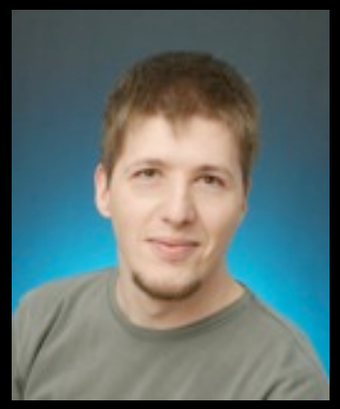
Quasars Probing Quasars (QPQ)





S. Cantalupo (IMPS,UCO)

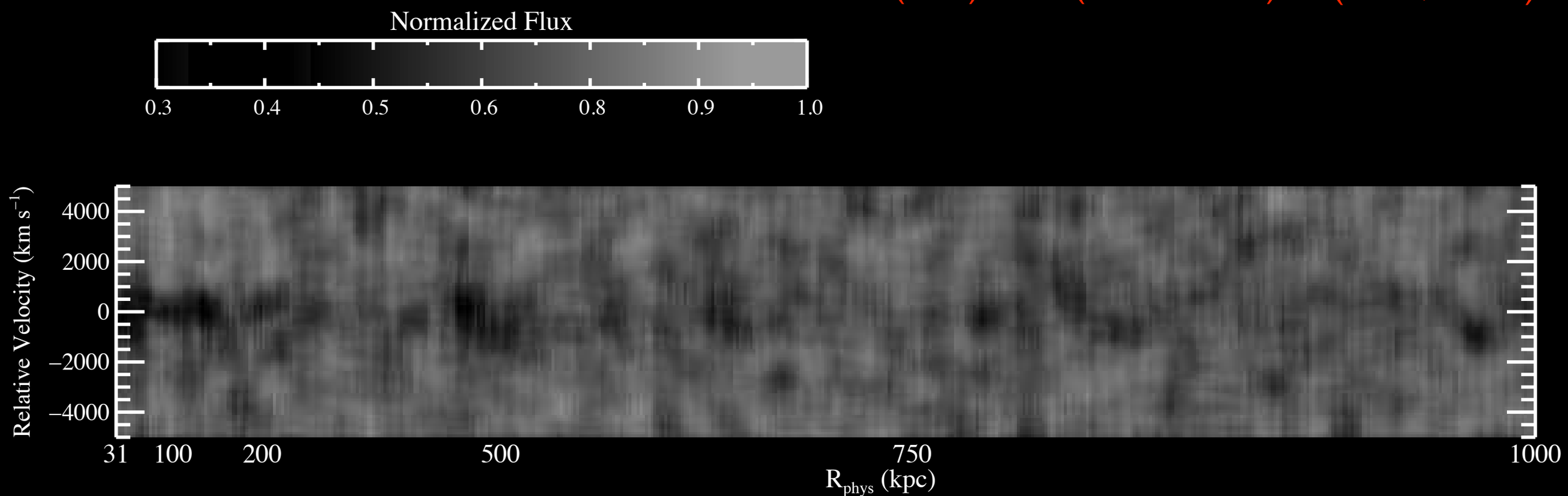
Michele Fumagalli (IMPS,UCSC)

Joseph Hennawi (MPIA)

Rob Simcoe (MIT)

Jessica Werk (IMPS, UCO)

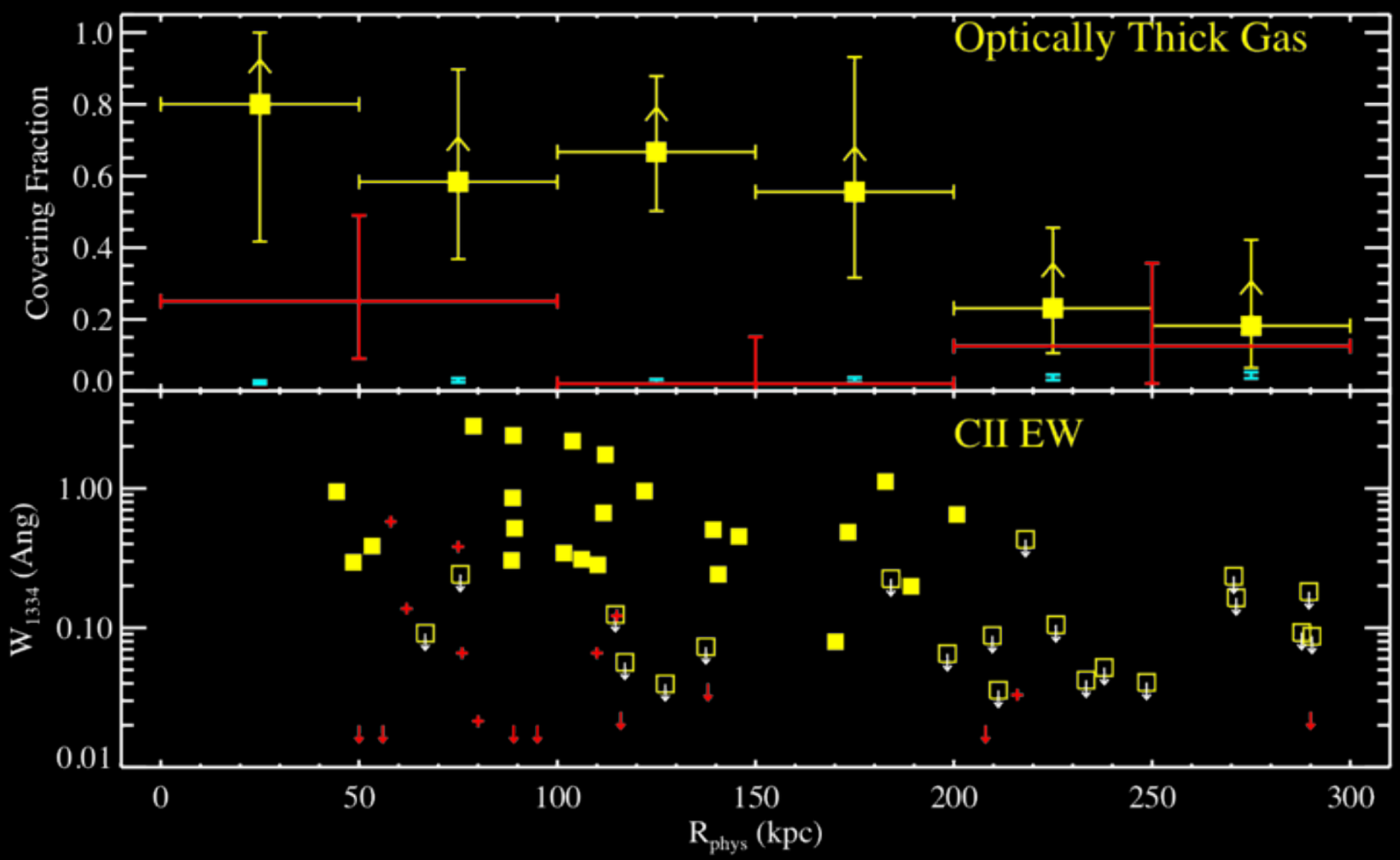
Gabor Worseck (IMPS, UCO)



J. Xavier Prochaska (UCO, UC Santa Cruz)

Inter(galactic+stellar) Medium Program of Studies [IMPS]

The CGM of Massive z~2 Galaxies



yellow: QSOs
red: LBGs

Low-ionization CII 1334 metal line equivalent width

Prochaska, Hennawi, Simcoe 2013
Prochaska+ 13
(aka QPQ5, QPQ6, QPQ7)

J. Xavier Prochaska (UCO, UC Santa Cruz)

Inter(galactic+stellar) Medium Program of Studies [IMPS]

How do galaxies acquire their gas?

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Fresh fuel is required (e.g., DLAs at $z>1$; PHW05)

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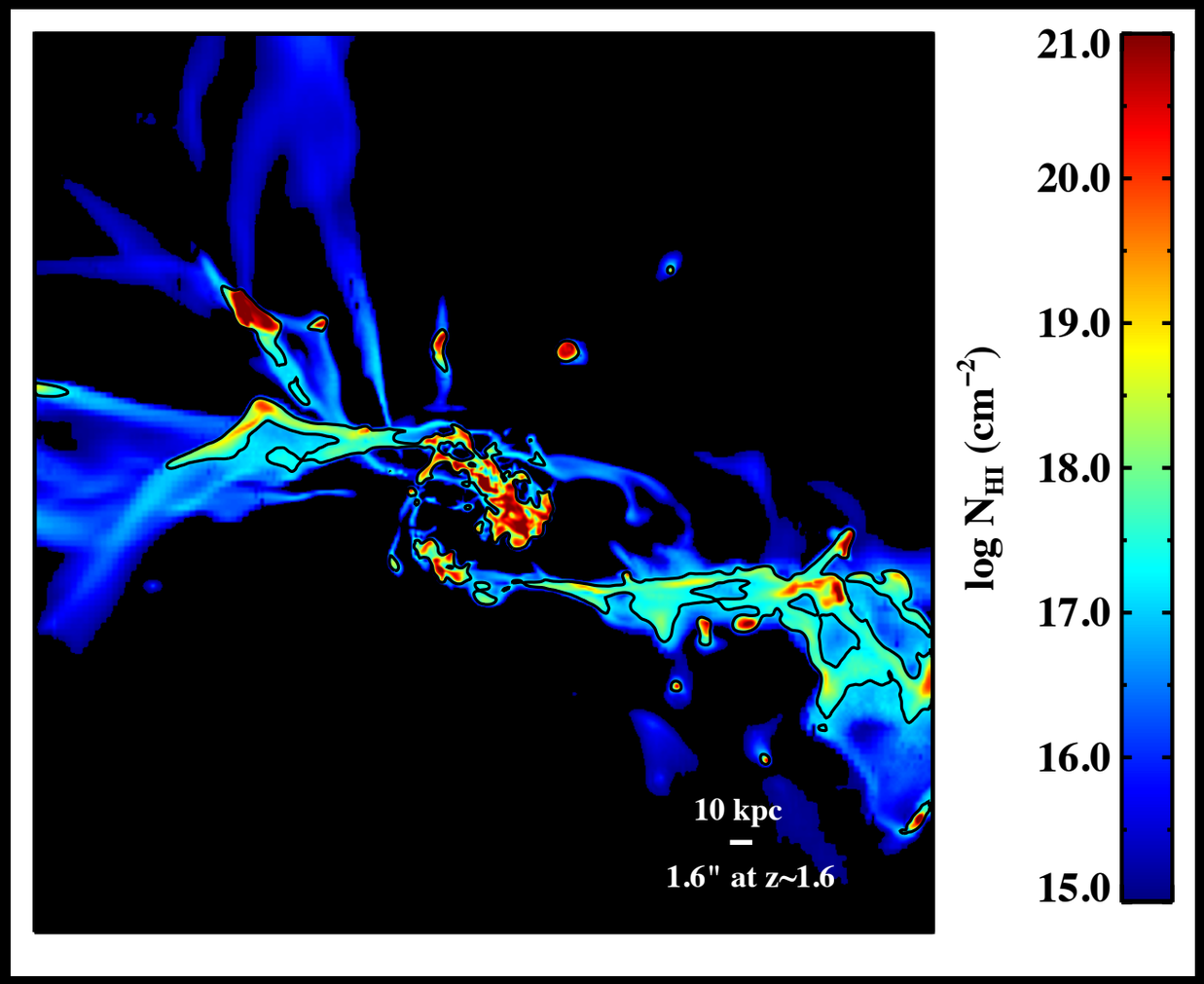

"Cold" stream gas,
e.g. Keres+05, F-G+10, Fumagalli+11

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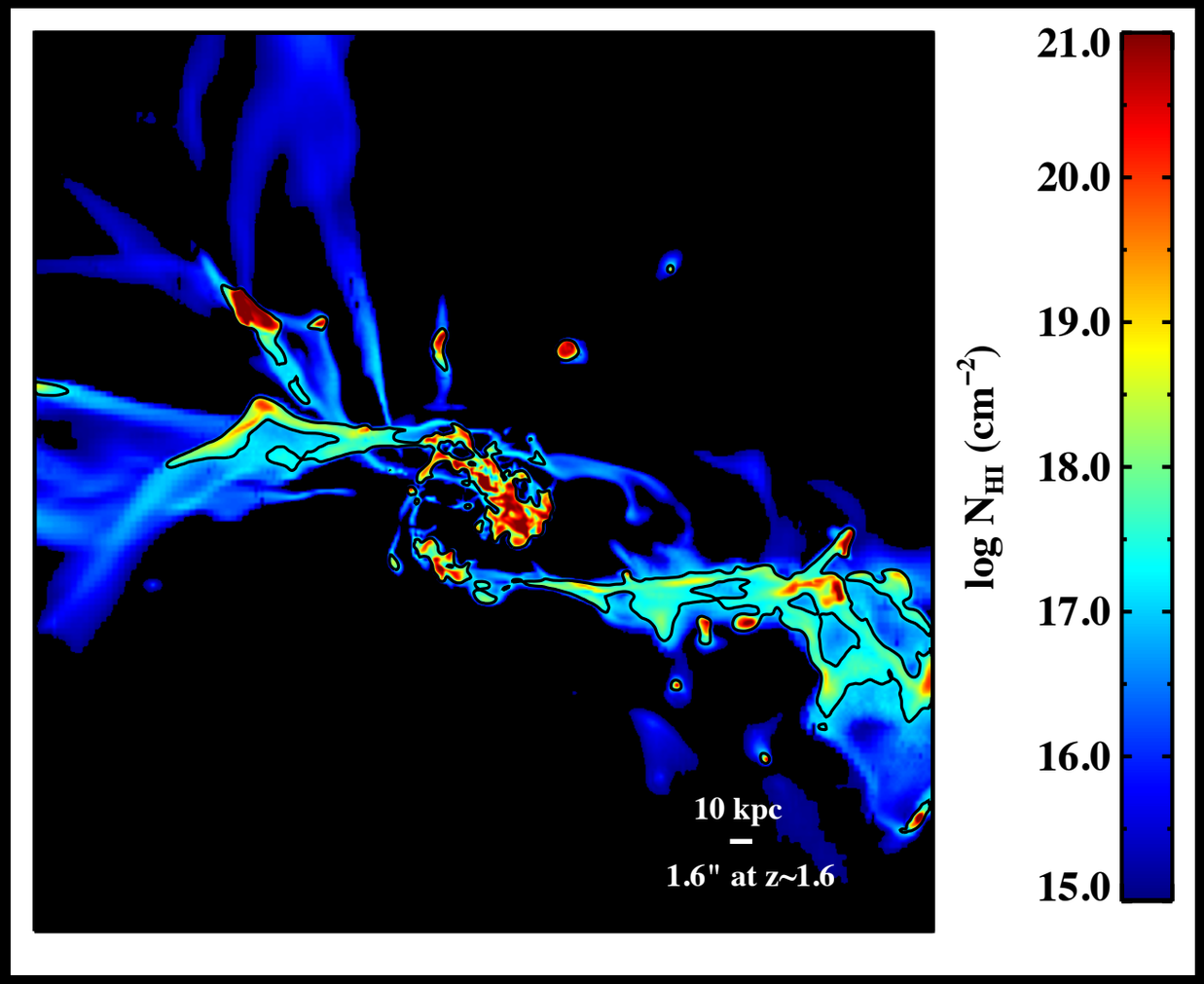

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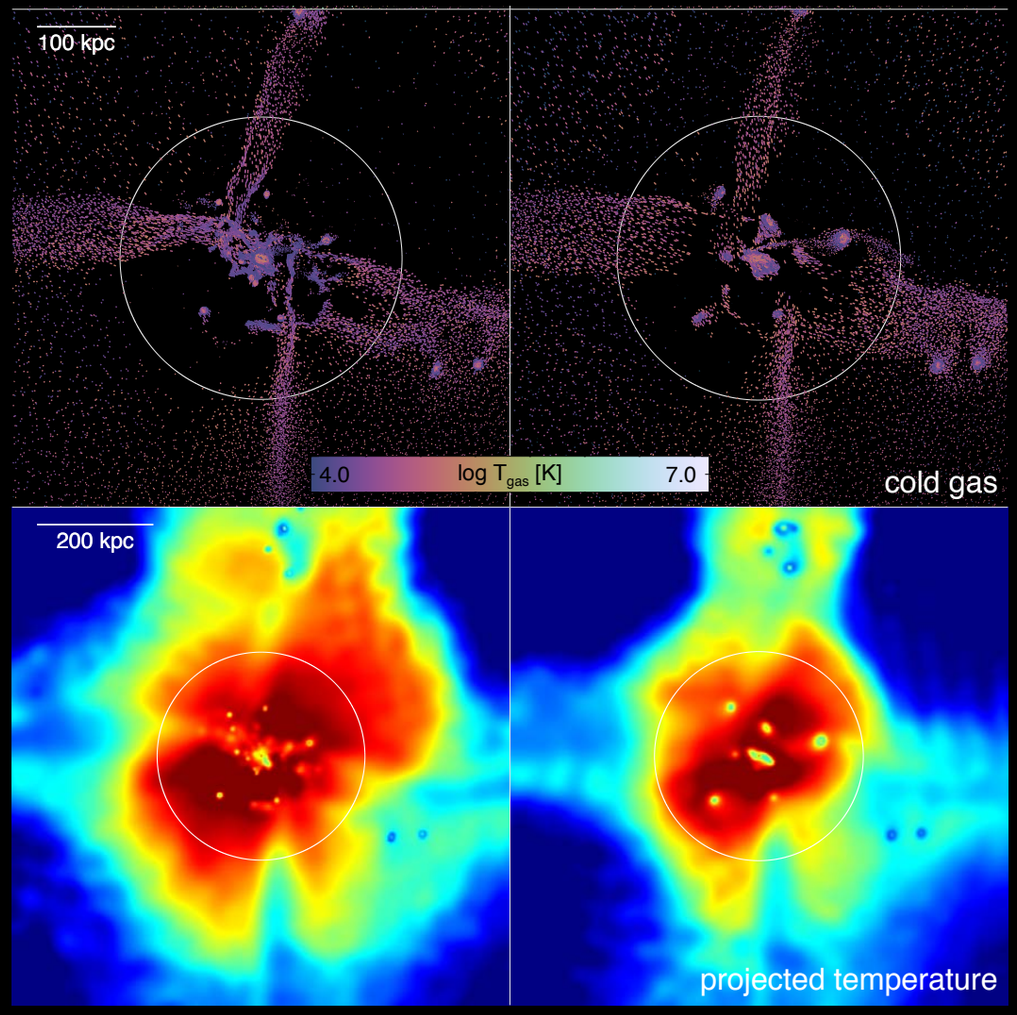

But the picture continues to develop...
e.g. Nelson+13

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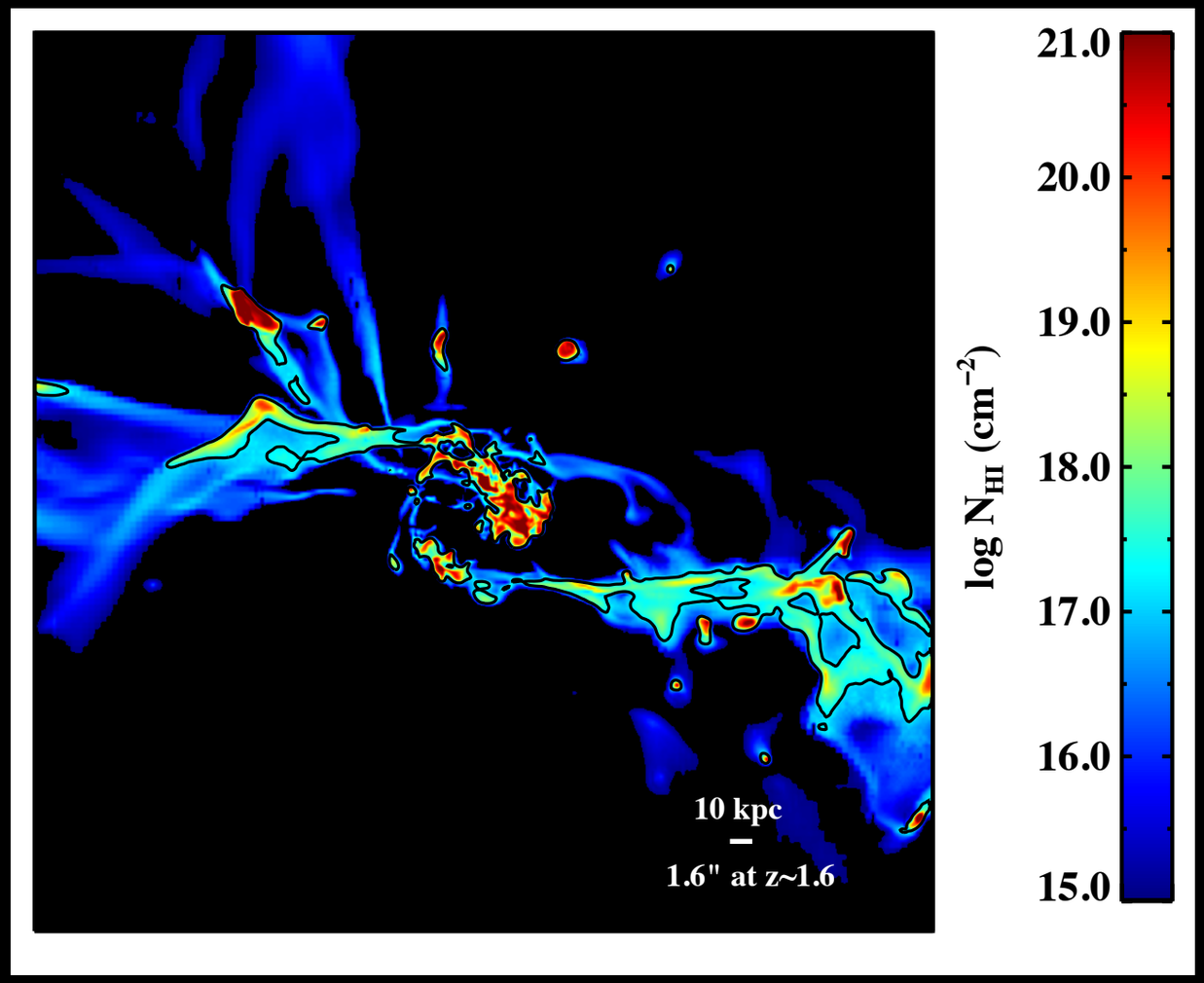
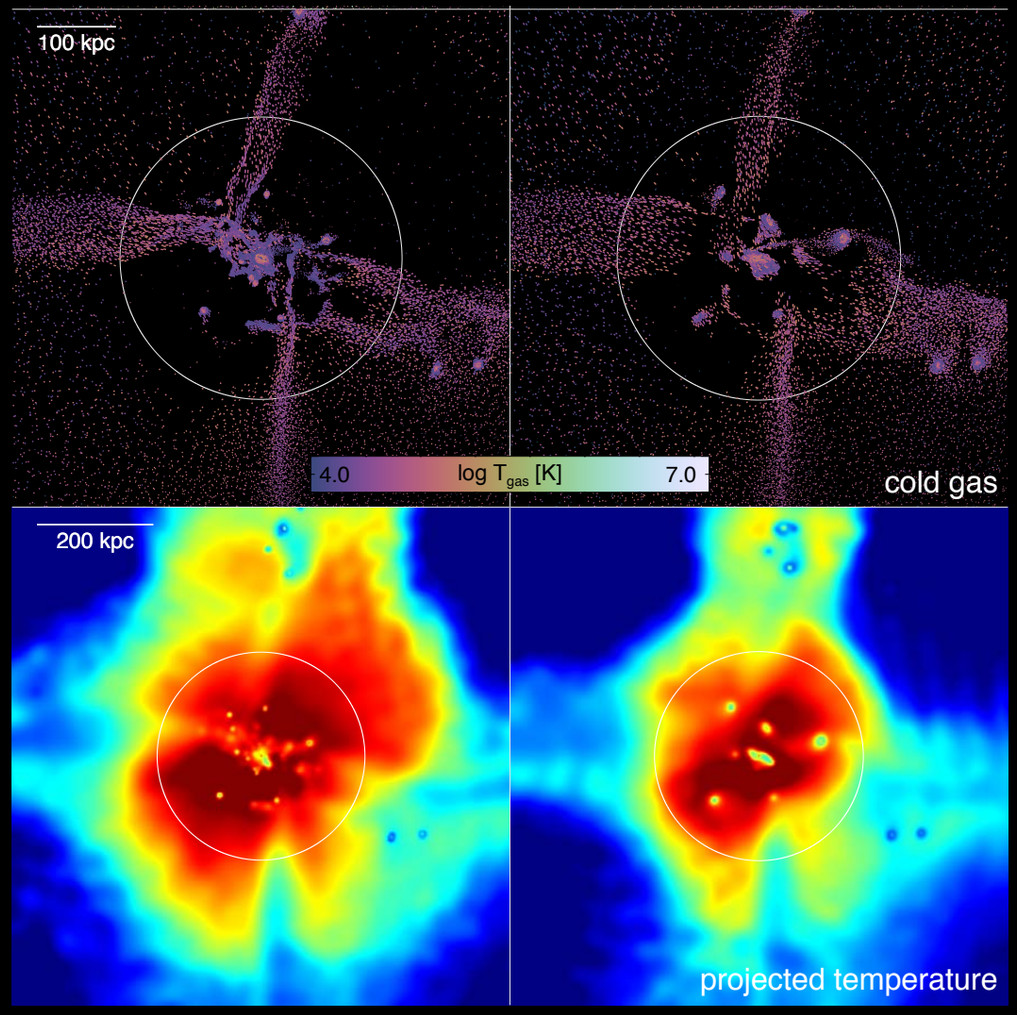




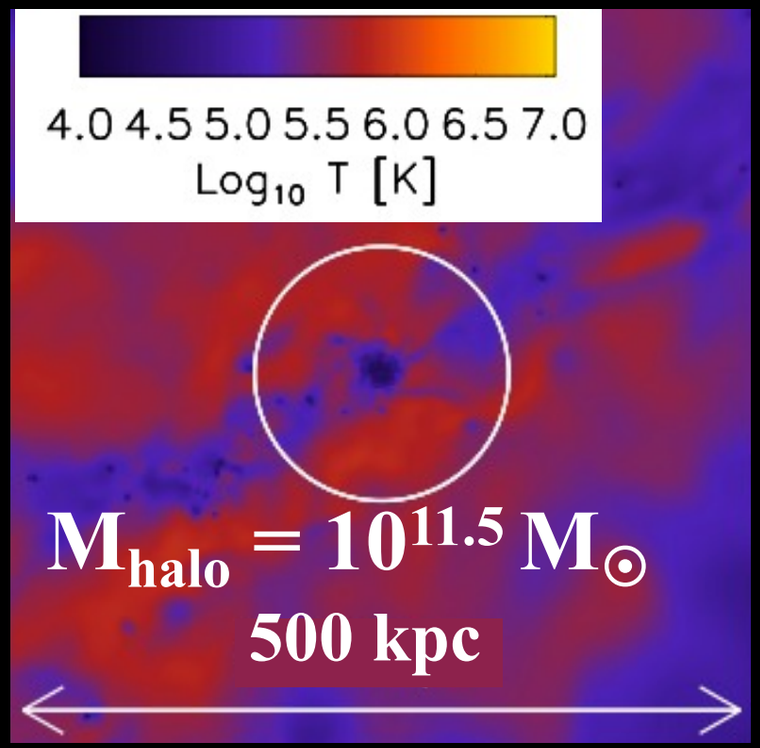
"Cold" stream gas,
e.g. Keres+05, F-G+10, Fumagalli+11

But the picture continues to develop...
e.g. Nelson+13

Theoretical ingredients: Gravity, hydrodynamics (cooling/heating), radiative transfer.

Not needed: Magnetic fields, star-formation, dust?!

What is the halo mass dependence?



SPH; z~2
van de Voort+ 11

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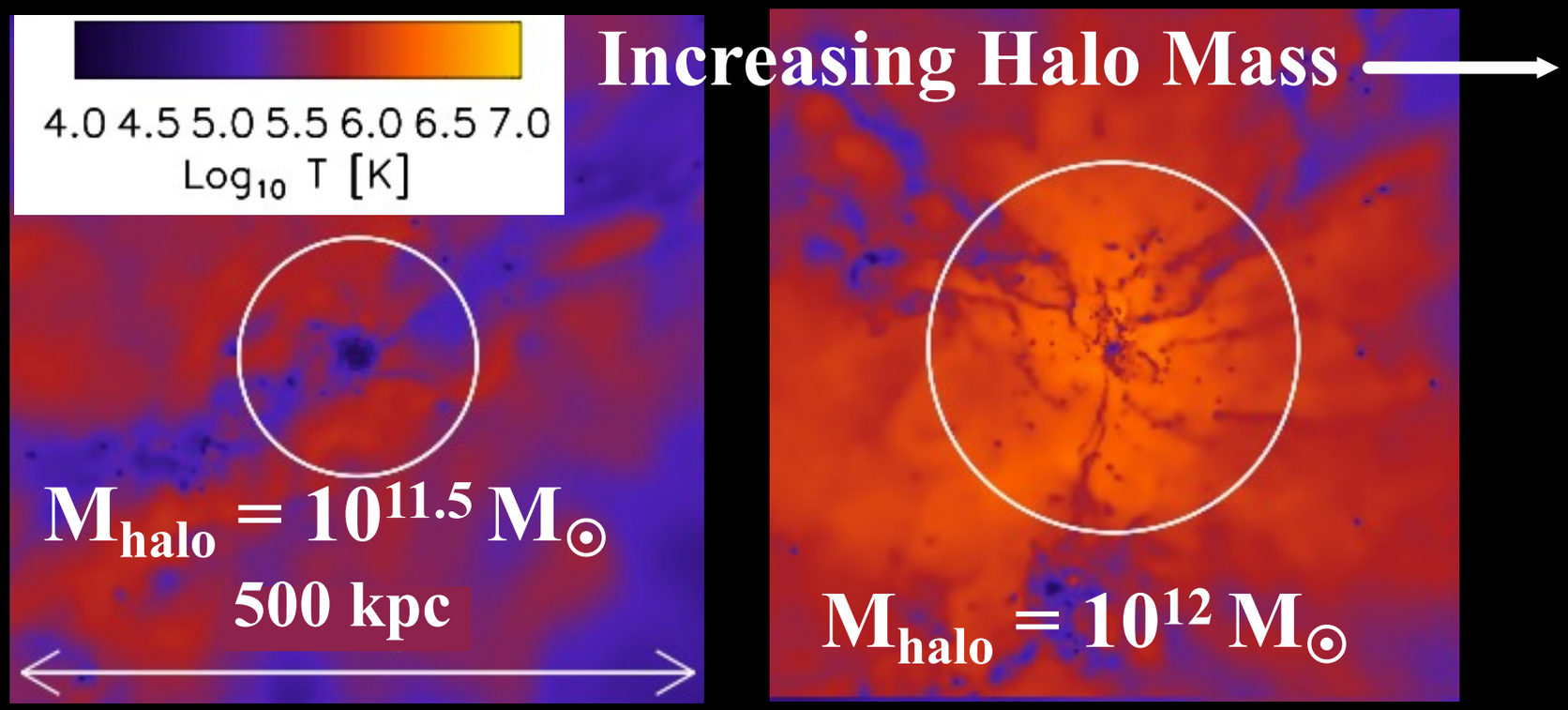

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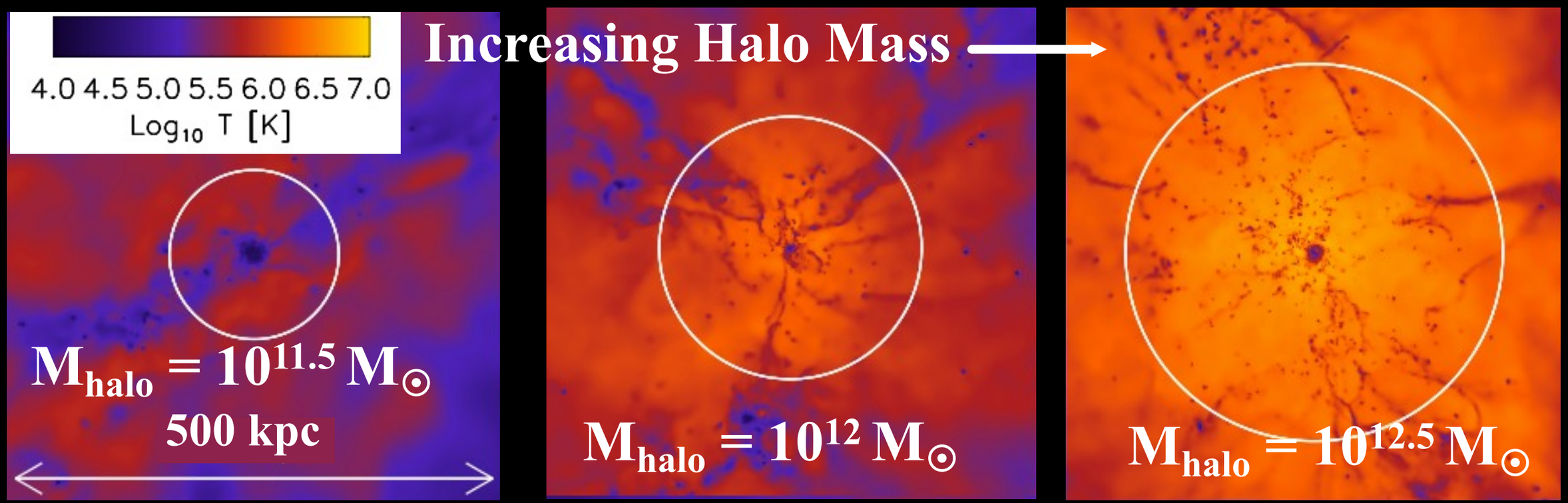

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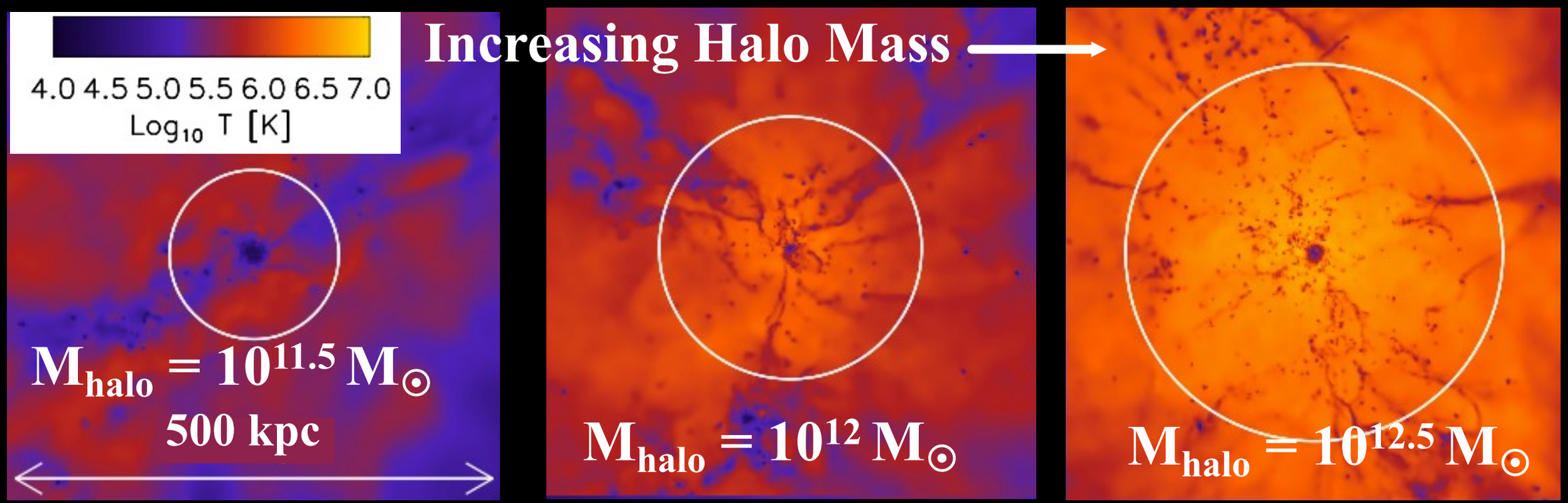


SPH; z~2
van de Voort+ 11

Zeroth-order prediction: More hot (virialized) gas in higher mass halos

Galactic Halo Gas

Galactic Halo Gas

ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1956

ABSTRACT

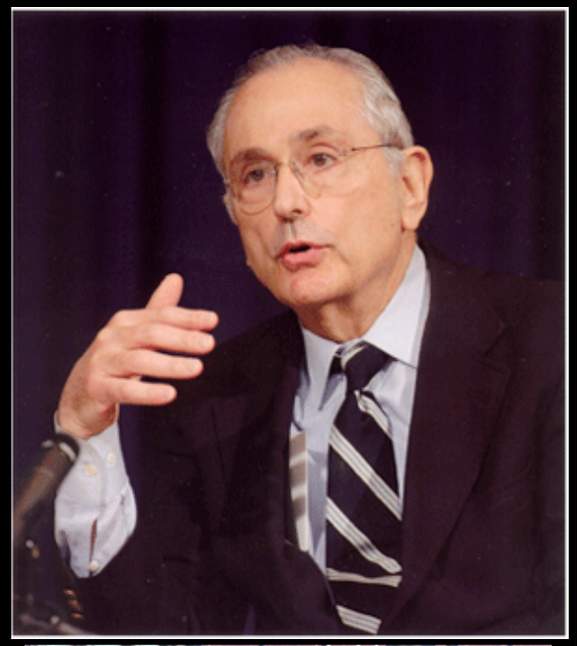
The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

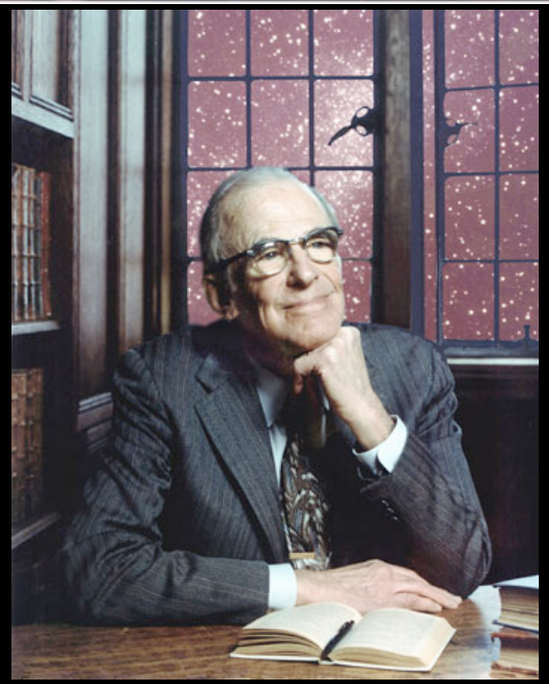
At a temperature of 10^6 degrees K, the electron density in the corona would be $5 \times 10^{-4}/\text{cm}^3$; the extension perpendicular to the galactic plane, 8000 pc; the total number of electrons in a column perpendicular to the galactic plane, about $2 \times 10^{19}/\text{cm}^2$; the total mass, about $10^8 M_\odot$. The mean free path would be 4 pc, but the radius of gyration even in a field of 10^{-15} gauss would be a small fraction of this. Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

Radiative cooling at 10^6 degrees would dissipate the assumed thermal energy in about 10^9 years. Cooling by conduction can apparently be ignored, especially since a chaotic magnetic field of only 10^{-15} gauss will sharply reduce the thermal conductivity At 3×10^6 degrees, near the maximum value consistent with confinement by the Galaxy's gravitational field, radiative cooling is unimportant, and a corona at this temperature might be primeval. The energy source needed at the lower temperatures may be provided by material ejected at high speed from stars or possibly by compressional waves produced by the observed moving clouds Condensation of cool matter from the corona may perhaps account for the formation of new spiral arms as the old ones dissipate.

Within recent years it has become well established that interstellar gas clouds are found within the "spiral" arms of our Galaxy. Interstellar absorption lines, H II regions around early-type stars, and the 21-cm line of neutral hydrogen all give concordant evidence. The mean density of hydrogen atoms within a spiral arm appears to be about $1/\text{cm}^3$. However, the density distribution is nonuniform. According to the present picture—summarized by Spitzer (1954)—within a typical cloud of neutral hydrogen, where the temperature is about 100° K, the density is about 10 atoms/cm^3, as shown by Strömgren (1948). Between the clouds the density is less by a factor of perhaps 100, and the temperature is presumably greater by the same factor. The interstellar gas may be assumed to be at a nearly uniform pressure within the galactic plane, this pressure amounting to 10^{-13} dynes/cm^2.

Galactic Halo Gas



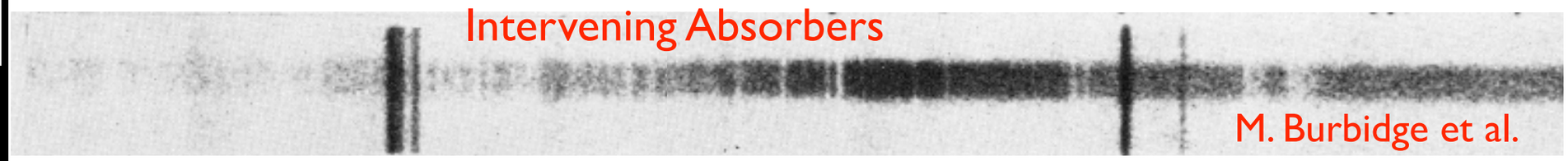


ABSORPTION LINES PRODUCED BY GALACTIC HALOS

JOHN N. BAHCALL*
Institute for Advanced Study

AND

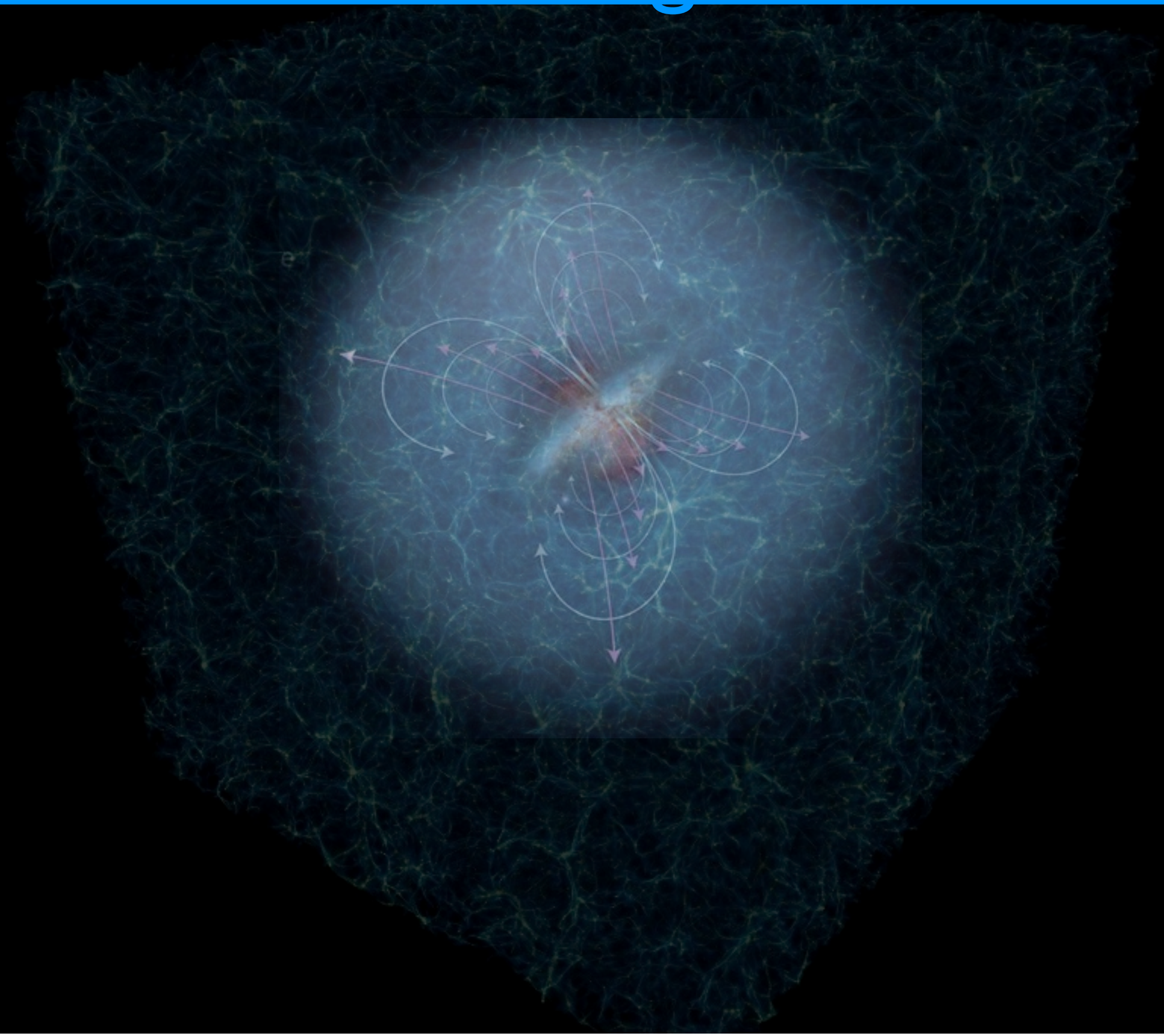
LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1969



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).

Proposed that the QSOALS then known arose in extended galaxy halos: R = 100 kpc versus the 10-20 kpc then believed based on optical and radio measurements.

What is the Circumgalactic Medium?



What is the Circumgalactic Medium?

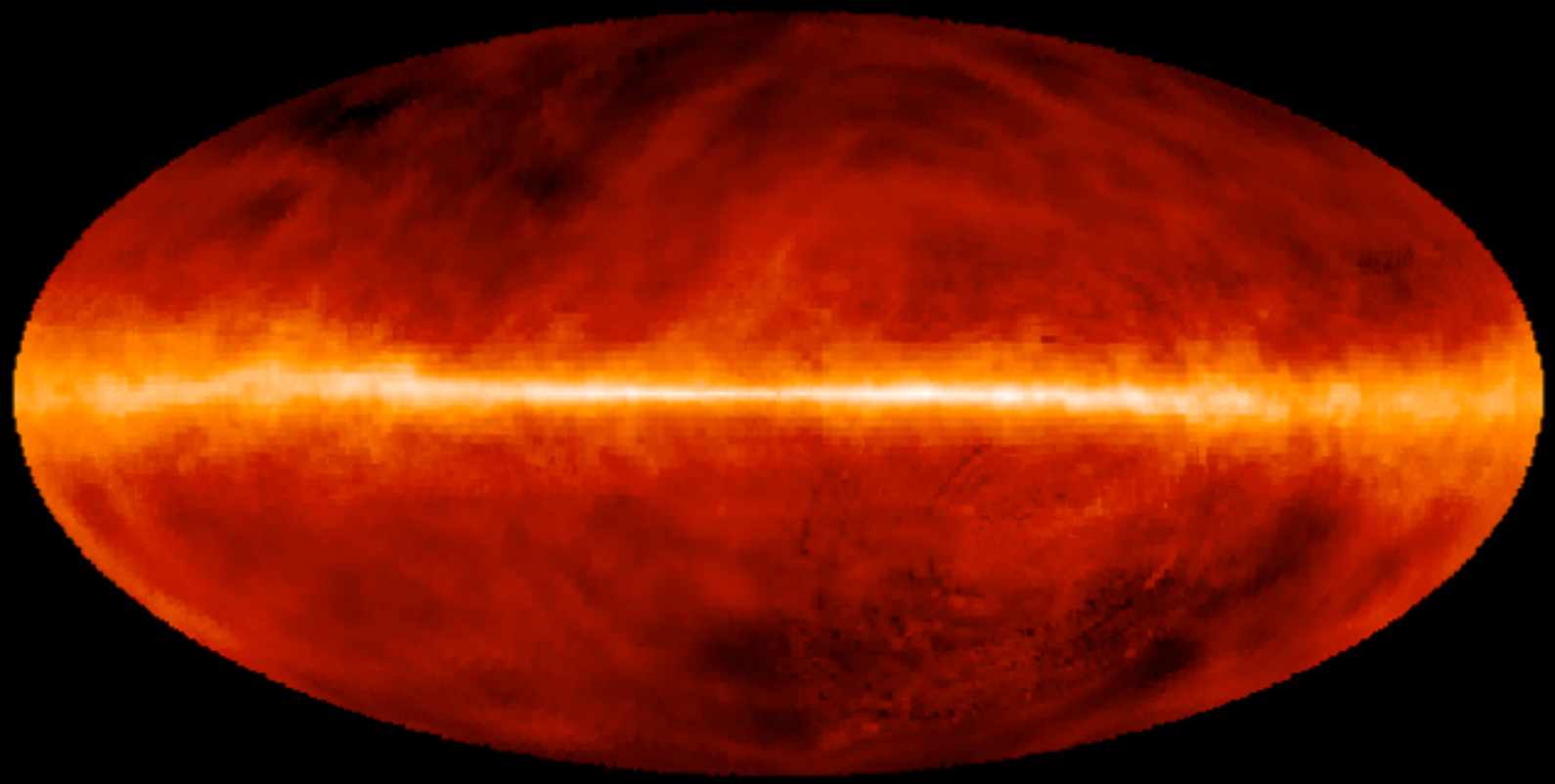
Let me offer a semi-quantitative definition.

The Interstellar Medium (ISM)

$T < 10^4$ K

$\delta\rho/\rho > 10^3$

$\Delta R < 10$ kpc



ISM: The gas, metals, and dust that fill the space between stars in a galaxy.

The Intergalactic Medium (IGM)

$T \sim 10^4$ K

$\delta\rho/\rho < 10$

$\Delta R > 300$ kpc

Norman+10

IGM: The diffuse and highly ionized gas that permeates the volume between (and far from) galaxies.

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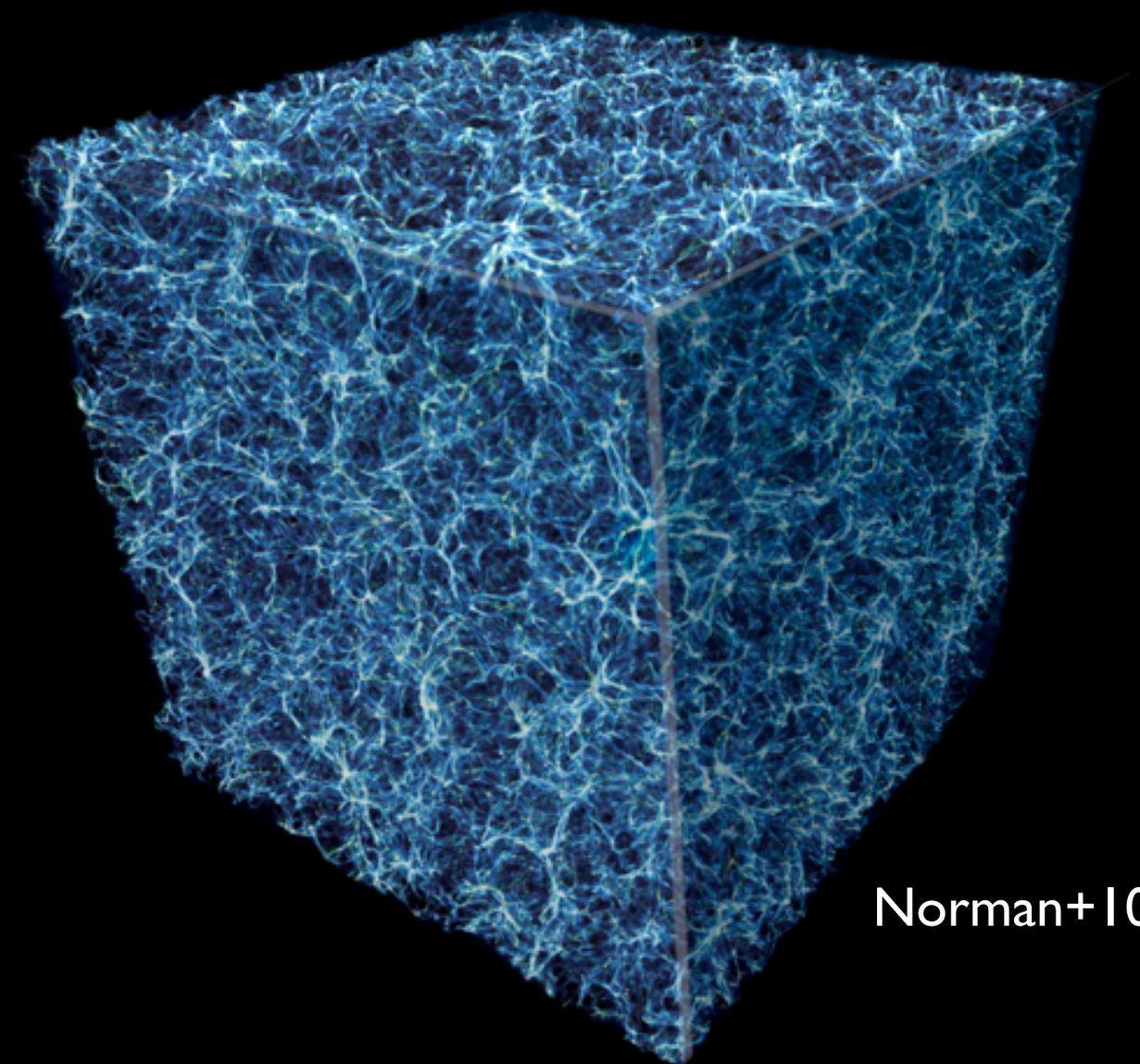

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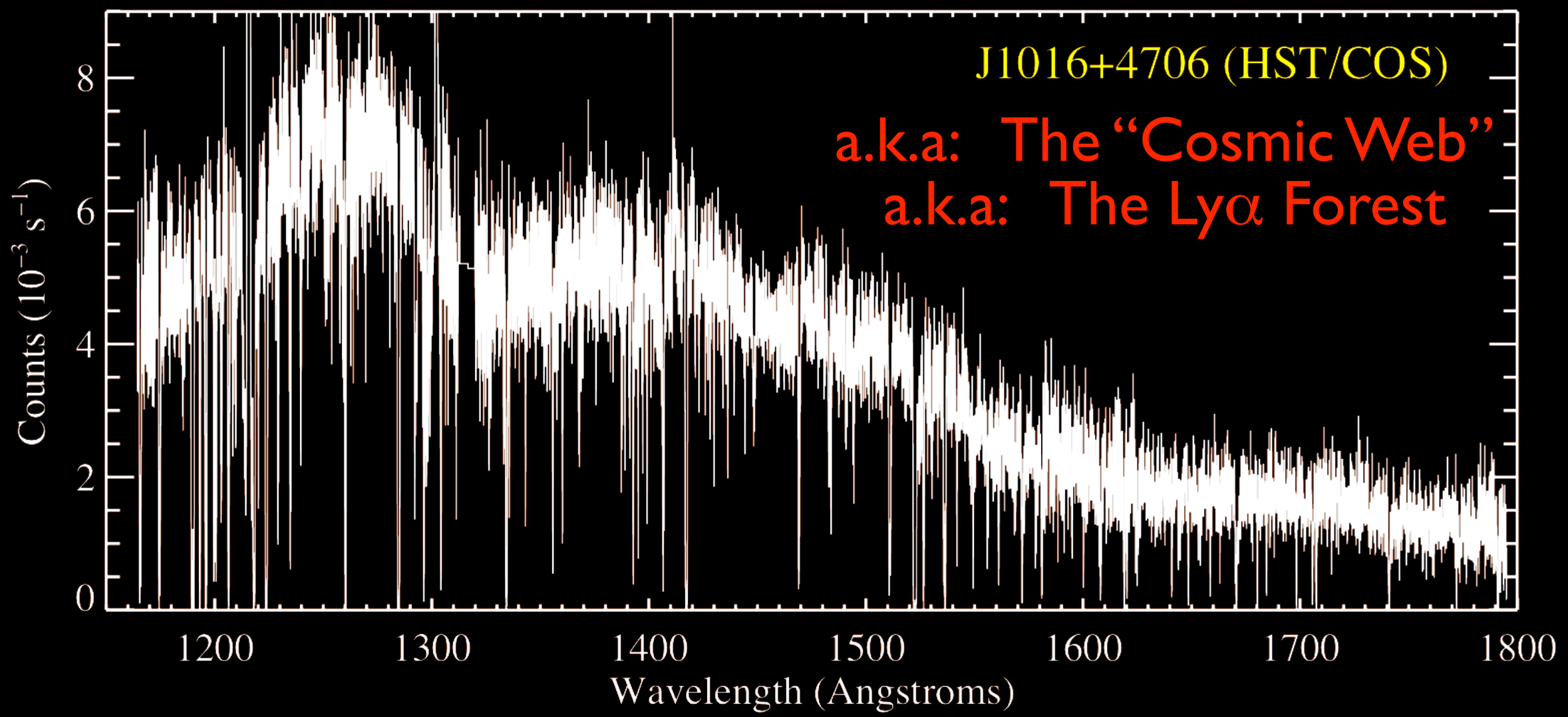


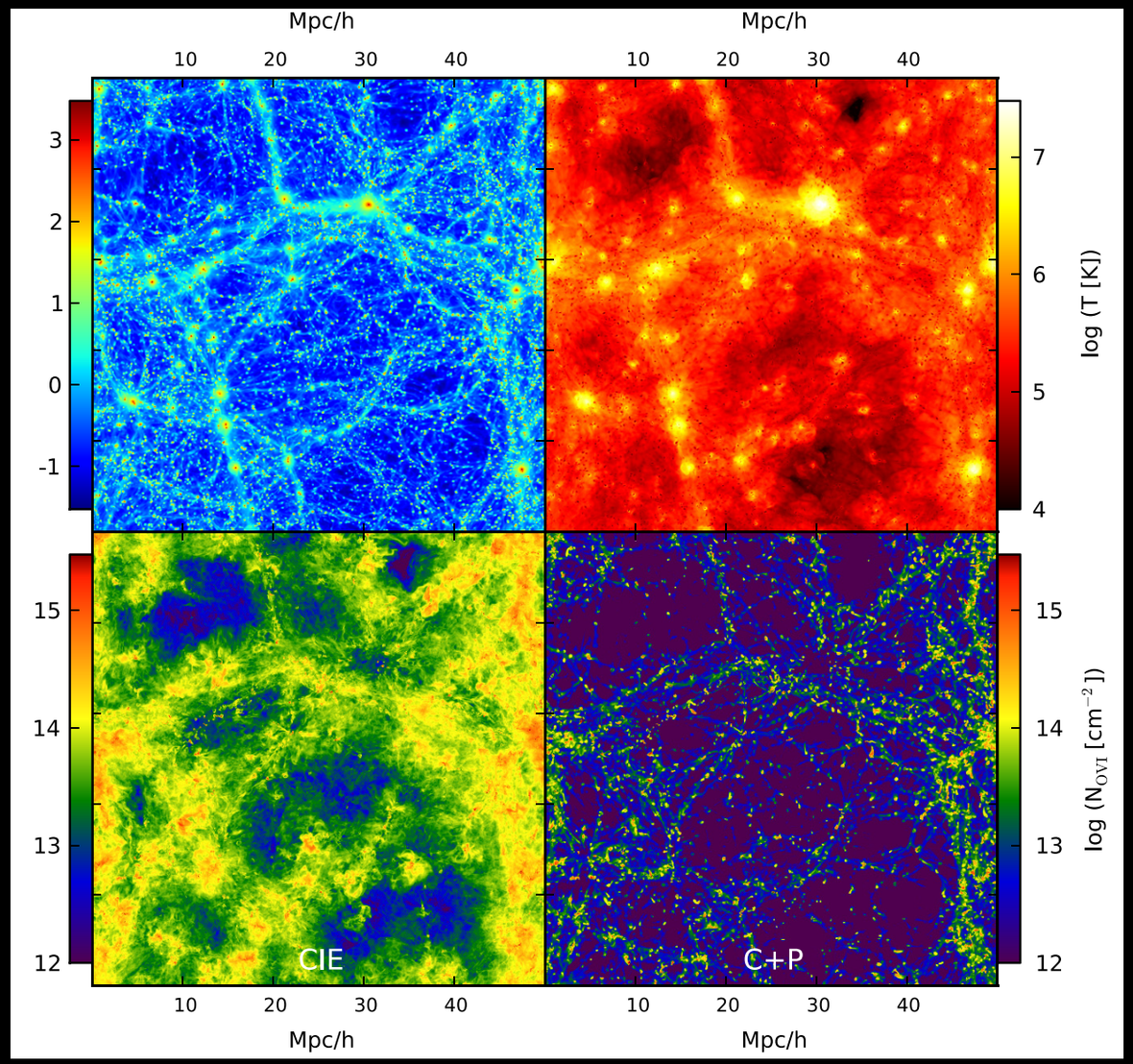
Old-school: Any absorption lines in QSO spectra

The Warm-Hot Ionized Medium (WHIM)

$T > 10^5$ K

$\delta\rho/\rho < 10$

$\Delta R > 1$ Mpc



Cen+Ostriker 97
Smith+ 11

WHIM: The shock-heated and highly ionized gas that permeates the volume between (and far from) galaxies.

Strictly speaking, this is also the IGM.

The Intracluster Medium (ICM)

$T > 10^6$ K

$\delta\rho/\rho = 10^2 - 10^3$

$\Delta R = 0.1 - 1$ Mpc

ICM: The gas, metals, and dust that fill the space between galaxies in a cluster.

