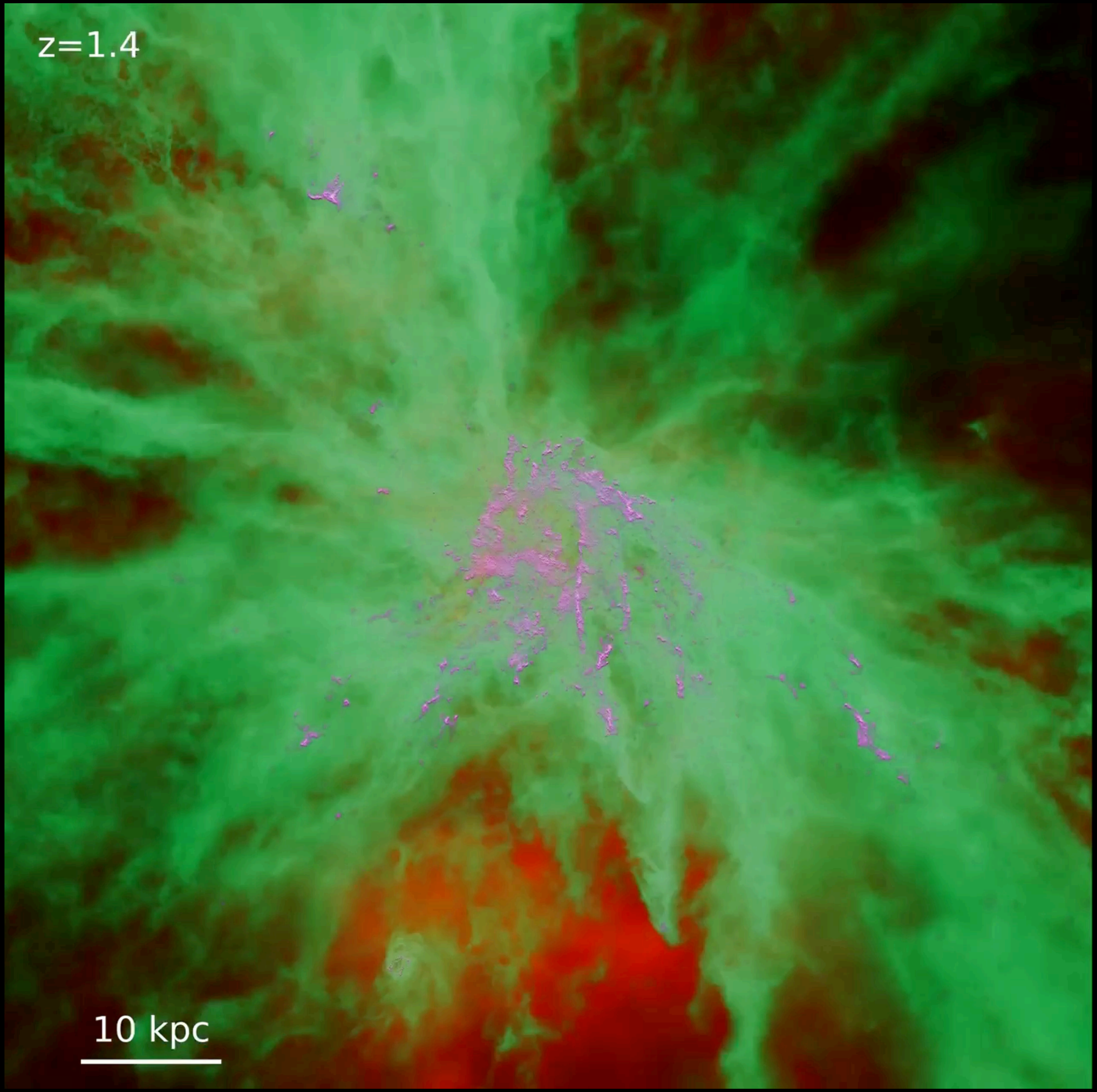
inside-out versus upside-down evolution of metallicity radial gradients in Milky Way-mass galaxies

