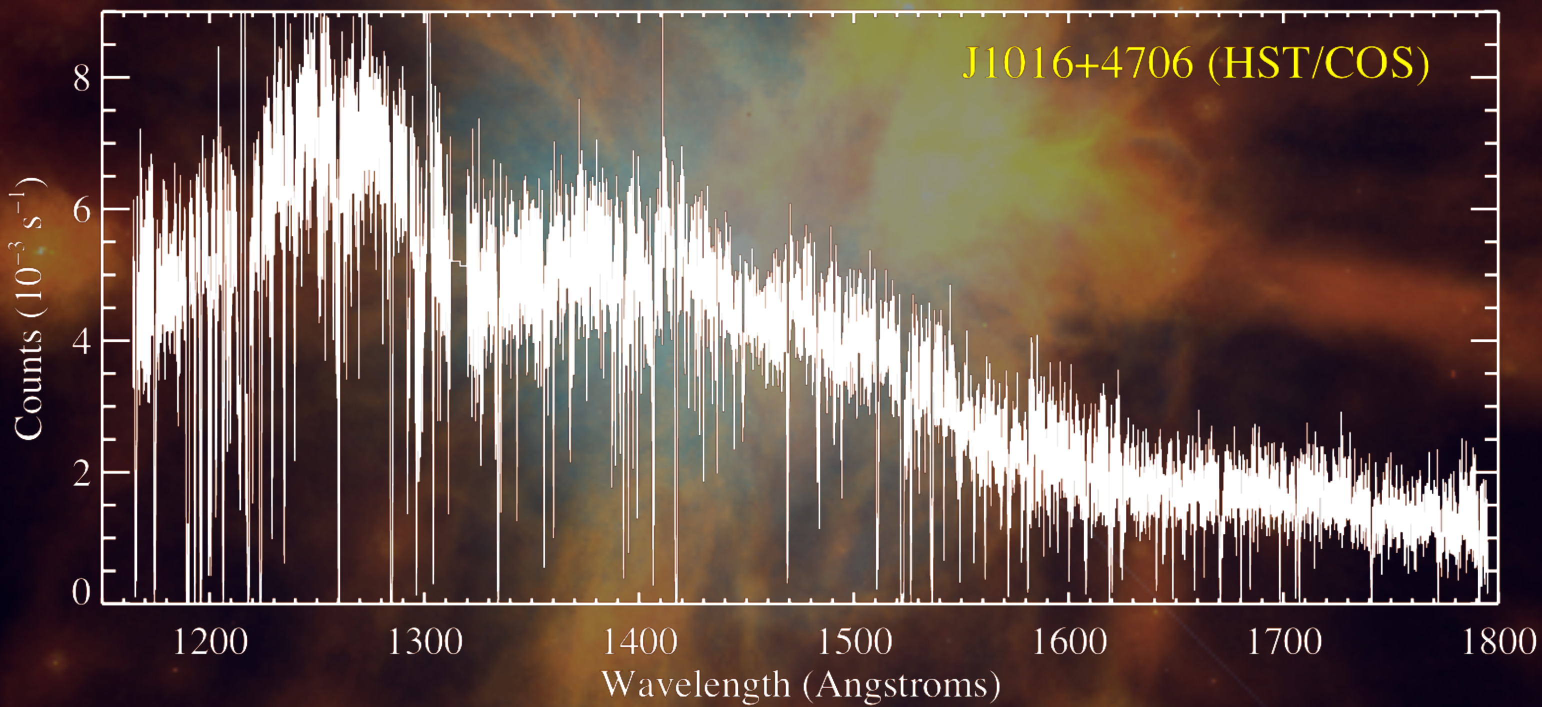
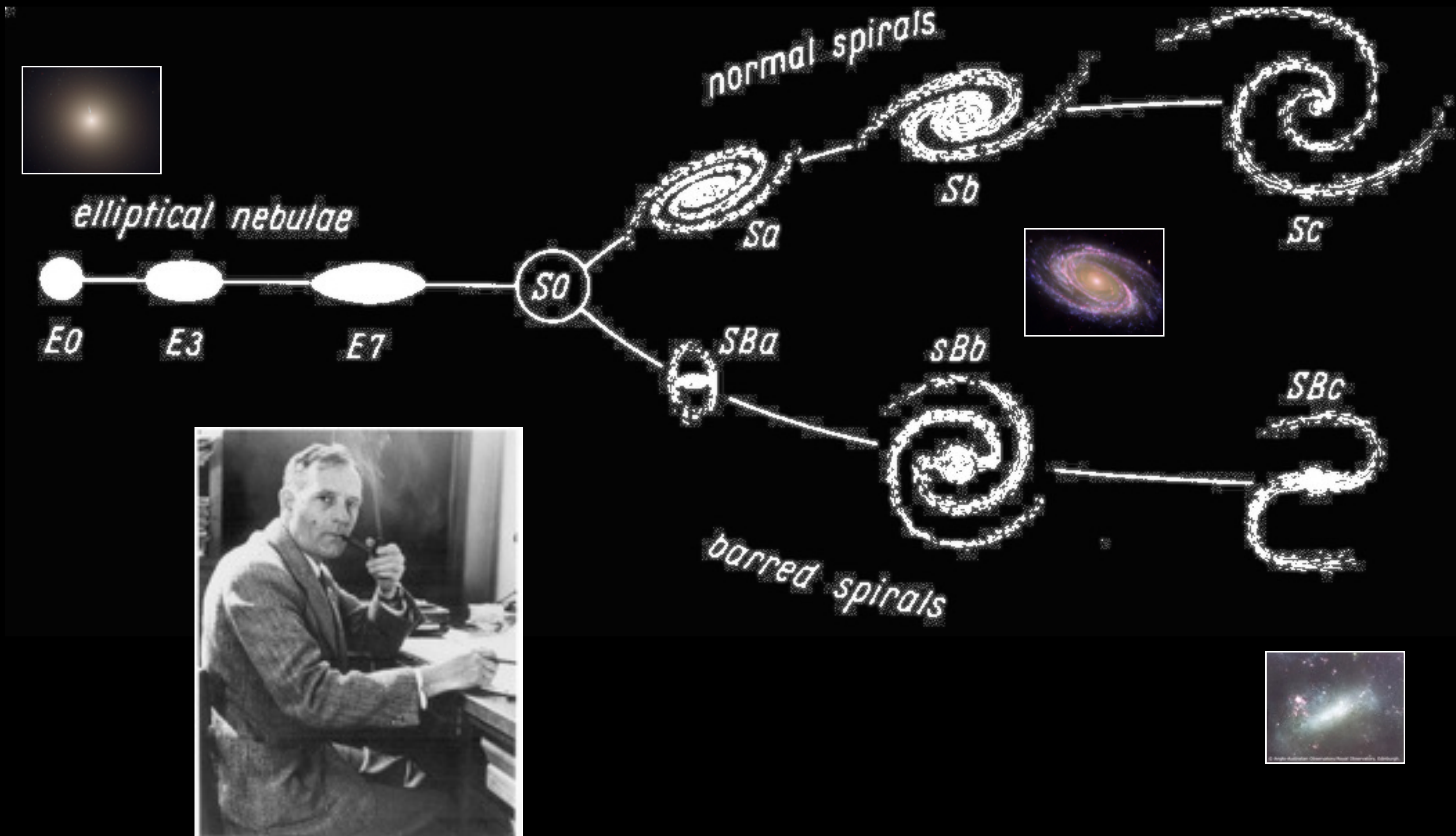
THE CIRCUMGALACTIC MEDIUM

A Present and Future Window on Galactic Fueling, Quenching, and Recycling

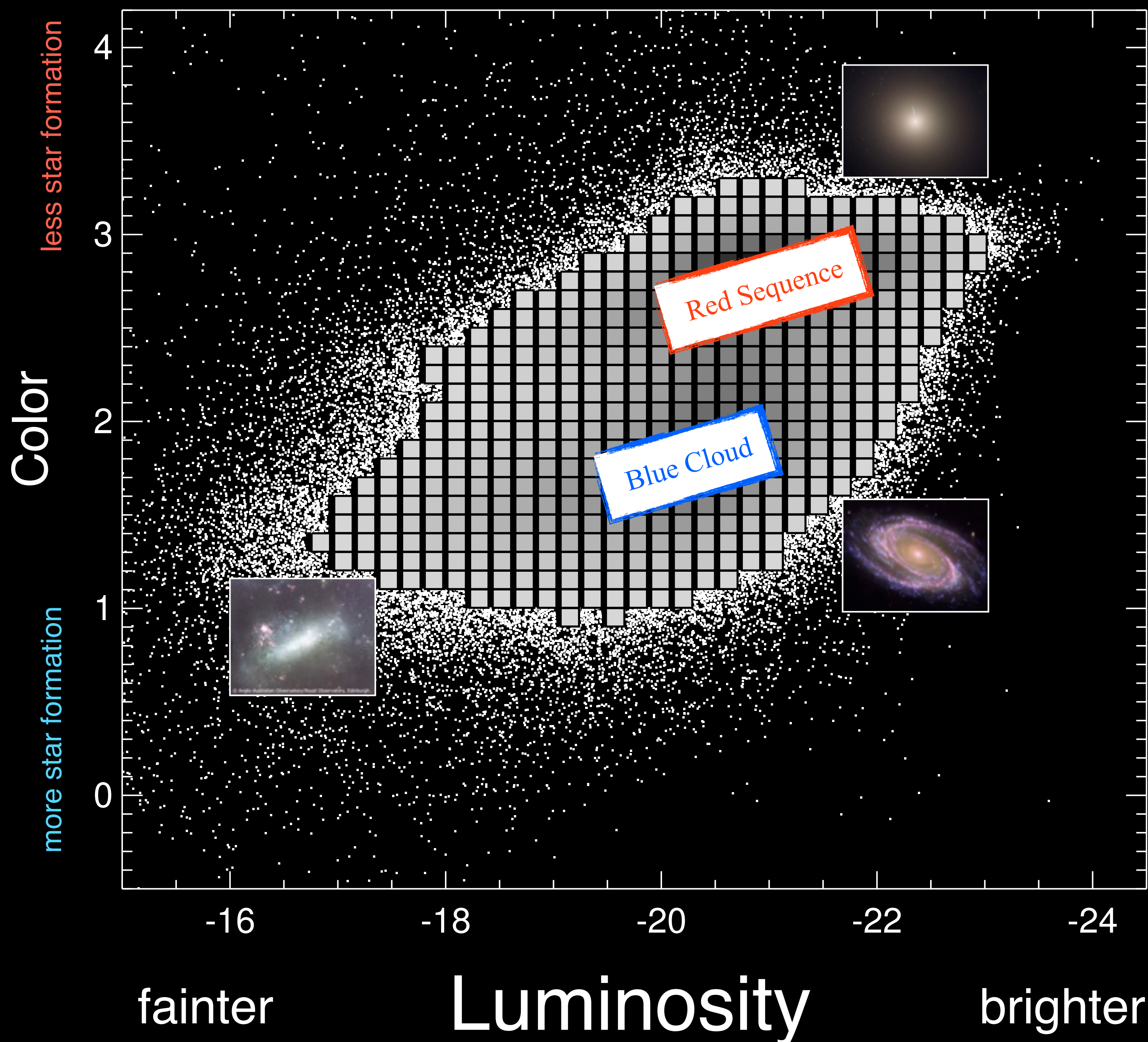


Jason Tumlinson (STScI)

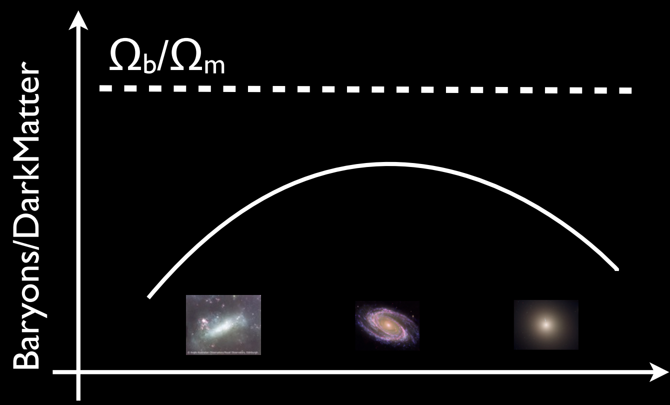
The Basic Puzzle: An early Hubble observation



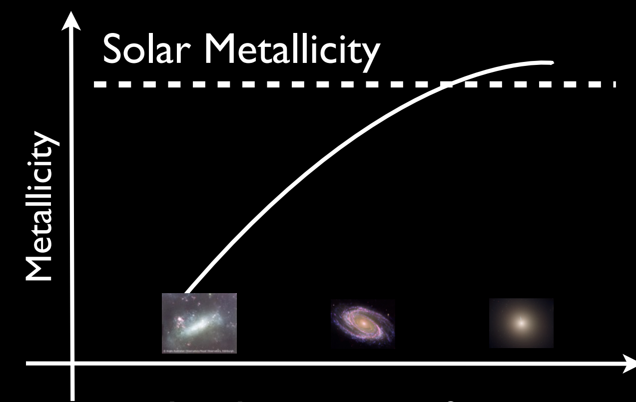
The Modern View: Color / Luminosity Bimodality



Modern Puzzles in Galaxy Formation

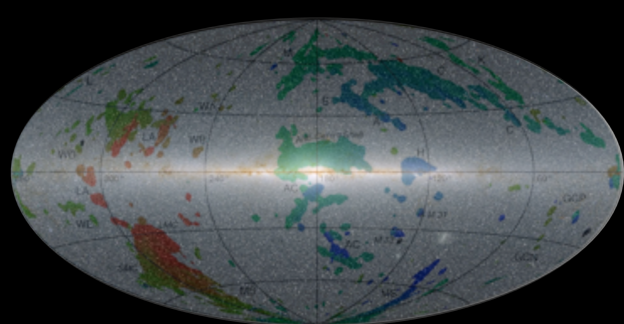


Why do galaxies appear to lack their full share of baryons?

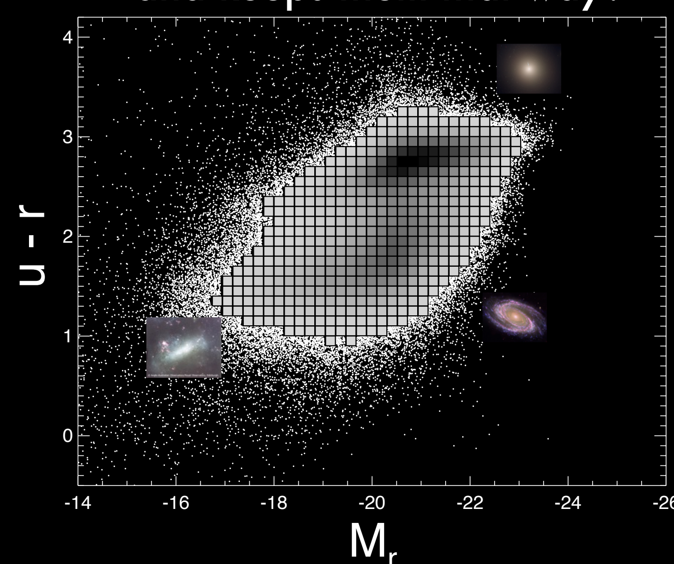


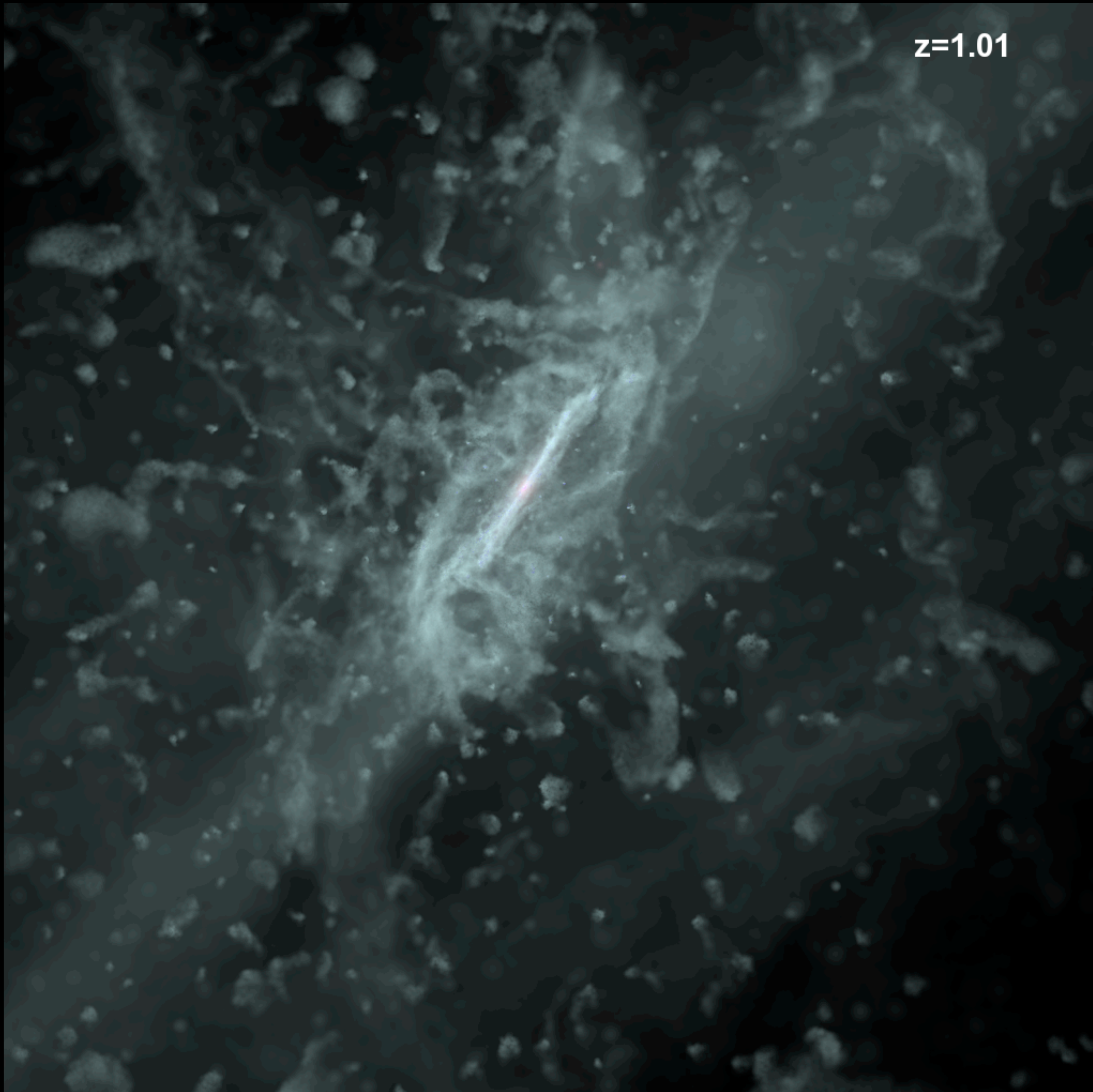
Why do galaxies follow a steep mass-metallicity relation?

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?





Eris simulation

Milky Way analog
at z = 0

Guedes/Madau/
Shen 2011

1969

ABSORPTION LINES PRODUCED BY GALACTIC HALOS

JOHN N. BAHCALL*
Institute for Advanced Study

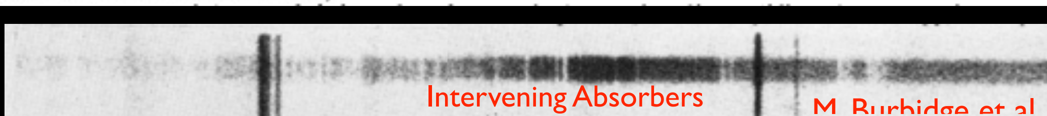
AND

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1969

ABSTRACT

We propose that most of the absorption lines observed in quasi-stellar sources with multiple absorption redshifts are caused by gas in extended halos of normal galaxies.

Recent work has established that some quasi-stellar sources have multiple redshift systems in absorption (Bahcall 1968; Bahcall, Greenstein, and Sargent 1968; Burbidge, Lynds, and Stockton 1968; Burbidge 1969; Bahcall, Osmer, and Schmidt 1969). A number of possible explanations have been suggested for this phenomenon (Bahcall *et al.* 1968; Burbidge *et al.* 1968; Peebles 1968), but none of the suggestions seem especially plausible when considered in the light of the observed features of the absorption systems. We propose that most of the absorption lines are caused by tenuous gas in extended halos of normal galaxies (see Spitzer 1956 for a review of some earlier work on galactic halos and for a preliminary discussion of the possibility of observing ultraviolet absorption lines formed in such halos).



The CGM: one of the key reasons the Hubble Space Telescope even exists.

1985

RECOMMENDATIONS OF THE SPACE TELESCOPE

WORKING GROUP ON THE ISM/IGM/SNR

C.F. McKee (Chair), E. Becklin, A. Boksenberg, J. Black,

L. Cowie, J. Danziger, E. Jenkins, R. Kirshner, R. McCray,

M. Peimbert, J. Raymond, P. Solomon, A. Vidal-Madjar, D. York

II Recommended Key Projects

1. Quasar Absorption Line Key Project

Two of the central problems in astrophysics are the distribution of matter in the Universe and the abundances of the elements. Observations of quasar absorption line—or, more generally, absorption lines in any bright, distant object—reveal the presence of diffuse baryonic matter which is not observable in emission. Ground—based observations have established the existence of three classes of quasar absorption line systems: (1) Lyman α systems, which are found to the blue of Lyman α in emission and show no evidence for metals. There is no evidence for clustering in redshift, as would be expected if the absorbing gas were associated with galaxies. These systems are interpreted as occurring in primordial intergalactic clouds, and

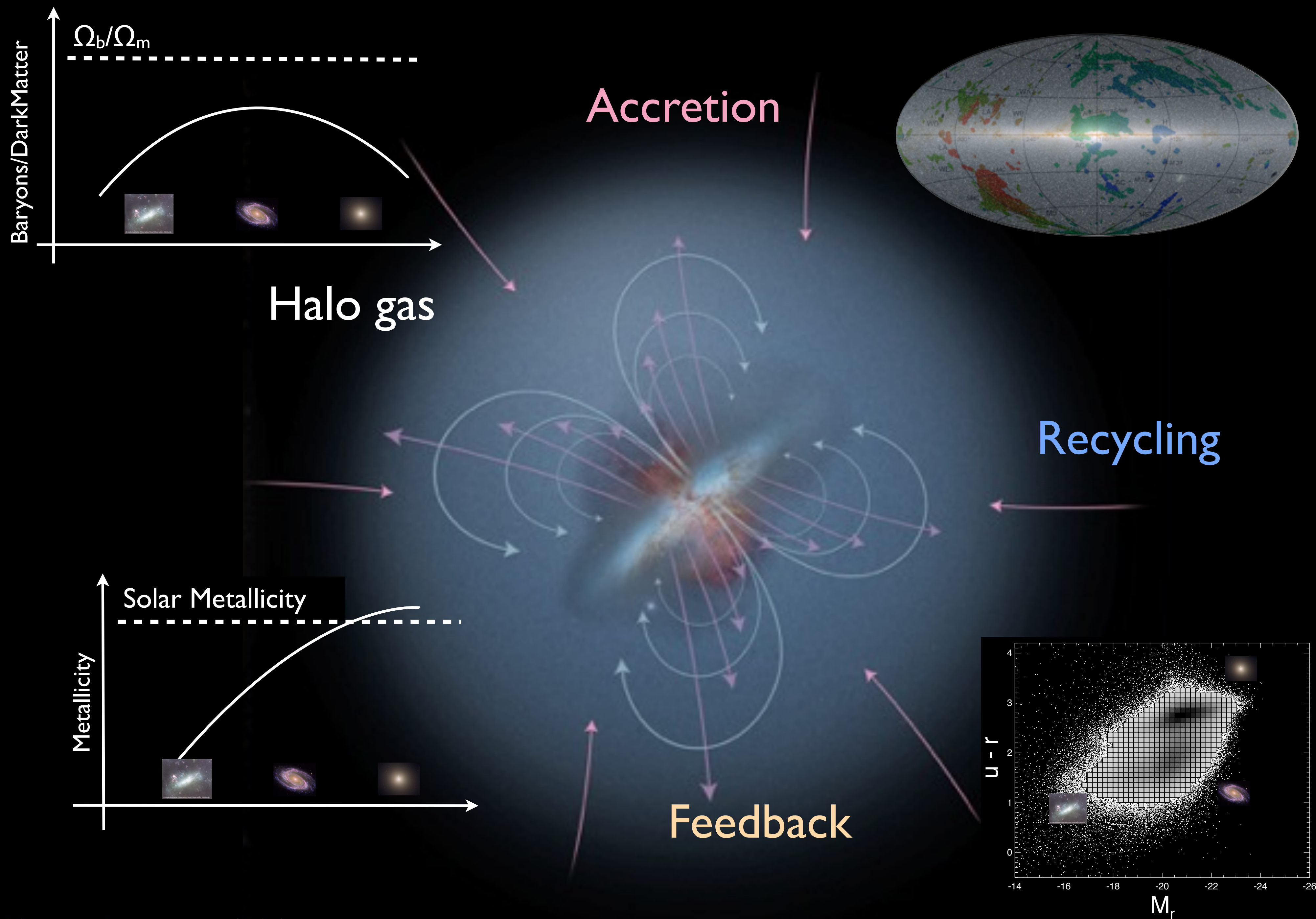
Lyman α systems:

* How do the number density and physical properties of these systems evolve with redshift for $z \lesssim 1.6$?
* Are any of the Lα systems actually high excitation metallic systems with OVI? Again, low redshifts are required to reduce confusion.