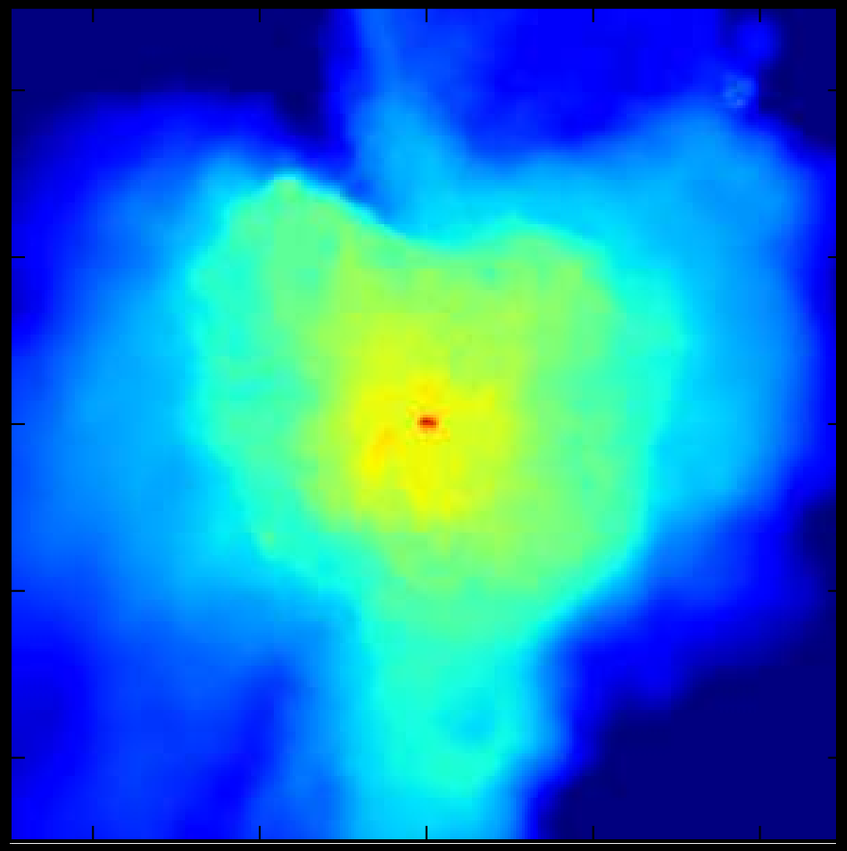
The Circumgalactic Medium (CGM)

$T = 10^4 - 10^6$ K

$\delta\rho/\rho = 10 - 10^3$

$\Delta R = 10 - 300$ kpc

Chynnoweth+08

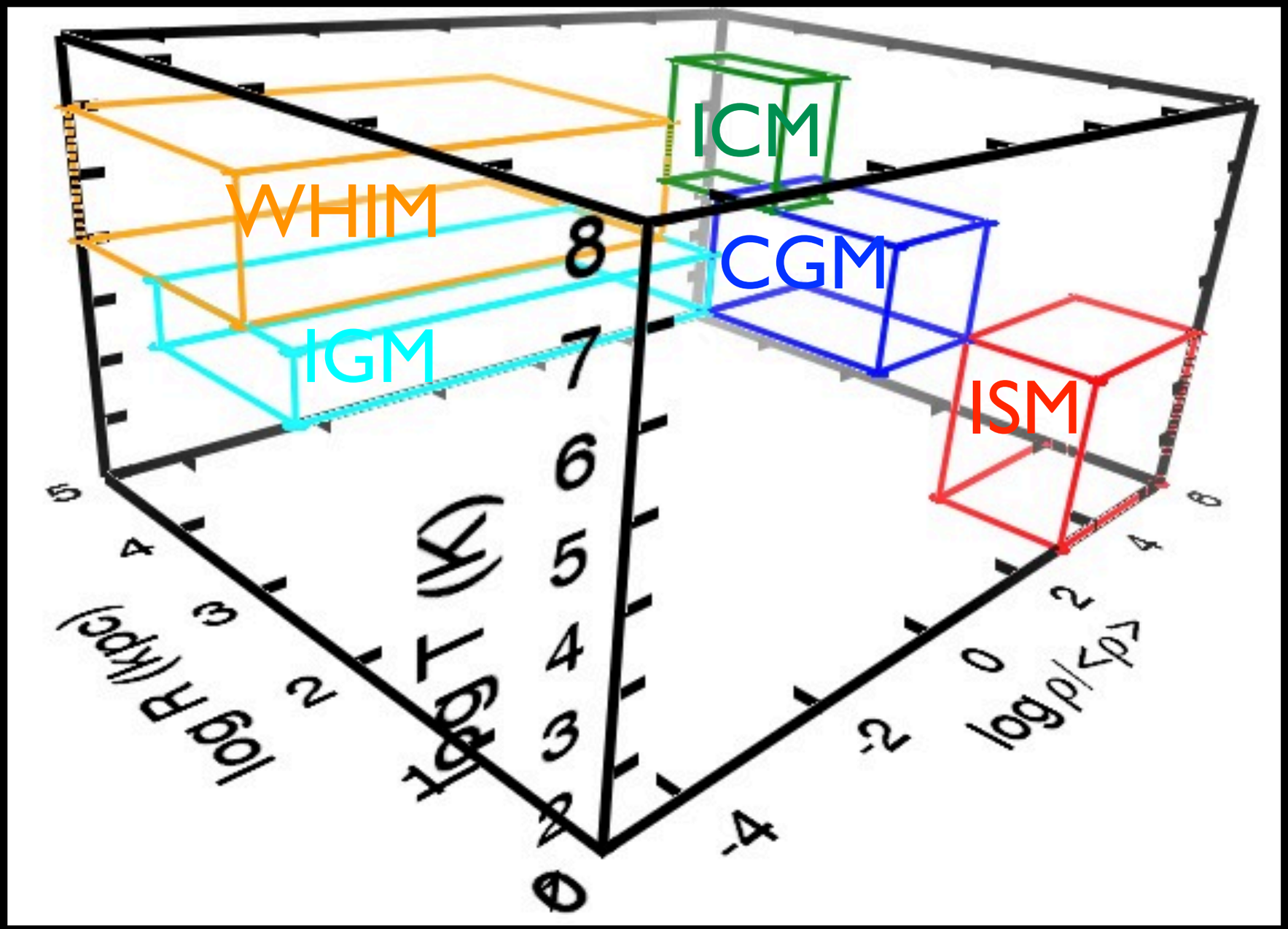


Stinson+12
Ford+12

CGM: The gas, metals, and dust that fill the space in (and around) a galaxy's dark matter halo.

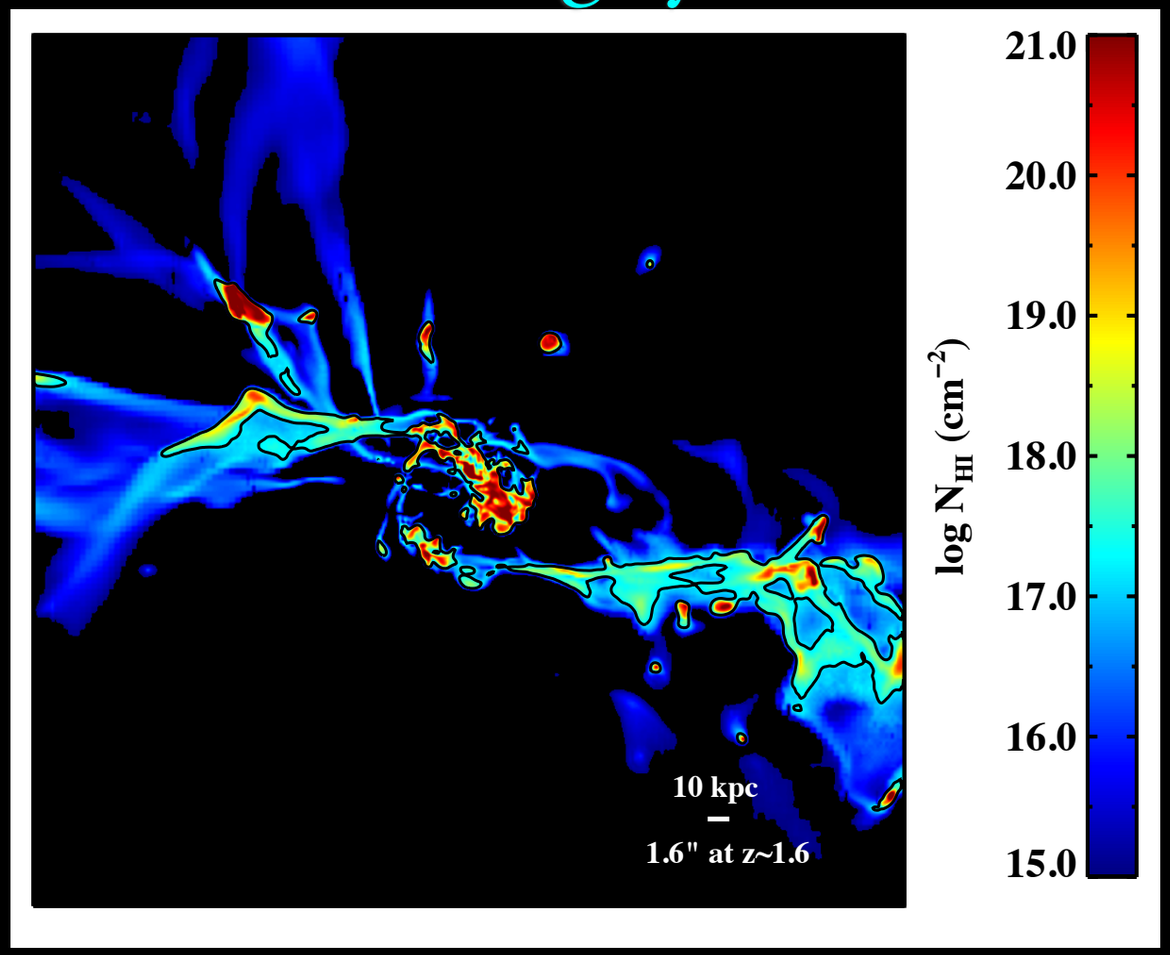
The Mediums

v1.0



The Circumgalactic Medium (CGM)

Diffuse gas, including metals, in the halos of galaxies (and beyond).
(Largely bound to the DM Halo)



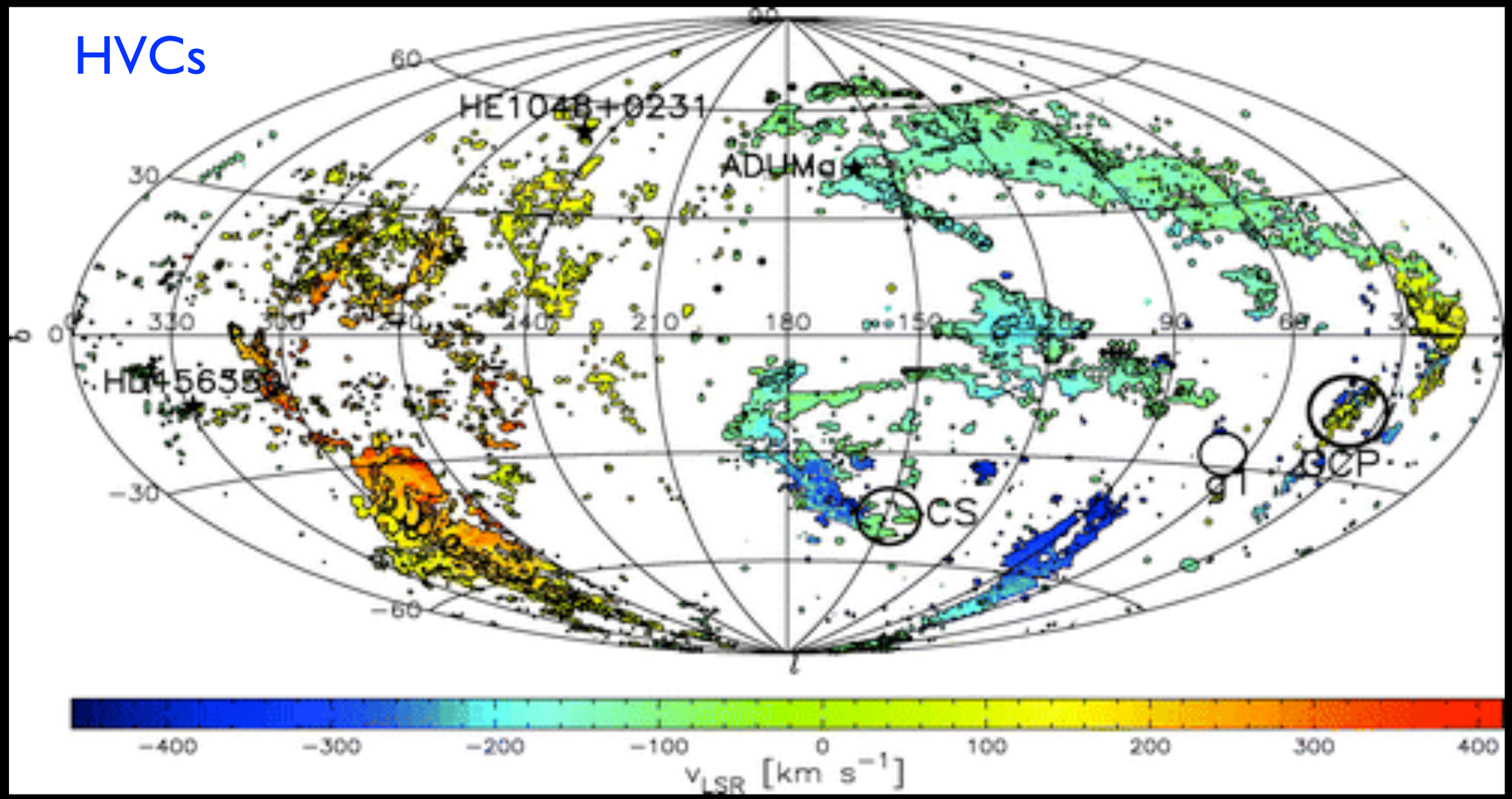
"Cold" stream gas, e.g. Fumagalli+11

Do all galaxies have a CGM?
How far does it extend?
Is the CGM enriched in metals?
What is its baryonic contribution?

Galactic-scale outflows; e.g. Weiner+09, Rubin+12

Does this medium feed galaxies?
Is there a warm/hot phase?
How does the CGM connect to feedback processes?

The Circumgalactic Medium at z=0

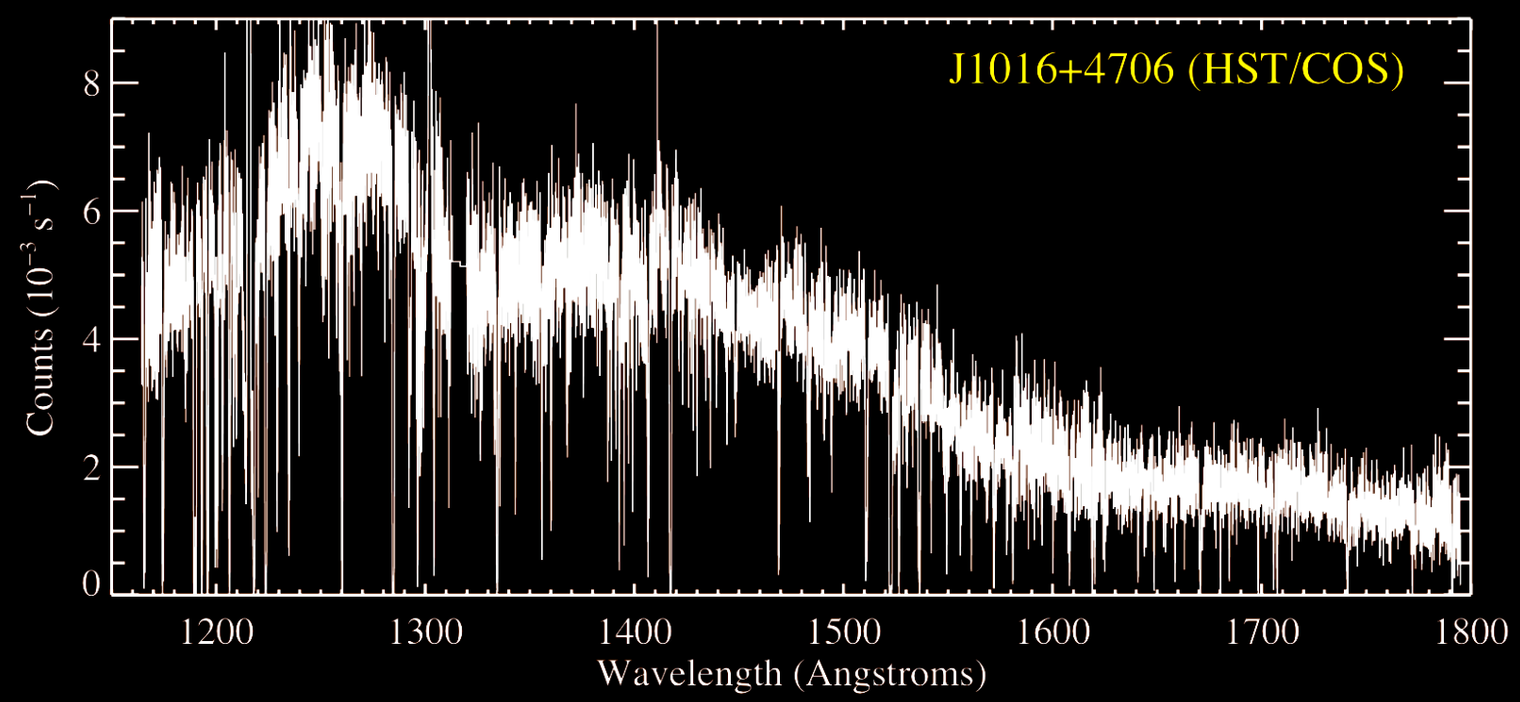


Wakker+08; Putman+11; Lehner&Howk 11

The Milky Way is surrounded by a cool, diffuse, HI complex of clouds, traced by 21cm emission. This gas may be fueling current star-formation.

The Circumgalactic Medium at z>0.001

Chynnoweth+08



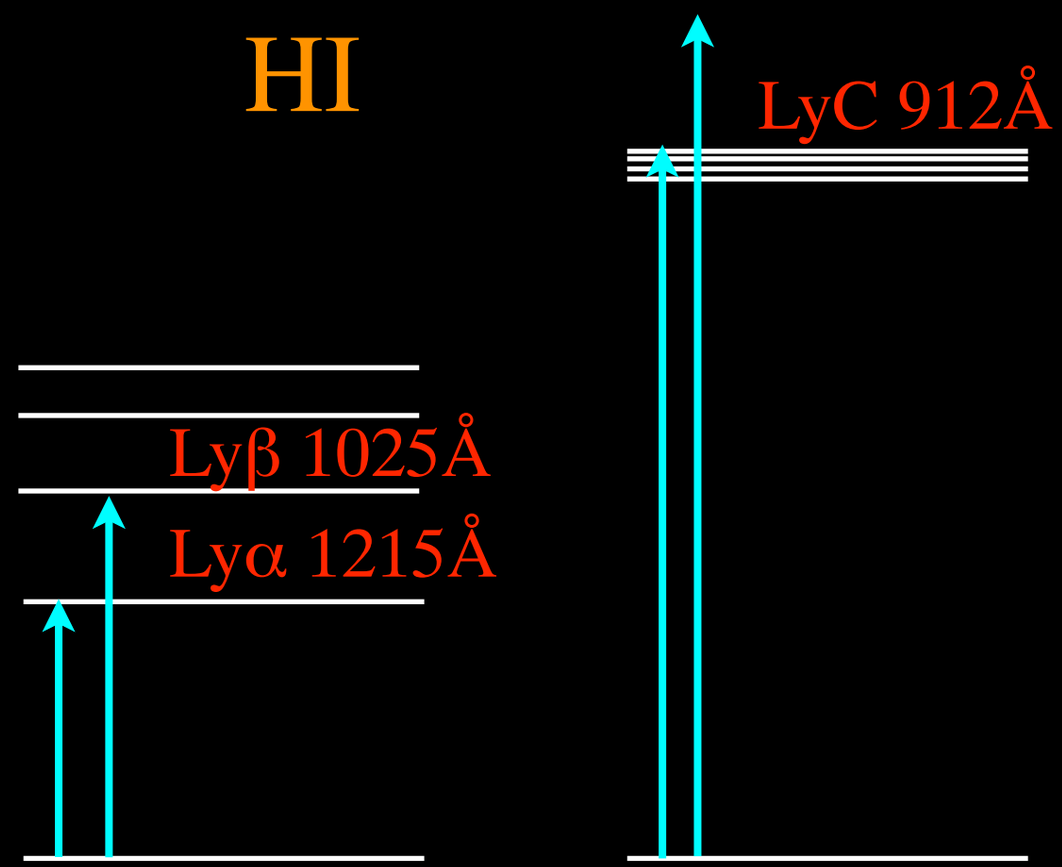
Tumlinson+10

The CGM is very difficult (too diffuse) to trace in emission beyond the Local Group.

Driven to absorption-line techniques which are orders of magnitude more sensitive.

(UV) CGM/IGM Diagnostics

$\Delta E \sim 1$ Ryd



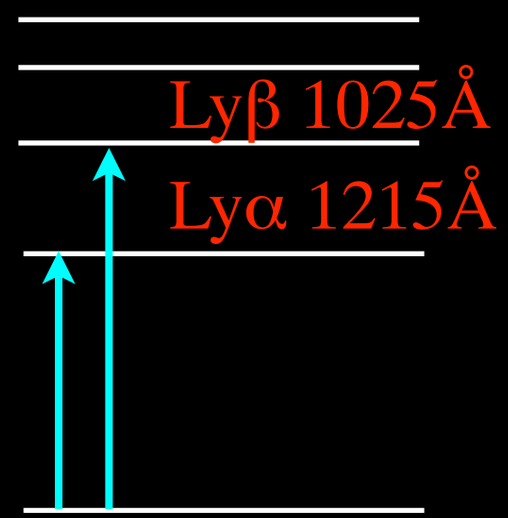
Lyman Series
Radiatively excited
Also follow recomb.

Lyman Limit
Photoionization

(UV) CGM/IGM Diagnostics

$\Delta E \sim 1$ Ryd

HI



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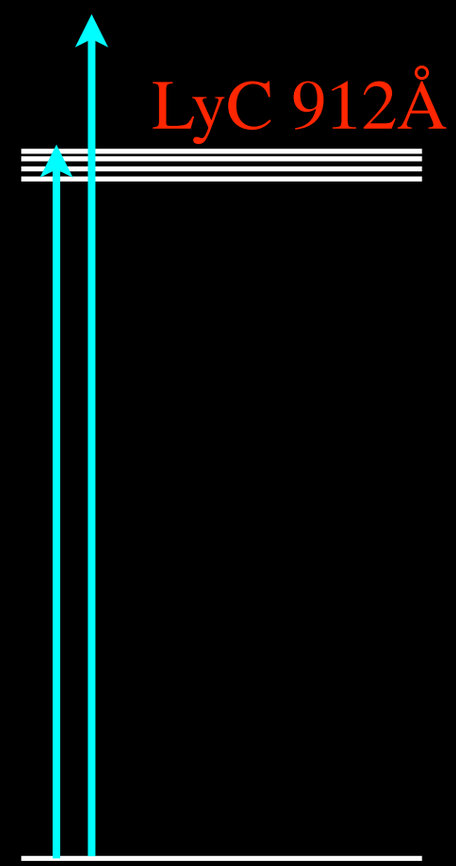


Lyman Limit
Photoionization

Metals (Resonance)

High { NeVIII λλ 770, 780 Å
OVI λλ 1031, 1307Å

High { SiIV λλ 1393, 1402Å
CIV λλ 1548, 1550Å

Inter. { CIII λ 977Å
SiIII λ 1206Å

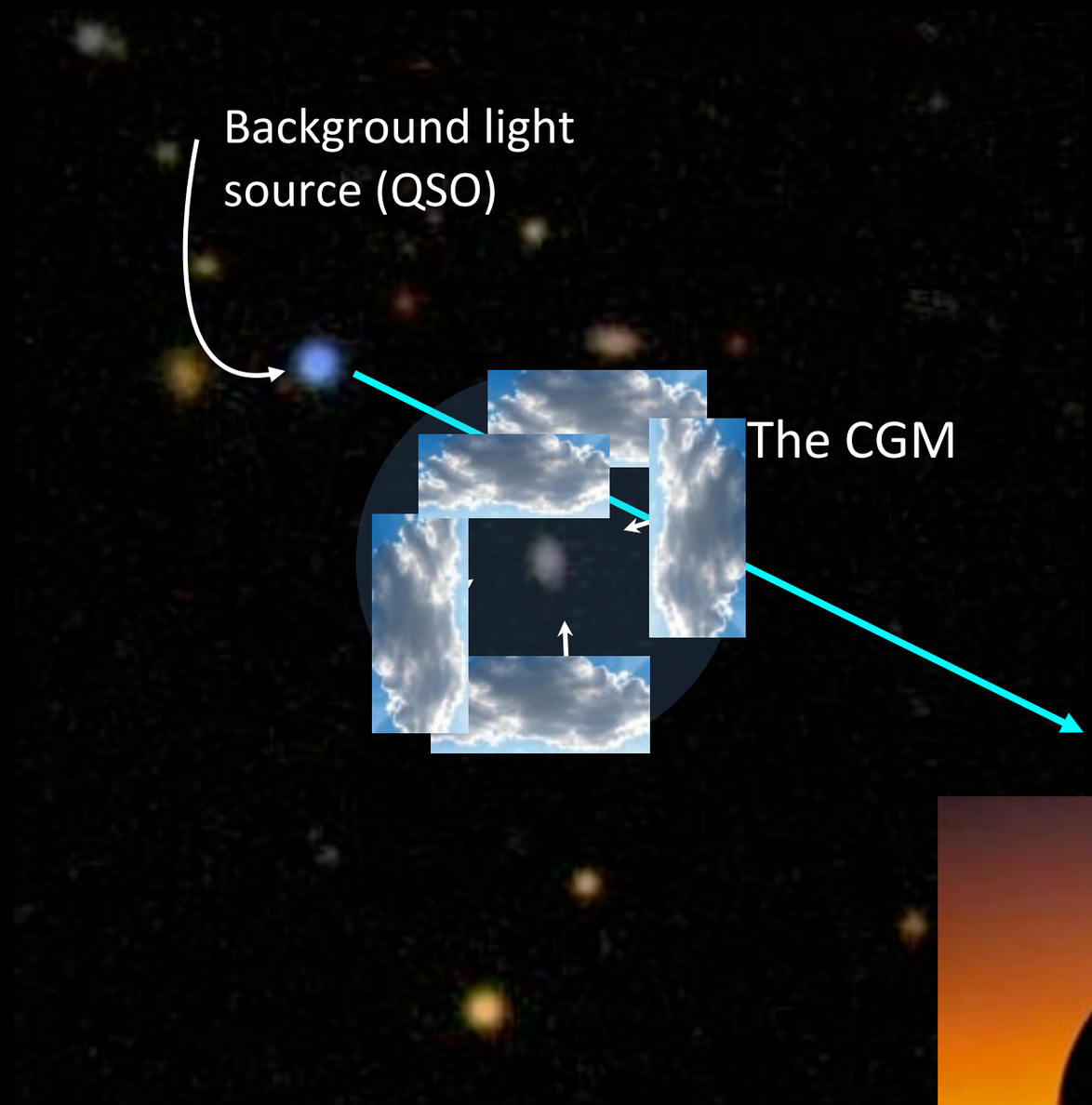
Low { CII λλ 1036, 1334Å
SiII λλ 1260, 1304, 1526Å
MgII λλ 2796, 2803Å

Low { CI λλ 1560, 1656Å

Probing the CGM of z~0 L* Galaxies

The "COS-Halos" Survey

Tumlinson, JXP, Werk, Thom, Tripp, Peeples, Ford, Dave, etc.

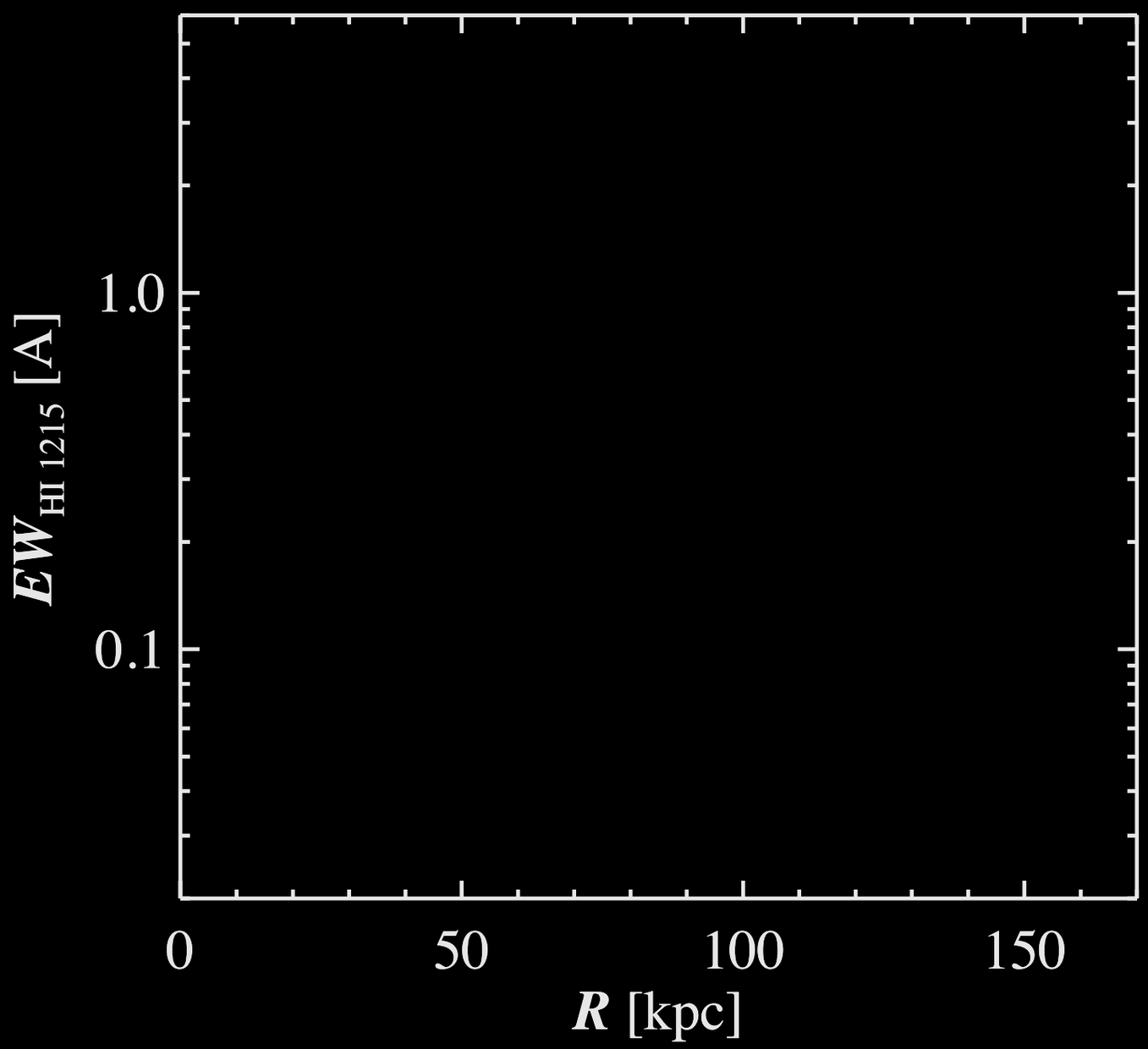


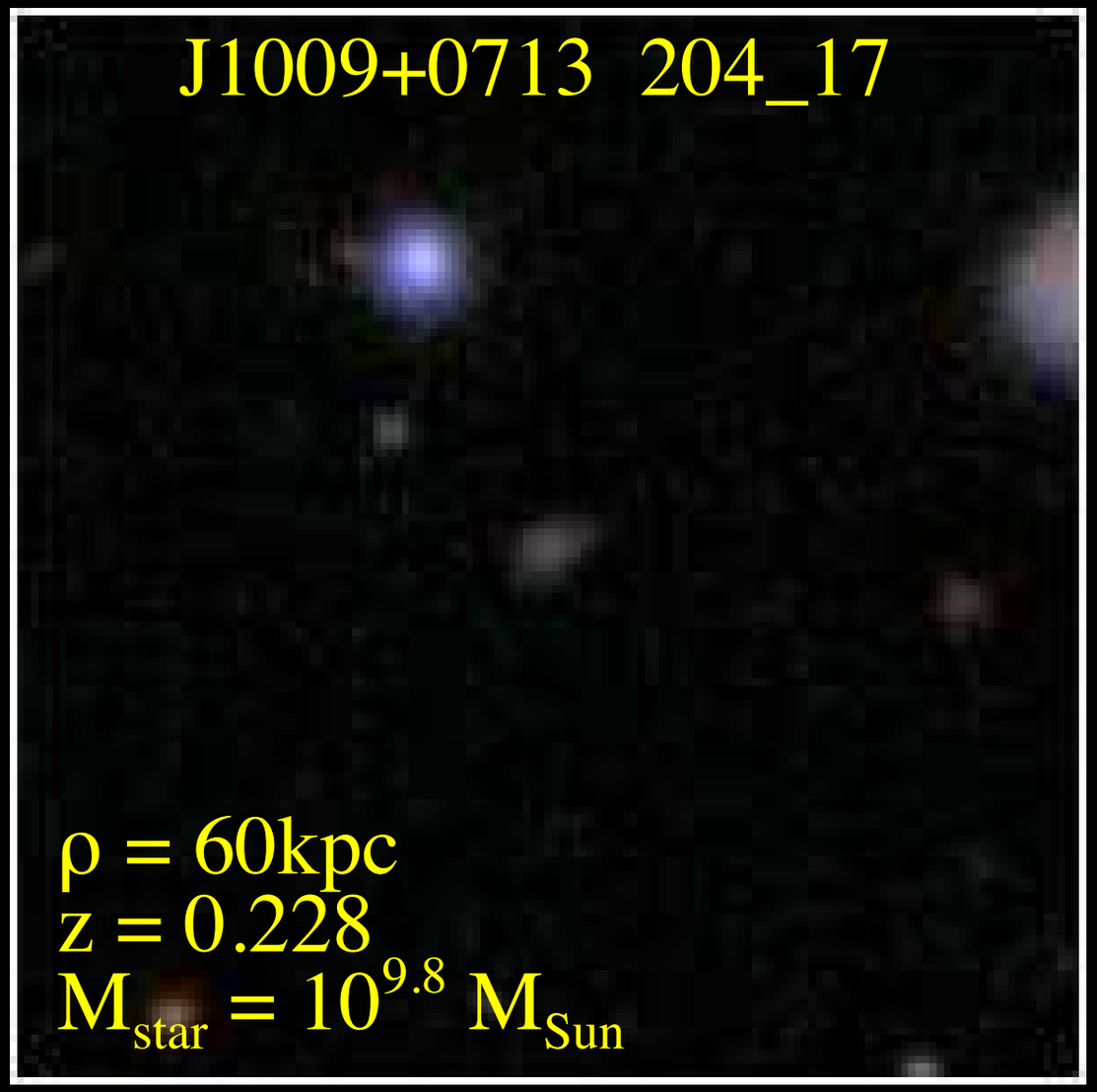
39 QSO sightlines in 134 HST orbits, and 3 Keck nights;
67 galaxy spectra in 3 Keck nights

The Circumgalactic Medium at z~0

Thom+12
Tumlinson+12
Werk+13

COS-Halos (L~L*, z~0 galaxies)
SDSS; GALEX
HST/COS; Keck/HIRES,LRIS





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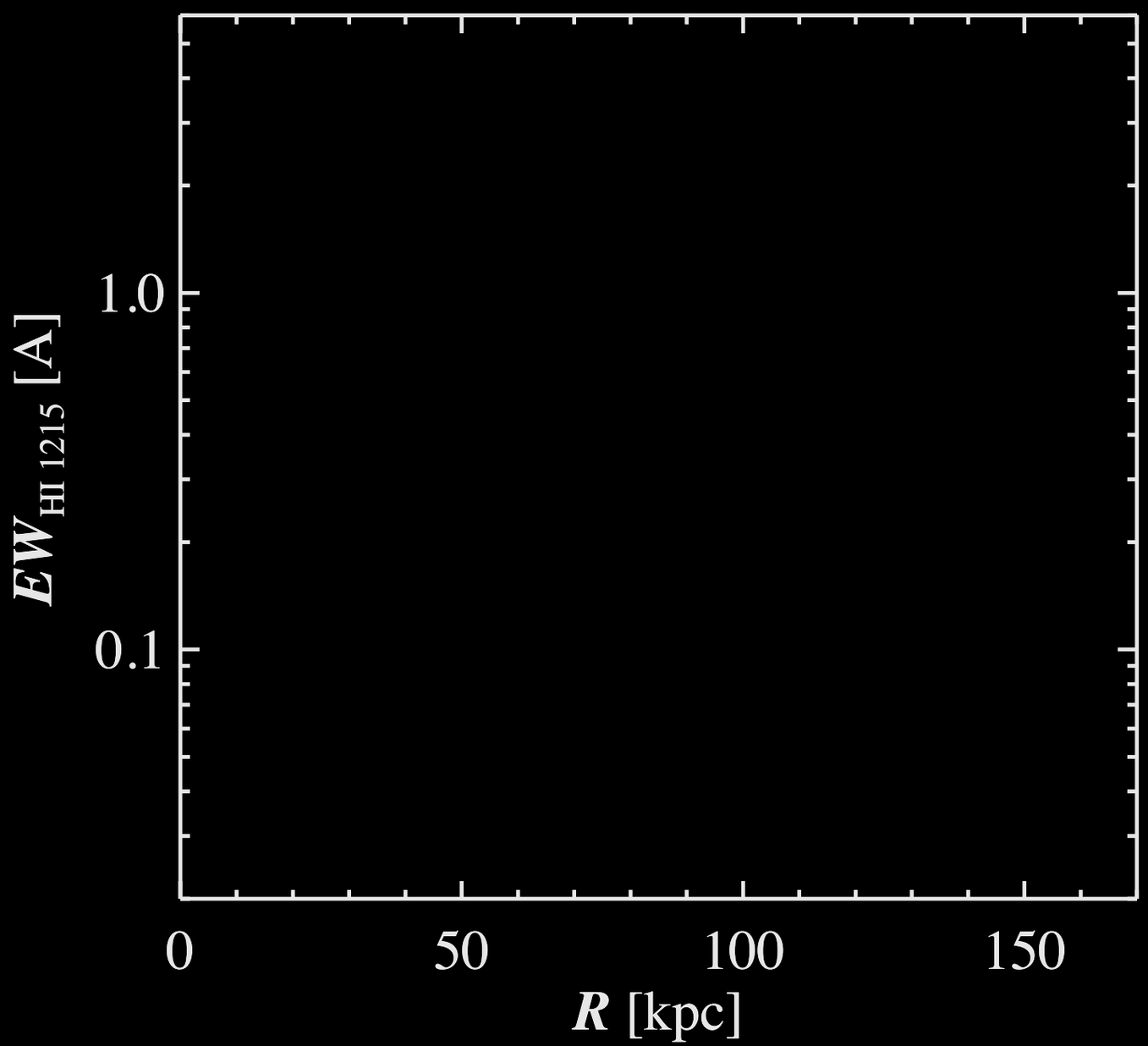

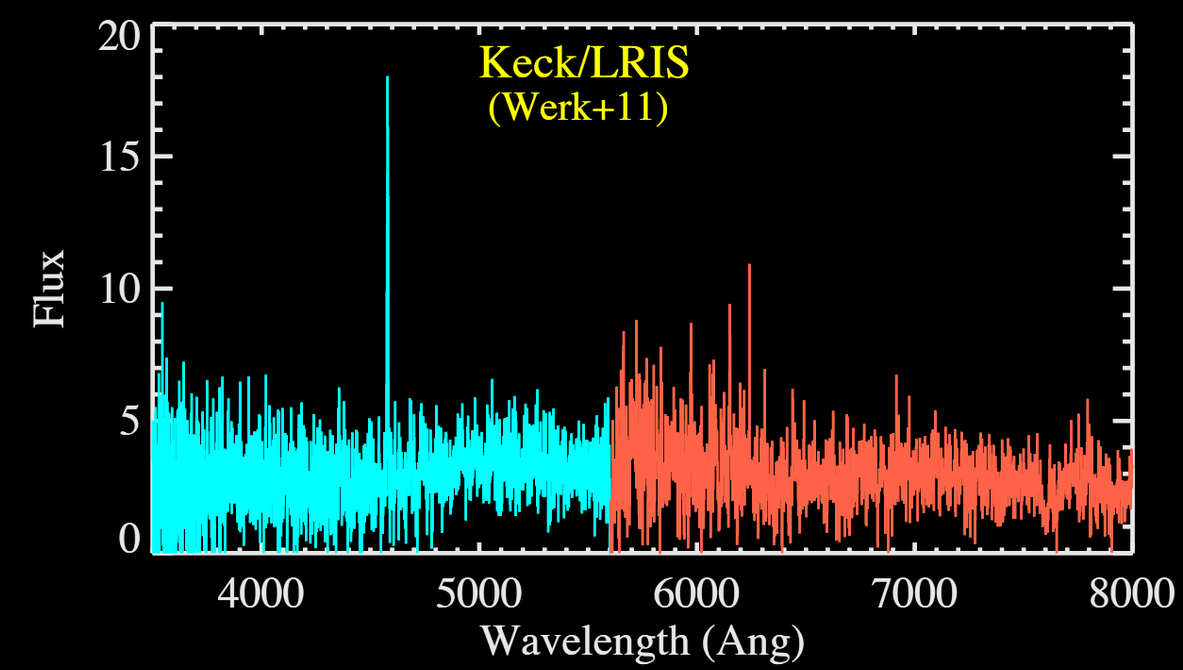

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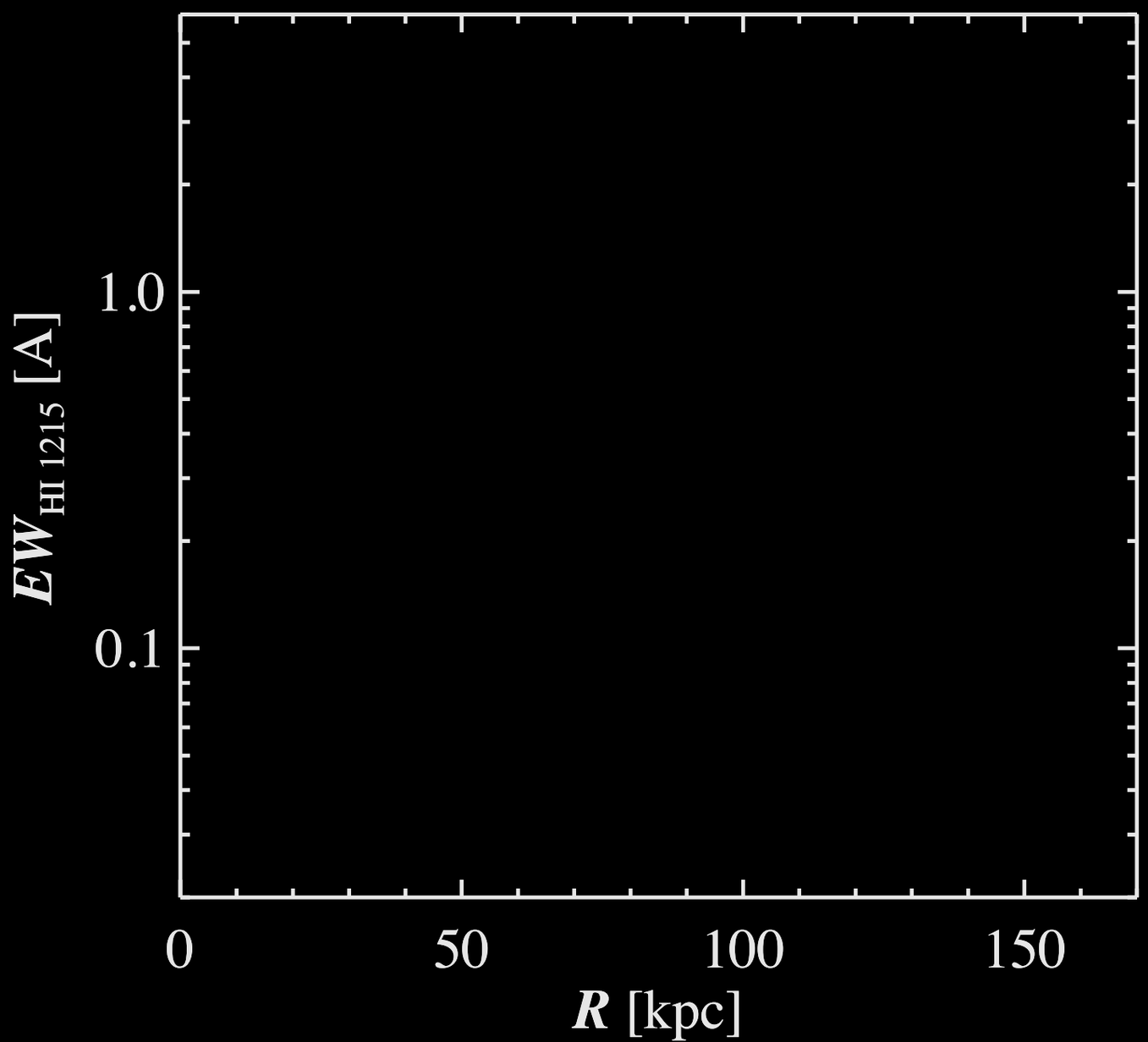

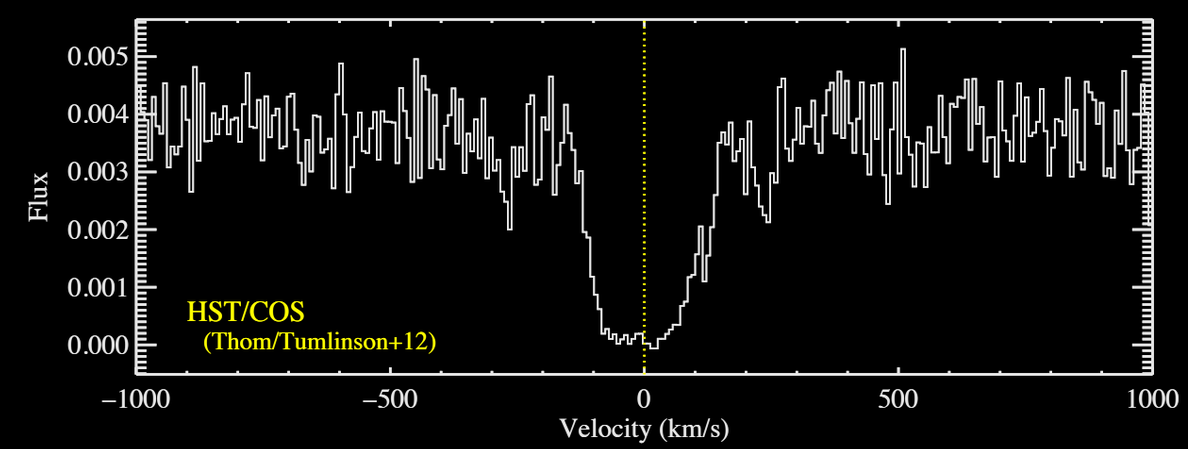

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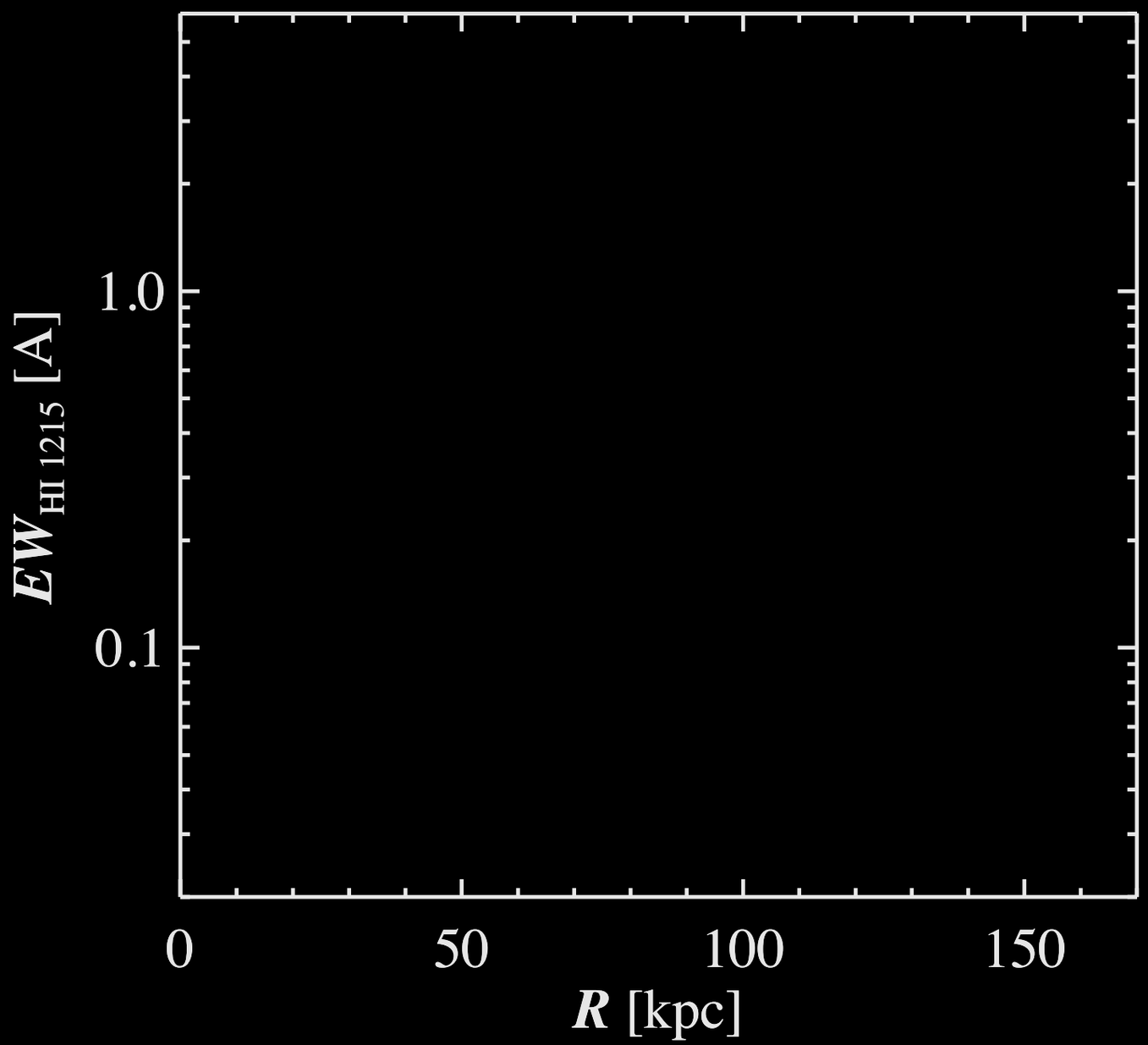

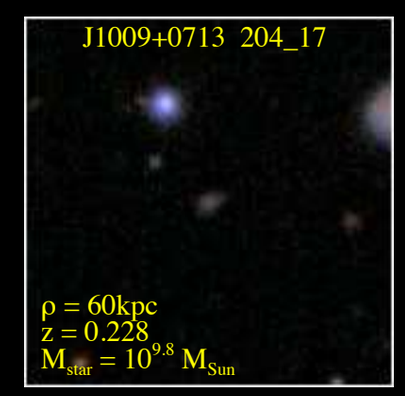

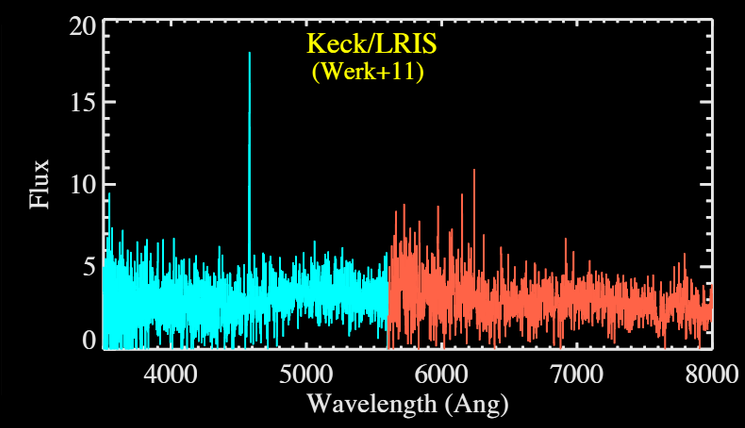

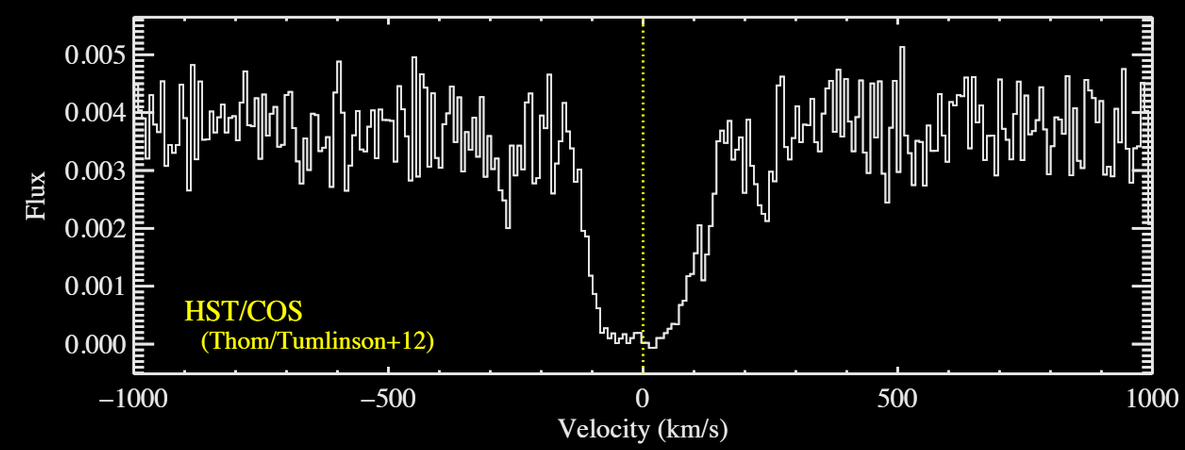

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COS-Halos (L~L*, z~0 galaxies)

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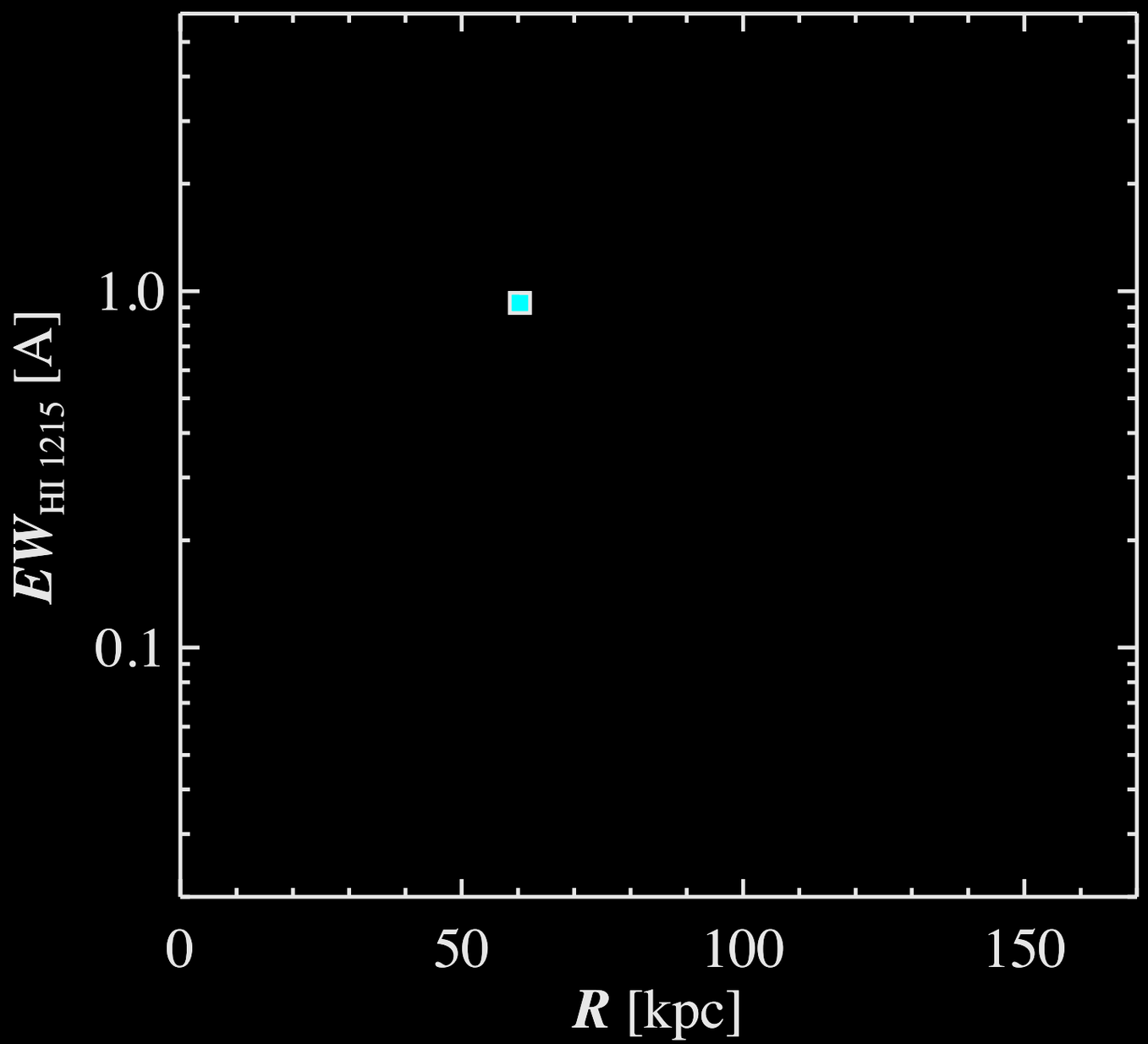