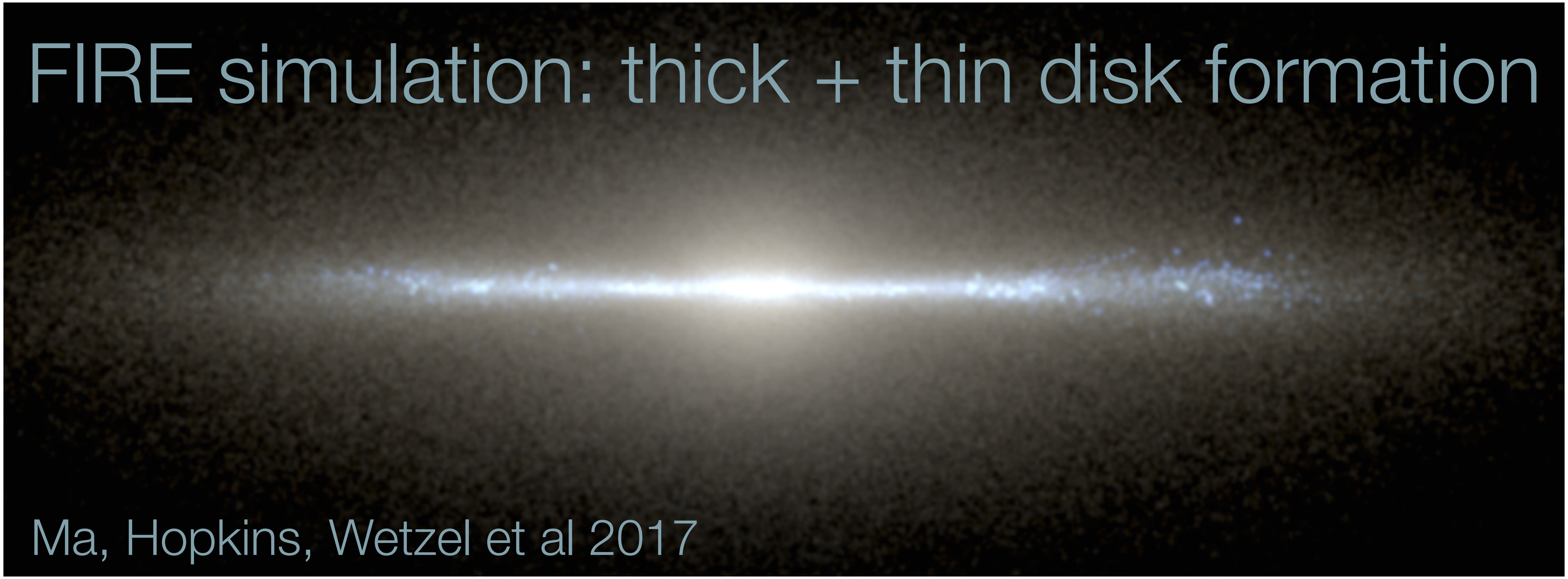


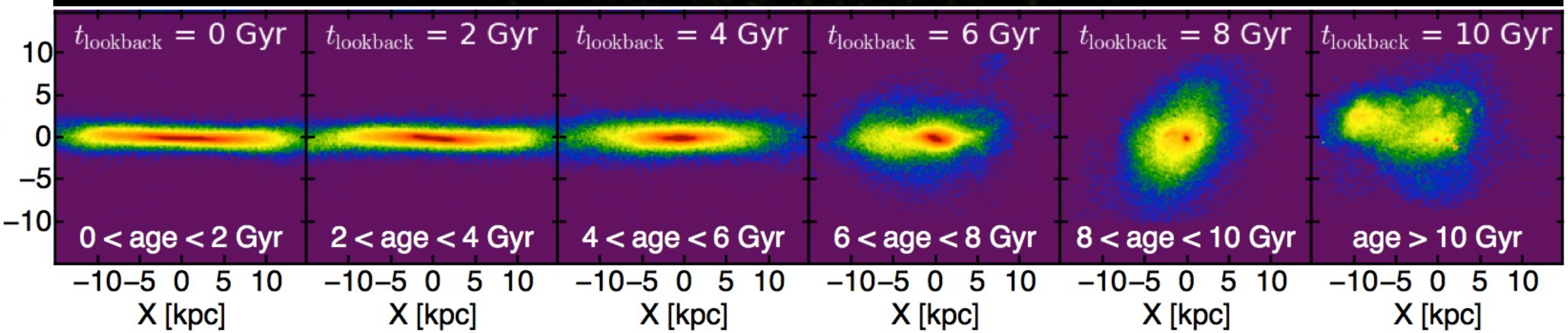
UC DAVIS
UNIVERSITY OF CALIFORNIA

Andrew Wetzel

FIRE
Feedback In Realistic Environments

FIRE simulation: thick + thin disk formation



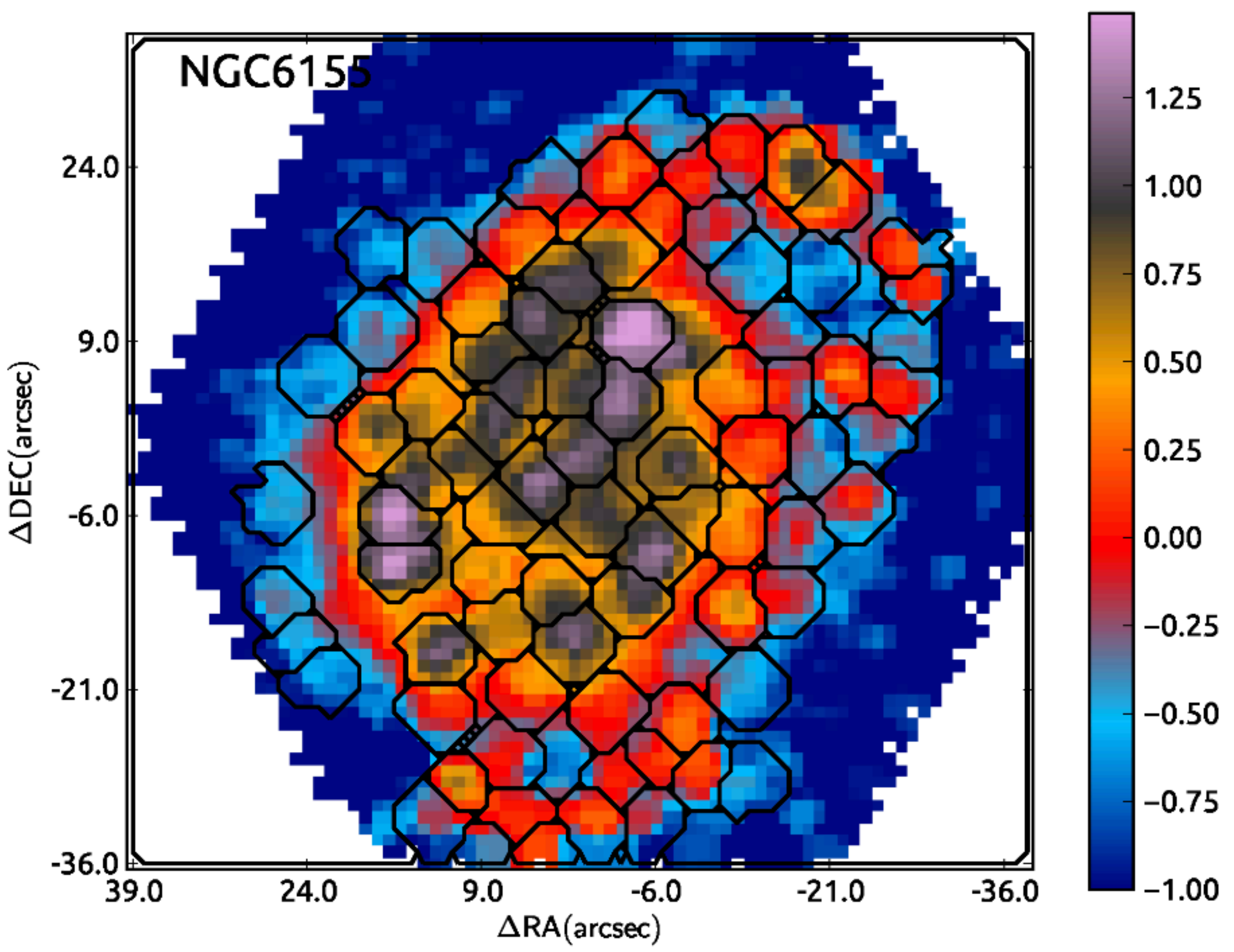


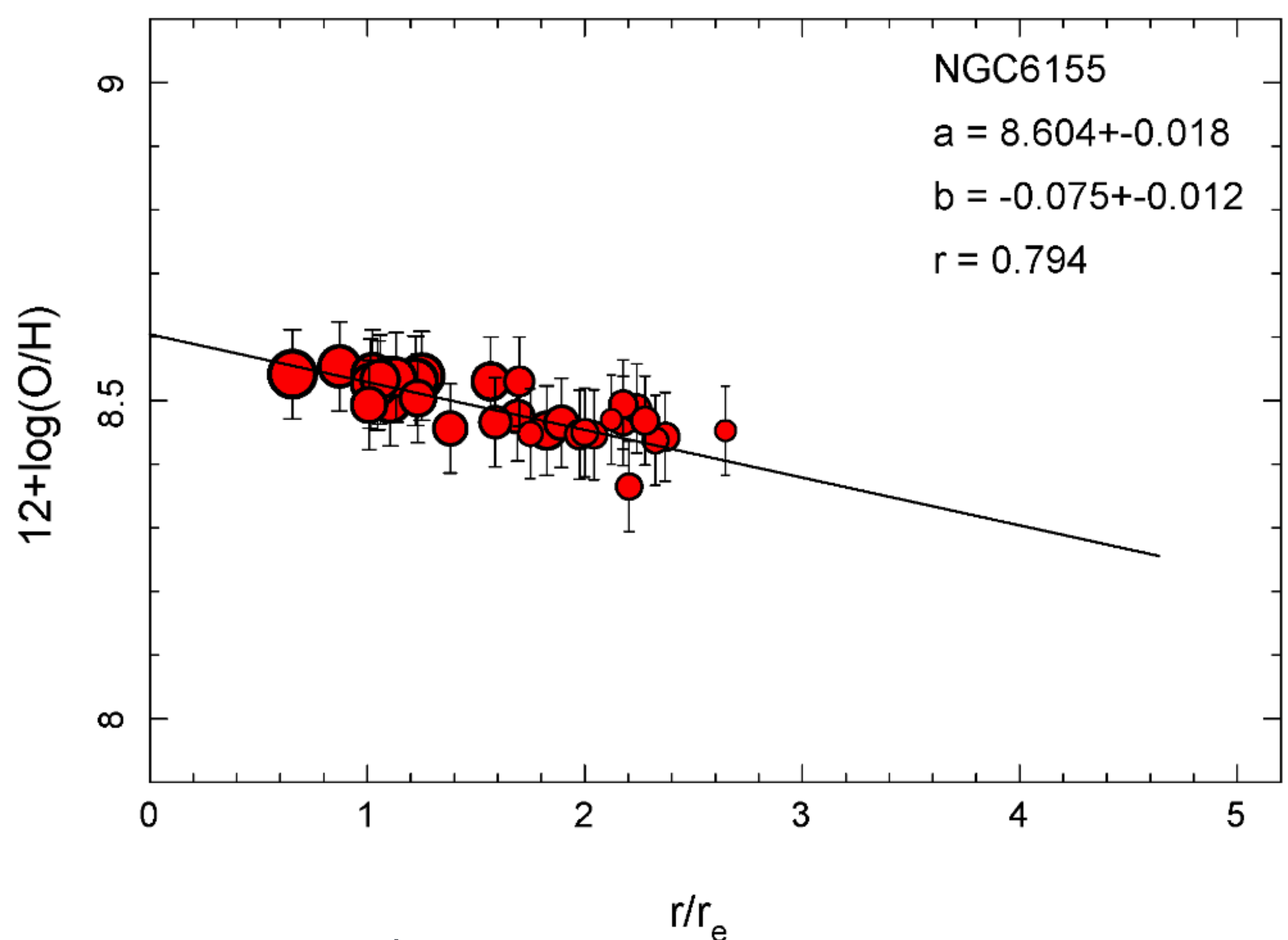
radial evolution: inside —> out

vertical evolution: upside —> down

e.g. Brook et al 2004, 2012; Stinson et al 2013; Bird et al 2013, 2021; Agertz & Kravtsov 2016, etc

MW and nearby disk galaxies have negative radial gradients in metallicity for gas and for (young) stars



