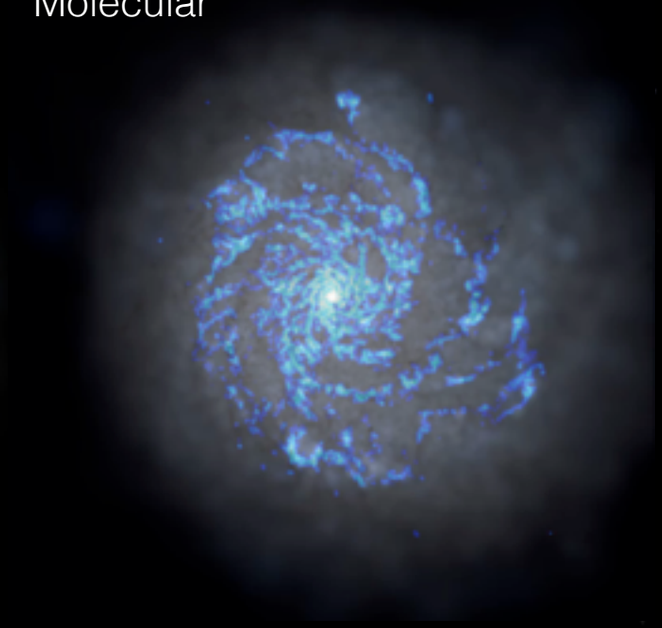
FIRE & the Baryon Cycle

Observed Starlight

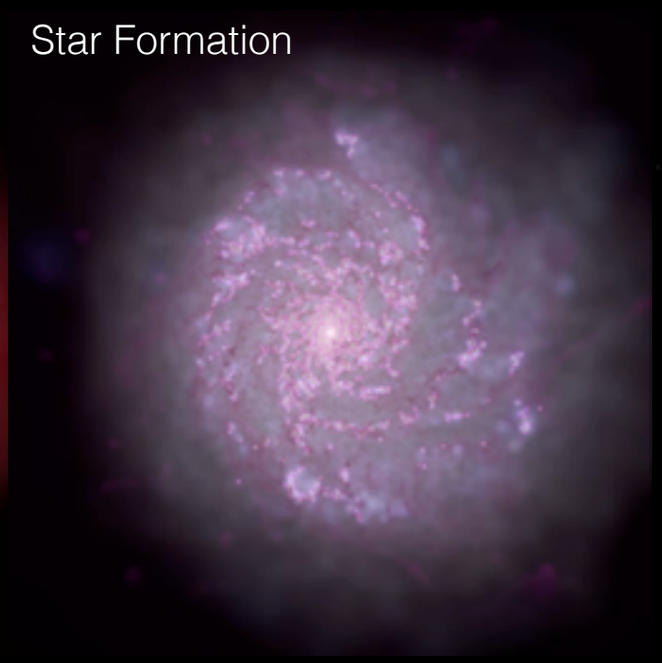
Molecular



Galaxy Merger

X-Rays

Star Formation



Philip F. Hopkins & the FIRE Team

Caltech

~10^{10} pc

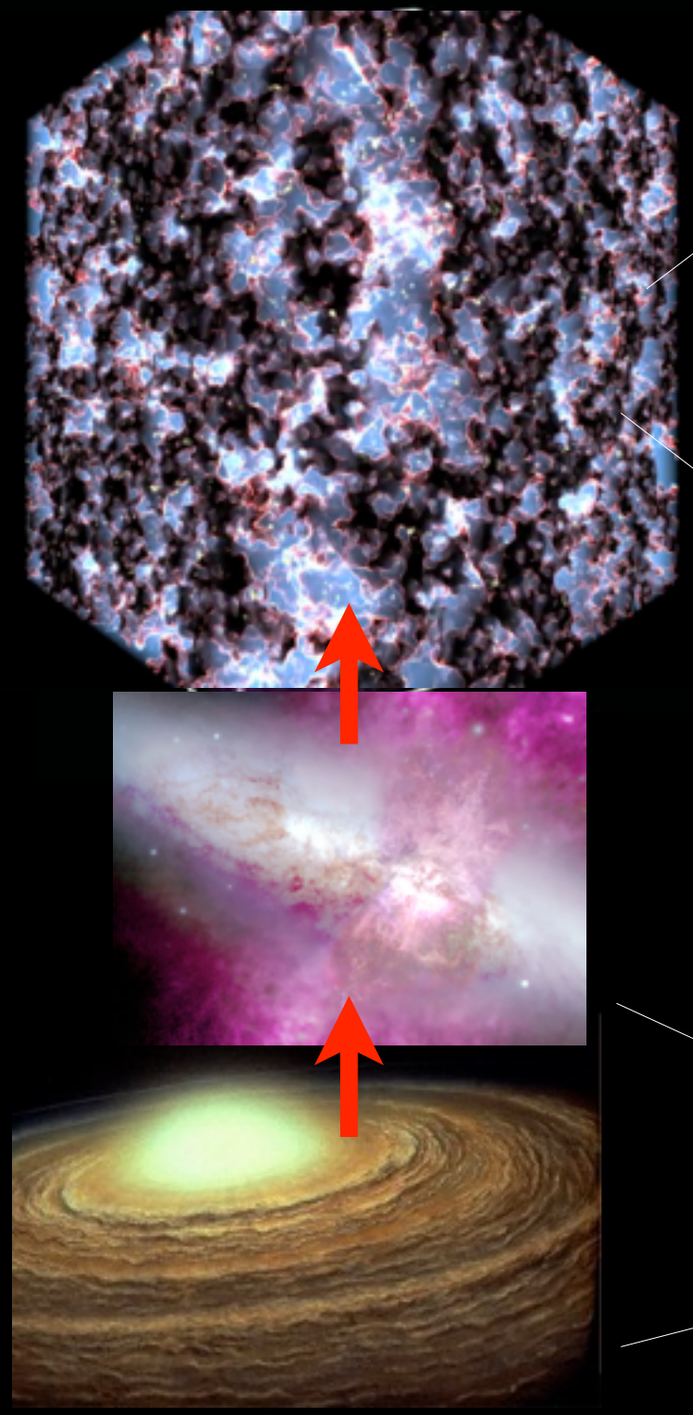
Hubble volume

~10^{7}-10^{8} pc

Clusters, Large-scale structure

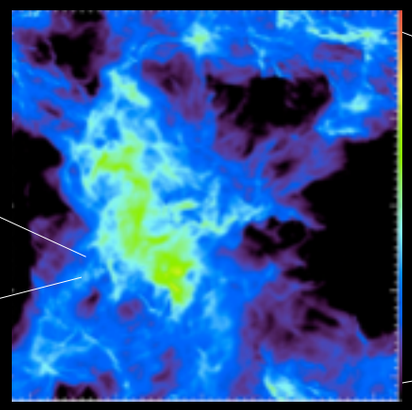
~10^{4-5} pc

Galaxy



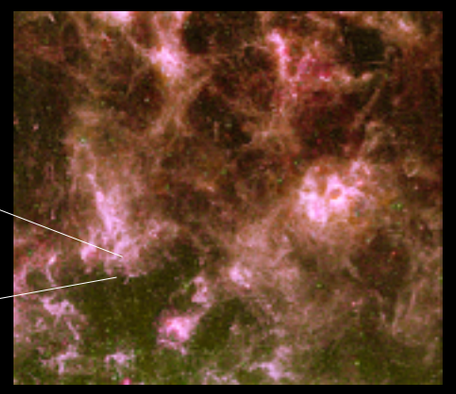
~10^{-5} pc

Stars, protostellar disks



~10^{-2}-10^{0} pc

Cores, clusters,
Supernovae blastwaves

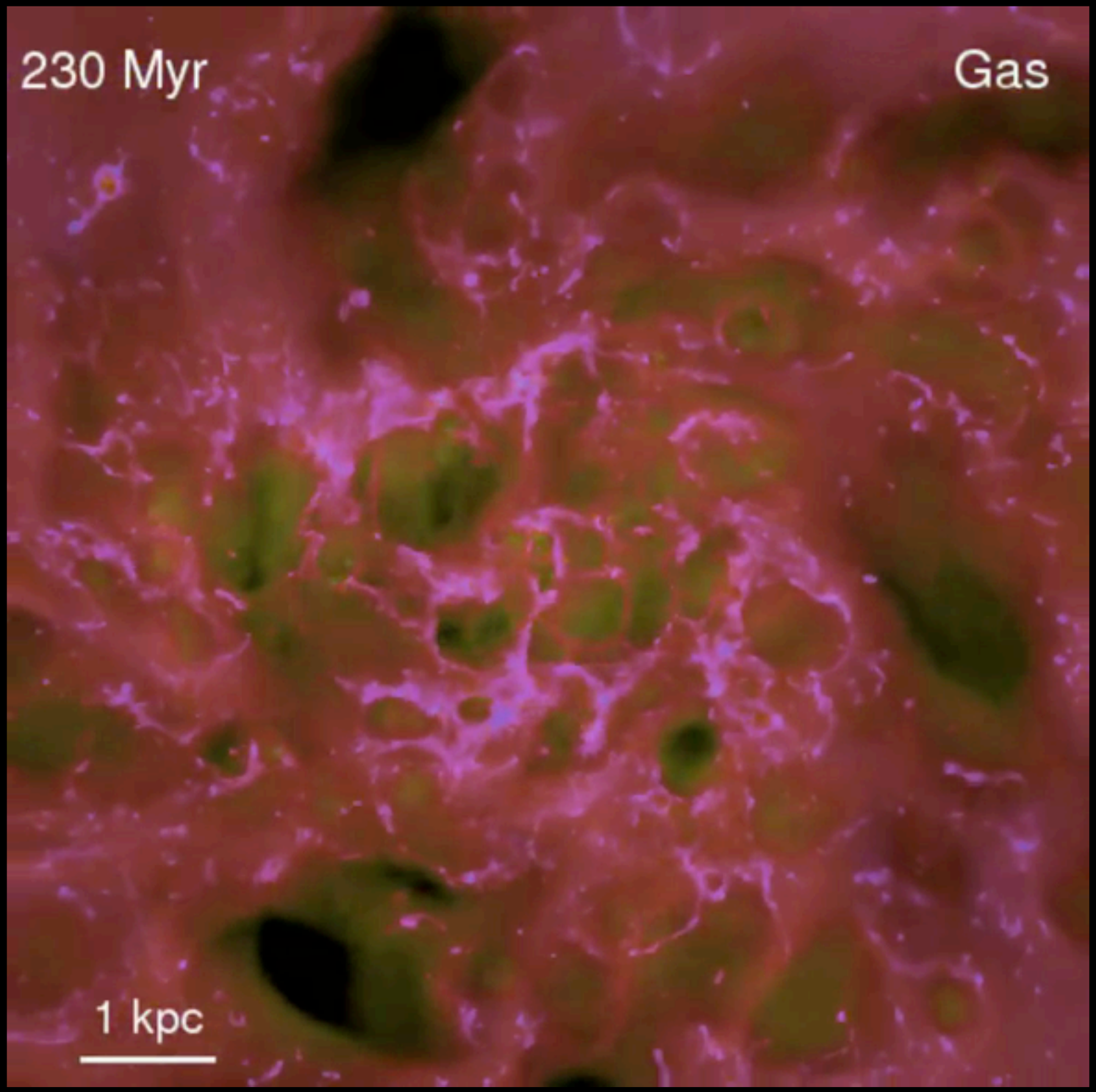


~10^{1}-10^{2} pc

Molecular clouds,
Star-Forming Regions

The FIRE Project

Feedback In Realistic Environments



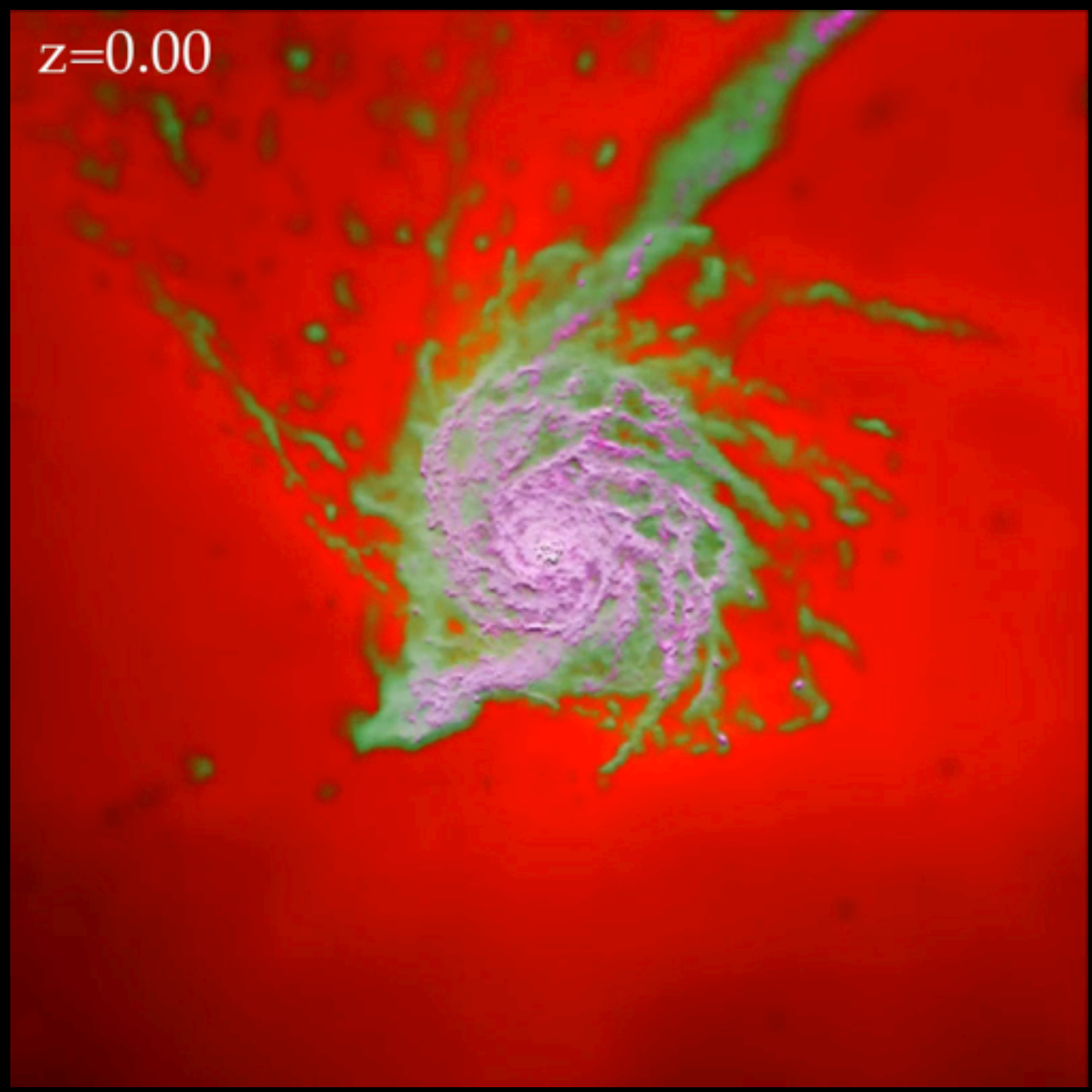
Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K

- **Feedback:**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)

- now with…
  - Magnetic fields
  - Anisotropic
    conduction & viscosity
  - Cosmic rays

www.tapir.caltech.edu/~phopkins



Stars (Hubble image):

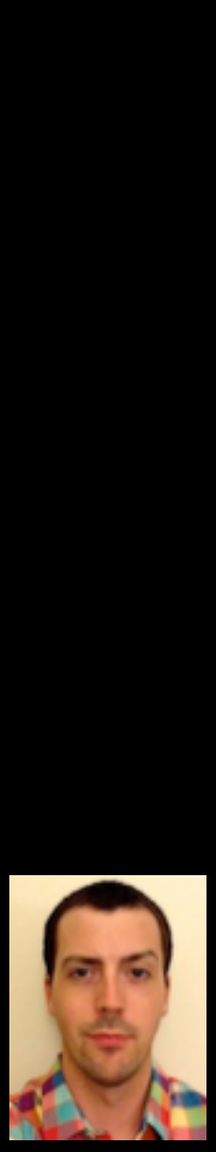
Blue: Young star clusters

Red: Dust extinction

Gas: Magenta: cold $(< 10^4\,K)$

Green: warm (ionized)

Red: hot $(> 10^6\,K)$

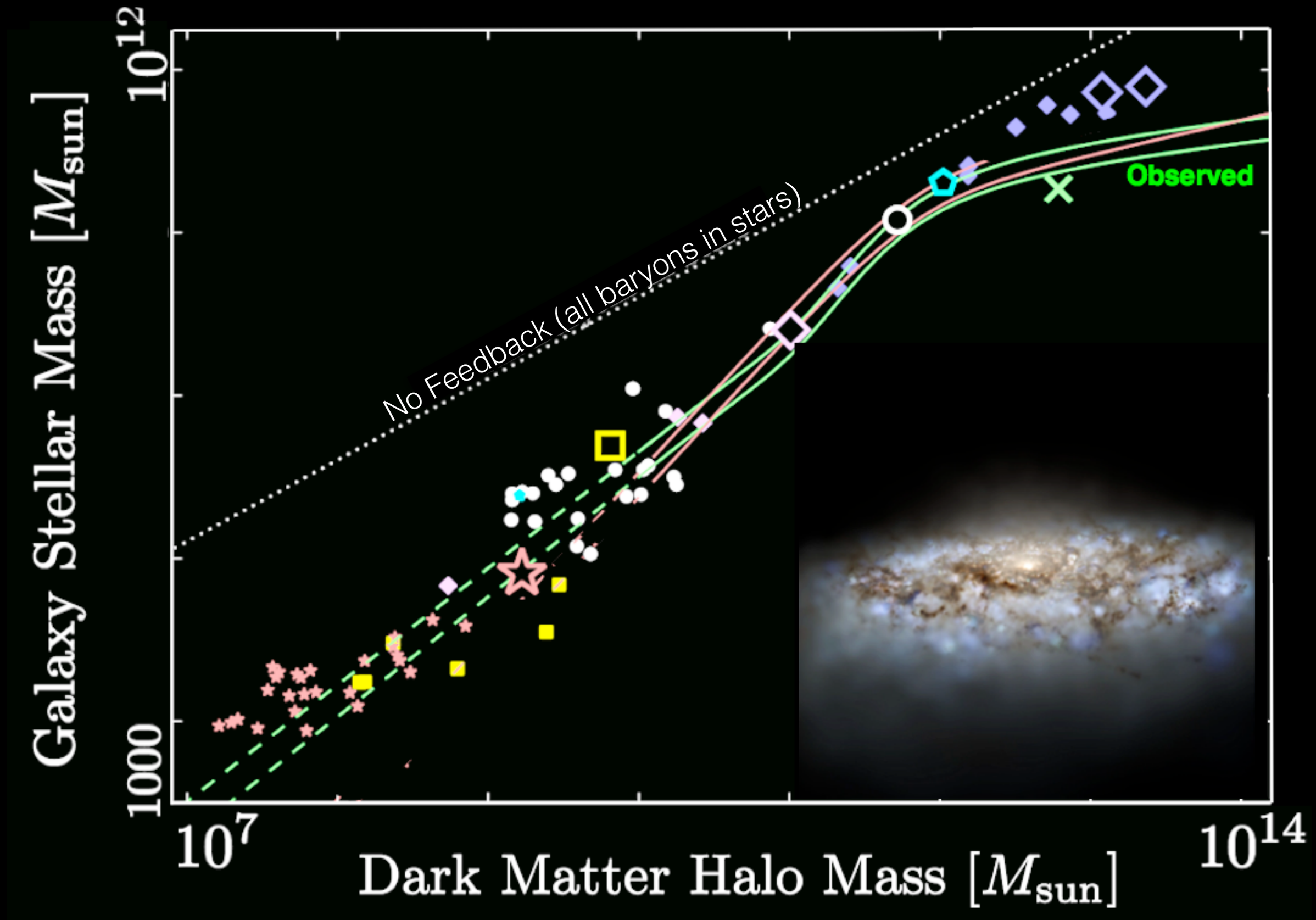


Andrew Wetzel
(arXiv:1602.05957)