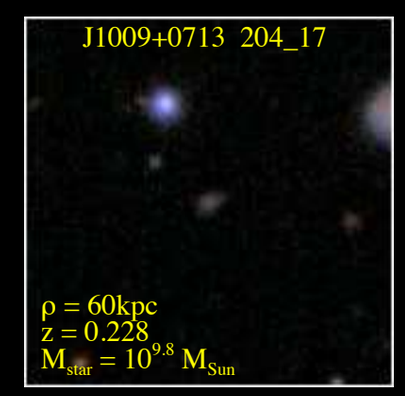

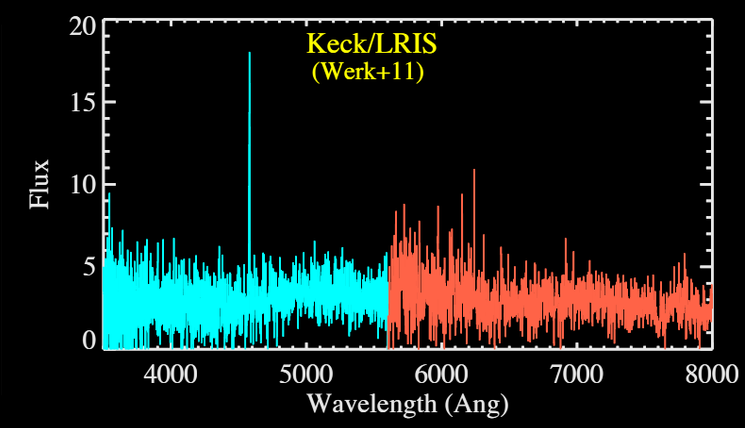

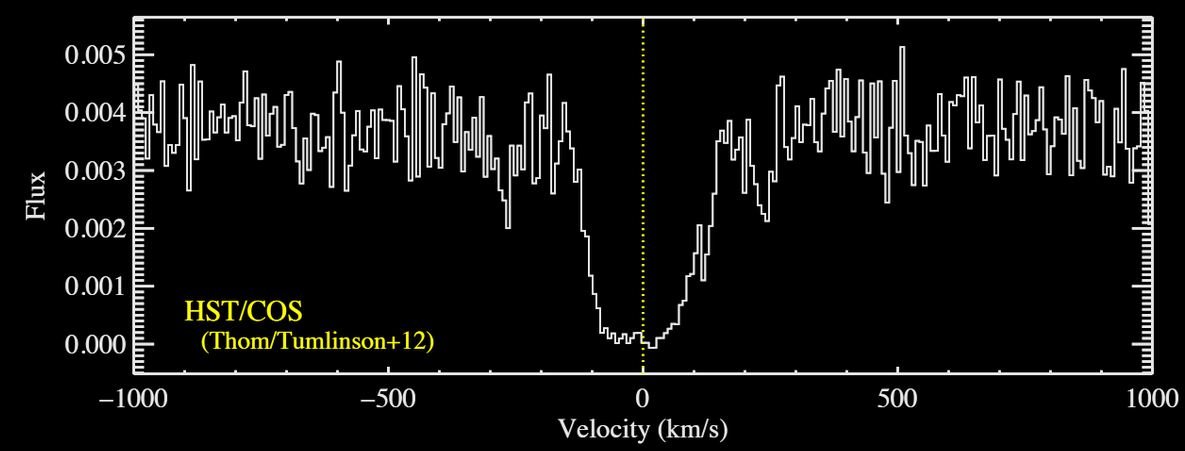

The Circumgalactic Medium at z~0

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Tumlinson+12
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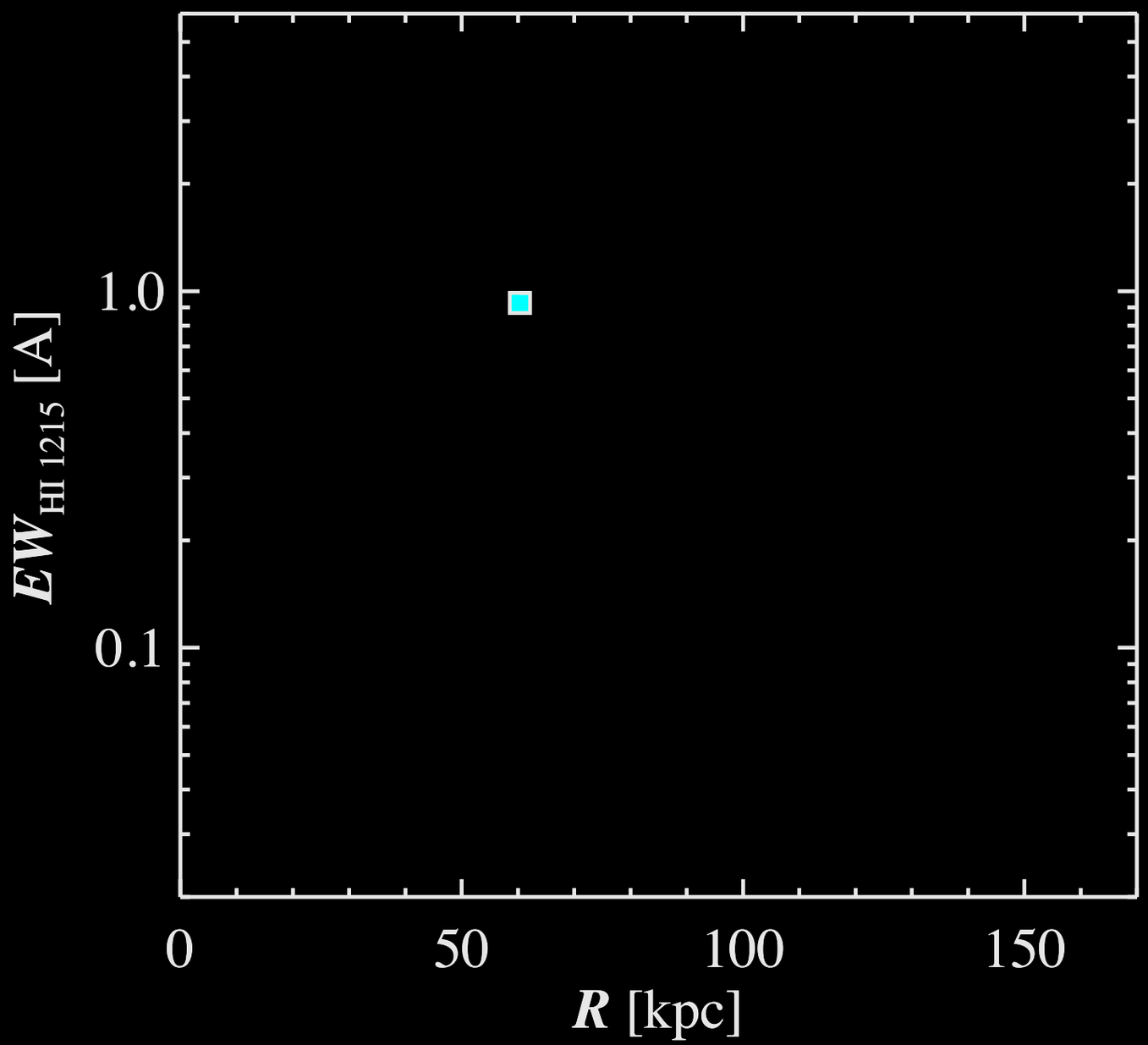

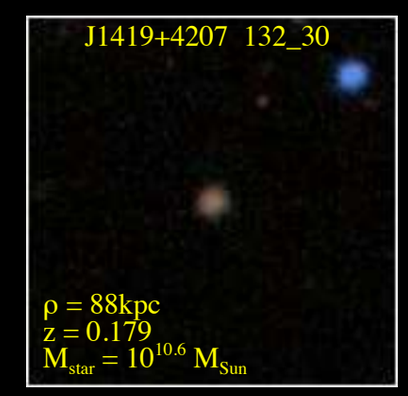

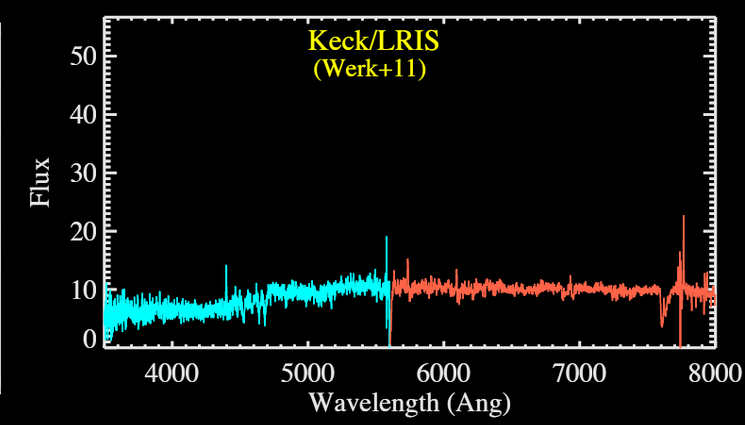

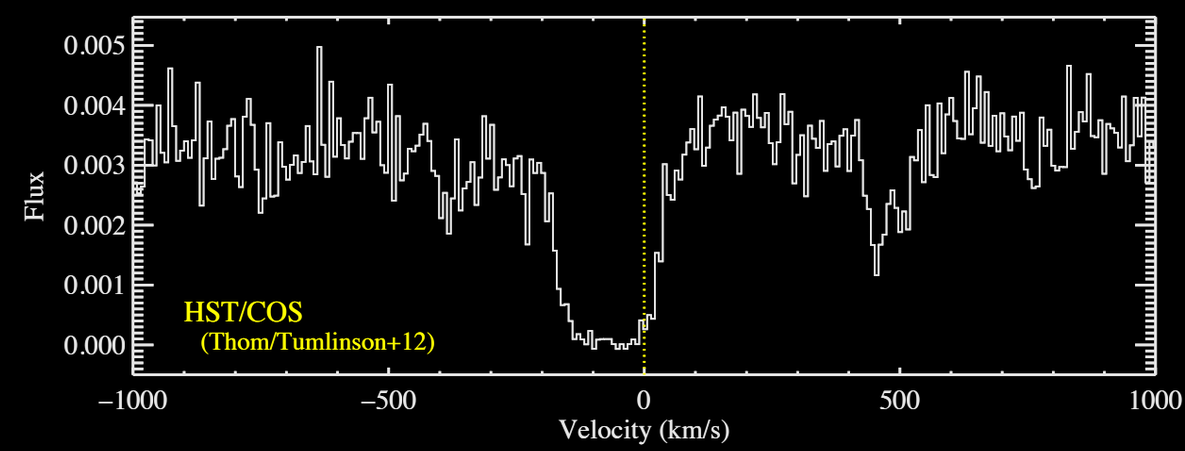

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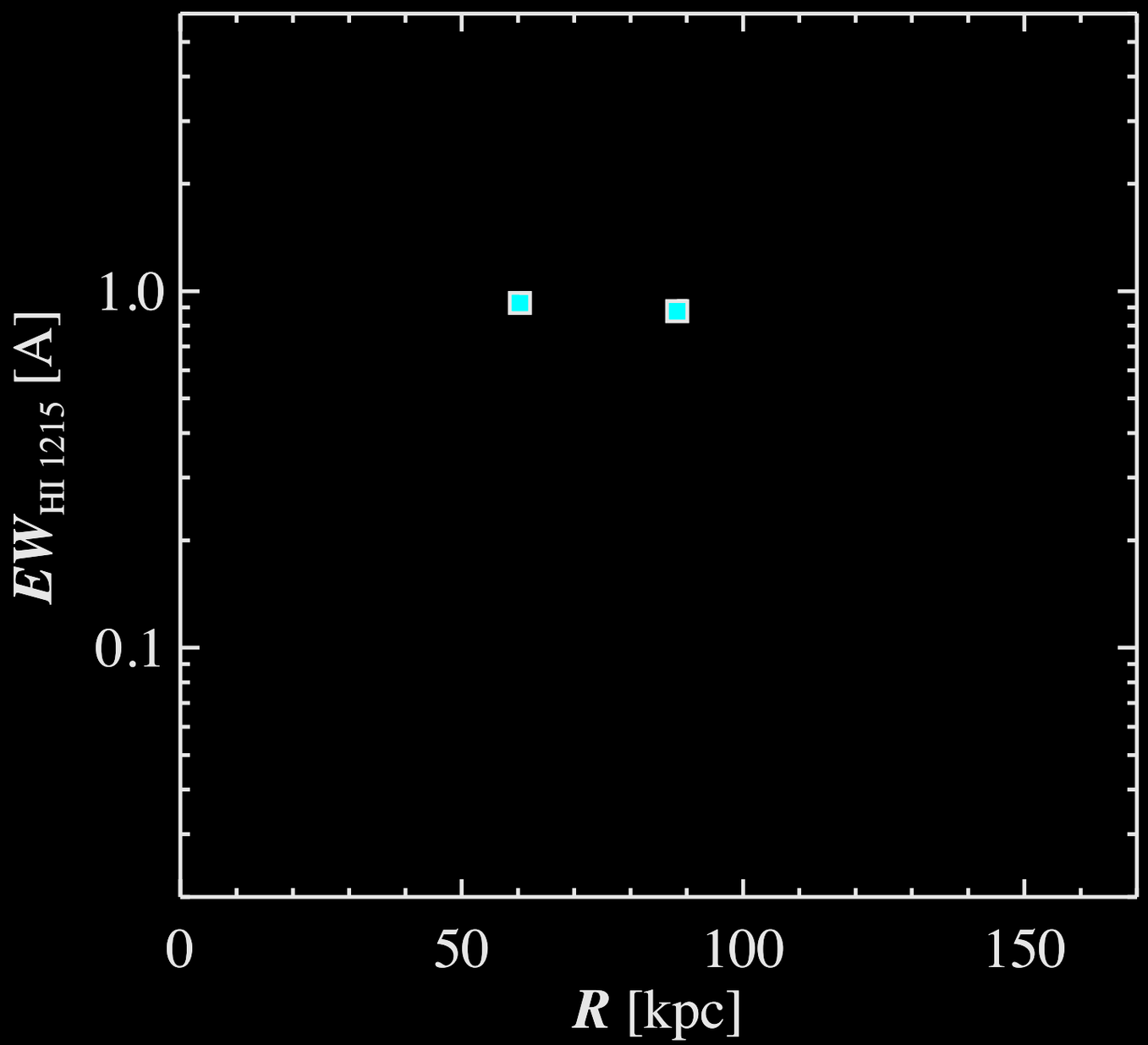

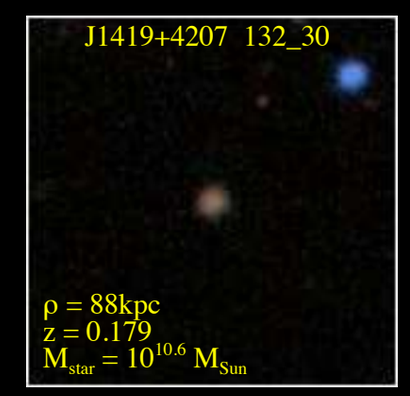

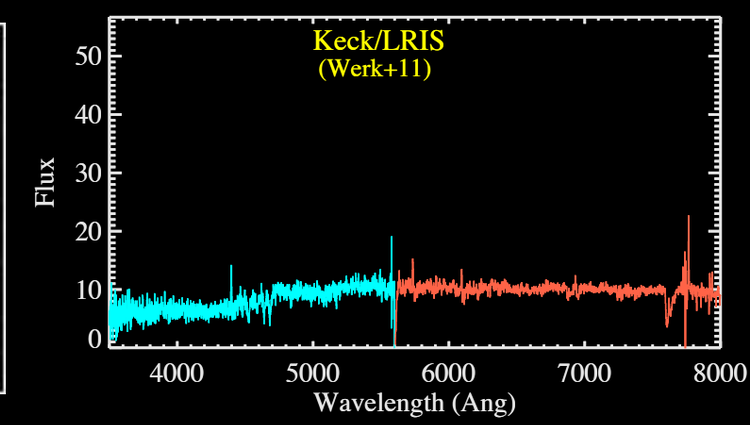

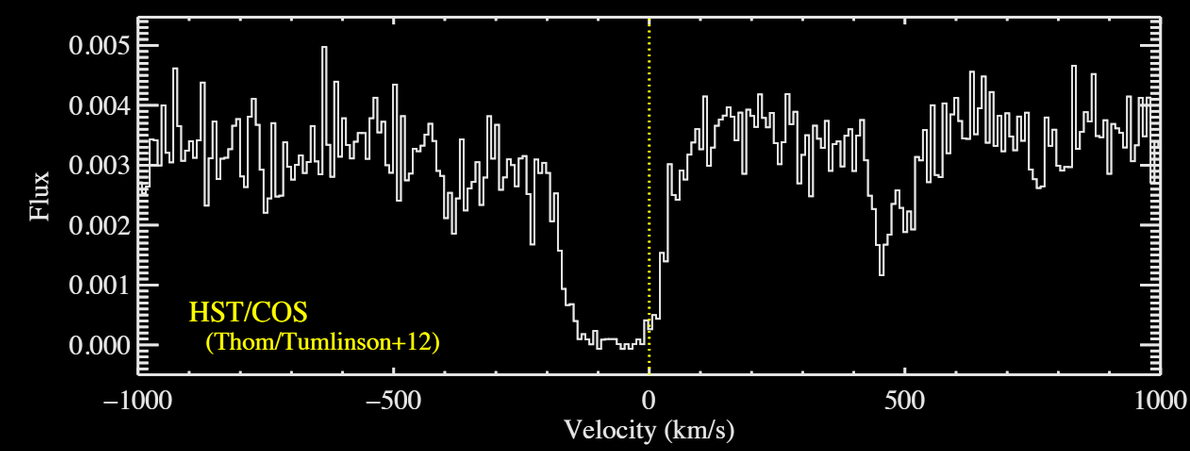

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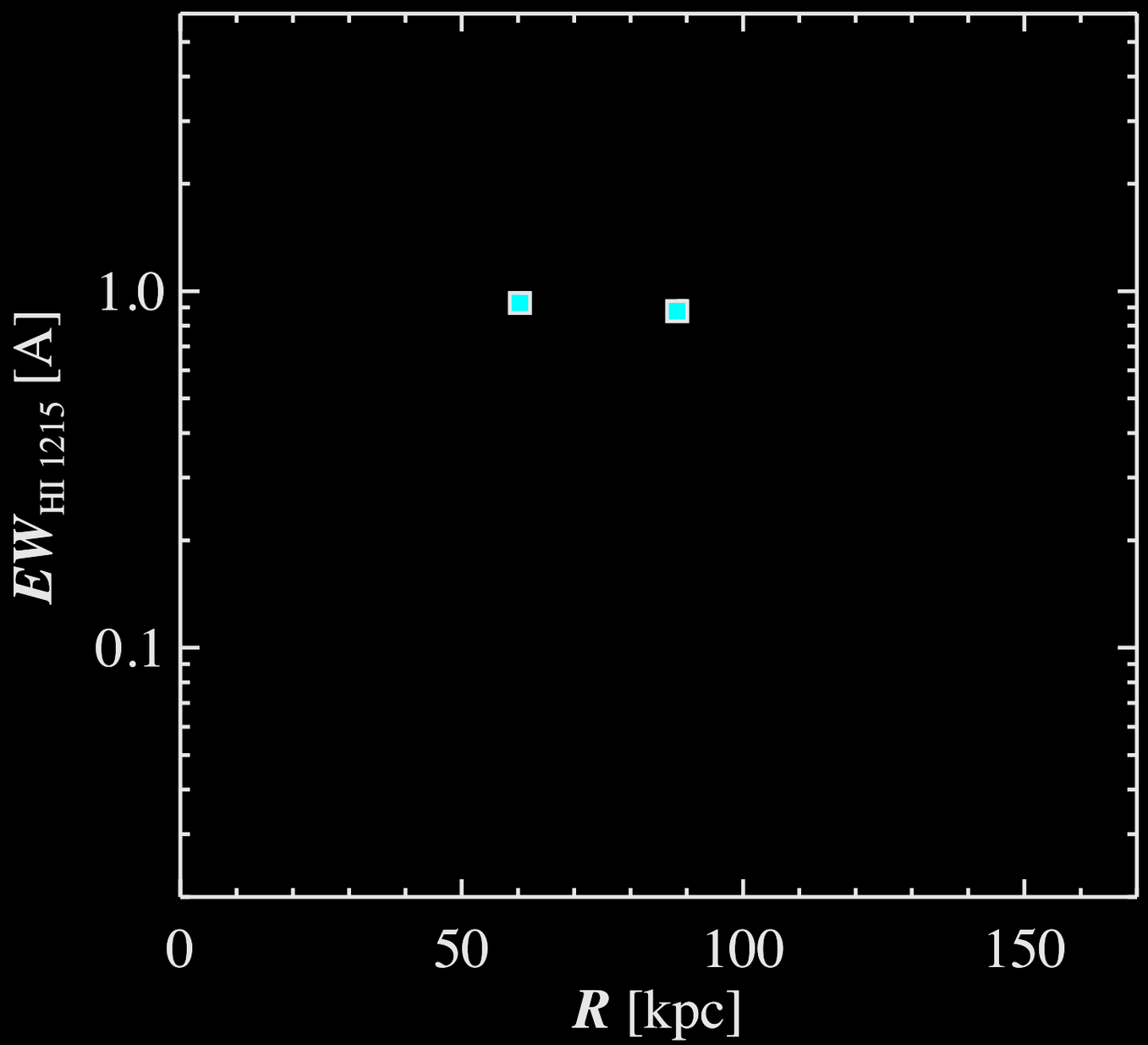

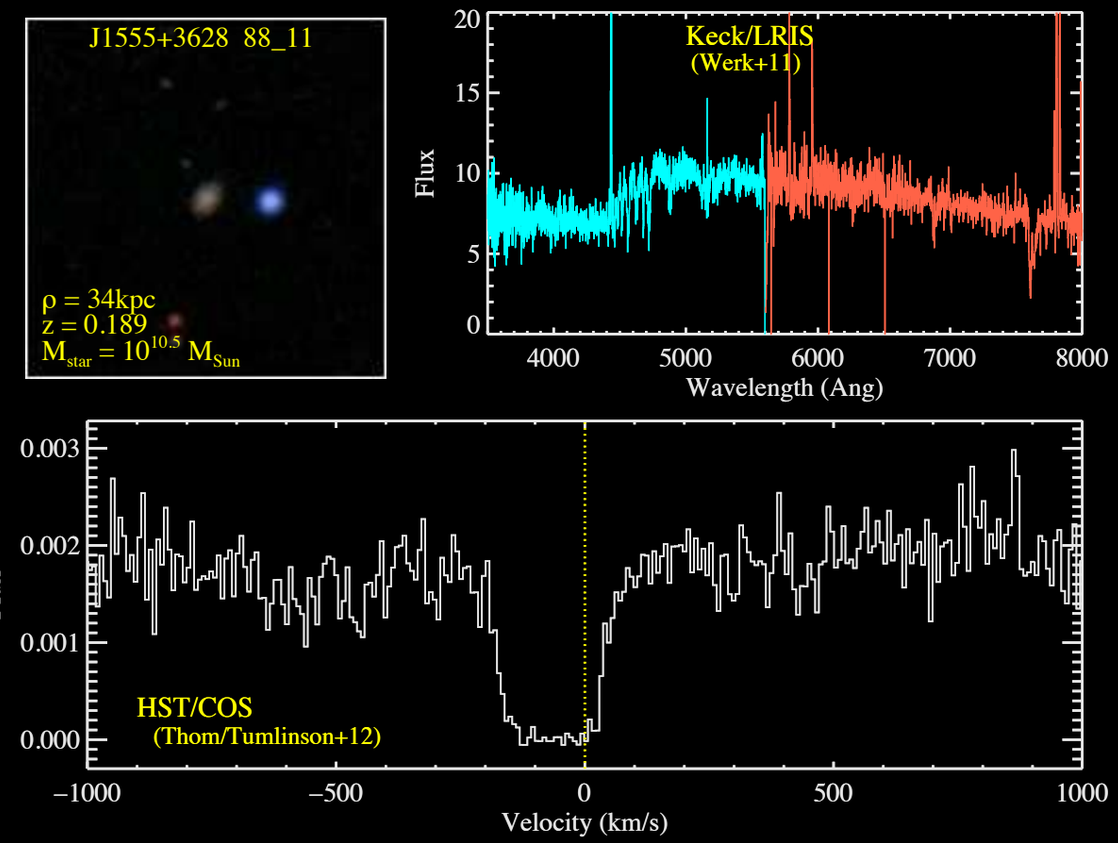

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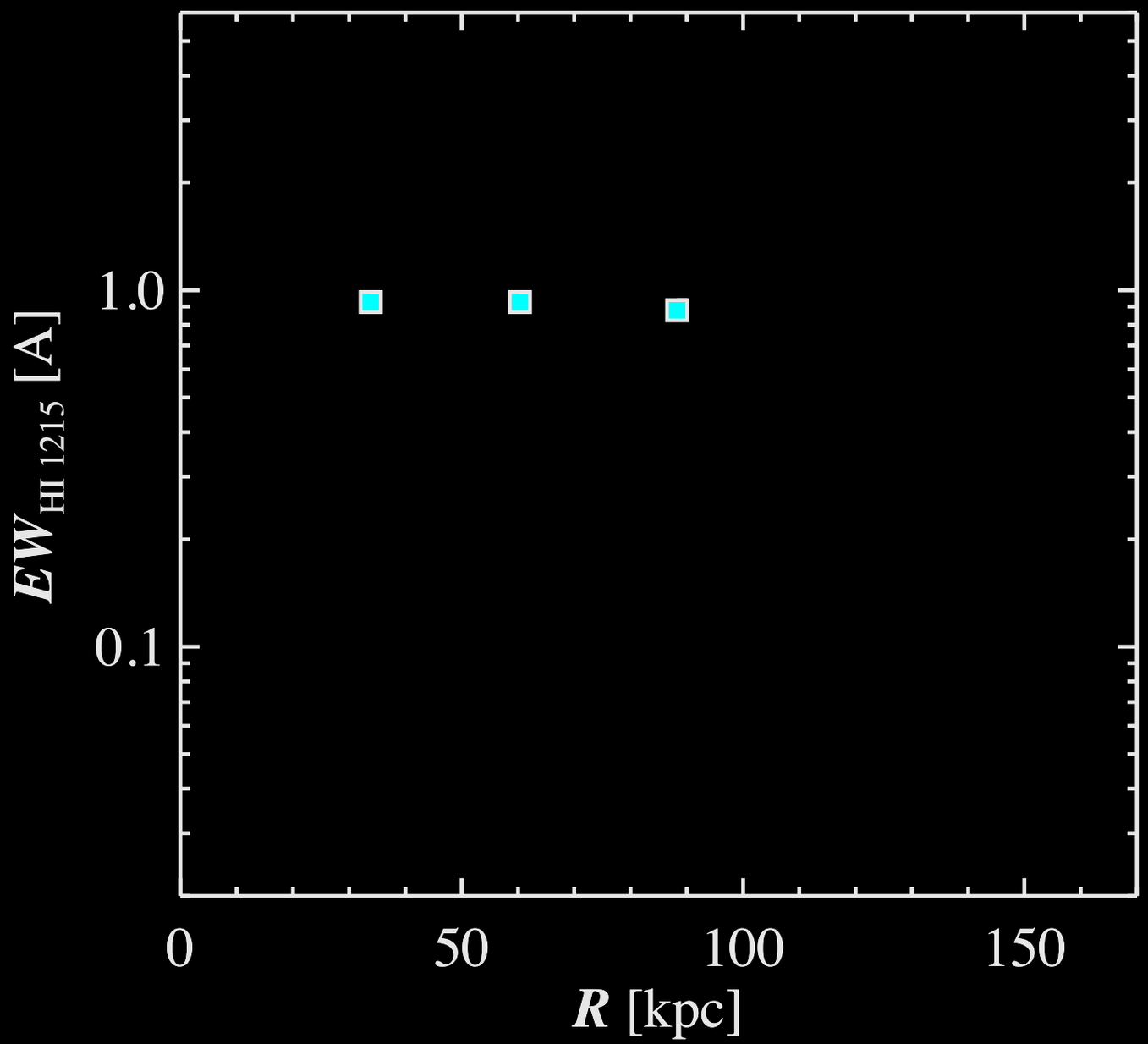

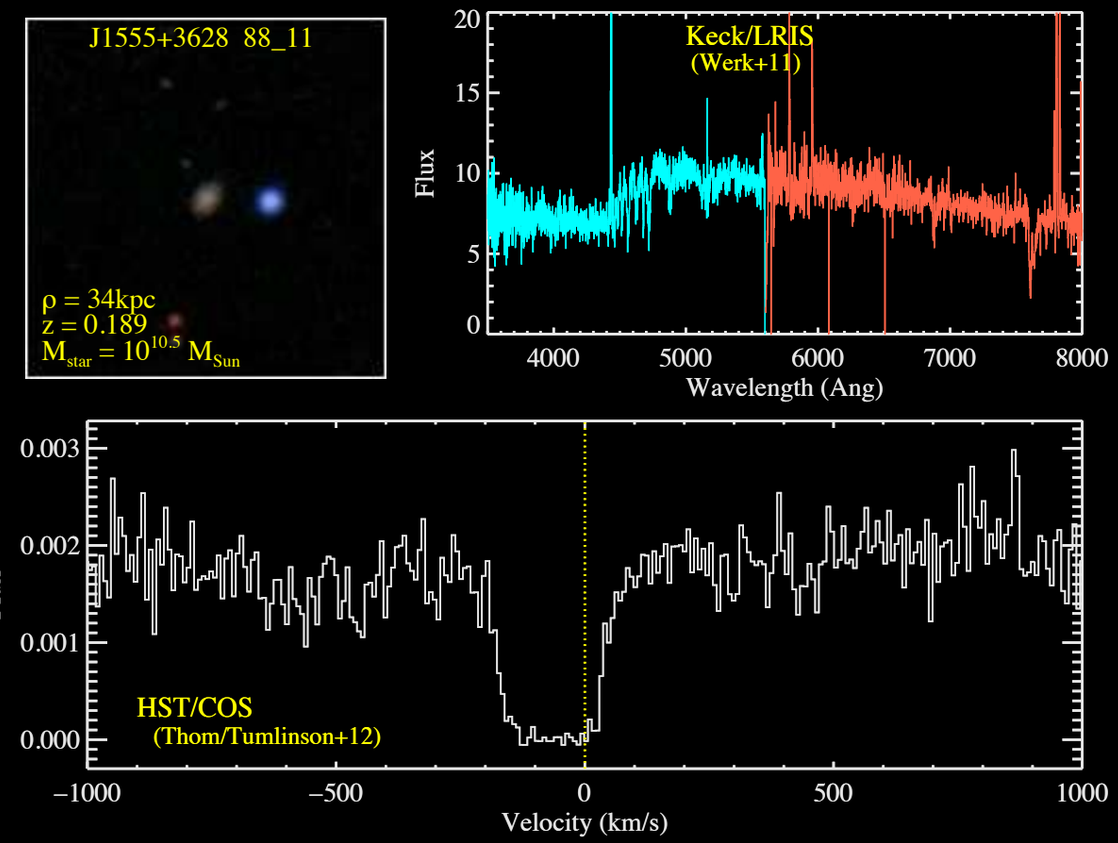

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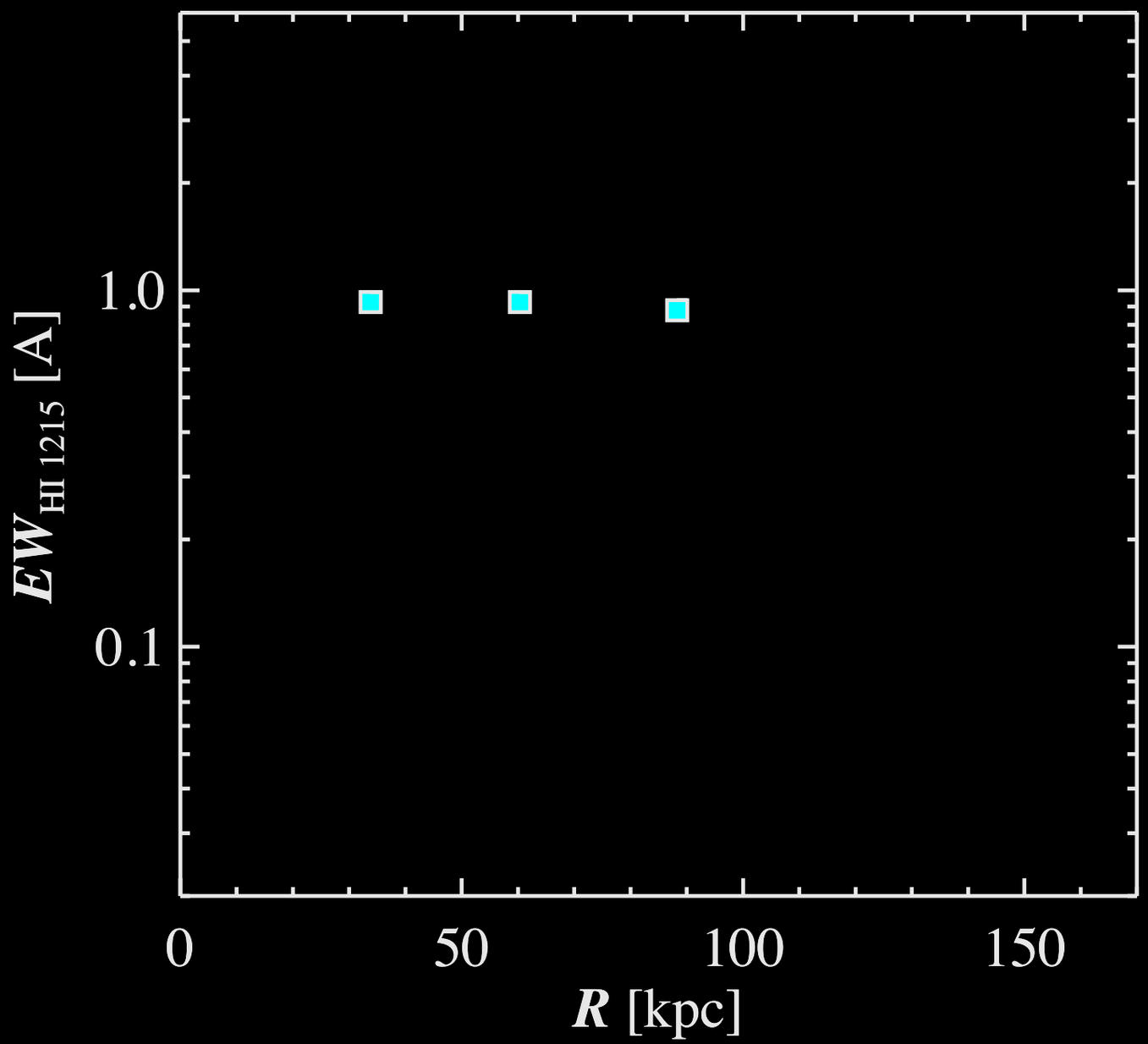

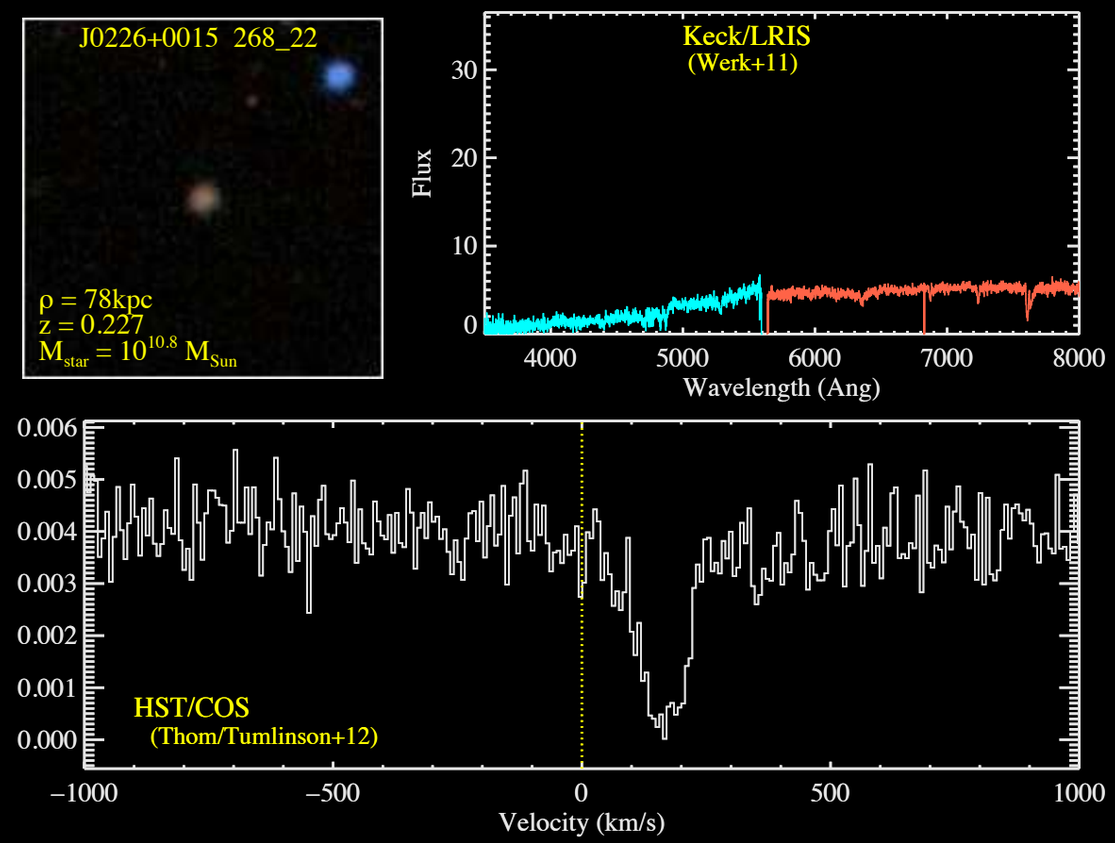

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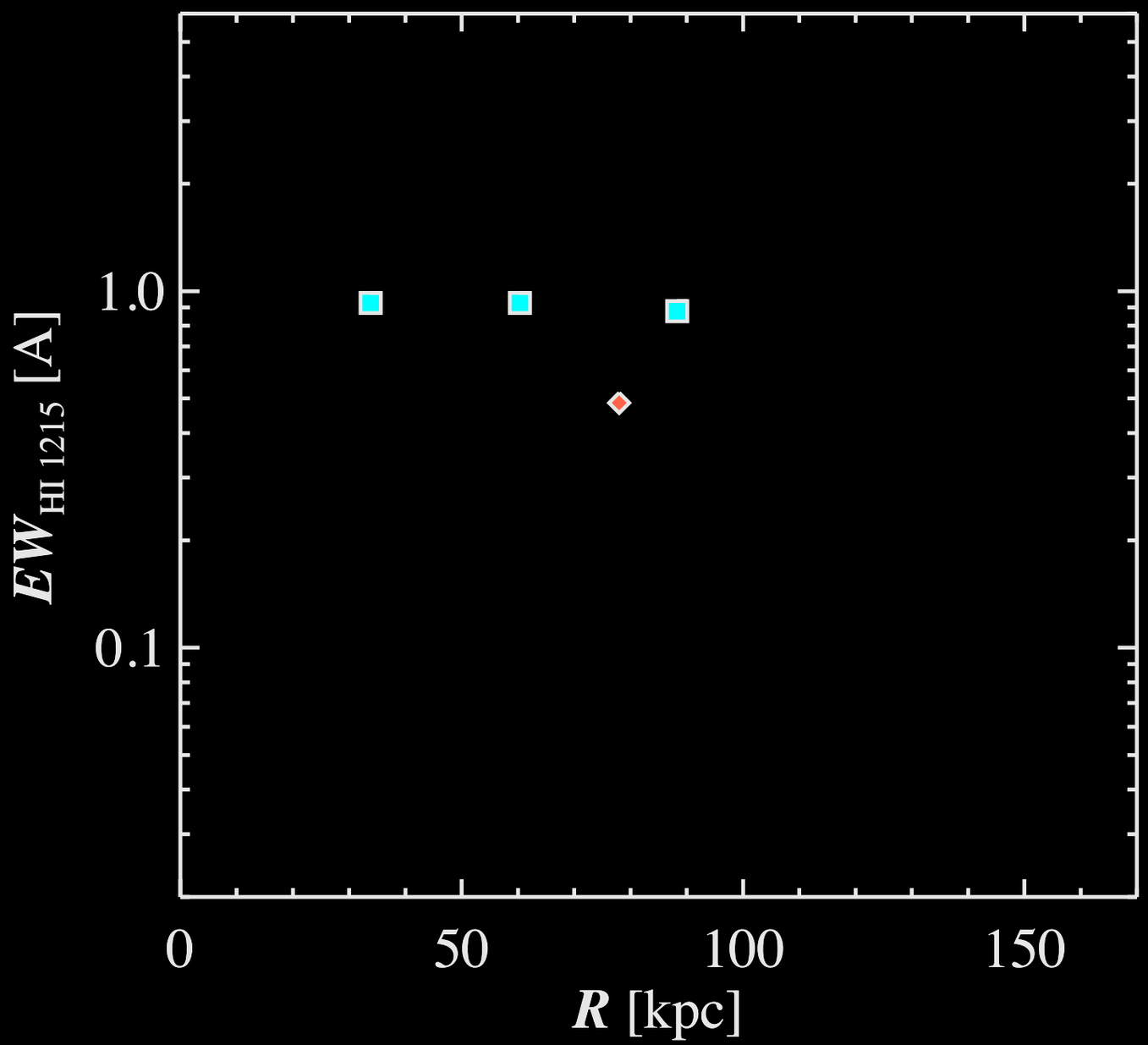

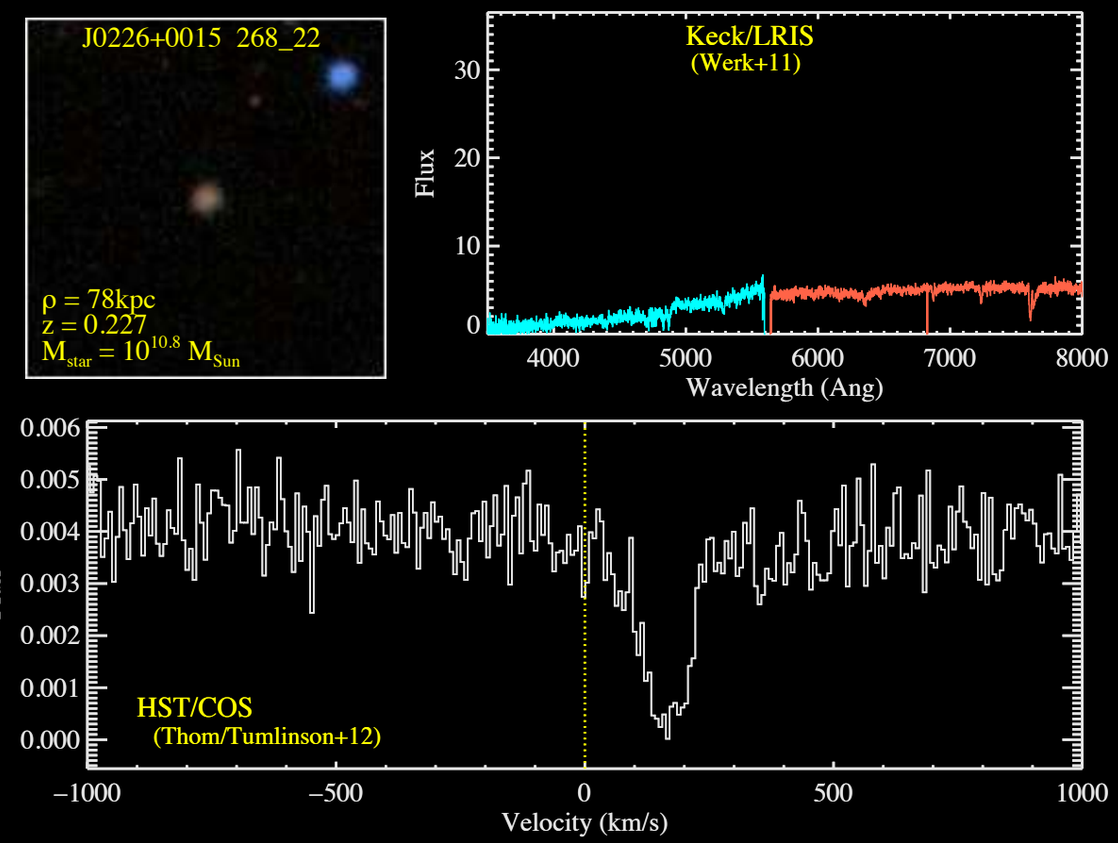

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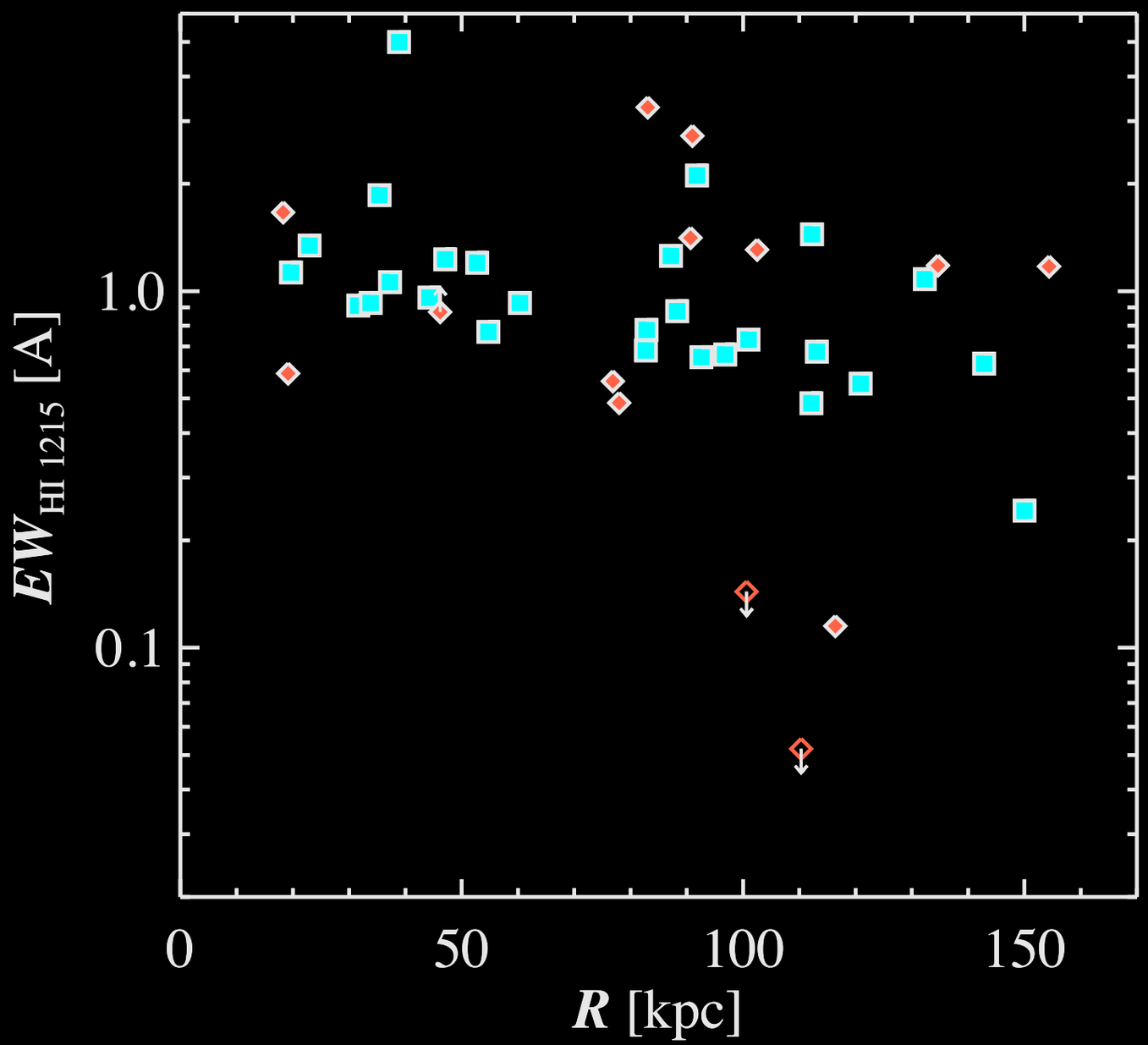

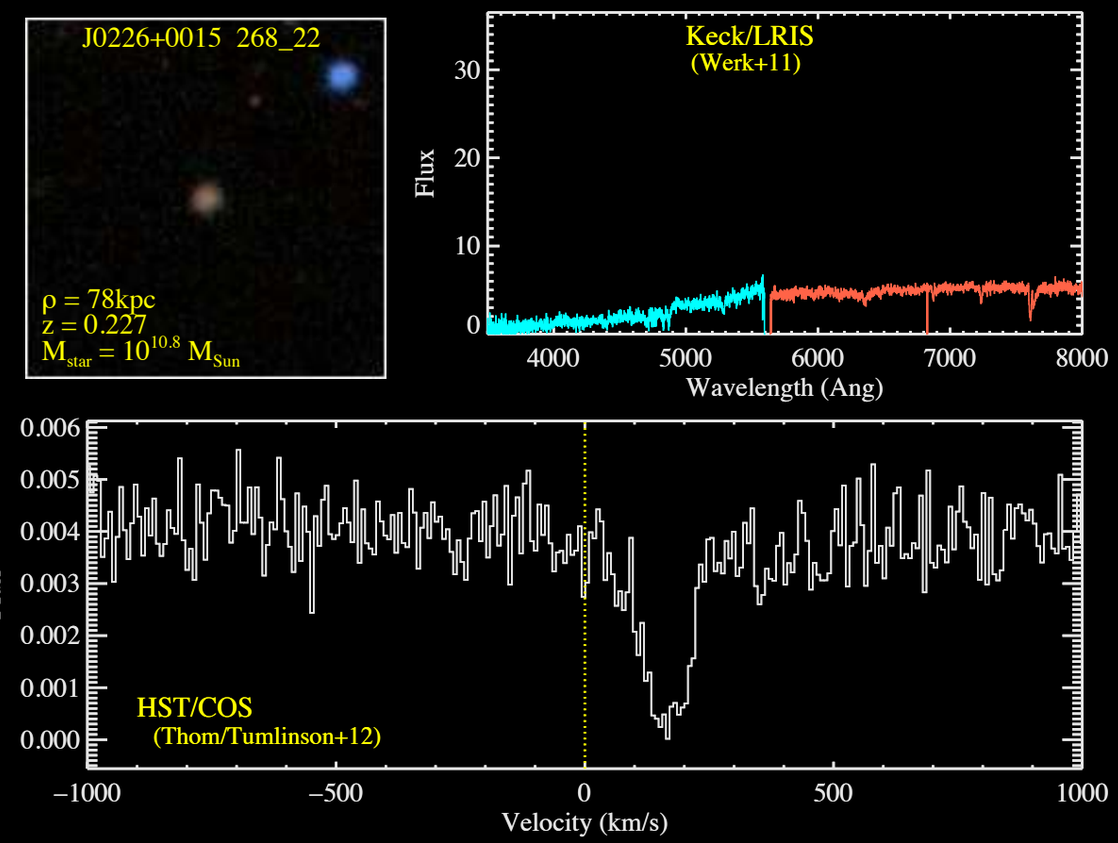

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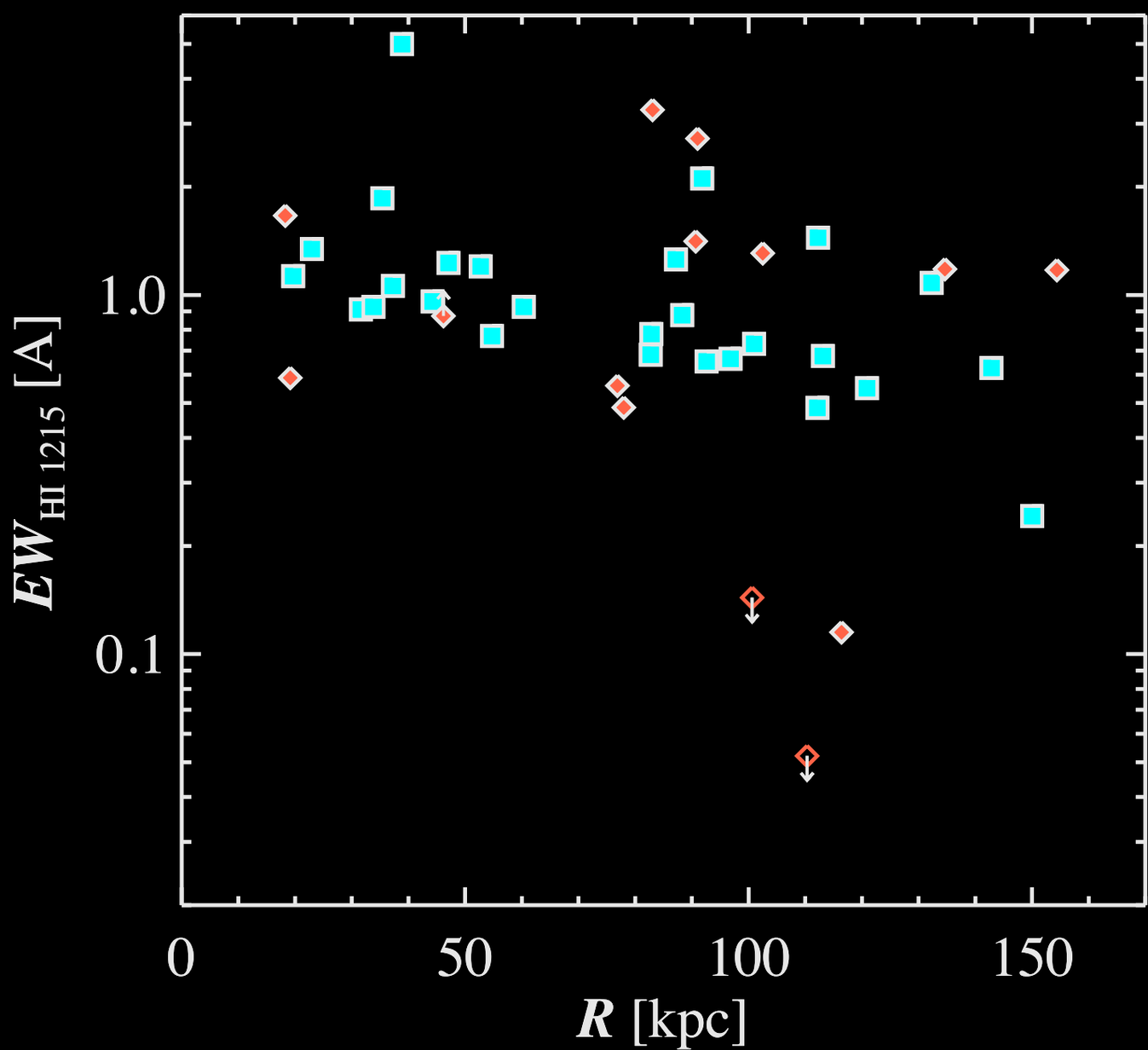

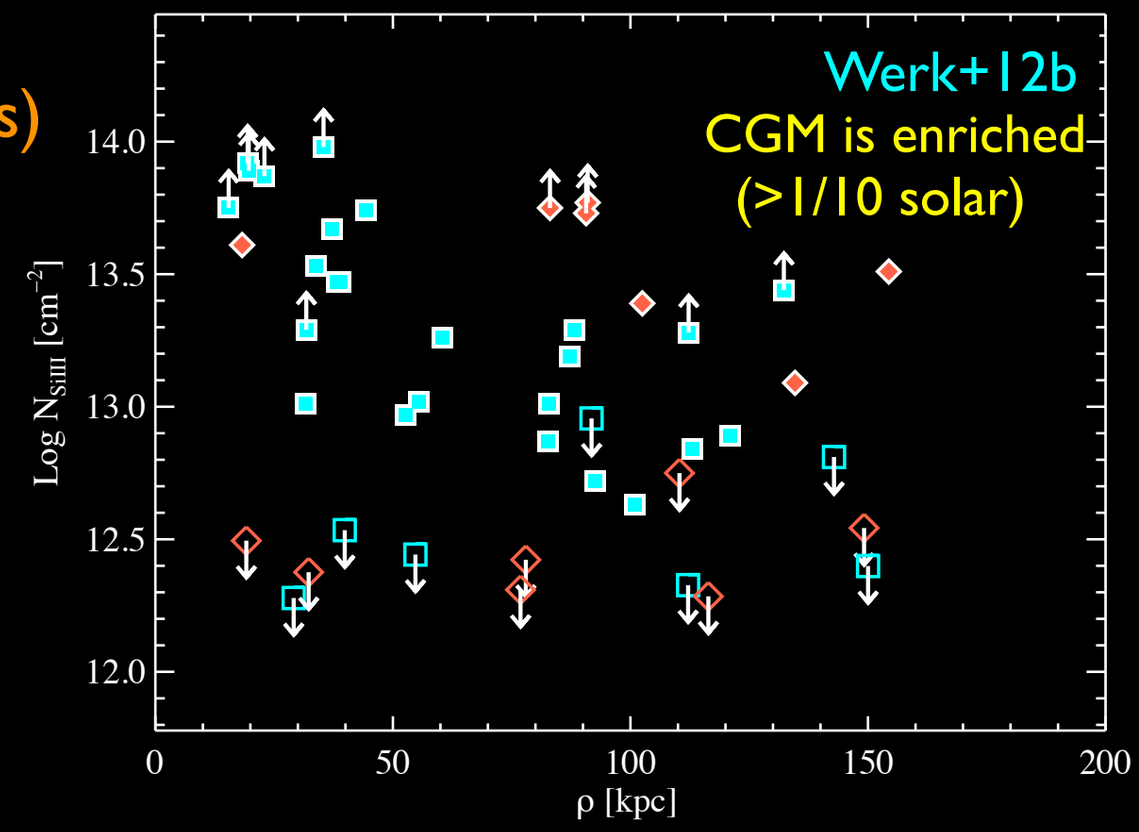

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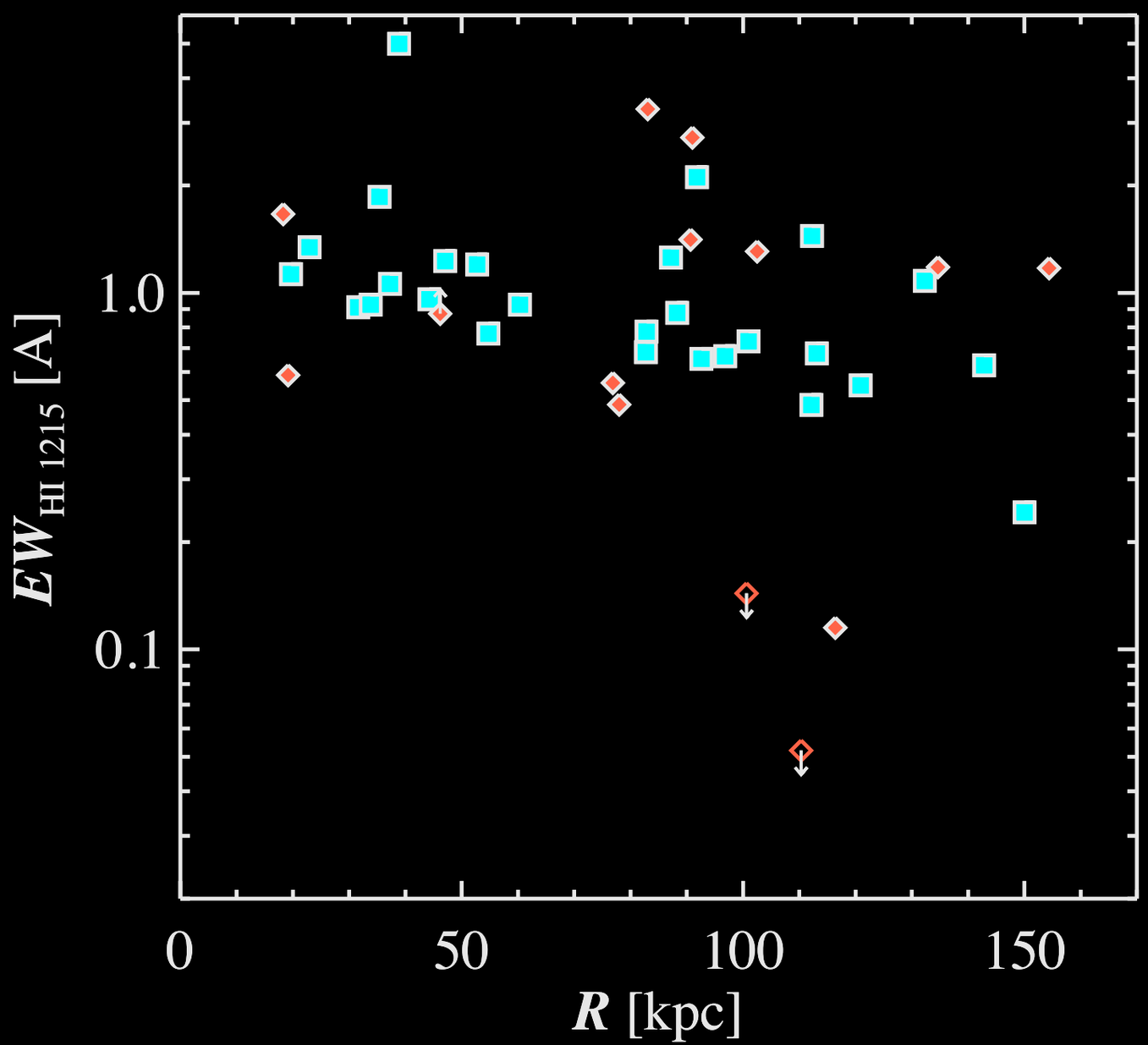

