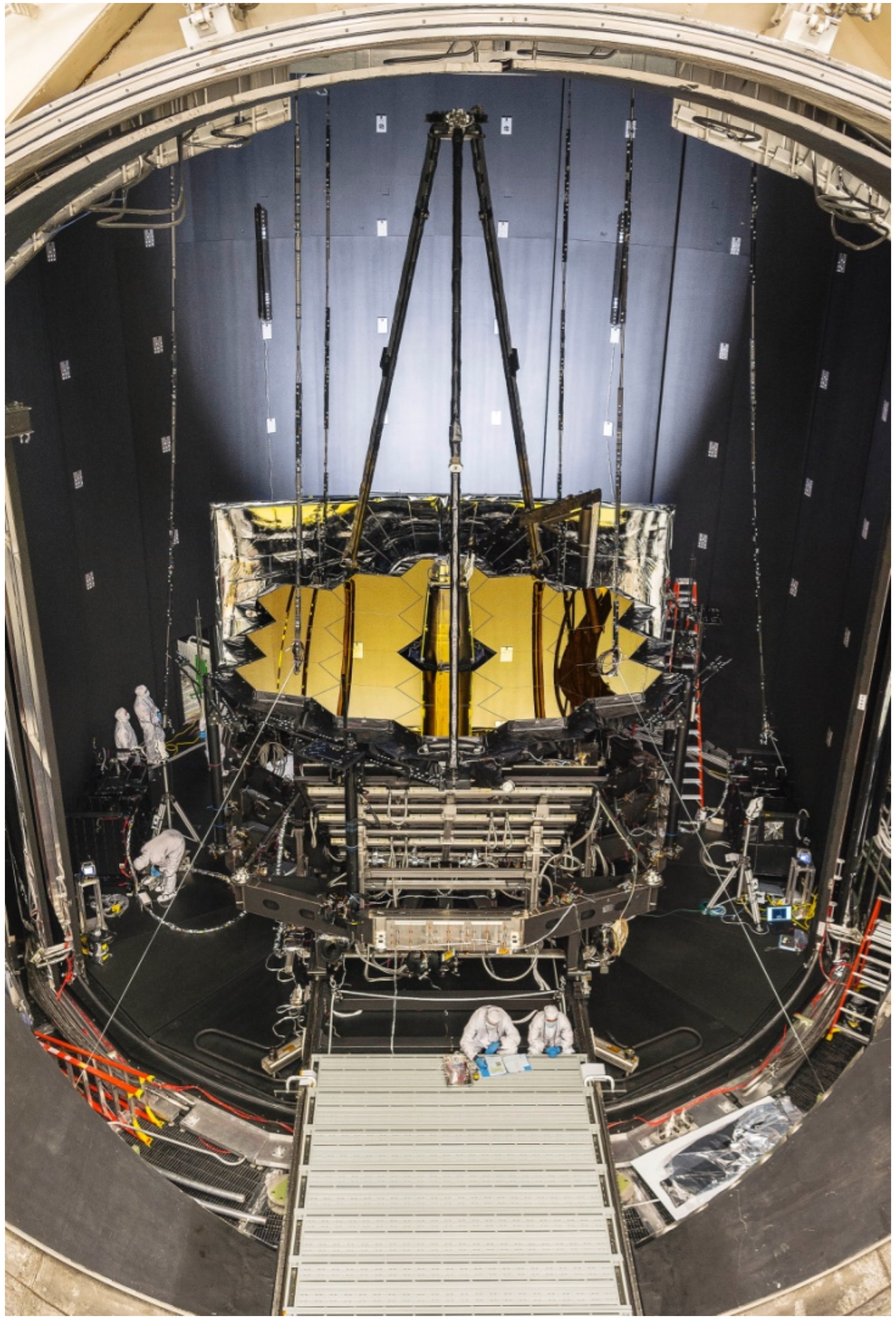
Circumgalactic Matters

Ann Field (STScI)

ARA&A 2017
Jason Tumlinson (STScI)
Molly Peeples (STScI)
& Jessica Werk (UW)

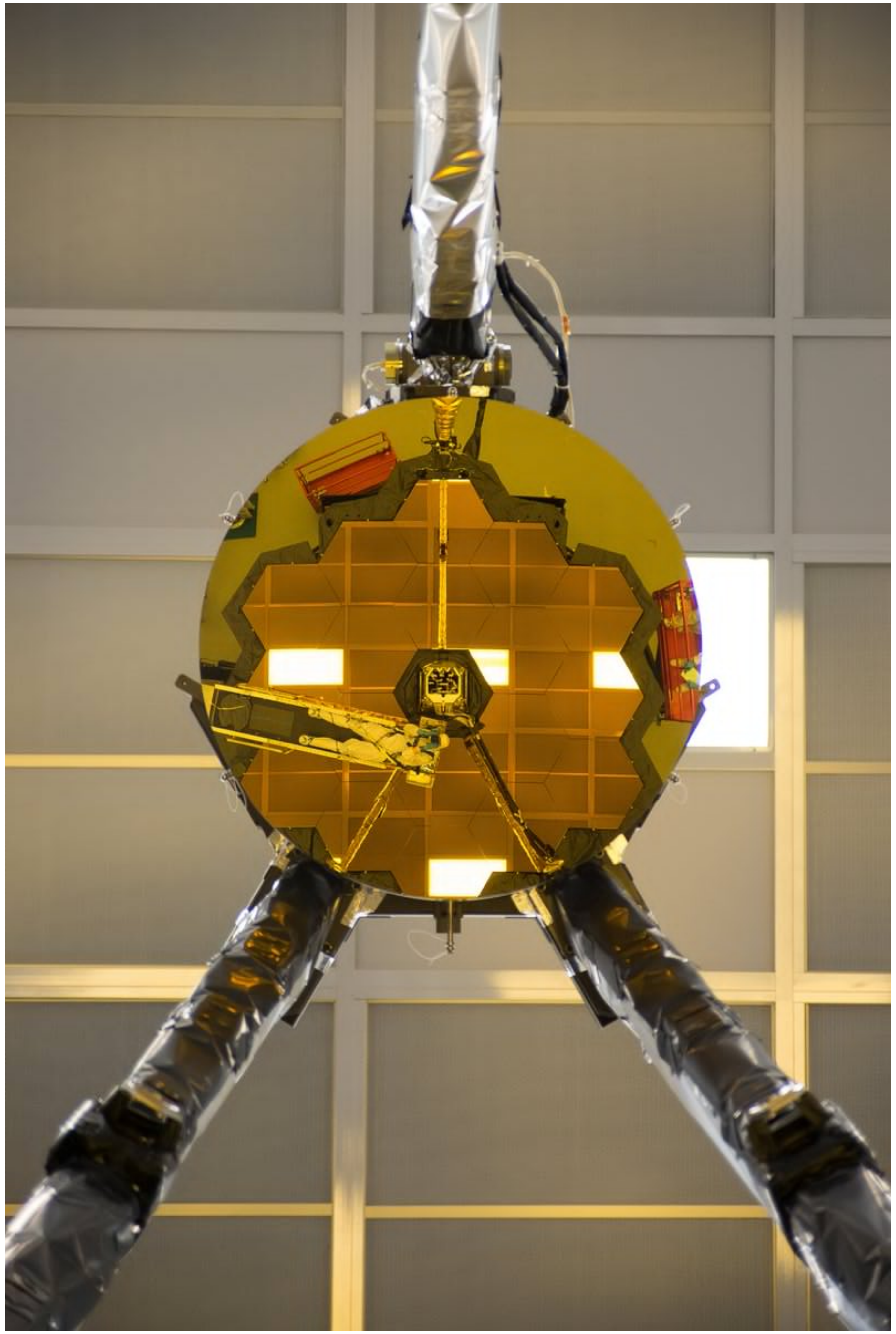


JWST

entering cryo tests at Johnson Space Center in Houston

Launch
Oct 2018

Cycle 1
proposals
due March 2018



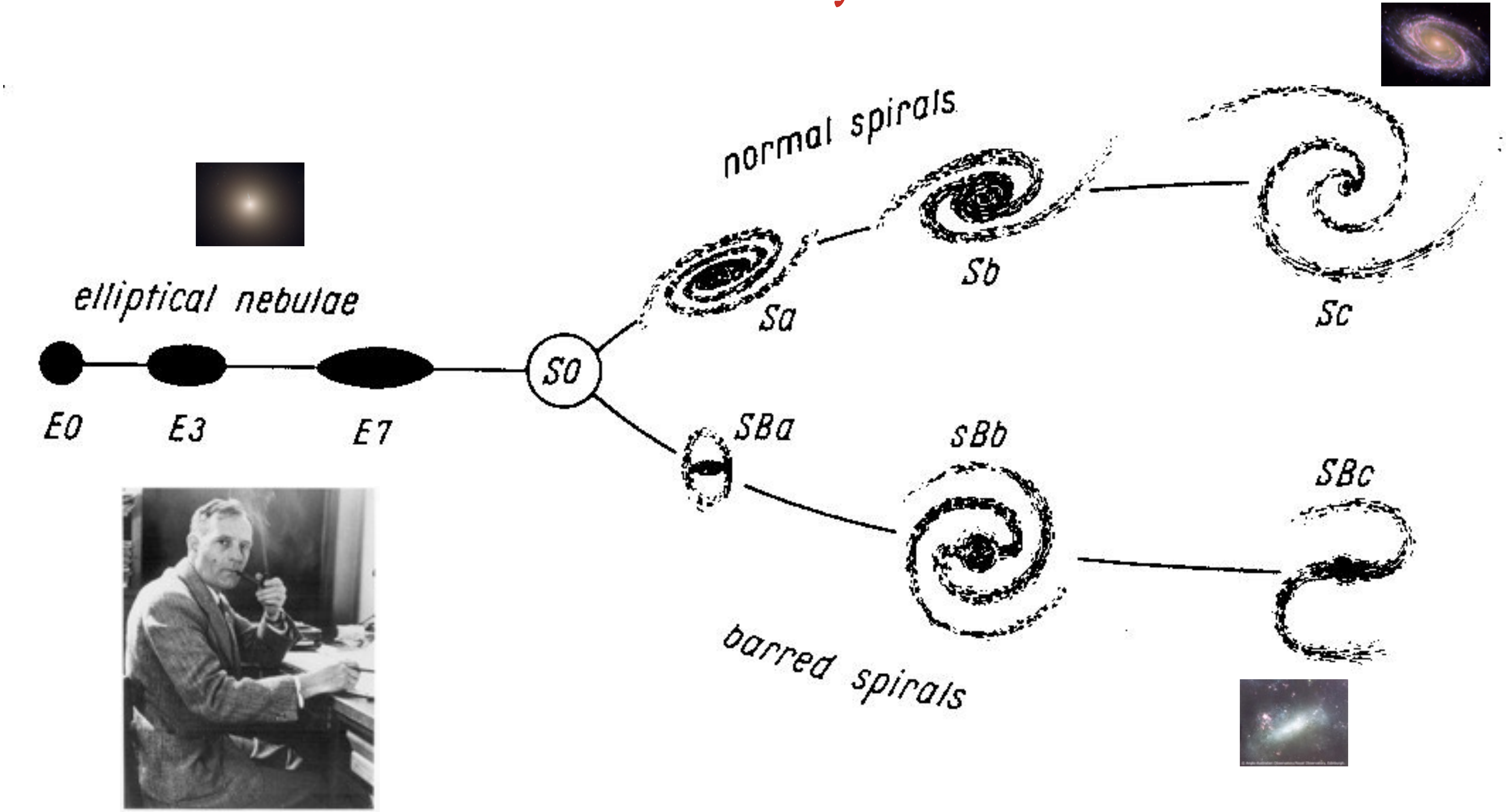
forge: v

1. to make, fashion, frame, or construct (any material thing)

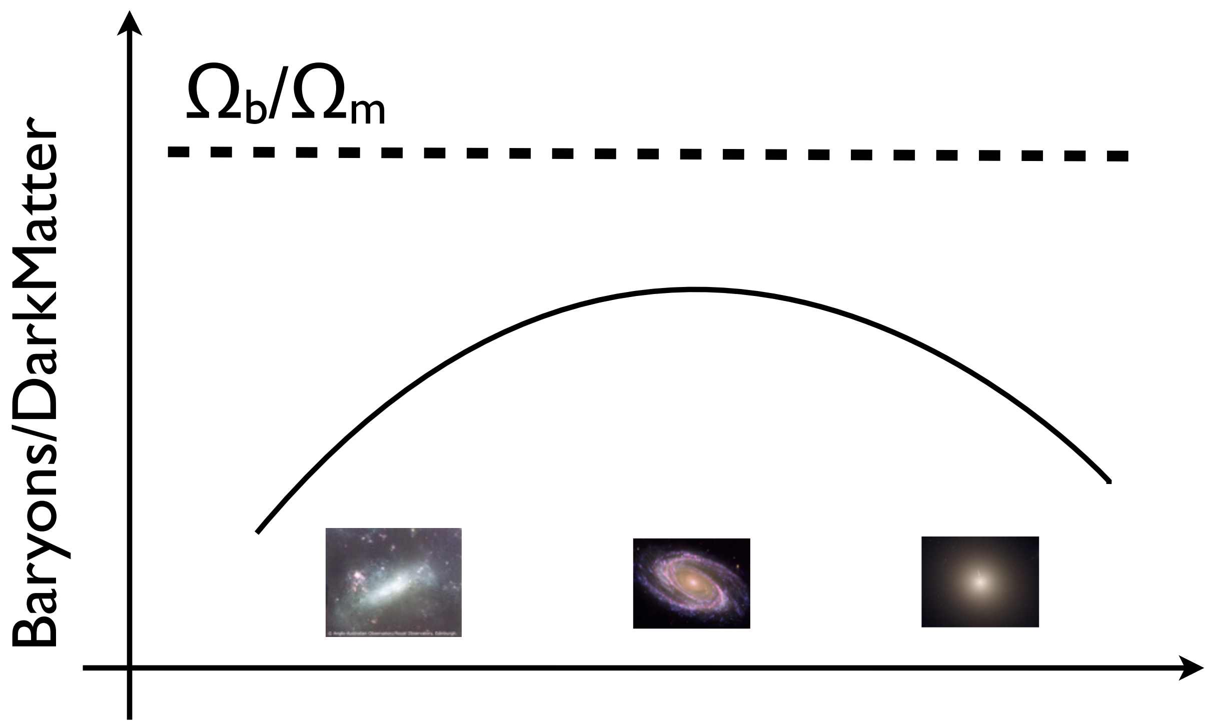
2. To fabricate, frame, invent (a false or imaginary story, lie, etc.); to devise (evil).

-Oxford English Dictionary

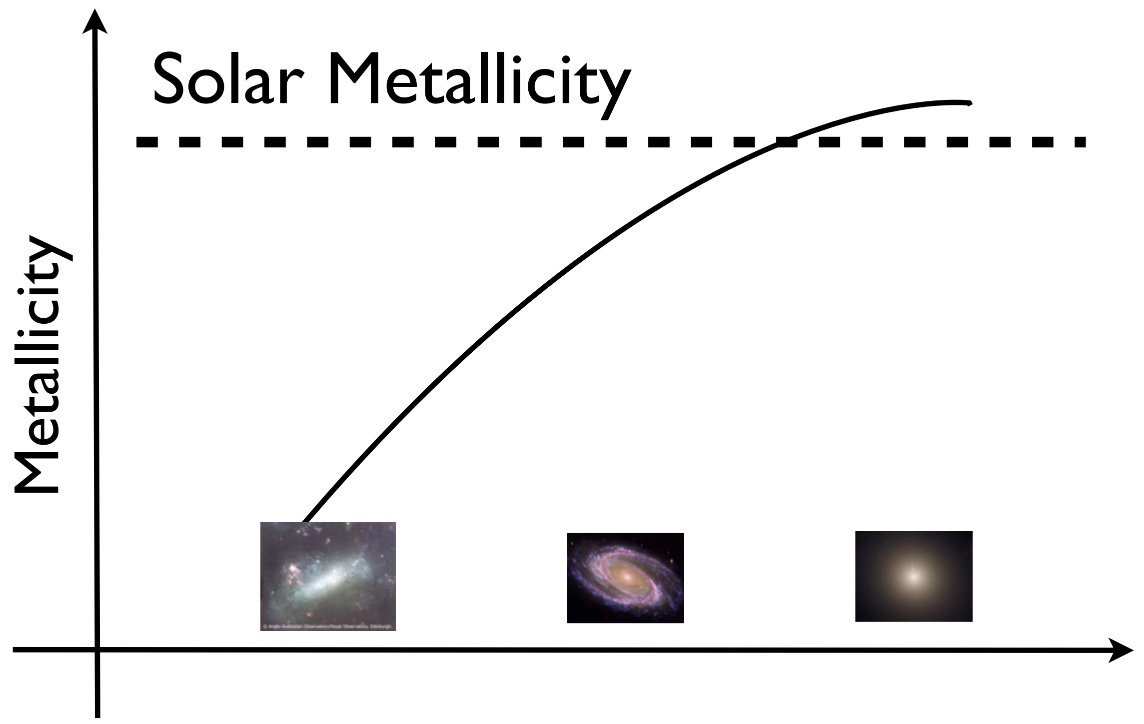
The Basic Puzzle: An early Hubble observation



Fundamental Problems in Galaxy Evolution



Why do galaxies appear to lack their full share of baryons?



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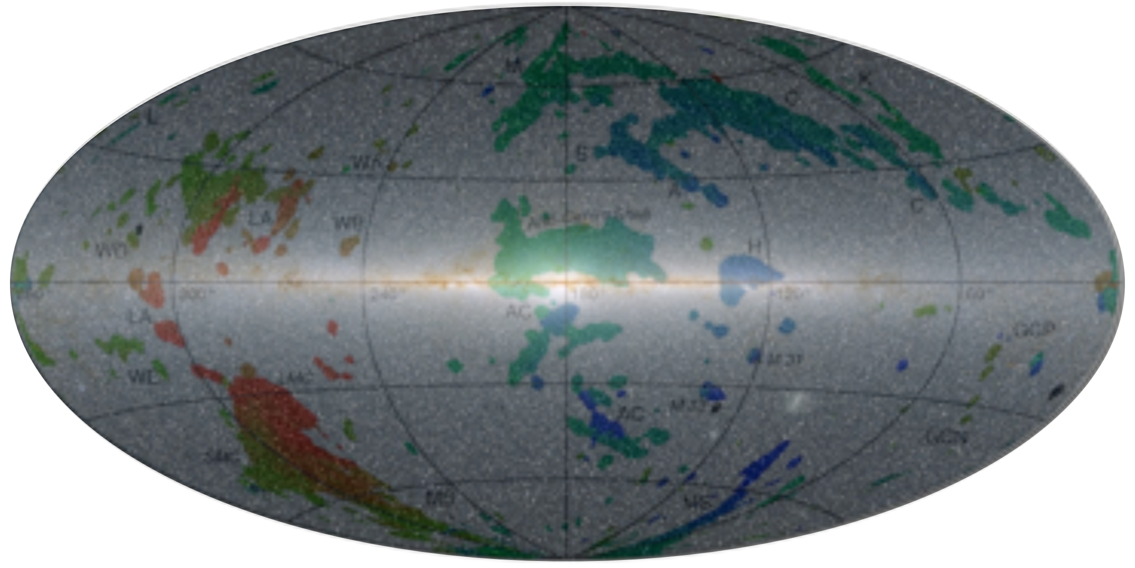
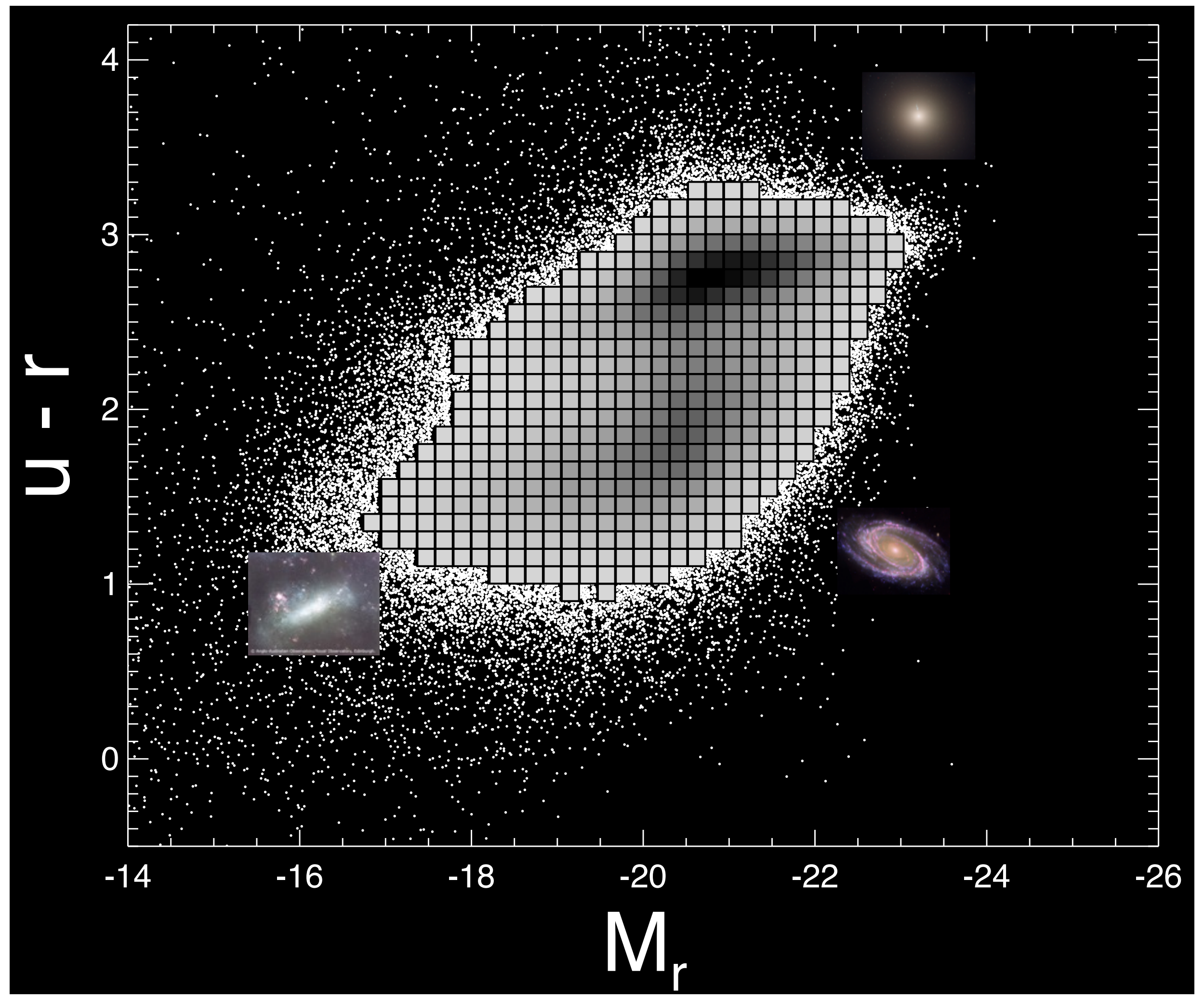
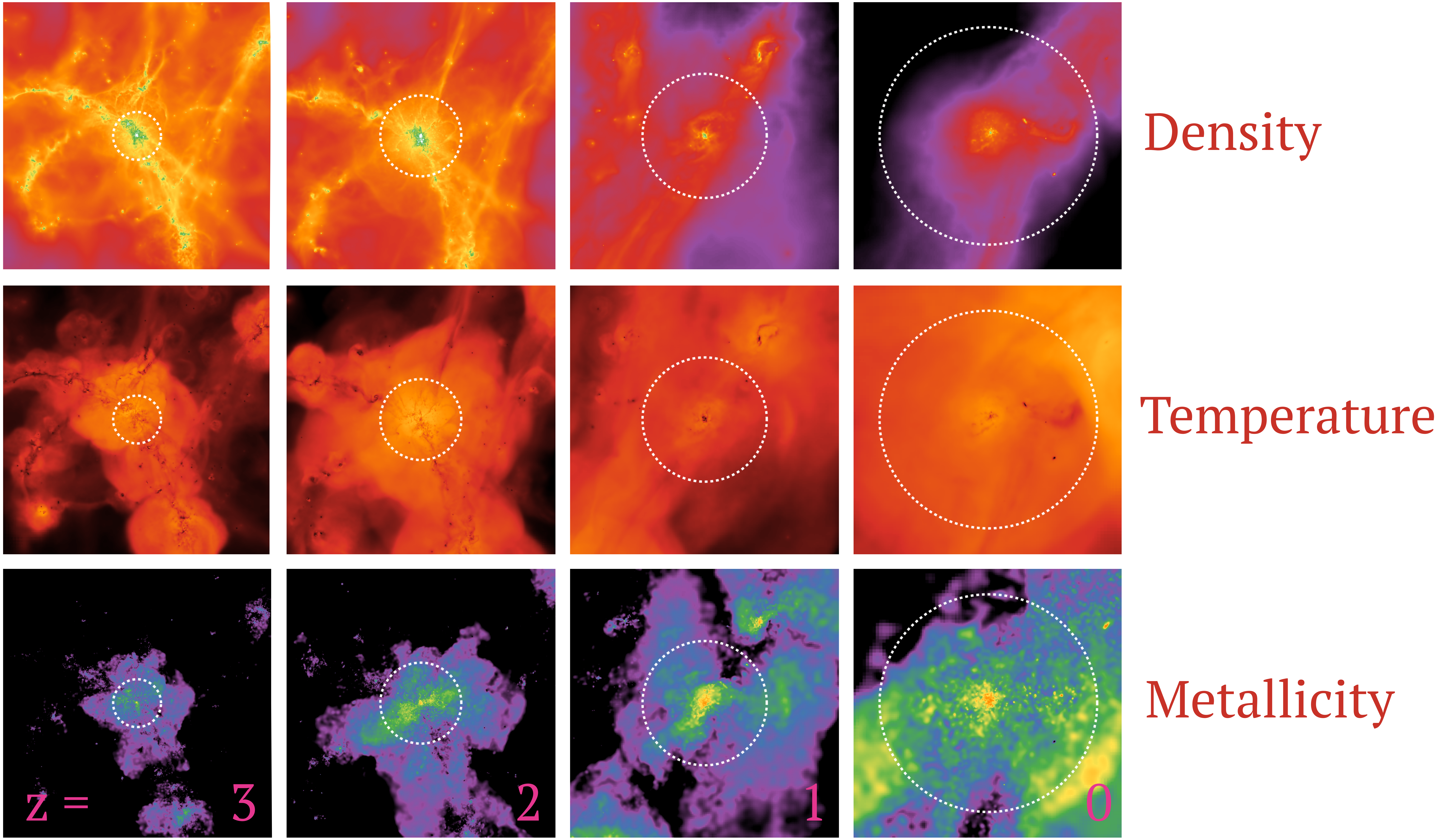
How is star formation sustained for 10 Gyr, if only 1 Gyr of gas is present now?

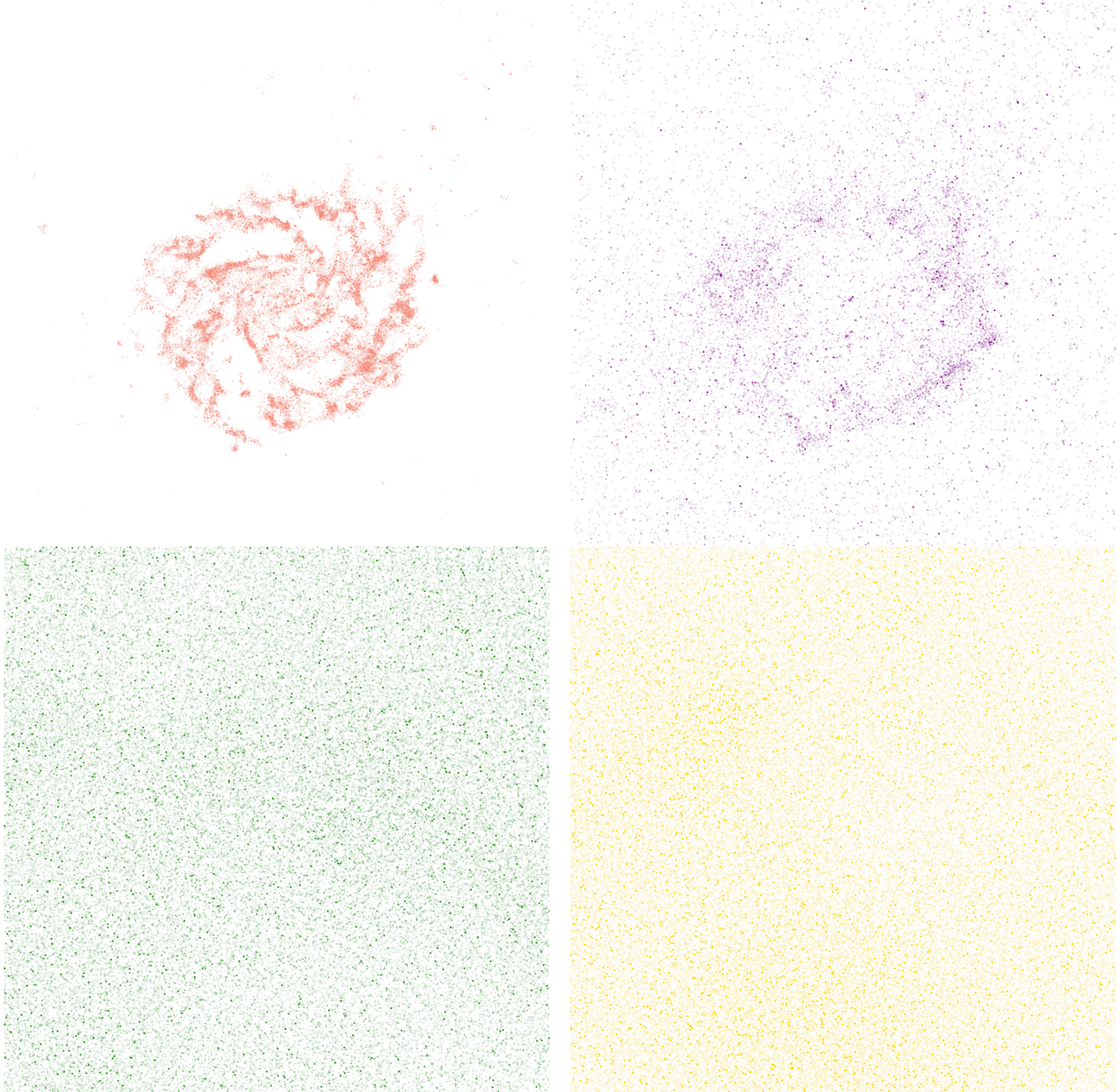


What quenches galaxies and keeps them that way?




