The IGM/Galaxy Connection

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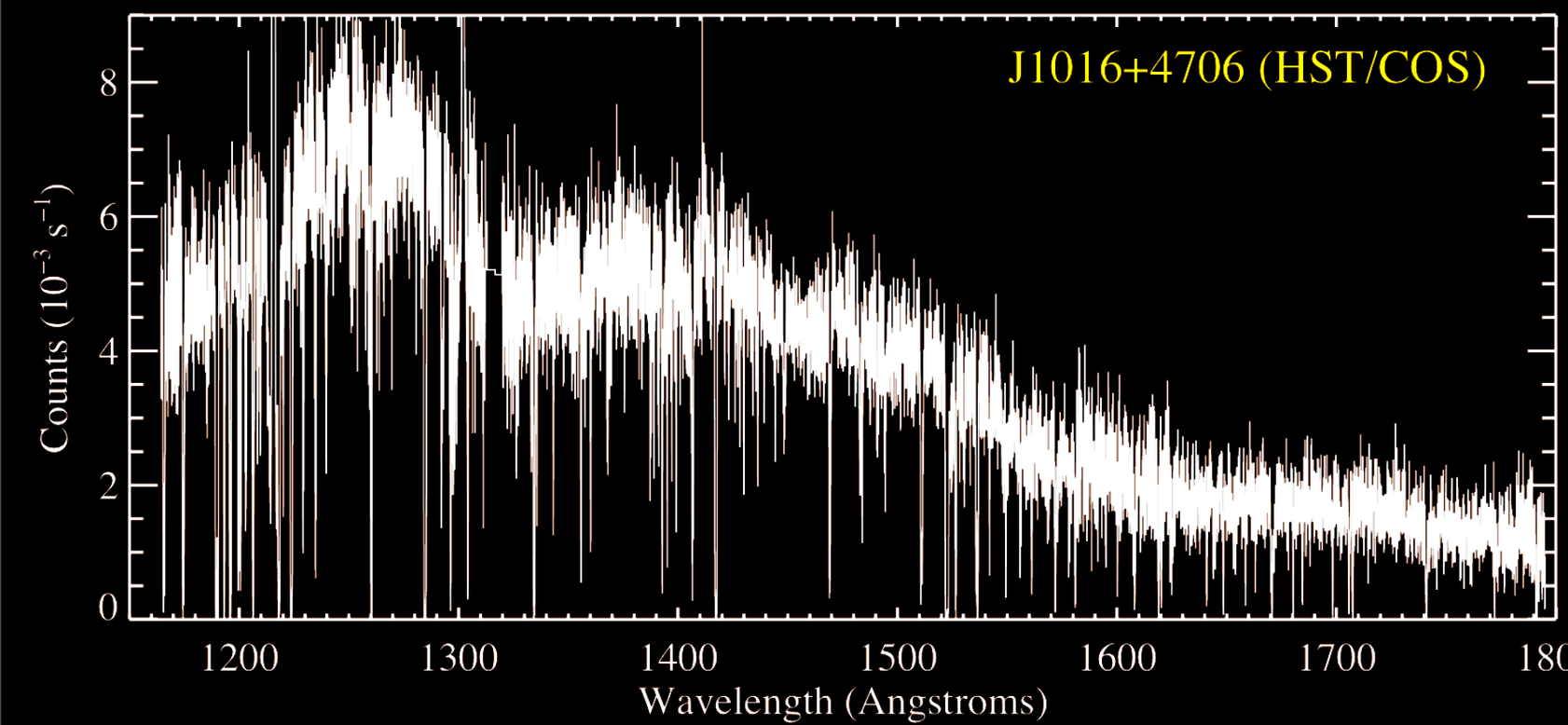
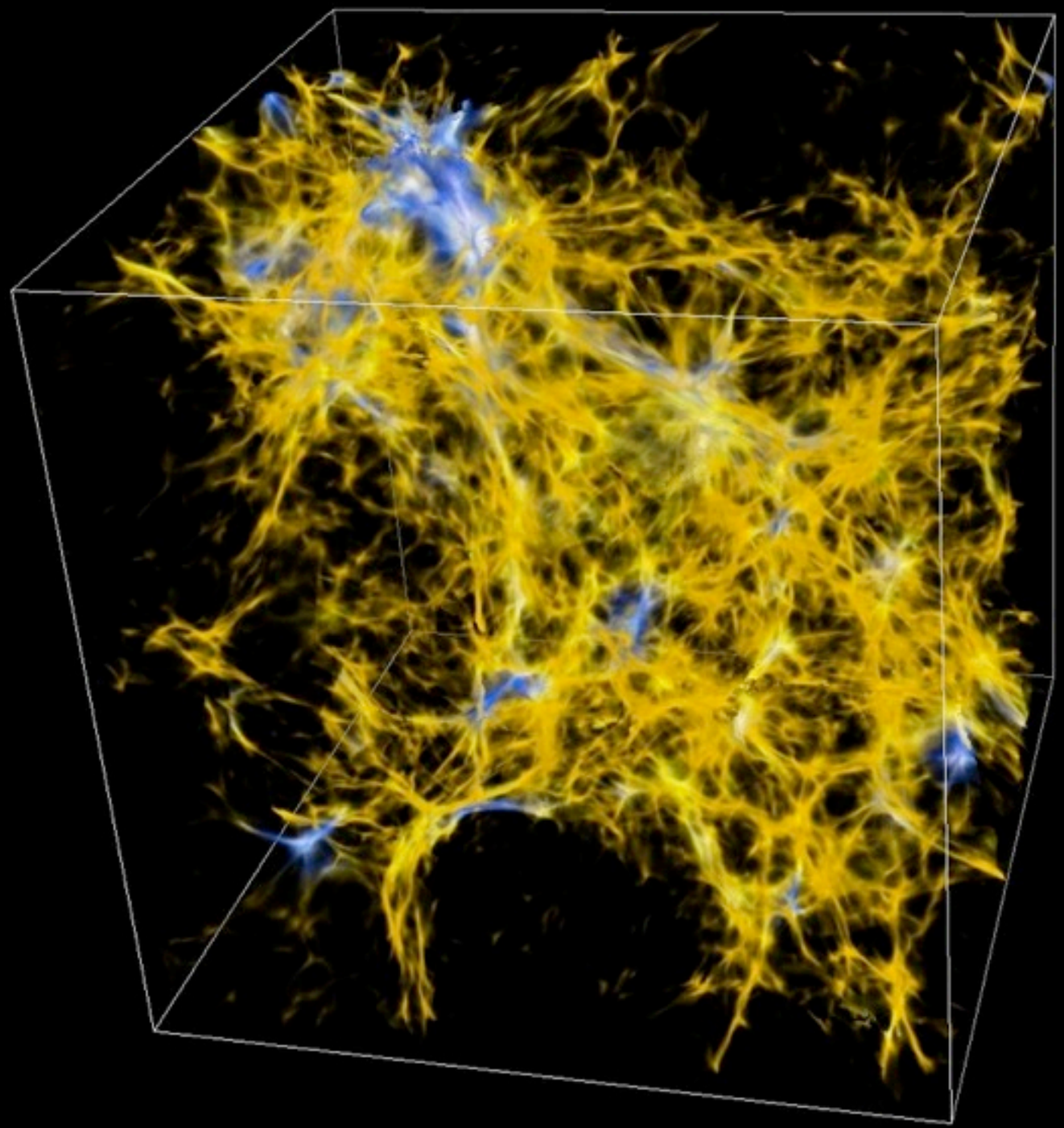


J. Xavier Prochaska (UCO, UC Santa Cruz)

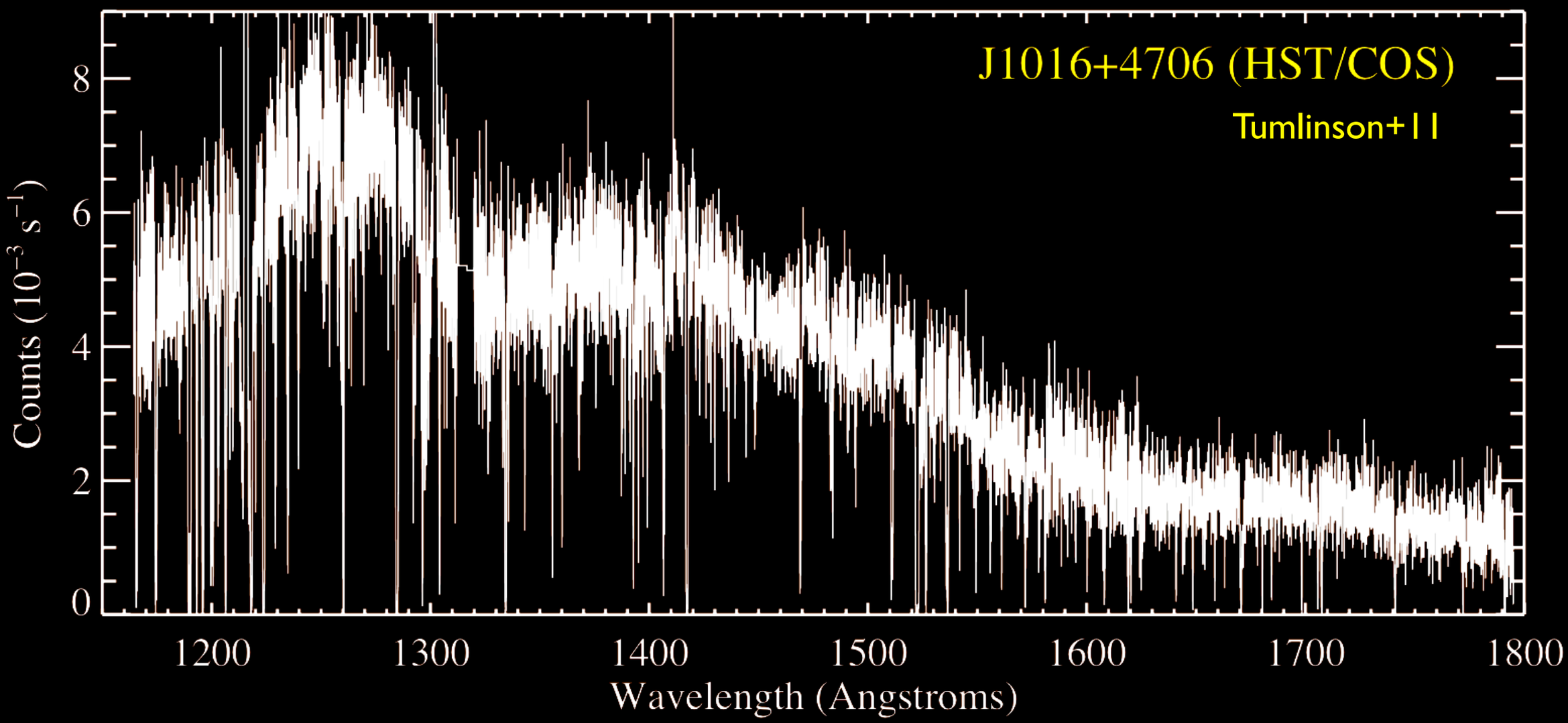
Inter(galactic+stellar) Medium Program of Studies [IMPS]

Outline: The IGM/Galaxy Connection

- IGM introduction
  - Absorption line systems
  - f(N,X), l(X)
- Exploring the CGM at z~0
  - Extended gaseous halos
  - Origin of the Lya/OVI "IGM"
- The IGM/CGM at z~2
  - Evolution?
- A few contrarian remarks on galactic-scale winds and the CGM
  - If you ask for them...



The Intergalactic Medium (IGM)



A Strict Definition: The diffuse (and highly ionized gas) that permeates the volume between galaxies.

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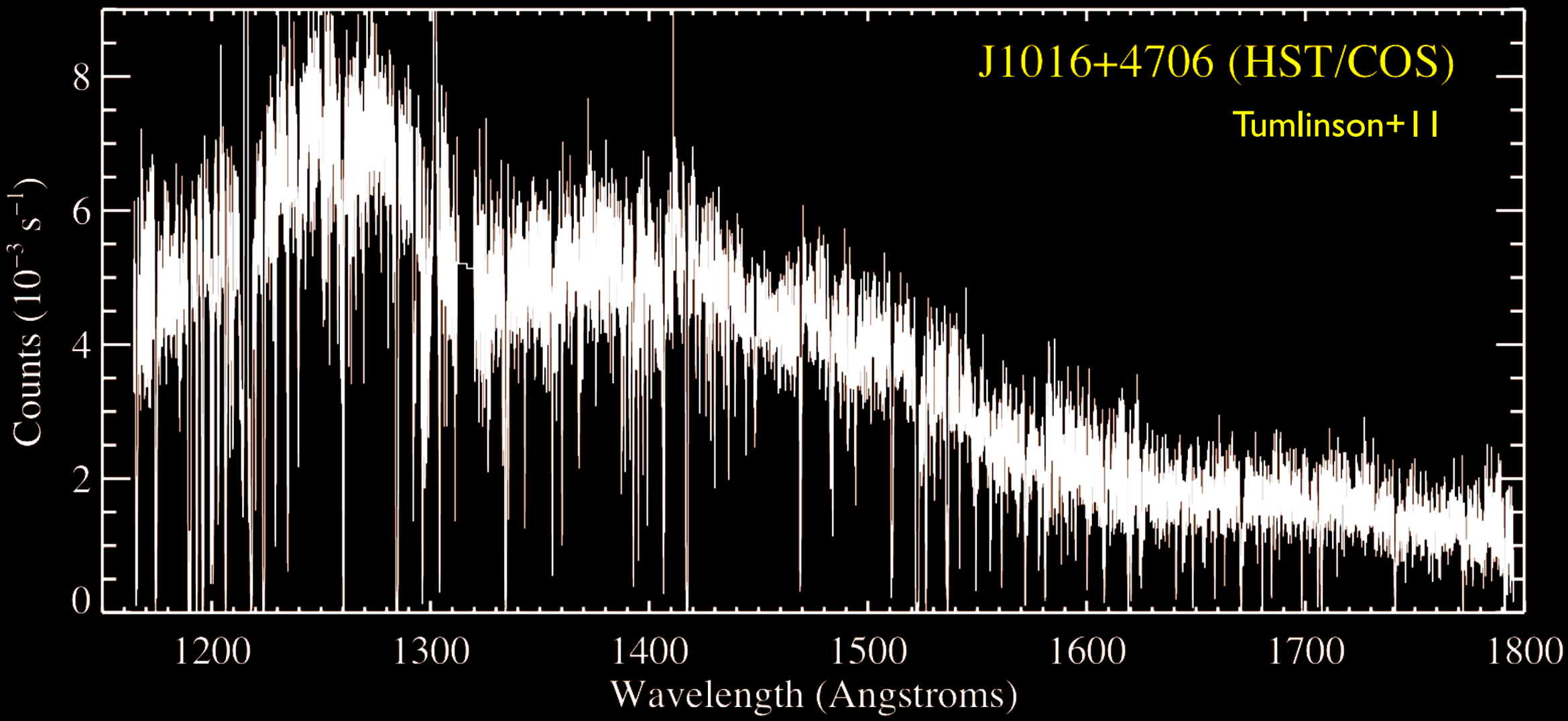

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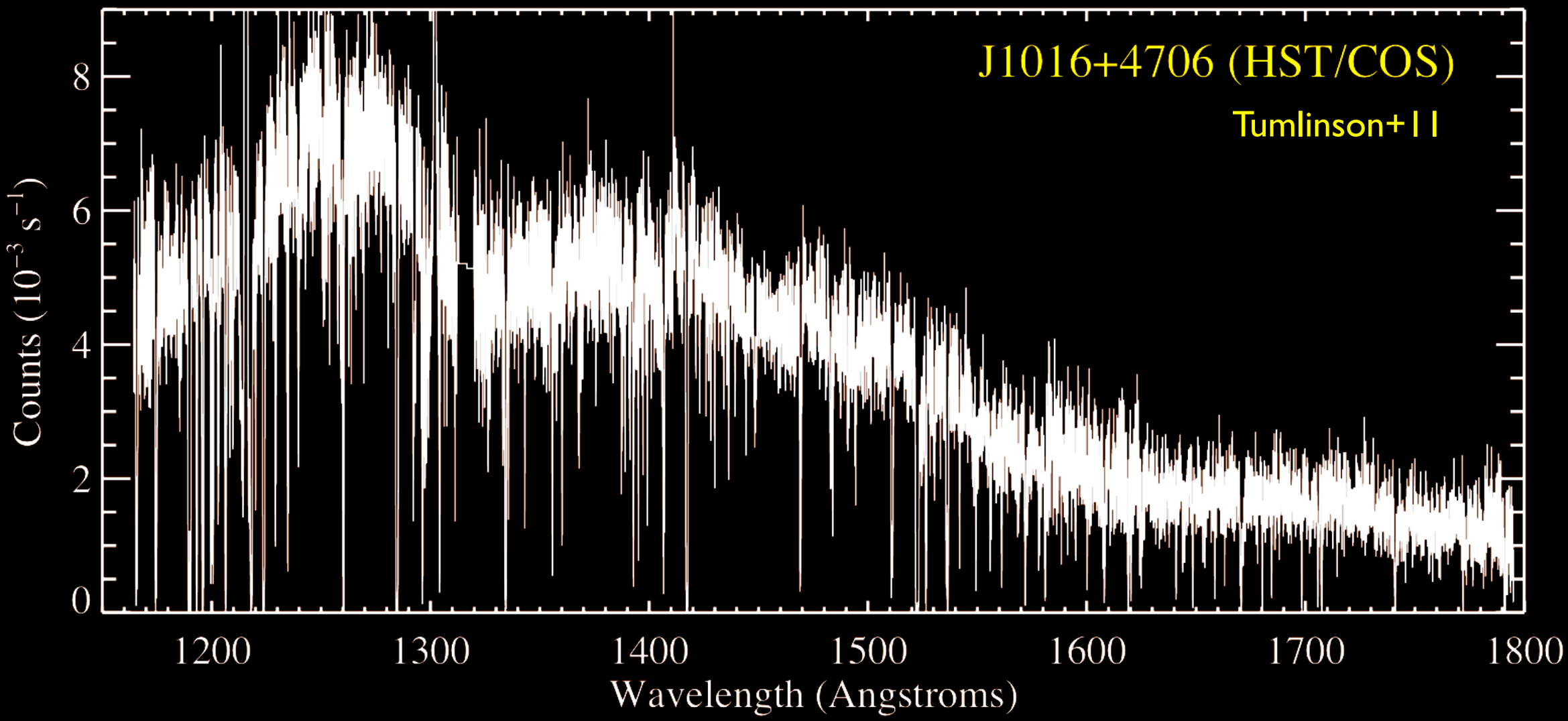

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Miralda-Escudé+95
Rauch+96
Katz+96
Davé+99
Davé+11
etc., etc.

Our LCDM paradigm predicts a diffuse, ionized medium that permeates the volume between galaxies.

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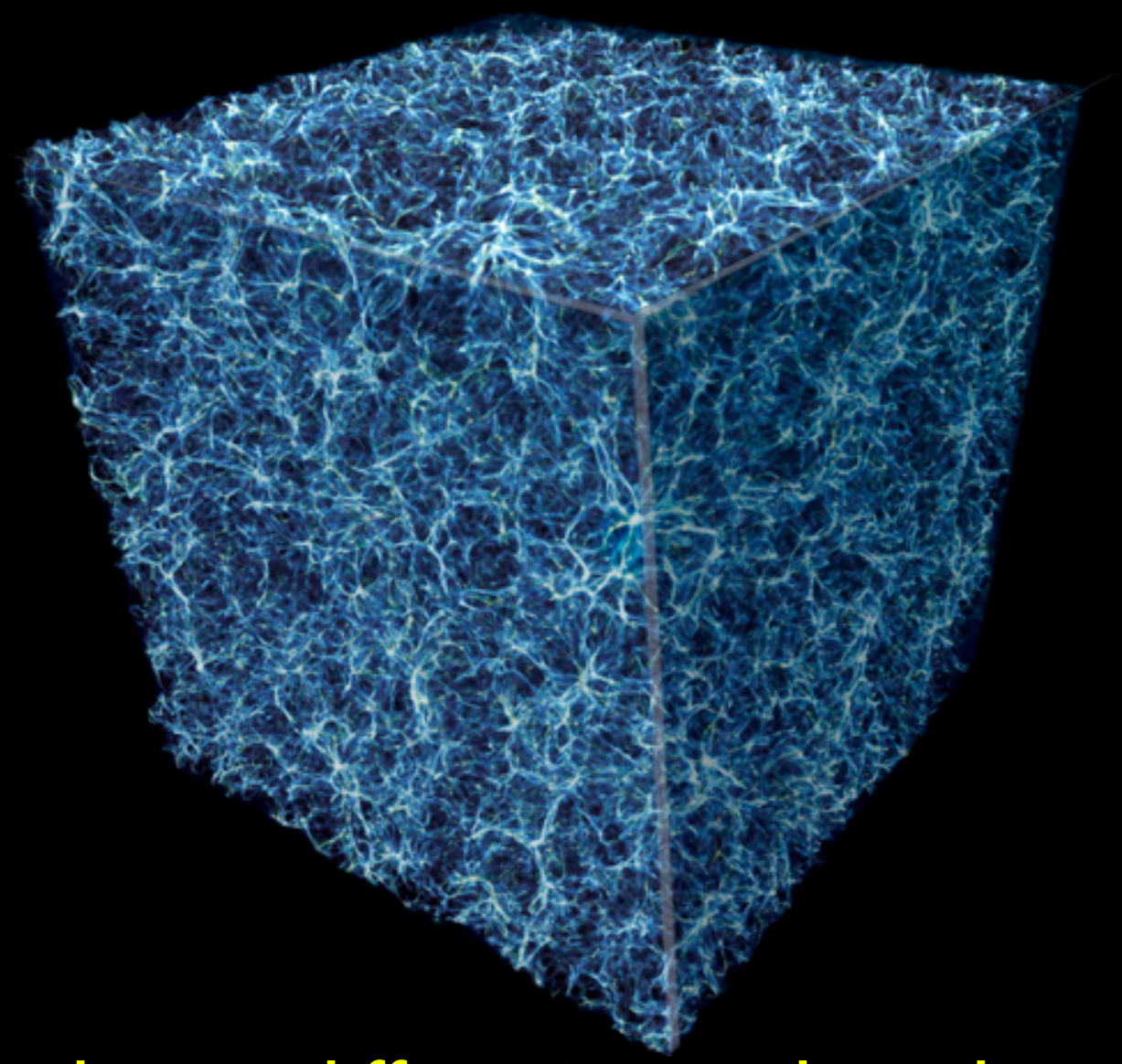

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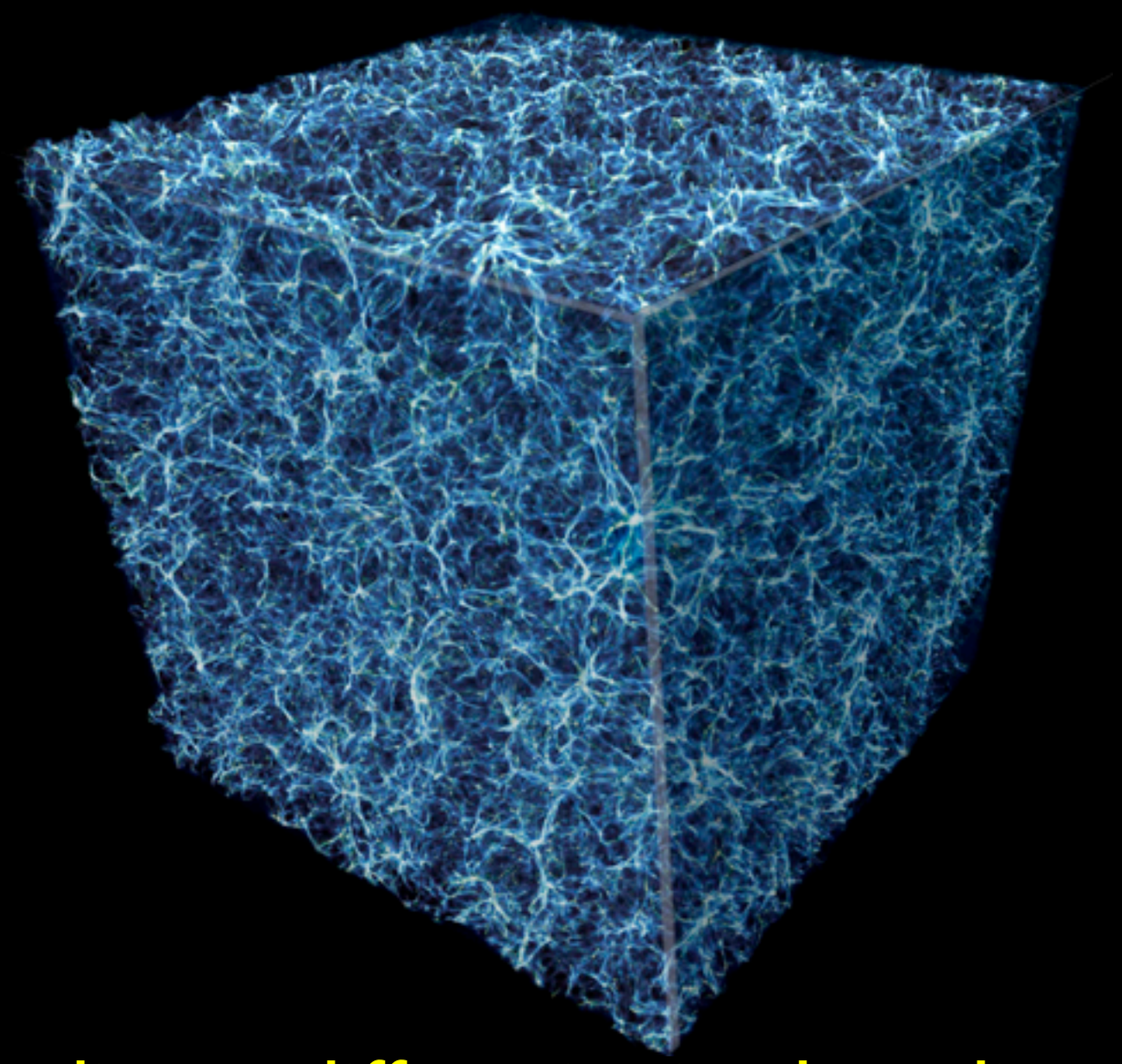

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This gas is predicted to be distributed in sheets and filaments, forming the so-called "cosmic web".

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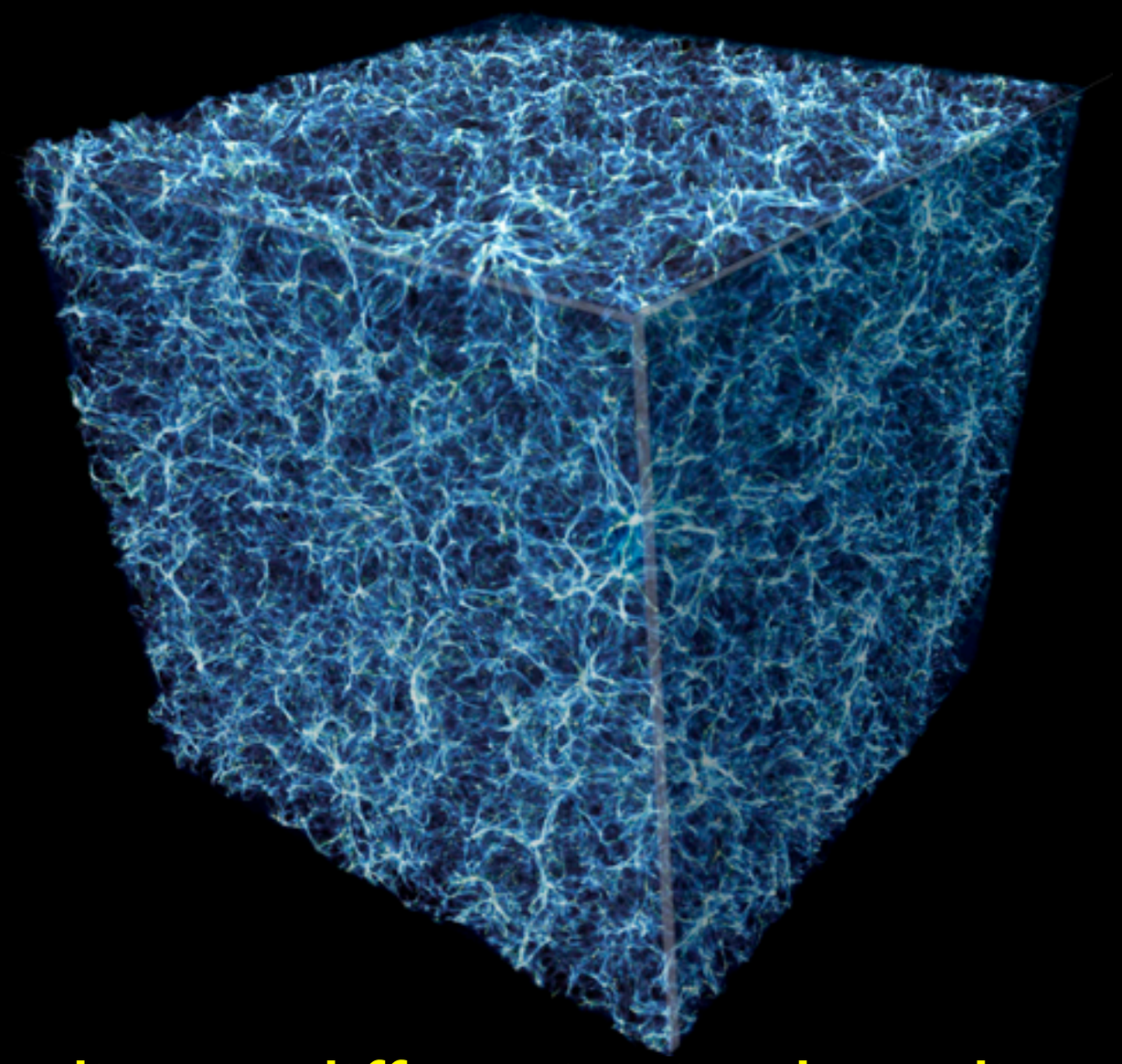

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Is this the proper picture? How does the IGM relate to galaxies?

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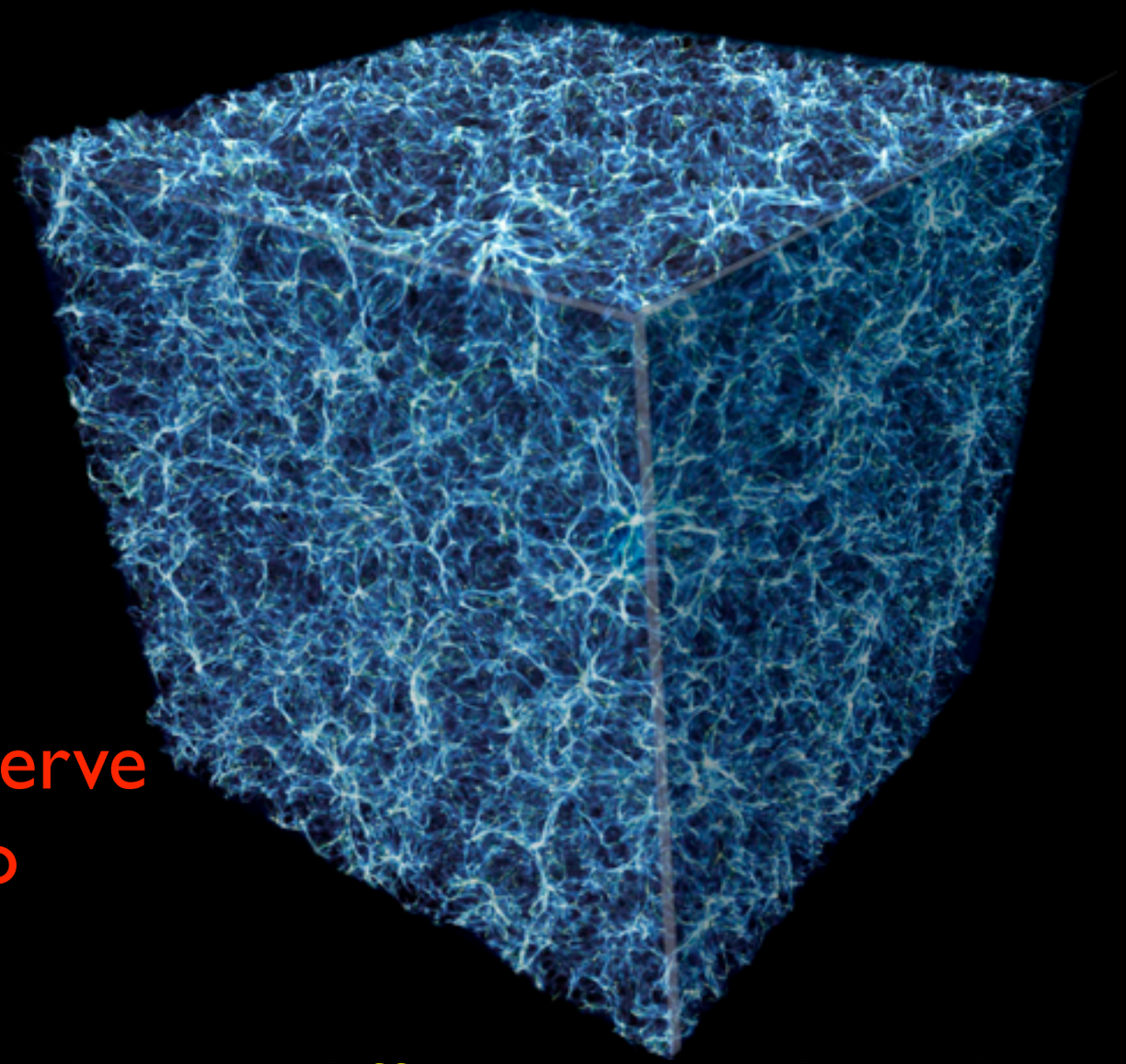

This gas is too diffuse to observe in emission. This forces us to absorption-line techniques.