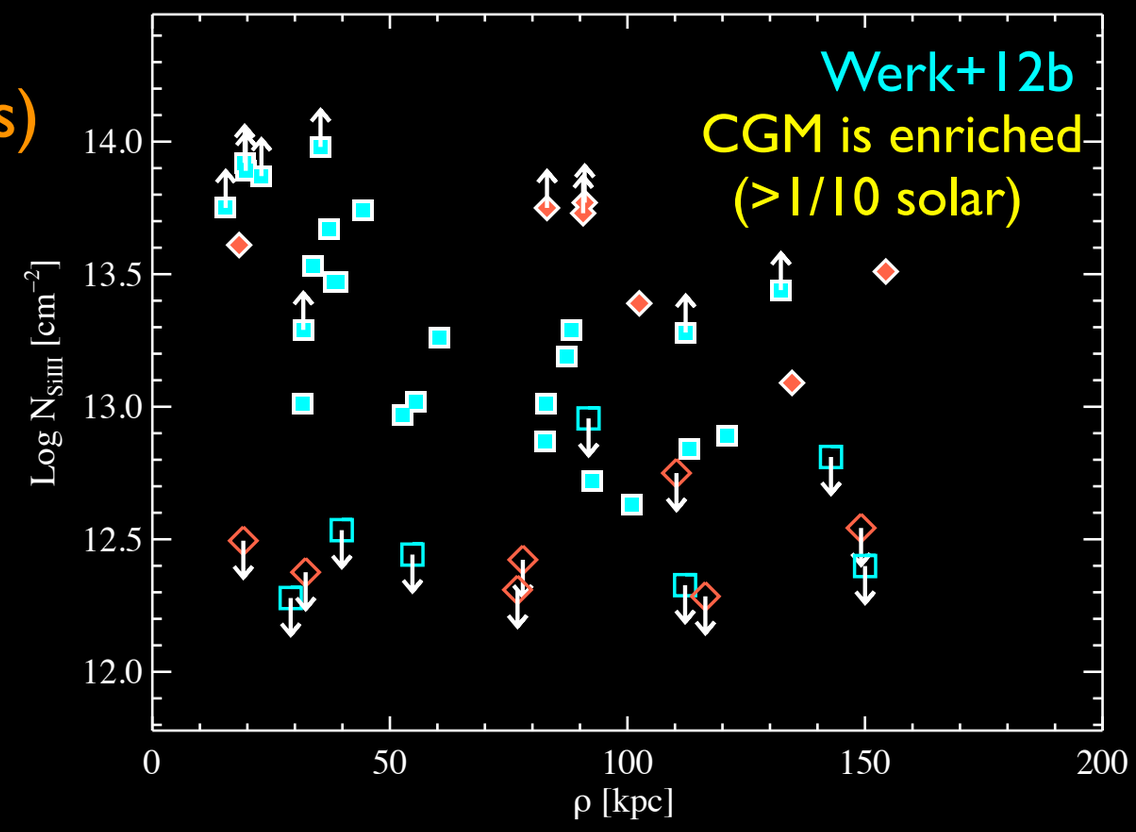

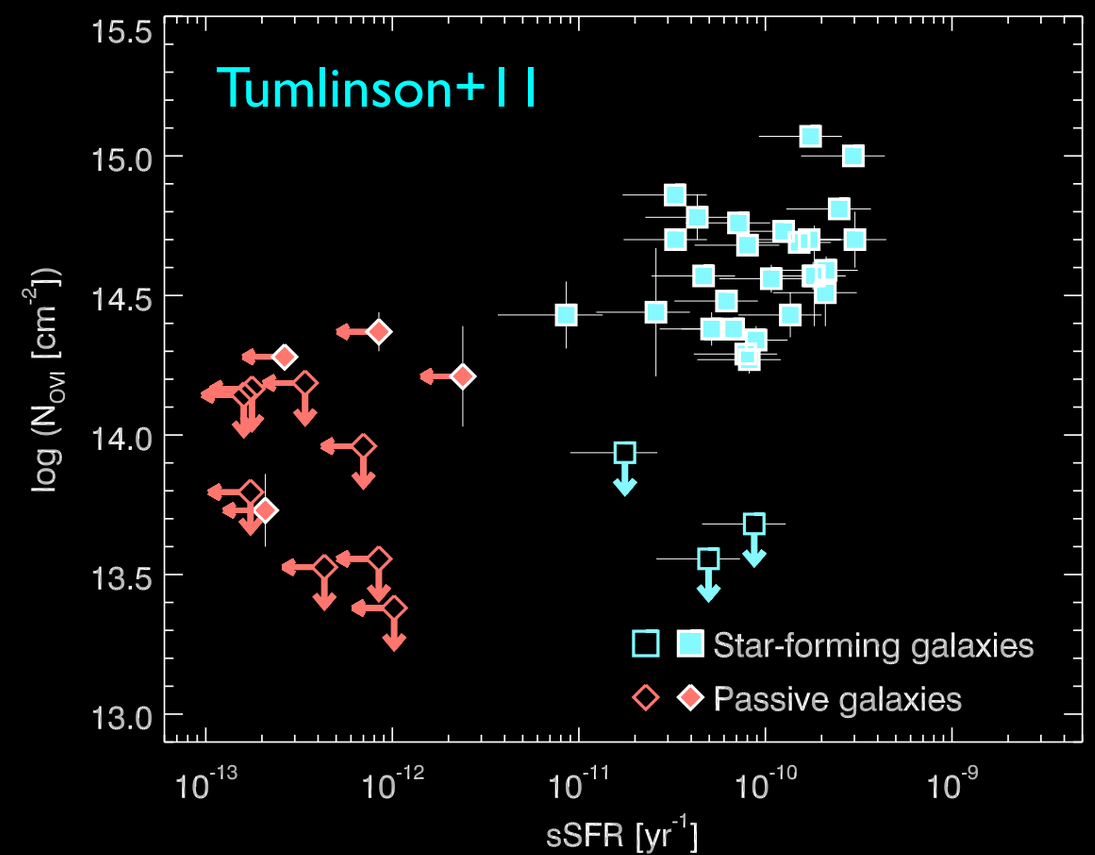

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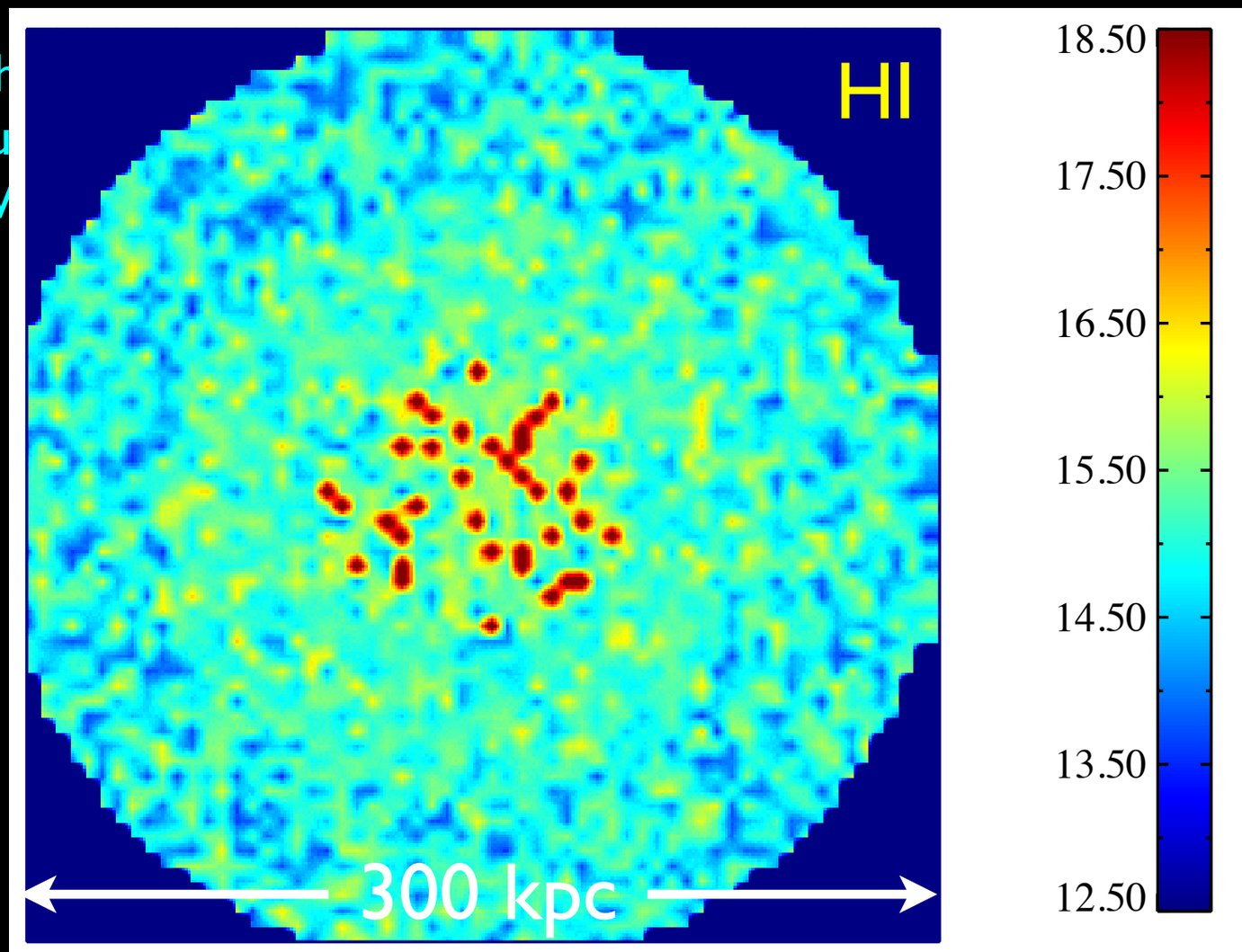

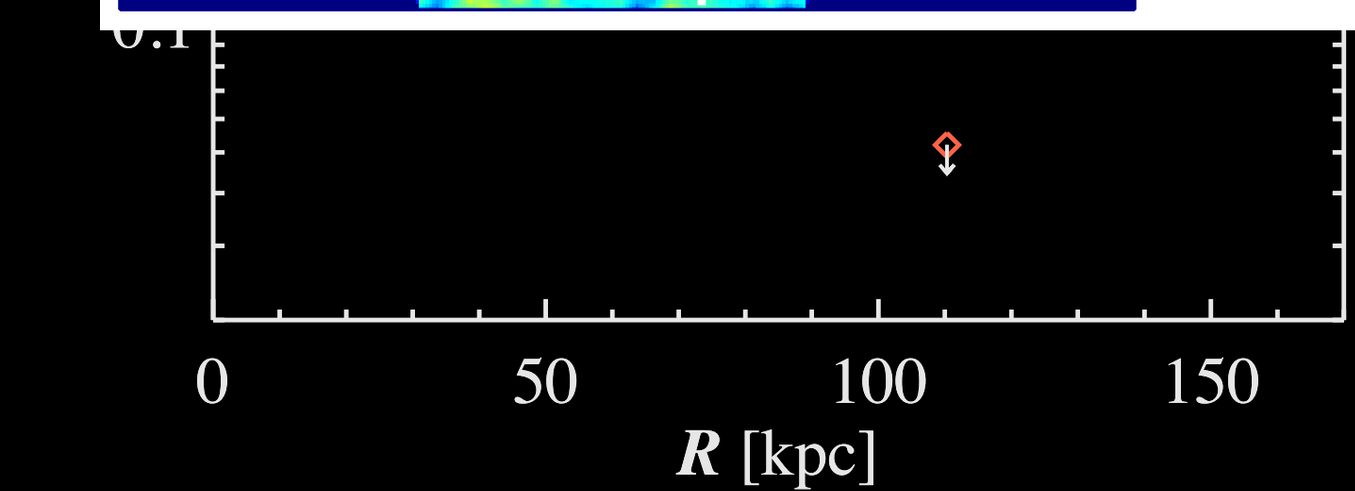

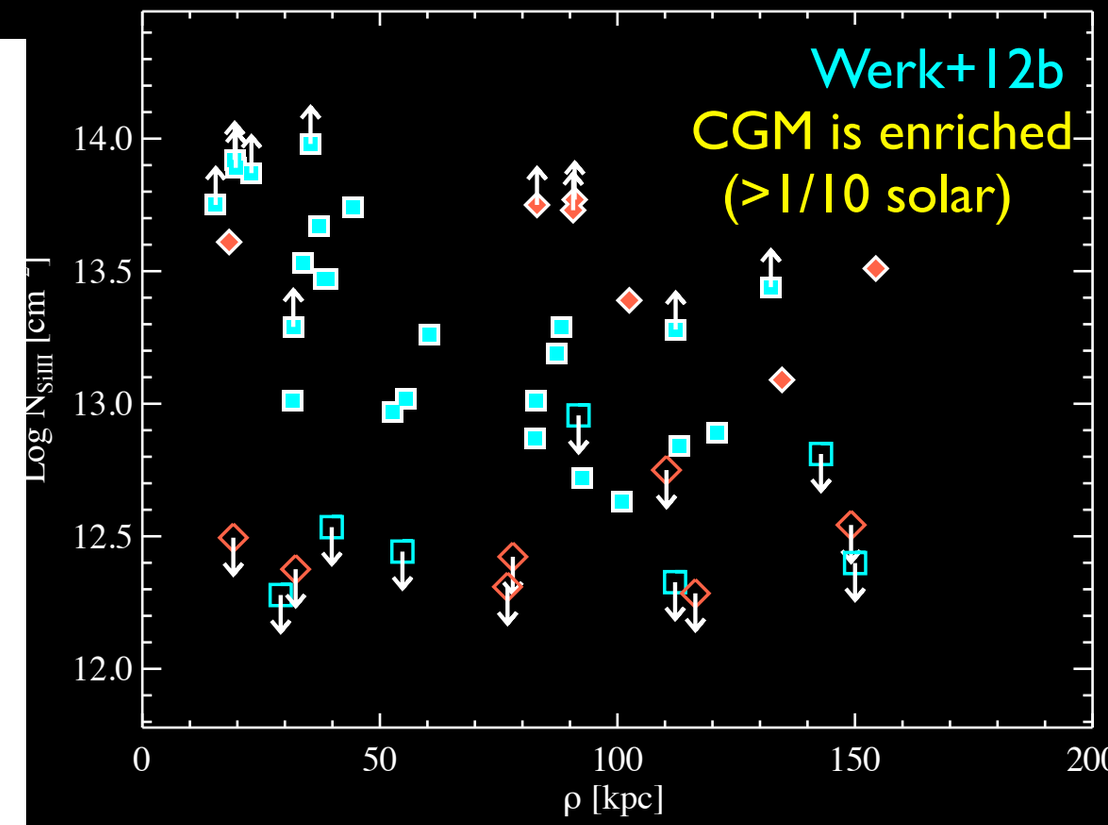

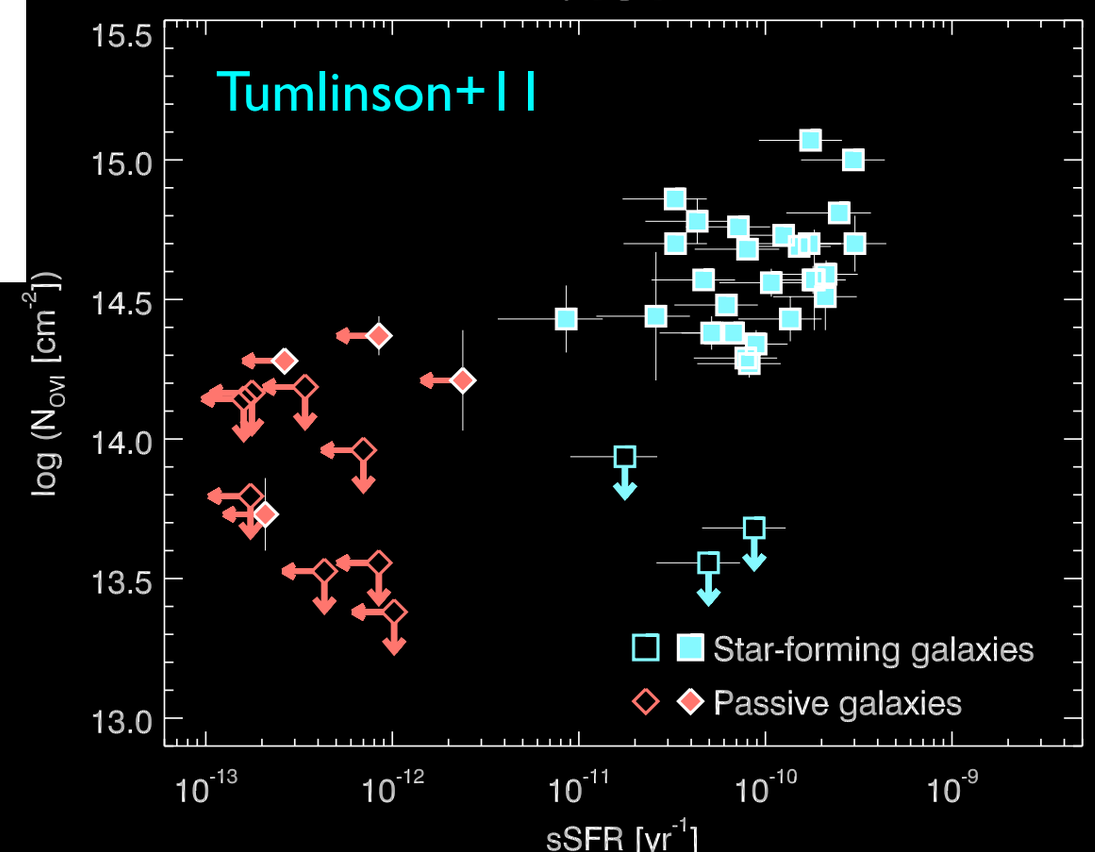

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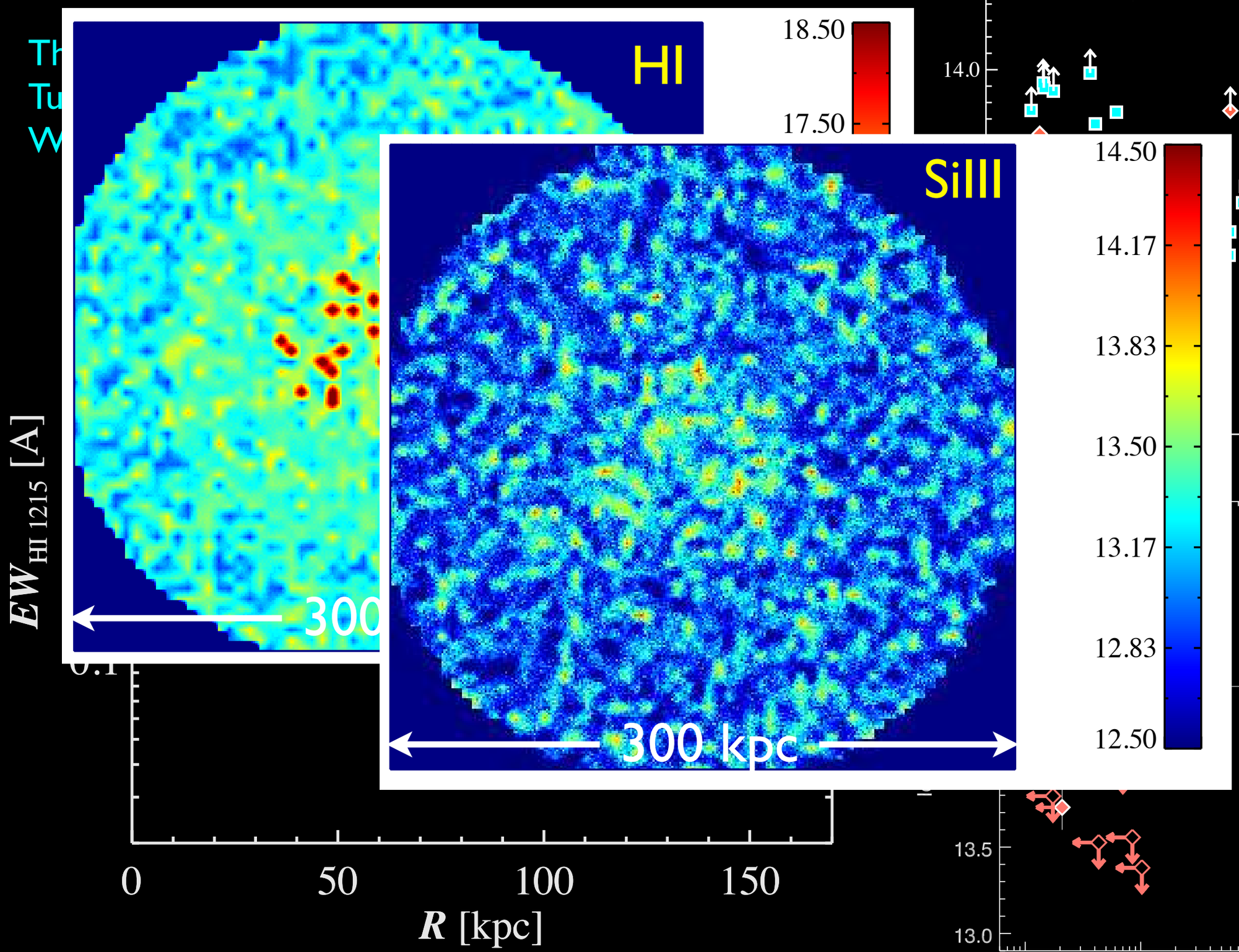

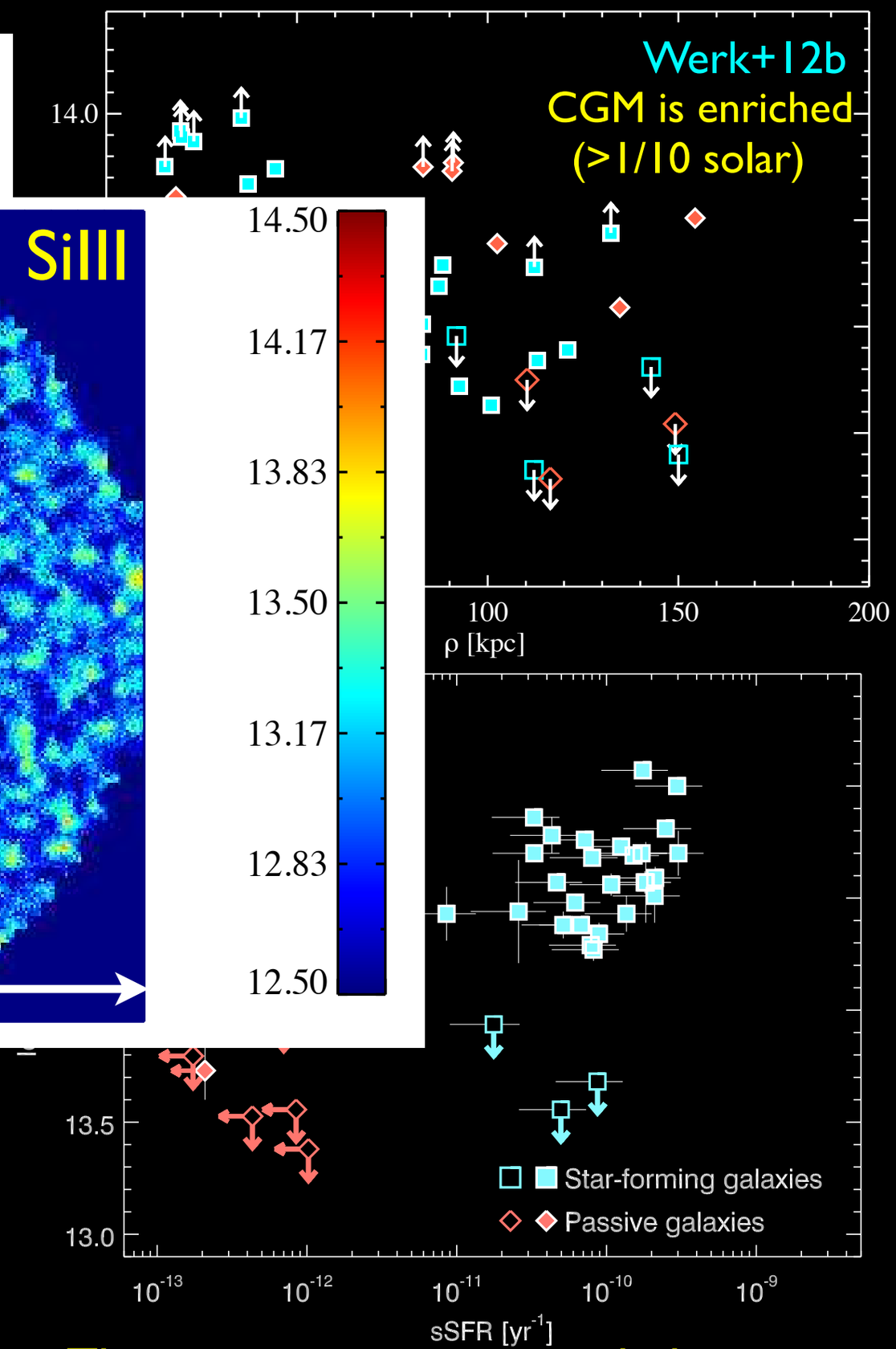

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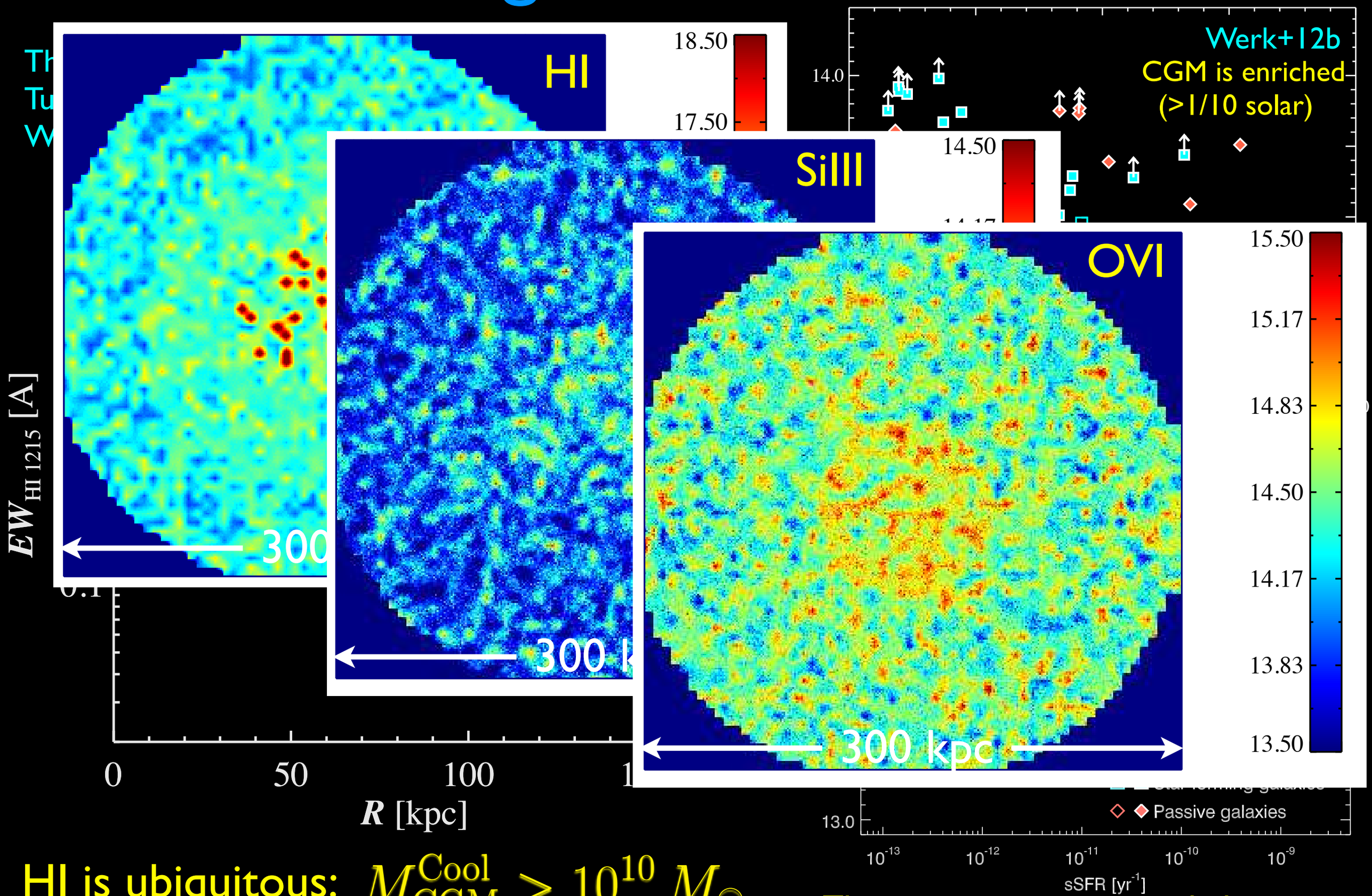

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The Low z CGM: A new view of Galaxies

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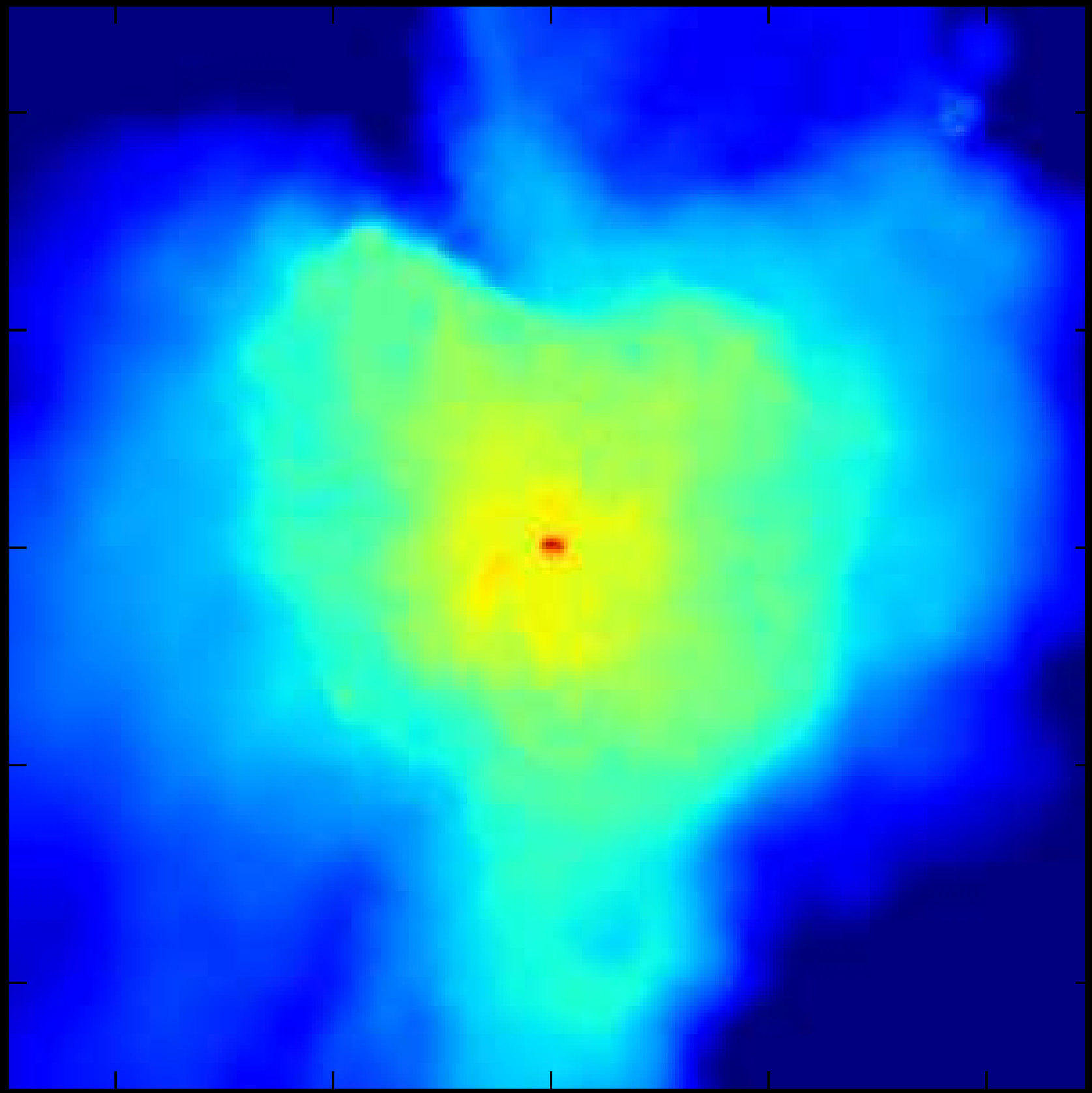
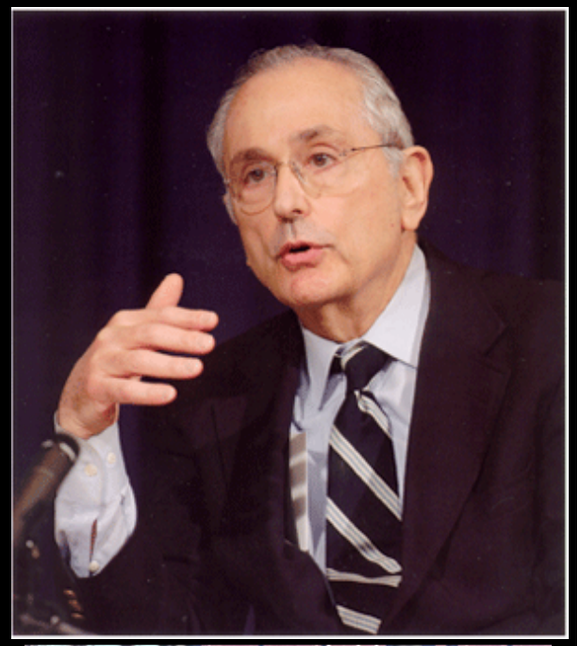
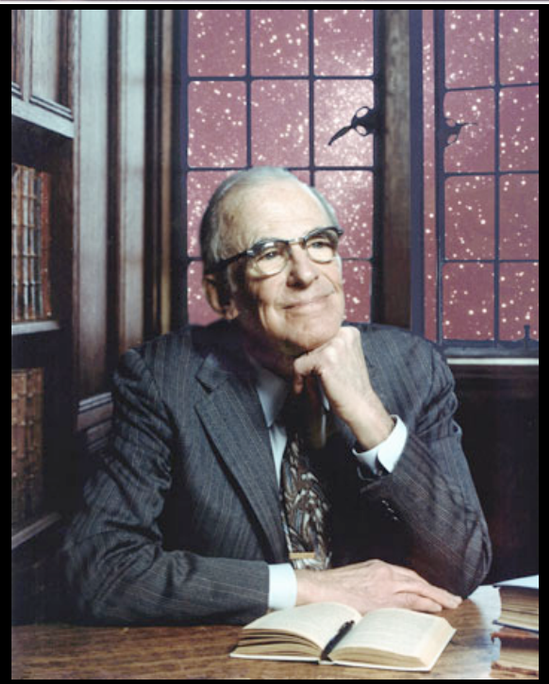


Galactic Halo Gas





ABSORPTION LINES PRODUCED BY GALACTIC HALOS

JOHN N. BAHCALL*
Institute for Advanced Study

AND

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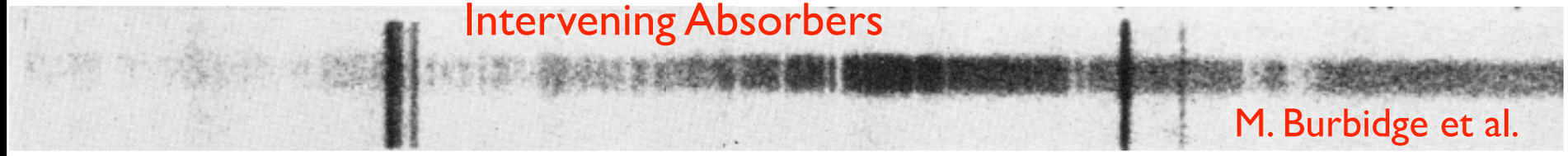
Princeton University Observatory

Received March 24, 1969

Intervening Absorbers



M. Burbidge et al.

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).

We are now recognizing that the CGM is (the?) a major reservoir of galactic baryons (Prochaska+11, Werk+13).

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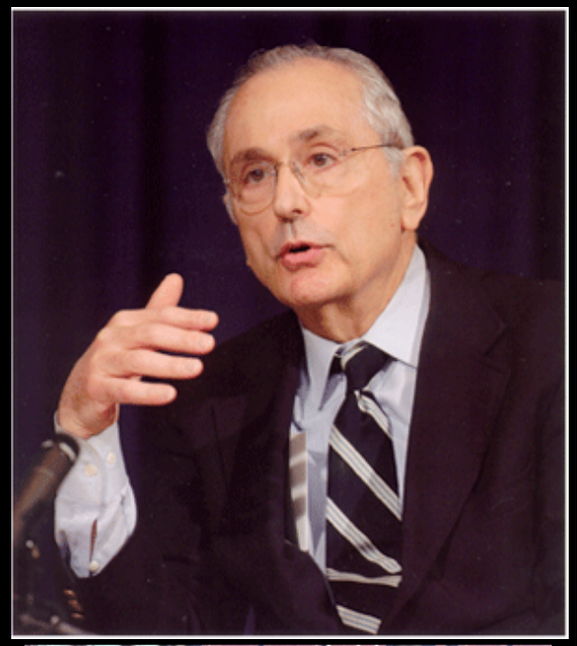

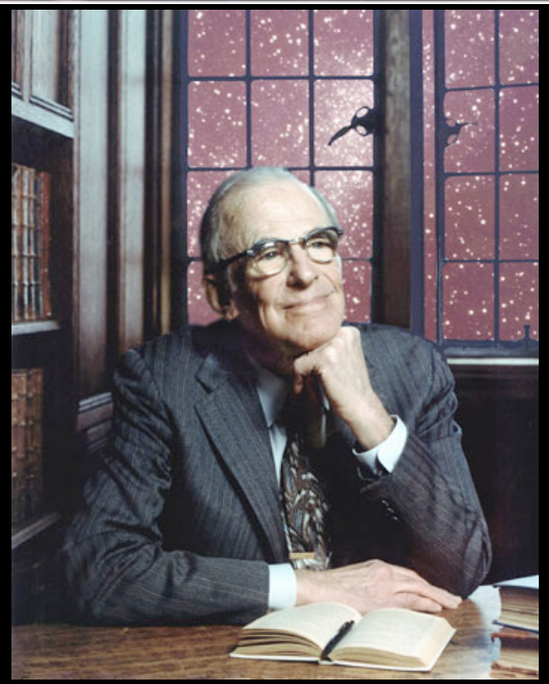

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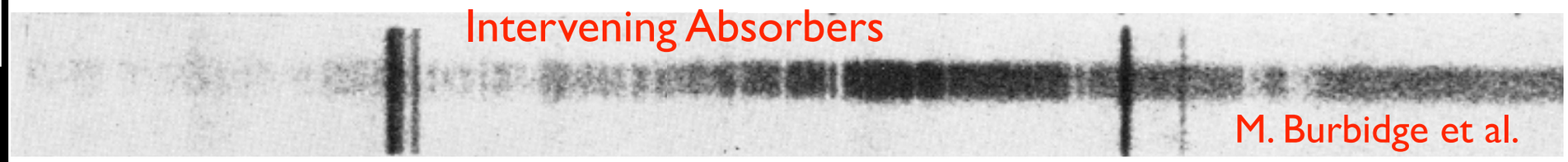

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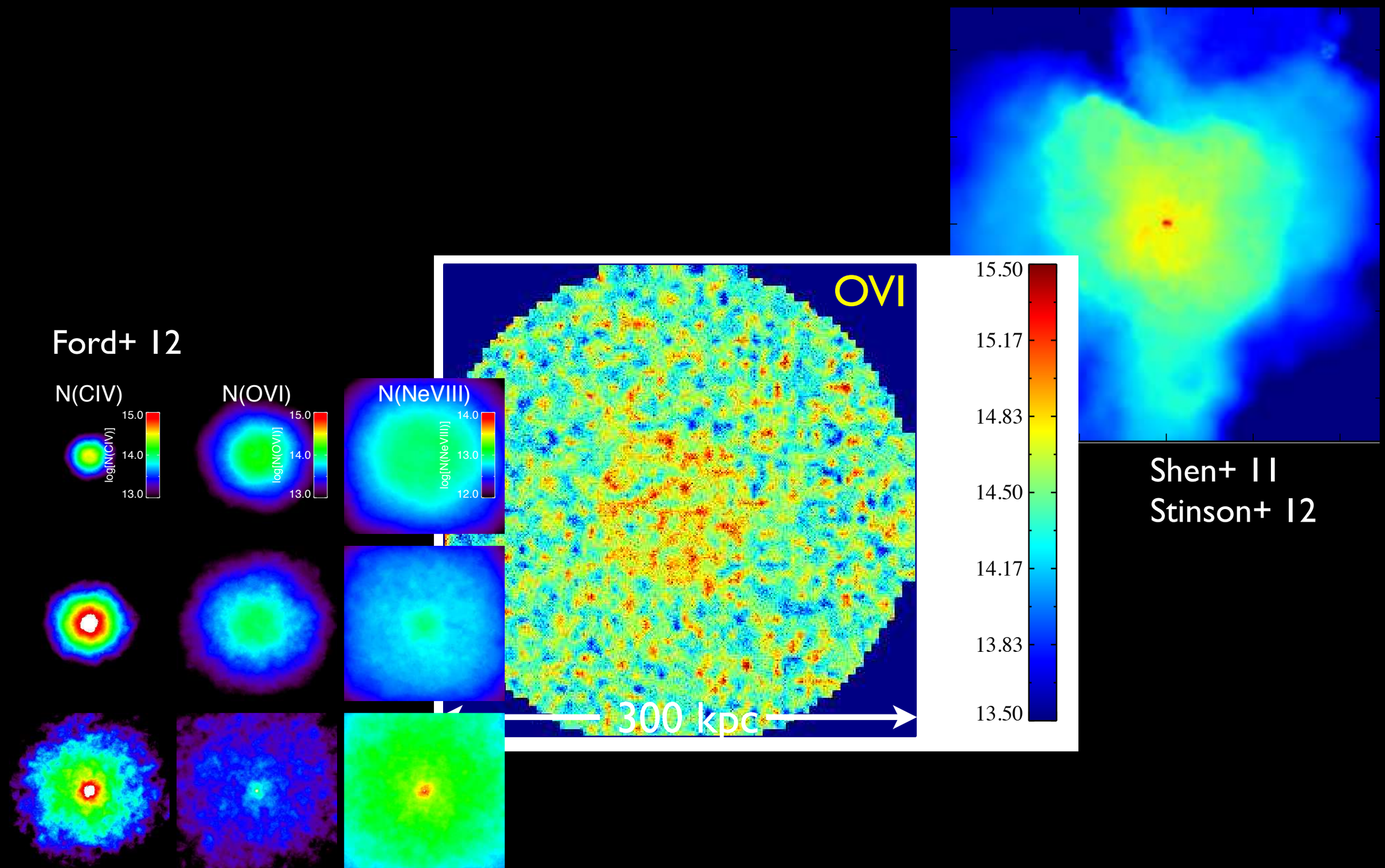

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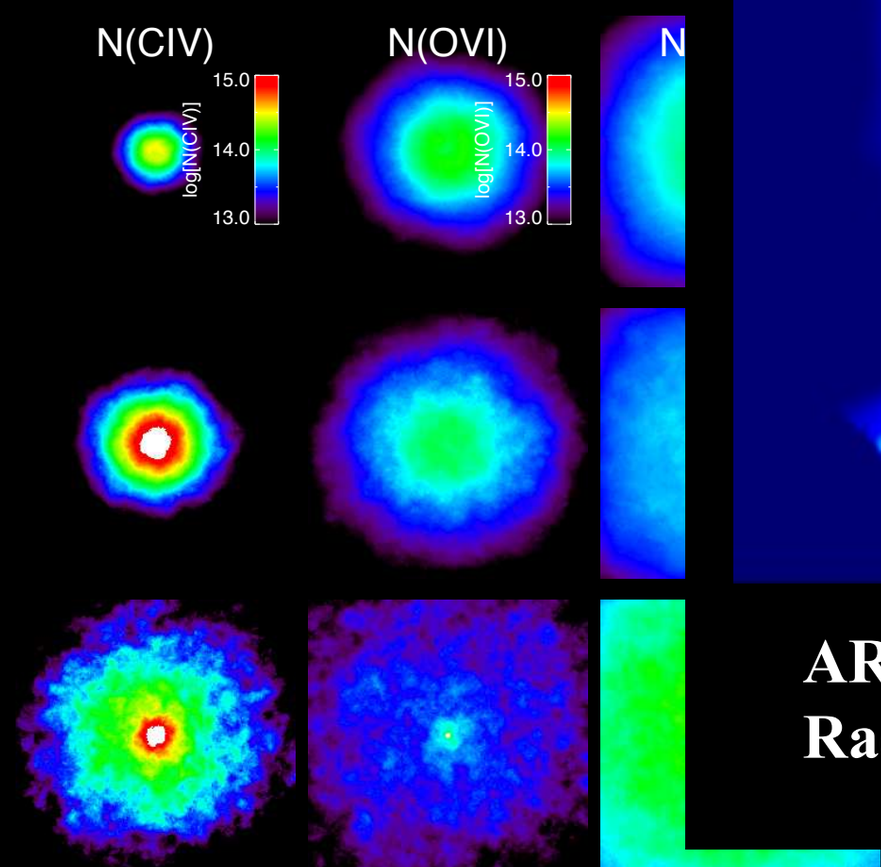
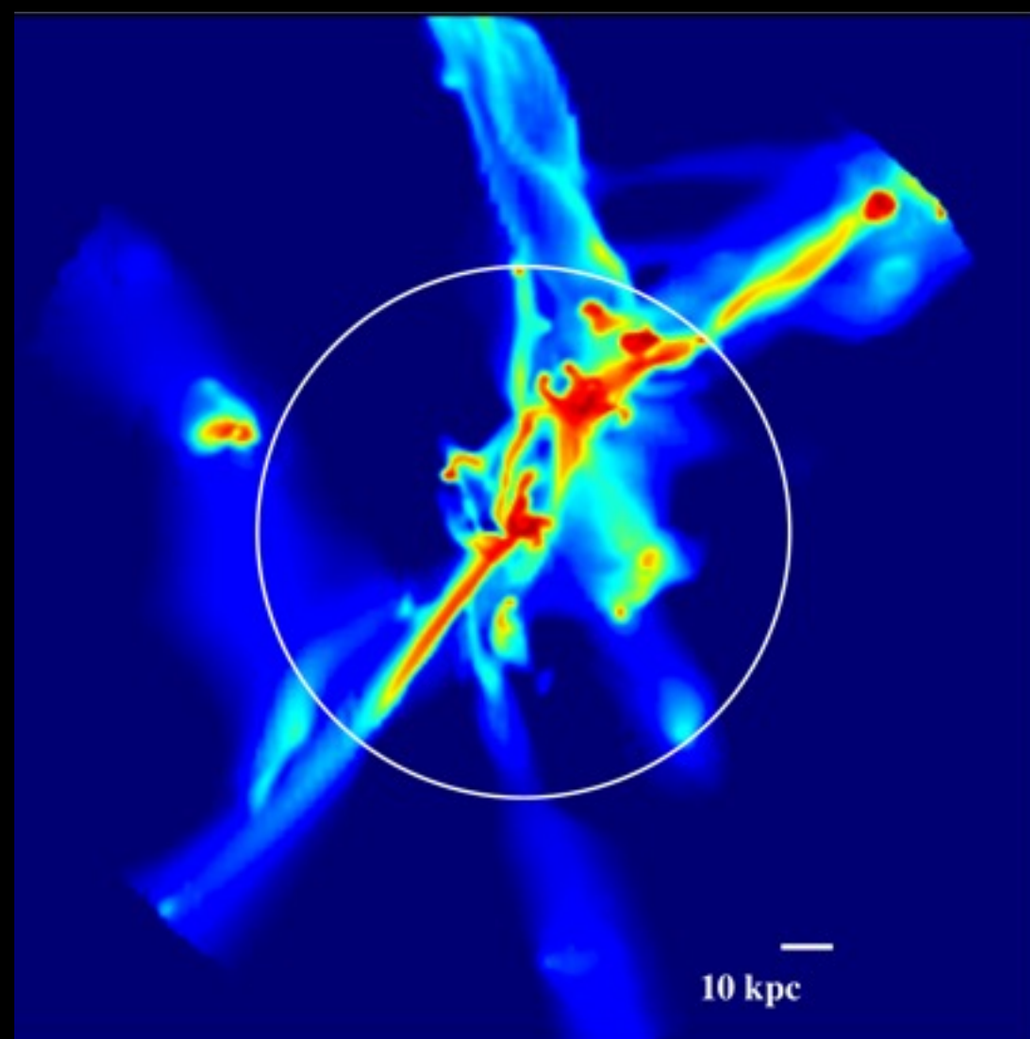
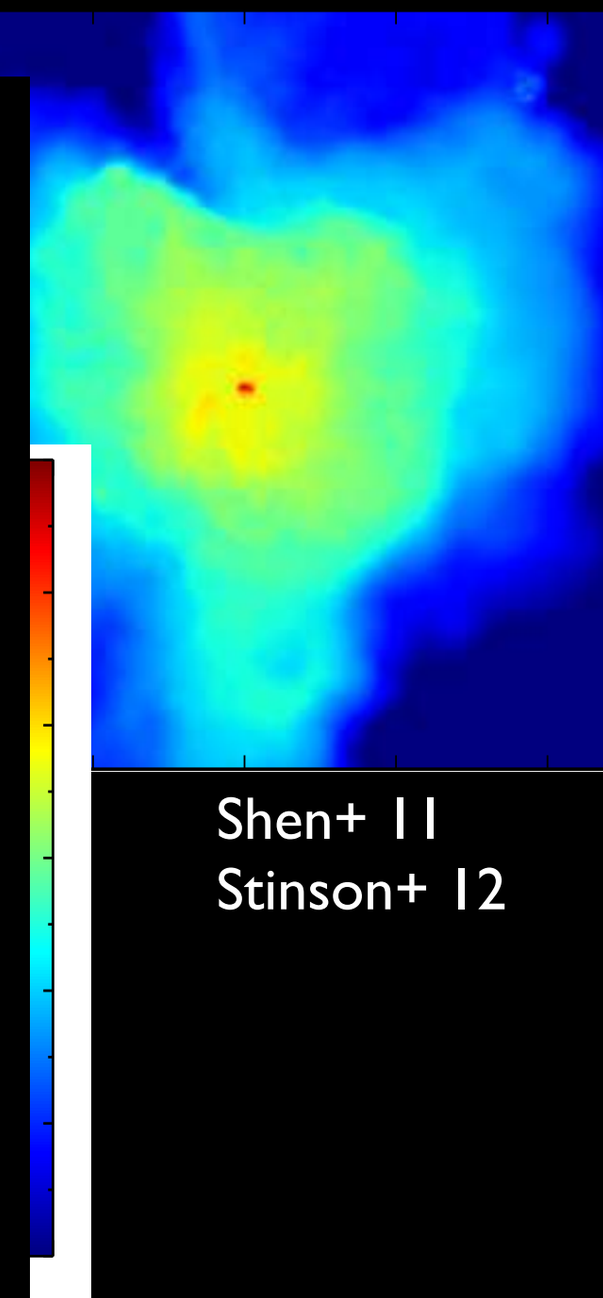
Ford+ 12



Simulated z~3 CGM



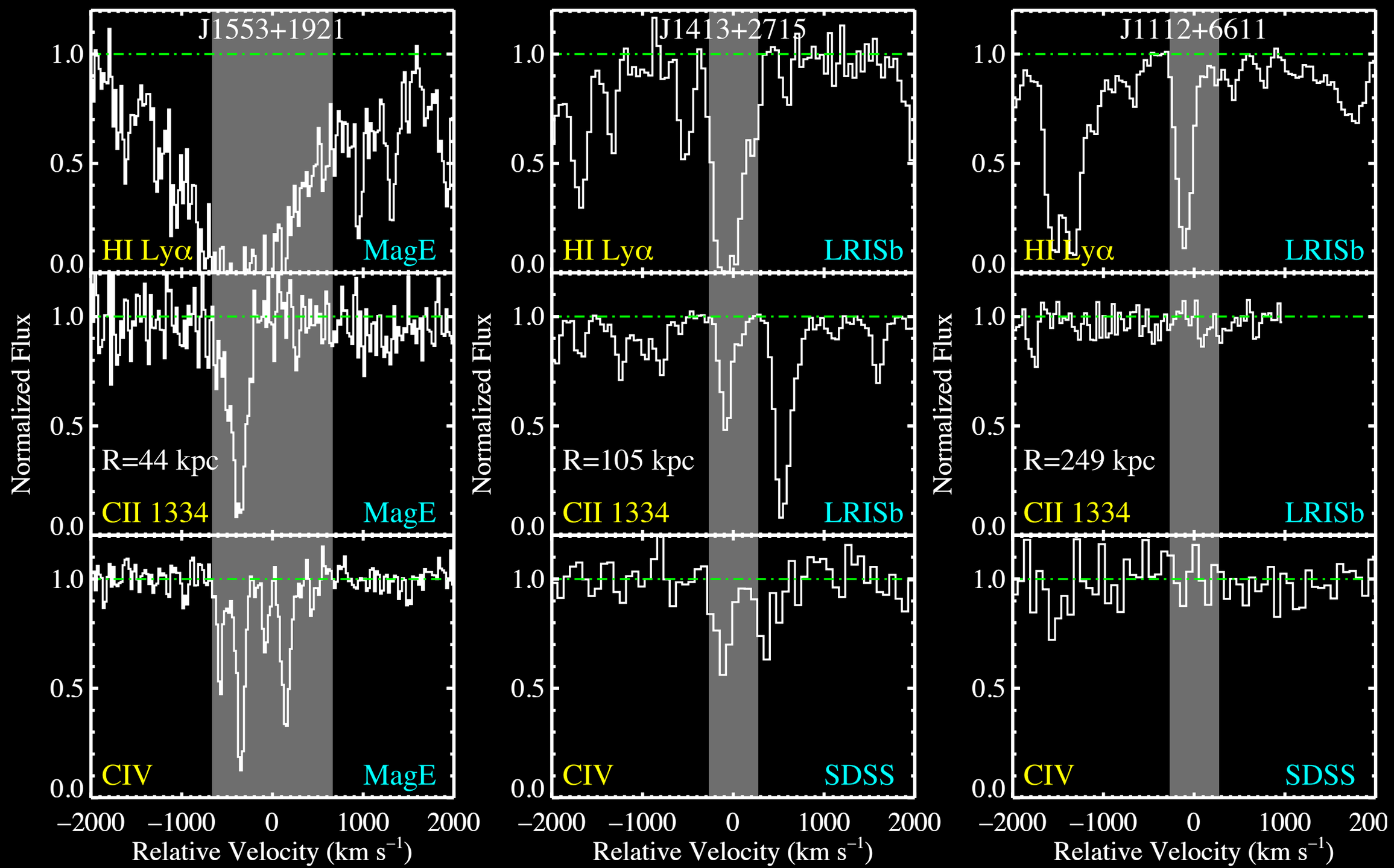


Shen+ 11
Stinson+ 12

ART AMR sims, (Ceverino+ 2010)
Rad. transfer (Fumagalli+ 2011)

CGM: Theoretical Exploration

The CGM of Massive z~2 Galaxies



J. Xavier Prochaska (UCO, UC Santa Cruz)

Inter(galactic+stellar) Medium Program of Studies [IMPS]

Quasar Pairs (Projected)

Hennawi+ 06

~200 pairs discovered in follow-up observations using candidates from SDSS, 2dF, etc.
Thousands with R>500kpc from SDSS/BOSS

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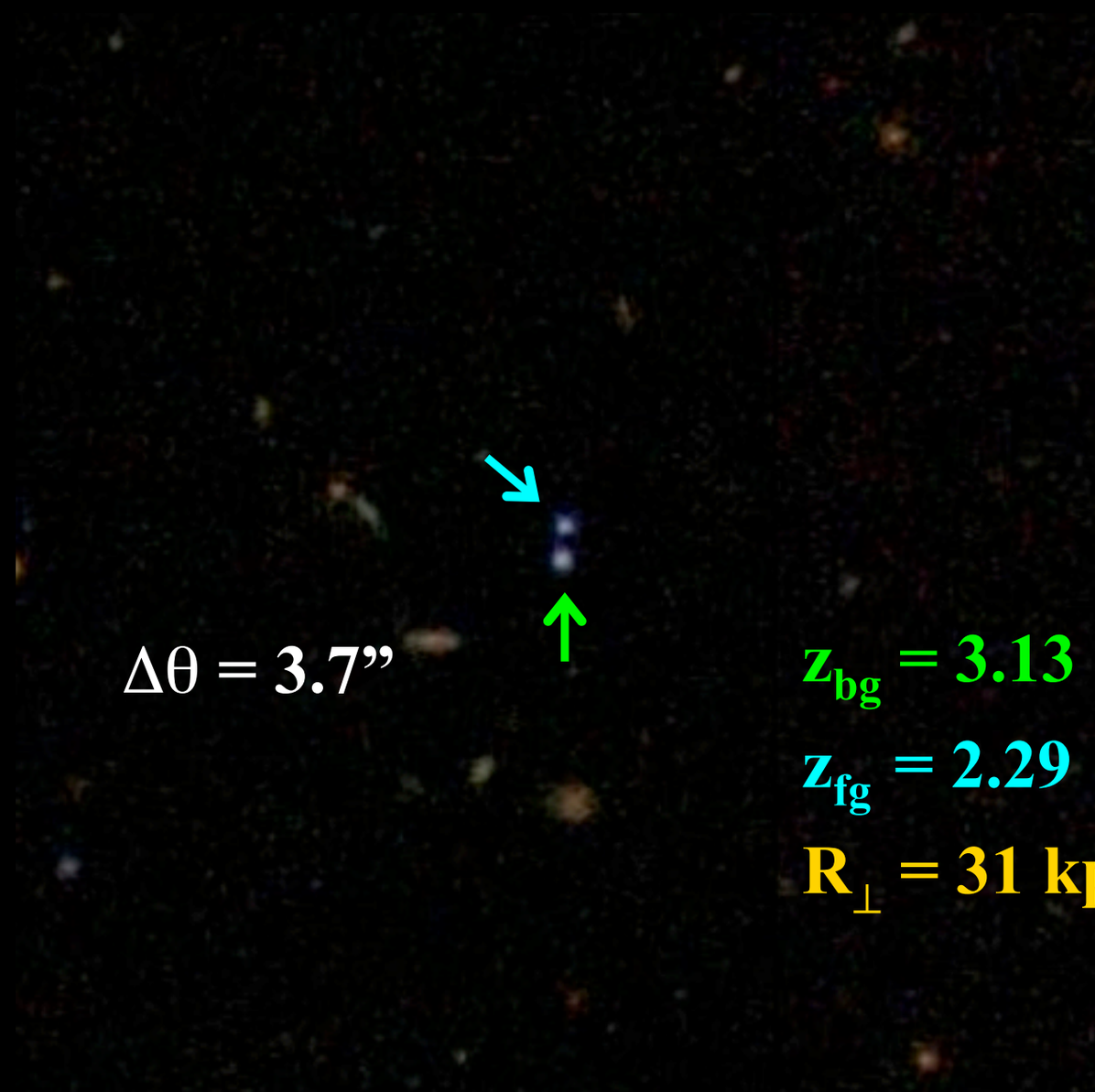

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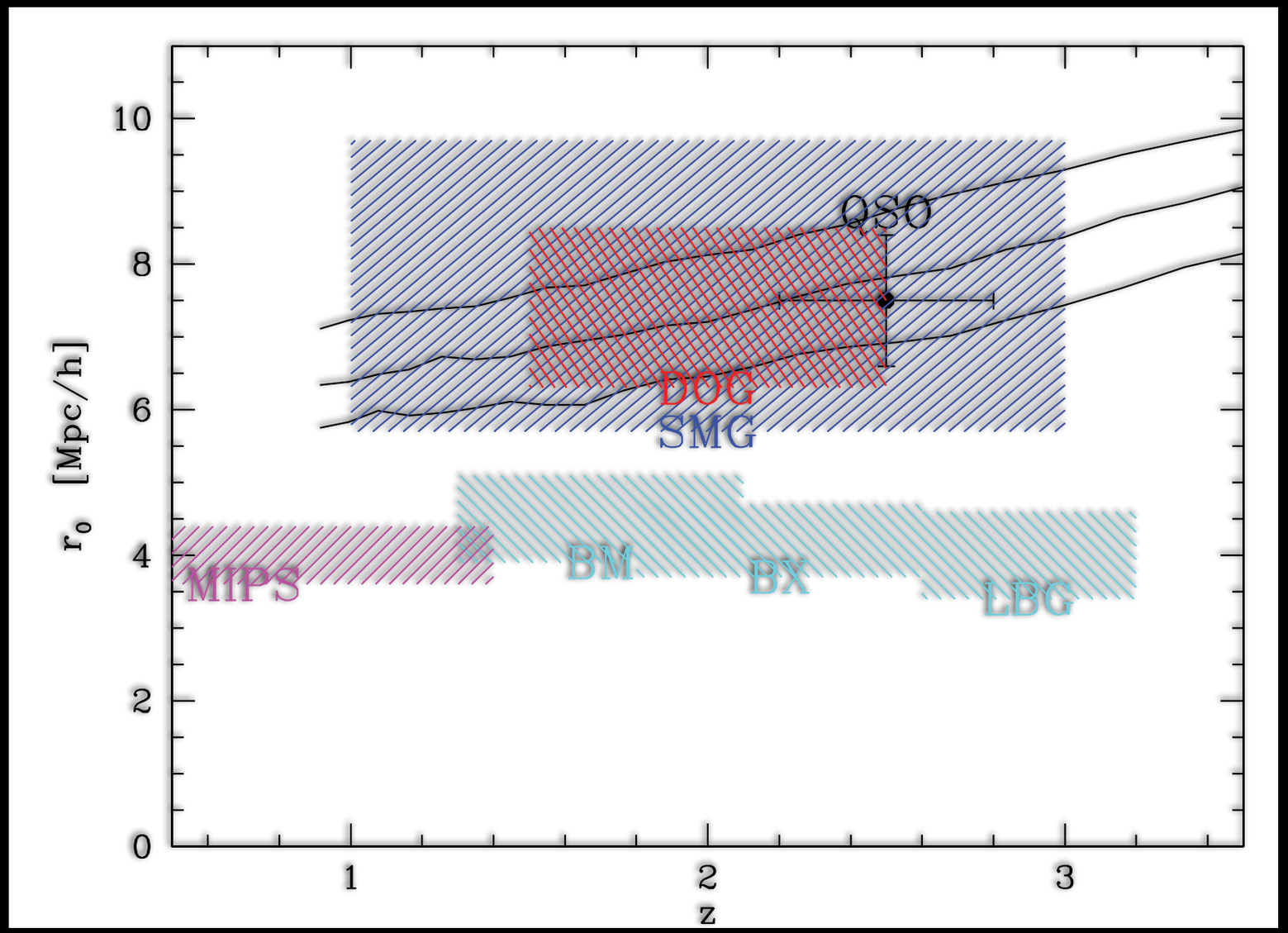
Quasar Clustering: Massive Galaxies



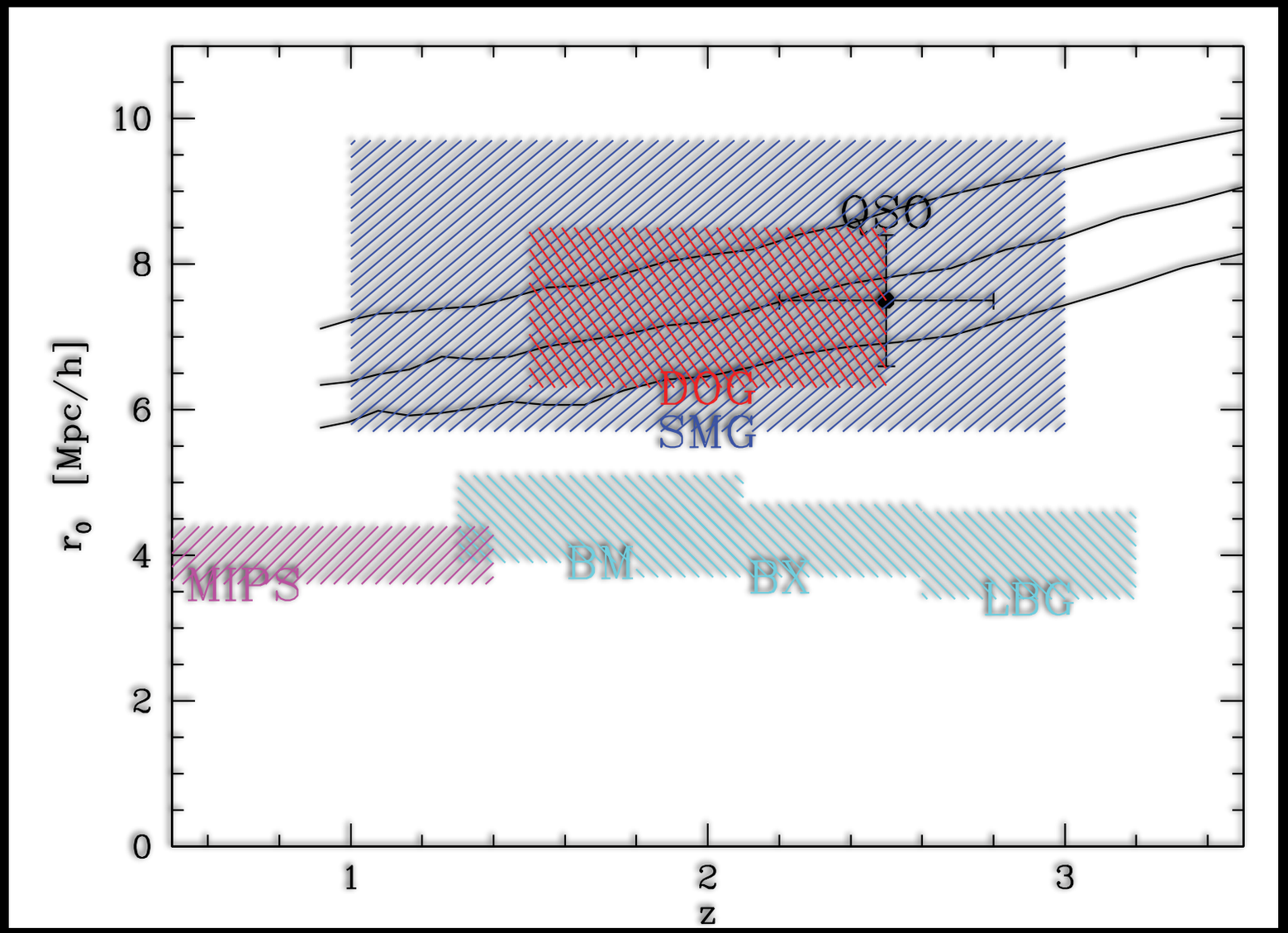
Porciani+07
White+12 (BOSS)

$r_0 \sim 7$ Mpc/h

$M_{halo} \sim 10^{12.5} M_{Sun}$

The f/g Quasar 'tags' a massive host galaxy.
These evolve (preferentially) into massive ellipticals.