Diffuse gas
Recycling gas
Accreting gas
15 kpc
Outflows
300 kpc


Density
Temperature
Metallicity
z = 3
2
1
0



Hot $>10^6$ K

Warm $10^{5\text{-}6}$ K

Cool $10^{4\text{-}5}$ K

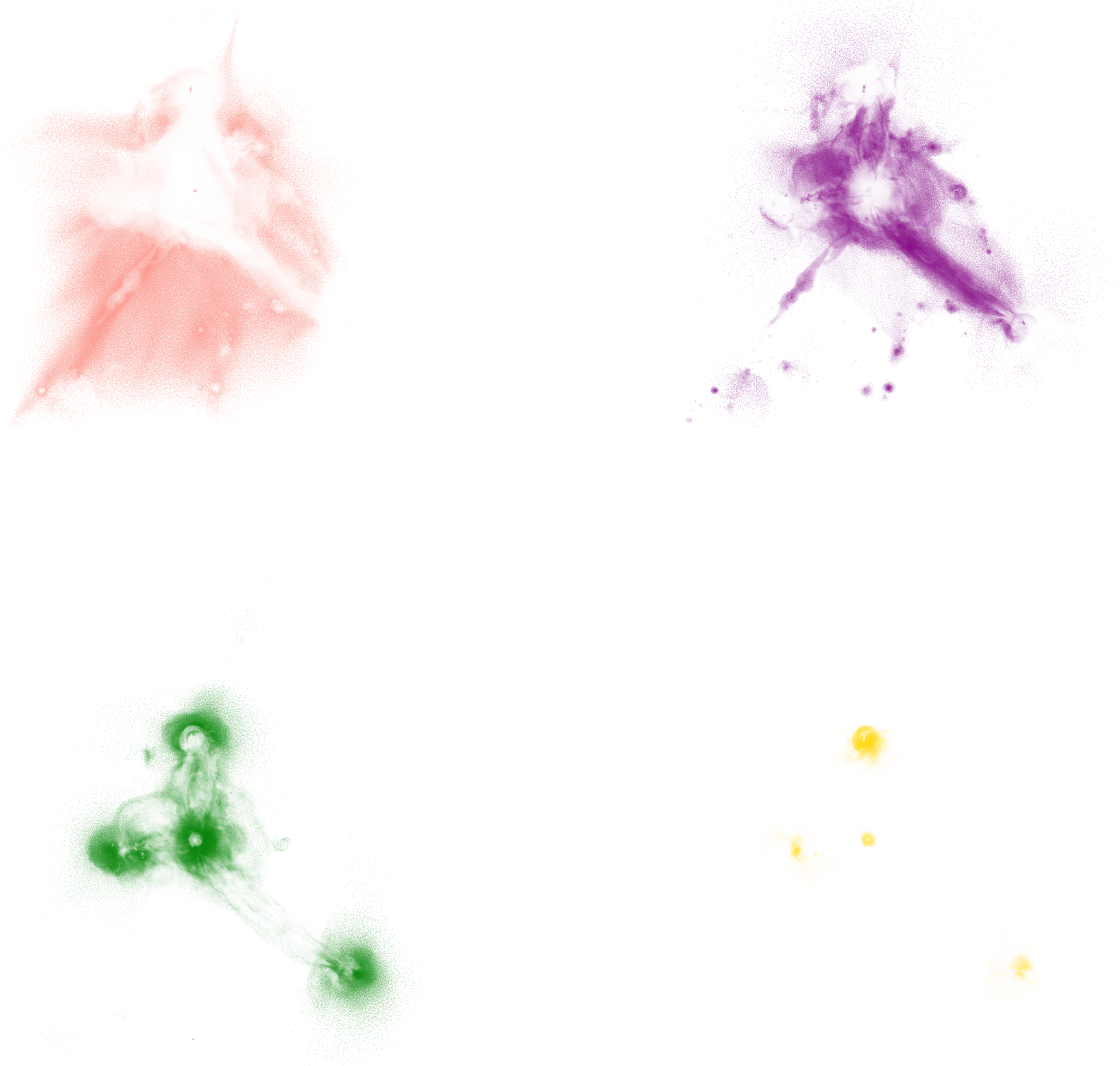
Cold $<10^4$ K

Hot $>10^{6}$ K

Warm 10^{5-6} K

Cool 10^{4-5} K

Cold $<10^{4}$ K



Hot $>10^6$ K

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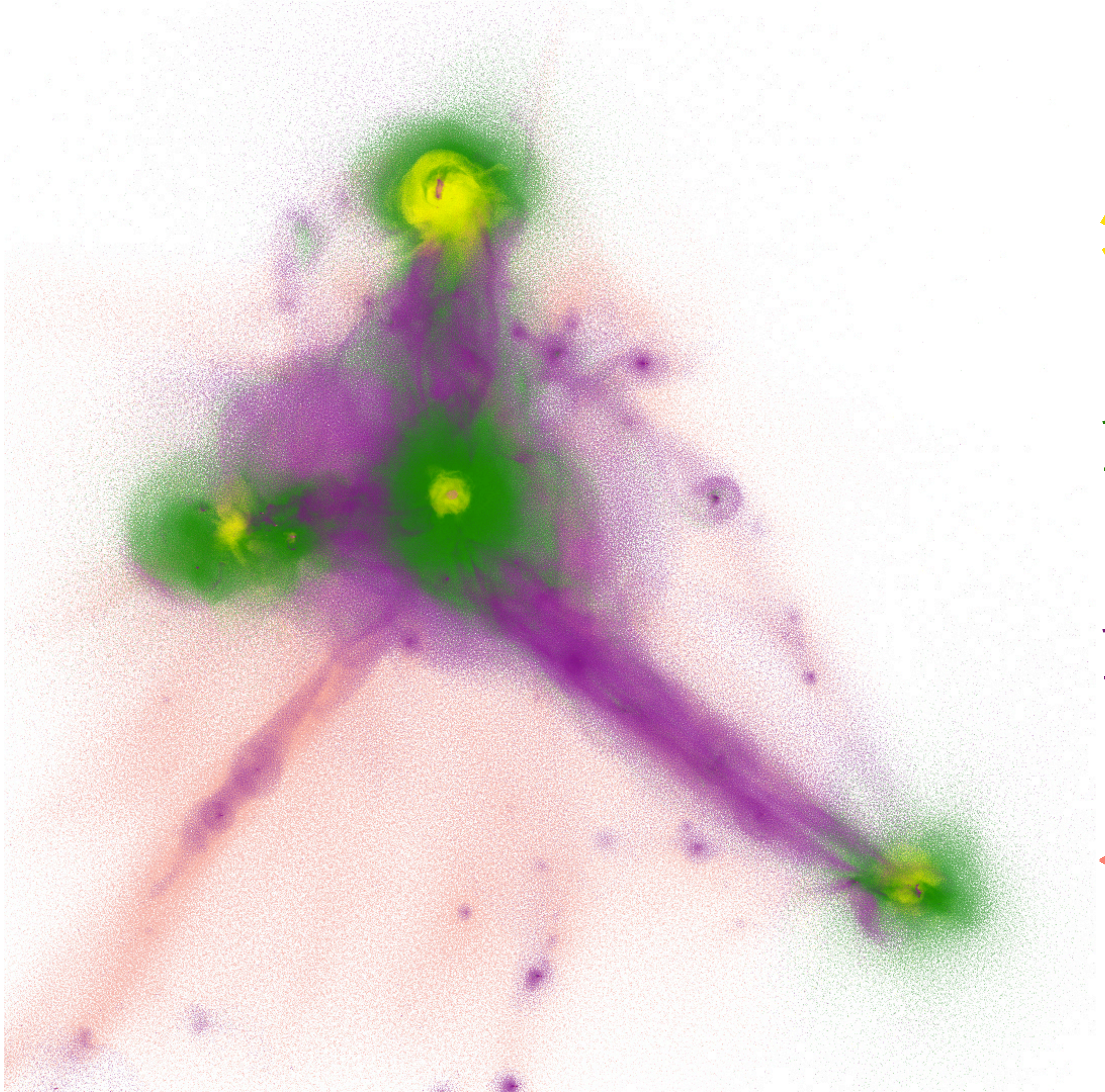
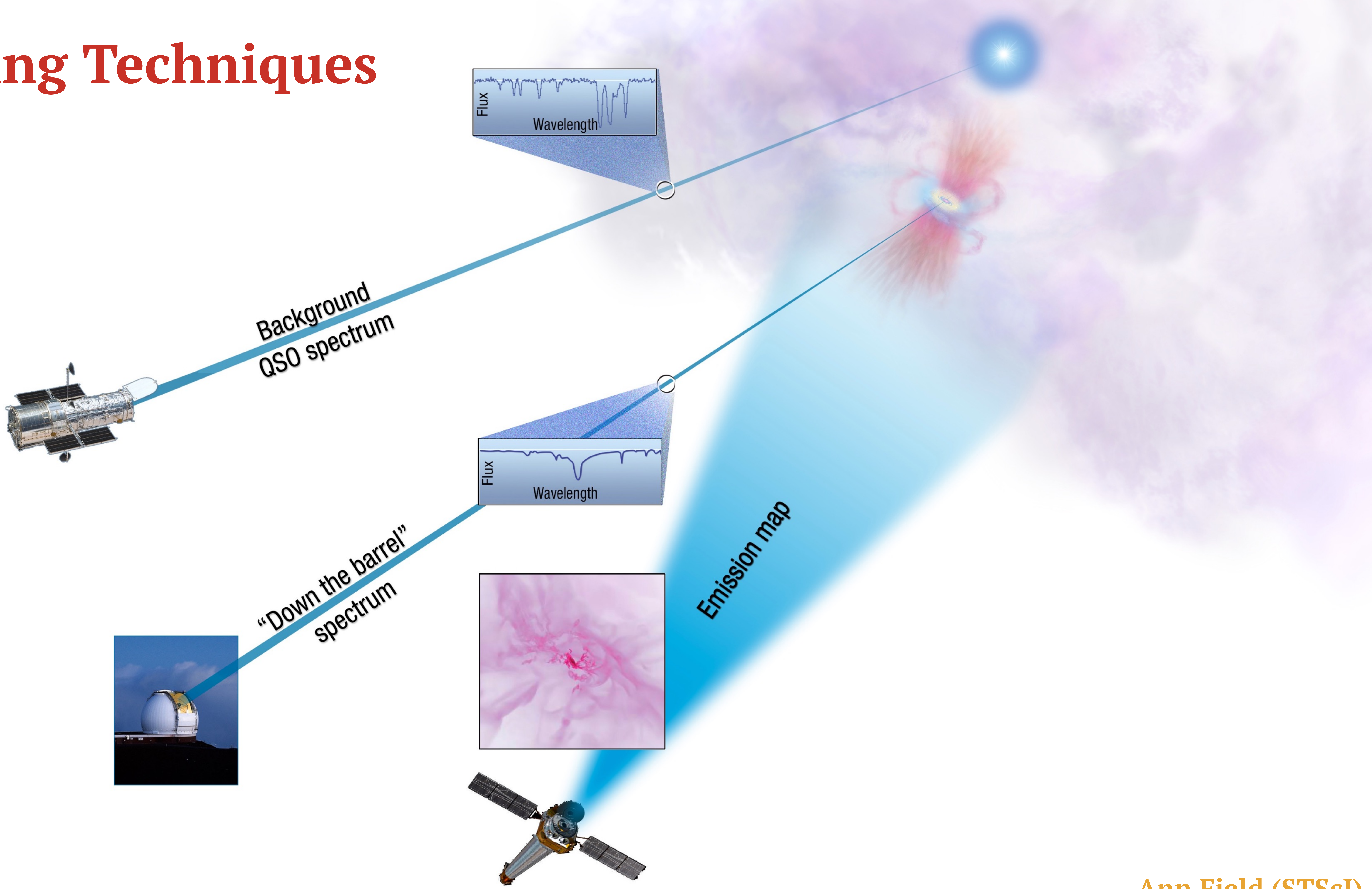


Observing Techniques



Ann Field (STScI)

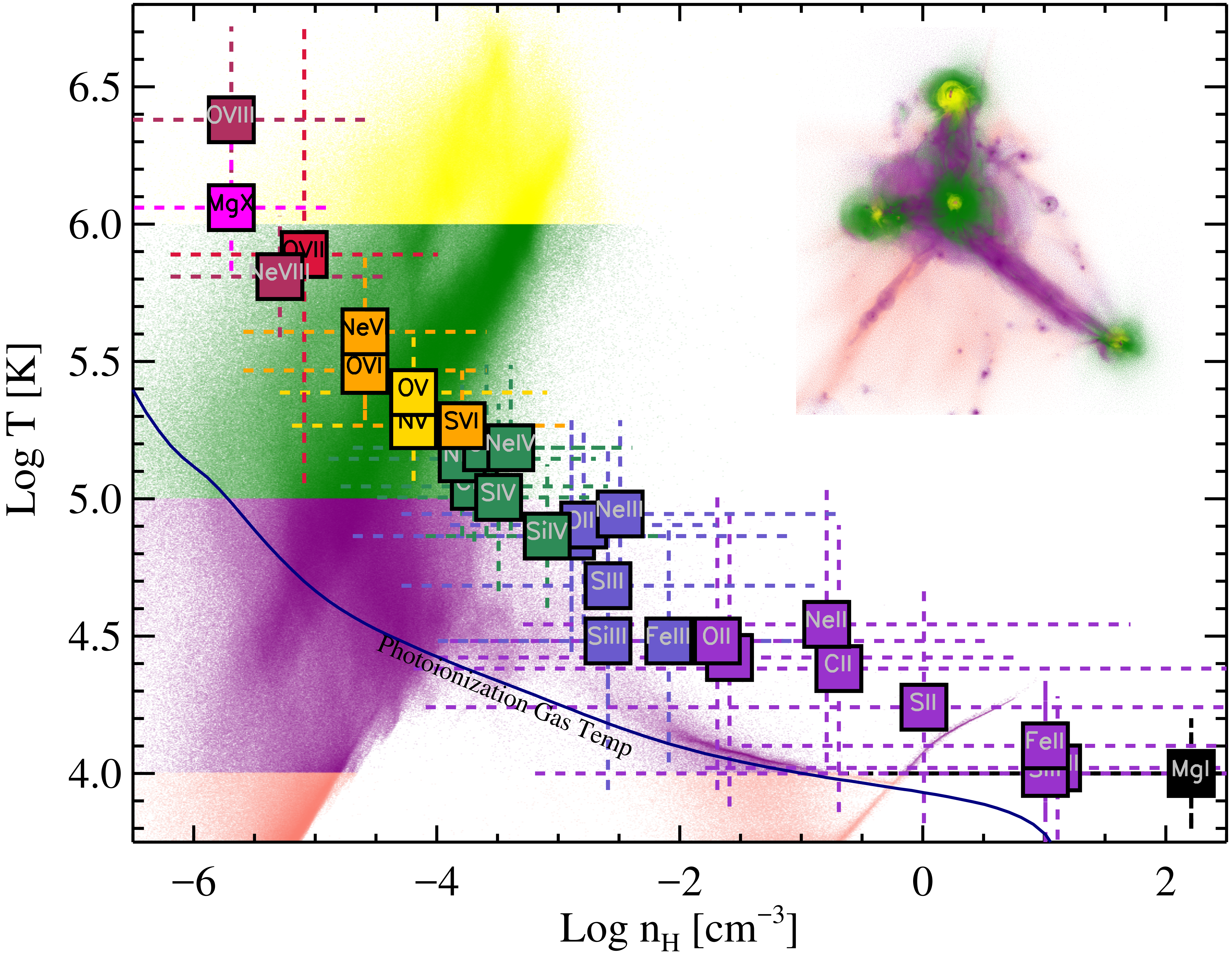
Phases and Diagnostics

Hot

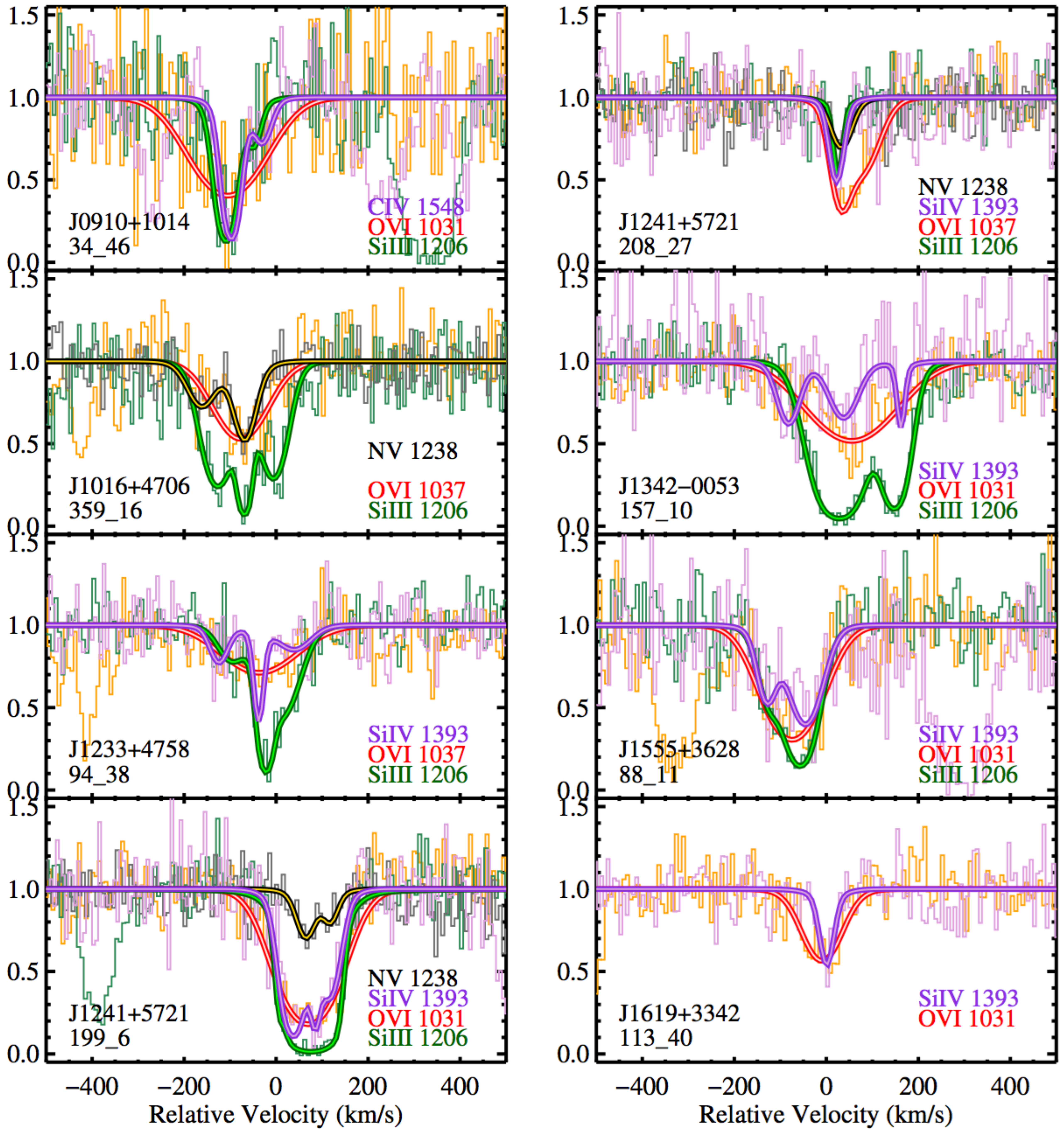
Warm

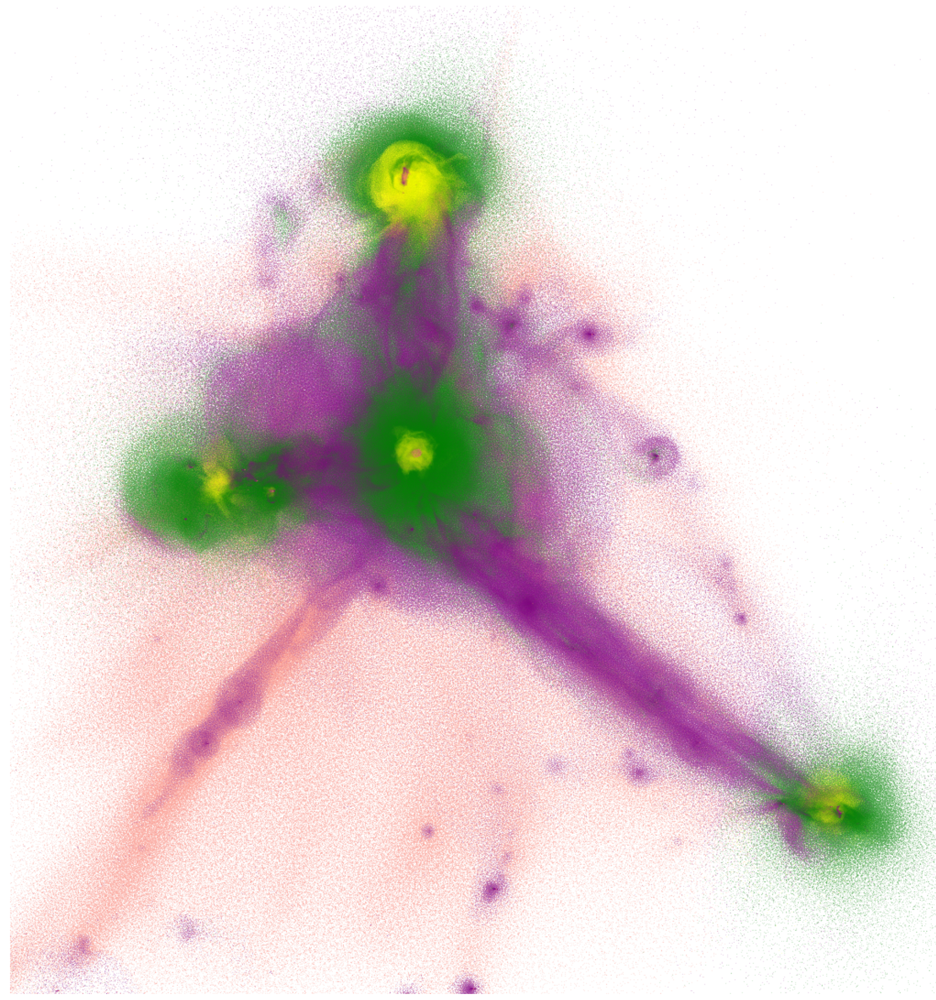
Cool

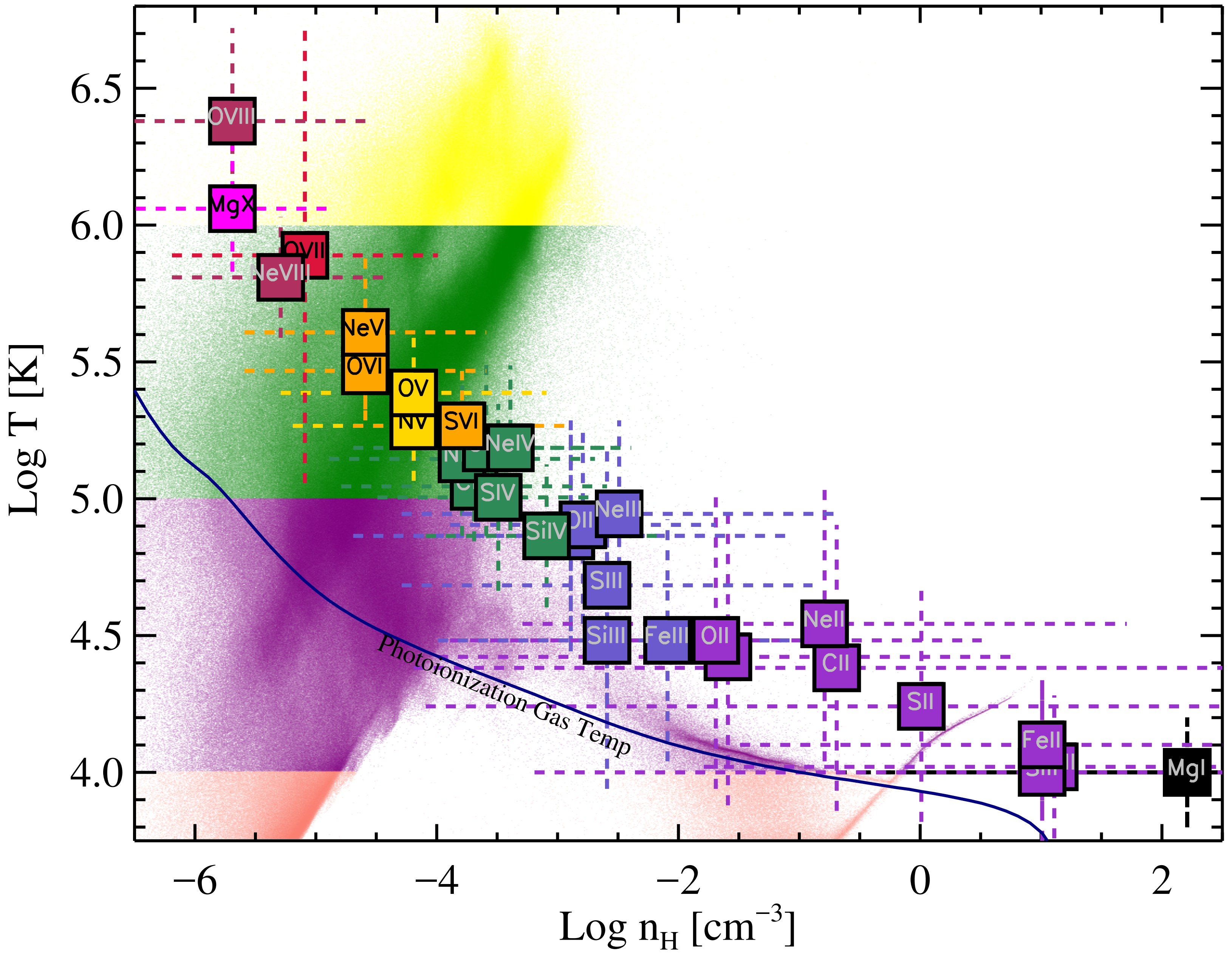
Cold

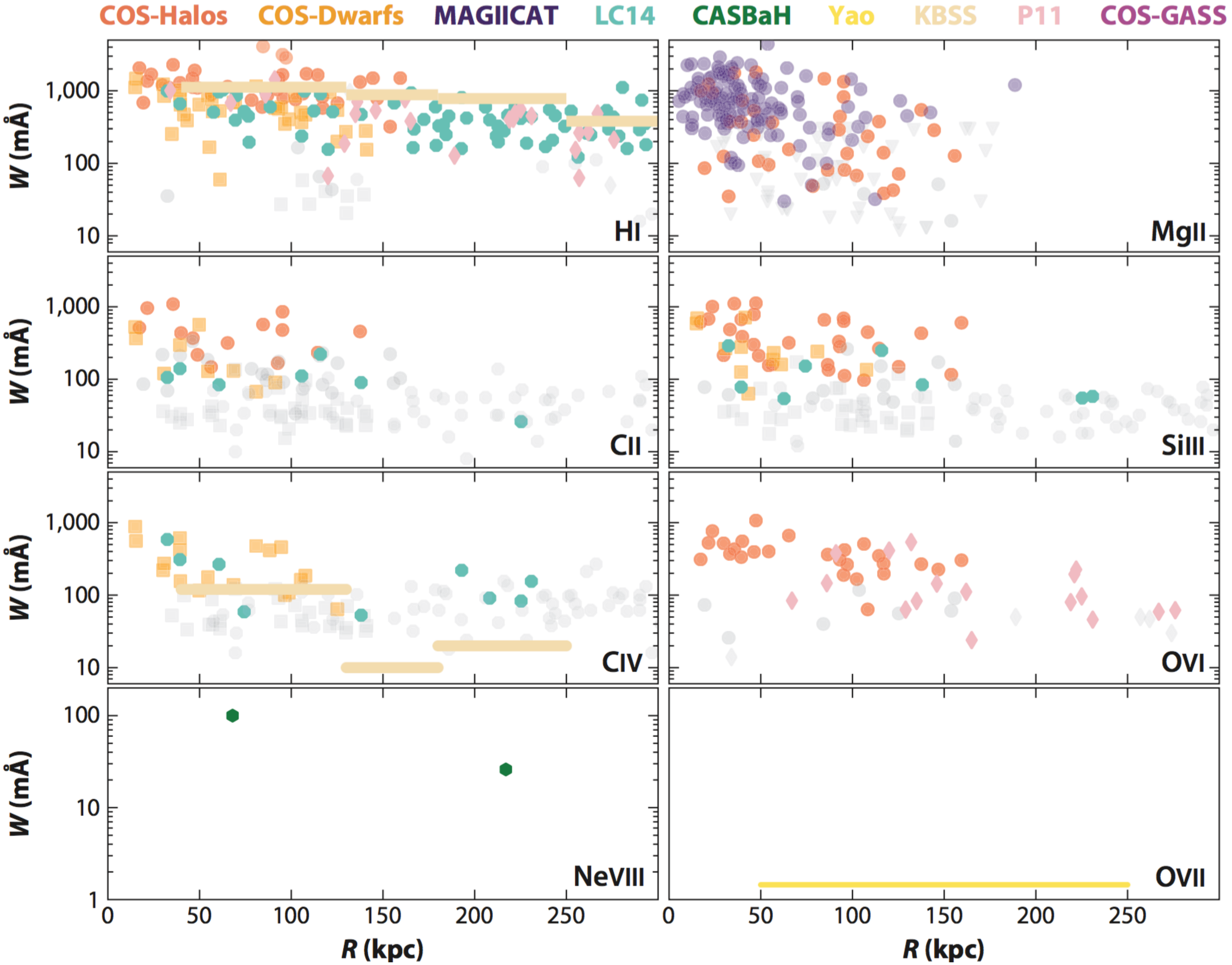


Absorbers and Phases



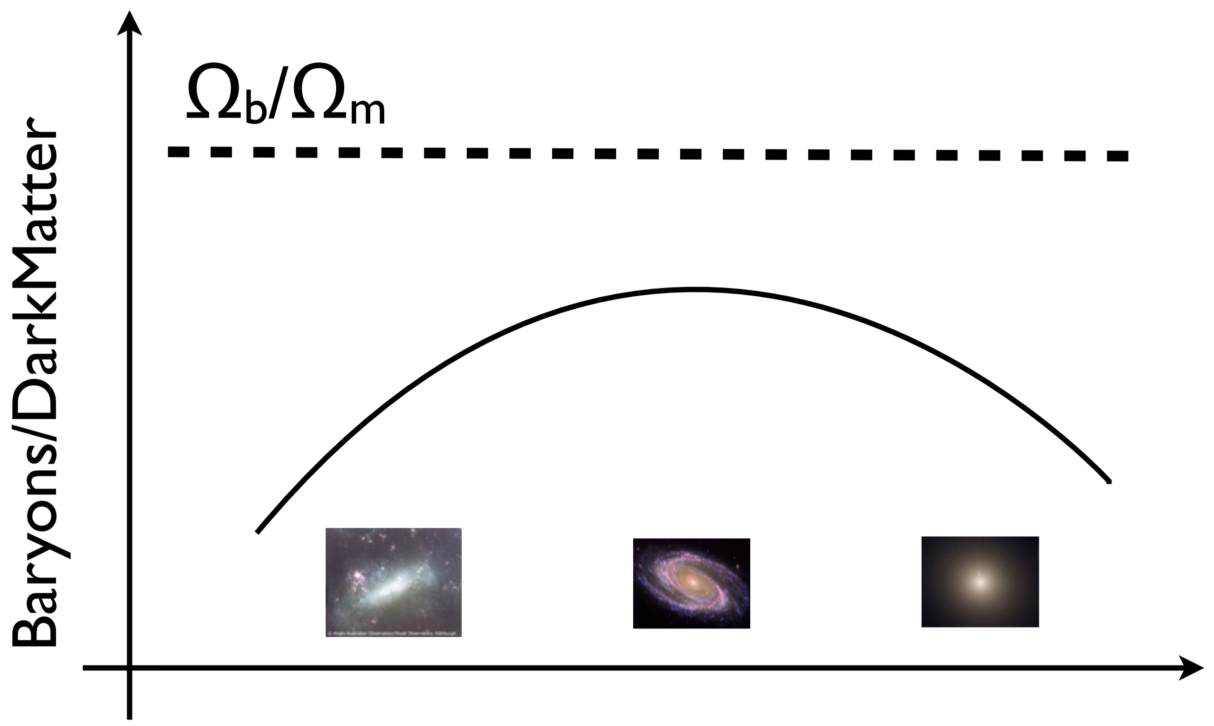






COS-Halos
COS-Dwarfs
MAGIICAT
LC14
CASBaH
Yao
KBSS
P11
COS-GASS
W (mÅ)
1,000
100
10
1
HI
MgII
CII
SiIII
CIV
OVI
NeVIII
OVII
0
50
100
150
200
250
R (kpc)

Fundamental Problems in Galaxy Evolution



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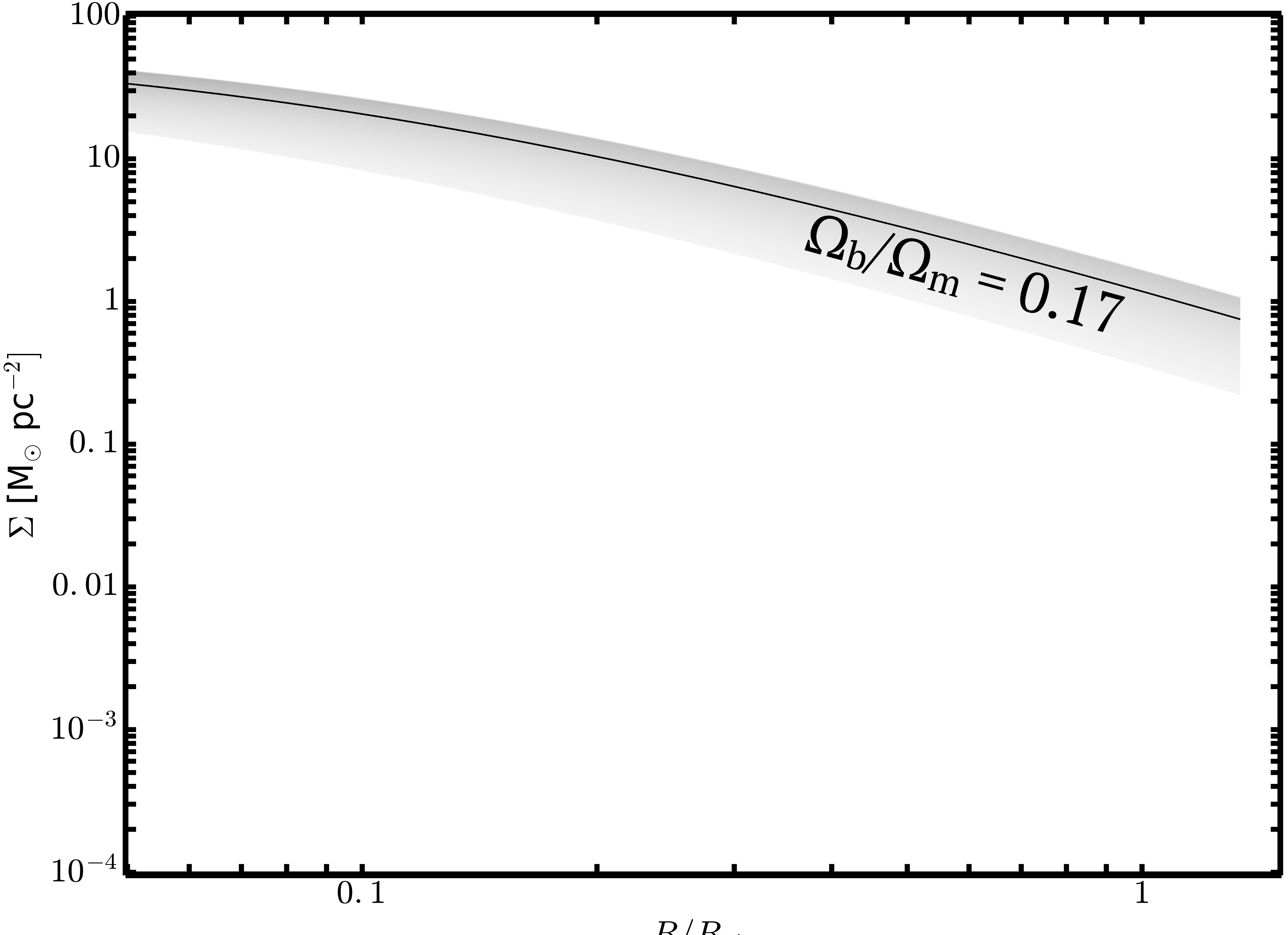
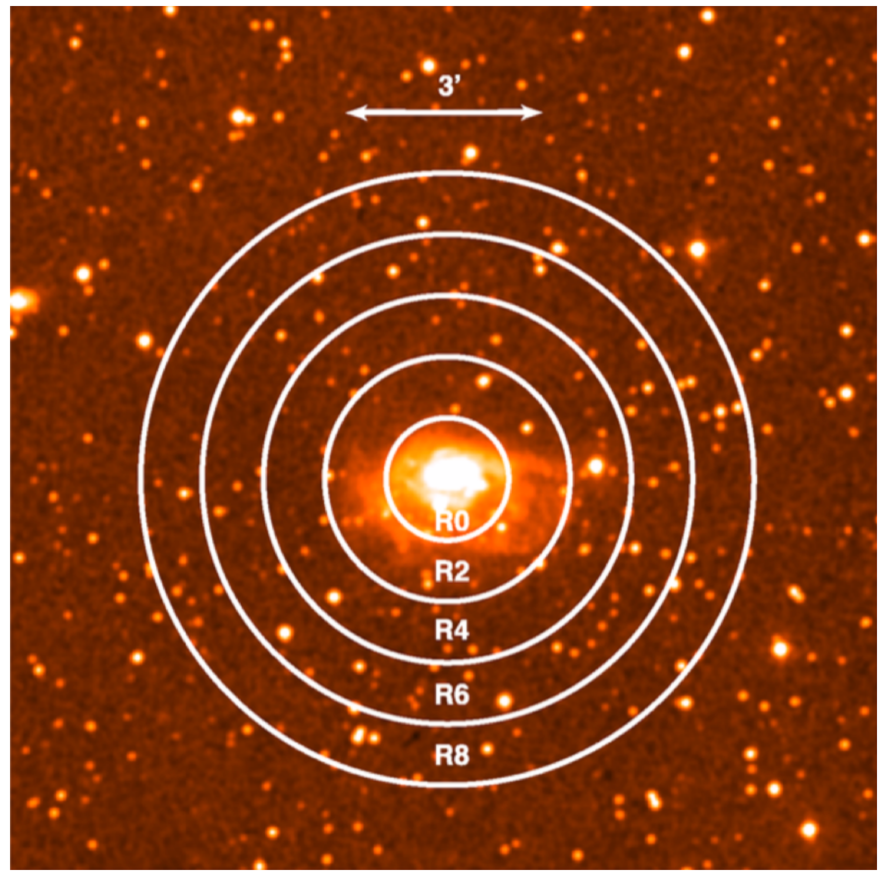
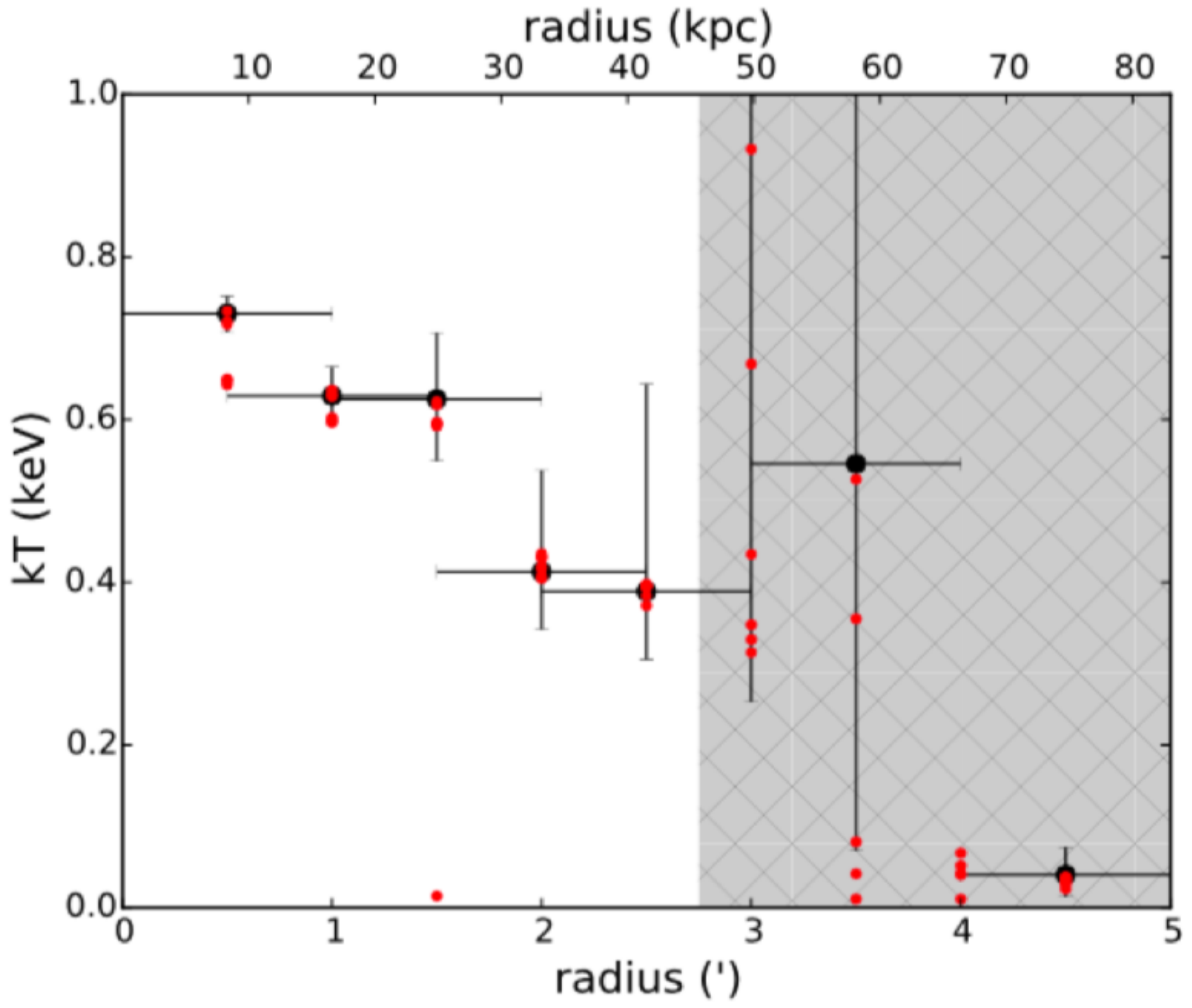