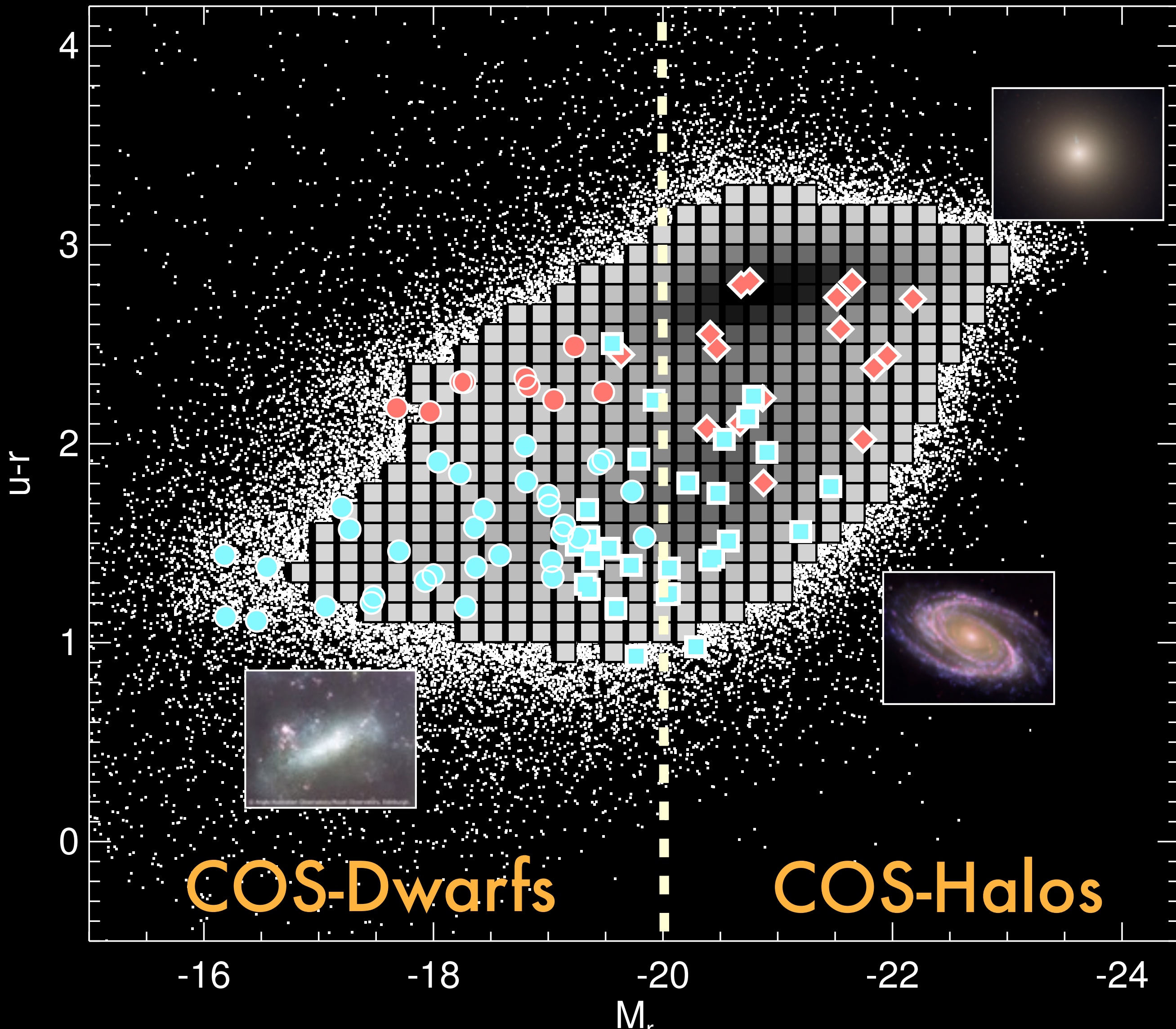
Distribution of gas in galactic halos, clusters of galaxies, and voids:

* What is the nature of the gas in the halo of the Galaxy, including the high-velocity clouds?
* How large are gaseous galactic halos, and how do they correlate with galaxy type? Such data could give insight into how gaseous halos affect galactic evolution, particularly the chemical evolution of the interstellar medium.

Gas Flows Drive Galaxy Formation



CGM Figure Credit: Ann Feild (STScI)



z = 0.02 - 0.08

log$M_\star$ = 8.5 - 10

optimal for CIV

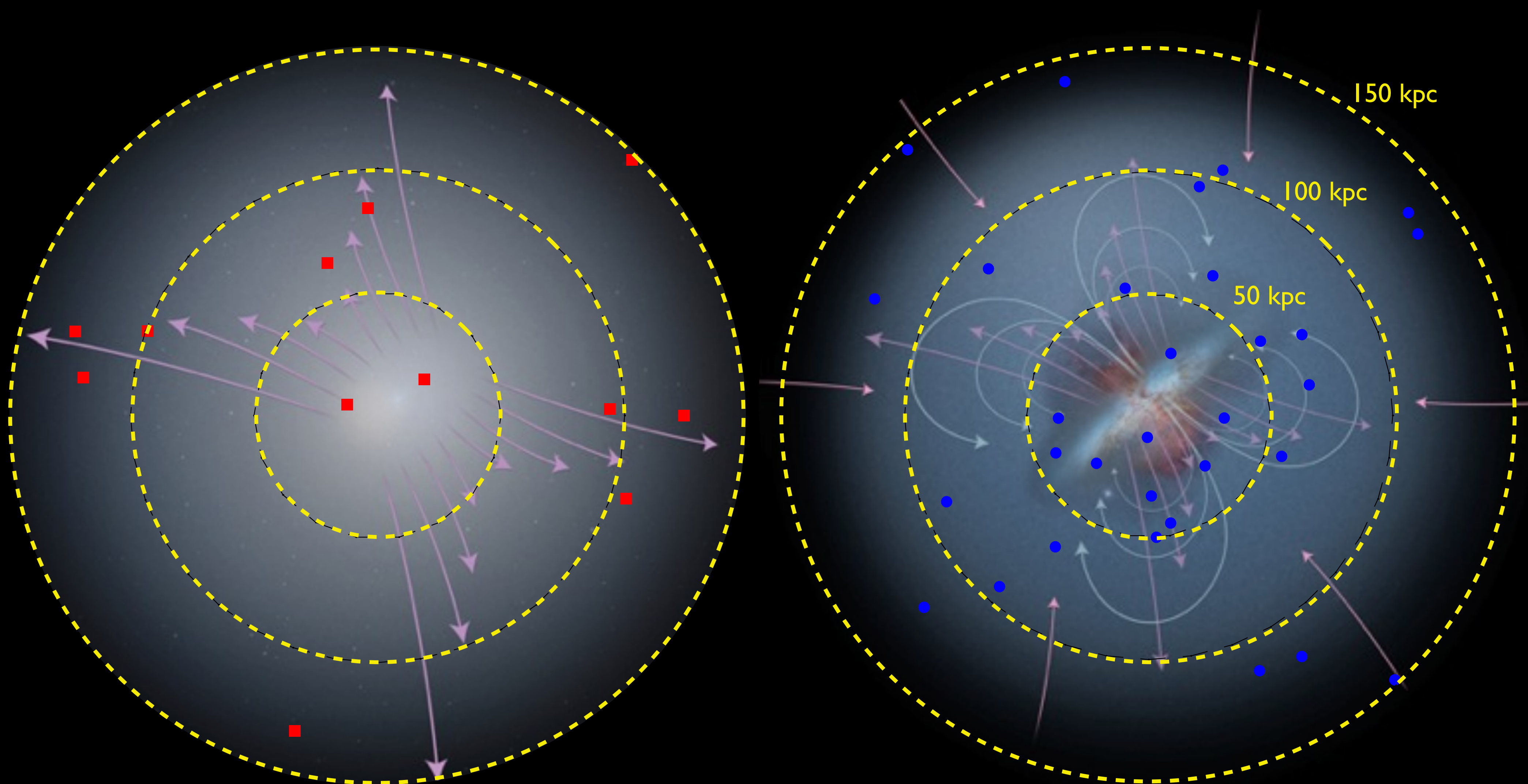
z = 0.15 - 0.35

log$M_\star$ = 10 - 11.5

optimal for OVI

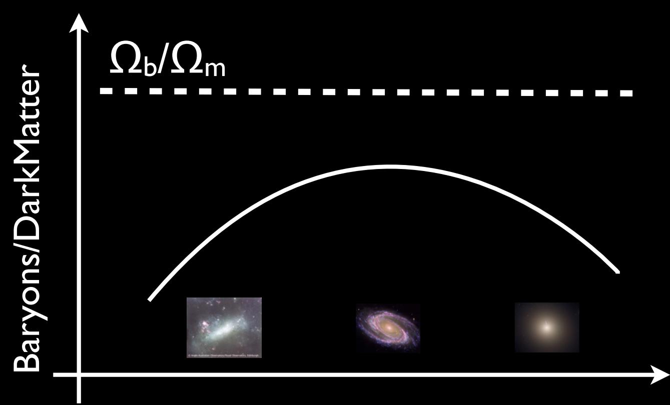
ALL GALAXIES SELECTED PRIOR TO ABSORPTION

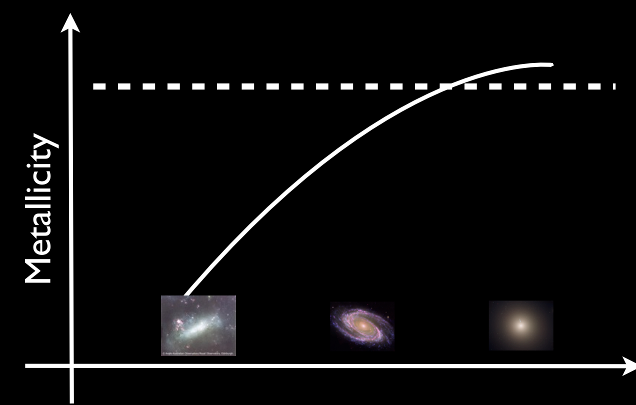
A Statistical Map of Galaxy Halo Gas



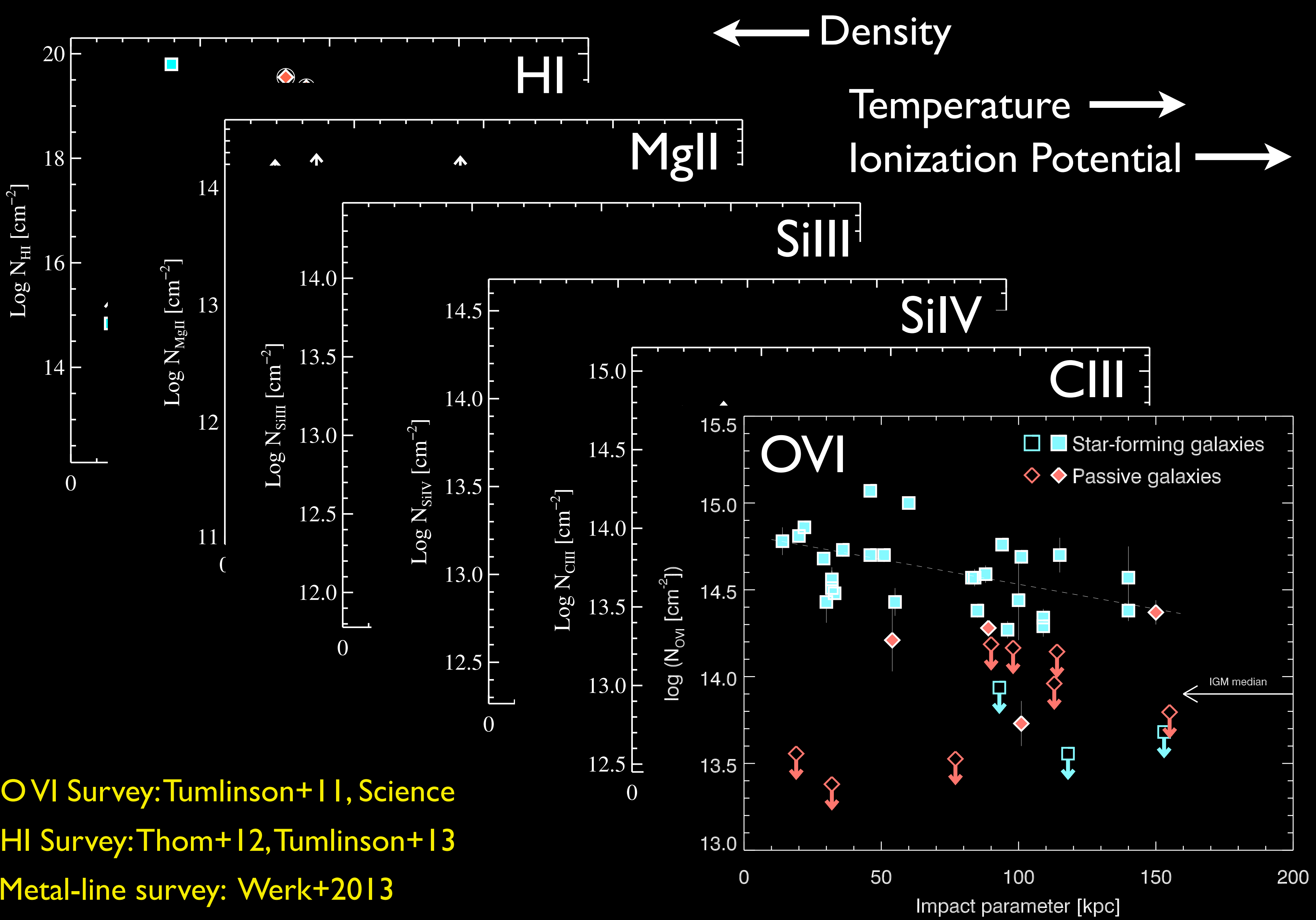
impact parameter R < 150 kpc

The Mass and Metal Content of the CGM





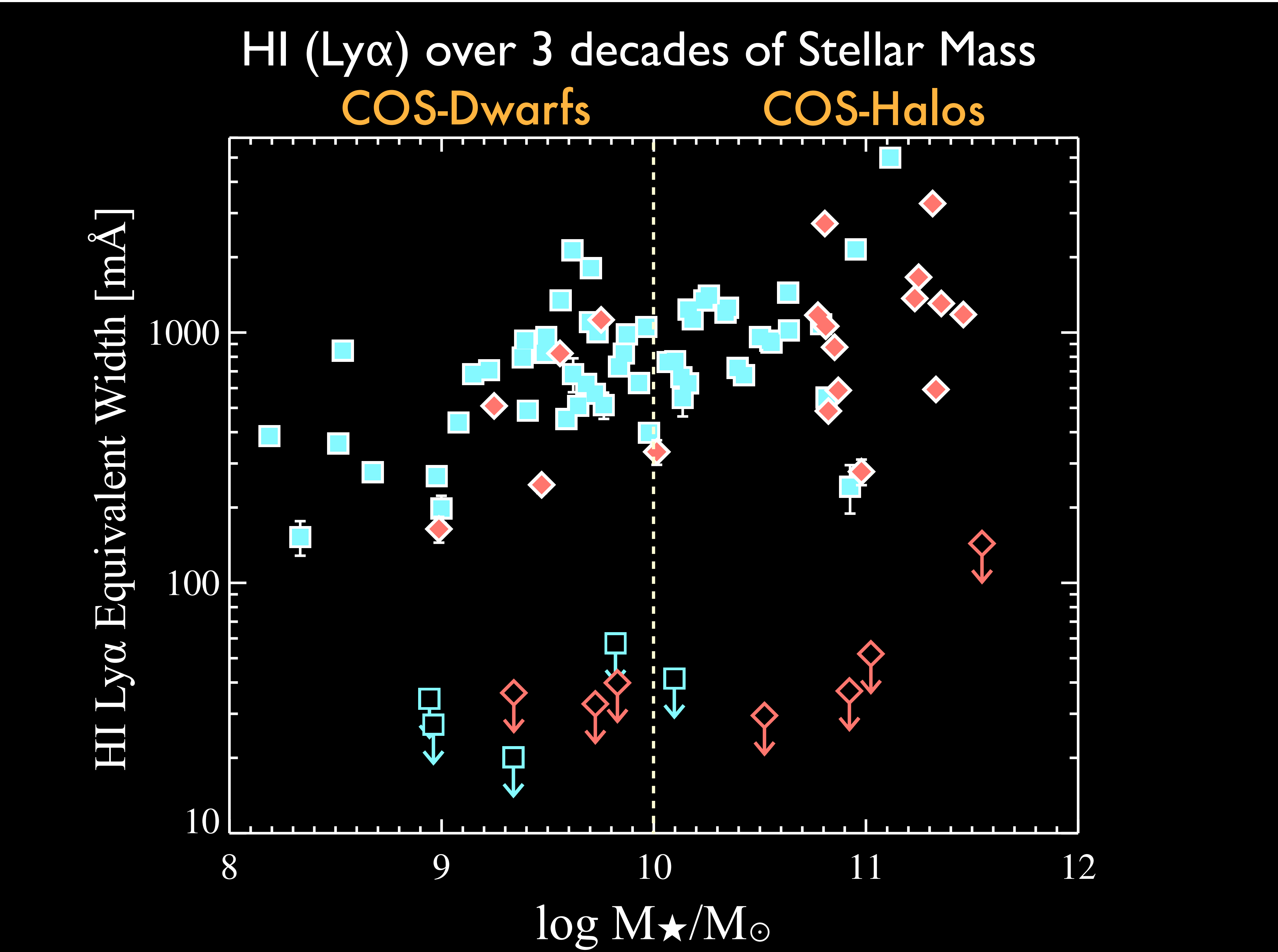
The Observed Content of the CGM



O VI Survey: Tumlinson+11, Science

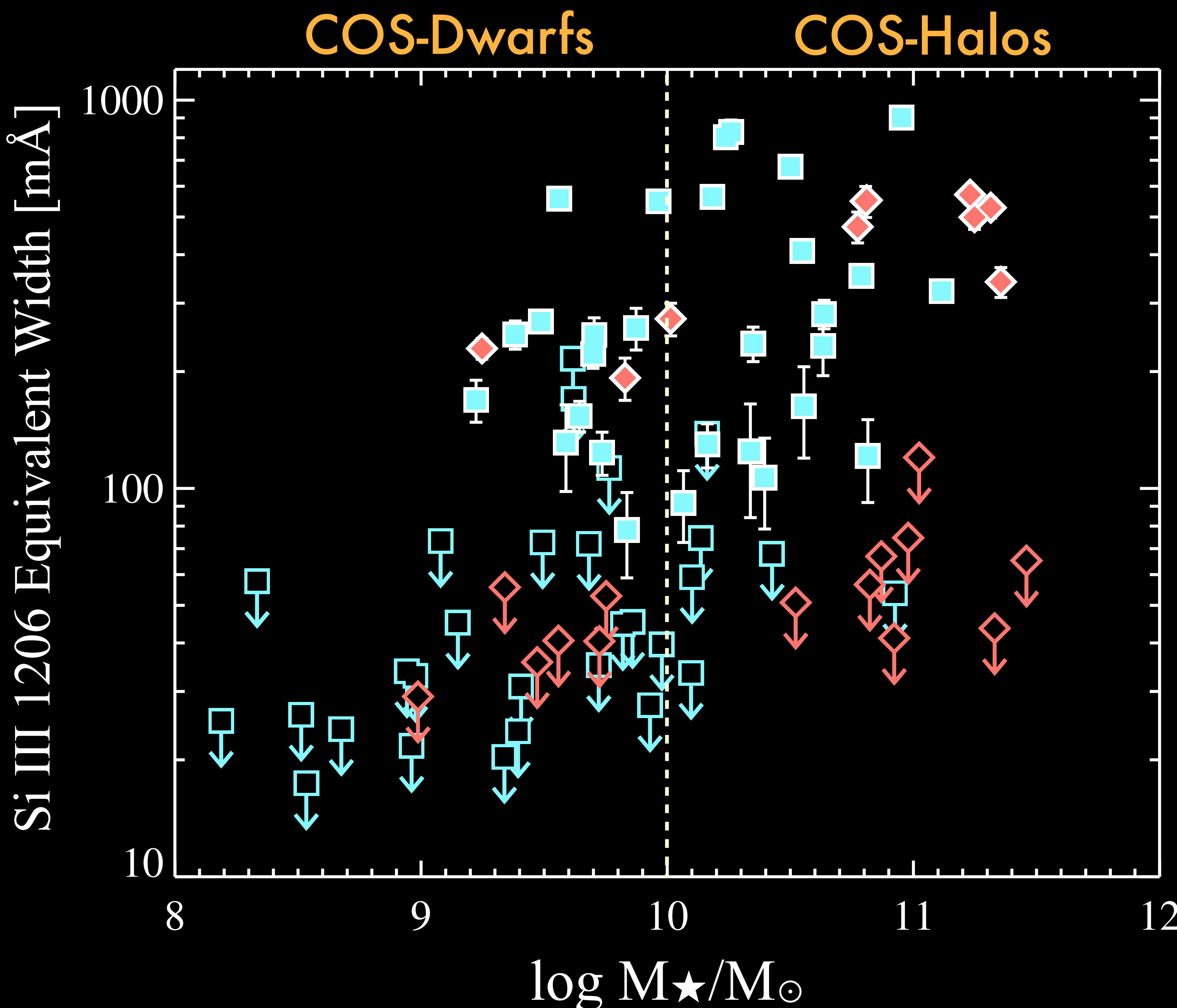
HI Survey: Thom+12, Tumlinson+13

Metal-line survey: Werk+2013

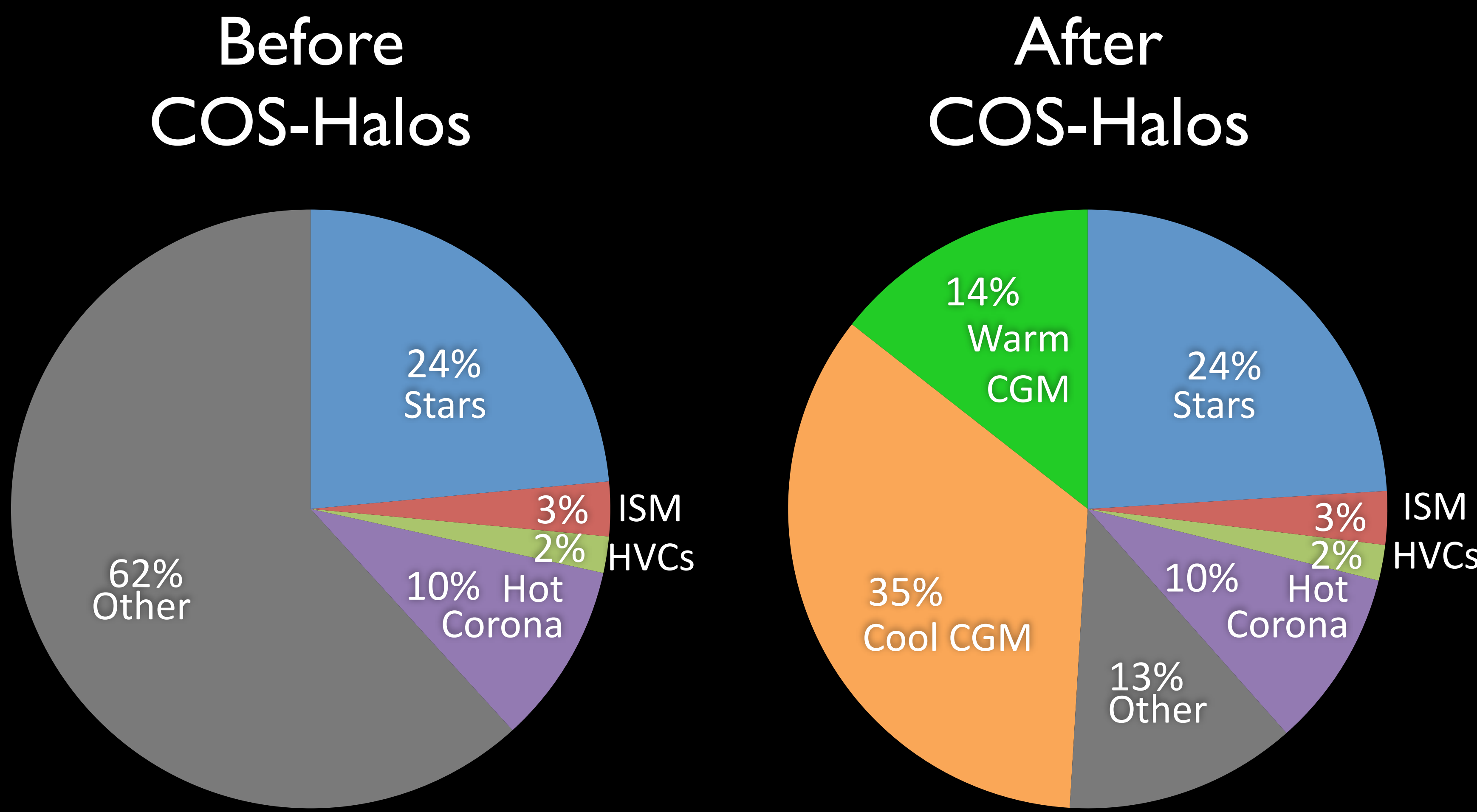


HI (Lyα) over 3 decades of Stellar Mass
COS-Dwarfs
COS-Halos
HI Lyα Equivalent Width [mÅ]
10
100
1000
8
9
10
11
12
log M★/M⊙

