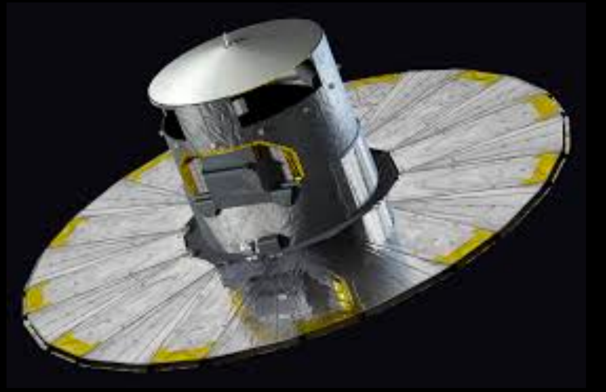
simulating the Milky Way and its satellite galaxies (or, the Milky Way in disequilibrium)

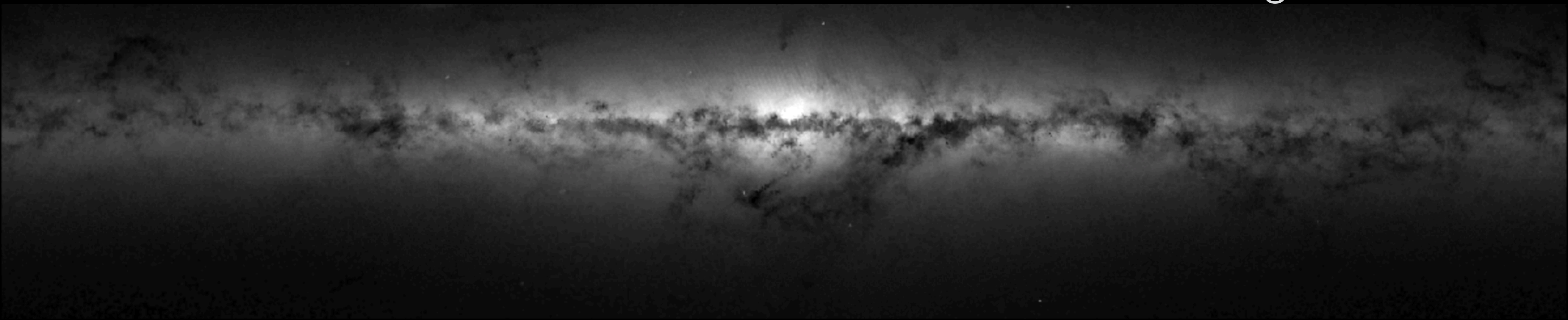
Andrew Wetzel

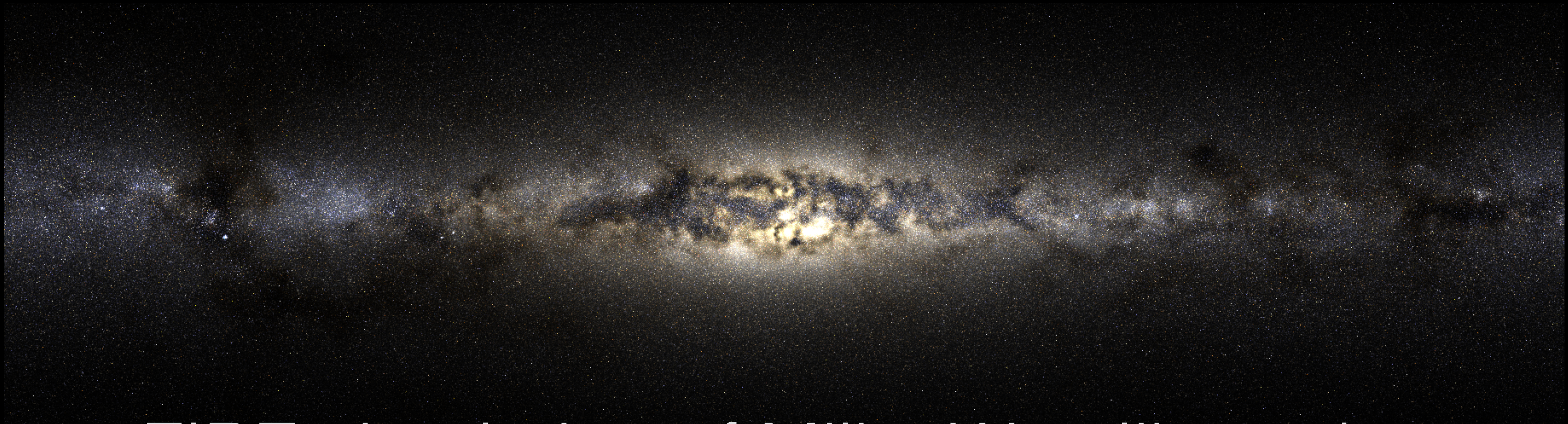
UC DAVIS
UNIVERSITY OF CALIFORNIA

observed Milky Way



gaia satellite





FIRE simulation of Milky Way-like galaxy

FIRE SIMULATION PROJECT

Feedback In Realistic Environments

Principal Investigators

Phil Hopkins (Caltech)
Dusan Keres (UCSD)
Claude-Andre Faucher-Giguere (Northwestern)
Eliot Quataert (UC Berkeley)
Andrew Wetzel (UC Davis)

Chris Hayward (Flatiron CCA)
Mike Boylan-Kolchin (UT Austin)
James Bullock (UC Irvine)
Robert Feldmann (U Zurich)
Robyn Sanderson (U Penn)
Norm Murray (U Toronto)

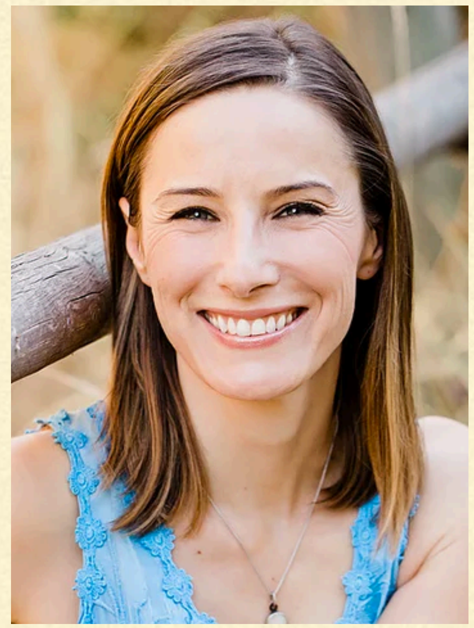
highlighted in this talk

Xiangcheng Ma (TAC fellow @ UC Berkeley)
Shea Garrison-Kimmel (Einstein fellow @ Caltech)
Kareem El-Badry (grad student @ UC Berkeley)
Gunjan Lakhlani (grad student @ U Toronto)

GALAXY SIMULATION GROUP @ UC DAVIS

Postdocs

Sarah Loebman
NASA Hubble Fellow
UC Davis Chancellor Fellow



Samantha Benincasa

Graduate Students

Jenna Samuel

Isaiah Santistevan

Matt Bellardini

Undergraduates

Sierra Chapman

THE MILKY WAY ON FIRE

Feedback In Realistic Environments

- FIRE physics model
- MW-like disks
- satellite dwarf galaxies

FIRE 2 model for gas and star formation

Hopkins, Wetzel et al 2018

goal: model dense multi-phase ISM gas in cosmological setting

resolution

- particle mass: 3500-7000 M_{sun}
- spatial resolution: 1 - 4 pc

gas cooling via atoms, molecules, and 9 metals down to 10 K

star formation in dense self-gravitating molecular clouds

$n_{SF} > 1000$ atoms / cm^3

FIRE 2
Feedback In Realistic Environments

model for stellar feedback

Hopkins, Wetzel et al 2018

goal: directly model individual stellar populations

supernovae

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

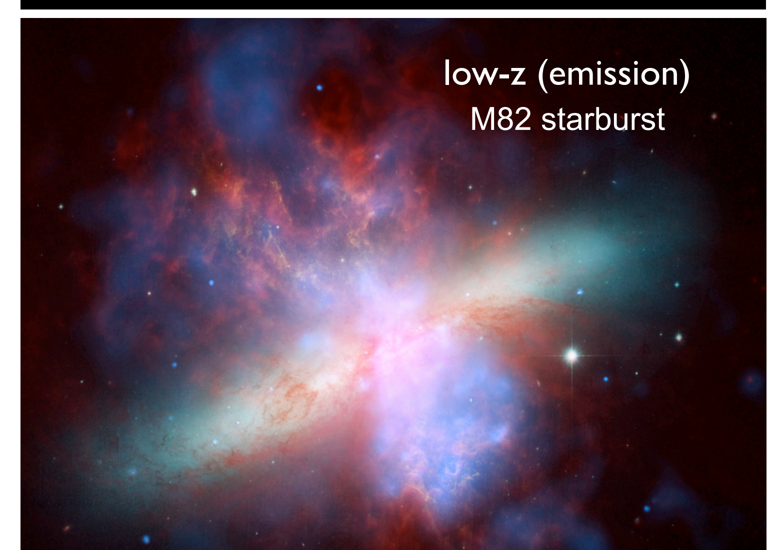
stellar radiation

- 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

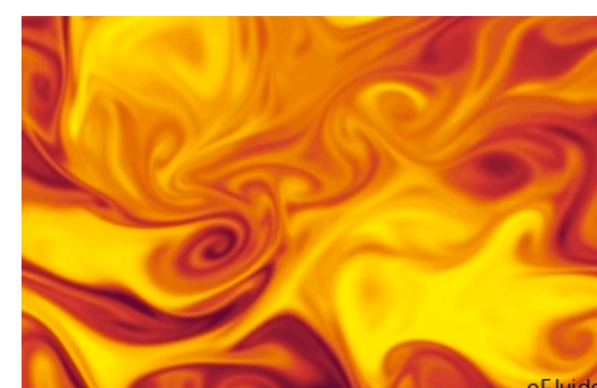
Hopkins, Wetzel et al 2018

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

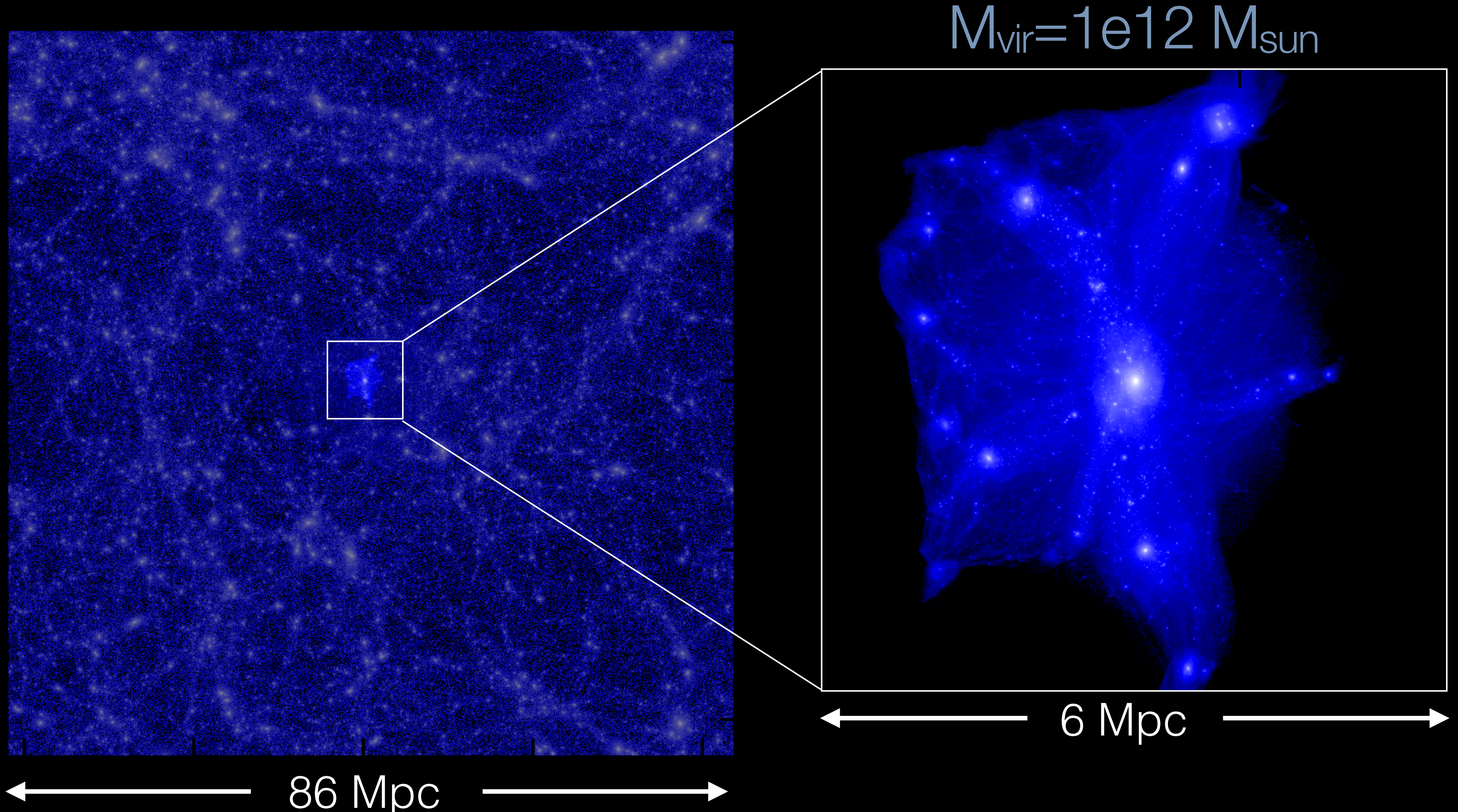
nucleosynthesis (generation of metals) via