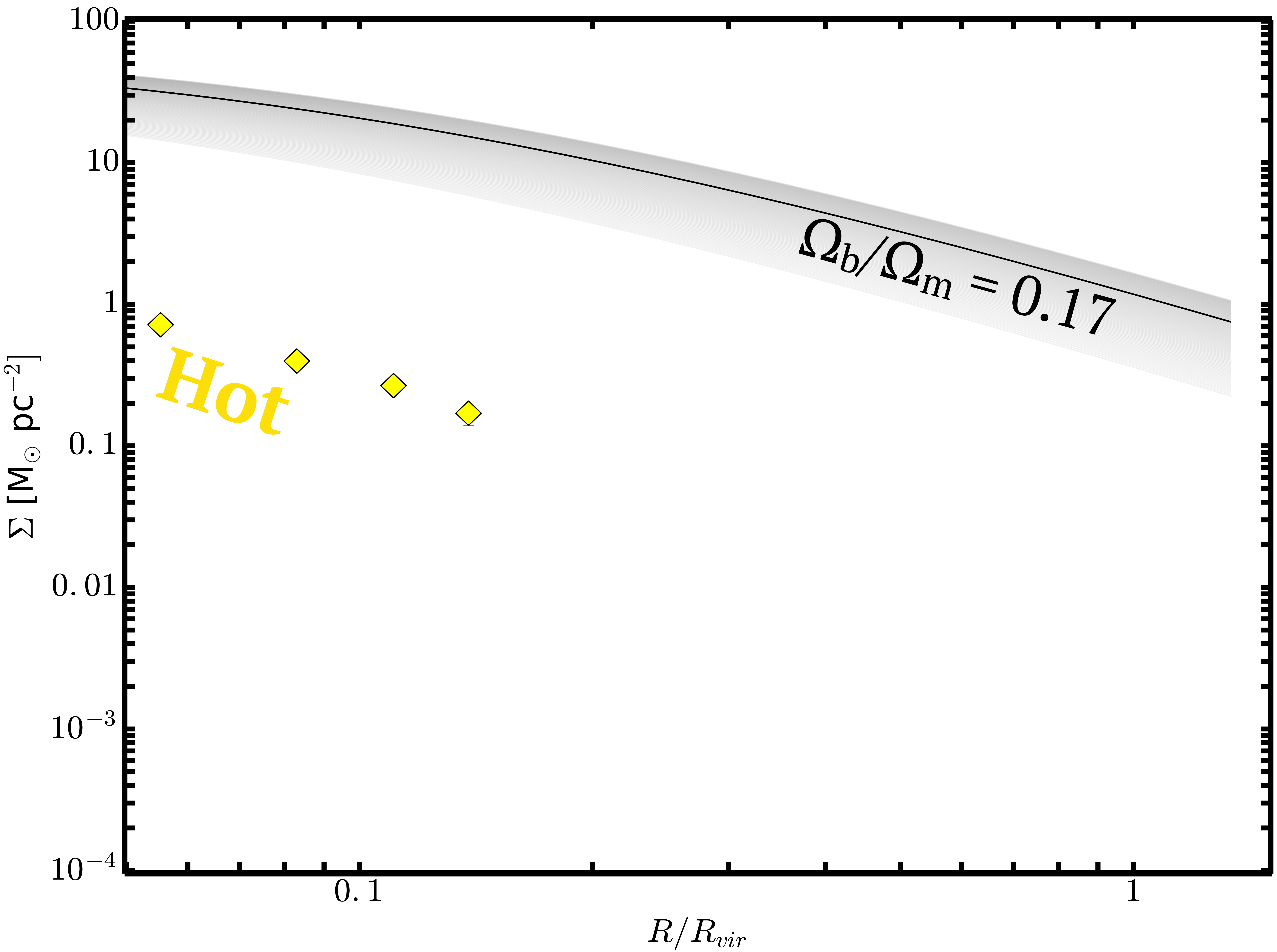
100
10
1
0.1
0.01
10^{-3}
10^{-4}
Σ [M$_\odot$ pc^{-2}]
0.1
1
R/R_{vir}
$\Omega_b/\Omega_m = 0.17$

