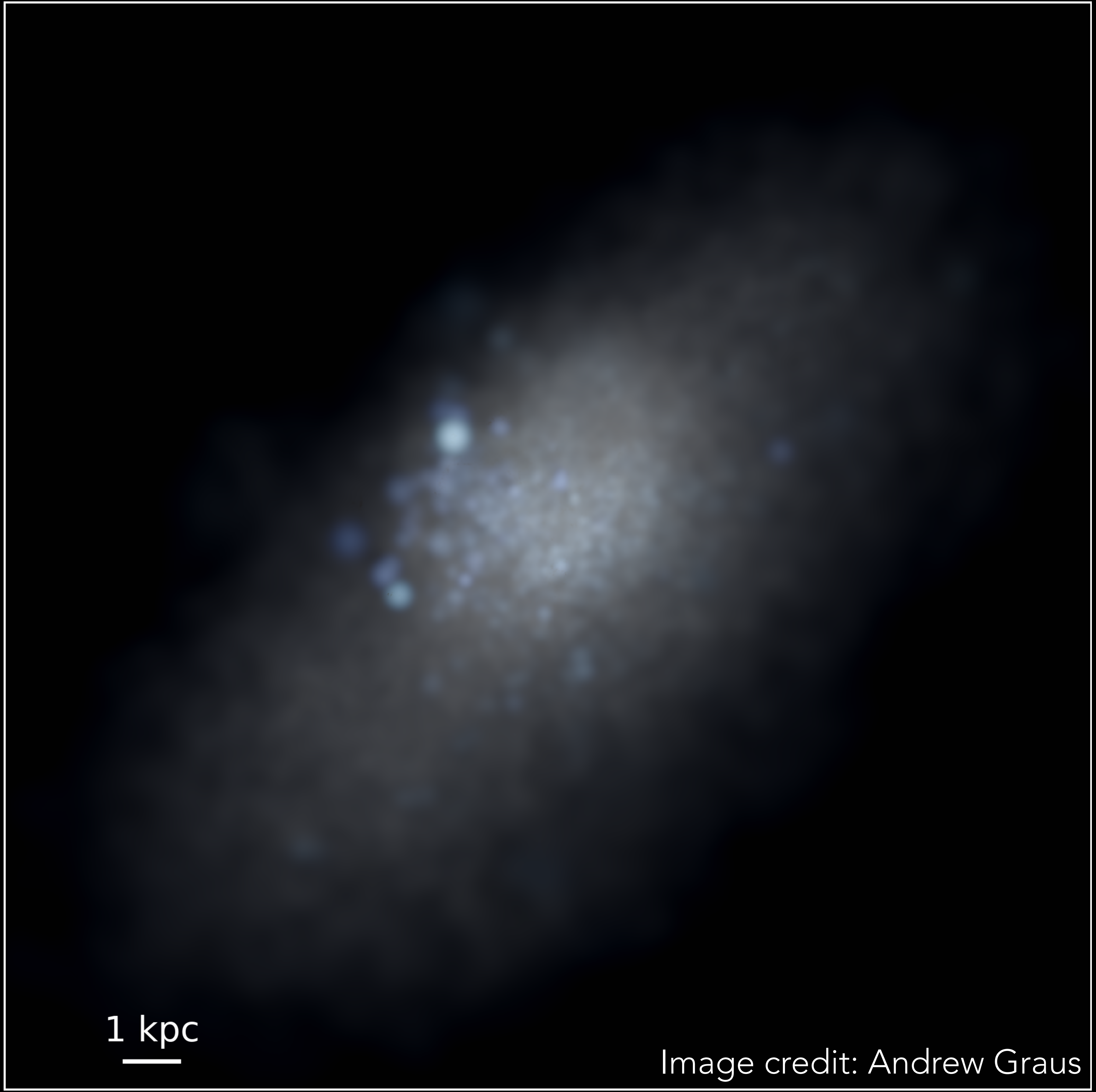
DWARF GALAXIES AS LABORATORIES FOR TESTING COSMOLOGY & GALAXY FORMATION

FRANCISCO J. MERCADO
UC IRVINE

COLLABORATORS:
JAMES BULLOCK
MIKE BOYLAN-KOLCHIN
ANDREW GRAUS
ALEX FITTS
+FIRE COLLABORATION

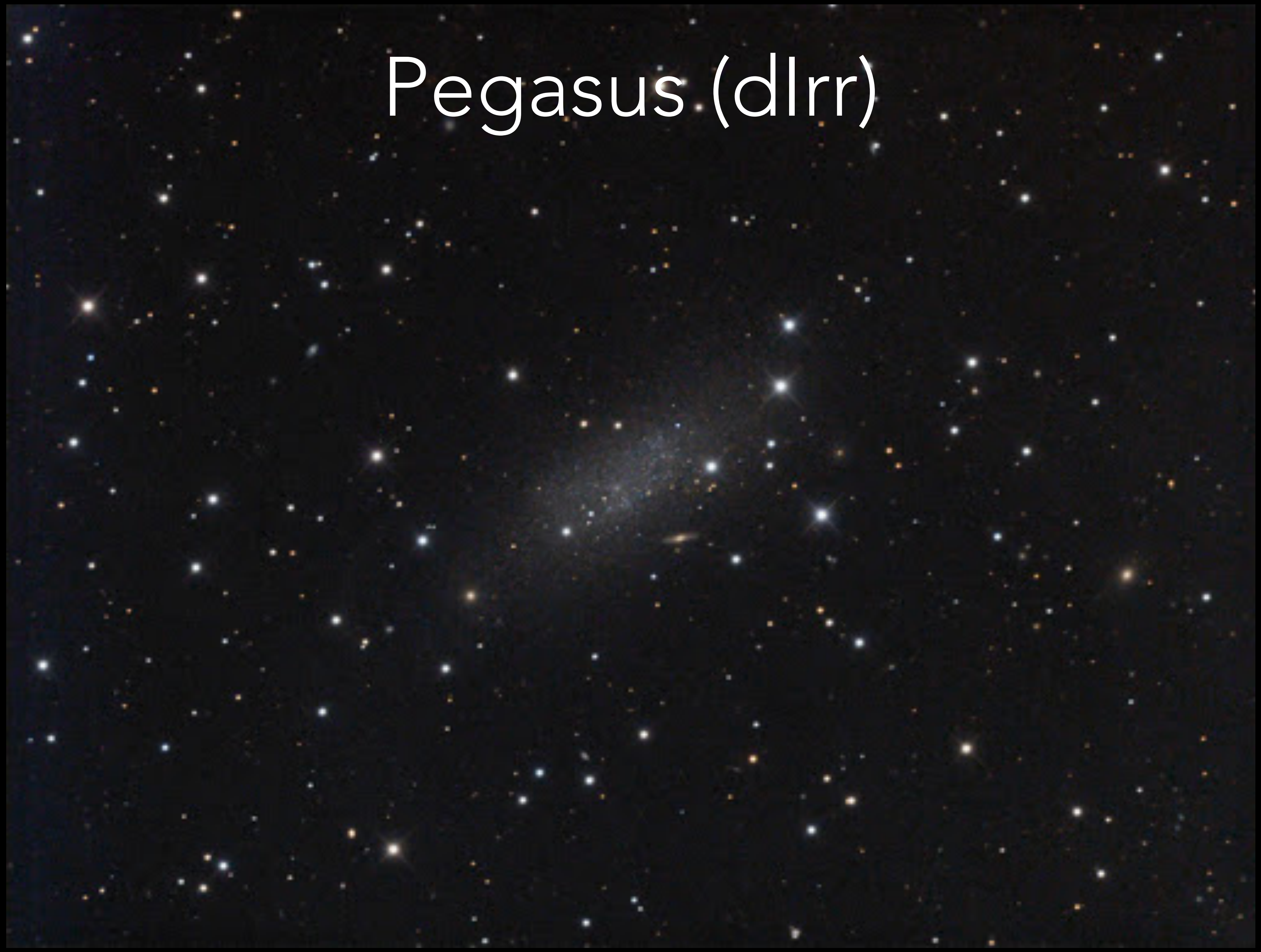


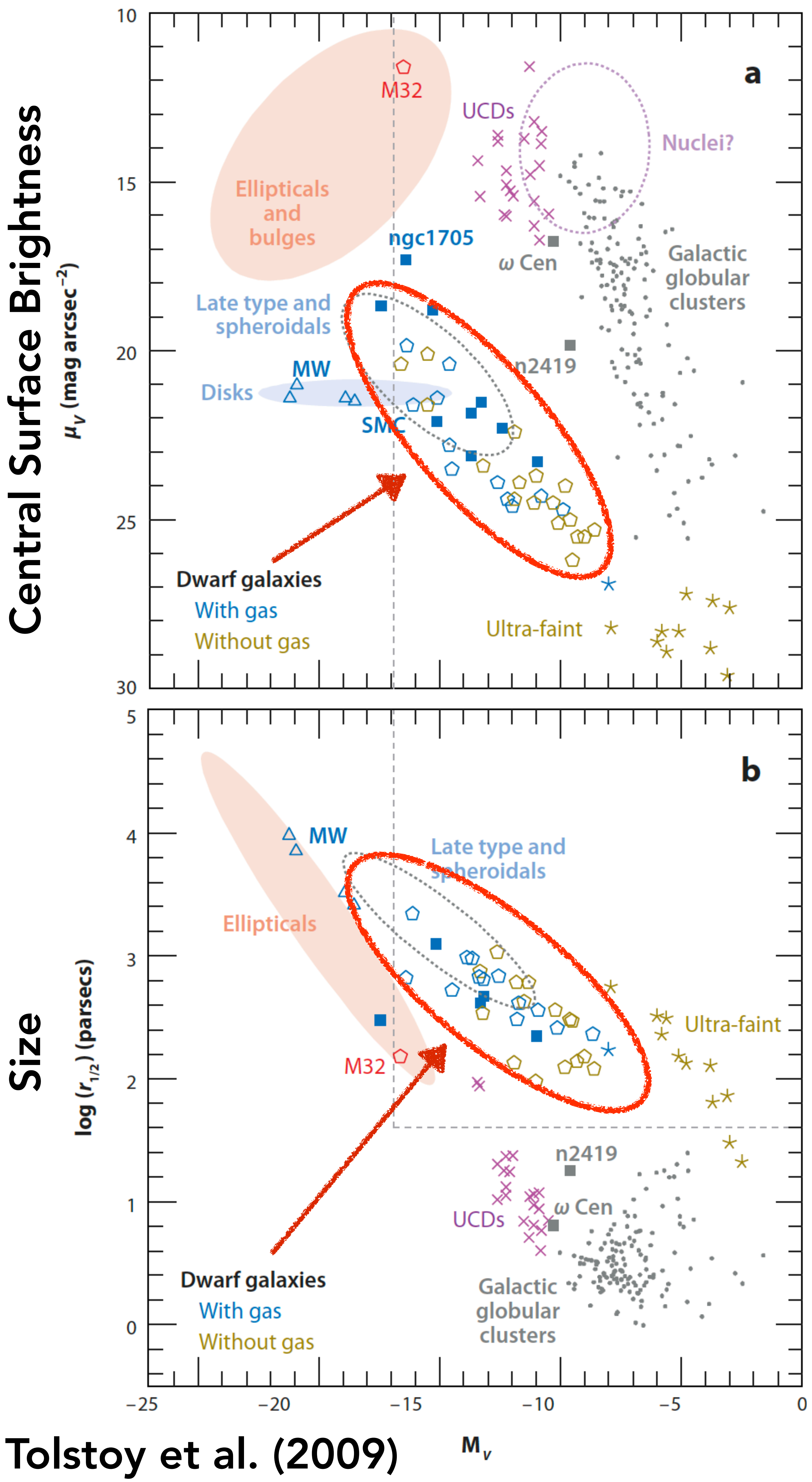
DWARF GALAXIES

- Important to study in order to **understand the full story of galaxy formation** over cosmic time
  - Dark matter dominated compared to their more massive counterparts
  - They lie at the threshold of galaxy formation
  - Progenitors of more massive galaxies

- Can be used as **laboratories to study**:
  - Star formation
  - Dark matter core formation
  - Reionization

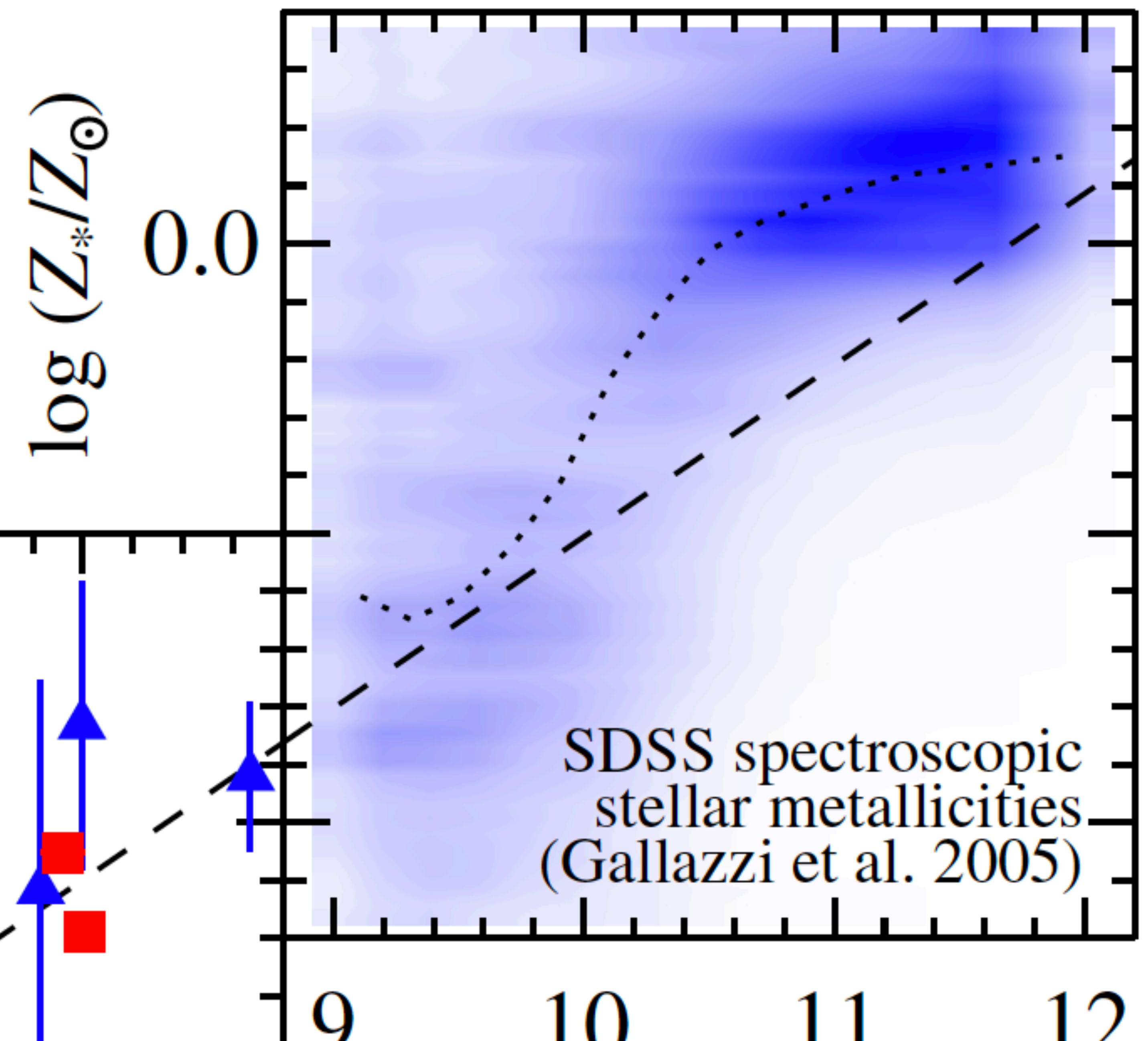
- 2 categories **(at least in the LG)**:
    - *Dwarf Irregulars (dIrrs)*: Gas rich, generally star forming, and live in isolated regions of space
    - *Dwarf Spheroidals (dSphs):* Gas poor with little to no star formation and live as satellites of more massive galaxies

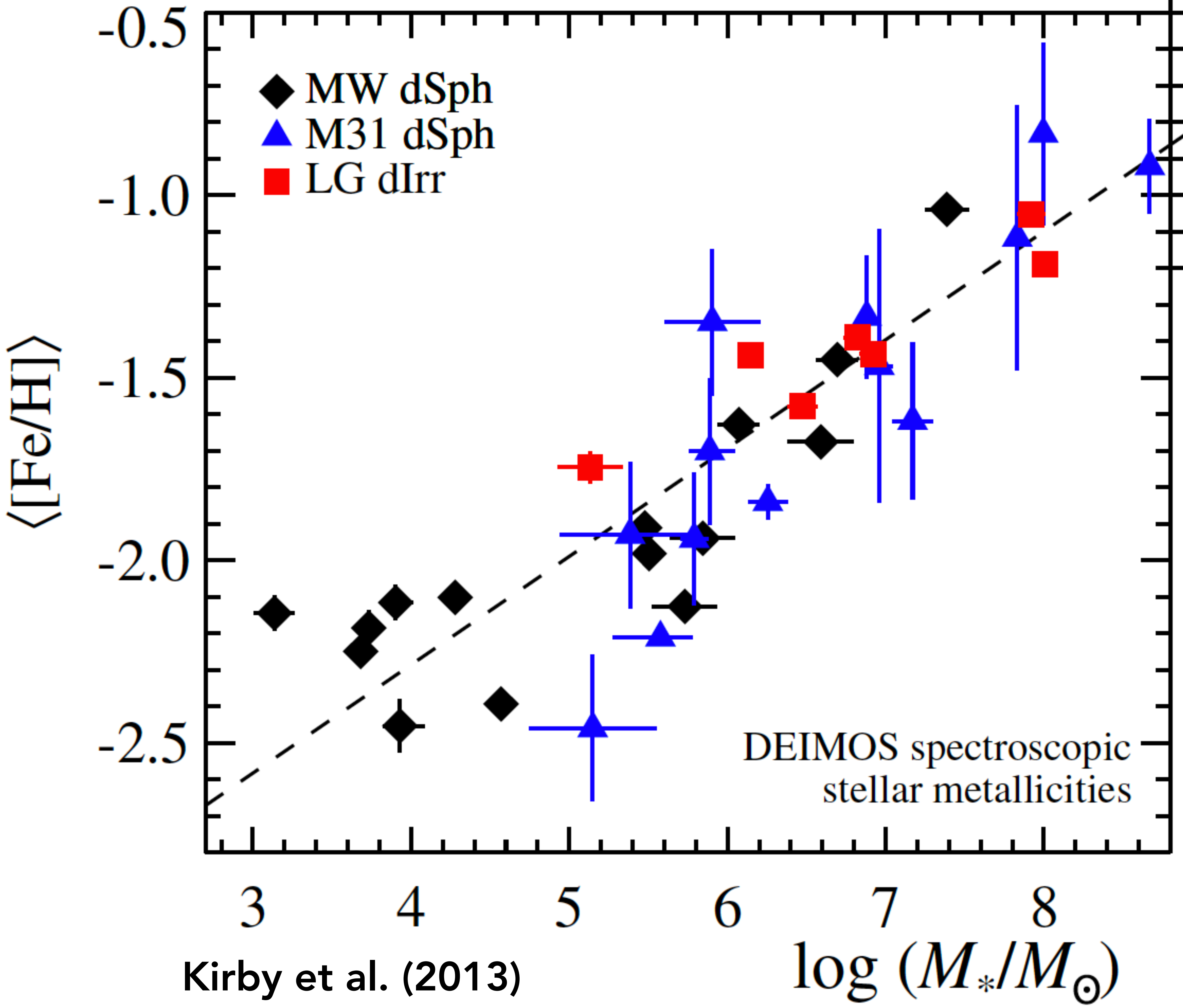




Tolstoy et al. (2009)