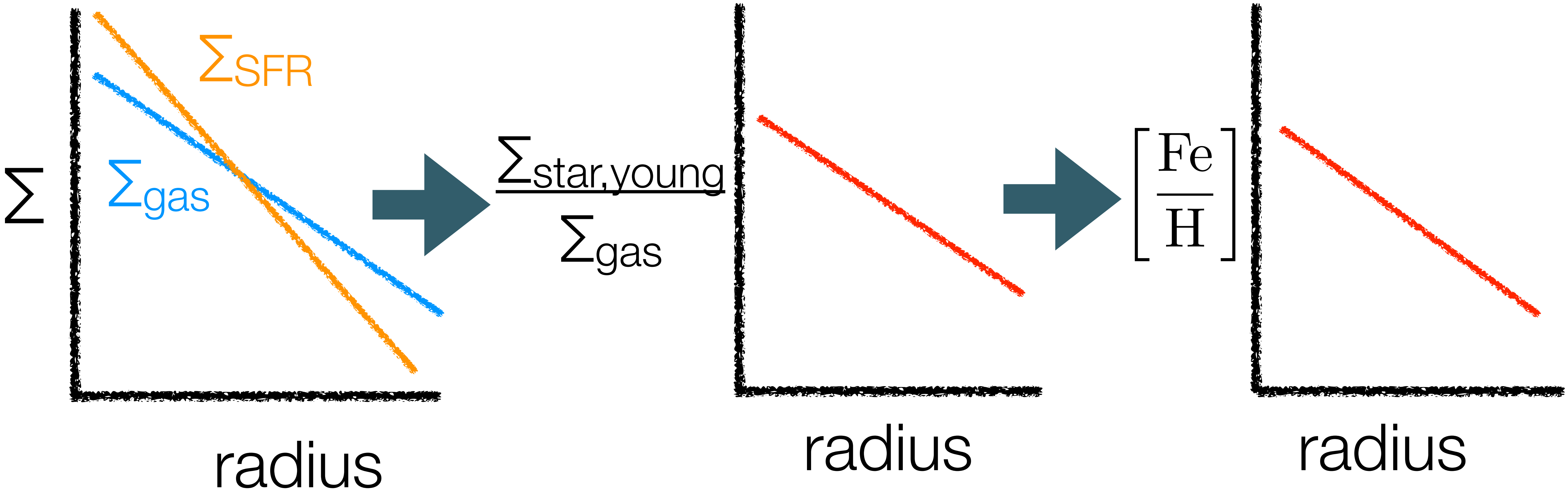


NGC 1655, CALIFA Survey (Sanchez et al 2015)

Why do galaxies form negative radial gradient in metallicity?

$$[\mathrm{Fe/H}](R) \approx \log\left(\frac{\Sigma_{\star,\mathrm{young}}(R)}{\Sigma_{\mathrm{gas}}(R)}\right) + C$$

Why do galaxies form negative radial gradient in metallicity?



$$\Sigma_{SFR} \propto \Sigma_{gas}^{n}$$ n ~ 1.4 (Kennicutt-Schmidt relation)

if $n > 1$, $\Sigma_{star,young}(R) / \Sigma_{gas}(R)$ declines with radius

negative radial gradient **if** metals stay where injected into ISM

Andrew Wetzel

as a Milky Way-mass 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, Acharyya et al 2024

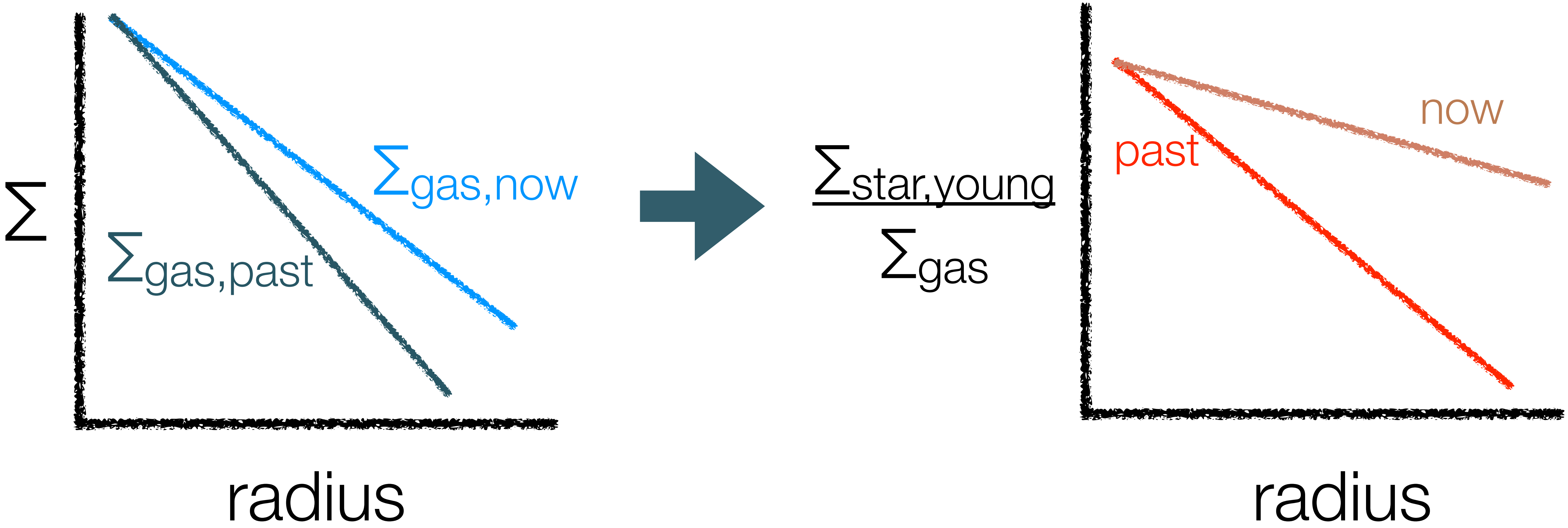
typically get steeper over time

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

typically ~no evolution (or depends on feedback model)

Pilkington et al 2012, Gibson et al 2013, Lu et al 2022, Tissera et al 2022, Johnson et al 2024

How does a metallicity radial gradient evolve?



(1) if $\Sigma_{SFR} \sim \Sigma_{gas}^{1.4}$, $\Sigma_{SFR}(R) / \Sigma_{gas}(R)$ declines with radius

(2) cosmic accretion makes $\Sigma_{gas}(R)$ shallower over time (inside-out radial growth)

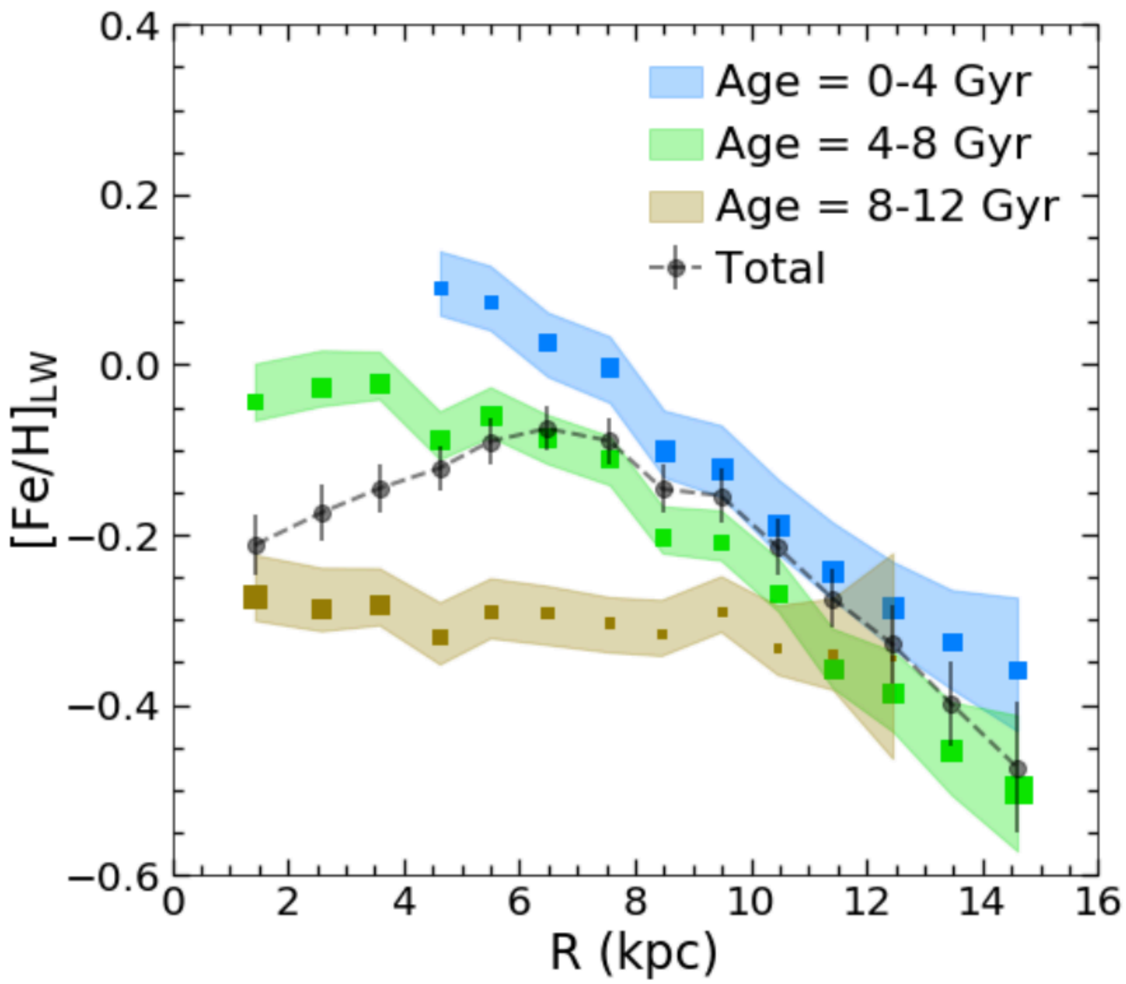
(1) + (2): $\Sigma_{star,young}(R) / \Sigma_{gas}(R)$ flattens over time

common expectation:

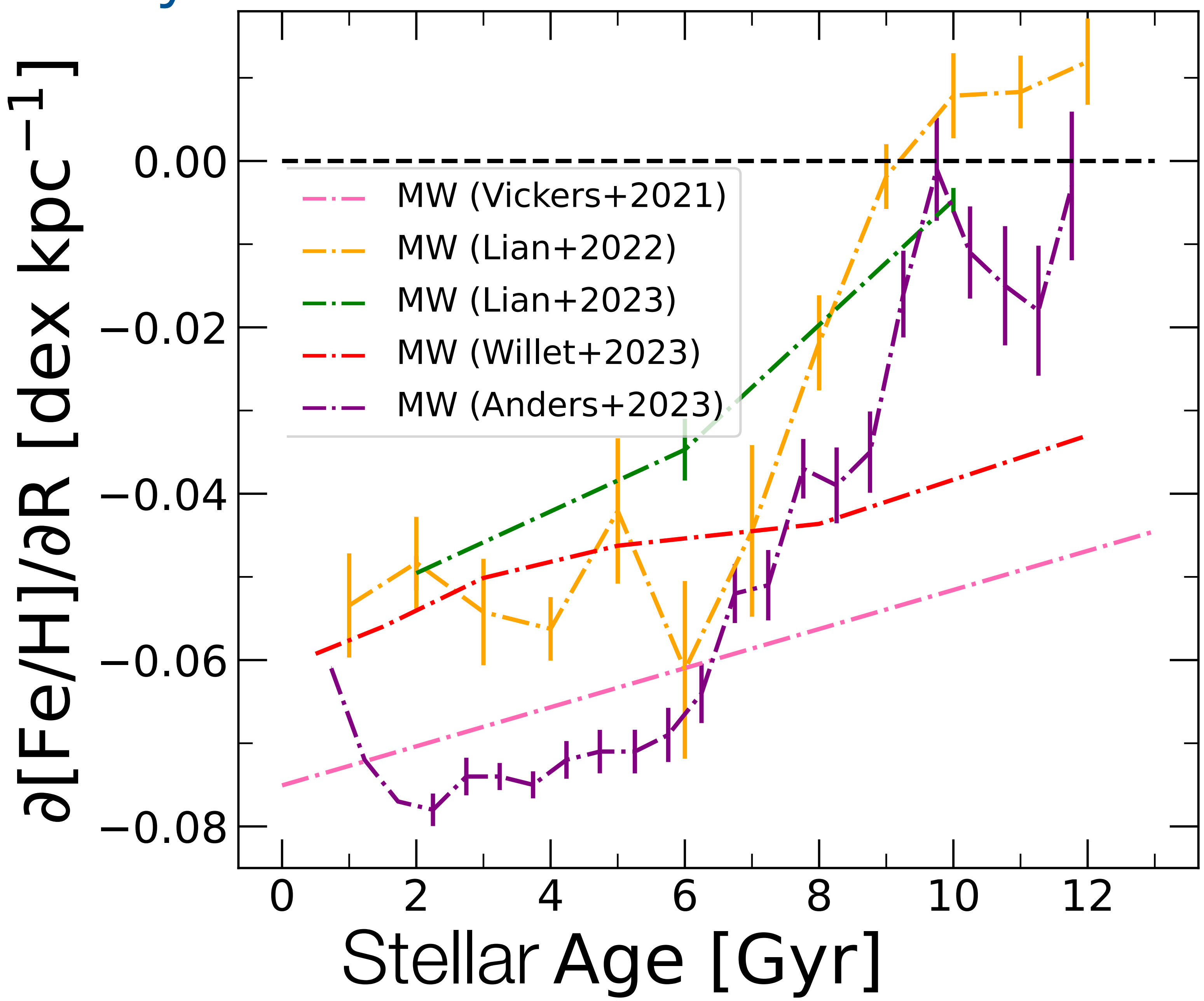
inside-out growth -> ISM metallicity gradient gets flatter over time

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

Lian et al 2023



Graf, Wetzel et al 2024



key question: what does this flattening for older stars primarily reflect?

(1) radial redistribution of stars (after birth) washing out the gradient?

(2) the metallicity gradient of the ISM steepened over time?

3D SPATIAL VARIATIONS OF METALS ACROSS MW-MASS GALAXY HISTORIES

Bellardini et al 2021
Bellardini et al 2022
Graf et al 2024, arxiv:2402.15614
Graf et al 2024, arxiv:2410.21377

Russell Graf, undergraduate -> masters student @ UC Davis

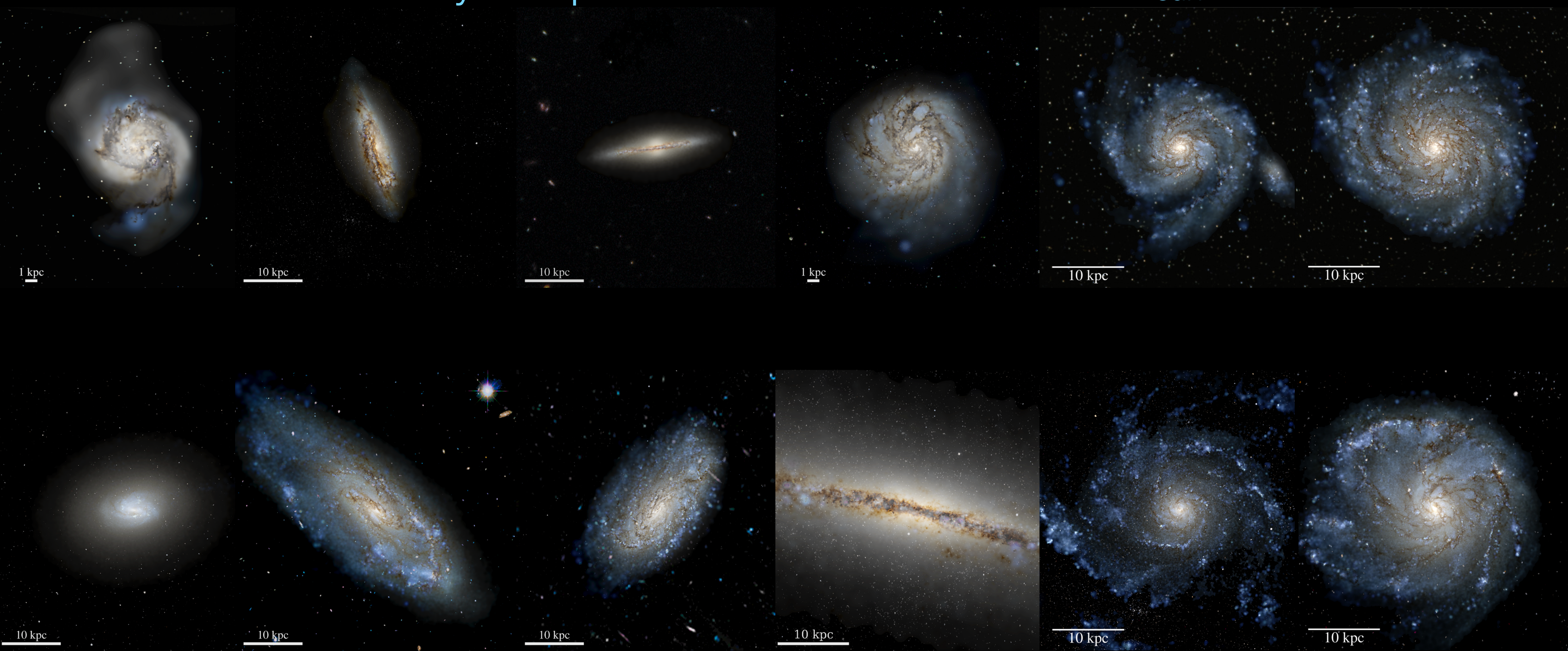
FIRE-2 simulation suite of MW/M31-mass galaxies