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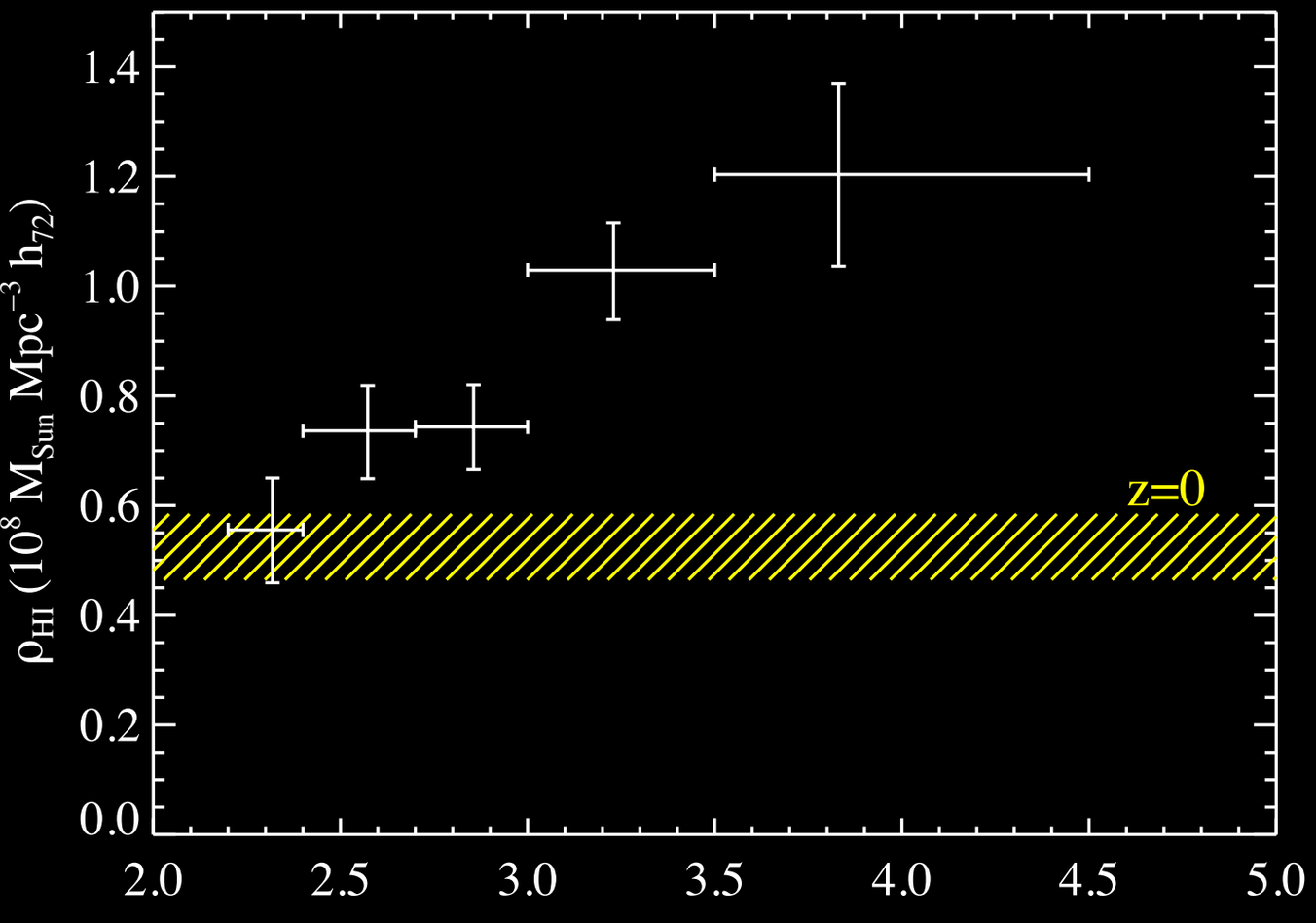
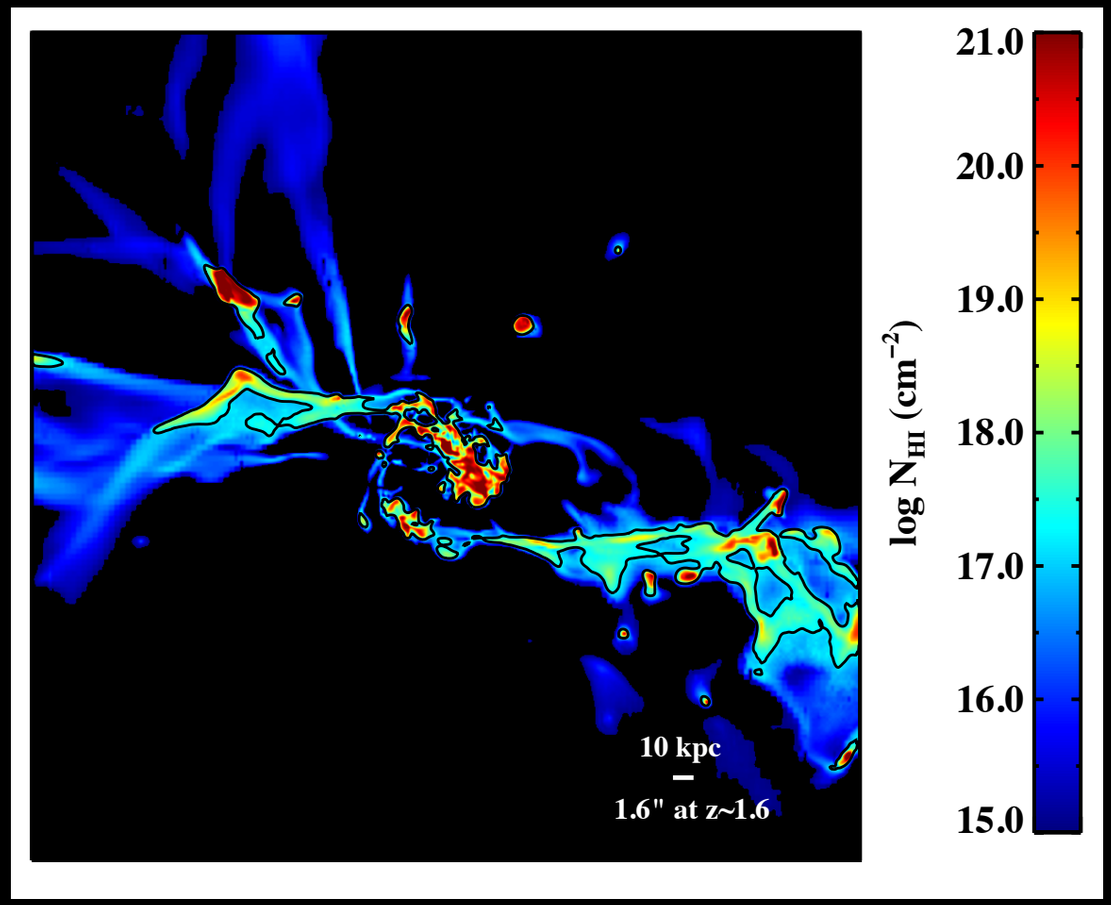
IGM and Galaxy Formation (Why bother?)

1. The IGM feeds galaxies. There is too little neutral gas in galaxies at z~3 to form all of the stars. Even the Galaxy needs a modest supply (e.g. Lehner & Howk 2011)



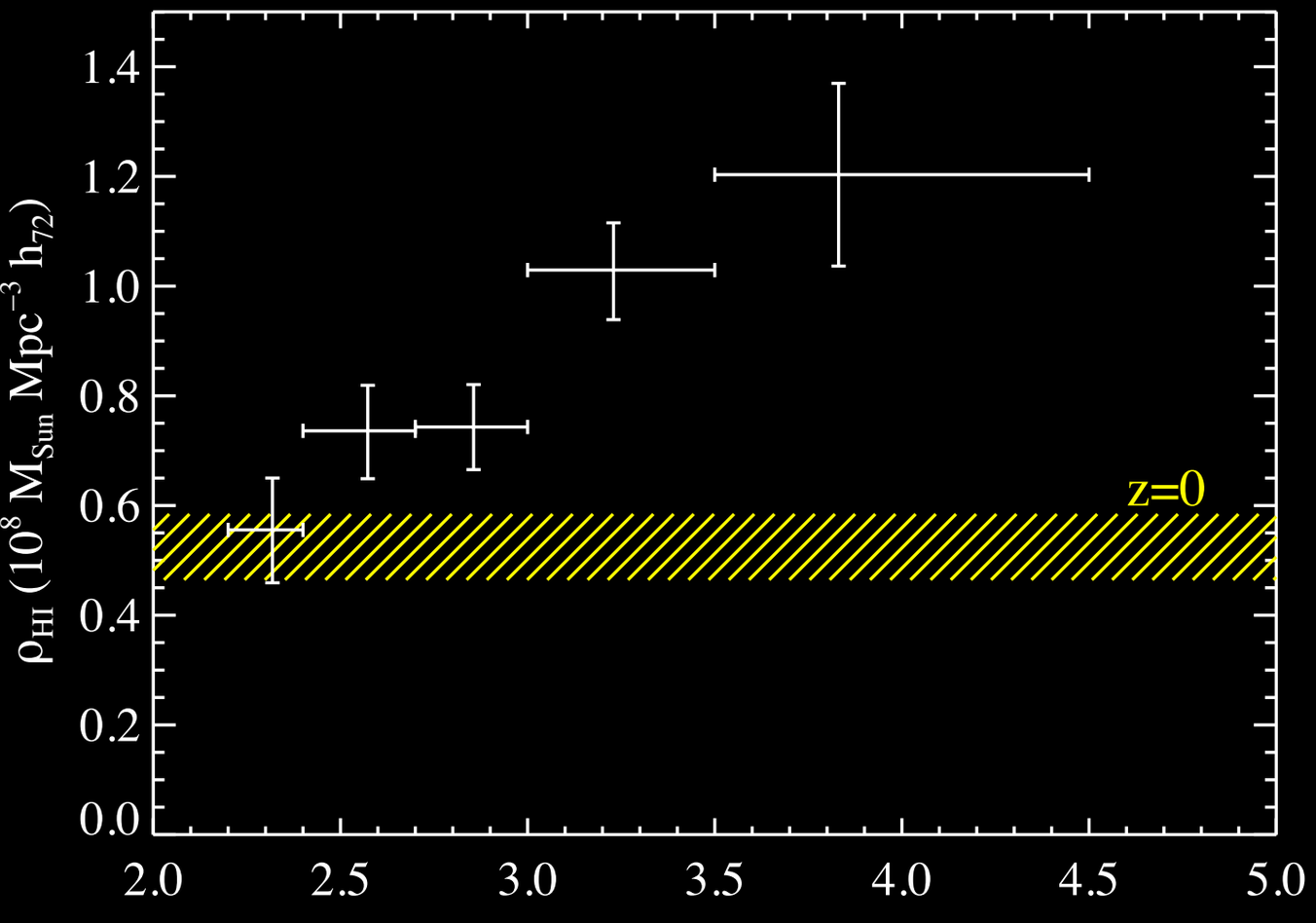
Cosmic mass density of HI
- Prochaska+05
- PW09
- Notredaeme+09



e.g. "Cold stream" gas
- Keres+05
- Dekel+06
- Fumagalli+11

IGM and Galaxy Formation (Why bother?)

2. IGM-type analysis is one of the most sensitive (often only) means of studying baryons in dark matter halos and the ISM of distant galaxies.



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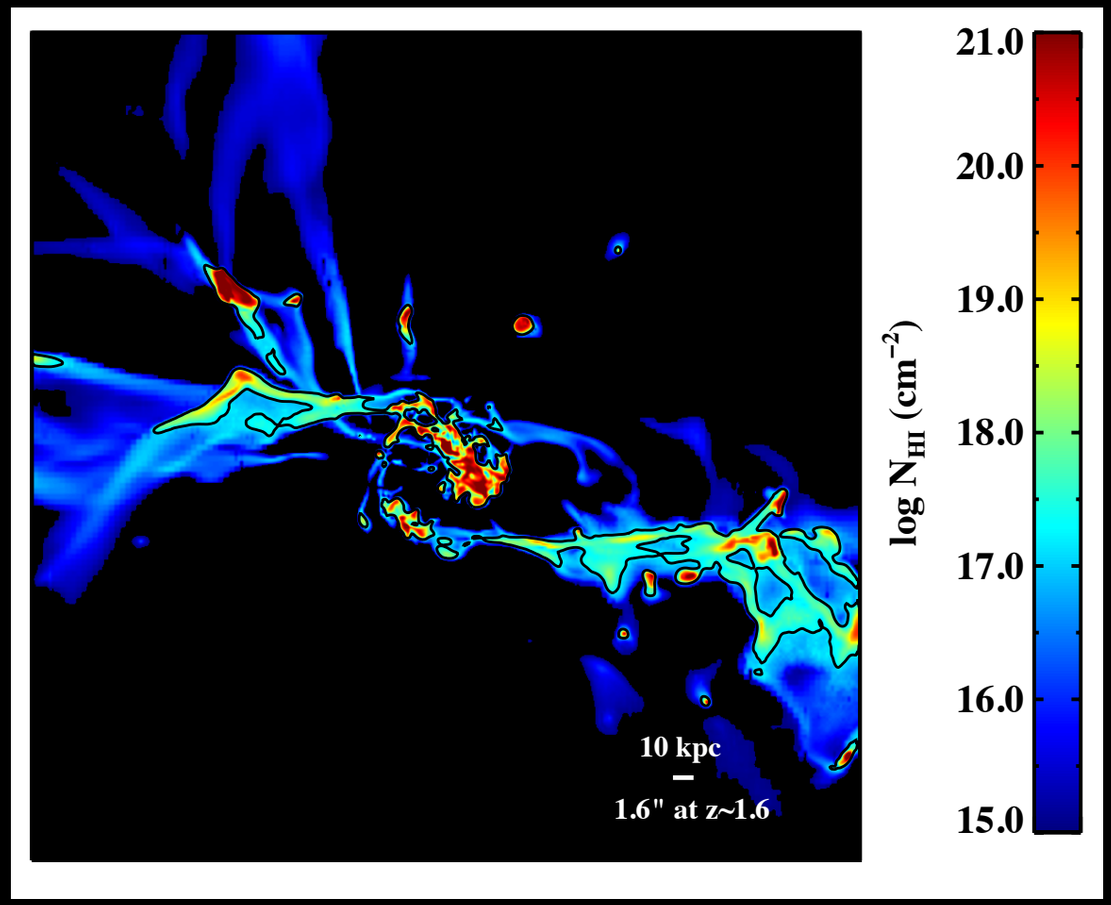

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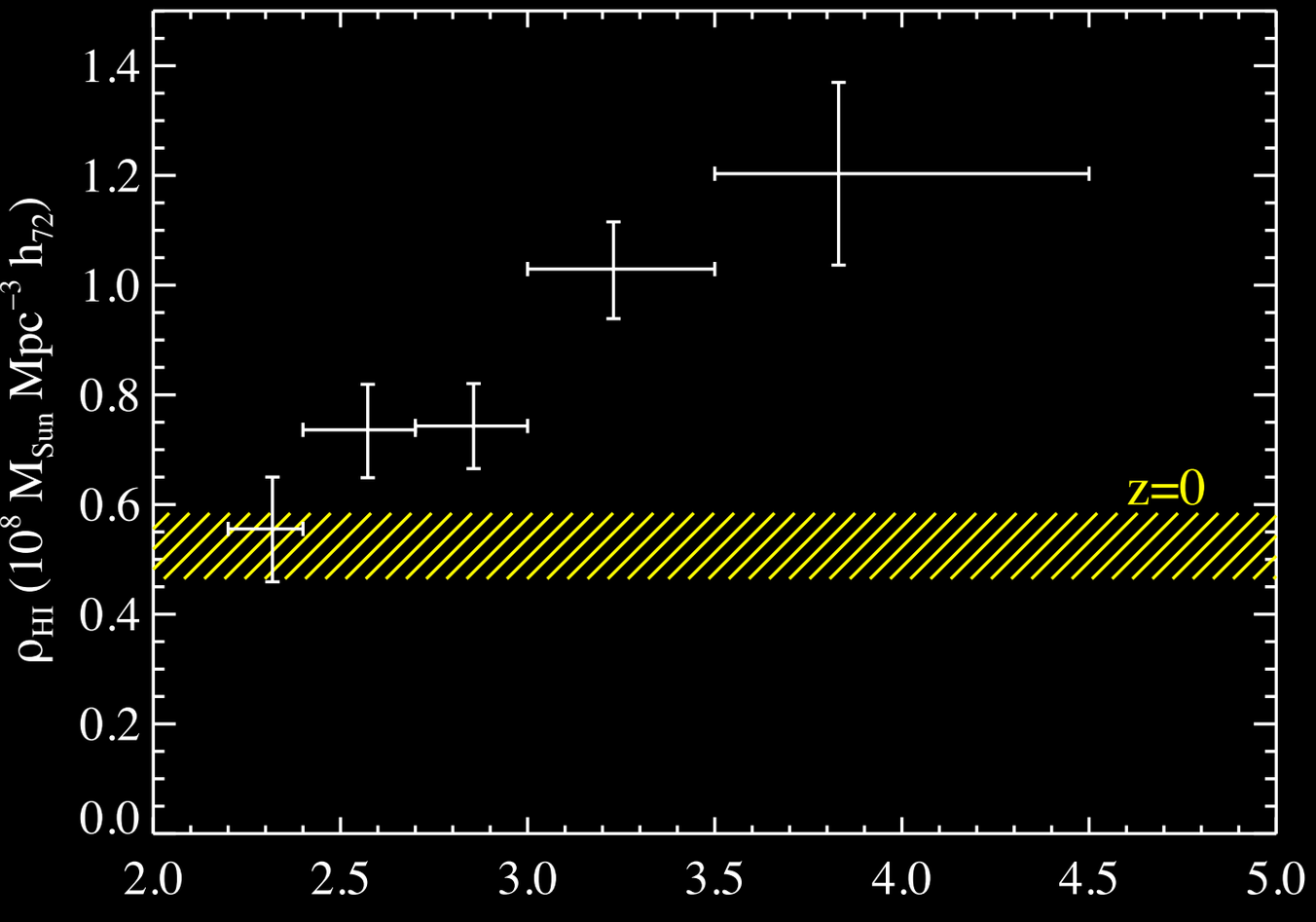
IGM and Galaxy Formation (Why bother?)

3. This includes searching for the signatures/relics of feedback.



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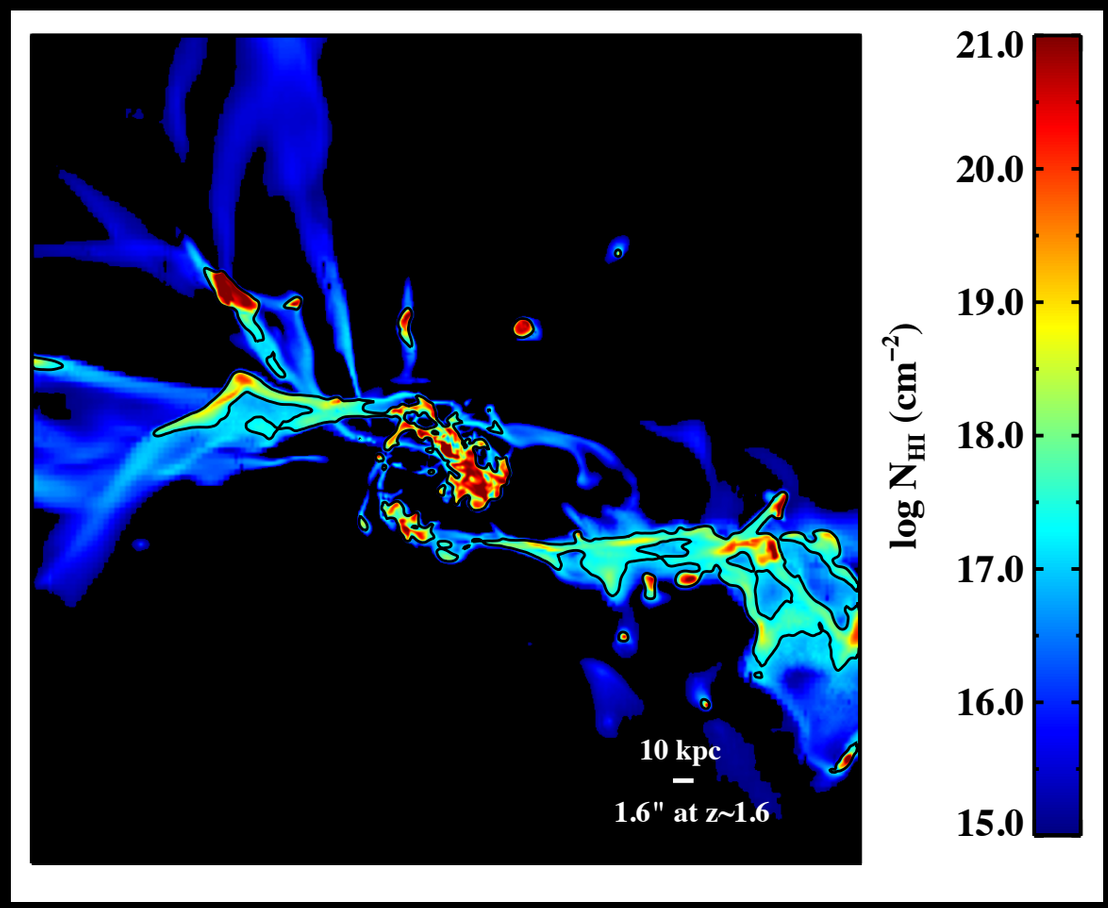

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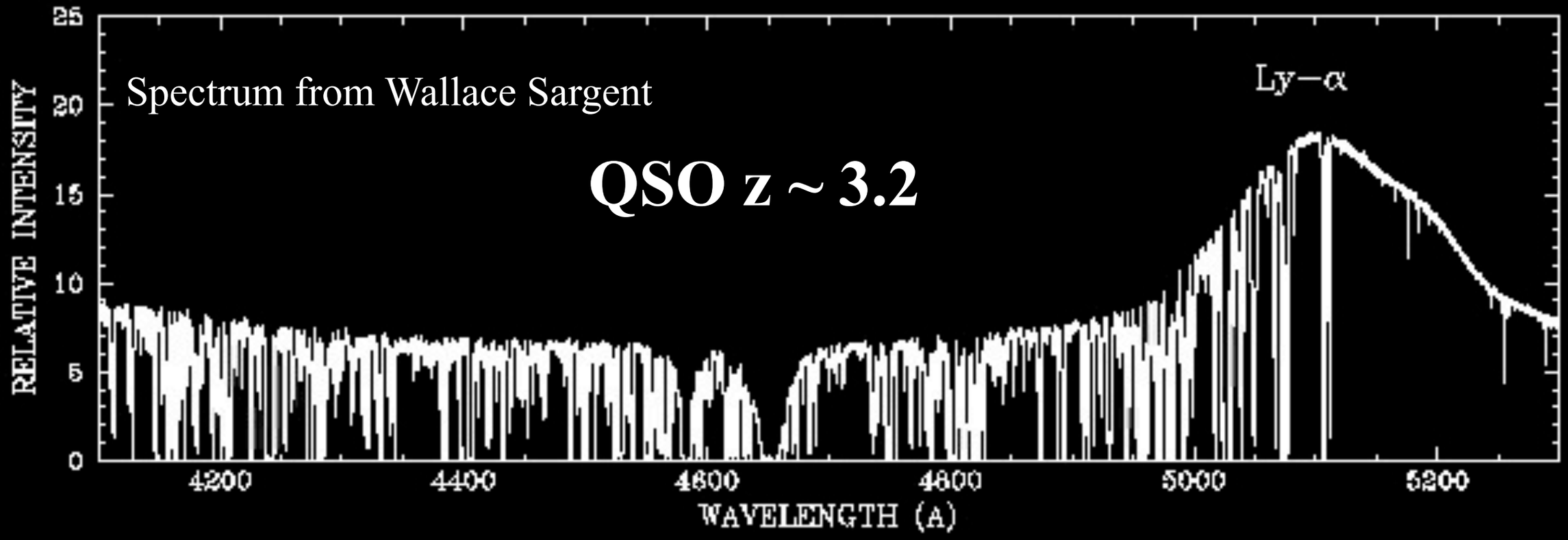
Quasar Absorption Lines

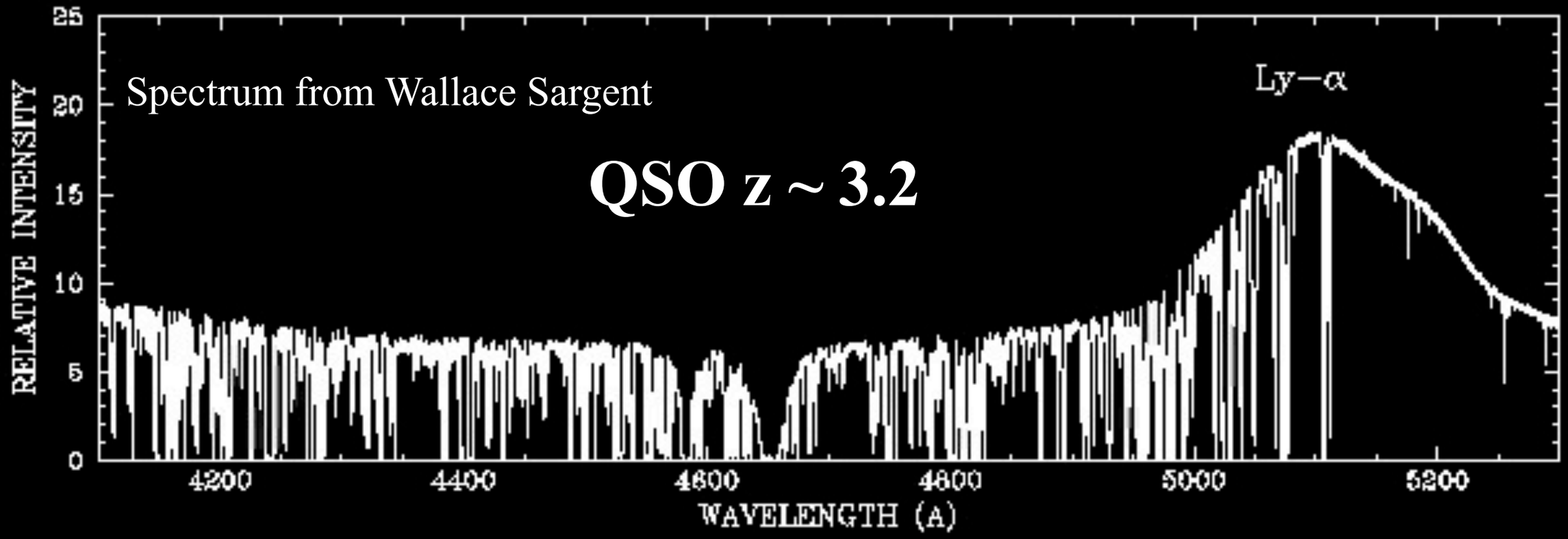


Decades of research on gas that lies foreground to the quasar.

From pc to kpc to Mpc to Gpc scales,
including the Intergalactic Medium (IGM)

Majority of spectral features lie in the UV (e.g. Lya 1215)

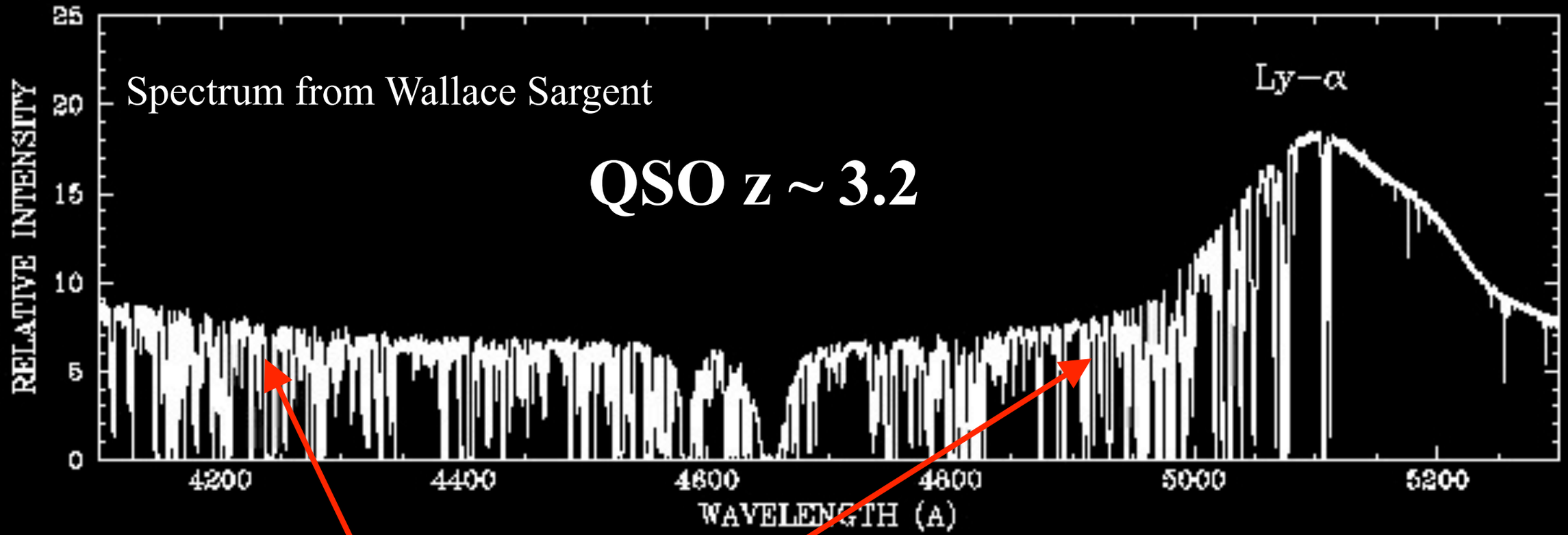
Quasar Absorption Lines



The ‘fauna’ or zoology of Quasar Absorption Lines

Primarily characterized by the column density of atomic hydrogen (HI): N_{HI}

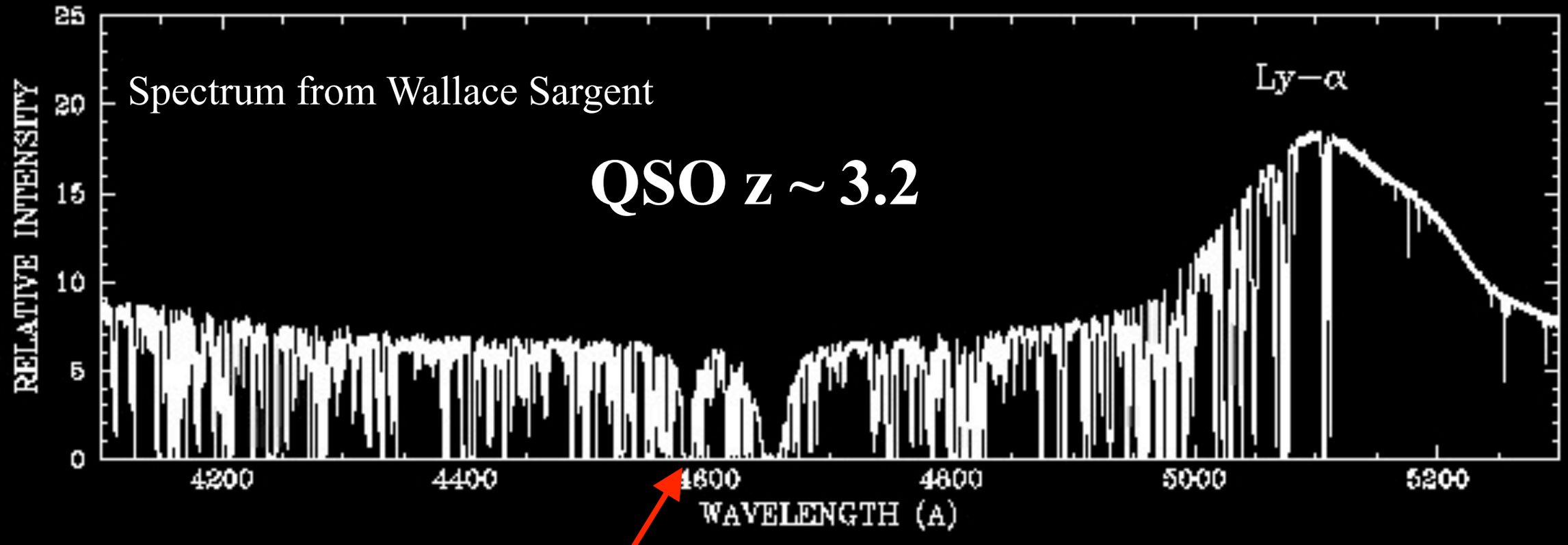
Quasar Absorption Lines



Lyα Forest

- Weak, most numerous lines
- 10^{12} cm^{-2} < N_{HI} << $10^{17.2}$ cm^{-2}

Quasar Absorption Lines

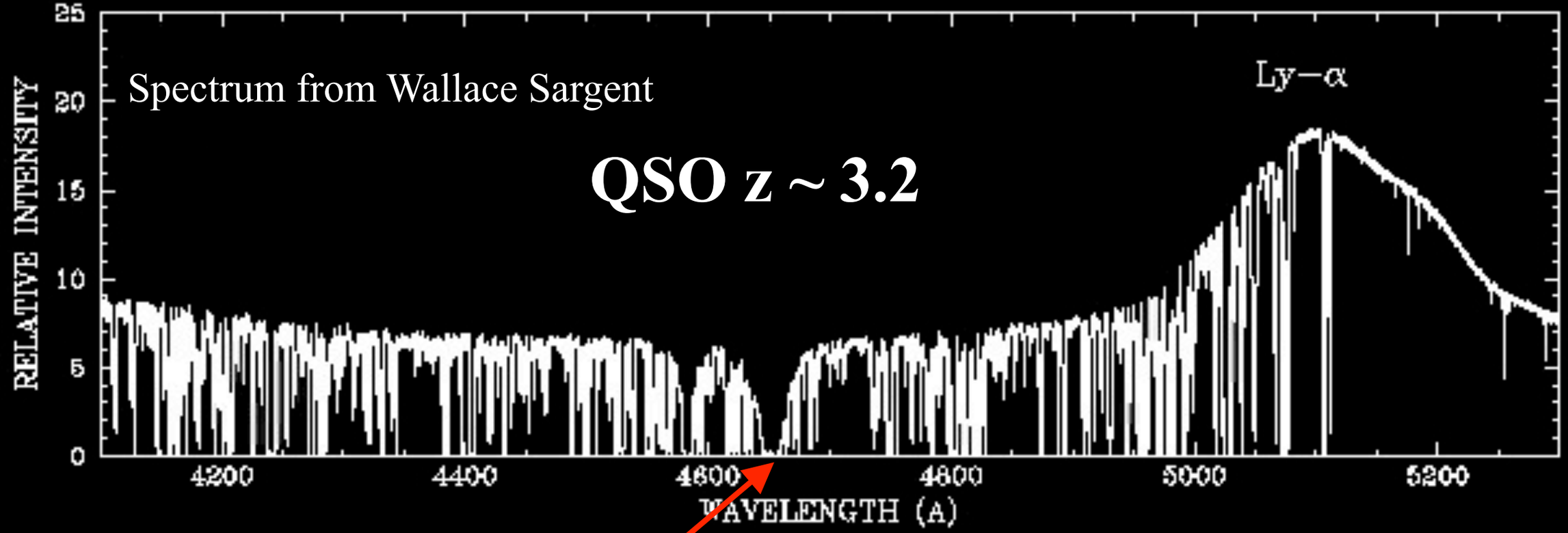


LLS

Lyman Limit System (LLS)

- **Optically thick to ionizing photons**
- **$10^{17.2}$ cm^{-2} < N_{HI} < $10^{20.3}$ cm^{-2}**

Quasar Absorption Lines



Damped Lyα System (DLA)

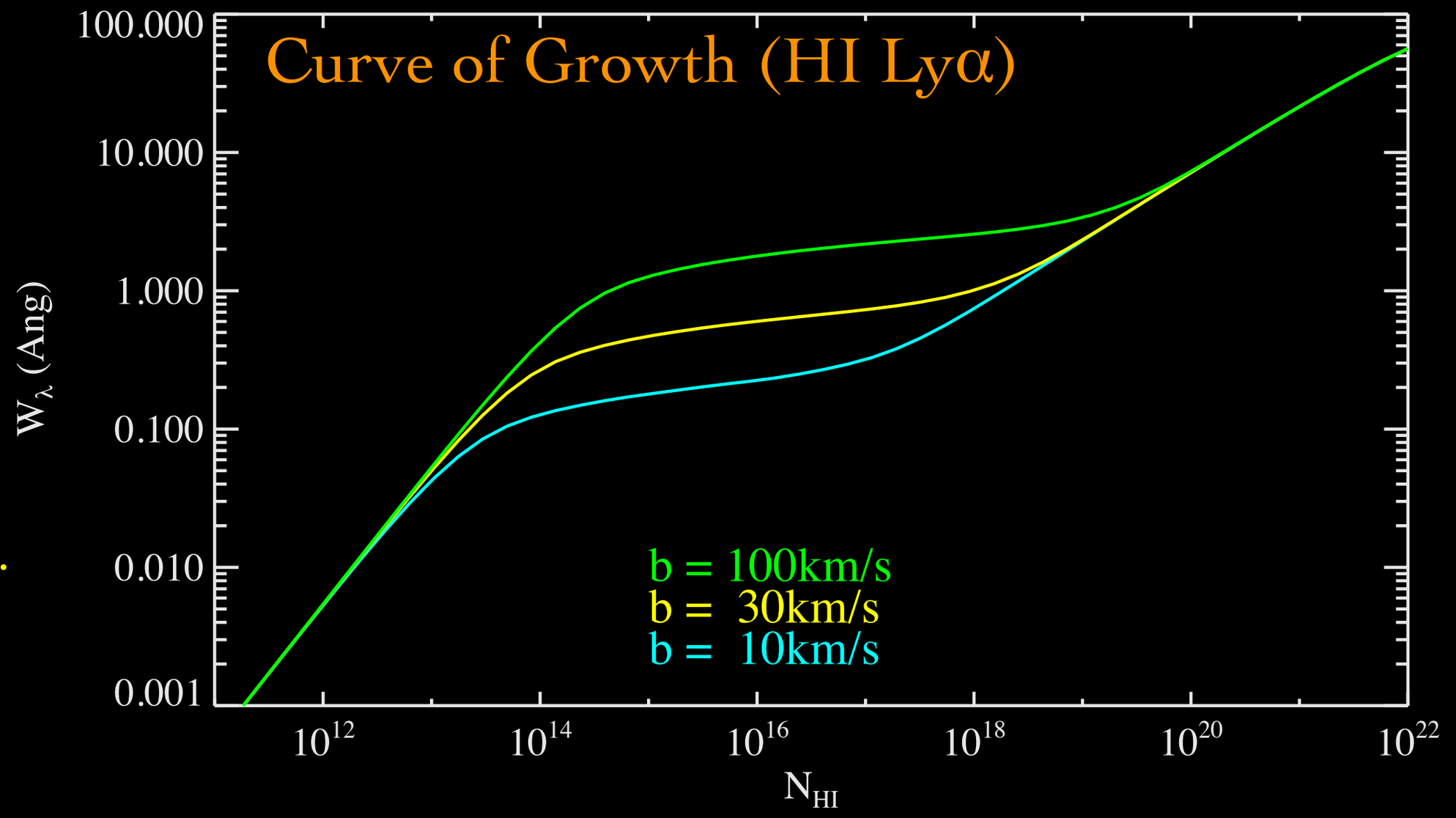
- galactic surface densities
- $N_{HI} > 10^{20.3}$ cm^{-2}

Absorption Line Basics

N_{HI}: Column of HI atoms

$W\lambda$: Equivalent width

b: Doppler param.