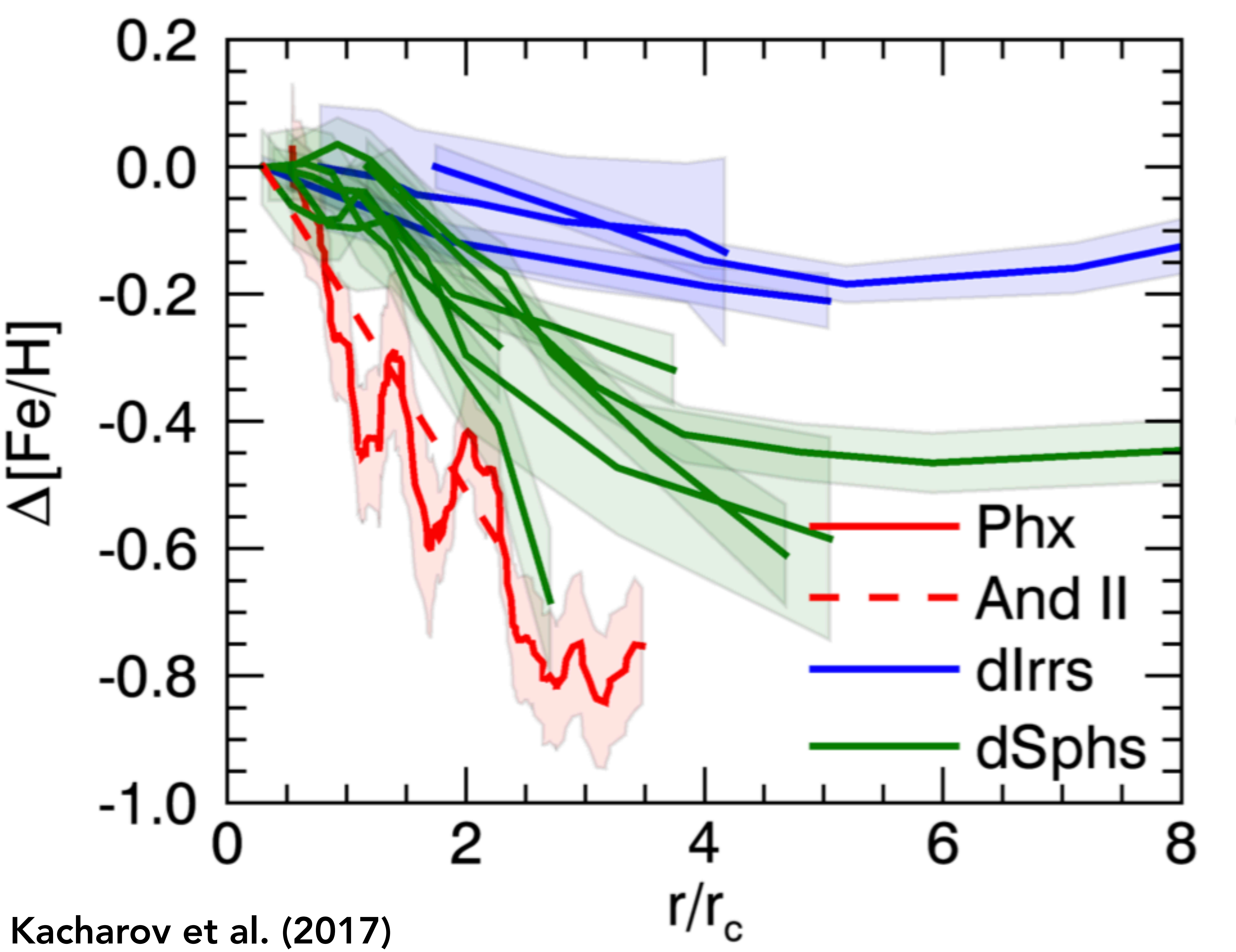
While dSphs and dIrrs are found in different environments and have distinct characteristics, they follow similar scaling relations and fall on the same MZR





Kirby et al. (2013)

METALLICITY GRADIENTS IN LG DWARF GALAXIES



Kacharov et al. (2017)

- Metal rich (poor) stars inhabit the central (outer) regions of the galaxy
- Recent studies point to a slight dichotomy in gradient strength
- Identifying systematic trends underlying differences in gradient strength can provide insight into their origin

MECHANISMS THAT MAY AFFECT METALLICITY GRADIENT STRENGTH

- *Internal:* Enriched gas in high angular momentum galaxies can avoid the center resulting in a weaker metallicity gradient (Schroyen et al. 2011)

- *Internal:* Star formation feedback can redistribute material within a galaxy and thus weakening or strengthening the gradient (De Young & Heckman 1994; El-Badry et al. 2016)

- *External:* Ram-pressure stripping of inflating satellites can shrink the star formation region of a galaxy leading to a stronger gradient (Mayer et al. 2001, 2007)

FIRE-2 simulations of dwarf galaxies

Feedback In Realistic Environments

- 9 from Fitts et al. 2017
  - $M_{vir} \sim 10^{10}\,M_\odot$
  - $M_\star \sim 10^{5\text{-}7}\,M_\odot$
  - $m_{dm} = 2500\,M_\odot$
  - $m_g = m_\star = 500\,M_\odot$
- 17 from Graus et al. 2019
  - $M_{vir} \sim 10^{10\text{-}11}\,M_\odot$
  - $M_\star \sim 10^{7\text{-}9}\,M_\odot$
  - $m_{dm} = 20000\,M_\odot$
  - $m_g = m_\star = 4000\,M_\odot$

Isolated (Field) Dwarfs

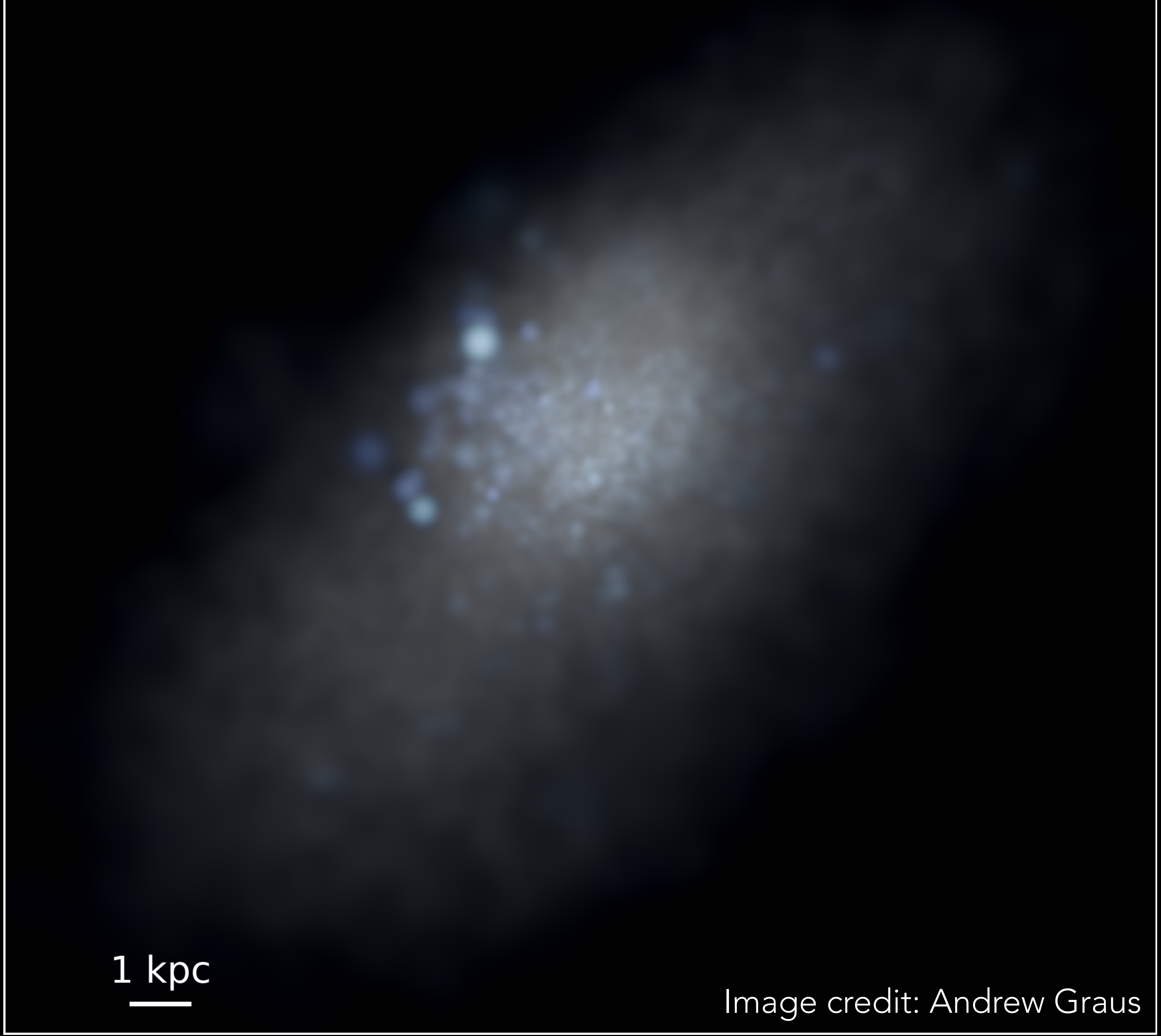


Image credit: Andrew Graus

FIRE-2 simulations of dwarf galaxies

Feedback In Realistic Environments

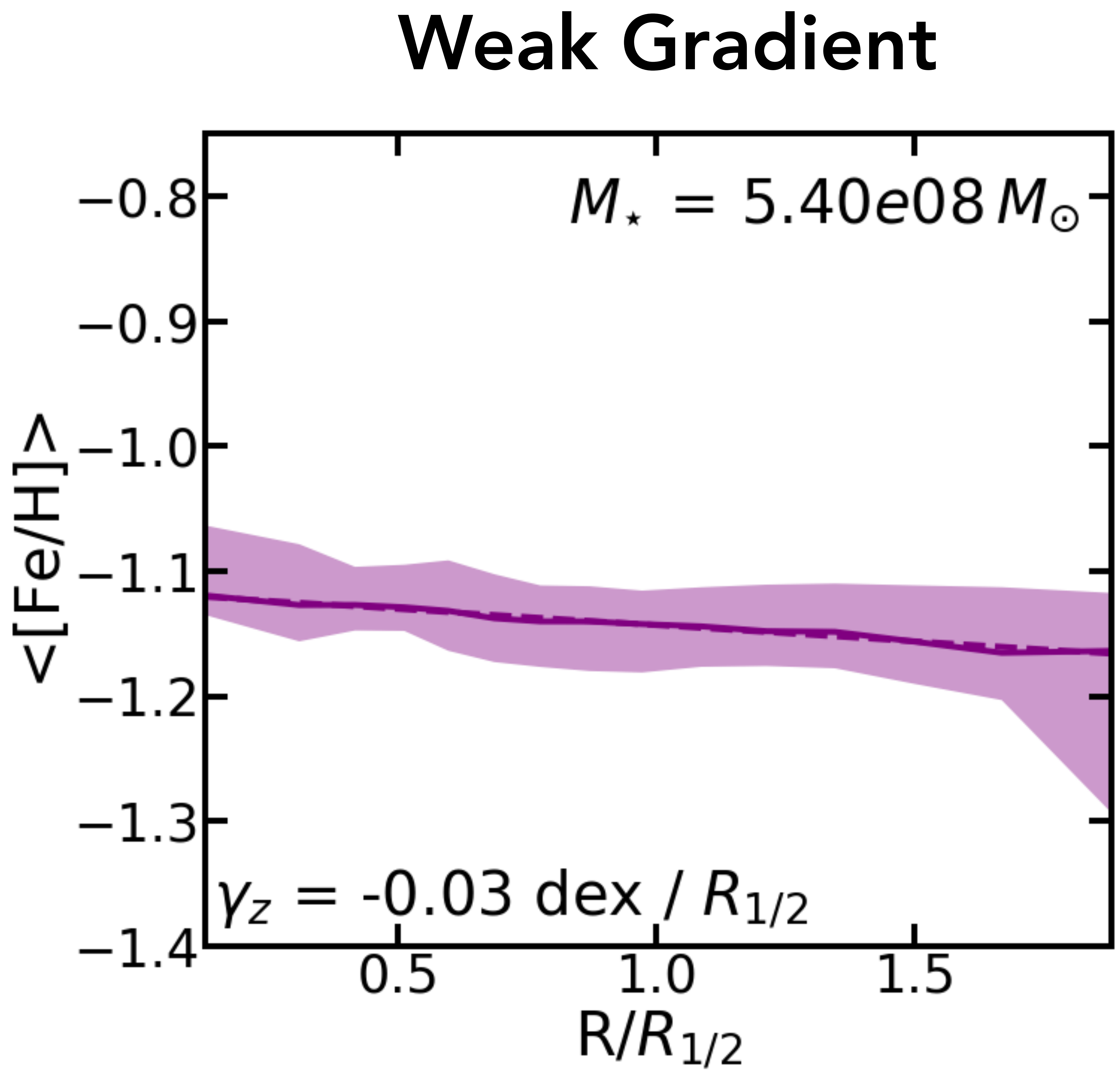
- Star formation in **dense self-gravitating molecular** clouds
  - $n_{SF} > 1000$ atoms / cm^3
- Mass and Metallicity inherited from progenitor gas particle
- Total metallicity along with 11 chemical species tracked for each star particle (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe)

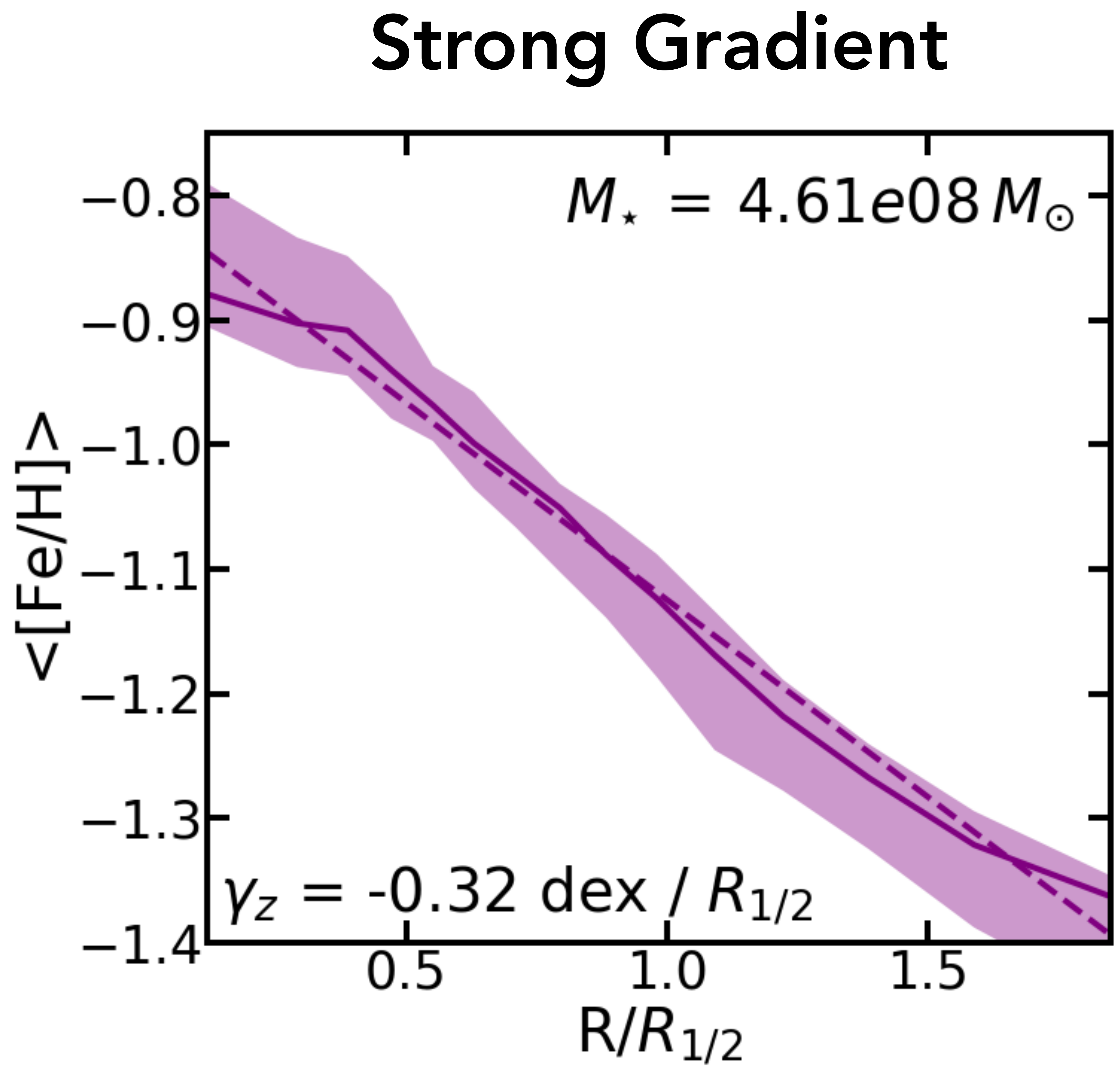
Model for stellar feedback:

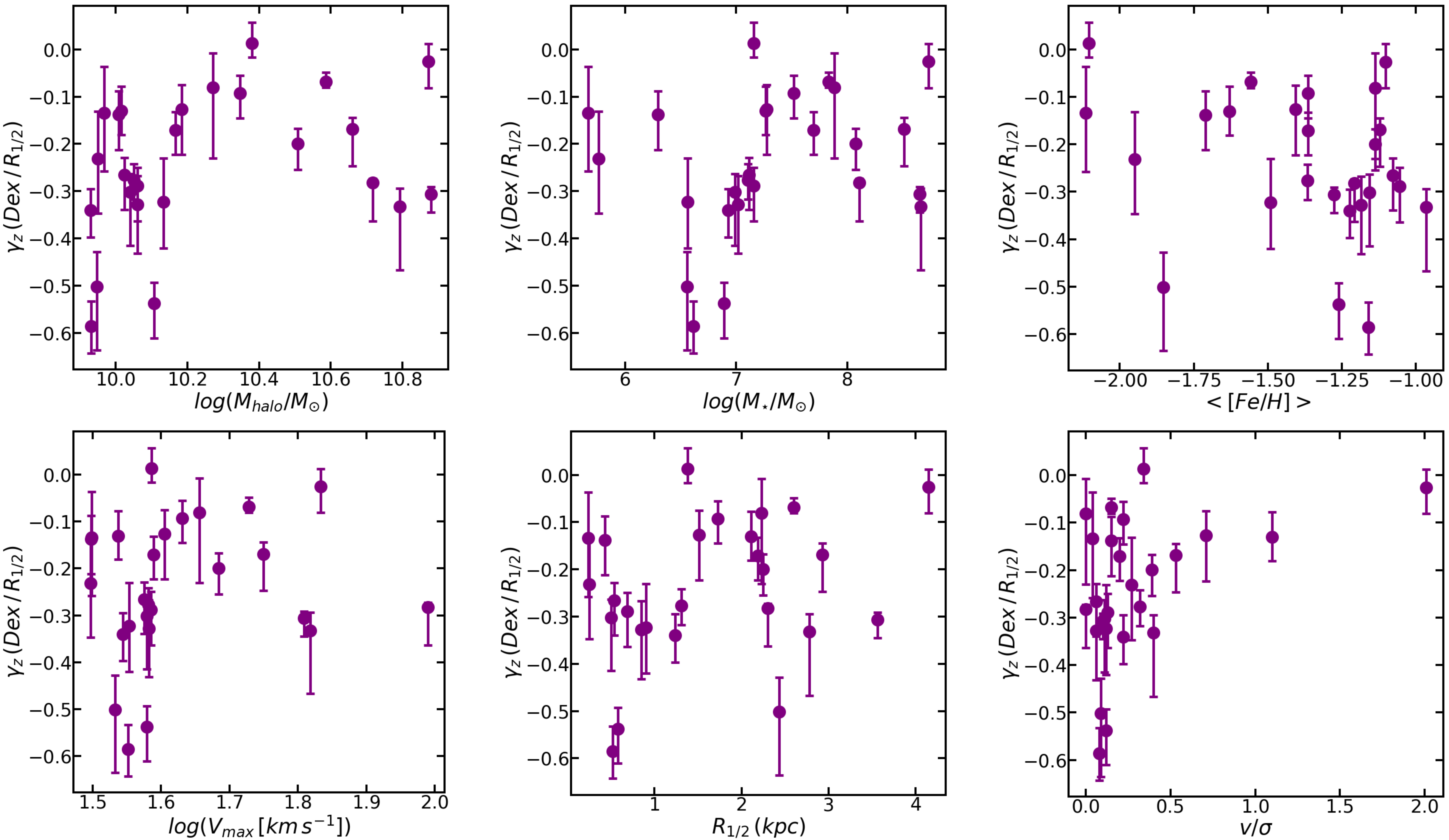
See Hopkins, Wetzel, Keres et al 2018

- Supernovae
  - core-collapse
  - type Ia
- Stellar radiation
  - radiation pressure
  - photoionization heating (HII regions)
  - photoelectric heating (via dust)
- Stellar winds
  - massive O & B stars
  - AGB stars

NEGATIVE METALLICITY GRADIENTS COMMON IN OUR SIM SAMPLE

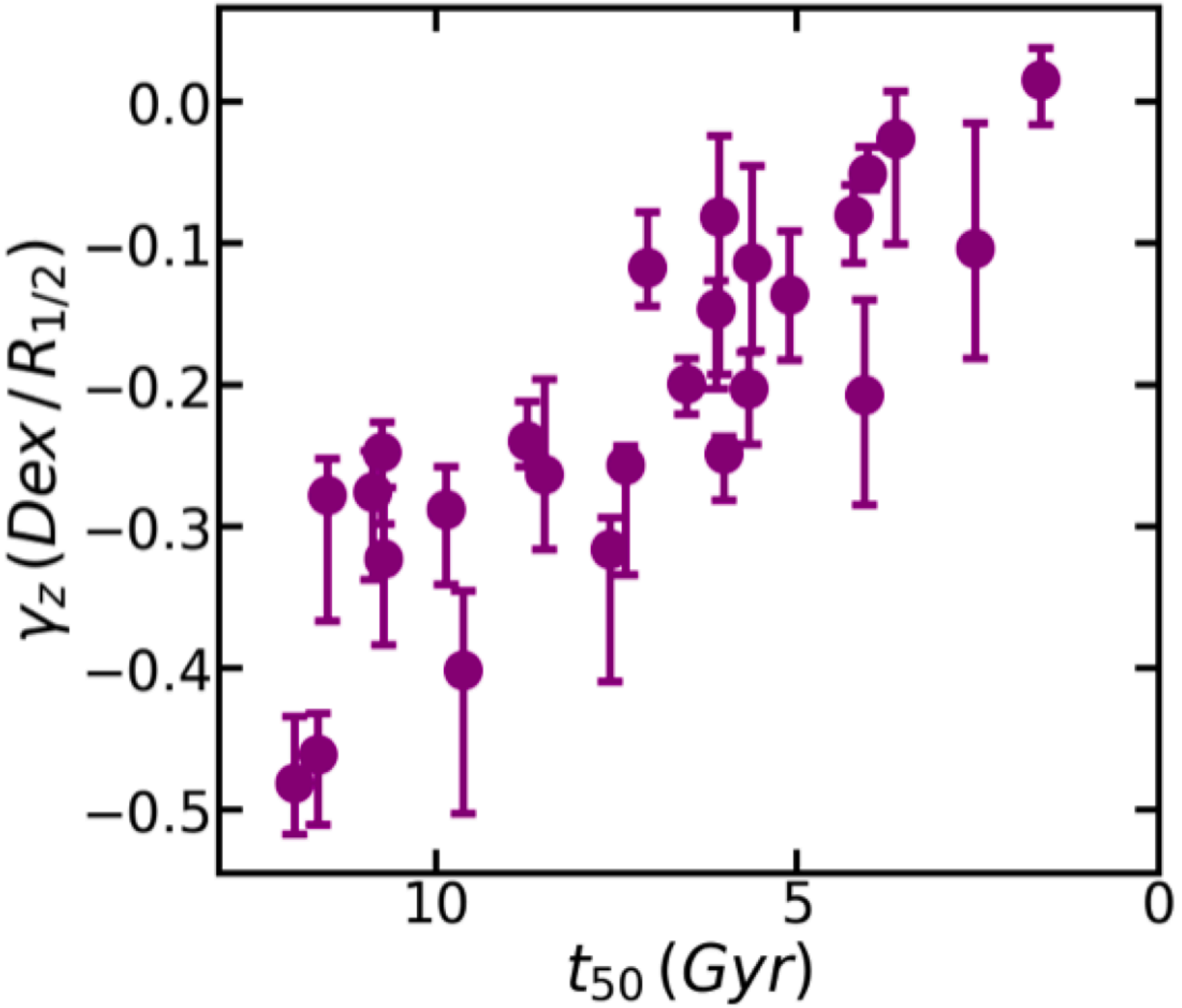


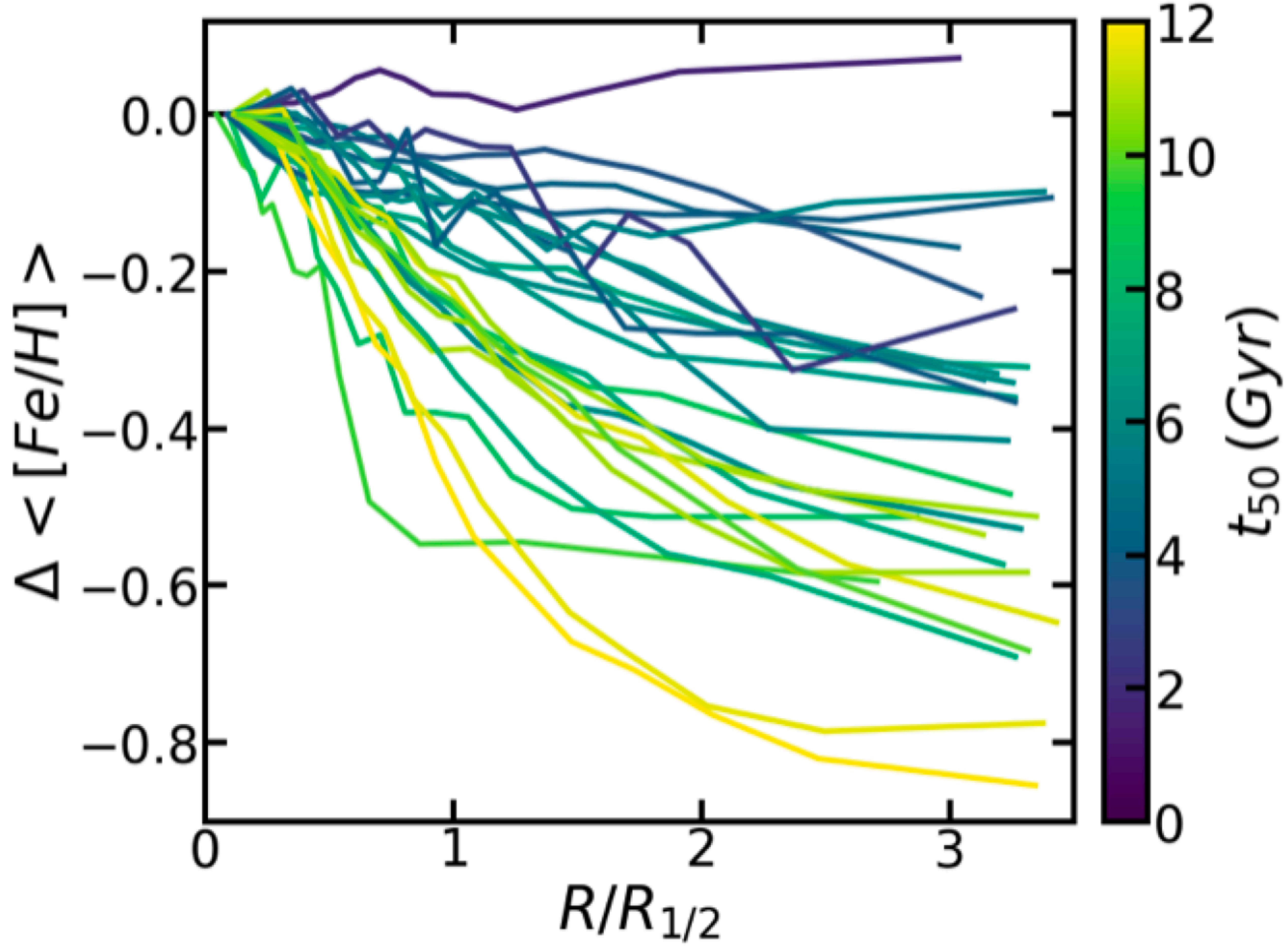



γz (Dex / R1/2)
log(Mhalo/M⊙)
log(M⋆/M⊙)
< [Fe/H] >
log(Vmax [km s−1])
R1/2 (kpc)
v/σ