Quasar Clustering: Massive Galaxies



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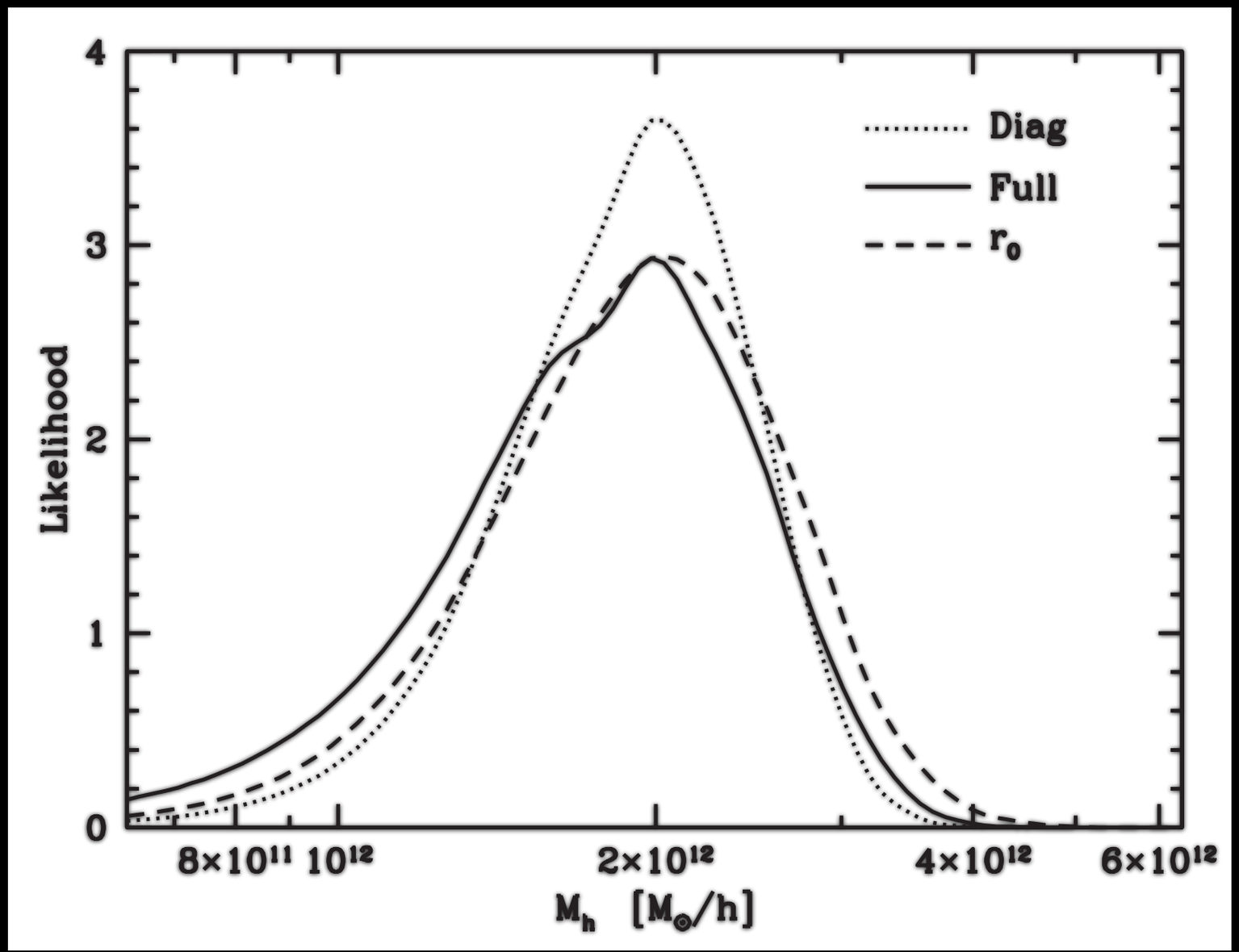
$r_0 \sim 7$ Mpc/h

$M_{halo} \sim 10^{12.5} M_{Sun}$

The f/g Quasar 'tags' a massive host galaxy.
These evolve (preferentially) into massive ellipticals.

Quasar Clustering: Massive Galaxies



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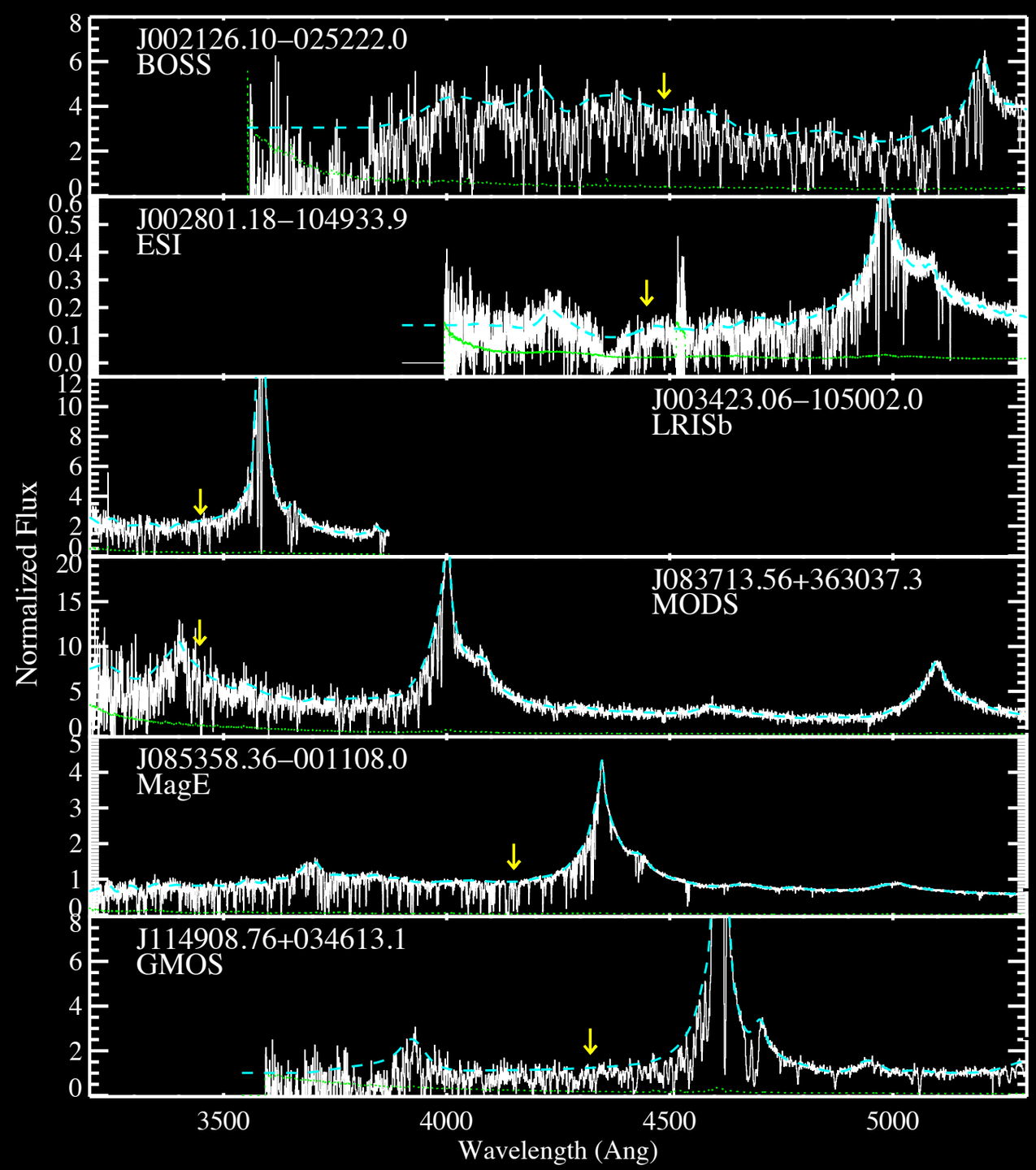
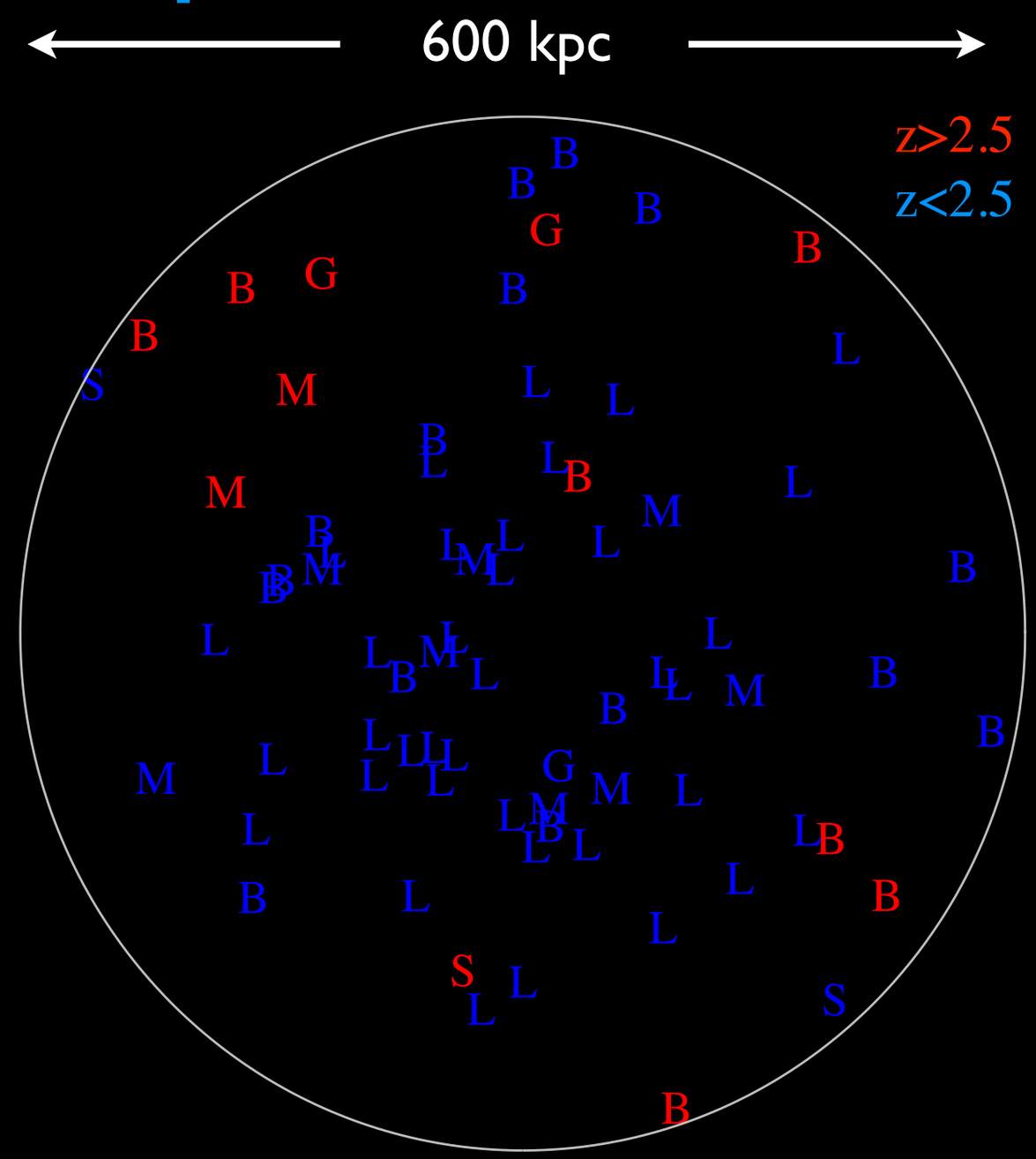
These evolve (preferentially) into massive ellipticals.

A "Subtlety": Quasar Feedback

The QSO *may* affect the CGM.
Radiatively and/or with kinetic feedback.

QPQ5 Sample





QPQ5: Pro,H,Simcoe 13

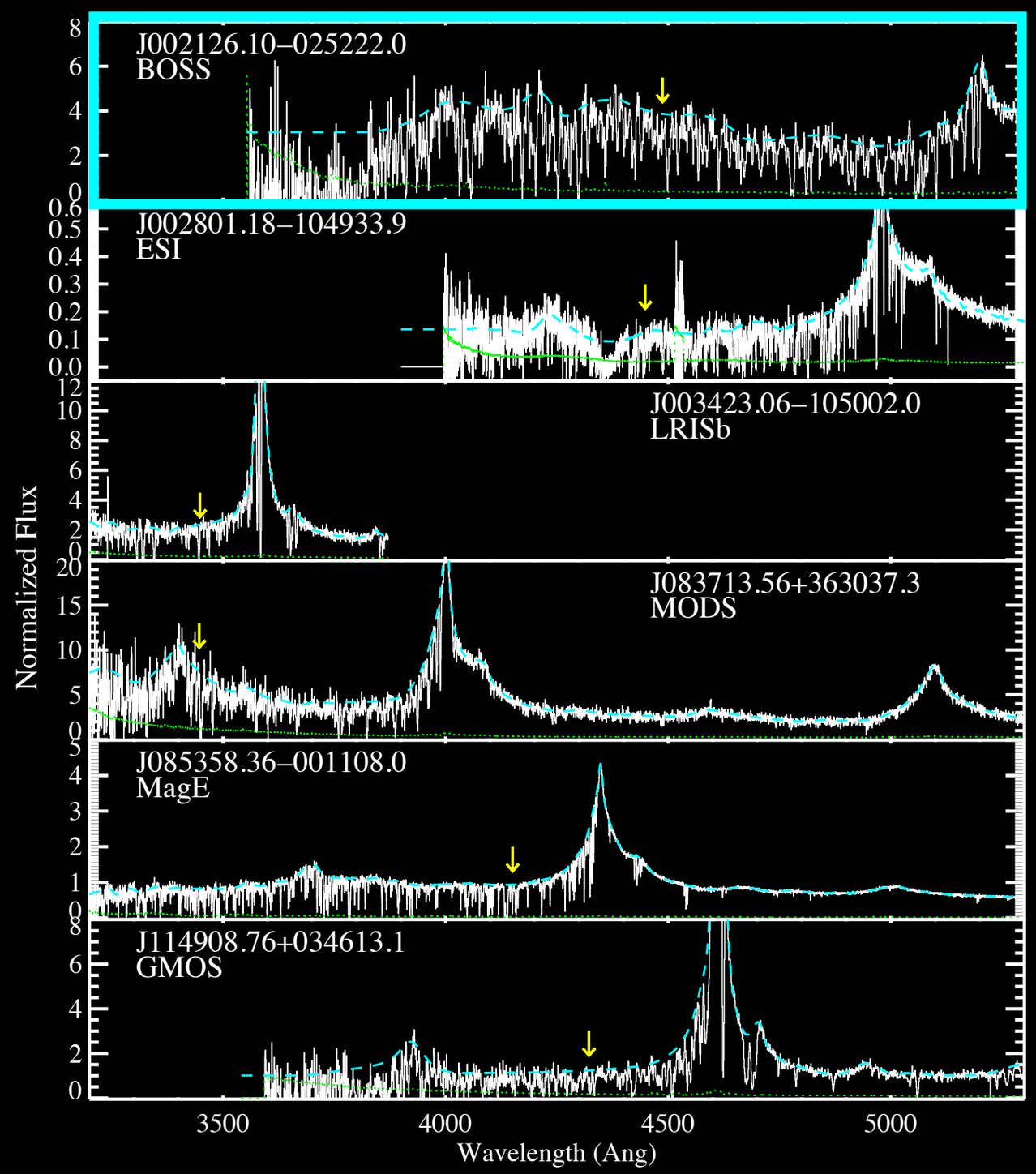
$\delta v > 4000$ km/s (40 Mpc)

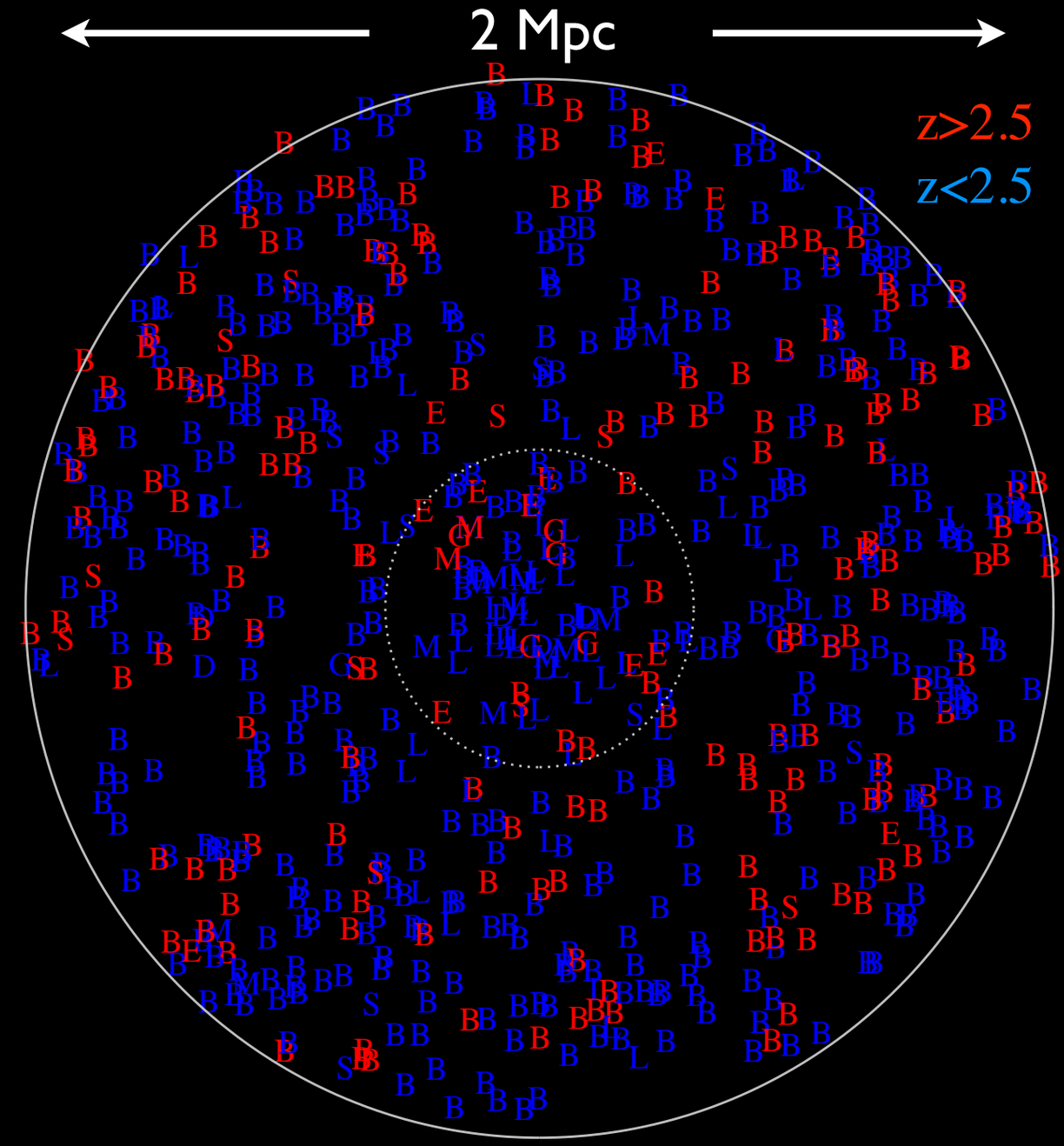
$R_{phys} < 300$ kpc

$z_{fg} > 1.7$

$L_{Bol} \sim 10^{46}$ erg/s

QPQ6/7 Sample





QPQ6/7: Pro+ 13

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$R_{phys} < 1$ Mpc

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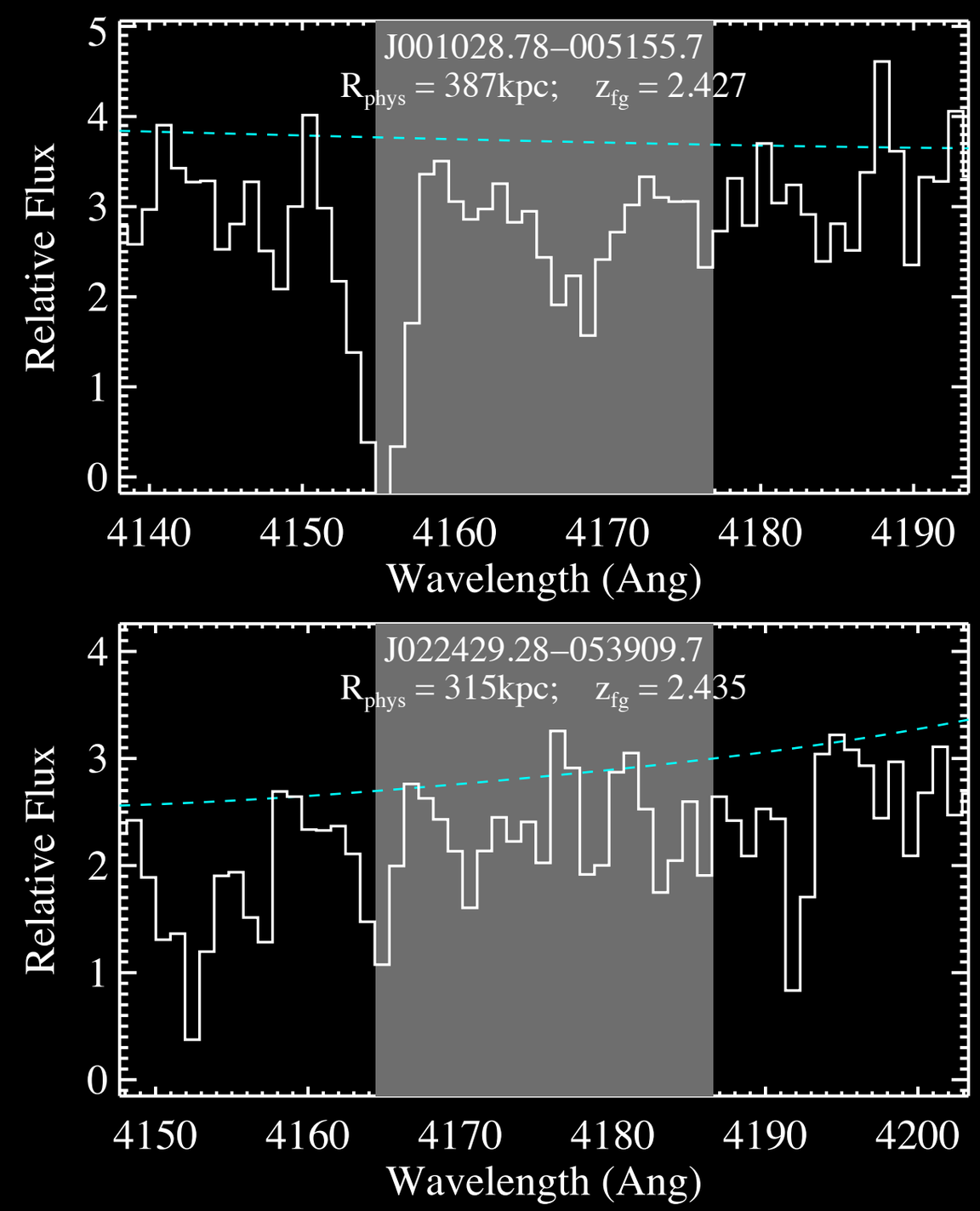
QPQ: Challenges to CGM Analysis

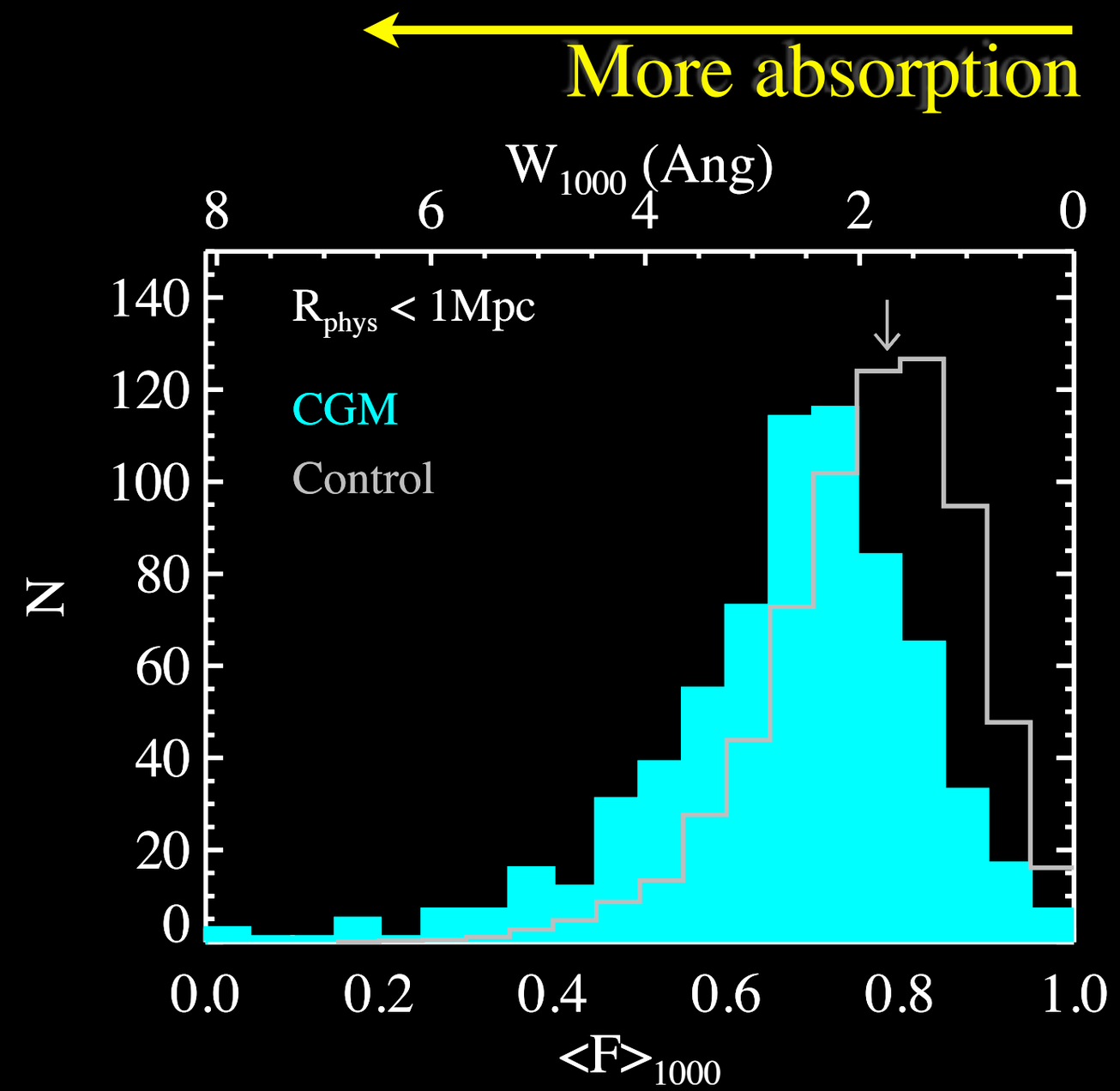
- QSO redshifts are notoriously uncertain
  - Re-analyzed every f/g spectrum
    - Restrict to higher quality cases
    - σ_{min} = 272 km/s; σ_{max} = 800km/s
- IGM presents a non-negligible 'background' at z>2
  - Is the absorption CGM?
- QSO continua are difficult
  - Especially at z>2.5
- Quasar emits copious ionizing radiation
  - Eliminate/modify the CGM?

4000 km/s region centered on Lyα of f/g QSO



Blunt HI Measure: Individual <F>

- Average flux
  - Centered on z_{fg}
    - Window of +/- 1000 km/s
  - Control sample drawn from QPQ6
- Enhanced HI absorption above the mean IGM
  - 15% lower <F>
  - Assessed from control
    - And independent IGM measures
- Enhancement extends to at least 1 Mpc
  - Signal is dominated by R>500 kpc sightlines



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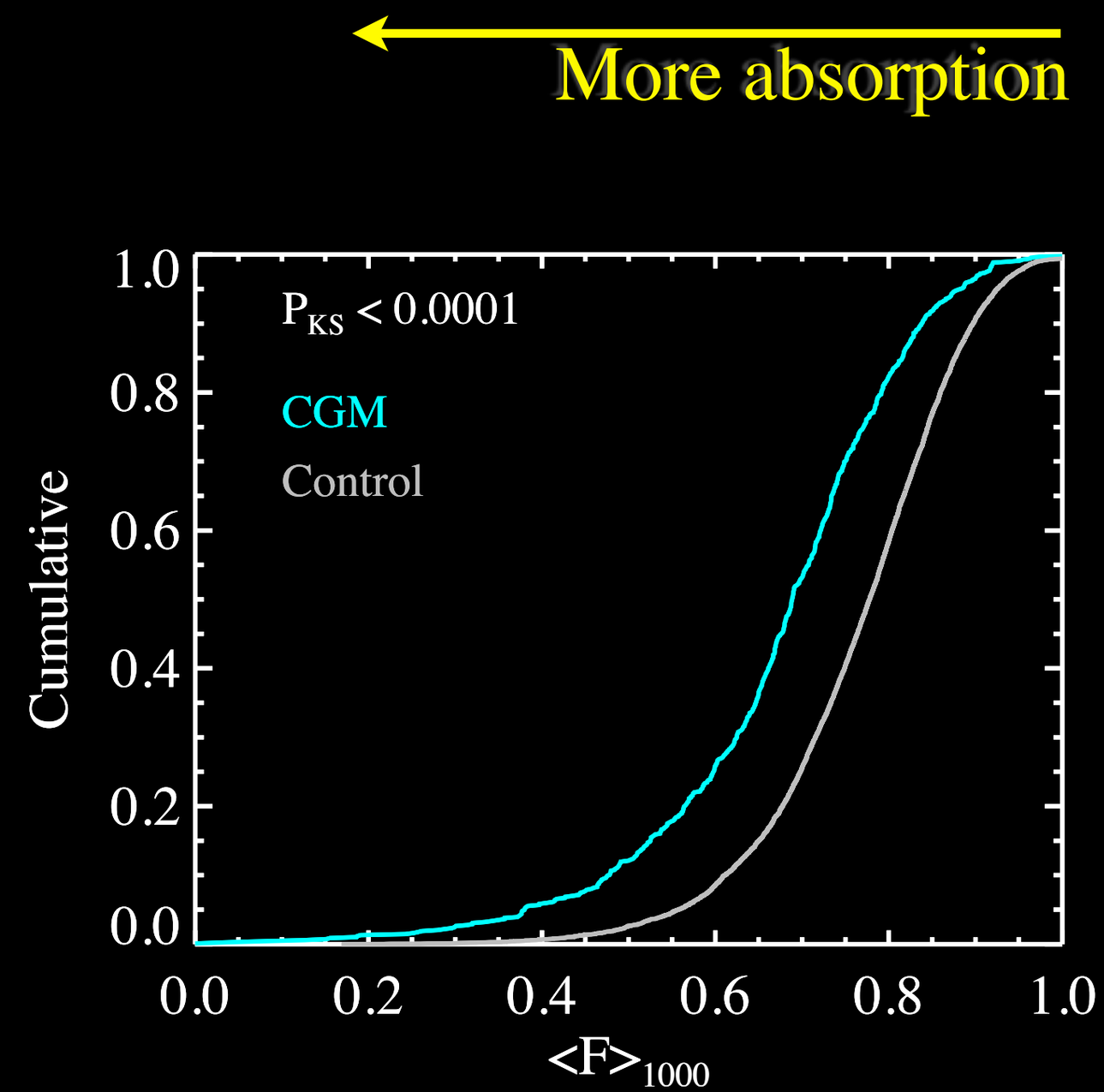
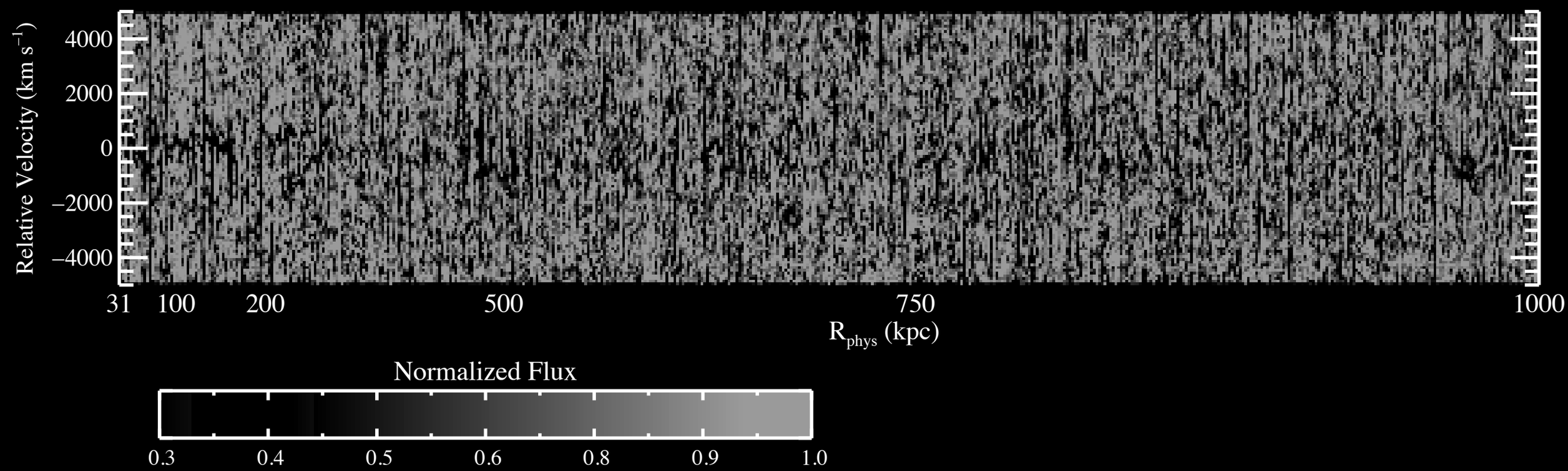
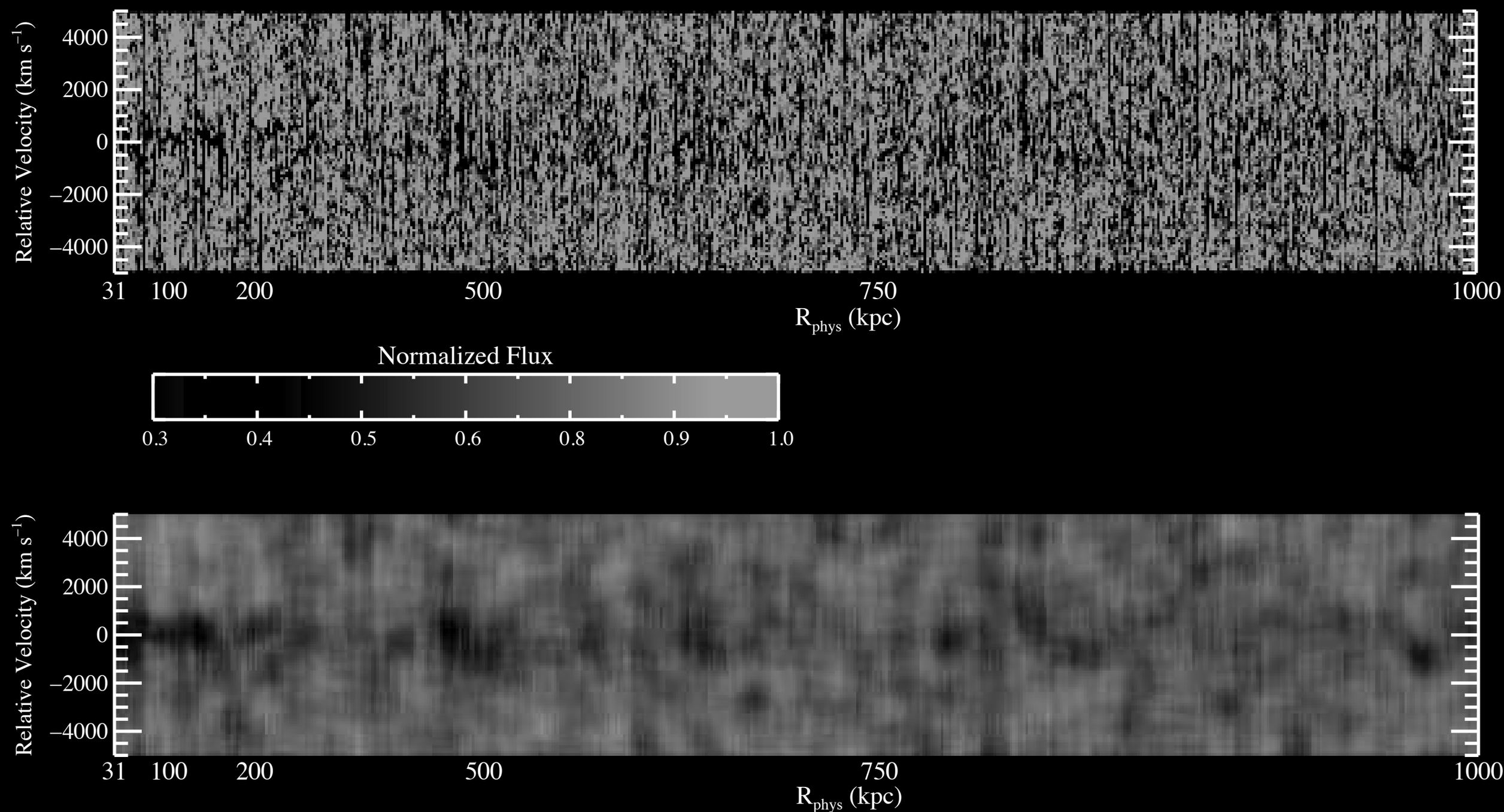


Mapping <F>


Relative Velocity (km s^{-1})
4000
2000
0
−2000
−4000
31
100
200
500
750
1000
R_{phys} (kpc)
Normalized Flux
0.3
0.4
0.5
0.6
0.8
0.9
1.0

Mapping <F>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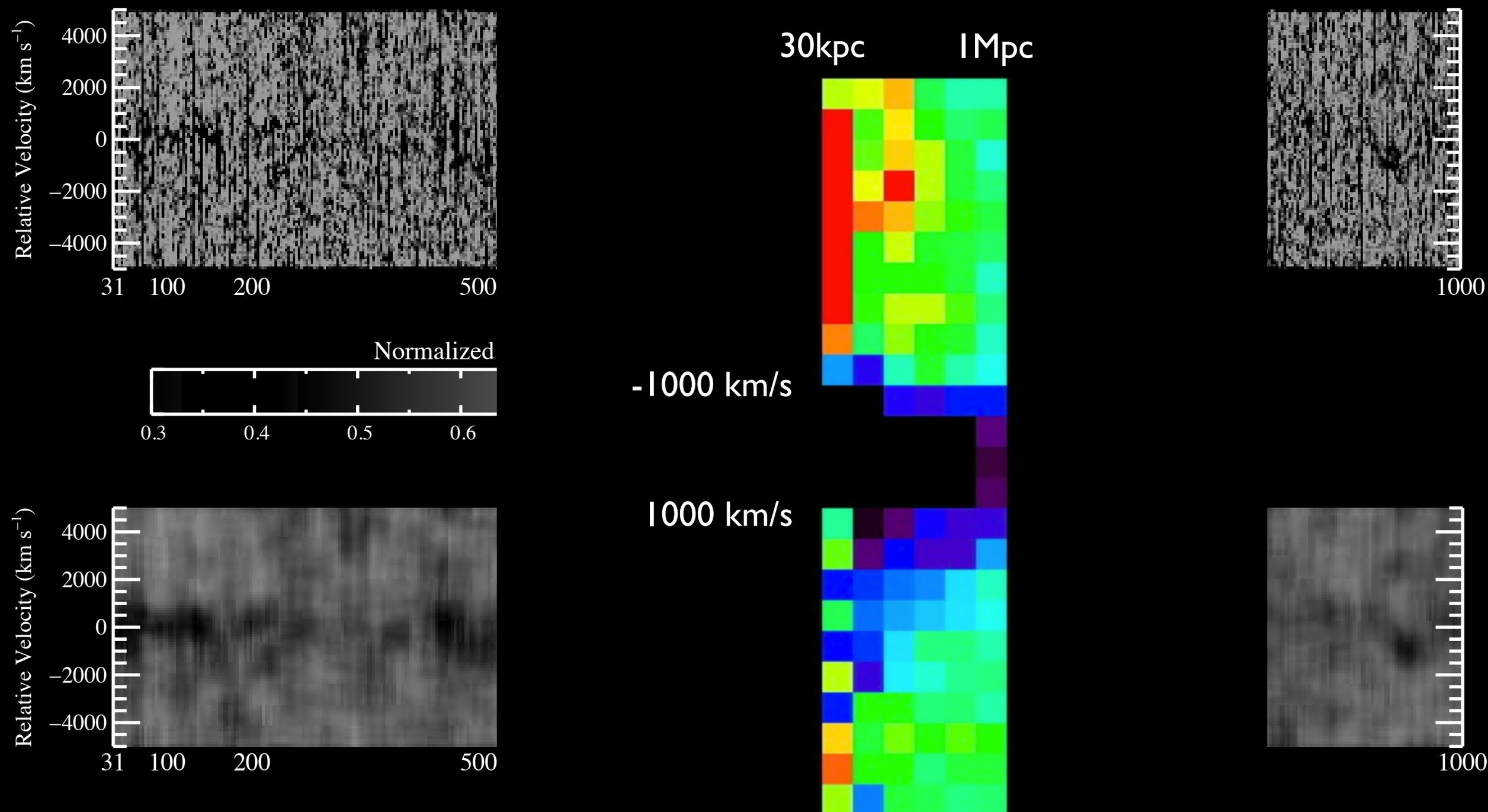
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0.4
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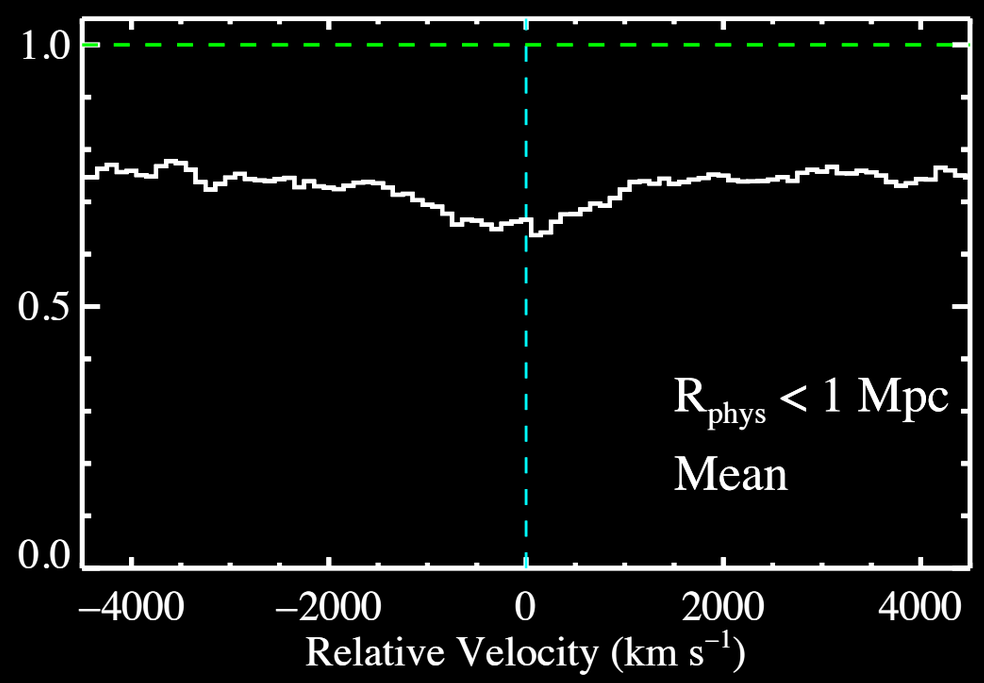
30kpc
1Mpc
-1000 km/s
1000 km/s

Stacked Spectra at HI Lya



QSO redshift errors are washed out.
So are continuum uncertainties and the IGM!

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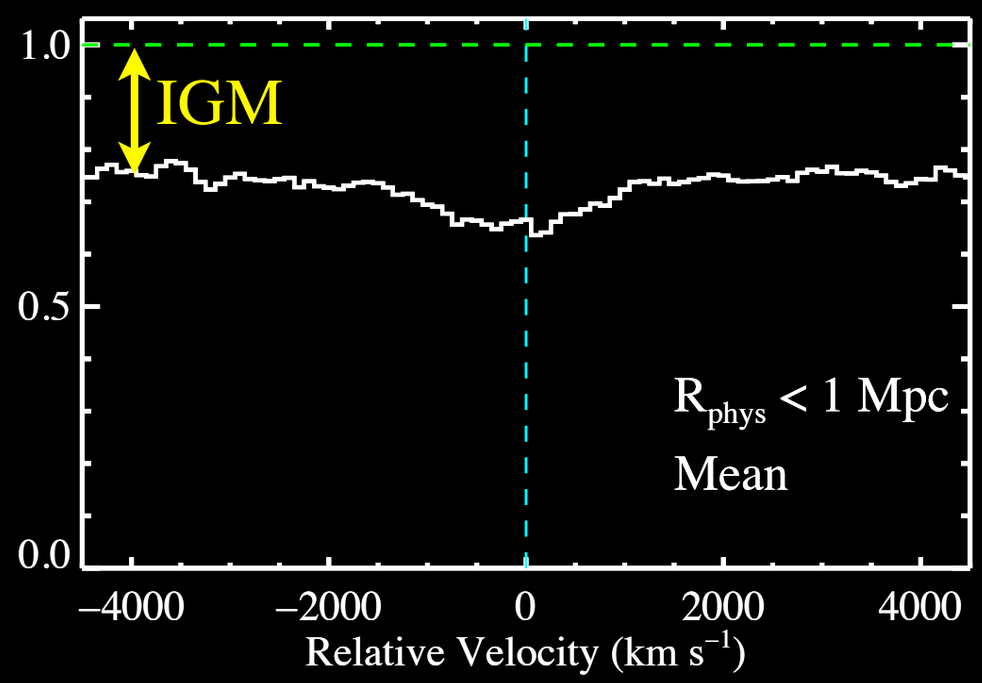

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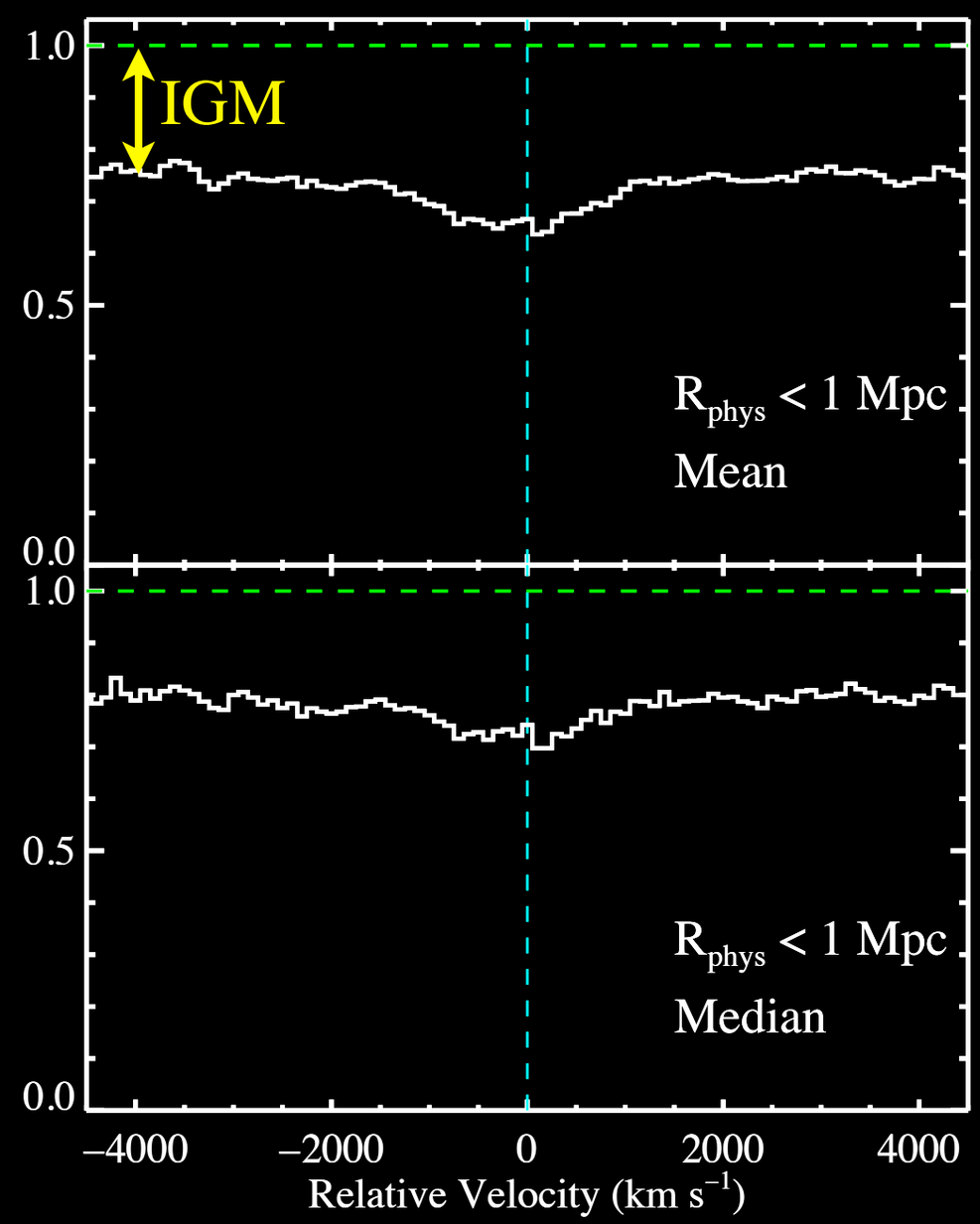

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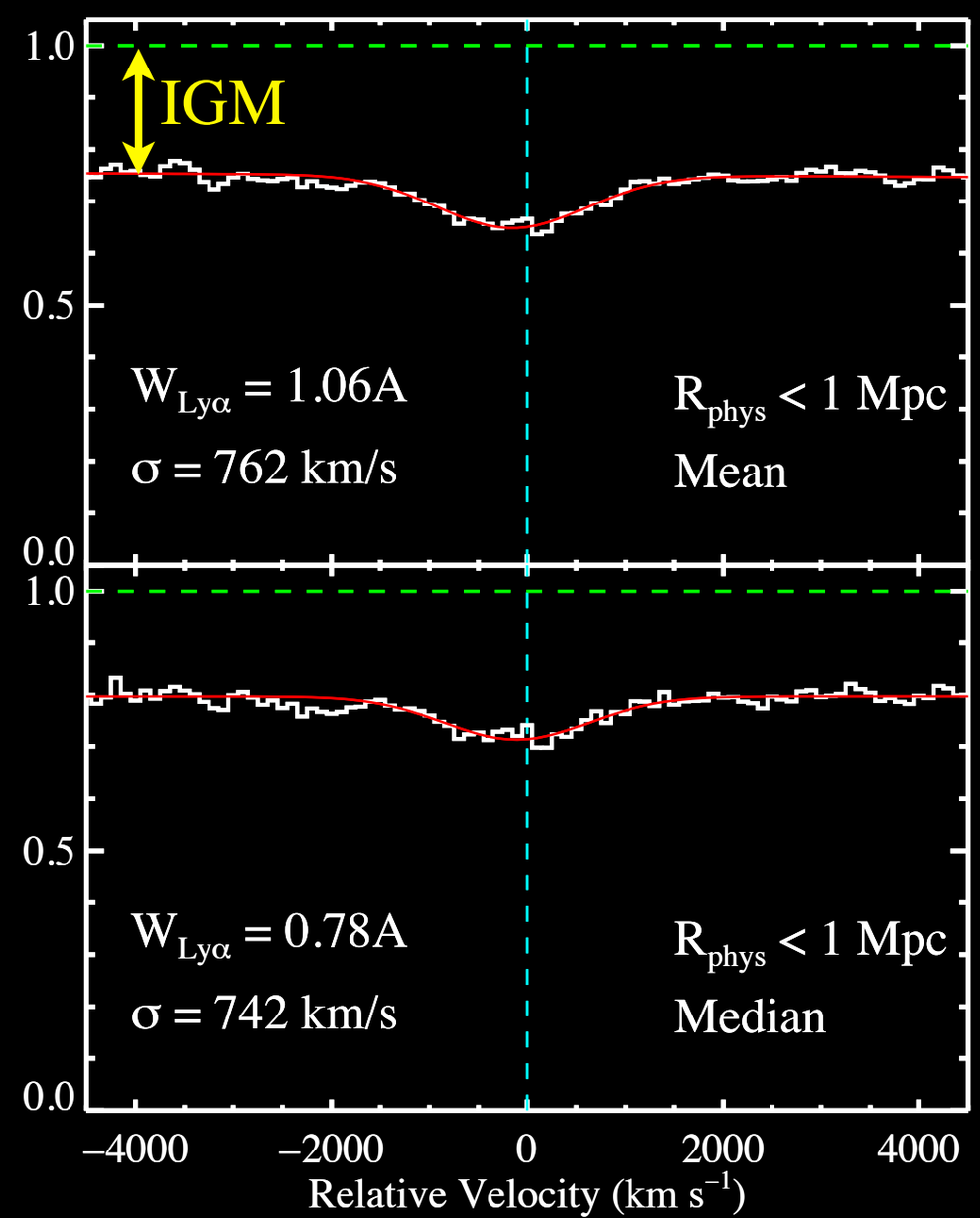

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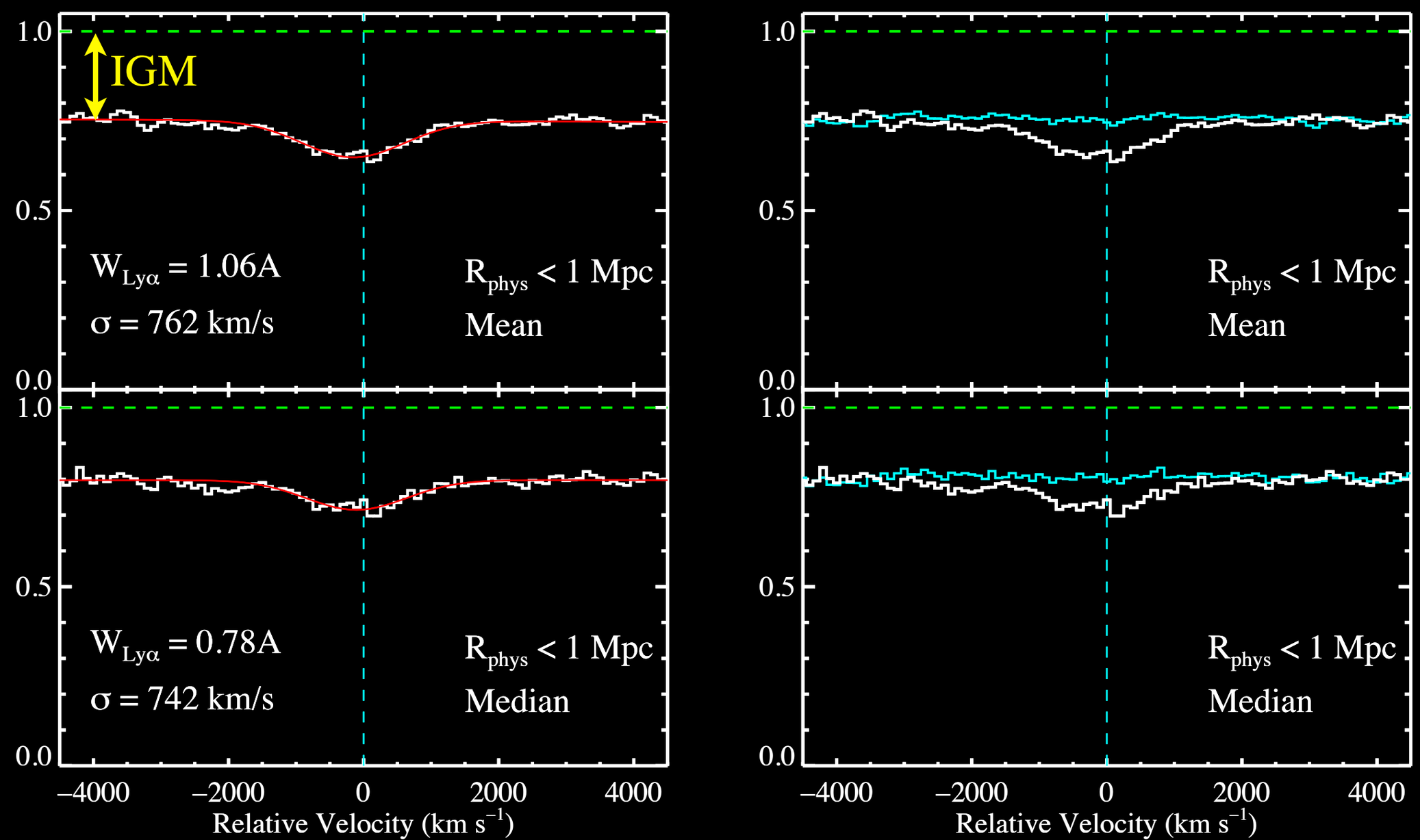

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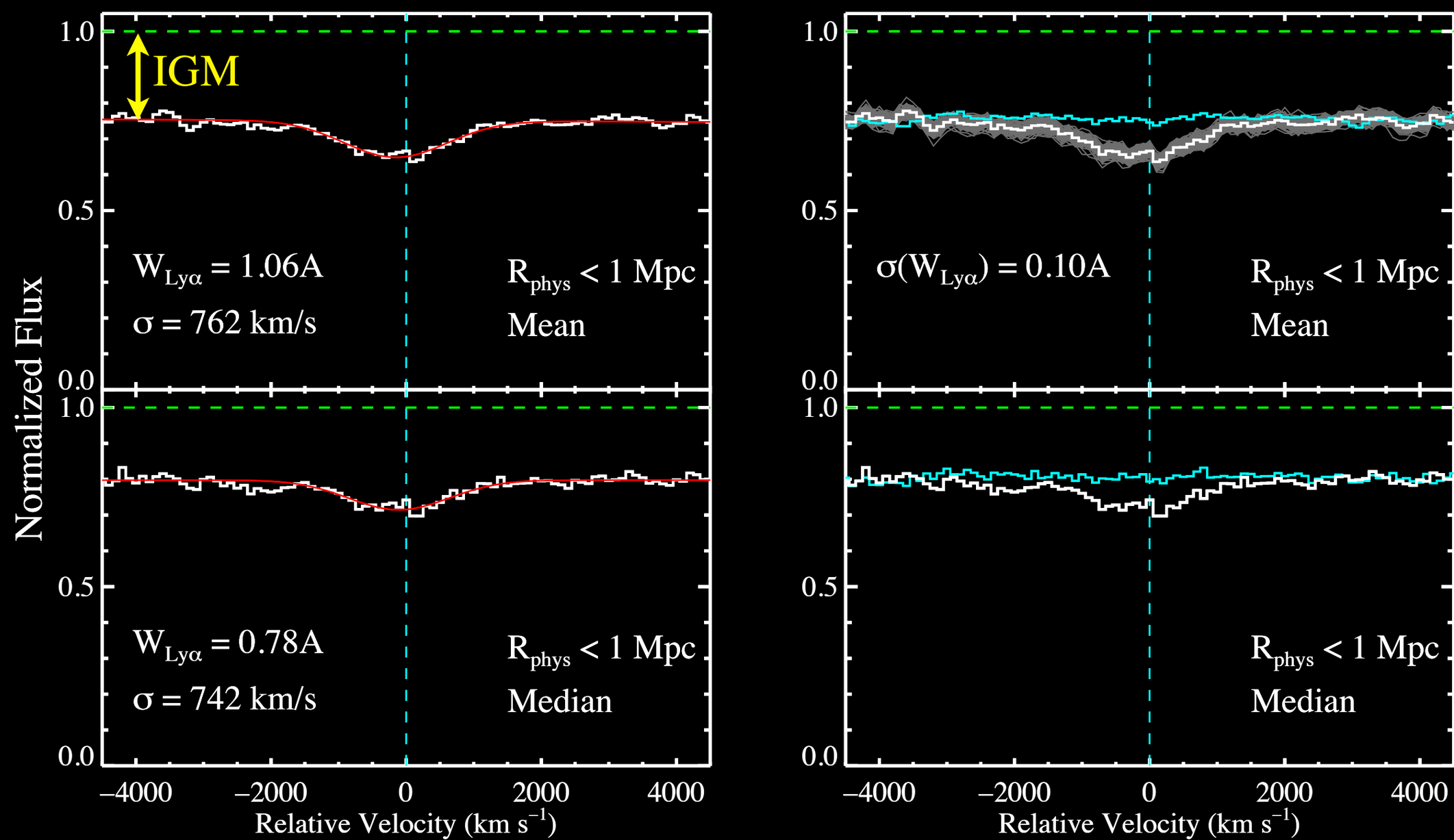

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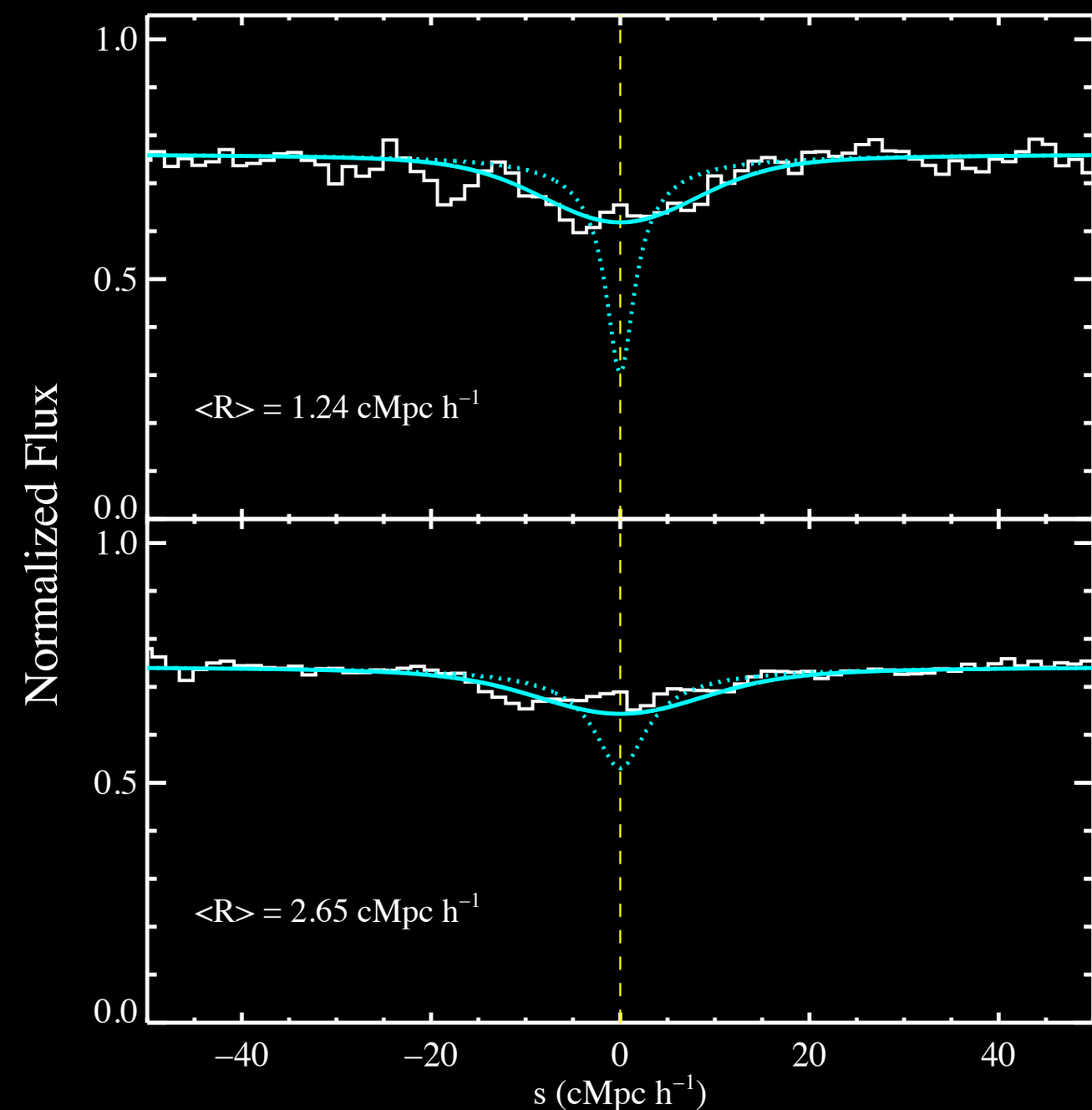
So are continuum uncertainties and the IGM!