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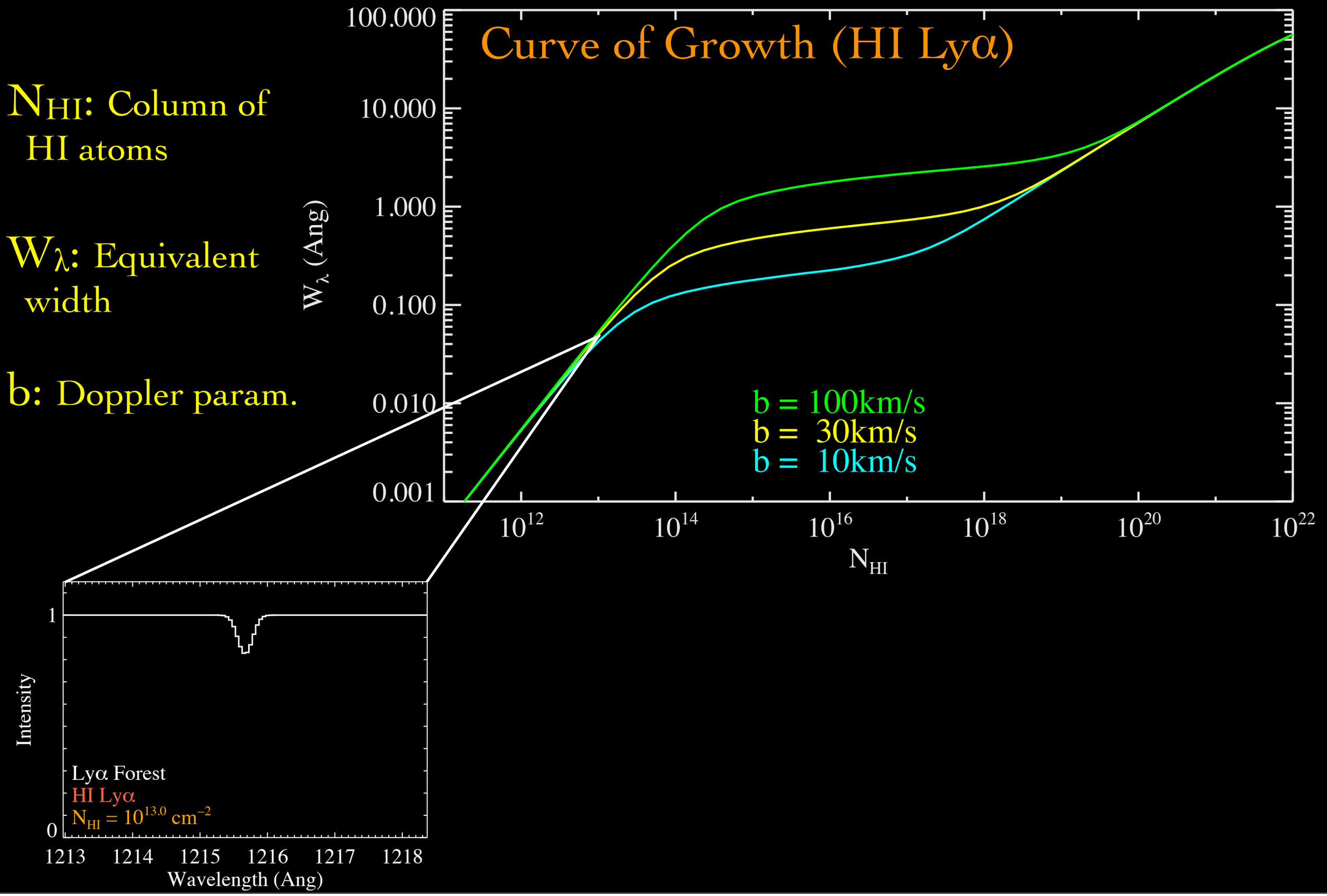

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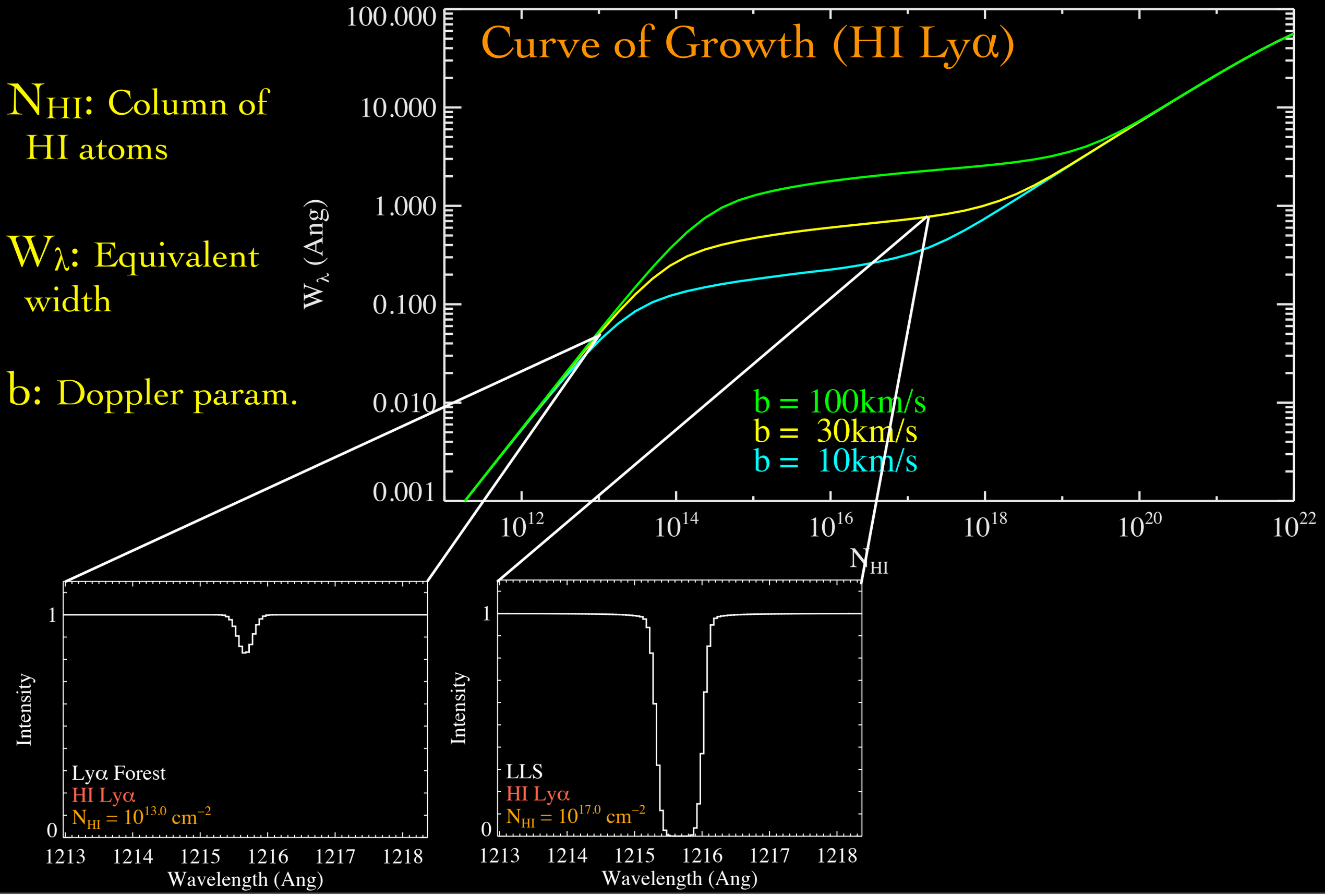

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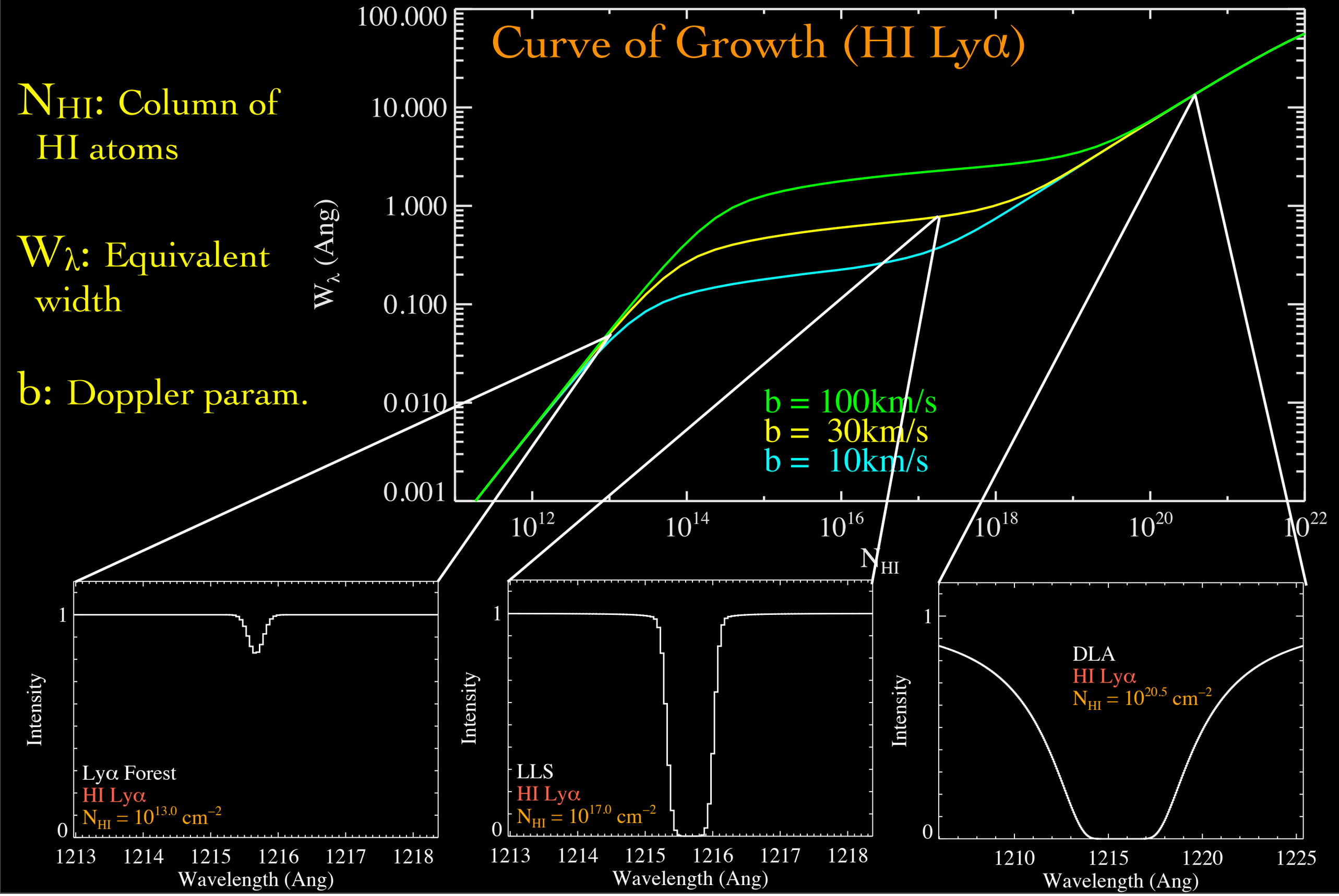
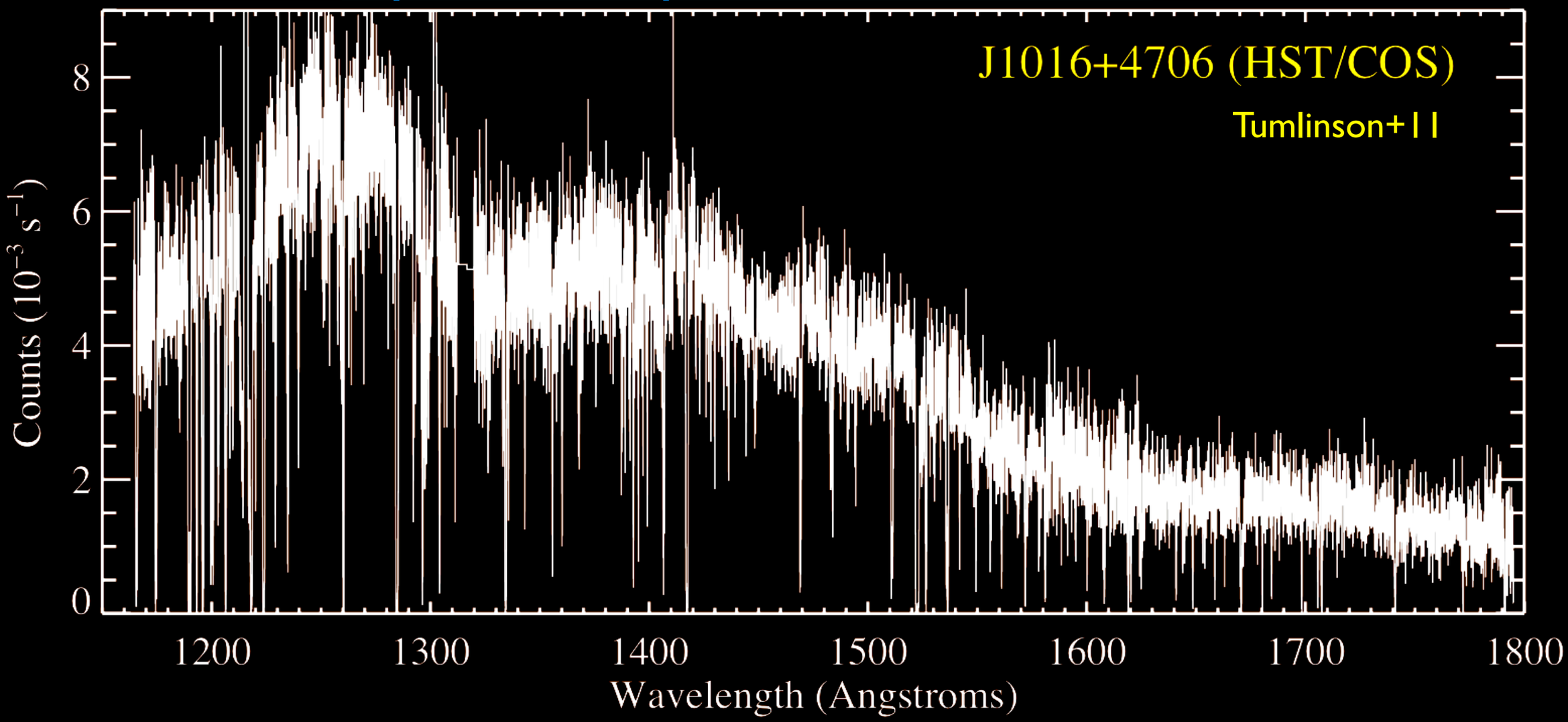


f(N_{HI}, X): Definition



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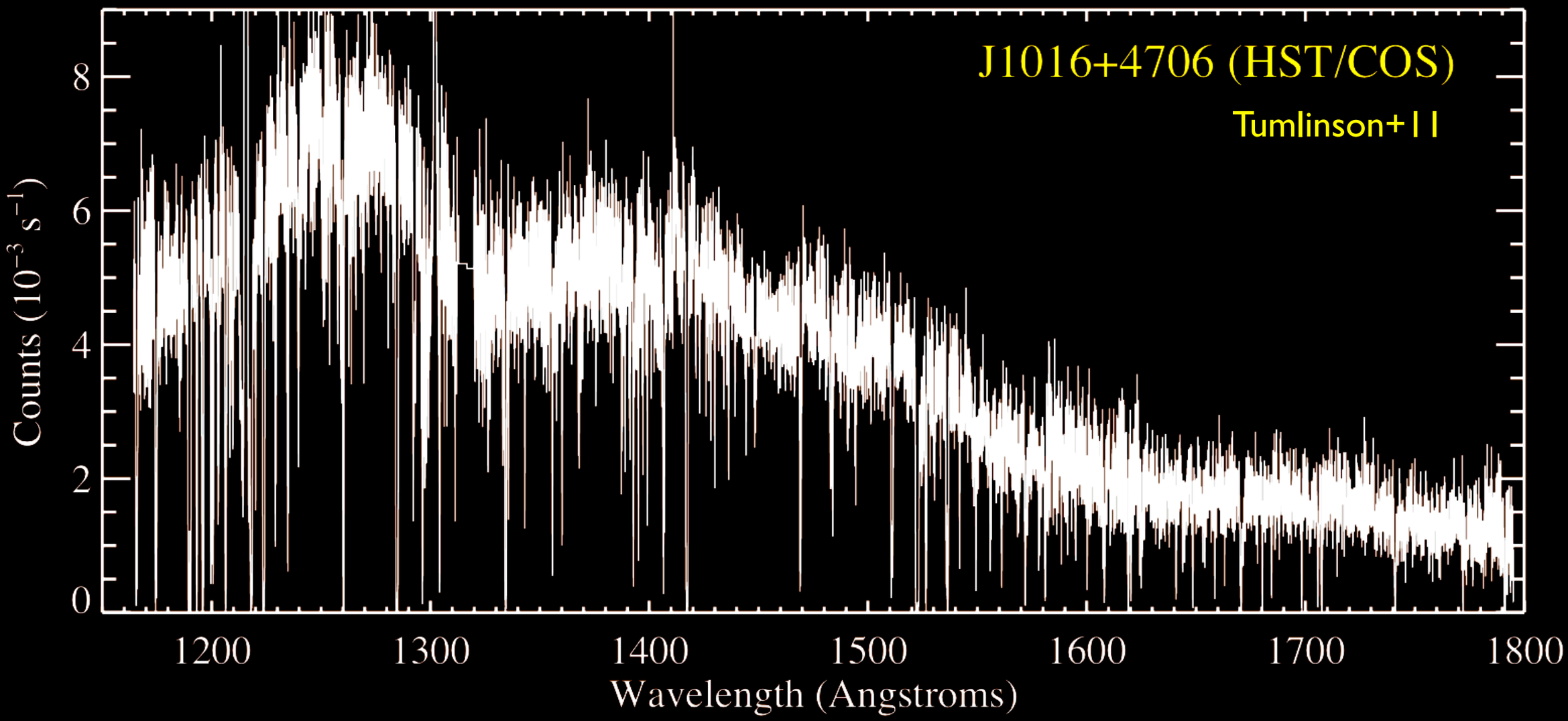

- N_{HI} frequency distribution
  - Characterization of IGM
  - Normalized to an "absorption path"

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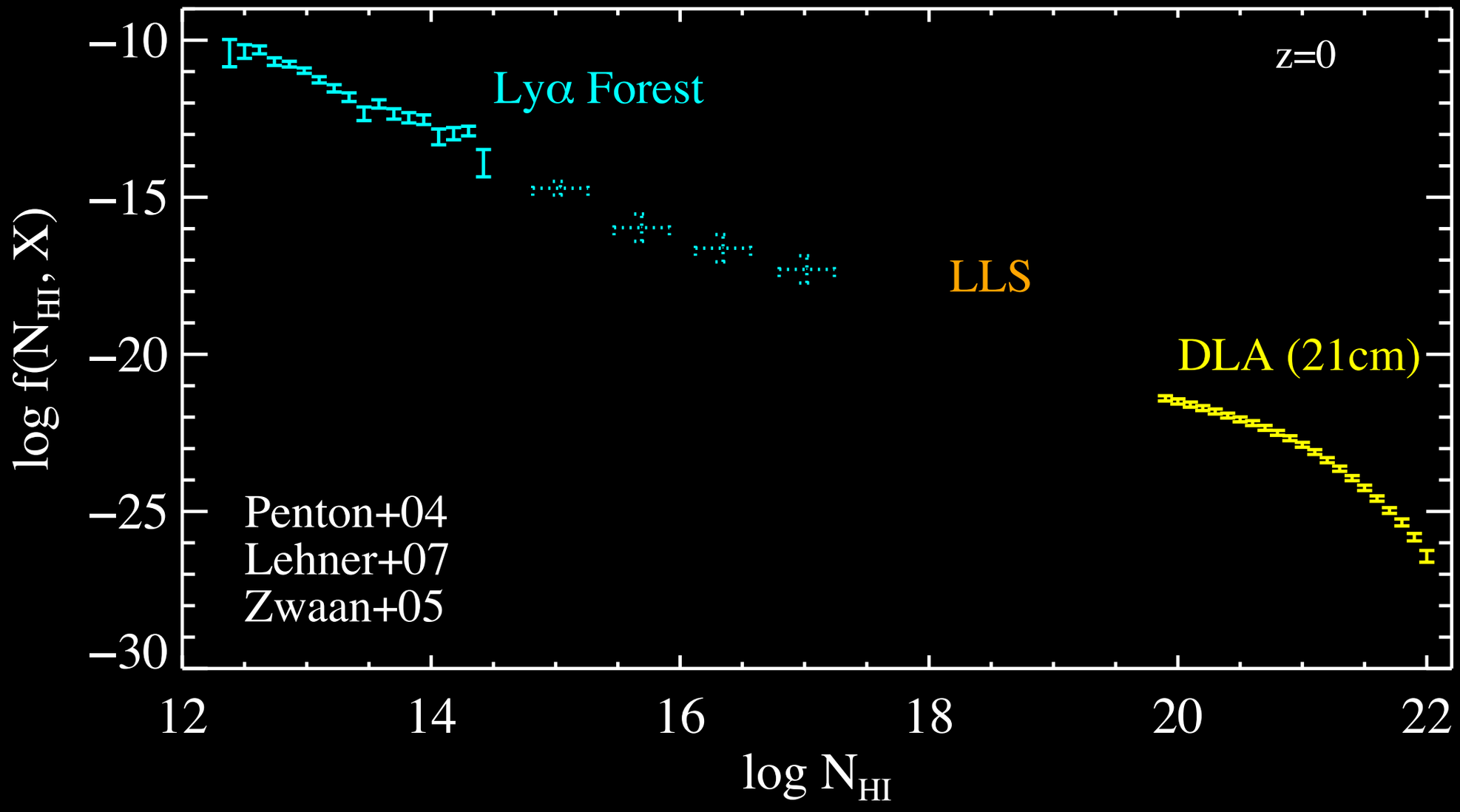
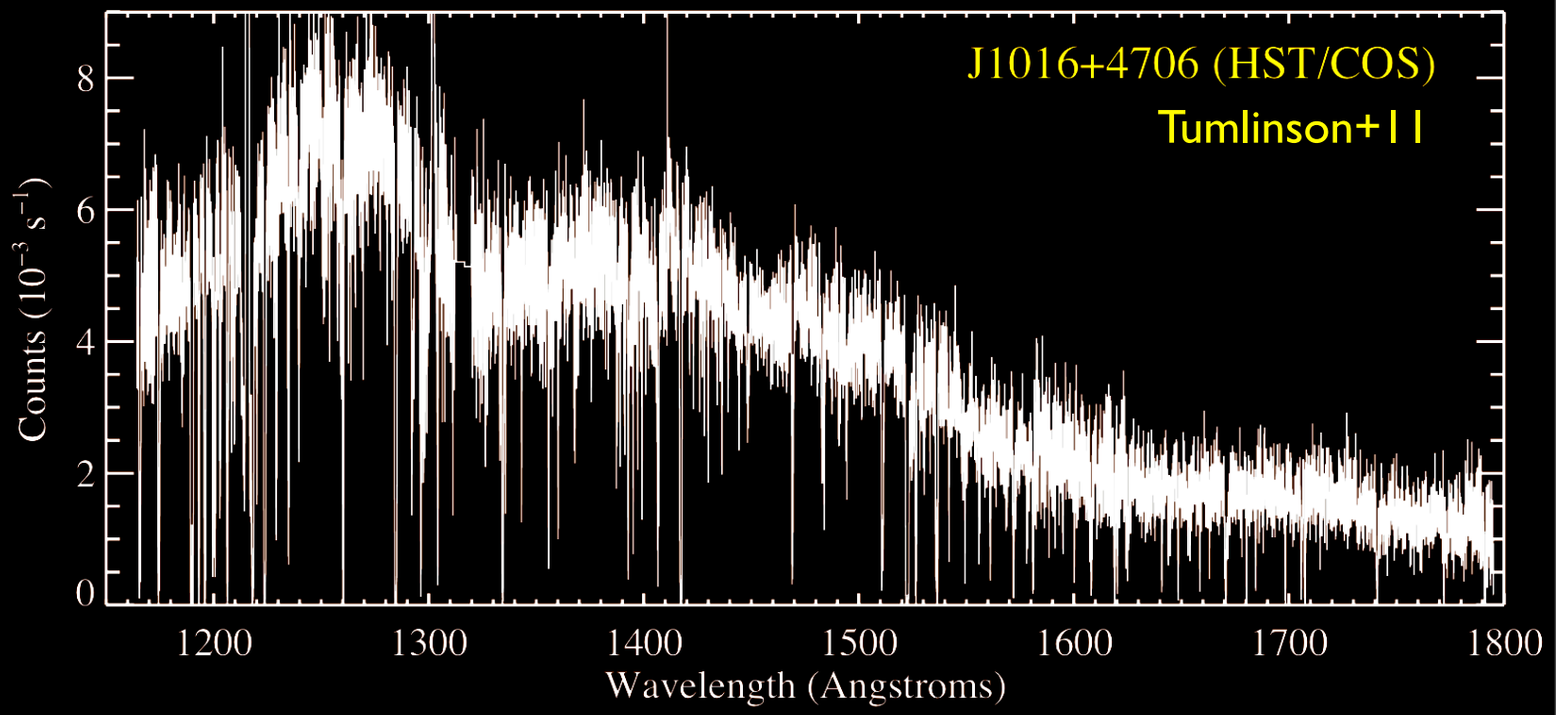


- N_{HI} frequency distribution
  - Characterization of IGM
  - Normalized to an "absorption path"
- $f(N_{HI}, X)$
  - # of systems with N_{HI} per dN_{HI} per absorption path length
  - Akin to a Luminosity function
    - ✦ Counting lines per pathlength

ℓ(z) and ℓ(X) Defined (Zeroth Moment)



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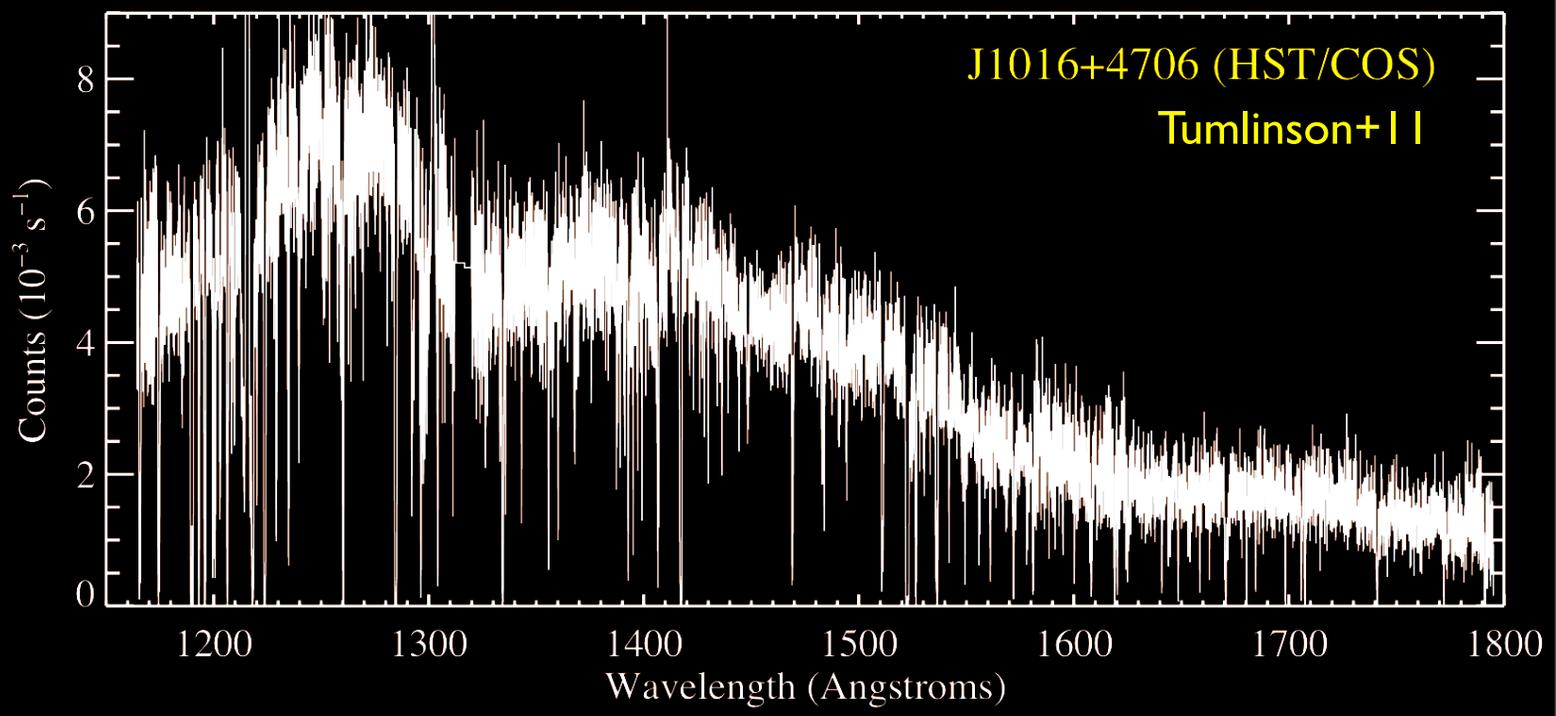
- ℓ(z) [a.k.a. *dN/dz*]
  - Number of lines per unit redshift
    - Integrated over an N_{HI} interval
  - Simple observable
    - akin to 'number counts'
    - Zeroth moment of f(N_{HI}, z)



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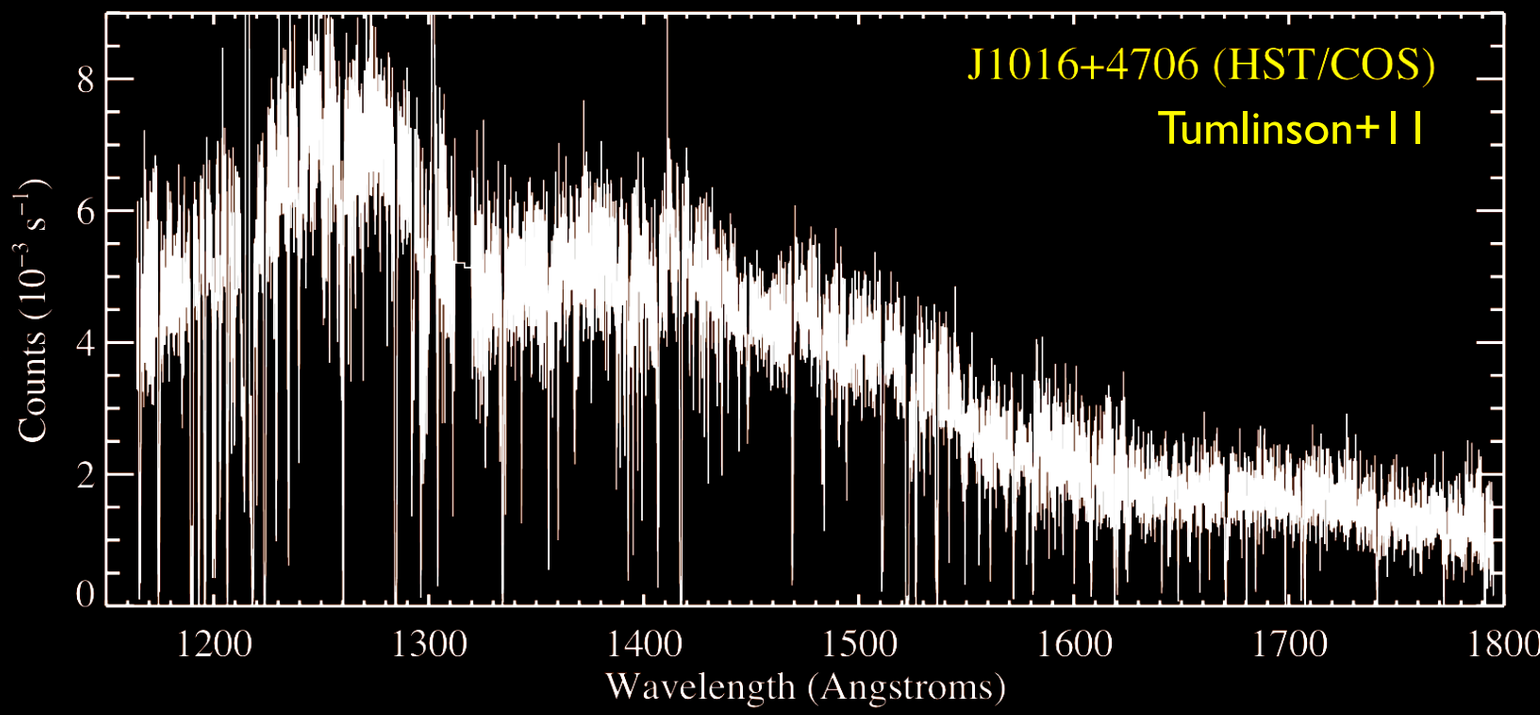
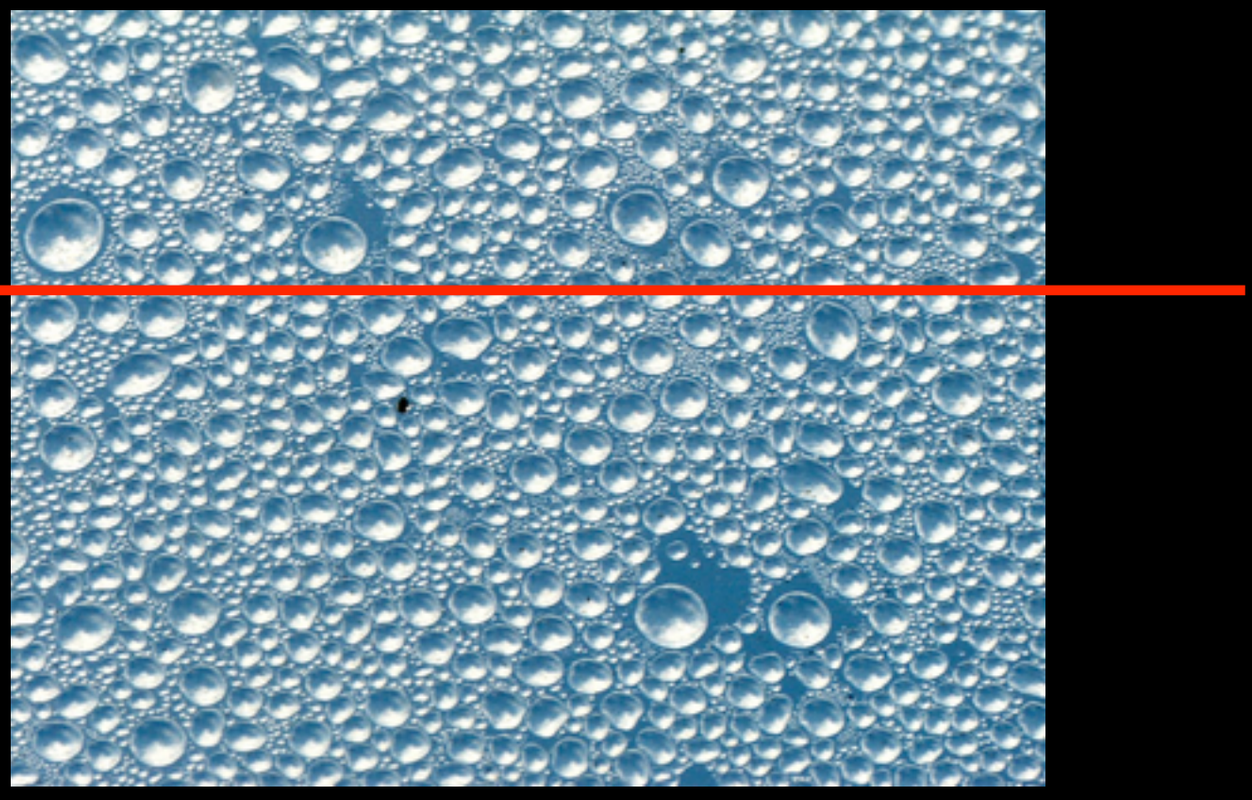
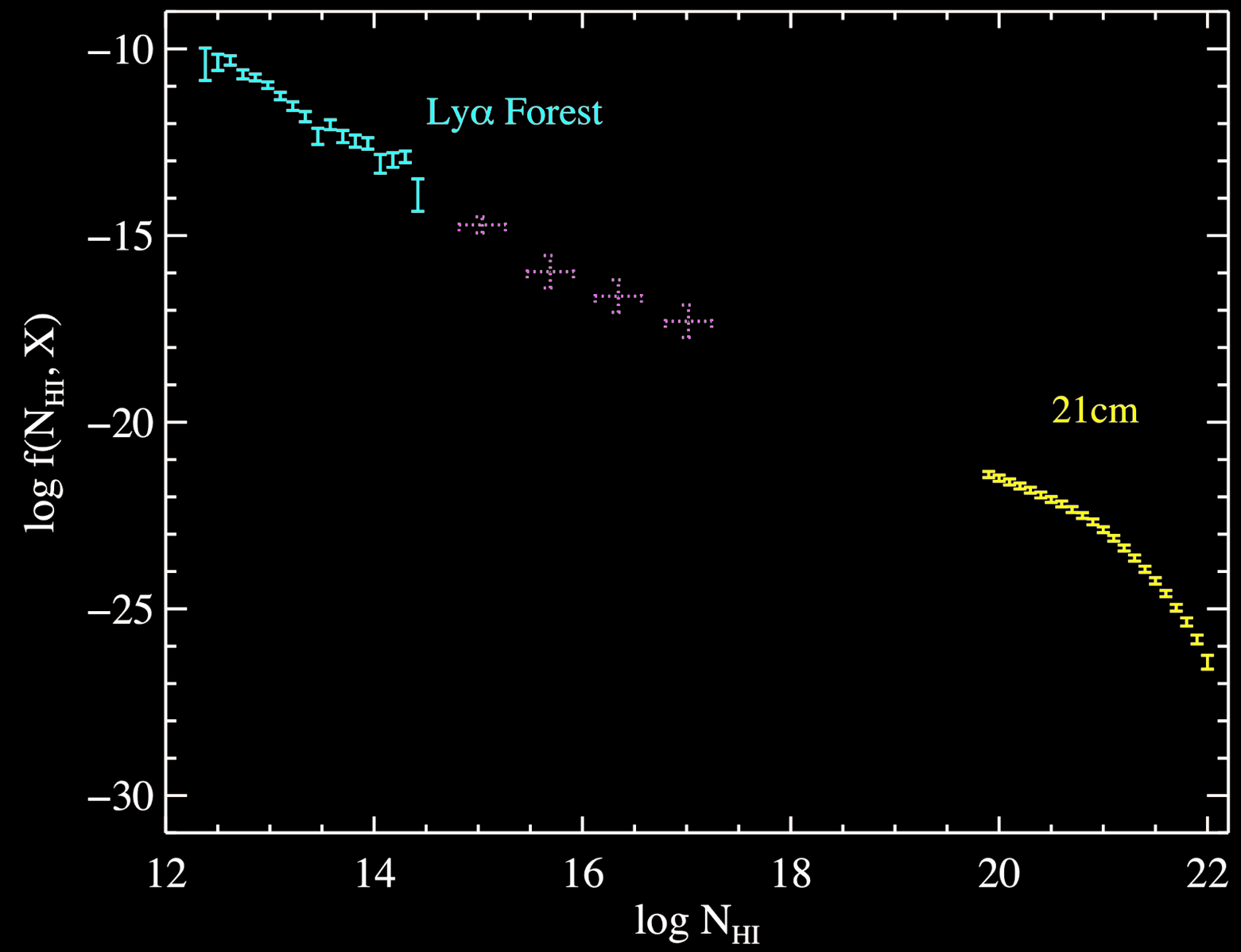