X-Ray Maps of Hot Gas

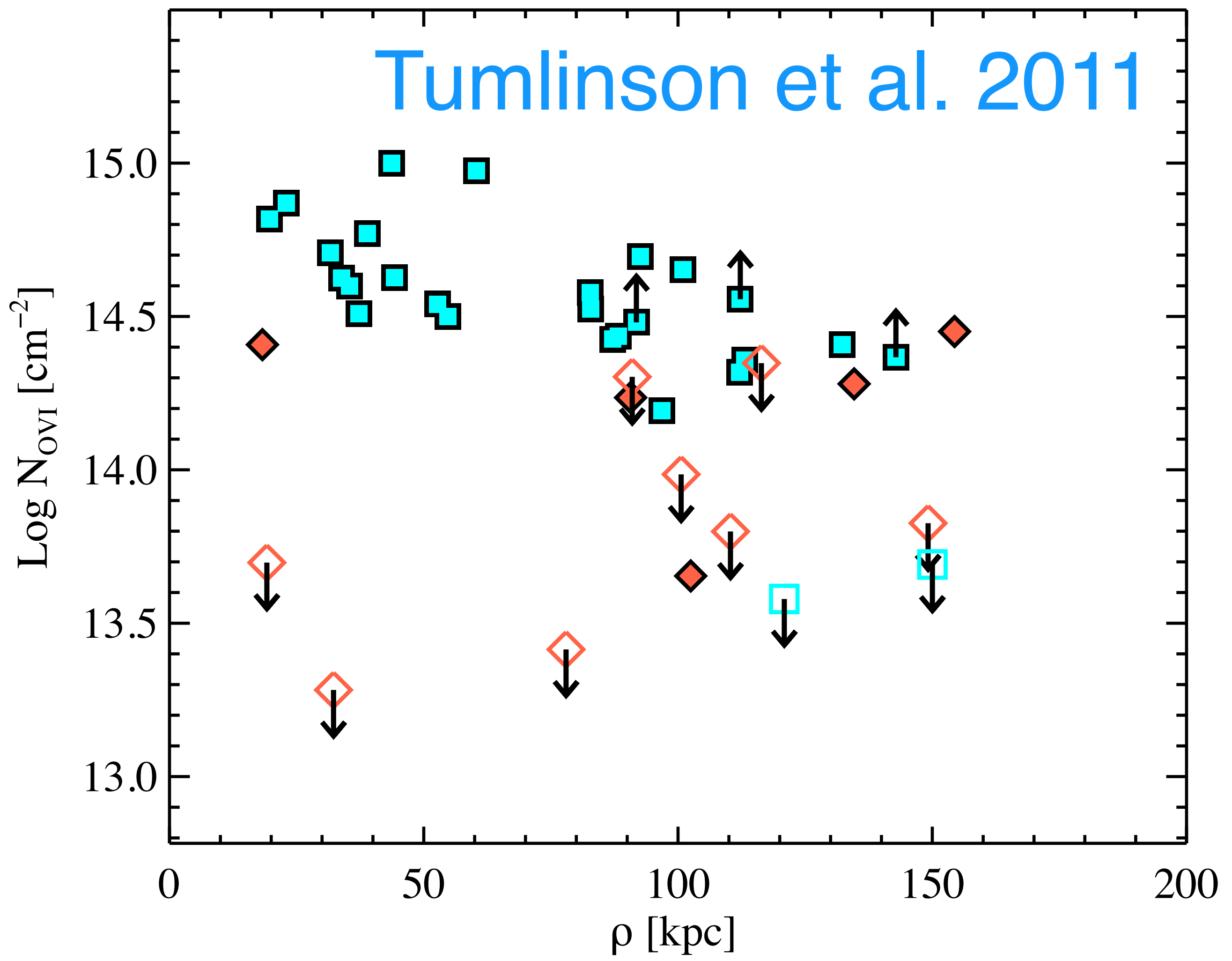


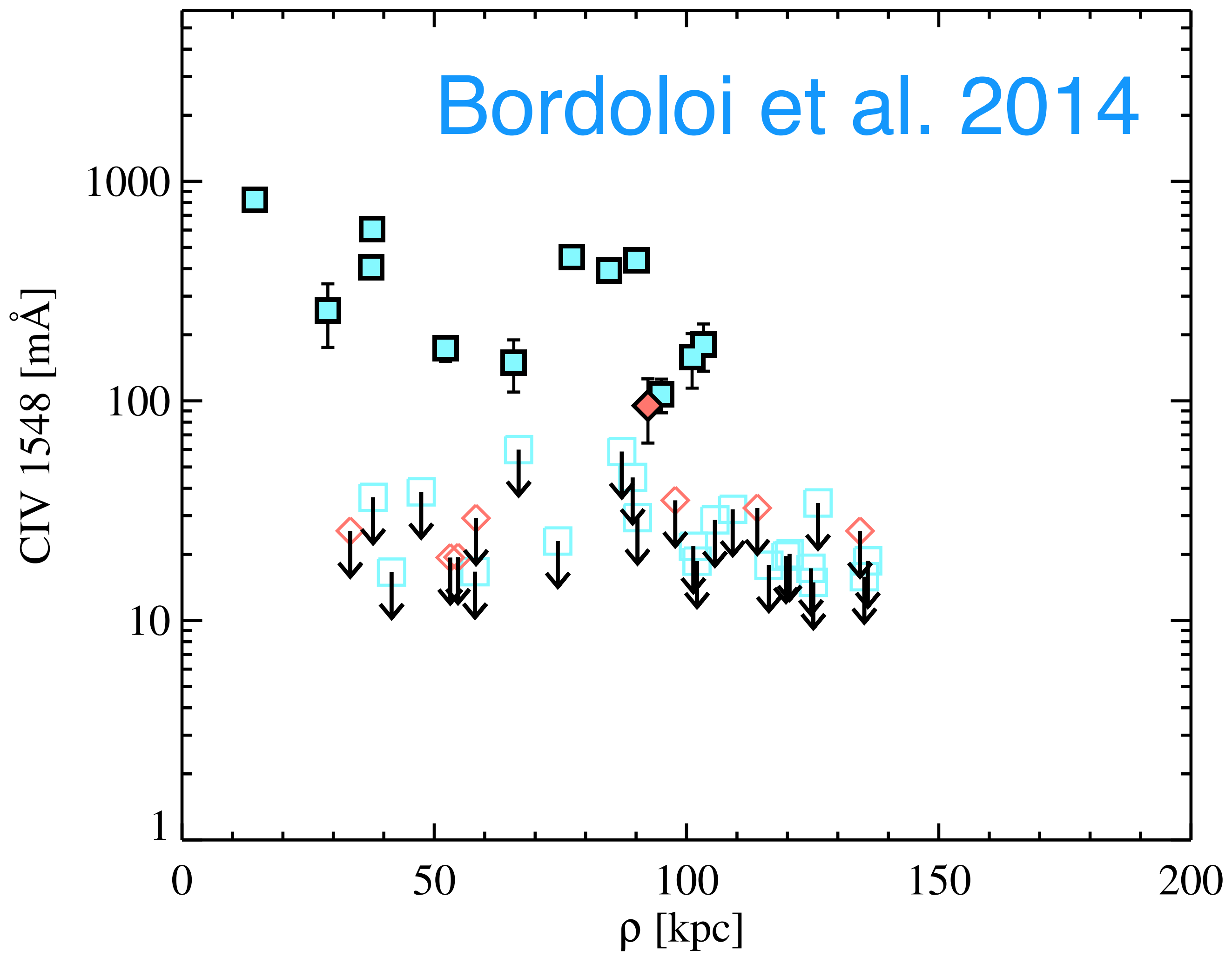
Anderson et al. 2013, 2016

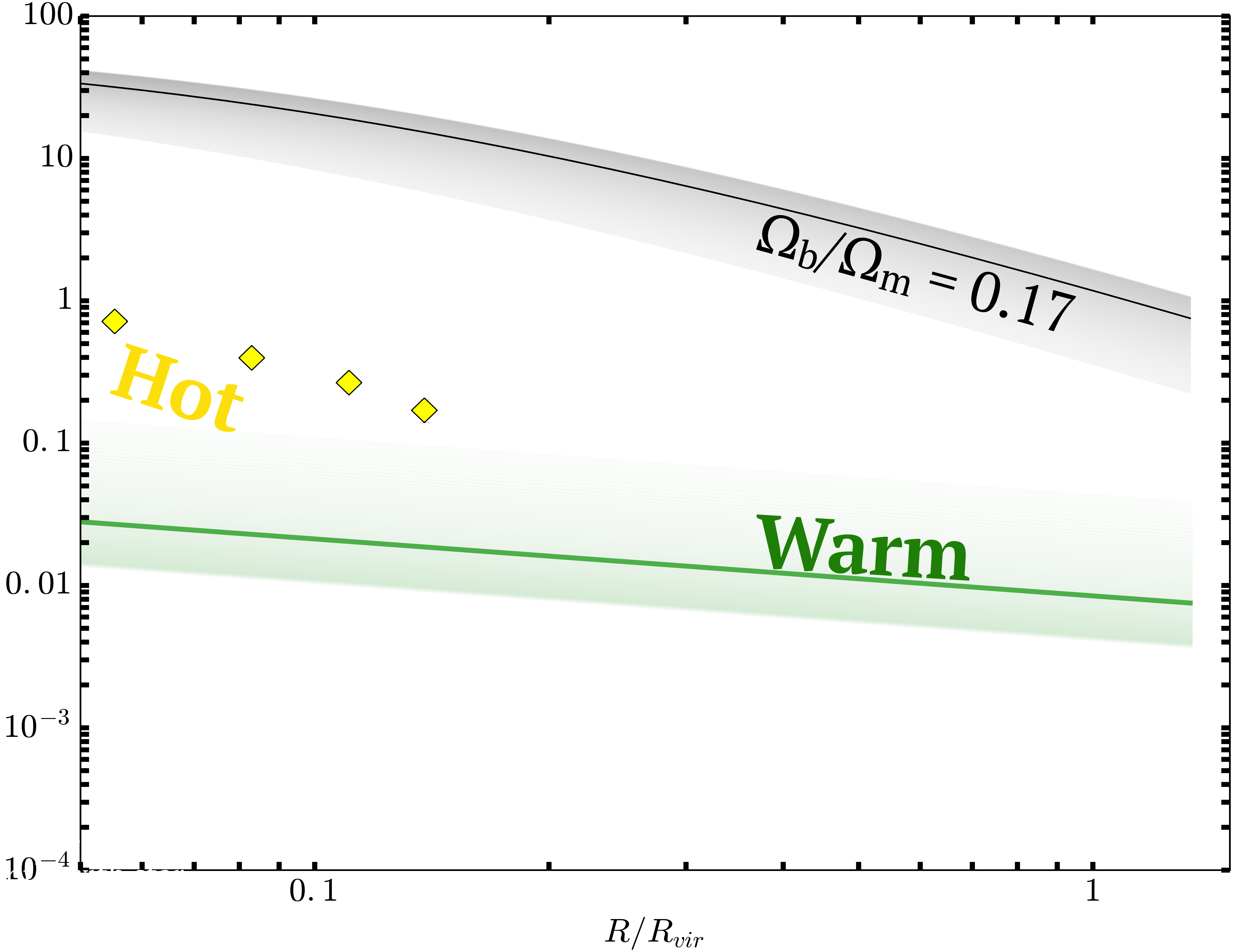




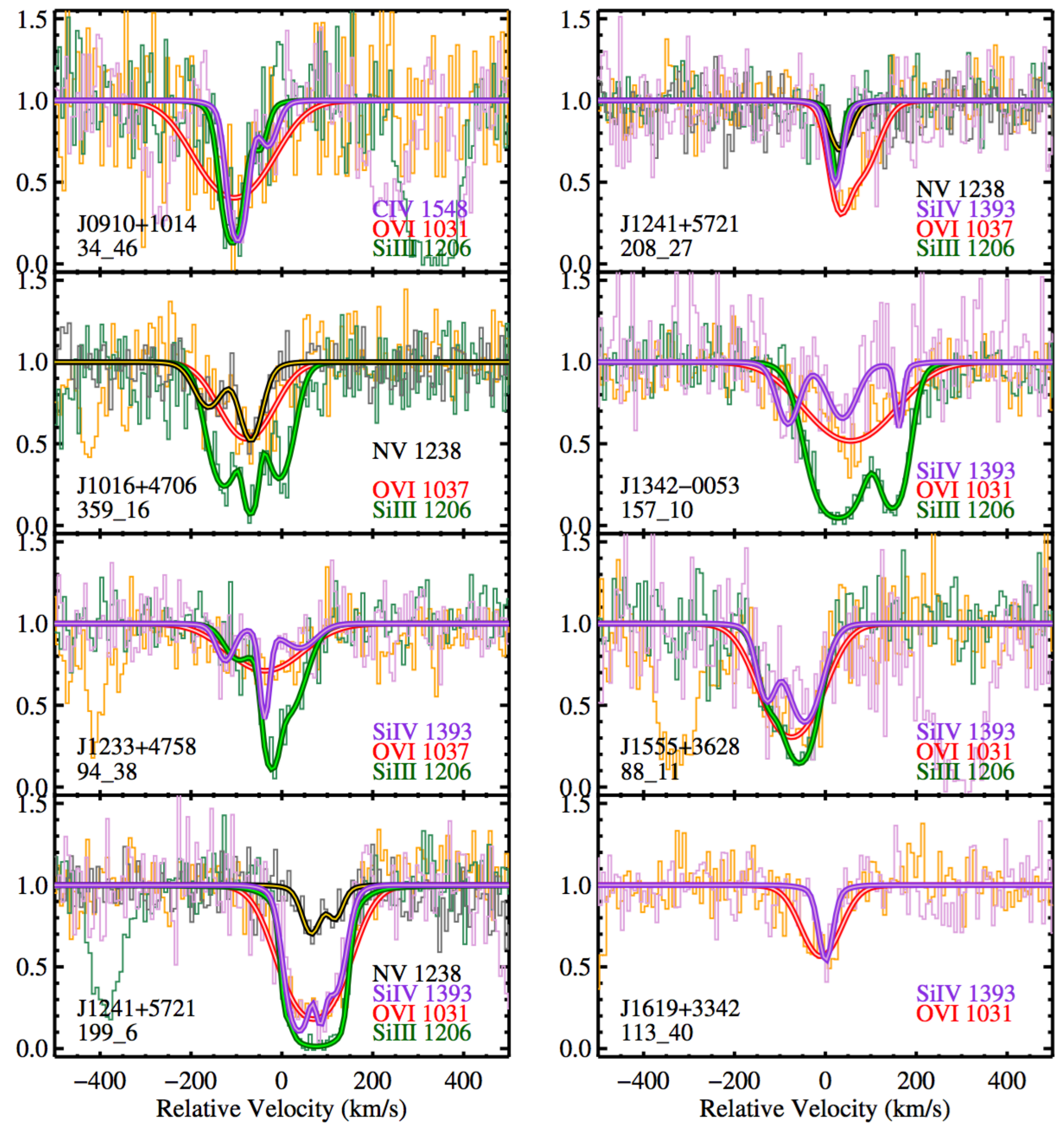
High Ions Trace "Warm" Gas

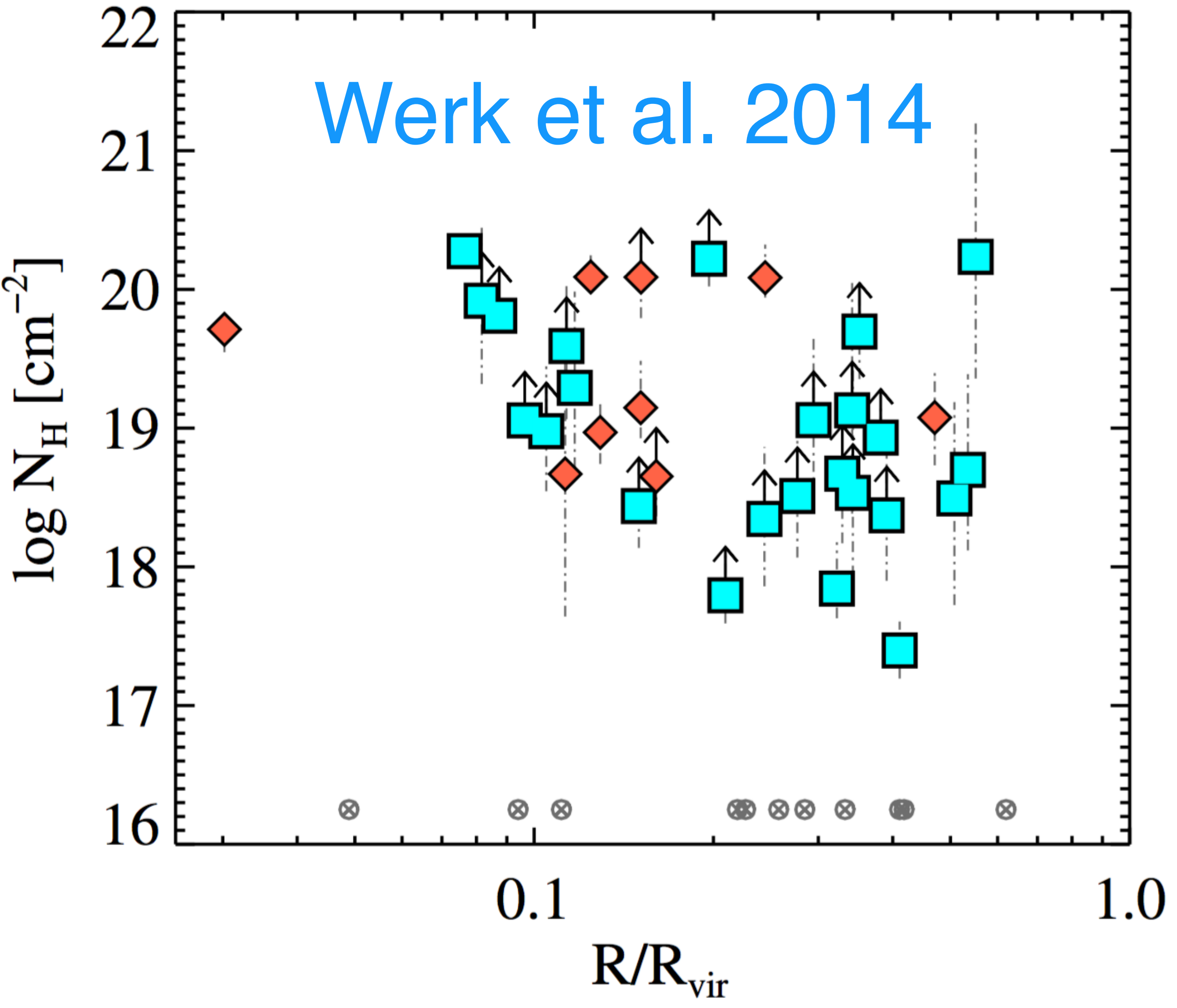


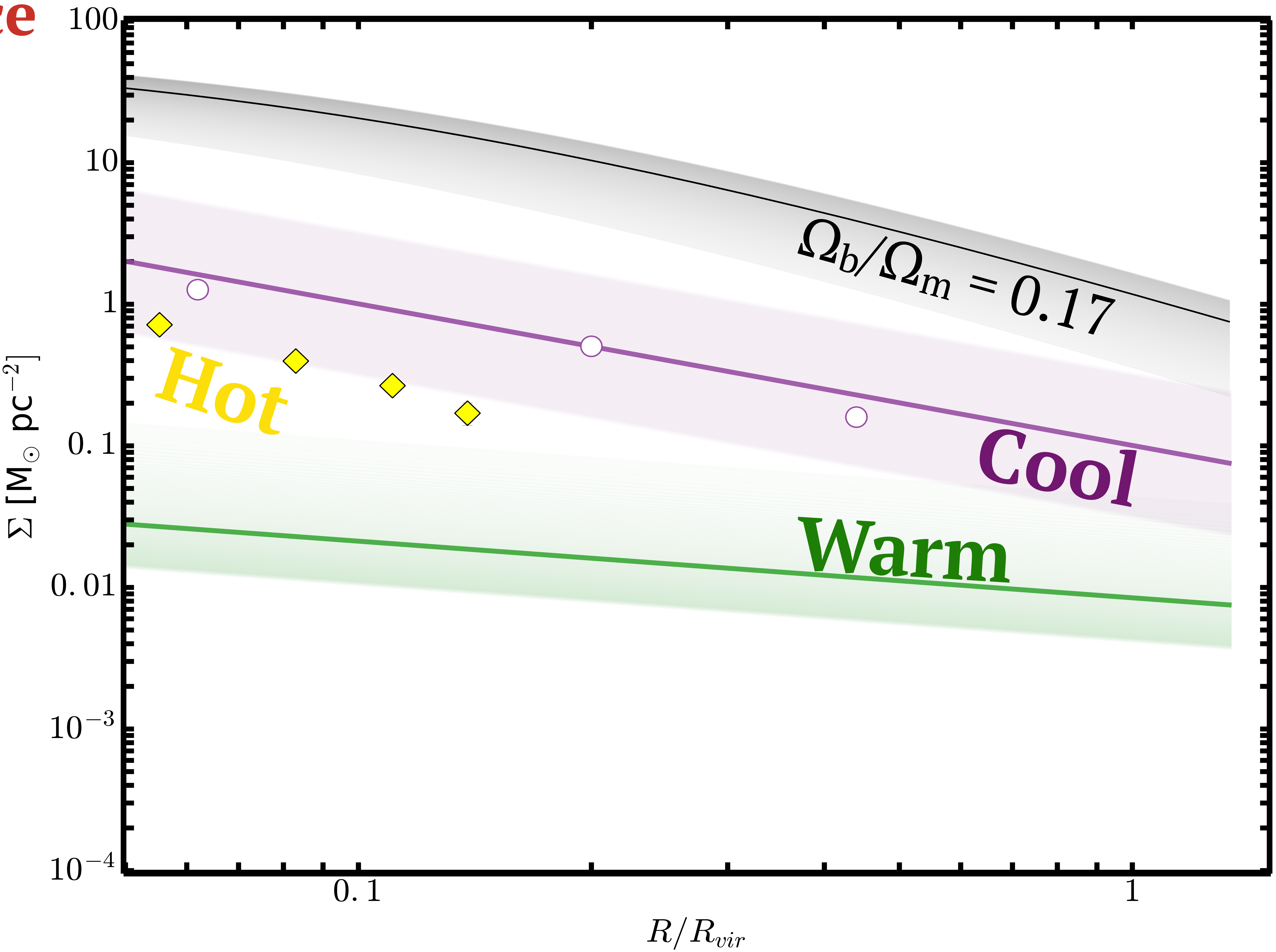




Low Ions Trace "Warm" Gas

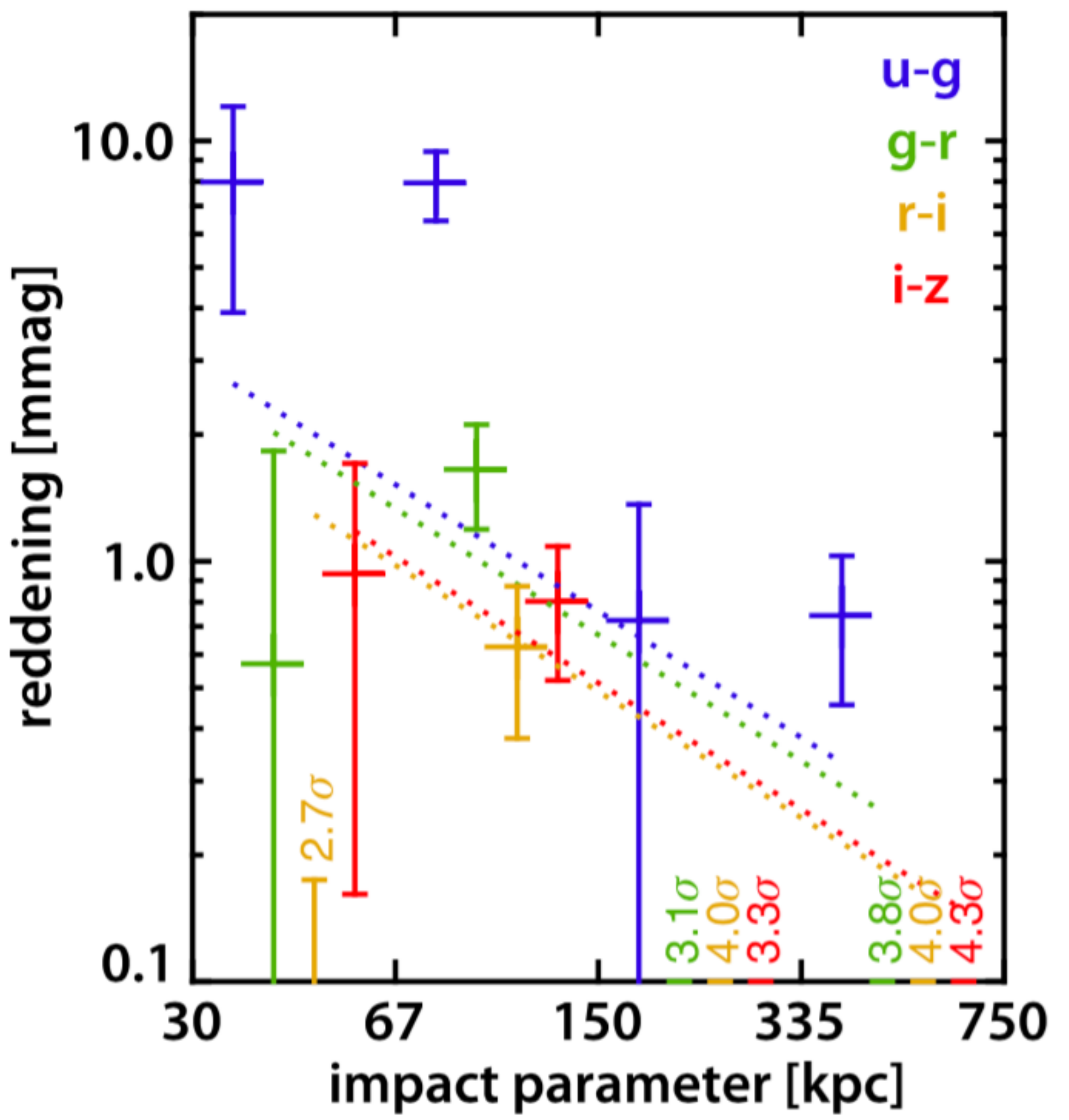


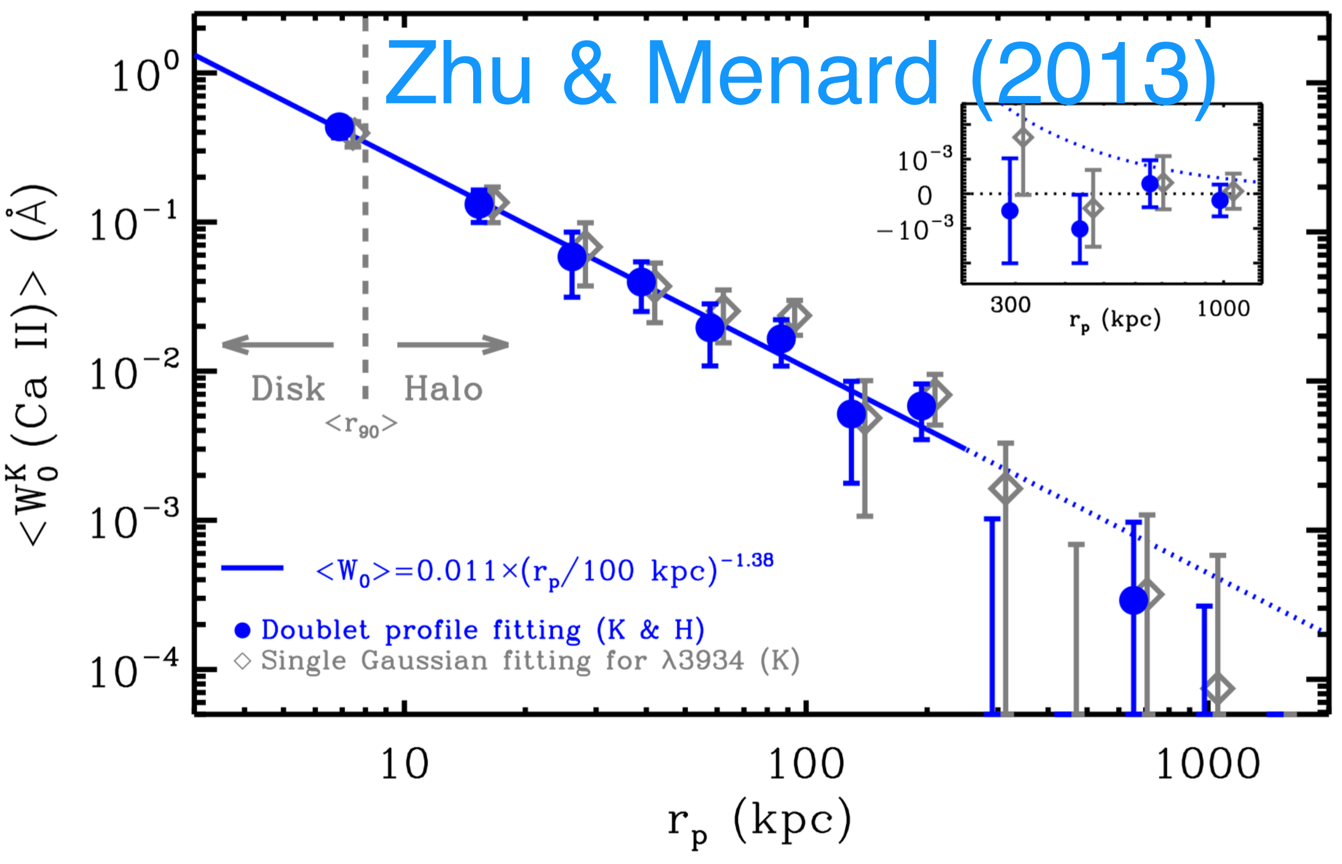


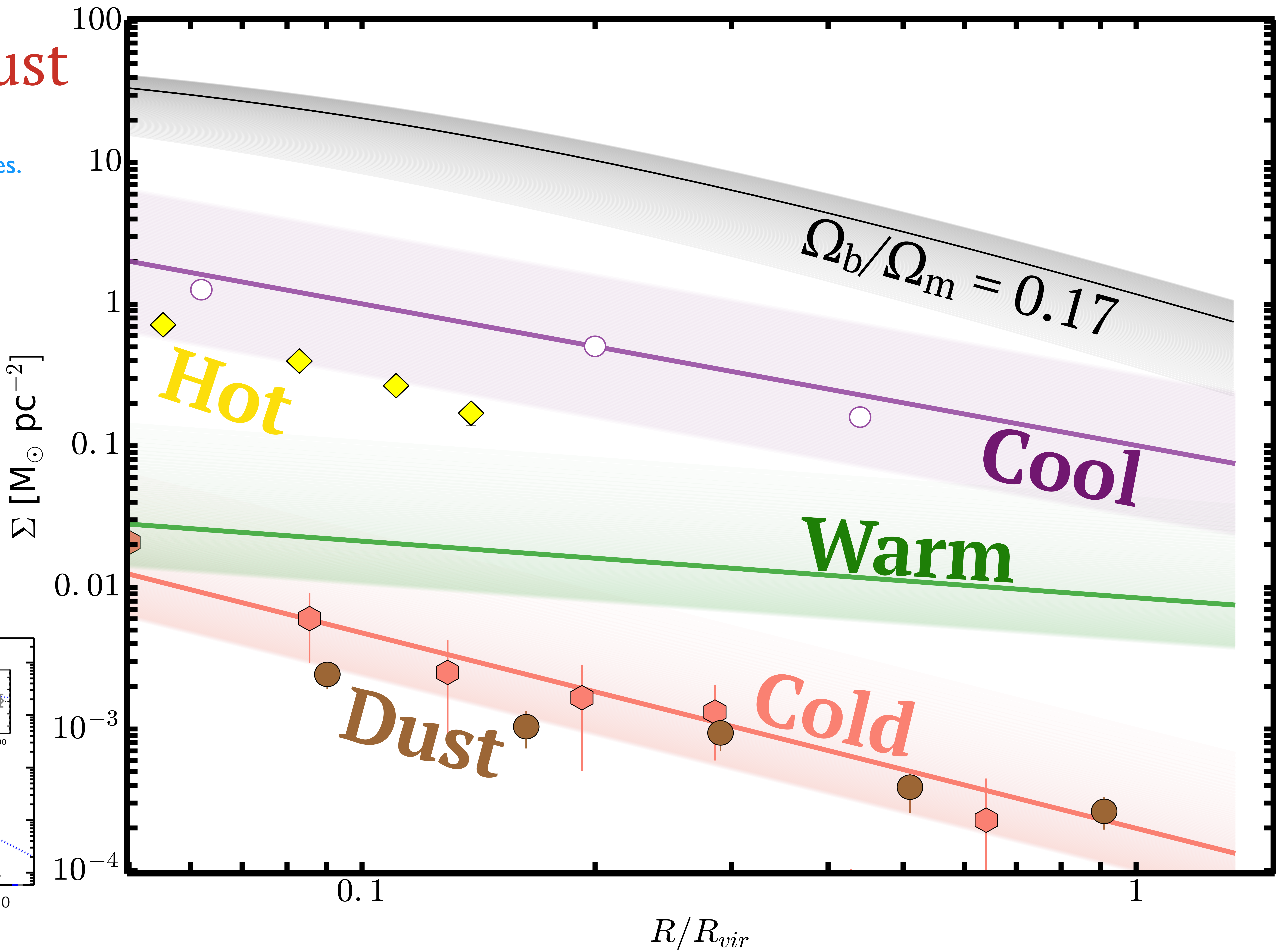


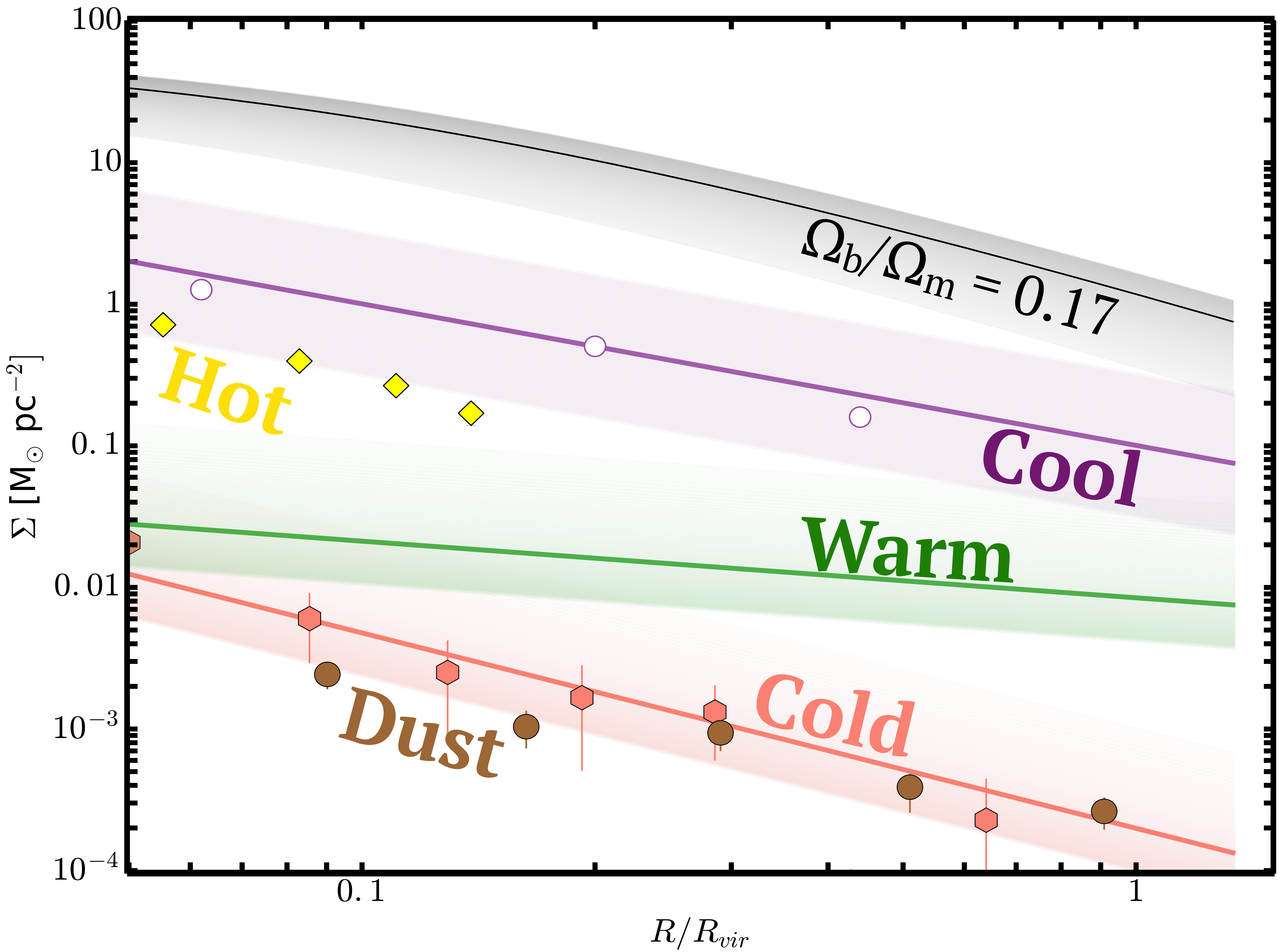
Cold Gas and Dust

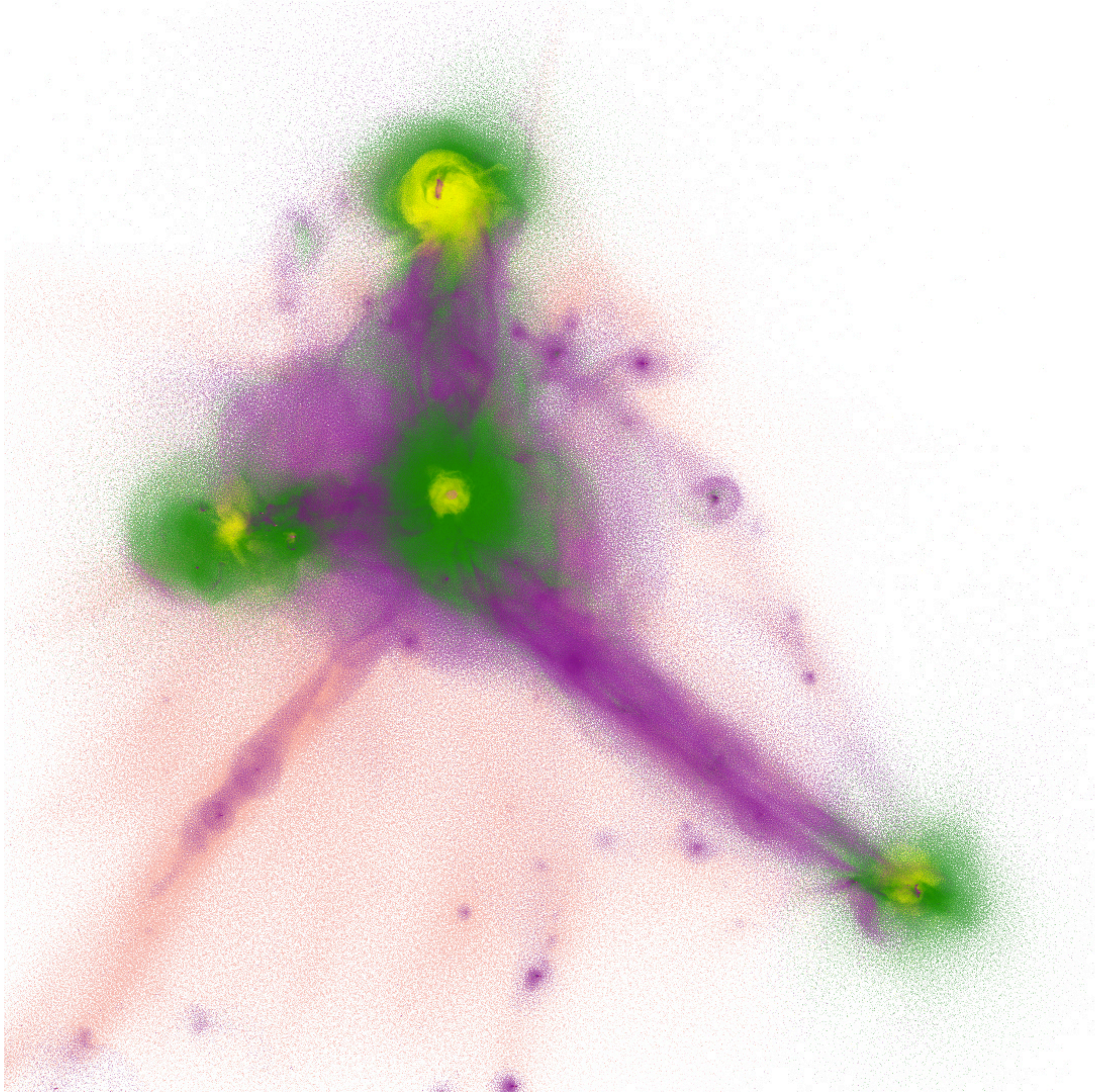
Peek et al. (2015)
reddening of "standard crayon" galaxies.





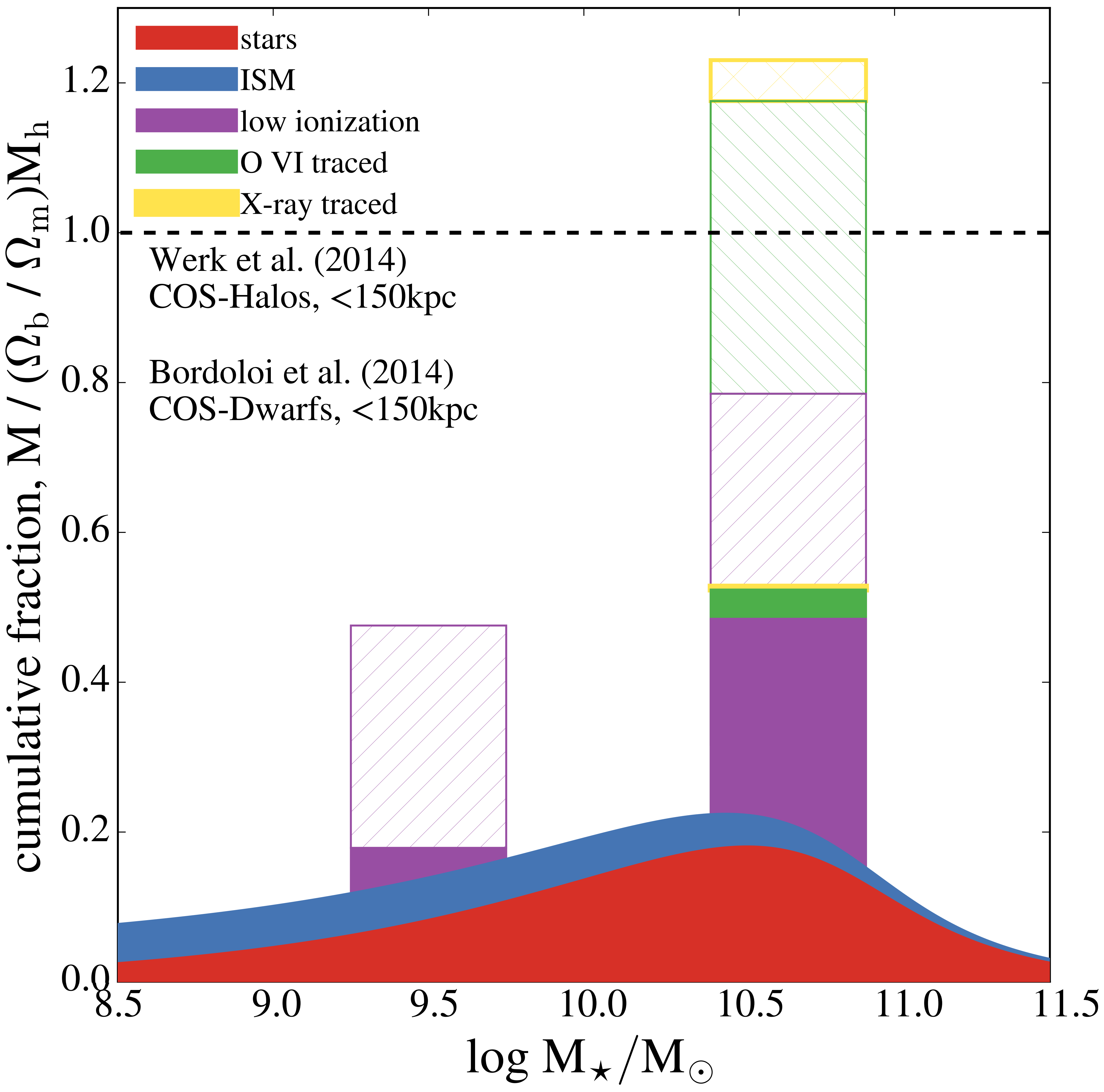


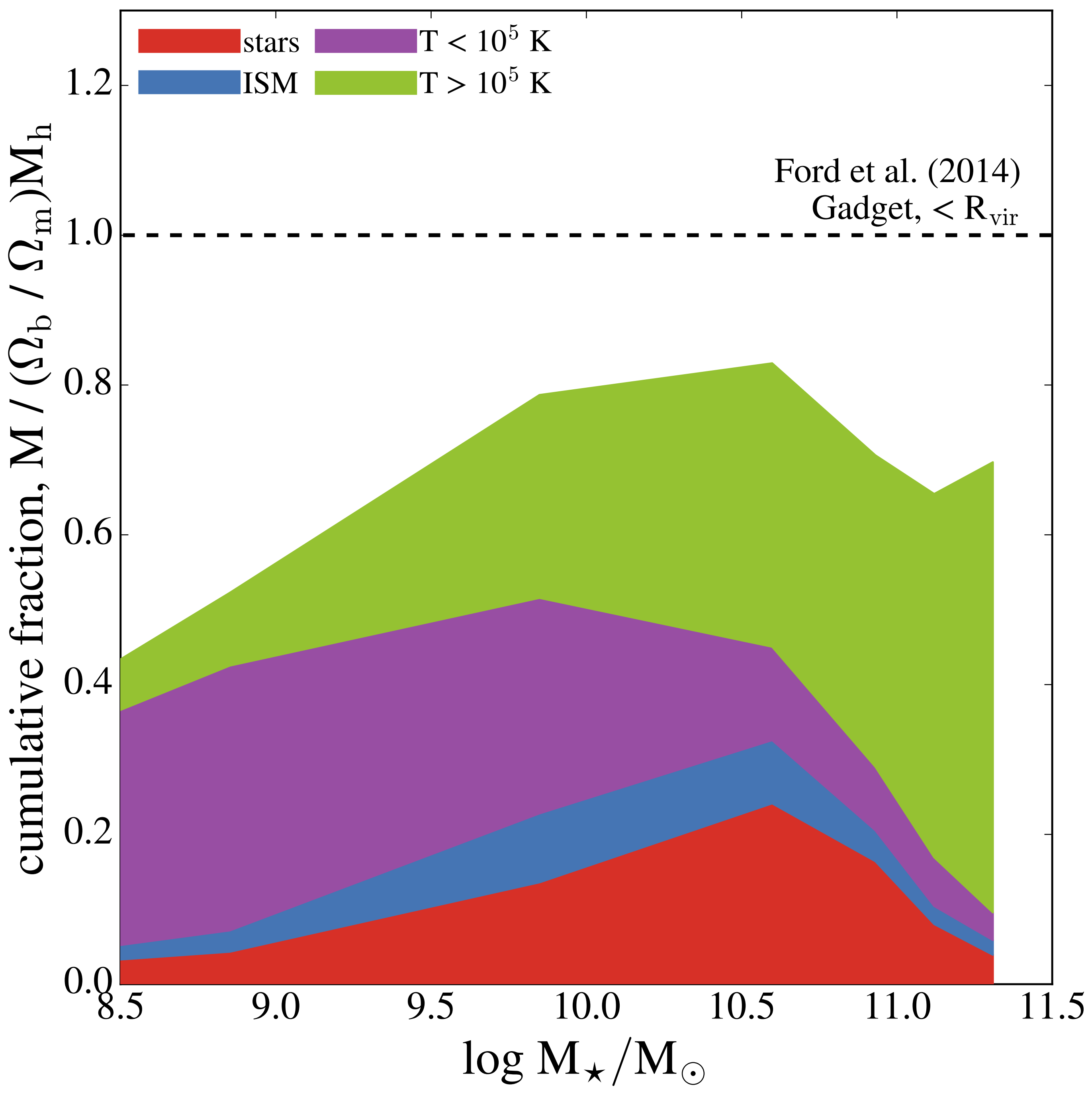

100
10
1
0.1
0.01
10^{-3}
10^{-4}
$\Sigma\,[\mathrm{M}_\odot\ \mathrm{pc}^{-2}]$
$\Omega_b/\Omega_m = 0.17$
Hot
Cool
Warm
Cold
Dust
0.1
1
R/R_{vir}

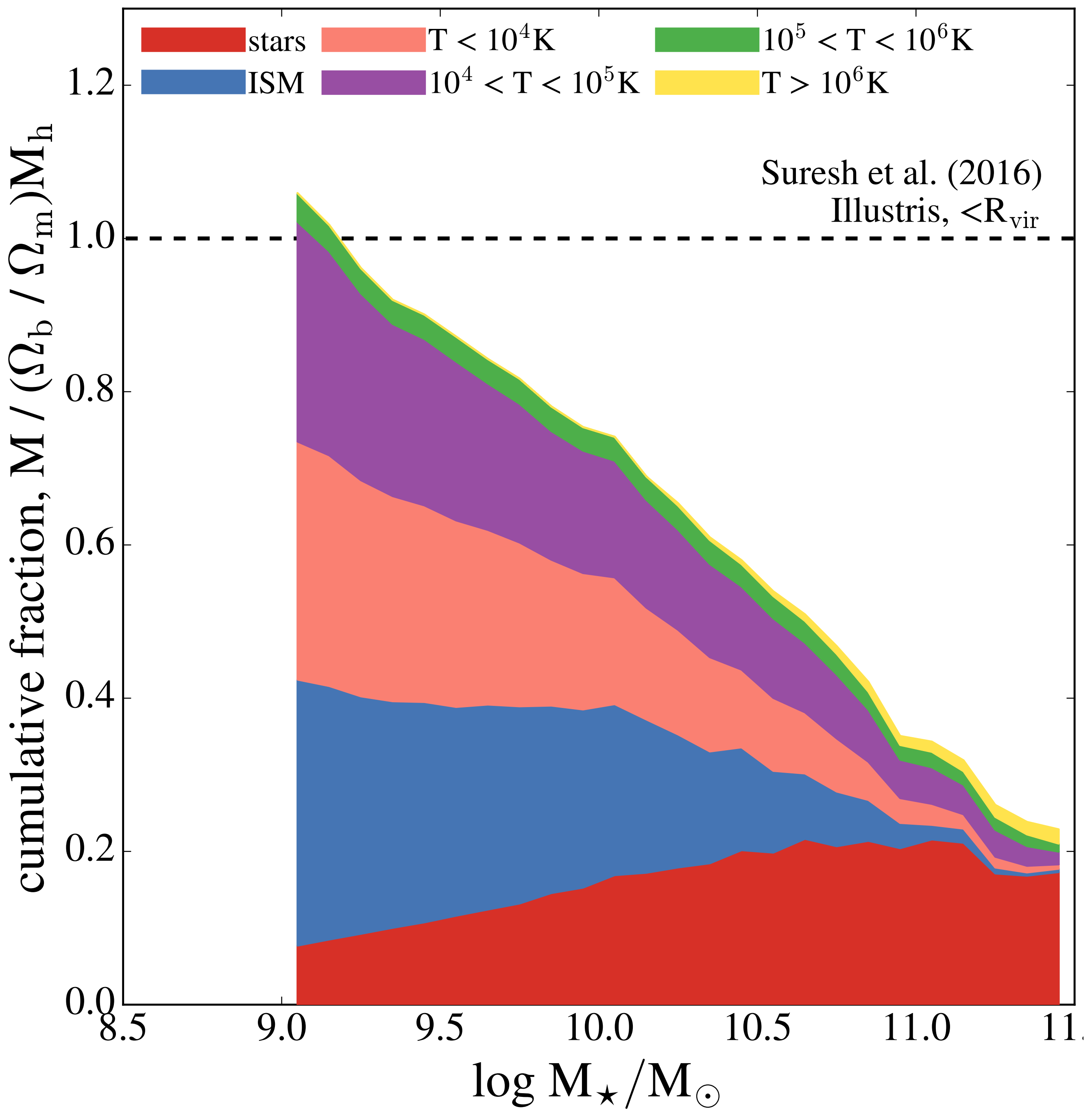


We now have a characterization of the mean surface density profile for the CGM of $L^\star$ galaxies (2010-now).

Baryon Census







Nearly complete at L*

Still working on < L*

Can constrain models, but perhaps not very well at the current level of precision.

Fundamental Problems in Galaxy Evolution

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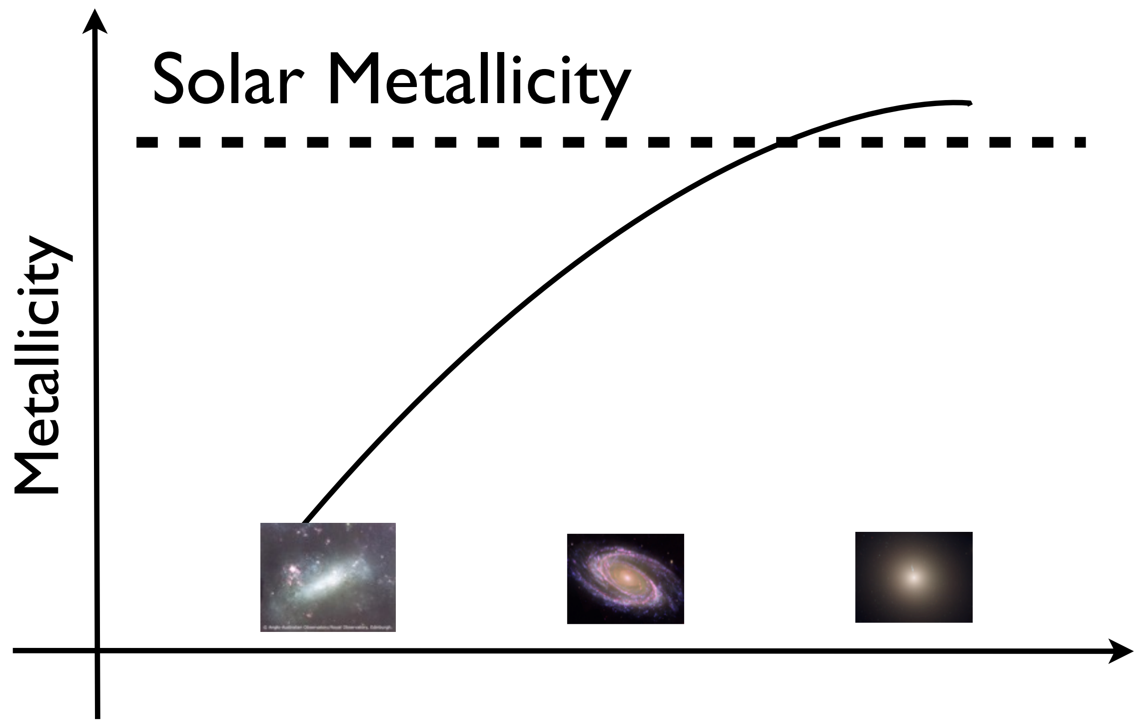

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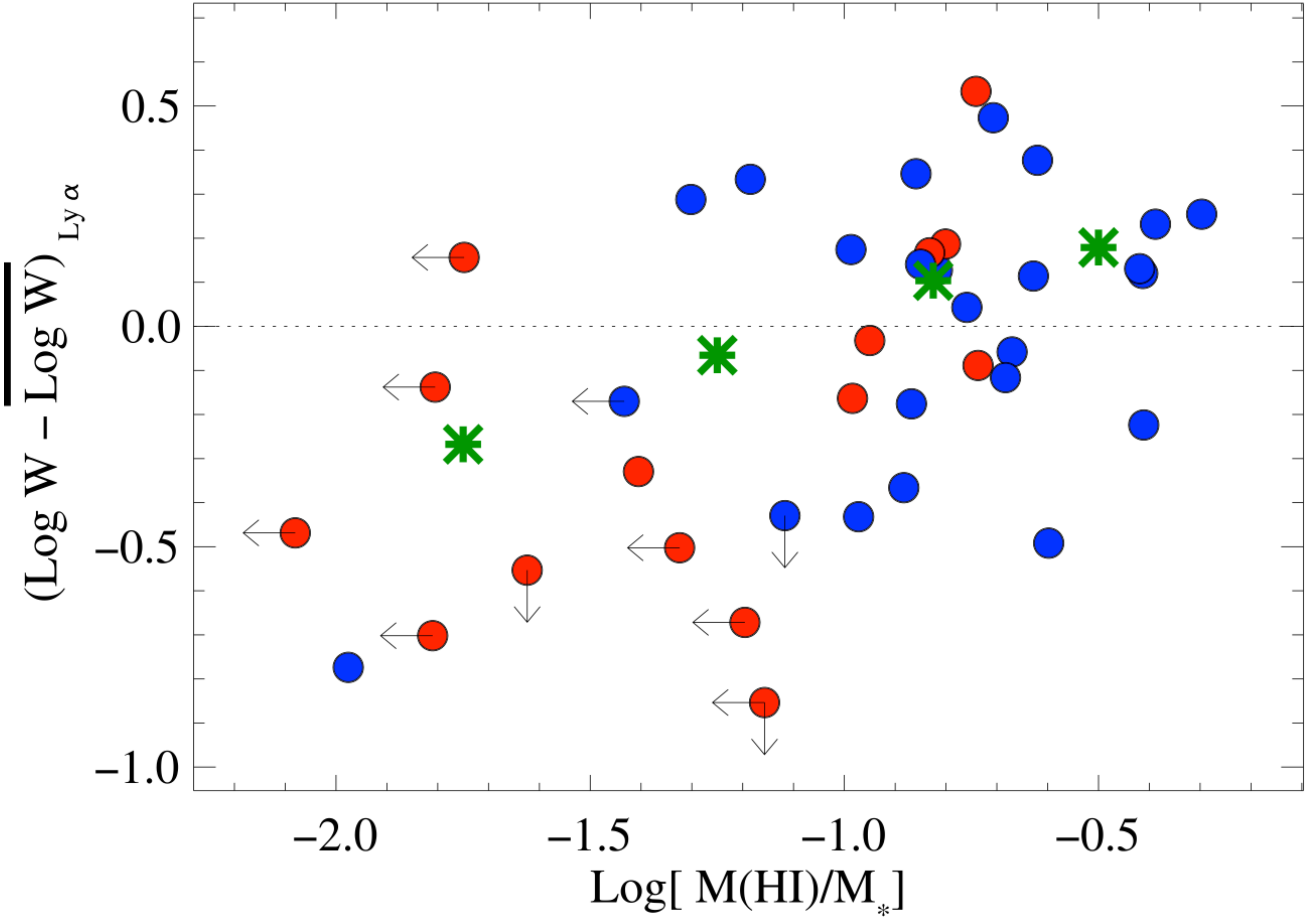
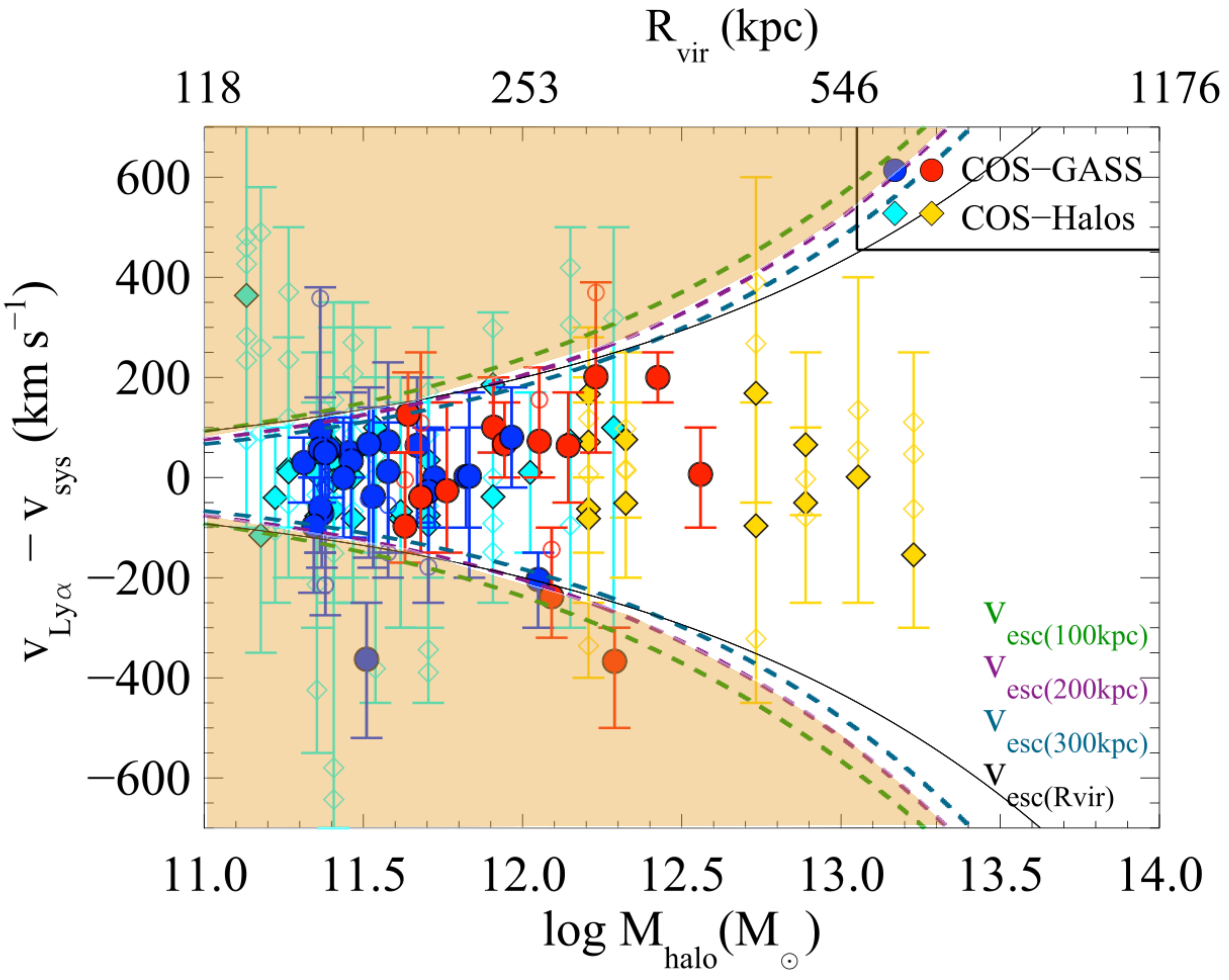
Accretion vs. Feedback?