QSO Host Mass: <F> at ~2 cMpc/h

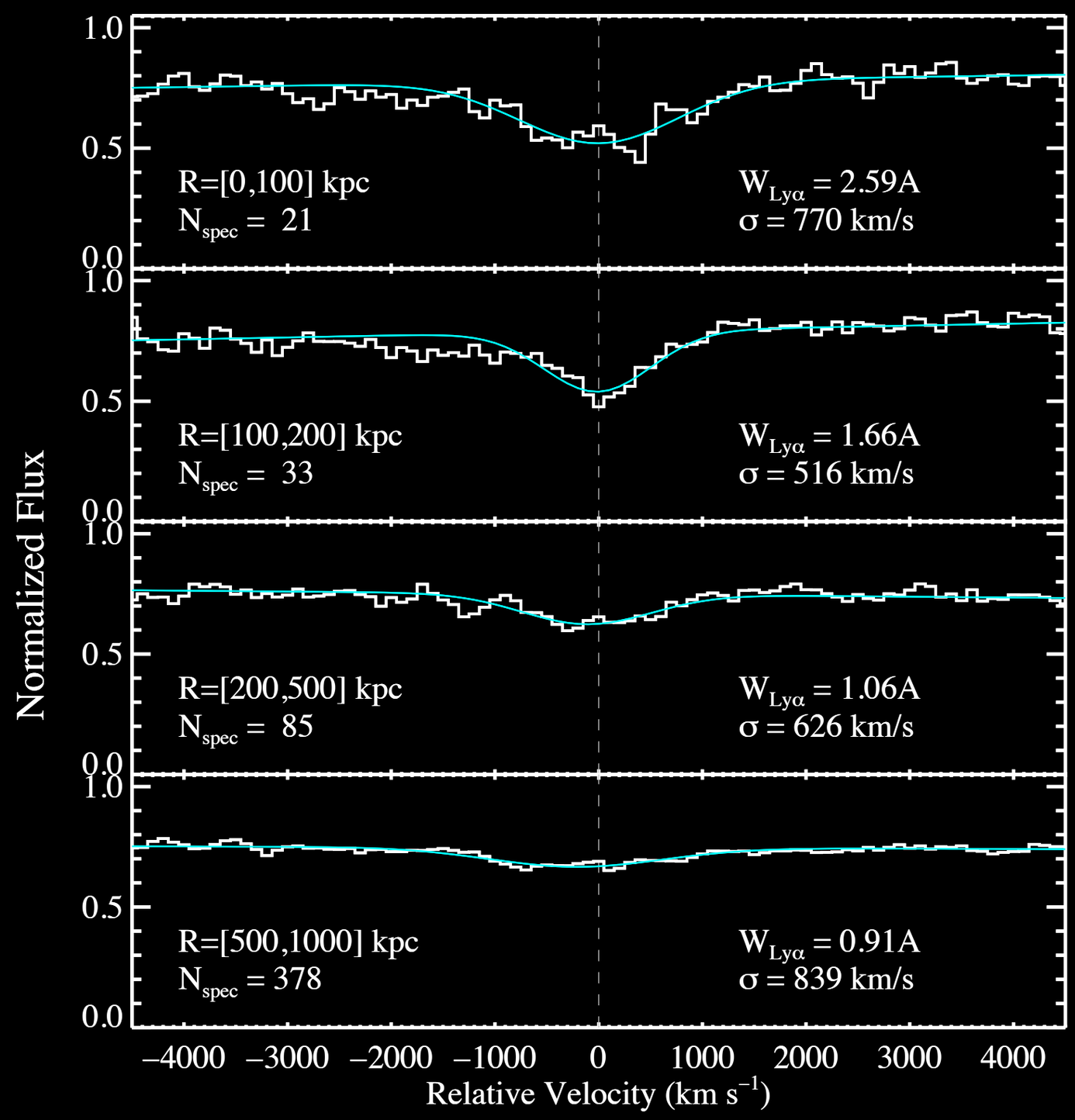
- IGM traces overdensity
  - Calculations in the quasi-linear regime
    - Must avoid the CGM
    - Need to run simulations on halos with $M >> 10^{12}\ M_{Sun}$
  - Cross-correlation yields mass
    - e.g. Kim & Croft 2008

$$< F(r) >= \exp\left\{ -\tau_{\rm eff} \left[1 + \left(\frac{r}{r_0} \right)^{-\gamma} \right] \right\}$$

- Current results
  - Entirely ignore QSO radiation!
  - Extrapolation of estimations from $M < 10^{12}\ M_{Sun}$
    - $M_{Halo} = 10^{12.5}\ M_{Sun}$ at $z \sim 2.5$
    - Consistent with clustering measures



$W_{Ly\alpha}$ vs. Impact Parameter



- $W_{Ly\alpha}$
  - Measured relative to the mean IGM opacity
    - Measured away from z_{fg}
  - Gaussian fit to the absorption
    - Reasonable model of the data
- Current results
  - Strong anti-correlation between $W_{Ly\alpha}$ and R_{phys}
    - $W_{Ly\alpha}$ at R<200 kpc exceeds 1.5 Ang!
  - Is there a distinct CGM??
    - Difficult to prove using stacked spectra...

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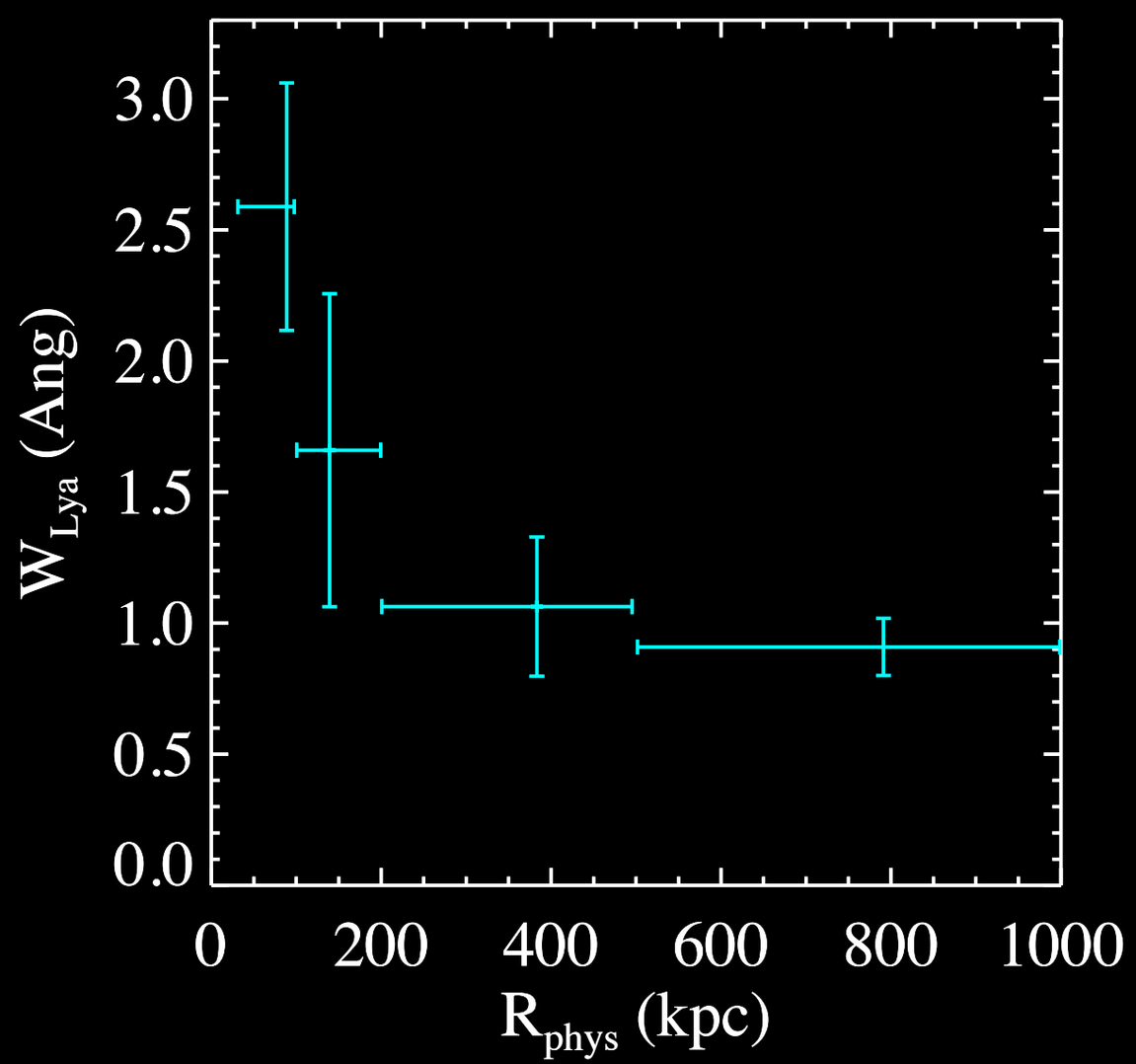

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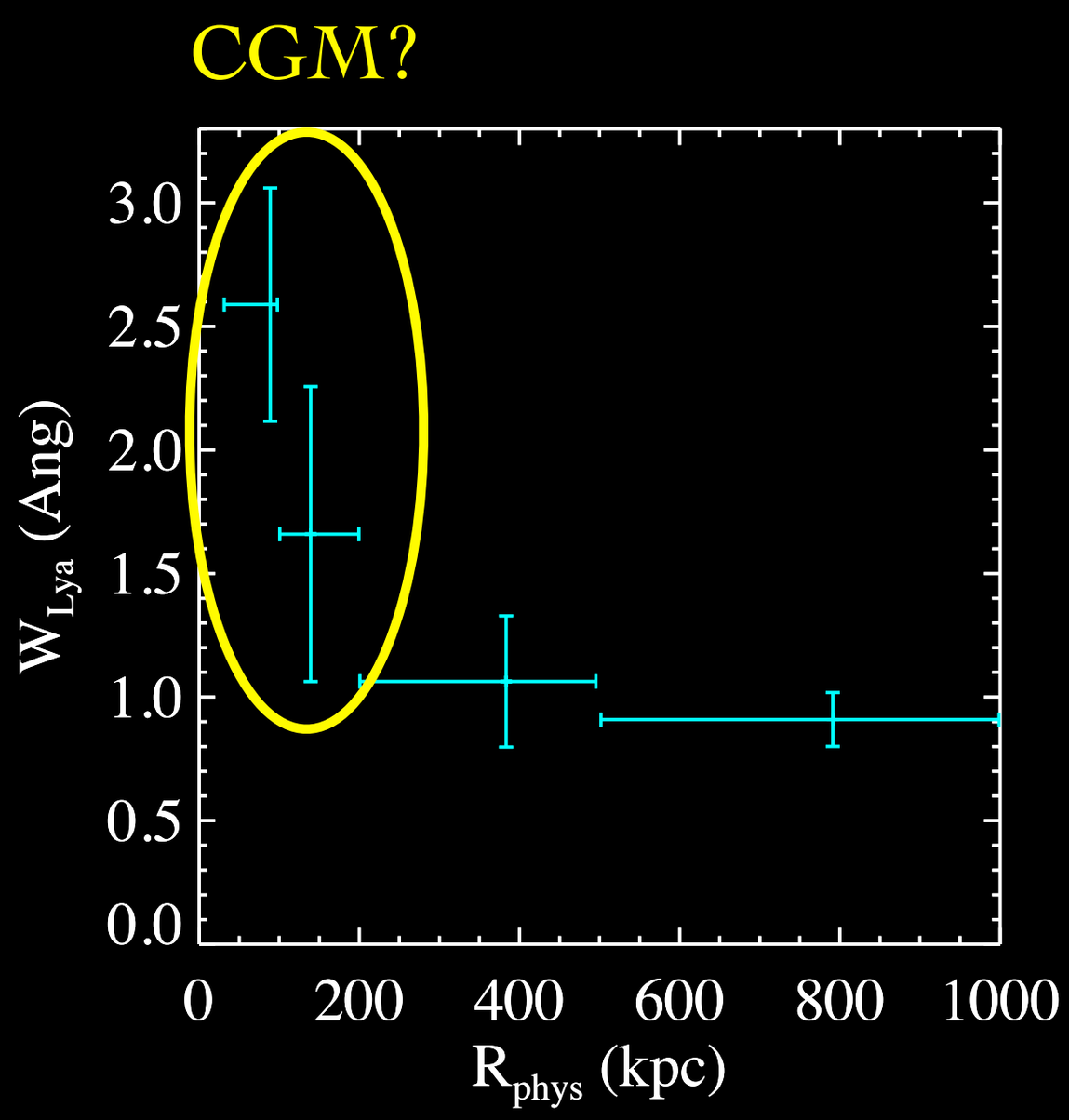

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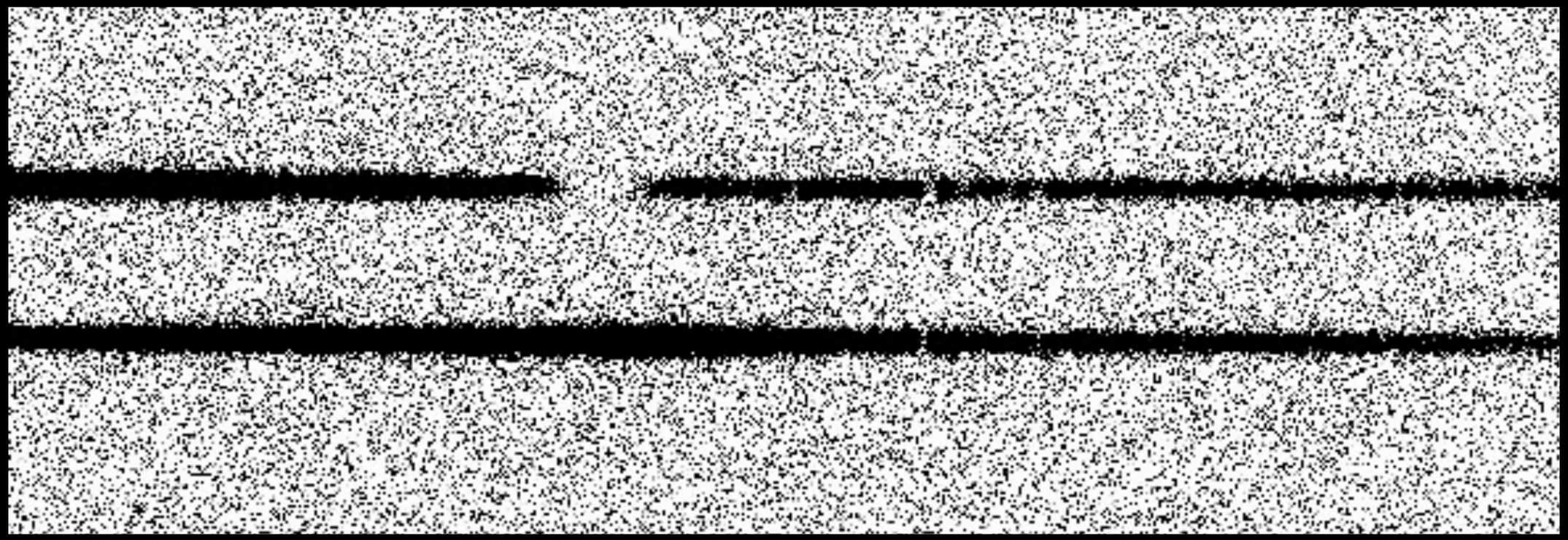
HI Absorption at R < 300 kpc

Keck/LRIS spectrum



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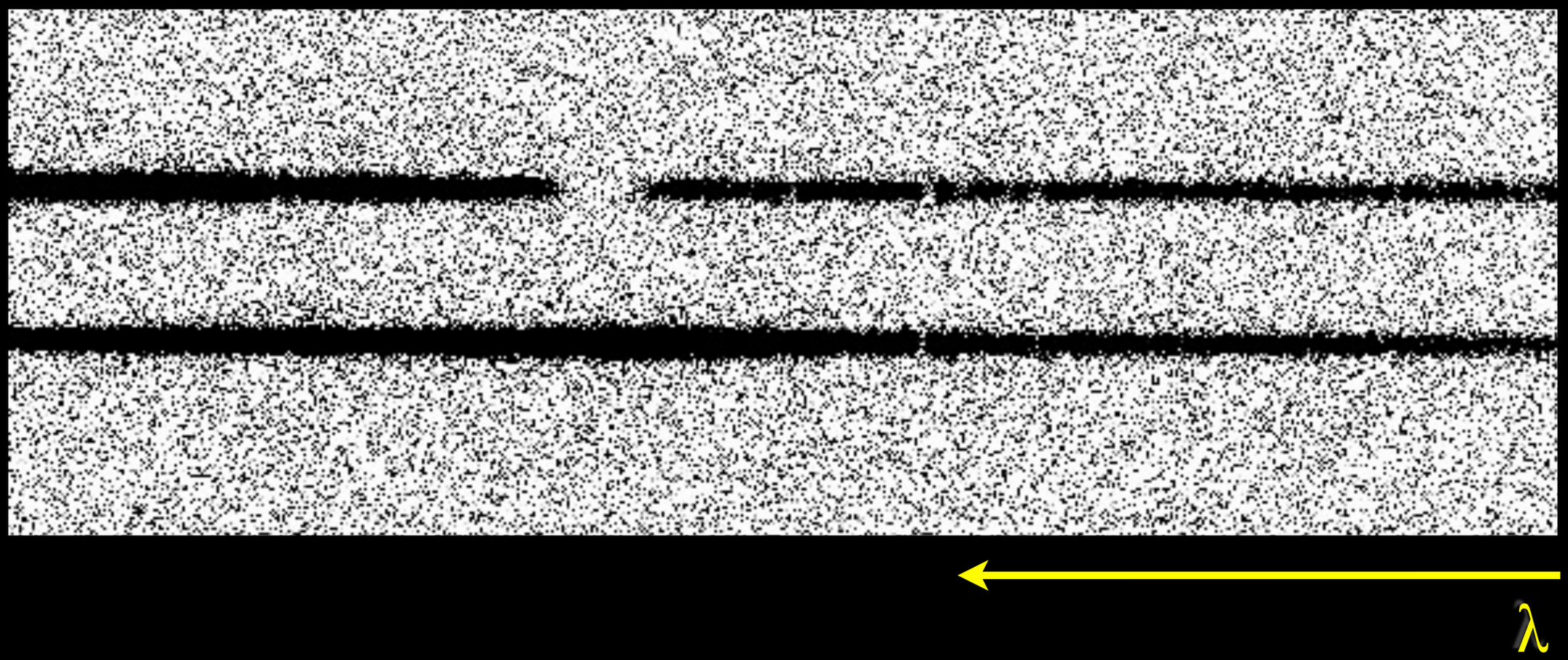

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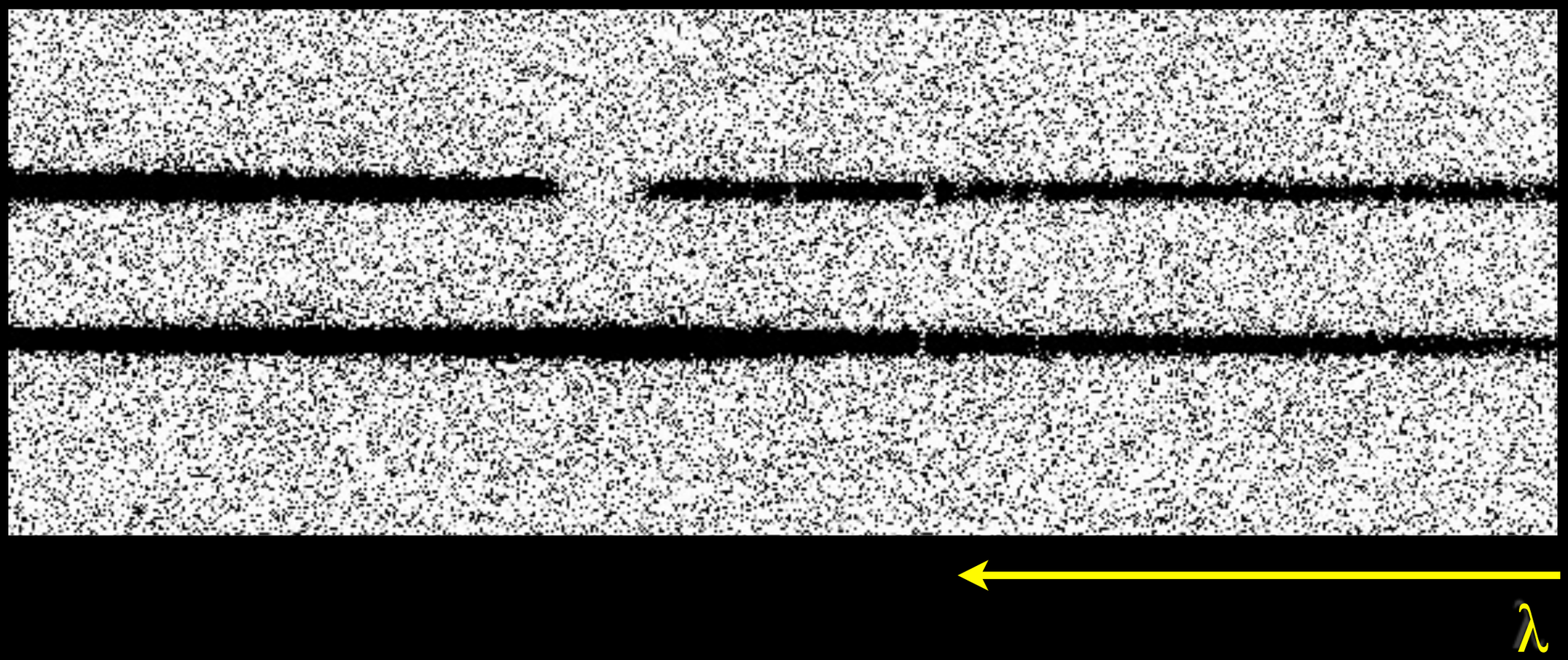
f/g QSO



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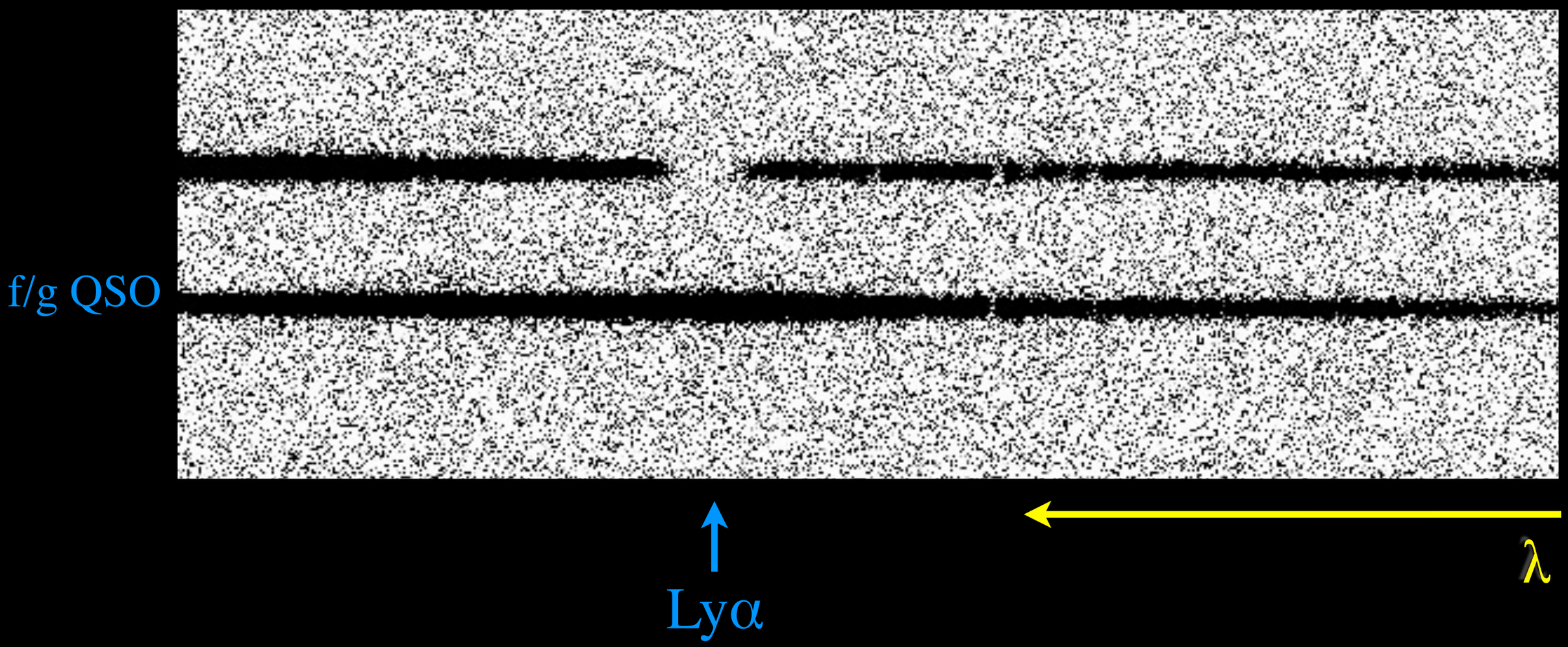

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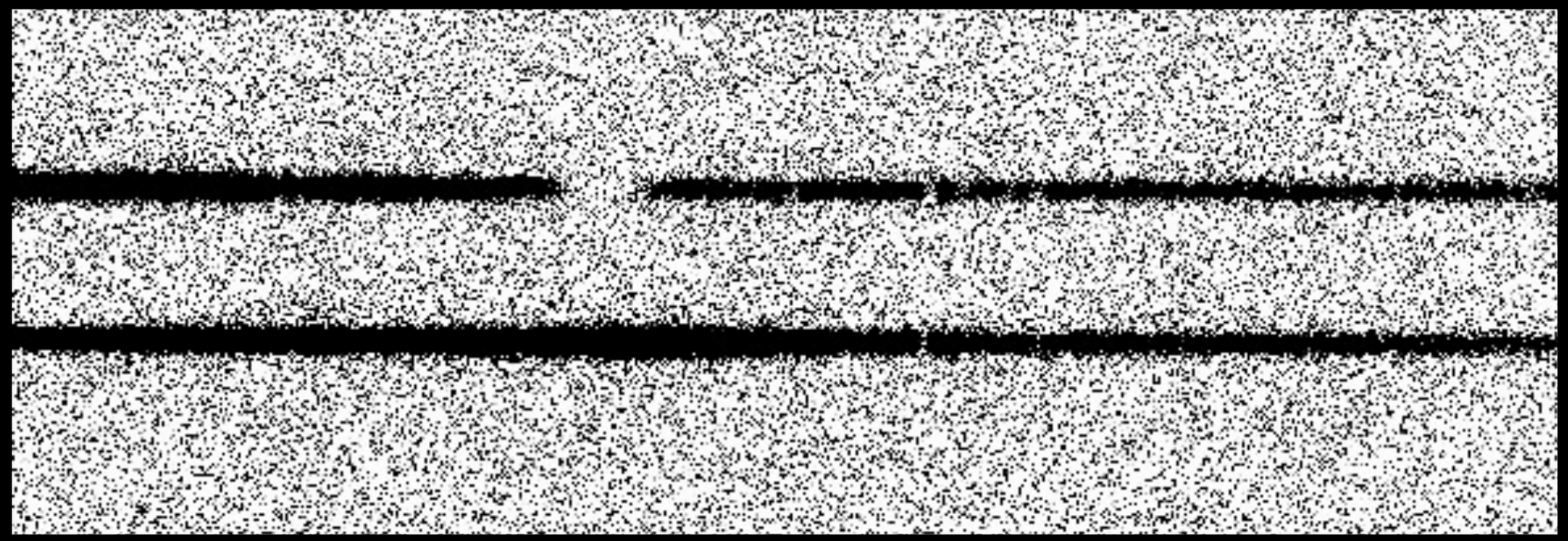

b/g QSO

f/g QSO

Lyα

λ

HI Absorption at R < 300 kpc

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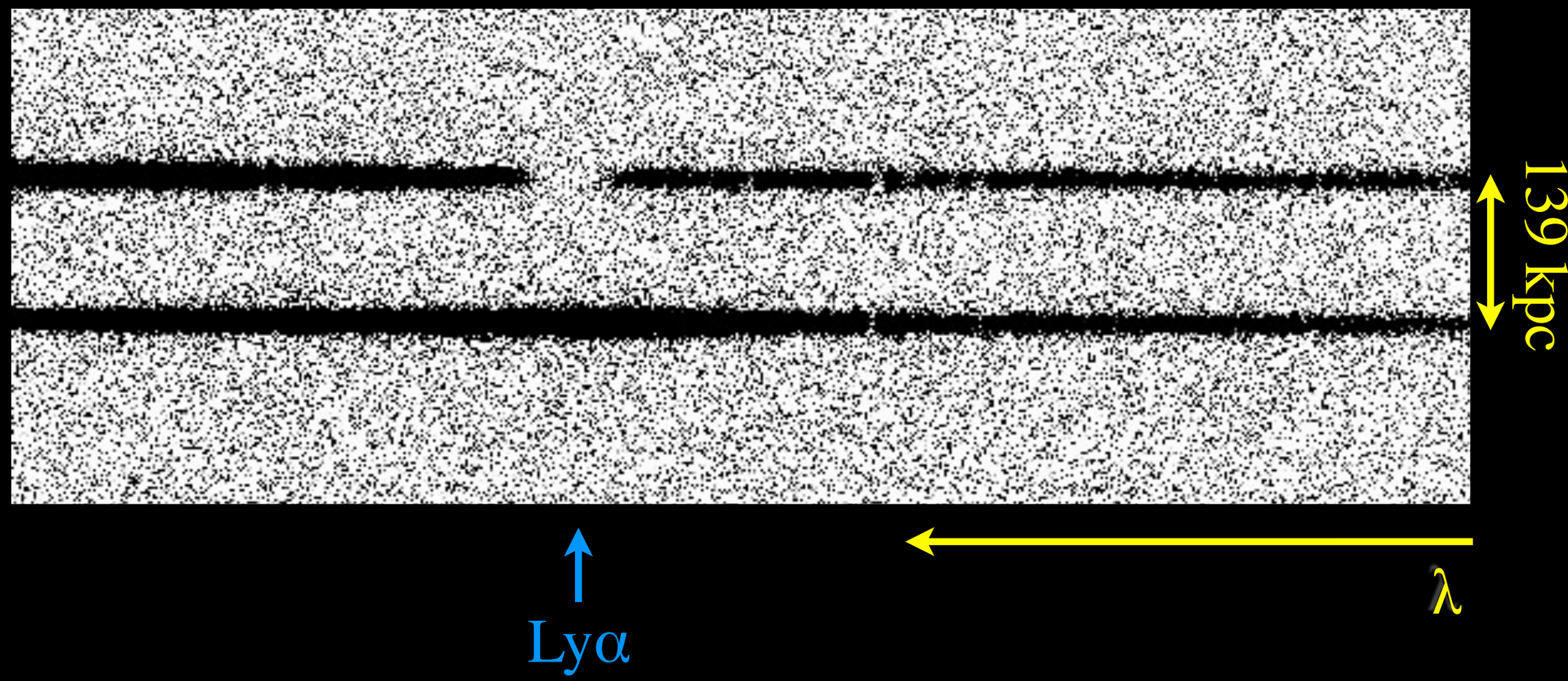
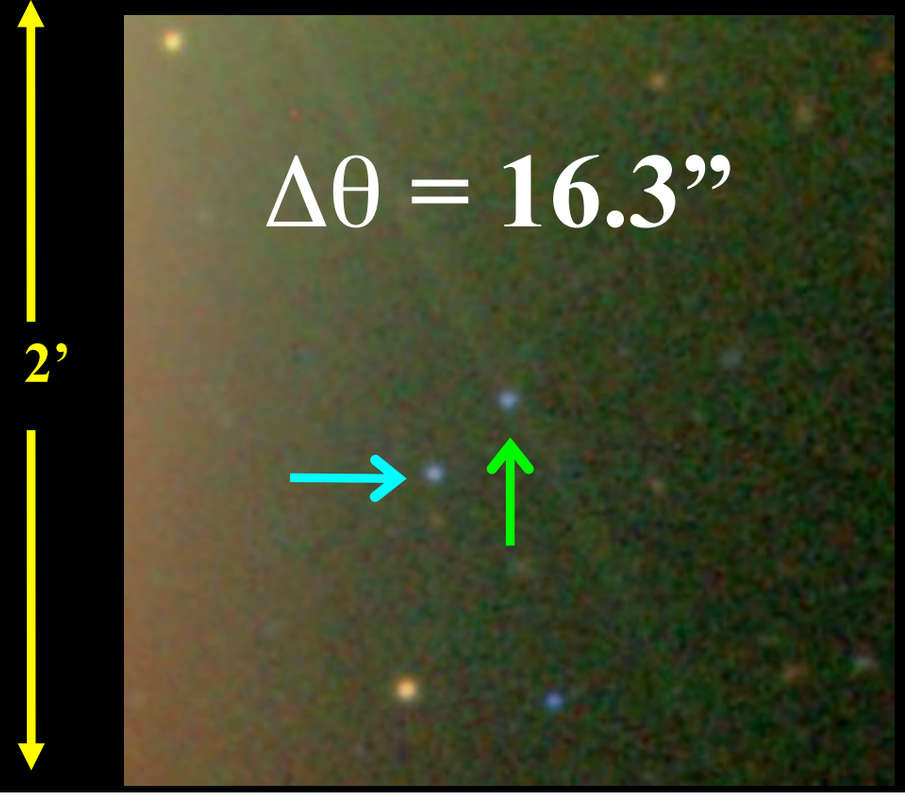


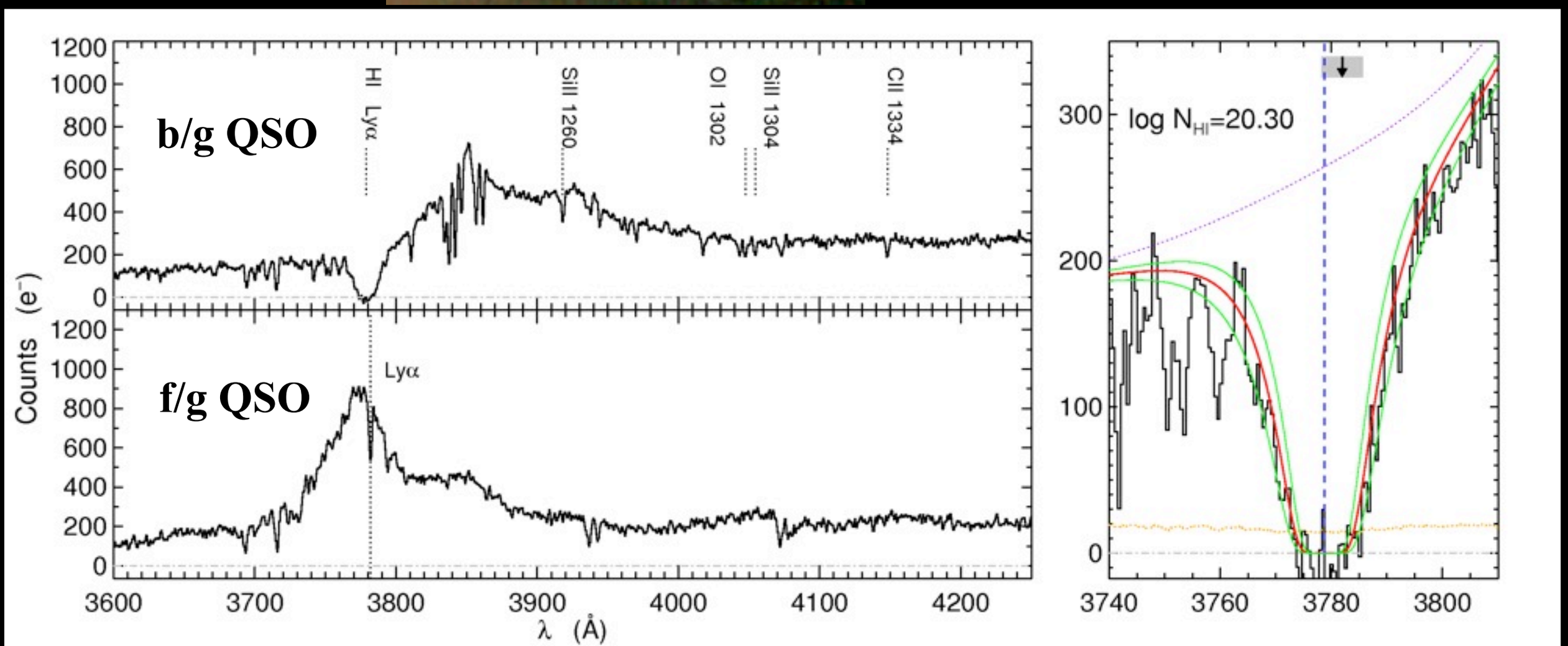


$z_{bg} = 2.17$

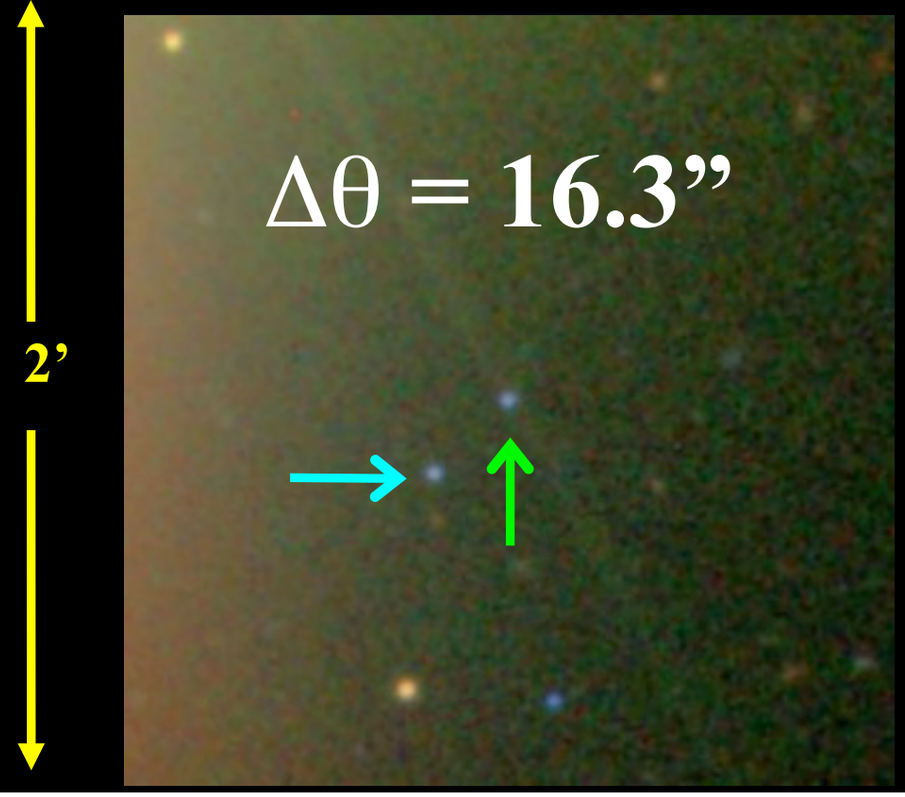
$z_{fg} = 2.11$

$R_{\perp} = 139$ kpc

$\log N_{HI} = 20.3$



Hennawi et al. (2007)



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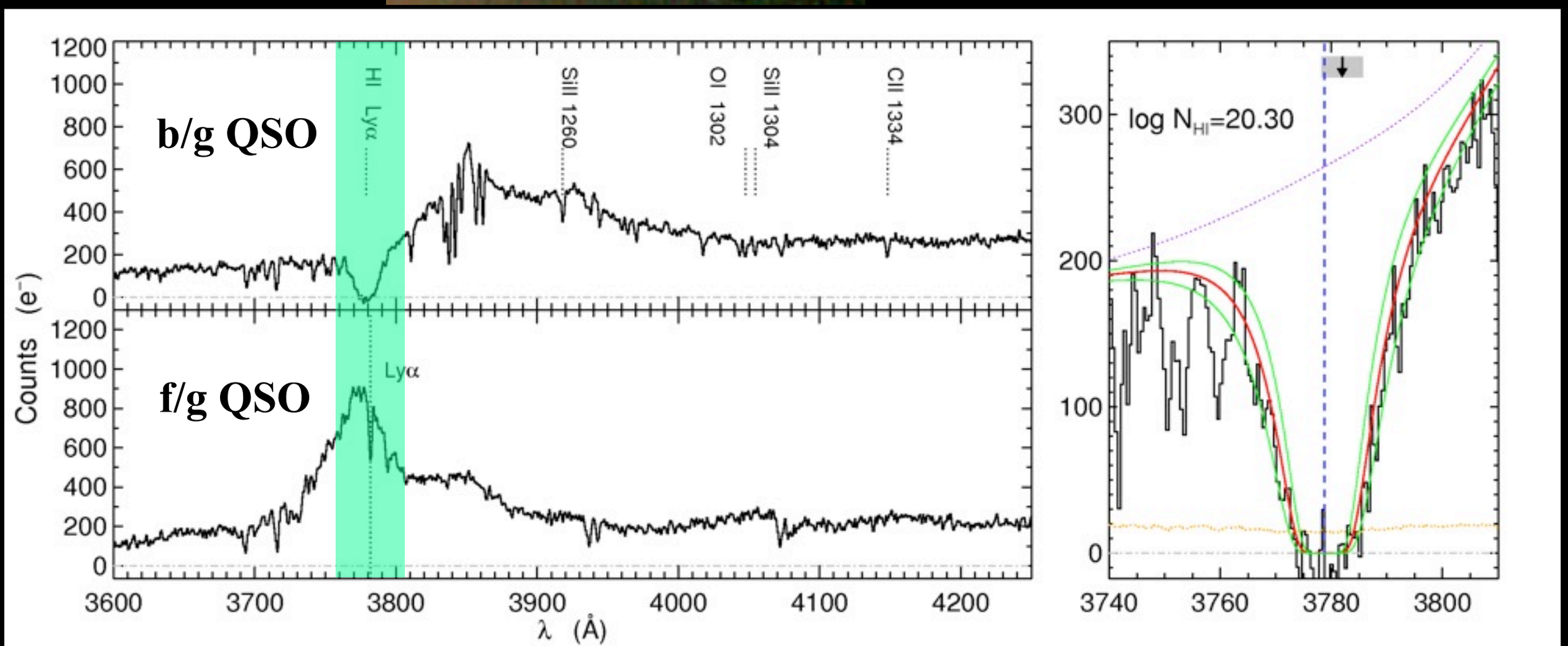

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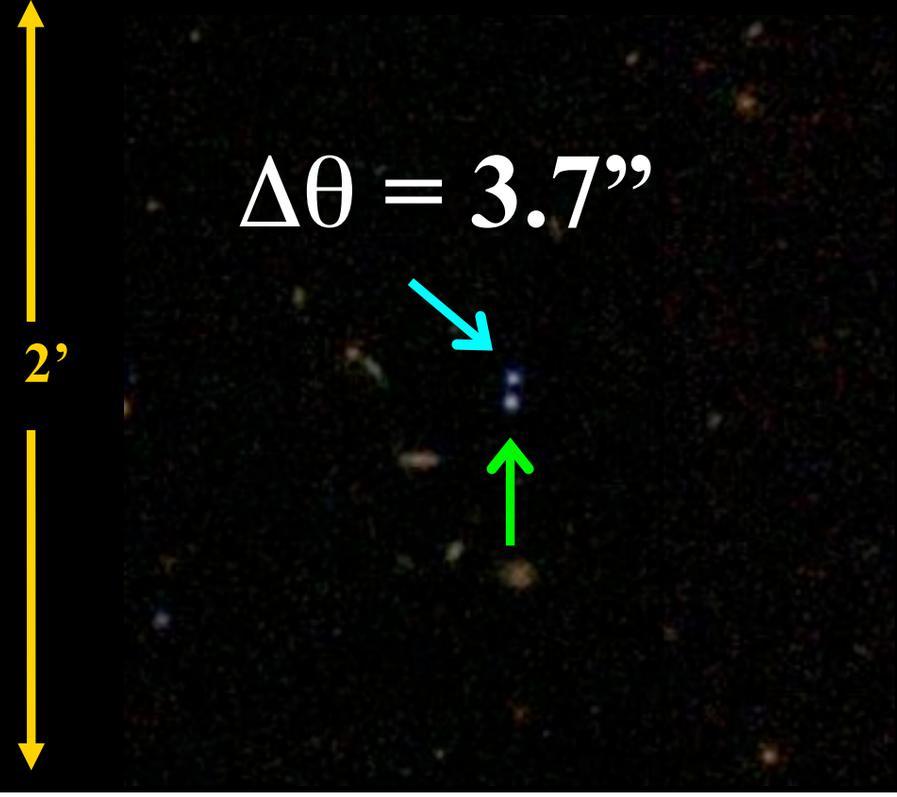
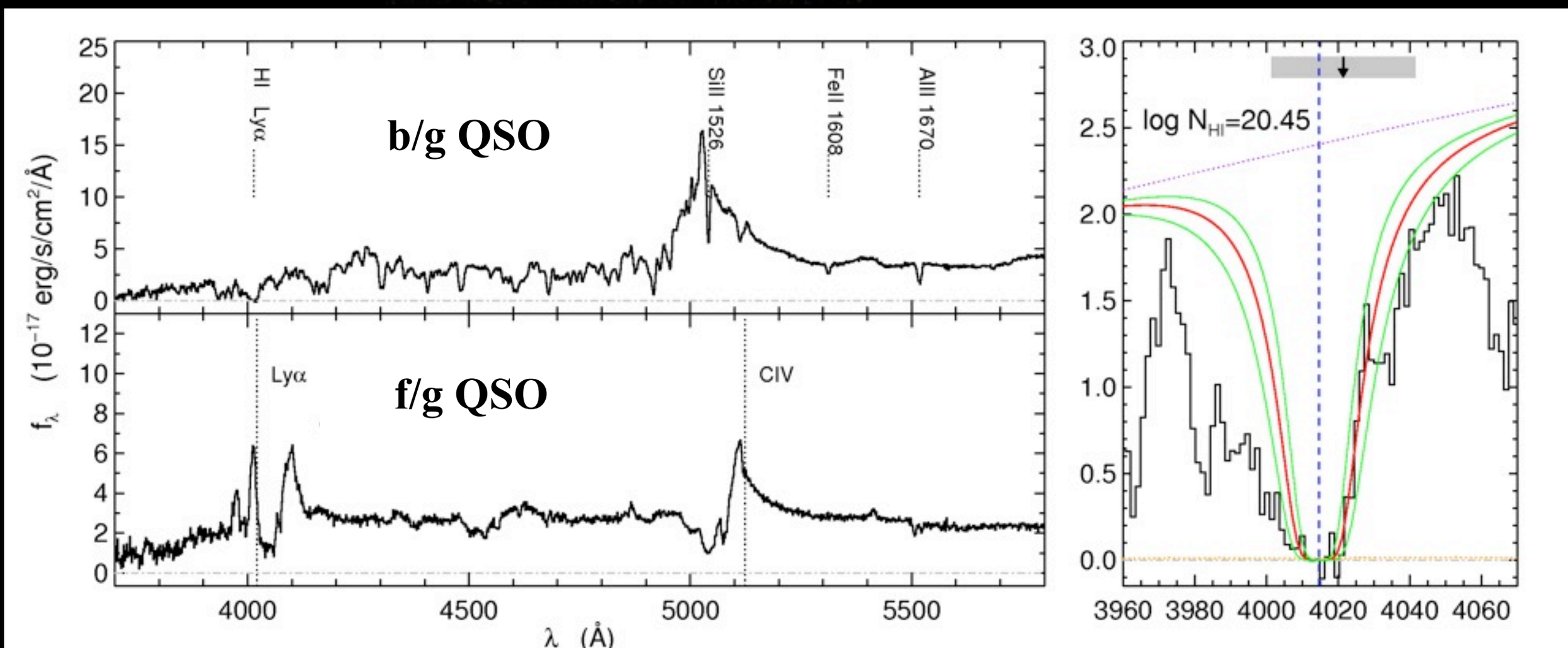


$z_{bg} = 3.13$

$z_{fg} = 2.29$

$R_{\perp} = 31$ kpc

$\log N_{HI} = 20.5$



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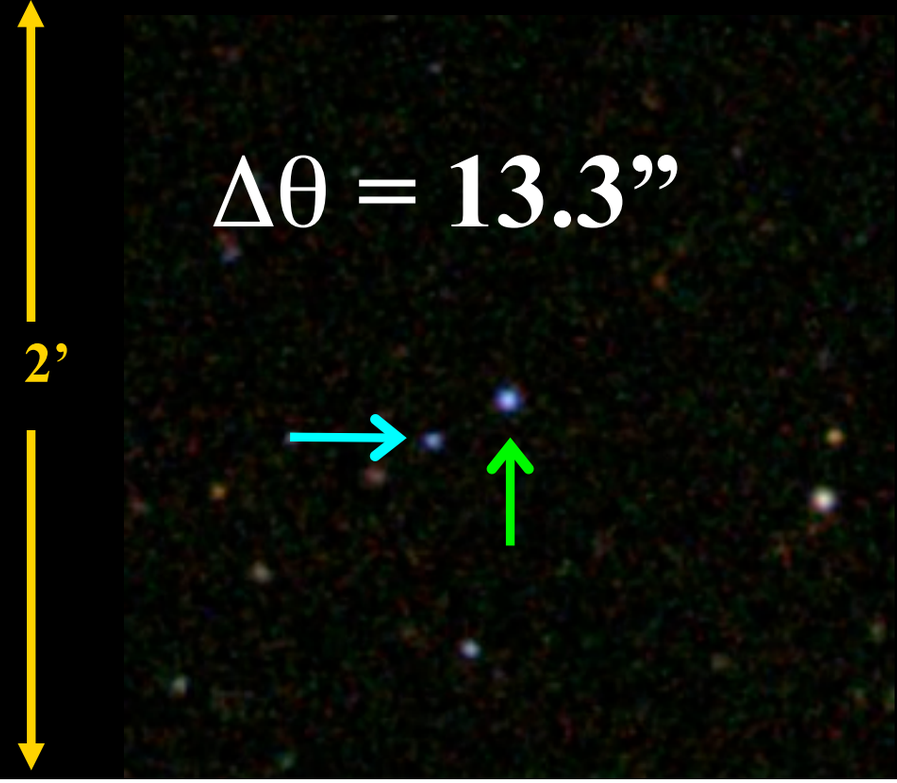
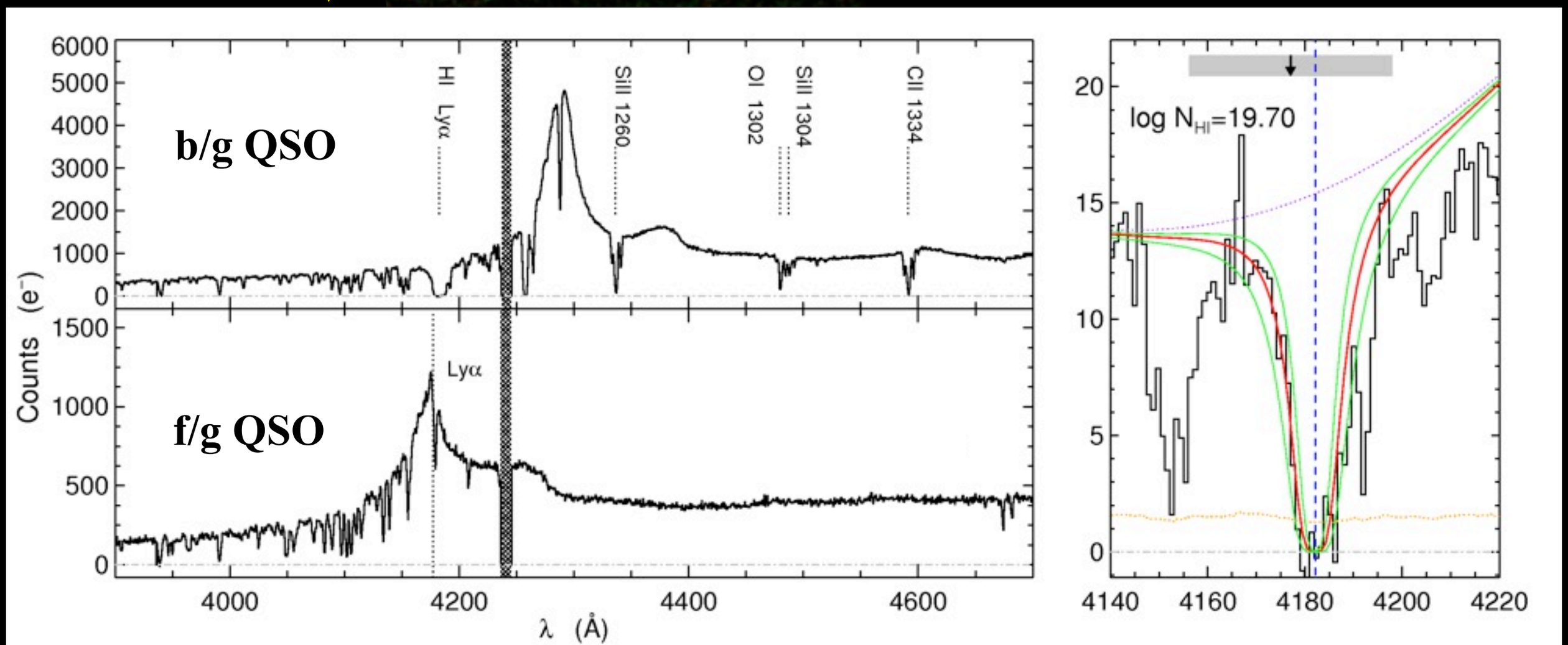