- ℓ(X) [a.k.a. *dN/dX*]
  - Number of lines per unit pathlength
    - $dX = [H_0/H(z)]\,(1+z)^2\,dz$
  - Defined to maintain a constant $n_c * A_p$
    - n_c: Comoving number density
    - A_p: Physical (effective) area
  - Evaluated over an N_{HI} range

$\ell(X) \sim n_c\, A_p$

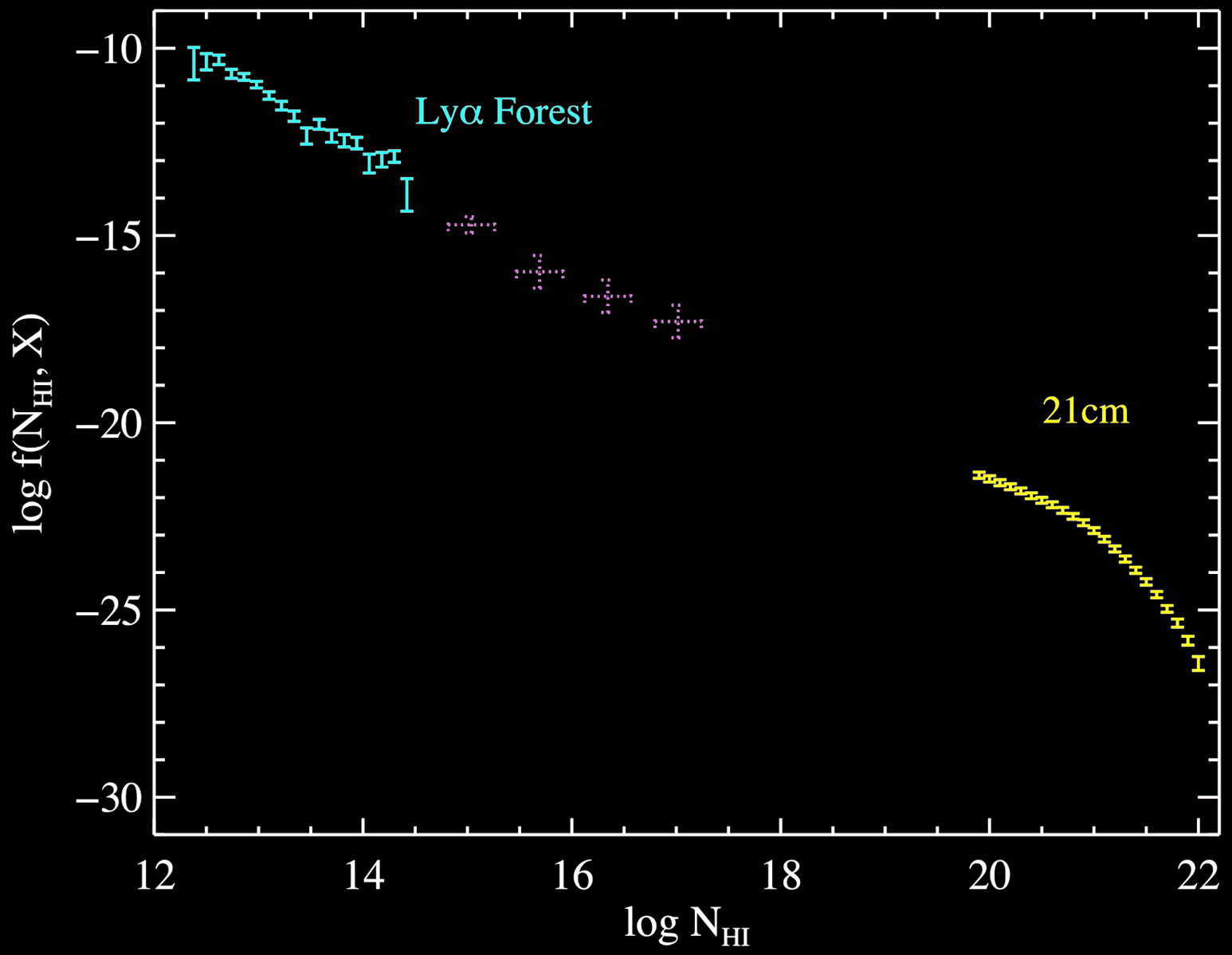


$\ell(X)$ and $\ell(z)$ [at z=0]



$\ell(X)$ and $\ell(z)$ [at z=0]

- Approaches
  - Count lines
    - Repeat for multiple quasars
  - Integrate $f(N_{HI},X)\, dN_{HI}$



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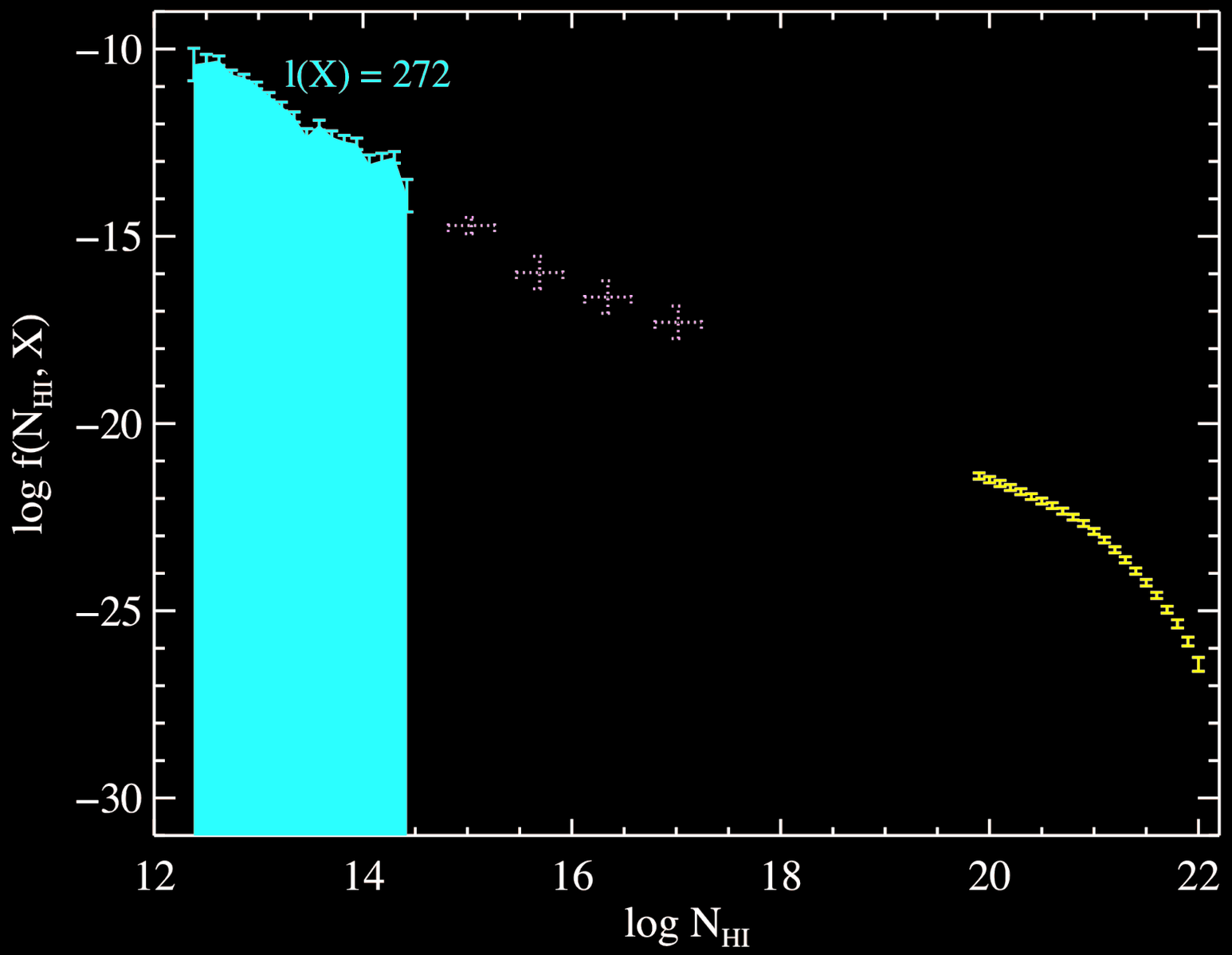
  1. Several hundred Lya forest lines per $\Delta X=1$ (or $\Delta z=1$)



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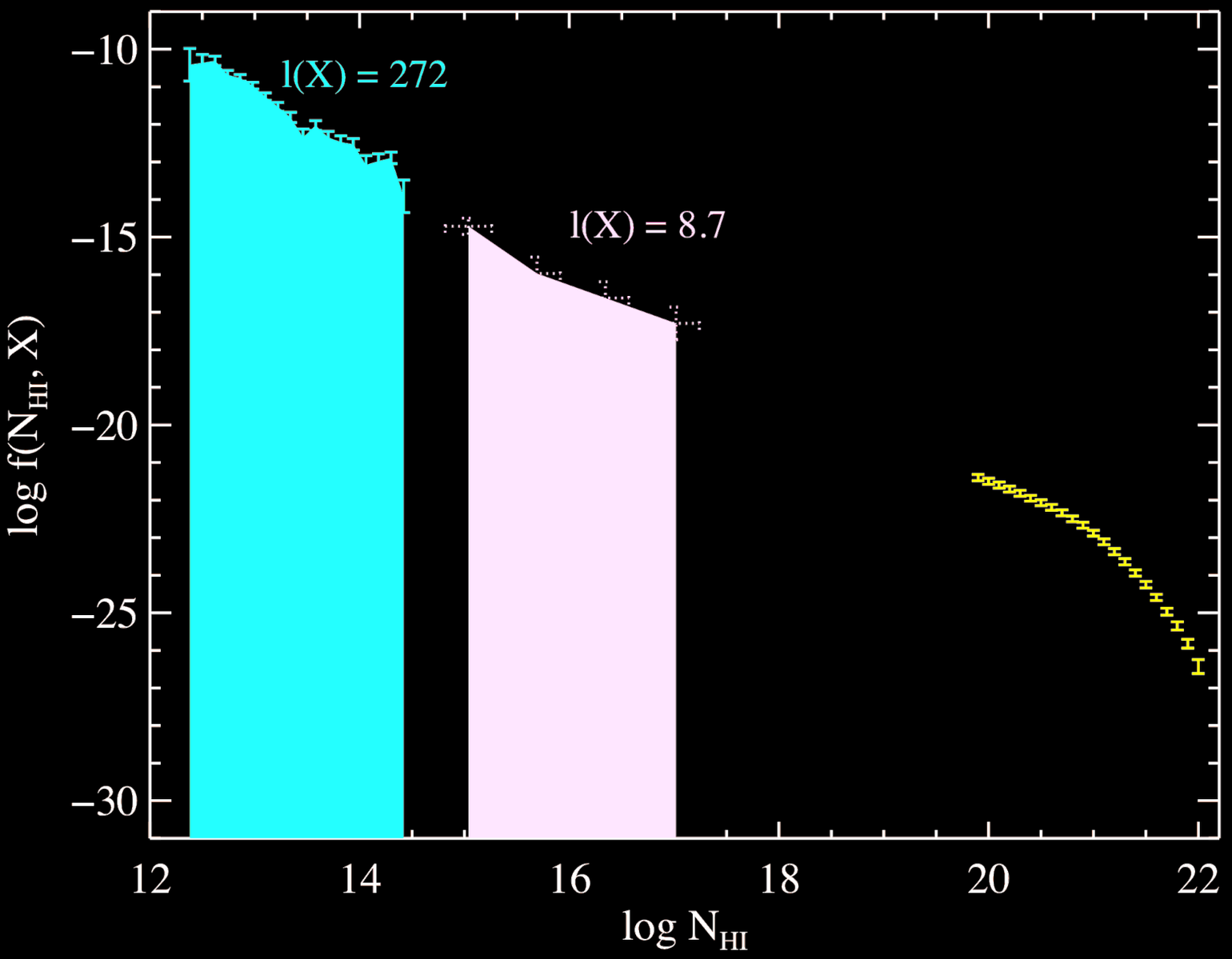

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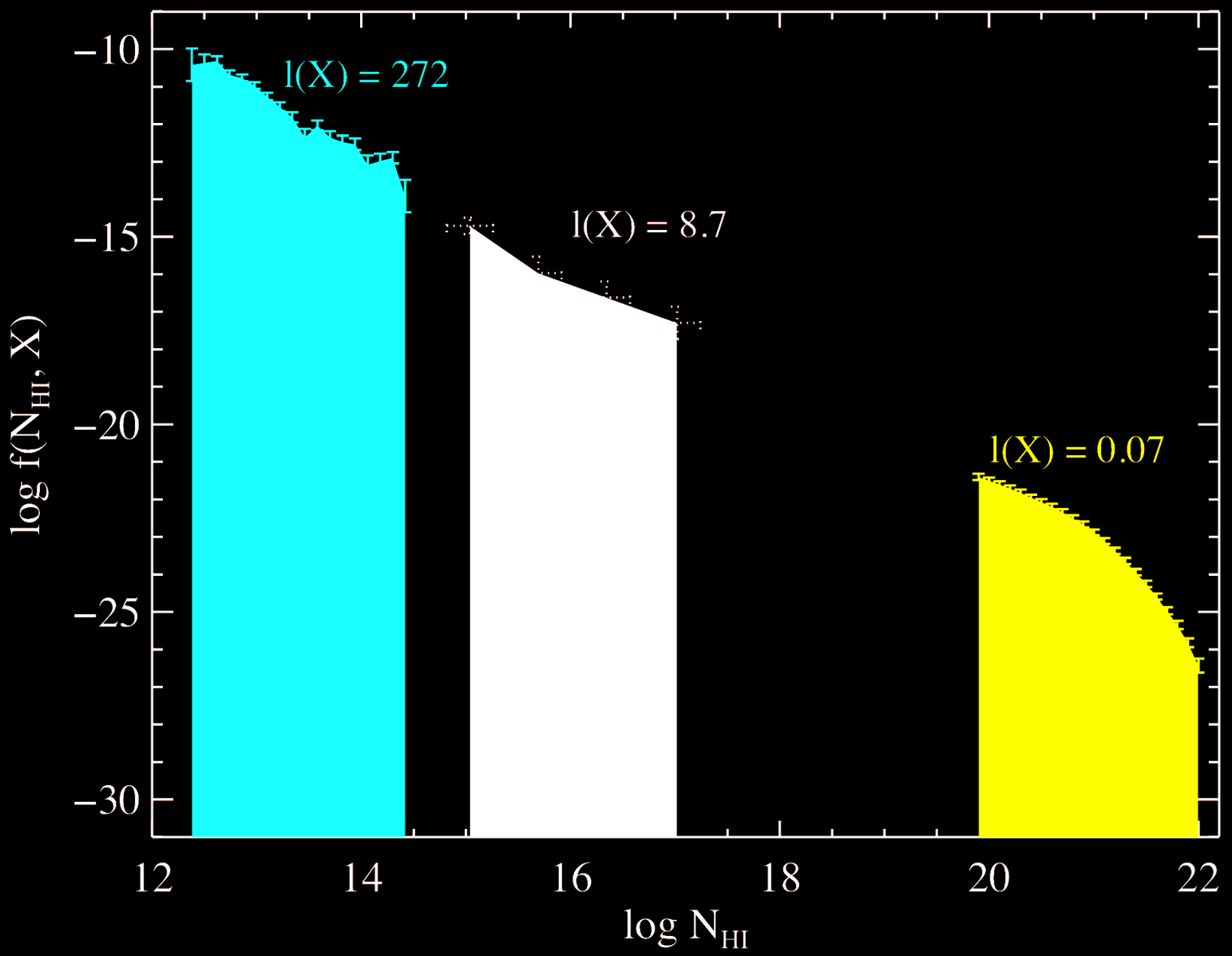
  3. Fewer than 1 galaxy (DLA) hit per 10 quasars observed



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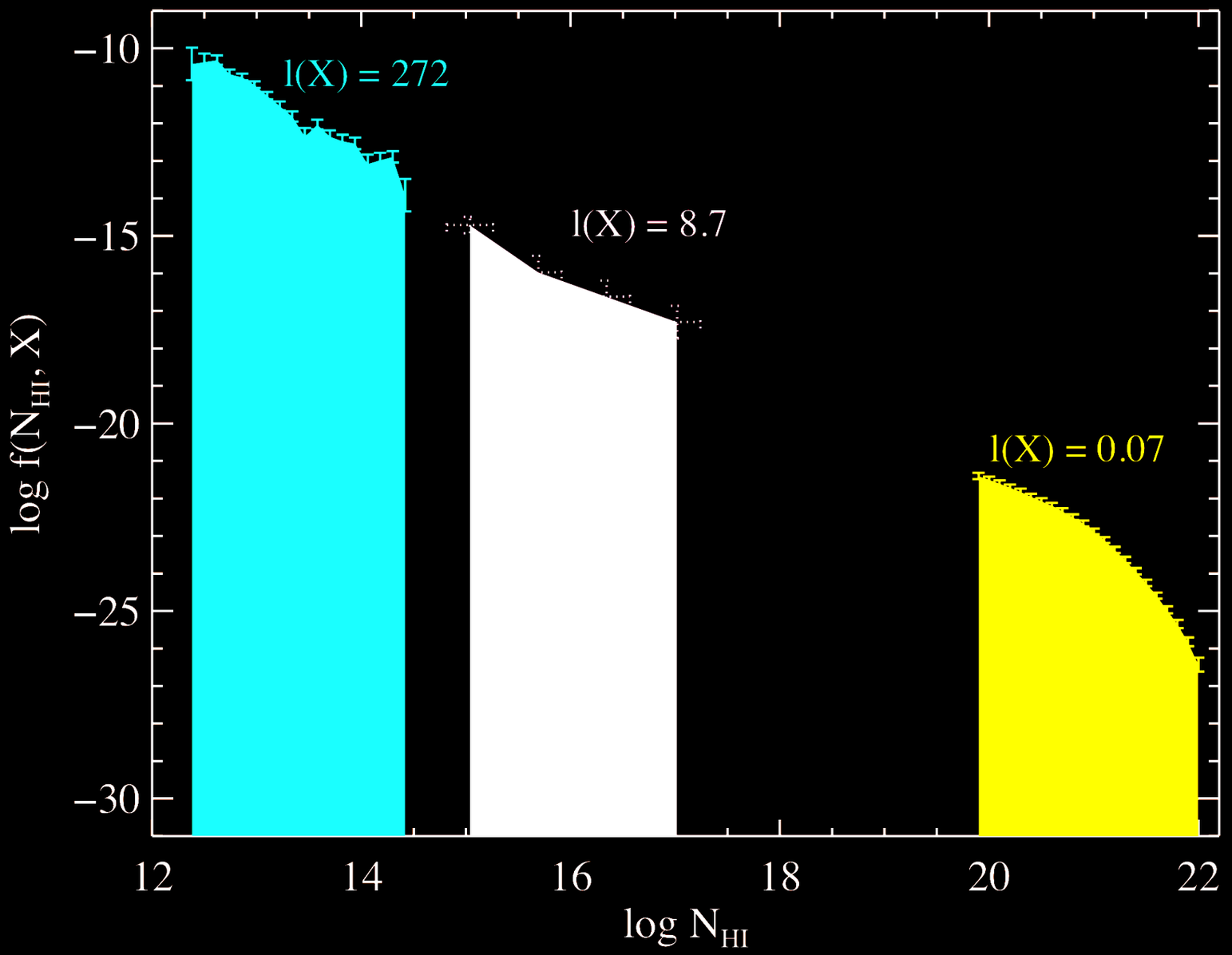
  4. ~10 metal systems per ΔX



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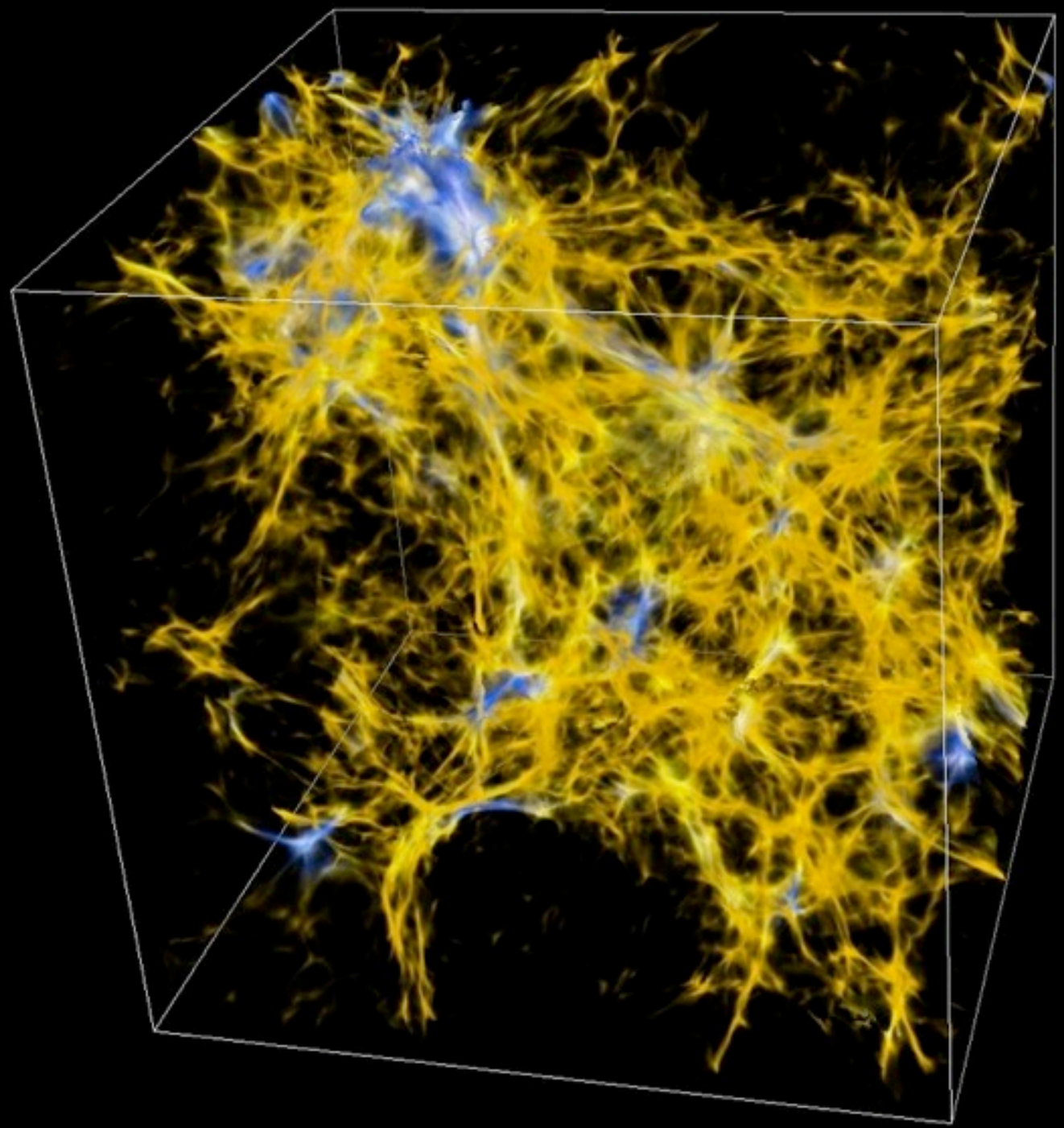
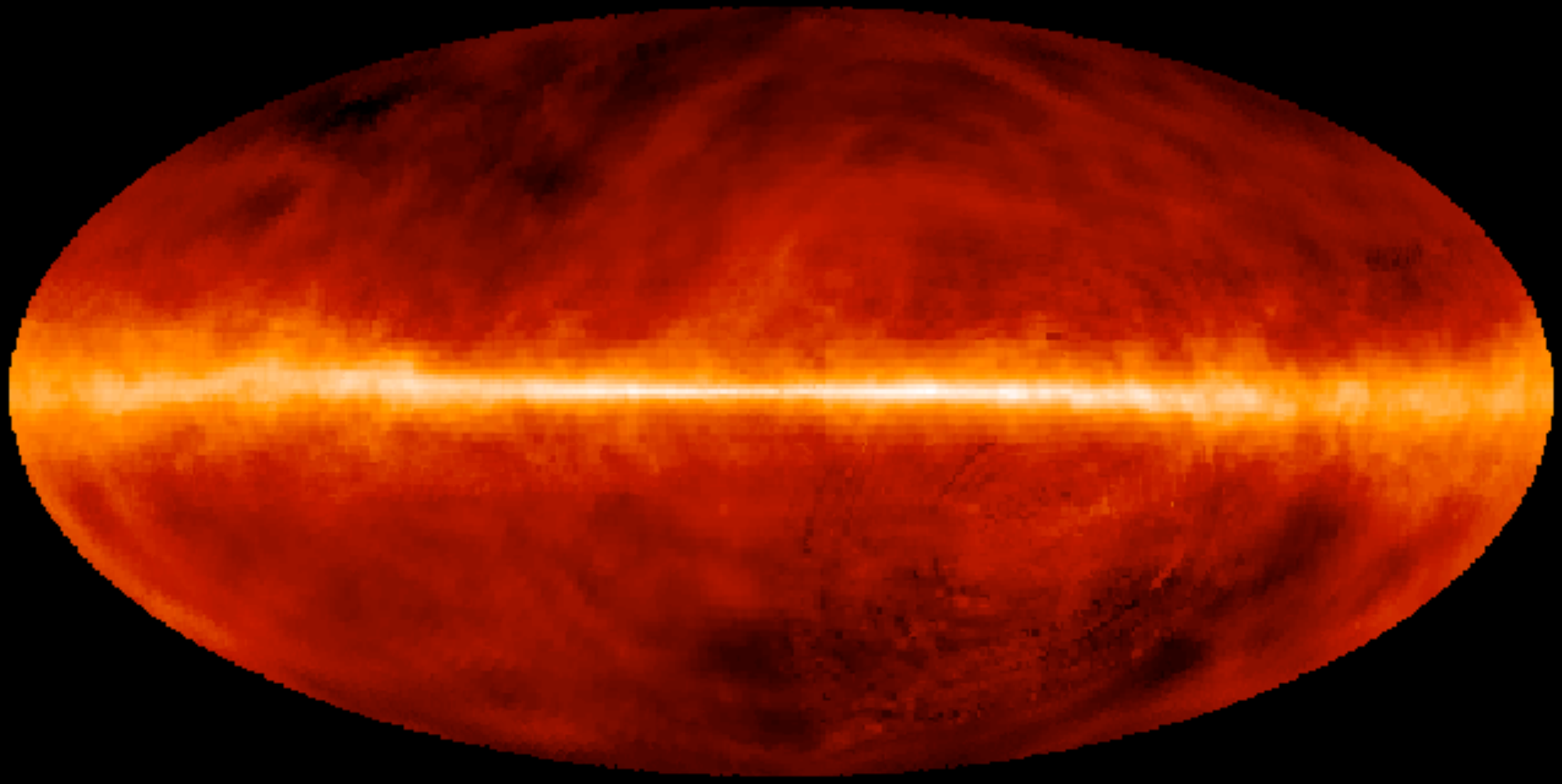


The Interstellar Medium (ISM)

Cold gas and dust that fills the disks of star-forming galaxies.



Zwaan+05,08,10

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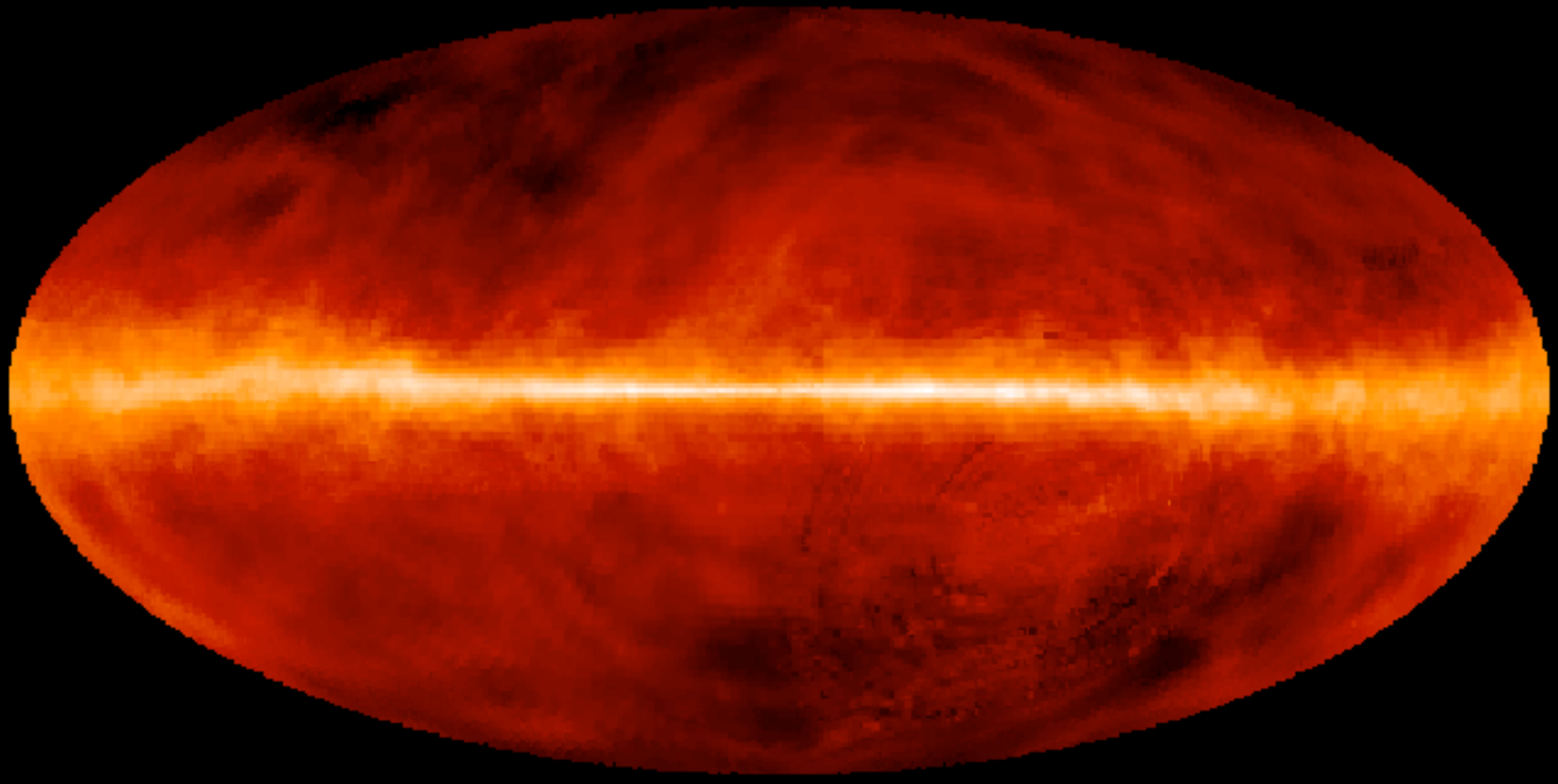
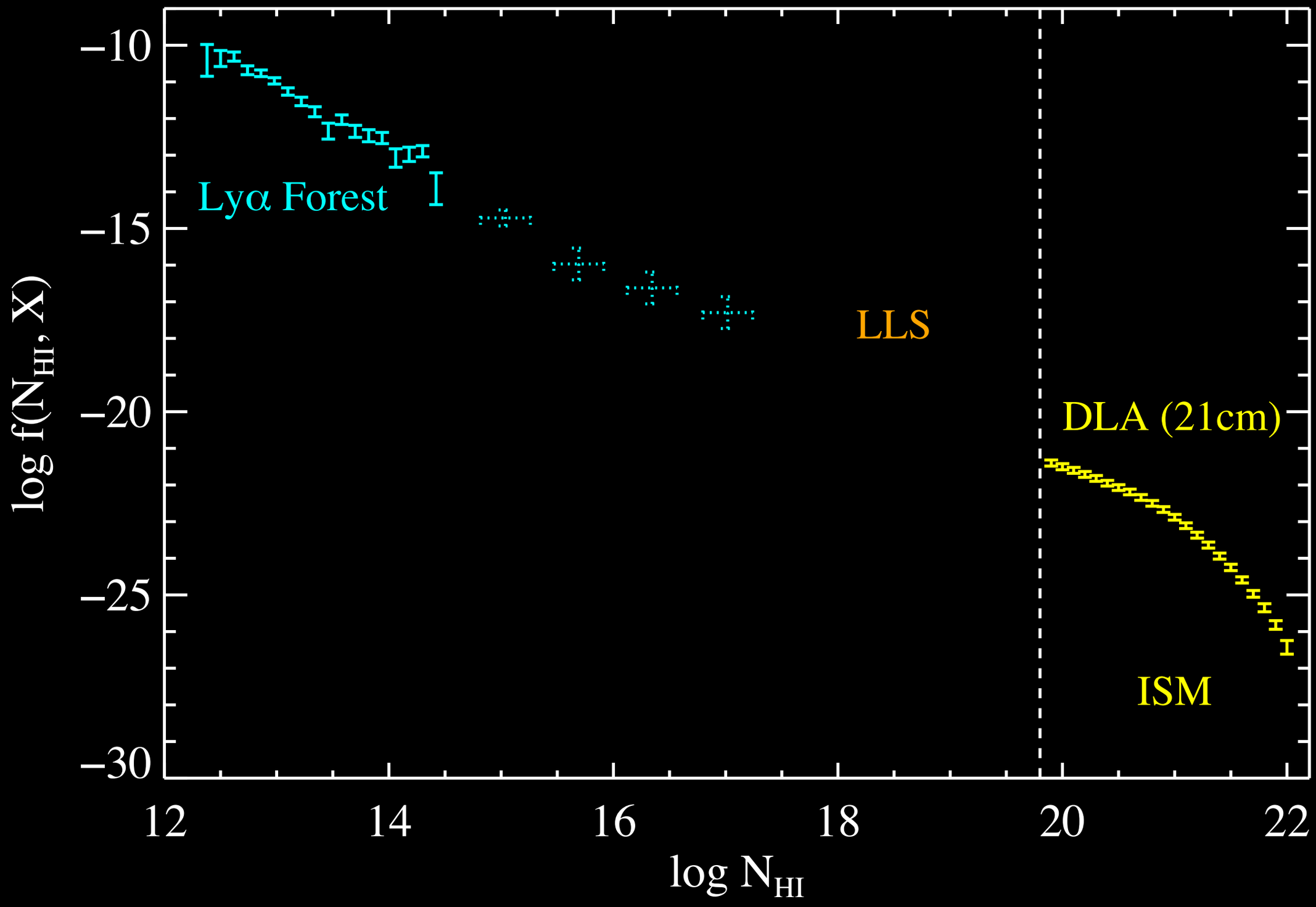


The ISM (at least at z~0) corresponds to the damped Lya systems (DLAs), but these are not the subject of today's talk.