This Works (More or Less) if You Resolve Key Scales

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)

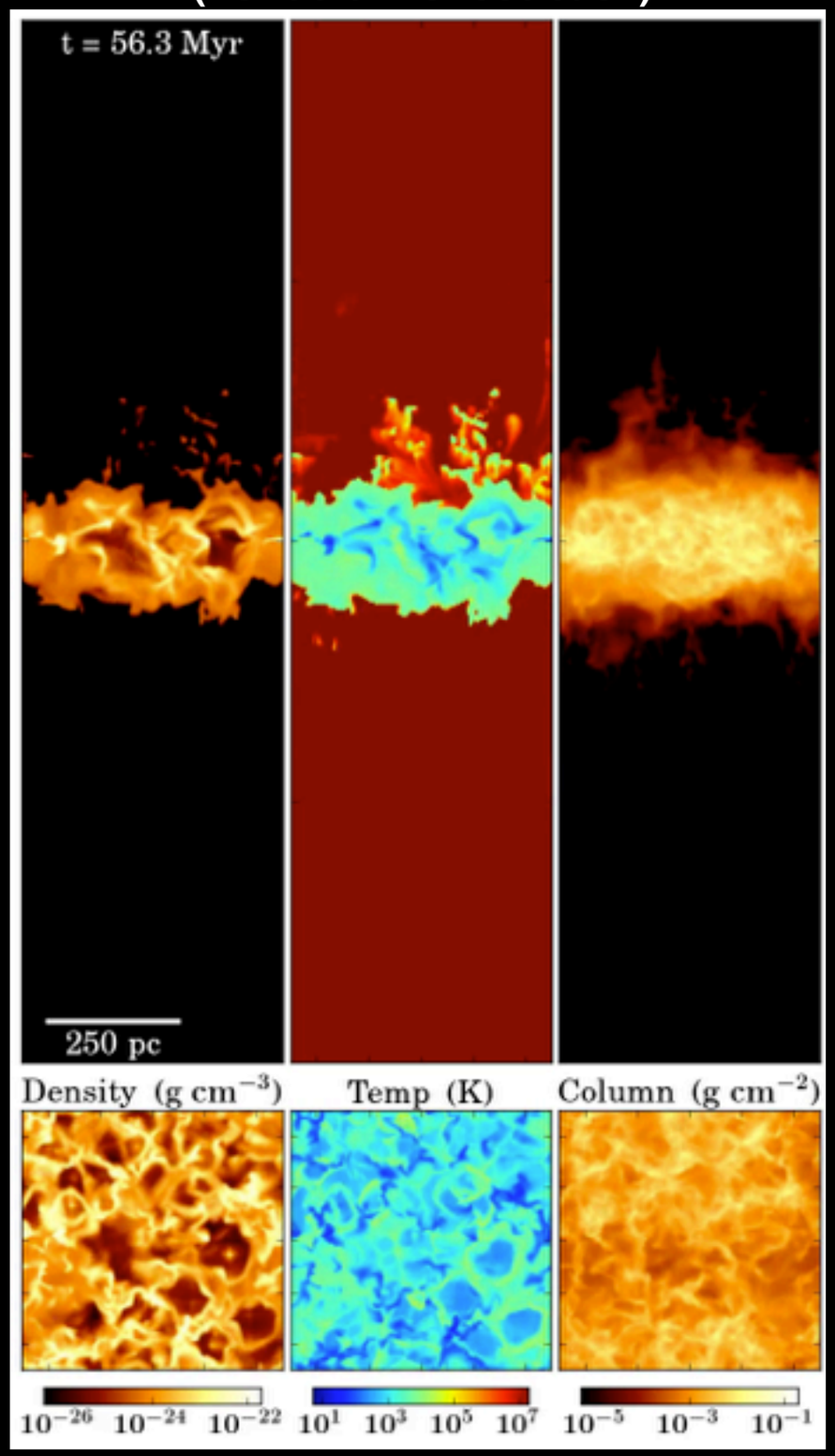


Remember Stellar Clustering?

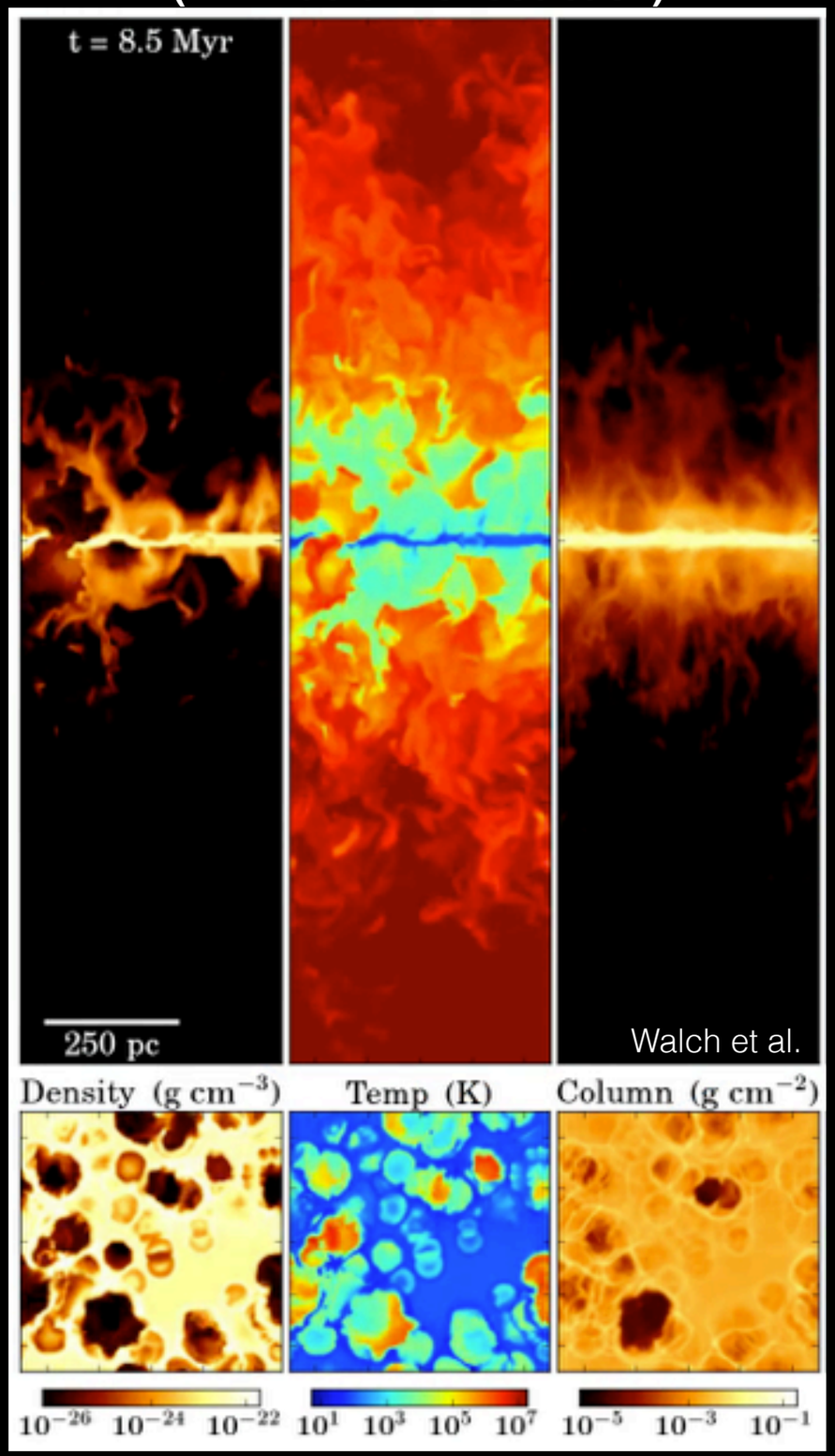
THIS MATTERS, A LOT!

Murray+, Martizzi+,
Walch+, Barnes+
Hopkins+, Hayward+,
Shetty+, Hennebelle+

SNe Explode in Density Peaks
(no radiative feedback)



SNe Clustered & Off-Peak
(with radiative feedback)



Walch et al.

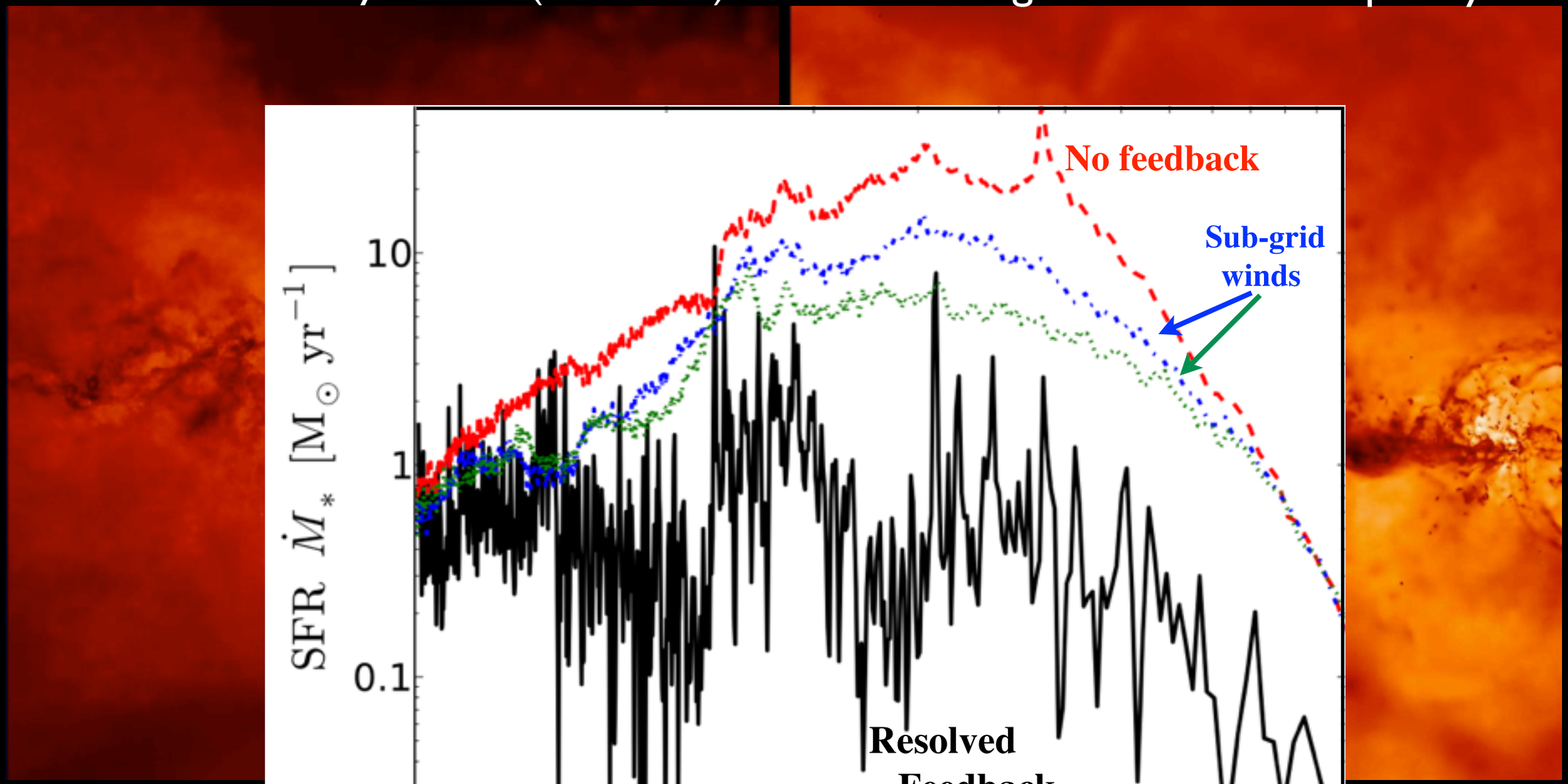
Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

PFH '14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

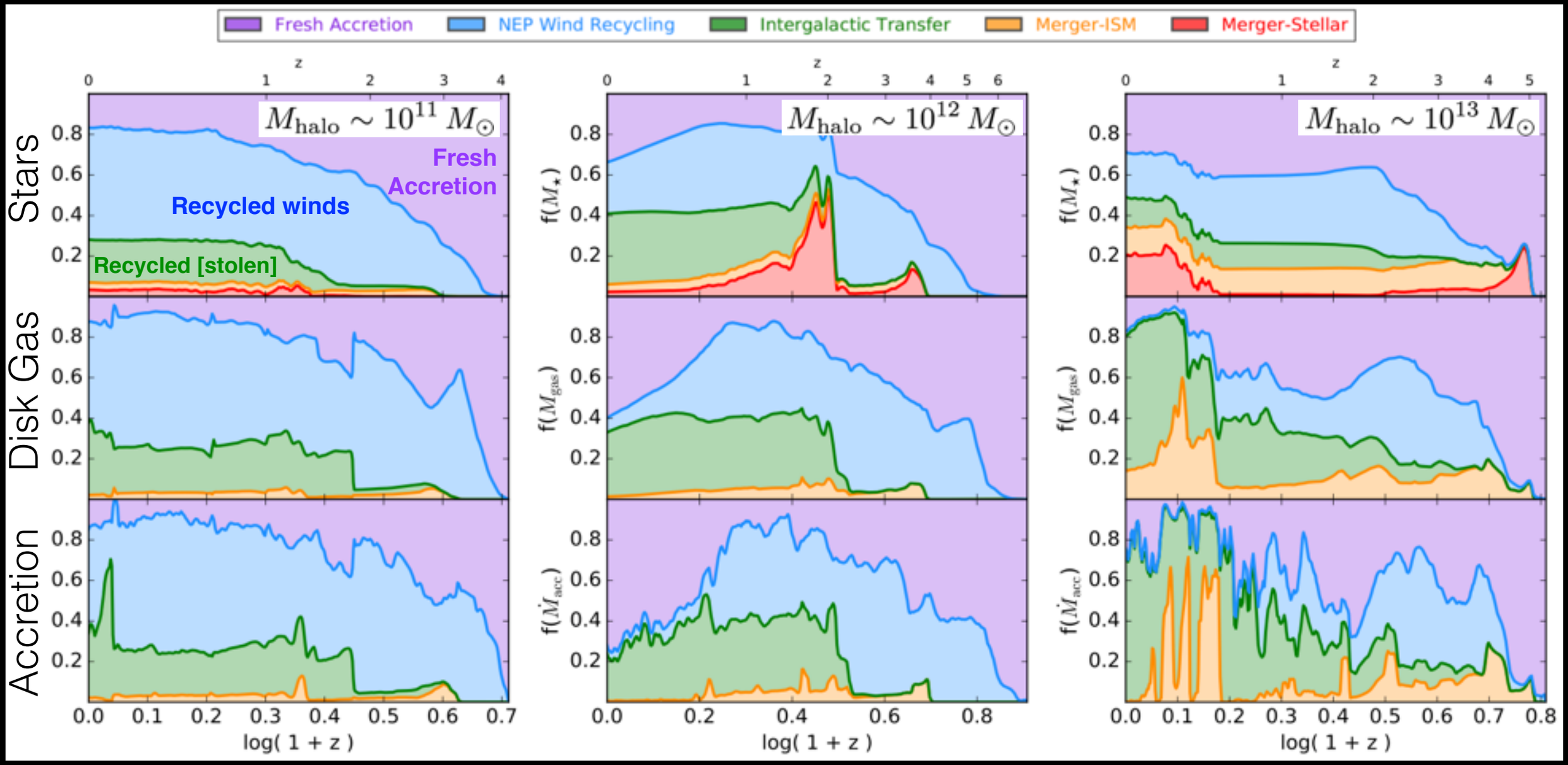
Insert Winds "By Hand" (Sub-Grid)

