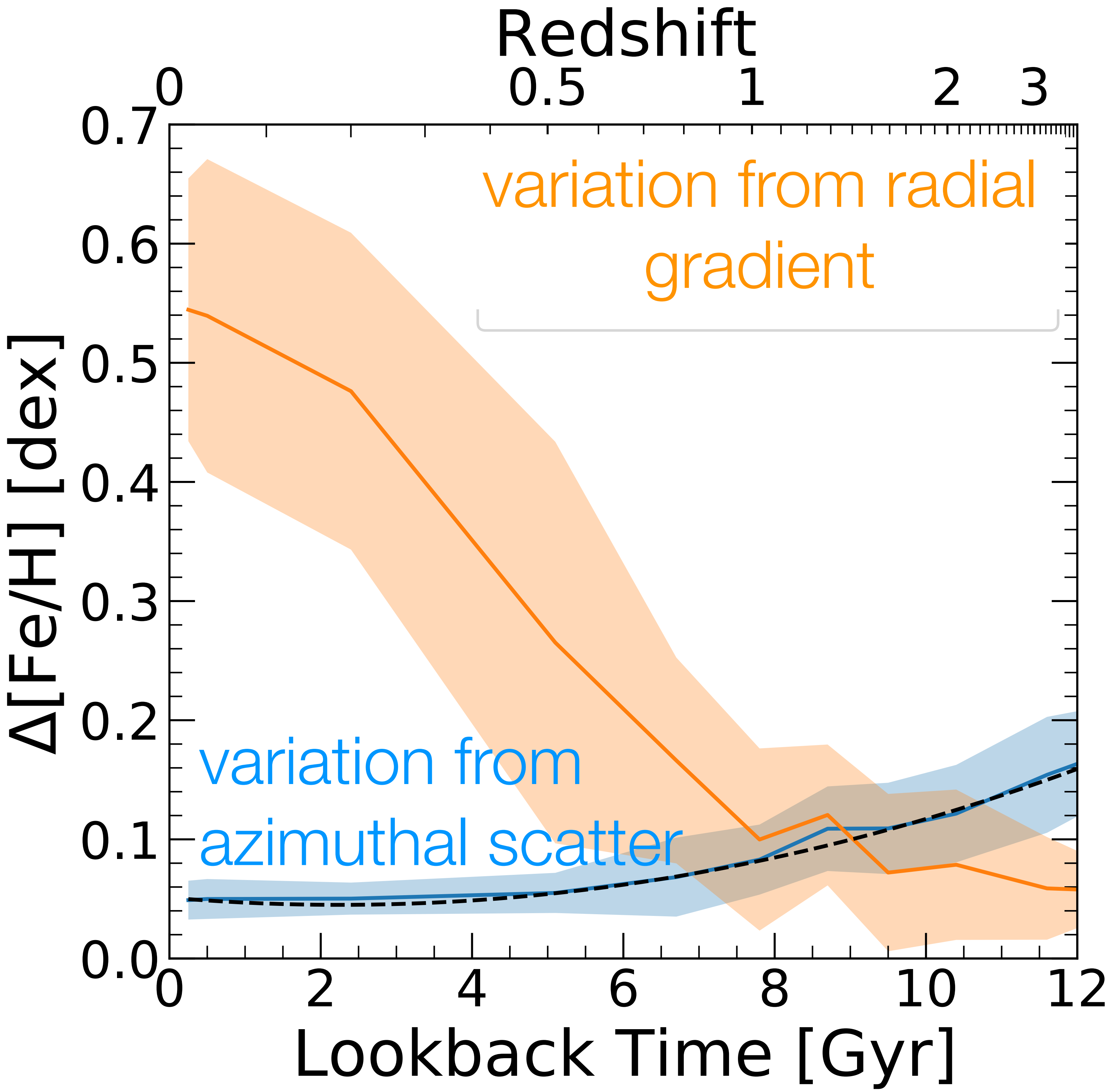
- **key argument** steepening of the metallicity radial gradient over time is caused by reduced radial mixing (turbulence, etc) in the **total** ISM over time
- this effect overwhelms the flattening of $\Sigma_{stars}(R)$ / $\Sigma_{gas}(R)$ over time from cosmological 'inside-out' formation