Zwaan+05,08,10

The "IGM"/Galaxy Connection (at z~0)



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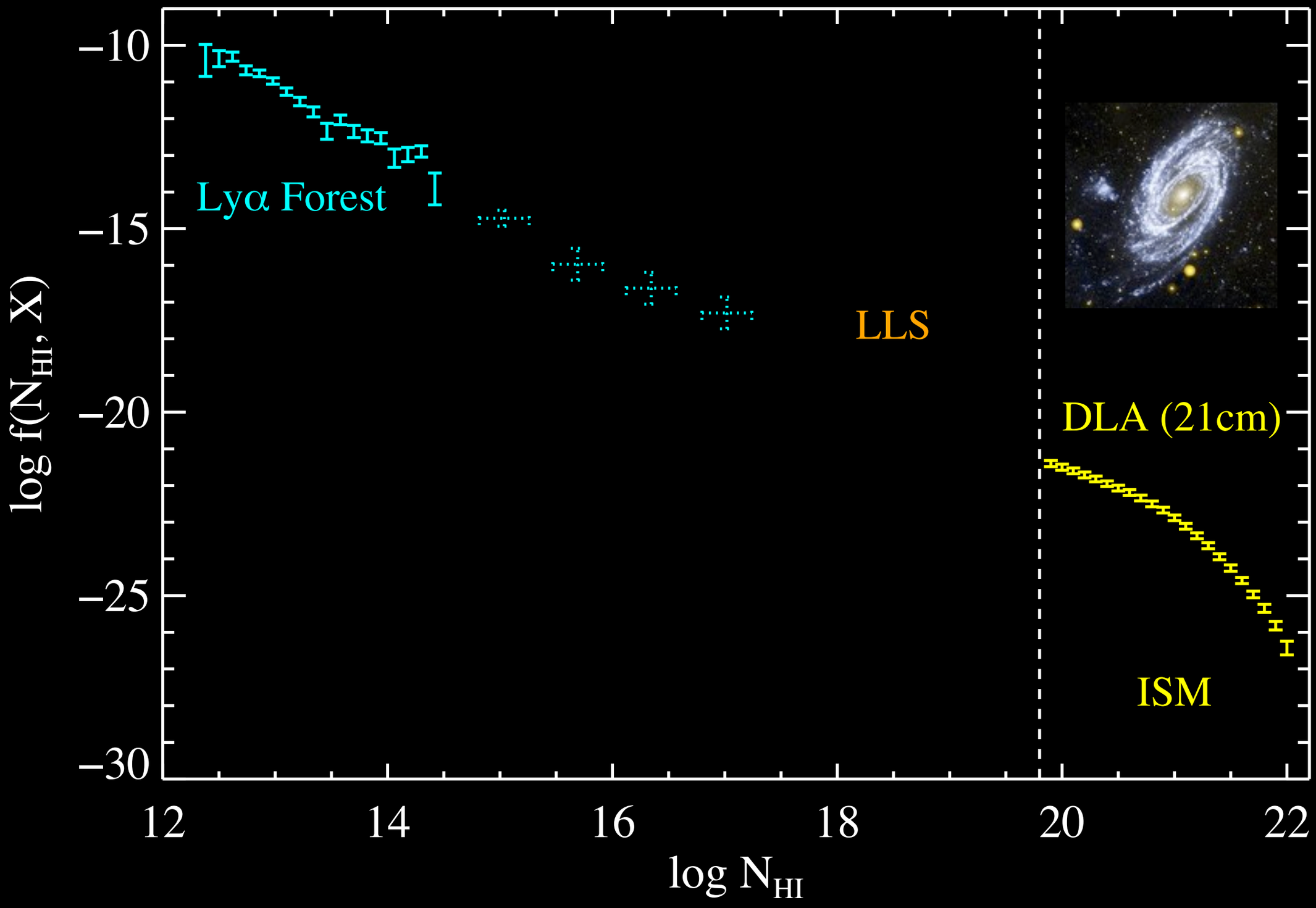
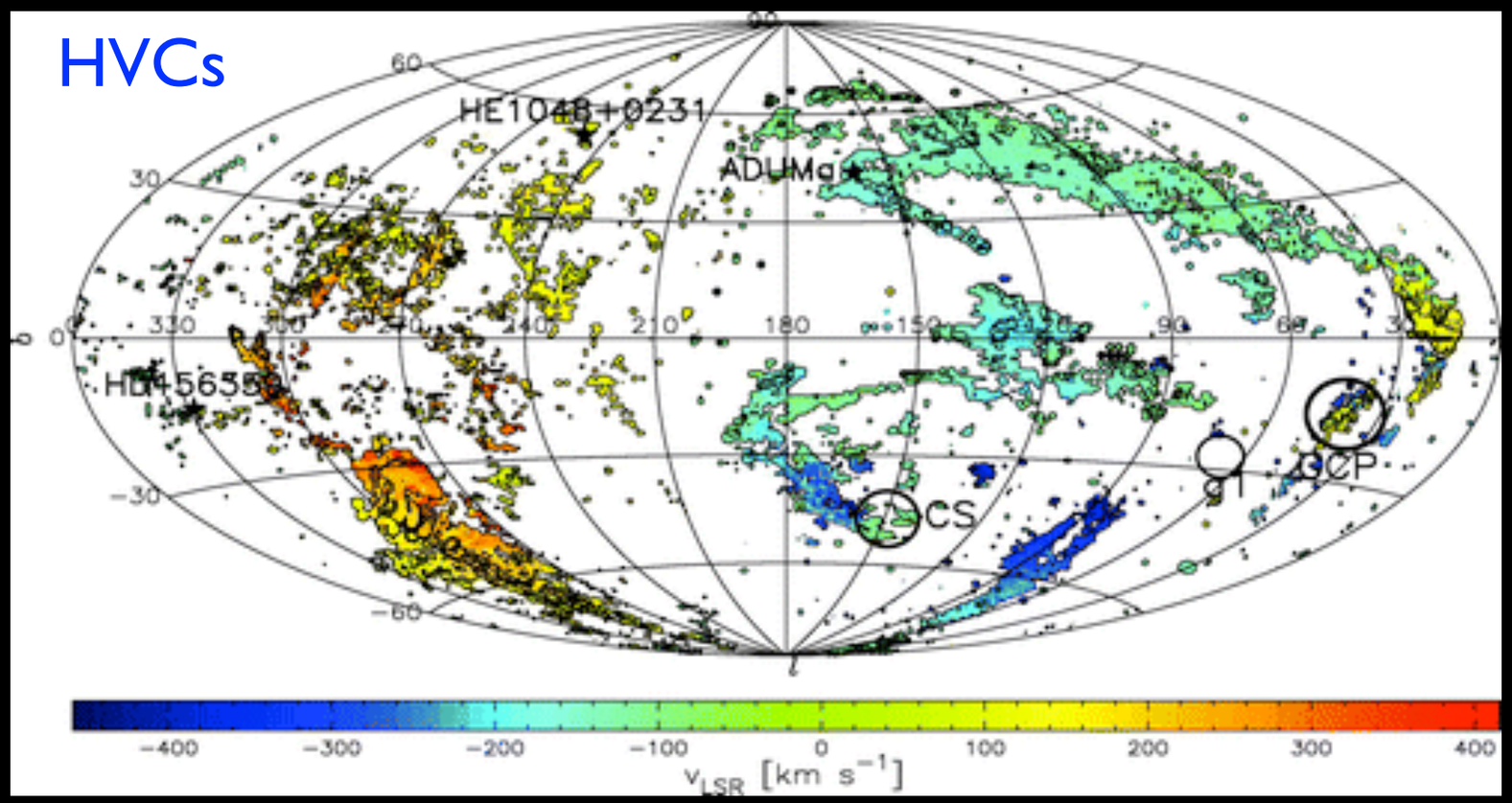


The Circumgalactic Medium (CGM)

Diffuse gas, including metals, in the halos of galaxies (and beyond).



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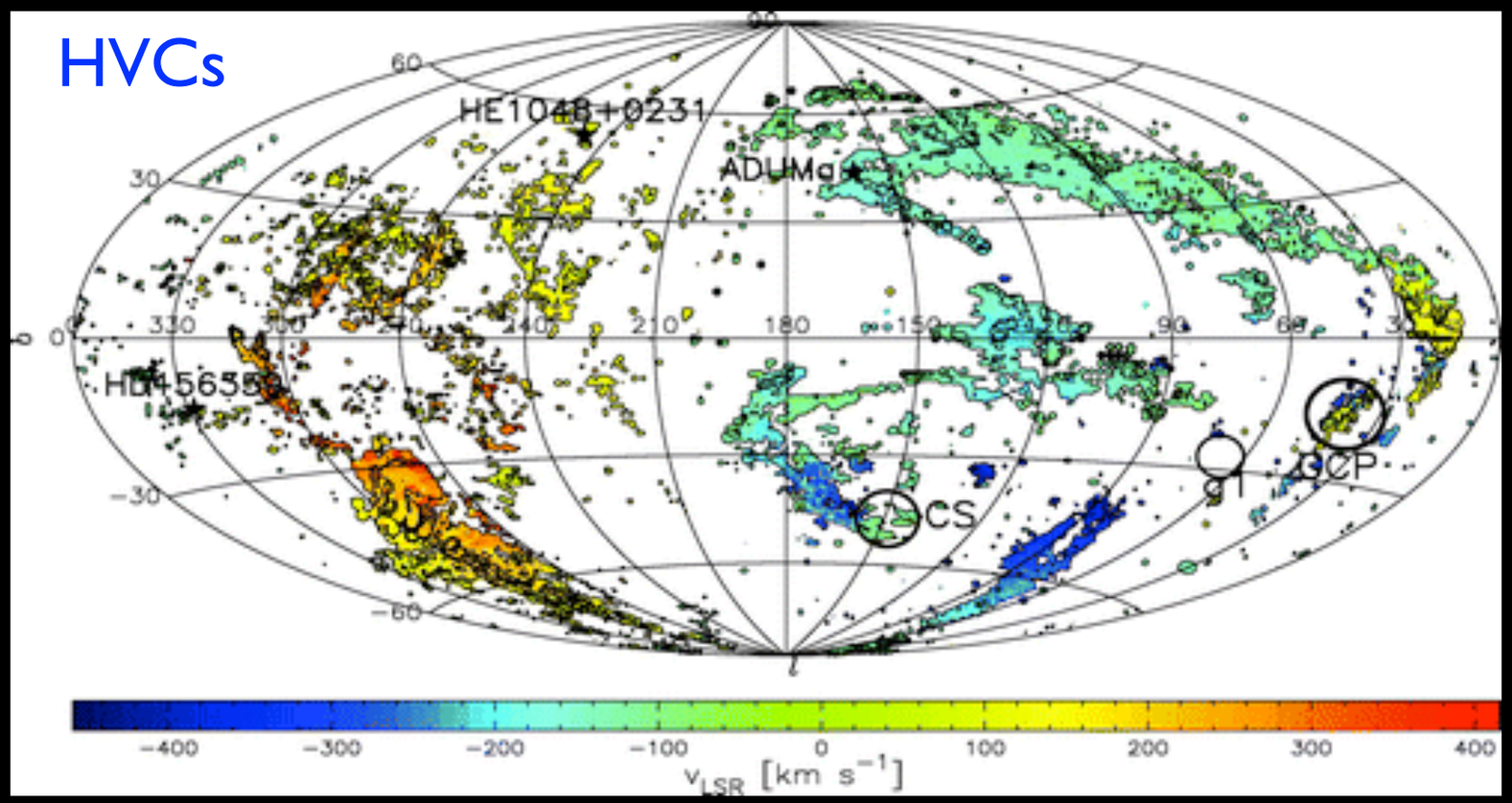

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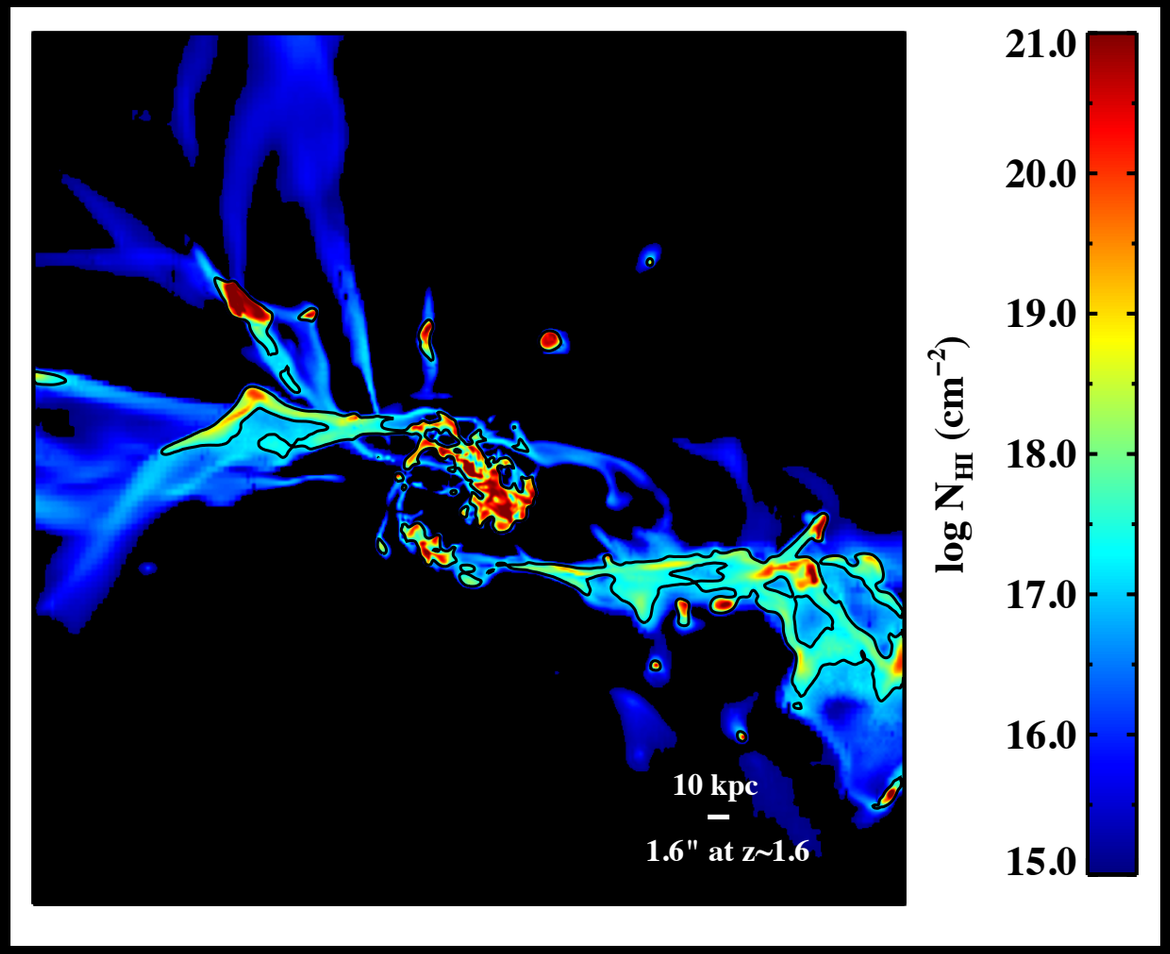

e.g. "Cold" stream gas
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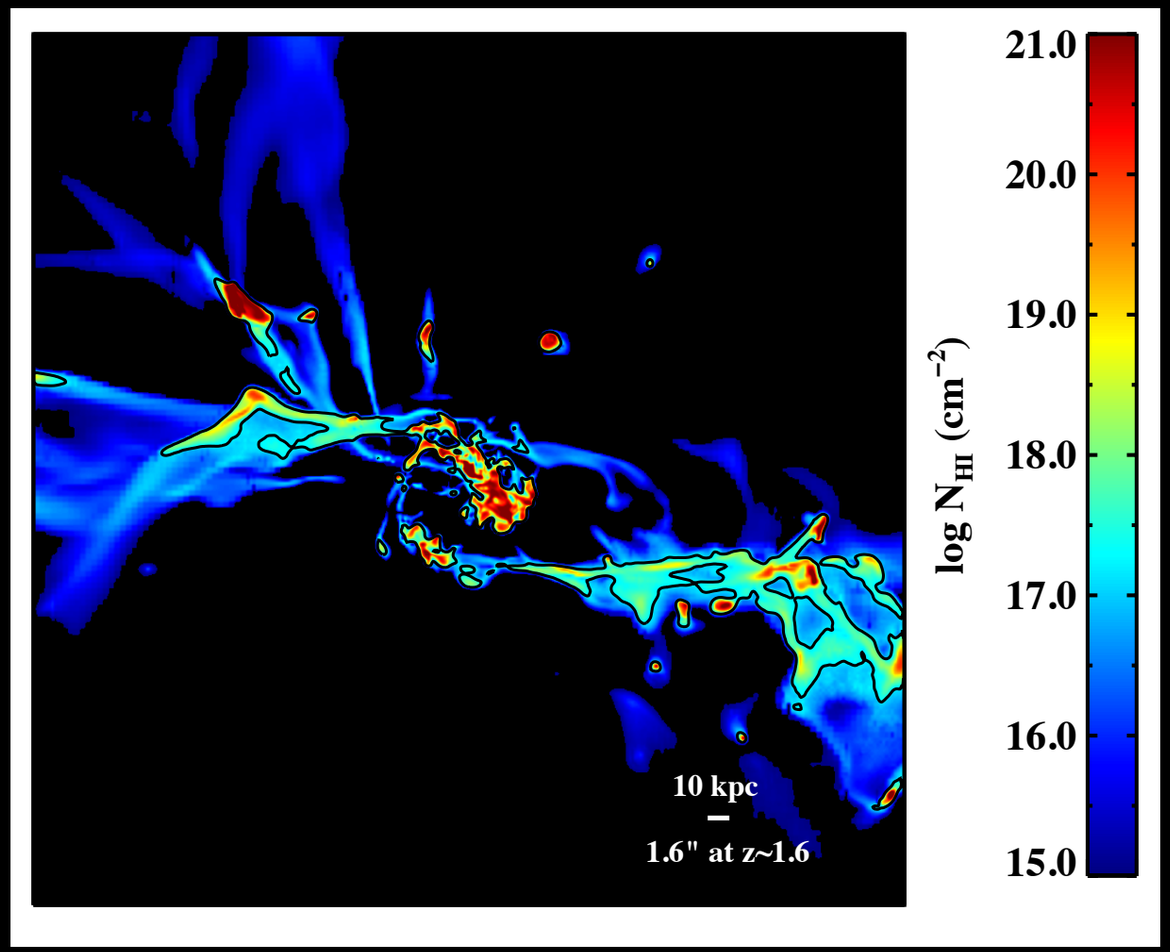

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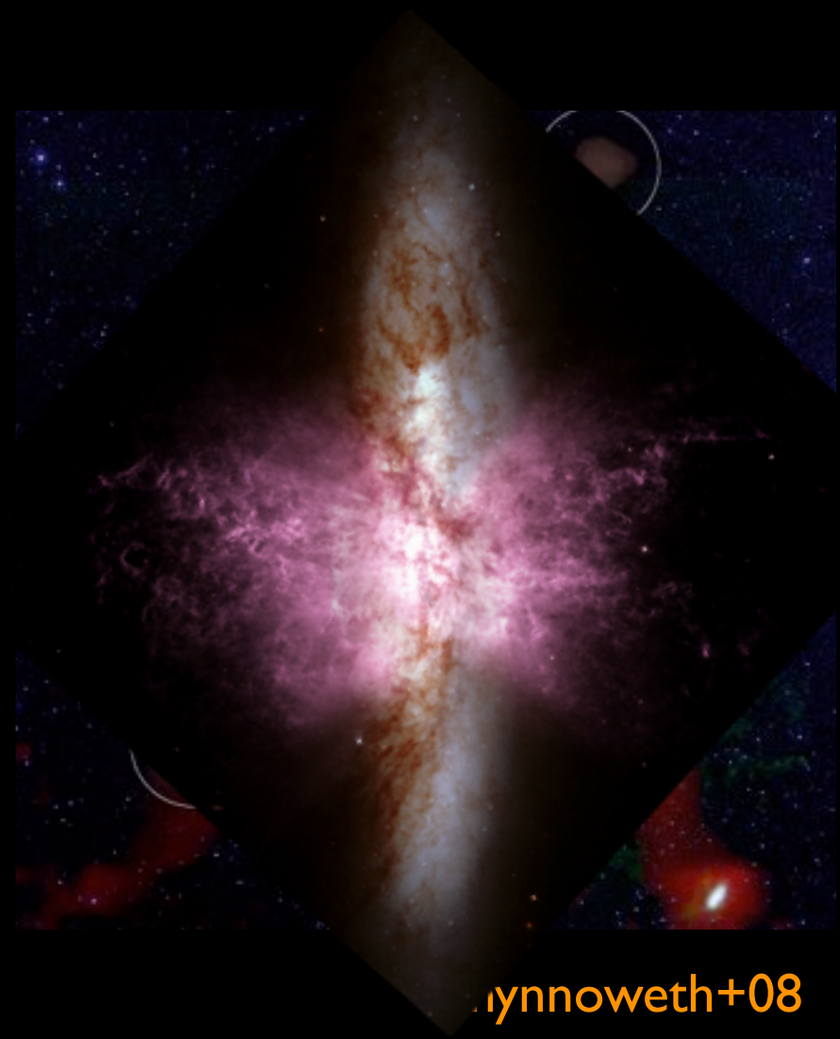

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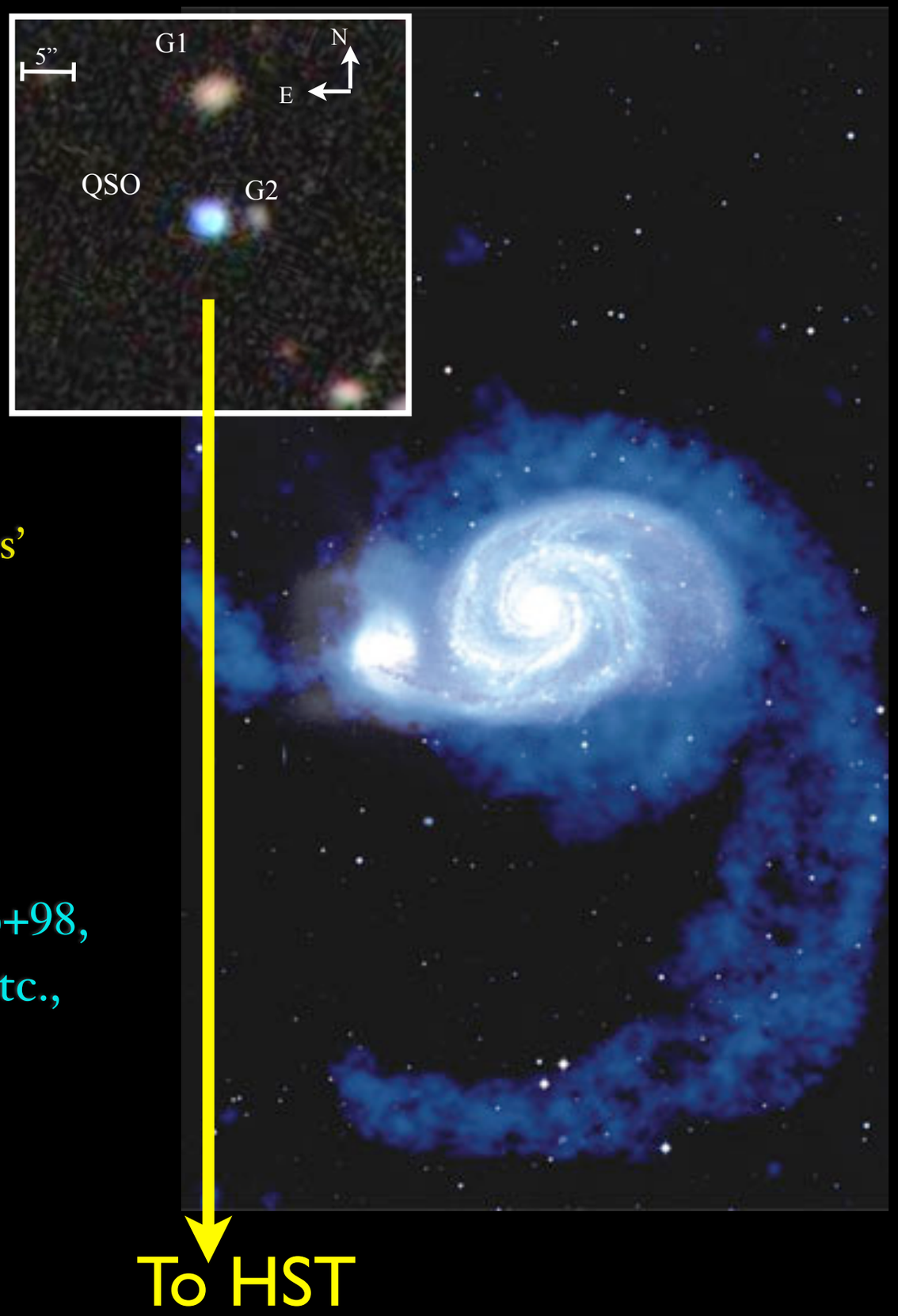
- Experiment
  - Examine the CGM of galaxies
  - Via coincident, background quasars
    - ✦ Spinrad+93, Morris+93, Lanzetta+95, Tripp+98, Chen+01, Bowen+01, Wakker&Savage09, etc., etc., etc.



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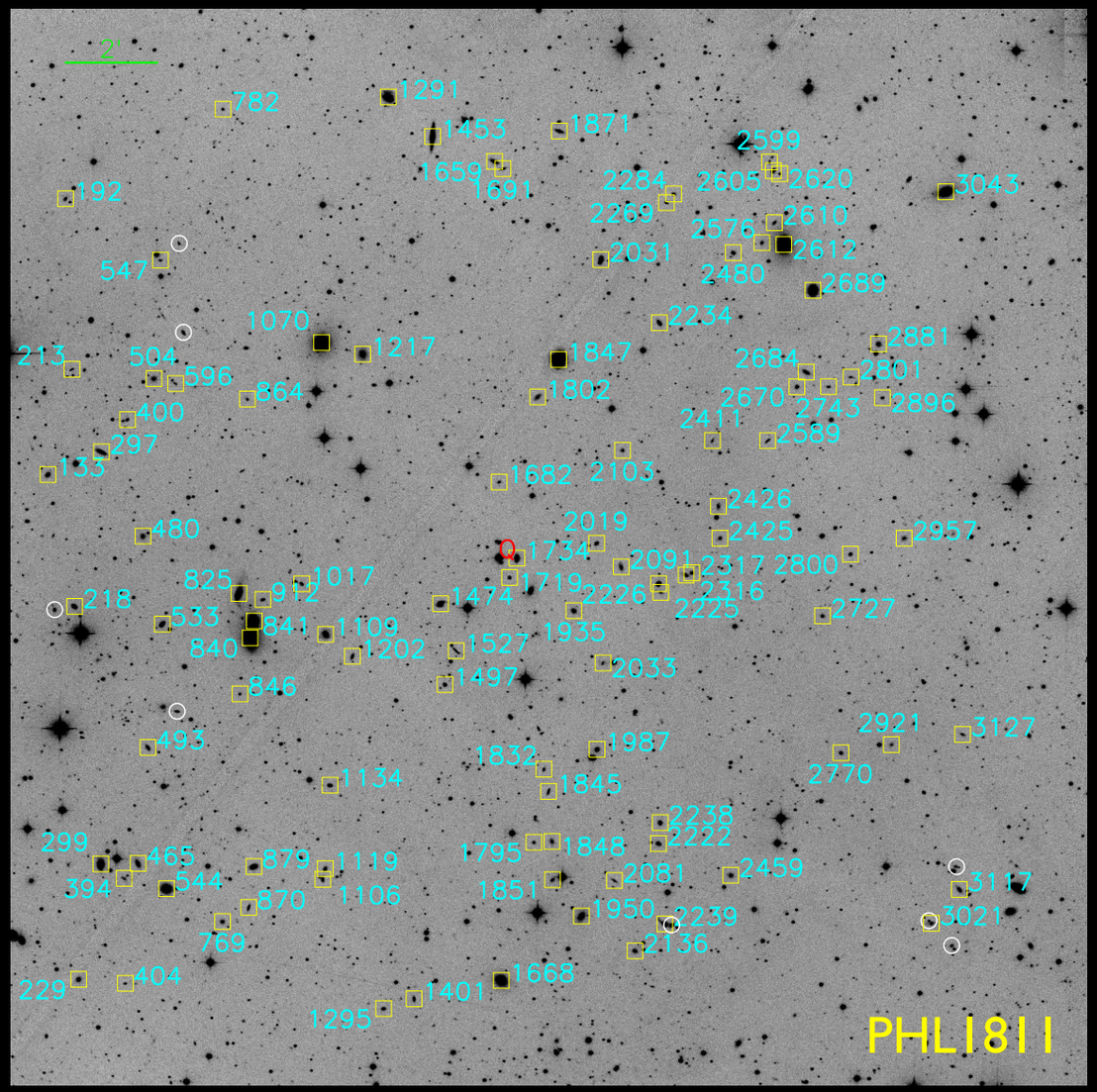
Prochaska, Weiner, Chen, Mulchaey, Cooksey 2011



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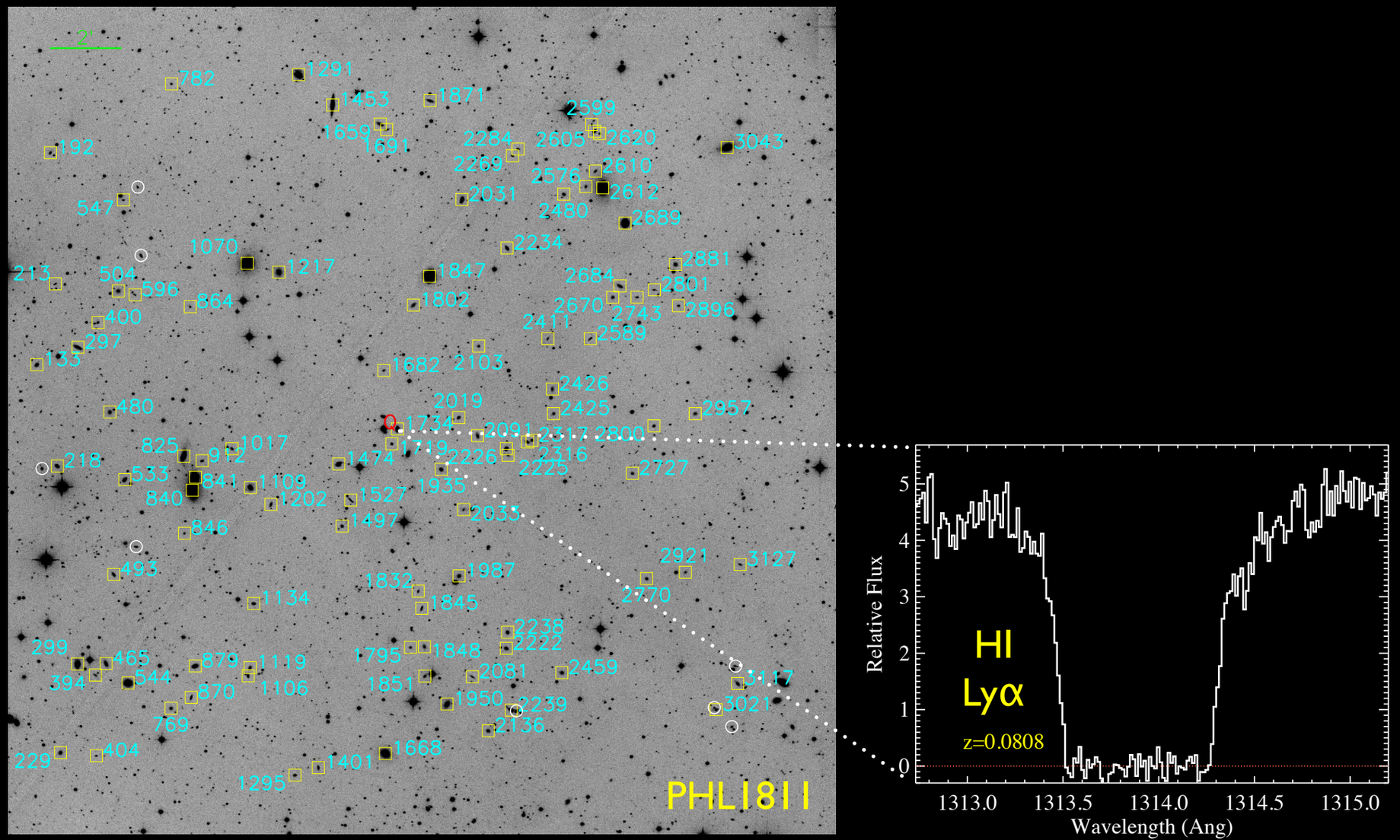

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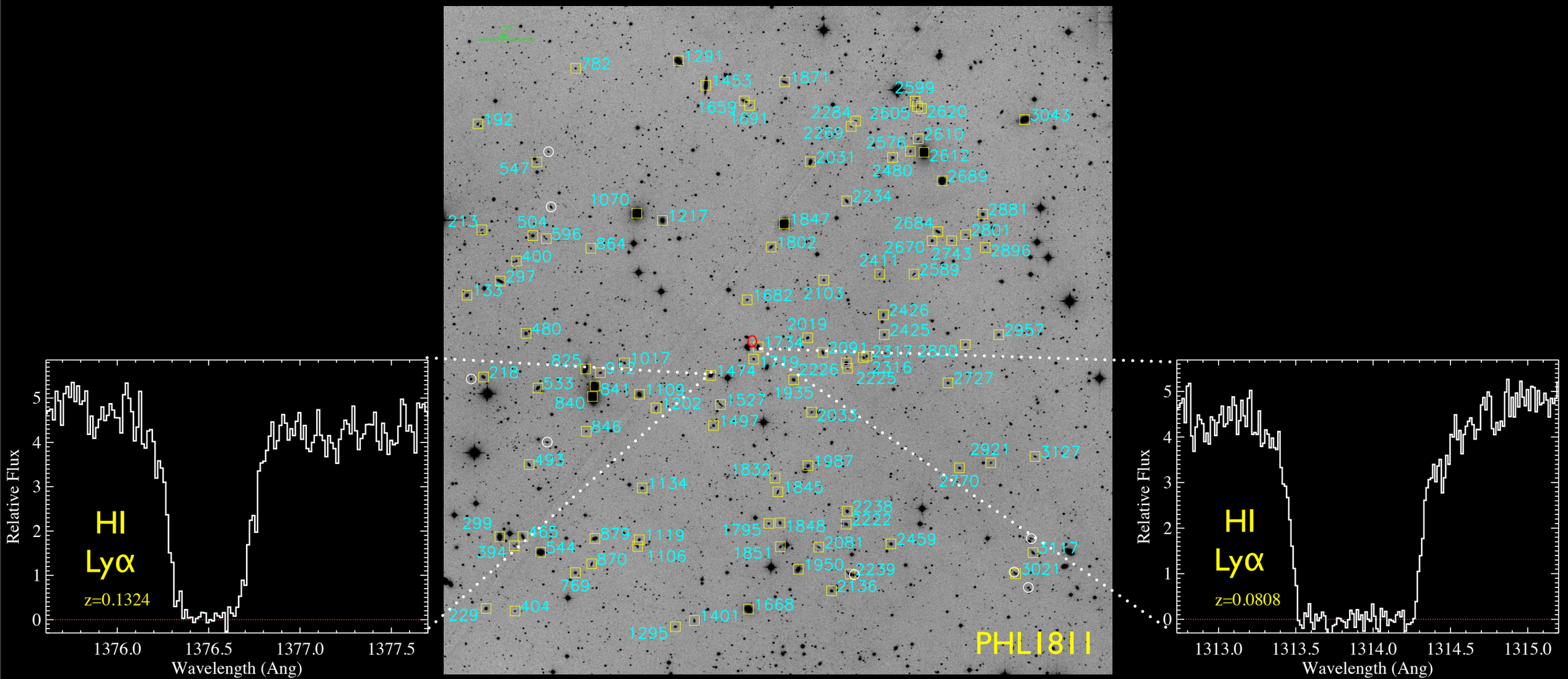

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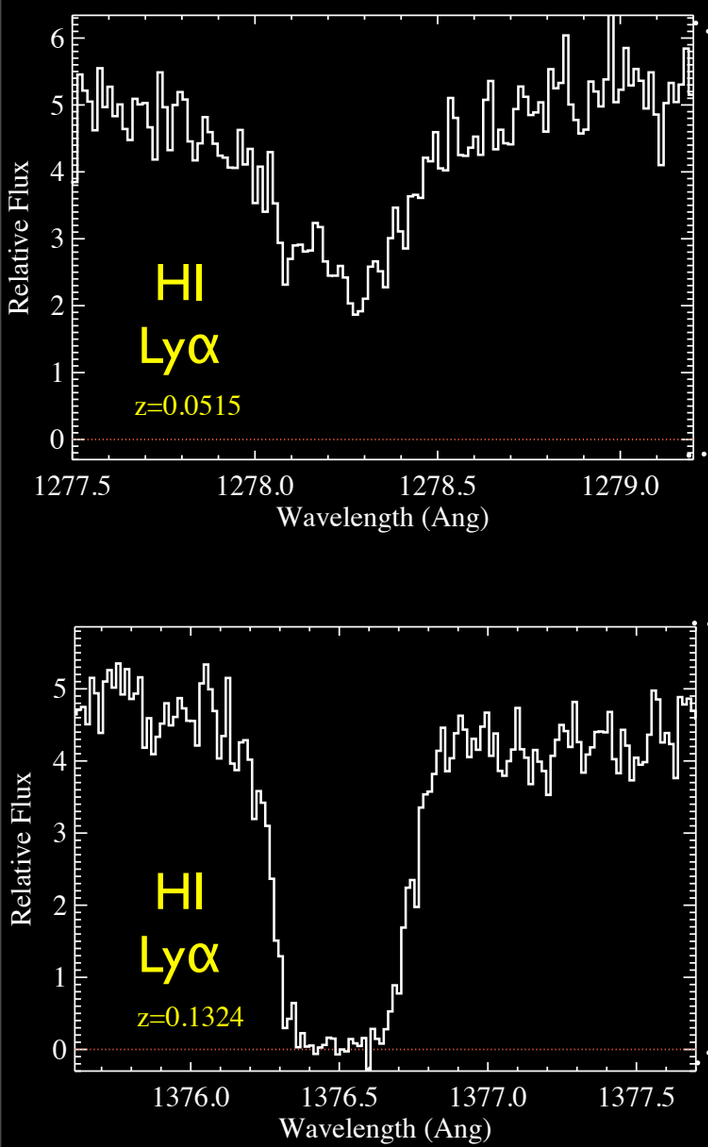