THE GRADIENT-STRENGTH-GALAXY-AGE RELATIONSHIP

Older Galaxies —> Stronger Gradients

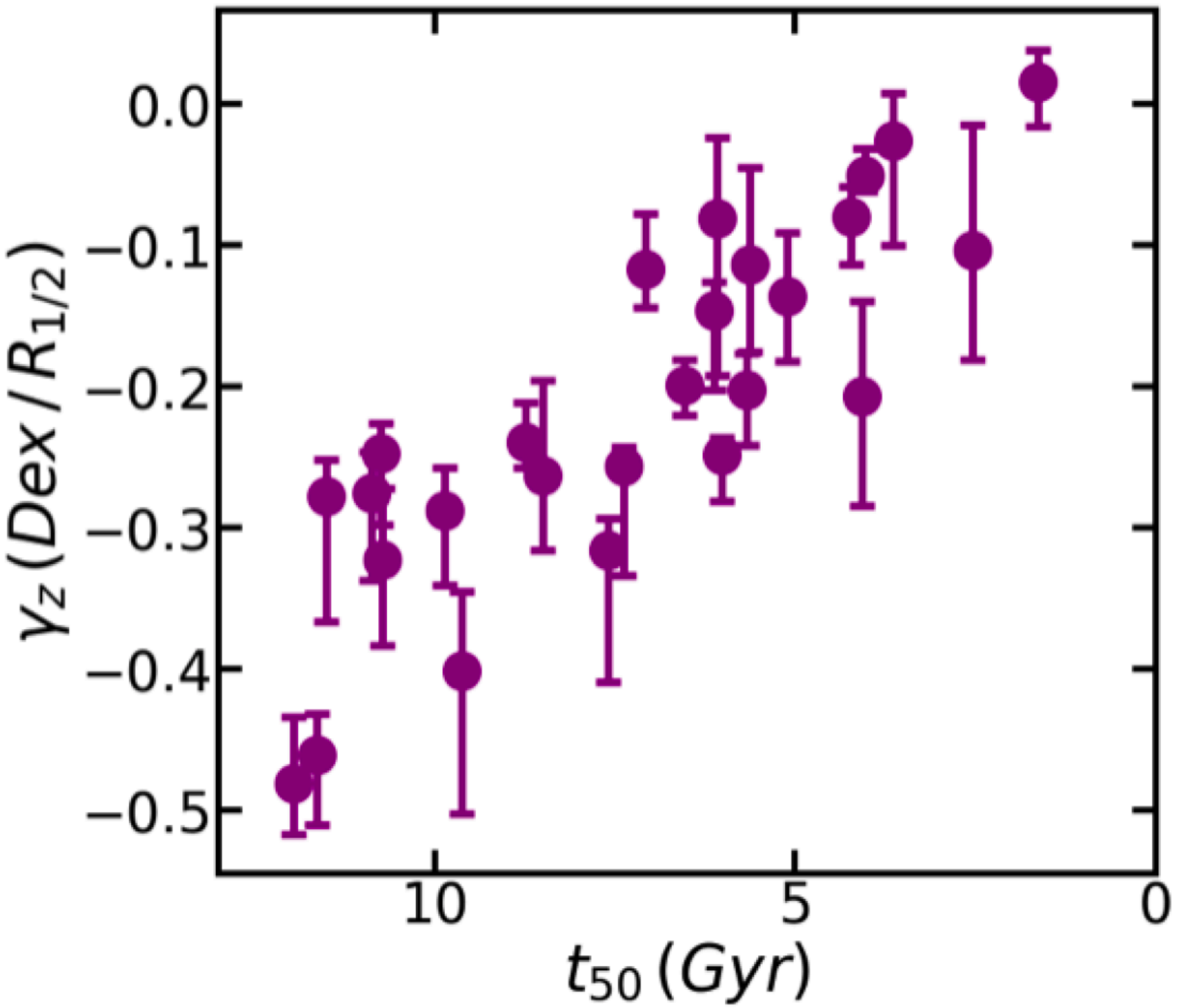


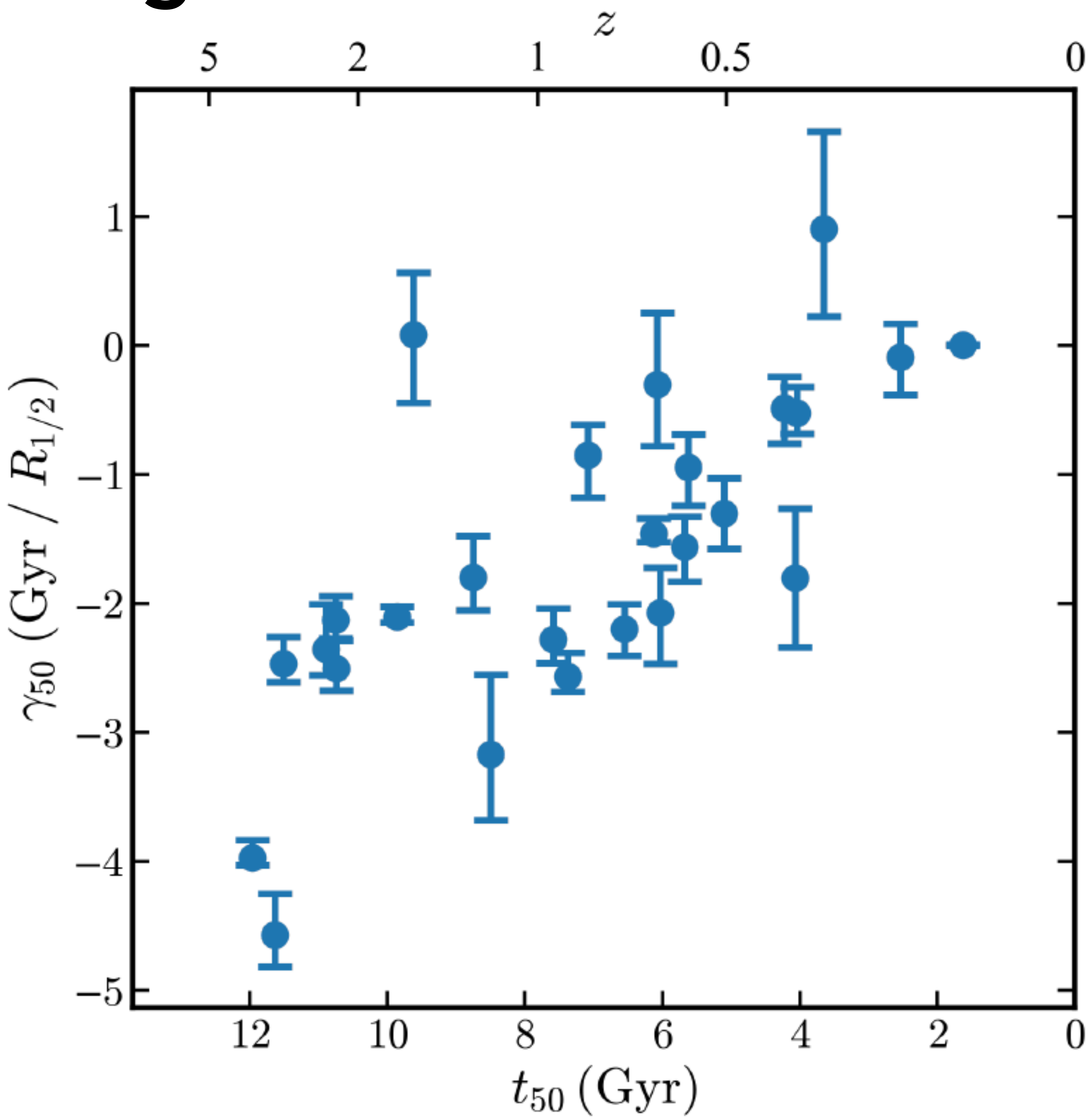


t_{50}: The median stellar age in a given galaxy

THE GRADIENT-STRENGTH-GALAXY-AGE RELATIONSHIP

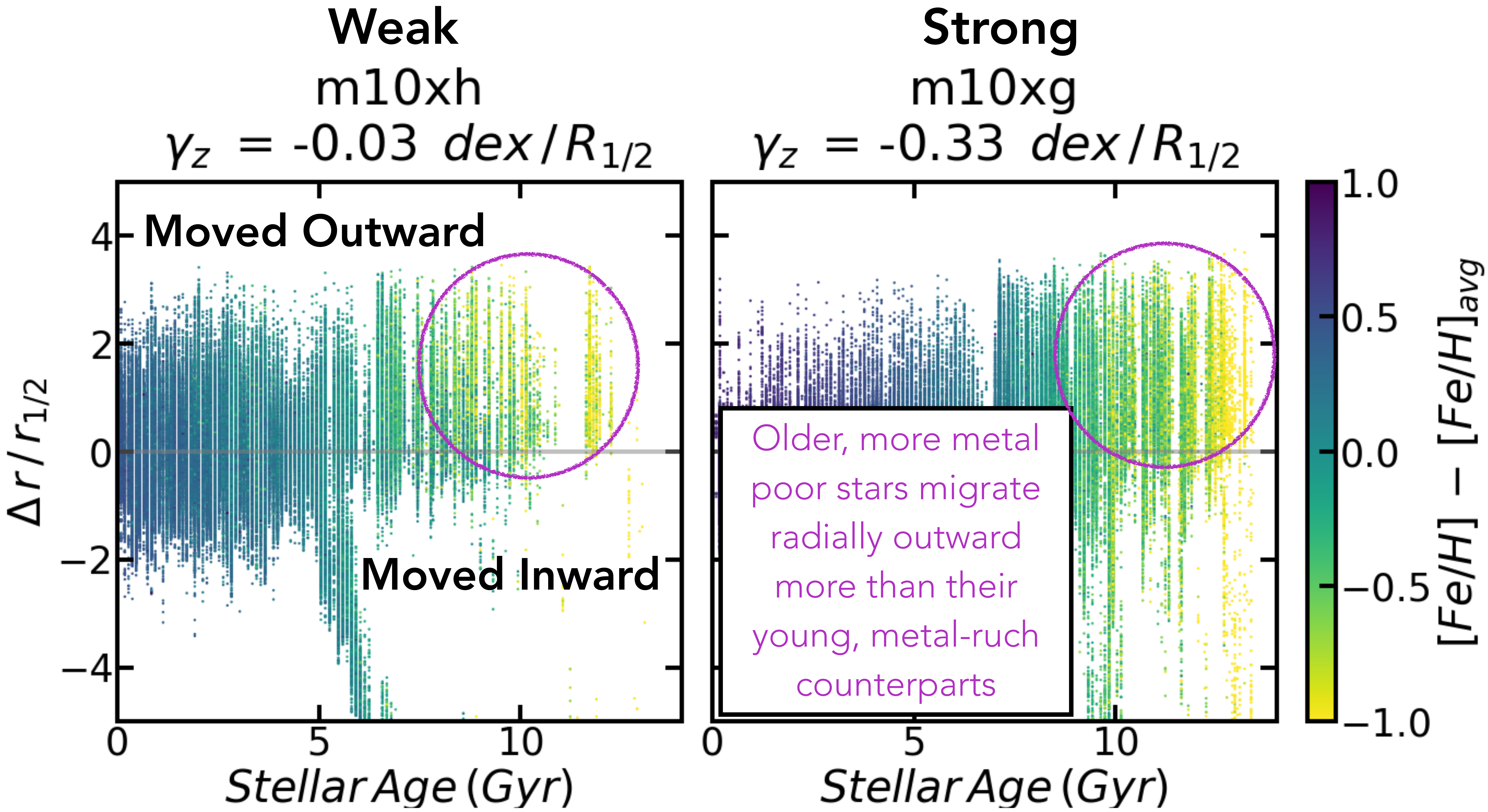
Older Galaxies —> Stronger Gradients



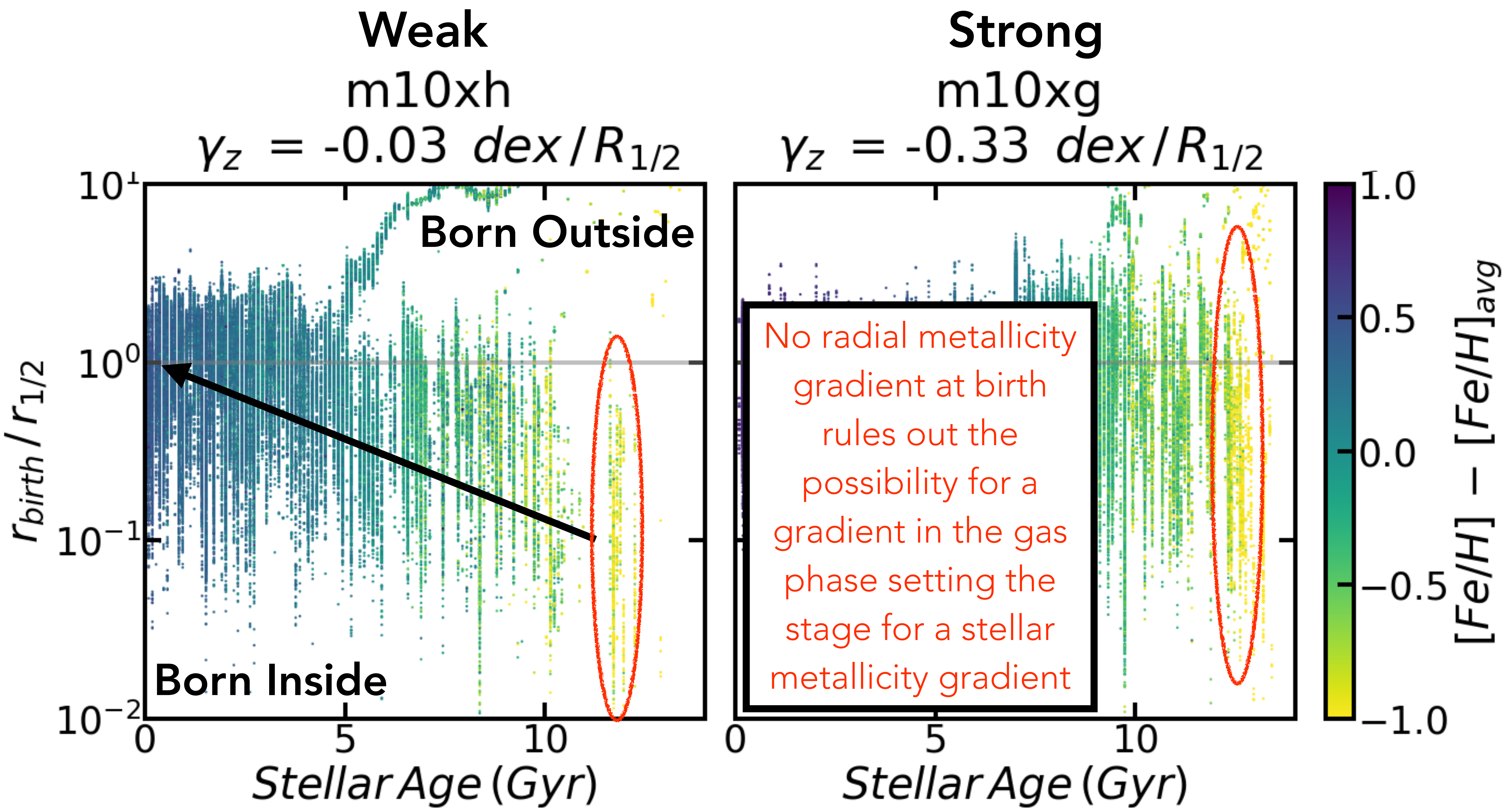


t_{50}: The median stellar age in a given galaxy

THE ORIGIN STORY: RADIAL STELLAR MIGRATION



THE ORIGIN STORY: RADIAL STELLAR MIGRATION



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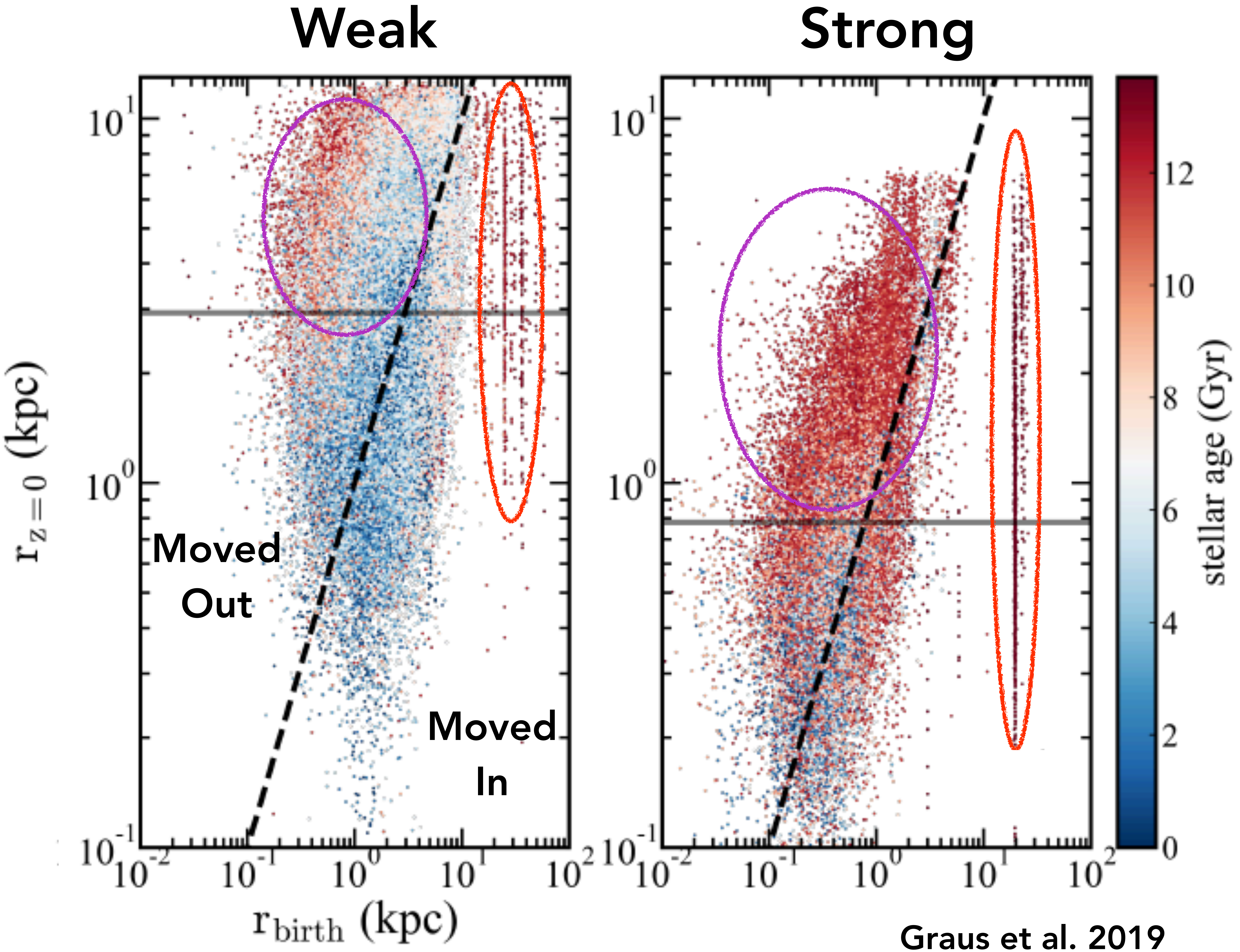
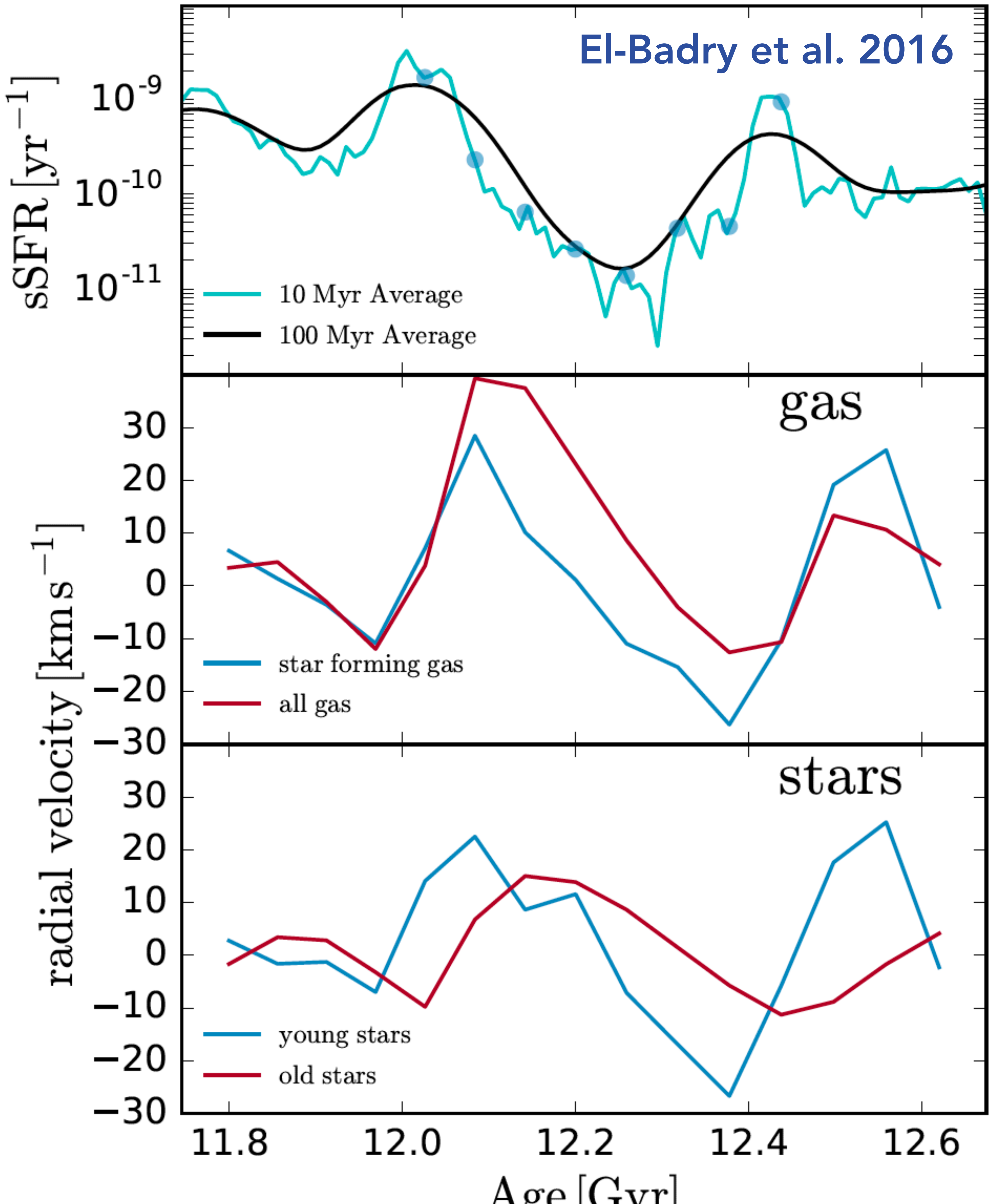


Accreted stars being distributed throughout the whole galaxy rules out the possibility of mergers significantly affecting gradients

Graus et al. 2019

THE ORIGIN STORY: RADIAL STELLAR MIGRATION



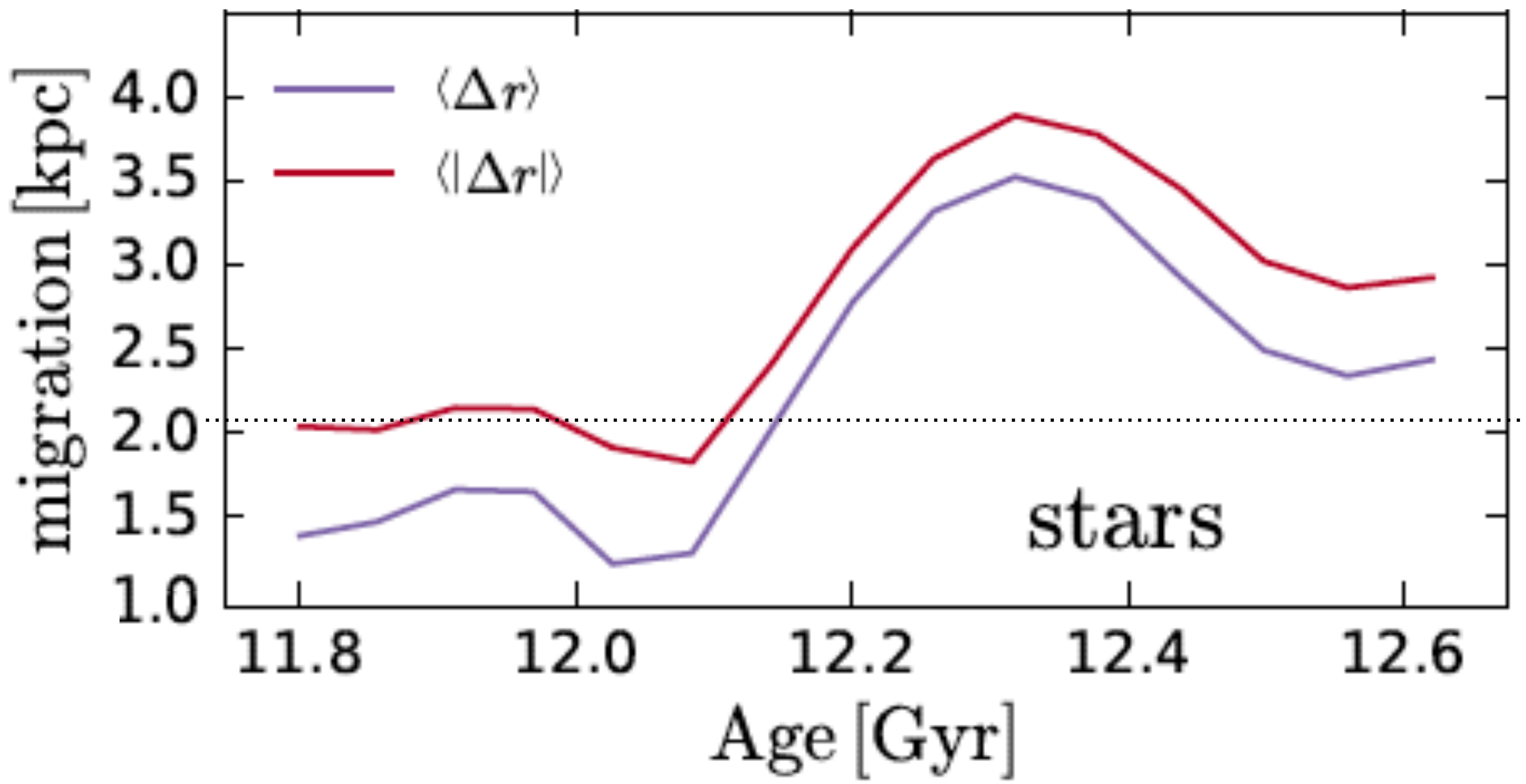
Use FIRE-2 galaxies to study what causes radial migration