Feedback In Realistic Environments

Latte suite: 8 isolated MW-mass systems

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

baryonic particle mass: 3500 - 7100 M_{sun}

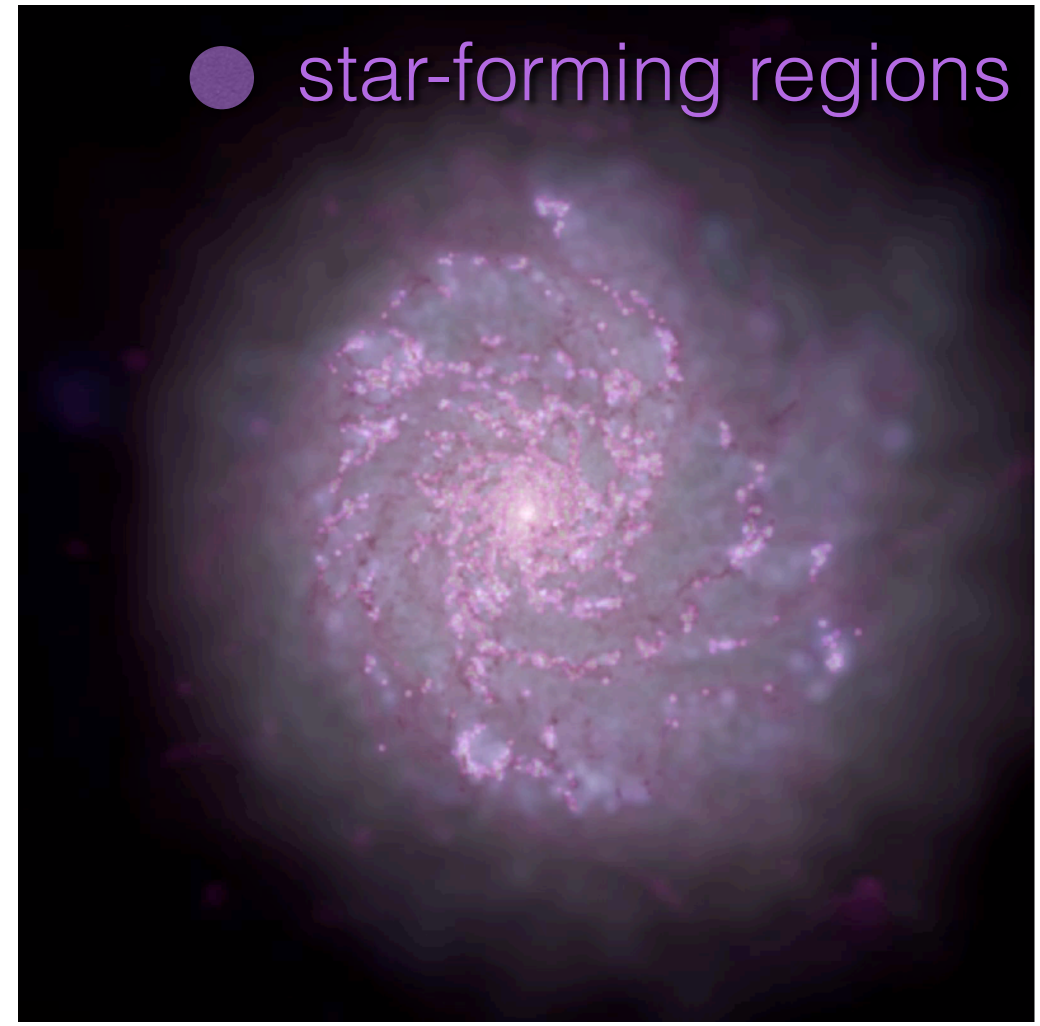


FIRE-2 model for gas + star formation

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:

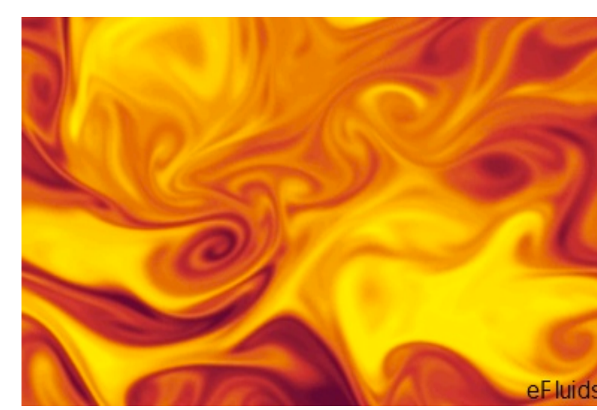
H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe

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

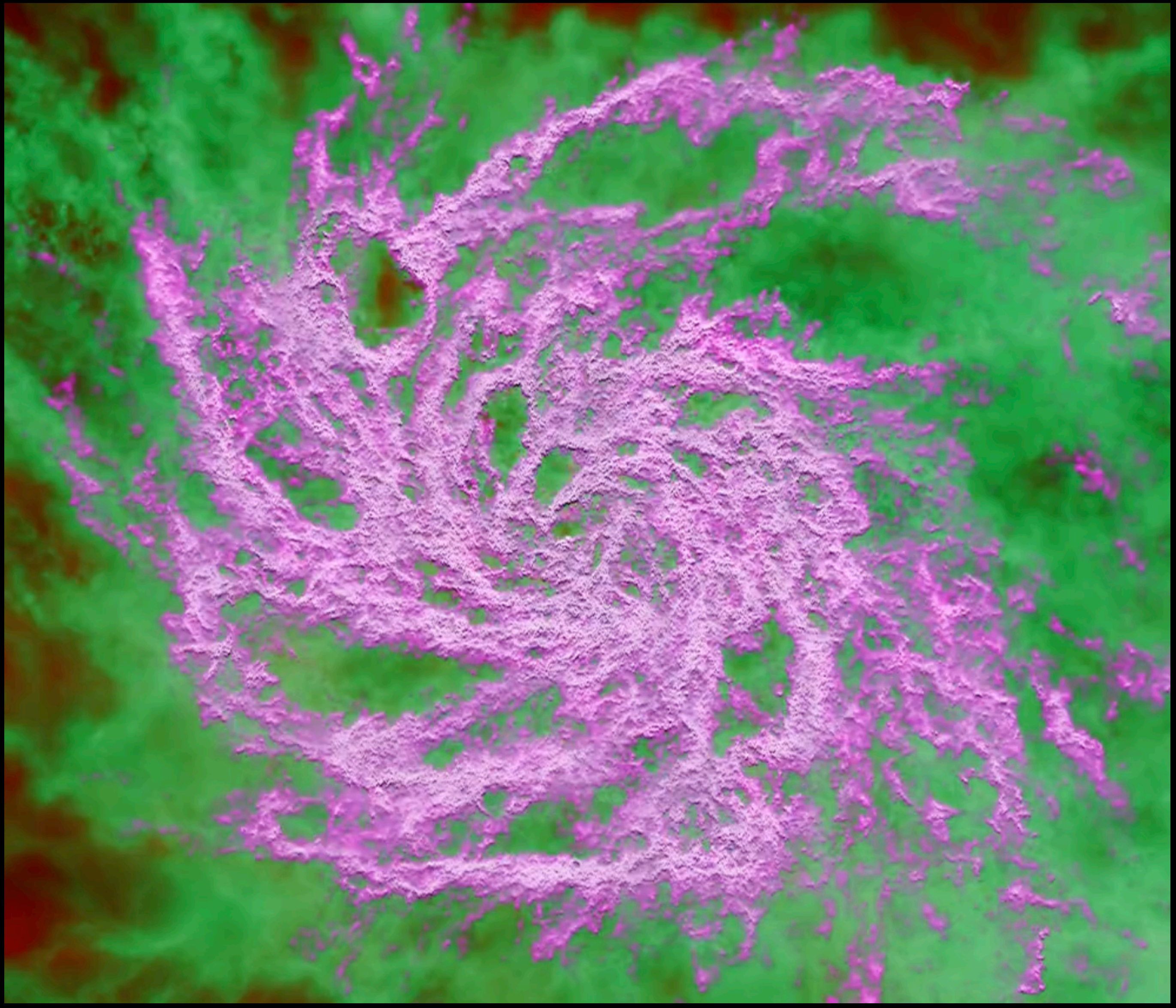
Escala, Wetzel et al 2017



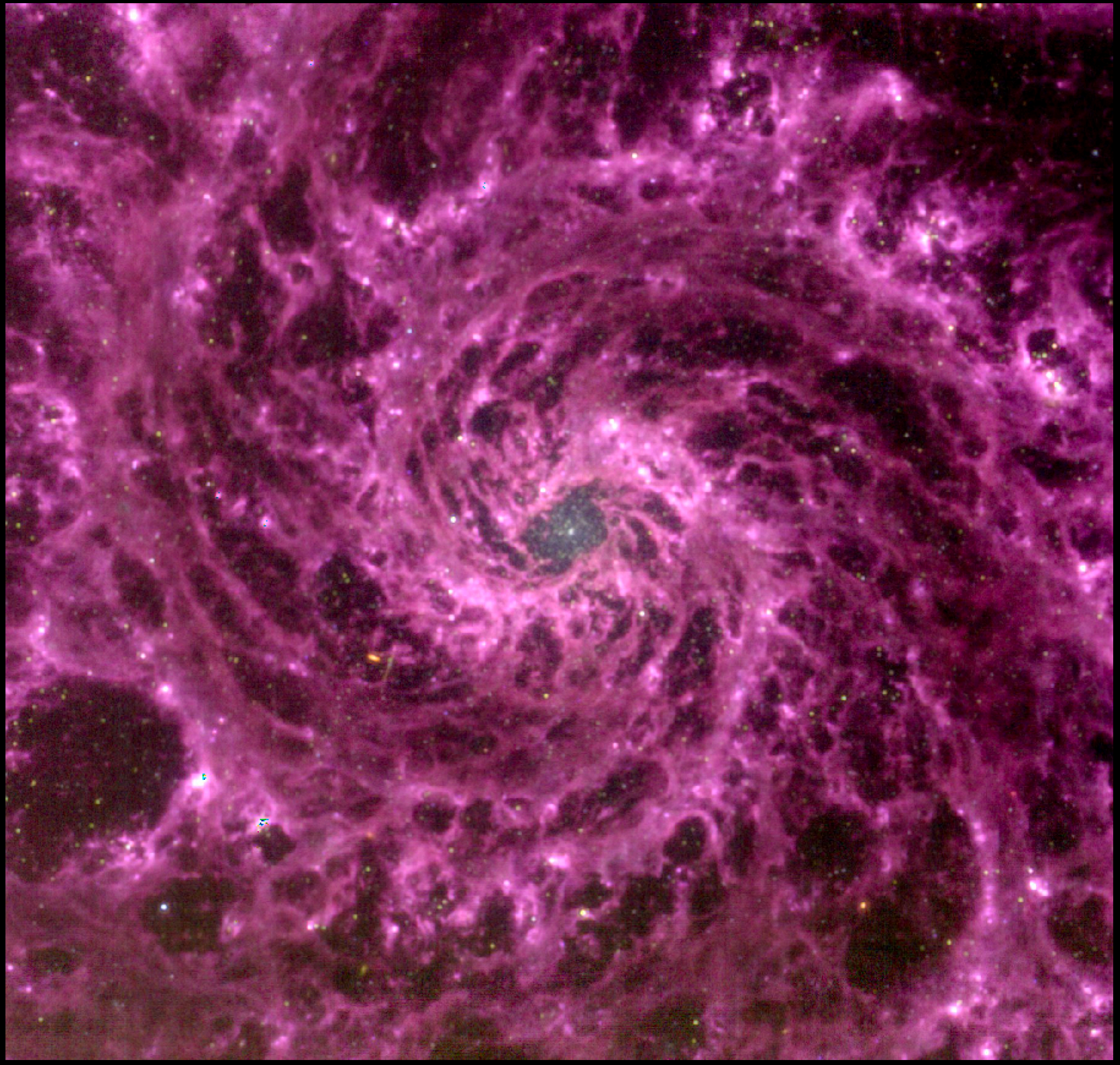
FIRE simulations model dense multi-phase ISM with emergent GMCs, HII regions, spiral arms, etc

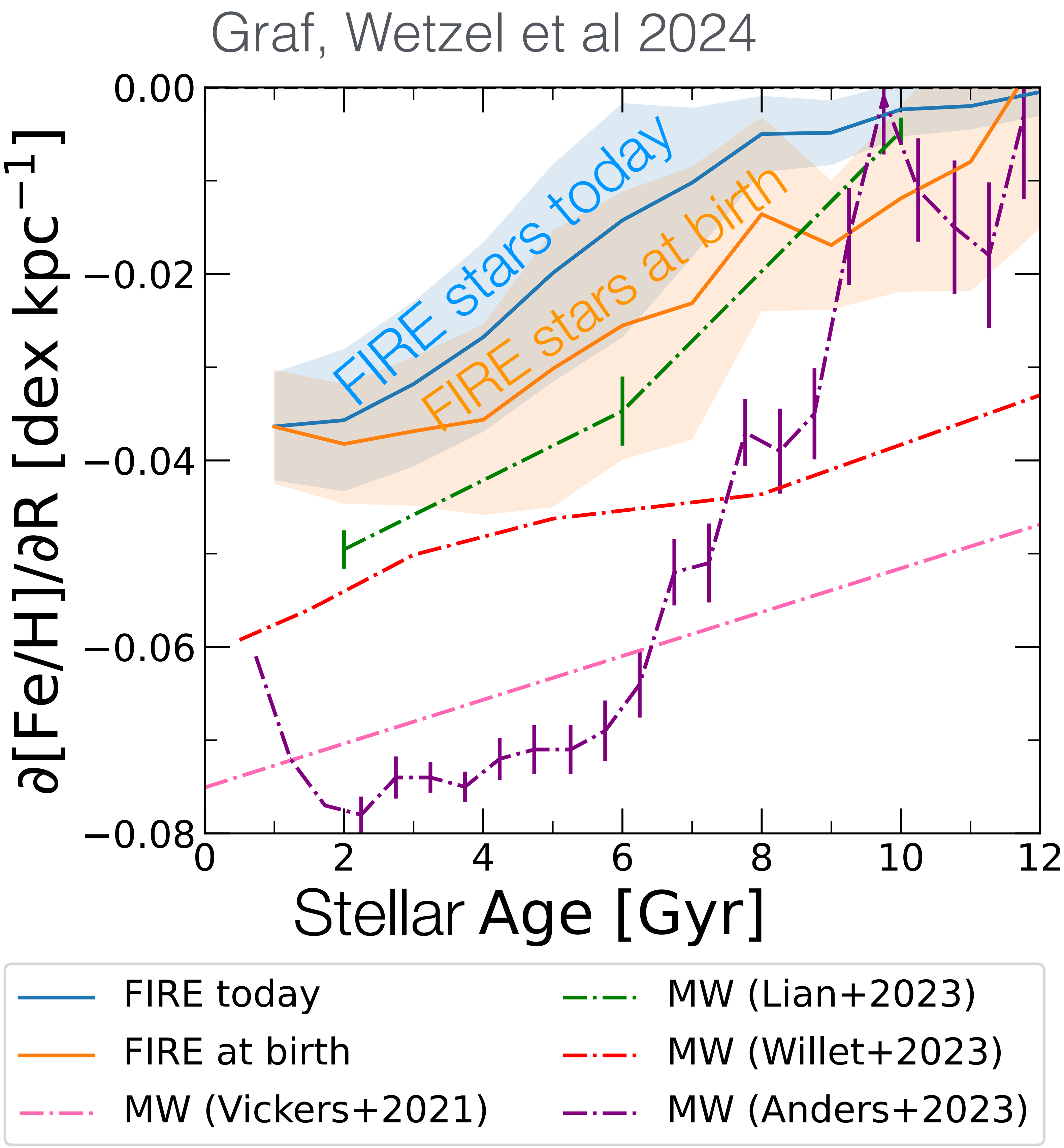
Benincasa et al 2020, Guszejnov et al 2020, Orr et al 2023, Ansar et al 2023

FIRE-2 (m12c)



PHANGS (M74)