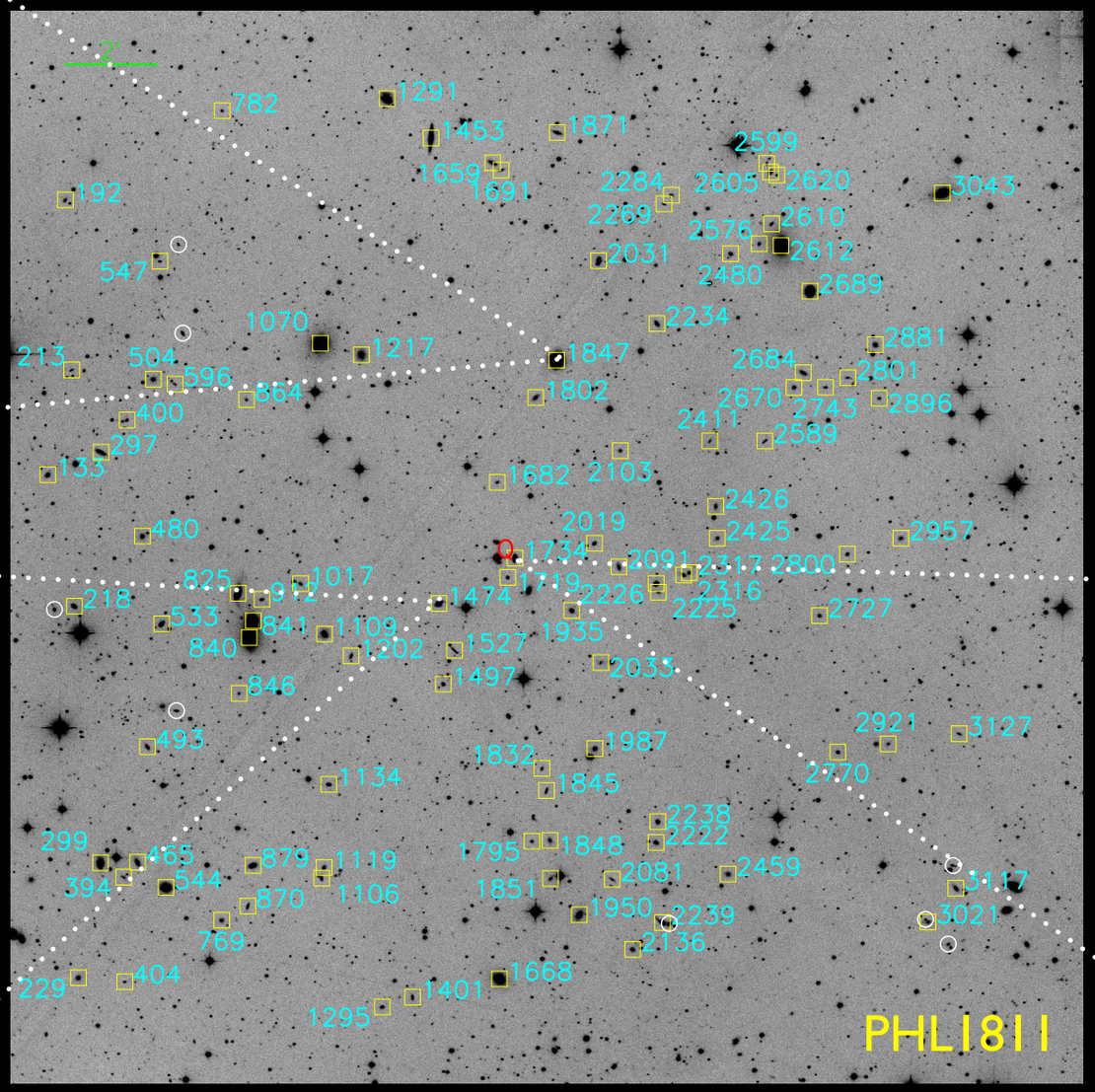

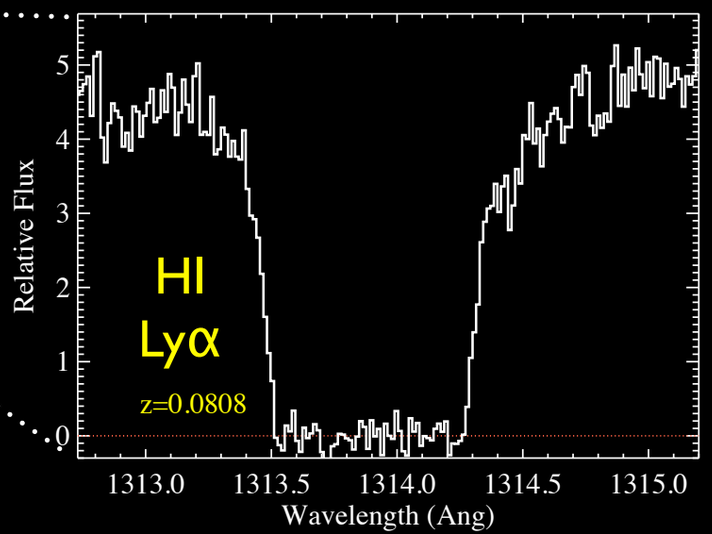

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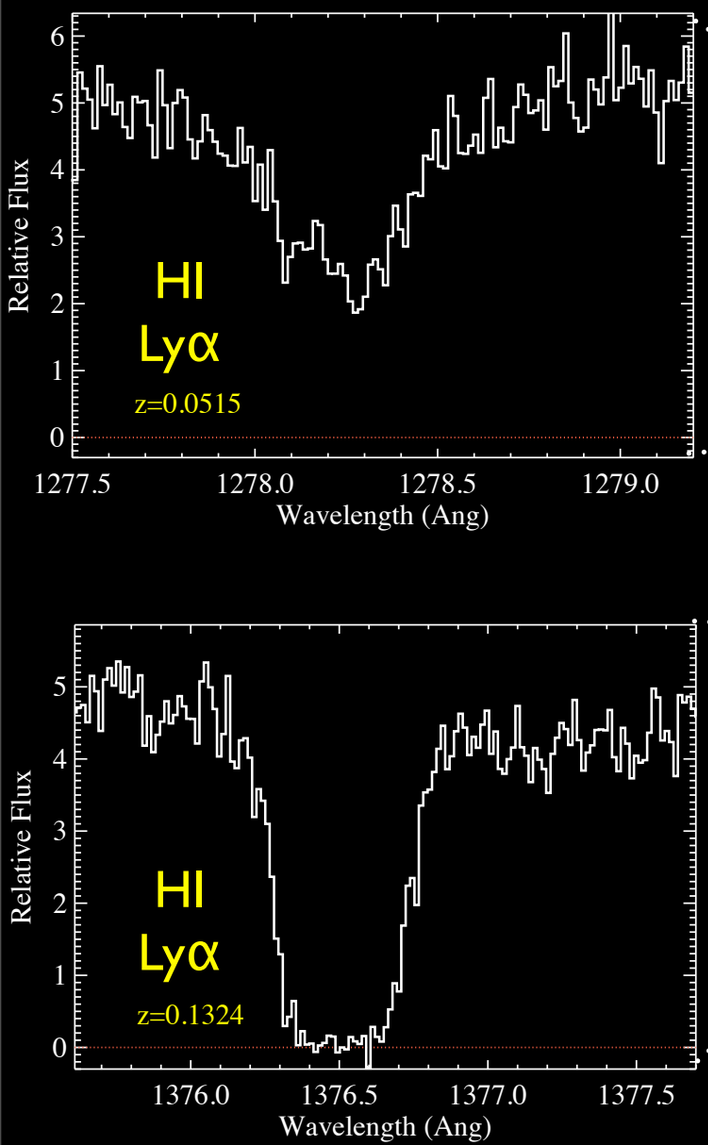

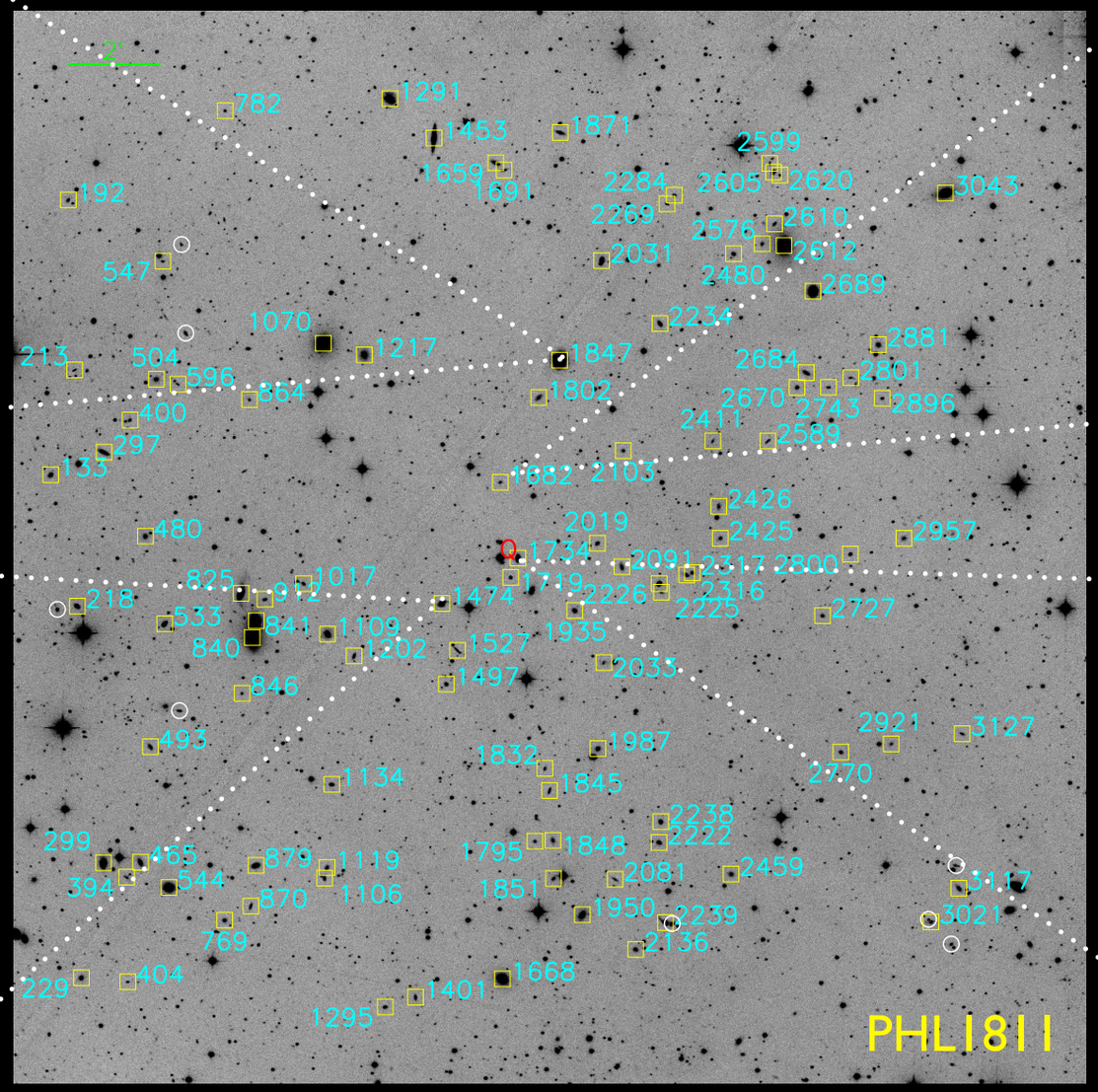

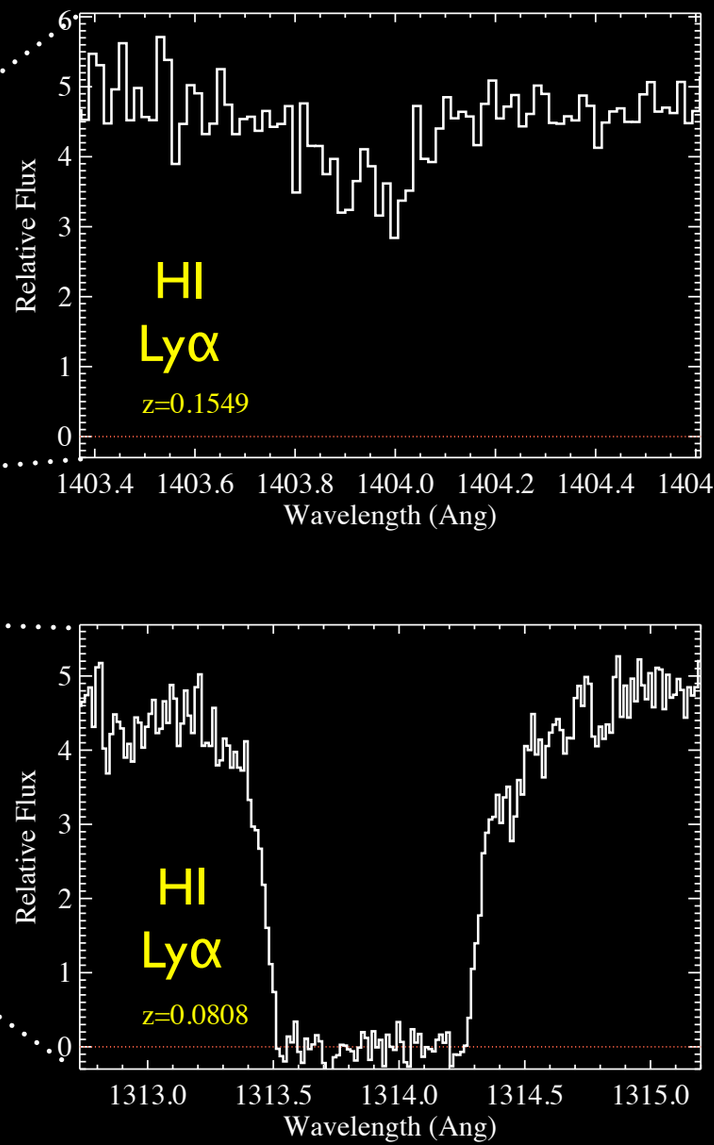

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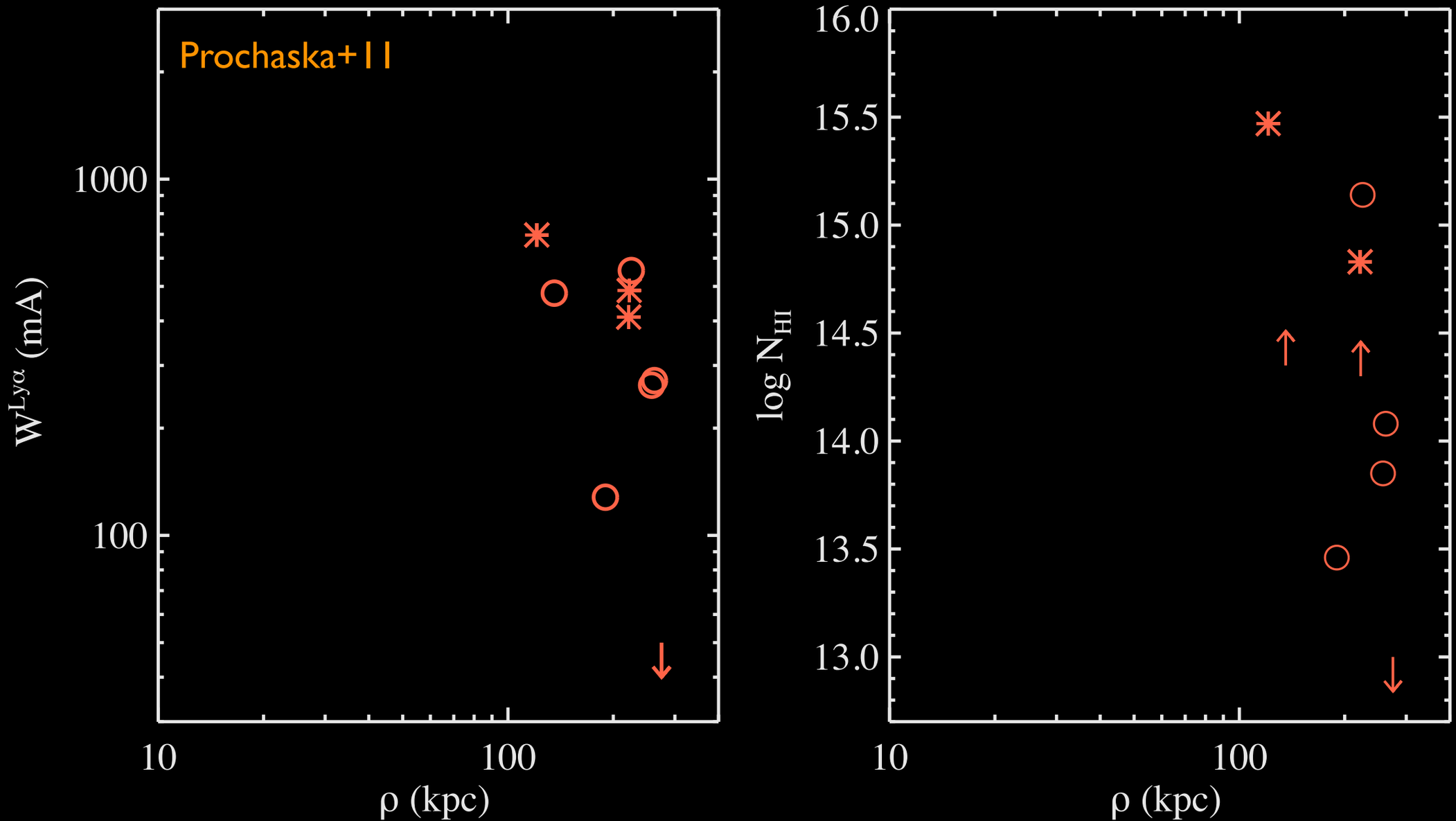
HI Gas Surrounding z~0 Galaxies



- L* Galaxies (L > L*)
  - Small sample (bright galaxies are rare!)
  - See "COS-Halos" program for r < 150 kpc
    - Tumlinson, Thom, Werk, etc.

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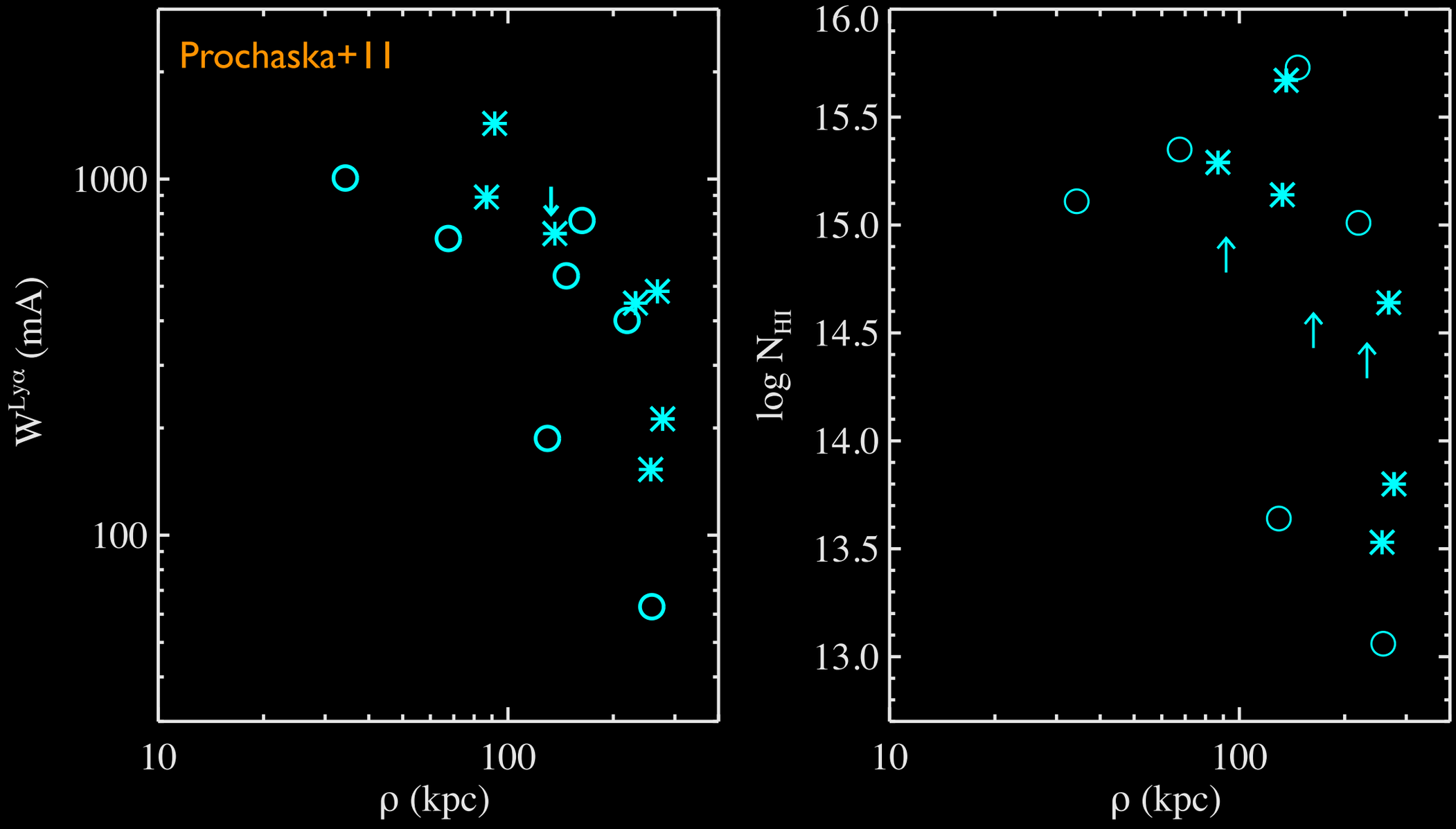

- Sub-L* Galaxies (L* > L > 0.1L*)
  - 100% covering with W^{Lya} > 100mA to 300 kpc
    - Early and late types
  - Rarely a brighter galaxy also within 300 kpc

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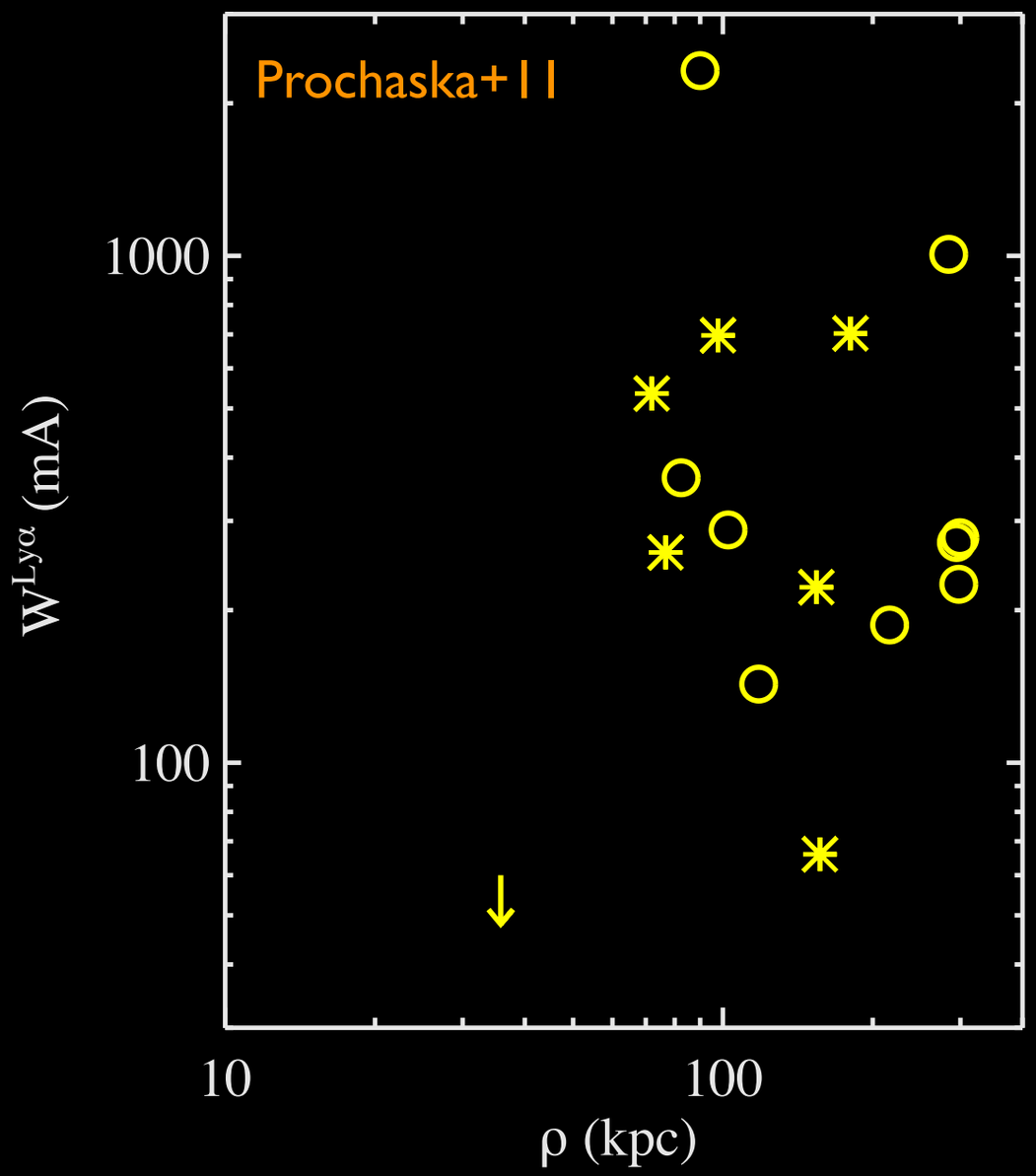

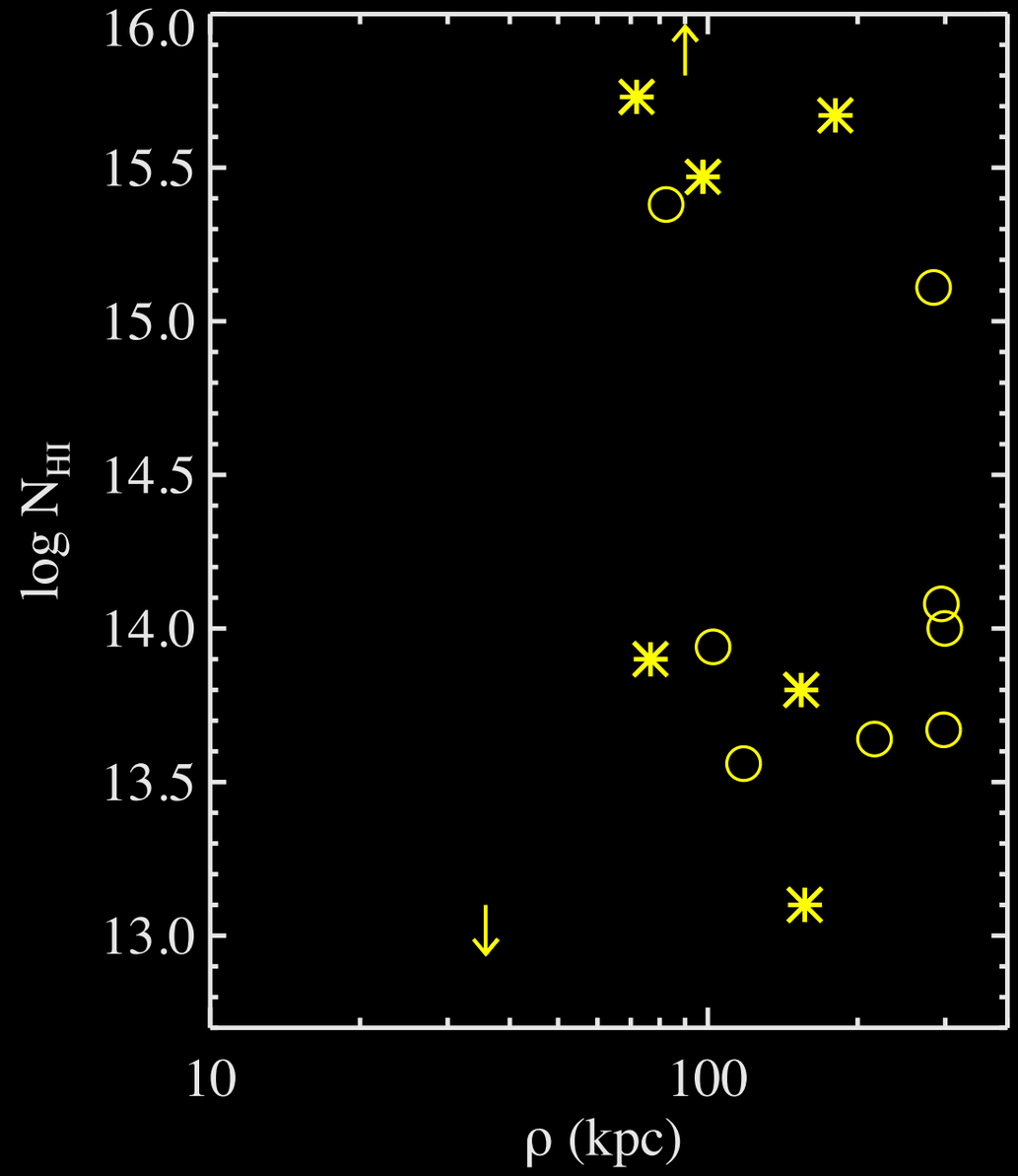

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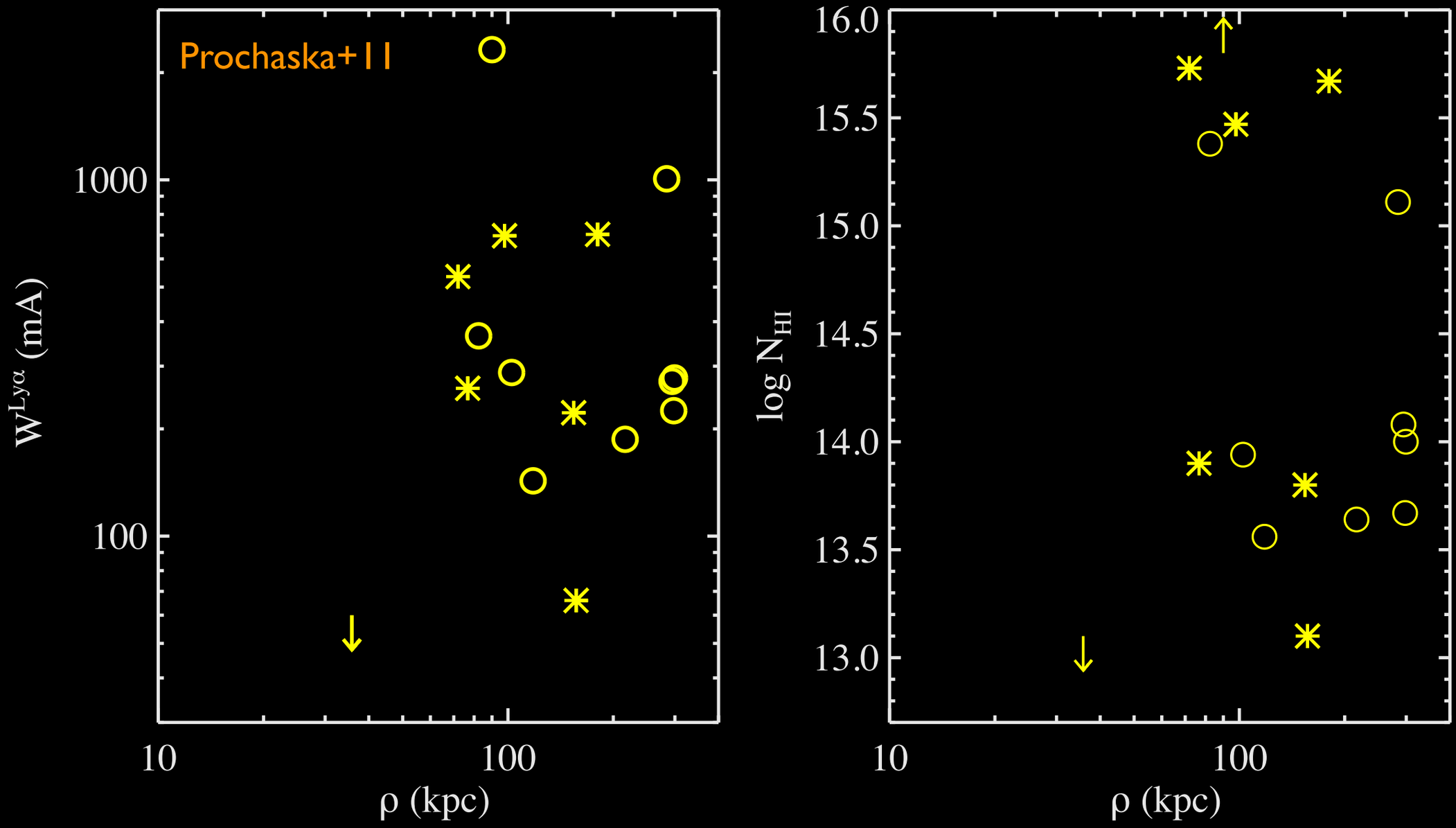