Plot by Borthakur et al. (2015; COS-GASS)

Clues to Accretion

more ISM means more CGM

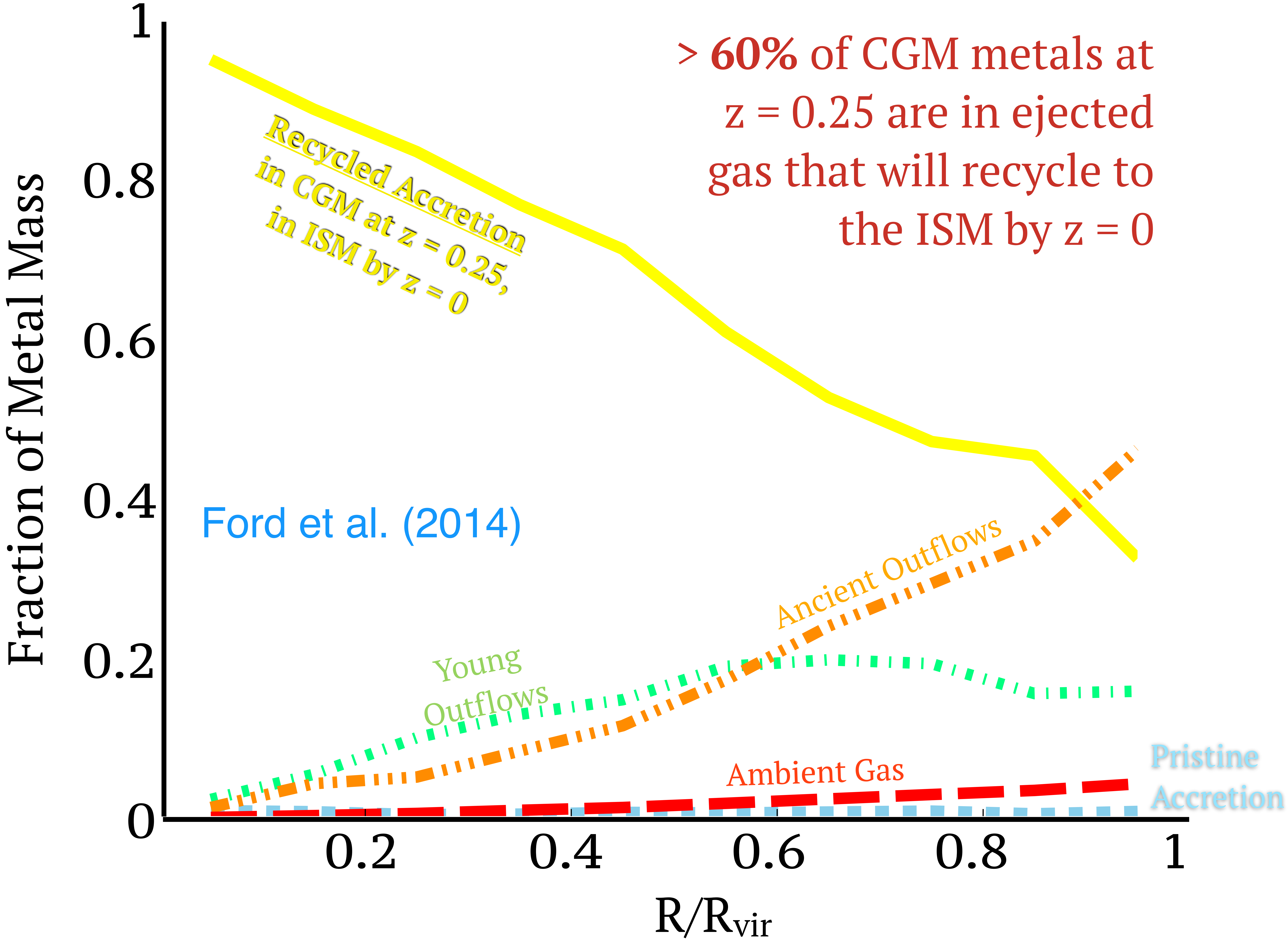


Plot by Borthakur et al. (2015; COS-GASS)

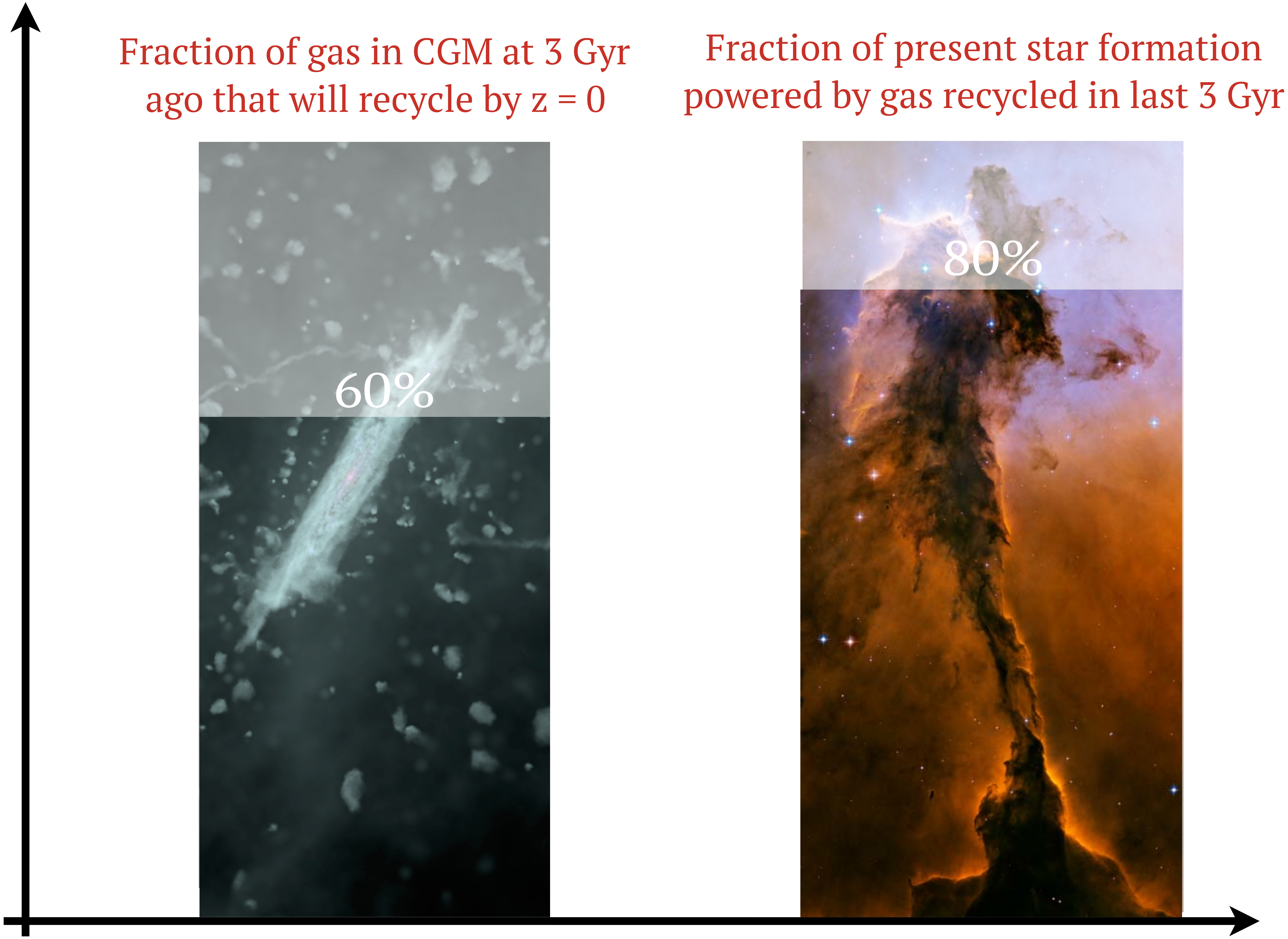
Clues to Accretion

Nearly all the mass traced by HI is **BOUND**

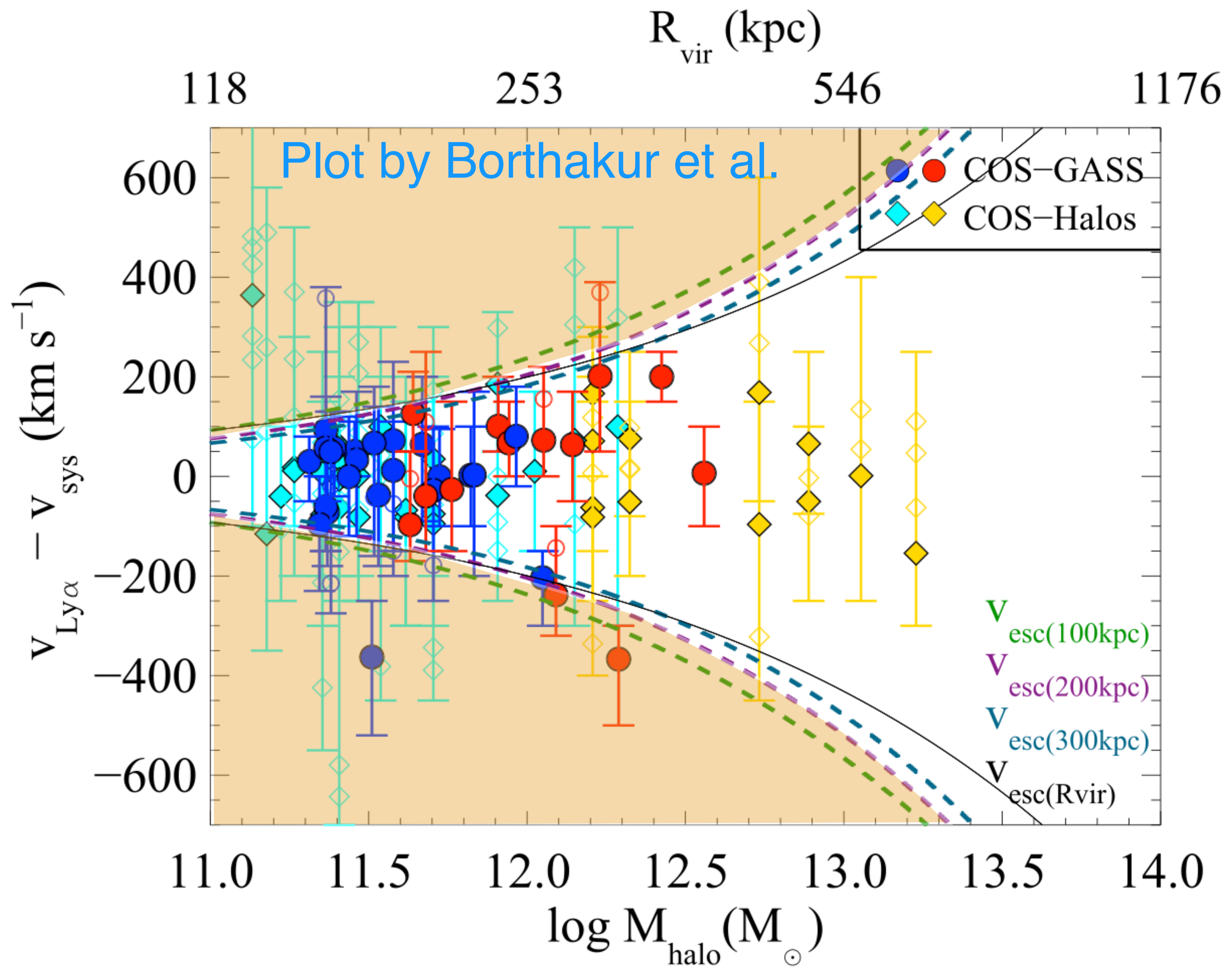
A large mass of gas and metals at sub-escape velocity implies RECYCLING

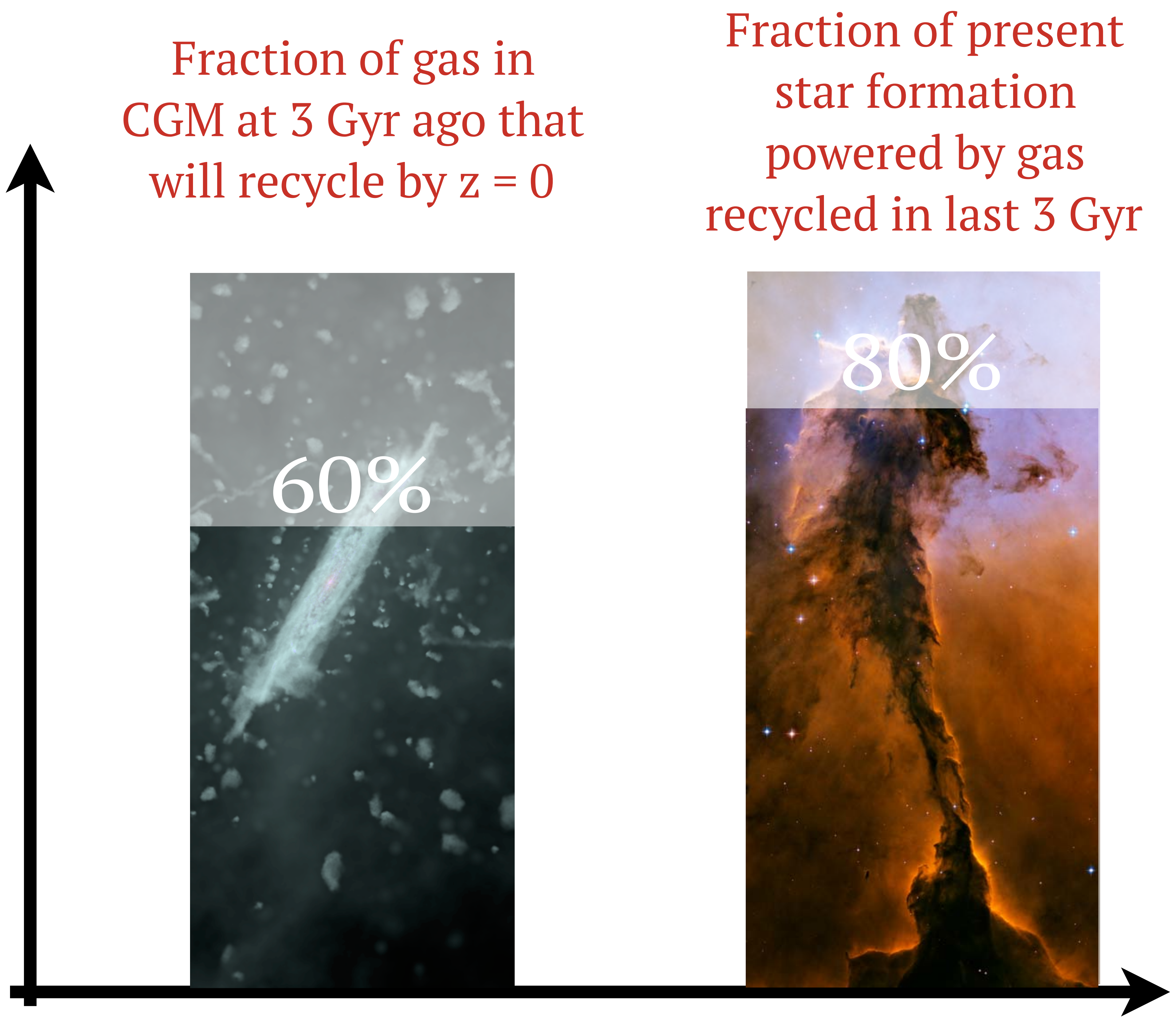


> 60% of CGM metals at z = 0.25 are in ejected gas that will recycle to the ISM by z = 0
Recycled Accretion in CGM at z = 0.25, in ISM by z = 0
Ford et al. (2014)
Ancient Outflows
Young Outflows
Ambient Gas
Pristine Accretion
Fraction of Metal Mass
R/R_vir
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1


Fraction of gas in CGM at 3 Gyr ago that will recycle by z = 0
60%
Fraction of present star formation powered by gas recycled in last 3 Gyr
80%

forged connection one





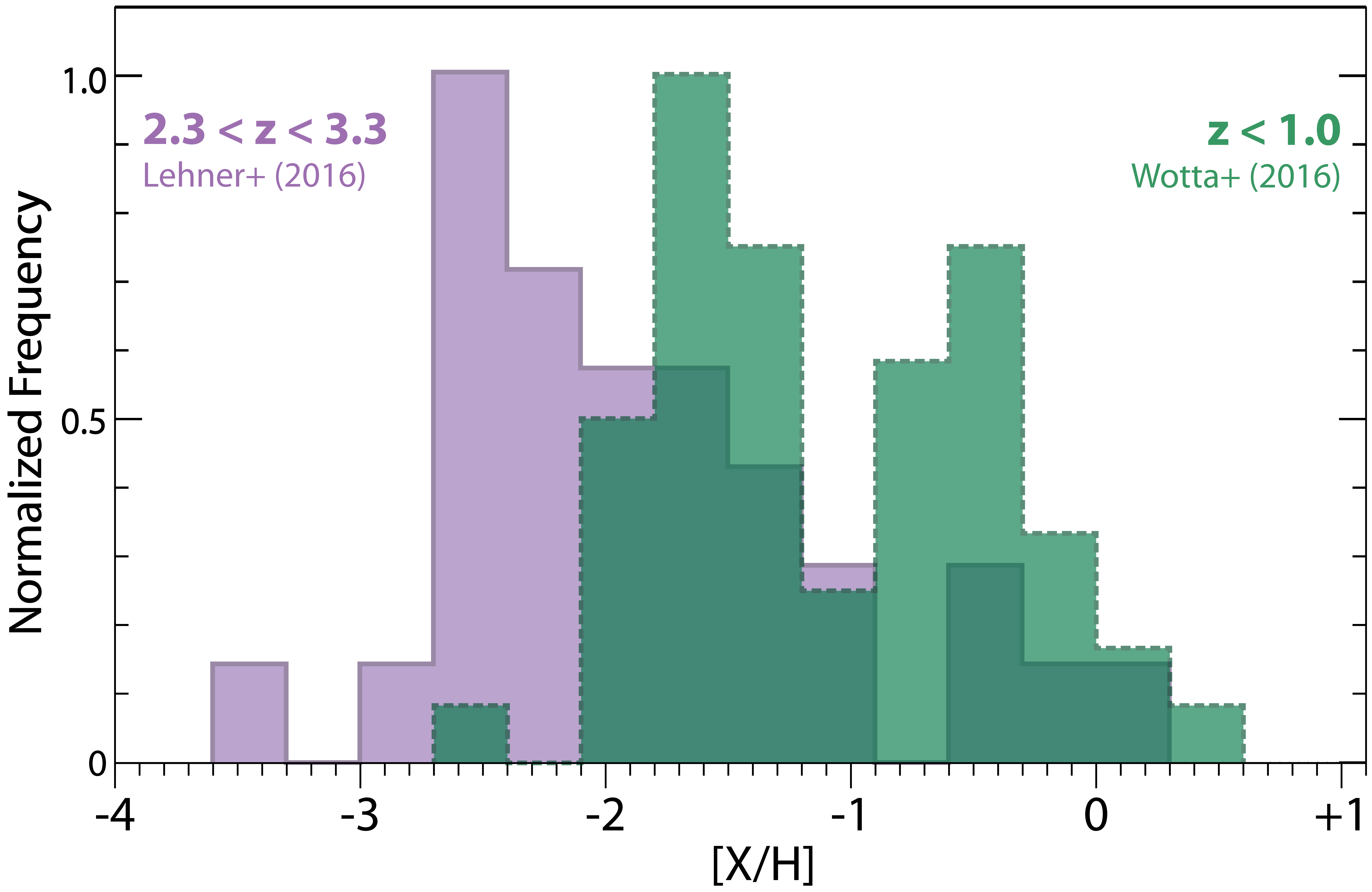
Recycling through the CGM is a big factor!


Diffuse gas
Recycling gas
You Are Here
Accreting gas
You Were Here
15 kpc
Outflows
300 kpc

To Understand Feedback, Follow the Metals

a.k.a. “Metals: the cause of, and solution to, all our problems.”

Feedback Gotta Feed Back

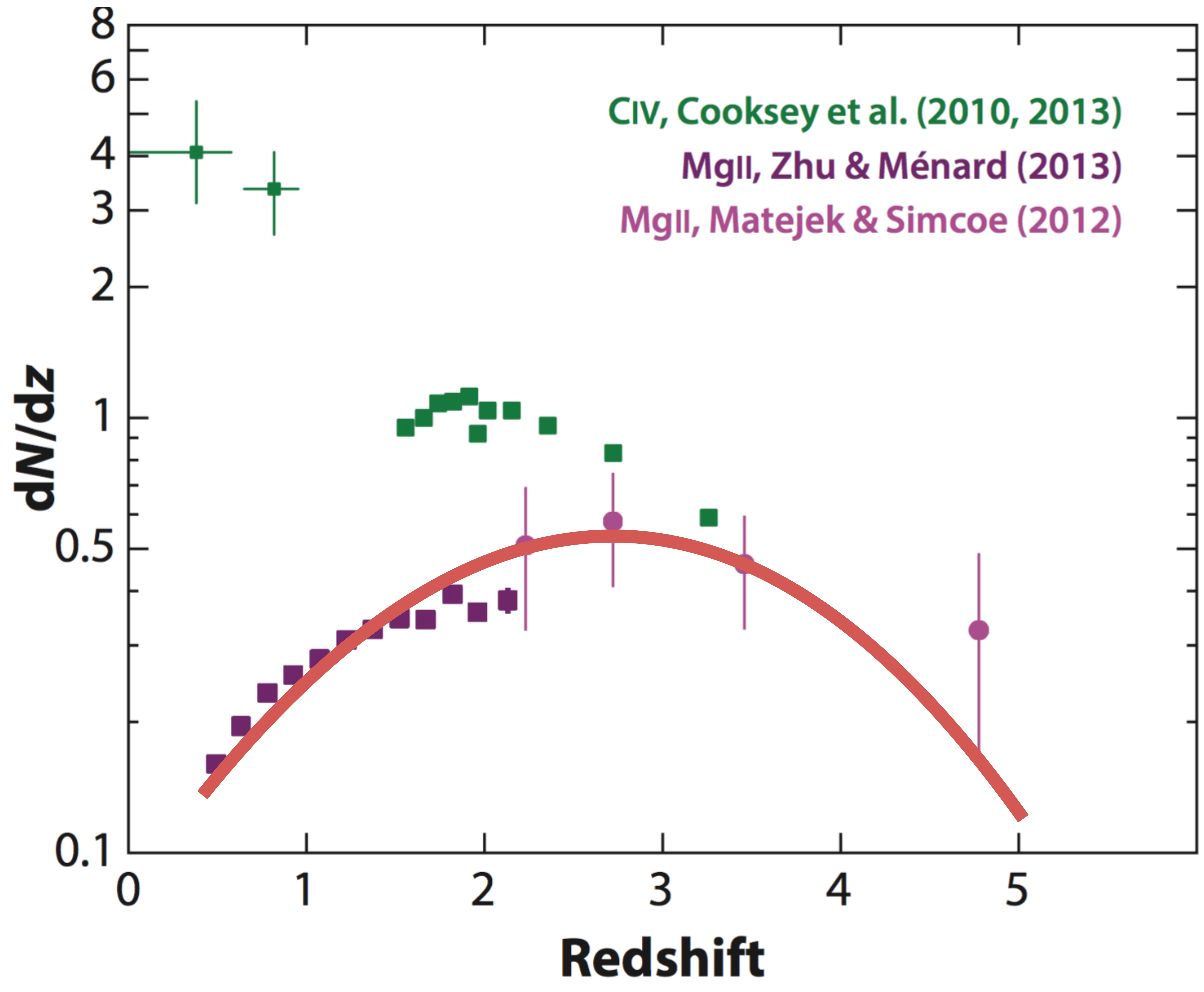


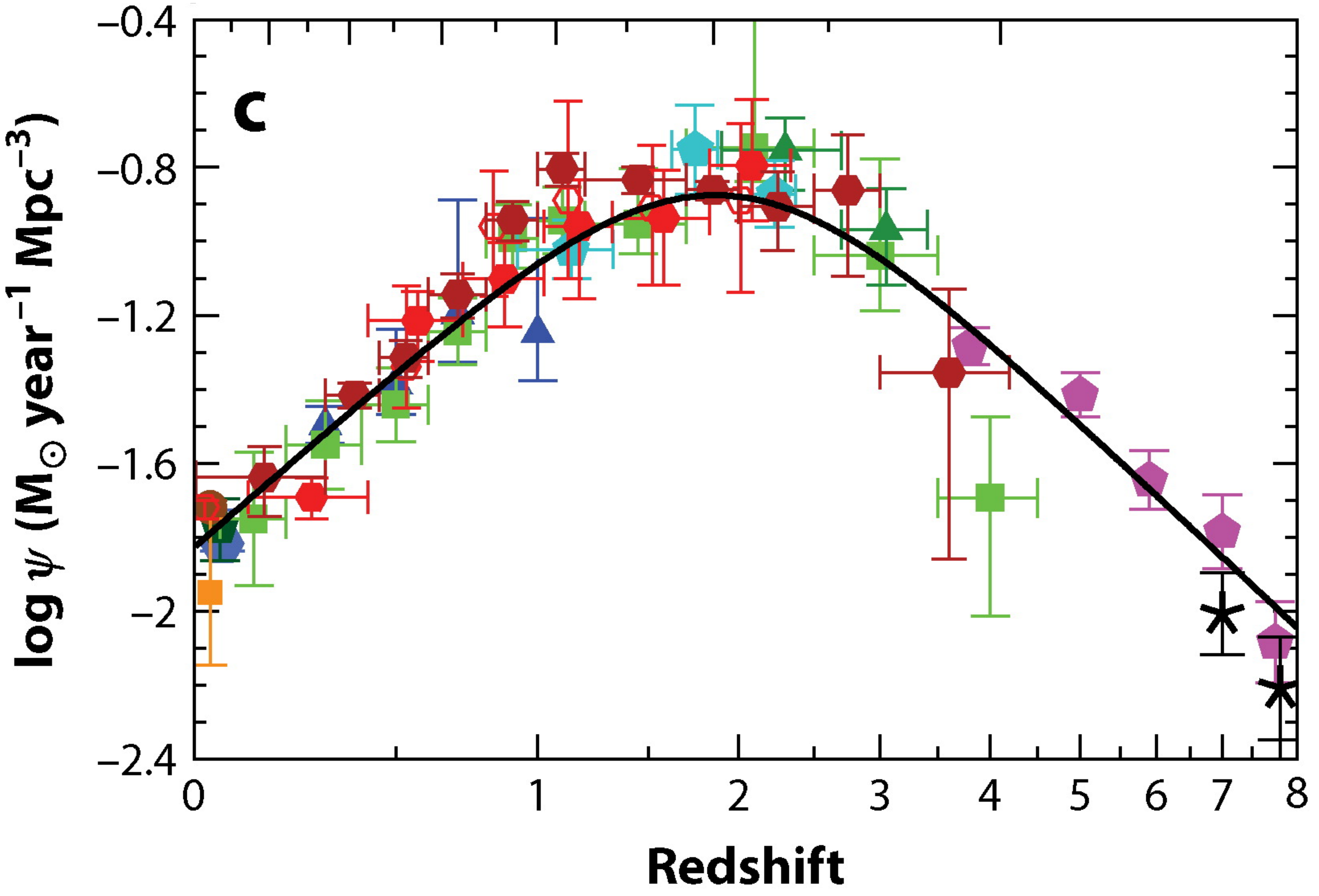
Metallicity of dense CGM is low at z > 2.

At low z, this distribution increases to higher metallicity, but. . .

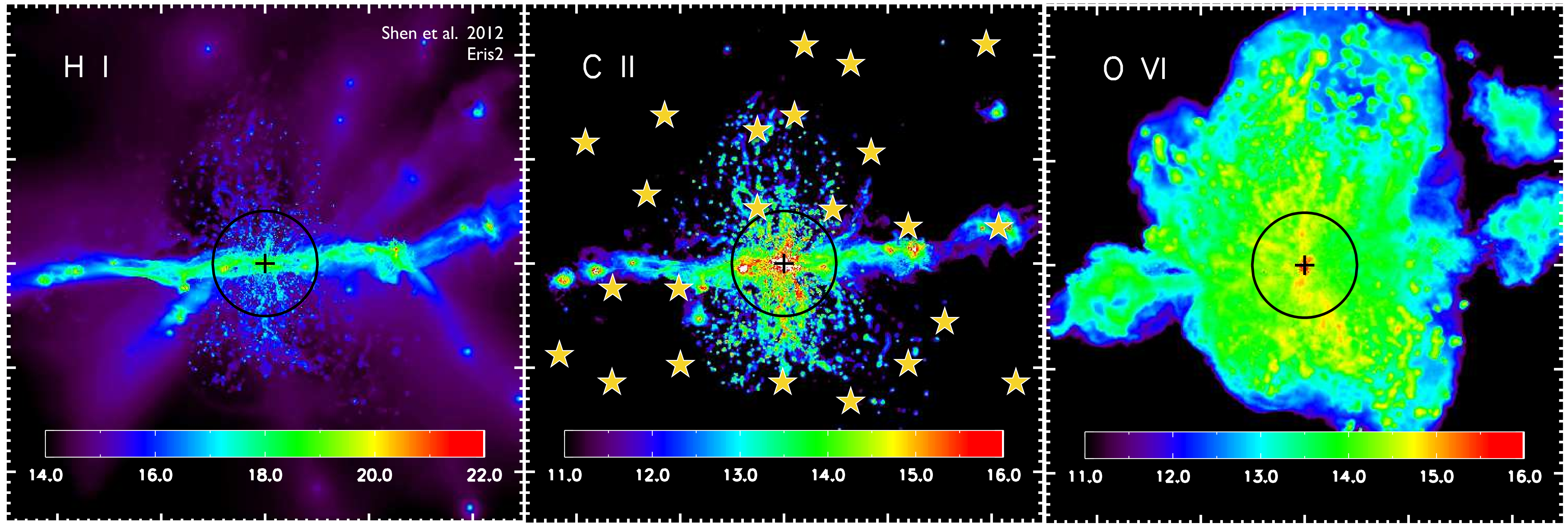
Bimodality implies accretion and feedback are about even?

forged connection two

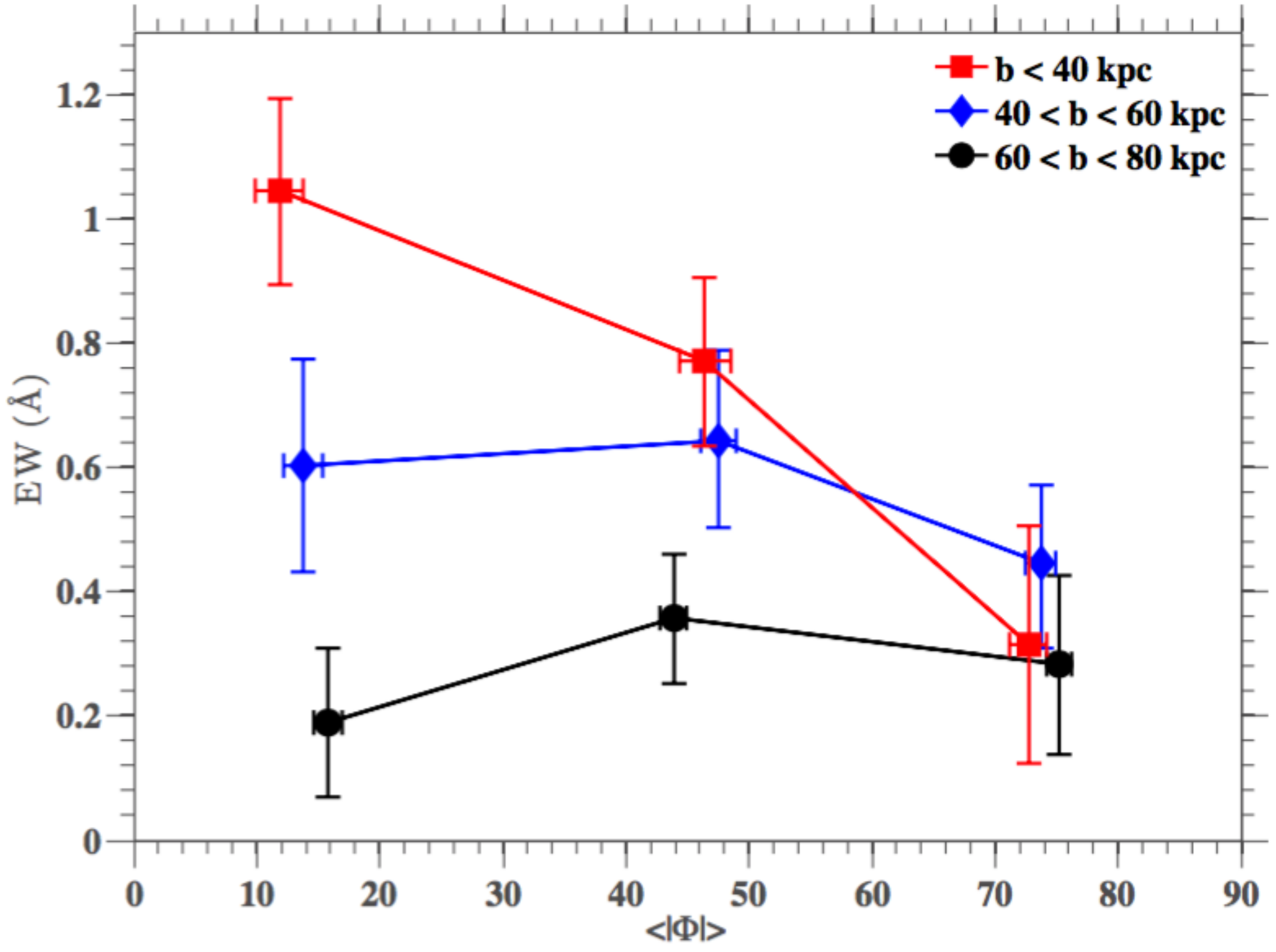




The CGM tracks with cosmic star formation!