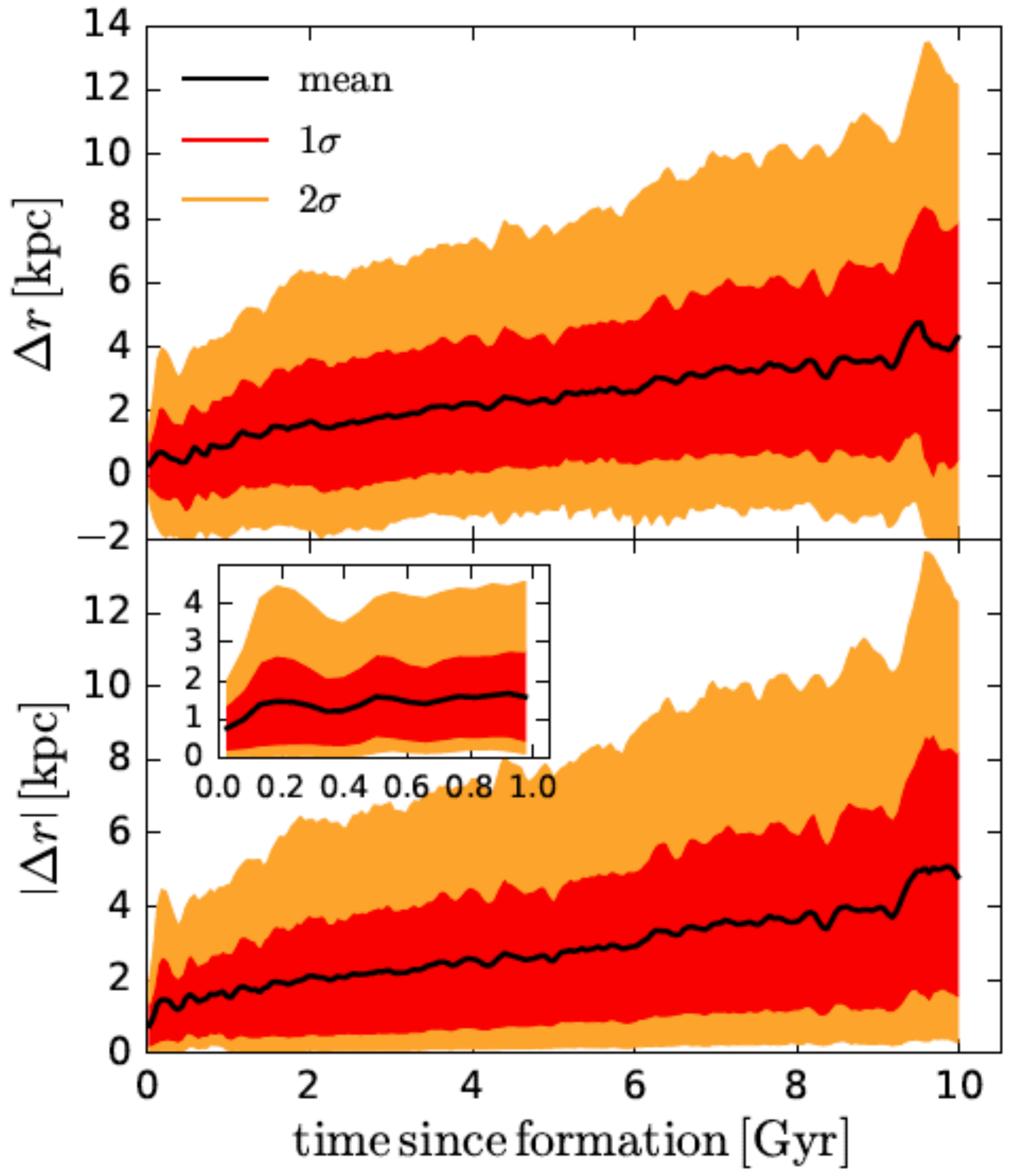
Gas responds to star formation events

Stars responds to change in potential well

THE ORIGIN STORY: RADIAL STELLAR MIGRATION

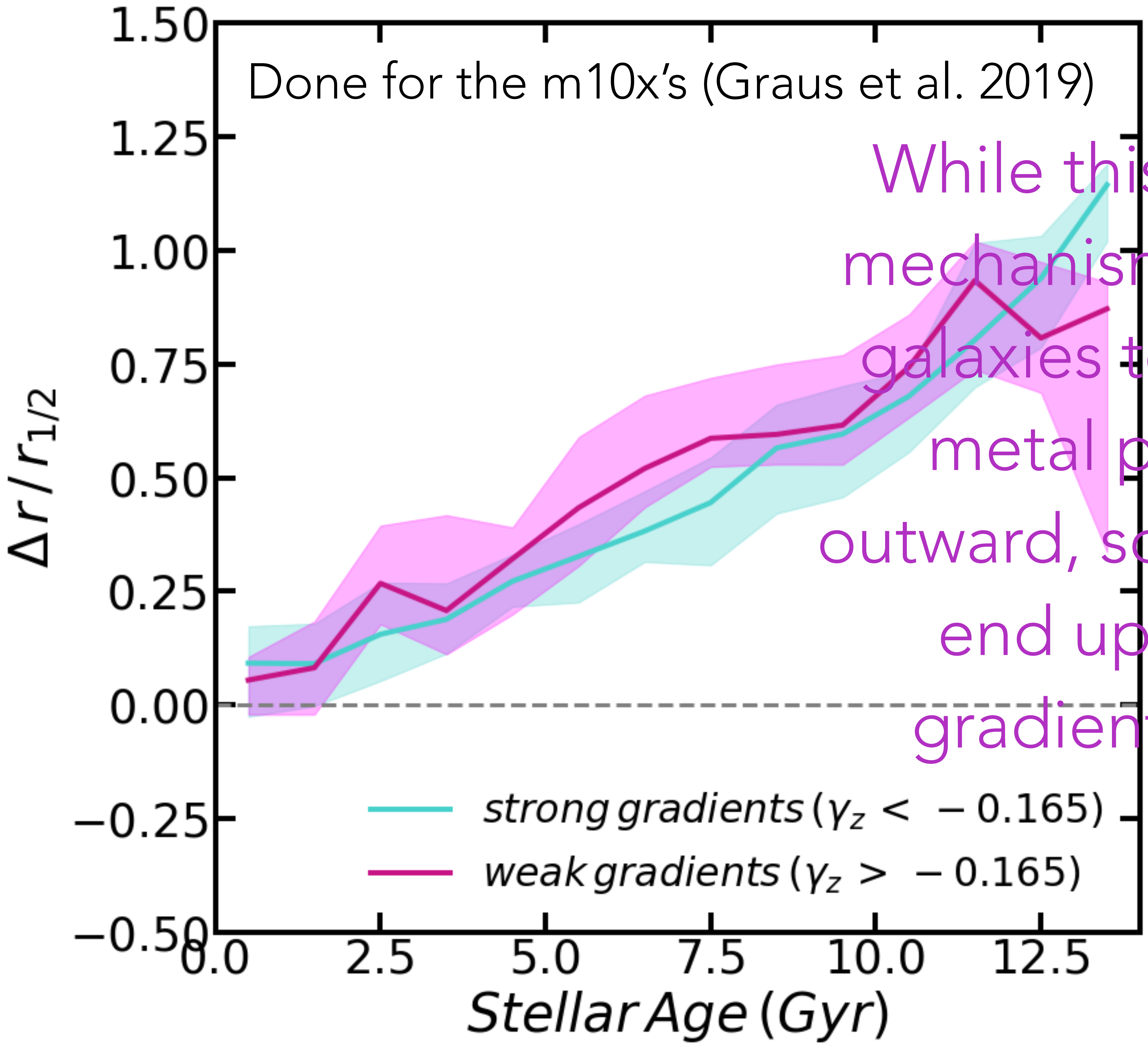
El-Badry et al. 2016





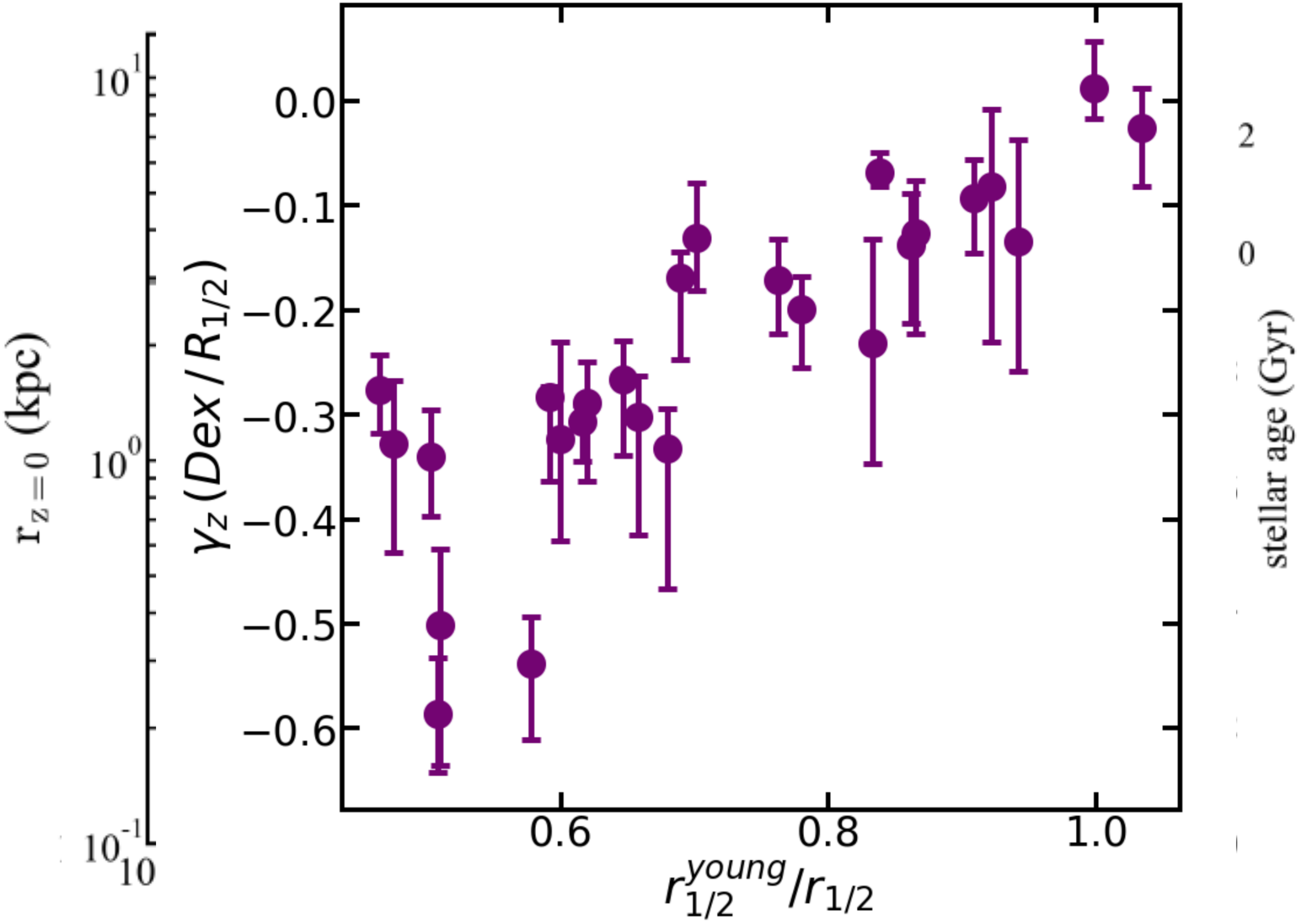
Stars that live through more "puffing cycles" will have migrated more than younger stars that lived through fewer

THE ORIGIN STORY: RADIAL STELLAR MIGRATION

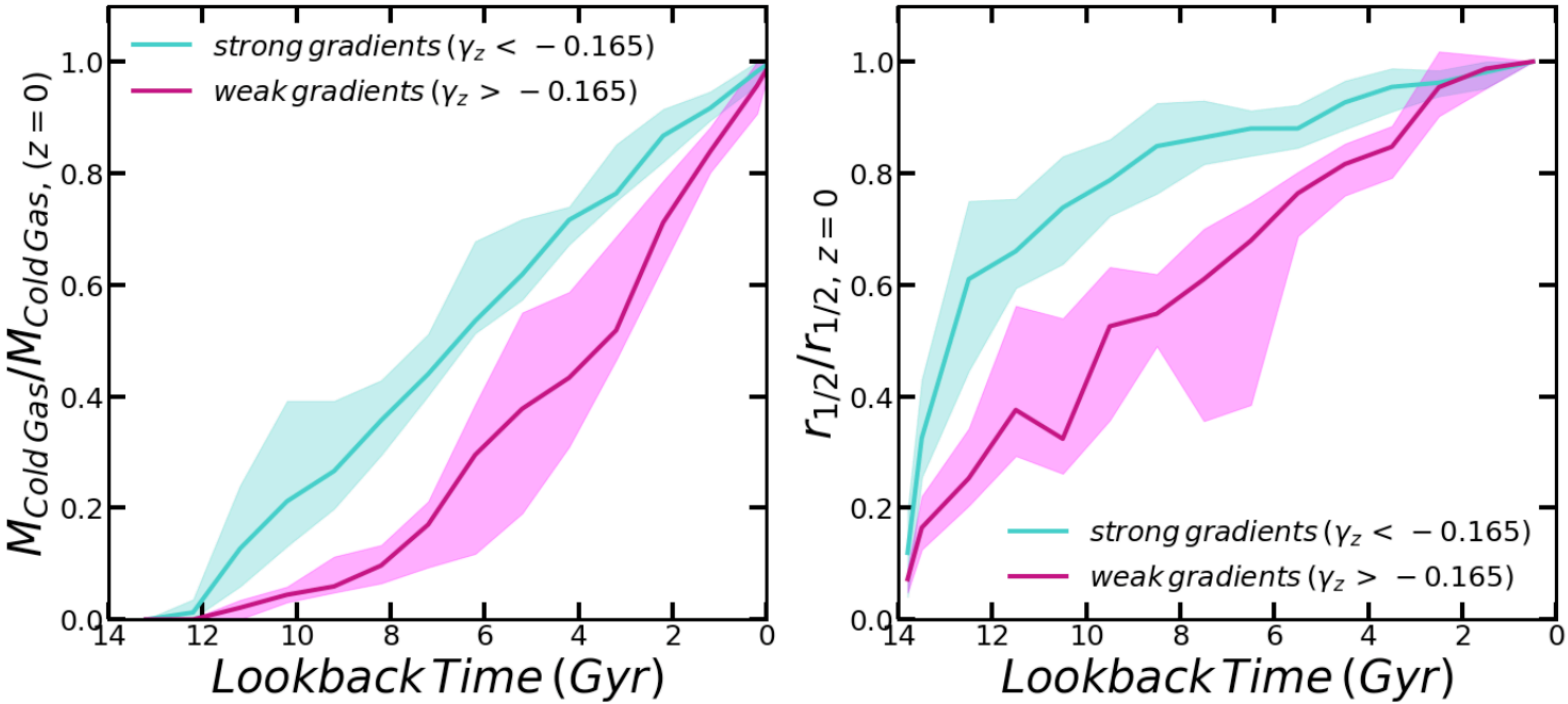


While this "puffing" mechanism acts on all galaxies to drive old, metal poor stars outward, some galaxies end up with flat gradients anyway

SETTING THE GRADIENT STRENGTH



SETTING THE GRADIENT STRENGTH



SETTING THE GRADIENT STRENGTH

FEEDBACK "PUFFING" CREATES GRADIENTS

- ANGLÉS-ALCÁZAR ET AL. 2017: RECYCLED GAS DOMINATES GAS ACCRETION AT LATE TIMES AT LOWER MASS SCALES
- ENRICHED MATERIAL MAKES HIGHER METALLICITY STARS & FLATTENS THE GRADIENTS