- Dwarf Galaxies (L < 0.1L*)
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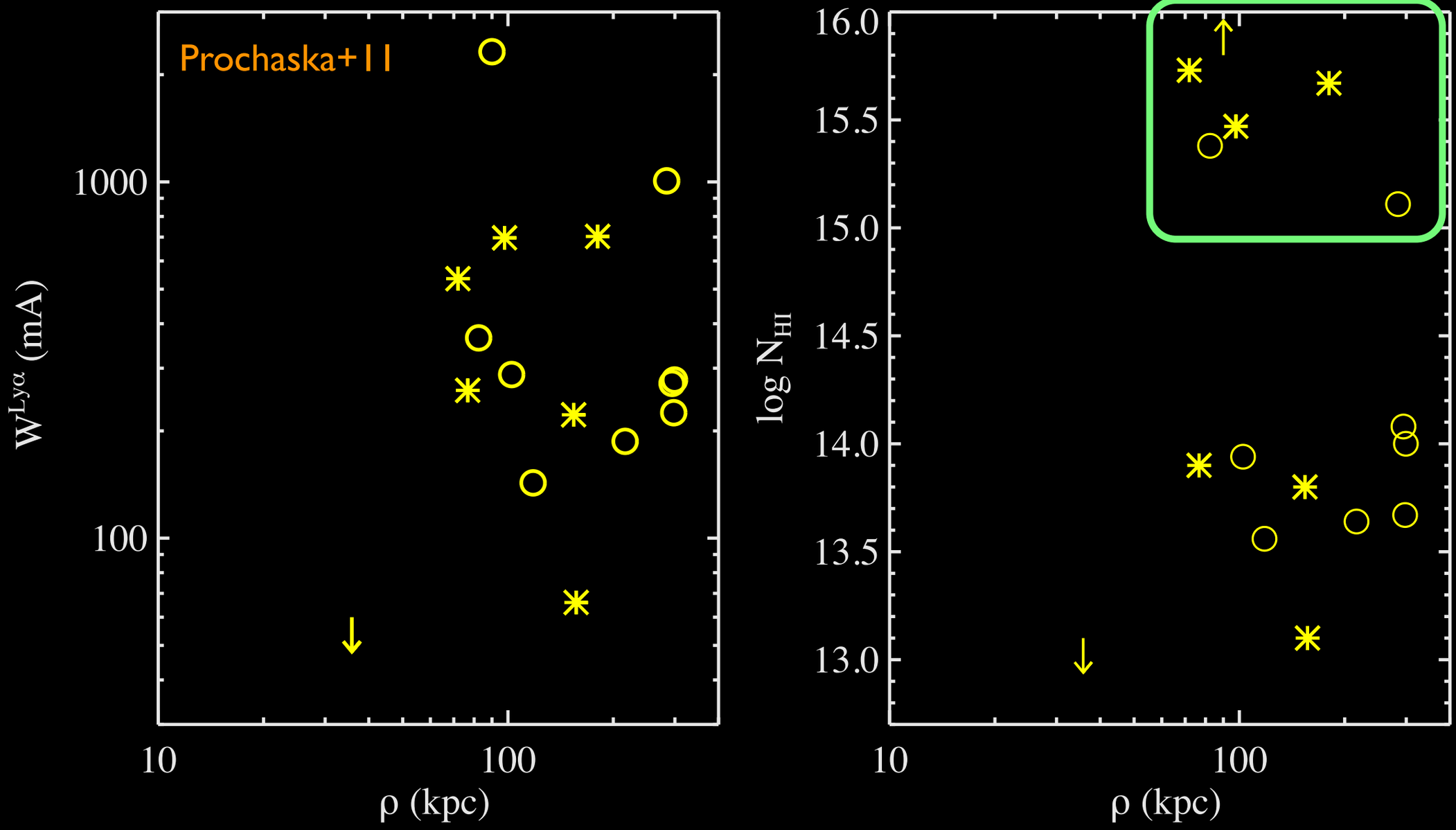
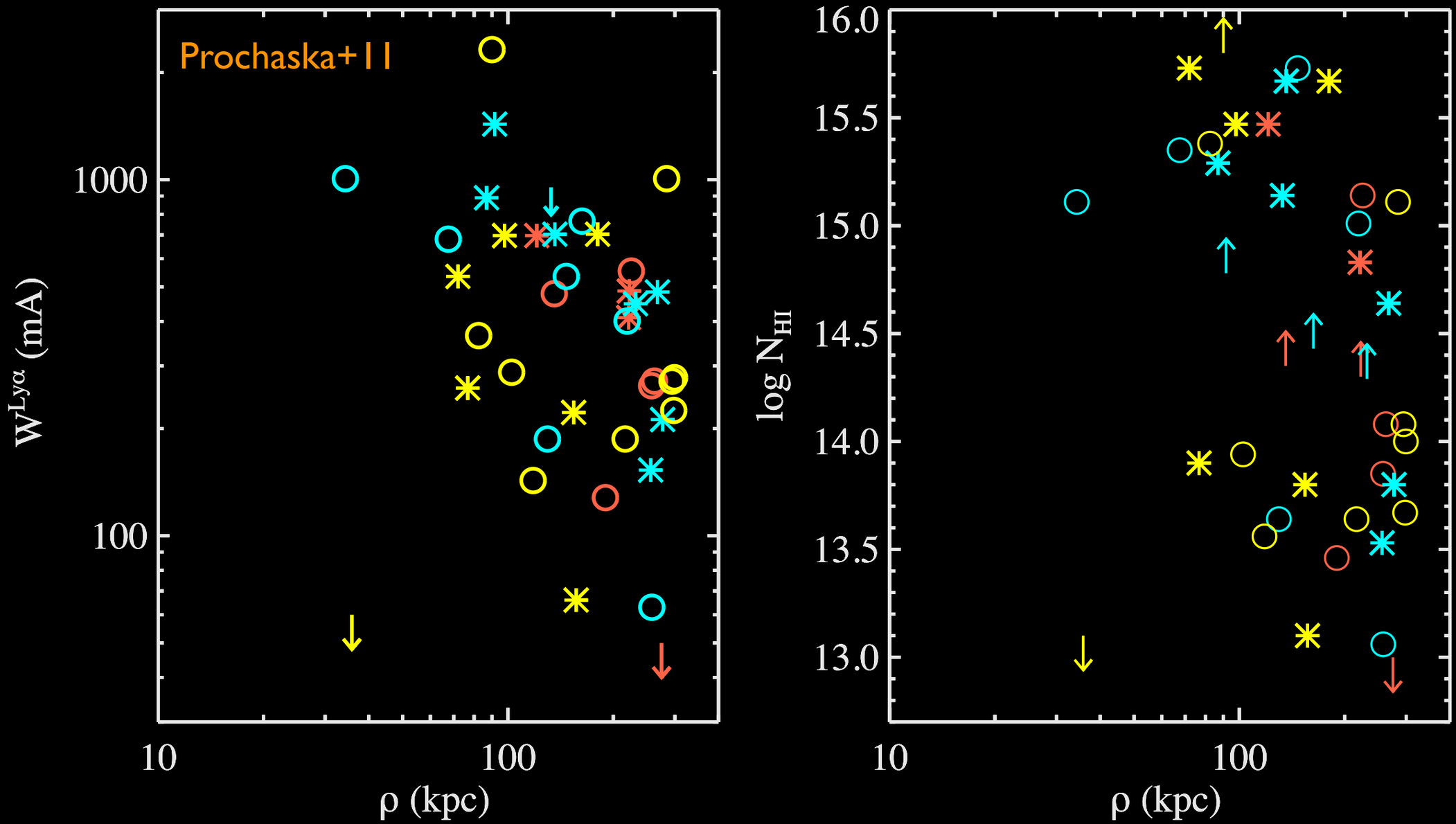


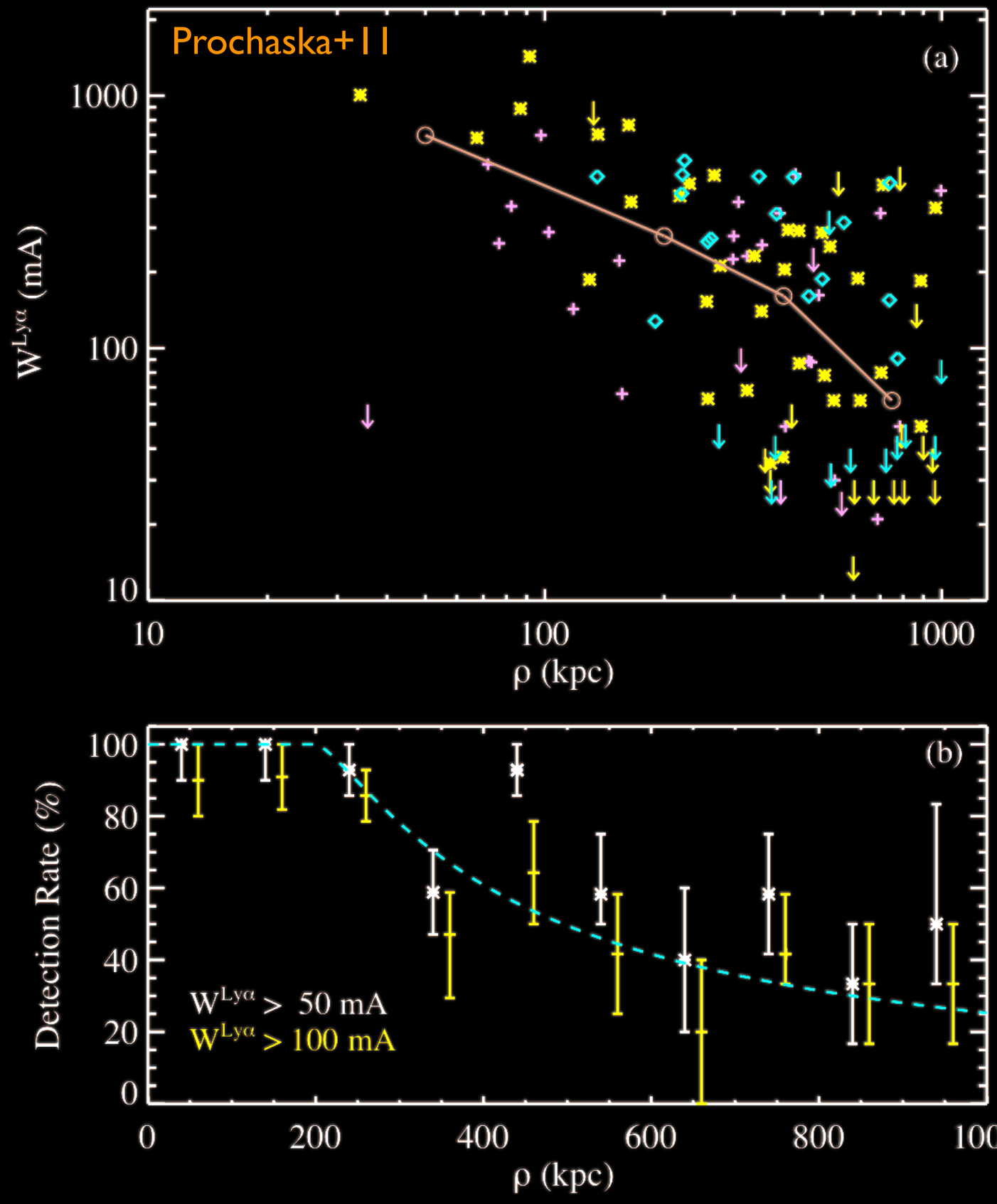
- Dwarf Galaxies (L < 0.1L*)
  - Nearly 100% covering with W^{Lya} > 100mA to 300 kpc
    - Early or late types
  - Largest W^{Lya} absorption has a nearby, brighter galaxy
    - Or Virgo!

HI Gas Surrounding z~0 Galaxies



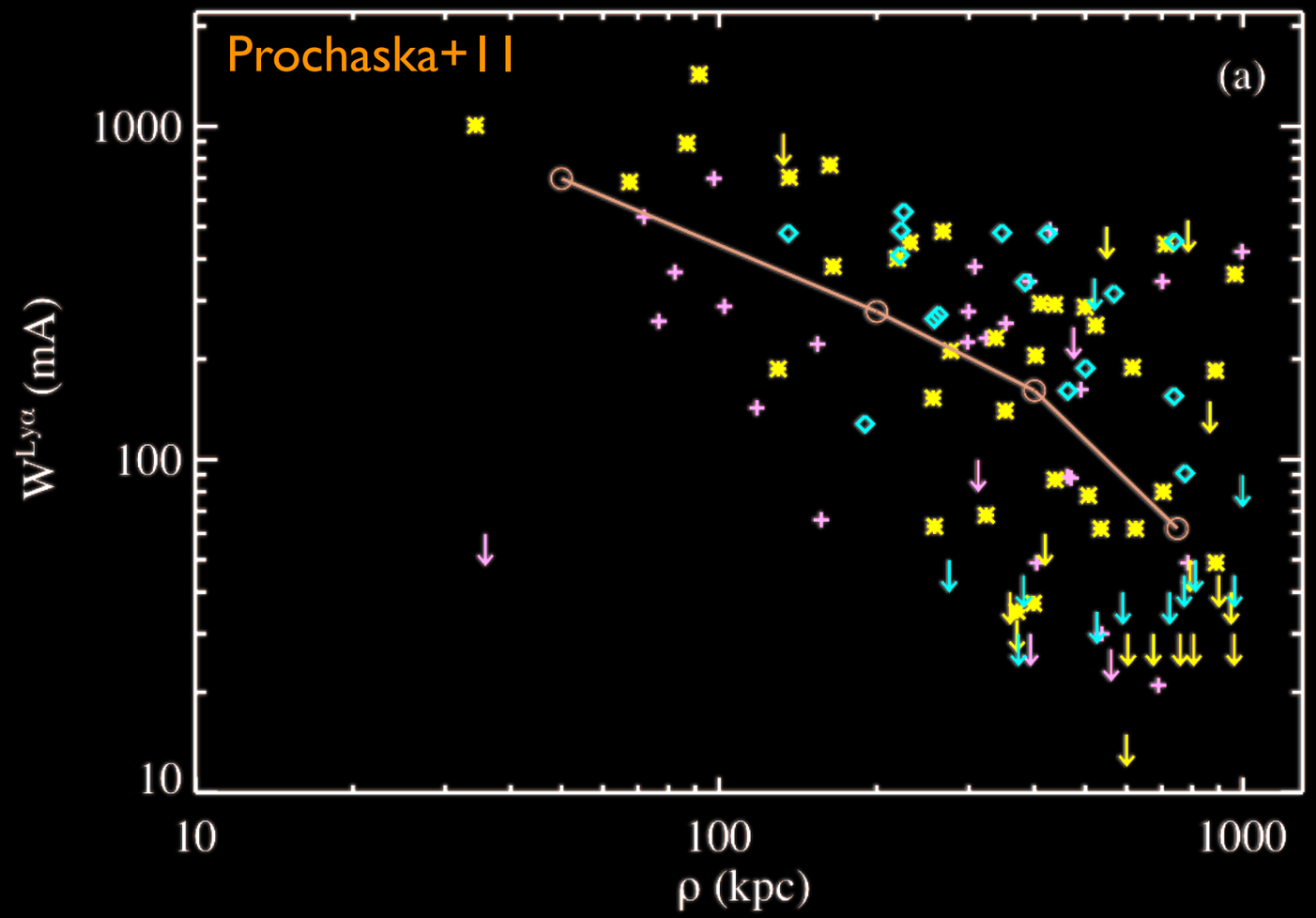
- All together now
  - Galaxies of all luminosity and spectral type show extended 'halos' (or CGM) of HI absorption to 300 kpc
    - Generally $W^{Ly\alpha} > 100$ mA
      - e.g. Lanzetta+95, Tripp+98, Wakker+09

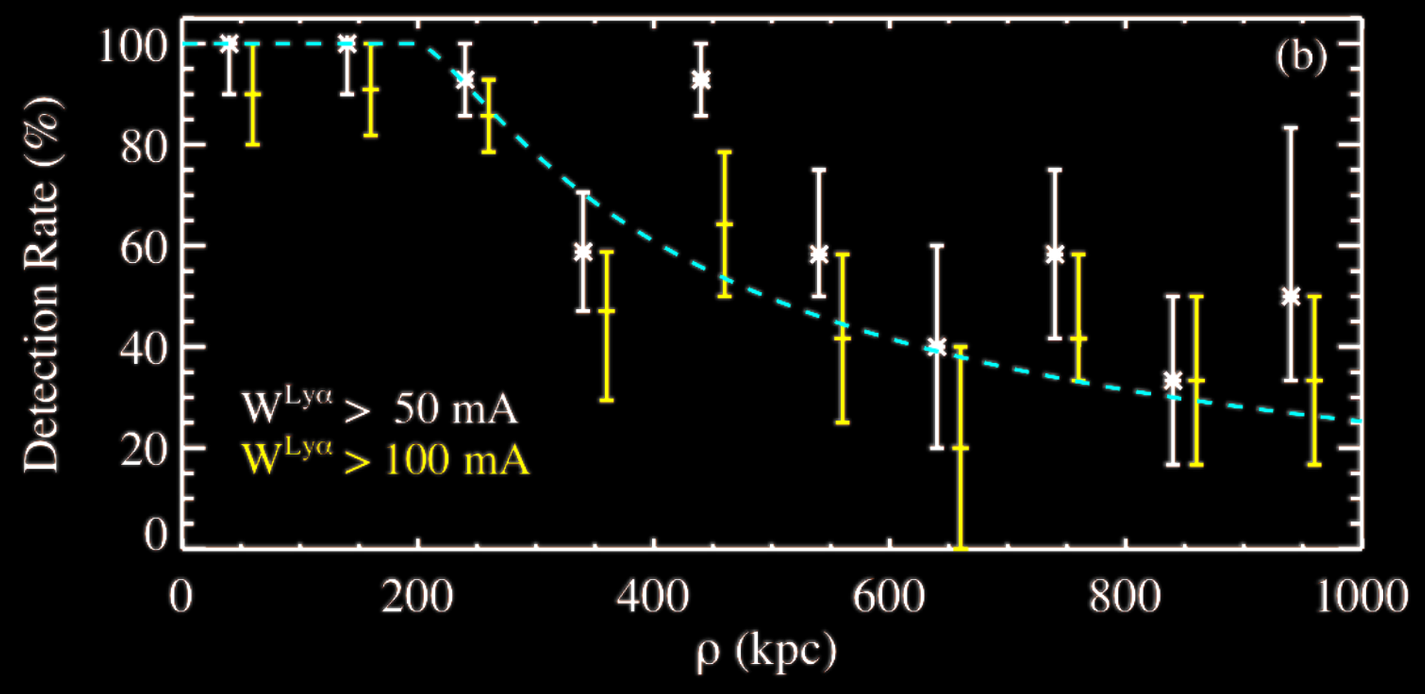
Extent of the CGM



Extent of the CGM

- HI covering fraction drops rapidly beyond ~300kpc
  - Associate CGM with this scale





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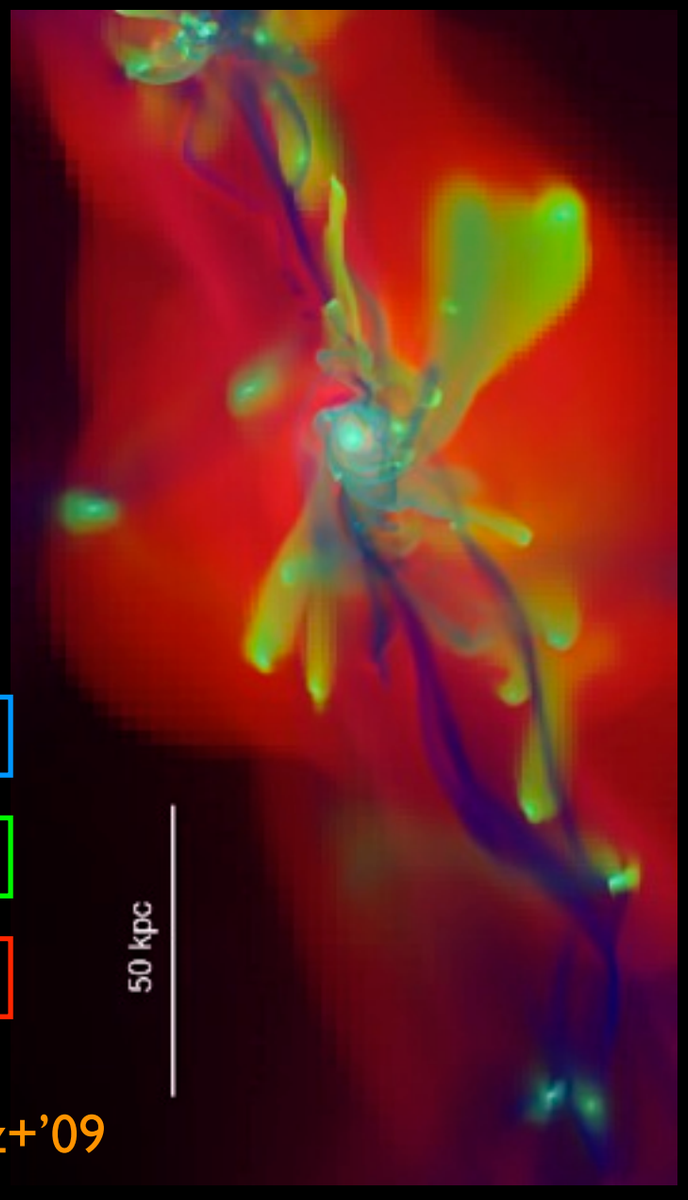
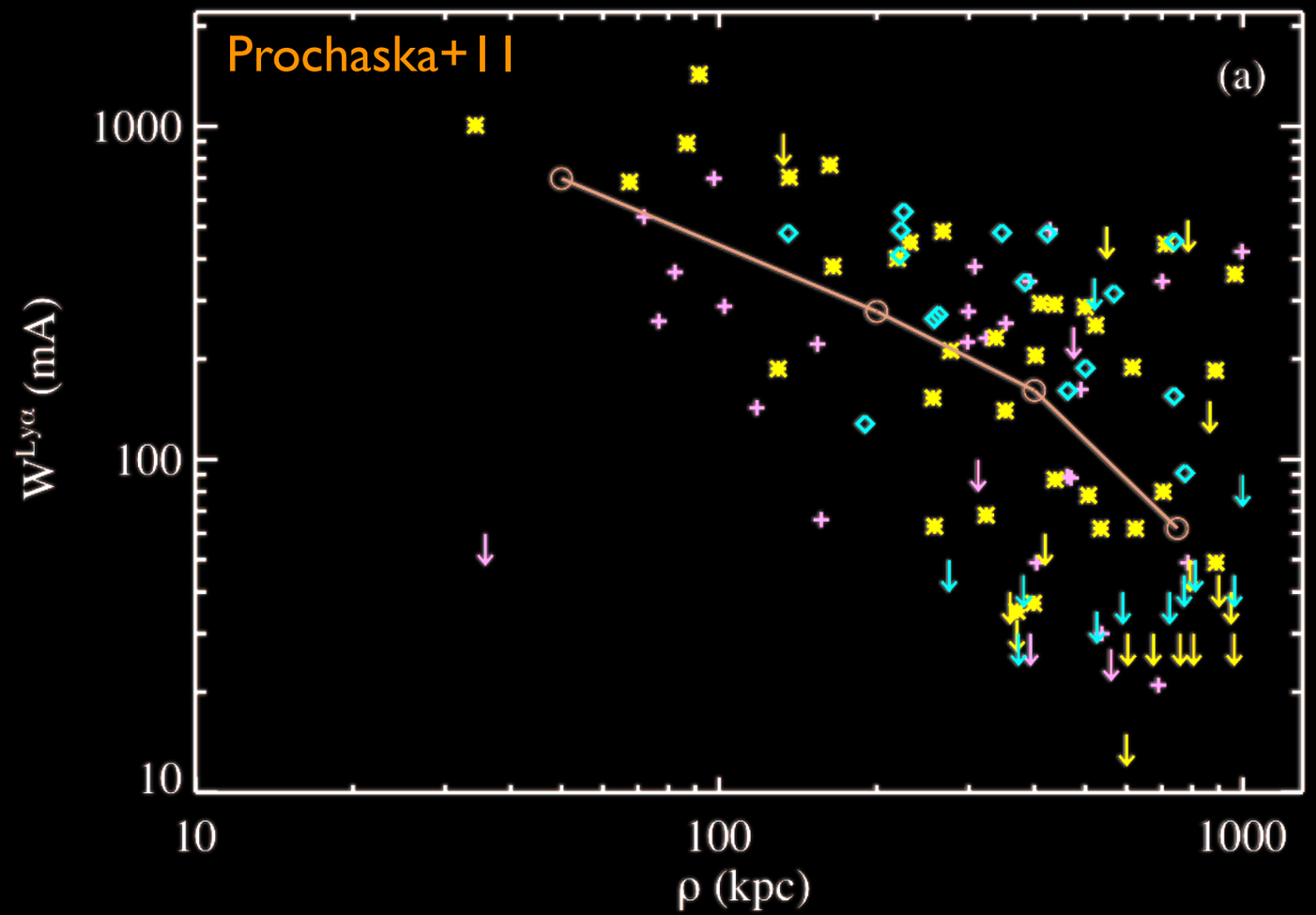
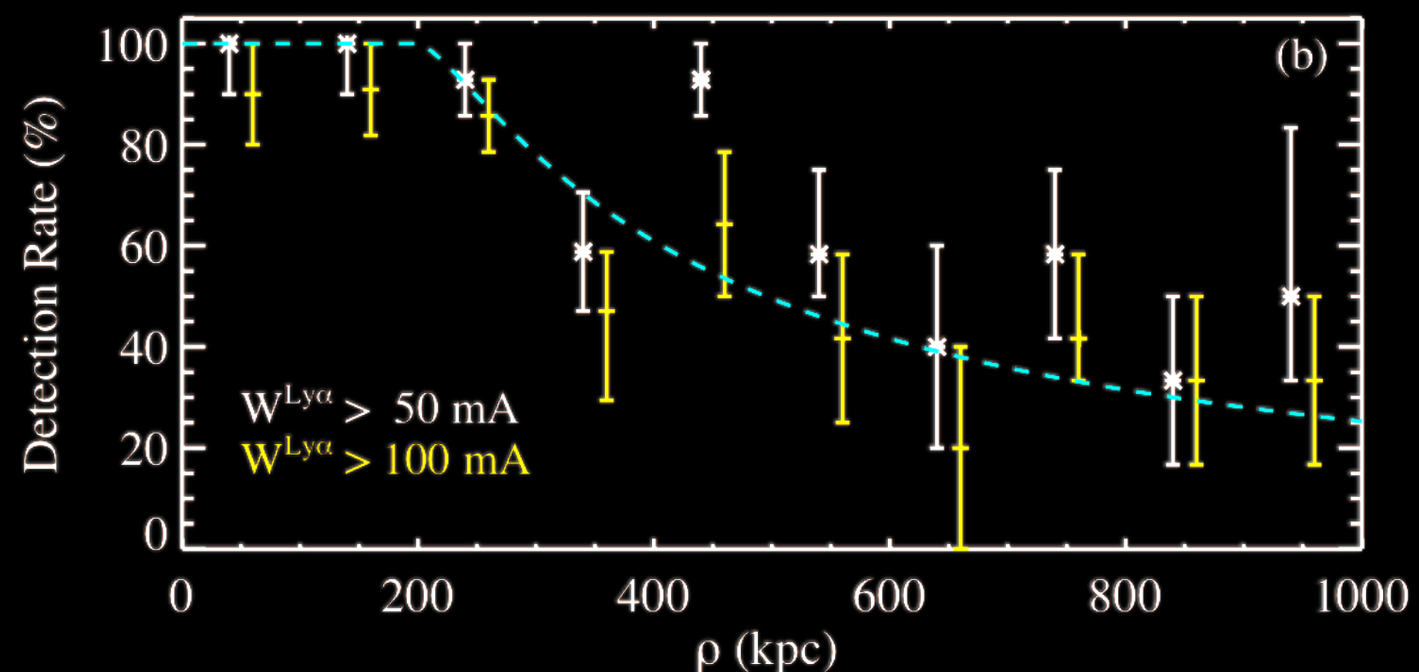
$f_V < 1\%$



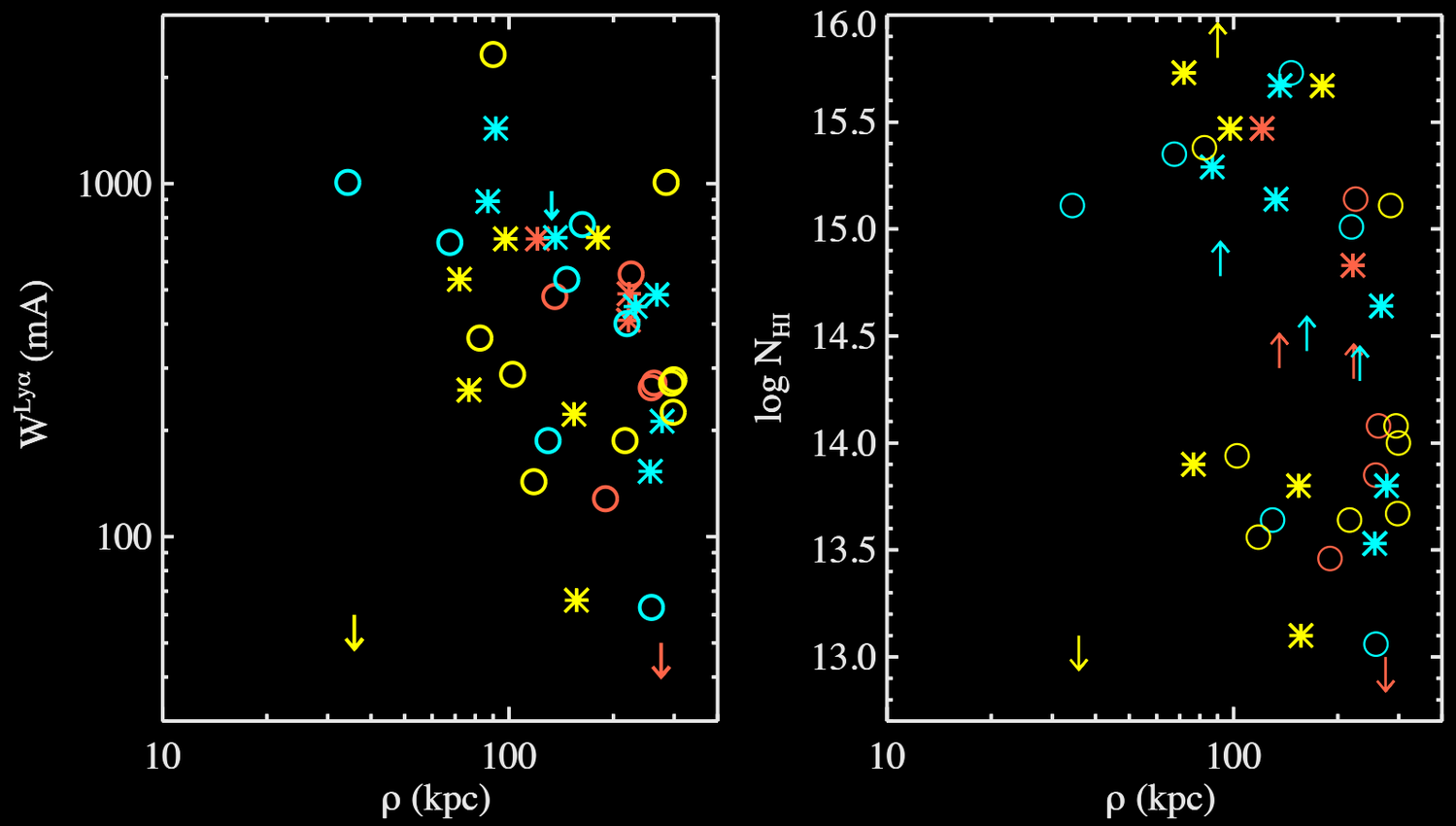
Agertz+'09





Mass of the CGM from z~0 Galaxies

Prochaska+11



- CGM Mass Estimate
  - Adopt (assume) a large ionization correction for N_{HI}
    - With $N_{HI,CGM} = 10^{15}$ cm^{-2}, $x_{HI}=10^{-4}$

$$M_{CGM} \approx 3 \times 10^{10}\, M_\odot \left(\frac{N_{HI,CGM}}{10^{15}\,\mathrm{cm}^{-2}}\right) \left(\frac{x_{HI}}{10^{-4}}\right)^{-1} \left(\frac{r_{CGM}}{300\mathrm{kpc}}\right)^{2}$$

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    - Enough 'missing' baryons for sub-L* galaxies
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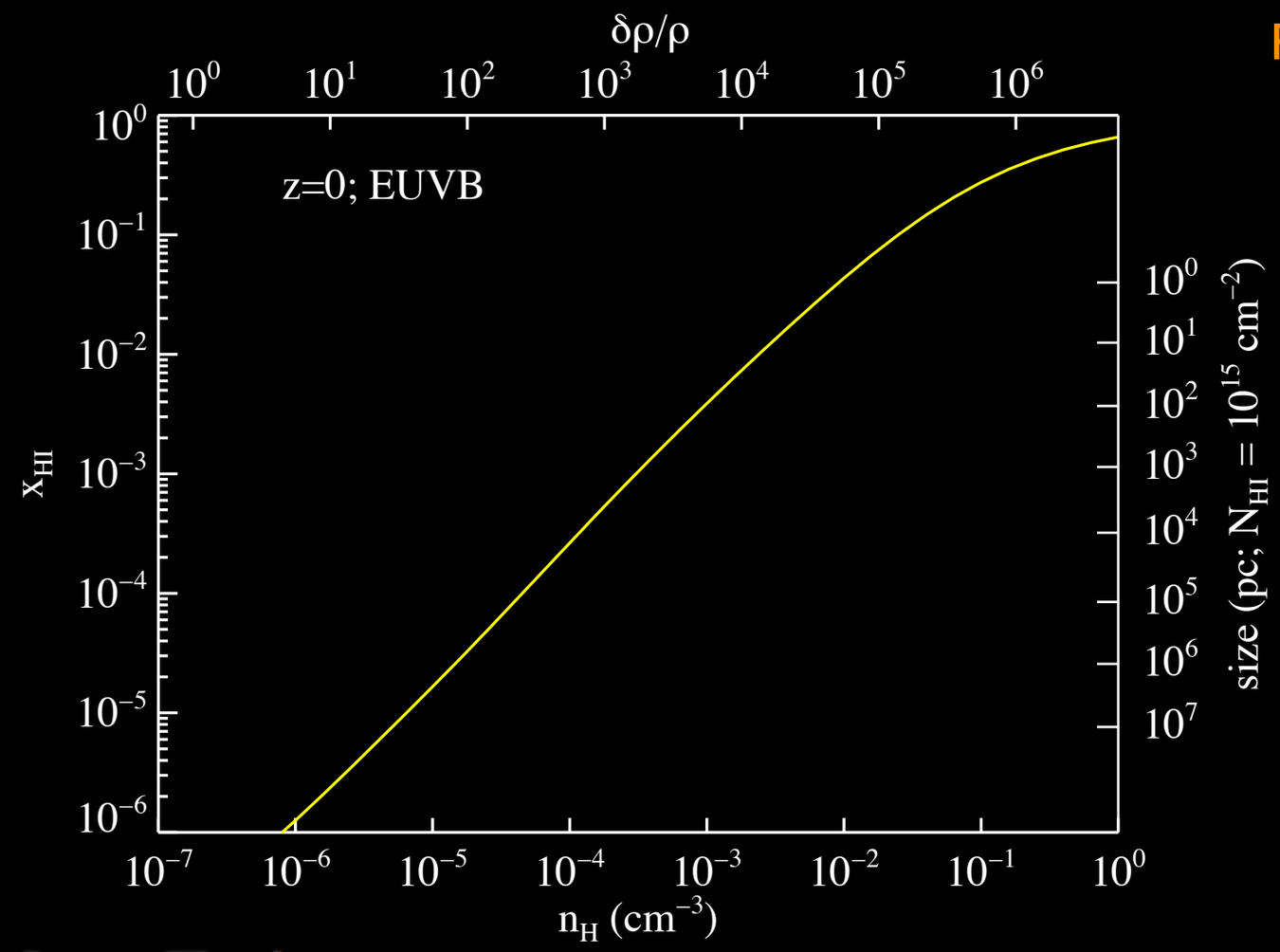

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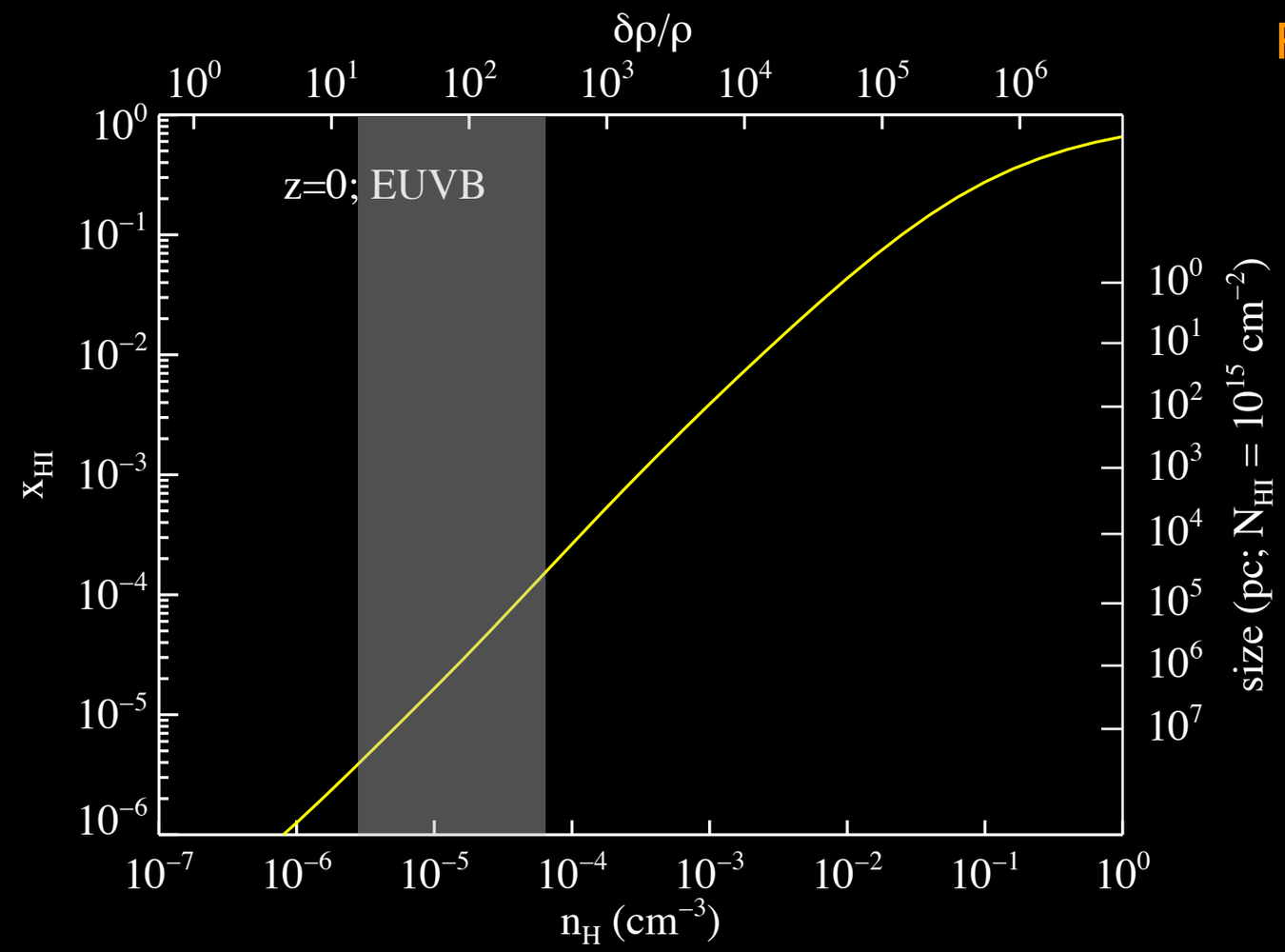