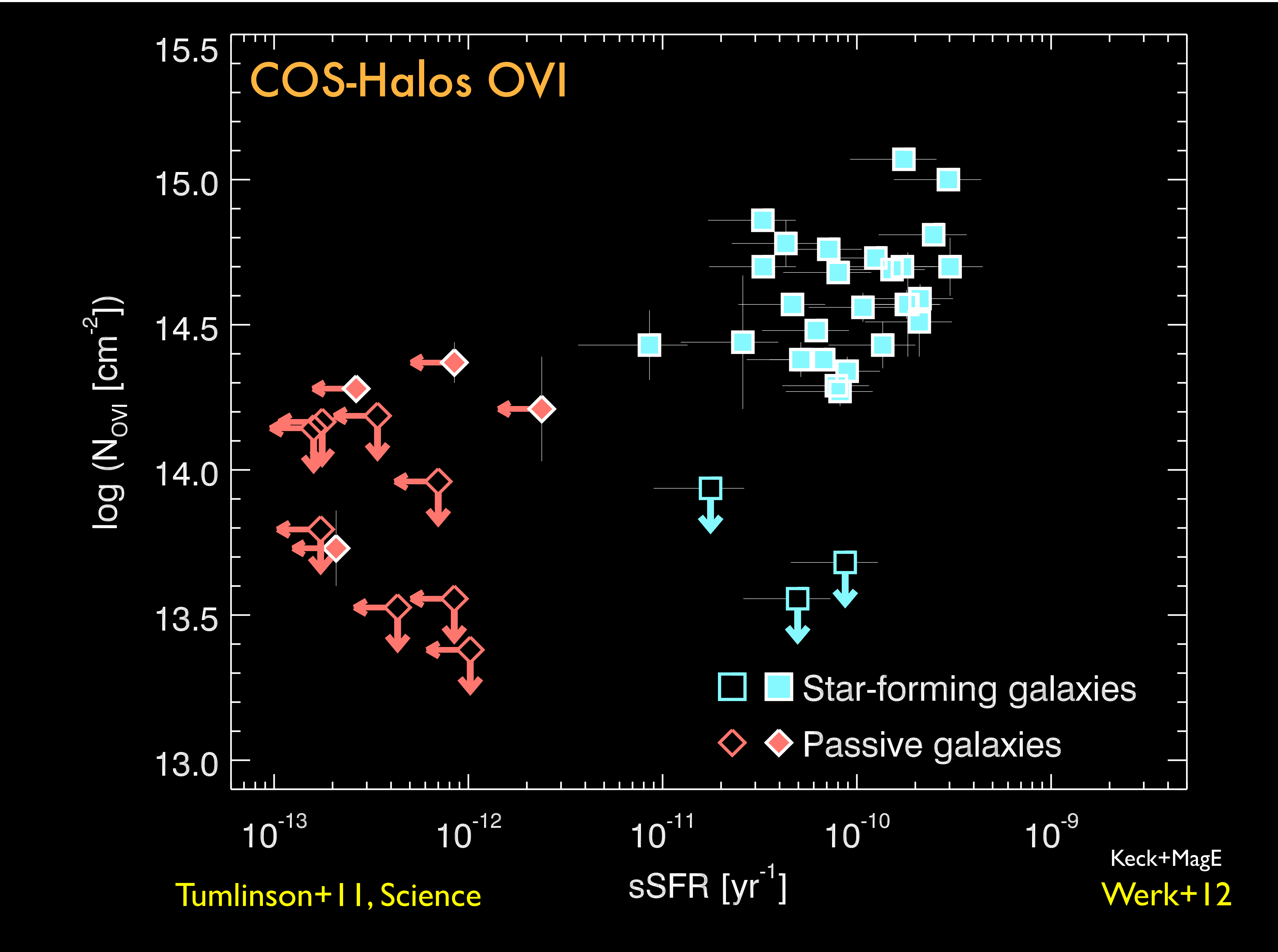
Si III over 3 decades of Stellar Mass



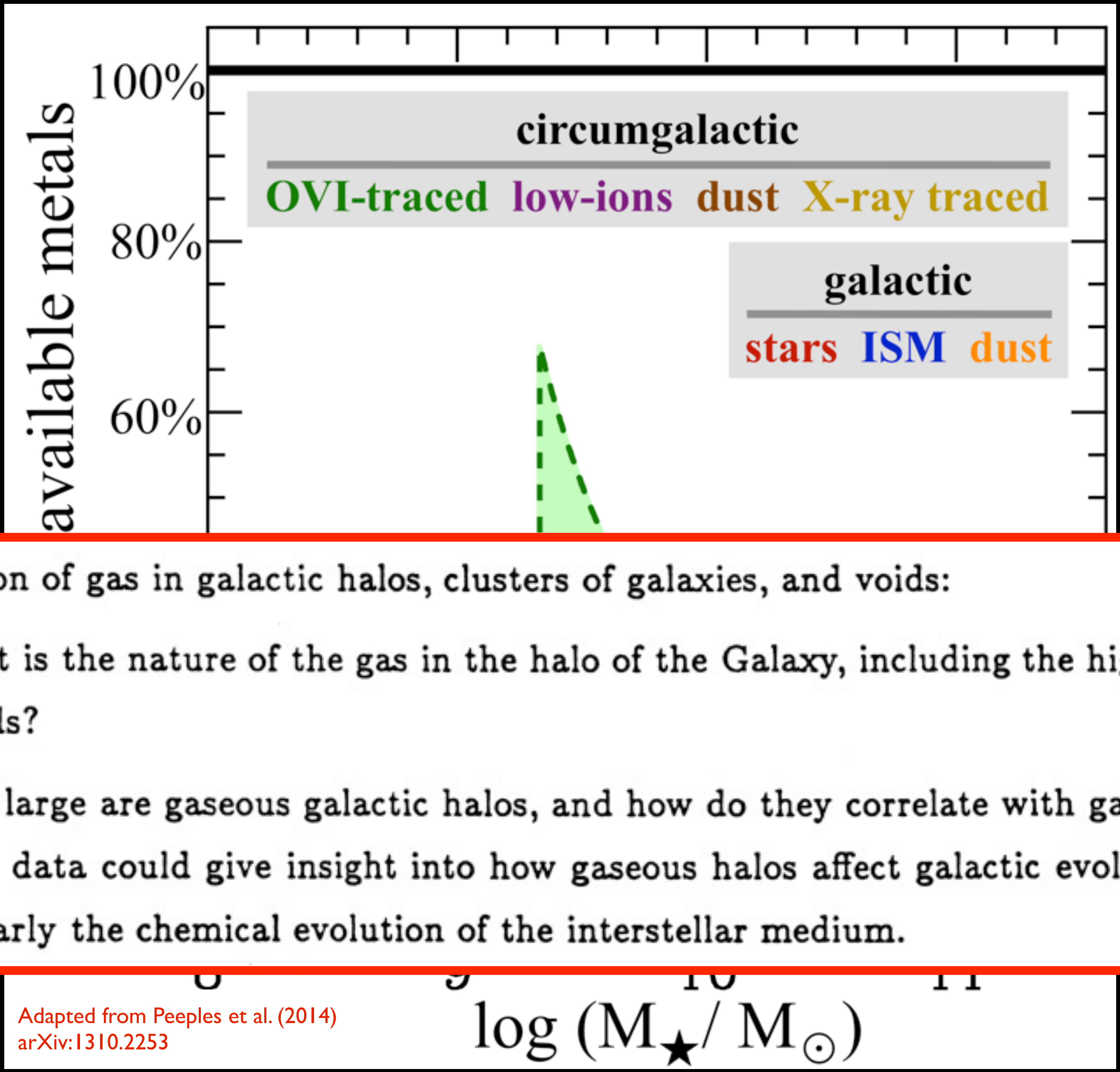
Baryonic Mass Budgets at ~L★



Werk et al. 2014


COS-Halos OVI
log (N_OVI [cm^-2])
sSFR [yr^-1]
15.5
15.0
14.5
14.0
13.5
13.0
10^-13
10^-12
10^-11
10^-10
10^-9
Star-forming galaxies
Passive galaxies
Keck+MagE
Tumlinson+11, Science
Werk+12

Total Inventory of Galactic Metals



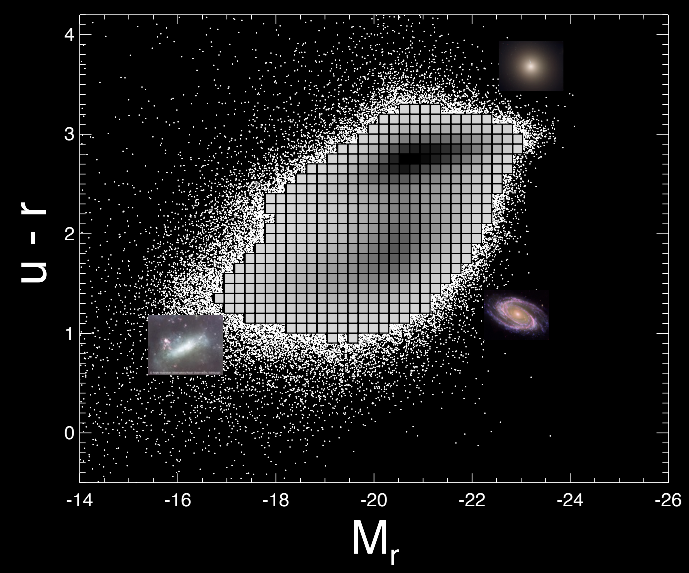
Distribution of gas in galactic halos, clusters of galaxies, and voids:

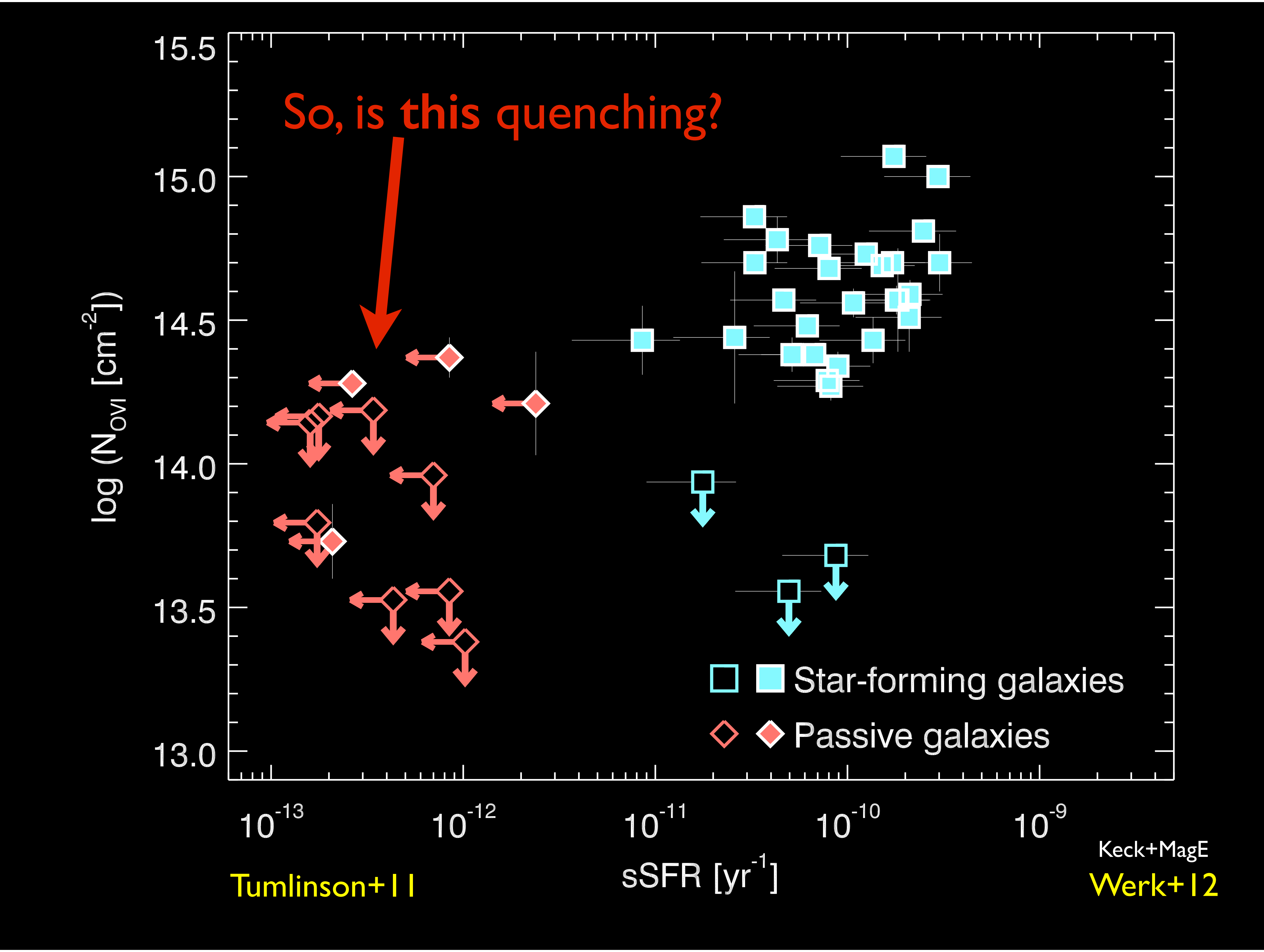
* What is the nature of the gas in the halo of the Galaxy, including the high-velocity clouds?

* How large are gaseous galactic halos, and how do they correlate with galaxy type? Such data could give insight into how gaseous halos affect galactic evolution, particularly the chemical evolution of the interstellar medium.

Typical star forming galaxies have ejected at least as many metals as they have retained.

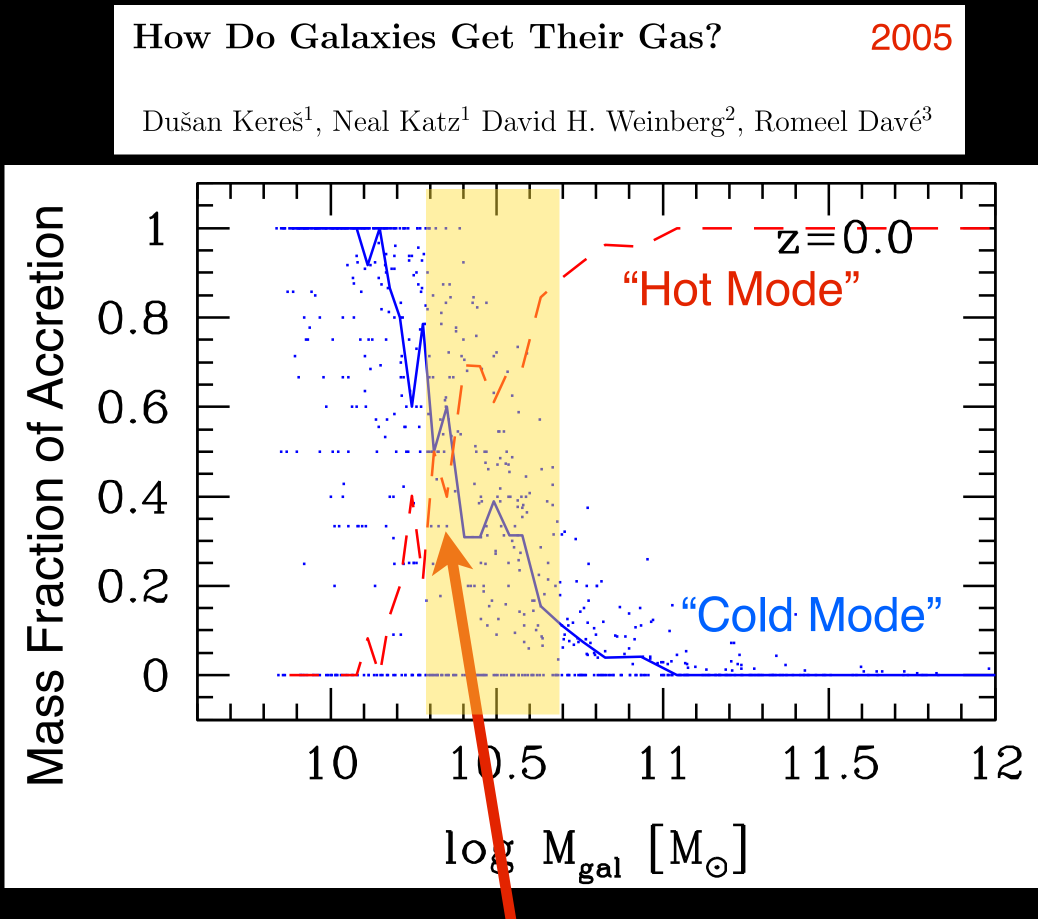
The Quenching of the CGM



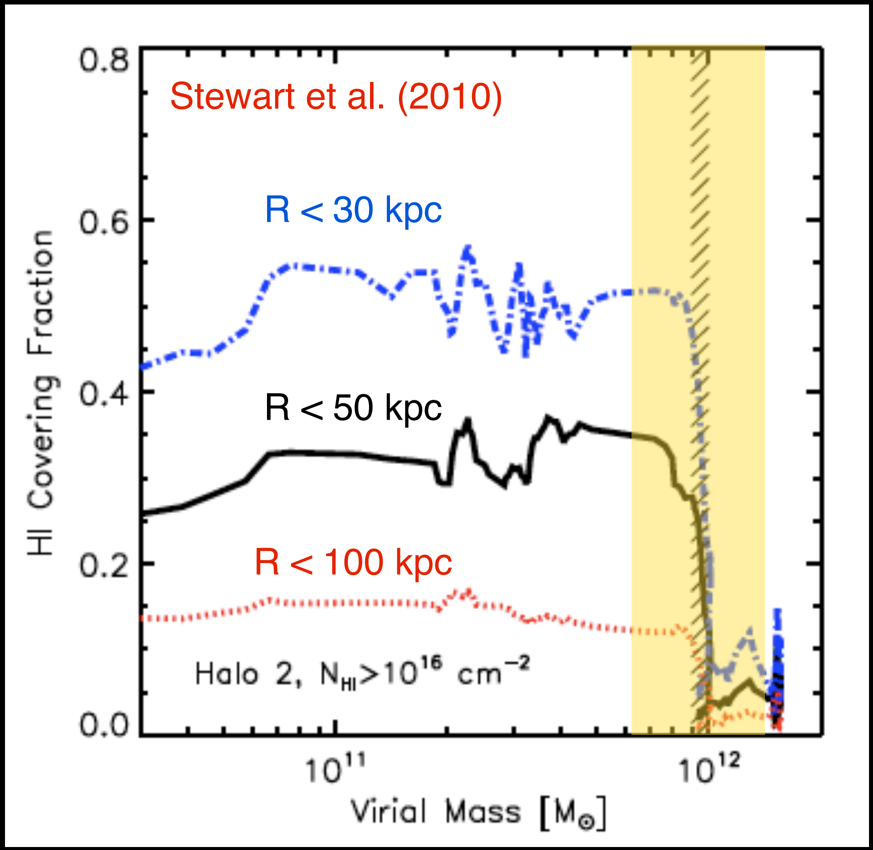


So, is this quenching?
log (N_{OVI} [cm^{-2}])
15.5
15.0
14.5
14.0
13.5
13.0
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
sSFR [yr^{-1}]
Star-forming galaxies
Passive galaxies
Tumlinson+11
Keck+MagE
Werk+12

What was supposed to happen. . .

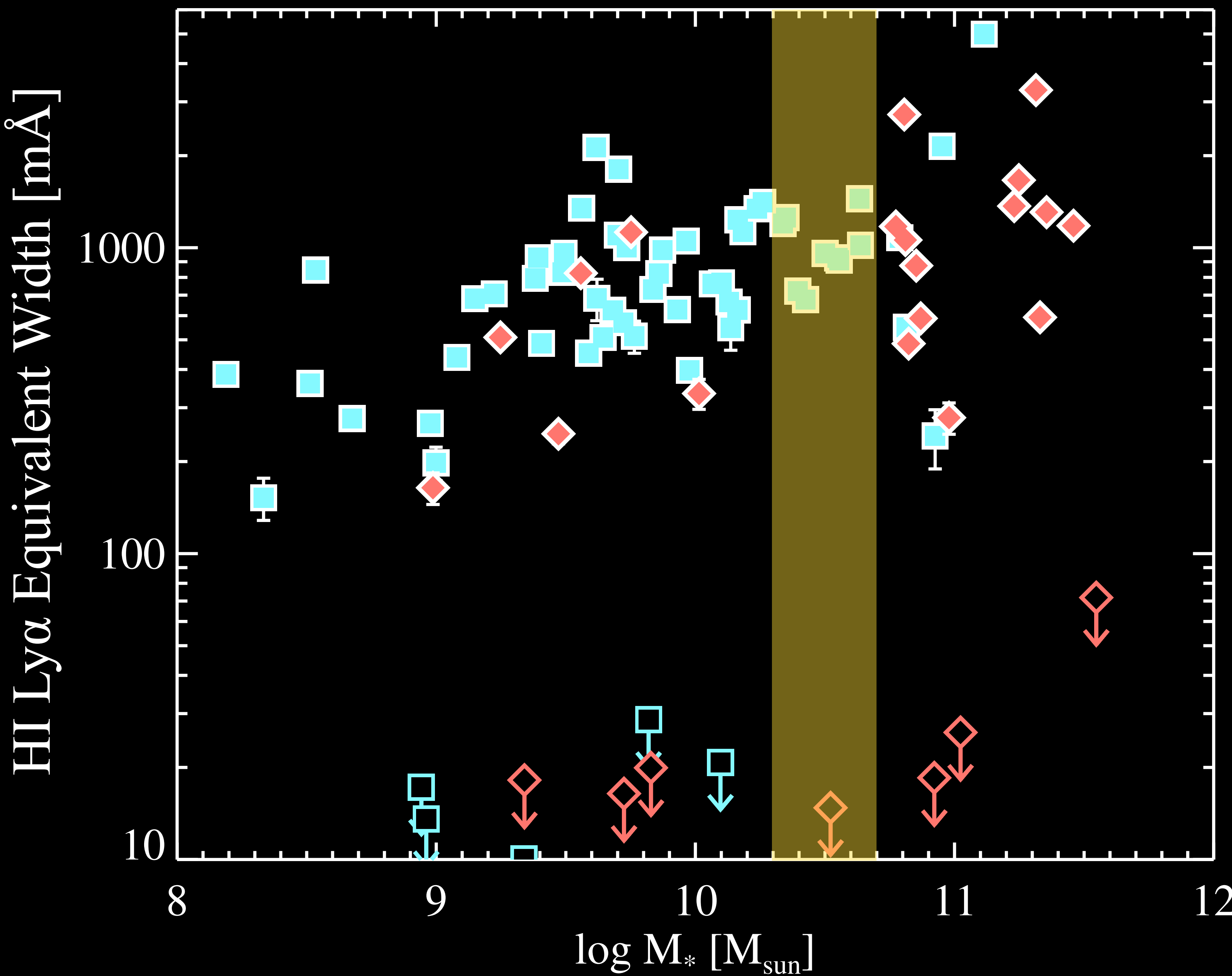


Halos less than this mass cannot sustain a virial shock and so smoothly accrete gas that never reaches the virial temperature of ~10^6 K (Birnboim & Dekel 2003).