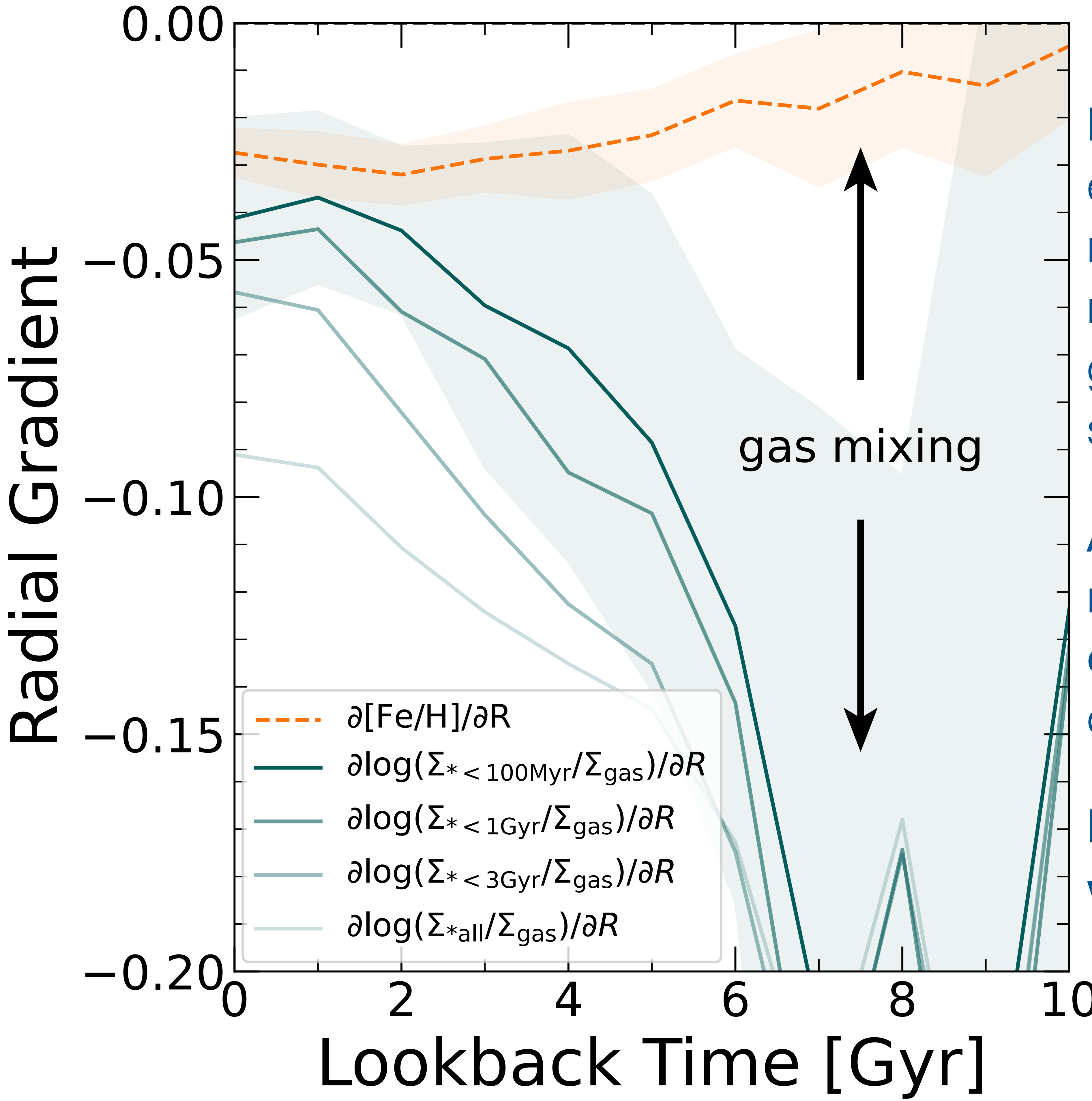


In FIRE-2 simulations:

Archeological histories of stars **qualitatively match** the MW

Radial redistribution of stars after birth only mildly changed the trend

The ISM metallicity radial gradient became steeper over time

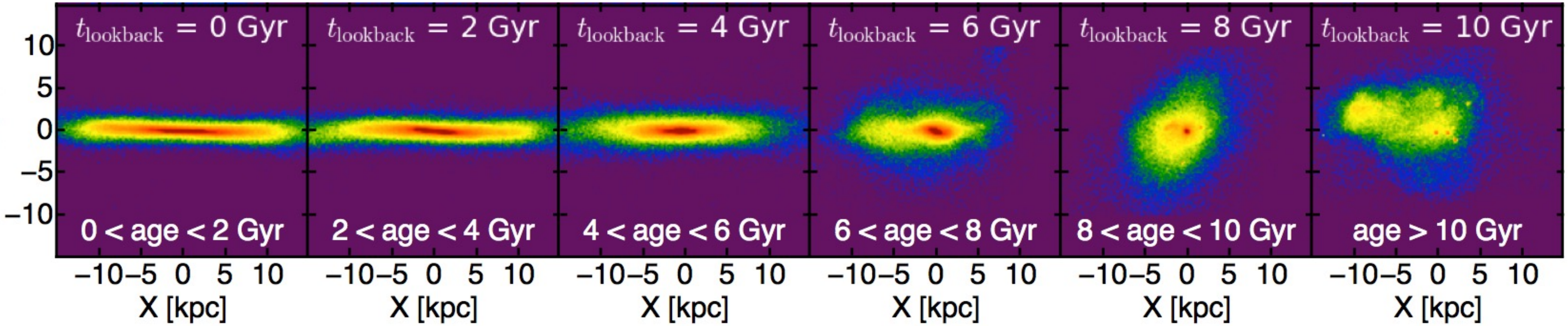


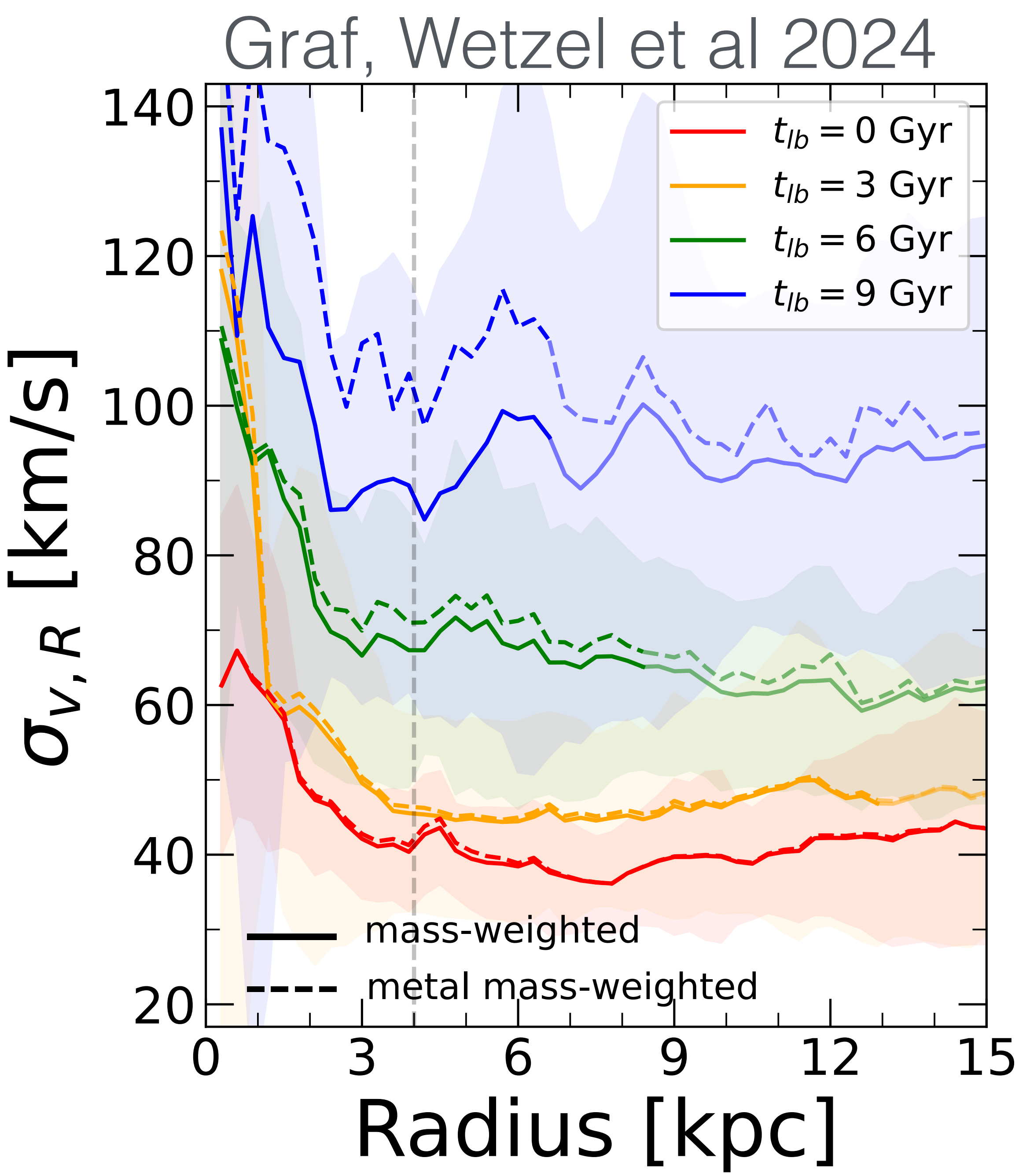
FIRE-2 galaxies experienced inside-out radial growth, naively implying gradients became shallower over time

Actual evolution of metallicity gradient is **opposite** (steepened over time)

Metals did not stay where injected!