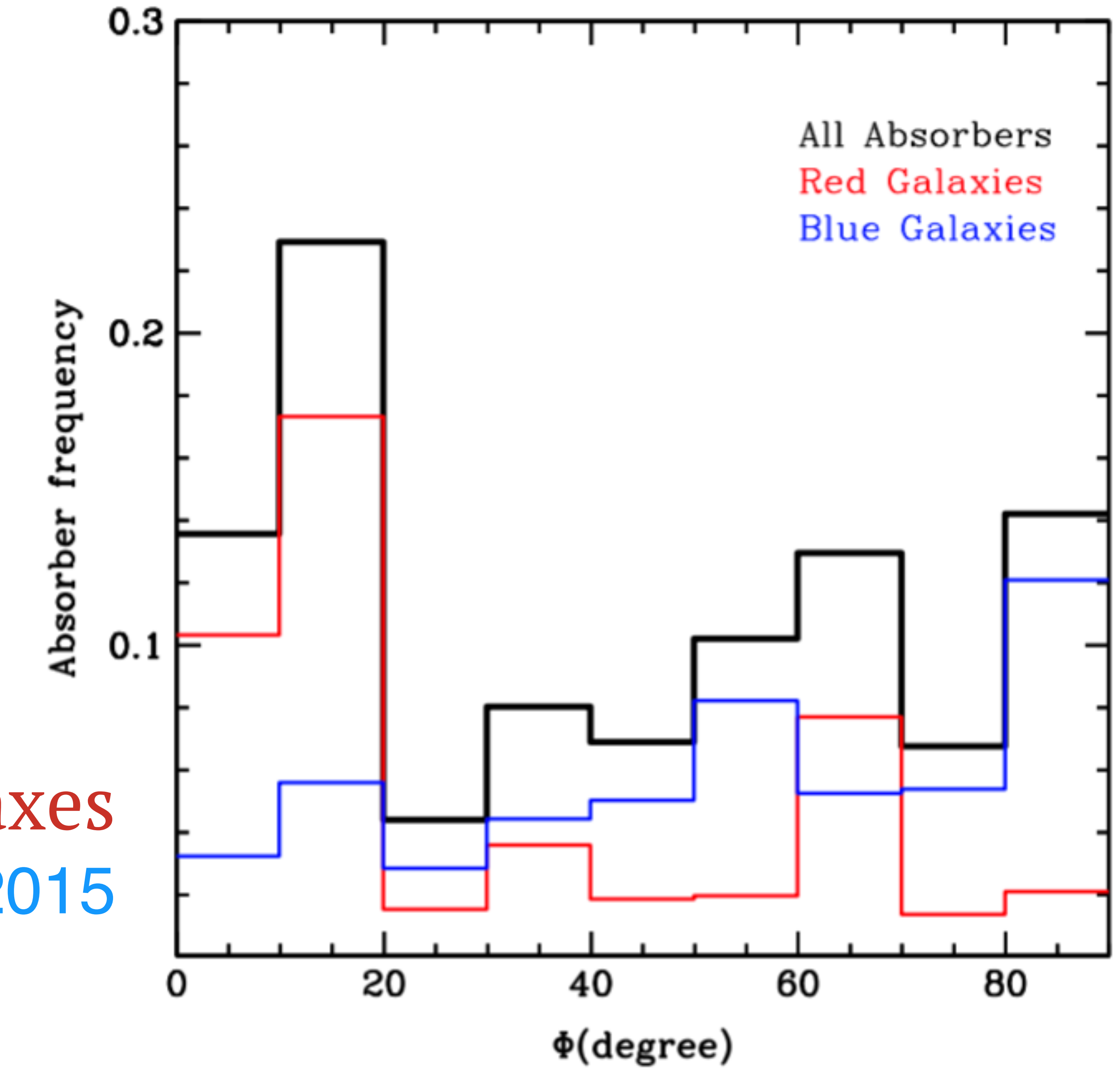


More clues to feedback

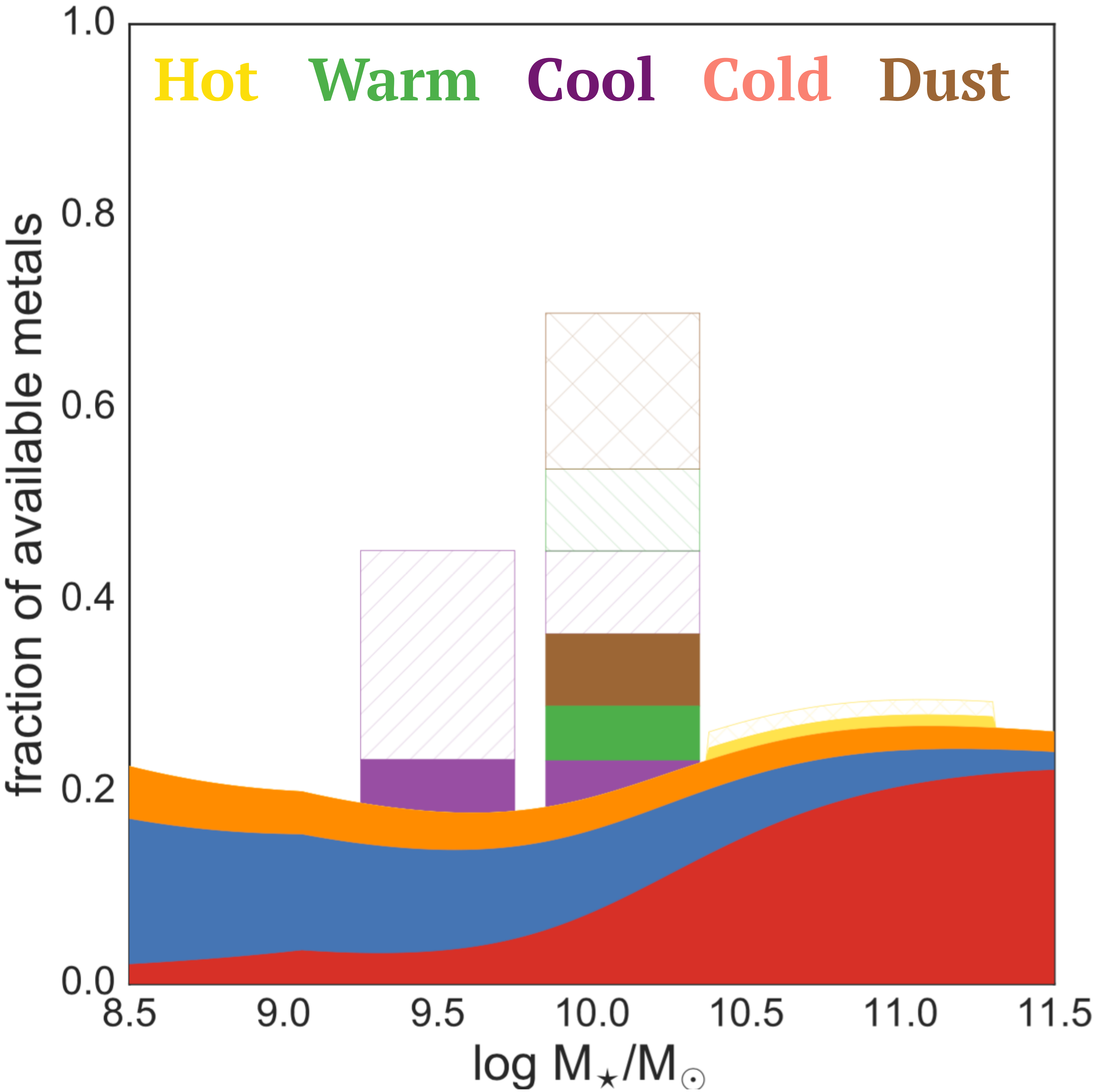


strong Mg II
prefers the semi-minor axis -
biconical outflows?
Bordoloi et al. 2011

while O VI occurs along both axes
Kacprzak et al. 2015



The Metals Census: Real and Mocked



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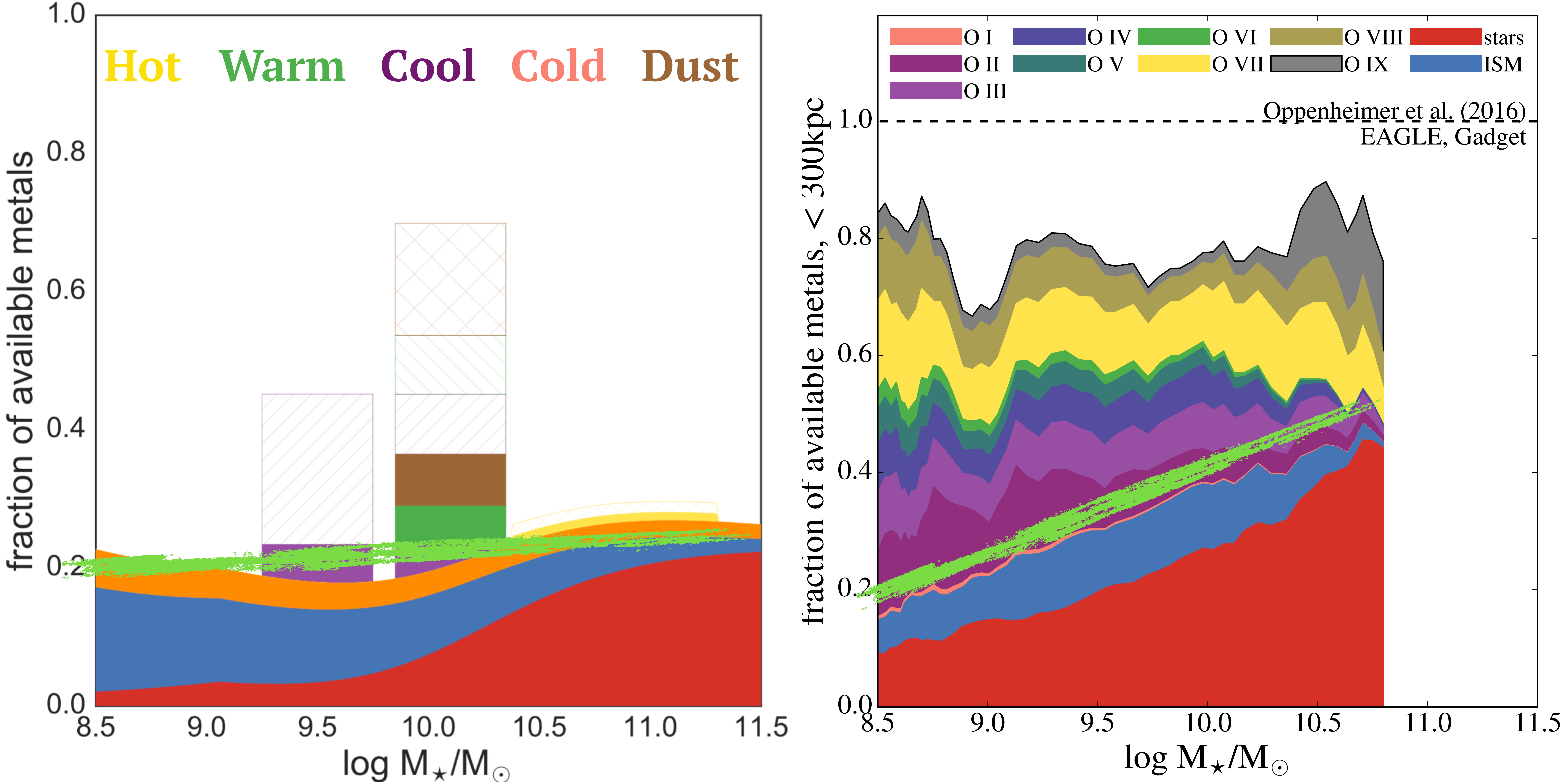
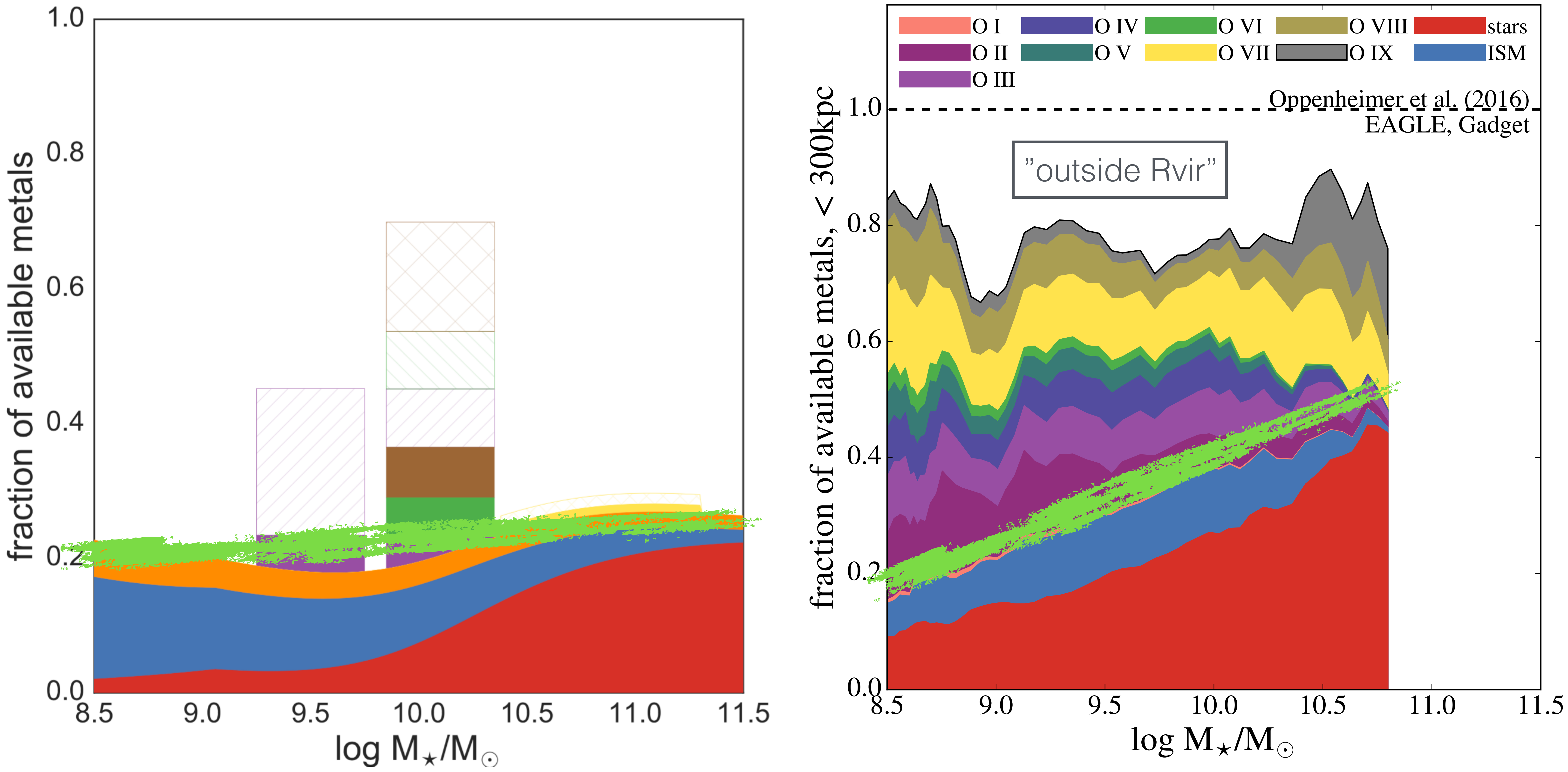


forged connection three



The CGM outweighs the ISM in metals!

Fundamental Problems in Galaxy Evolution

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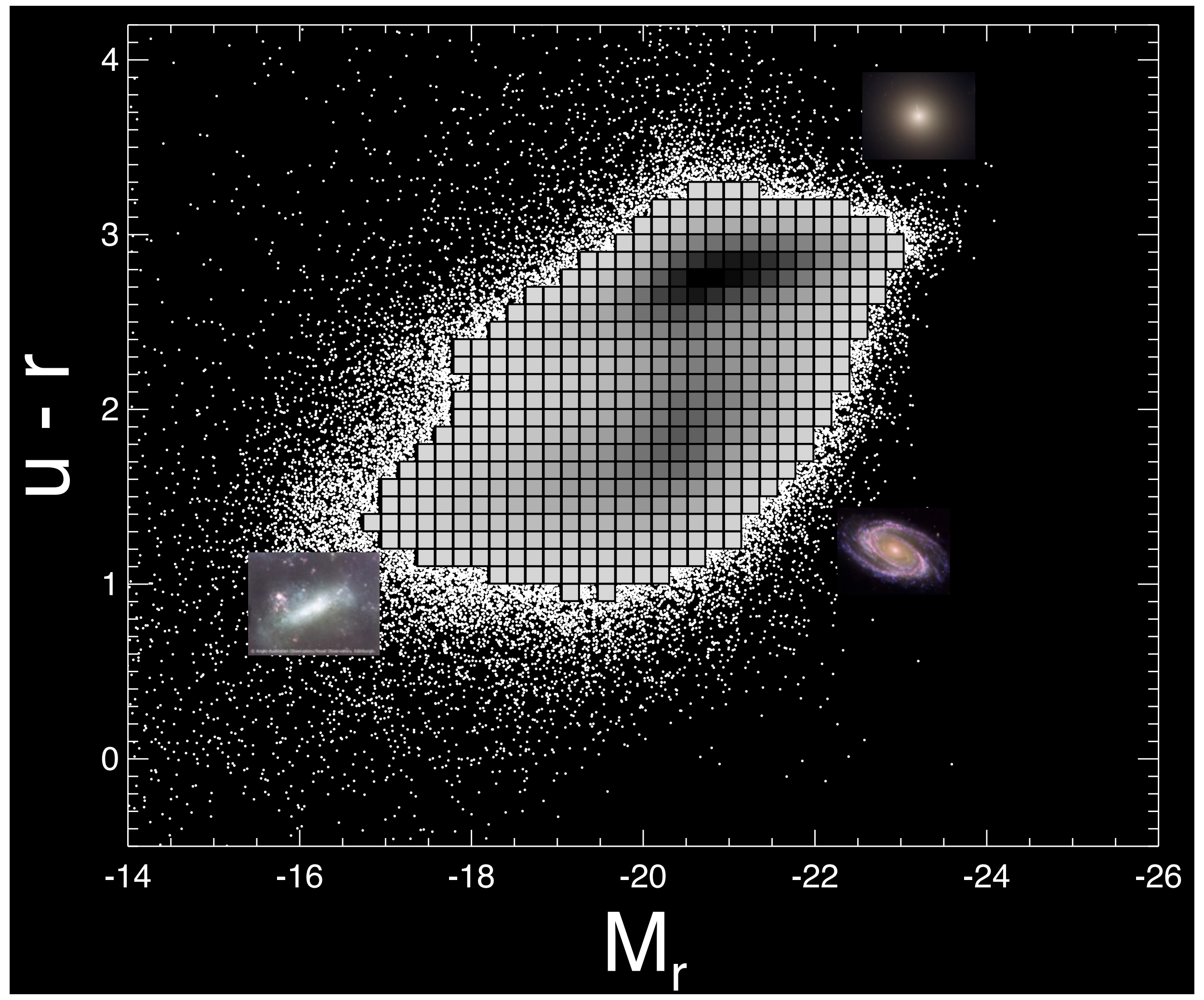
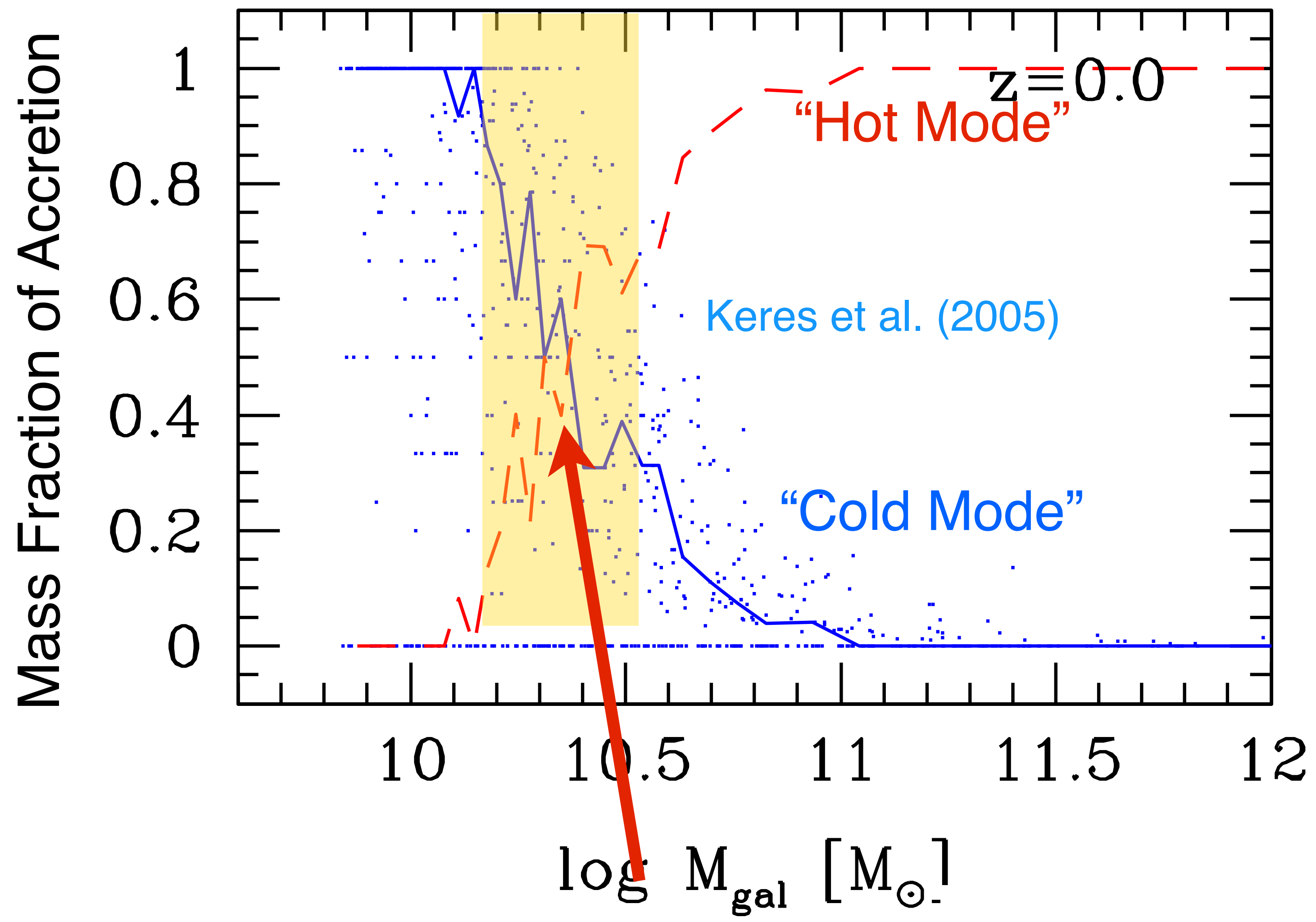
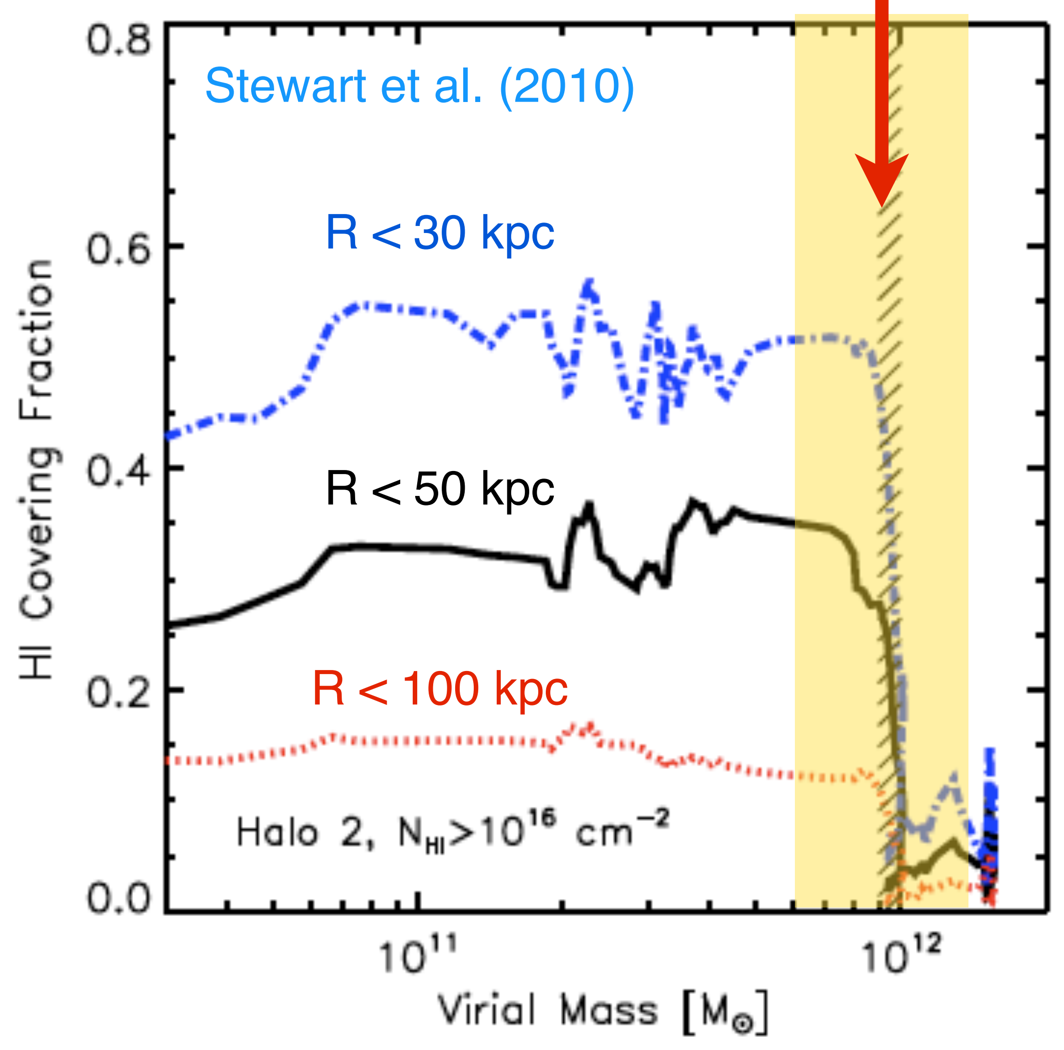


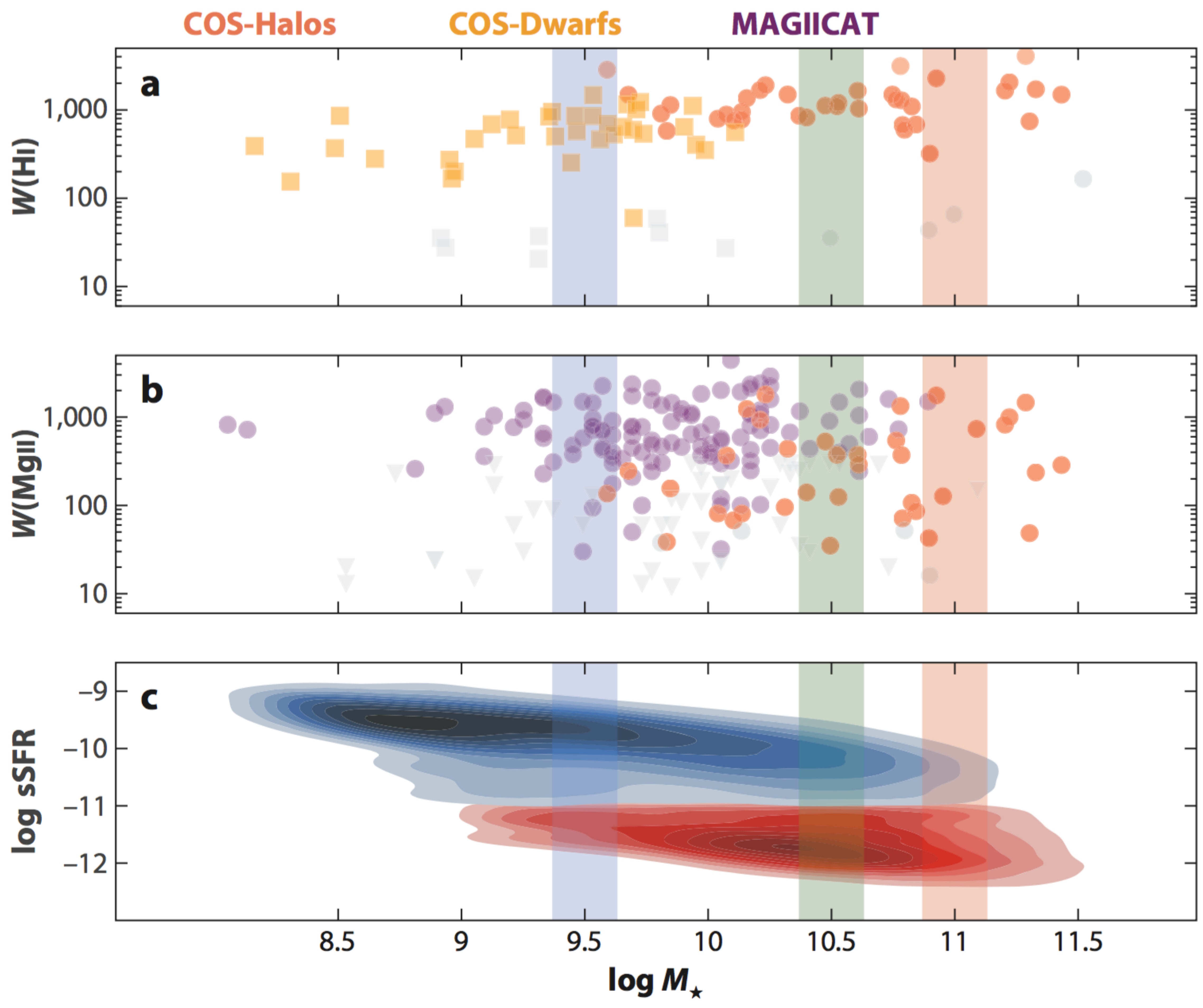
Quenching?