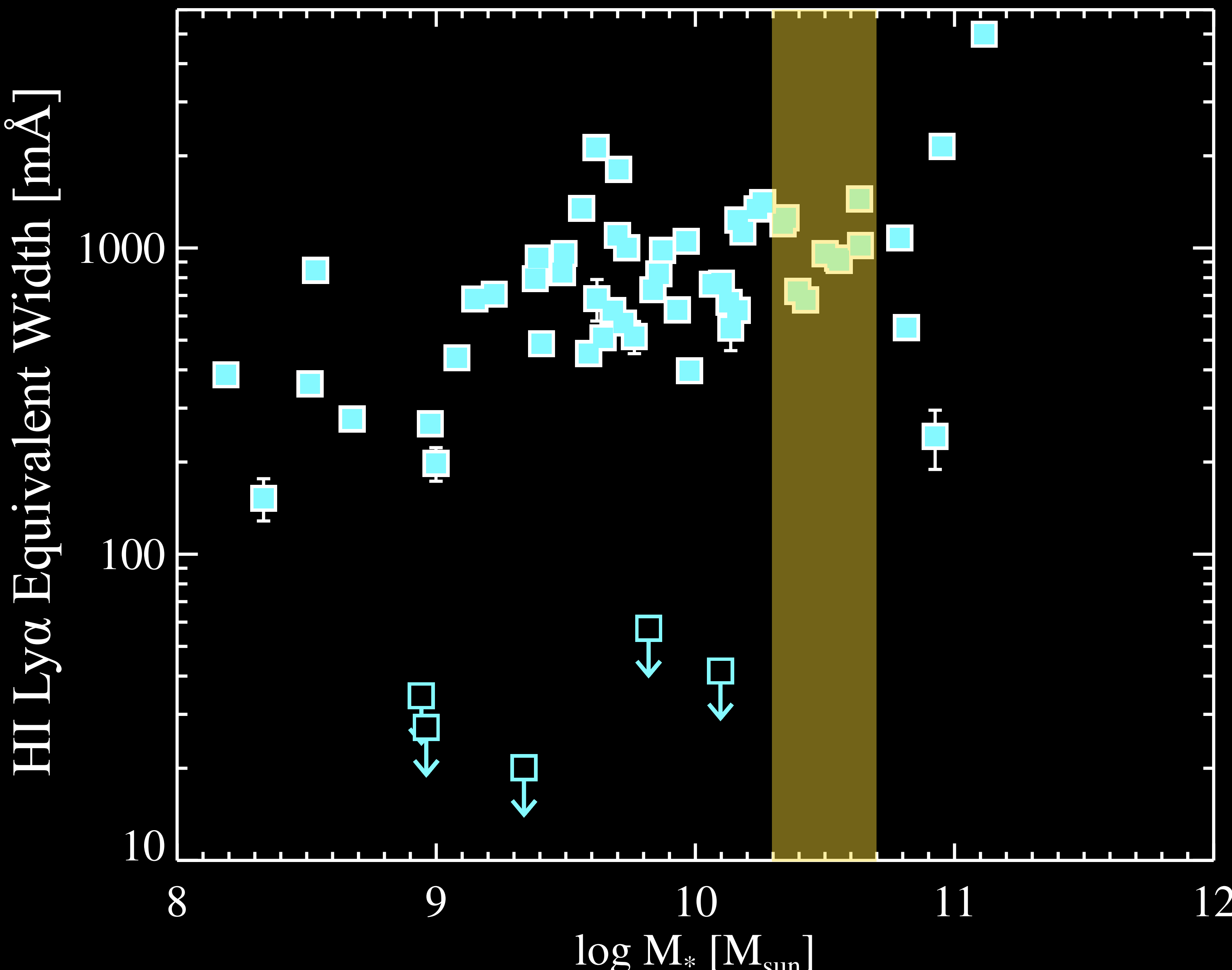


This transition from "cold mode" to "hot mode" should result in a sharp drop in the covering fraction of strong HI absorption at < 100 kpc.

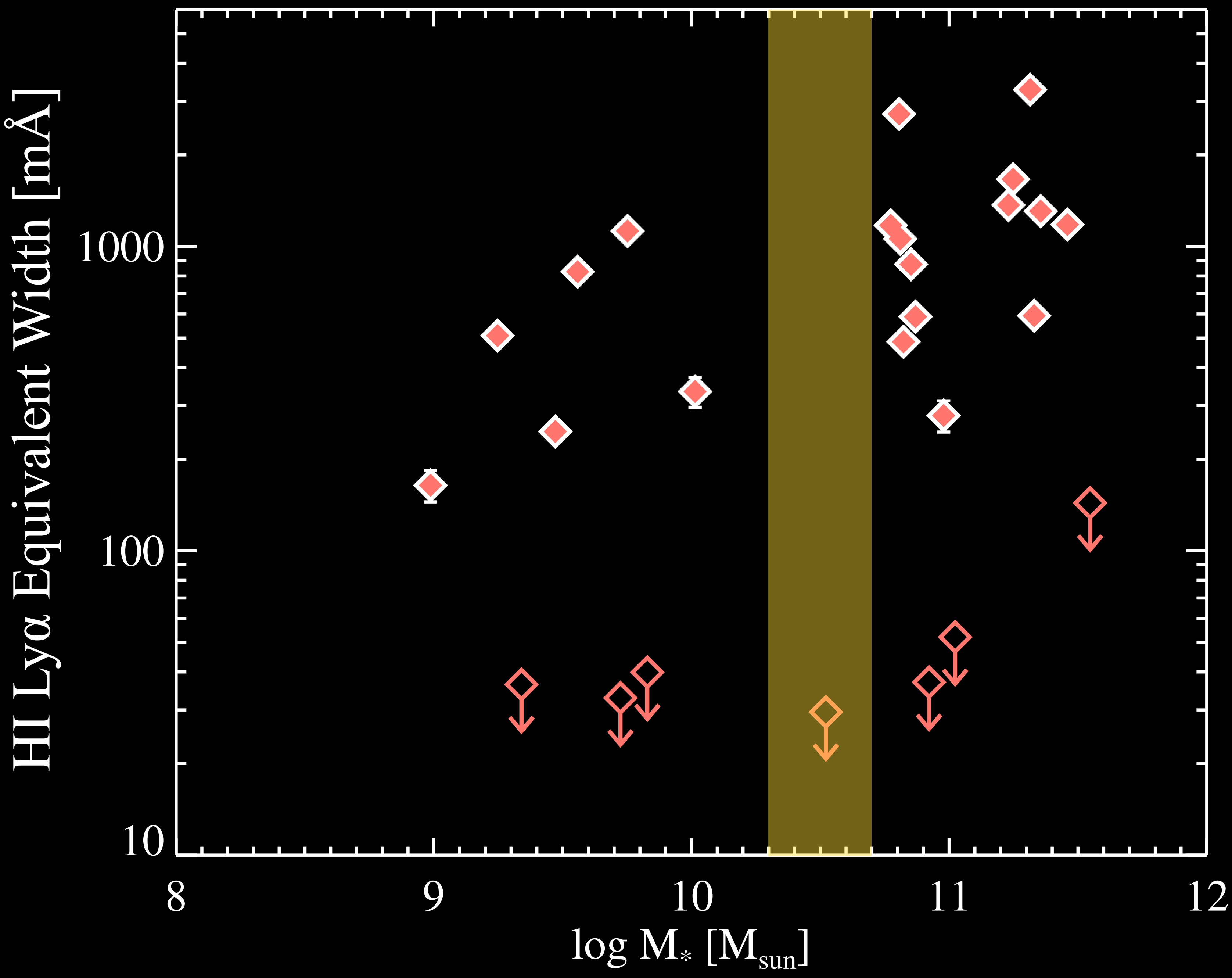
So What Actually Happened: Quenching?



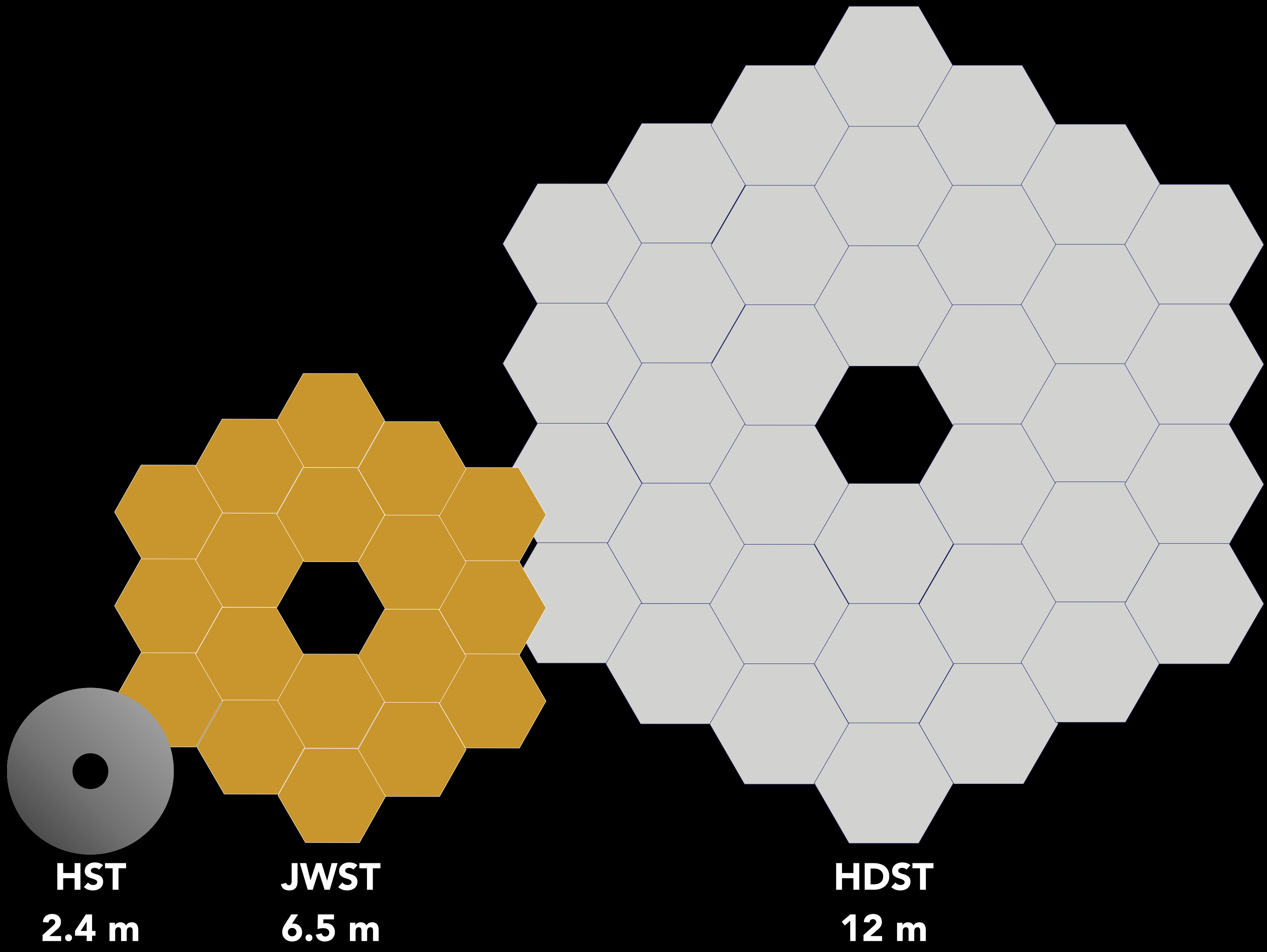
So What Actually Happened: Quenching?



So What Actually Happened: Quenching?



What can a Large Space Telescope Do?

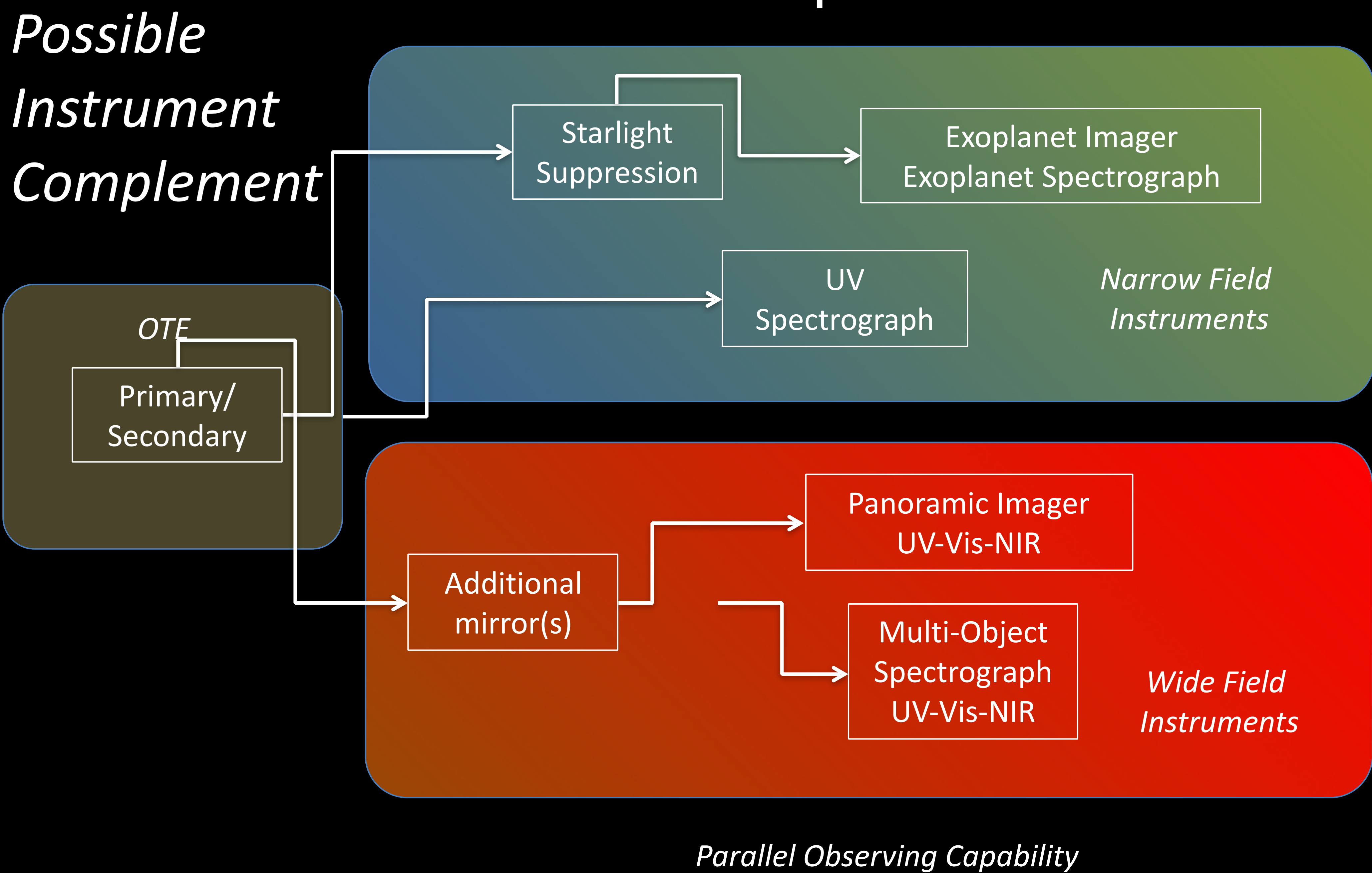


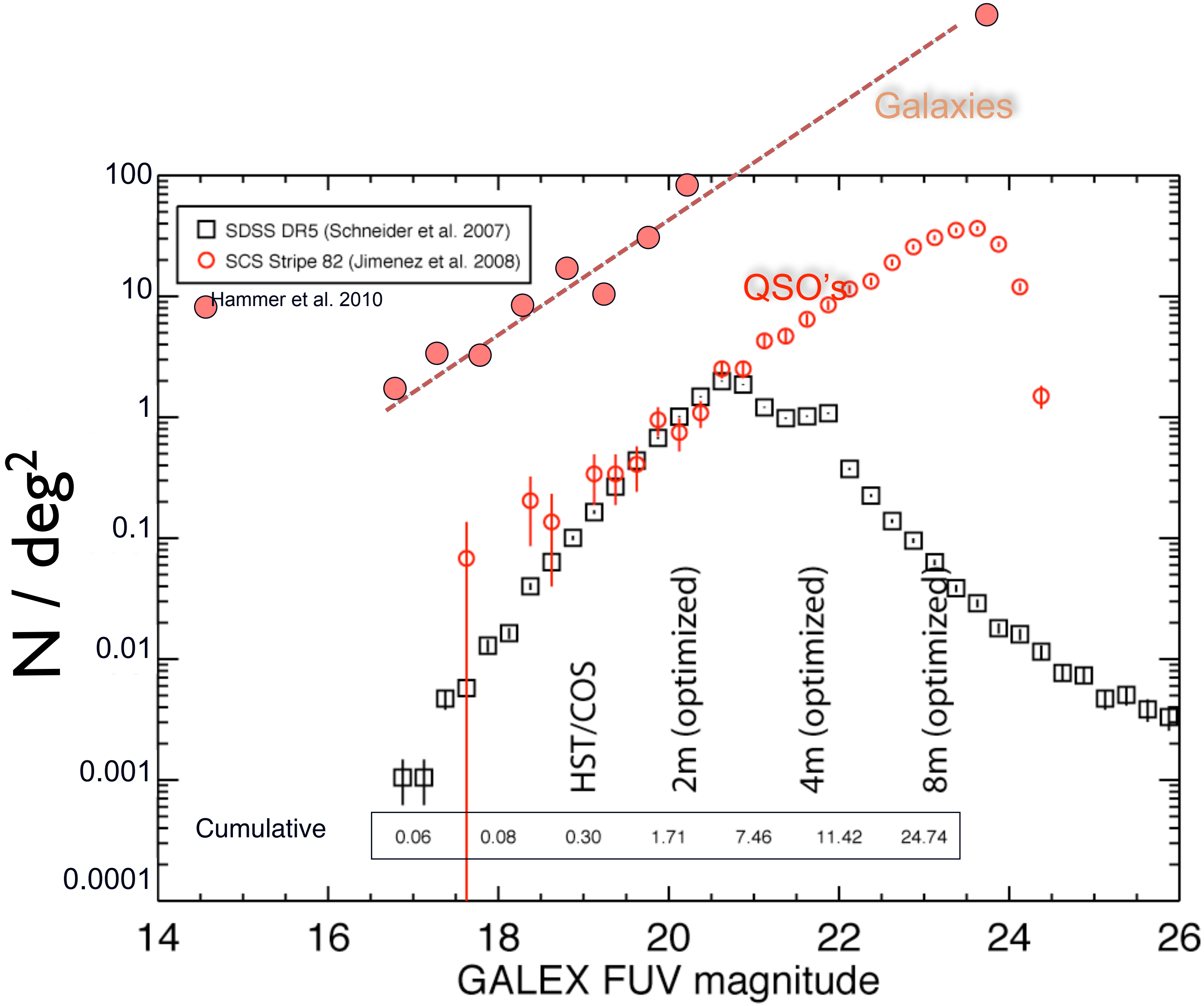
HDST Requirements

as a Large Aperture Space Telescope

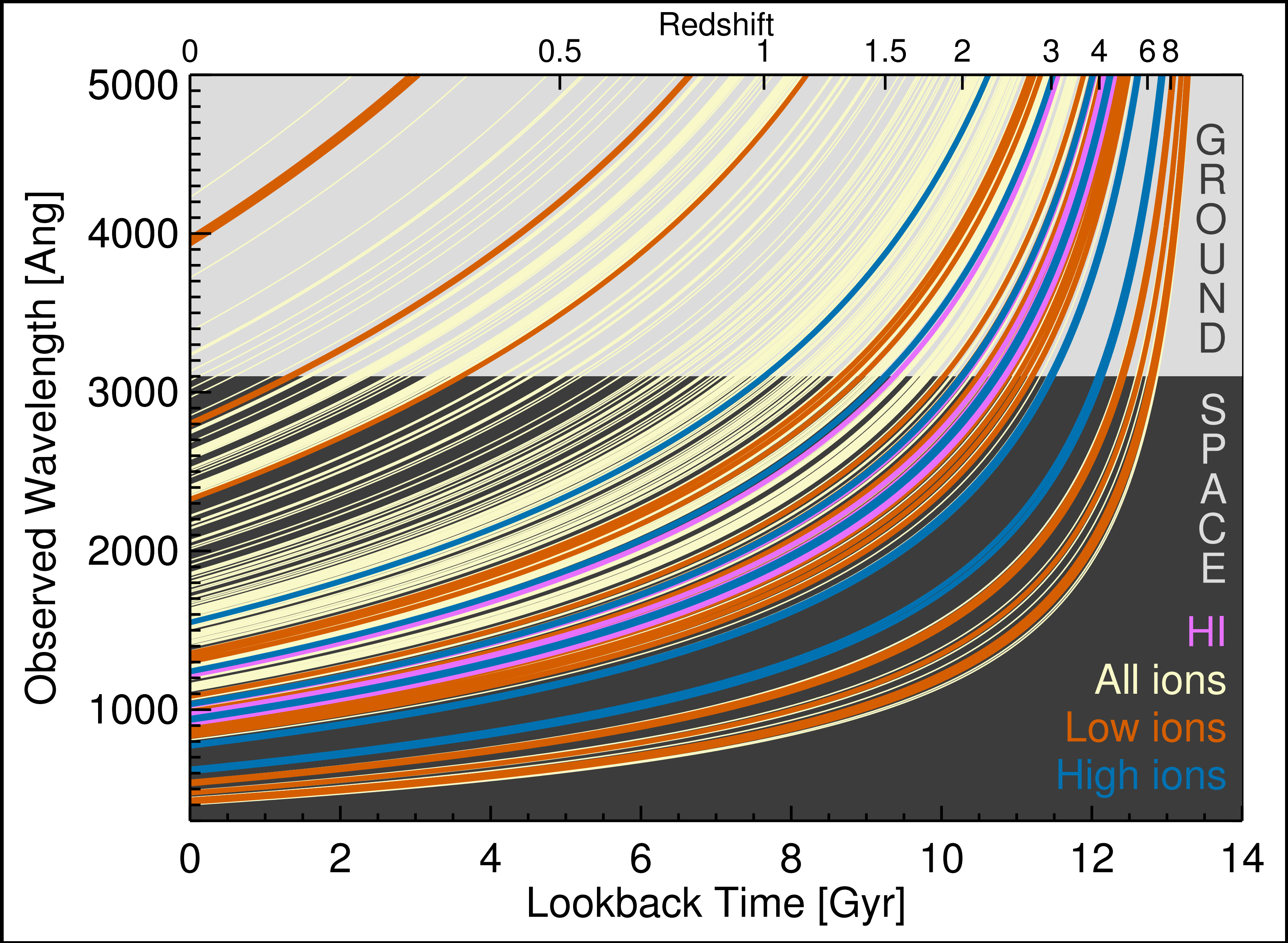
Capability		*HDST* Gain vs.	
Parameter	***Requirement***	***HST***	***JWST***
Aperture	***10-12 m***	***x5***	***x1.5-2***
Wavelength	***0.10 to 2 microns***	***Same***	***HDST: UV-vis***
Field of View	***6 arcminutes***	***x3***	***x3***
Pixel Count per Instrument Channel	***0.5-1 gigapixel***	***x30 (vs. Wide Field Camera 3)***	***x25 (vs. NIRCAM)***
Angular Resolution	***0.01" (Diff lim. @ 500 nm)***	***x5 @ 500 nm***	***x1.5-2 @ 1 um***

HDST Requirements




Galaxies
QSO's
SDSS DR5 (Schneider et al. 2007)
SCS Stripe 82 (Jimenez et al. 2008)
Hammer et al. 2010
HST/COS
2m (optimized)
4m (optimized)
8m (optimized)
Cumulative
0.06
0.08
0.30
1.71
7.46
11.42
24.74
N / deg^2
GALEX FUV magnitude
100
10
1
0.1
0.01
0.001
0.0001
14
16
18
20
22
24
26