- supernovae: core-collapse   Nomoto et al 2006
- supernovae: type Ia   Iwamoto et al 1999
- stellar winds (dominated by O, B, & AGB stars)
  van den Hoek & Groenewegen 1997, Marigo 2001, Izzard 2004

explicitly model sub-grid turbulent mixing of each abundance in gas



cosmological zoom-in simulation to achieve ultra-high resolution



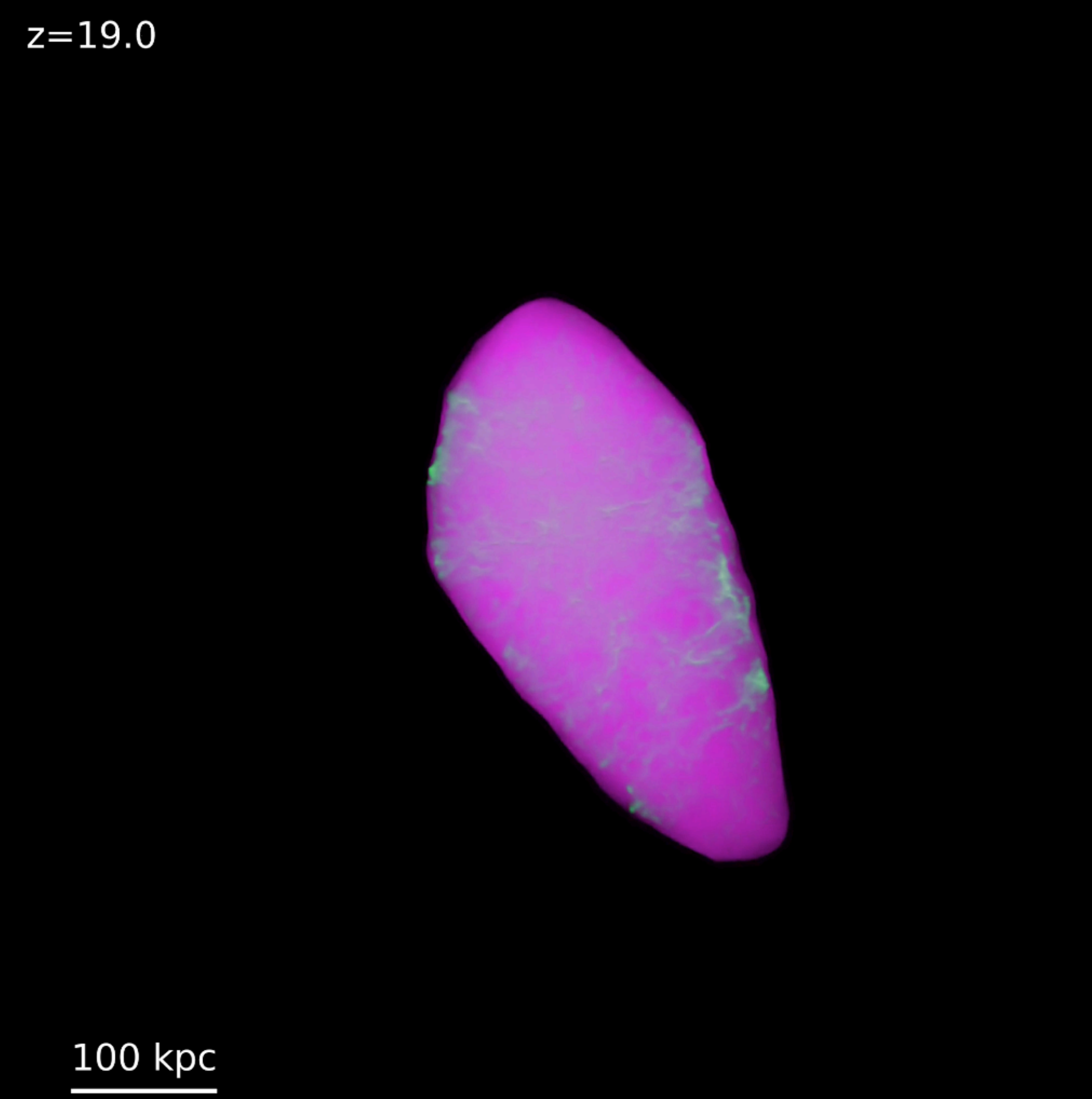
FIRE-2 simulation of MW-mass galaxy

Feedback In Realistic Environments

z=19.0

movie: Shea Garrison-Kimmel

100 kpc



Stars

real-color SED with
dust attenuation

Gas

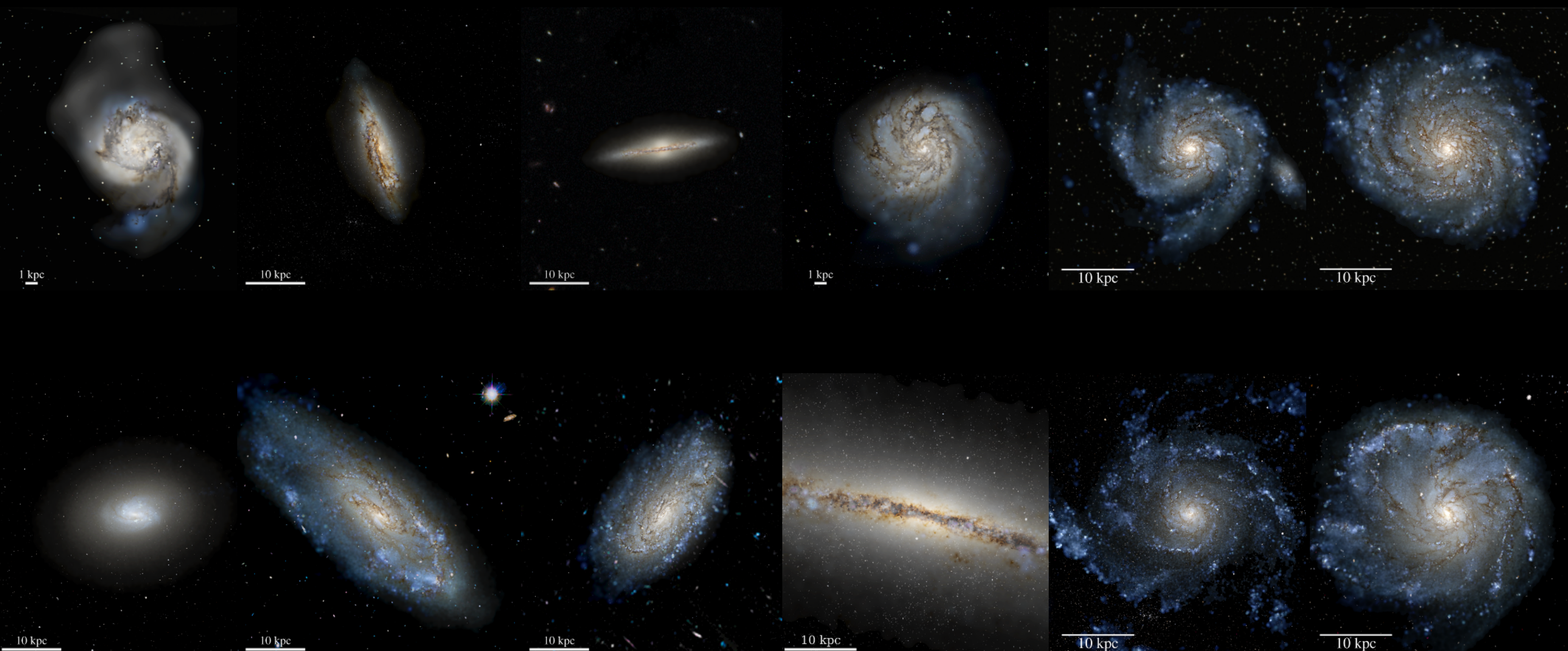
magenta: cold (< 10^4 K)
green: warm (ionized)
red: hot (> 10^6 K)

FIRE-2 simulation suite of MW-mass systems

Feedback In Realistic Environments

Latte suite: 8 isolated MW-mass systems

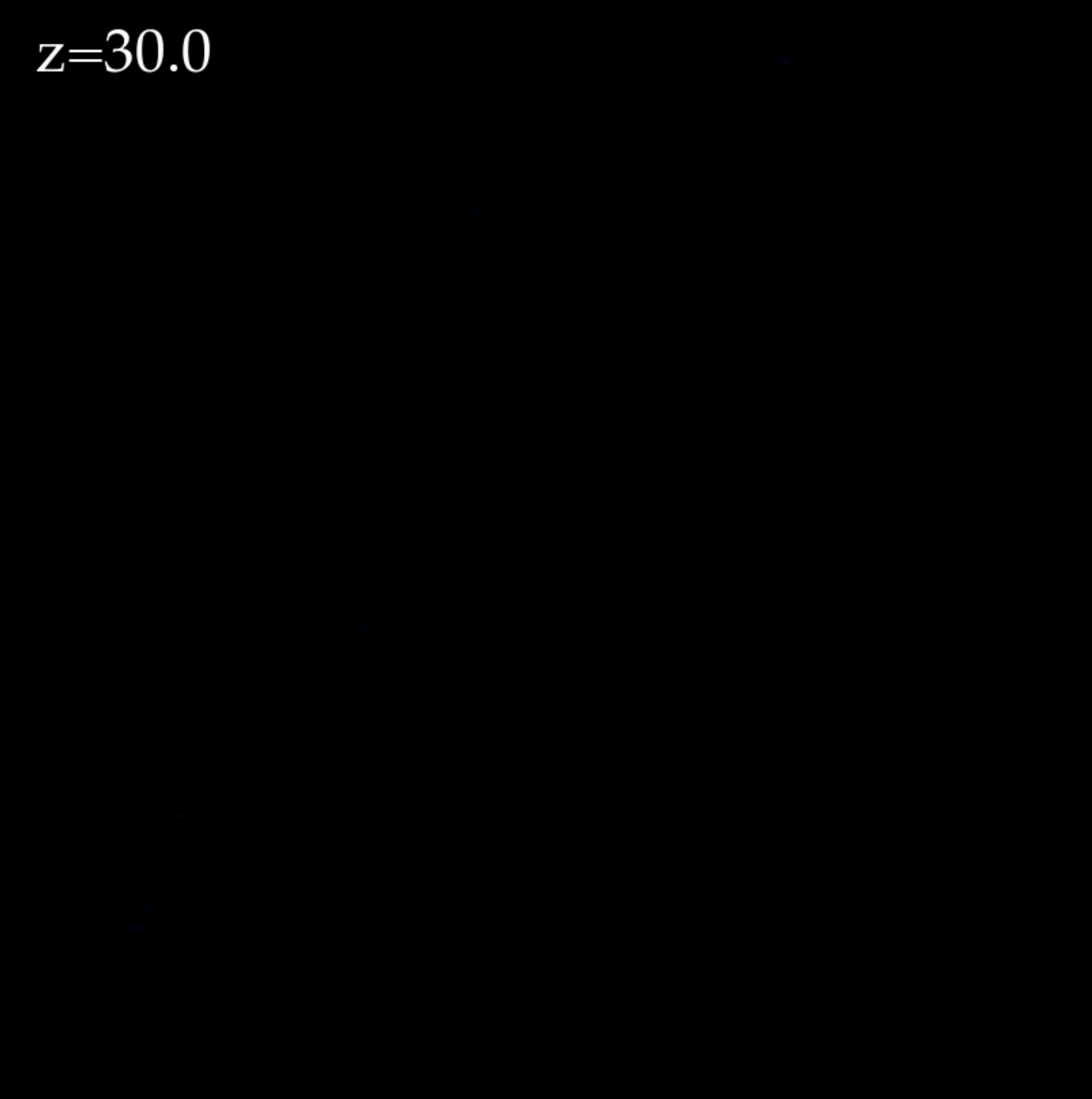
ELVIS suite: 2 LG-like pairs (4 halos)



THE MILKY WAY ON FIRE

Feedback In Realistic Environments

- FIRE physics model
- MW-like disks
- satellite dwarf galaxies



← 50 kpc →

Stars

real-color SED with
dust attenuation

Gas

Magenta: cold $(< 10^4\ K)$
Green: warm (ionized)
Red: hot $(> 10^6\ K)$

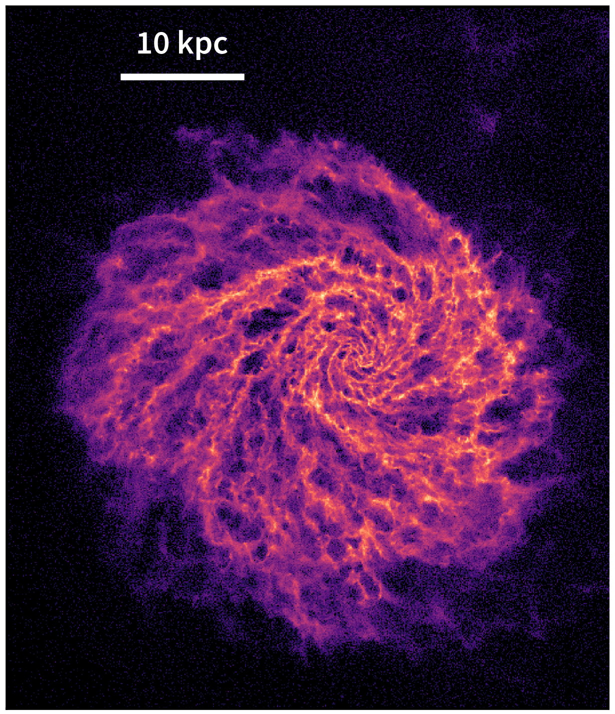
PROPERTIES OF GAS DISK

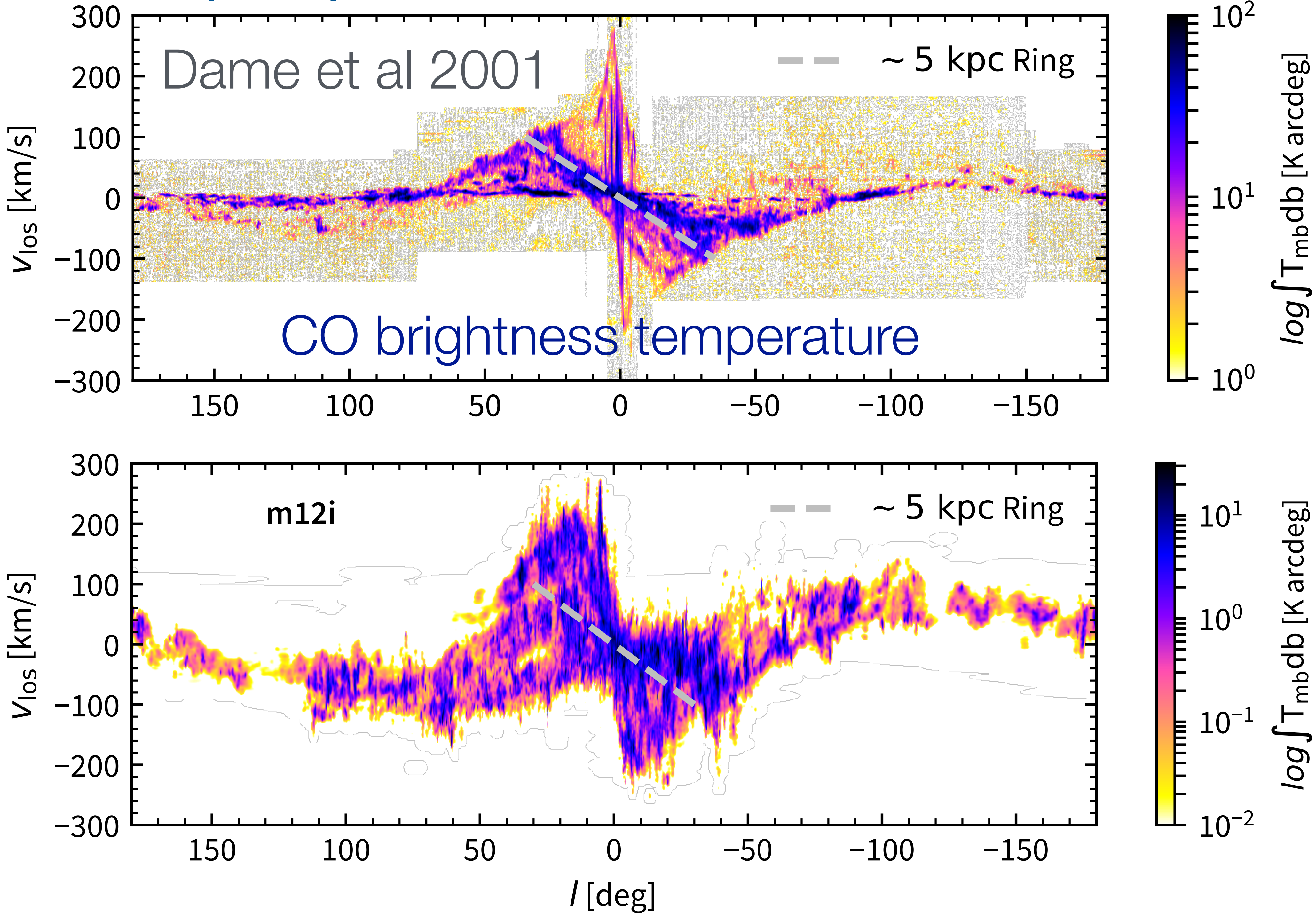
COLD ISM + MOLECULAR CLOUDS

Gunjan Lakhlani
(grad student @ U Toronto)

Samantha Benincasa
(postdoc @ UC Davis)