STOP GROWI
DON'T ACC
MUCH GA

NTINUE TO
W & ACCRETE
CYCLED GAS

Strong Gradients Preserved

Weak Gradients Created

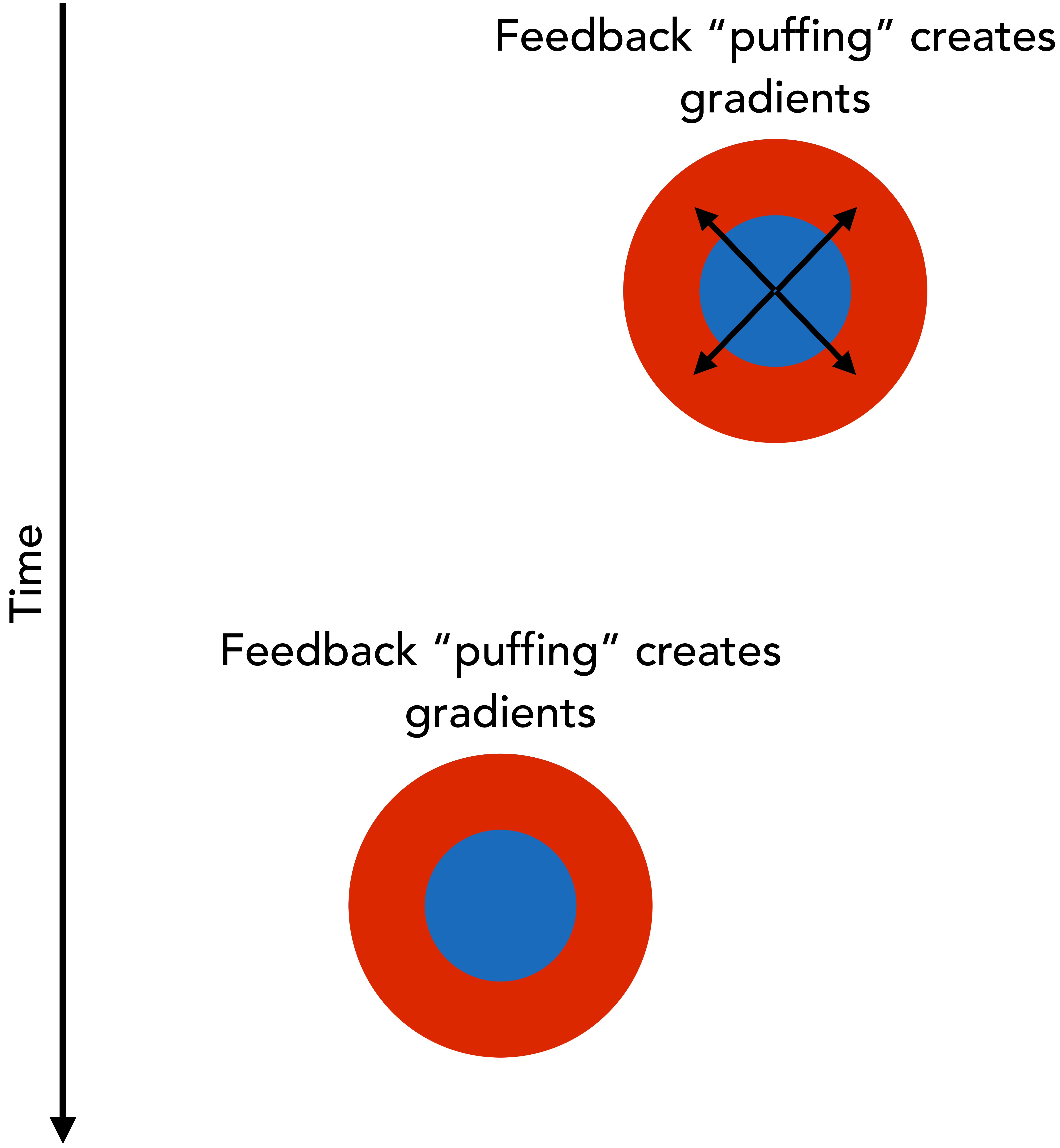
FEEDBACK “PUFFING” CREATES GRADIENTS

STOP GROWING & DON’T ACCRETE MUCH GAS

Strong Gradients Preserved

CONTINUE TO GROW & ACCRETE RECYCLED GAS

Weak Gradients Created


Feedback "puffing" creates gradients
Time
Feedback "puffing" creates gradients

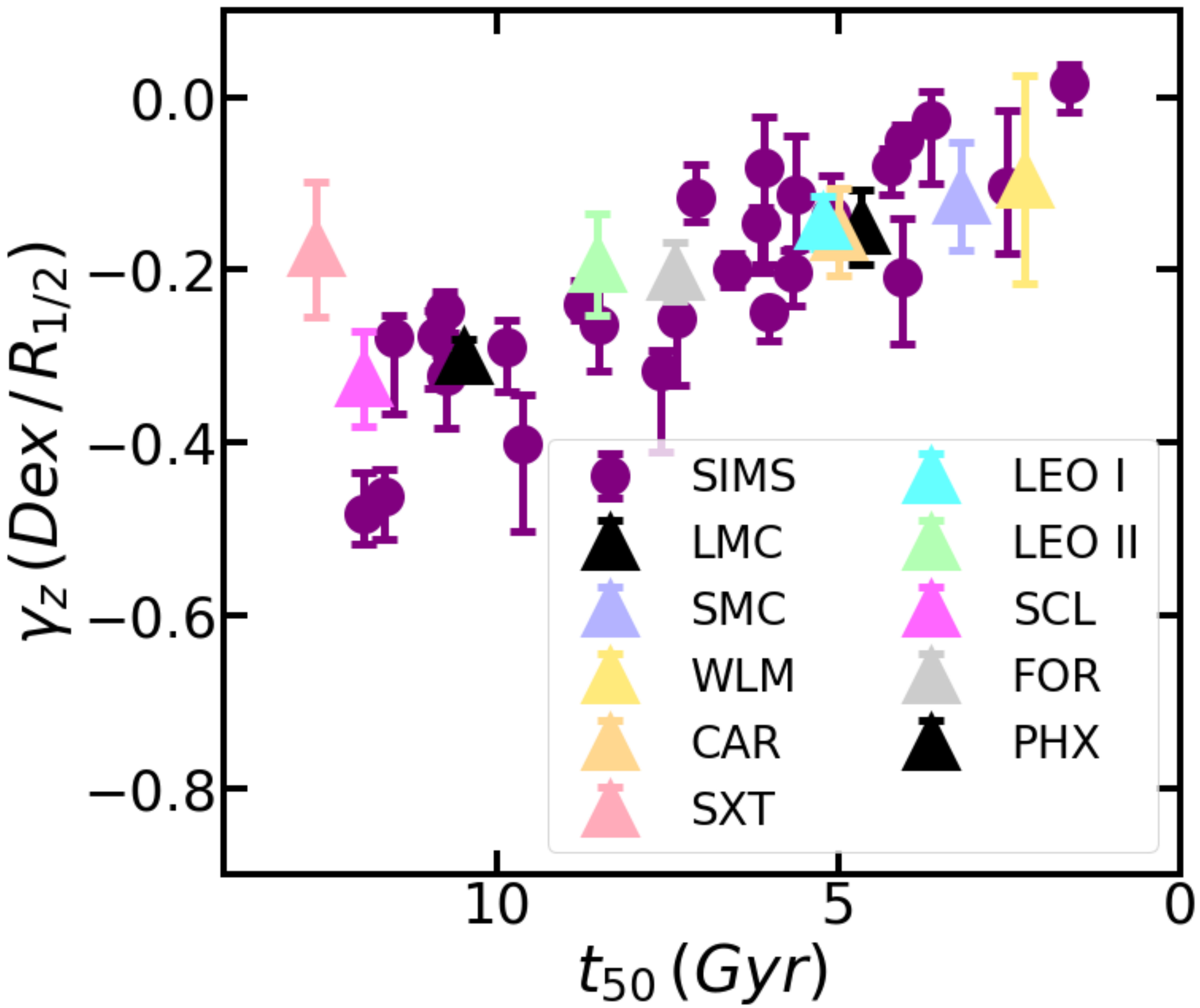
THE OBSERVED GRADIENT-STRENGTH-GALAXY-AGE RELATIONSHIP

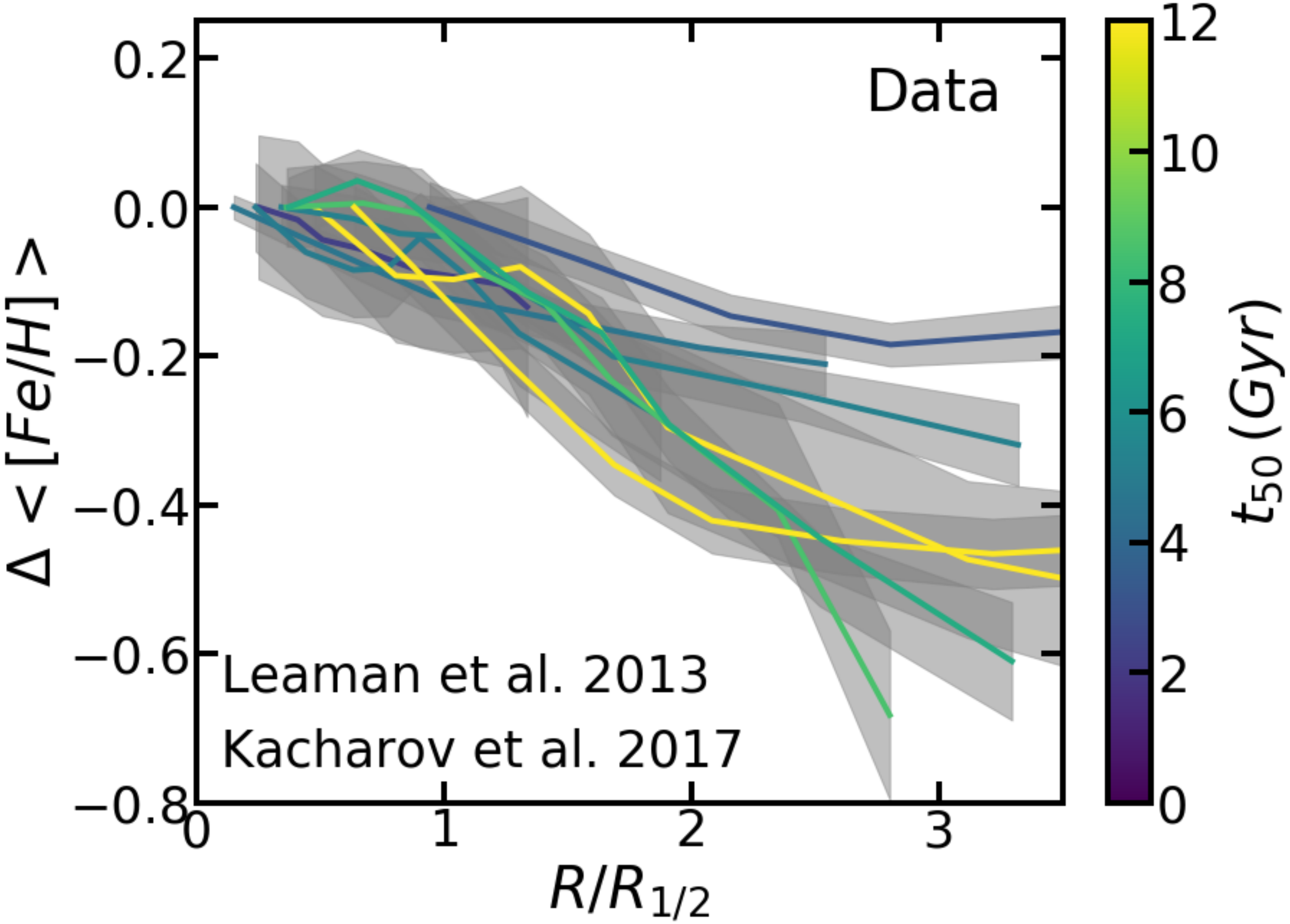
- t_{50} values taken from SFHs presented in Weisz et al. (2014a,b) and Bettinelli et al. (2018)
- $R_{1/2}$ values taken from McConnachie (2012), Muñoz et al. (2018), and Simon (2019)
- Metallicity profiles presented in Leaman et al. (2013) and Kacharov et al. (2017)

Galaxy Name	t_{50} [Gyr]	γ_z $[Dex/R_{1/2}]$	$R_{1/2}$ [kpc]
MW Dwarfs	(1)	(2)	(3)
WLM	2.28	-0.11 ± 0.12	2.111
SMC	3.21	-0.13 ± 0.07	1.106
LMC	4.68	-0.15 ± 0.04	2.697
Carina	4.99	-0.16 ± 0.05	0.311
Leo I	5.22	-0.15 ± 0.02	0.270
Fornax	7.40	-0.21 ± 0.03	0.792
Leo II	8.54	-0.18 ± 0.06	0.171
Phoenix	10.48	-0.30 ± 0.02	0.454
Sculptor	11.95	-0.33 ± 0.06	0.279
Sextans	12.64	-0.16 ± 0.07	0.456

γ_z and errors determined by bootstrapped sampling the observed profile data

THE OBSERVED GRADIENT-STRENGTH-GALAXY-AGE RELATIONSHIP





THE OBSERVED GRADIENT-STRENGTH-GALAXY-AGE RELATIONSHIP

SUMMARY

- In observed galaxies negative metallicity gradients are common such that more **metal rich** stars populate the **central regions** while more **metal poor** stars inhabit the **outer regions**
- In FIRE-2 galaxies we see such gradients and also predict a **Gradient-Strengeth-Galaxy-Age Relationship**
- Galaxies with **older** stellar populations tend to have **stronger gradients**
- **Gradients are formed by steady "puffing"** from feedback effects that drive the oldest, more metal poor stars outward over time (El-Badry et al. 2016)

SUMMARY: CONTINUED

- We predict that **late time, radially extended star formation** acts to **flatten out gradients**
- These **stars form from recycled gas** that fell back onto the galaxy after being ejected by feedback processes
- We use data from **10 observed LG dwarfs** to show that they **also follow a Gradient-Strength-Galaxy-Age Relationship**, similar to that of the simulated sample
- **These results suggest that metallicity gradients in real galaxies may be governed by feedback puffing and late-time accretion of recycled gas**

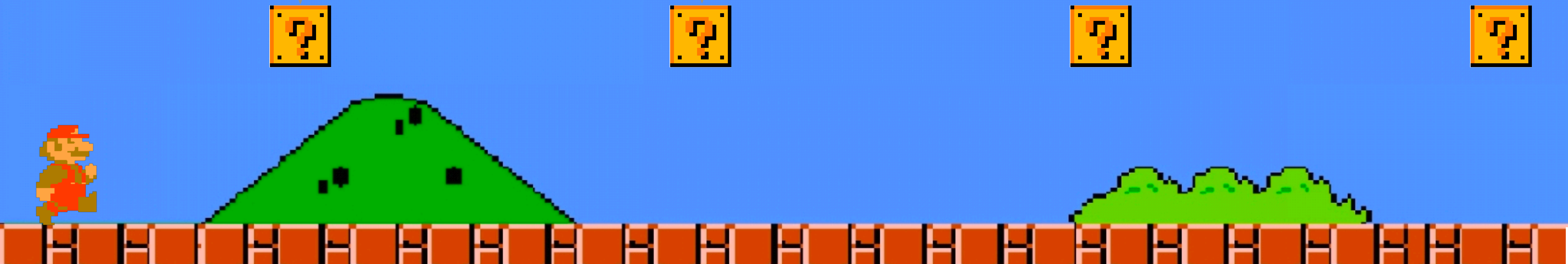
FUTURE WORK - PLAN

By the end of AUG 2020:

Submit this paper

Fall 2020

- Gizmo/Arepo code comparison
- HI gas in ELVIS on FIRE



SIDM CODE COMPARISON: GIZMO VS AREPO

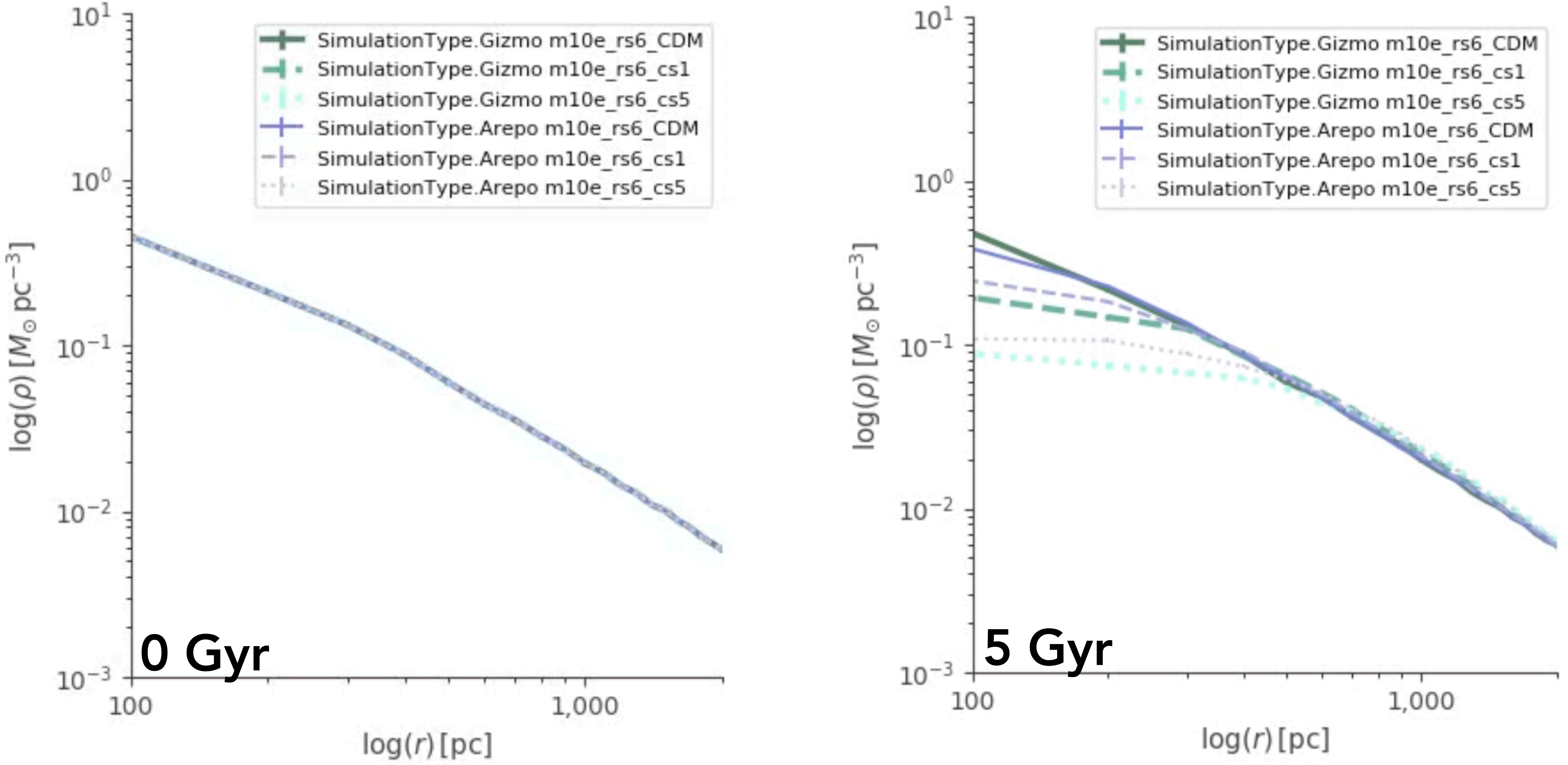
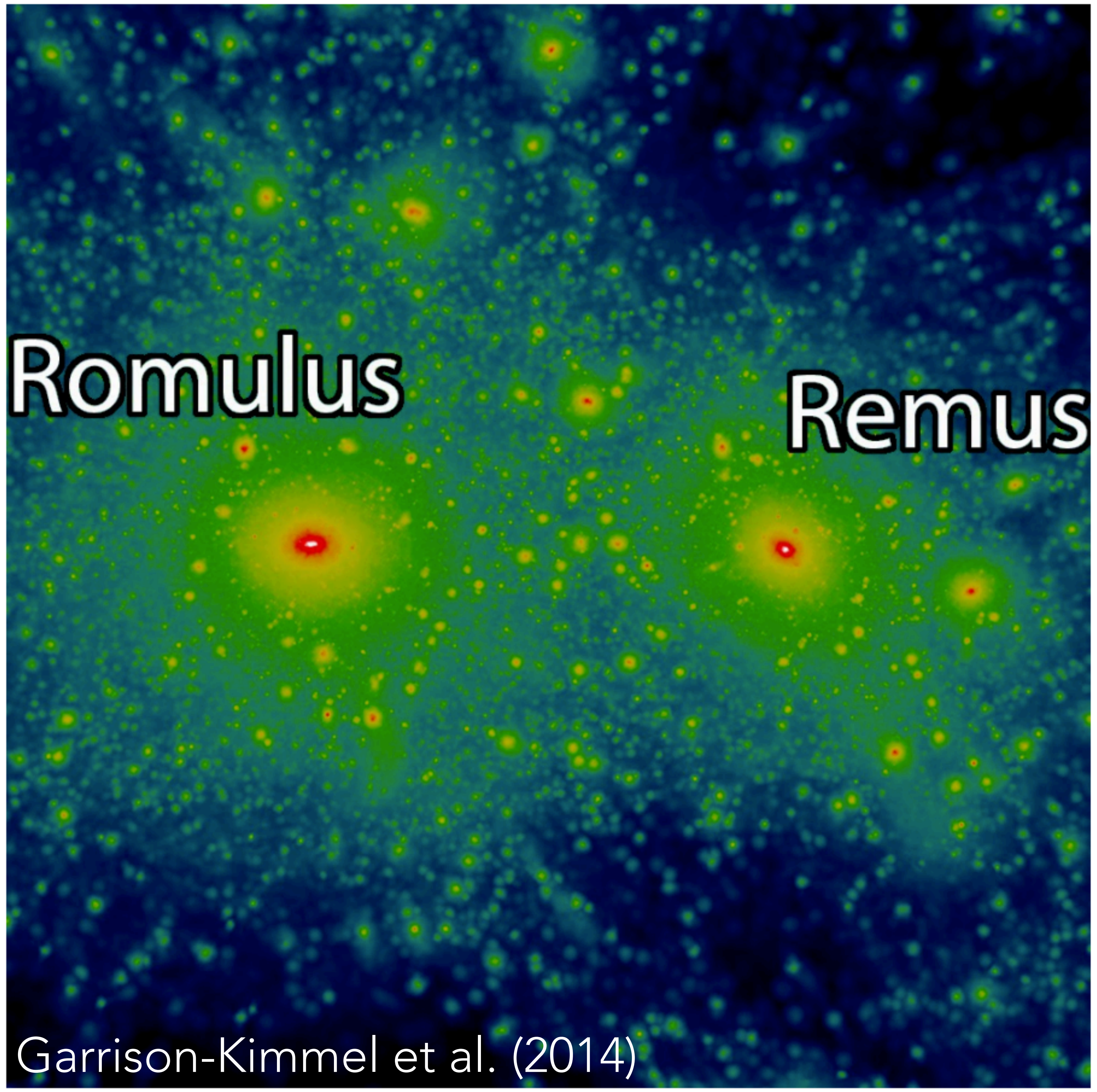