what was supposed to happen





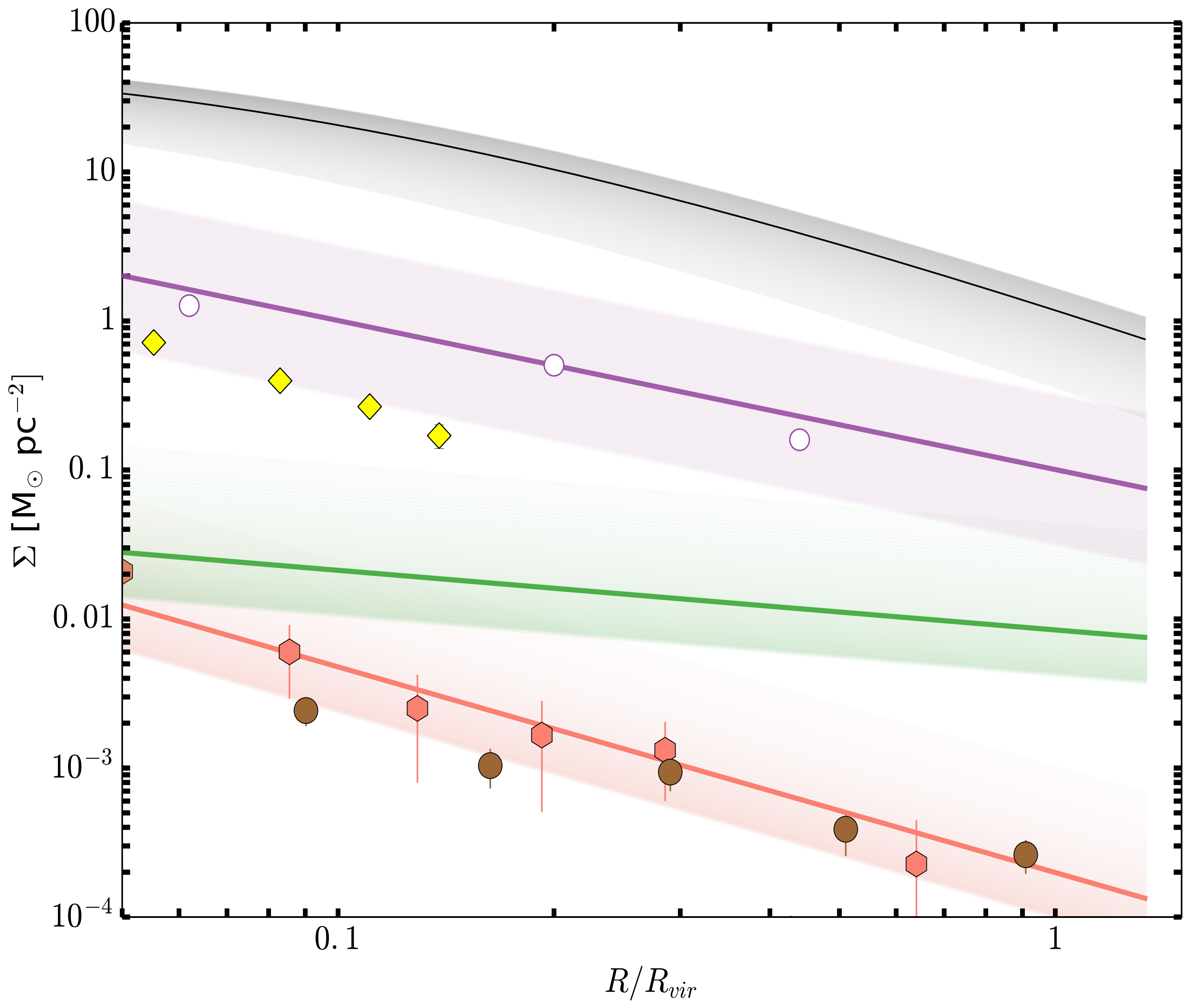
what actually happened

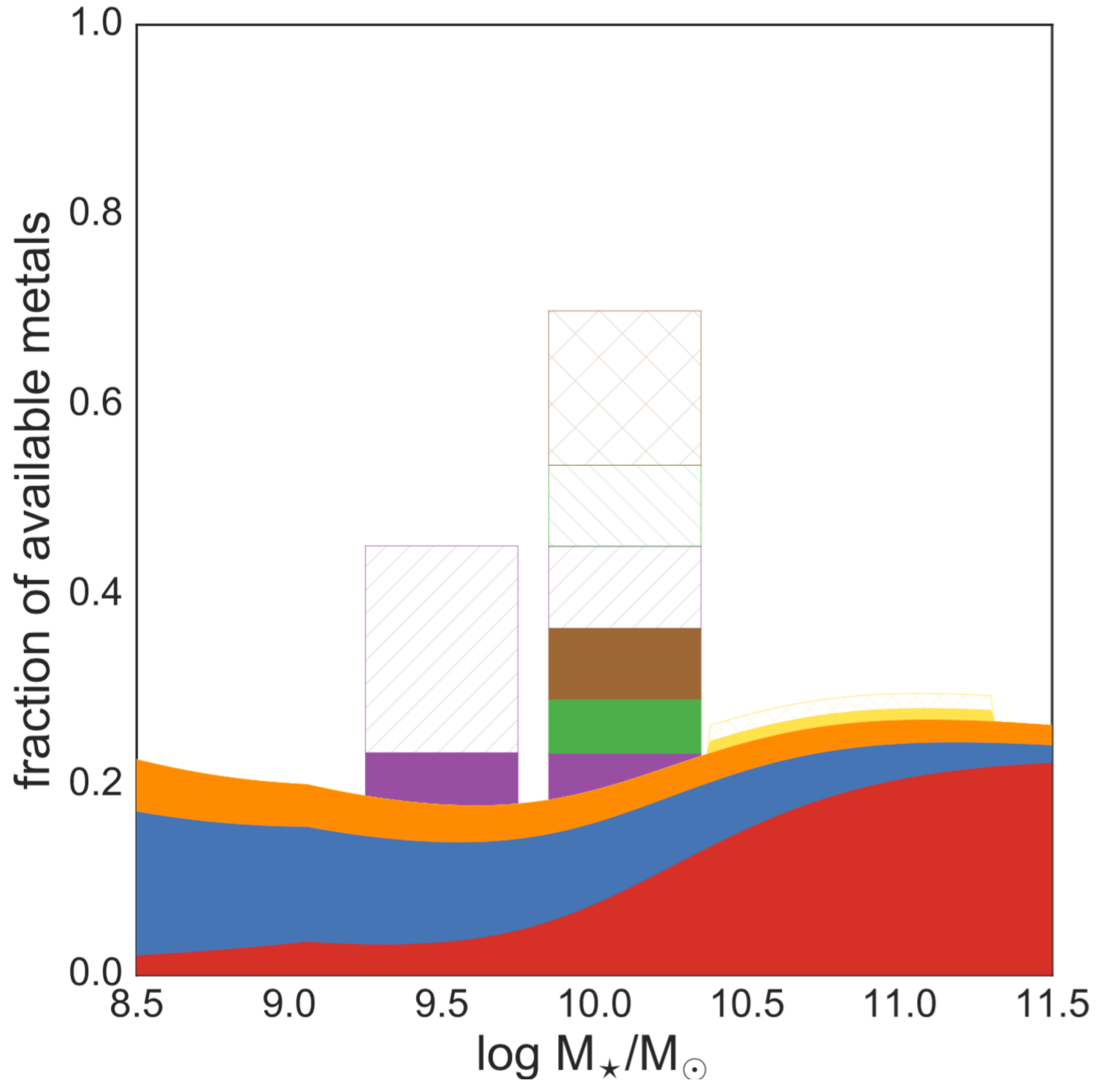


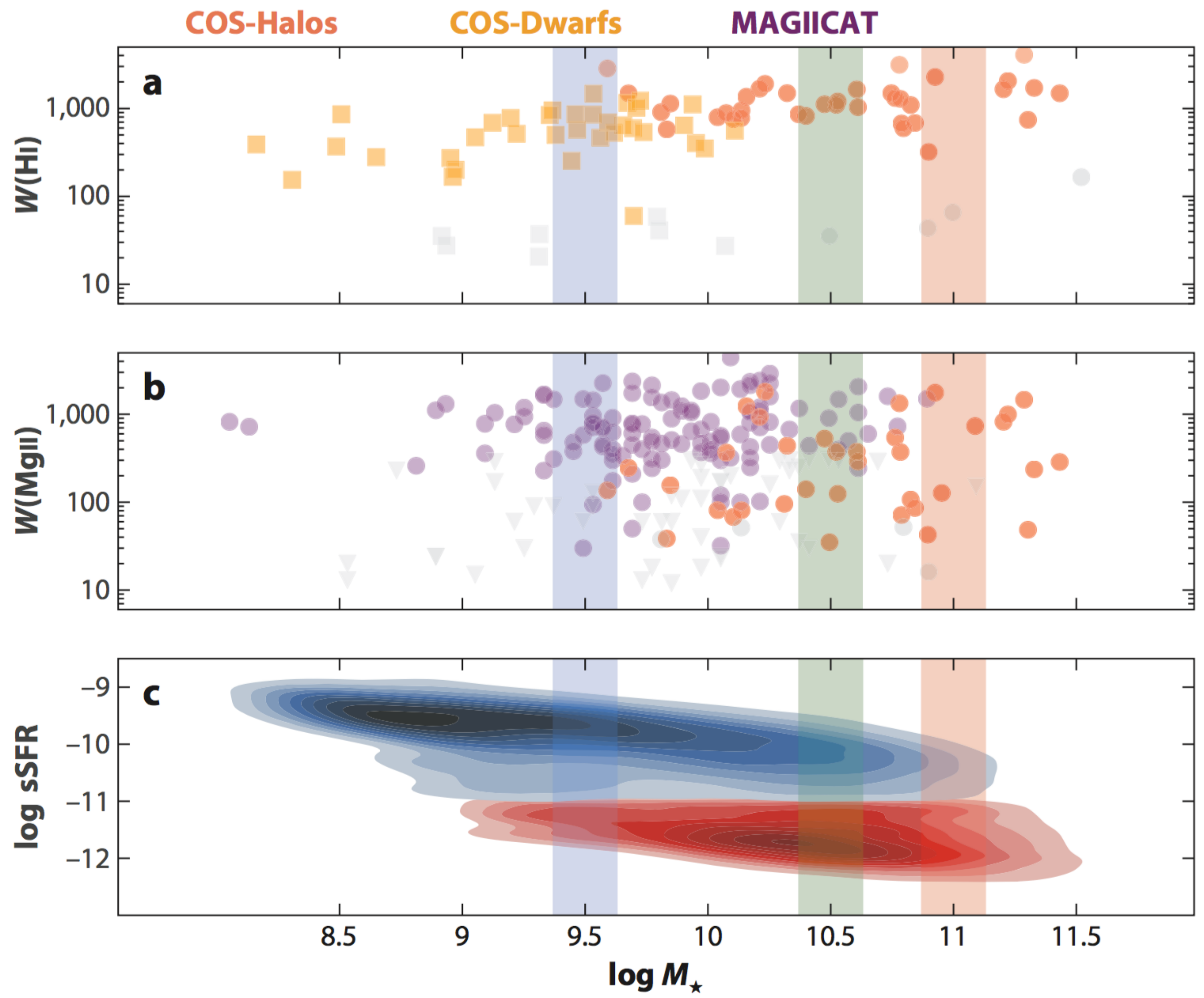
forged connection four

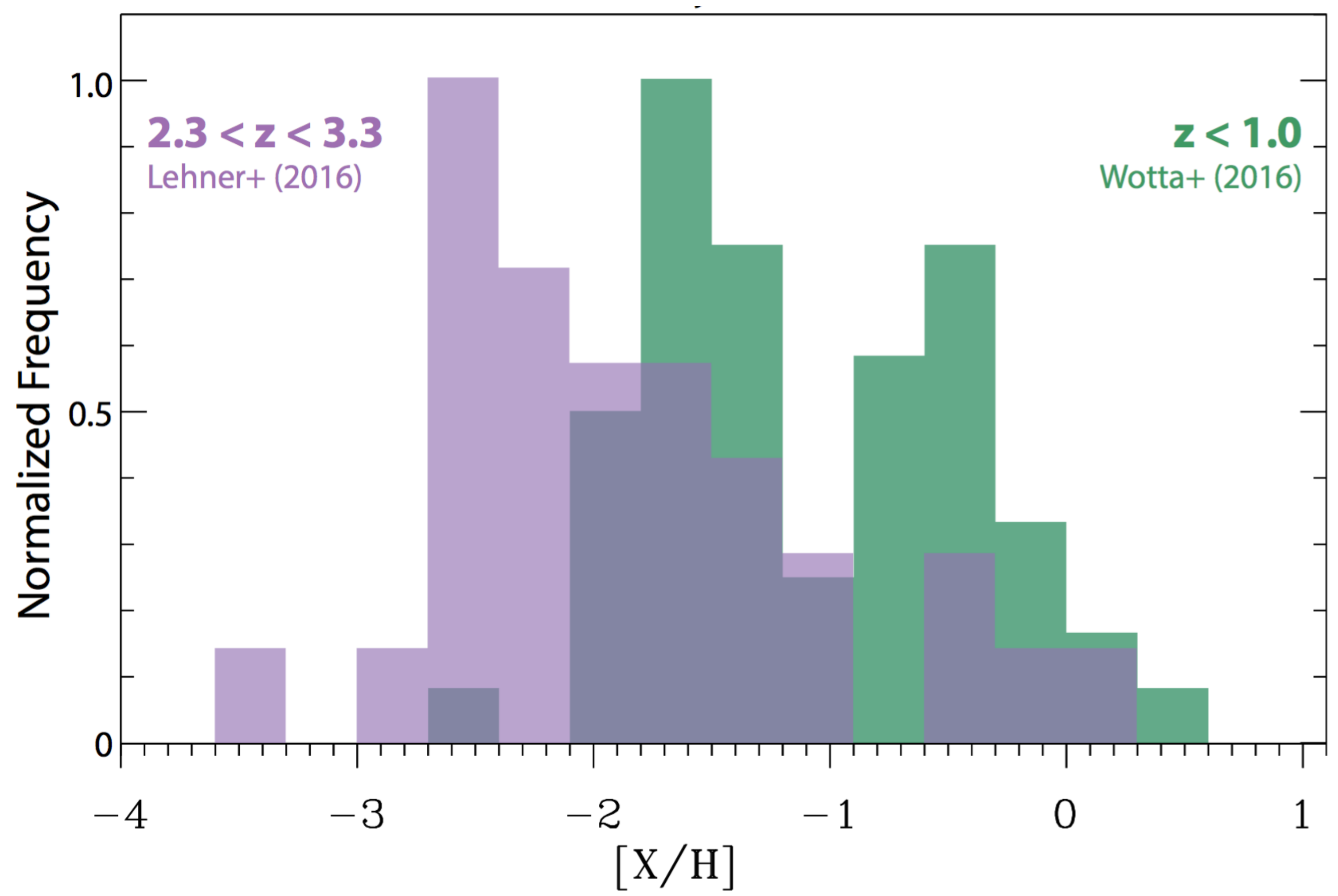
Like Charlie said, nobody understands why galaxies turn passive and remain that way.

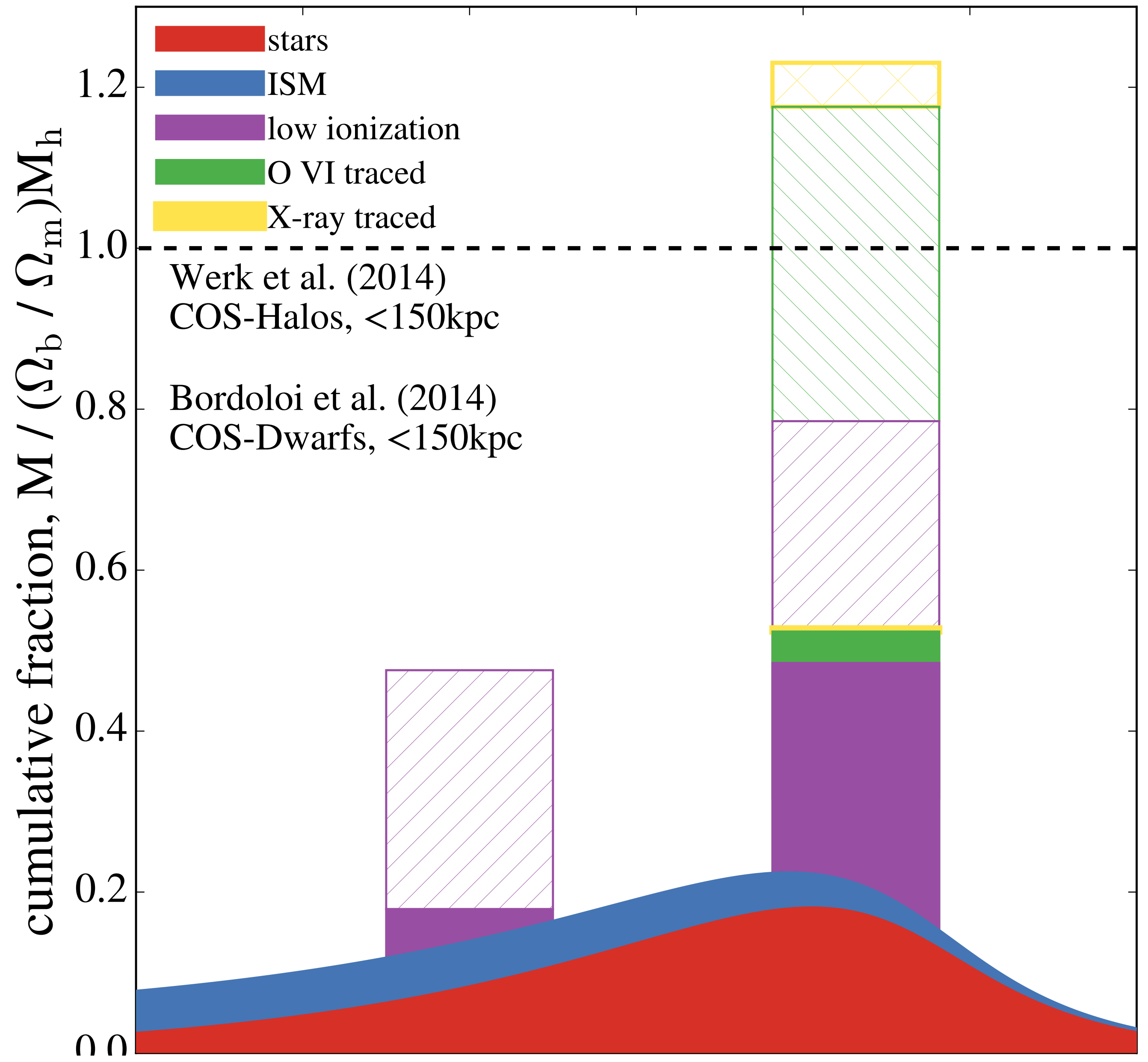
What we have learned

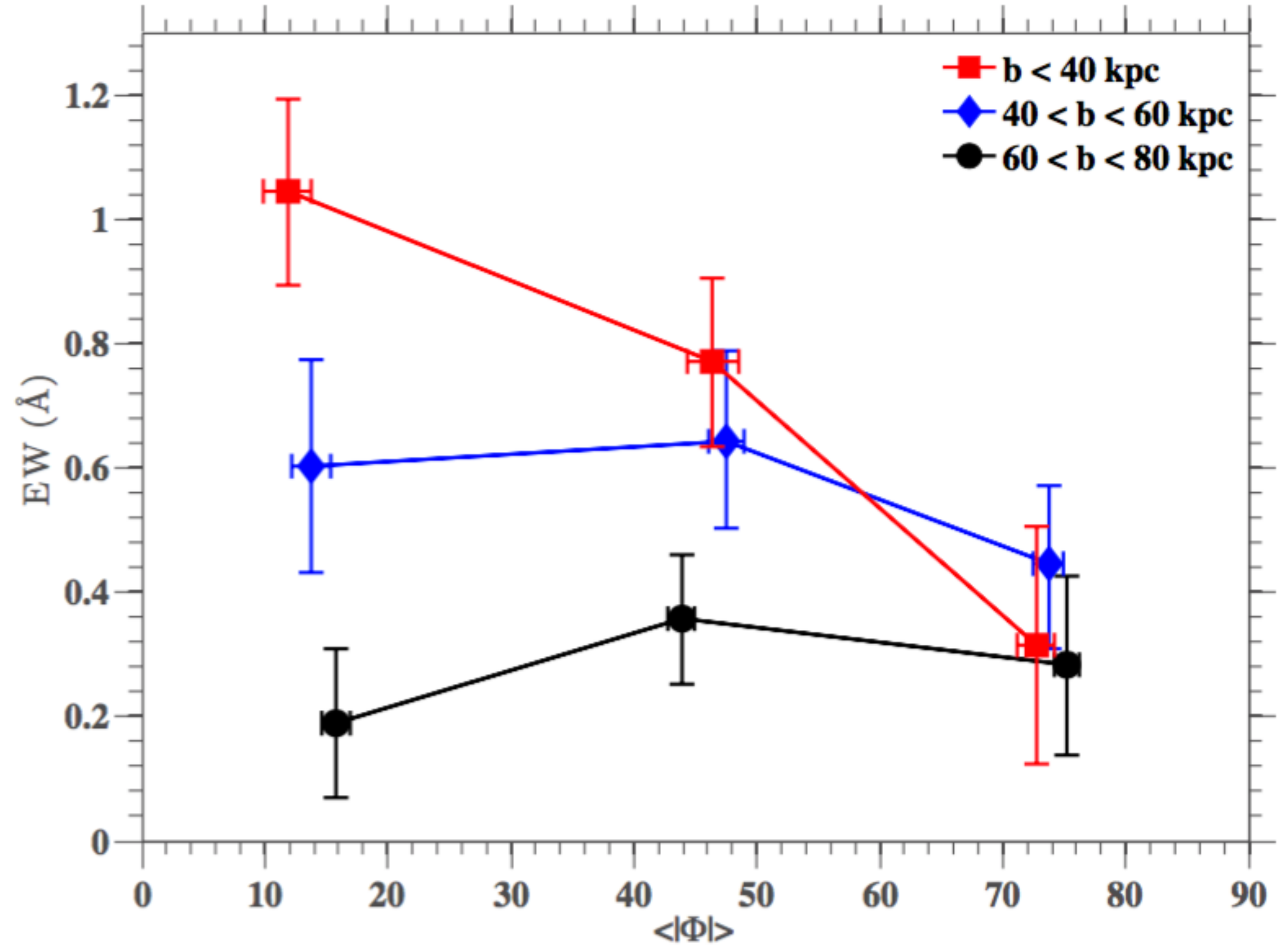












forged connection five

The CGM is a critical venue for chemical evolution: just as important as the ISM!

Outlook

AMIGA: Absorption Maps of Gas In Andromeda

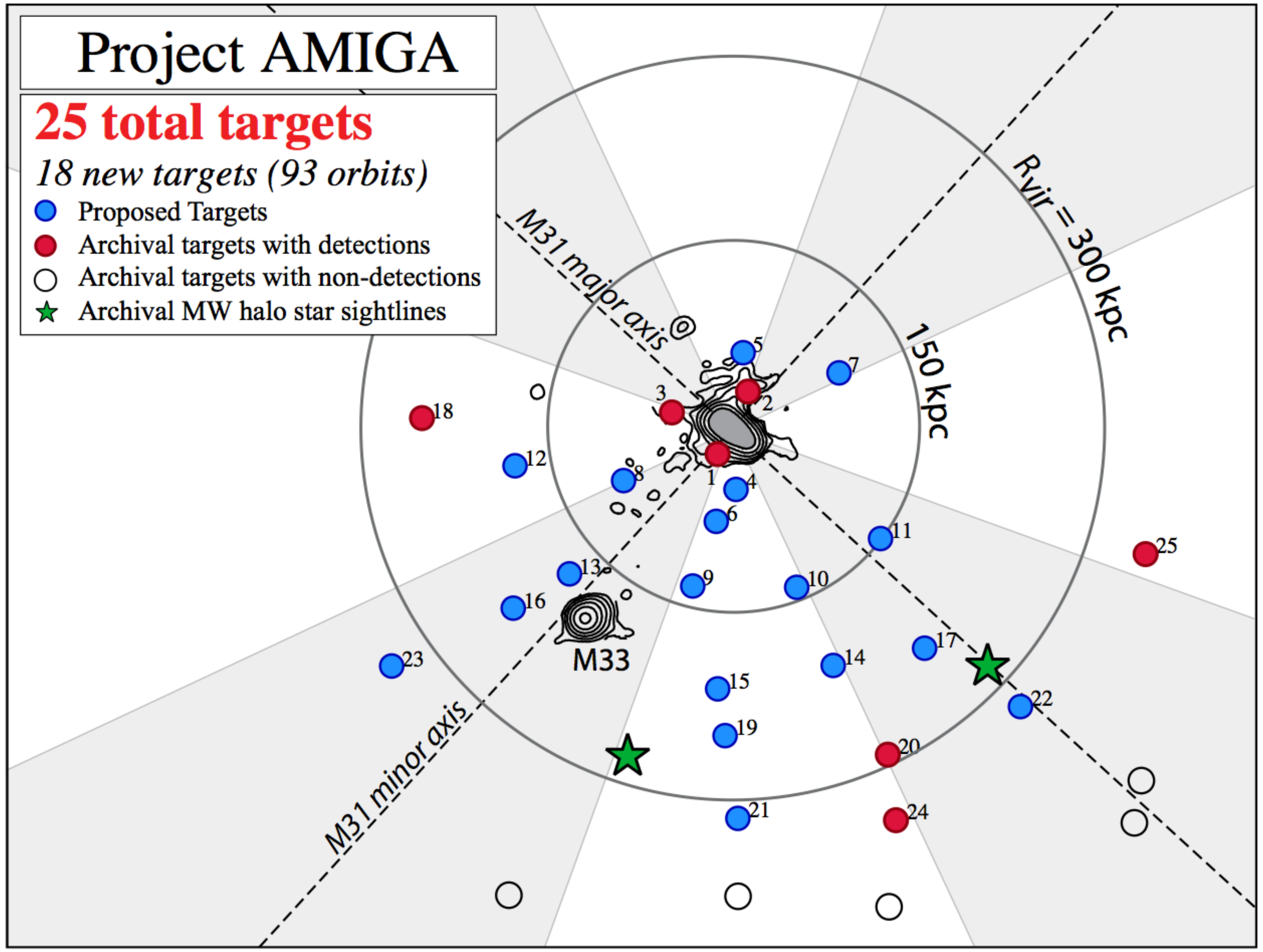
(PI: N. Lehner, Notre Dame)

COS-Disks

(PI: S. Borthakur, Arizona State)

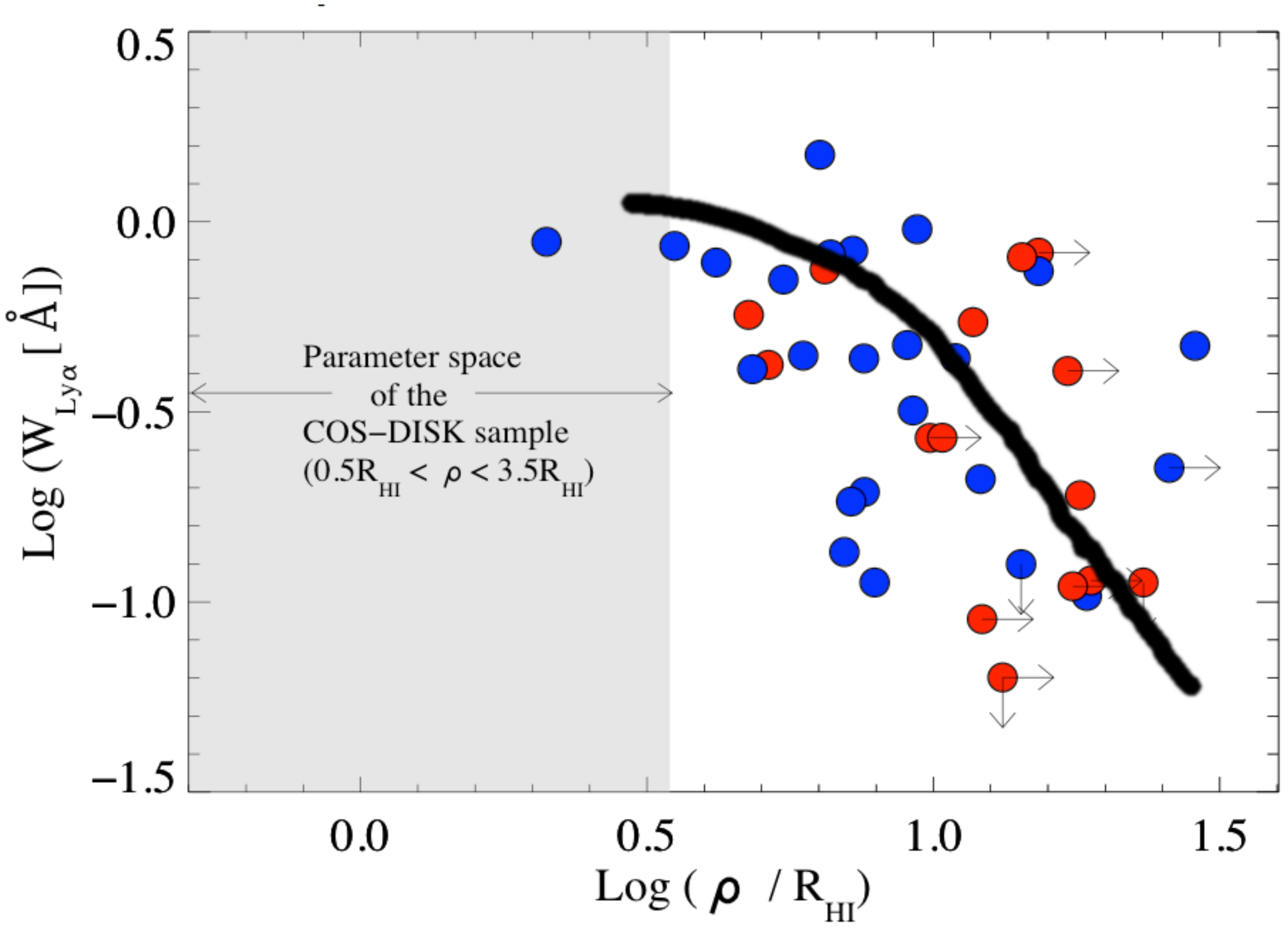
93 *Hubble* orbits with COS
+ parallel imaging with both WFC3 and ACS to map the *stellar* halo at roughly same locations

Data still being collected, but preliminary analysis of archival data reveal interesting trends within *one* halo versus what COS-Halos saw in aggregate.



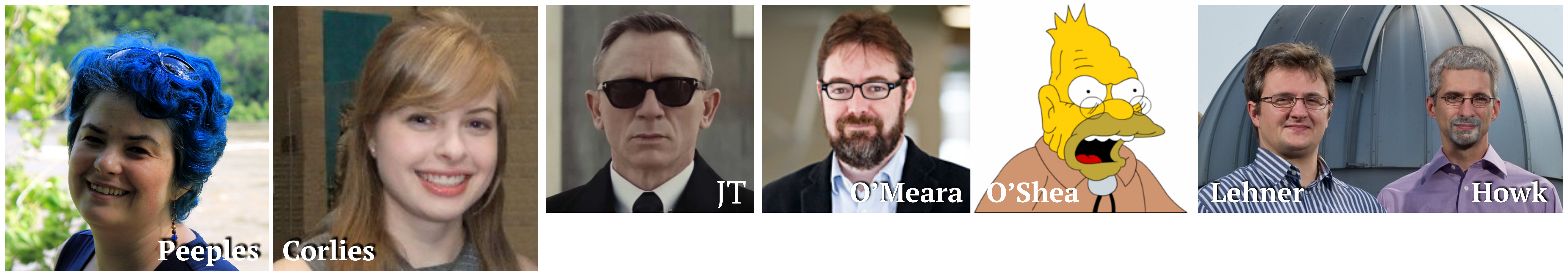
99 *Hubble* orbits with COS
supporting HI data from Arecibo, with star formation measures from SDSS, GALEX, and other sources.

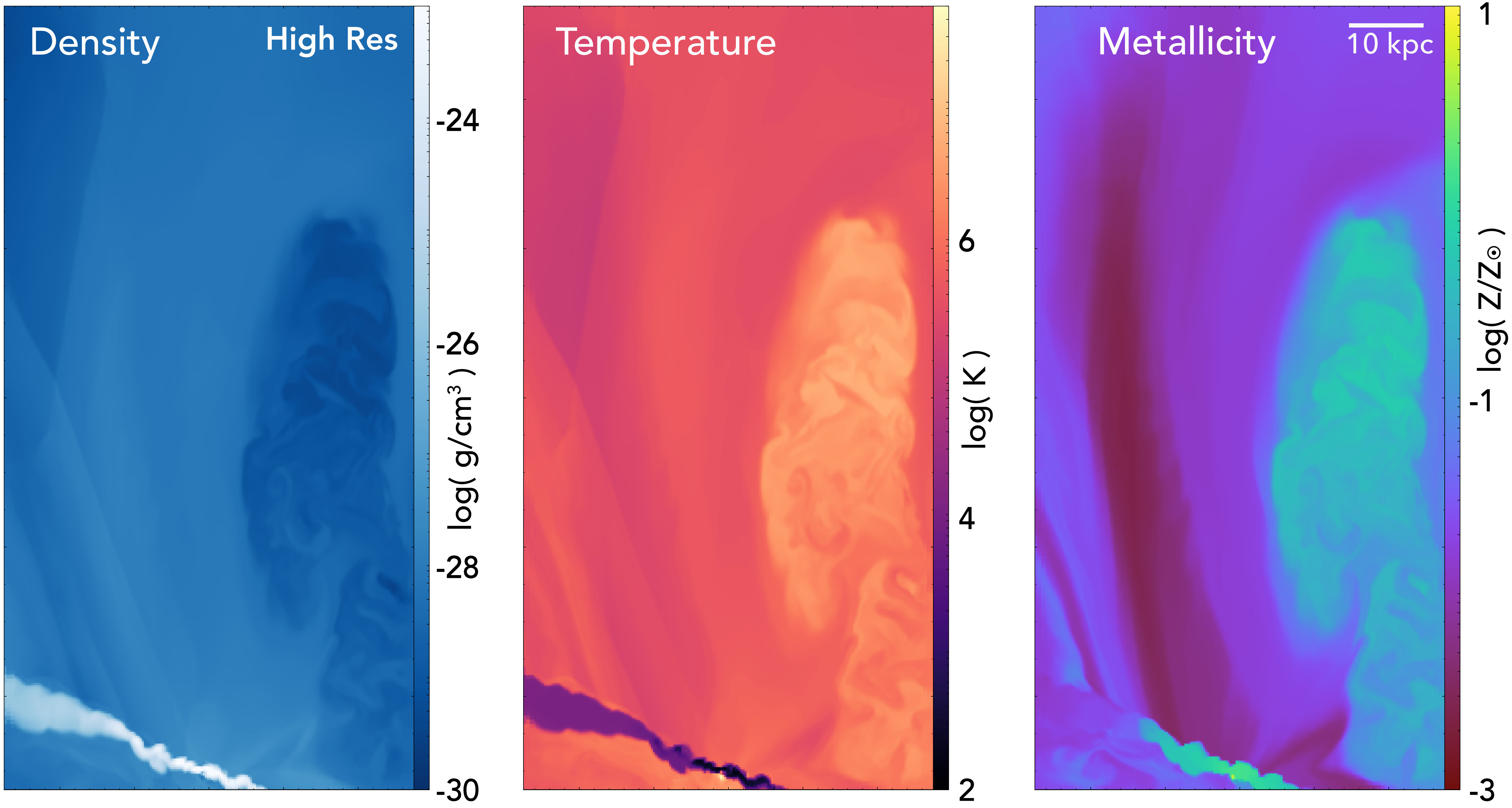
Key goal is to map CGM gas in absorption as close as possible to the disk, address accretion where it happens and feedback where it starts.