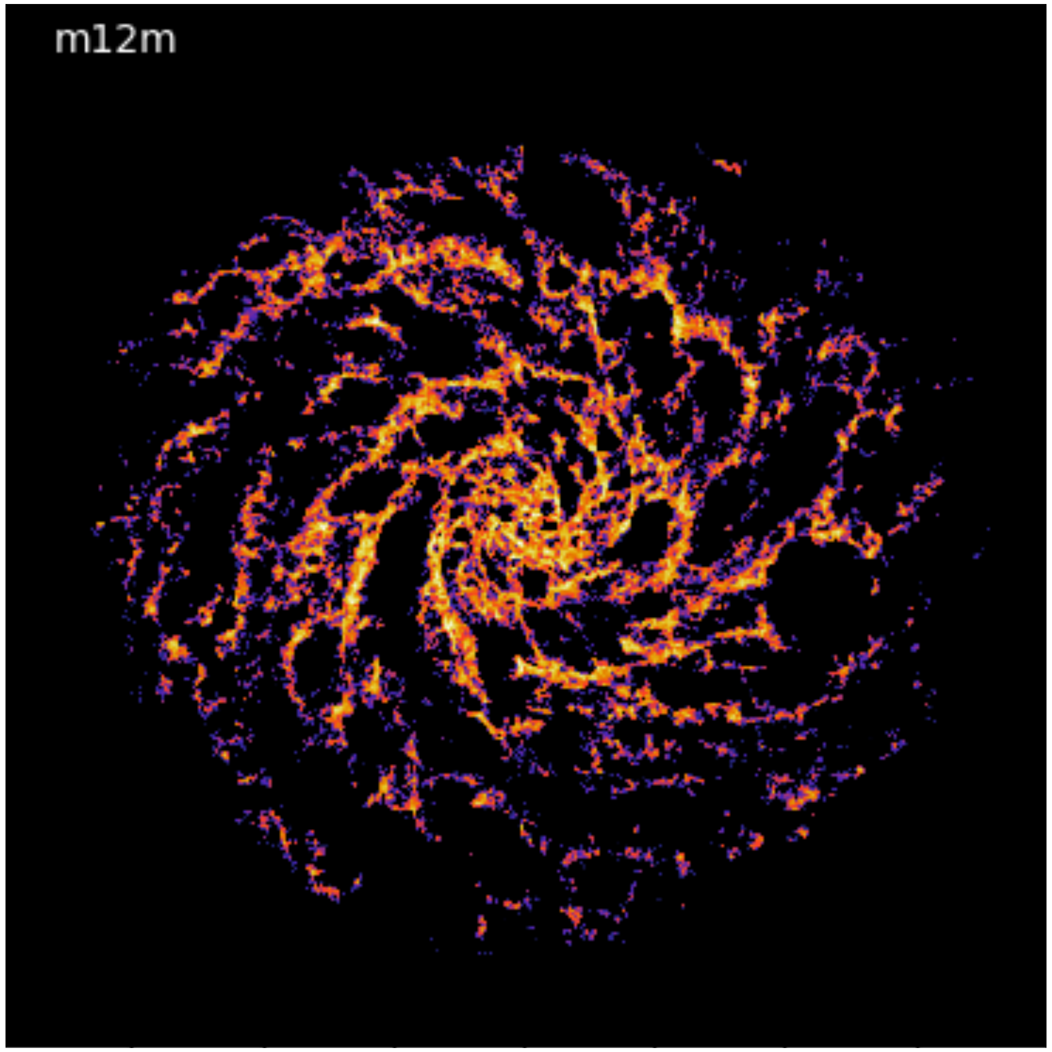
properties of cold ISM

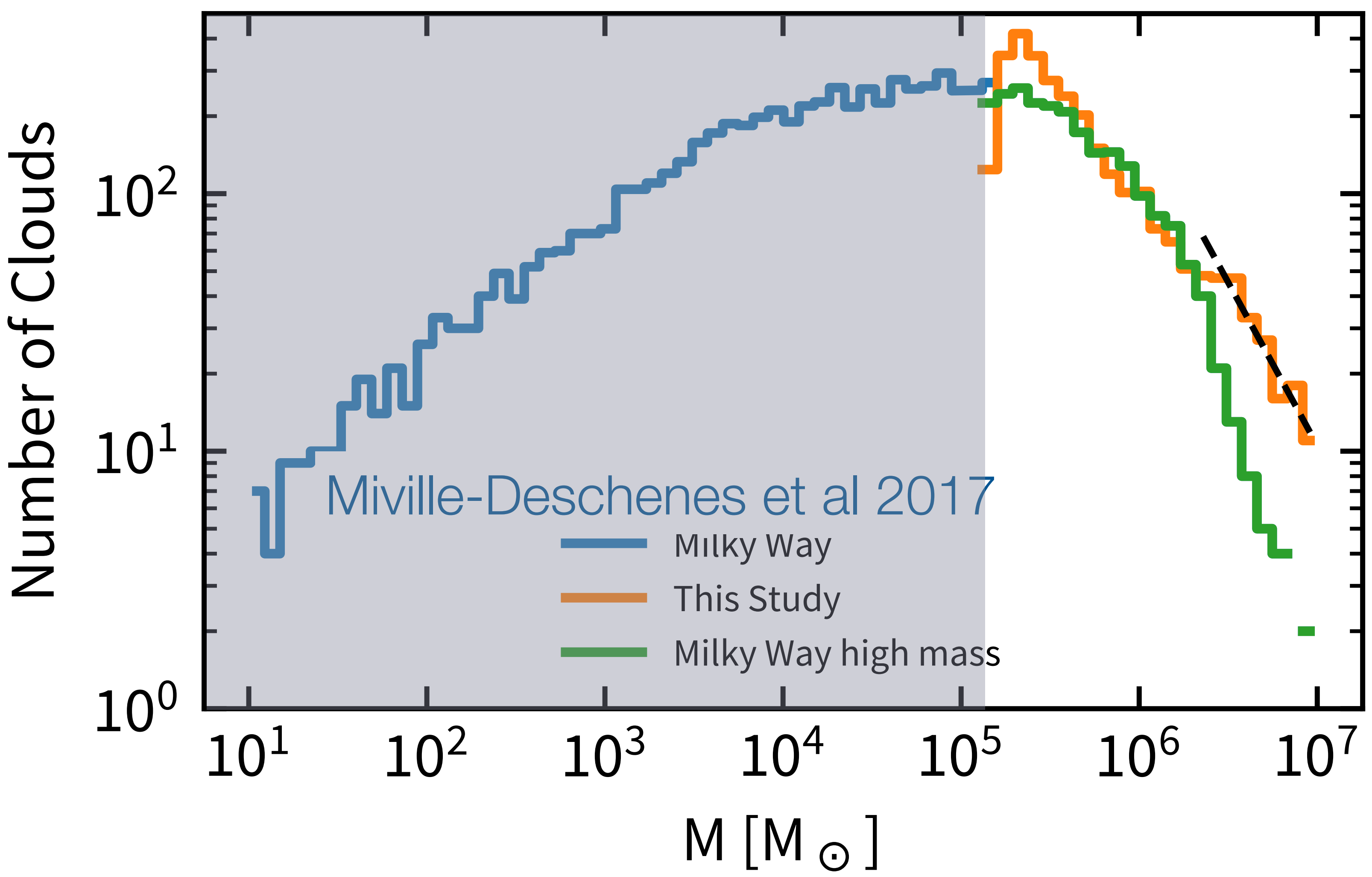




Gunjan Lakhlani et al in prep

resolving (massive) GMCs



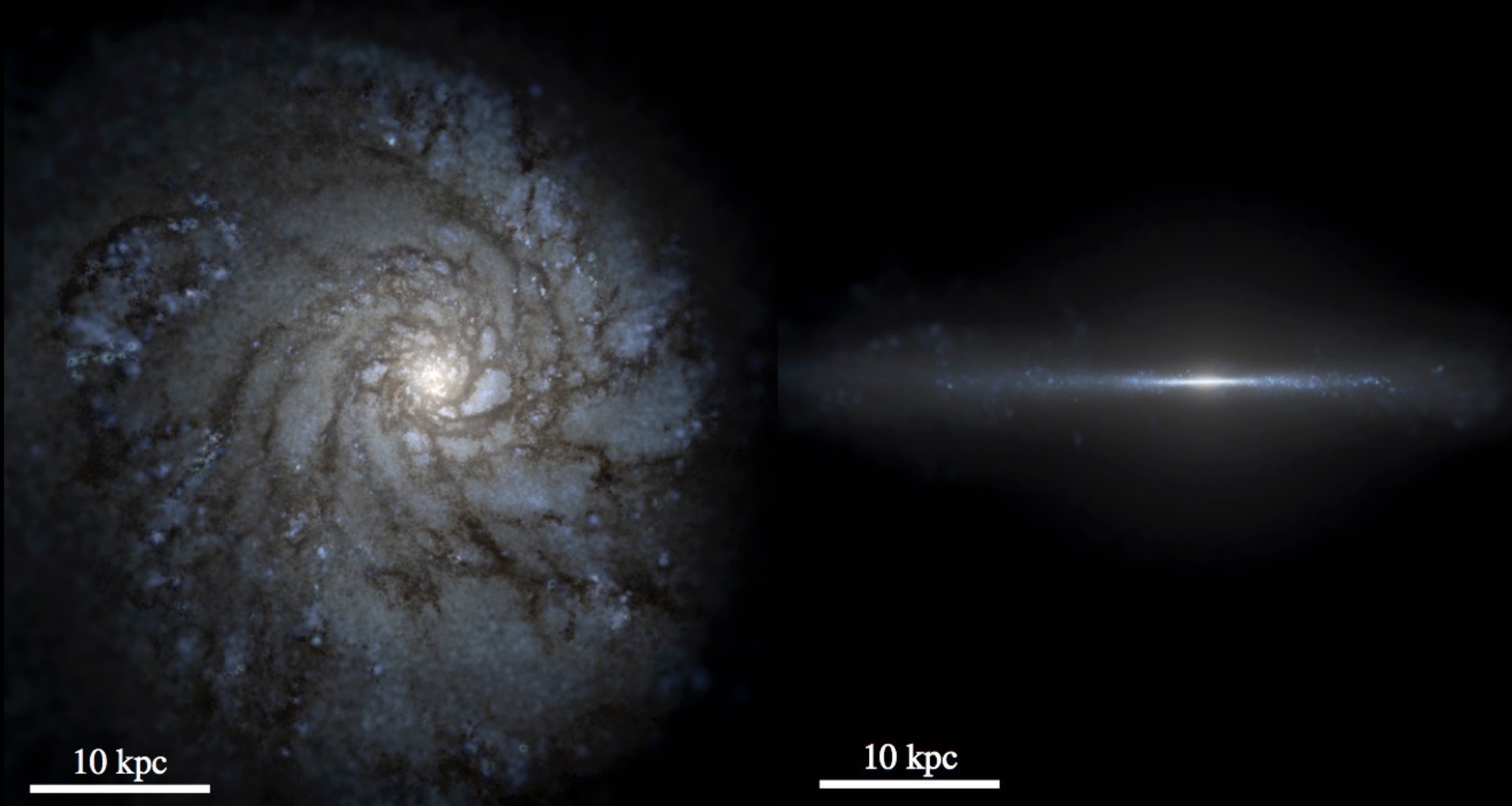


Gunjan Lakhlani et al in prep

Samantha Benincasa, Wetzel et al in prep

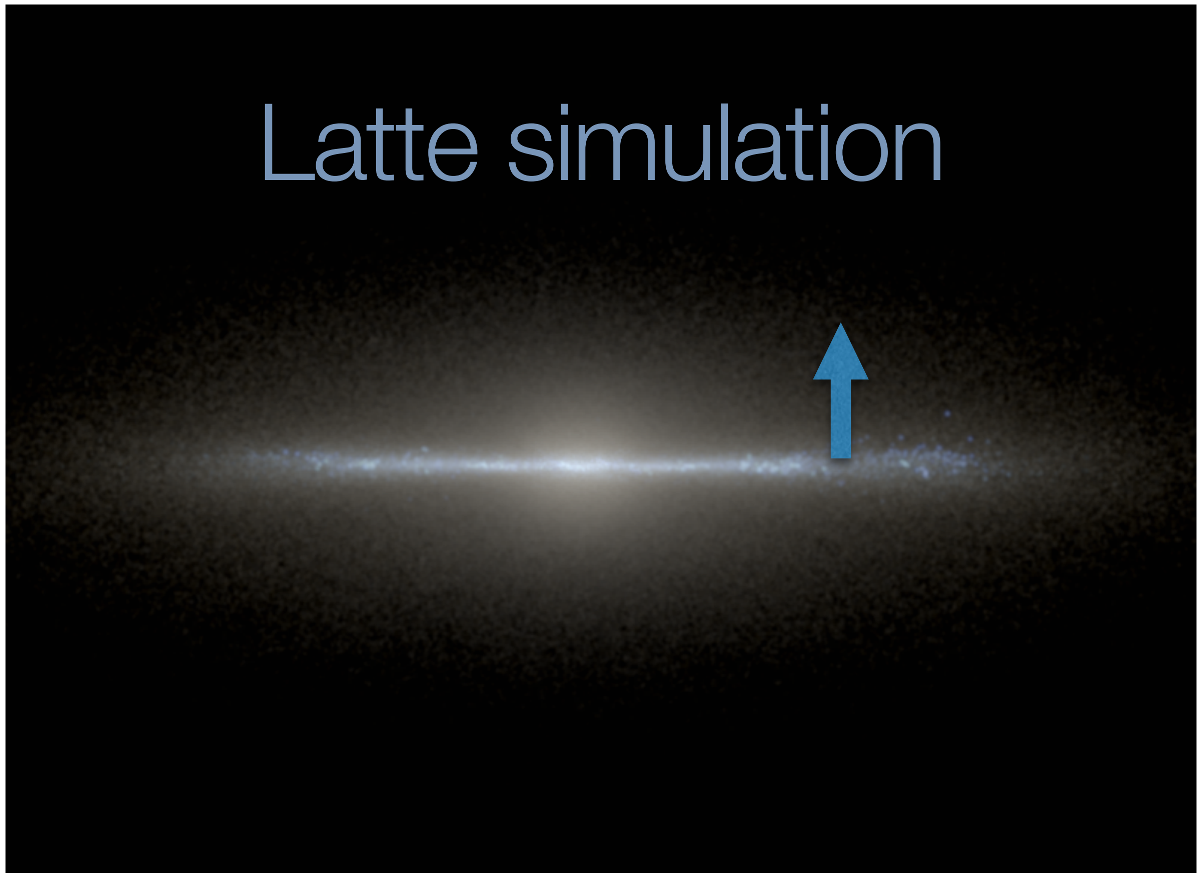
PROPERTIES AND FORMATION OF STELLAR DISK