Following Feedback/ISM Explicitly

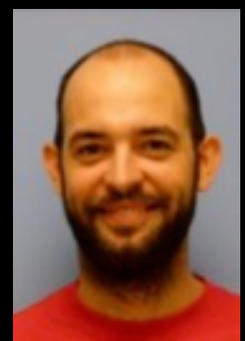


Recycling Matters

MORE IMPORTANT AT LOW-Z, ESPECIALLY FOR DWARFS

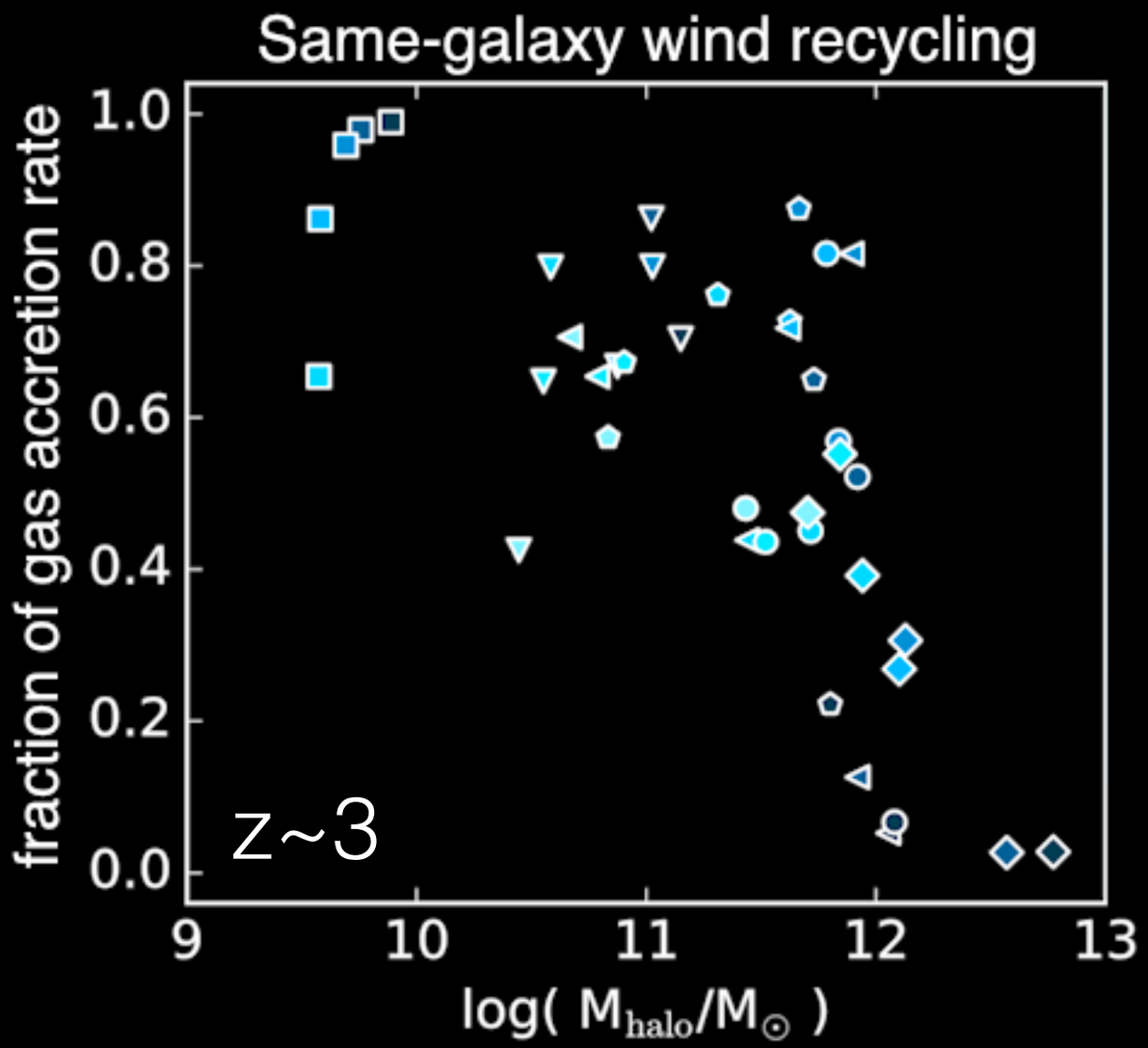


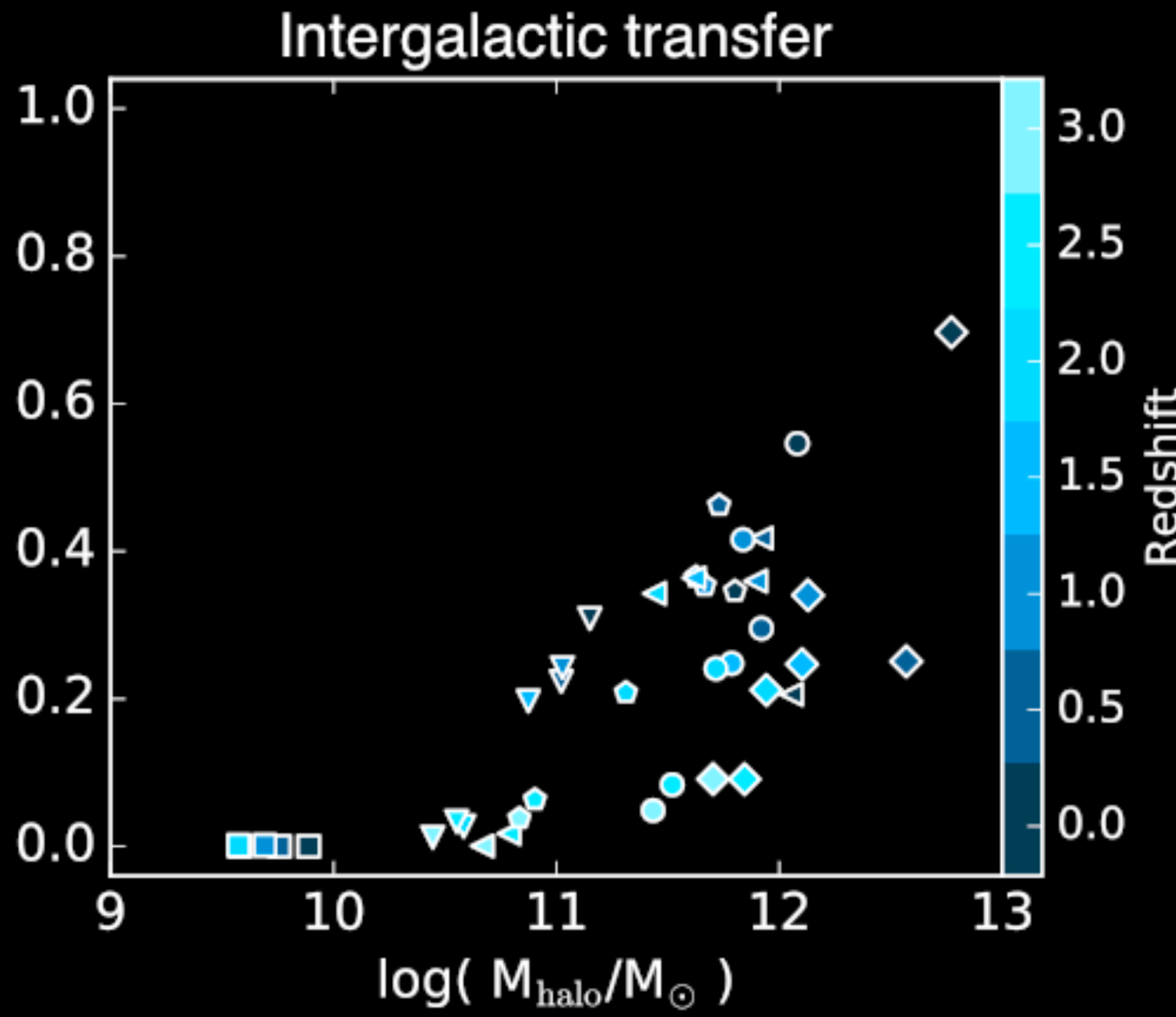
Anglés-Alcázar+17



Recycling Matters

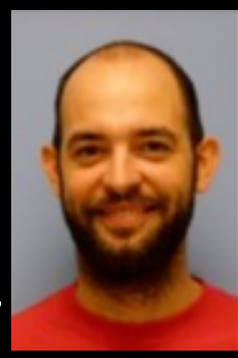
SMOOTH ACCRETION DOMINATES = NEW GAS ~ RECYCLING ~ "TRANSFER"





→ peaks in dwarfs
(high wind mass loading)

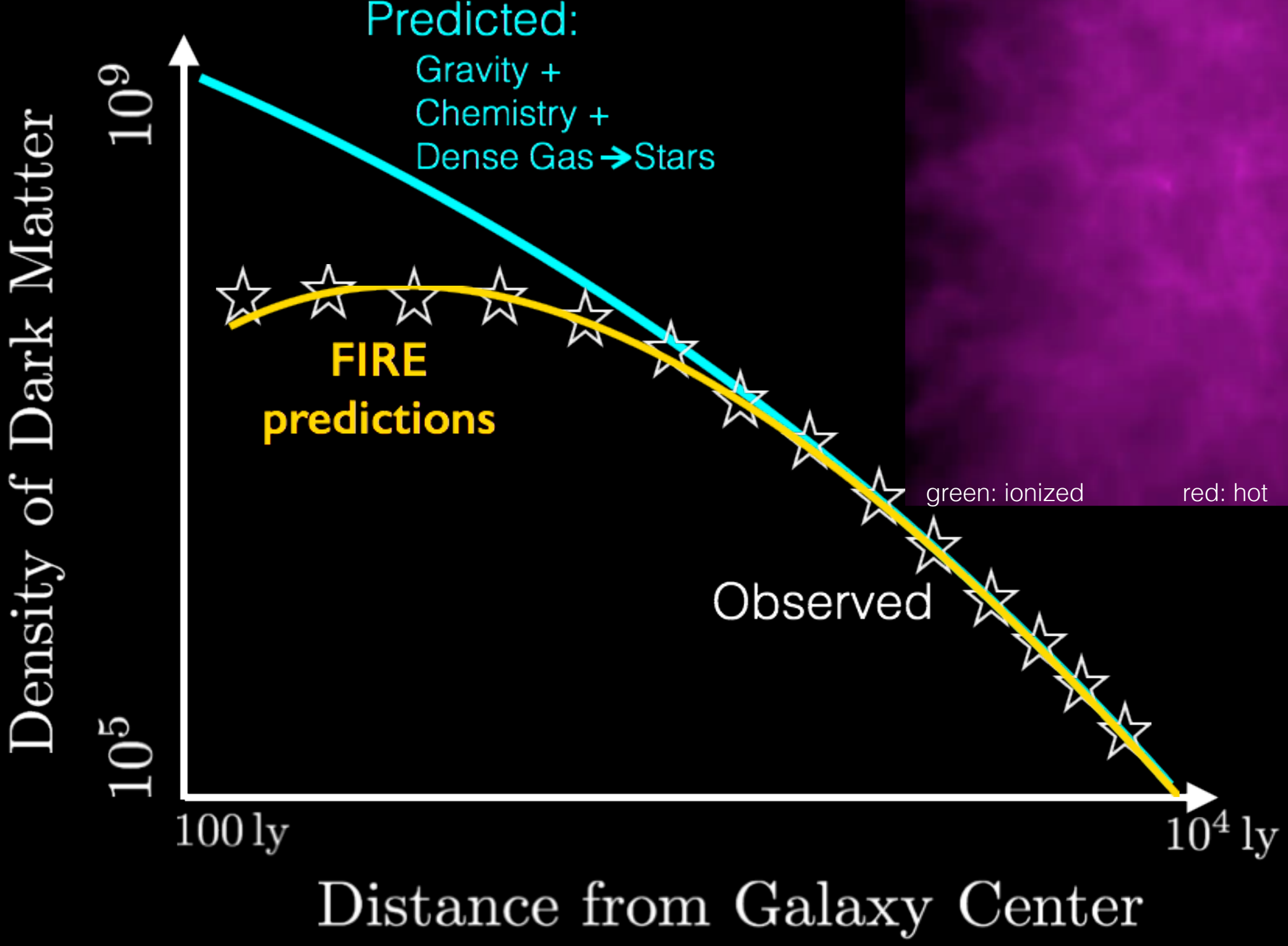
→ peaks in massive galaxies
(correlates with mergers)

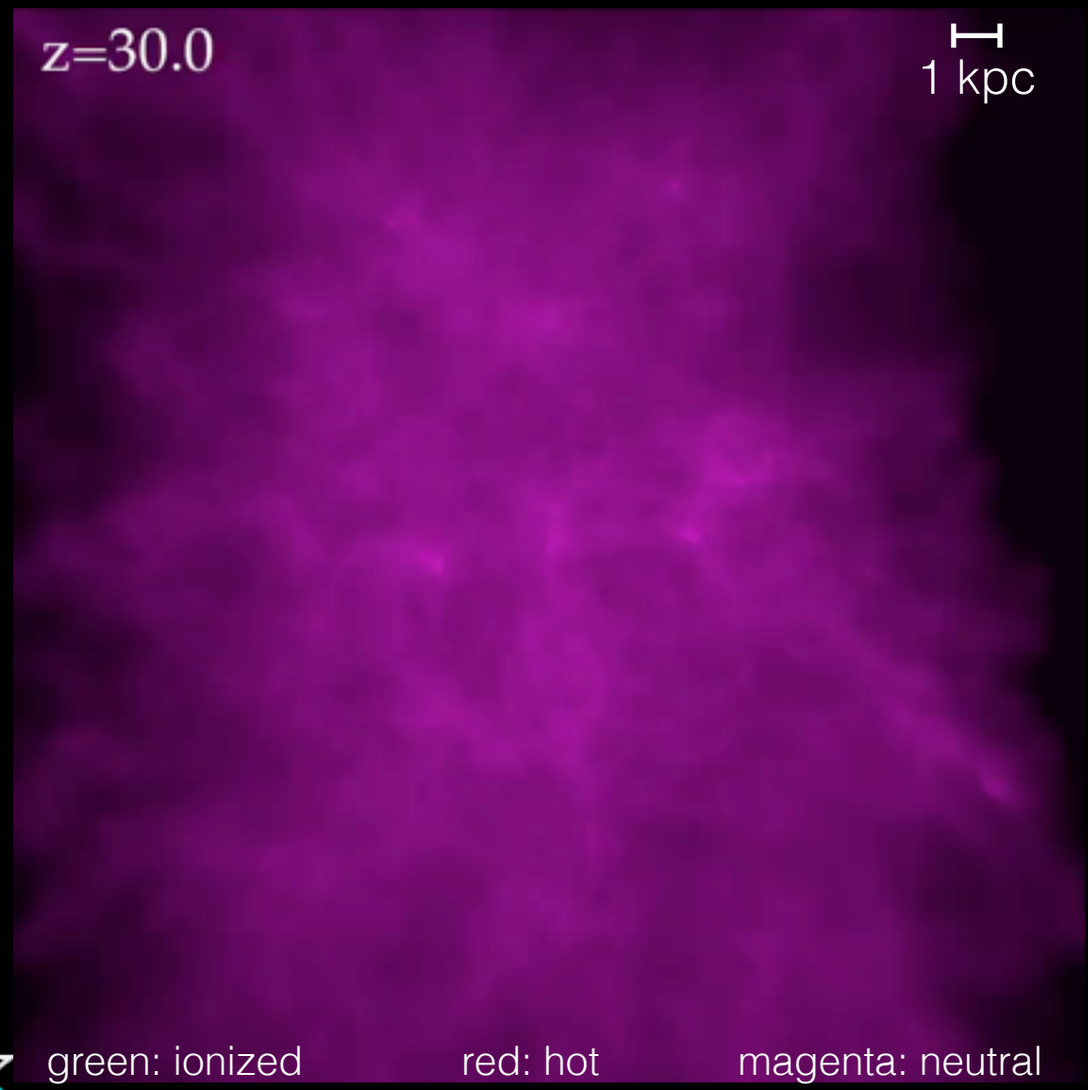


Anglés-Alcázar+17

Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY





Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)

z=0.84

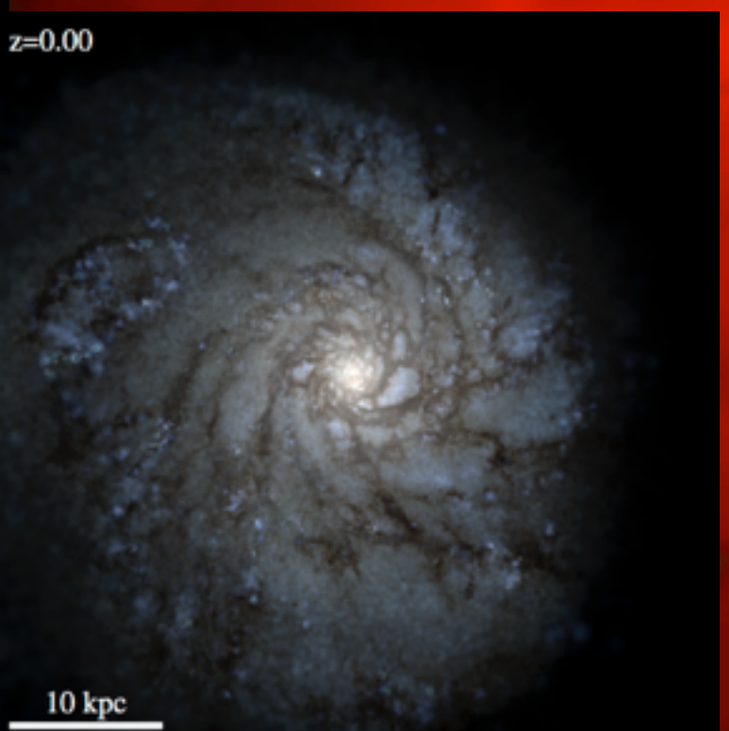
10 kpc

S. Muratov
(arXiv:1501.03155)

"feedback-dominated"
low mass
gas rich
cold, violent outflows

to

"gravity-dominated"
high mass
gas poor
gentle hot gas "venting"



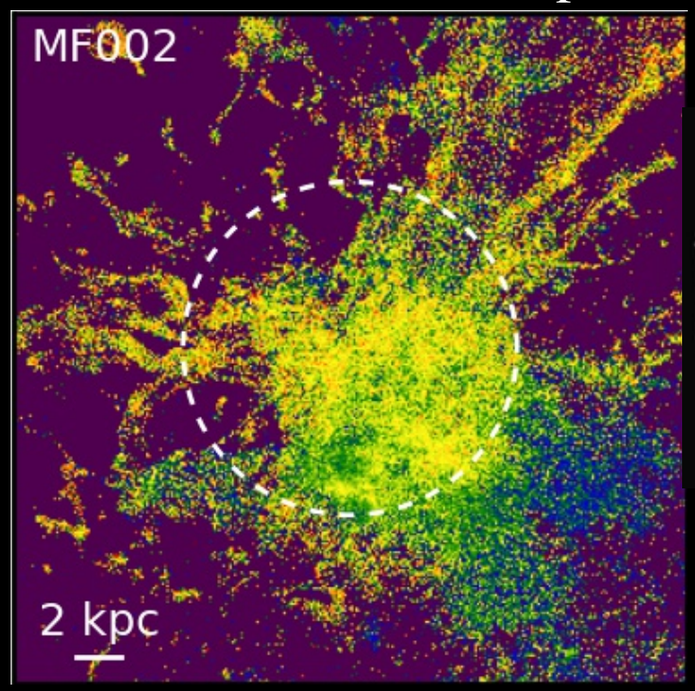
C. Hayward
(arxiv:1510.05650)

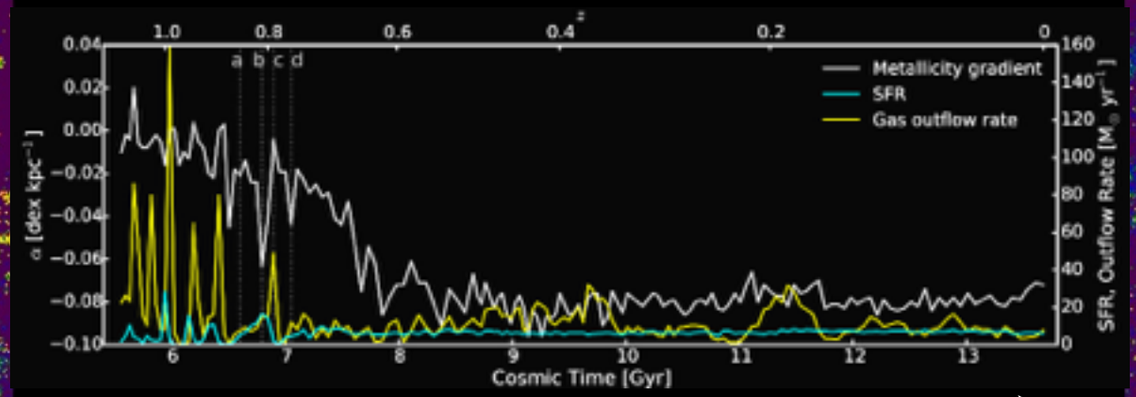
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