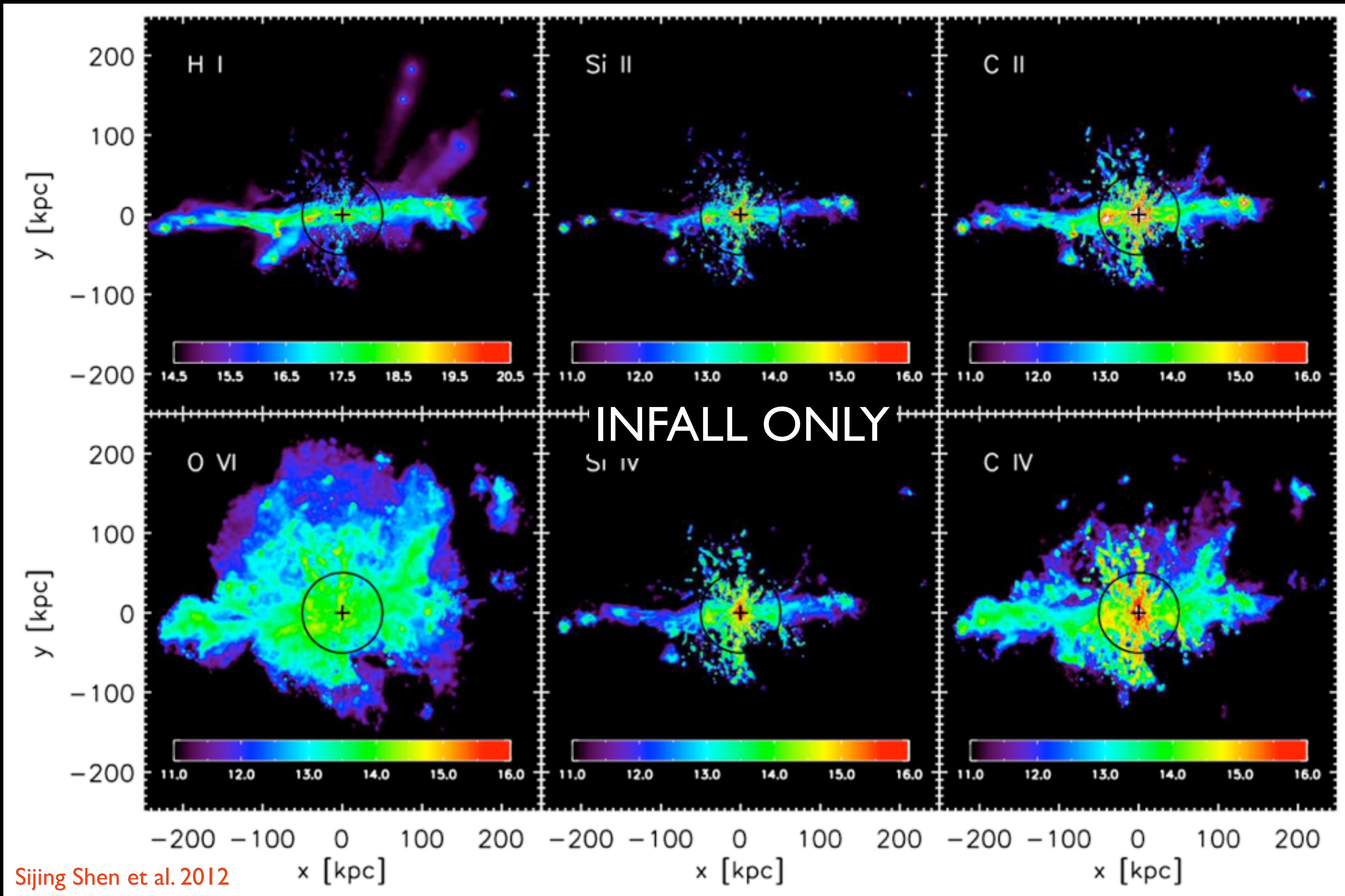
The Power of the UV: Physical Diagnostics



Application No. 1

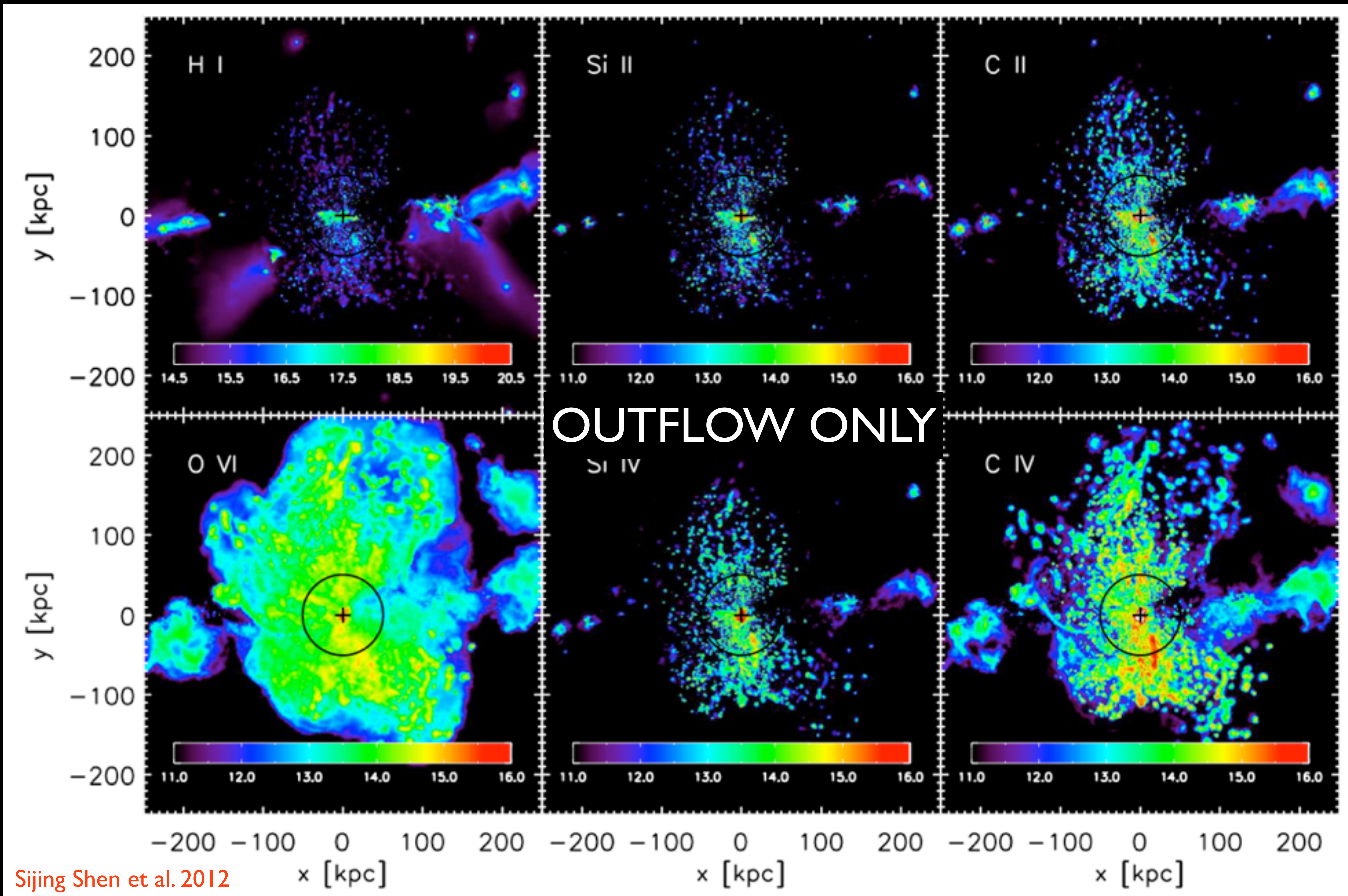
Probing Gas Flows with
densely sampled nearby halos.

CGM Dynamics Reflected in its Appearance

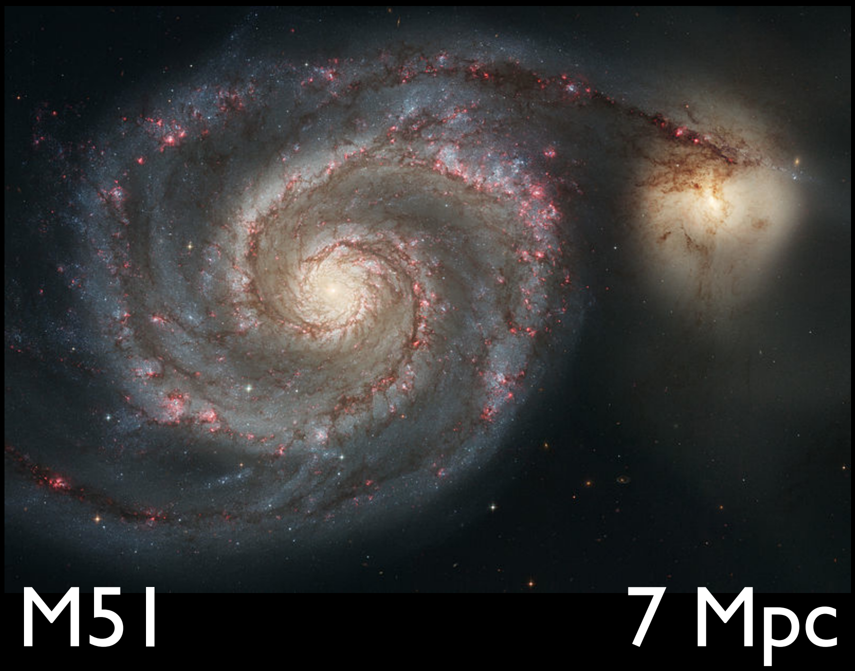
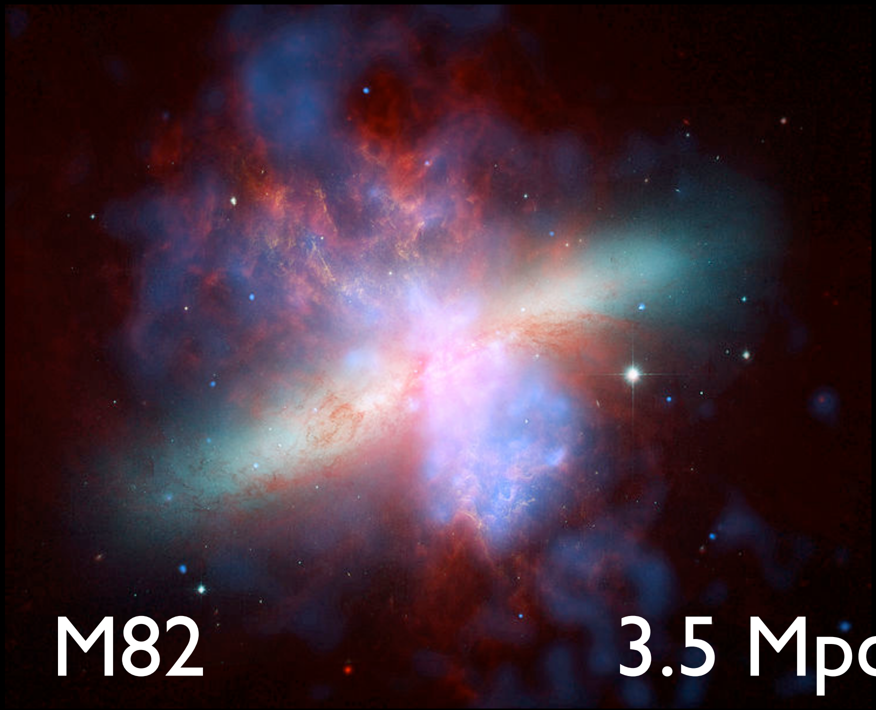
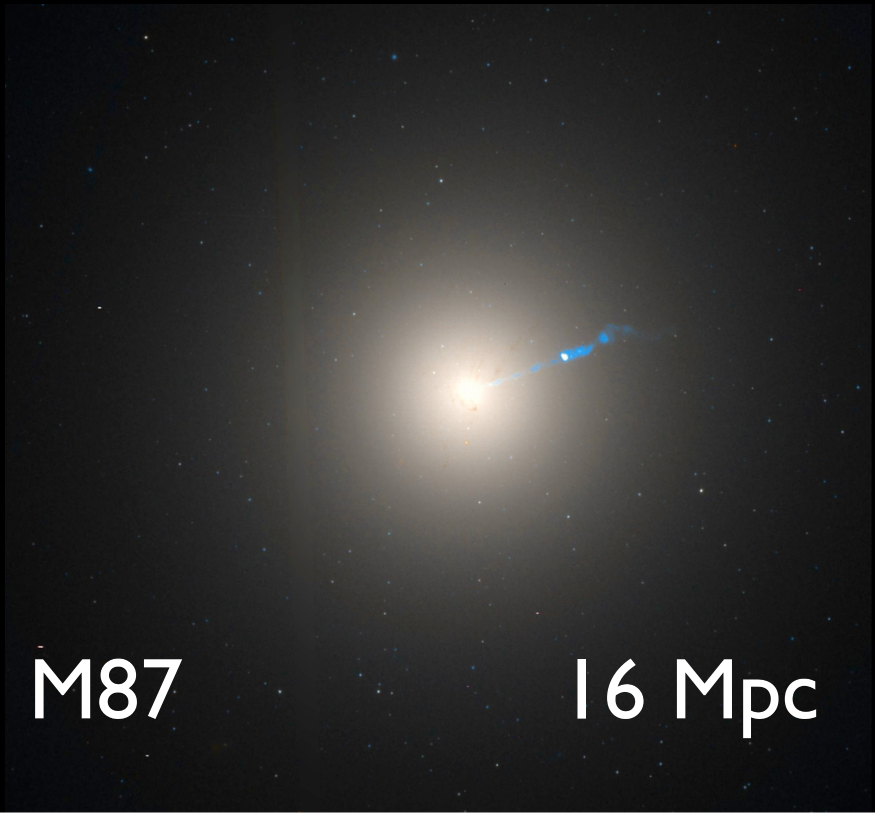
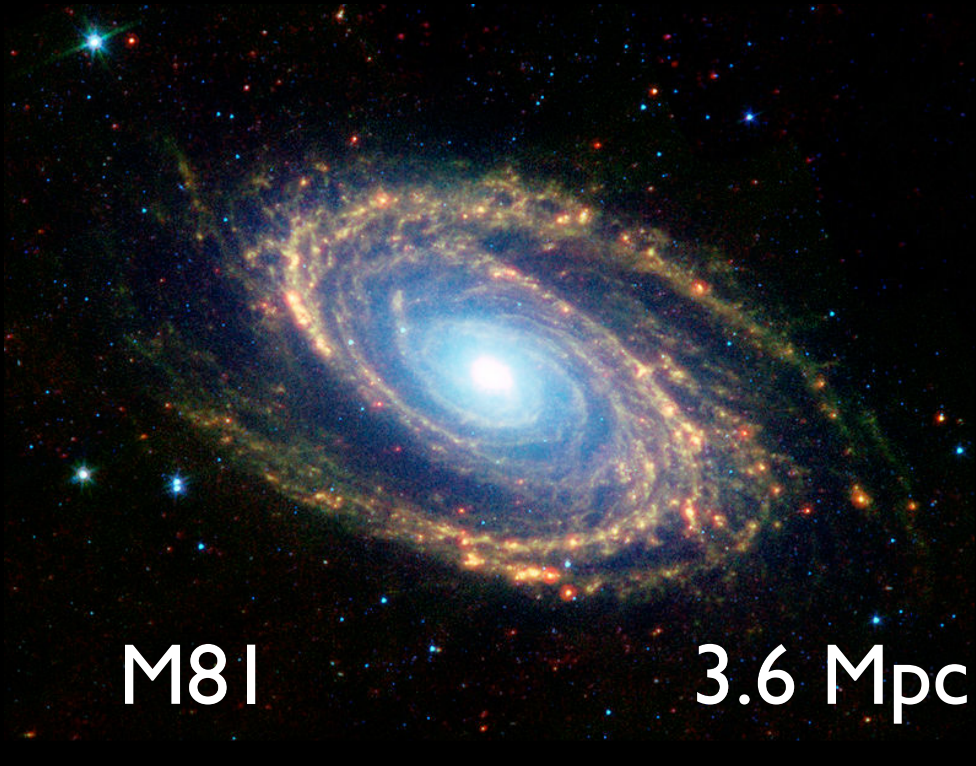


Sijing Shen et al. 2012

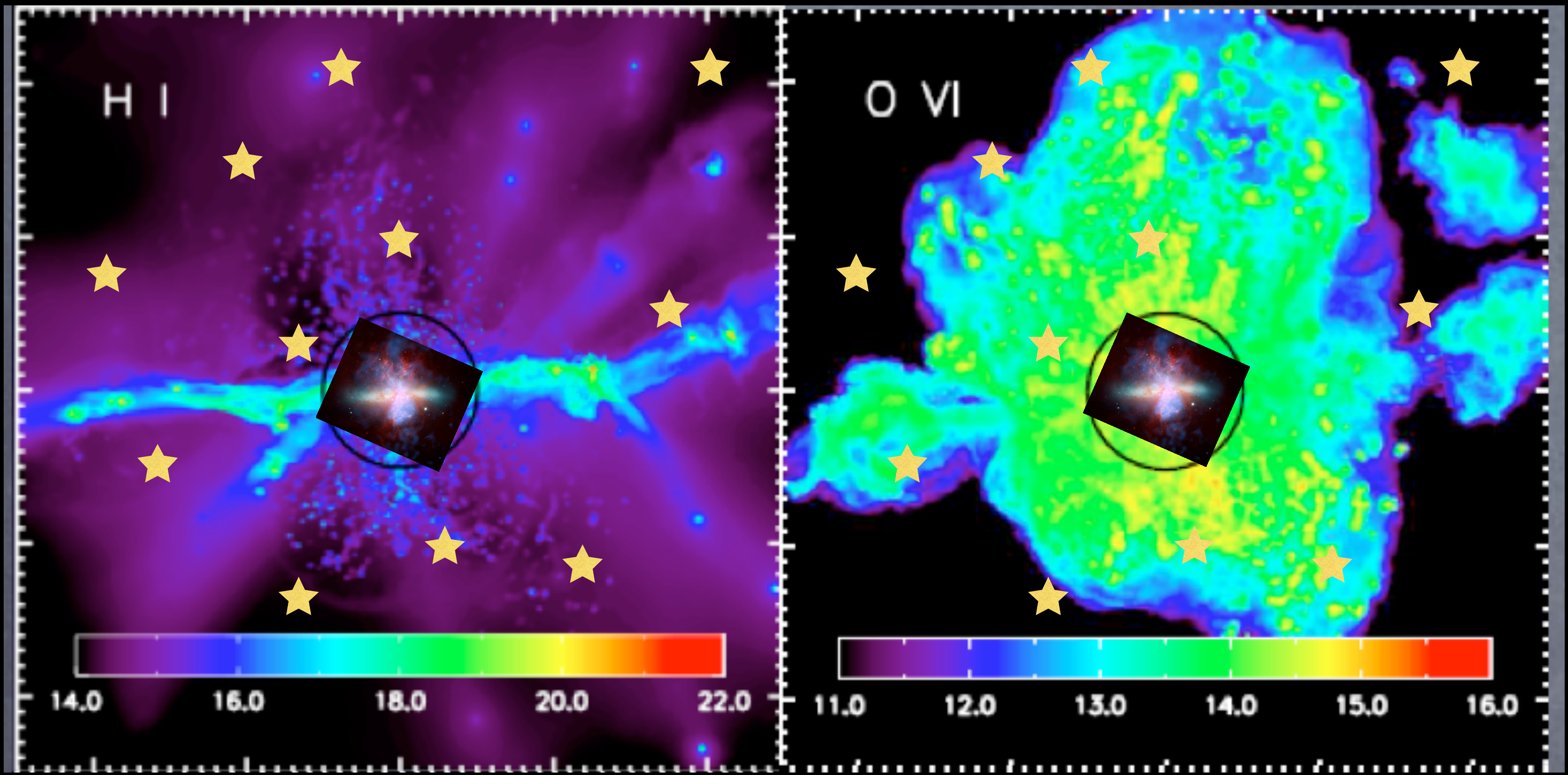
CGM Dynamics Reflected in its Appearance



Sijing Shen et al. 2012


M51
7 Mpc

M82
3.5 Mpc

M87
16 Mpc

M81
3.6 Mpc

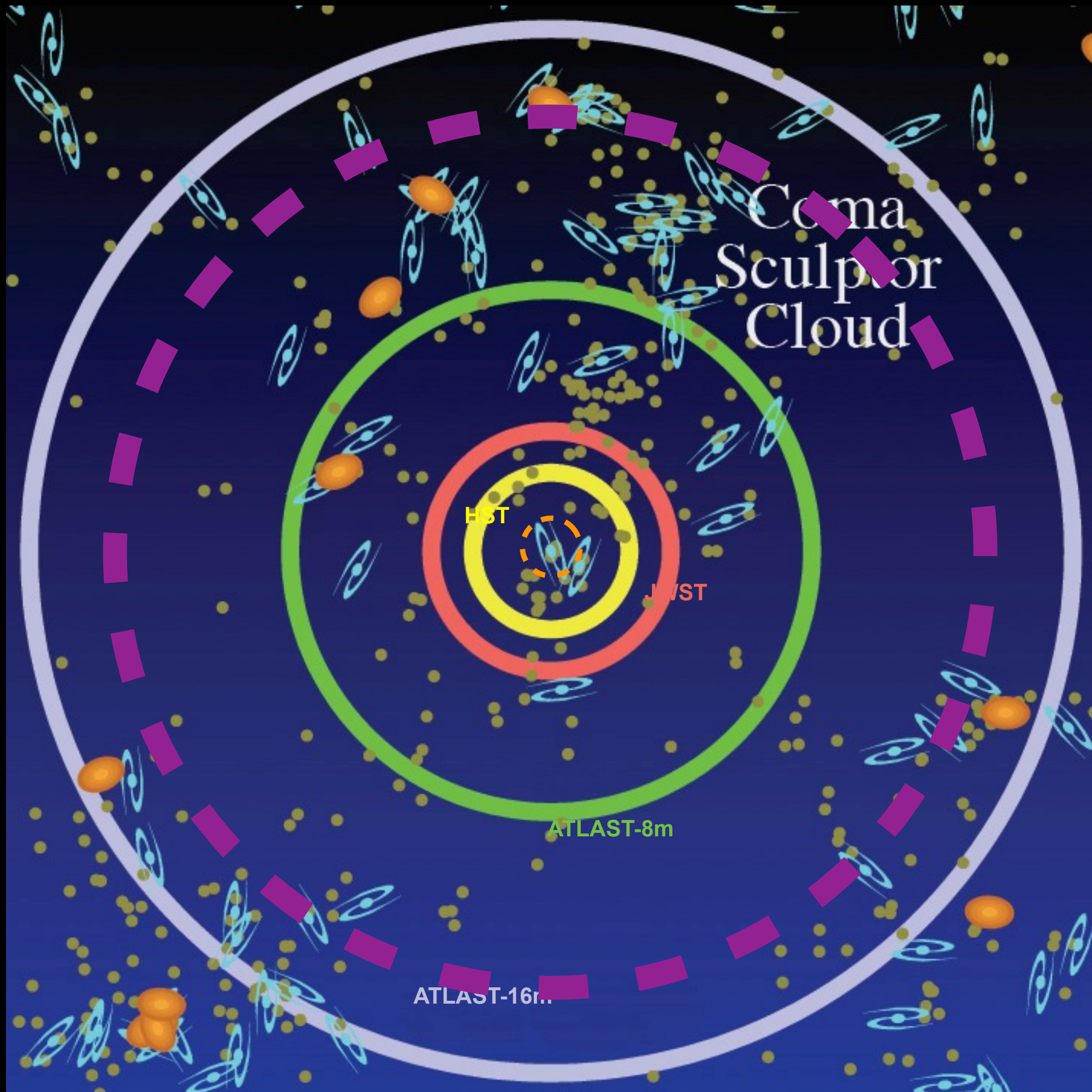
Halo gas dissection with M82.



Note: FUV from 900 - 1150 Å needed to obtain reliable HI column densities from Lyman series **and** O VI, the most sensitive probe of highly ionized gas.

Halo gas dissection with nearby galaxies.

Map of Galaxies within 12 Mpc of Our Galaxy



COS can in principle observe ~10 QSOs within 100 kpc of Andromeda. (small orange circle).

An 8-m can reach QSOs at m_{FUV} ~ 22, where there are ~ 10 / deg^2.

At this sky density, multiple probes of individual fully-resolved nearby galaxies becomes possible.

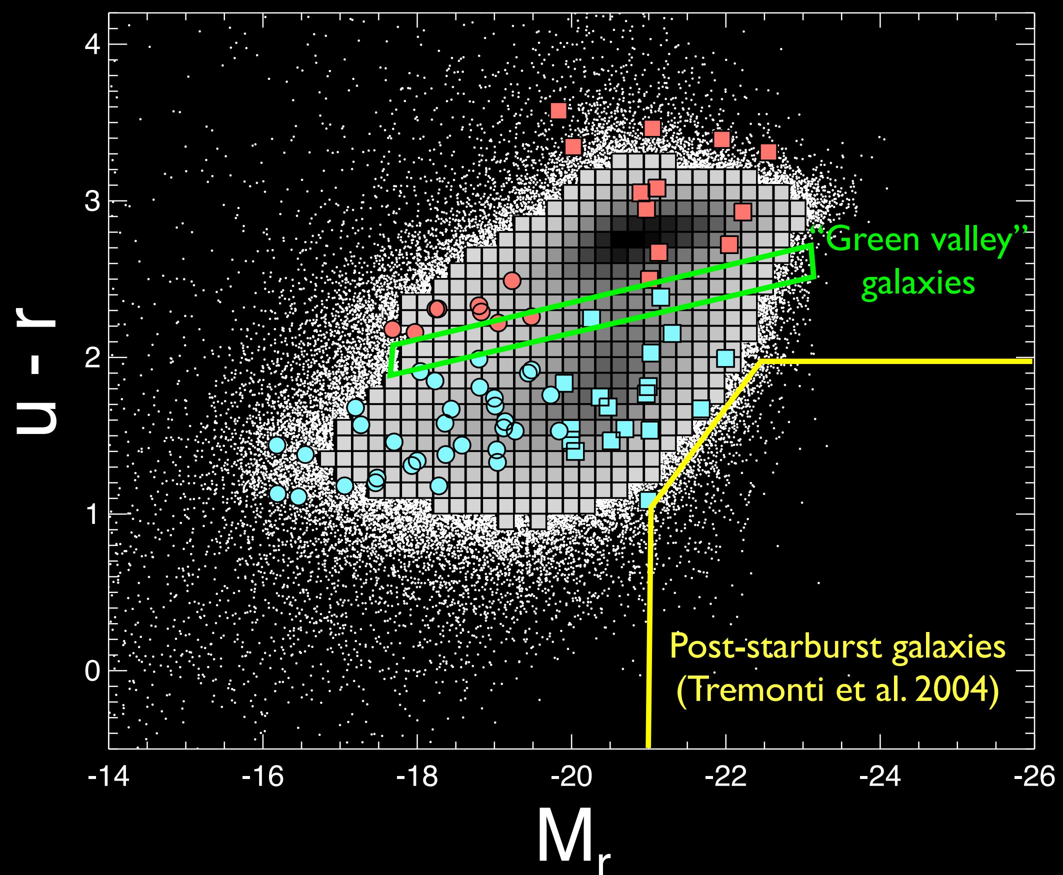
An 8-m can observe ~10 QSOs behind all galaxies within ~ 10 Mpc and > 1 out to 30 Mpc (purple line).