Graf, Wetzel et al 2024





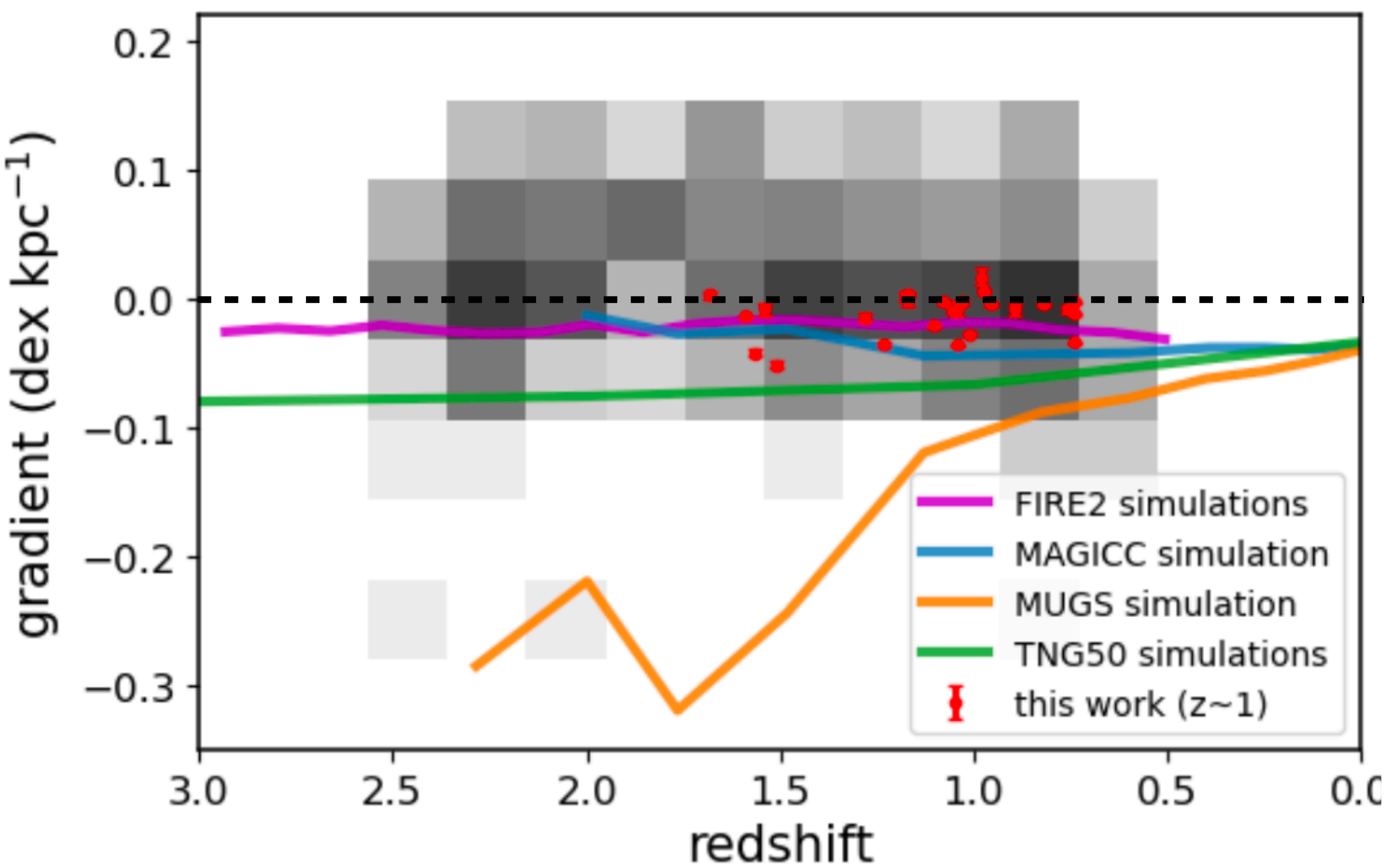
key argument

Steepening of metallicity radial gradient caused by reduced mixing in ISM over time (via turbulence, radial redistribution of gas, etc)

Declining turbulence also causes ‘upside-down’ vertical growth

This ‘wins out’ over the effects of inside-out radial growth

Connection with new JWST observations of MW-progenitor-mass galaxies at high redshift



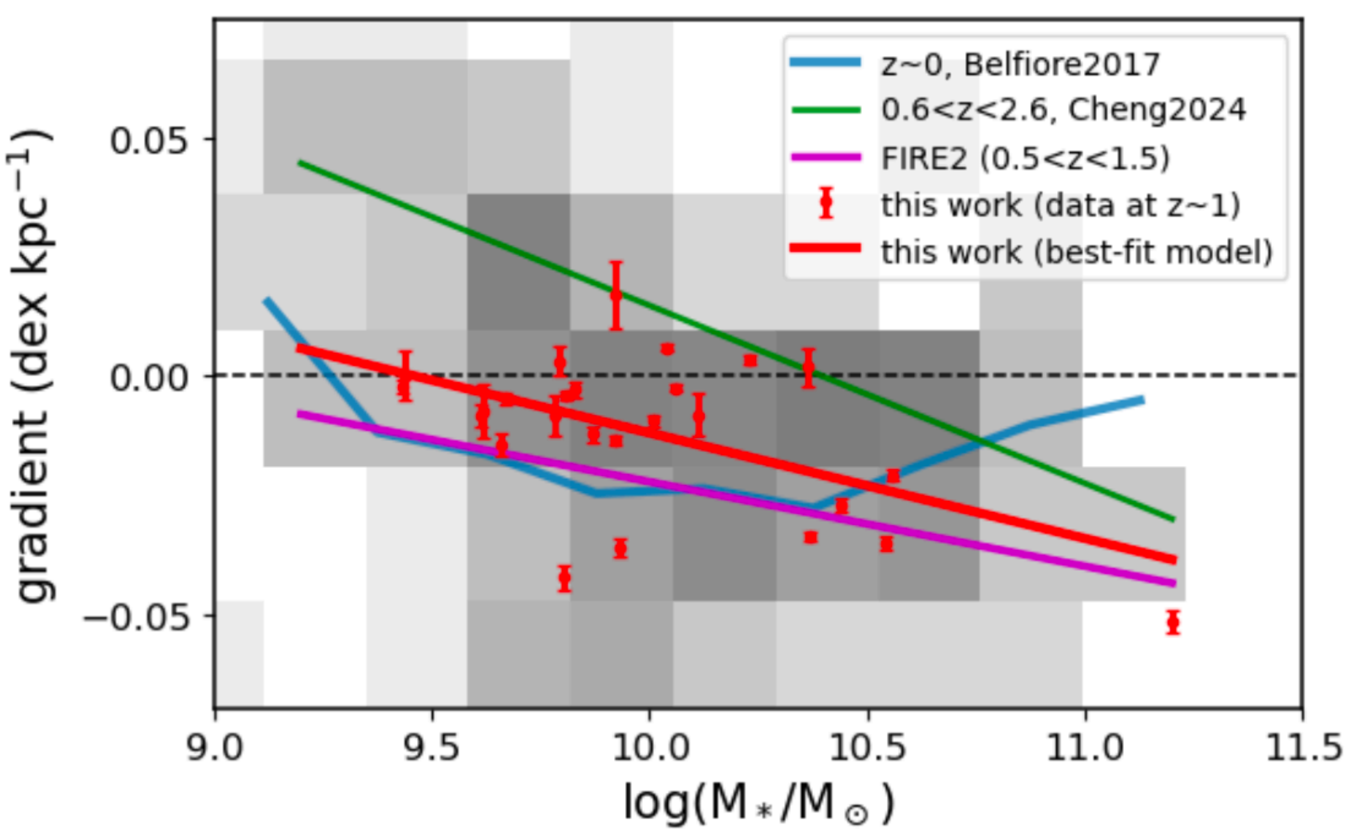
Ju, Wang, Jones et al 2024

JWST observations of ISM metallicity radial gradients in 26 MW-progenitor-mass galaxies at z <~ 1.5

Mostly **shallow** gradients

More massive (diskier) galaxies have **steeper** gradients

FIRE-2 simulations show **same** trends



EVOLUTION OF METALLICITY RADIAL GRADIENT

- MW-mass disk growth over time
  - **radially 'inside-out'** $\Sigma_{gas}(R)$ and $\Sigma_{star}(R)$ / $\Sigma_{gas}(R)$ become shallower
  - **vertically 'upside-down'** disk settles, gas turbulence and mixing decreases
  - these drive the evolution of metallicity radial gradient in opposite ways!
- FIRE simulations: effect of upside-down wins out over inside-out
  ISM metallicity radial gradient steepens over time
- FIRE trends match the MW: older stars have shallower metallicity gradients
- FIRE matches JWST measurements of ISM in MW-progenitor-mass galaxies at z ~ 1: shallow (~flat) radial gradients that steepen with mass