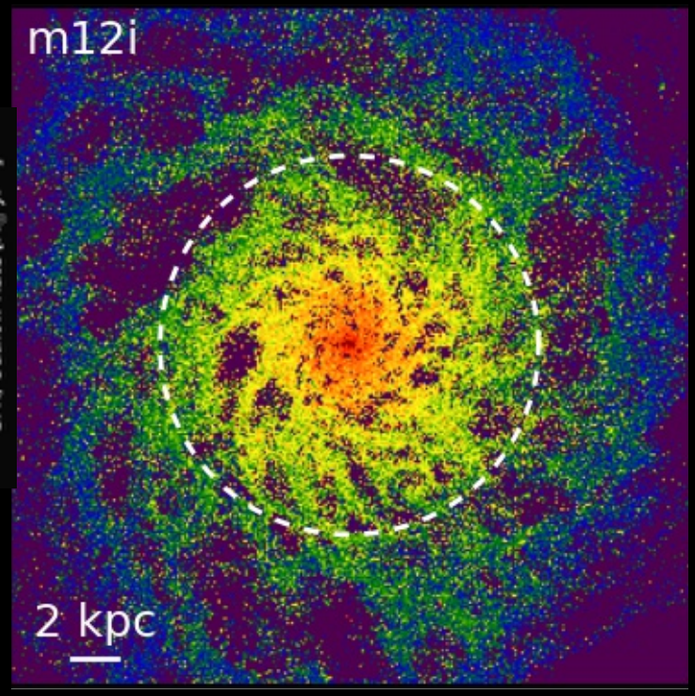
Xiangcheng Ma
(arXiv:1610.03498)

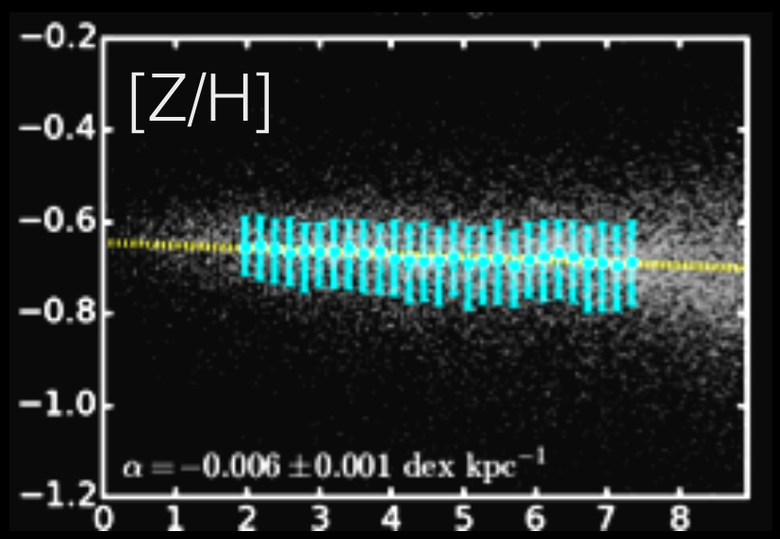
"feedback-dominated" phase



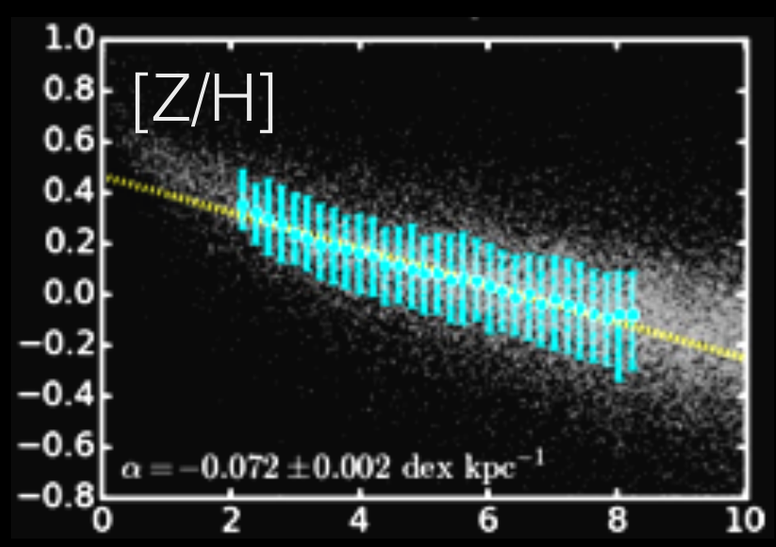


"gravity-dominated" phase





R [kpc]

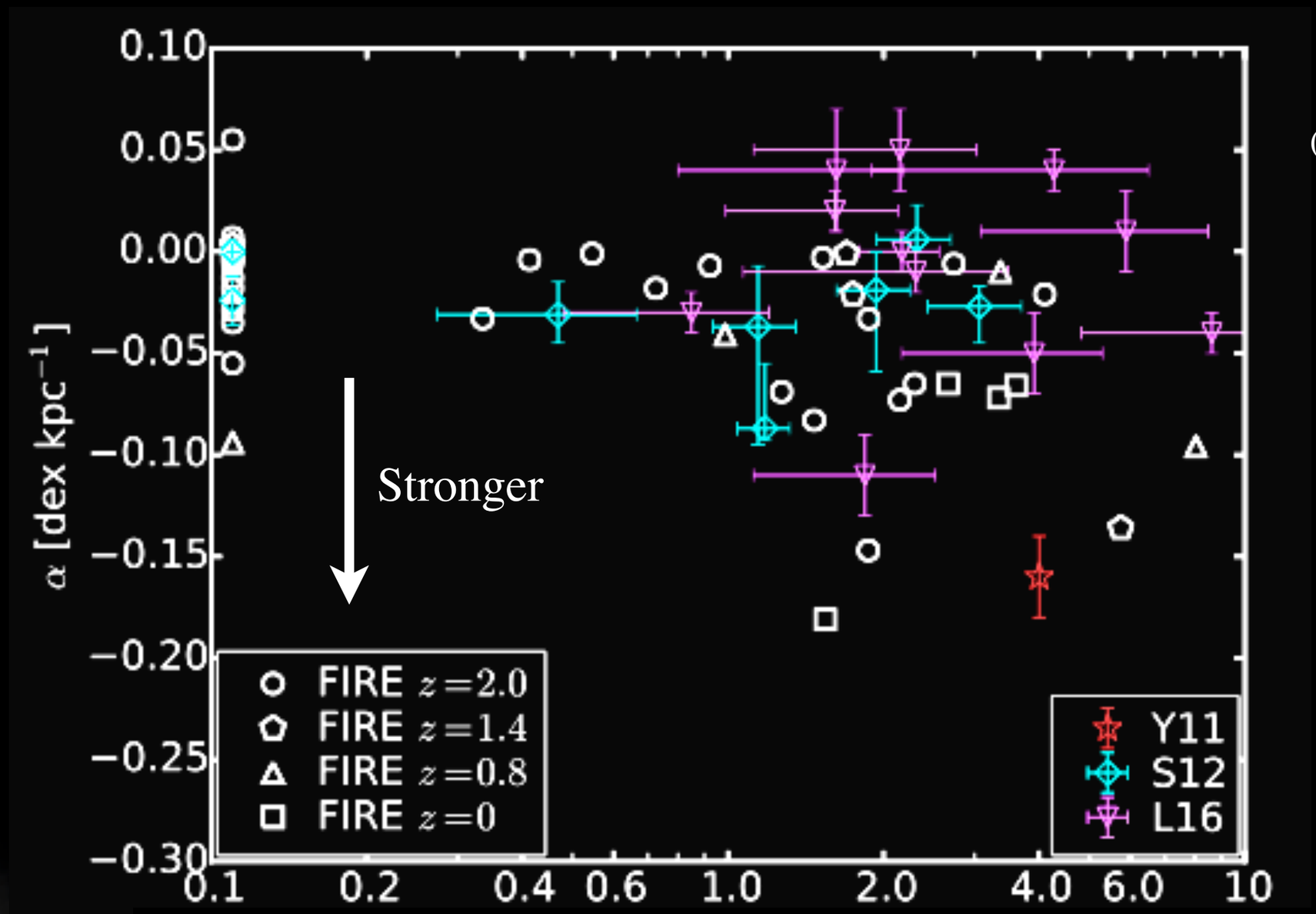


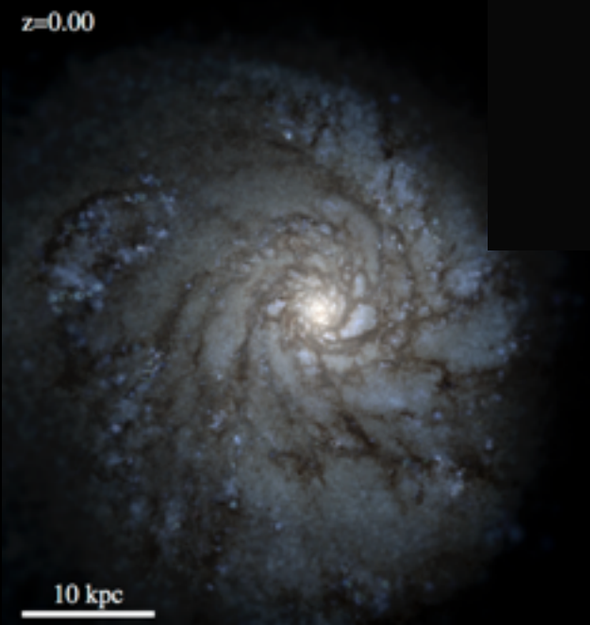
R [kpc]

Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

Xiangcheng Ma
(arXiv:1610.03498)

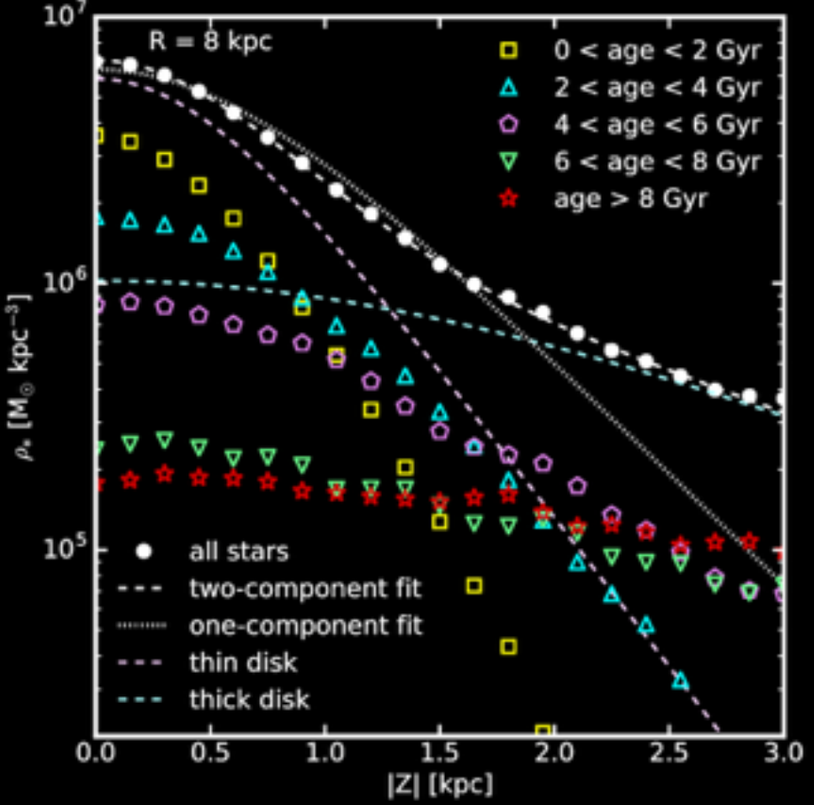


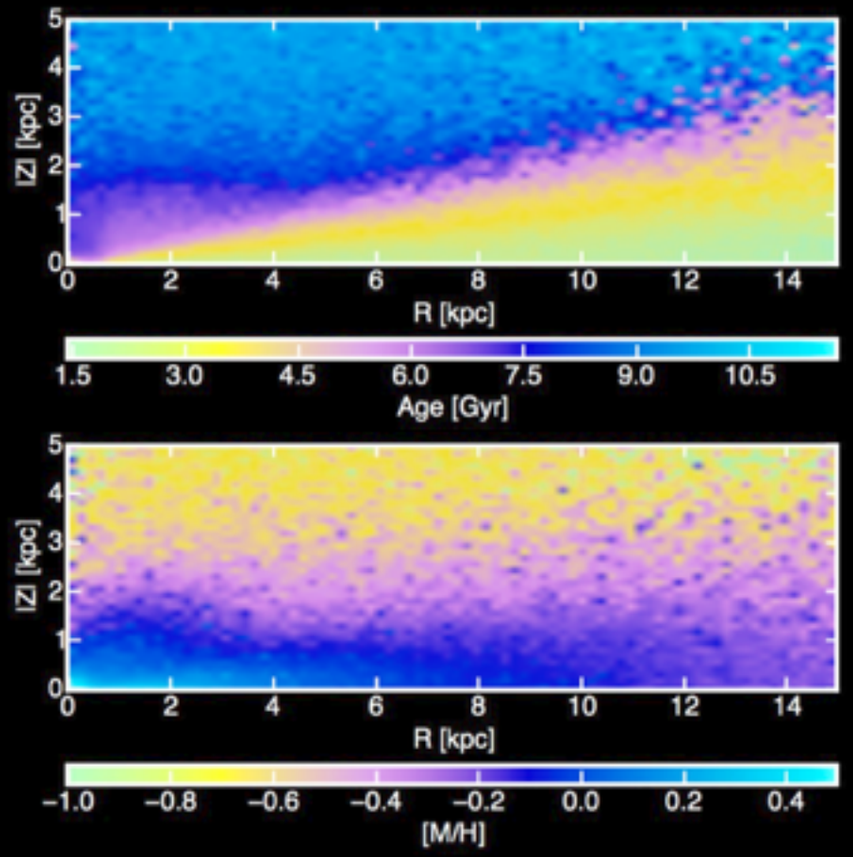


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

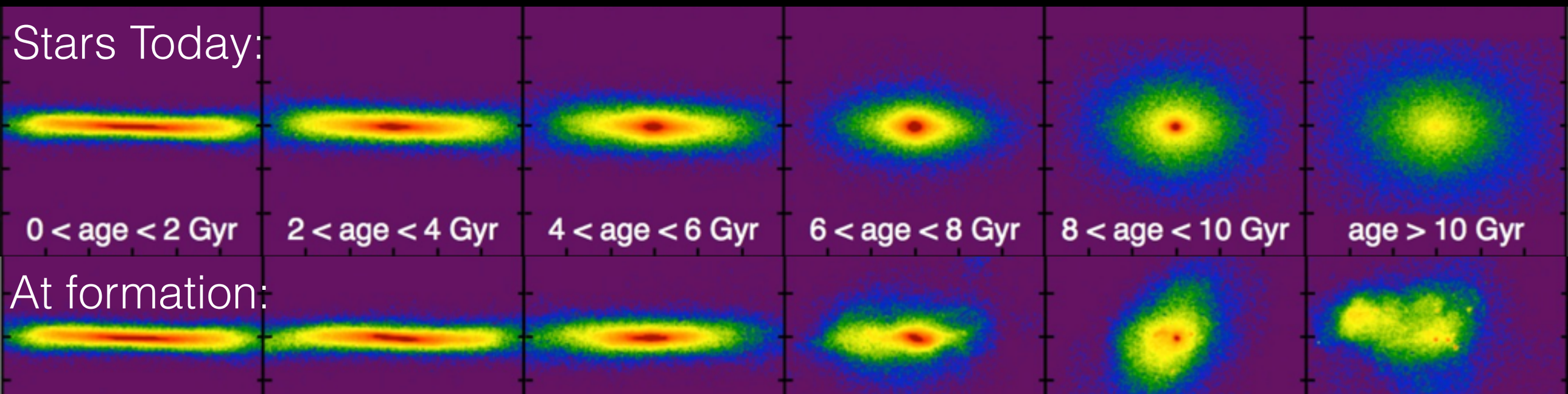
THICK -> THIN DISK

Xiangcheng Ma
(arXiv:1608.04133)
Ana Bonaca
(arXiv:1704.05463)

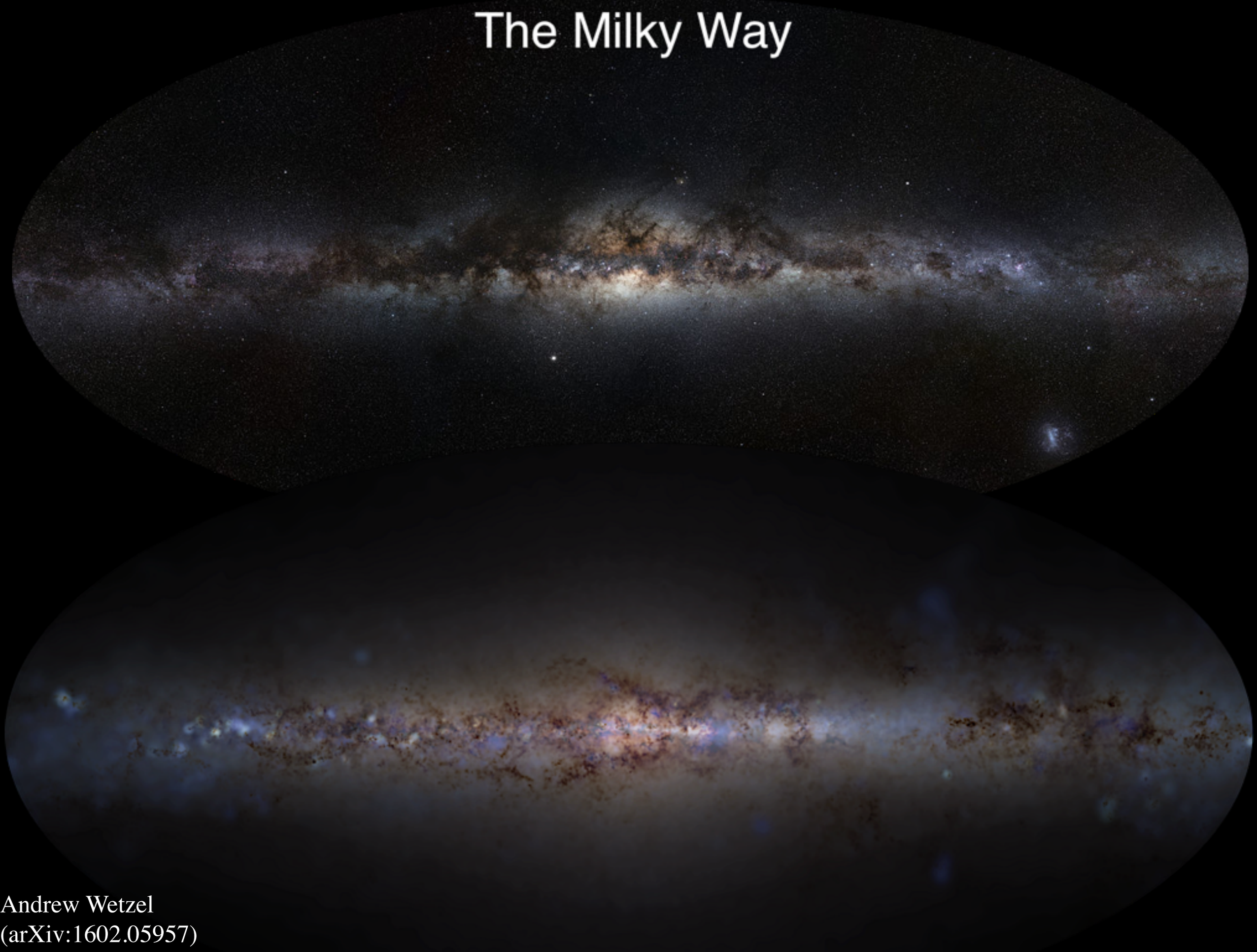




Detailed vertical+radial
abundance gradients & kinematics
of thin/thick disk populations