An 8m could dissect the gaseous halos of the same local galaxy population where it can measure the star formation histories from resolved stellar populations!

Application No. 2

Relating short or rare phases of galaxy evolution to their gas flows.

Gas Flows and Galaxy Evolution with 10,000 QSOs.



The SDSS+GALEX QSO catalog contains 1200 QSOs bright enough for COS (m_{FUV} = 18.5, S/N ~ 10 in < 5 orbits).

An 12 m can access 10^5 in this same region of the sky (m_{FUV} < 22).

COS has "transcended serendipity" for mainstream galaxy populations; i.e. the main sequences of the red and blue clouds.

But COS is limited in its ability to study short evolutionary phases that are correspondingly rare, such as "green valley" and "post-starburst" galaxies (cf. Tripp+11)

An 8-m could "transcend serendipity" for these rarer galaxies, allowing us to directly probe the gas flows that drive these phases of evolution.

For example, models indicate that a 12-m could get 100 green valley and 50 post-starburst galaxies in a ~ 100 hr program

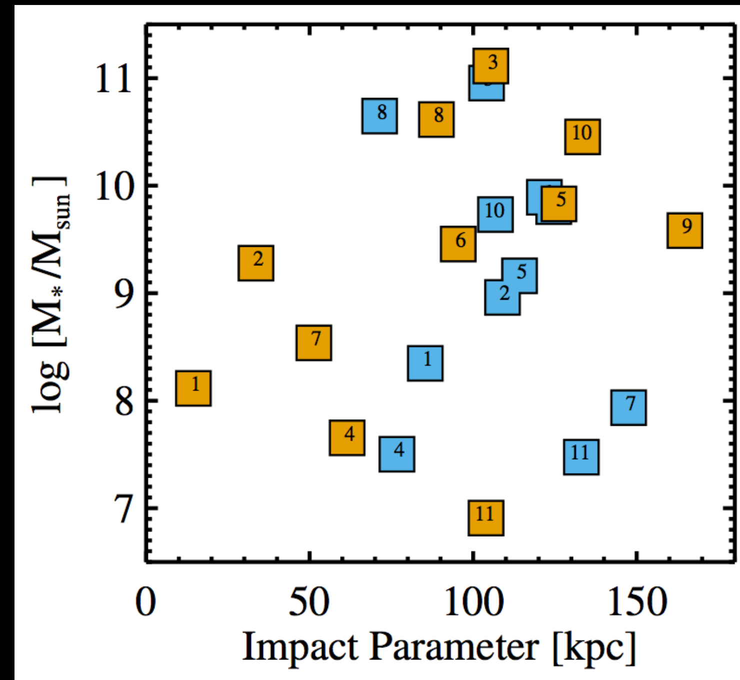
How Galaxy Mergers Affect Their Environment: Mapping the Multiphase Circumgalactic Medium of Close Kinematic Pairs

Scientific Category: QUASAR ABSORPTION LINES AND IGM

Scientific Keywords: Galaxy Halos, Interacting And Merging Galaxies, Interstellar And Intergalactic Medium

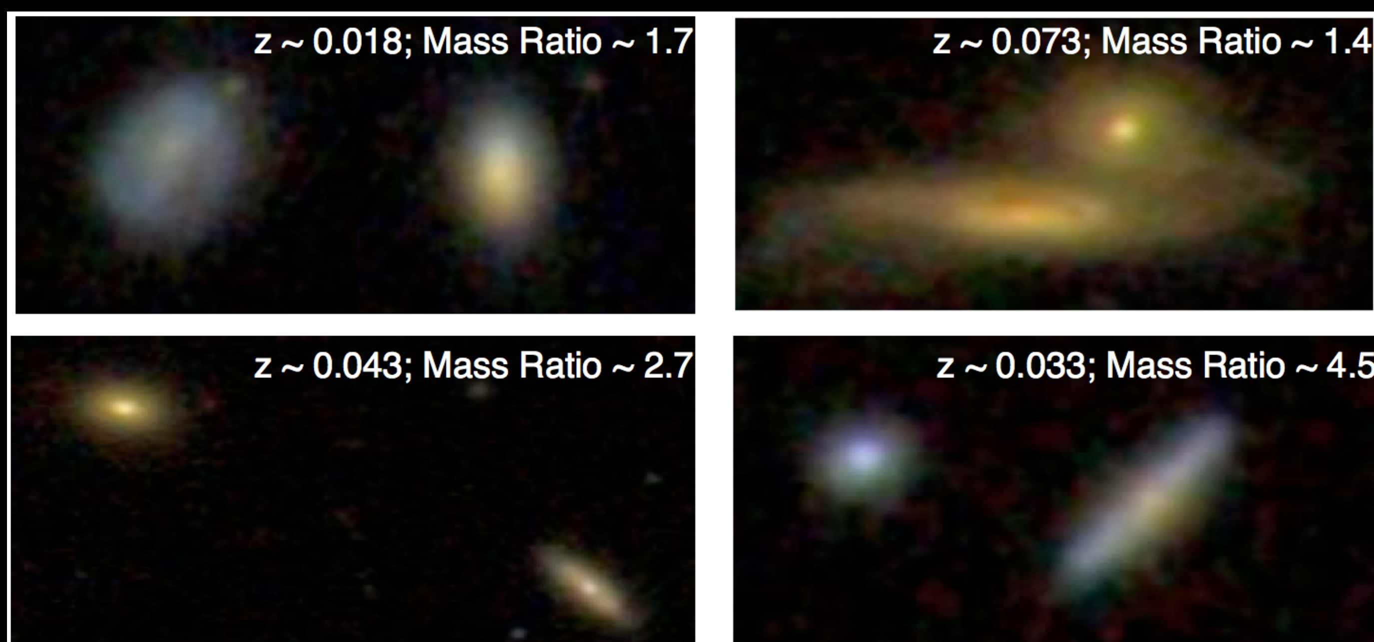
Instruments: COS

PI: Rongmon Bordoloi (STScI—>MIT)



What does the CGM do during mergers?

What do mergers and loss of gas have to do with quenching?

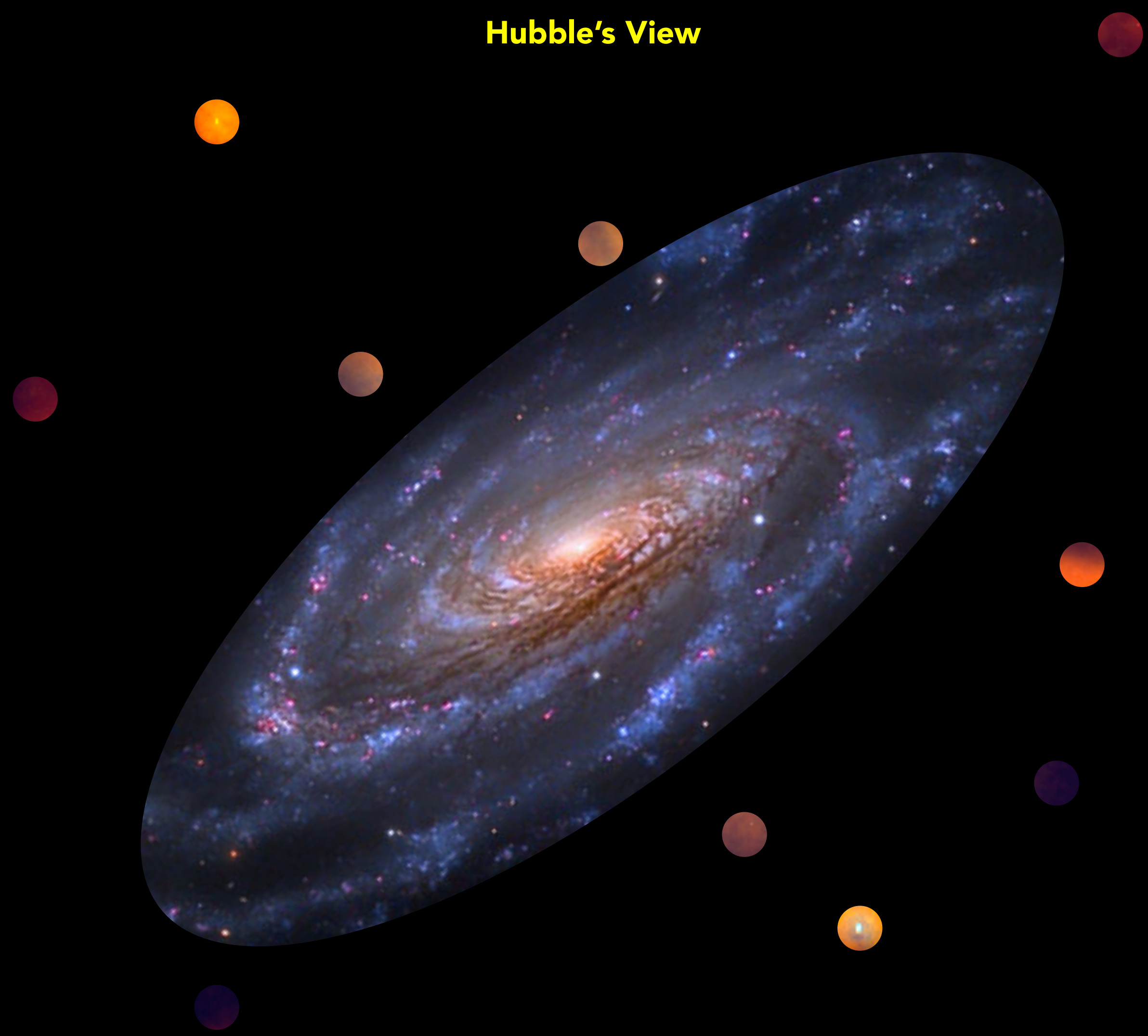


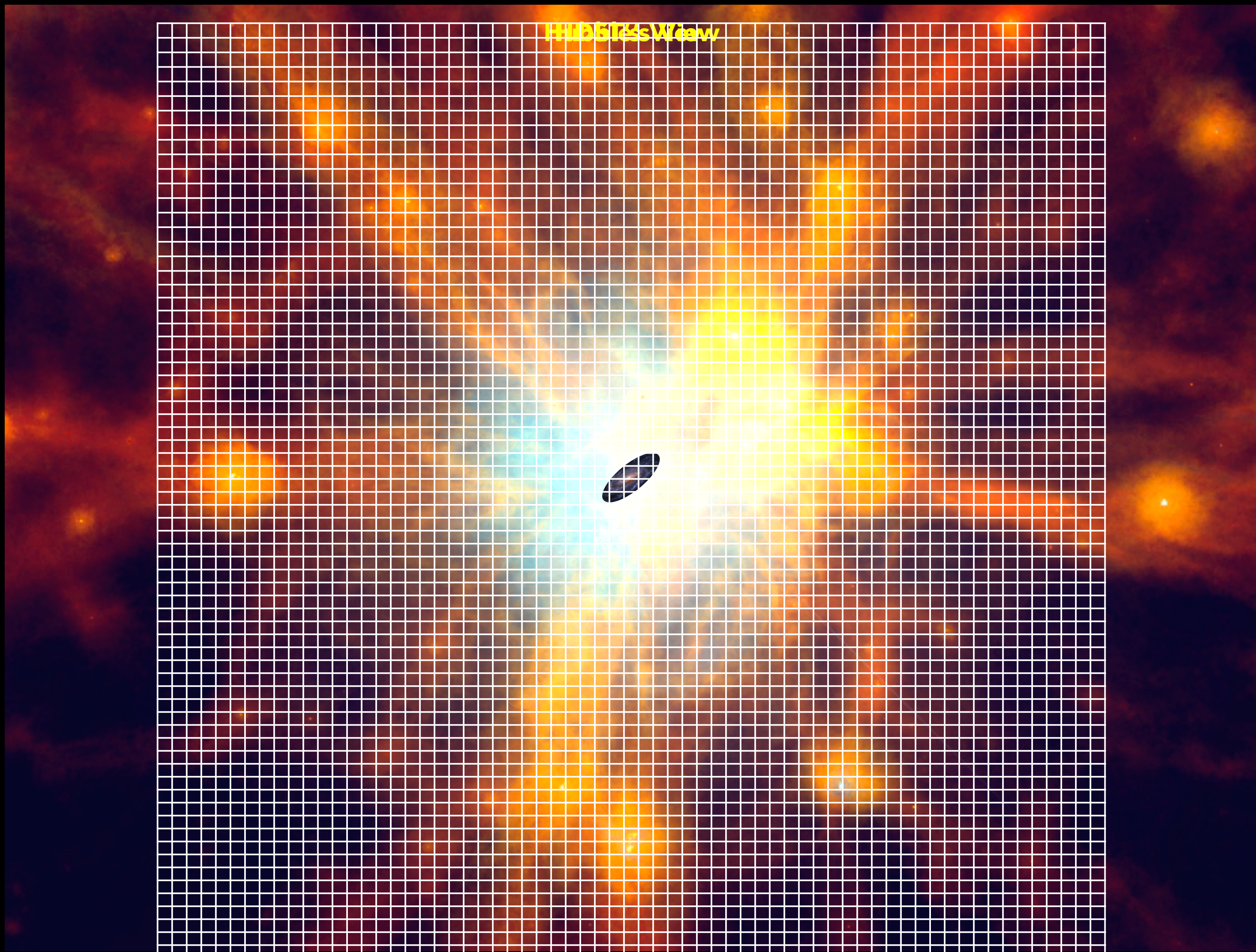
Only 11 mergers with background QSOs in ALL OF SDSS that COS can reach!

Application No. 3

Taking a picture of the CGM!

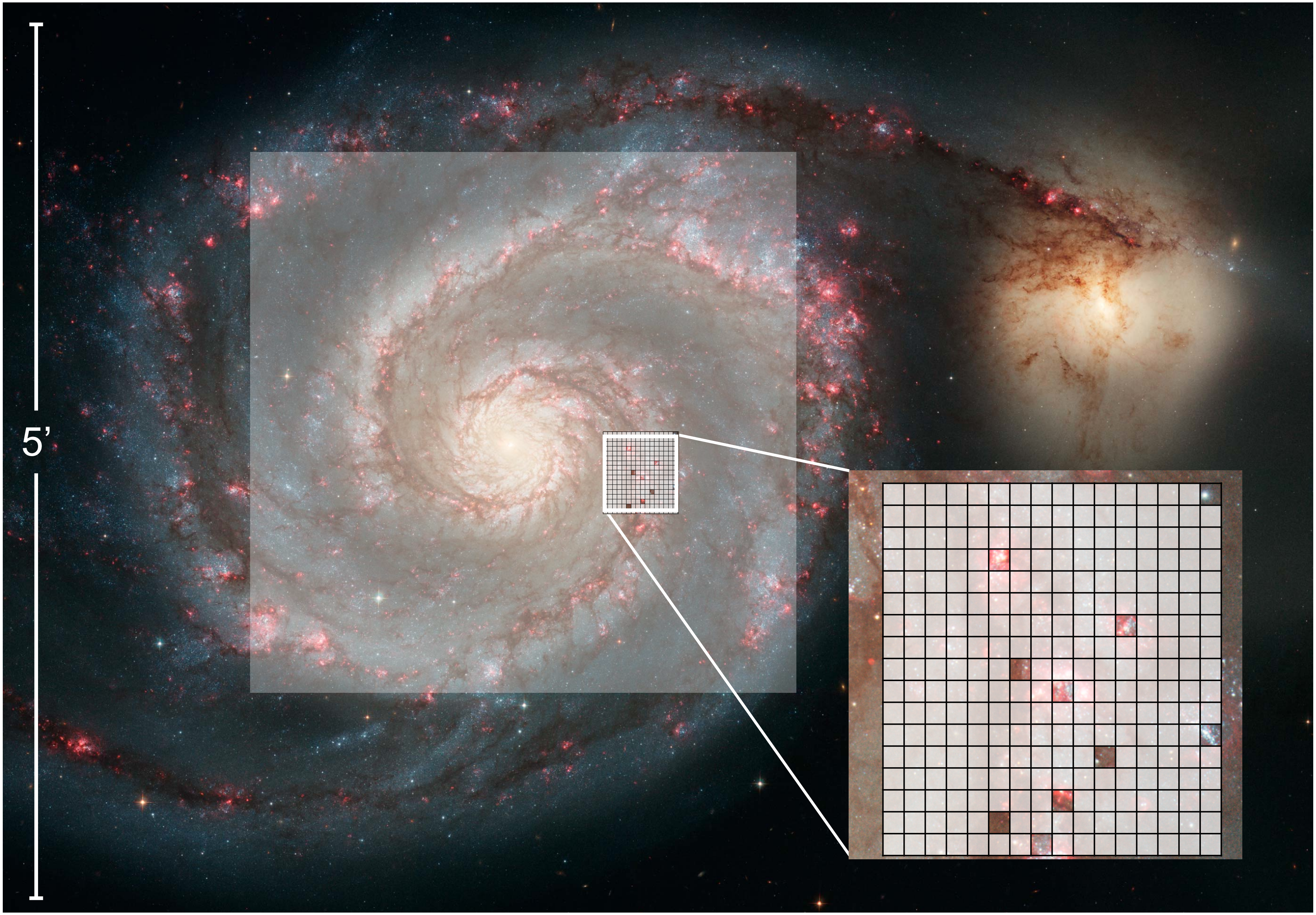
Hubble's View





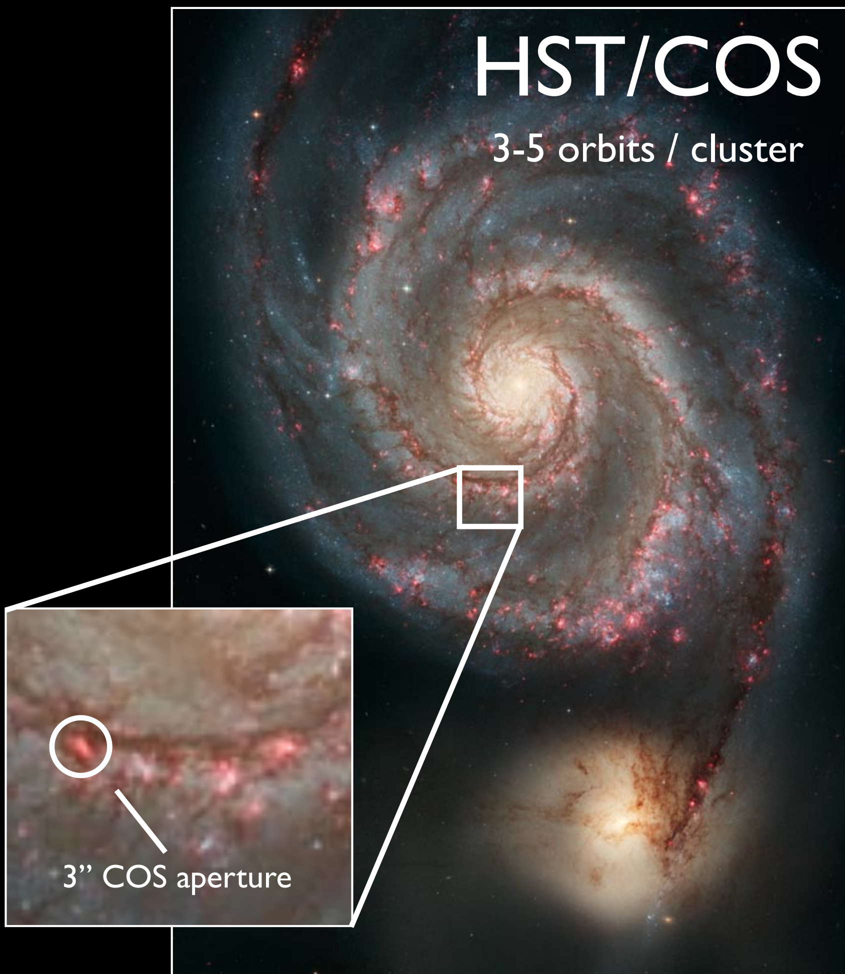
Application No. 4

Trace galactic outflows to the source.

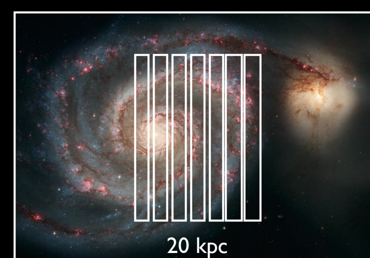

5’

Revolutionary UV Capability

- Could achieve 50-100 times HST/COS sensitivity for point-source spectroscopy.
- Some of the gain in photons collected can support multiplexing.



3′ MOS
at z ~ 0

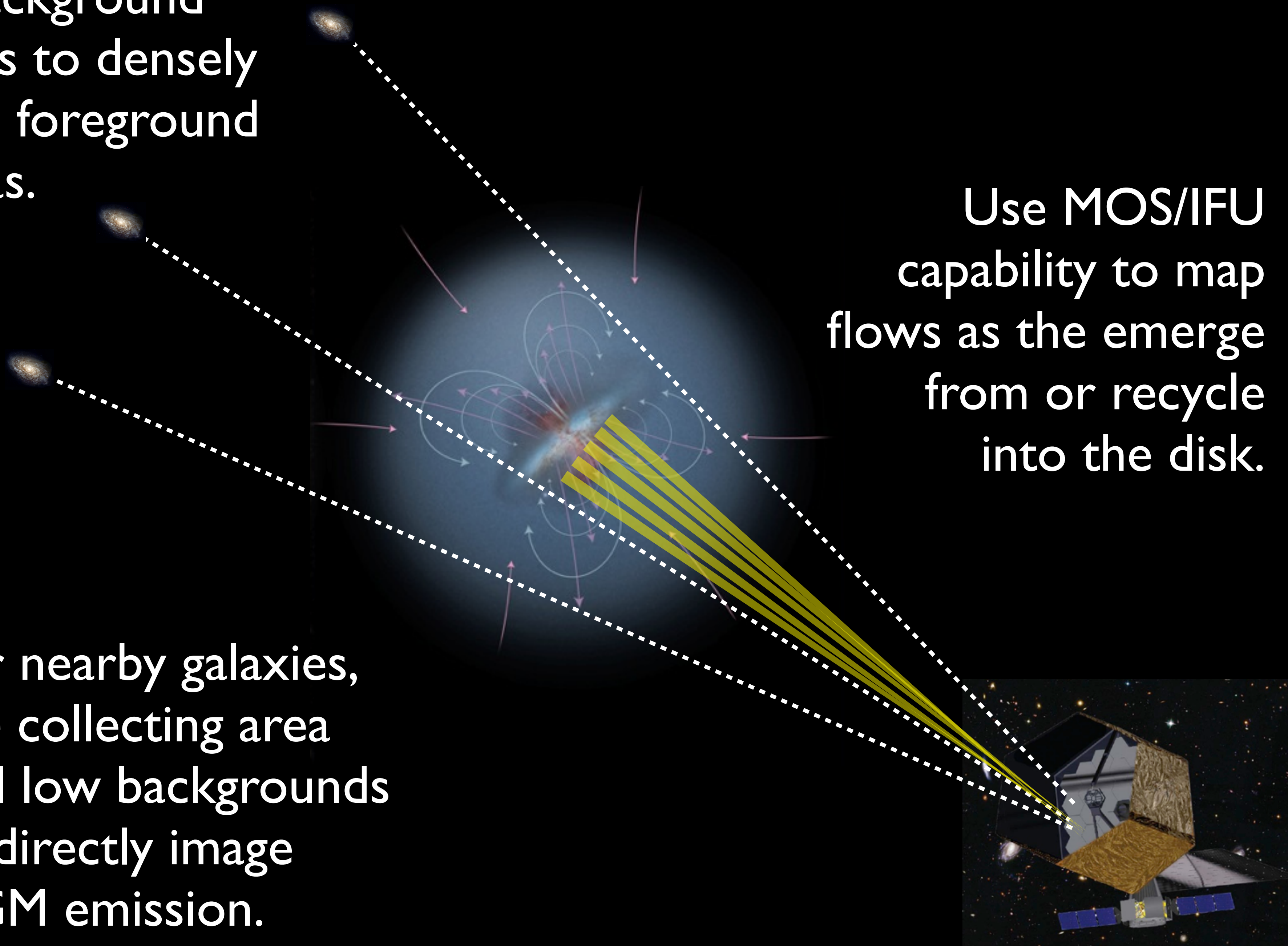


3″ IFU
at z ~ 0.5

Also would permit detailed mapping of UV continuum and line SFR metrics, spatially resolved, from z = 0 - 1.