$z_{bg} = 2.53$

$z_{fg} = 2.43$

$R_{\perp} = 108$ kpc

$\log N_{HI} = 19.7$



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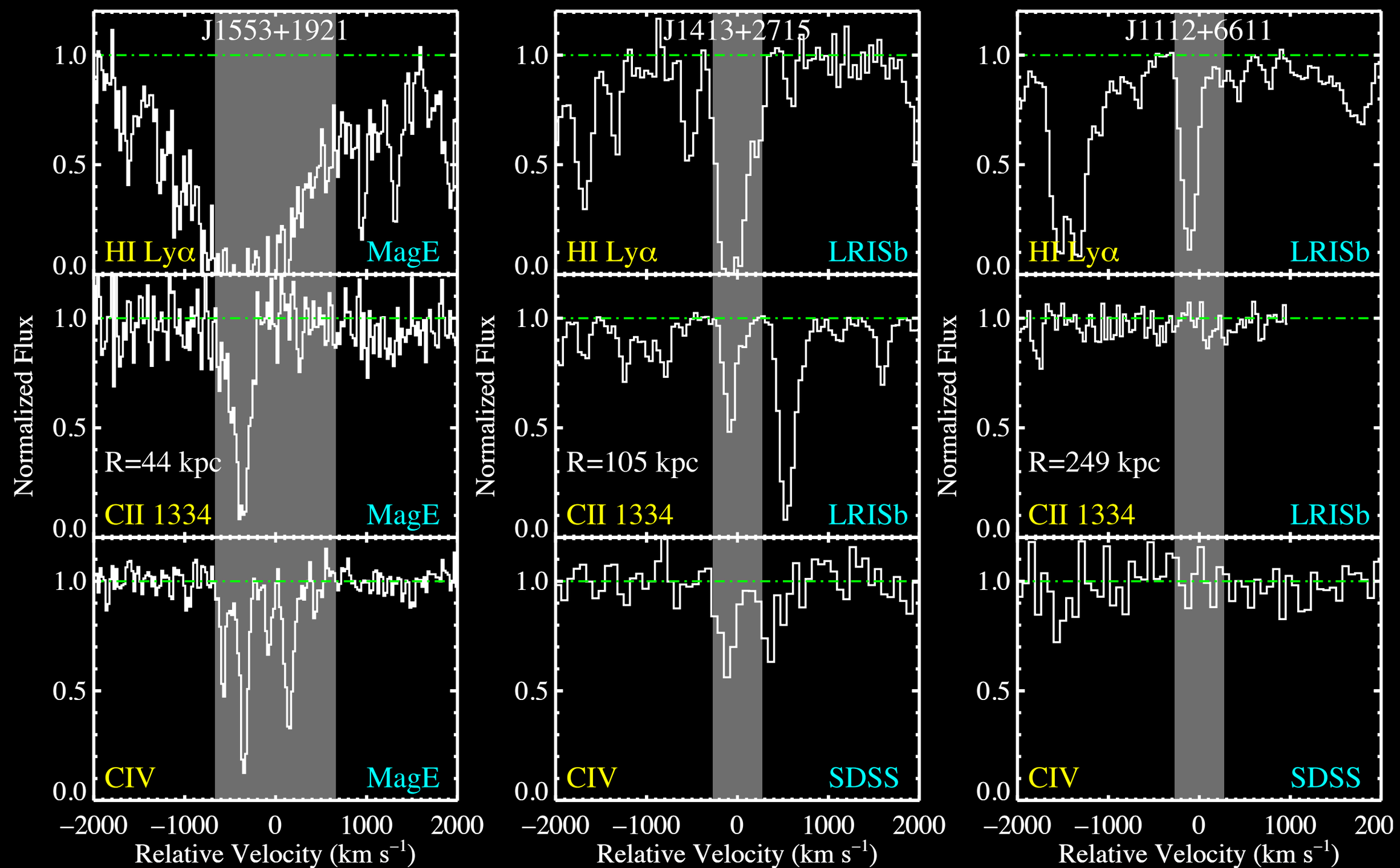
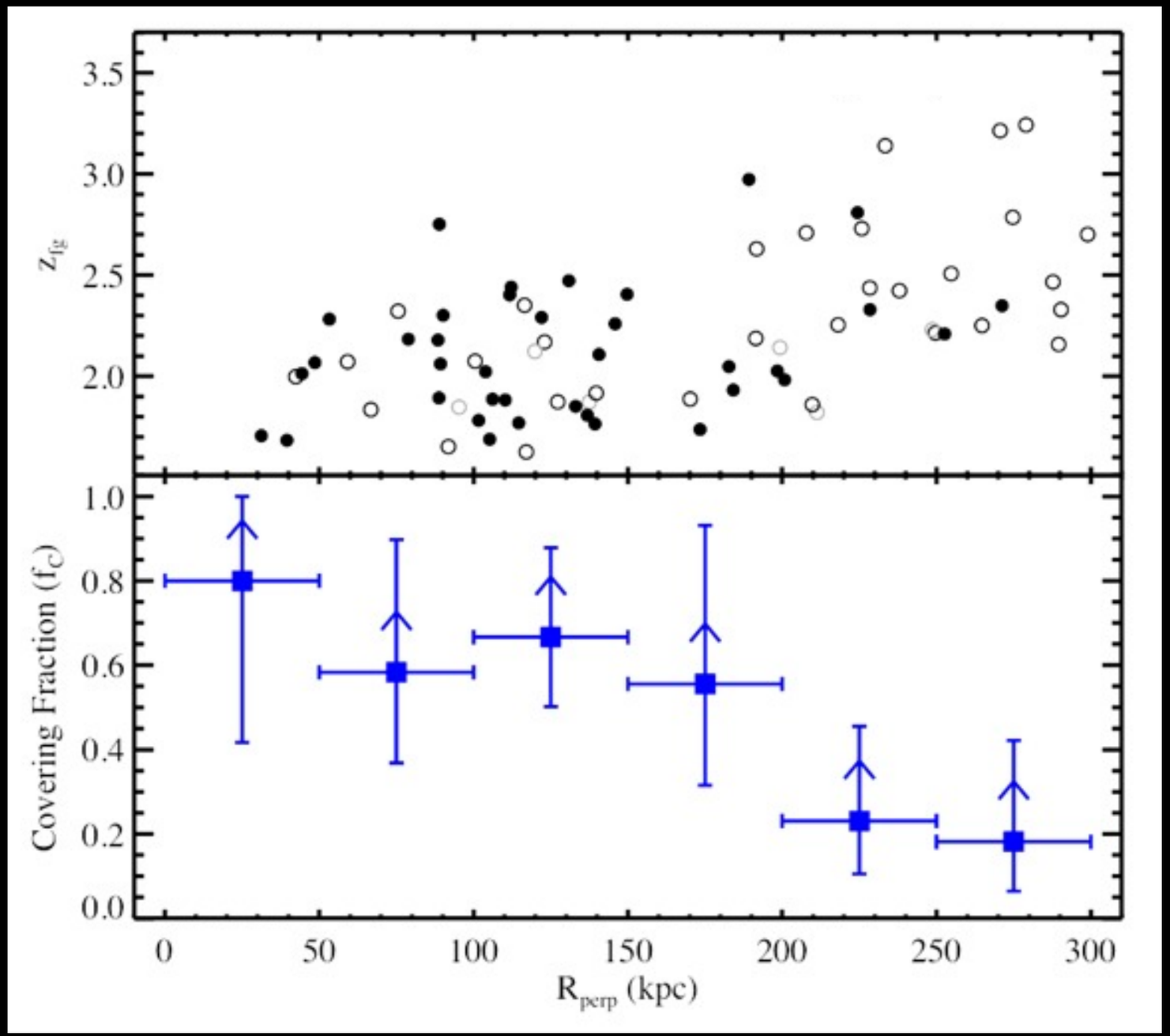
QPQ5: Probing the CGM



Prochaska, Hennawi, & Simcoe 2013

Optically Thick Gas at R < 300kpc



strong absorber $N_{HI} > 10^{17.2}$ cm^{-2}

no strong absorber

Hennawi+ 2006, 2007

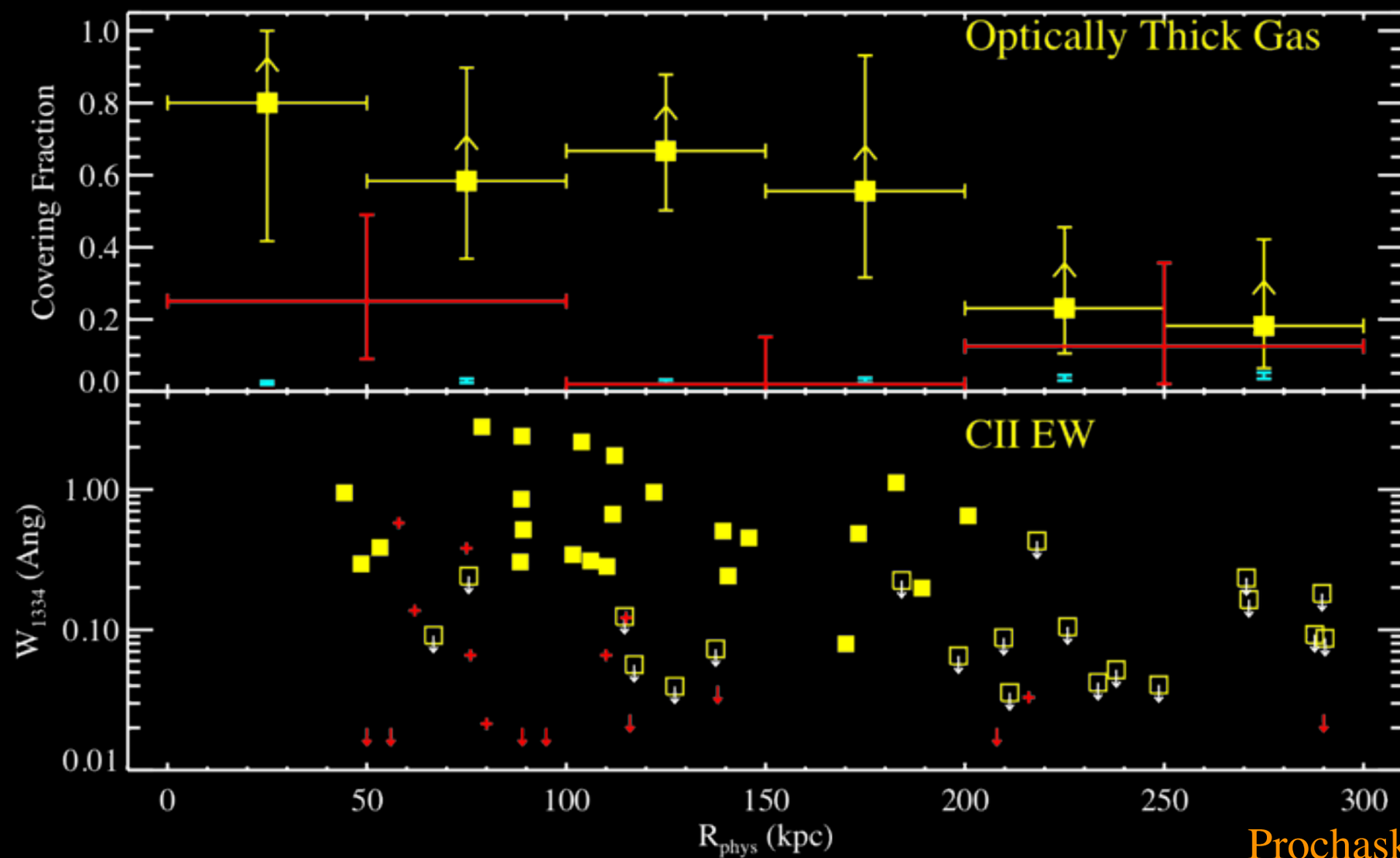
P, Hennawi, Simcoe 2013

72 sightlines with

$R_\perp$ < 300 kpc

- High ~60% covering factor for R < r_{vir} (160 kpc)
- This cold gas is <u>not</u> seen along the QSO line-of-sight

The Perplexing CGM of Massive Halos



yellow: QSOs
red: LBGs

Low-ionization CII 1334 metal line equivalent width

Prochaska, Hennawi, & Simcoe 2013

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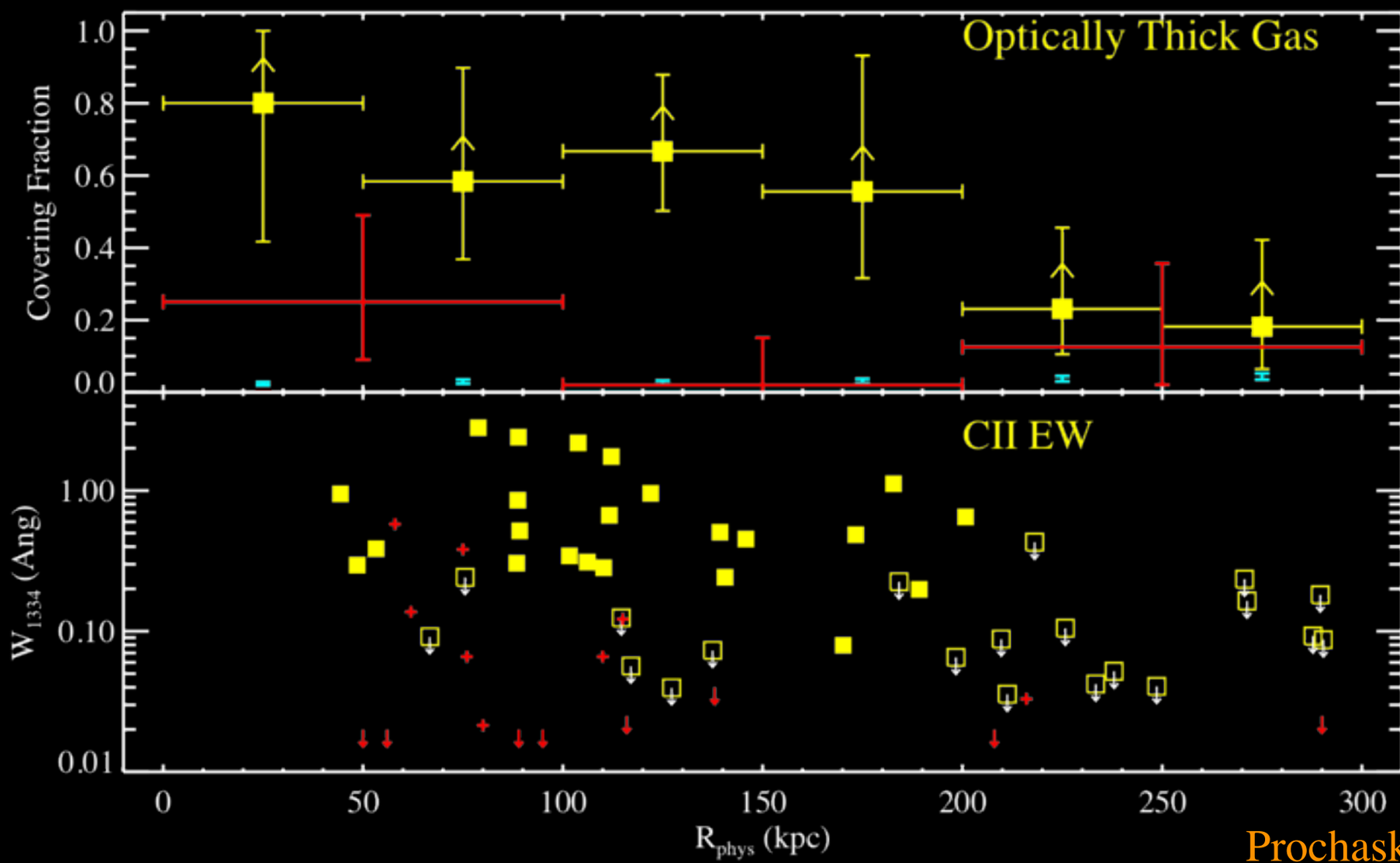

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Prochaska, Hennawi, & Simcoe 2013

- **Massive z~2 halos have M > 10^{10} $M_\odot$ in cool optically thick gas**
- **This CGM is metal rich (Z > $0.1Z_\odot$), comparable to the z~0 ICM**
- **QSO-CGM is distinct from co-eval LBG-CGM**

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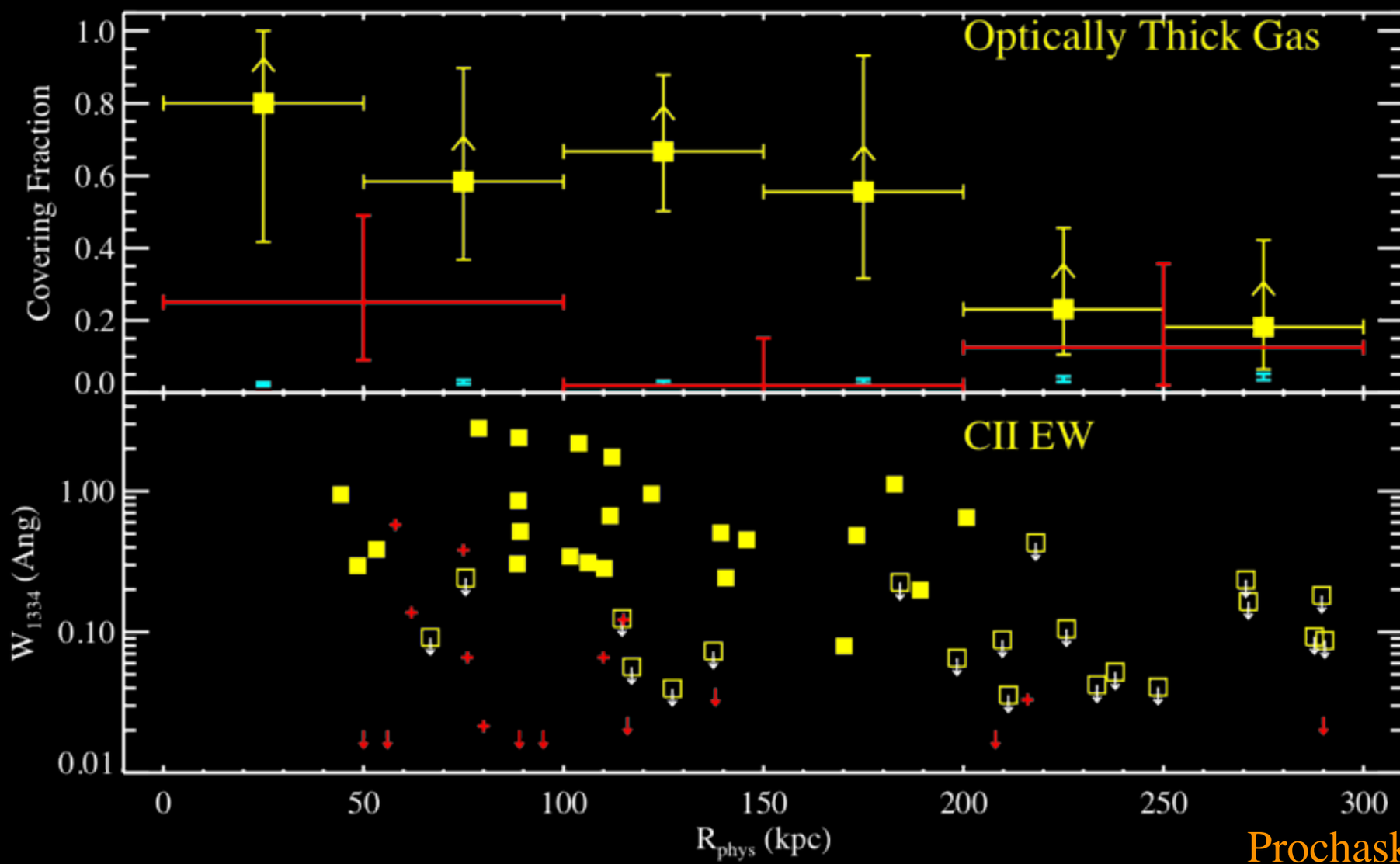

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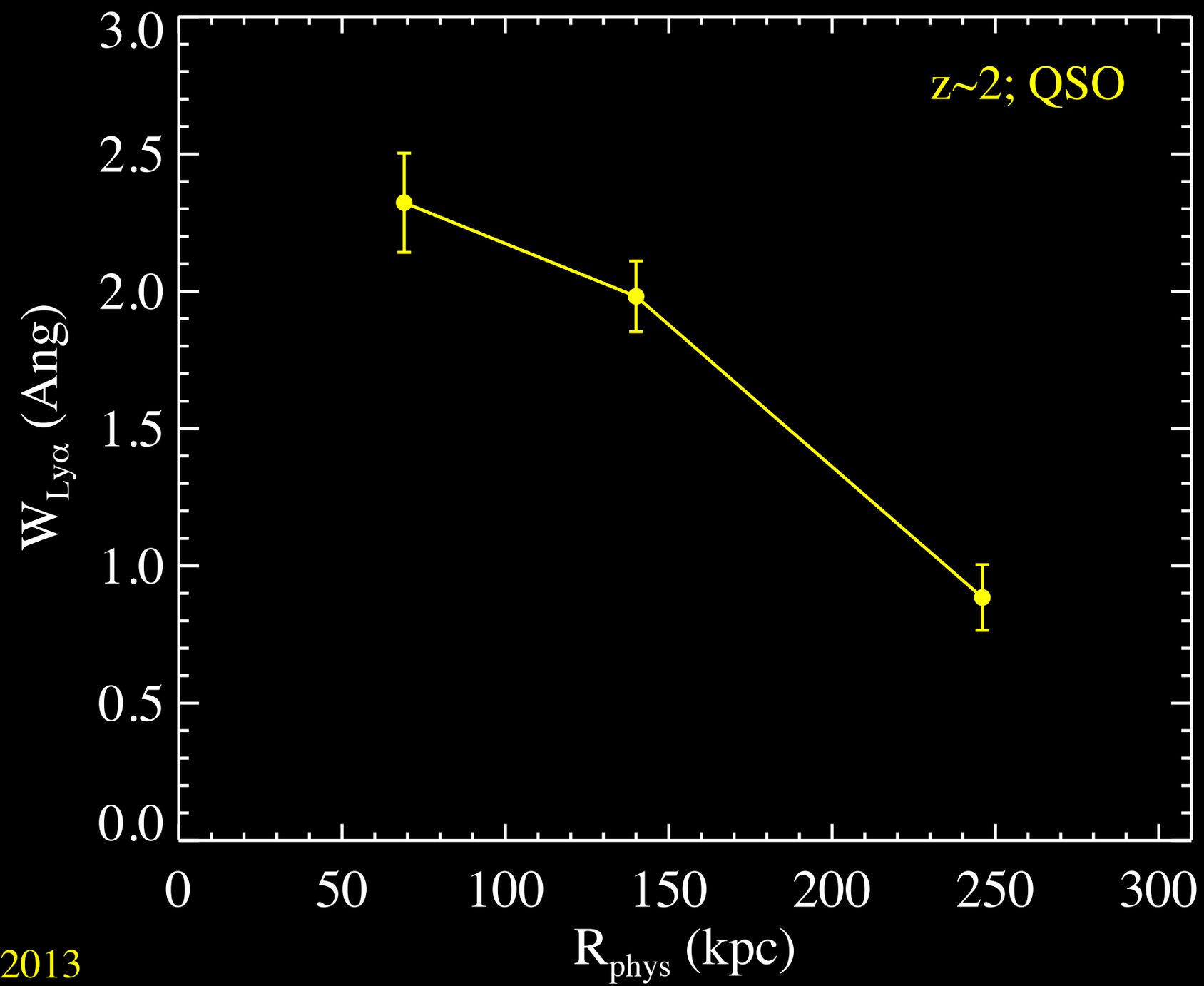
- **This CGM is metal rich (Z > $0.1Z_\odot$), comparable to the z~0 ICM**
- **QSO-CGM is distinct from co-eval LBG-CGM**
- **Why so much cold gas given high virial temp T_{vir} ~ 10^7 K?**
- **QSOs evolve into z ~ 0 ellipticals. Transition to IGrM/ICM??**

The Perplexing CGM of Massive Halos

- QSO hosts show stronger cool CGM absorption than any other population
  - Halo mass
  - And epoch?



Prochaska, Hennawi, & Simcoe 2013

Rudie+12; Rakic+12; Crighton+13

P+11; Tumlinson+12; Werk+13

The Perplexing CGM of Massive Halos

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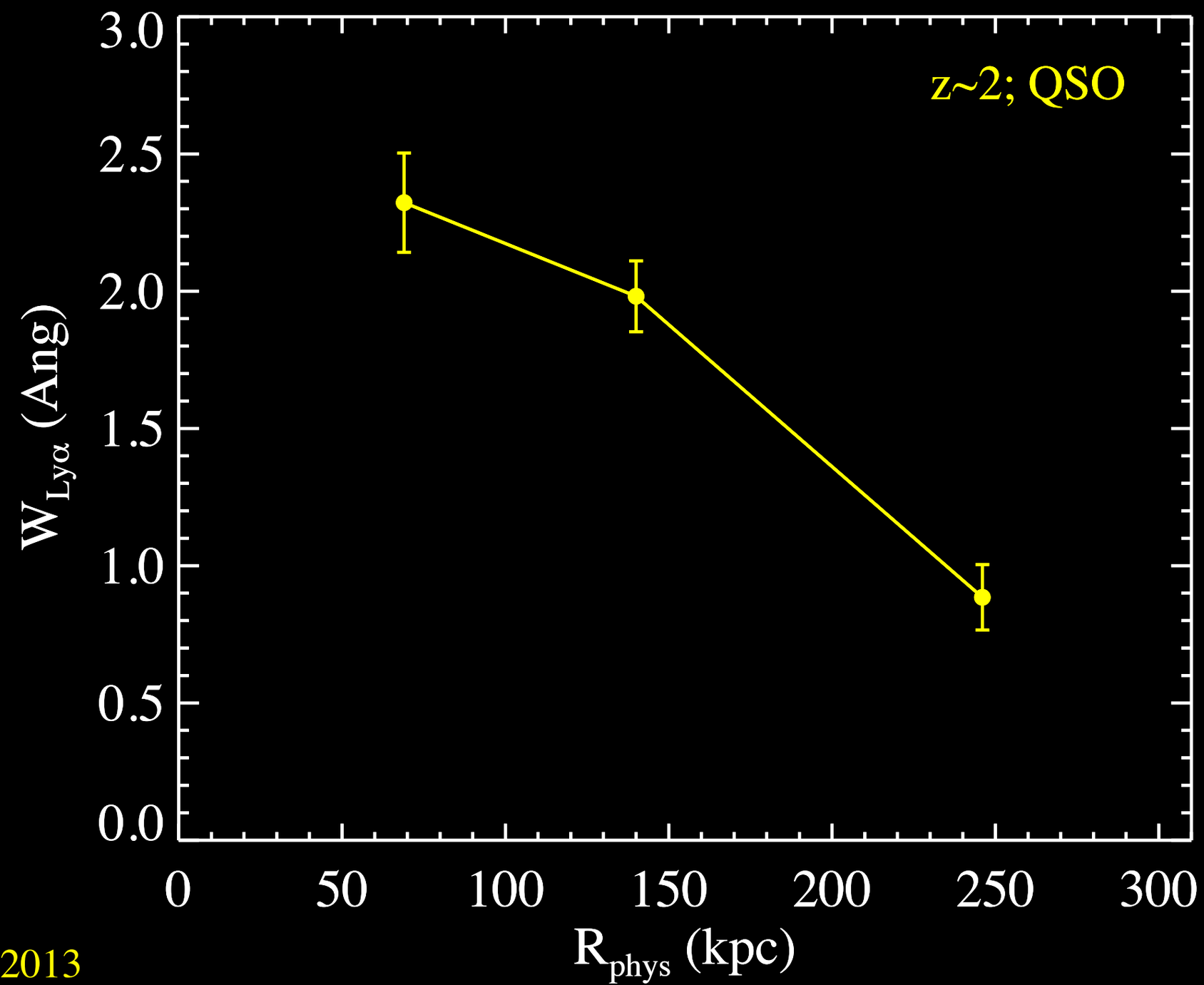

Prochaska, Hennawi, & Simcoe 2013

Rudie+12; Rakic+12; Crighton+13

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The Perplexing CGM of Massive Halos

- QSO hosts show stronger cool CGM absorption than any other population
  - Halo mass
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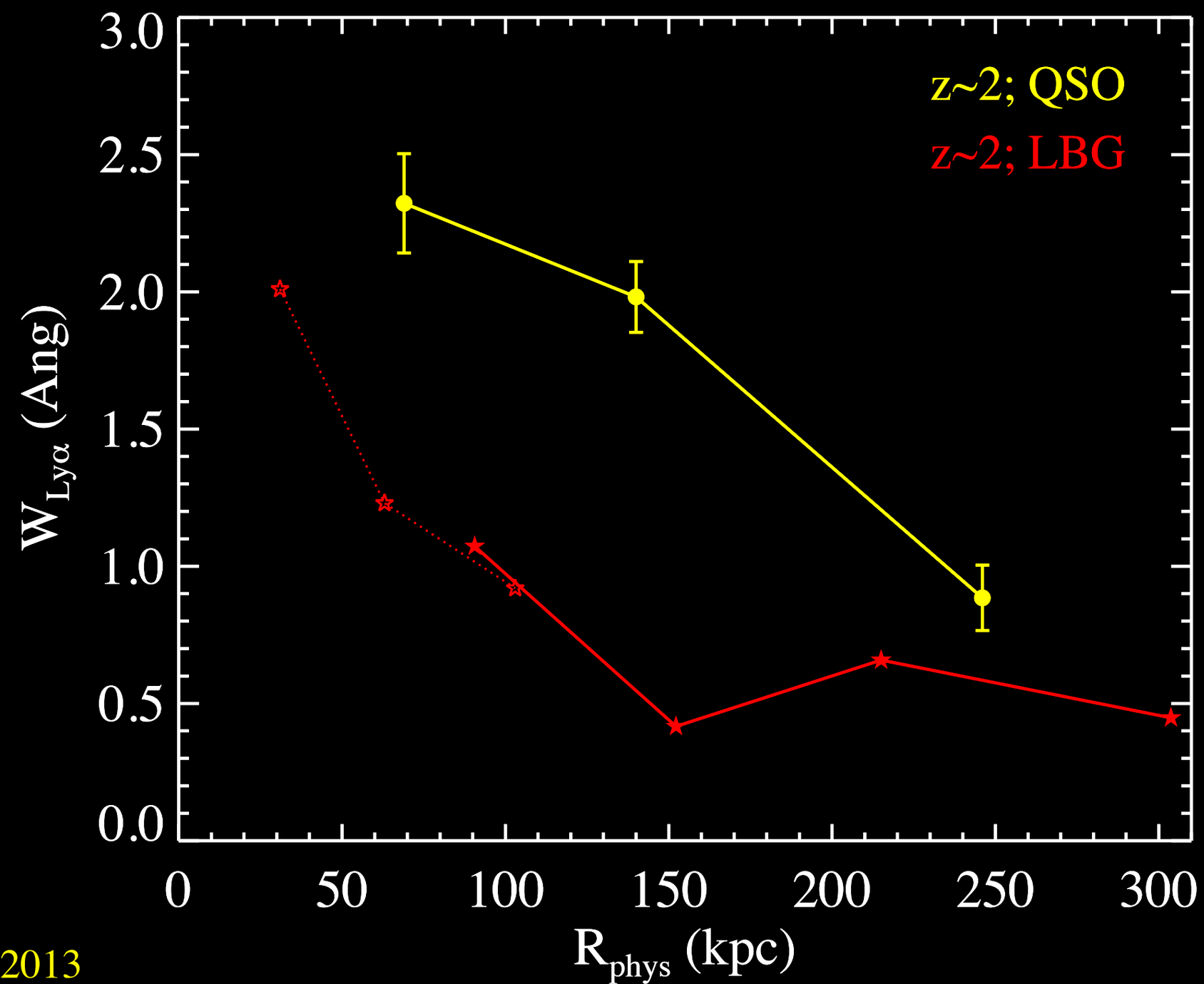

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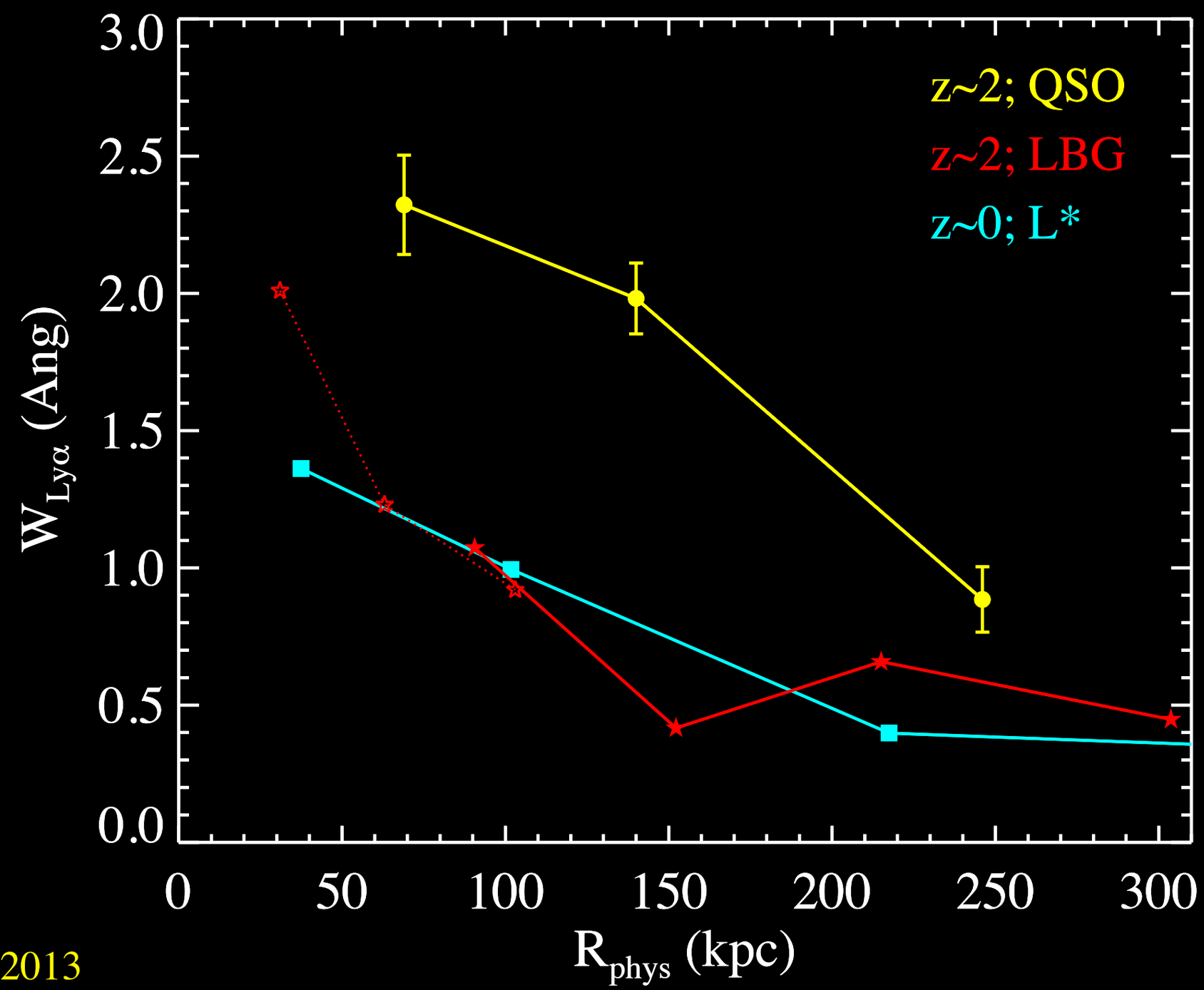

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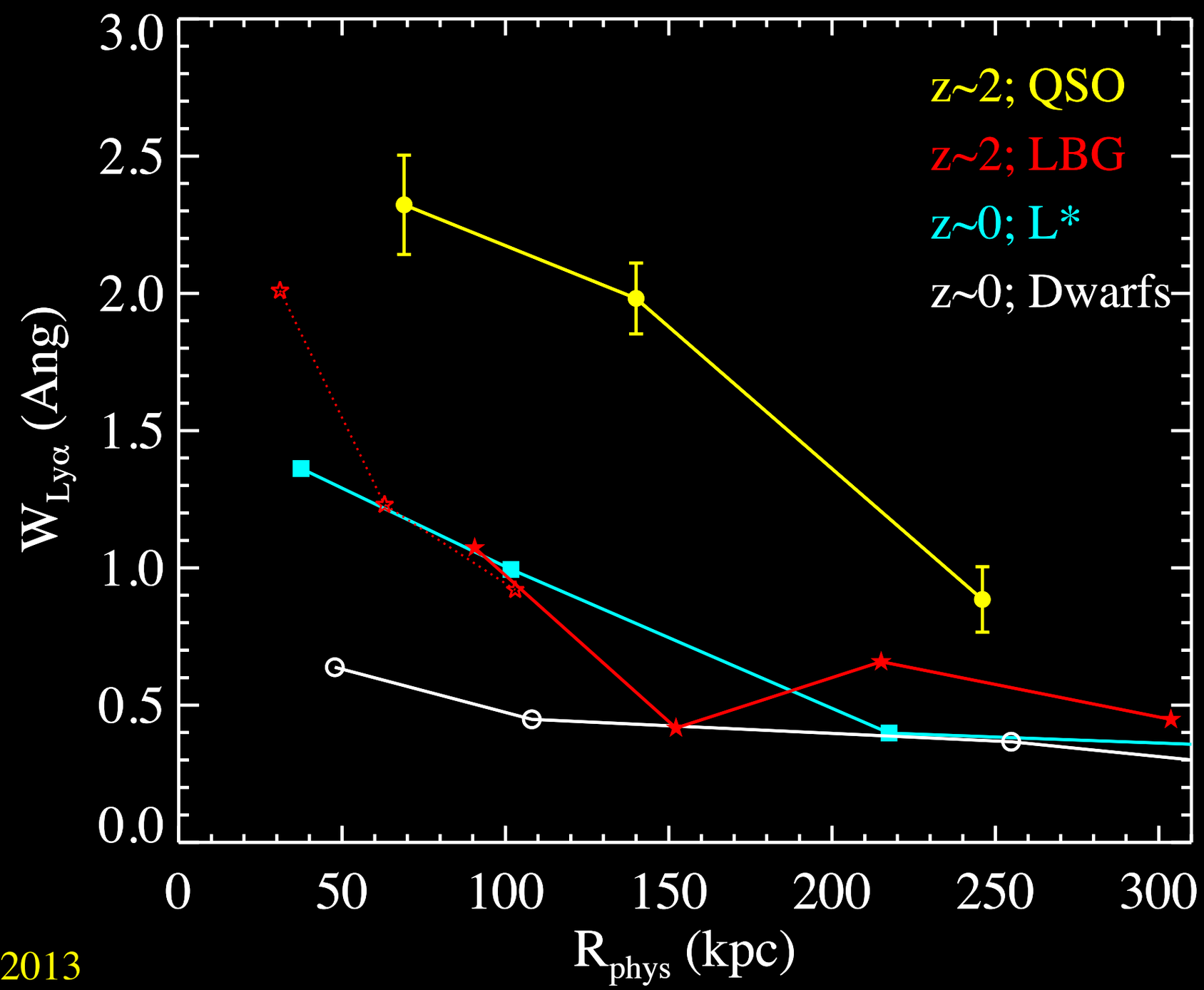

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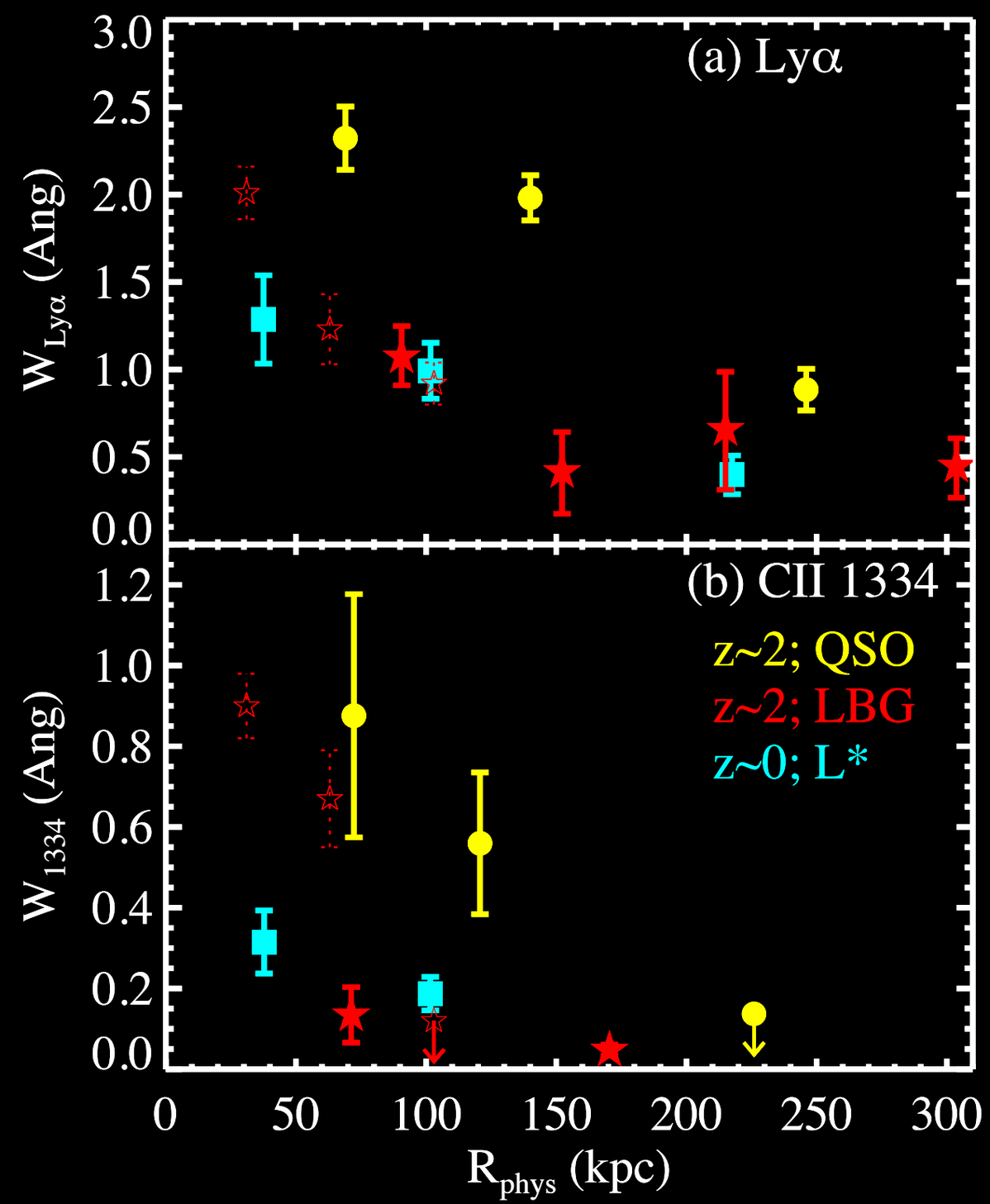

Prochaska, Hennawi, & Simcoe 2013

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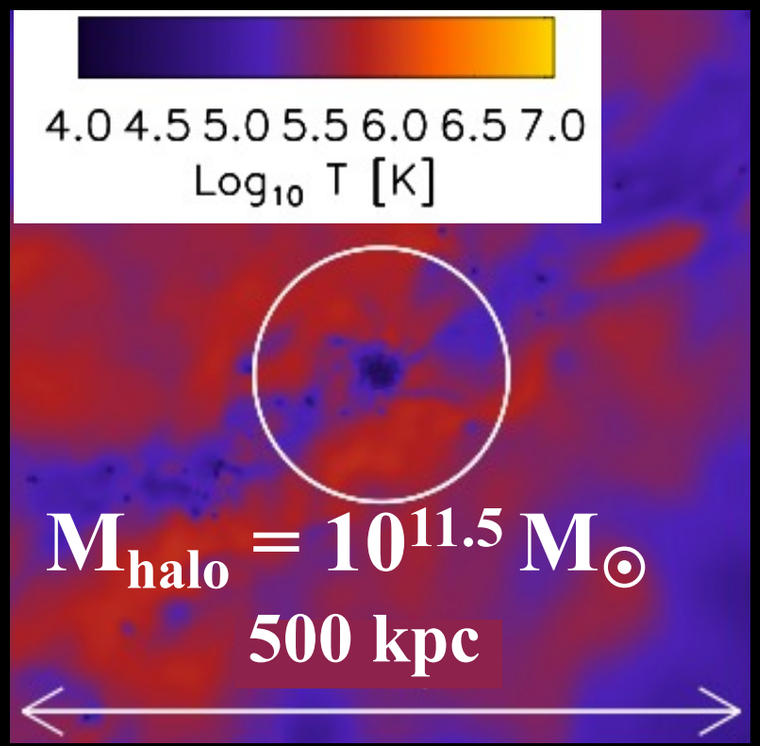
Implications: Contradicting Cold Accretion



van de Voort+ 11

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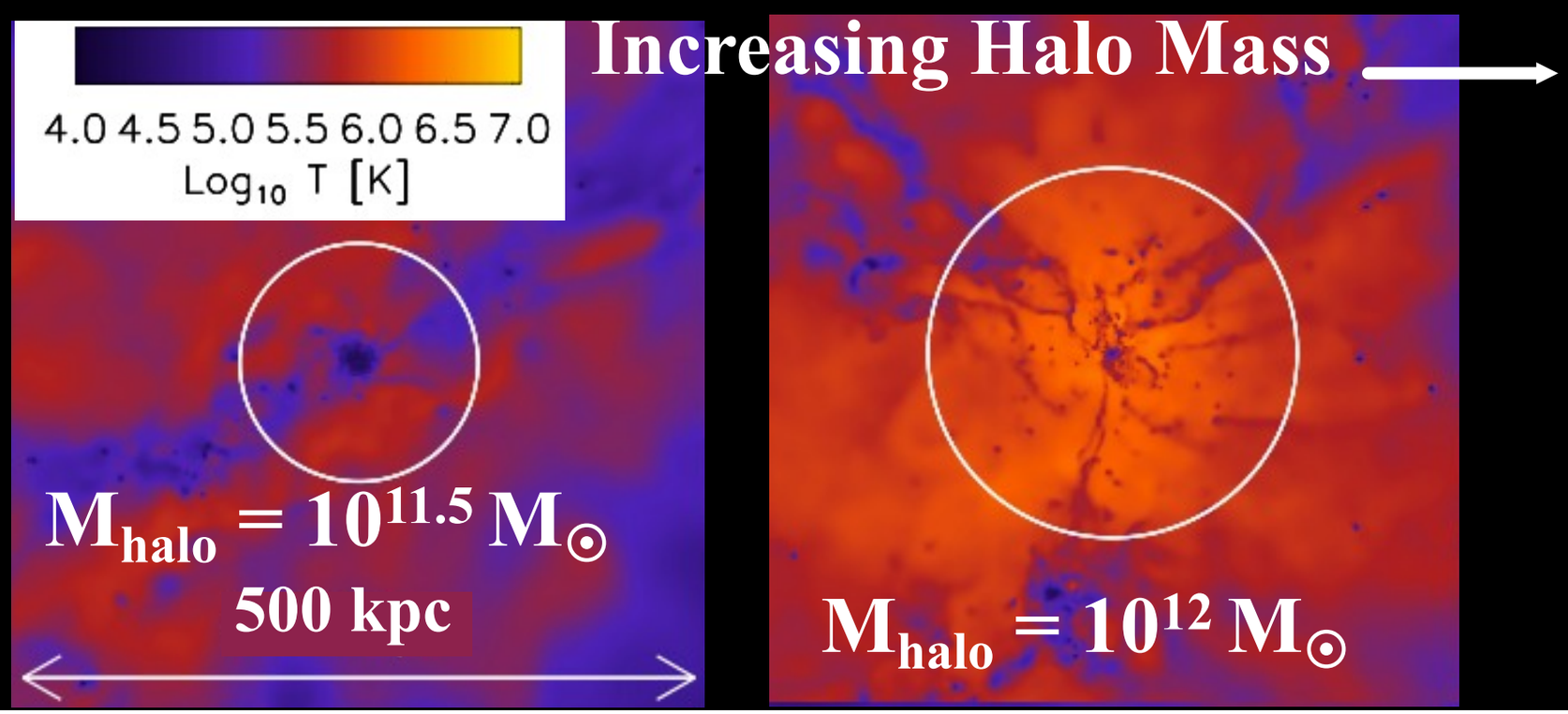

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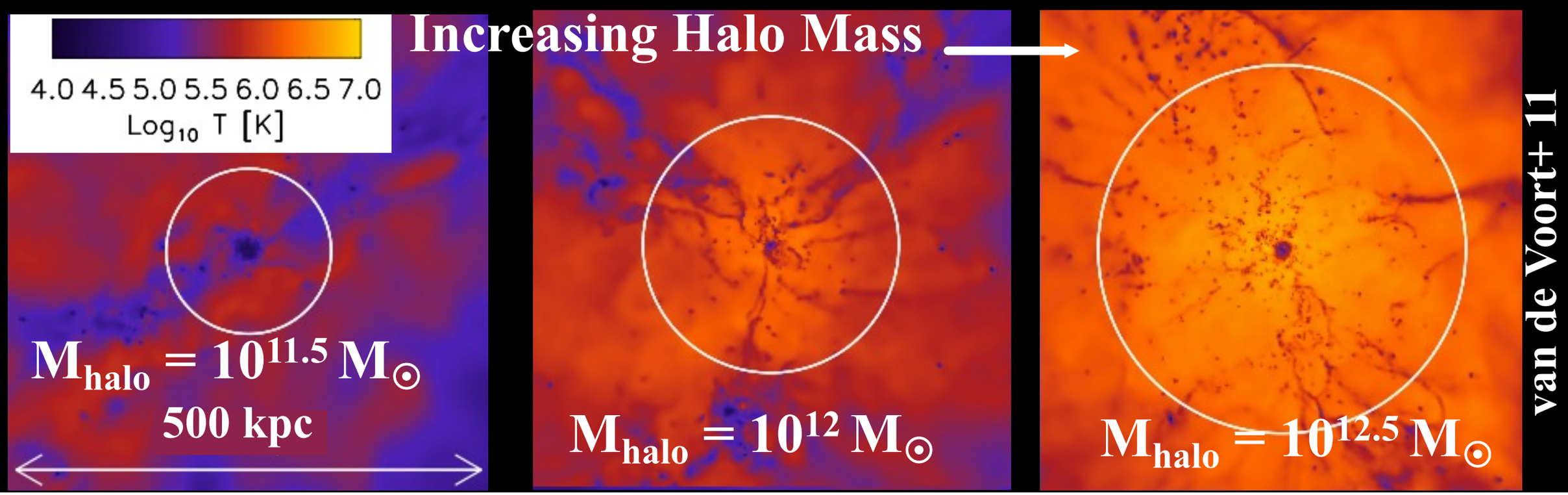
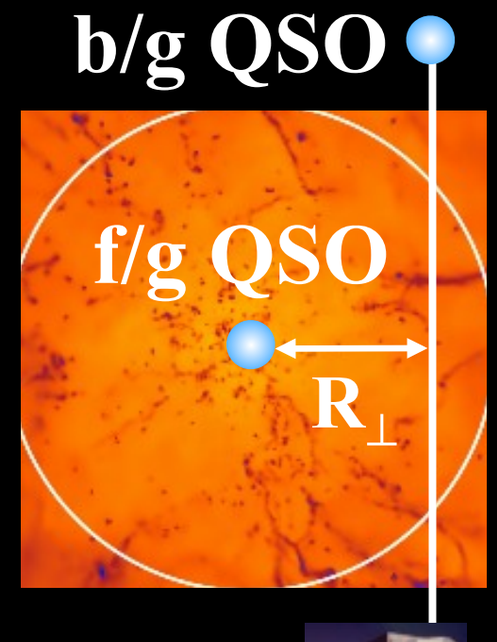
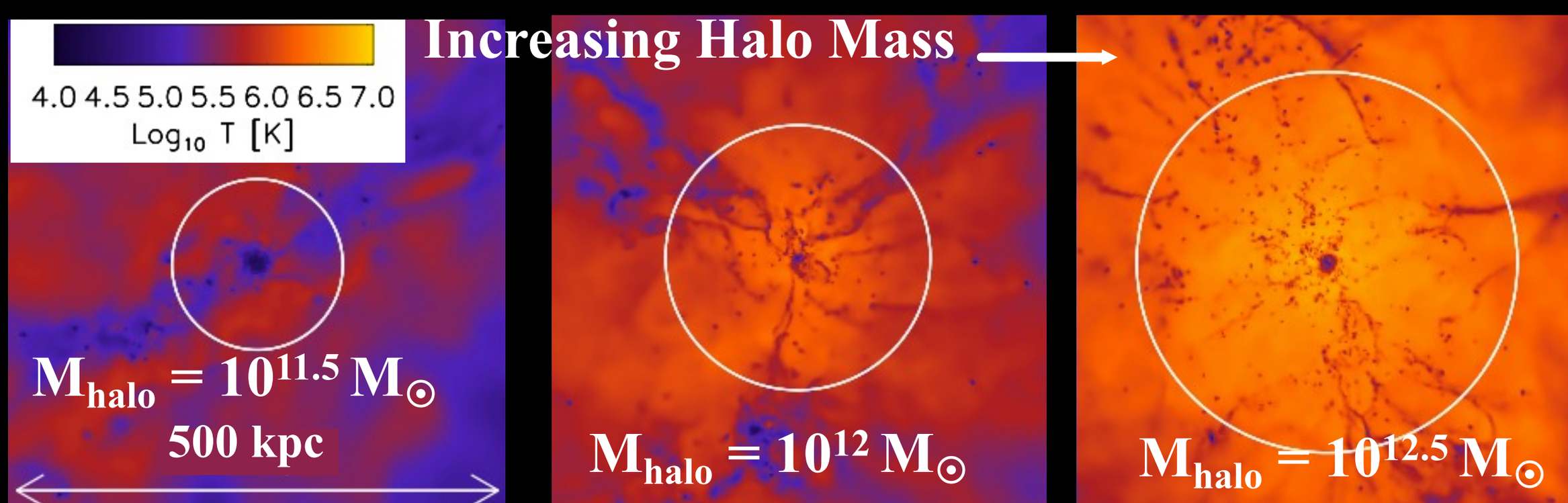


Implications: Contradicting Cold Accretion

$M_{halo} = 10^{12.5} M_\odot$



Pro+13



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$M_{halo} = 10^{11} M_\odot$?

Rubin+13

$M_{halo} = 10^{11.7} M_\odot$

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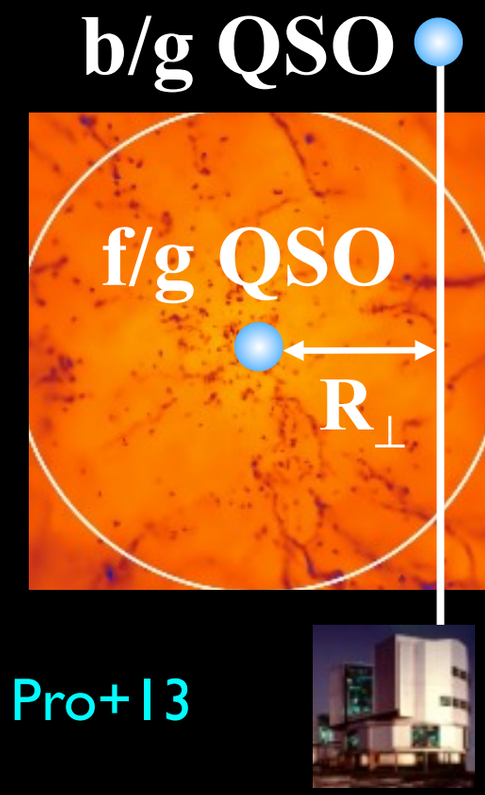

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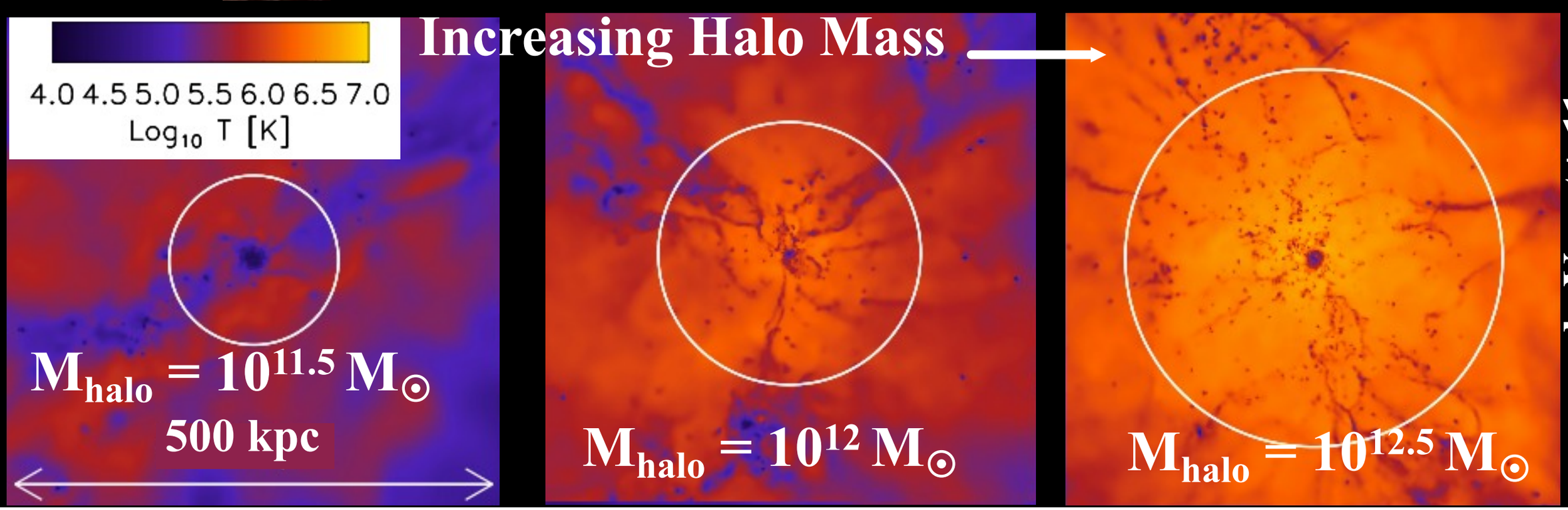

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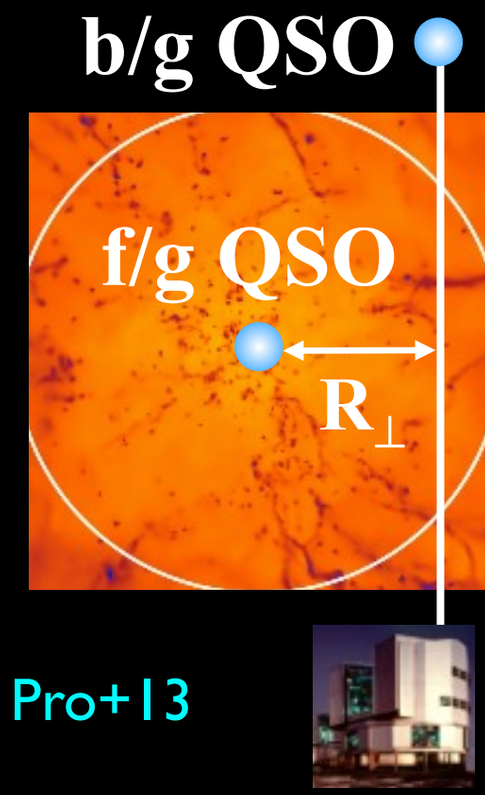

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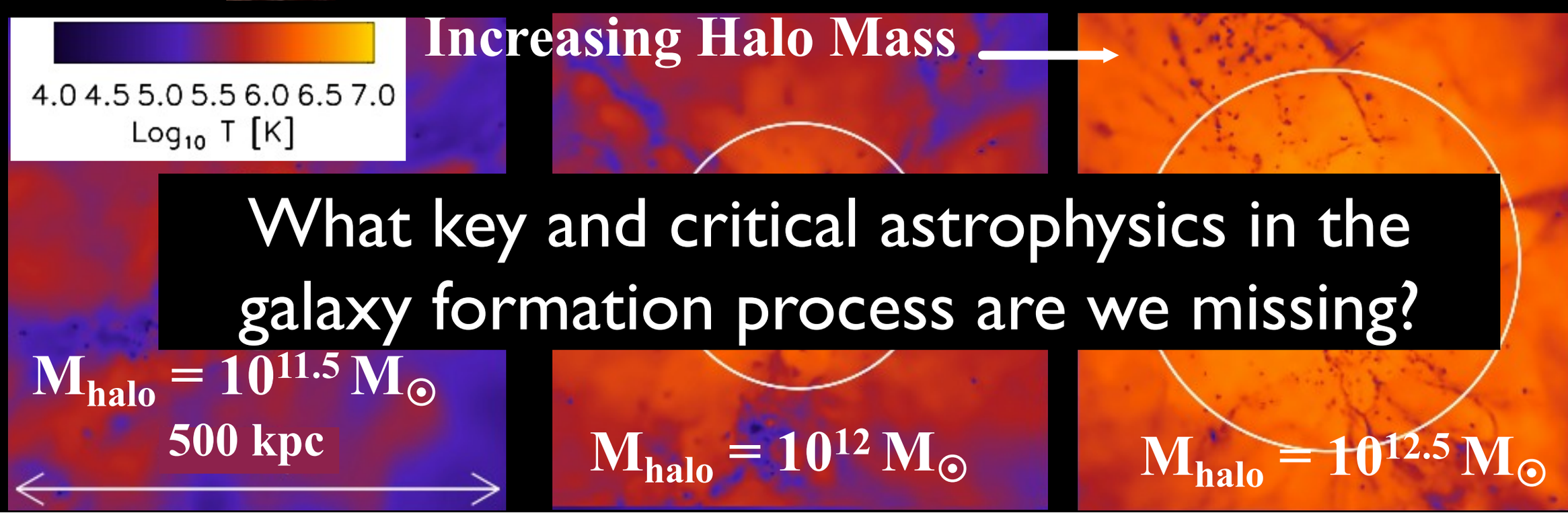
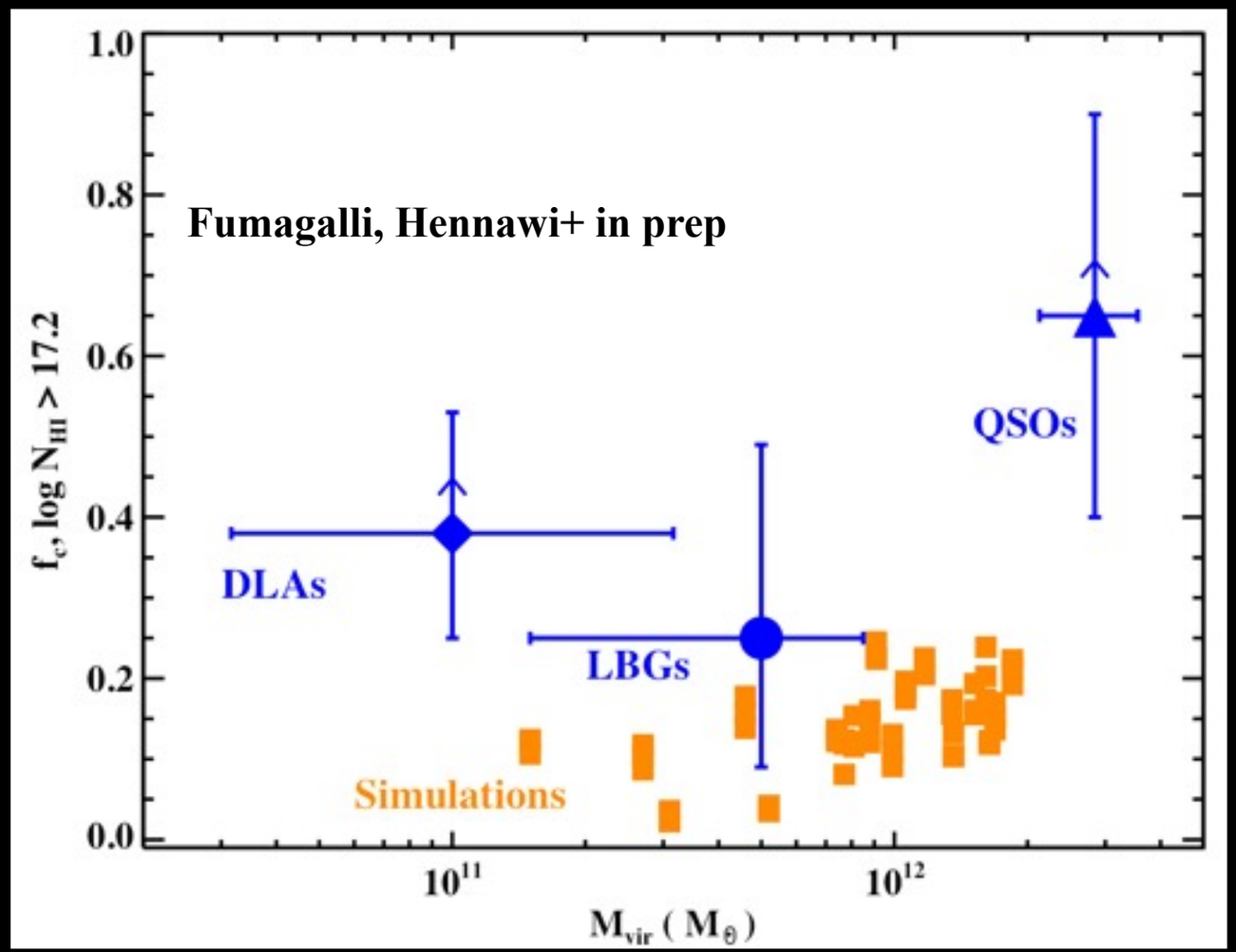


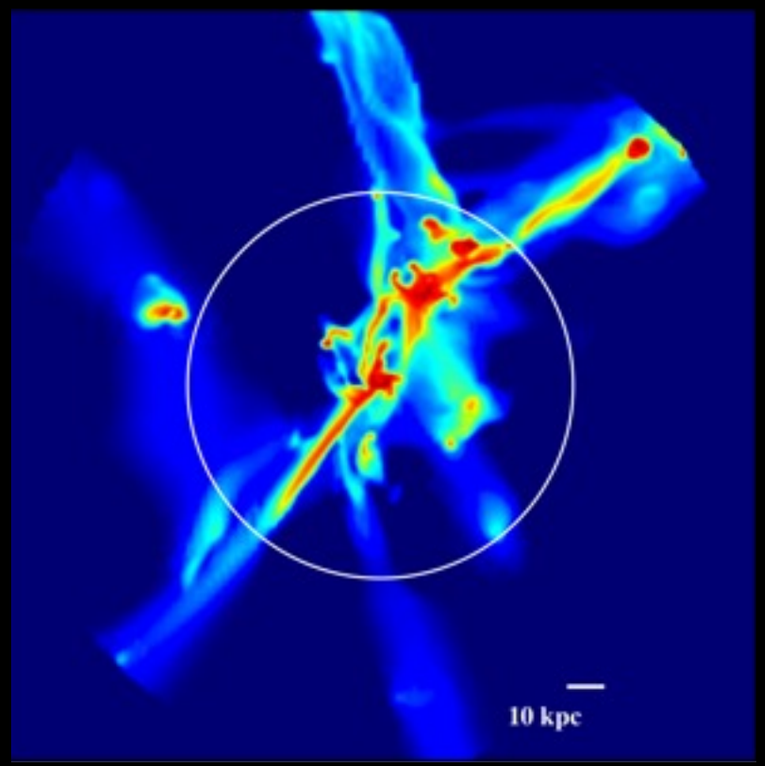
van de Voort+ 11

What key and critical astrophysics in the galaxy formation process are we missing?