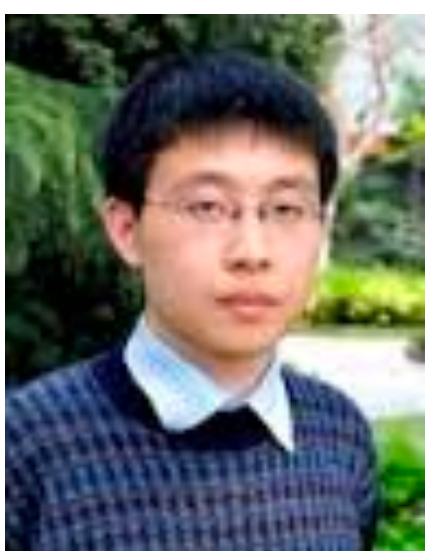
Milky Way-like galaxy at z = 0



$M_{star} = 6 \times 10^{10} M_{sun}$

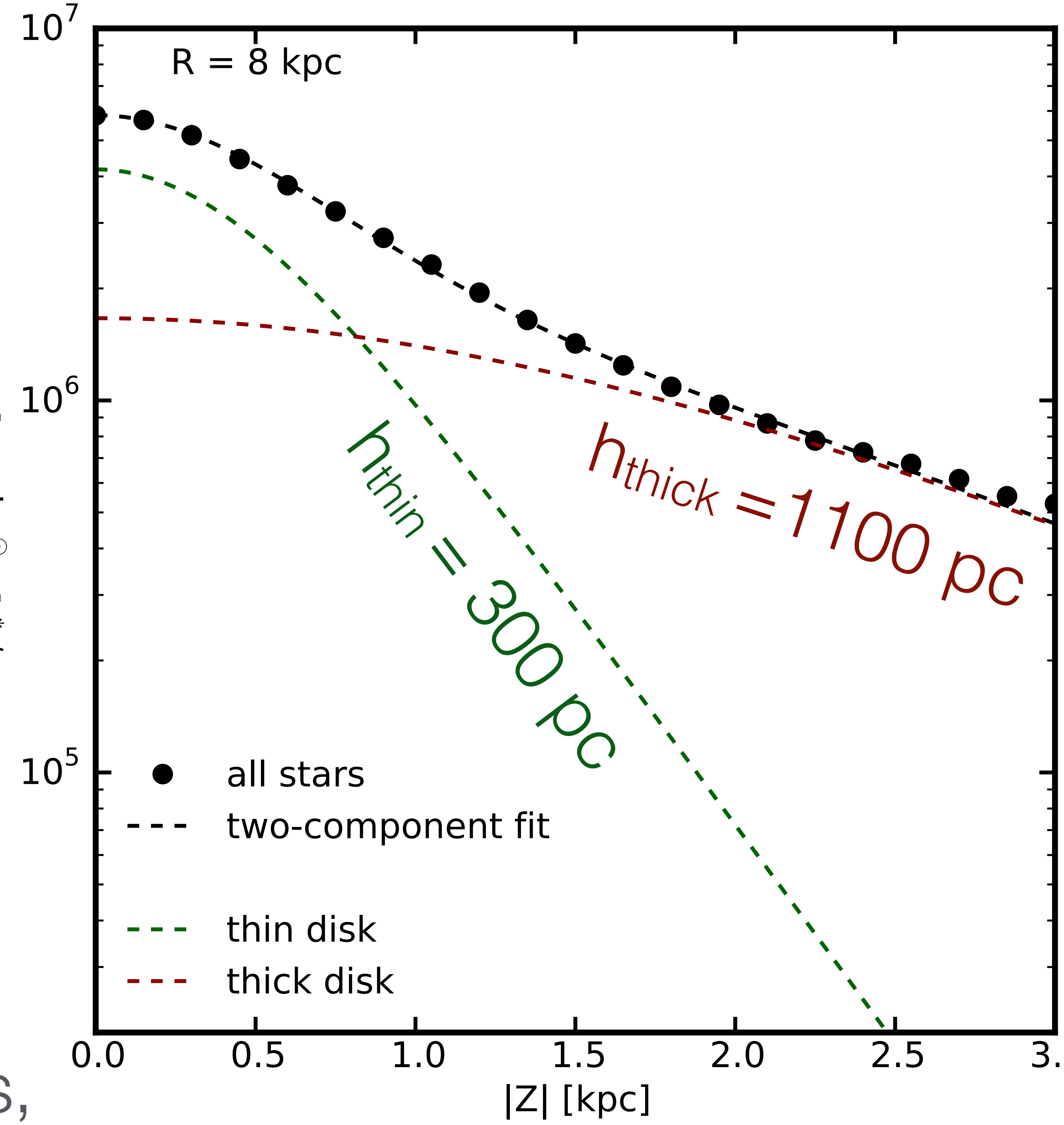
successful formation of ‘thin’ and ‘thick’ stellar disk similar to Milky Way





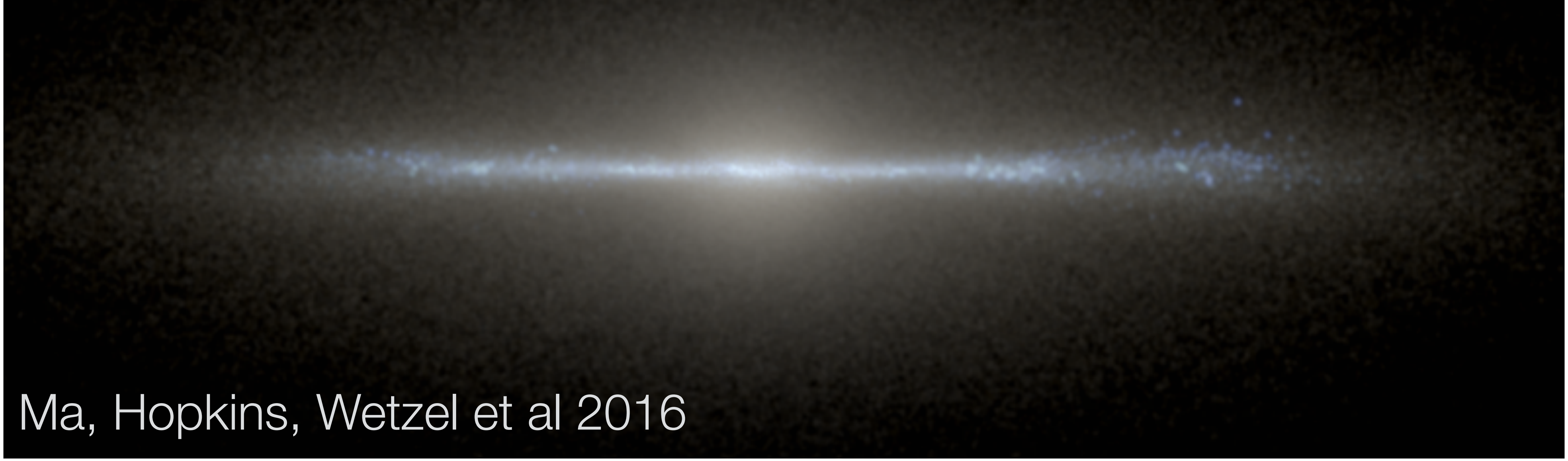
Xiangcheng Ma, Hopkins, Wetzel et al 2016