HDST: The Ultimate Gas Flows Machine

Use background galaxies to densely sample foreground halo gas.



Use MOS/IFU capability to map flows as the emerge from or recycle into the disk.

For nearby galaxies, use collecting area and low backgrounds to directly image CGM emission.

Application No. 5

Find the rest of the “missing baryons”.

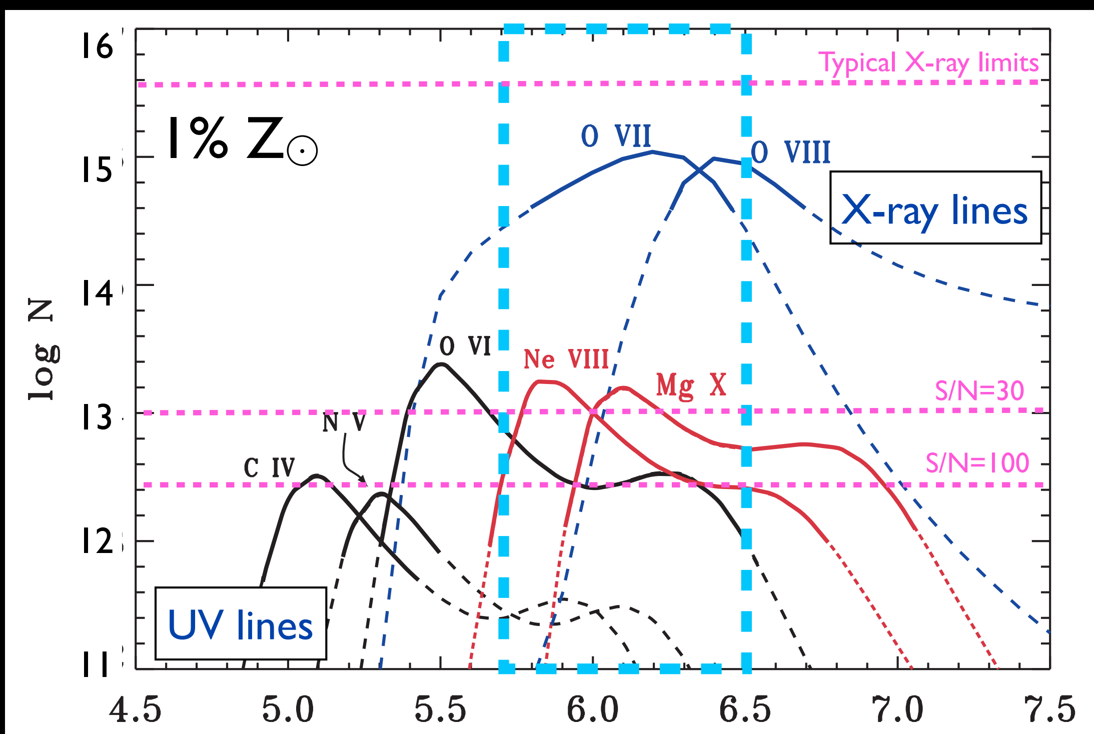
What to Look For, and How: Turn the UV into an X-ray telescope

- Deep spectroscopy (S/N ~ 80-100) would look for diagnostics that are invisible or very weakly detected in shallower data (typically S/N = 30 in existing COS data):

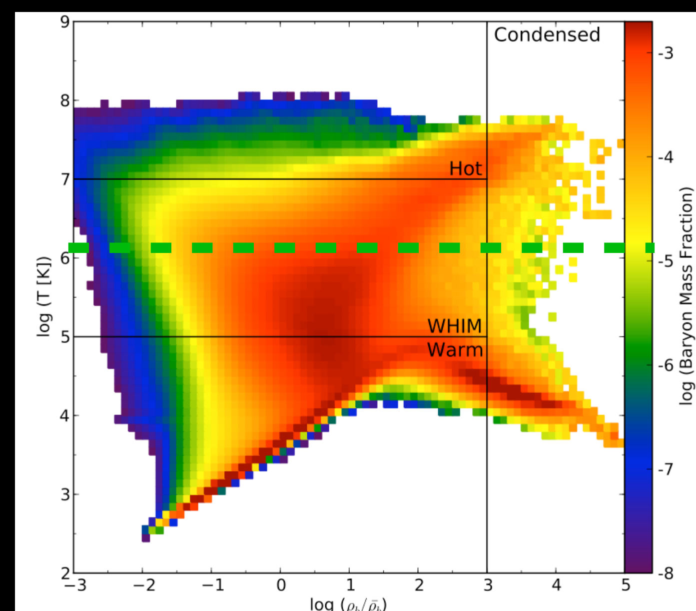
- Ne VII and Mg X are a lithium-like ions with a doublets at 780 and 625 Å, so seen only at $z > 0.5$.
  - a unique tracer of true $> 10^6$ K gas, IF IT IS METAL ENRICHED.

- "Broad Lyman Alpha" is thermally broadened HI gas, with high ionization
  - an effective tracers of 10^{5-6} K gas, EVEN IF IT IS NOT METAL ENRICHED

- So deep observations open two avenues to the missing baryons, the spread of metals, and their implications for galactic feedback and quenching.



courtesy of Chris Howk

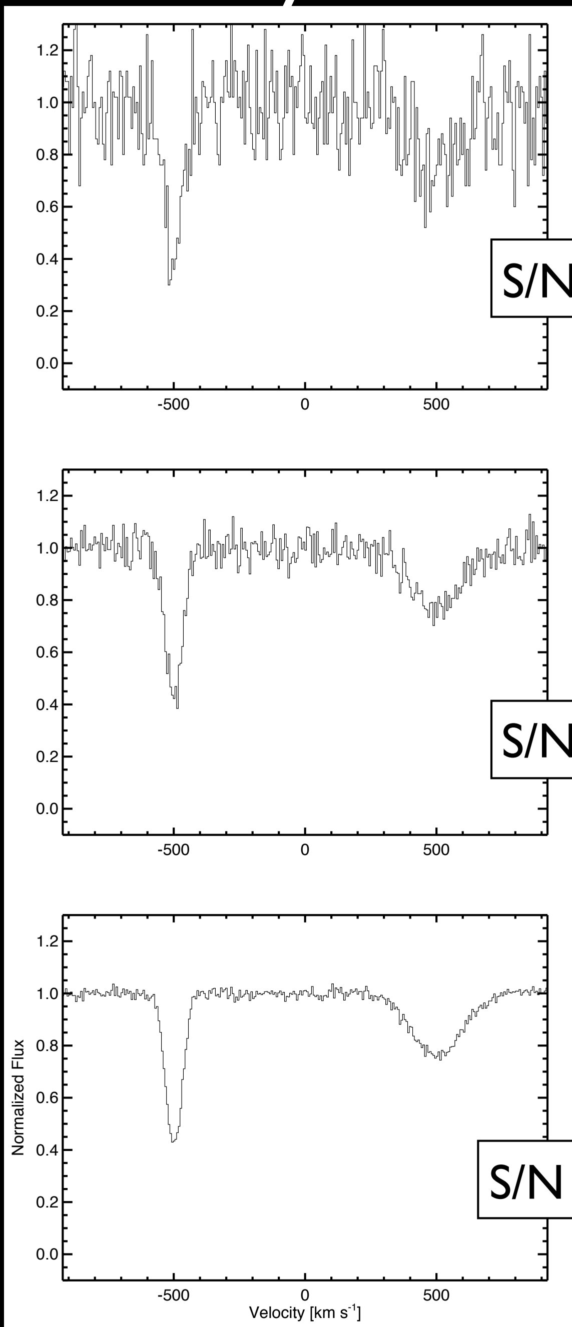


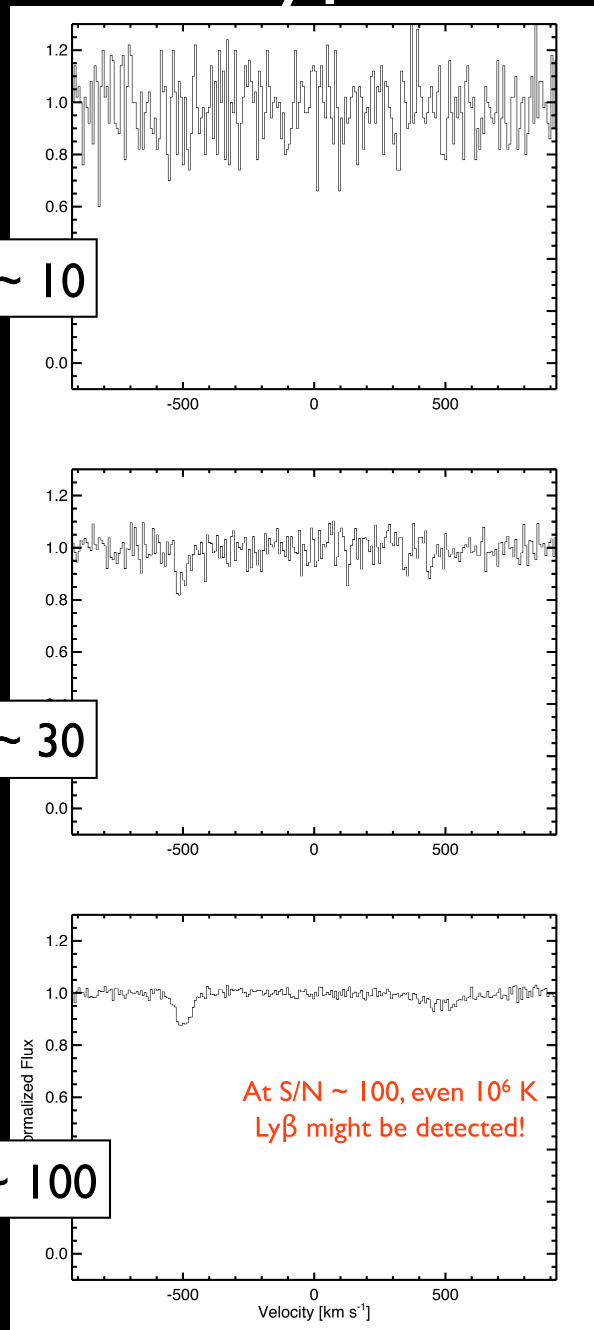
Broad Lya Finds Hot Baryons Even Without Metals

10^5 K Lyα 10^6 K

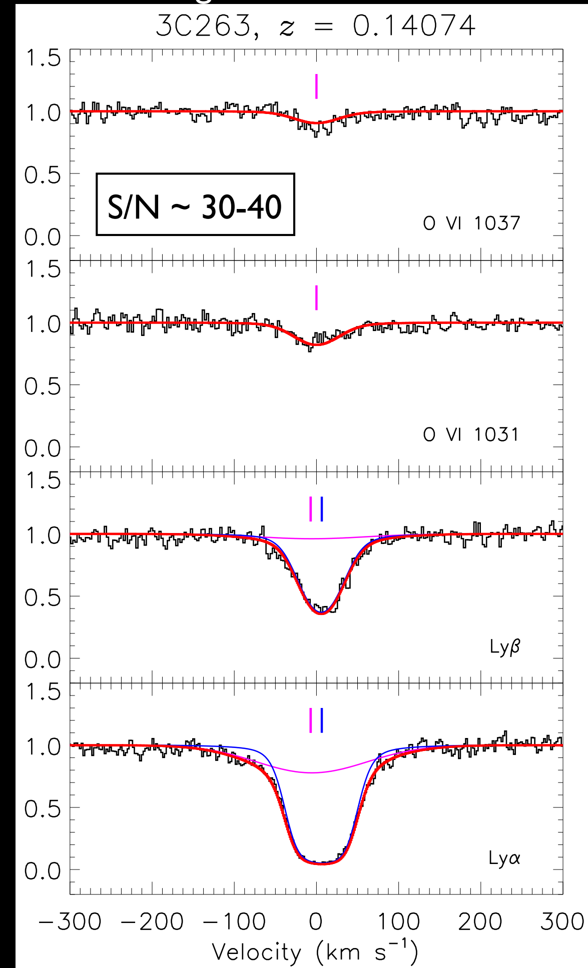
log NHI = 13.5

10^5 K Lyβ 10^6 K





Such things have been detected.



Savage et al. arXiv:1205.0752

log N_{HI} = 13.5
b = 87 km s^{-1}
log T = 5.6 or
500,000 K

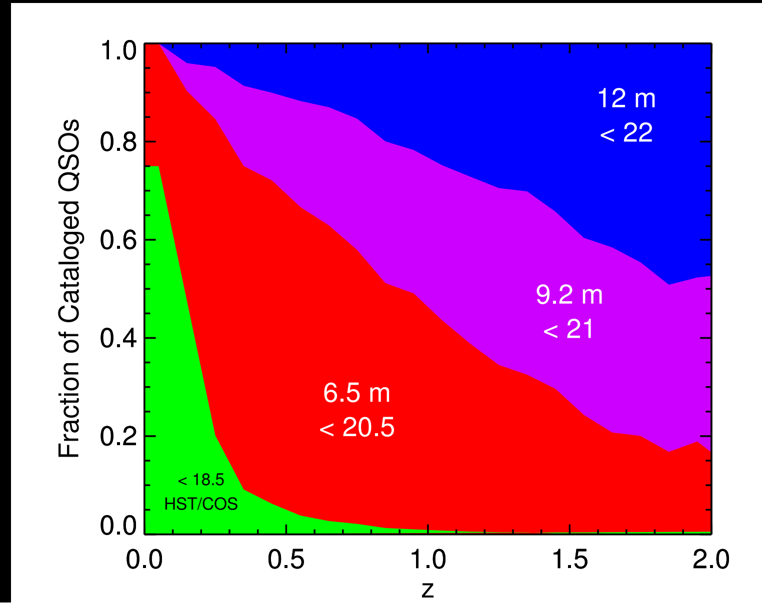
But this sightline goes only to z = 0.6, barely far enough for Ne VIII and not far enough for Mg X

Application No. 6

Examine the CGM and Quenching
when it happened.

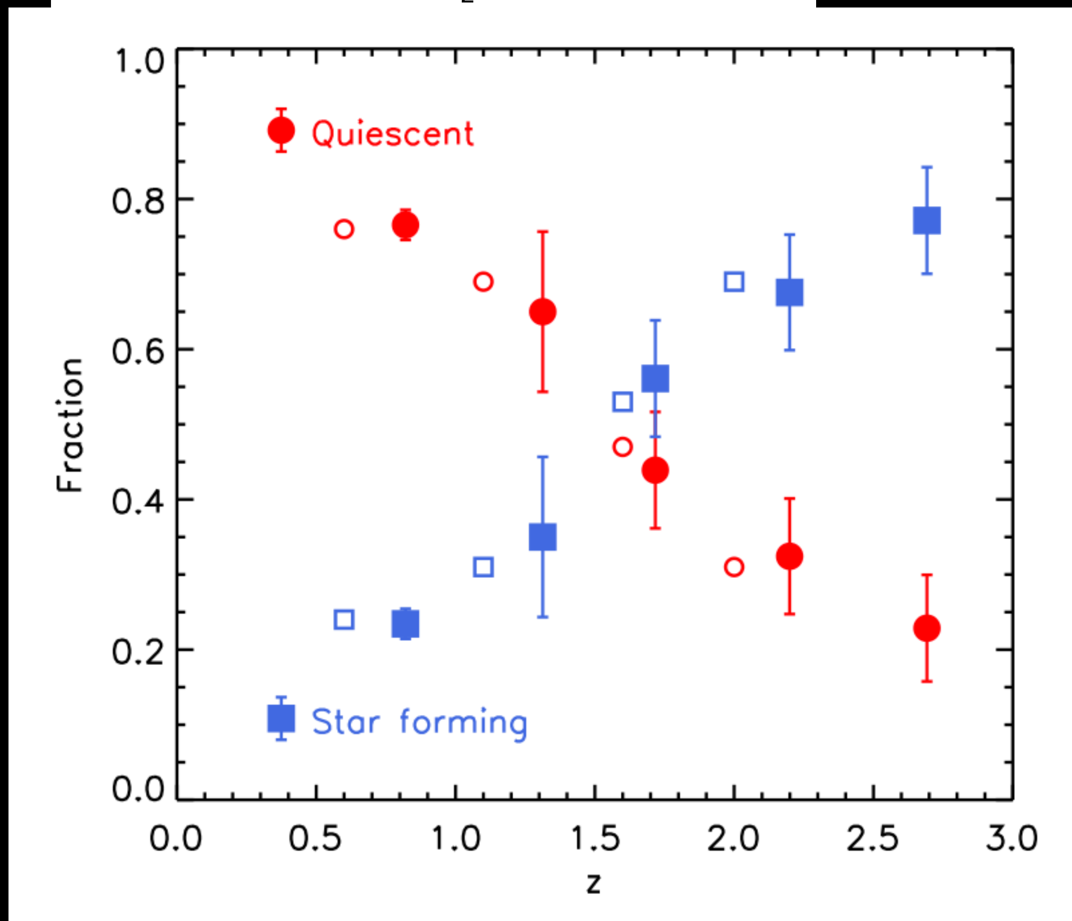
QSOs too faint for < 4m telescope

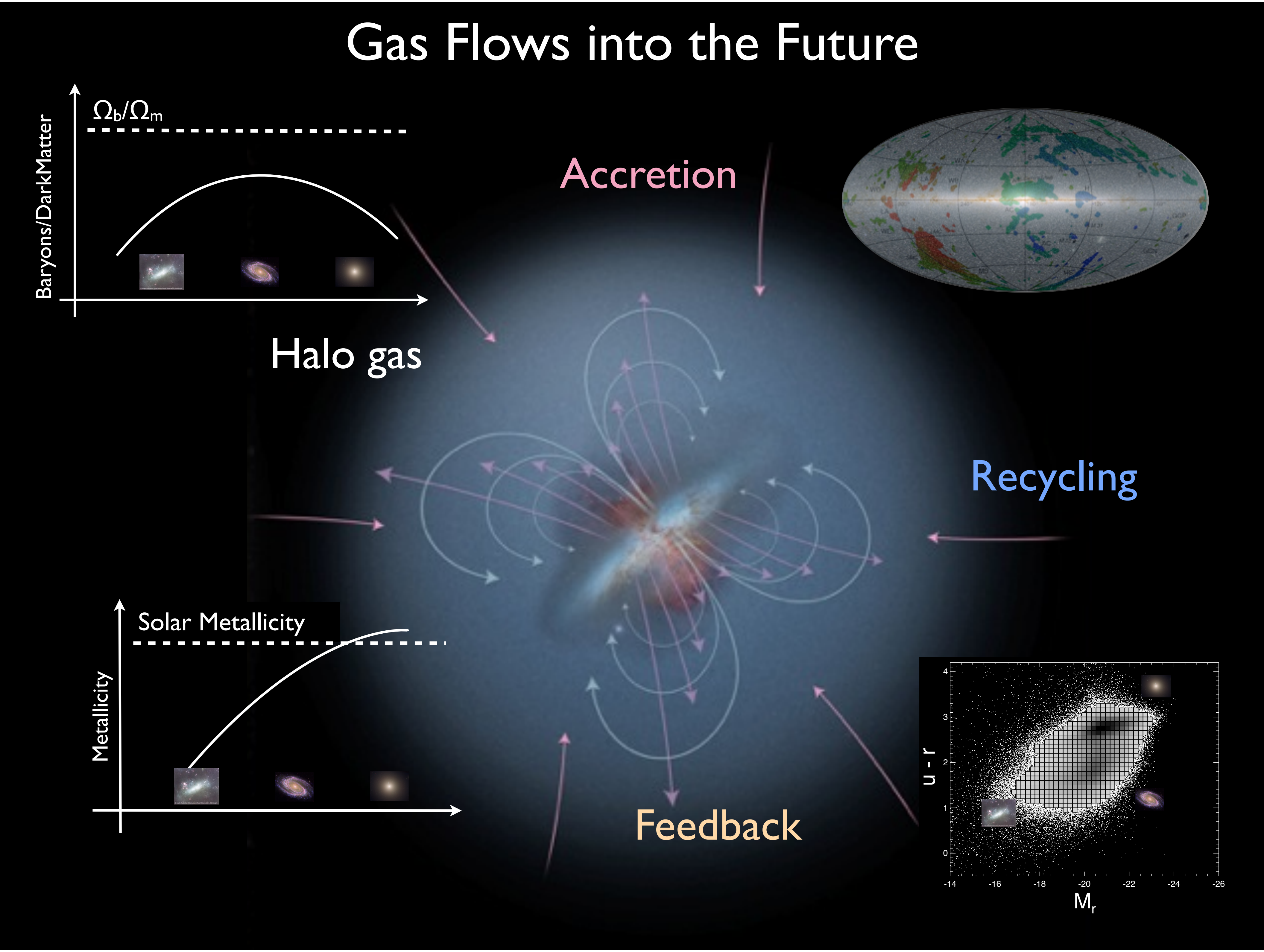
QSO Availability



Large Aperture Needed to do CGM work at z = 1-2

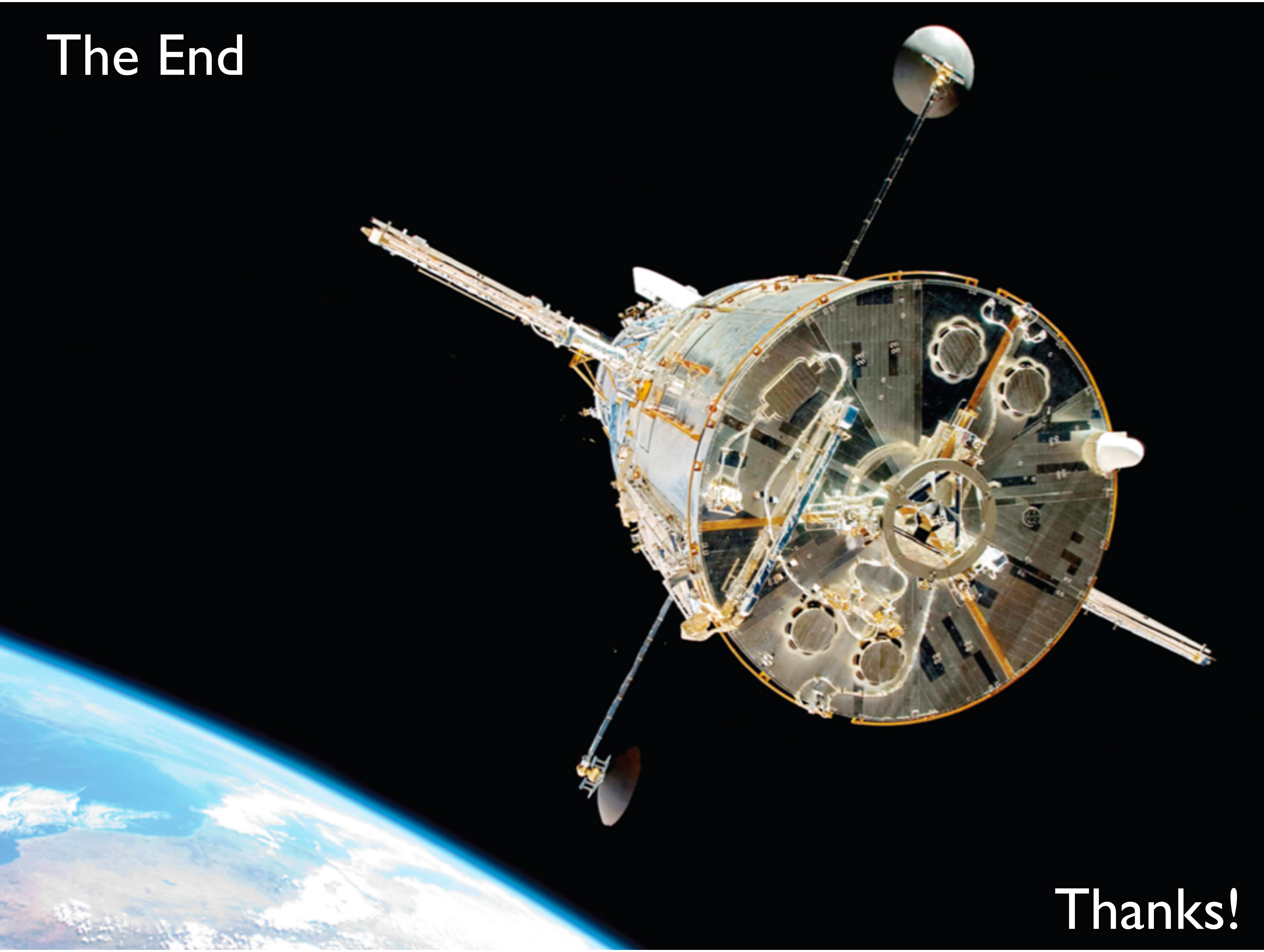
Galaxy Transformation





Gas Flows into the Future
Ωb/Ωm
Baryons/DarkMatter
Halo gas
Accretion
Recycling
Feedback
Solar Metallicity
Metallicity
u - r
M_r
-14
-16
-18
-20
-22
-24
-26
0
1
2
3
4