Figure credit: Helen Meskhidze (Grad student; LPS)

HI GAS IN ELVIS ON FIRE

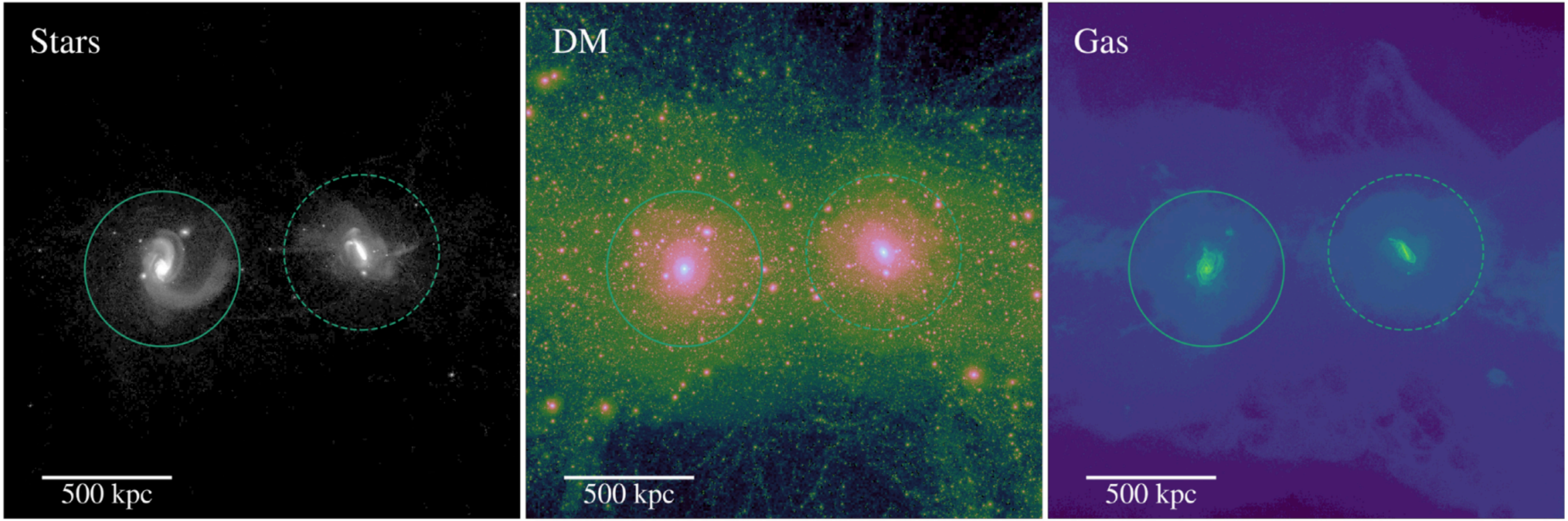


Evangelina Chicas (CSUF)
Imani Ware (SFSU)

Tollerud & Peek (2018) generate mock HI catalogs using ELVIS DM only to determine how many (cold) gas rich sub halos should be detected by HI surveys in the local volume

Their Answer: 5-20 galaxies according to their mock catalogs vs 0 in real H1 surveys

H1 GAS IN ELVIS ON FIRE



FUTURE WORK - PLAN

By the end of AUG 2020:

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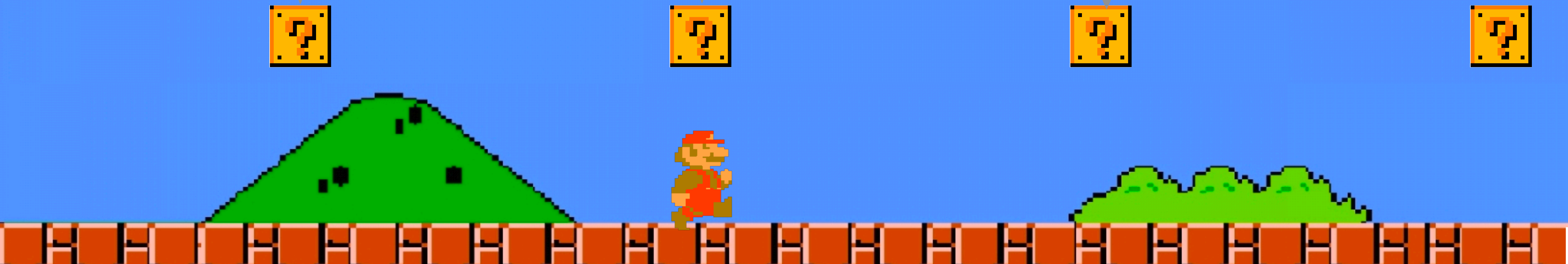
Start of Fall 2020

Finish analysis for:

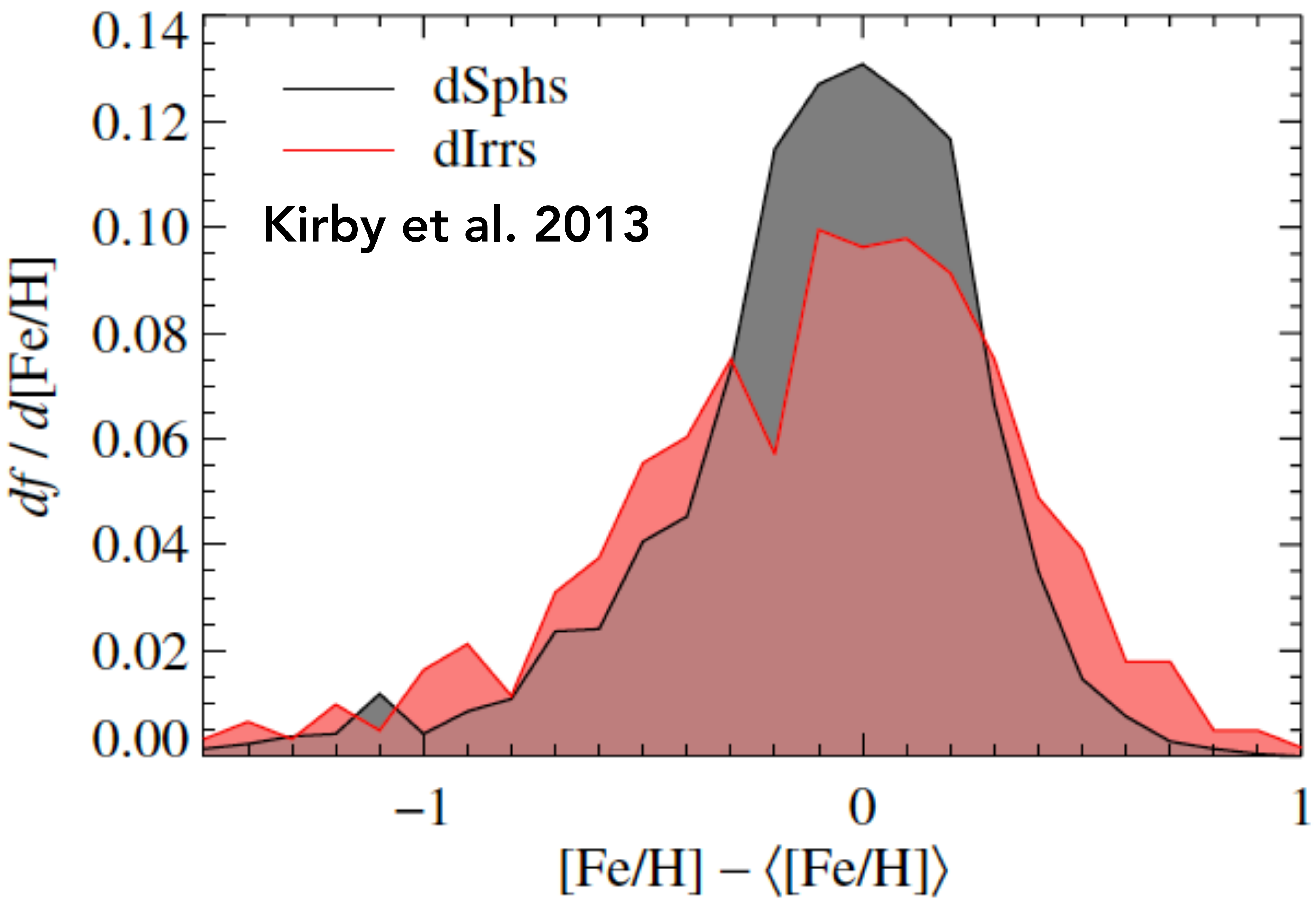
- Gizmo/Arepo code comparison
- H1 gas in ELVIS on FIRE

Winter/Spring 2021:

Metallicity distributions in dwarf galaxies

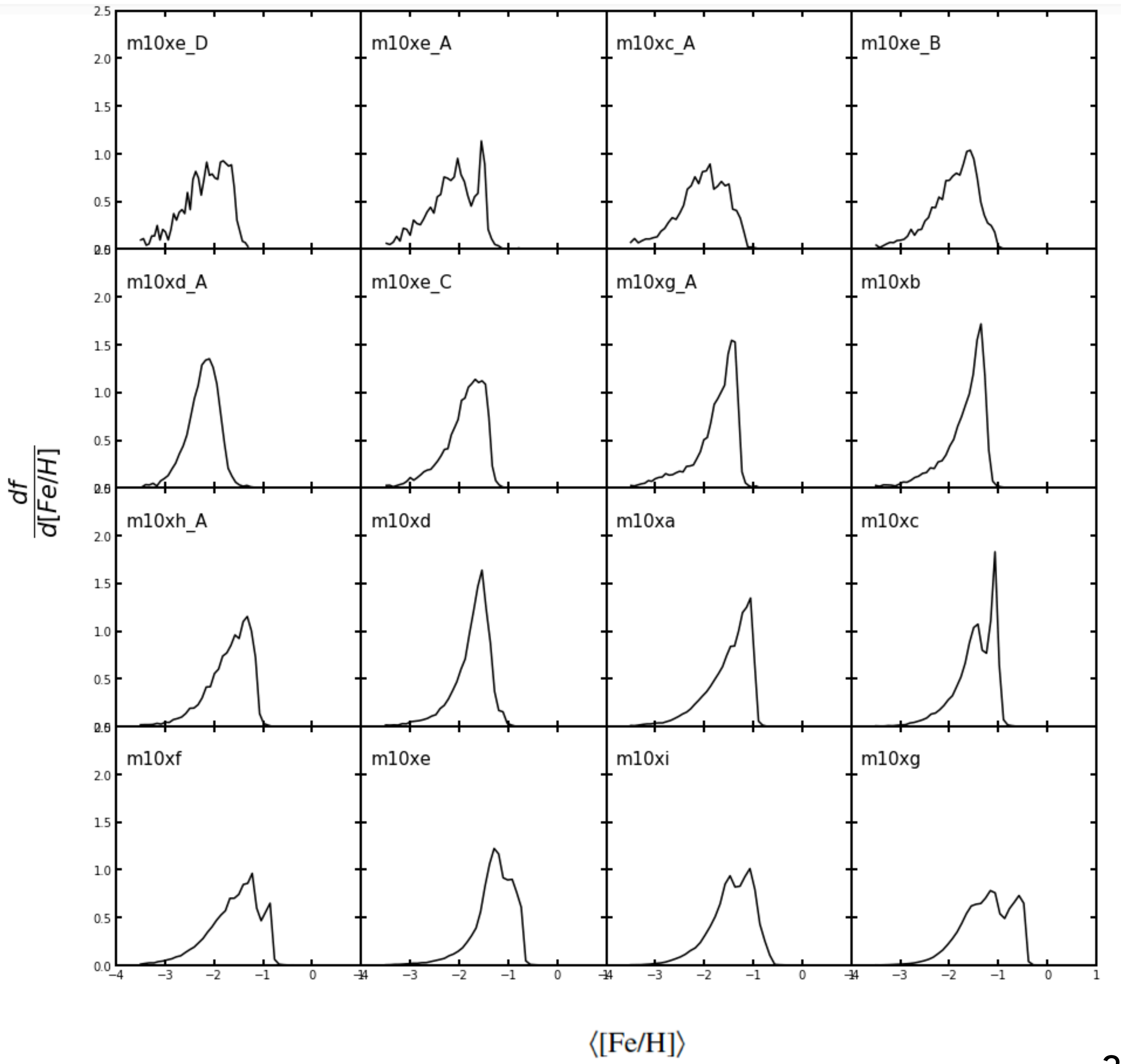


METALLICITY DISTRIBUTIONS IN DWARF GALAXIES



Questions to Ask:

- Is there diversity in the simulated (isolated) galaxy MDFs?
- What brings about this diversity?
- Which MDFs derived from different GCE models fit the the simulated galaxy MDFs?