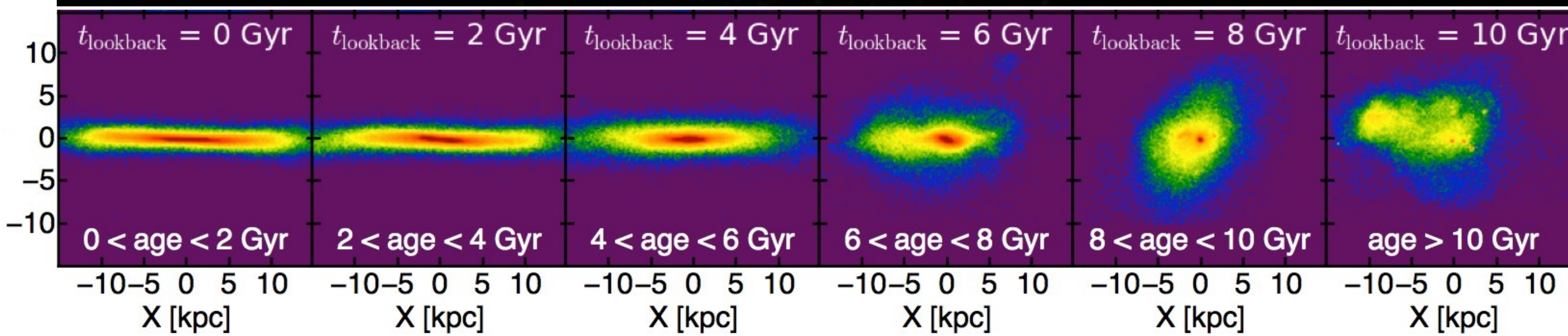
stellar density



vertical height

thick —> thin disk formation



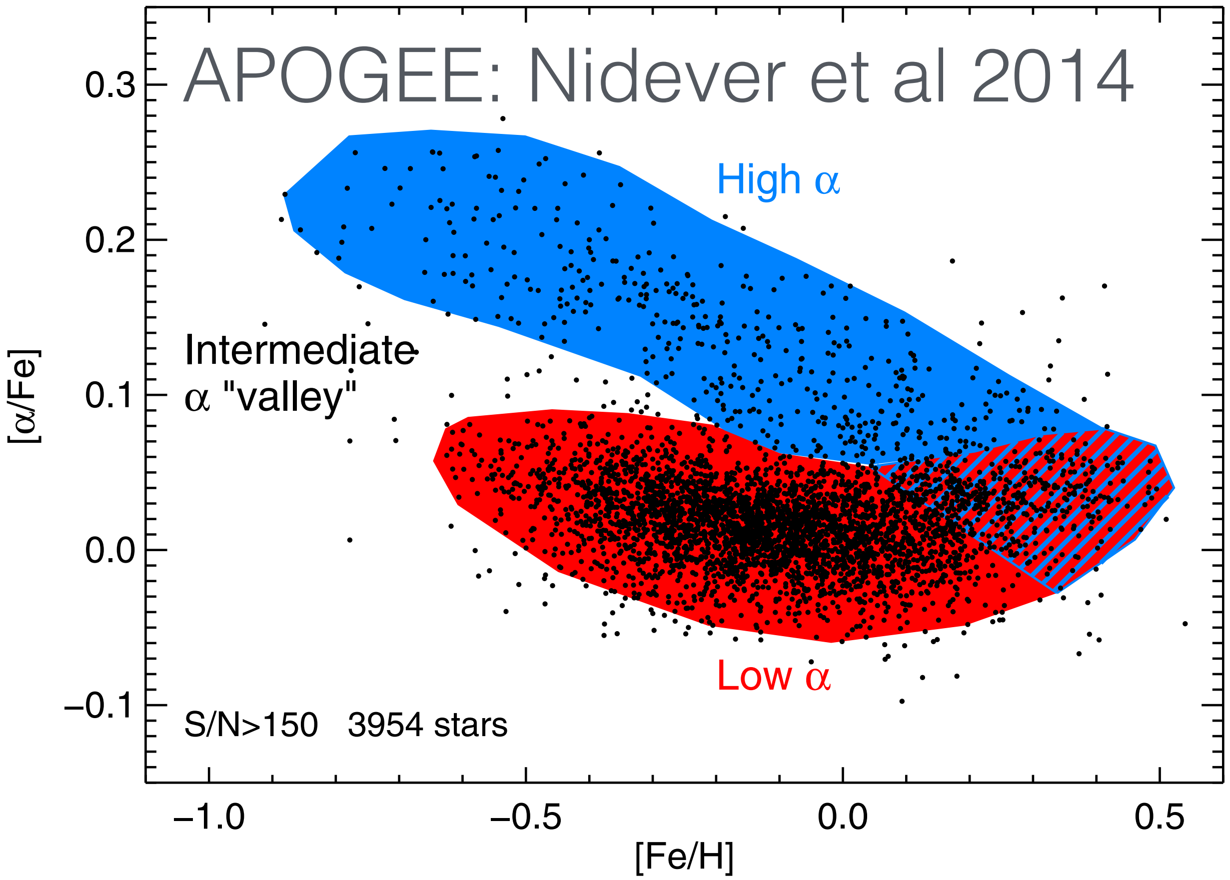


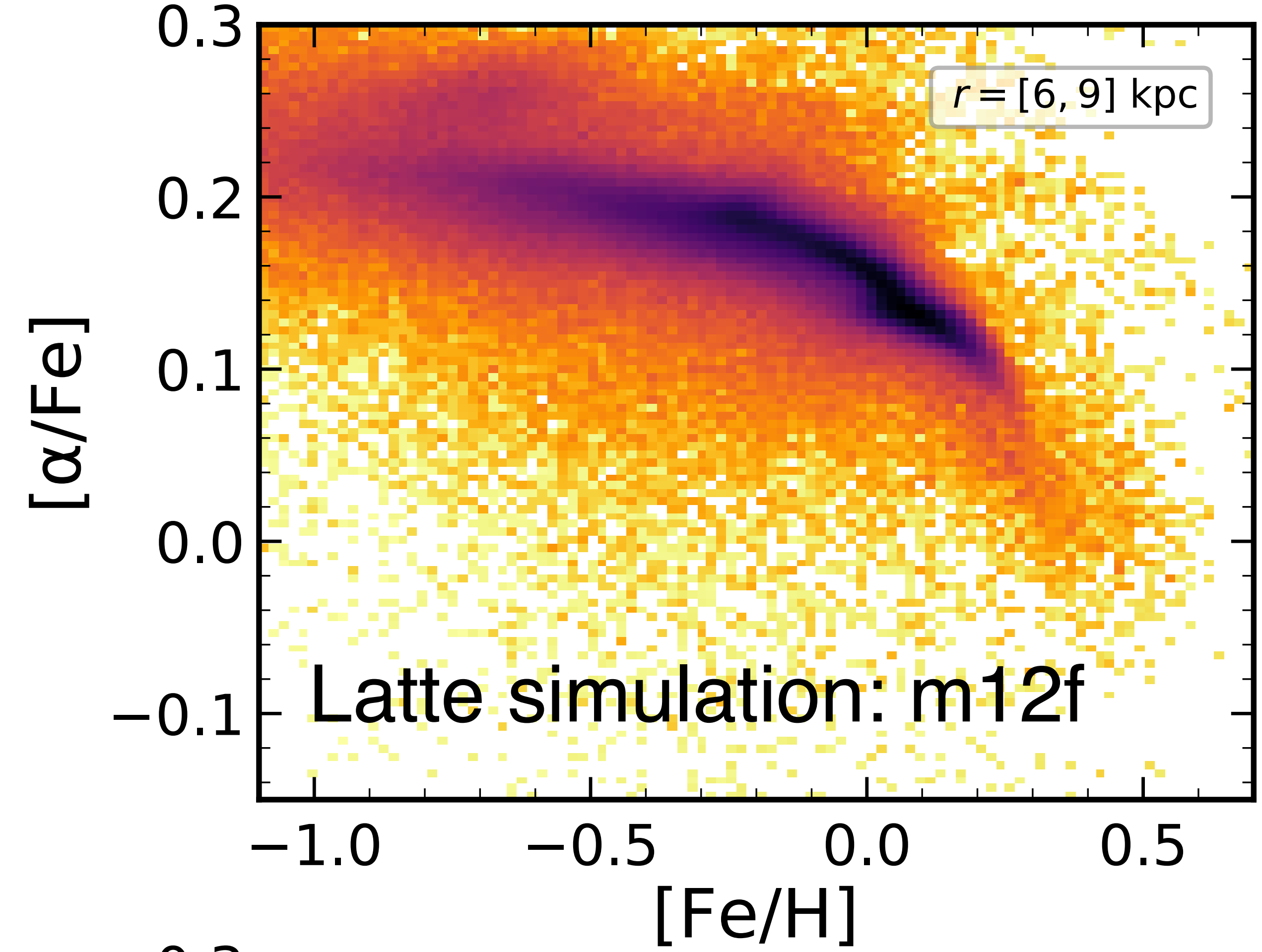
radial evolution: inside —> out

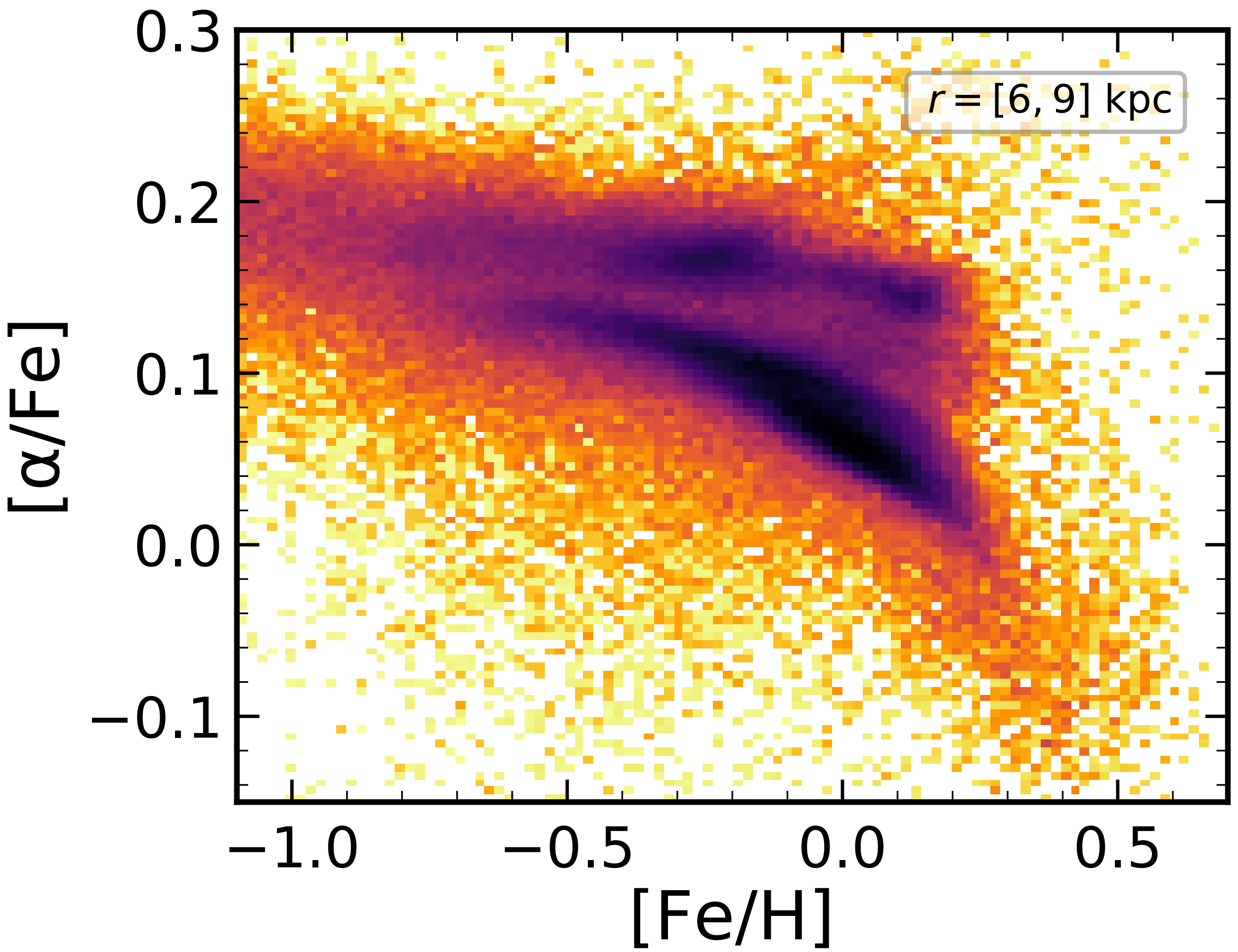
vertical evolution: upside —> down

also Brook et al 2004, 2012, Stinson et al 2013, Bird et al 2013, Agertz & Kravtsov 2016, etc

ELEMENTAL ABUNDANCE PATTERNS IN STELLAR DISK


APOGEE: Nidever et al 2014
High α
Intermediate α "valley"
Low α
S/N>150 3954 stars
[α/Fe]
[Fe/H]
0.3
0.2
0.1
0.0
−0.1
−1.0
−0.5
0.0
0.5


r = [6, 9] kpc
Latte simulation: m12f
[α/Fe]
[Fe/H]
0.3
0.2
0.1
0.0
−0.1
−1.0
−0.5
0.0
0.5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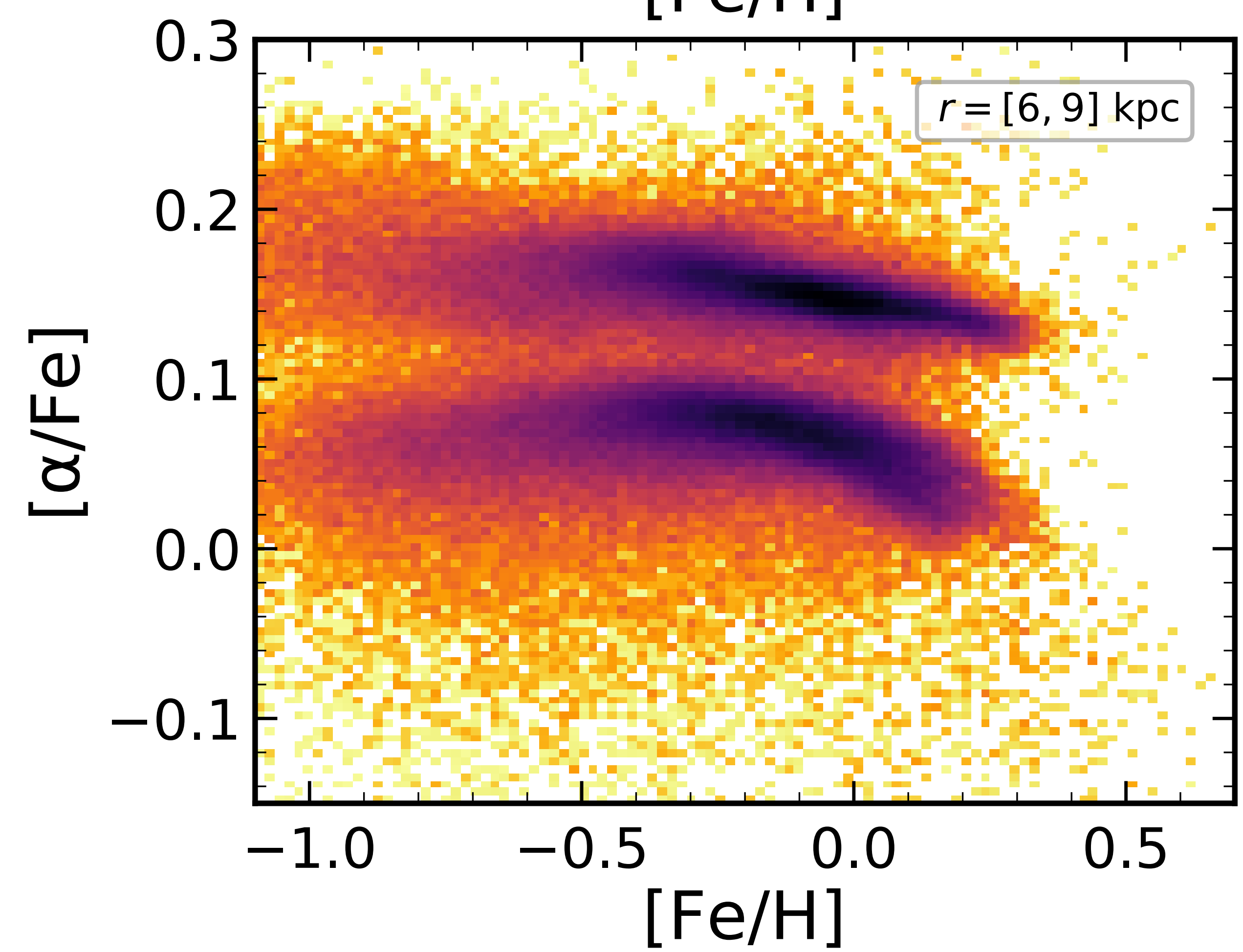
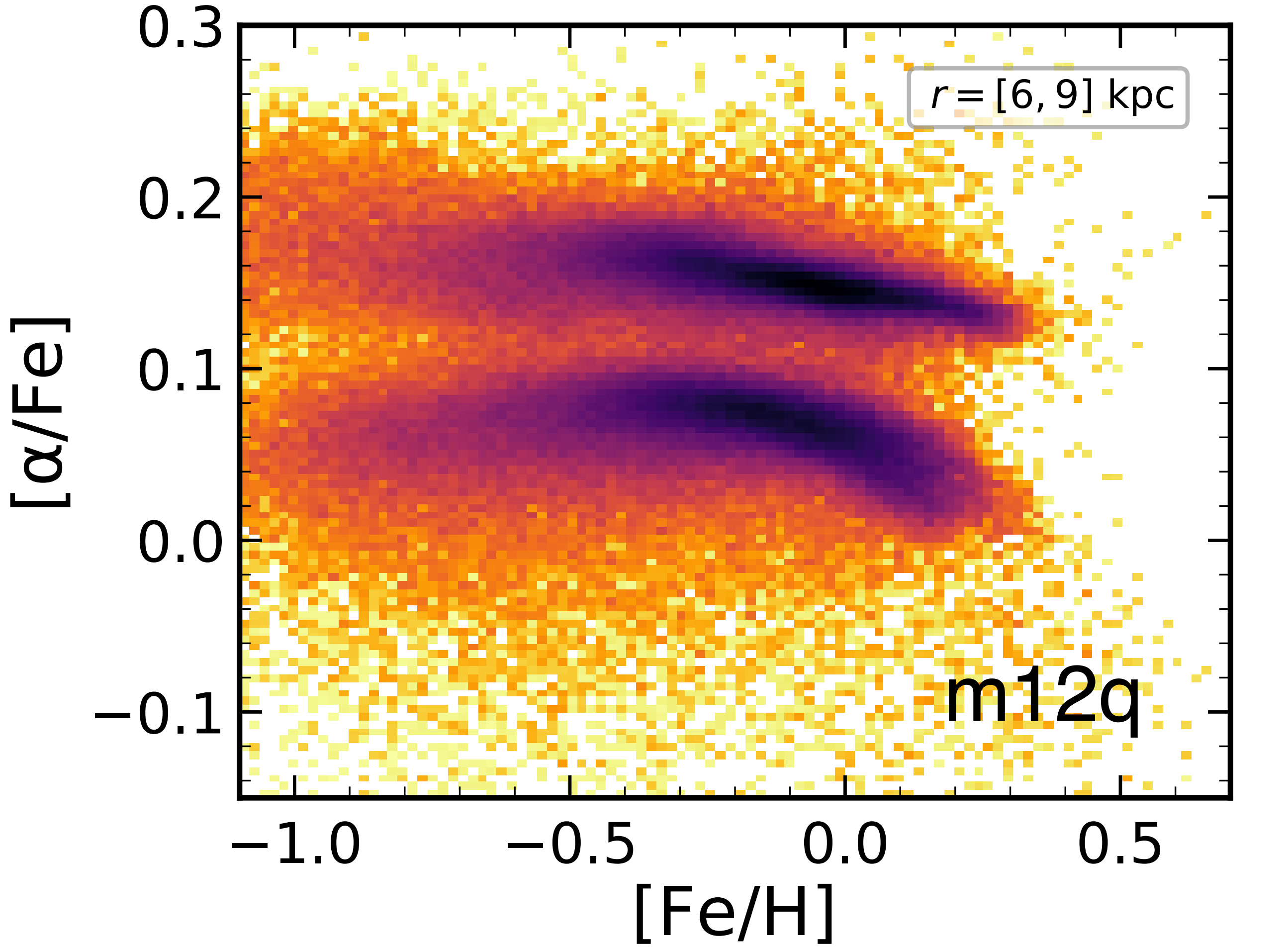
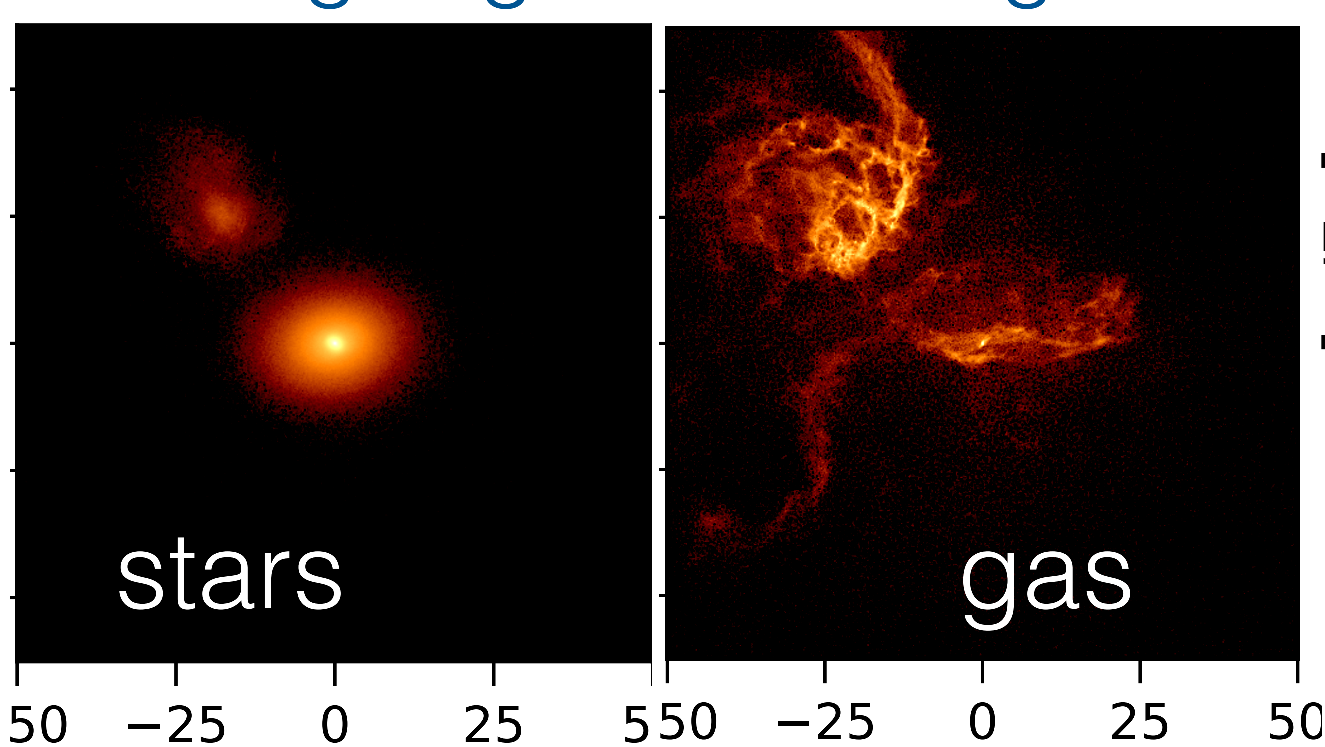
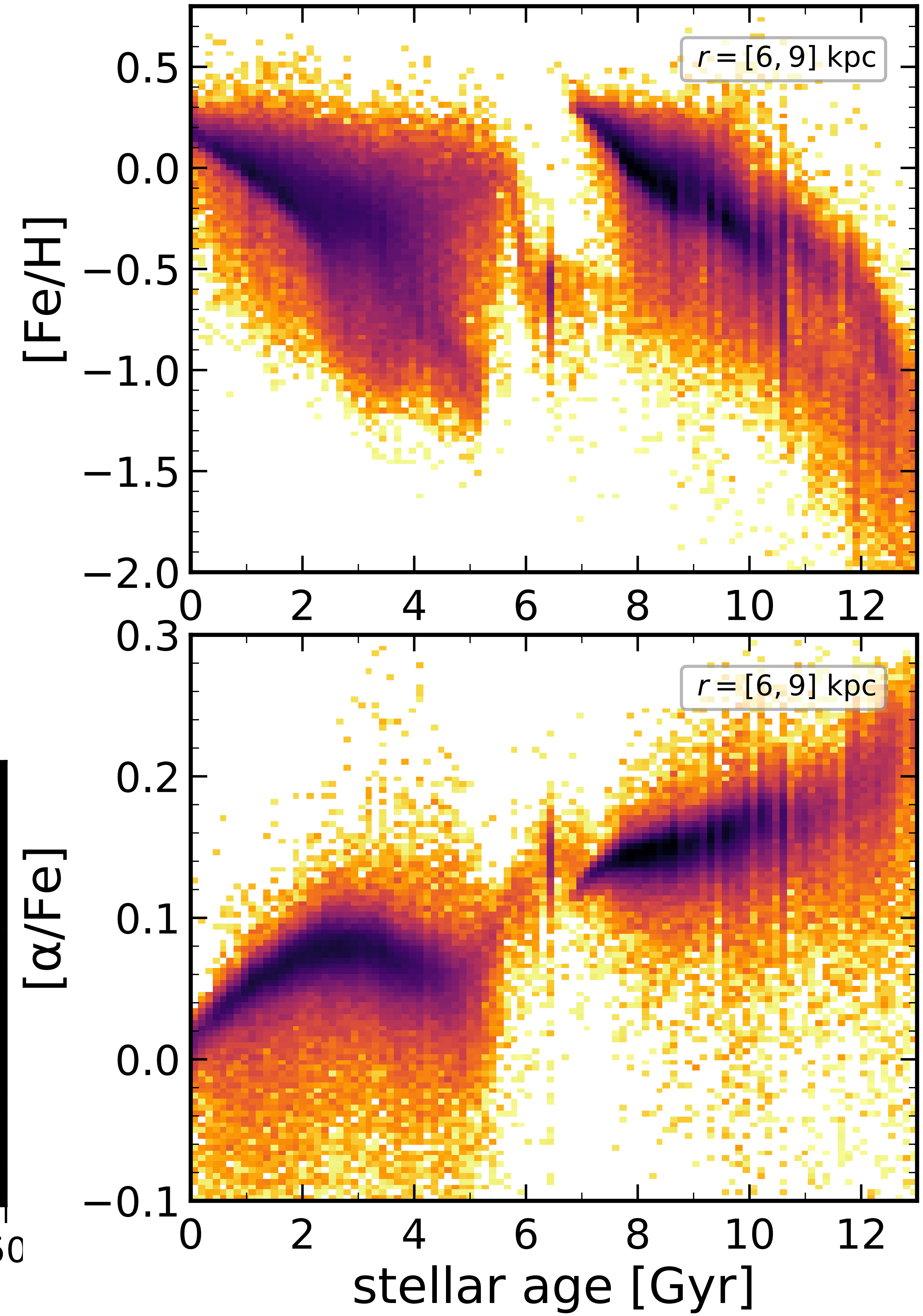
0.3
0.2
0.1
0.0
−0.1
−1.0
−0.5
0.0
0.5