The End



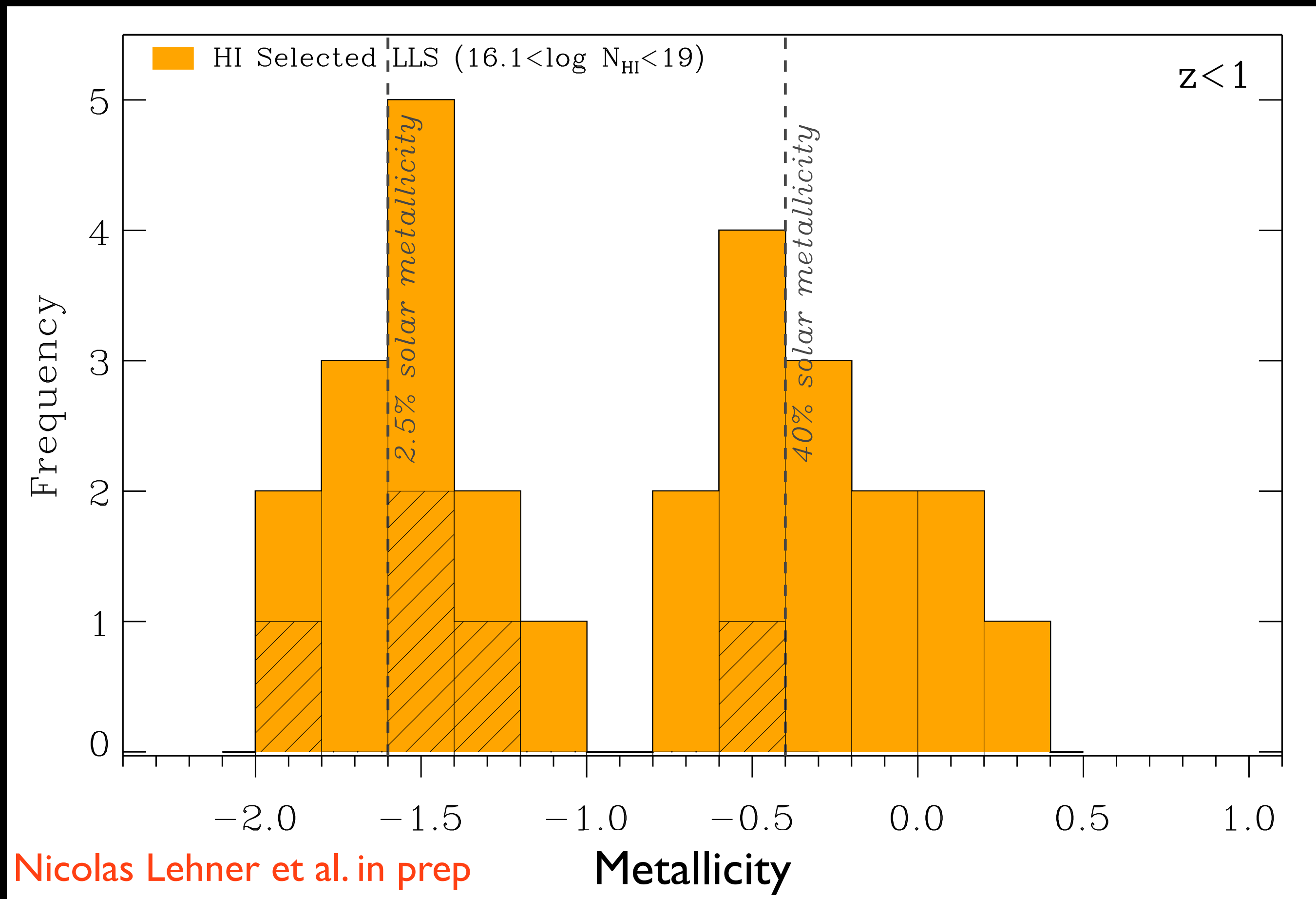
Thanks!

EXTRAS

THE BIMODAL METALLICITY DISTRIBUTION OF THE CIRCUMGALACTIC MEDIUM AT $z \lesssim 1$[1]

N. LEHNER[2], J.C. HOWK[2], T.M. TRIPP[3], J. TUMLINSON[4], J.X. PROCHASKA[5], J. O'MEARA[6], C. THOM[4], J.K. WERK[5], A.J. FOX[4], J. RIBAUDO[7]

To be submitted to the ApJ – version October 19, 2012

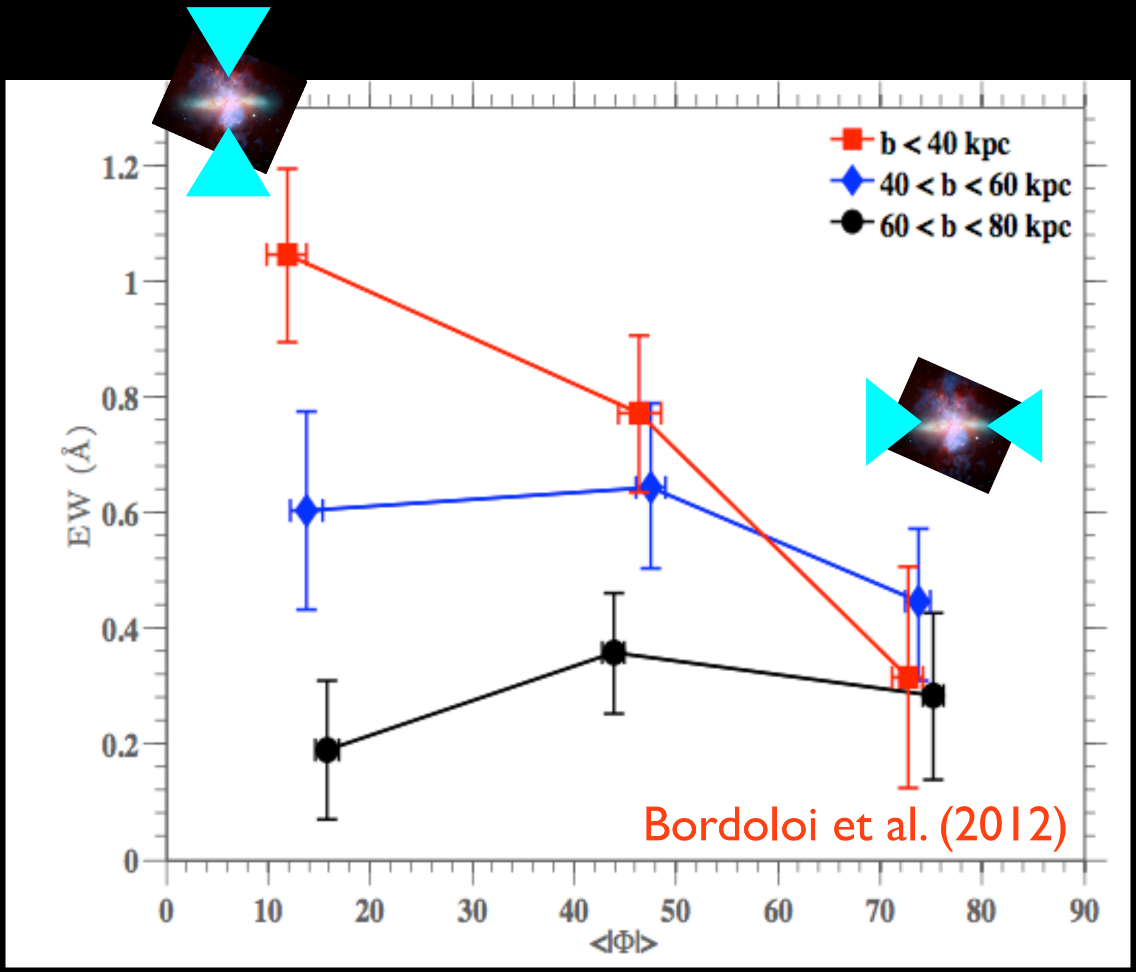


These are CGM-like strong HI absorbers with robust metallicities estimated from metals detected (or not) in spectra from COS (C II, Si II) or Keck/HIRES (Mg II).

Intervening from COS-Halos and Tripp large program - galaxies not yet identified.

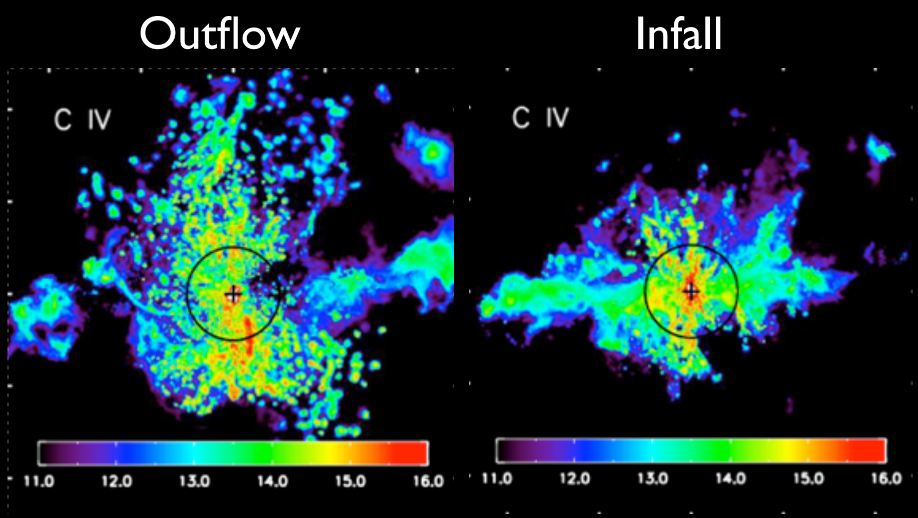
Why go to $z > 0.5$

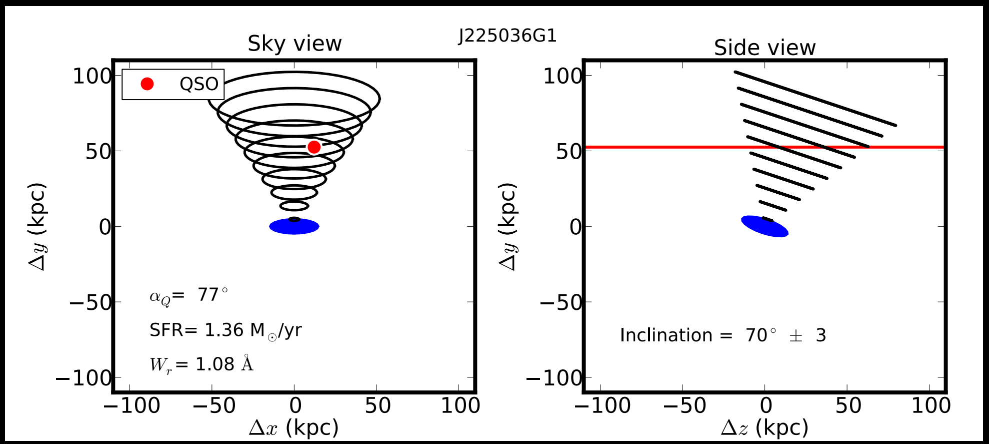
Feedback in the act: Winds emerging from disks

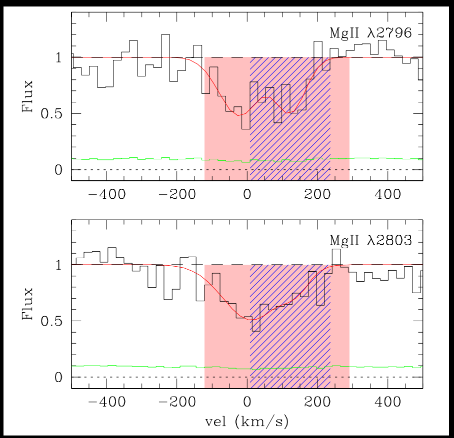


7000 FOREGROUND galaxies in zCOSMOS probed in stacked spectra of BACKGROUND galaxies.

Evidence of Mg II preference on the semi-major axis... interpreted as bi-polar outflow.

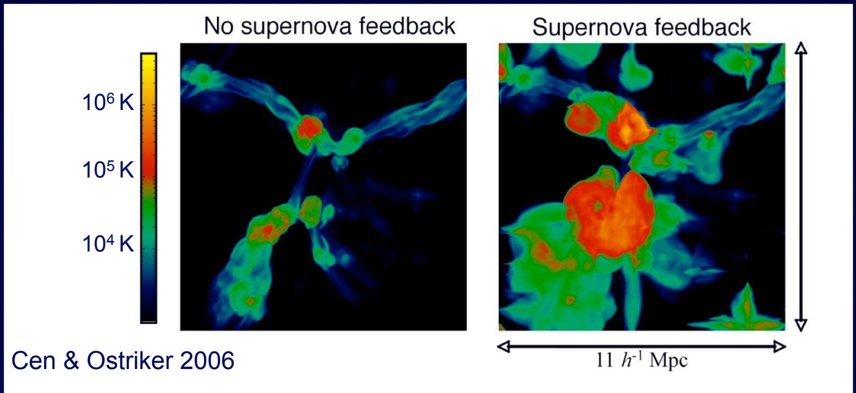






Biconical Outflows match Mg II kinematics: Bouché et al. (2012) and Kacprzak et al.

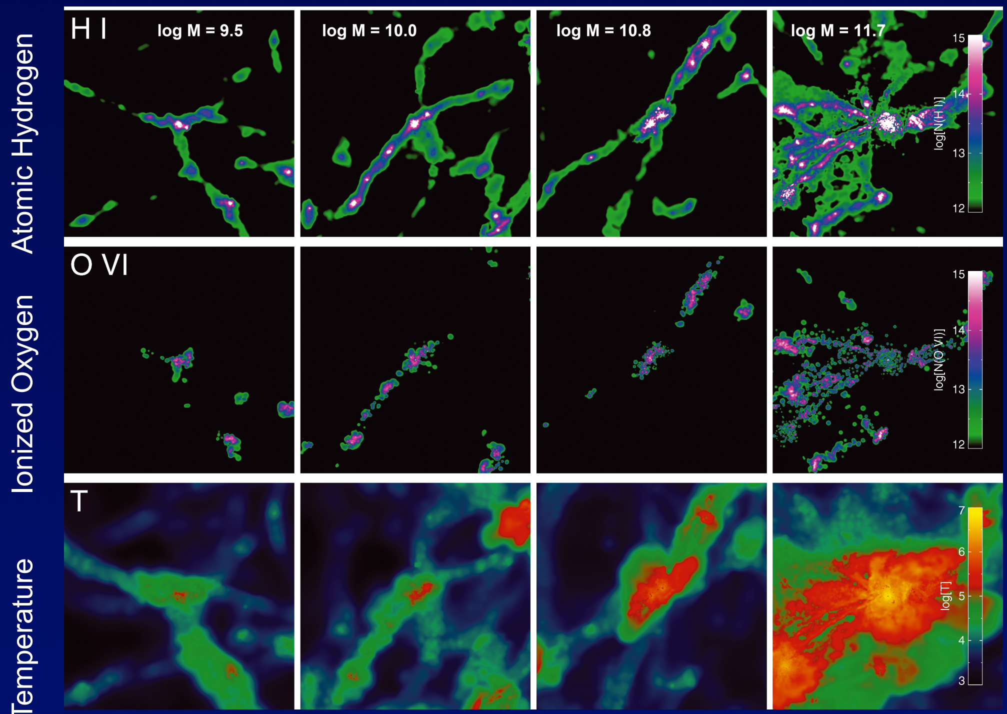
Understanding the Galaxy - IGM Interplay



Above: IGM gas temperature distribution for cosmological models with and without supernova feedback.

Below: Gas ionization and Temperature Distribution vs. Galaxy Mass

Lower Mass → Higher Mass



Oppenheimer et al. 2009

Most of the matter in the Universe is located in intergalactic space outside of galaxies.

The key questions are:

HOW IS INTERGALACTIC MATTER ASSEMBLED INTO GALAXIES?

TO WHAT DEGREE DOES GALAXY FEEDBACK REGULATE AND ENRICH THE IGM?

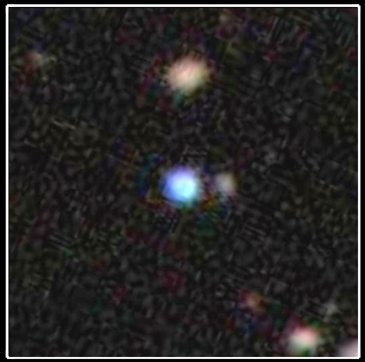
WHERE AND WHEN DO THESE PROCESSES OCCUR AS A FUNCTION OF TIME?

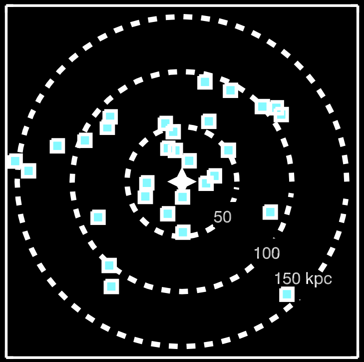
Understanding the answers to these questions lies at the heart of understanding galactic evolution.

Depending on the mass of the galaxy halo, infalling gas may be shocked and heated or accrete in cold mode along narrow filaments. Gas can also be *removed* from galaxies via tidal and ram pressure stripping, supernova-driven winds, or during the accretion of gas-rich dwarfs onto giant galaxies.

These hypotheses need to be tested!

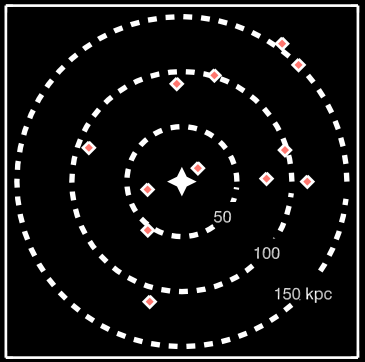
The CGM of mainstream blue and red galaxies with HST/COS





Star Forming

Sample
Sightline
Map



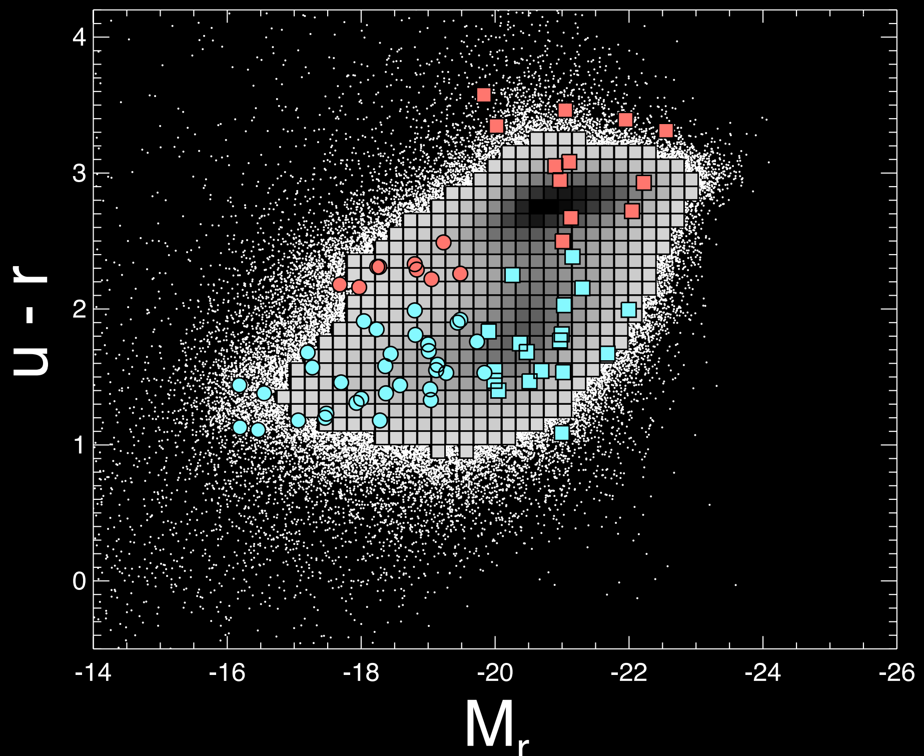
Passive

> 200 orbit investments by HST/COS required to obtain ~100 QSO/galaxy pairs over 0 - 150 kpc.

The CGM holds a gas mass comparable to the stellar mass, and a metal mass comparable to the ISM.

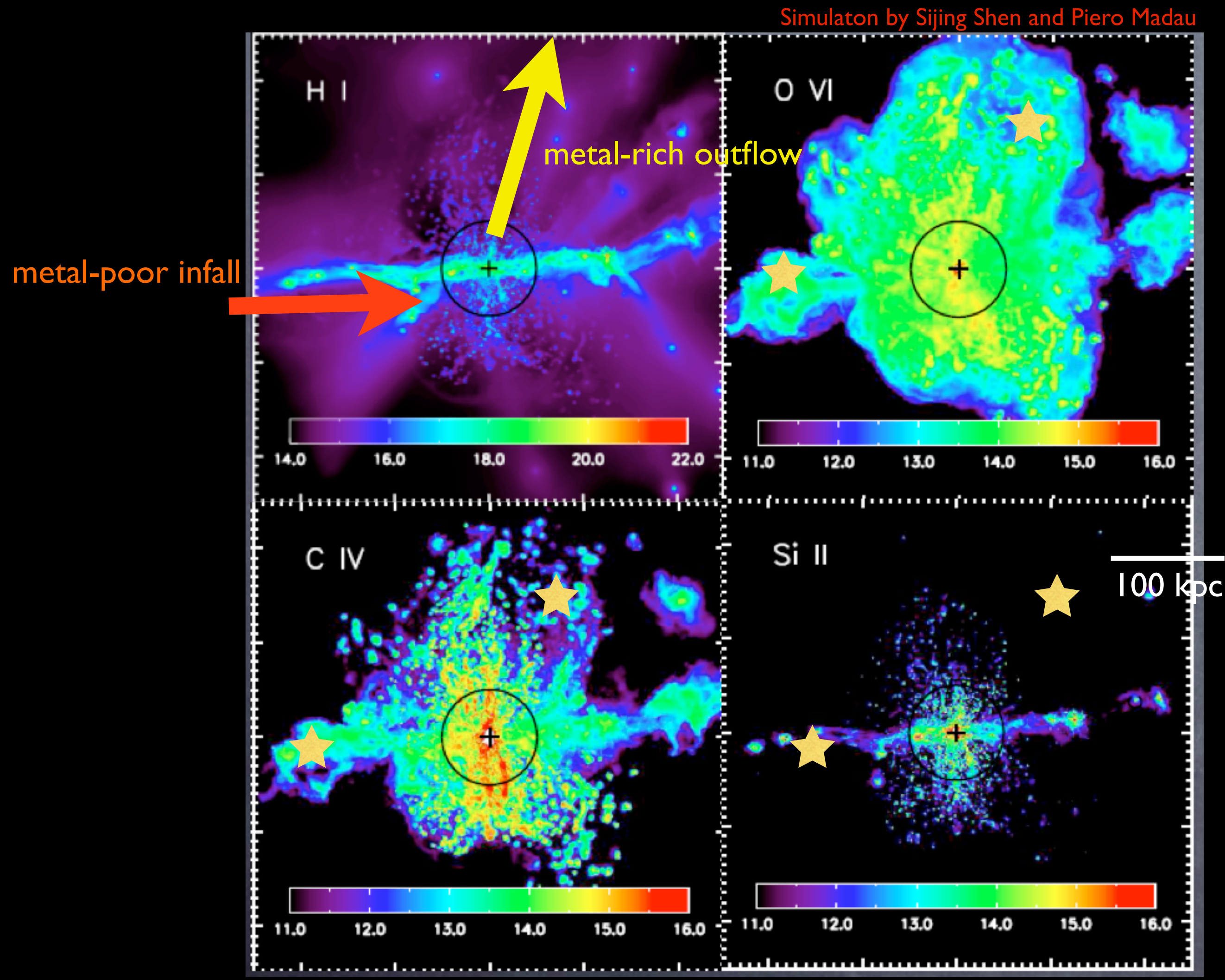
QSOs bright enough for COS are still relatively rare.

The next frontier is to expand to less common galaxy types (AGN, post-starbursts) and relate these phases directly to the gas processes they generate.



COS-Halos: Tumlinson et al. (2011), Thom et al. 2011, Werk et al. 2012

Probing infall and outflow with many sightlines



There are already indications of disk/filament infall and bipolar outflow, based on "stacking" low S/N background galaxy spectra.
(Bordoloi et al. 2012, Kapczak et al. 2012)

Using multiple QSOs on the same galaxy would detect these flows with much higher significance. This becomes more practical with fainter more numerous QSOs and nearer galaxies.