Mass Dependence of the CGM



Simulated LBG CGM



ART AMR sims, (Ceverino+ 2010)
Rad. transfer (Fumagalli+ 2011)

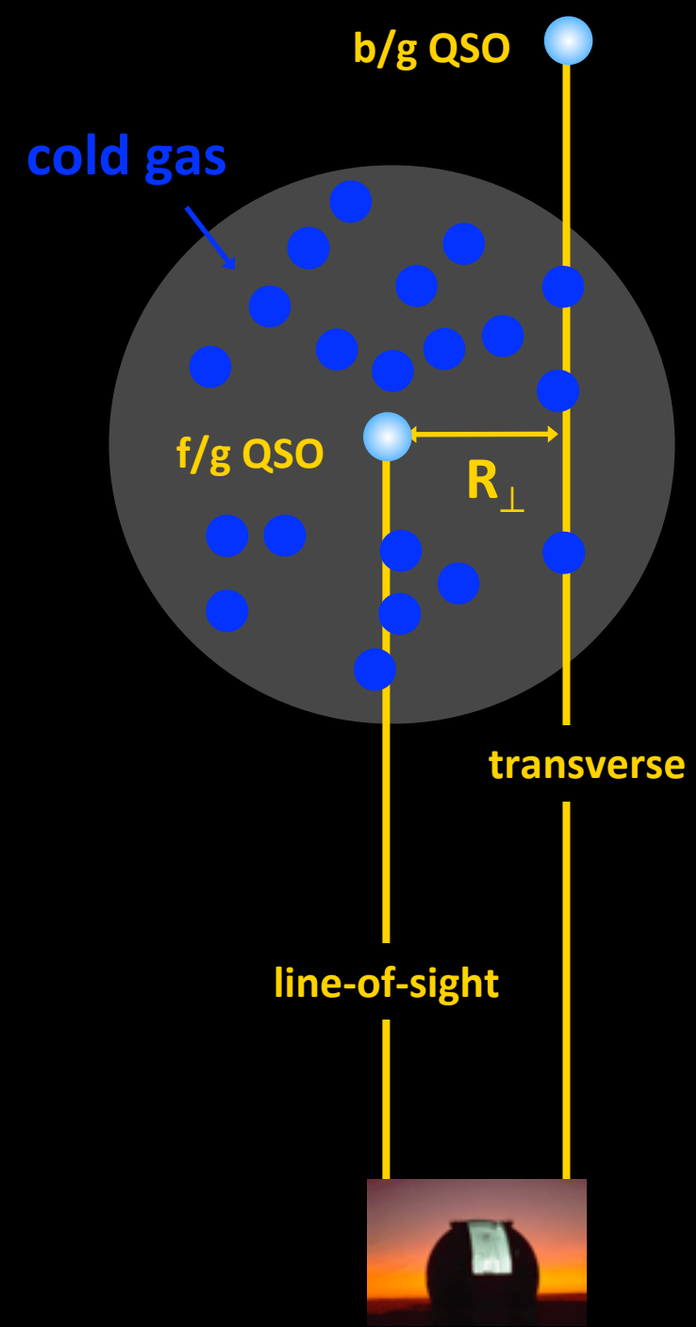
- Likely inconsistency between data and simulations
- But, these are early days for the simulations of the CGM
  - Limited mass range
  - Unaggressive feedback prescriptions
  - Unresolved astrophysics?

Implications: IGrM/ICM Formation

- The IGrM/ICM formed at z<2
  - QPQ results are not definitive on this matter
    - Not too sensitive to hot gas
  - But, the halo must lose the cool gas
    - Violently or gradually??
    - Does the QSO play a role?

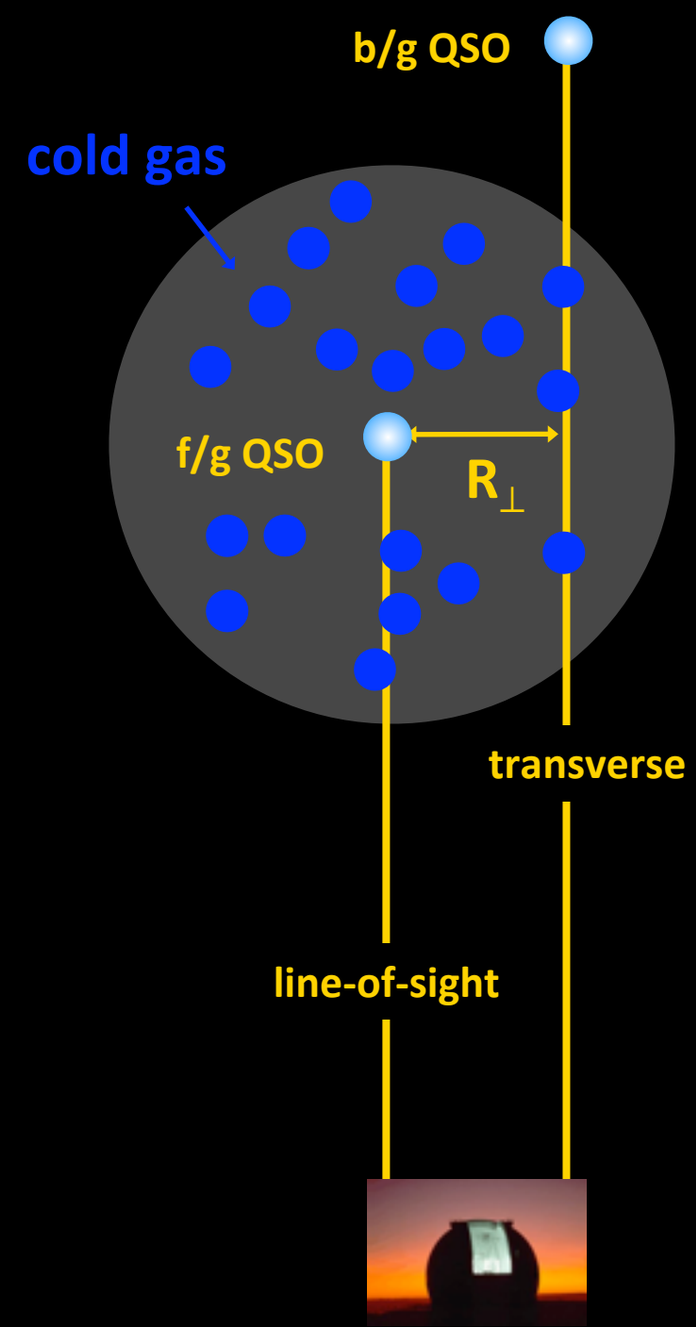
- Current *CGM* properties
  - Major baryonic component
    - Easily exceeding 10^{10} M_{Sun}
    - Cosmological fraction?
  - Metal-enriched
    - Easily 1/3 Solar
  - Is there a hot phase, confining the cool gas?
    - Probable, but with what mass and T?
    - Will it 'destroy' the cool gas??

Implications: Anisotropic Emission



Implications: Anisotropic Emission

- Distribution of Absorbers is highly anisotropic
  - Line-of-sight is highly ionized
    - Transverse is unilluminated!
  - Quasar UV emission is highly anisotropic
    - Or intermittent
    - This may be tested by looking for transverse emission



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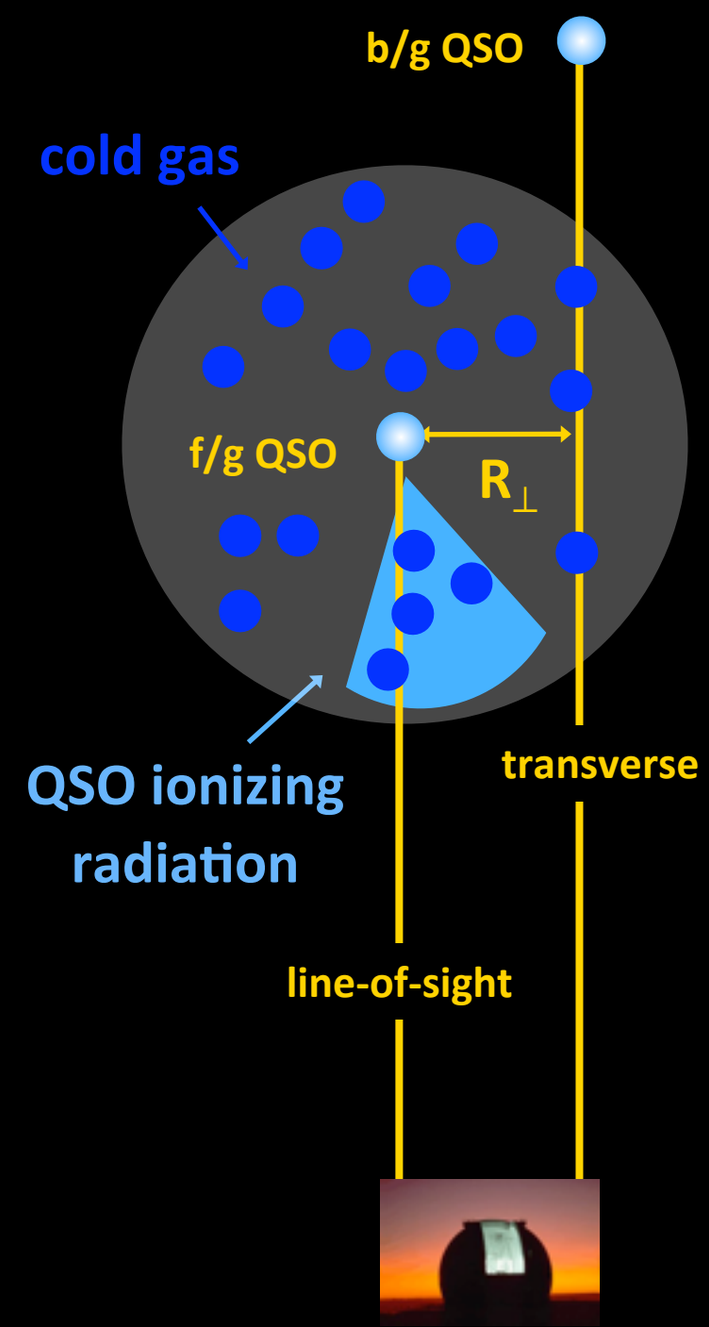

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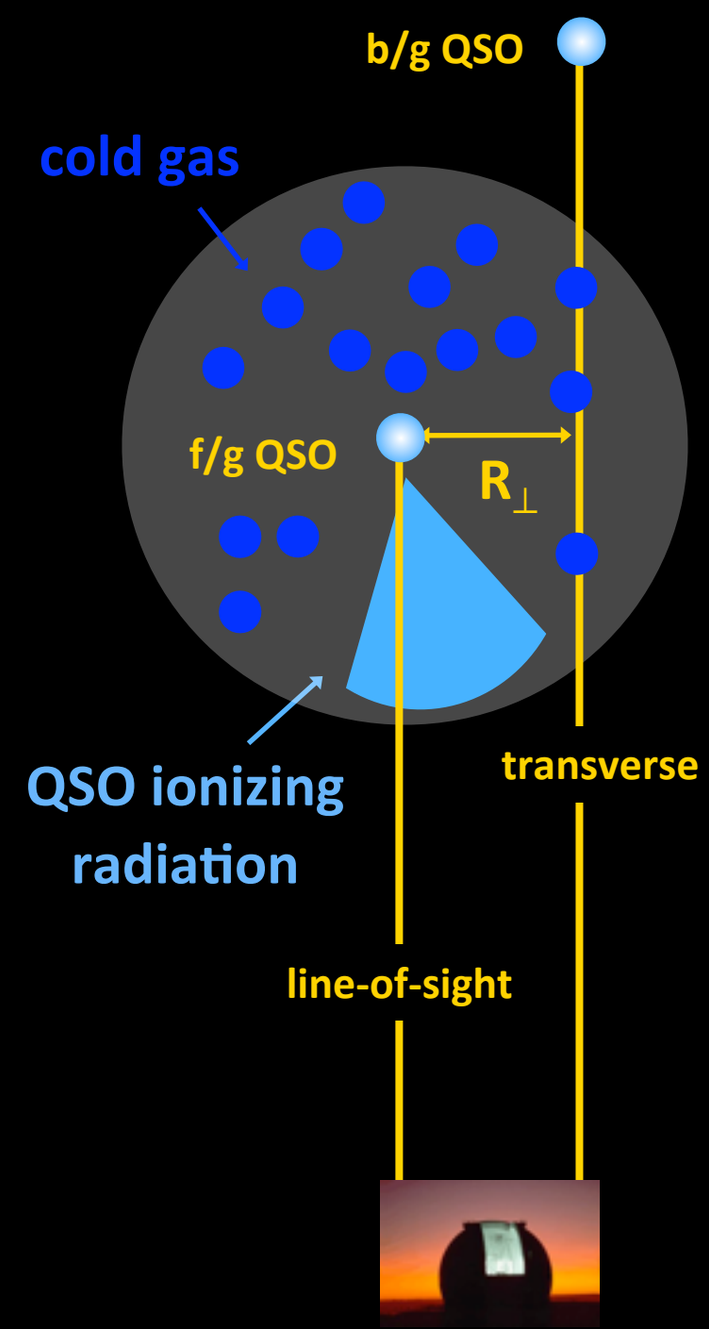


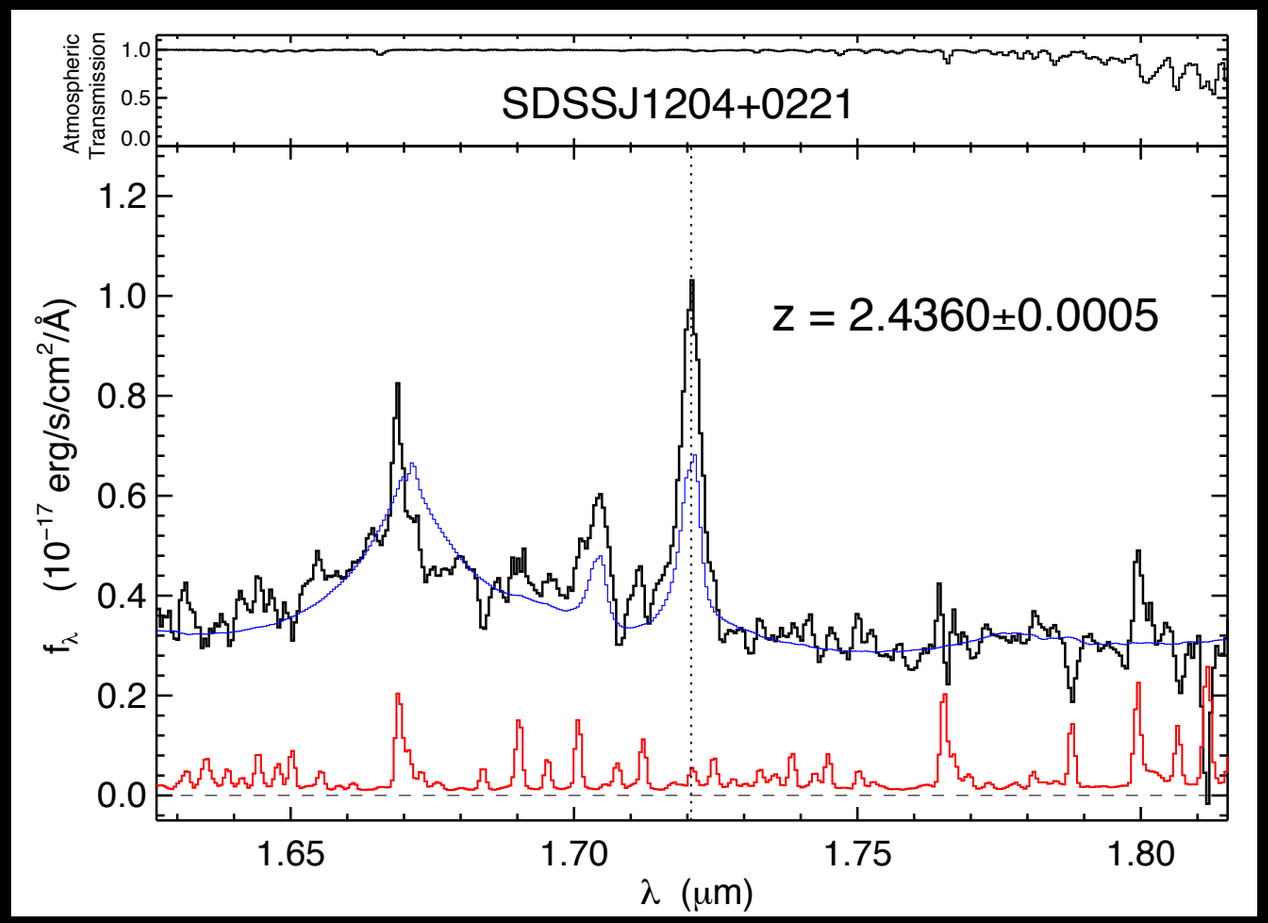
- Implications
  - Are we vastly under-predicting the quasar luminosity function using UV/optical sources?
    - Consistent with obscured AGN fractions?
    - Is all (most) of the variation viewing angle?
    - Test with Transverse Proximity Effect (TPE)
  - Is AGN radiative feedback important?
    - On what scales?
    - Where is the NV?

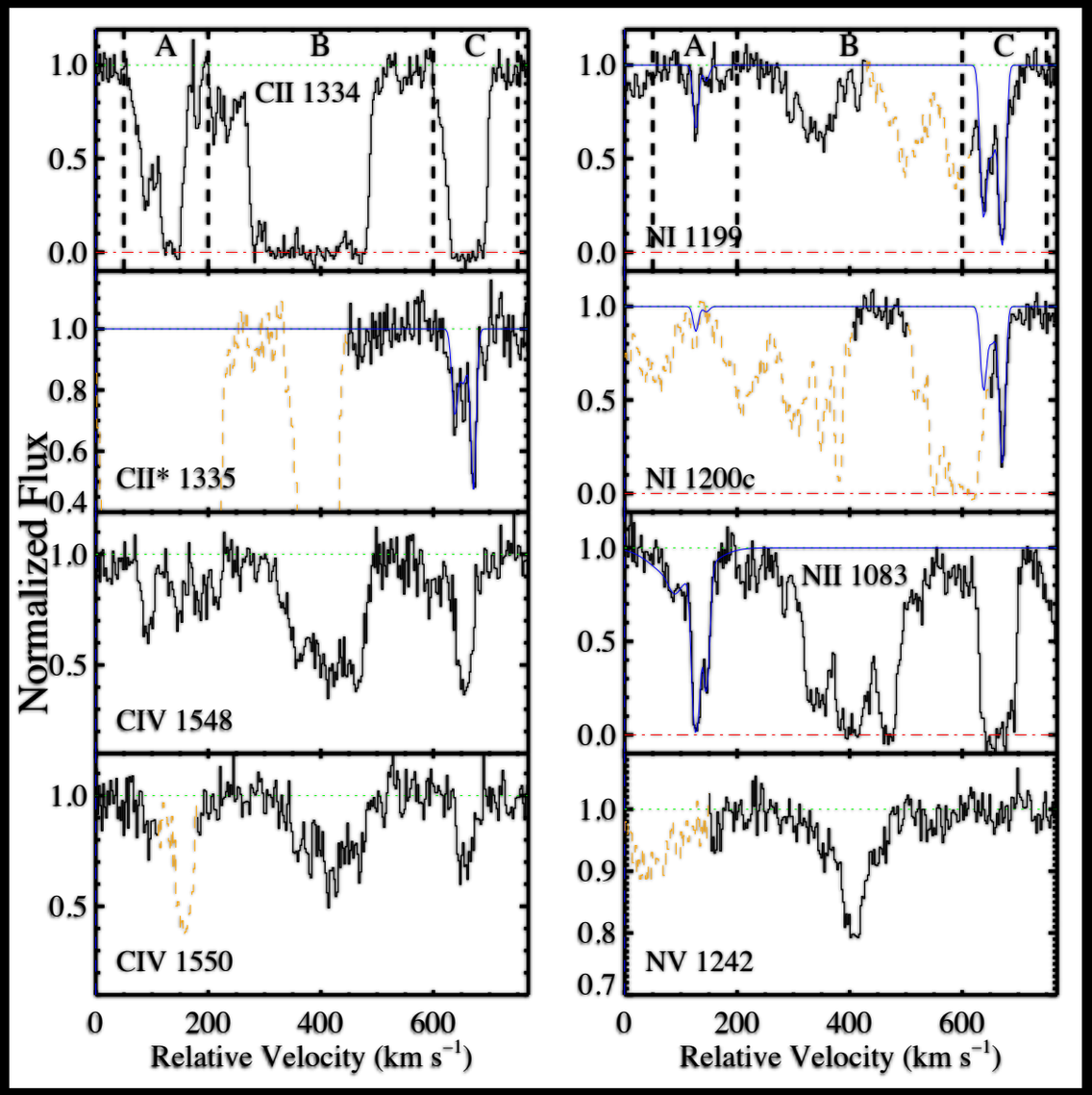
Implications: Feedback

- Is the observed CGM driven by galaxy/ AGN feedback?
  - Metal-enriched
  - Higher covering fraction than predicted by 'cold streams' in numerical simulations
    - Feedback driven CGM?

- But...
  - Cool gas dominated by low ionization states
    - Is this really a signature of active feedback?
  - Generally modest kinematics
    - Gas bound to the system
    - With impressive exceptions (QPQ3)

Future Directions: Kinematics

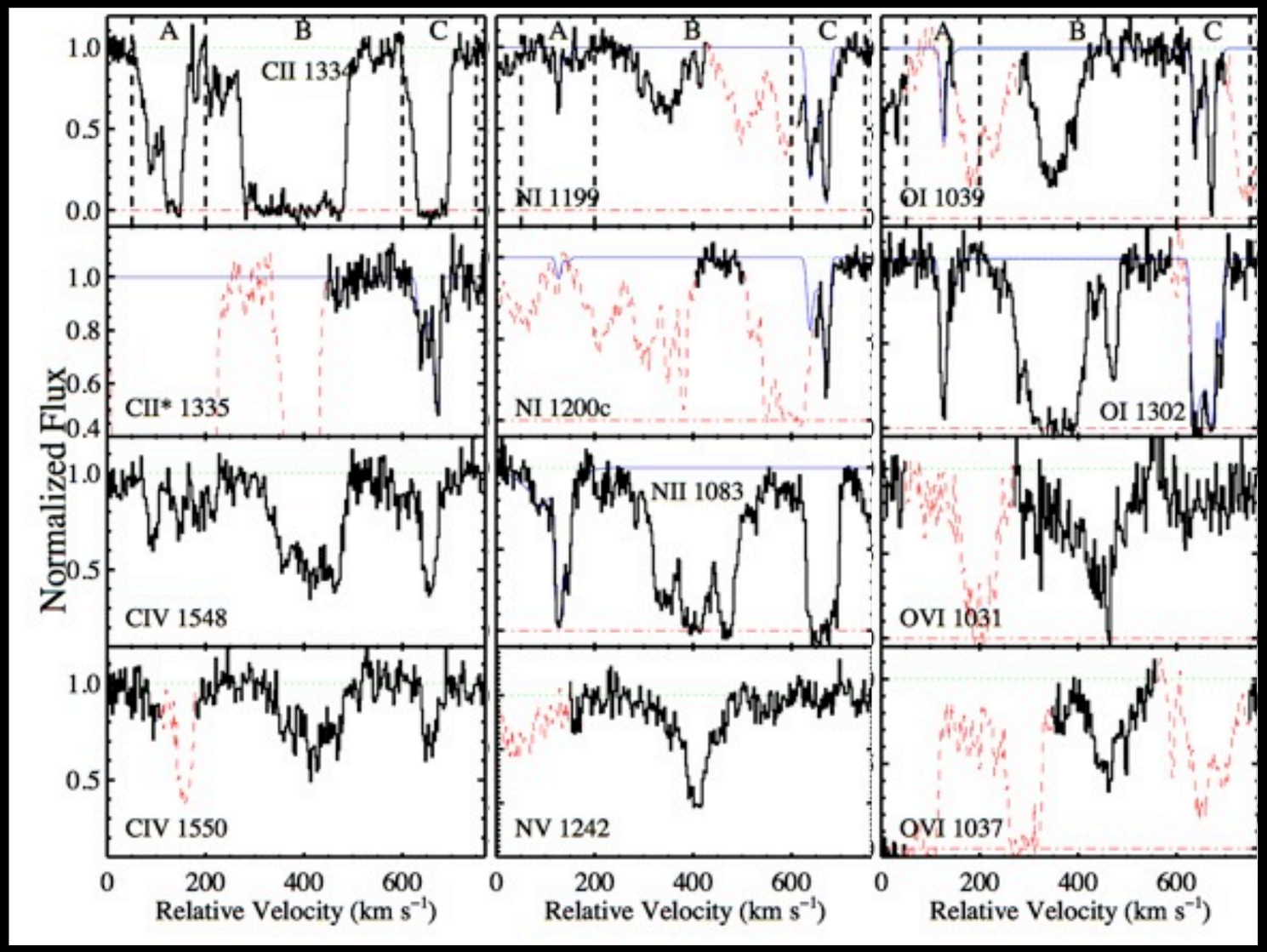




- Near-IR spectroscopy to precisely establish z_{fg}
- Science impacts
  - Trace CGM dynamics
  - Search for inflow into QSO host (along the sightline)
  - Properly perform Transverse Proximity Effect measurements

Future Directions: Metallicity, Ionization

- High-resolution spectroscopy
  - Column density measurements
  - Ionization modeling
    - Significant uncertainties
- Science products
  - Ionization fraction
    - x=0.9
  - Metallicity
    - [O/H] = 0.3 - 1 Solar
  - Density
    - $n_H = 1–5\ cm^{-3}$
  - Temperature
    - $T \sim 10^4$ K
  - Highly ionized gas?
    - None detected



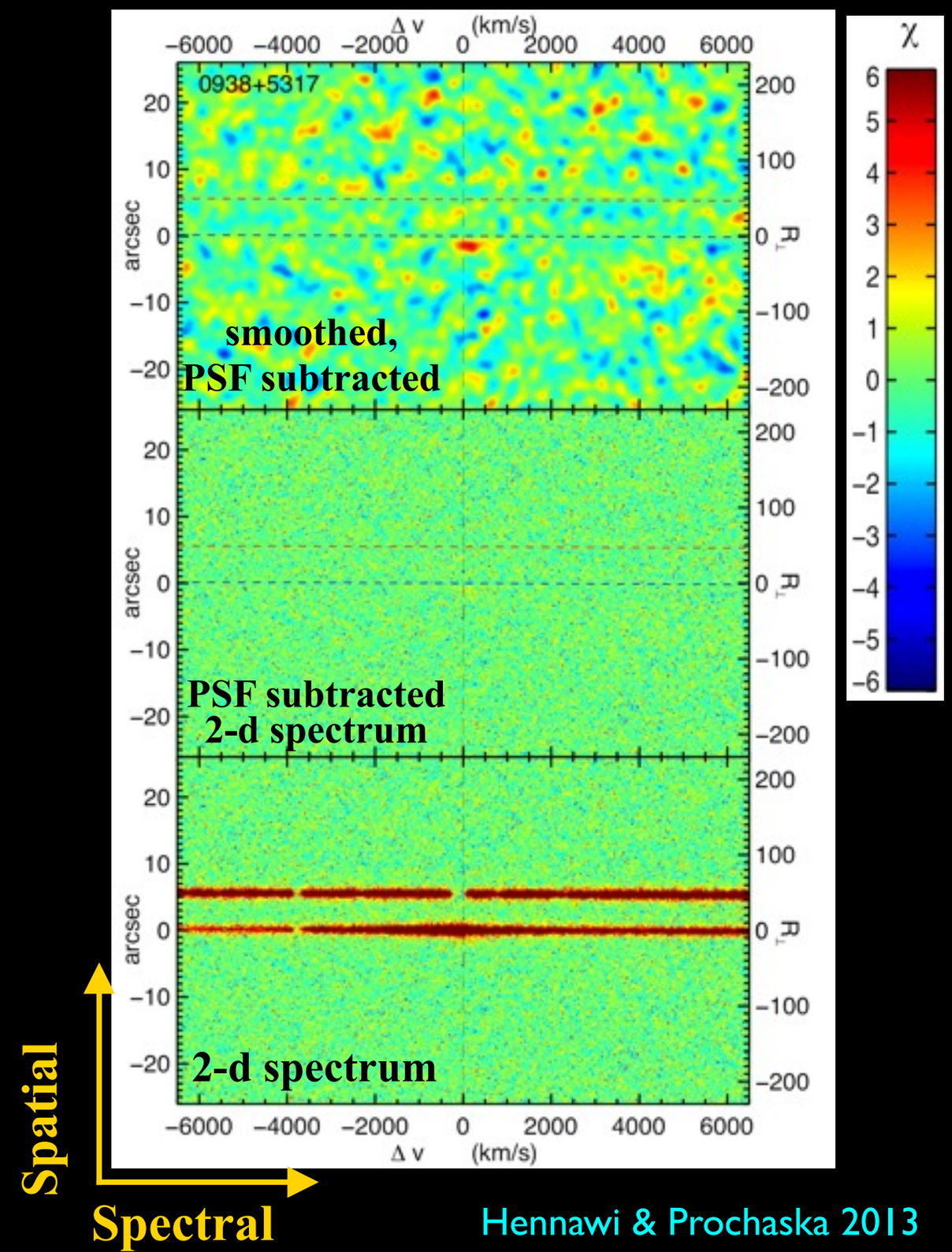
Prochaska & Hennawi (2009)

Lau+13

Future Directions: Lyα Emission

- Spectral search for Lyα emission
  - Relatively sensitive (10^{-17} erg/s/cm^2)
  - Sources of interest
    - Quasar fluorescence
    - Cooling radiation in massive halos
    - Lyα scattering

- Current results (QPQ4)
  - No evidence for 'mirrored' fluorescence
  - Occasional weak 'fuzz' at R<50kpc
  - One spectacular, putative "filament" spanning over 100 kpc



Hennawi & Prochaska 2013

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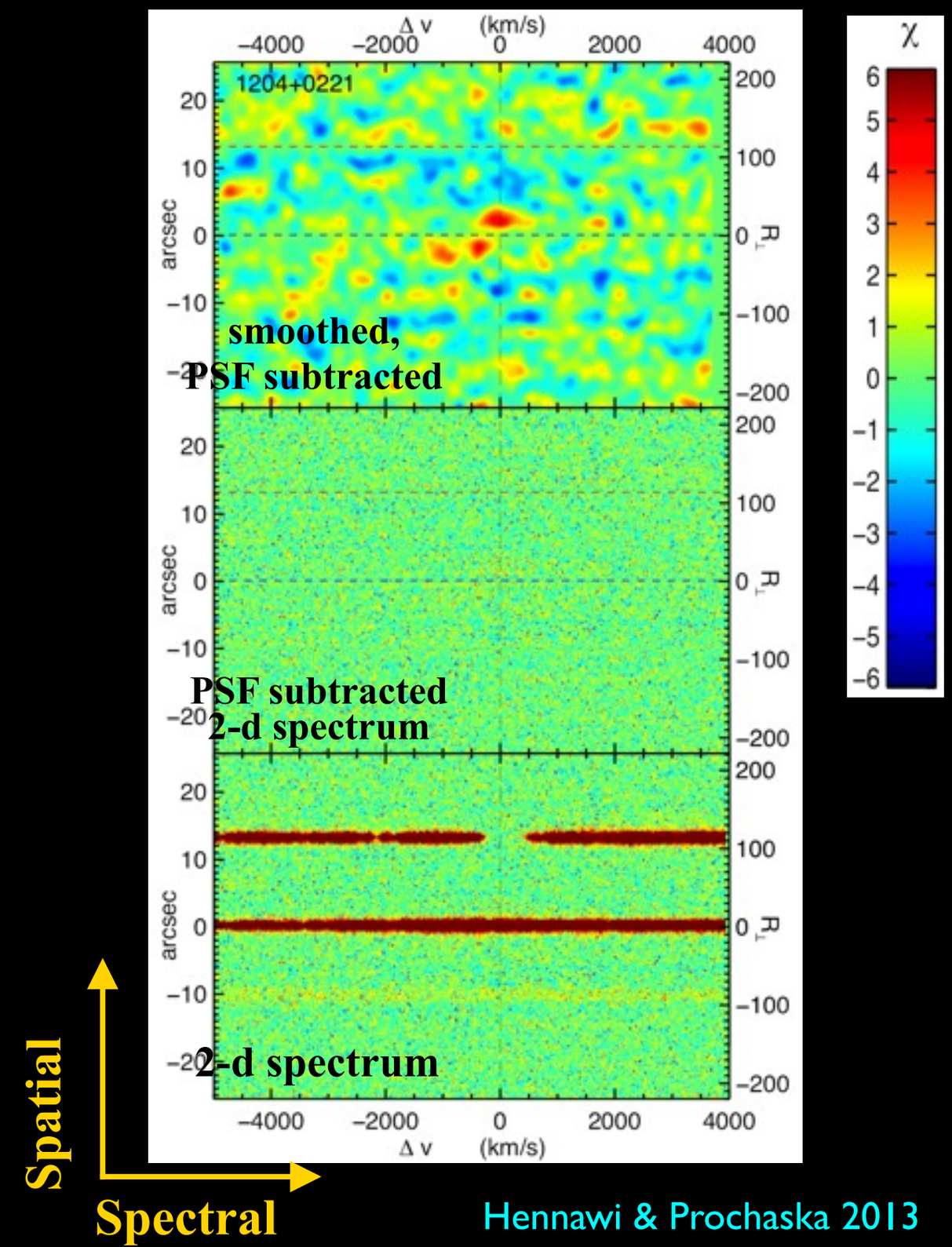

Hennawi & Prochaska 2013

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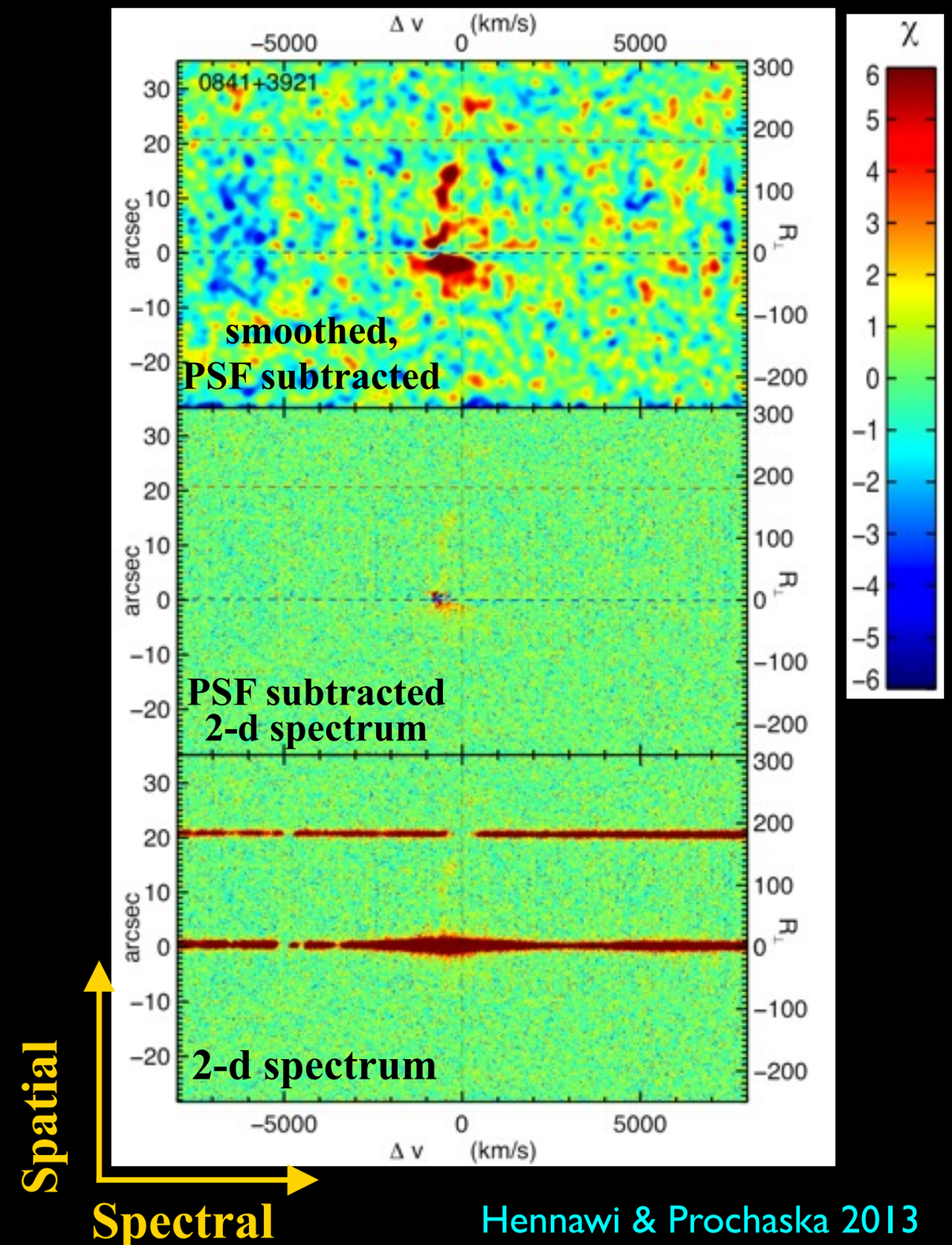
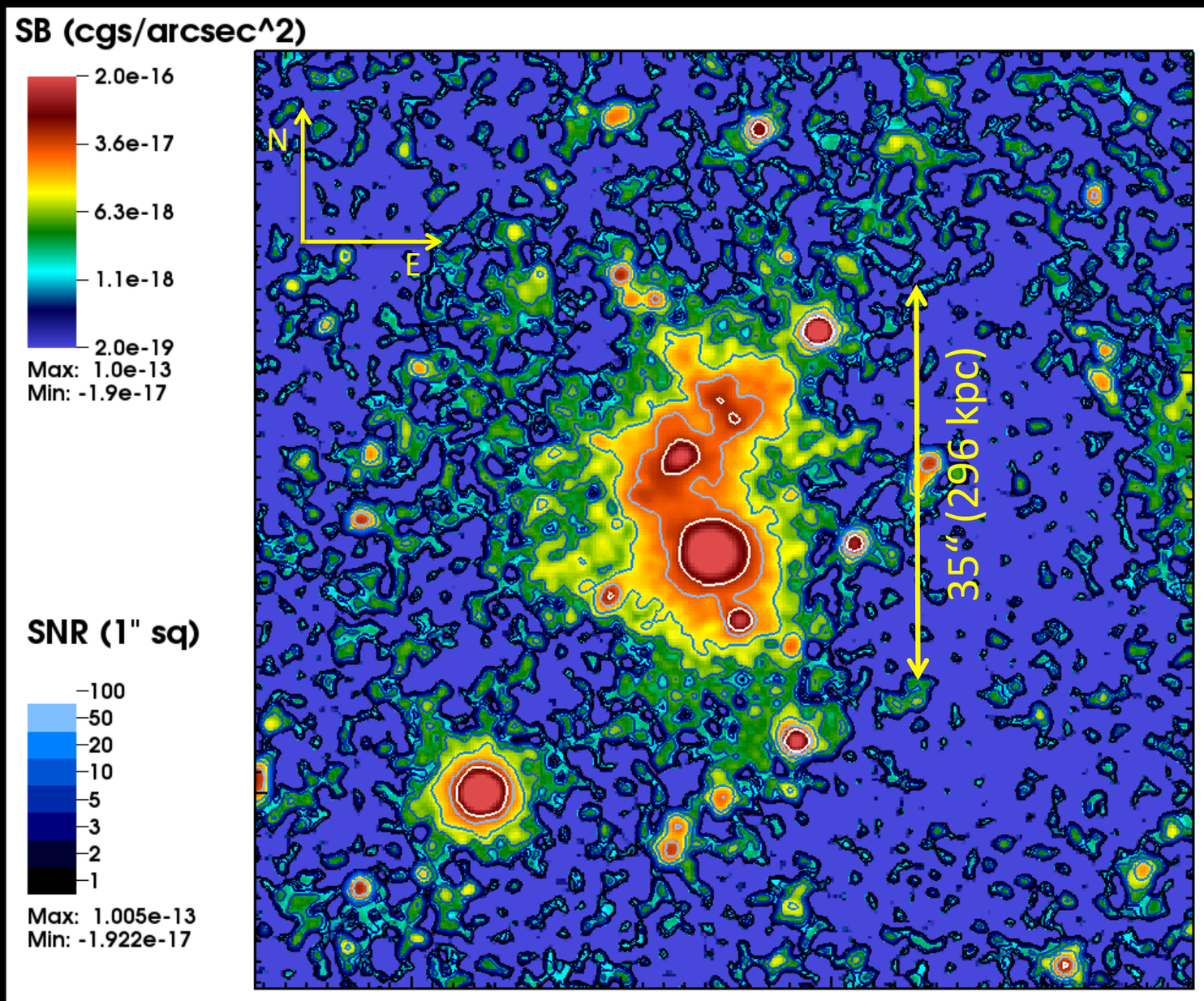
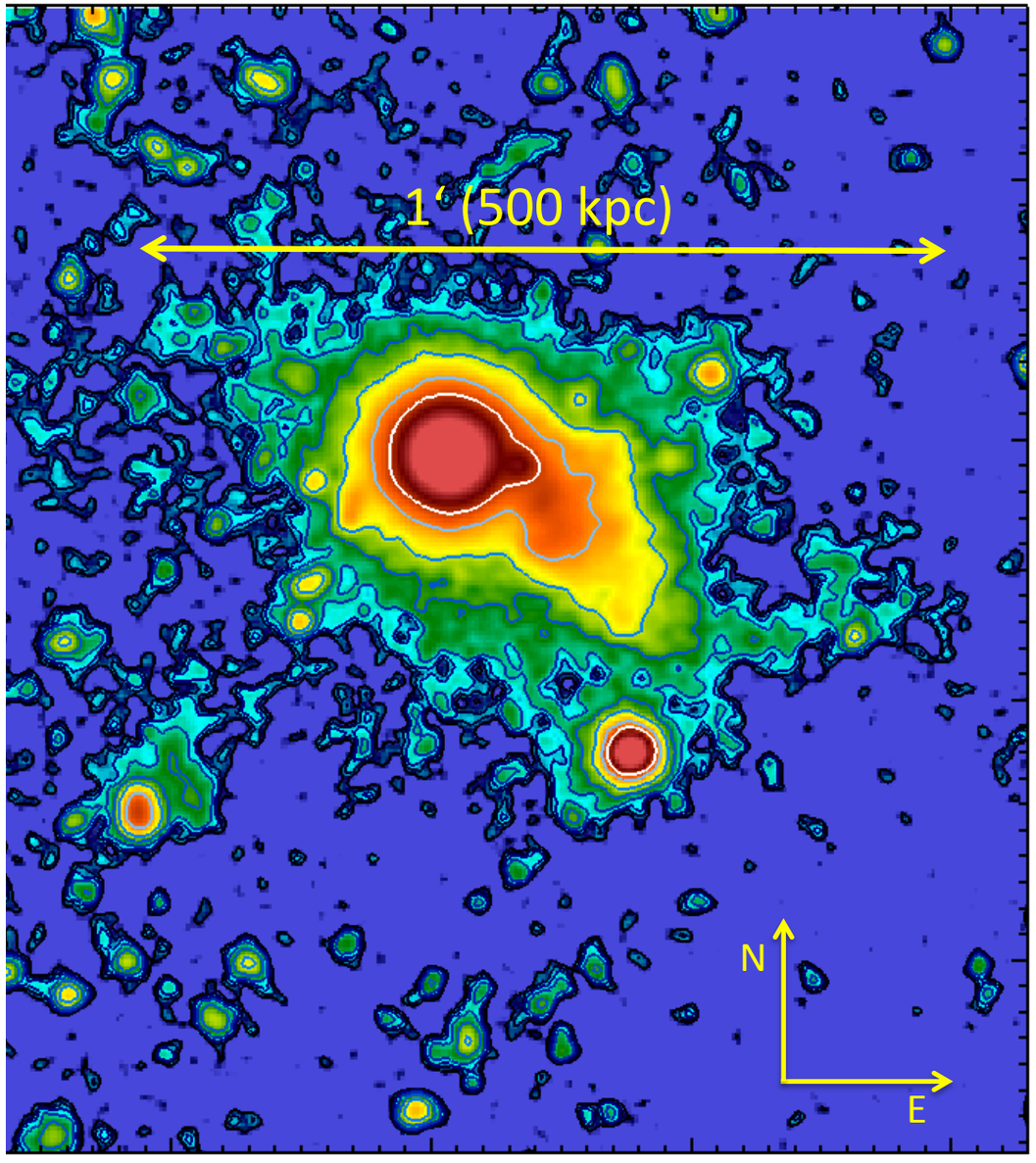


Hennawi & Prochaska 2013

Future Directions: Lyα Emission

Keck/LRIS Narrow Band Imaging





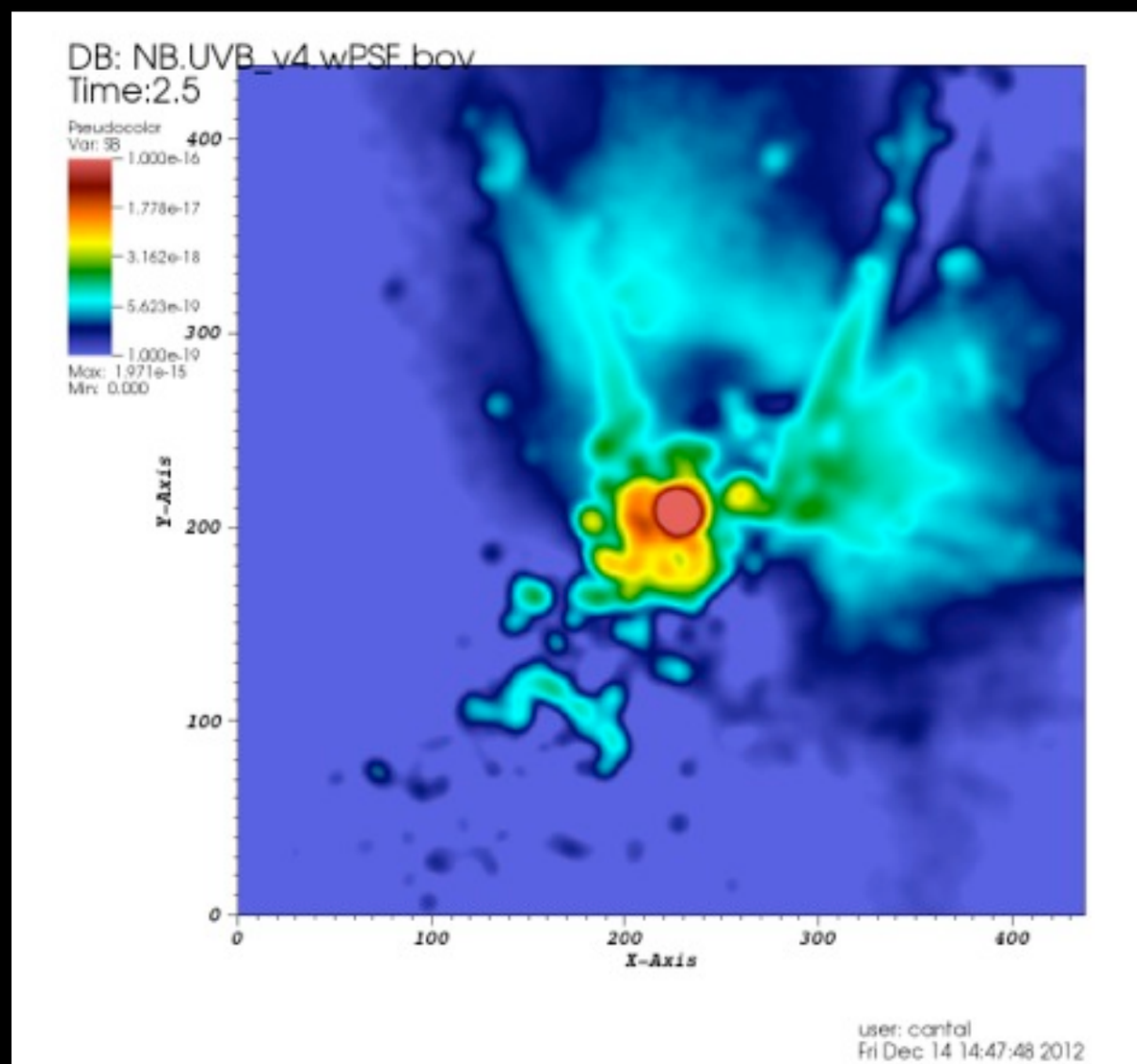
Hennawi+ 2013

"Jackpot" Nebula --
Illuminating a gas filament connecting 4 AGN

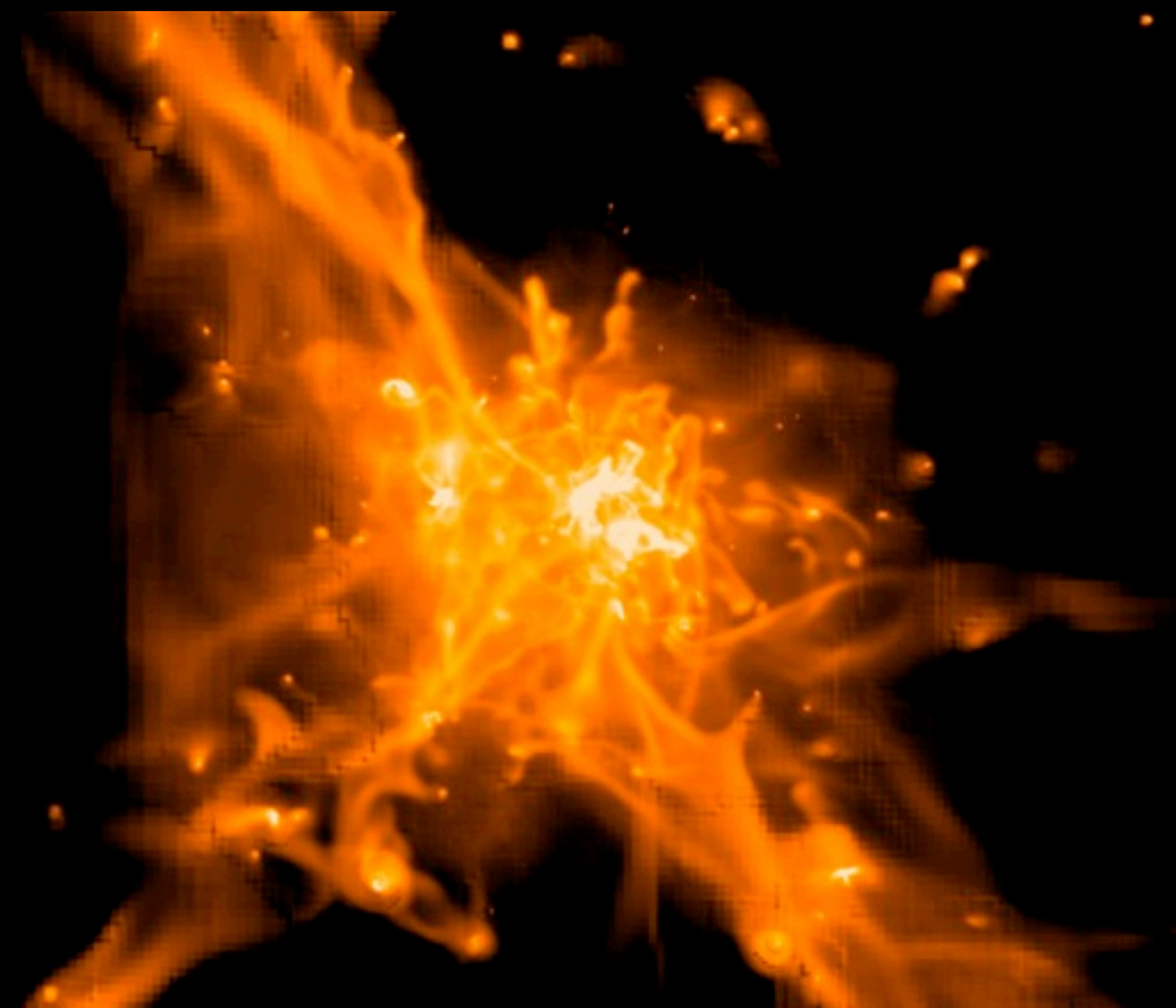
Cantalupo+ 2012, 2013

"Slug" Nebula --
Illuminating the Cosmic Web

Future Directions: Simulations



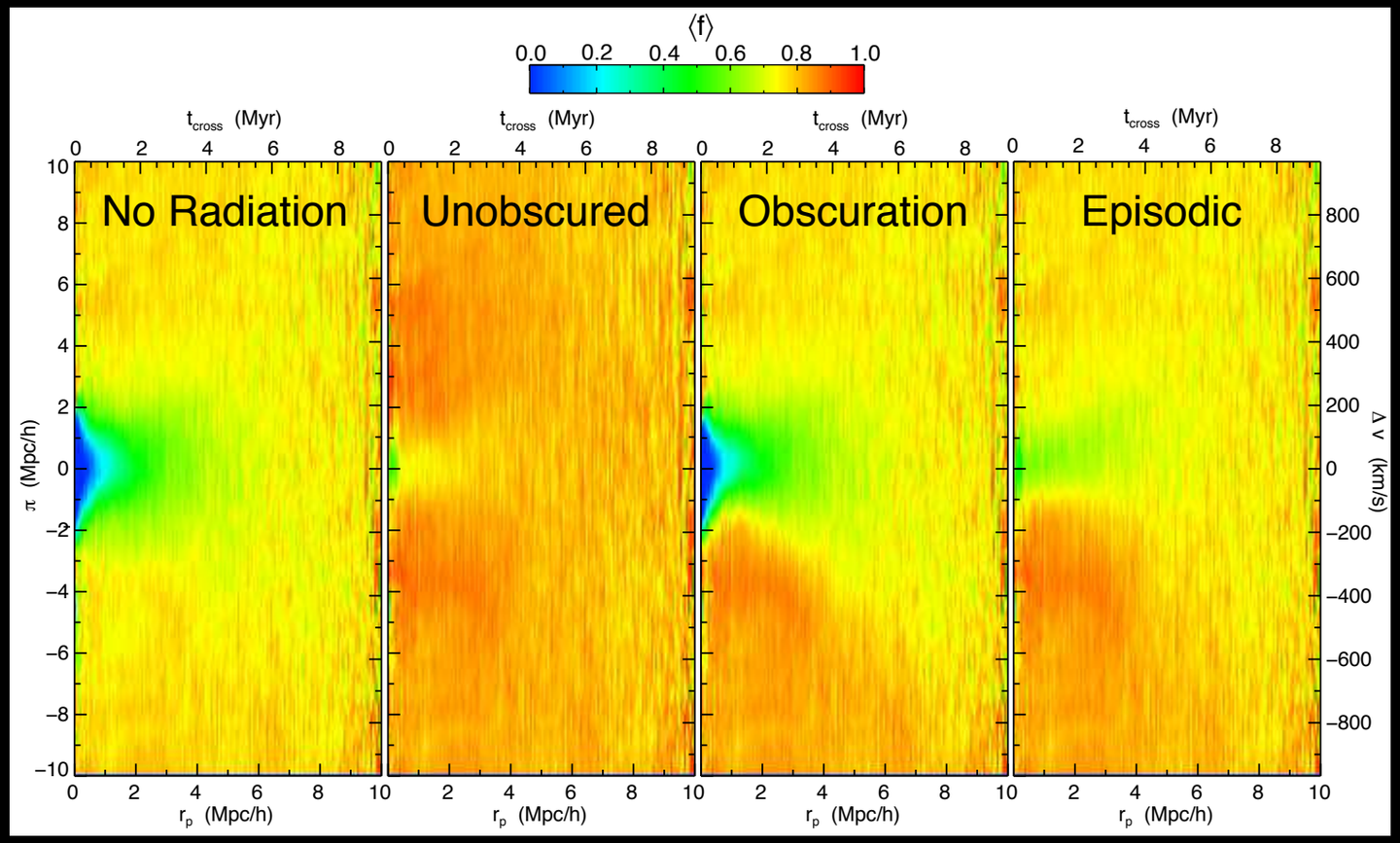
Cantalupo+ in prep



Fumagalli+, in prep

Other QPQ Science

- Transverse Proximity Effect (TPE)
  - Constrain quasar angular emission, lifetime and duty cycle
- Jeans Smoothing
  - Thermal history of the IGM
- HeII Reionization
  - Quasar 'feedback' on the IGM
  - Pan-STARRS mining



Summary

- CGM at z~0
  - Nearly ubiquitous
    - Extending to R_{vir} and beyond
  - Cool, diffuse, metal-enriched
    - Highly ionized (warm/hot?) phase too
  - Major baryonic reservoir
    - In Hydrogen and metals
    - Fuel/gutter for star-formation
- CGM of Massive z~2 galaxies
  - Optically thick gas abounds
    - Cool, massive component
      - $M>10^{10}$ M_{Sun}
      - Predominantly ionized
    - Enhanced HI to 1Mpc
      - $M_{host} = 10^{12.5}$ M_{Sun}
  - Metal-enriched gas
    - [C/H] > -1 (approaching solar)
  - Kinematics
    - Modest, but occasionally extreme
- Implications/puzzles
  - Contradicts cold-flow paradigm
    - Gas has been 'well cycled' by z=2
  - Anisotropic quasar emission
    - Is AGN feedback hidden?
  - When does the IGrM/ICM form?
    - Does the QSO matter?
- Future+Ongoing work
  - CGM emission (Lya)
  - CGM across a wide mass range
  - Transverse proximity effect
  - IGM thermal history (Jeans scale)
  - HeII Reionization