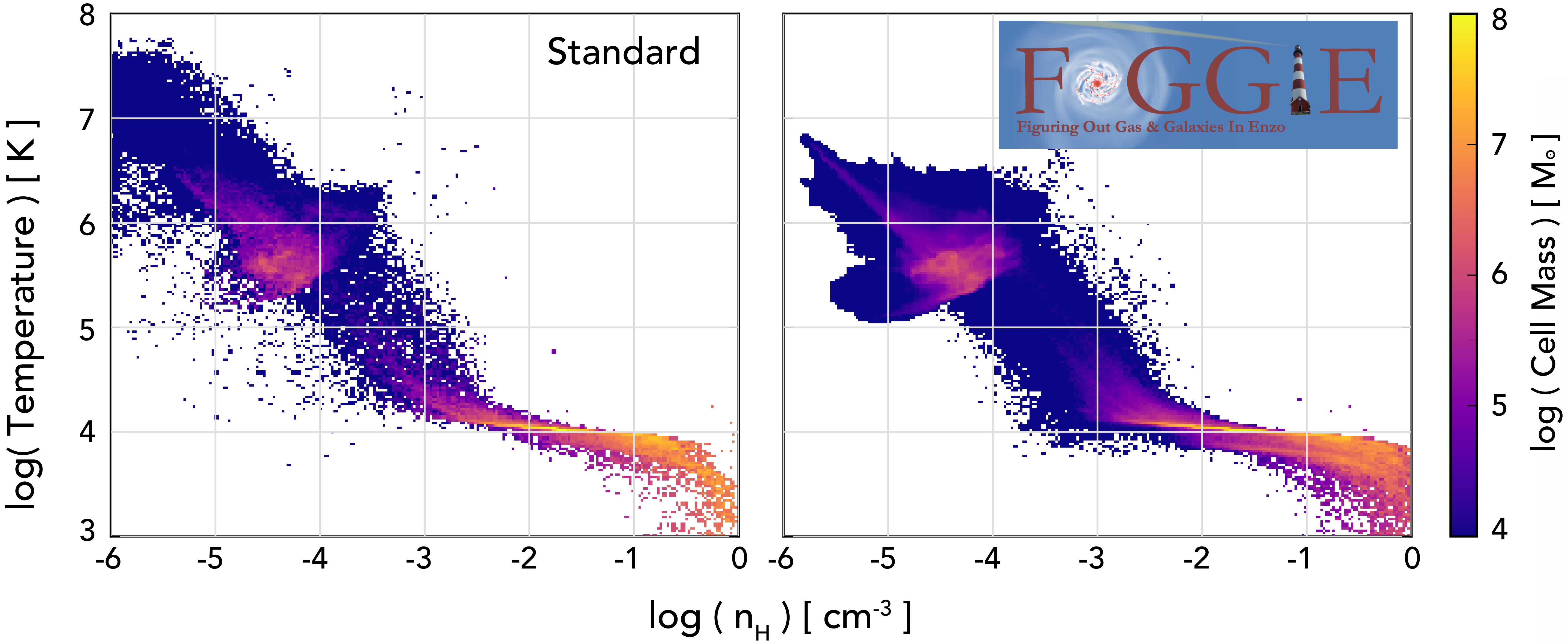
FOGGIE

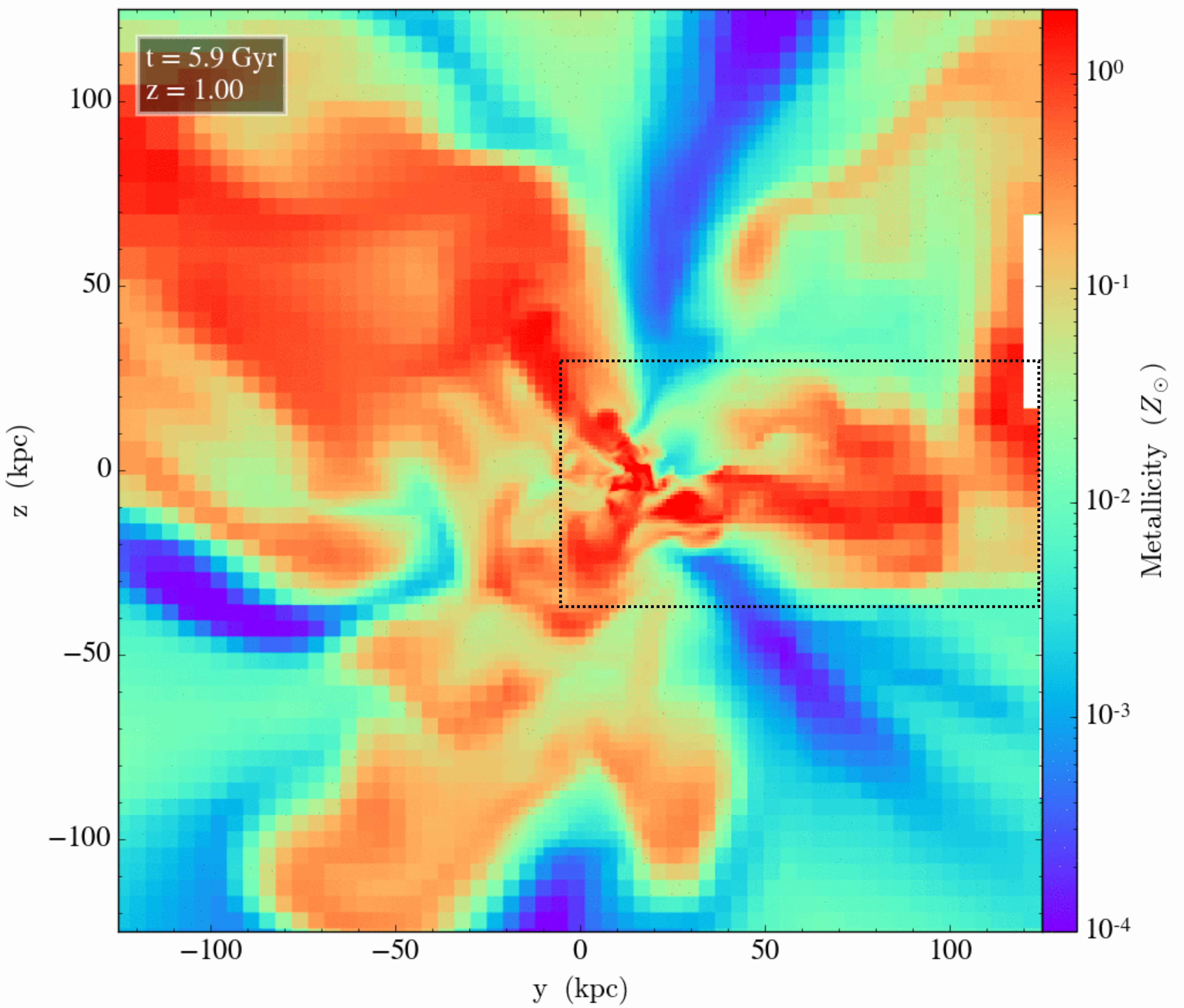
Figuring Out Gas & Galaxies In Enzo





FOGGIE
Figuring Out Gas & Galaxies In Enzo



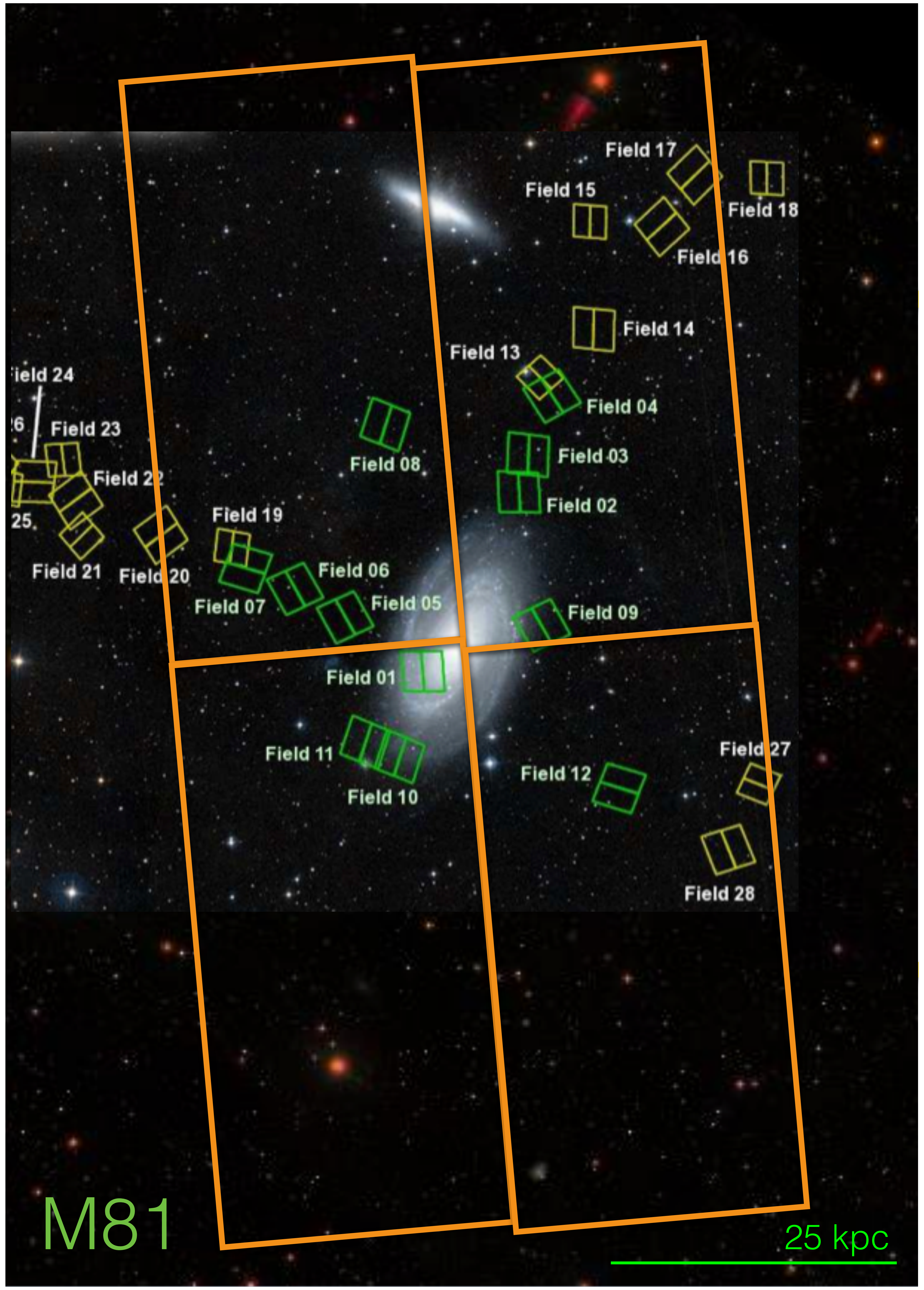


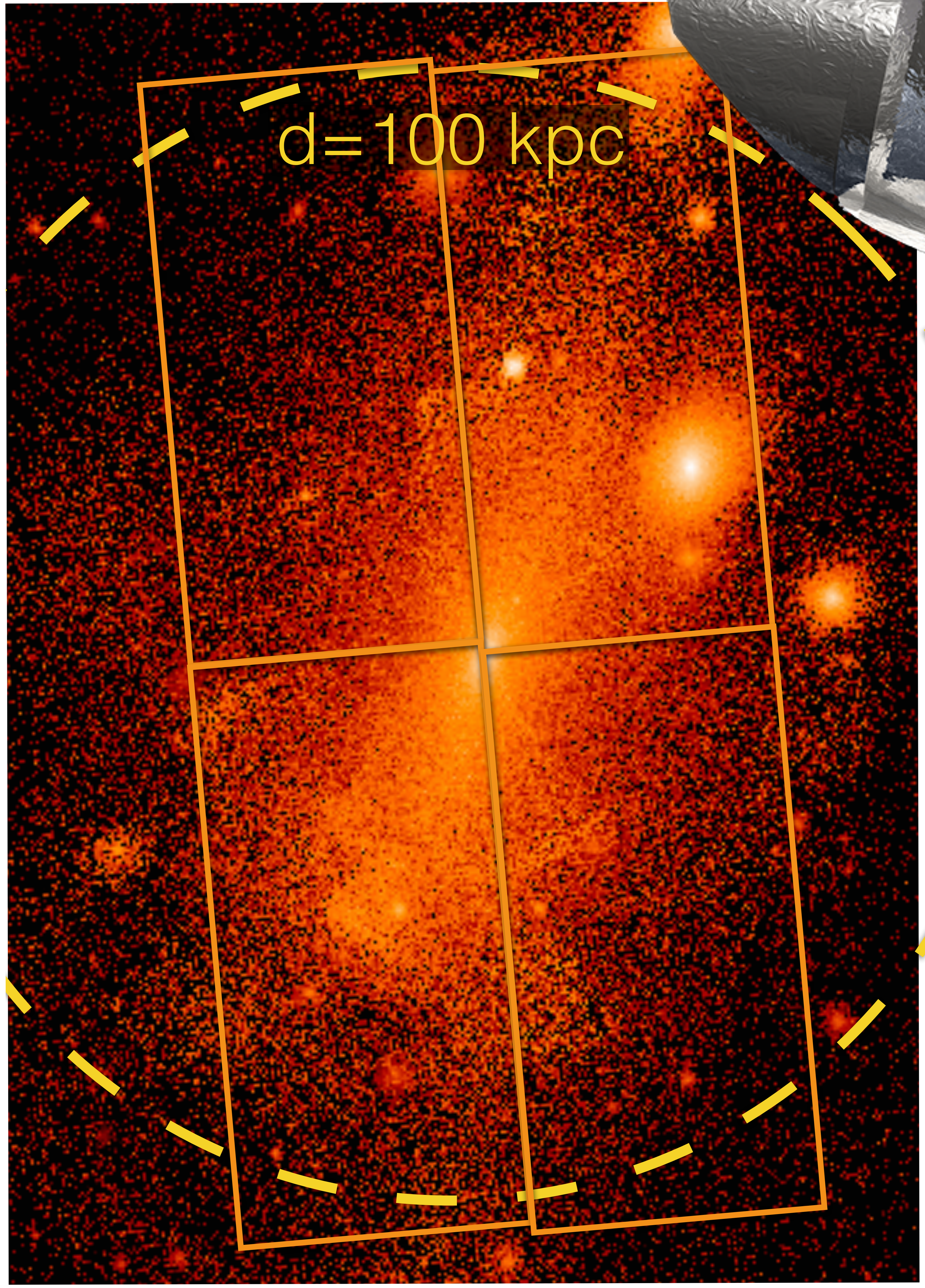
mass resolution
as low as **~100-500 $M_\odot$** in low density gas
cf. 10^{5-7} $M_\odot$ in typical particle-based simulations (such as FIRE/Latte)

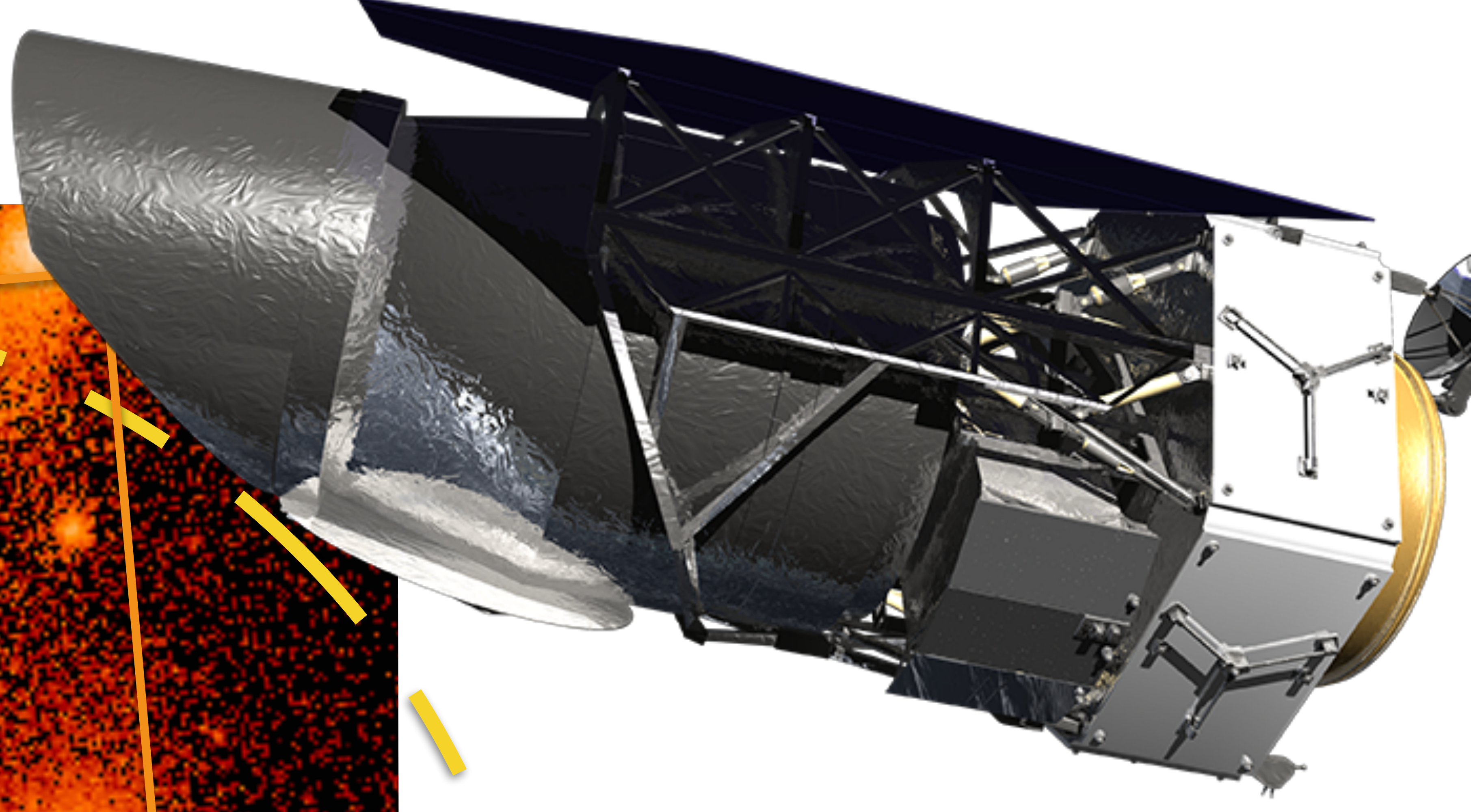
Back to stars for a bit
[just for JB-H]

Hubble resolution at 100x FOV

2025 launch







4 fields cover M81 halo

LUVOIR: A NASA Study for the 2020 Decadal

Large UV / Optical / Infrared Surveyor (LUVOIR)

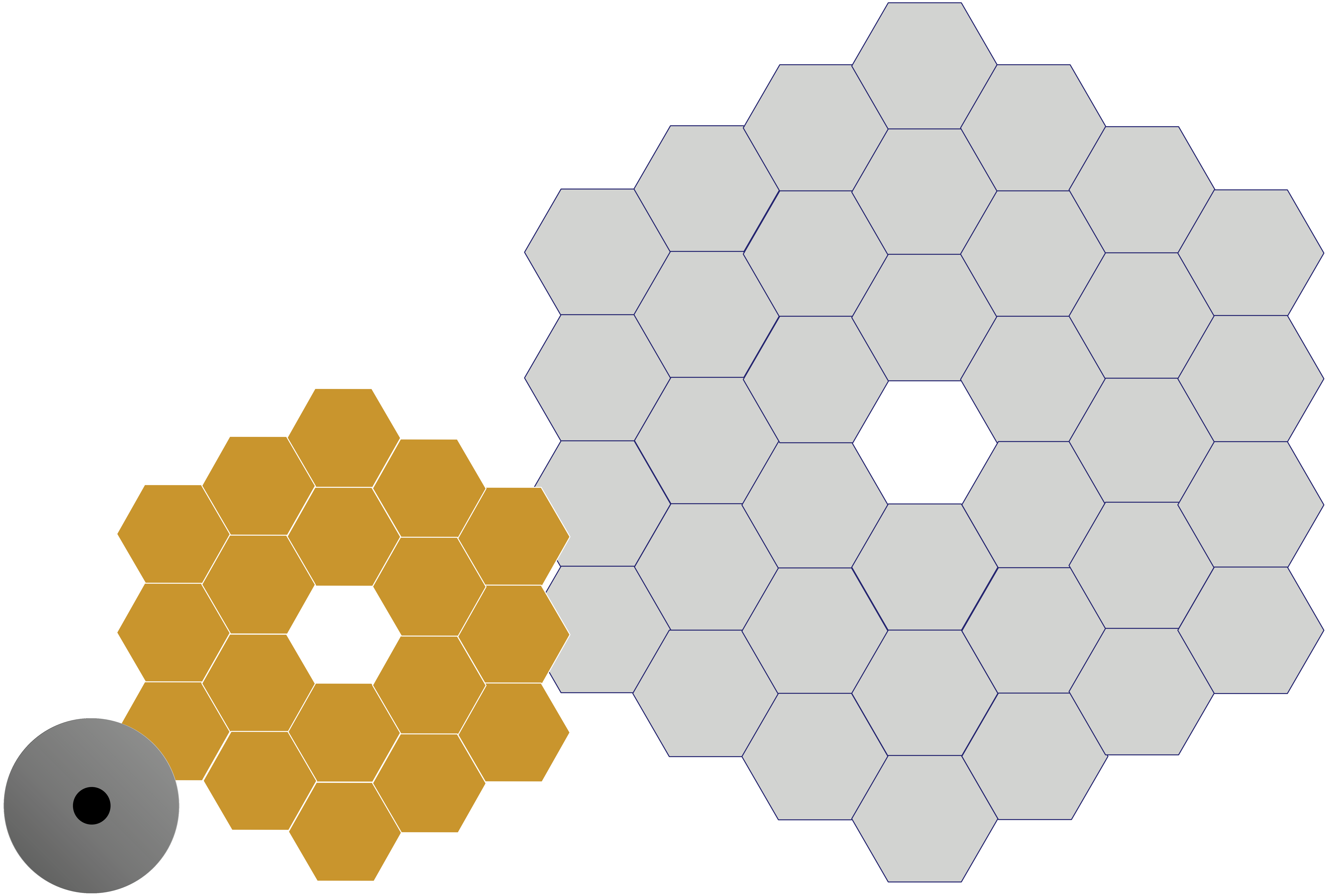
A space telescope concept in tradition of Hubble

- Broad science capabilities
- Far-UV to Near-IR bandpass
- ~ 8 – 16 m aperture diameter
- Suite of imagers and spectrographs
- Serviceable and upgradable
- Hubble-like guest observer program

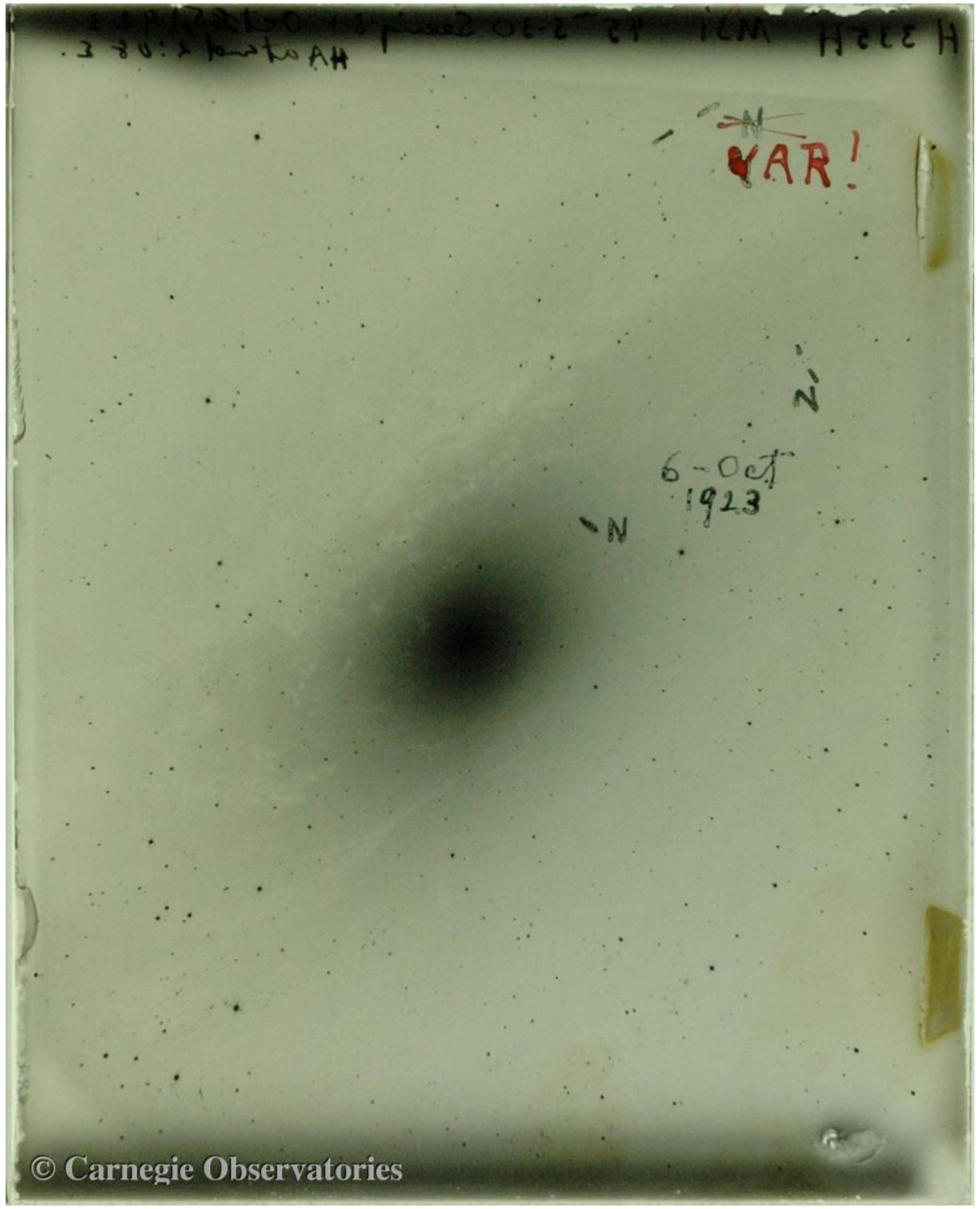
Aimed for 2030 launch.

"Space Observatory for the 21st Century"

Ability to answer questions we have not yet conceived

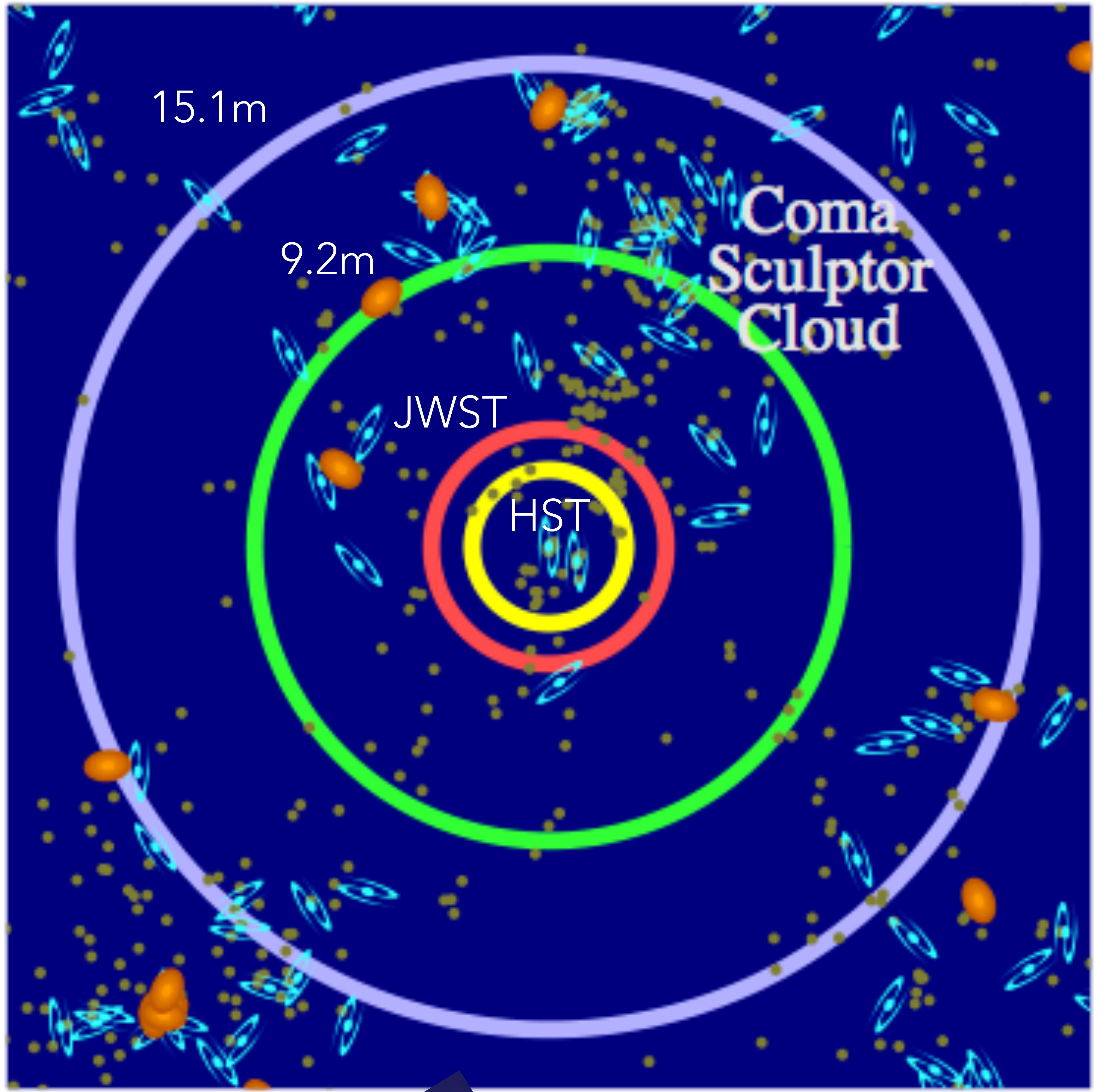


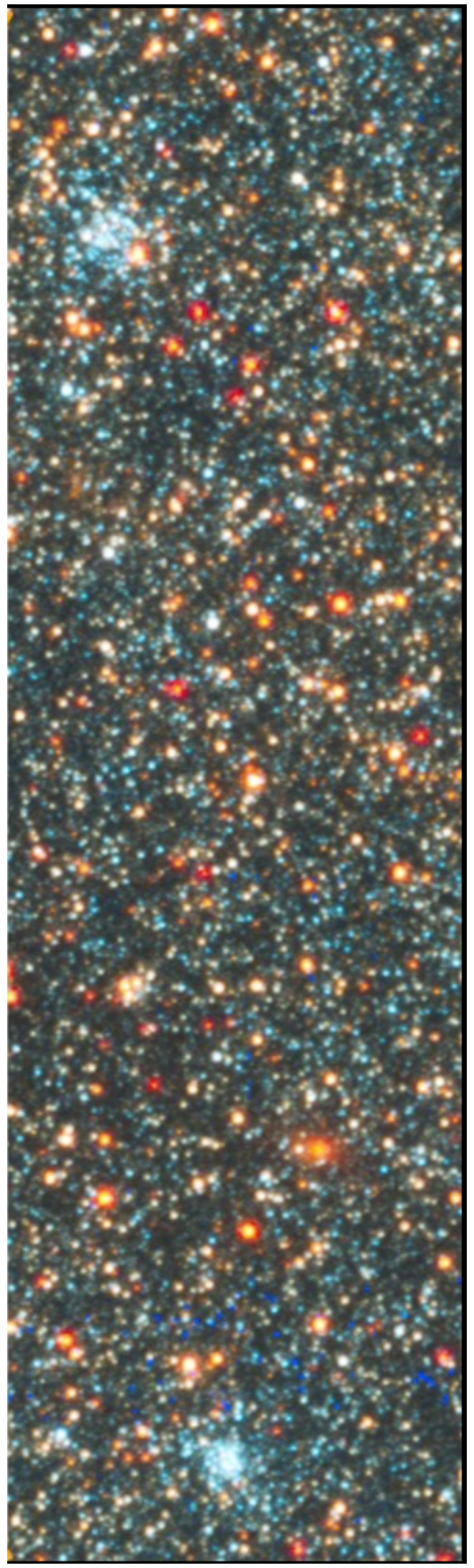
THE POWER OF APERTURE: OLD SCHOOL EDITION



GALACTIC ARCHAEOLOGY

GALACTIC ARCHAEOLOGY

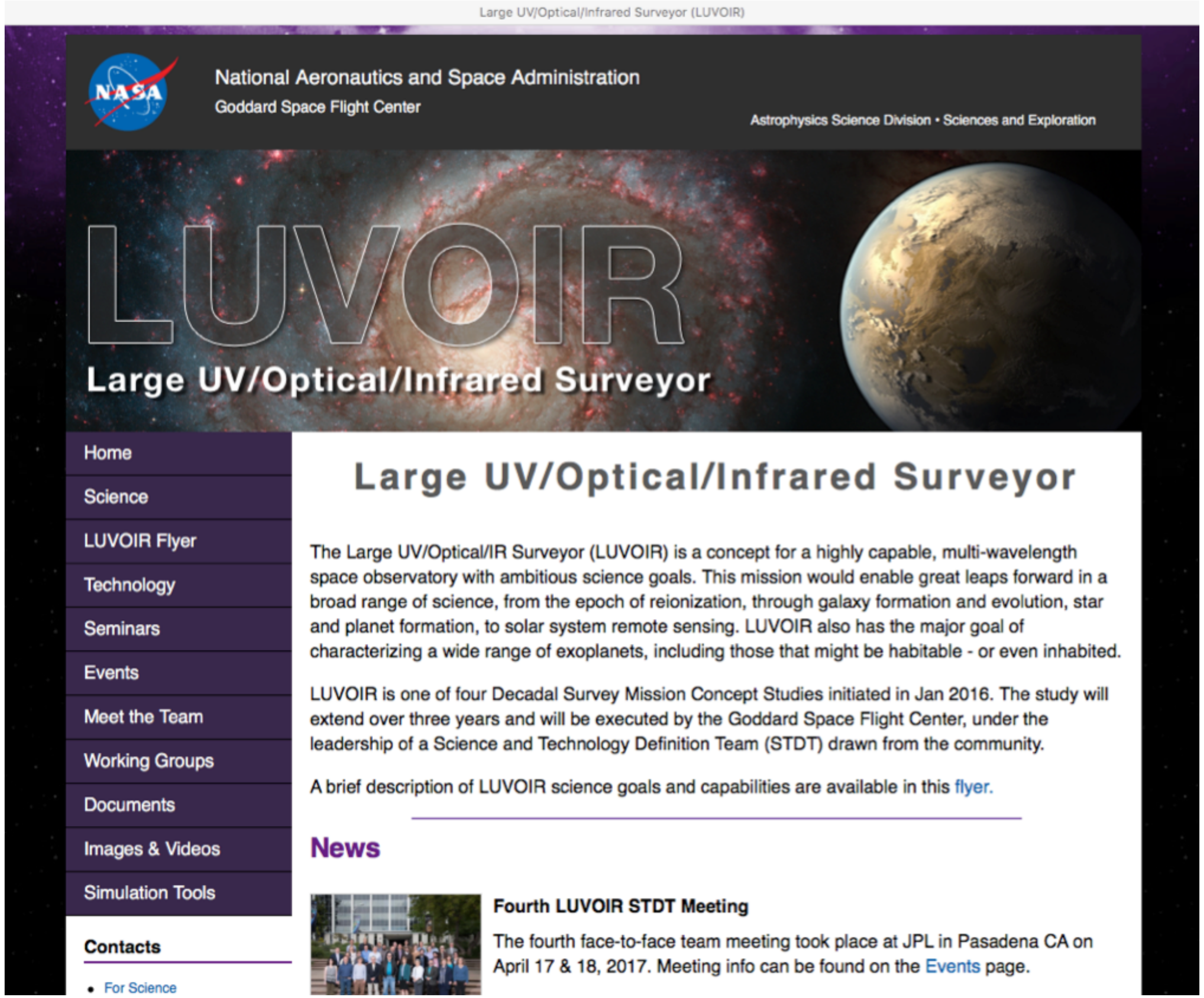




= Large Elliptical Galaxy = Large Spiral Galaxy = Dwarf Galaxy

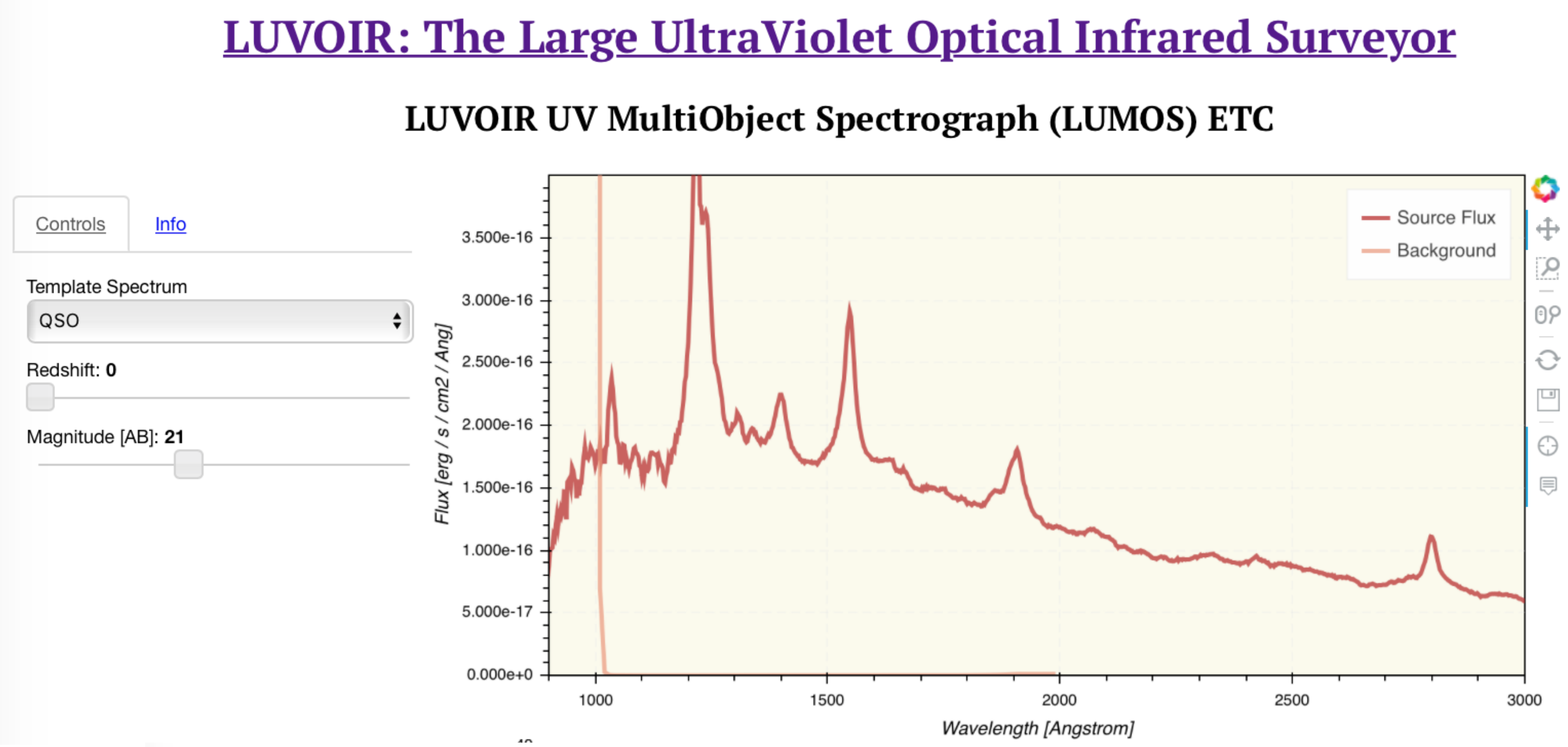
Get involved with LUVOIR

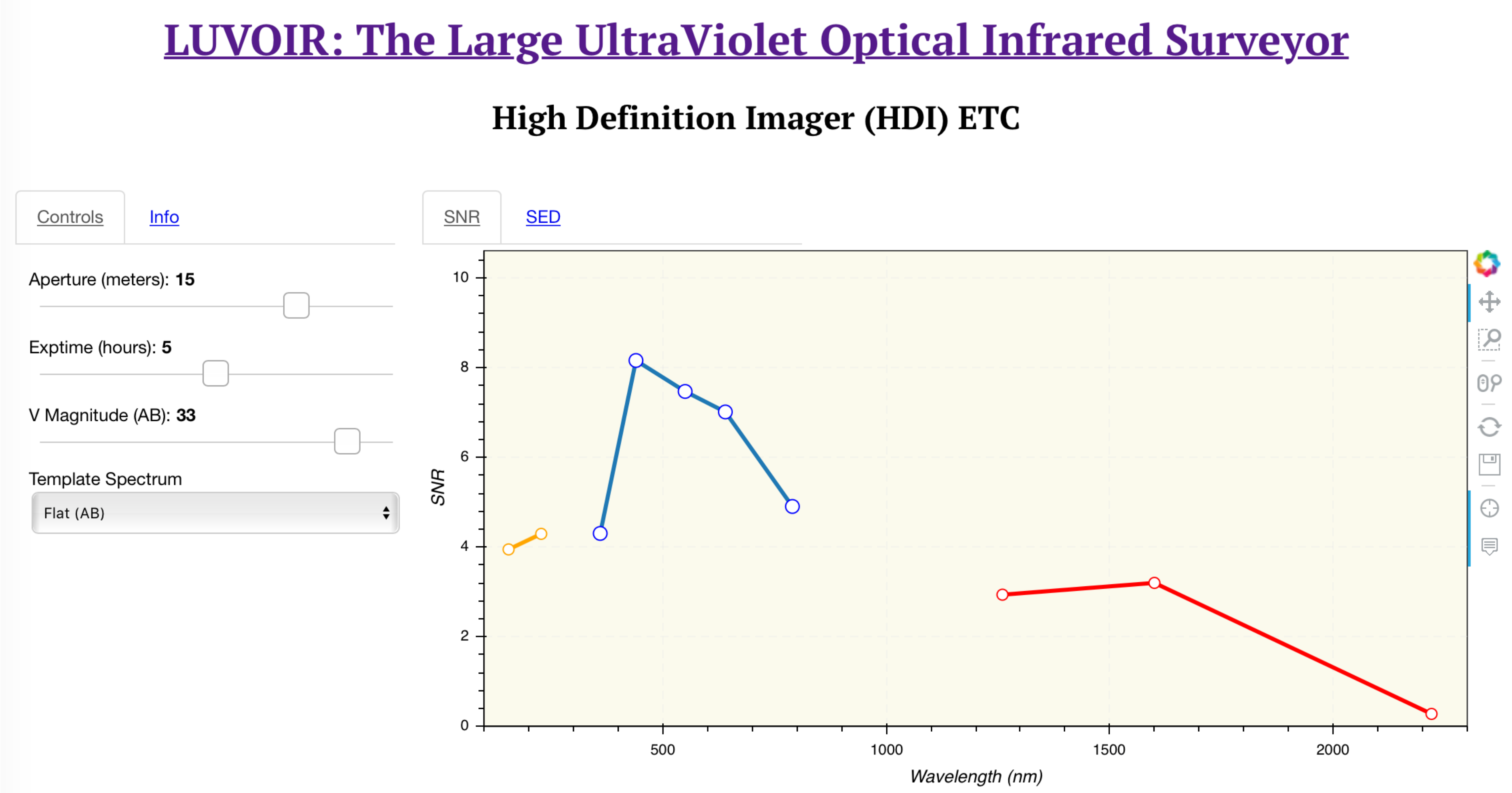
http://asd.gsfc.nasa.gov/luvoir/



ETCs and simulation tools at:

https://asd.gsfc.nasa.gov/luvoir/tools/






The
End
Diffuse gas
Recycling gas
Accreting gas
15 kpc
Outflows
300 kpc
Ann Field (OPO)