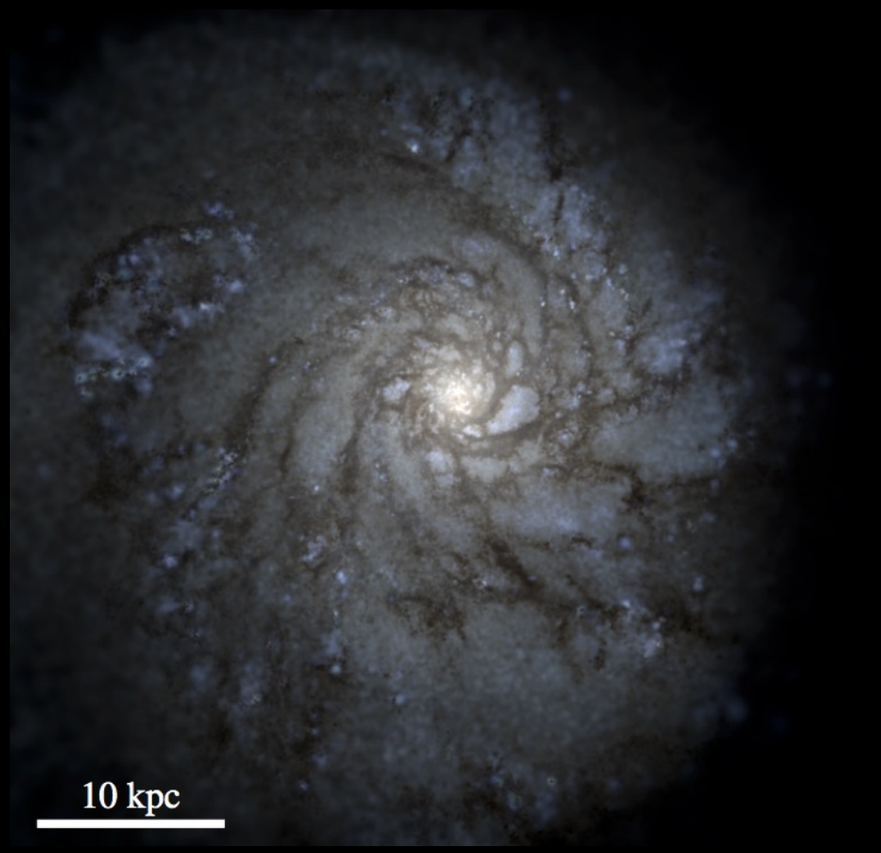
The Milky Way

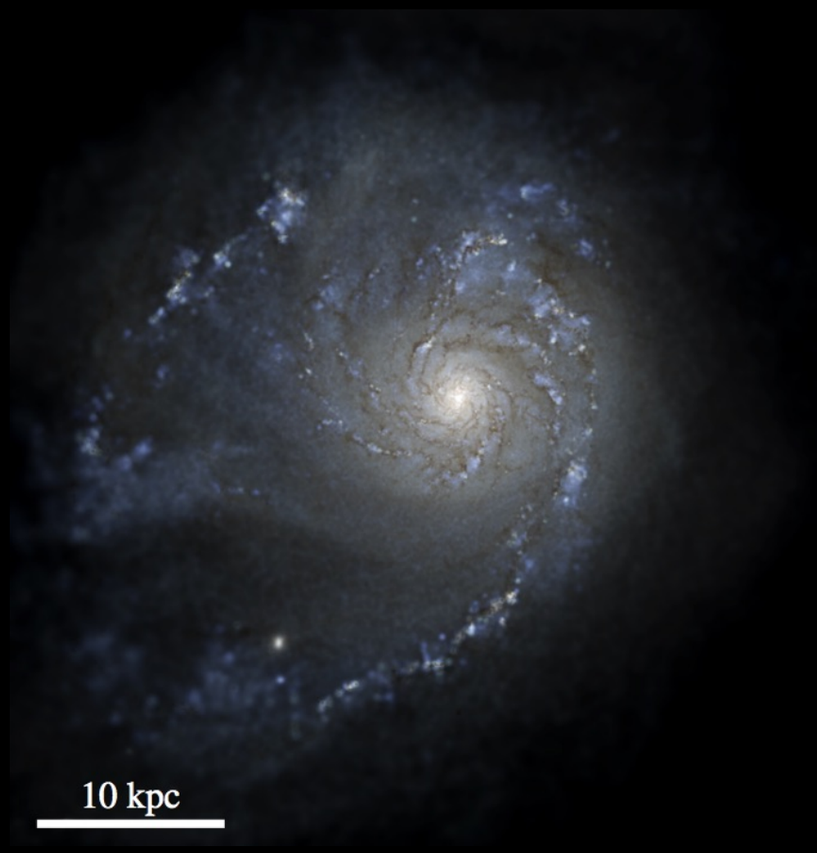


Andrew Wetzel
(arXiv:1602.05957)

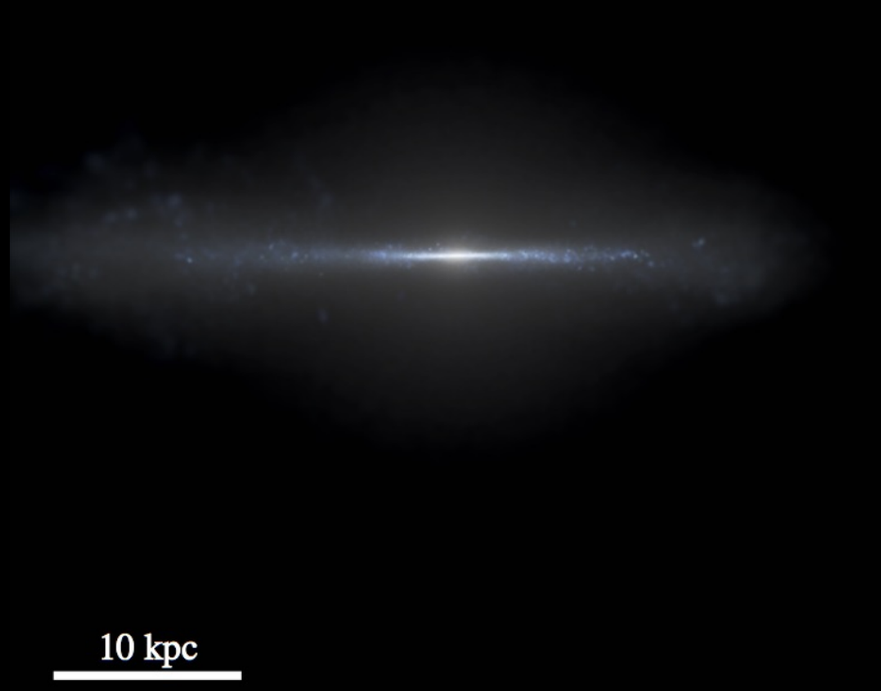
Thin Disks Emerge Naturally

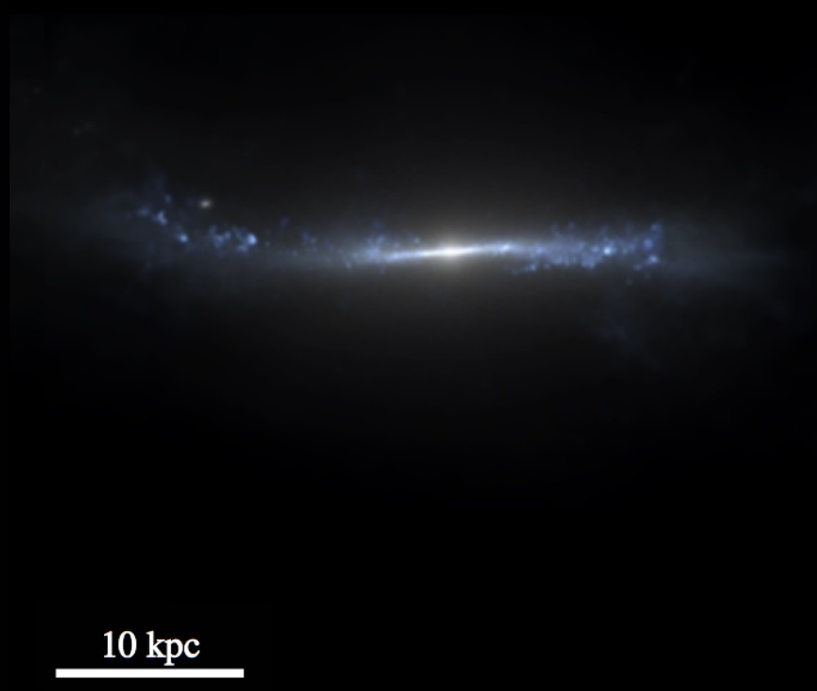
Garrison-Kimmel et al., in prep





+ baryons & feedback (stars)

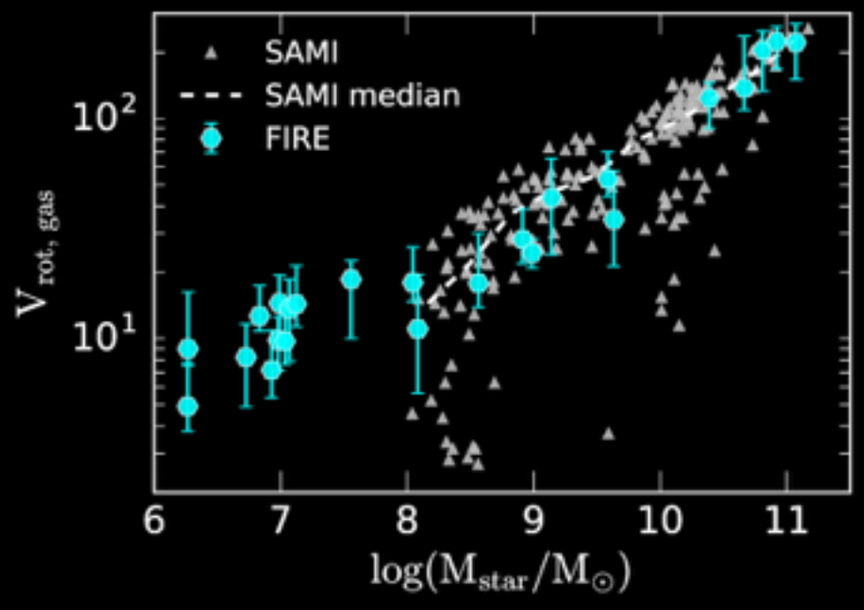


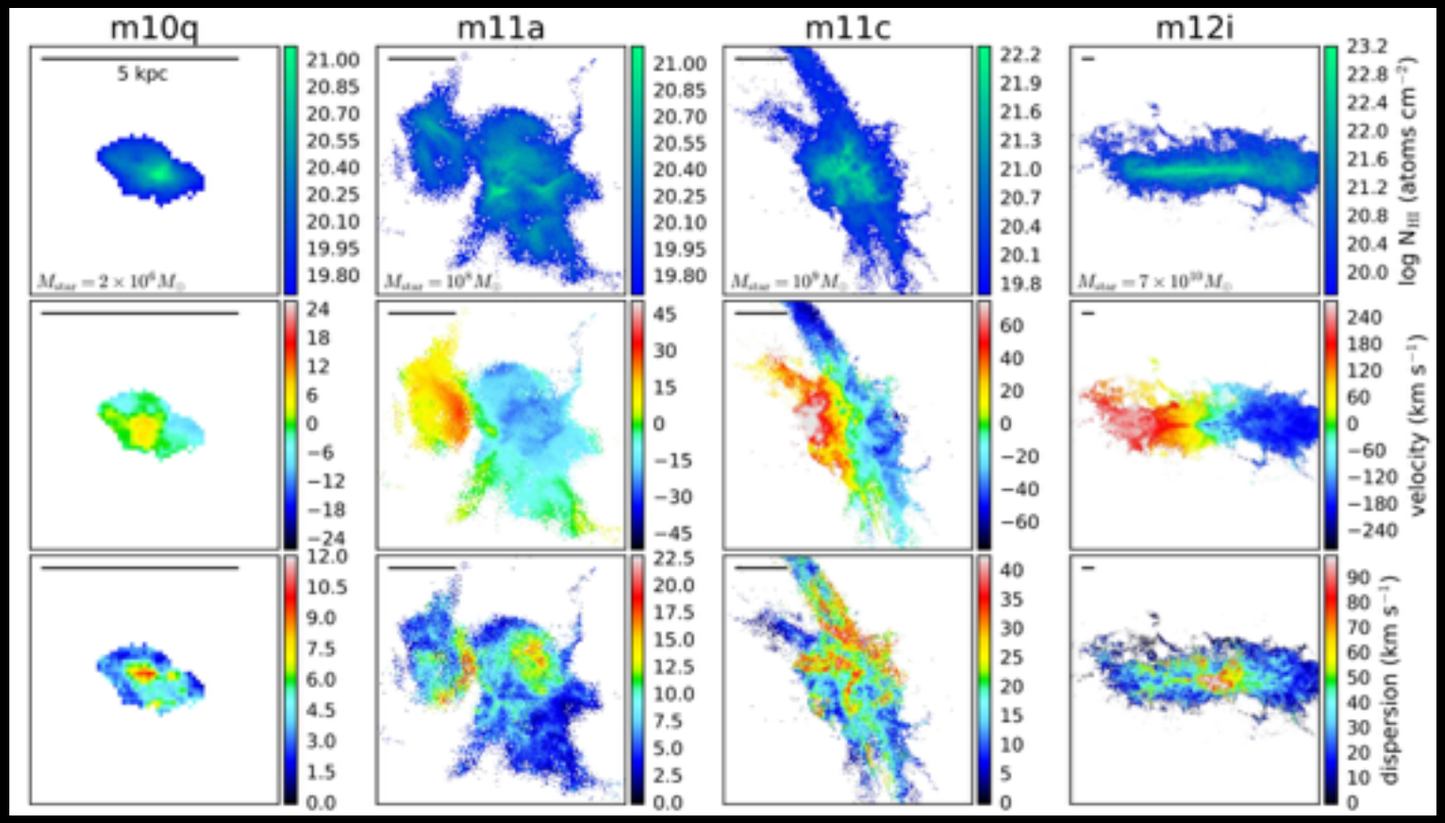


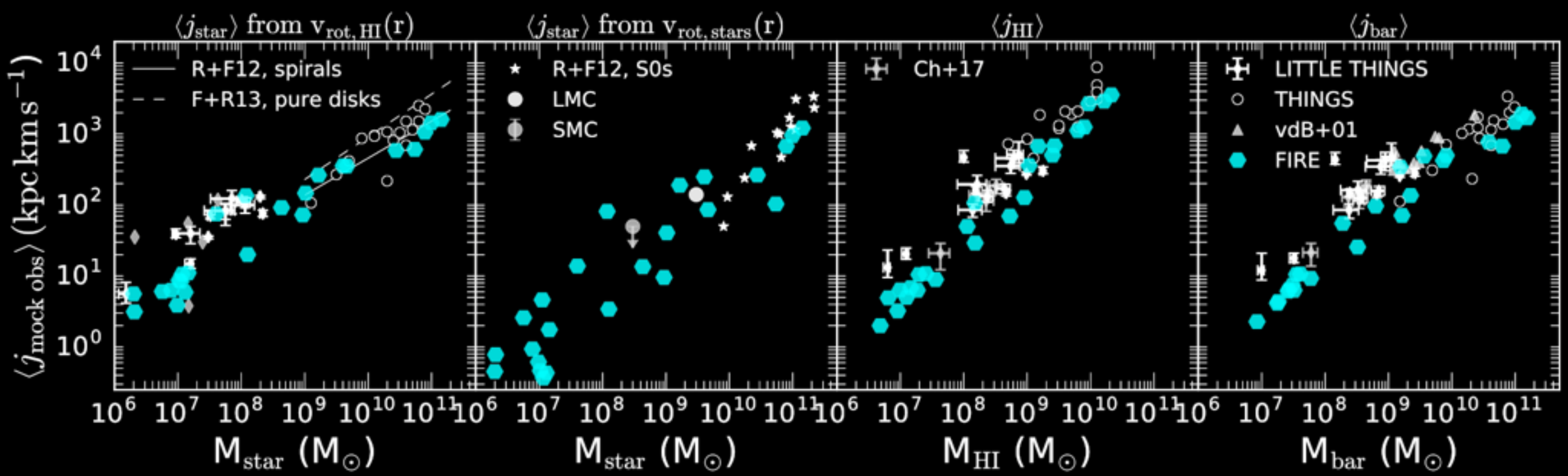
Angular Momentum of Gas+Stars

AGREES WELL WITH OBSERVATIONS, LOW IN DWARFS

Kareem El-Badry
(arXiv:1705.10321)