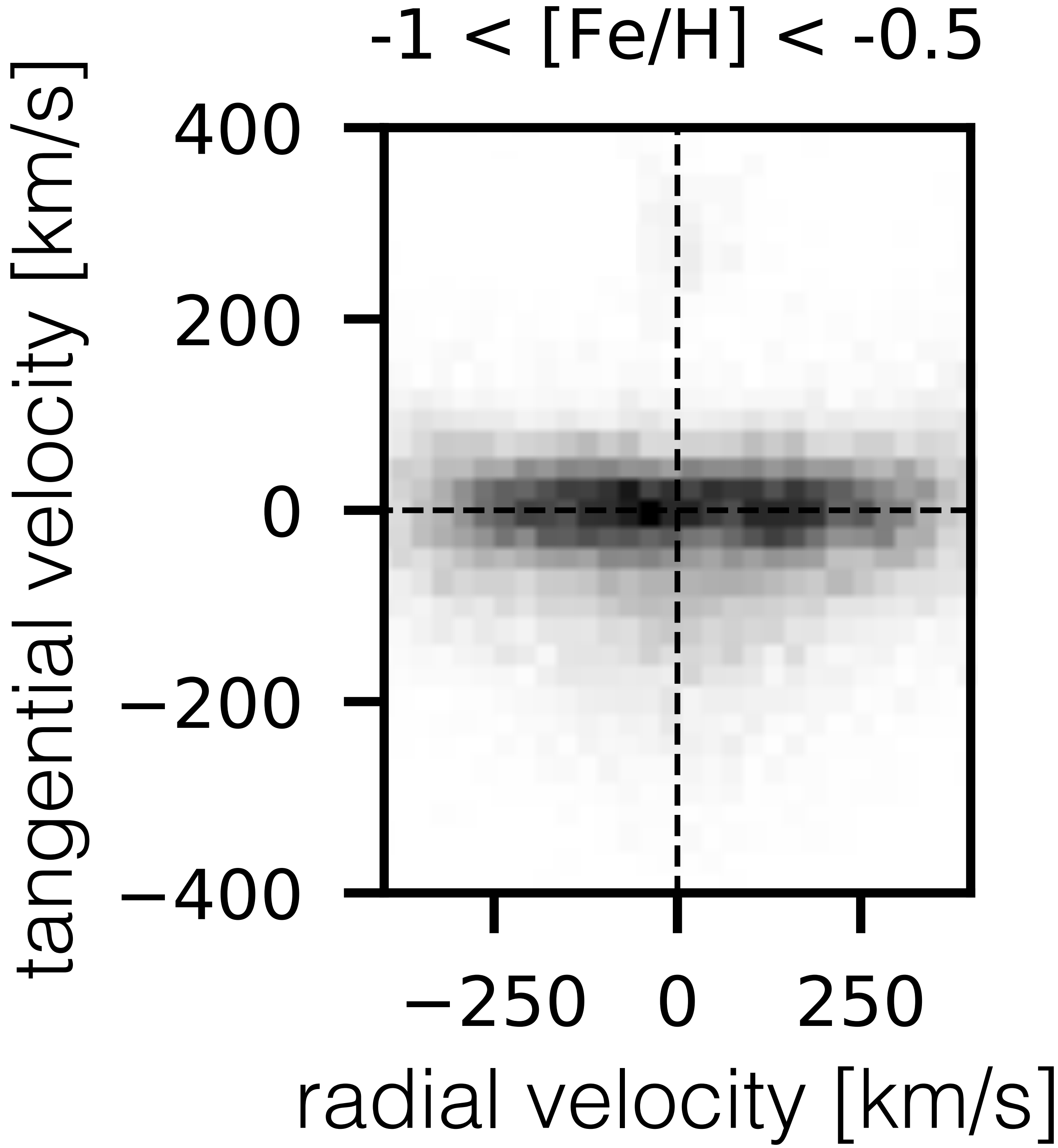

r = [6, 9] kpc
[α/Fe]
[Fe/H]
0.3
0.2
0.1
0.0
−0.1
−1.0
−0.5
0.0
0.5

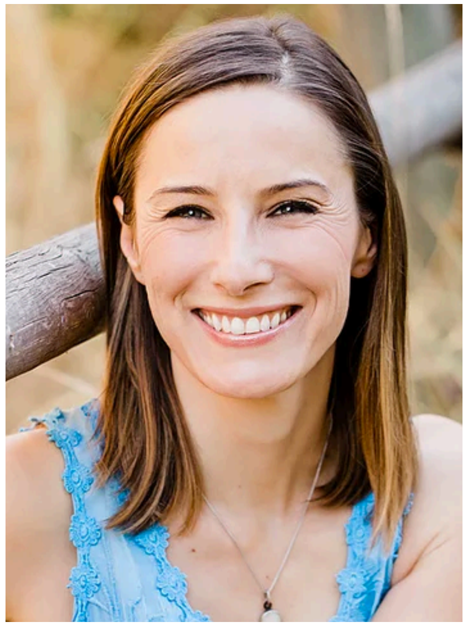


origin: gas-rich merger



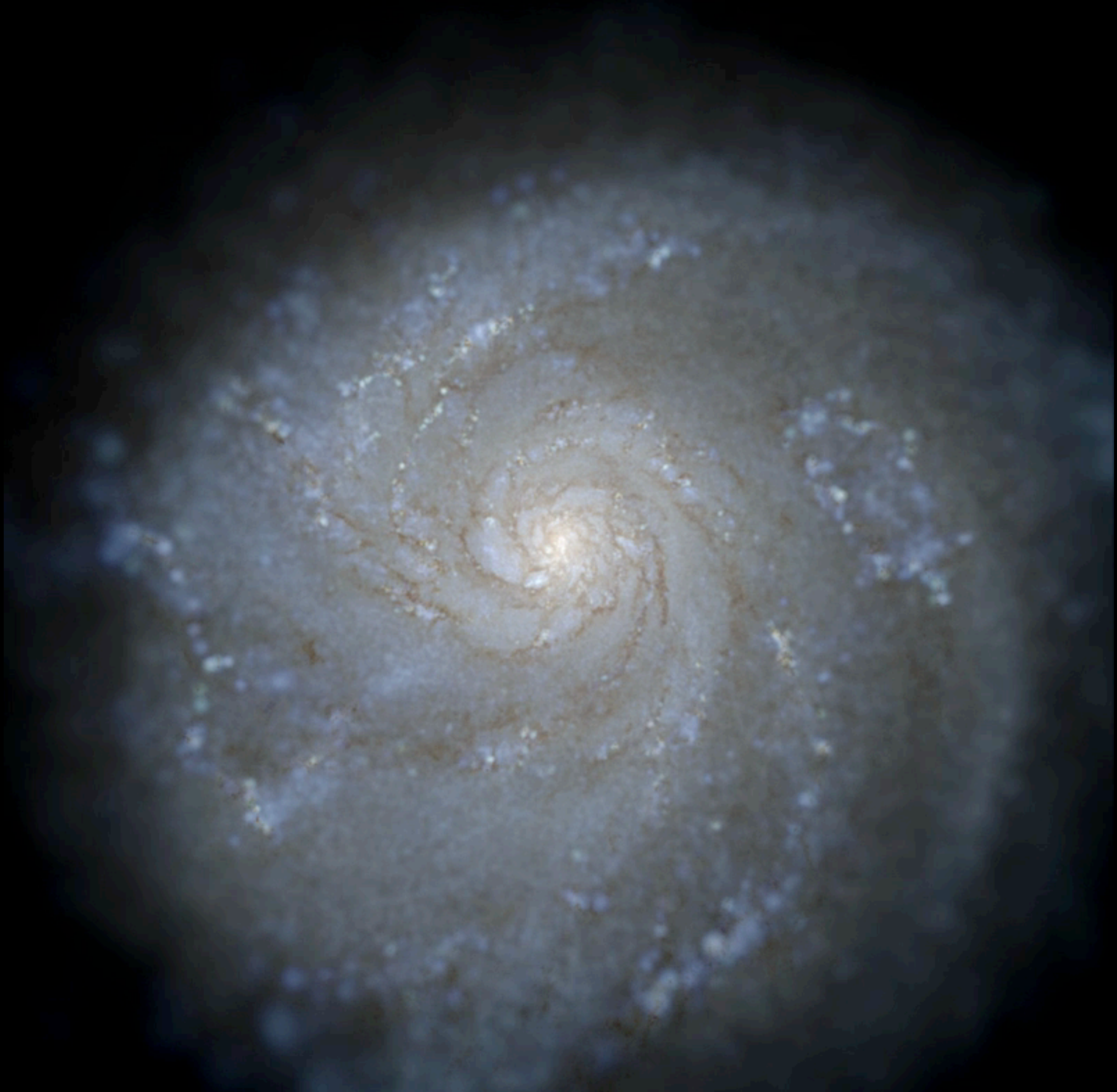




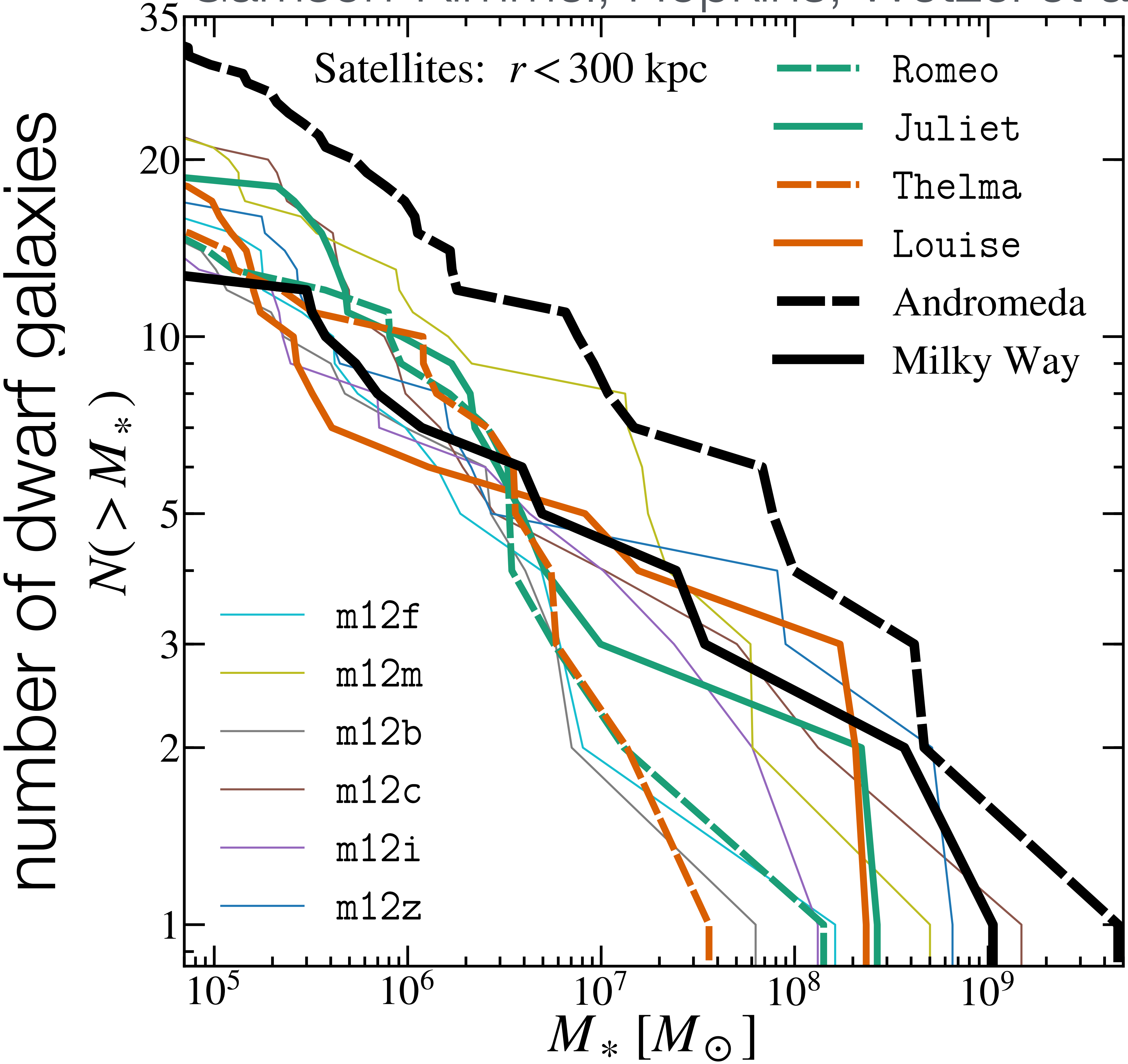


Loebman, Wetzel et al in prep

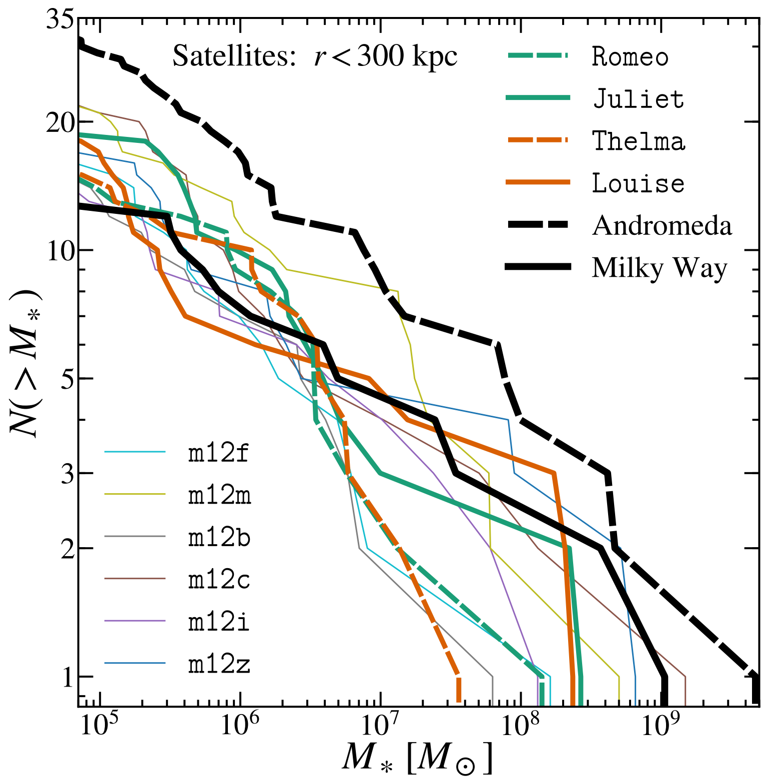
this merger event becomes analogue to Gaia ‘sausage / Enceladus / enchilada’