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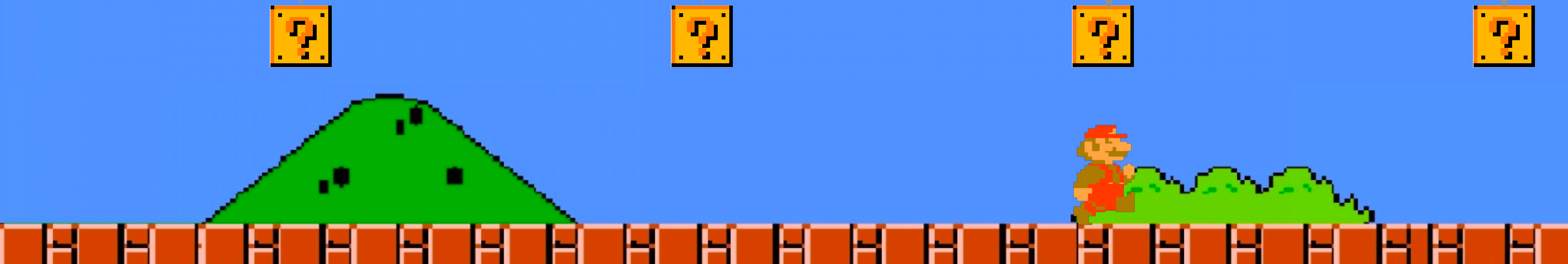
Winter/Spring 2021:

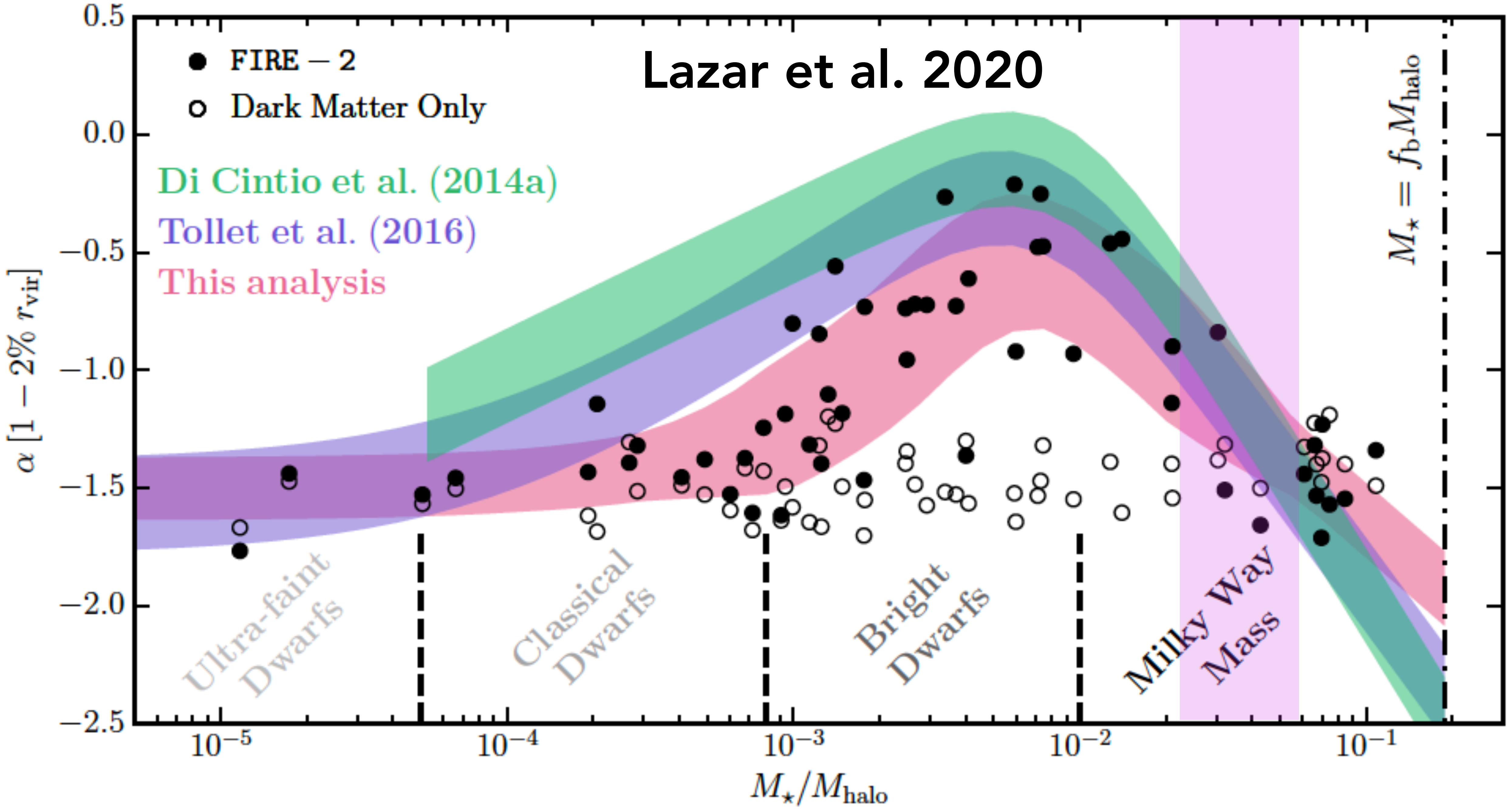
Metallicity distributions in dwarf galaxies

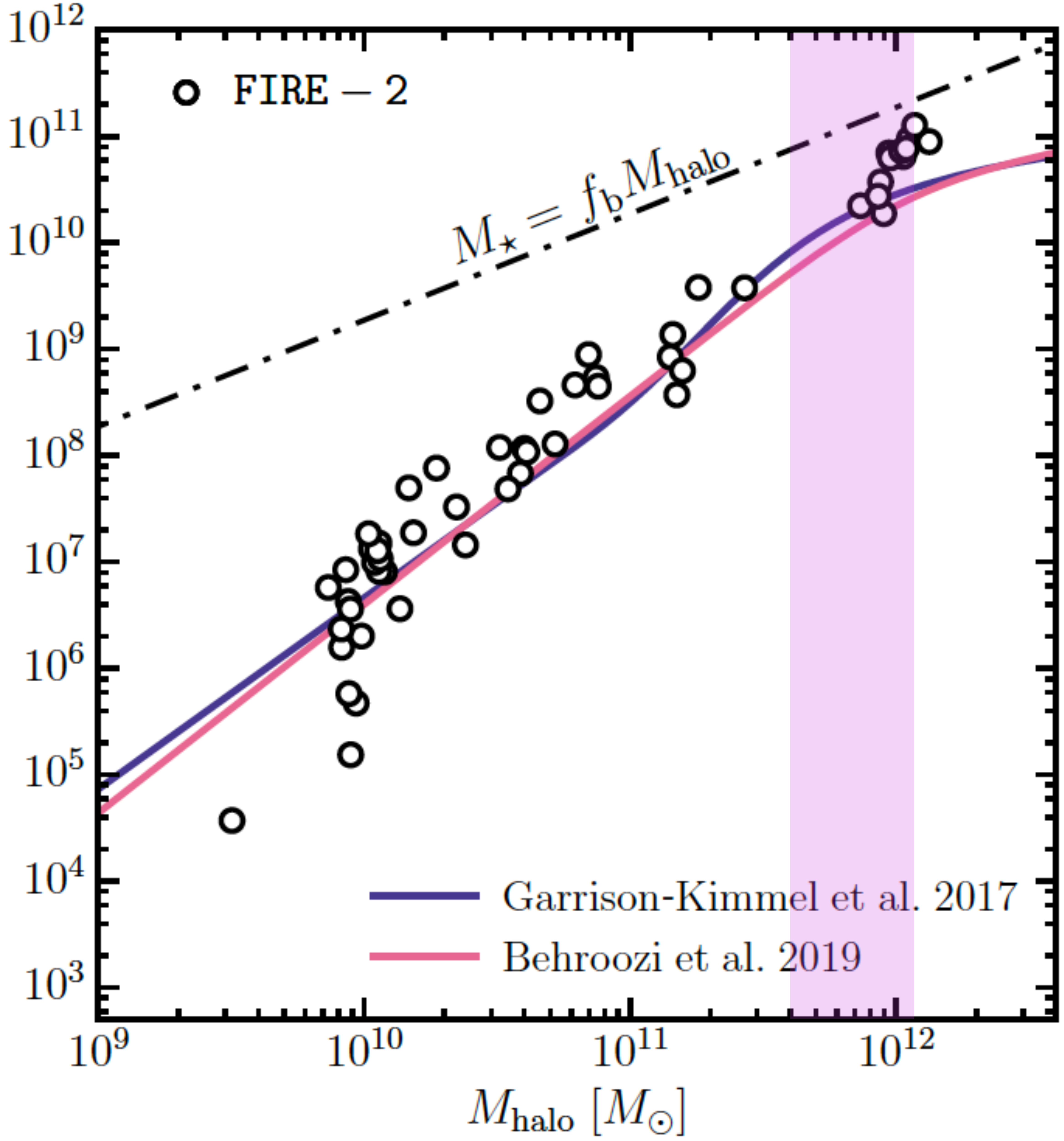
AY 2021-2022:

Run suite of galaxies at $M_{vir} \sim 10^{11\text{-}12}\, M_{\odot}$



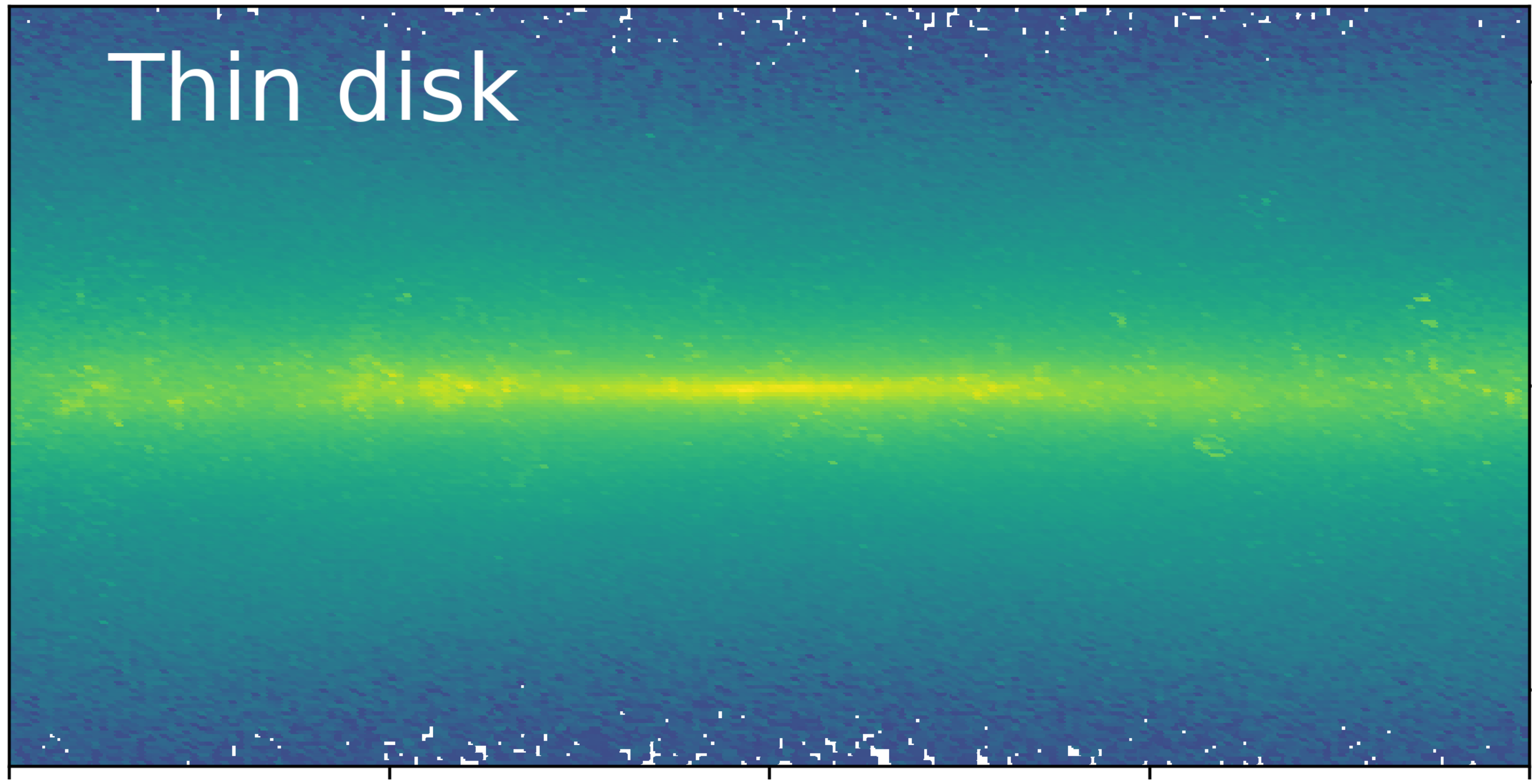
RUNNING SIMULATIONS AT $M_{VIR} \sim 10^{11\text{-}12}\, M_\odot$

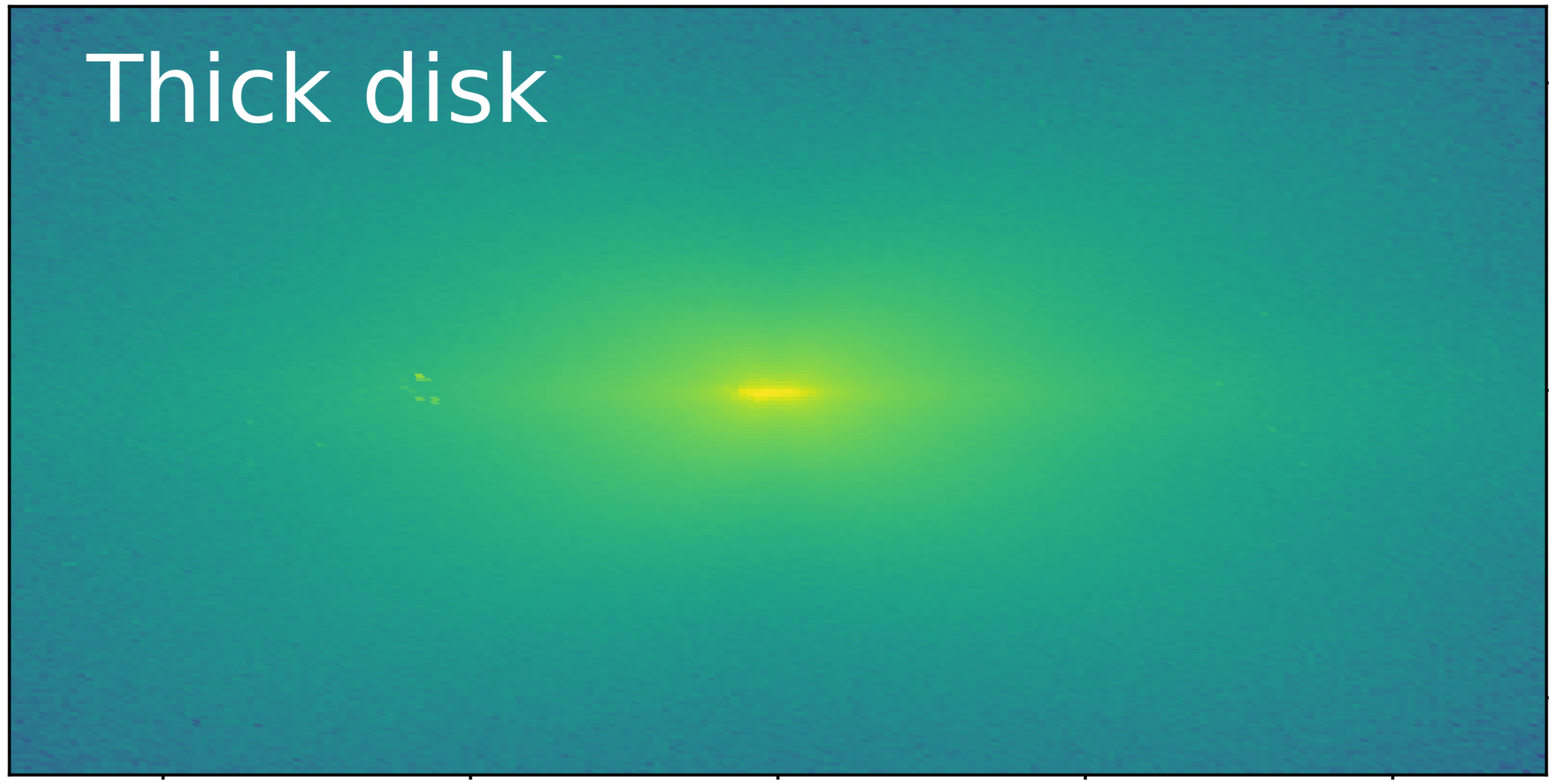




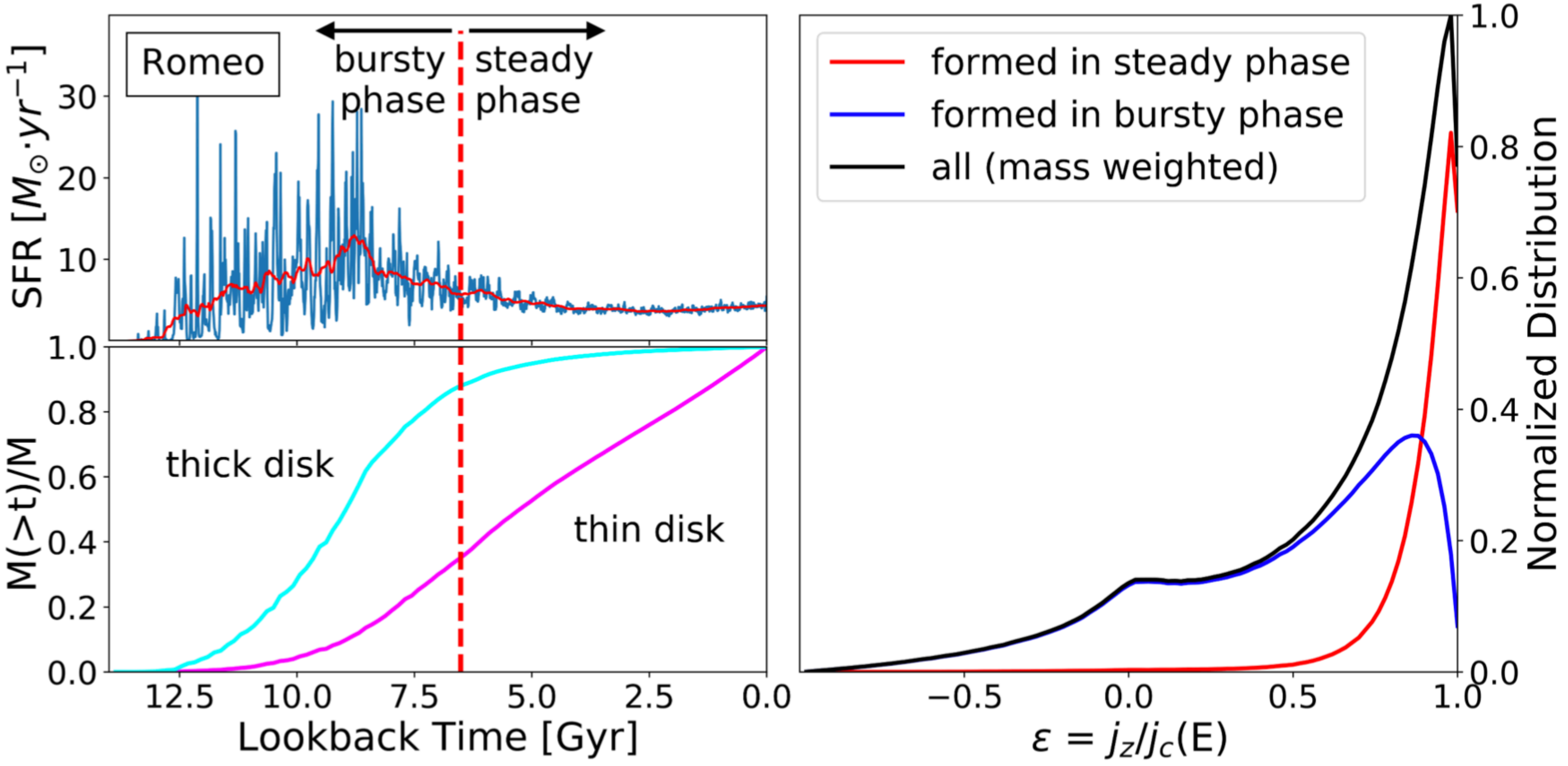
- We would like to run galaxies with "normal" stellar mass fractions
- It would be nice to fill out the gap of "missing" sims

RUNNING SIMULATIONS AT $M_{VIR} \sim 10^{11\text{-}12}\, M_\odot$





Yu et al. 2020 (in prep)



- SFR behaves differently at lower masses
- At what mass does bursty/non-bursty phase disk formation cease to be the case?

FUTURE WORK - PLAN

Fall 2020

- Gizmo/Arepo code comparison
- H1 gas in ELVIS on FIRE

Winter/Spring 2021:

Metallicity distributions in dwarf galaxies

AY 2021-2022:

Run suite of galaxies at M_{vir} ~ $10^{11\text{-}12}$ $M_\odot$

2022/2023:

Graduate!

THANK

YOU