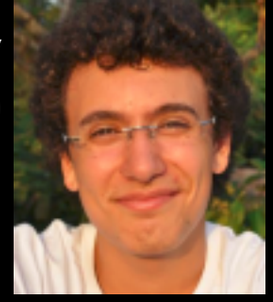


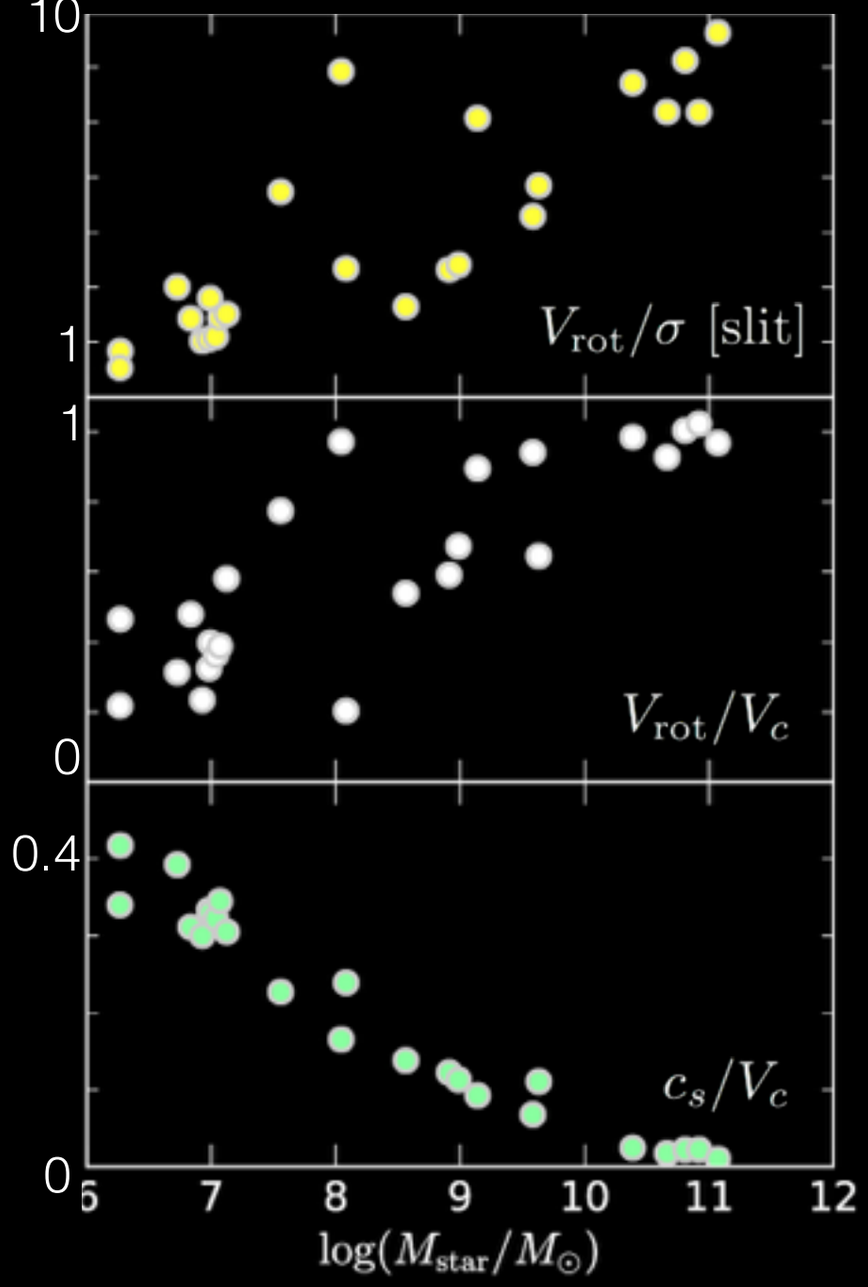


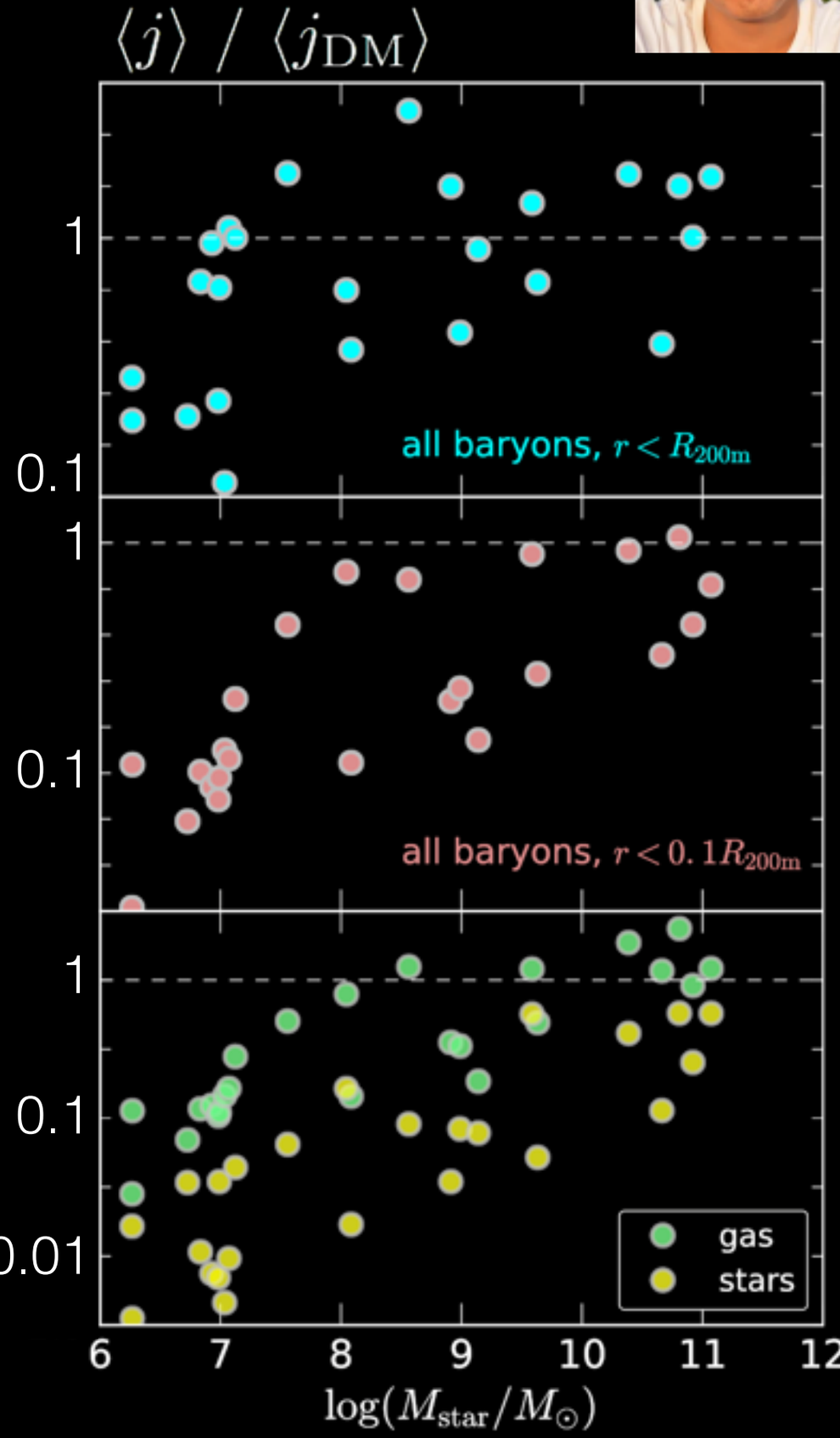
Angular Momentum of [Halo] Gas

LOWER [EVEN IN HALO] IN DWARFS

Kareem El-Badry
(arXiv:1705.10321)





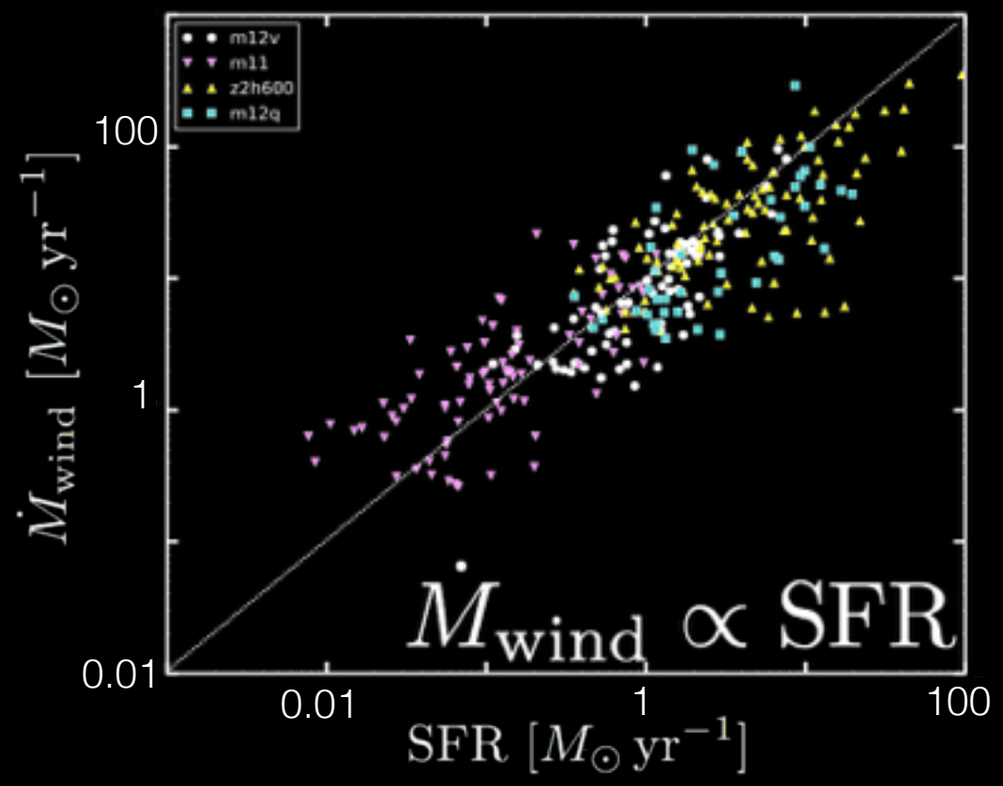


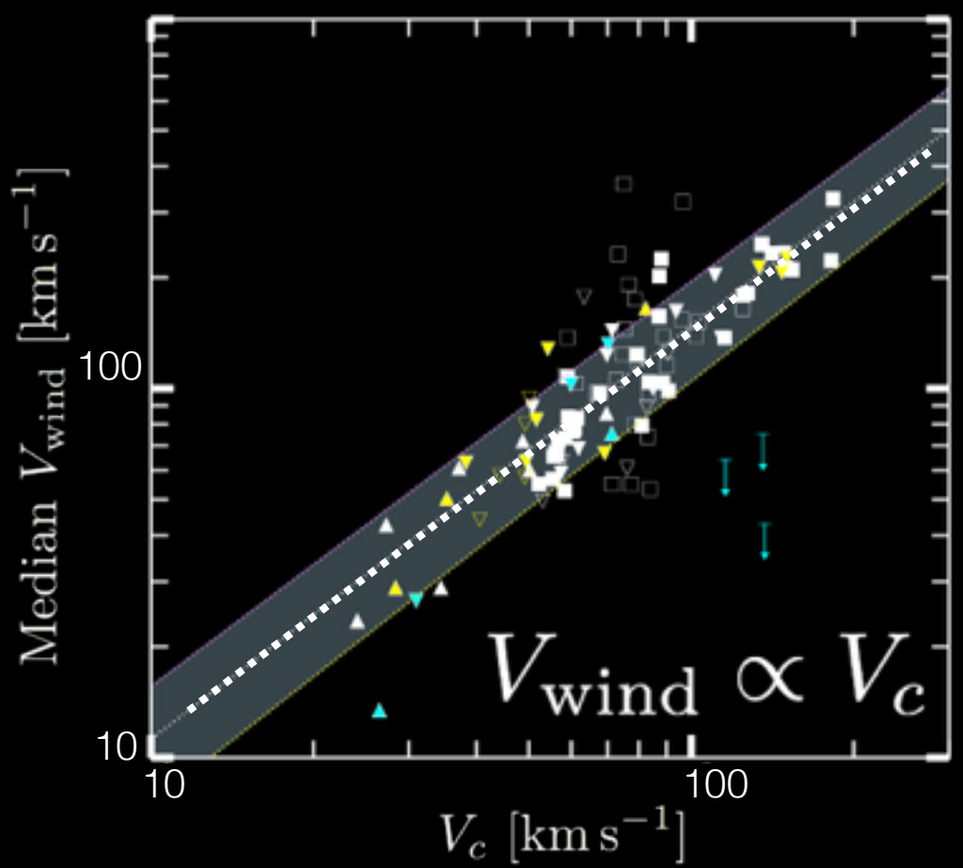
- Thick/irregular [clumpy gas+bursts+pressure]
- Suppressed late-time accretion [UVB + stellar FB]

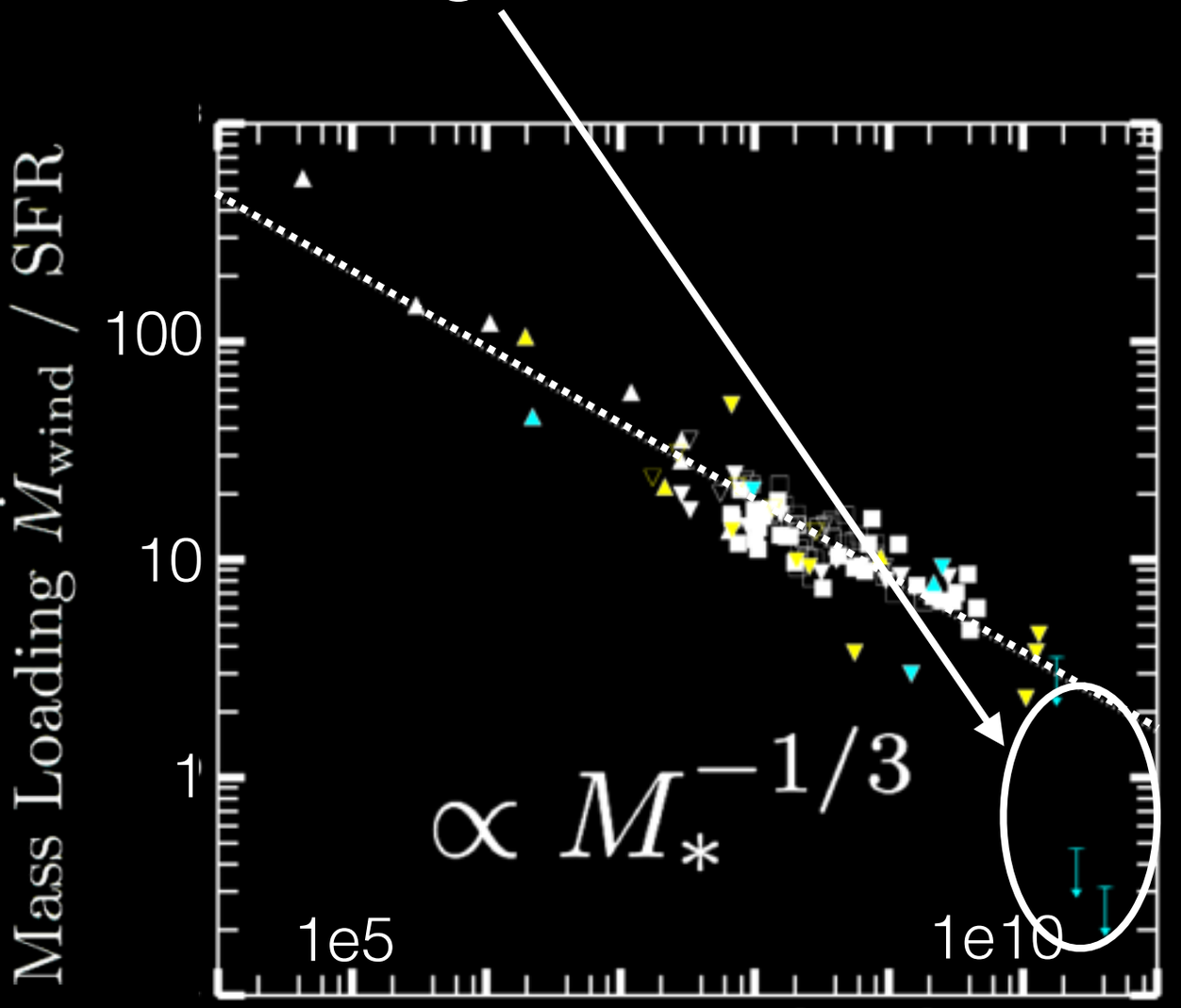
How Efficient Are Galactic Super-Winds?

WHAT MECHANISMS DRIVE THEM?