Garrison-Kimmel, Hopkins, Wetzel et al 2019

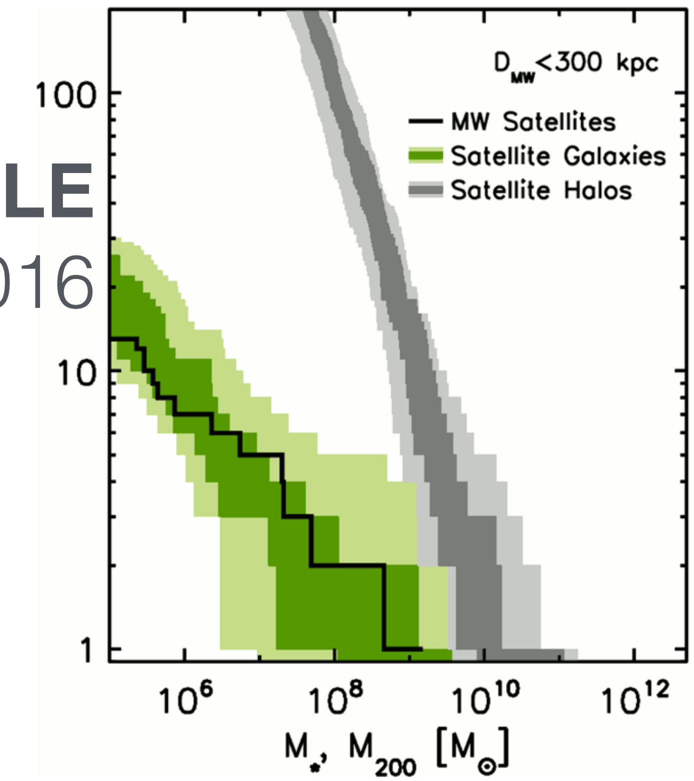


multiple cosmological zoom-in baryonic simulations now form realistic populations of satellites

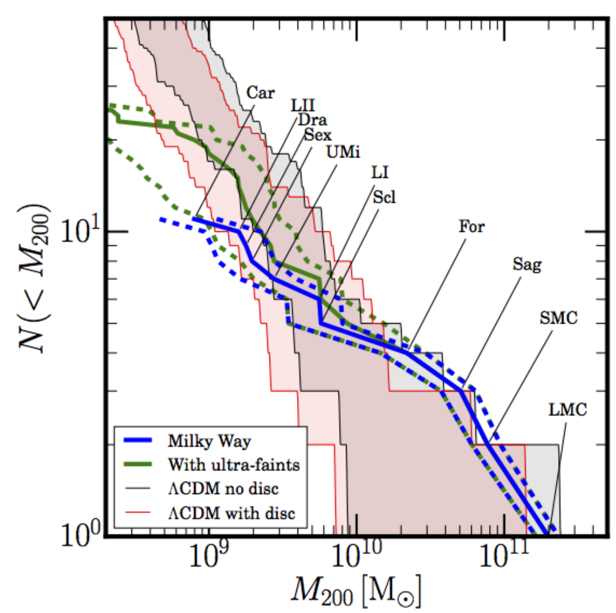


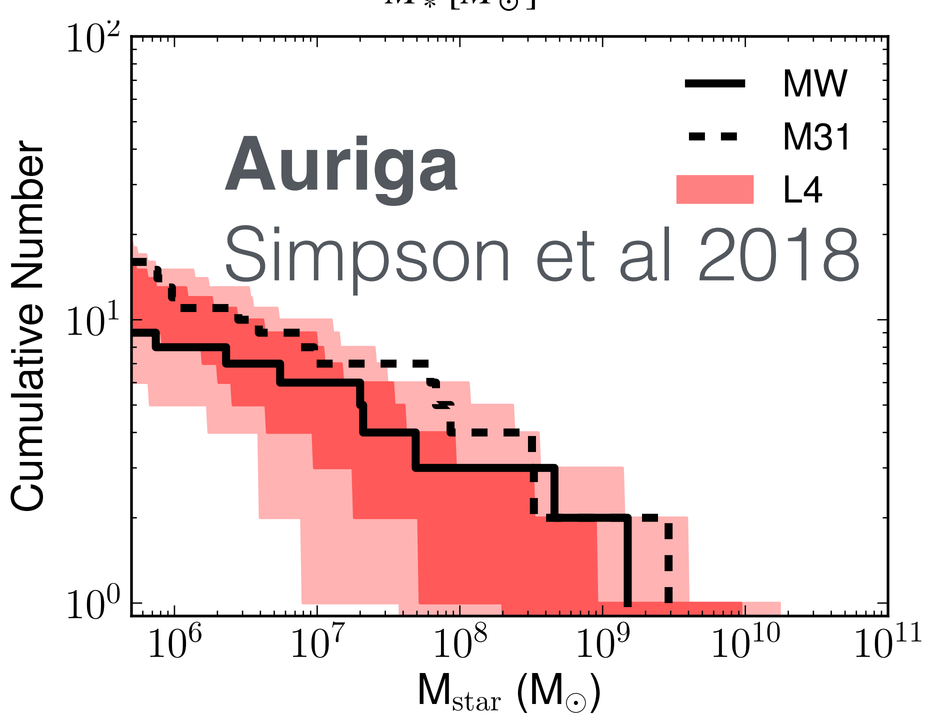
FIRE
Garrison-Kimmel et al 2019

APOSTLE
Sawala et al 2016

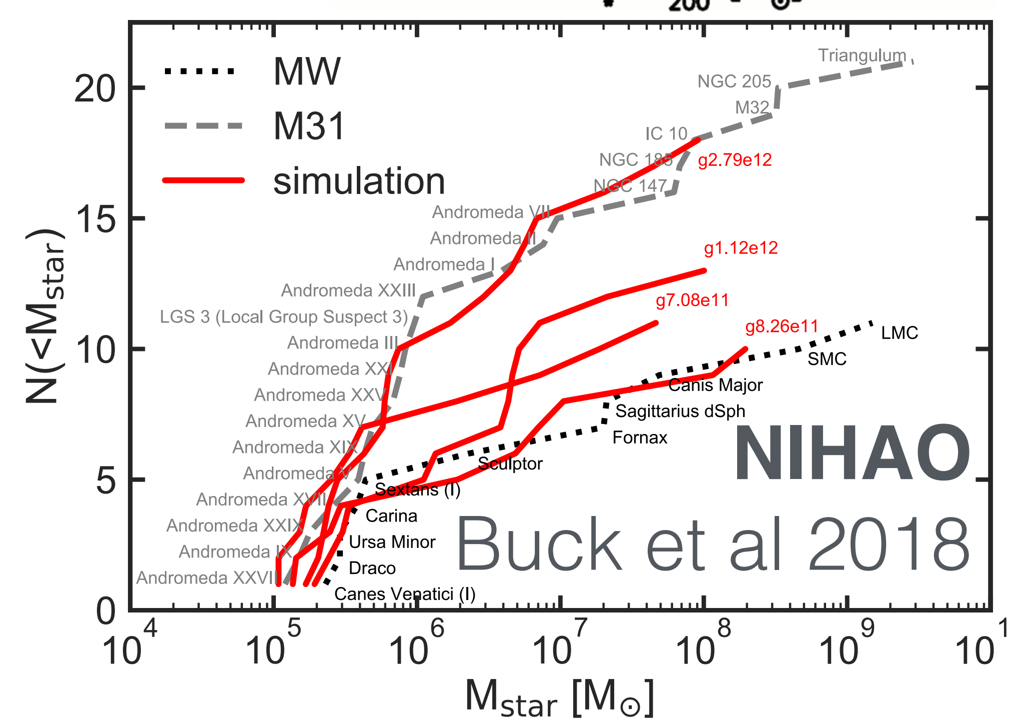


Read & Erkal 2018





Auriga
Simpson et al 2018



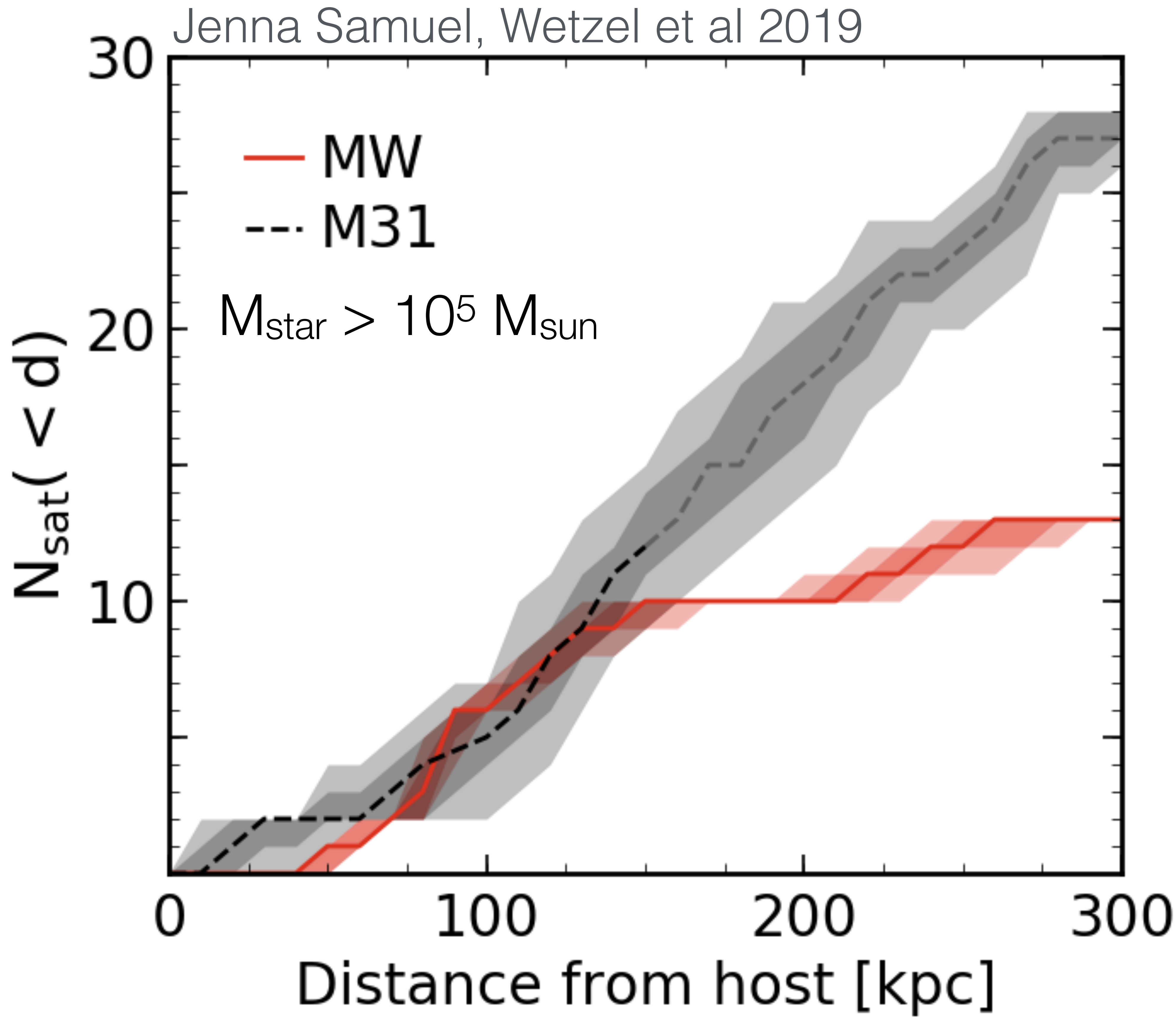
NIHAO
Buck et al 2018

MORE RIGOROUS TEST

WHAT ABOUT SPATIAL DISTRIBUTION OF SATELLITES?

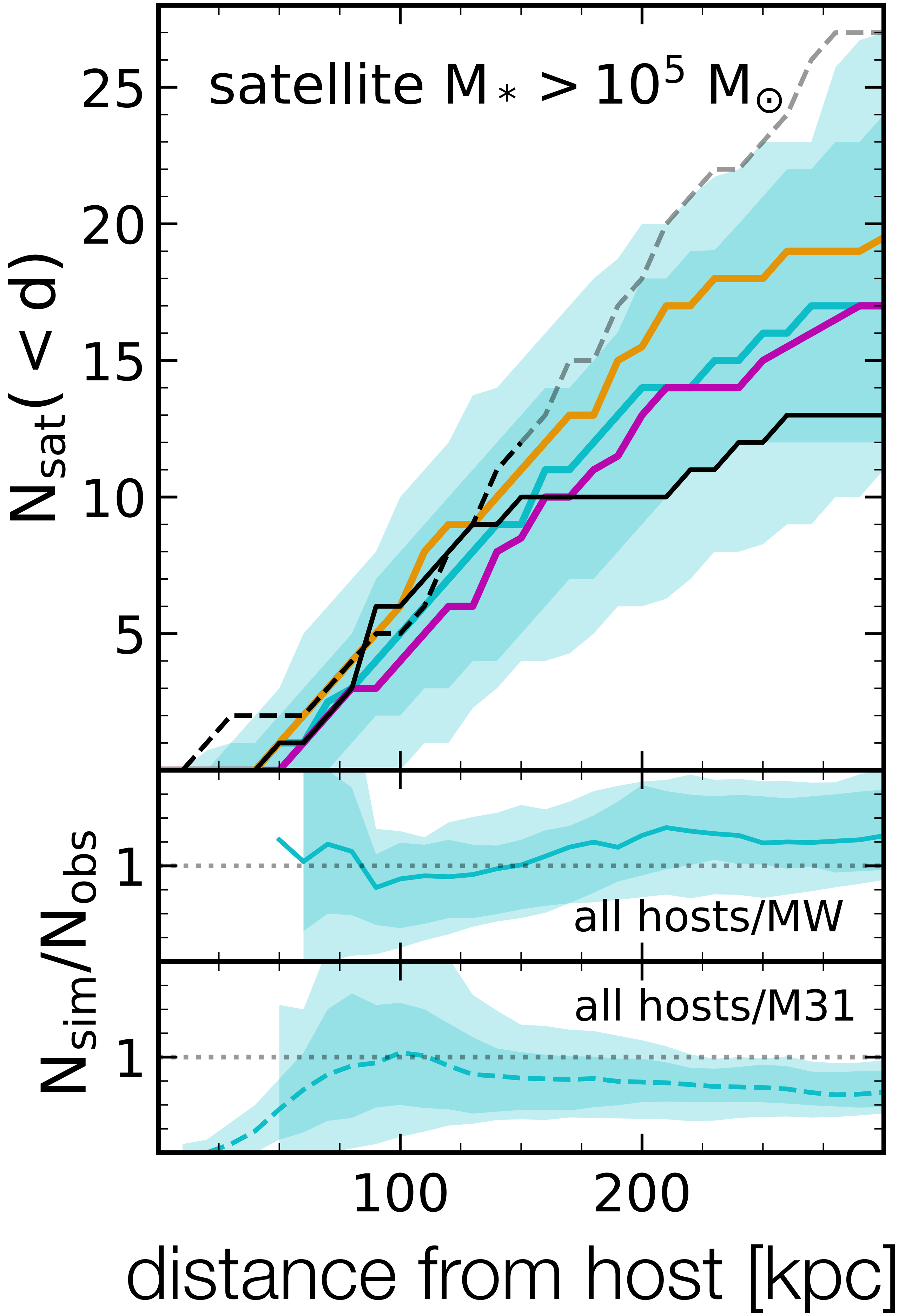
Jenna Samuel
(grad student @ UC Davis)