van Dokkum et al 2013



observed high-redshift progenitors of MW-mass galaxies were increasingly turbulent, thicker disks, with lower v_ϕ/σ_v

for example, Elmegreen & Elmegreen 2006, Flores et al 2006, Elmegreen et al 2007, Shapiro et al 2008, Genzel et al 2008,2011, Law et al 2009, Forster-Schreiber et al 2009, Overzier et al 2010, Jones et al 2010, Gnerucci et al 2011, Kassin et al 2012, Tacconi et al 2013, Wisnioski et al 2015, Mieda et al 2016, Simons et al 2016, Stott et al 2016, Mason et al 2017, Elmegreen et al 2017, Mason et al 2017, Ubler et al 2019

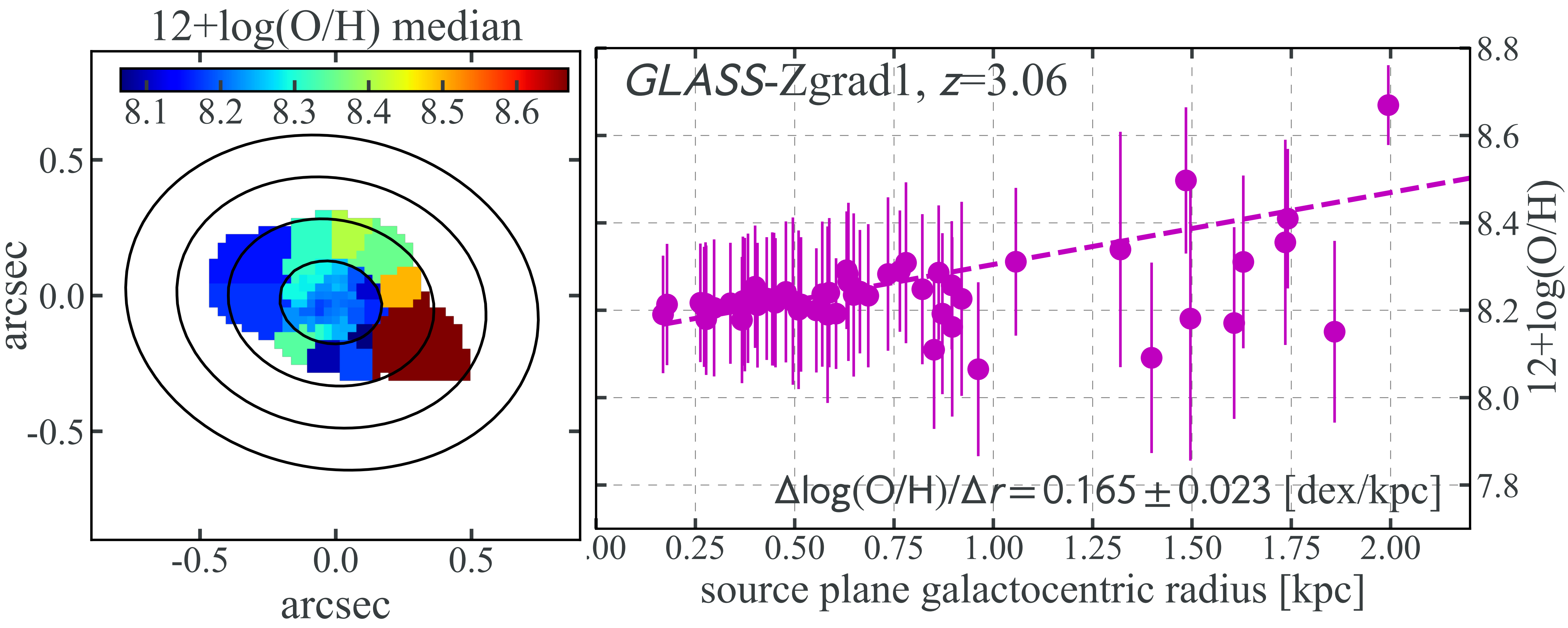


radial gradient dominates today, but **not** at early times

azimuthal variations dominate at z >~ 1 (ages >~ 8 Gyr)