S. Muratov
(arXiv:1501.03155)



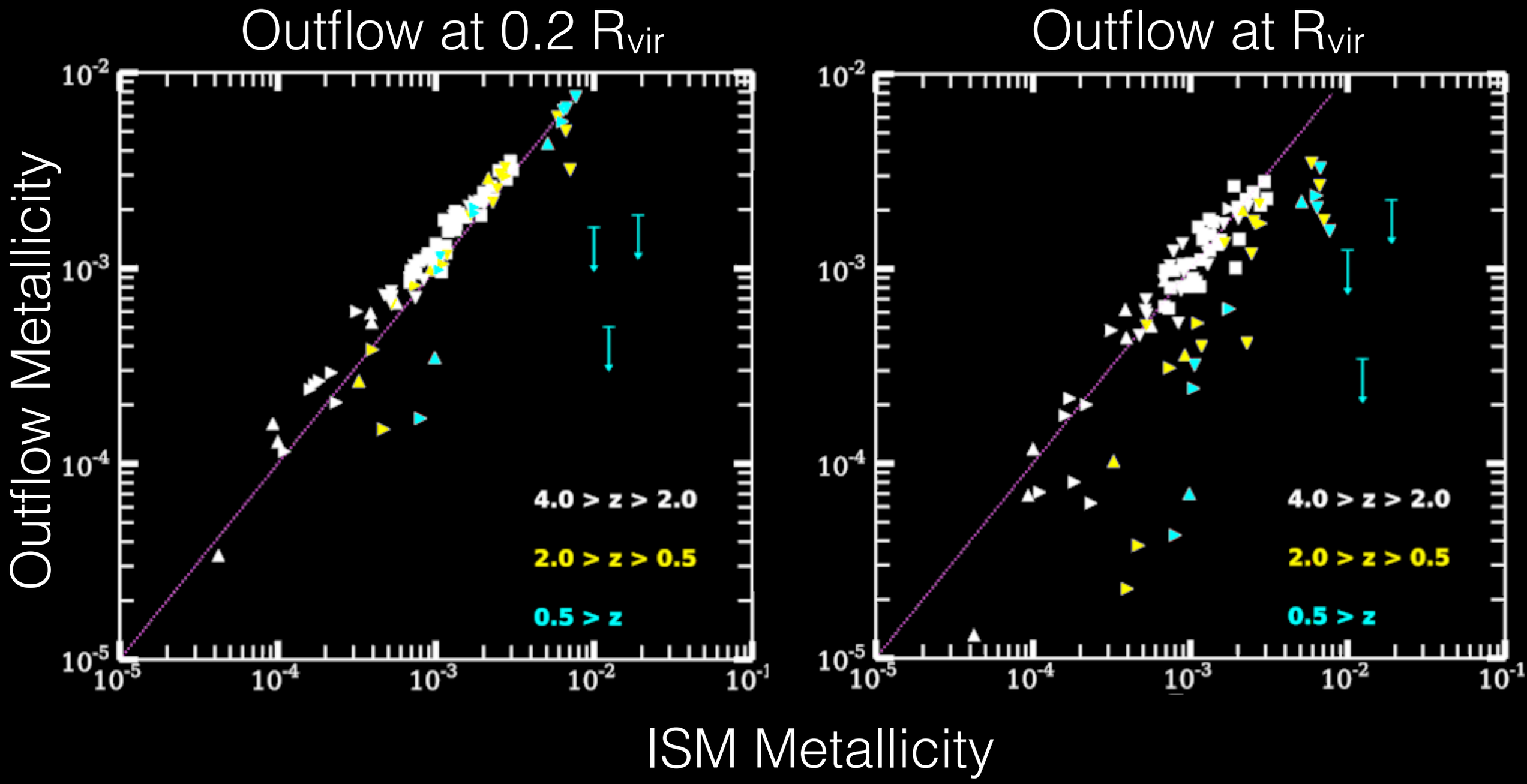




Wind Metallicity: Diagnostic of Suppressive Feedback

Muratov+17

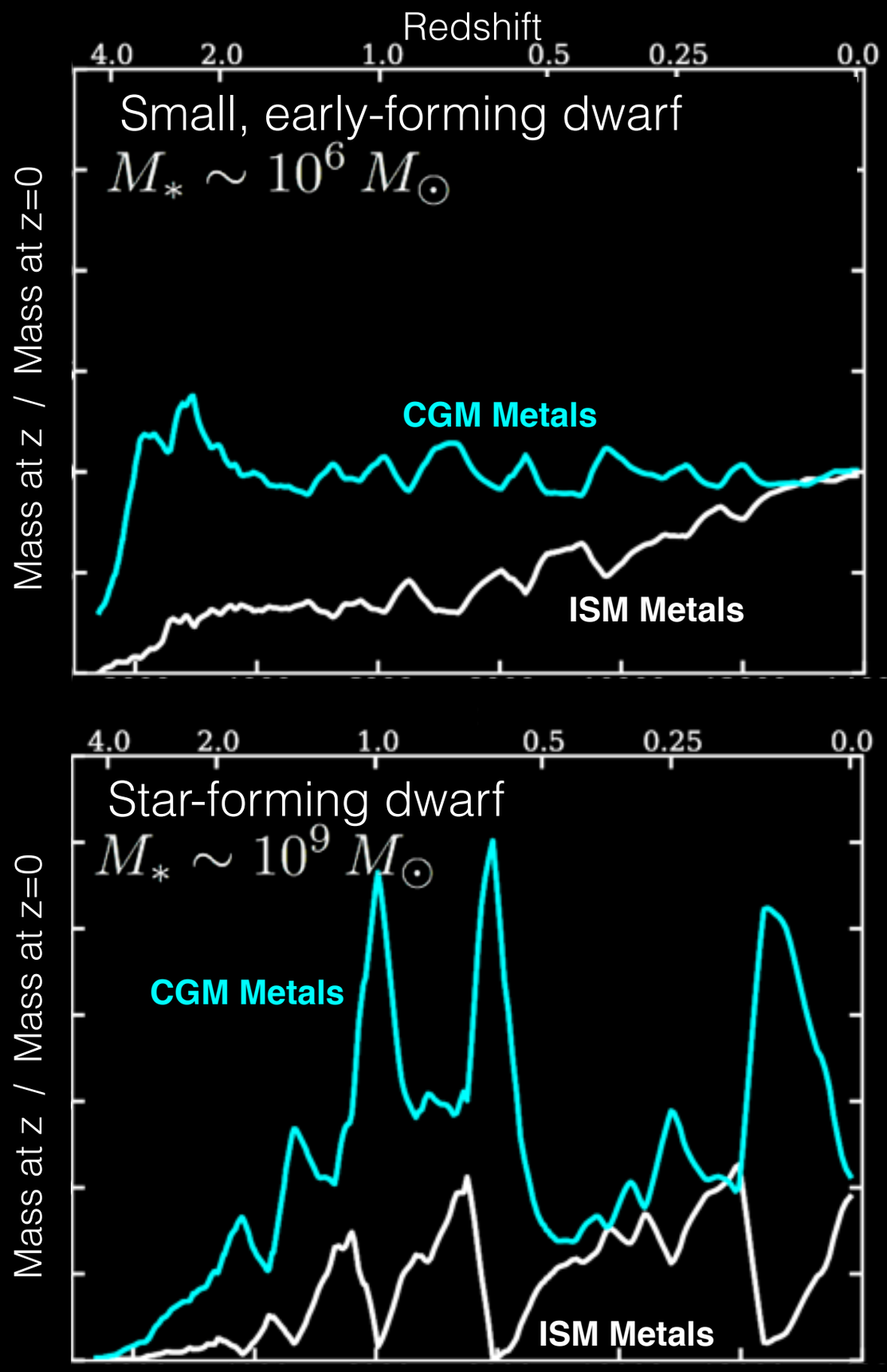
~ ISM METALLICITY IN INNER HALO, DECREASES AS MASS-LOAD



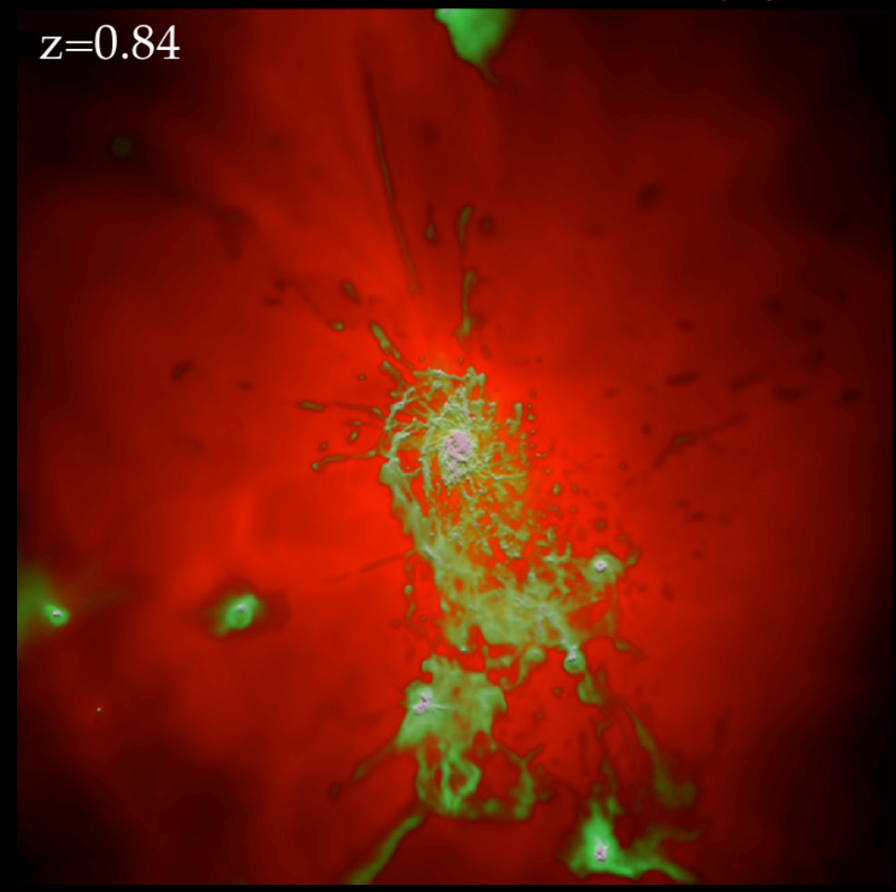
- **Suppressive feedback:** lots of “outflow” *never reached the galaxy*

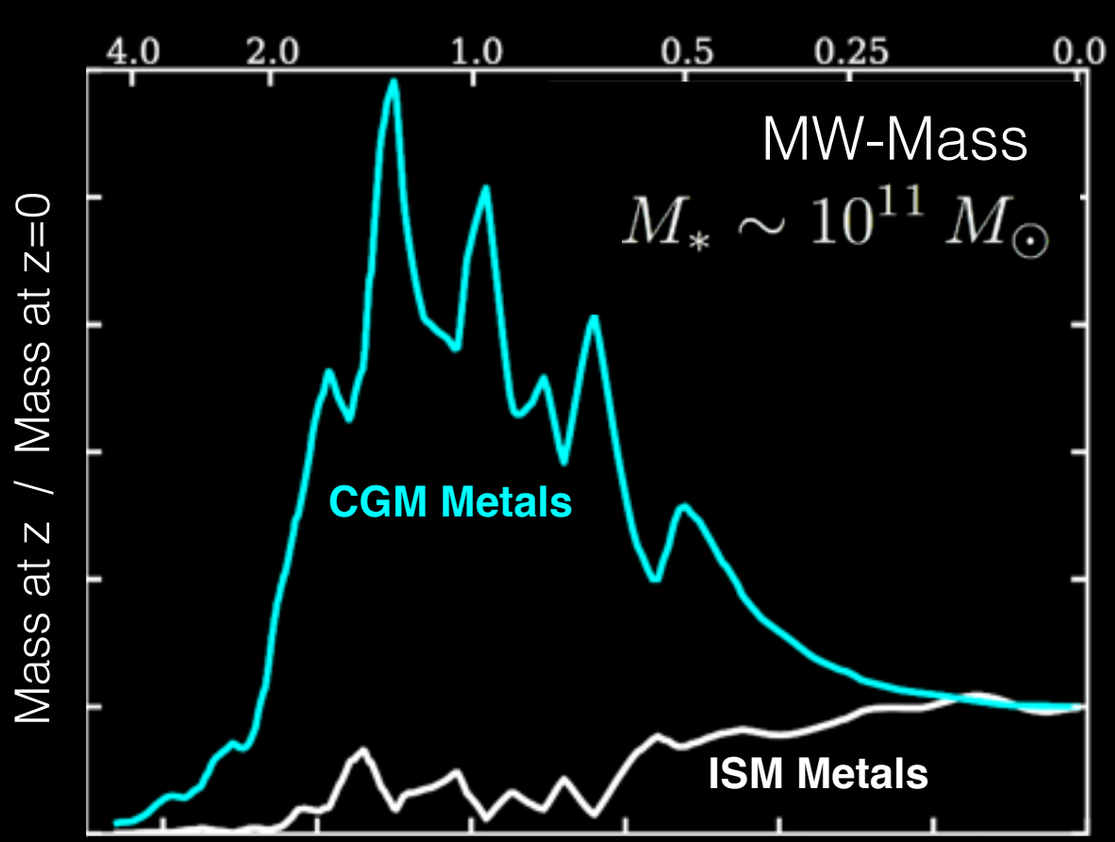
CGM Metals Delivered in "Bursty" Mode

CGM ENRICHMENT TRACES FORMATION HISTORY



Muratov+17





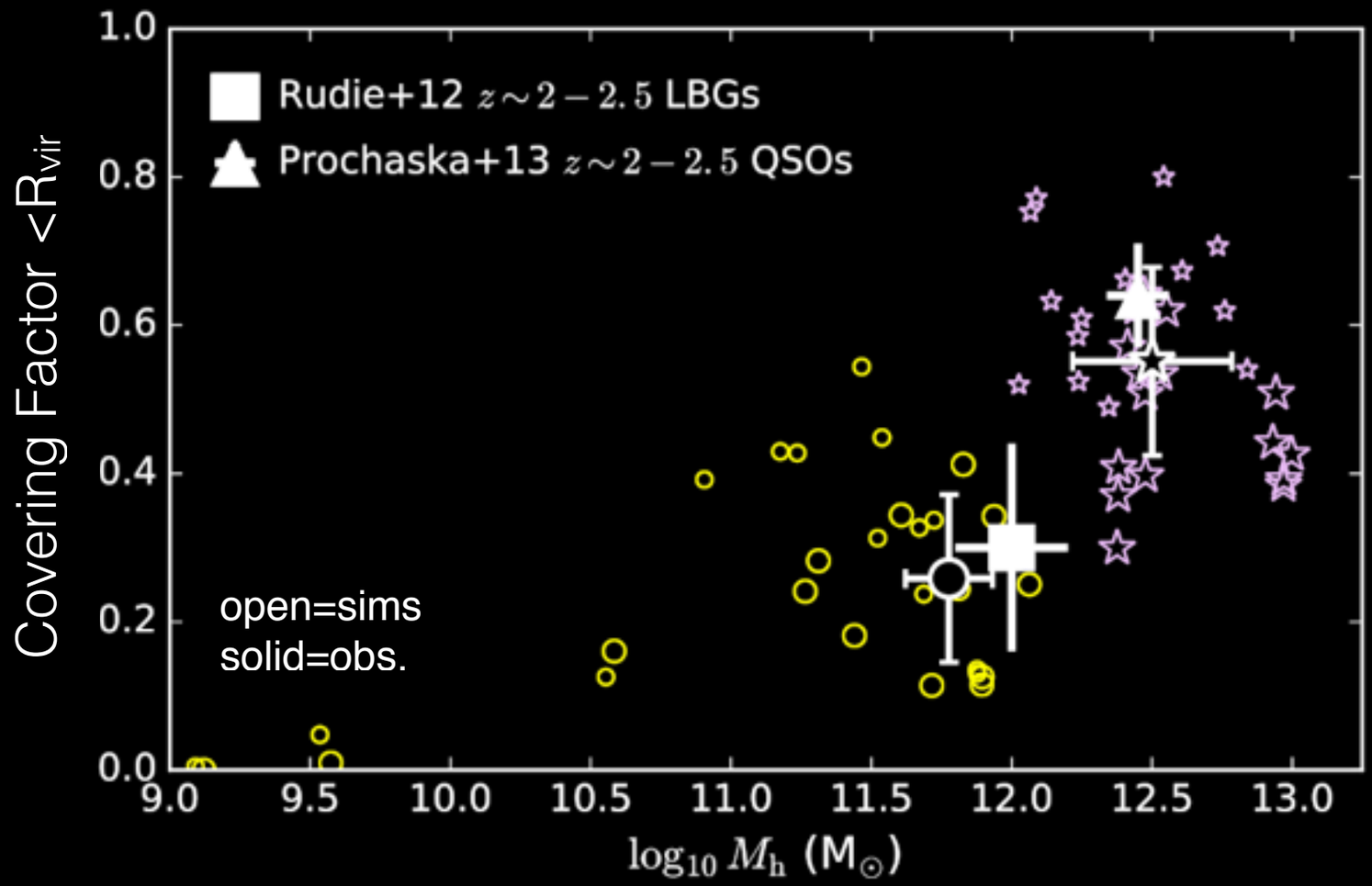
Consequences for CGM Observables

Lyman Limit Covering Factors

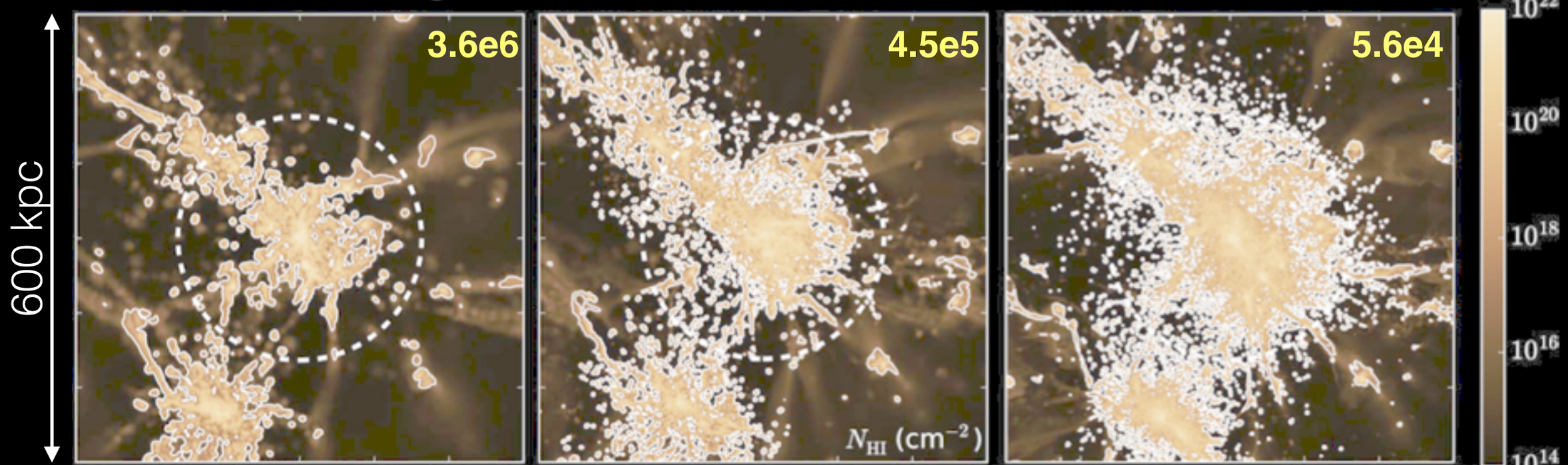
WINDS IMPORTANT, RESOLUTION KEY *FOR THE WINDS*

Faucher-Giguere+ ’15,16

- No AGN needed
- Satellites contribute
- Winds depend on clustered SF, resolved ISM structure

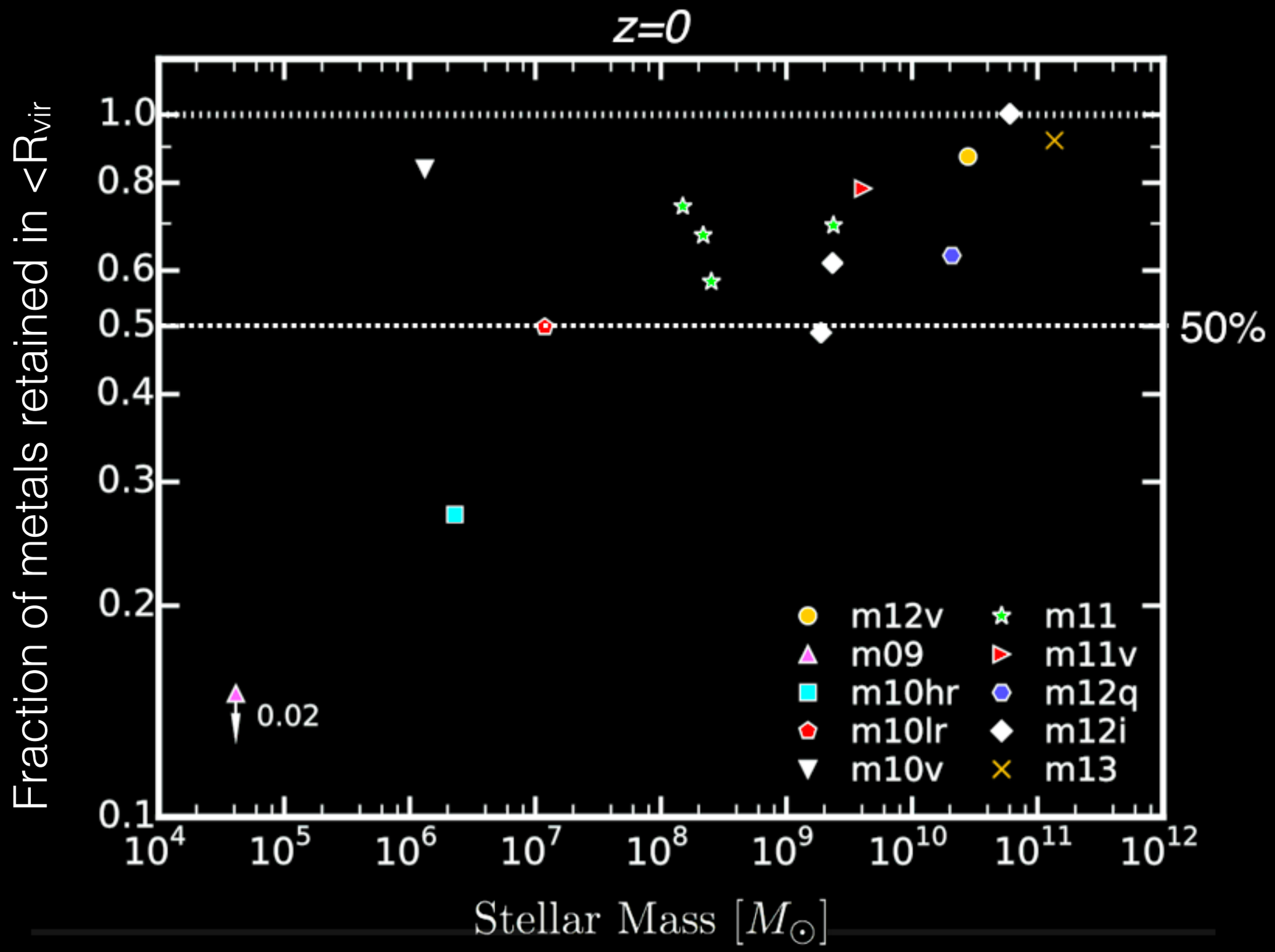


Mass resolution [$M_\odot$]:



Halos Retain Most of their Metals
(EXCEPT LOW-MASS DWARFS)

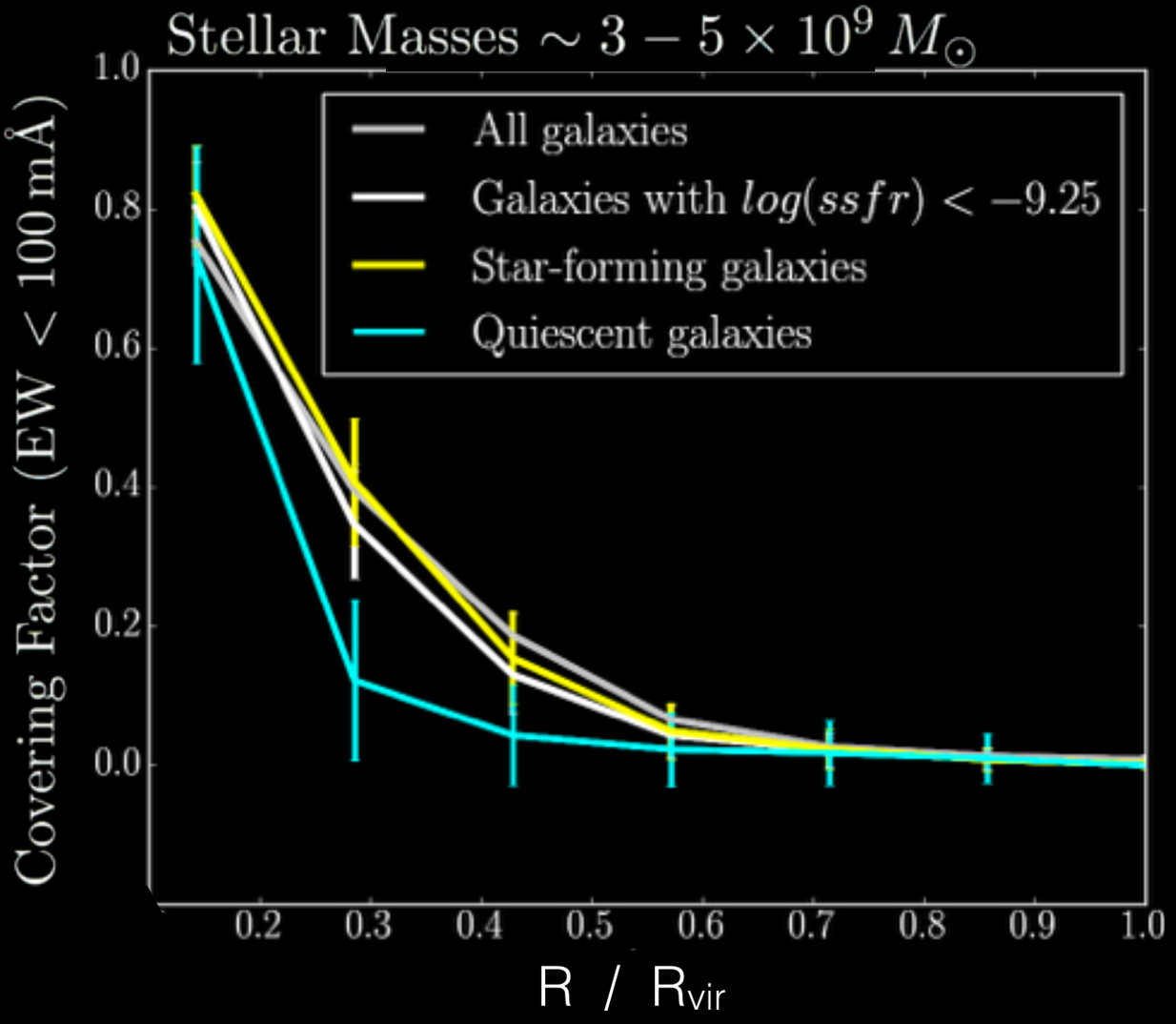
Ma+16

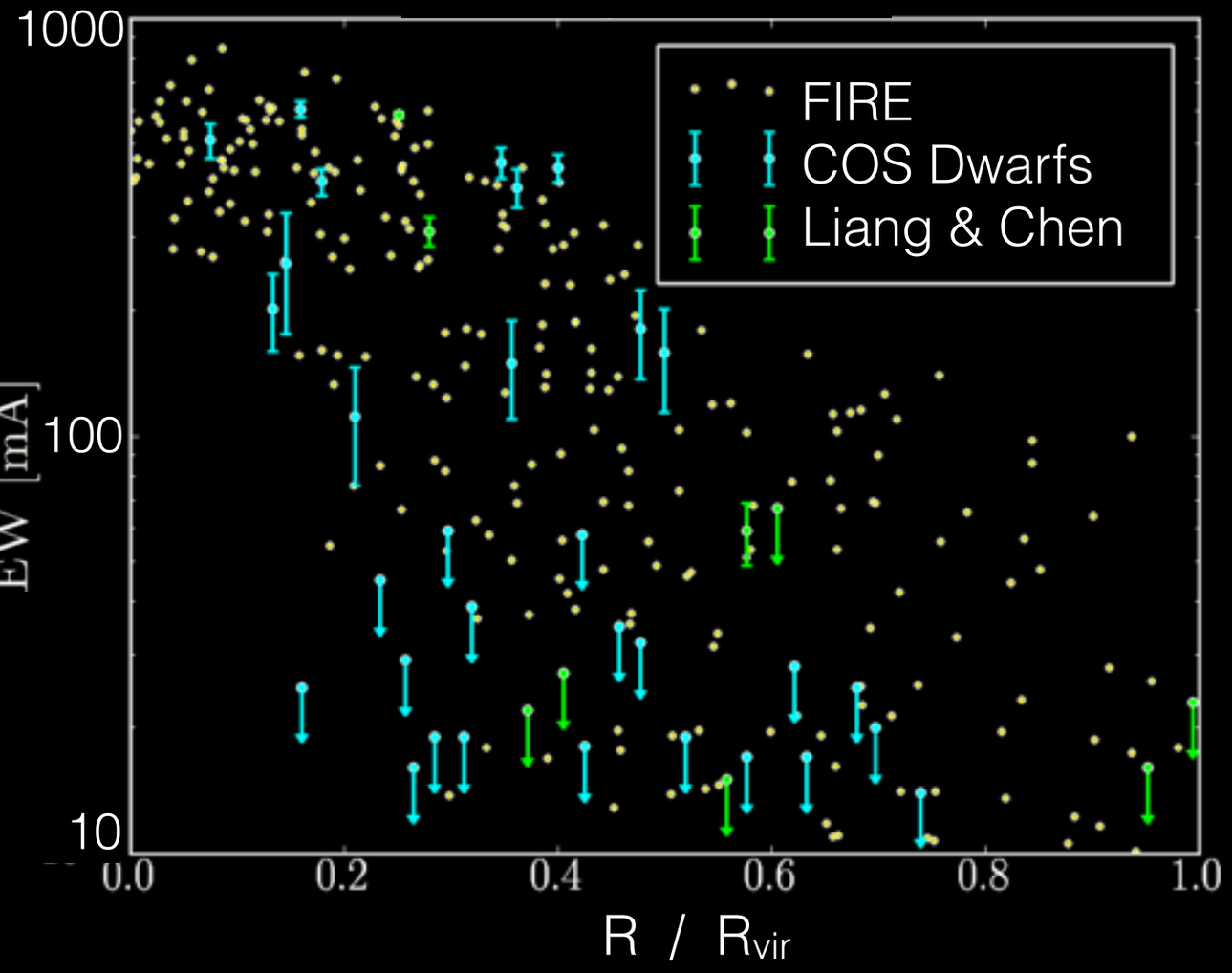


- Where they are (stars/ISM/CGM) is more sensitive

Metals in the CGM at Dwarf Masses

RELATED TO BURSTY STAR FORMATION





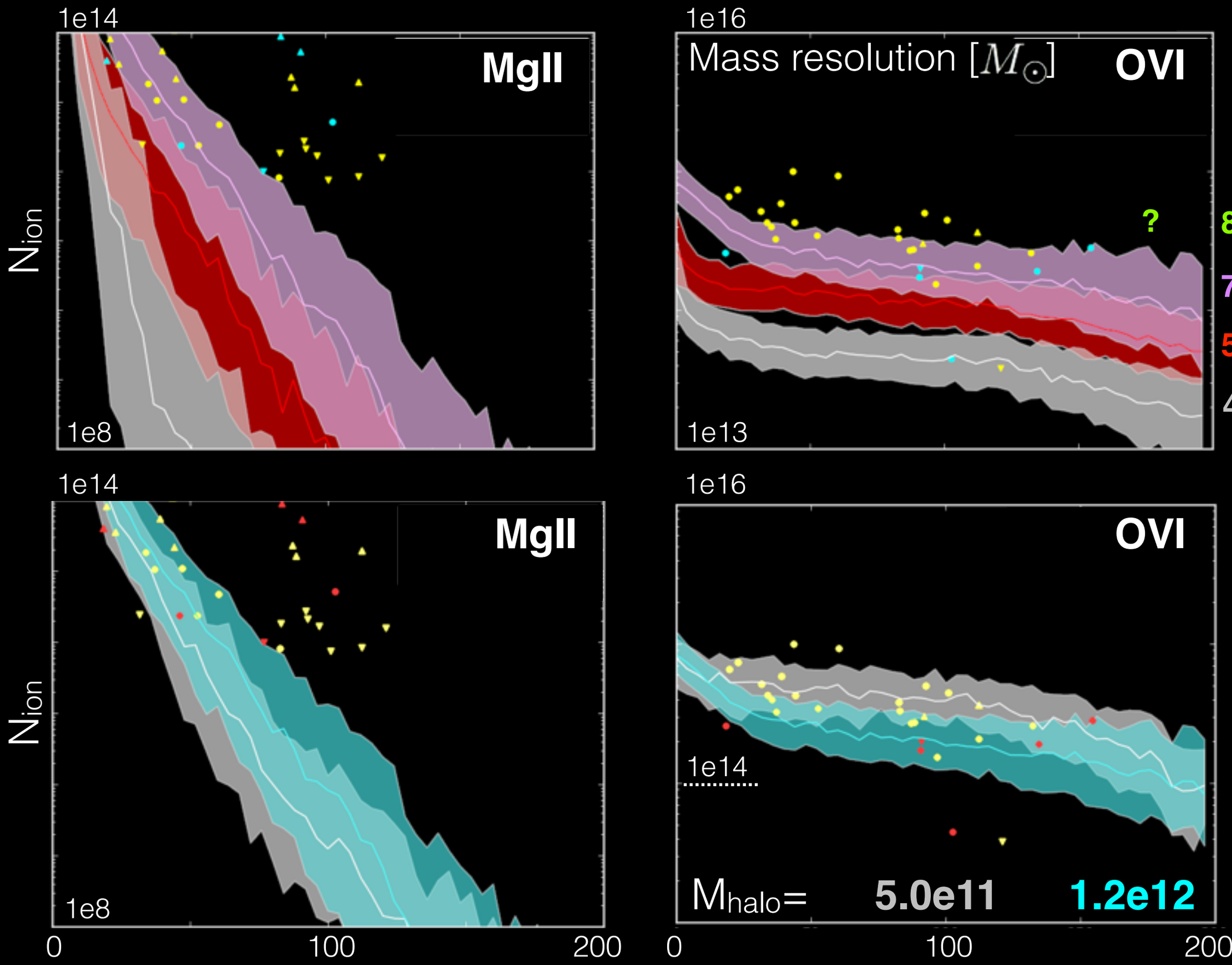
- Resolutions are good (~30 - 7000 M_{sun}): appears converged
- Weaker “quiescent” = lack of winds

Li, Murray, CAFG, PFH+ (in prep)

Metals in the CGM at L*: Resolution Matters

MASS DOES TOO

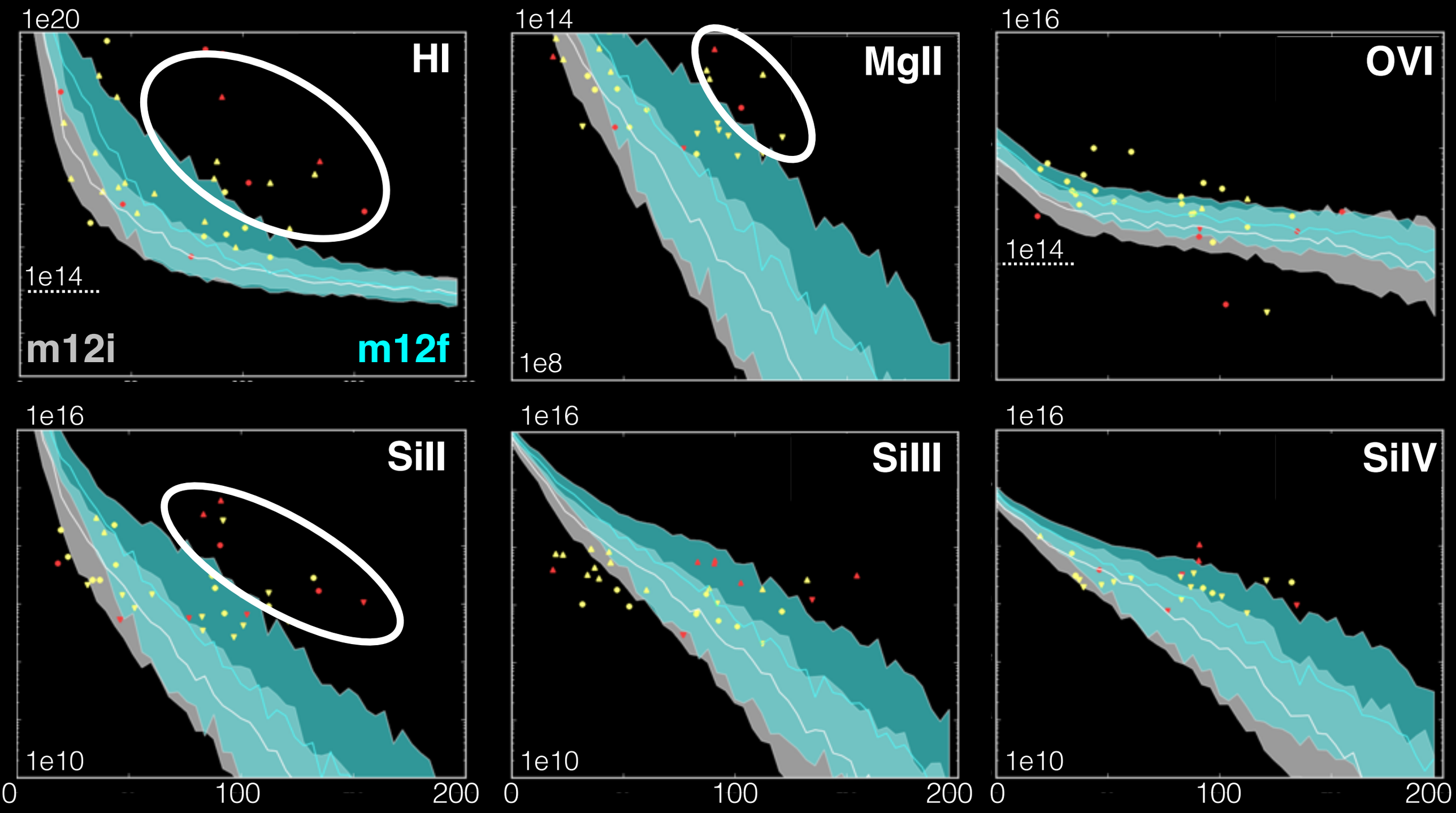
Cameron Hummels (in prep)

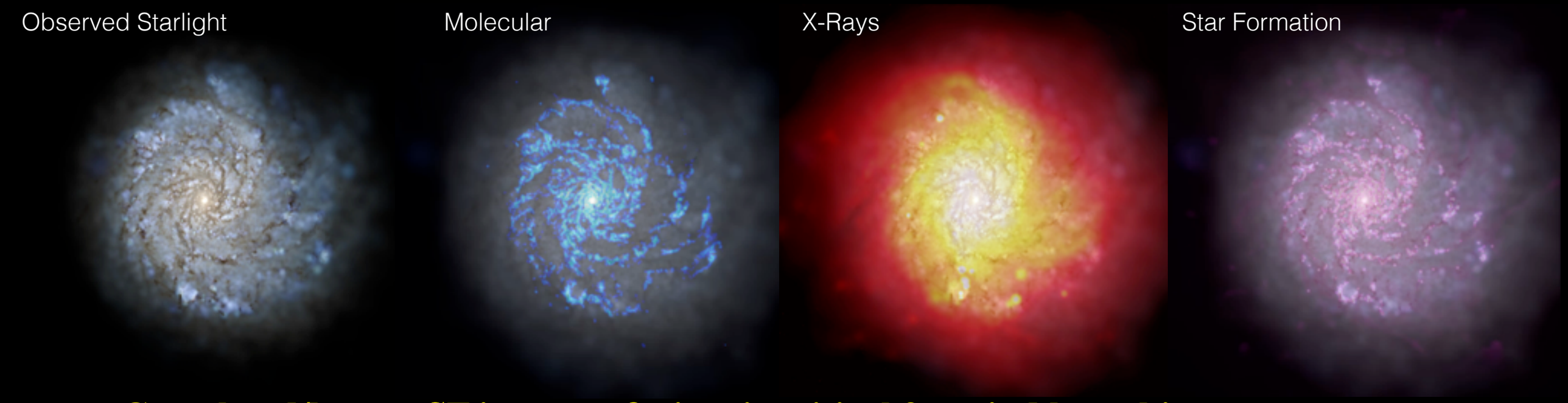


Dense, Low Ions at >100 kpc Still a Problem

BUT HIGH-IONS & LOW-DENSITY LOW-IONS EMERGING

Cameron Hummels (in prep)





- **Correlated/bursty SF in space & time is critical for wind launching**
  - Multi-phase ISM critical for SF clustering, mass & phases of outflow
  - Cool gas & metals primarily ejected in “bursty” mode
- **Winds = “suppressive” or “preventive” feedback in dwarfs**
  - Not all baryons cycle through galaxy
  - Suppressed baryon fraction, late-time accretion, angular momentum
- **Winds recycle many times**
  - Metals all trapped in CGM [except small dwarfs]
  - Reprocessed wind + “transfer”/stolen material dominate late accretion
- **Massive galaxies transition to “calm” mode late**
  - Thick [formed in-situ in “bursty” mode] to thin disk transition
  - Winds less efficient, esp. for cool gas & metals
- **Simulations reaching warm ions, resolution key for CGM+Wind structure**