observed distances of satellite dwarf galaxies



FIRE simulations broadly agree with MW + M31

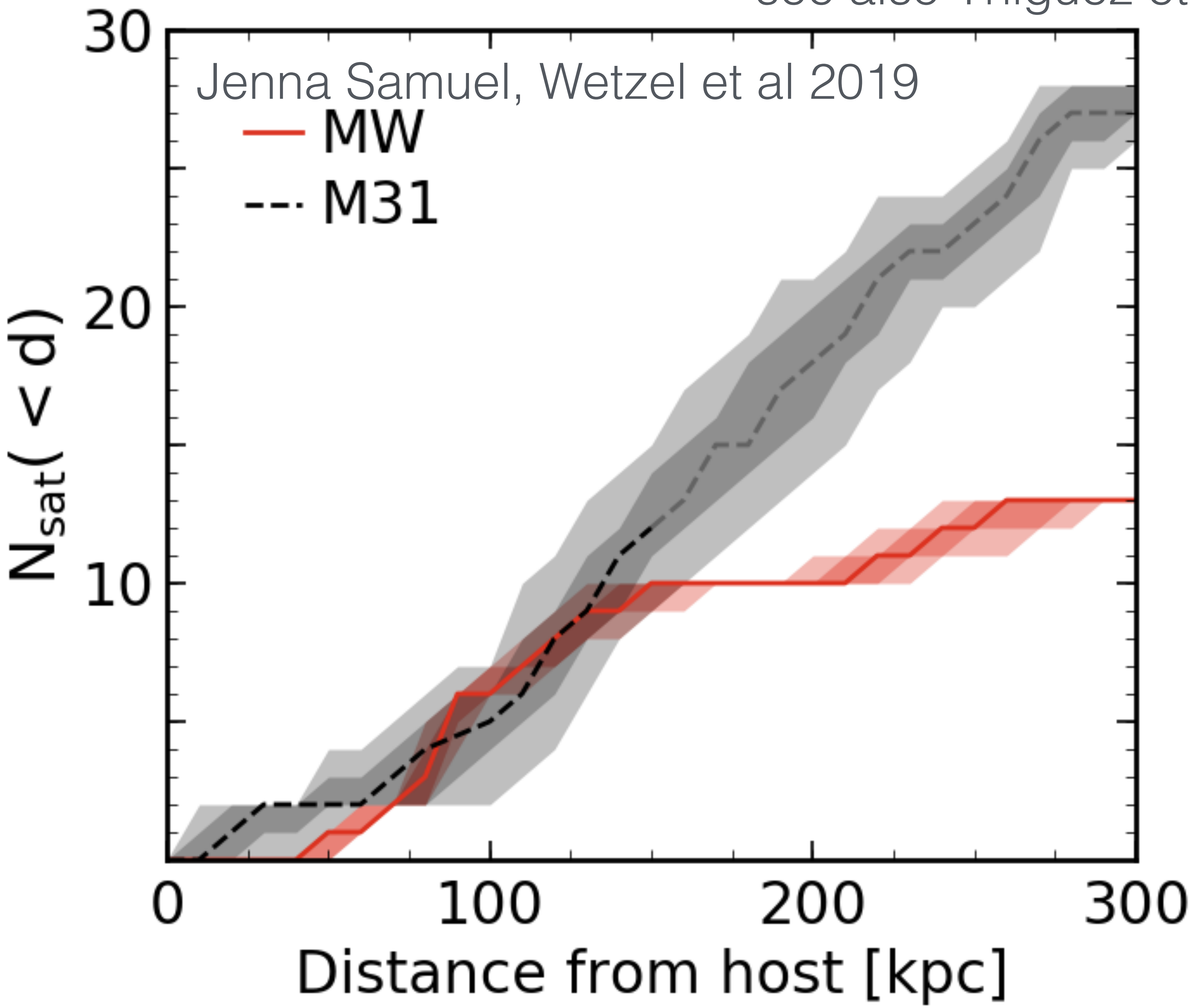
numerically well resolved (even at d <~ 50 kpc)



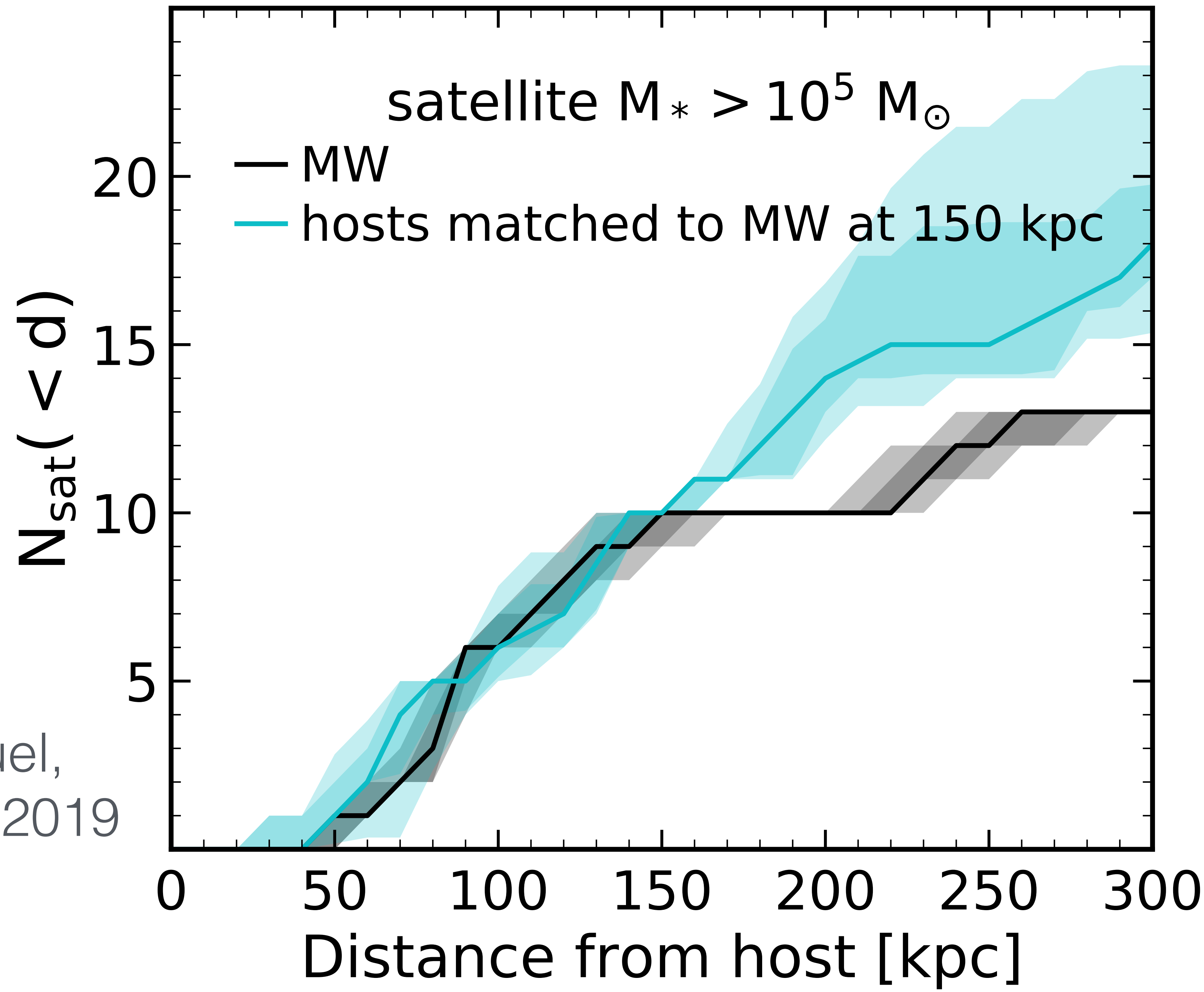
Jenna Samuel, Wetzel et al 2019

MW satellites are unusually (?) concentrated

see also Yniguez et al 2014



MW satellites are unusually (?) concentrated



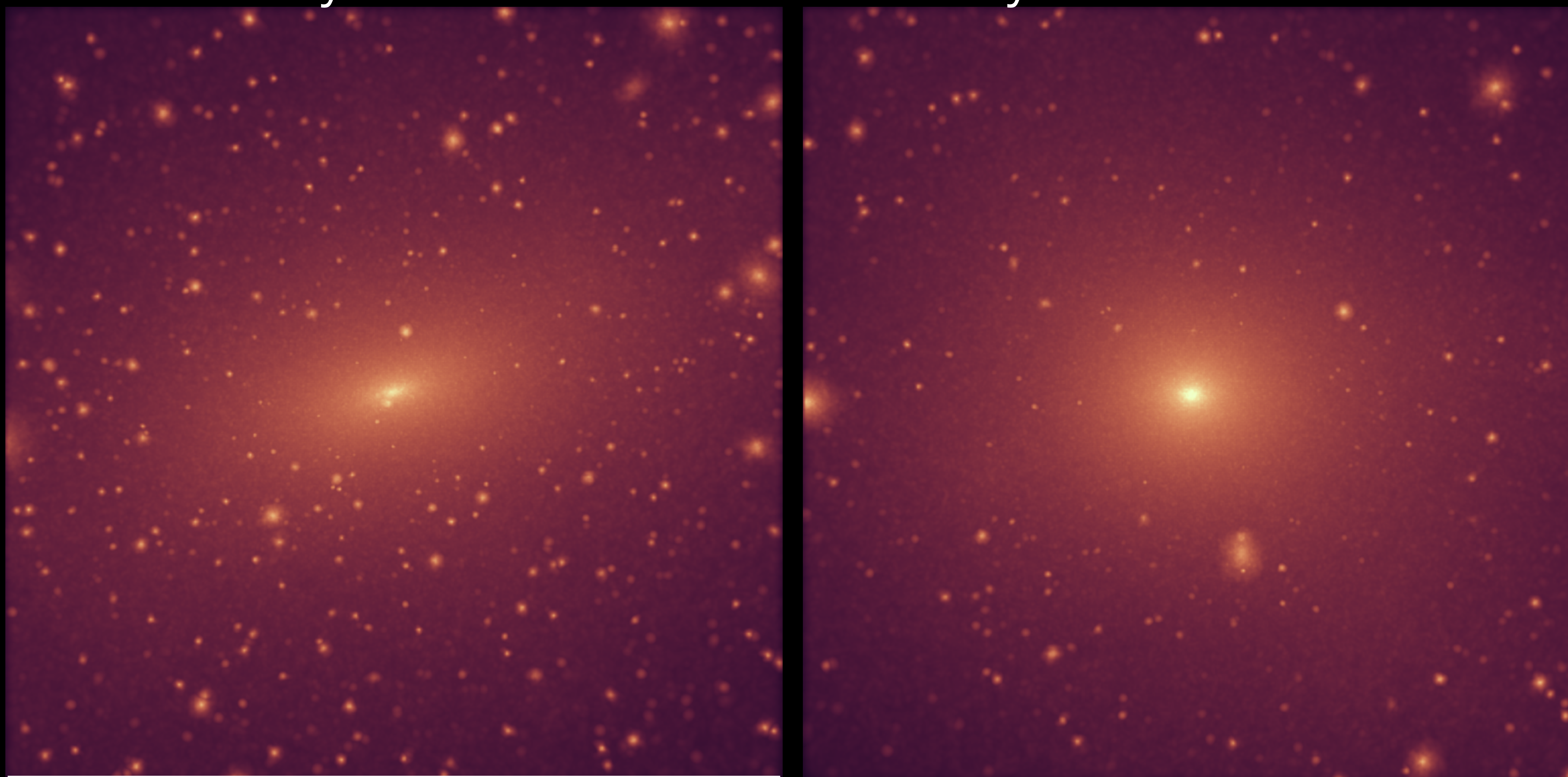
Jenna Samuel, Wetzel et al 2019

- no simulated host (even across time) is as concentrated as MW
- predict 2 (min) 4 (med) more ‘classical’ dwarf galaxies around MW

images of dark matter in

DM-only simulation

baryonic simulation



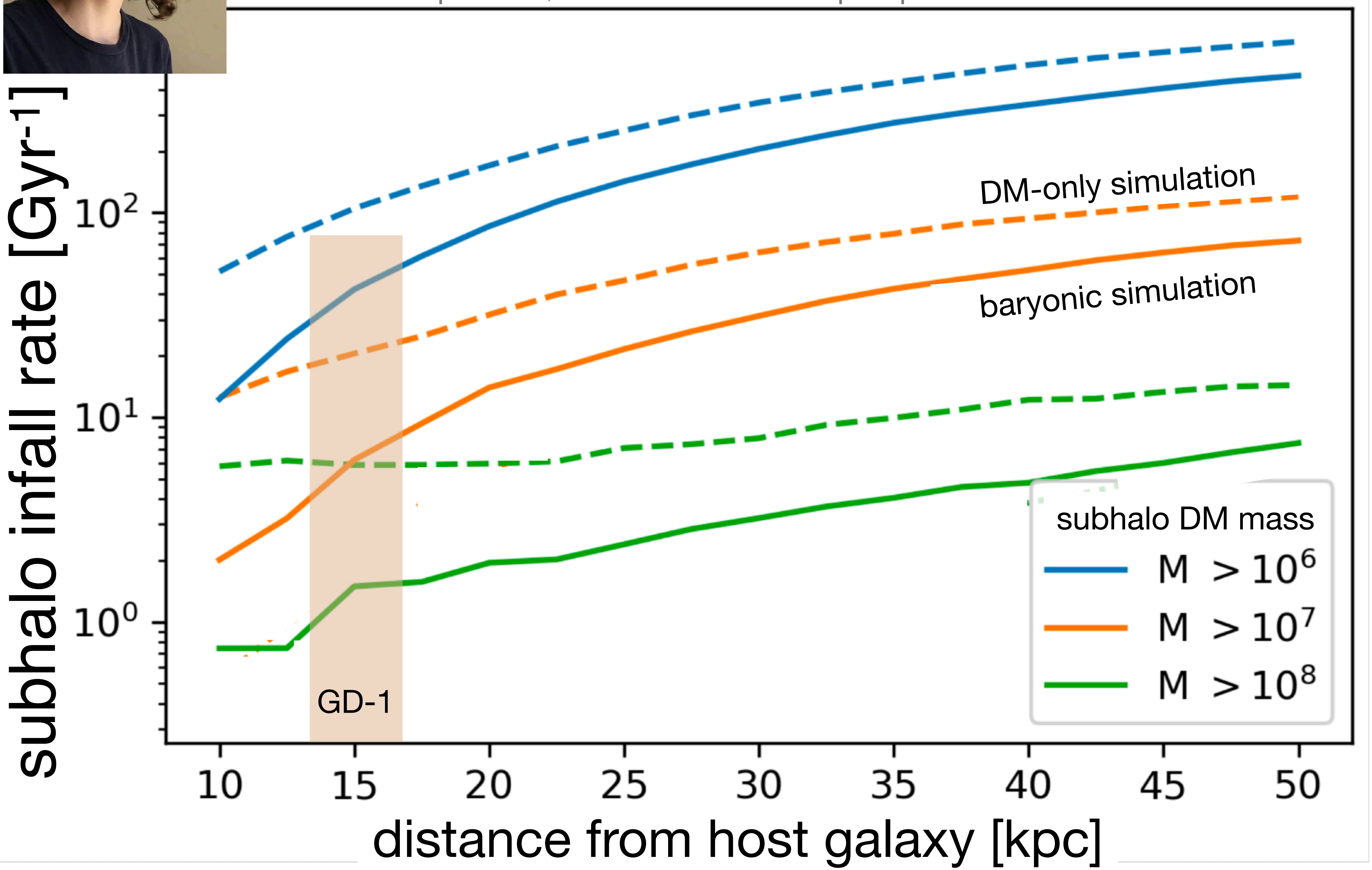
100 kpc

Garrison-Kimmel, Wetzel et al 2017

central galaxy destroys subhalos

predicting DM subhalo infall rates near MW

Sierra Chapman, Wetzel et al in prep



THE MILKY WAY ON