Bellardini, Wetzel et al 2022

JWST observations of gas metallicity in a MW-progenitor-mass galaxy: M_{star} ~ 10^9 M_{sun} at z ~ 3 strong patchy (azimuthal) variations!



Wang, Jones et al 2022

FIRE-2 public data release

Feedback In Realistic Environments

Wetzel et al 2023, ApJS

FlatHUB flathub.flatironinstitute.org/fire

- full suite of 46 simulations, up to 39 snapshots z = 0 - 10
- all properties of stars, gas, and dark matter, including 11 elemental abundances
- 3D formation coordinates for all stars at z = 0
- galaxy/halo catalogs at all snapshots
- synthetic Gaia + APOGEE surveys

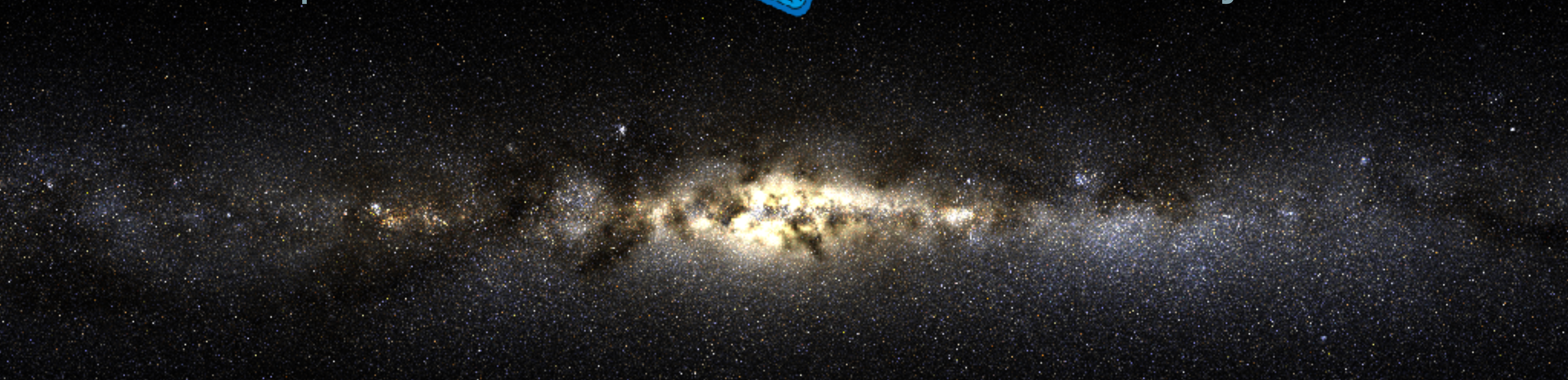
synthetic surveys of the Milky Way

Gaia DR2: Sanderson et al 2020

Gaia DR3: Nguyen et al 2023

SDSS-APOGEE: Nikakhtar et al 2021

public release: ananke.hub.yt



EVOLUTION OF METALLICITY RADIAL GRADIENTS

- **FIRE-2 simulations qualitatively match the MW: shallower/flatter gradients for older stars (as measured today)**
- in FIRE, the ISM of a disk galaxy evolves as:
  - v_ϕ / σ_v increases, as disk becomes more rotationally supported
  - radial mixing in gas (turbulence, etc) decreases
  - metallicity radial gradient **steepens (strengthens)**
- this reduction in gas radial mixing over time 'wins out' over $\Sigma_{stars}(R)$ / $\Sigma_{gas}(R)$ flattening from cosmological 'inside-out' formation
- **radial gradient of stars today set primarily by ISM when stars formed**