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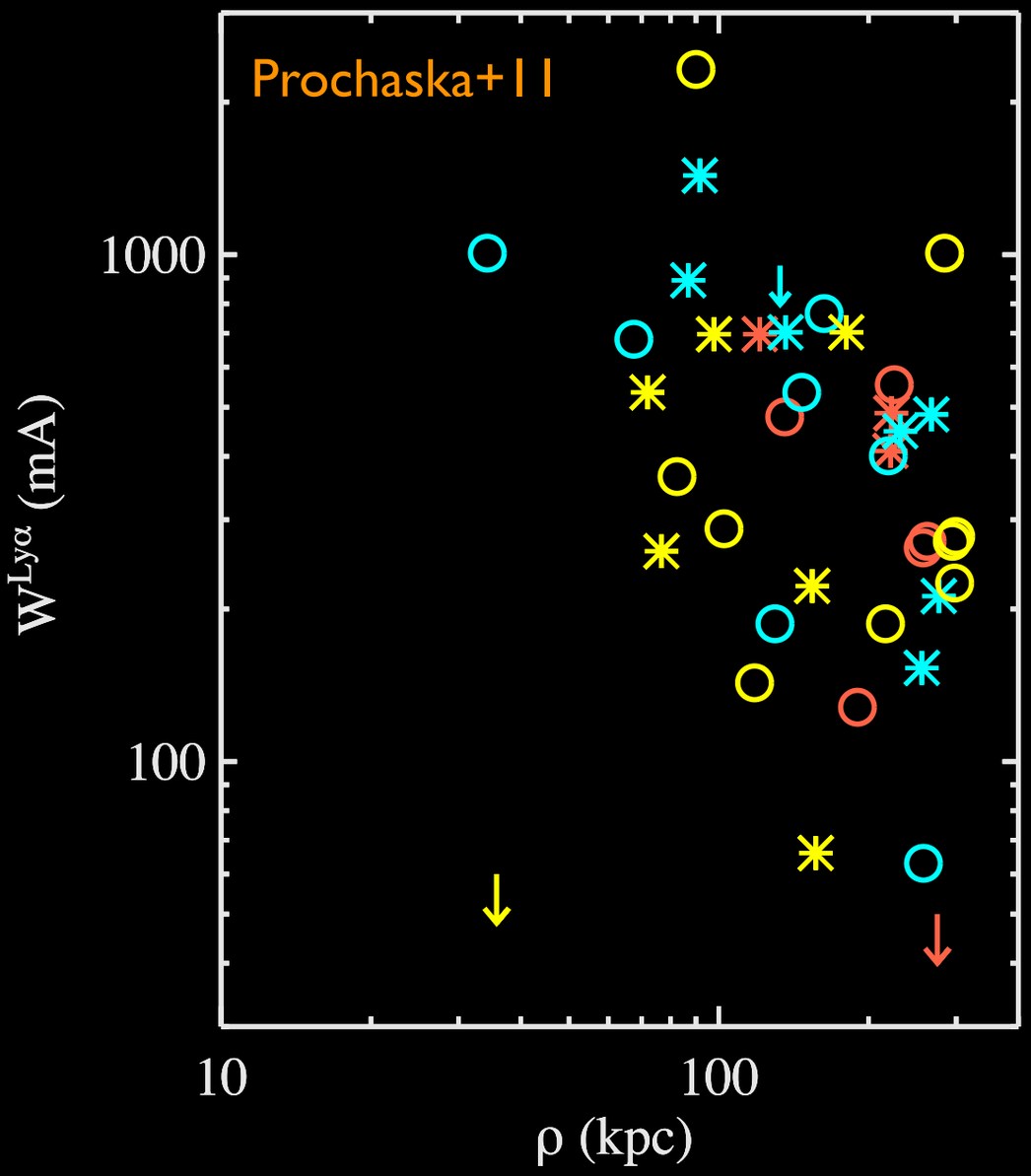
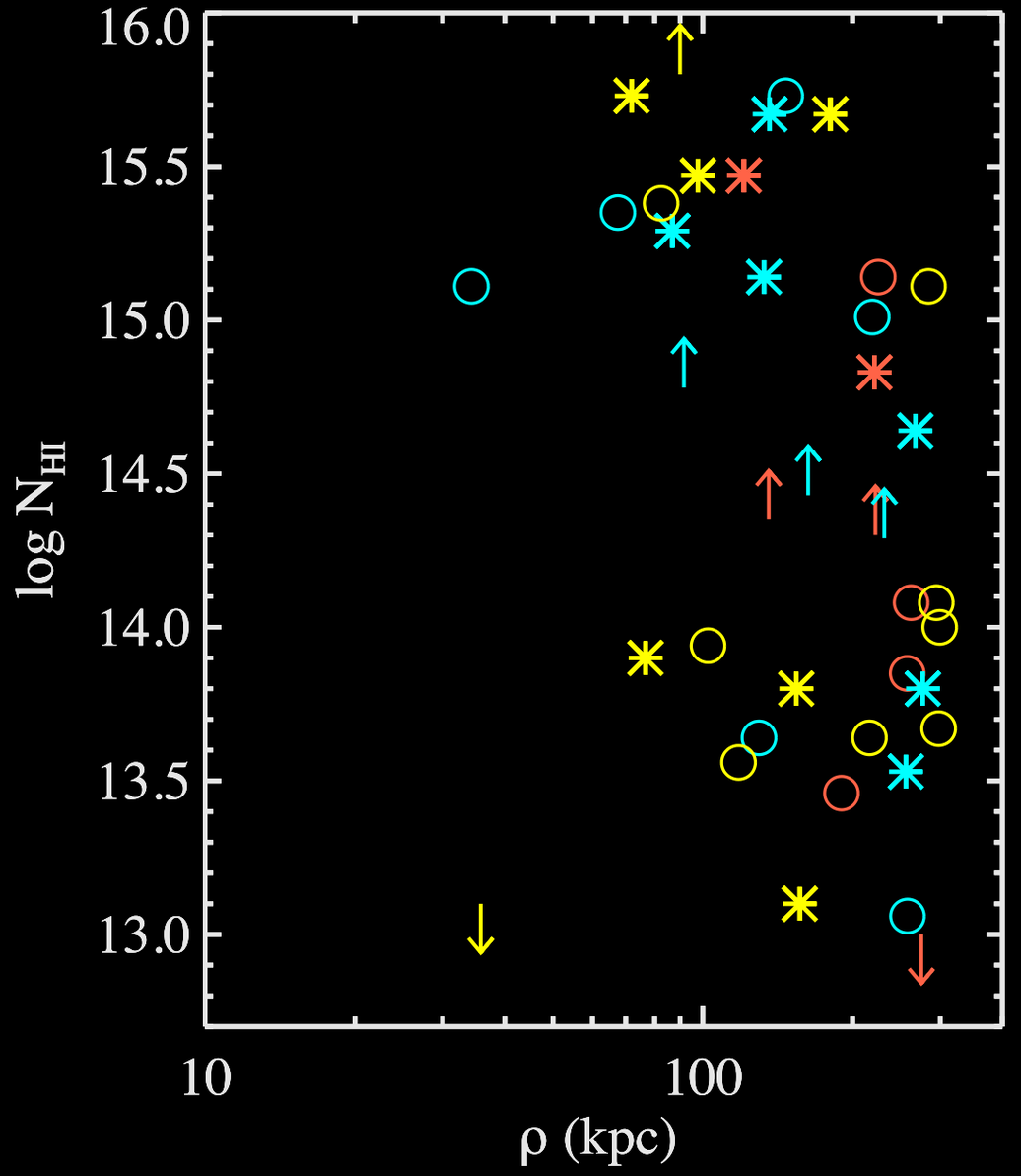
Is the "IGM" just CGM gas from galaxies?





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Statistical argument: $\ell(X) \sim n_c A_p$

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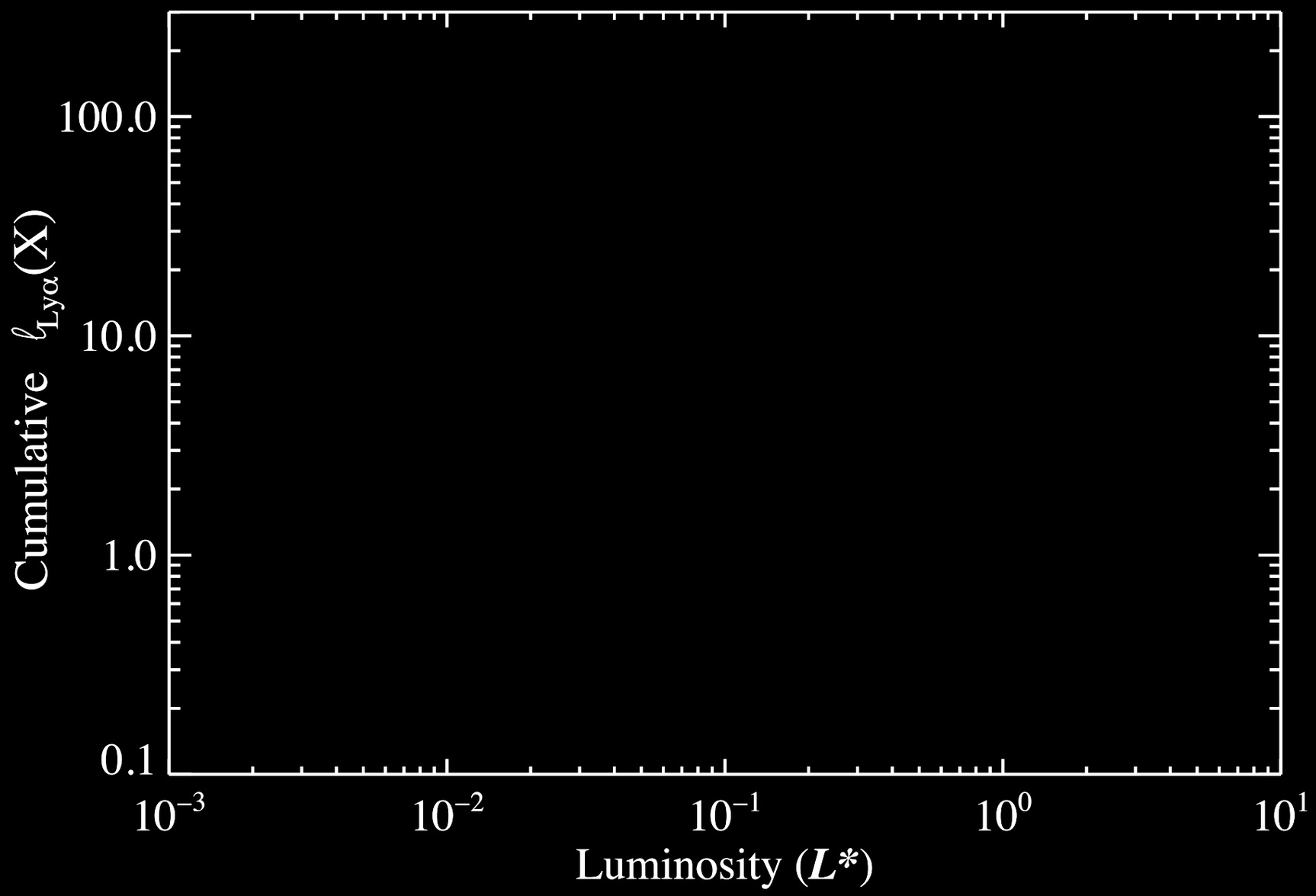

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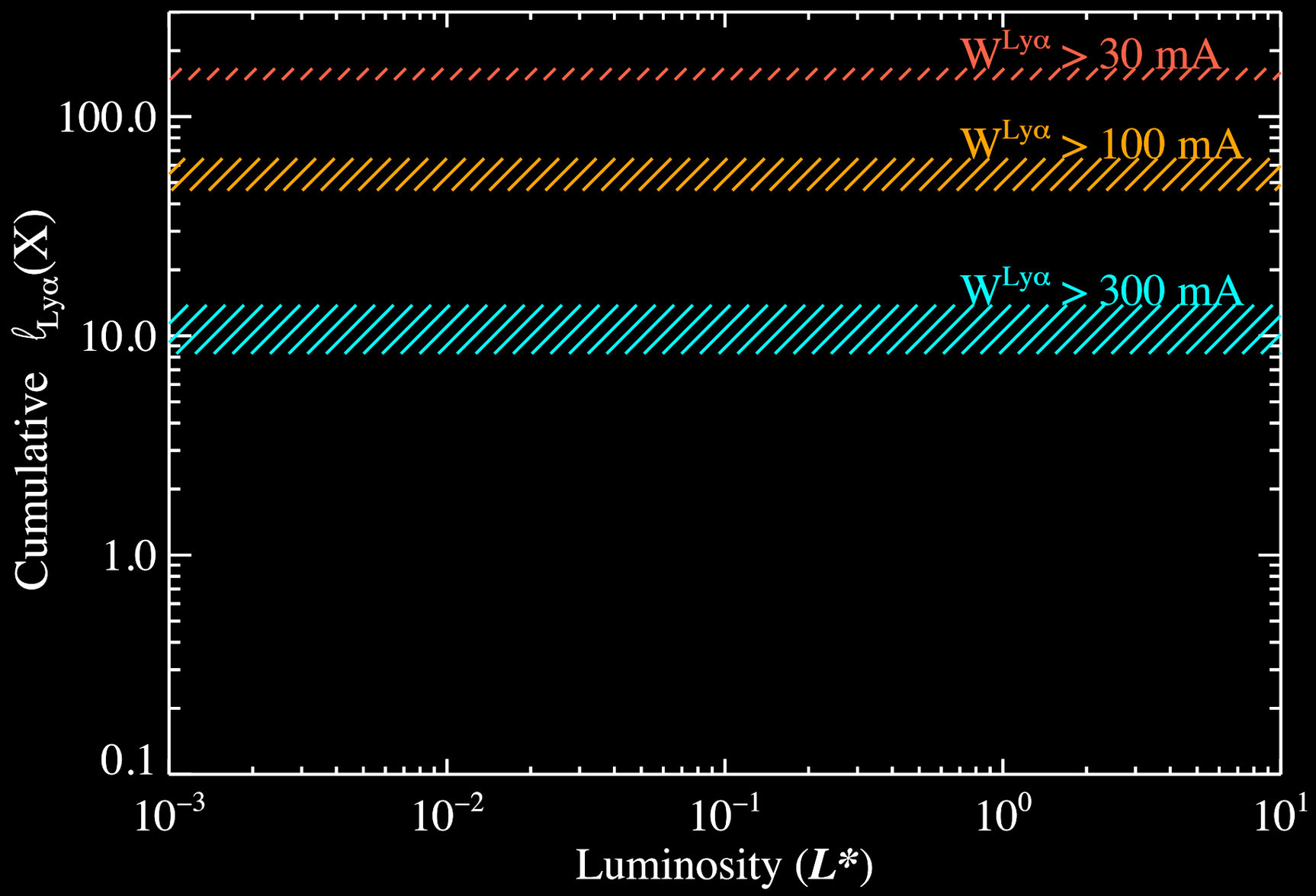

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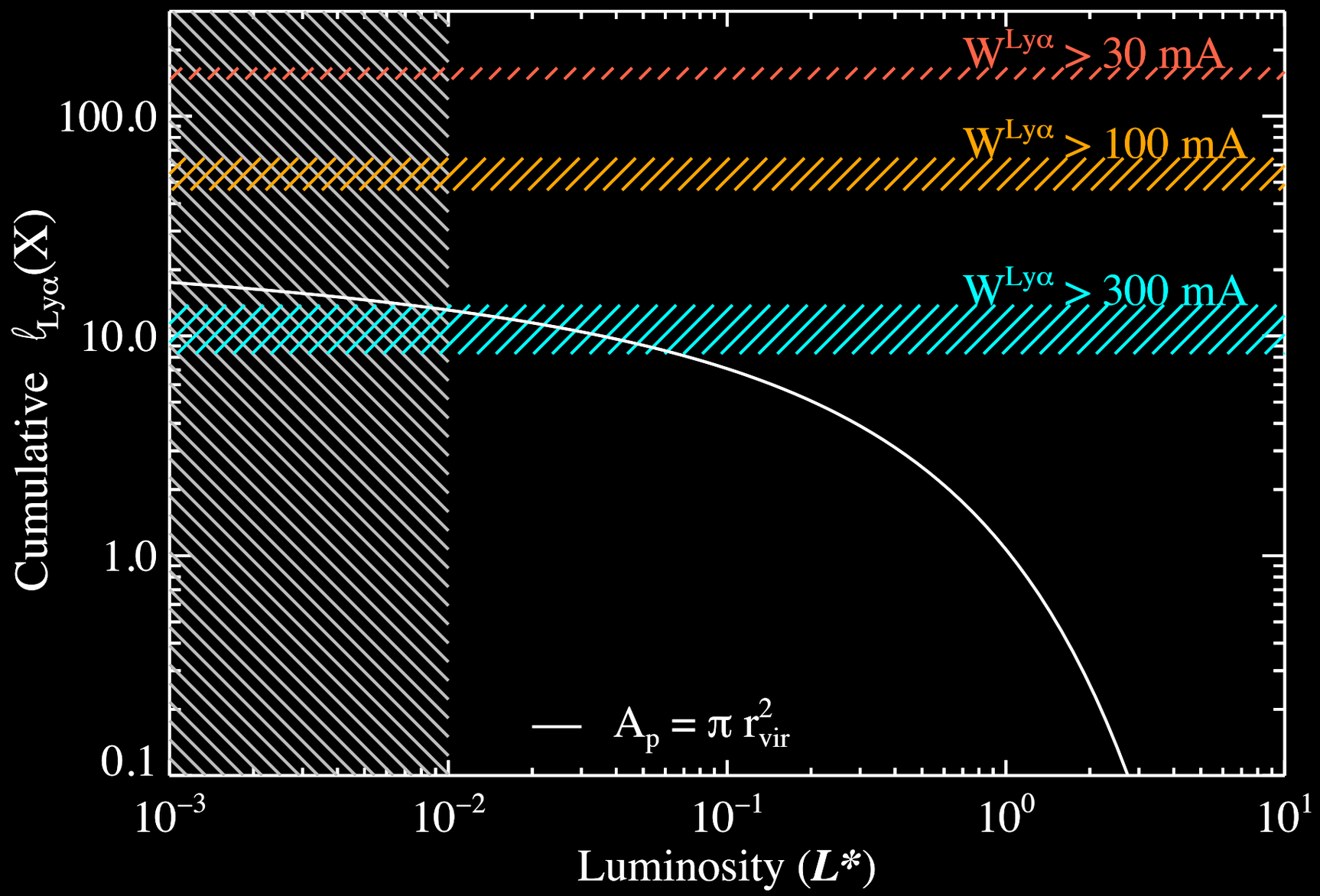

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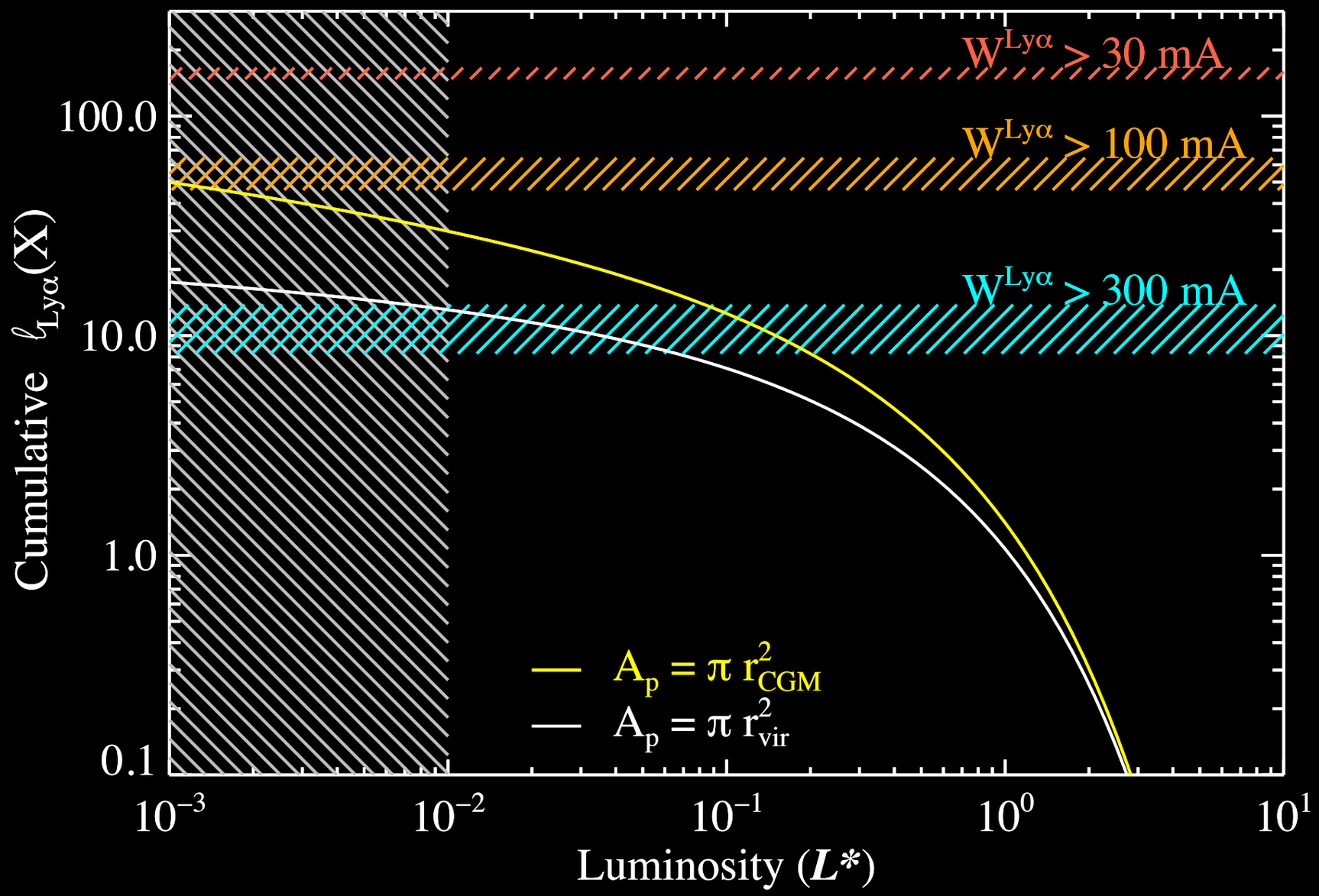
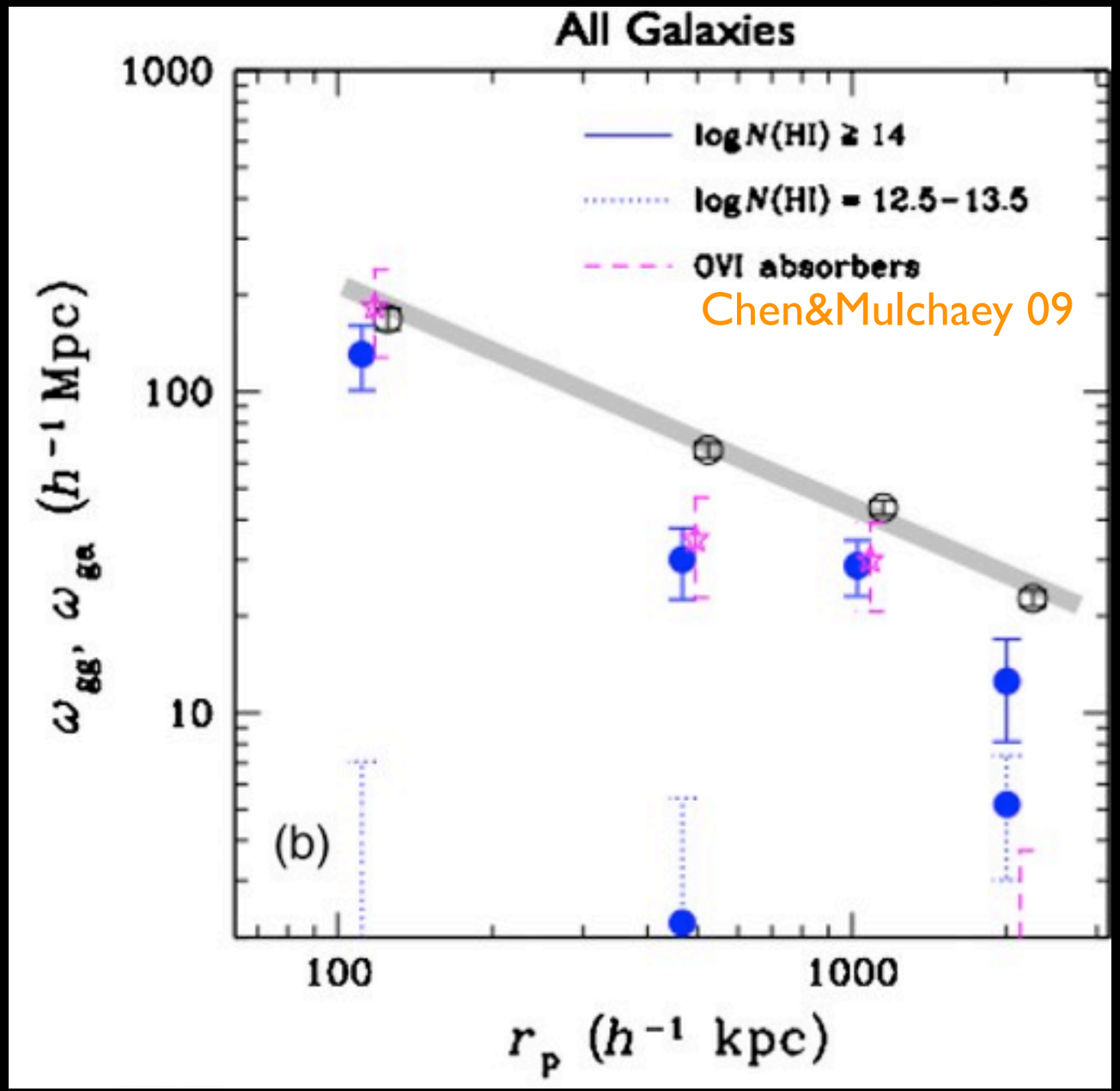


- Galaxies are simply too rare for low N_{HI} gas
  - Majority of IGM arises from gas at r>>300kpc from galaxies
- But, the CGM does explain all of the strong Lya systems

Is the IGM just CGM gas from galaxies?

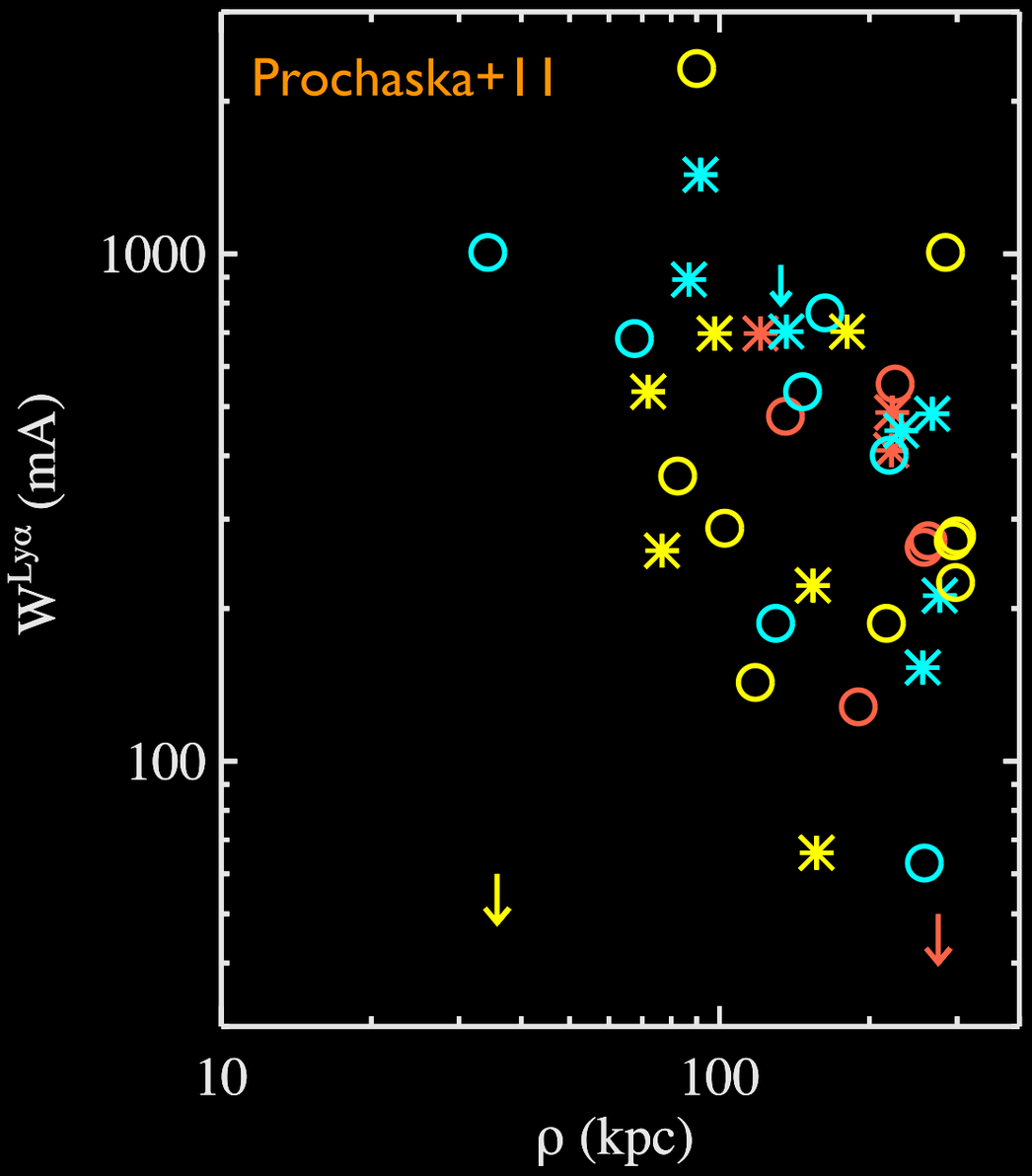
Statistical argument: ξ(r)

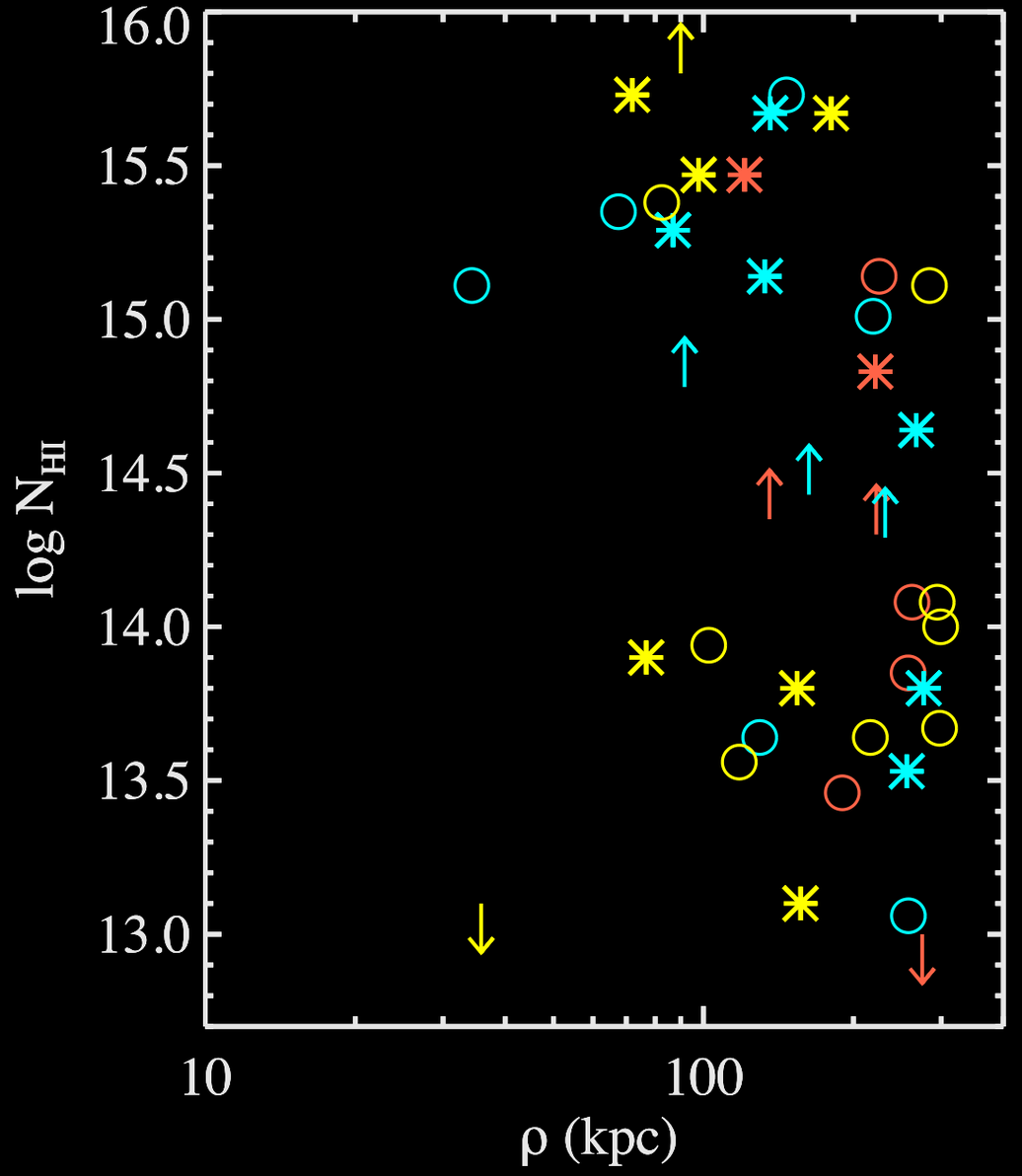


See also:
Chen+05
Wilman+07
Shone+10
Borthakur+1X
Tejos+1X

- Galaxies only cluster with strong Lya lines
  - $N_{HI} > 10^{14}$ cm^{-2}
    - ✦ Weak lines are the IGM

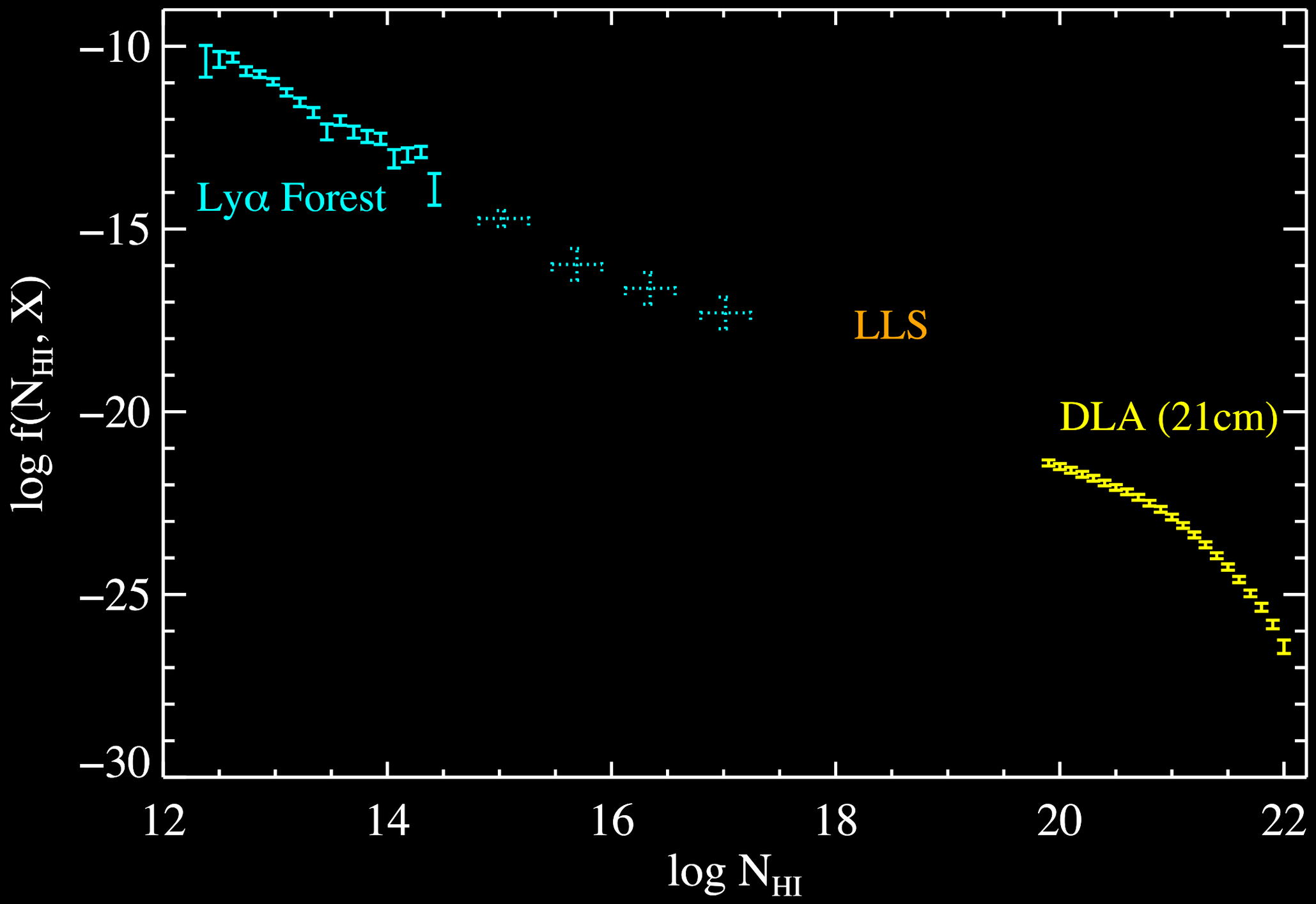
Is the "IGM" just CGM gas from galaxies?





No! But the majority of strong Lya lines certainly are.

The IGM/Galaxy Connection (at z~0)



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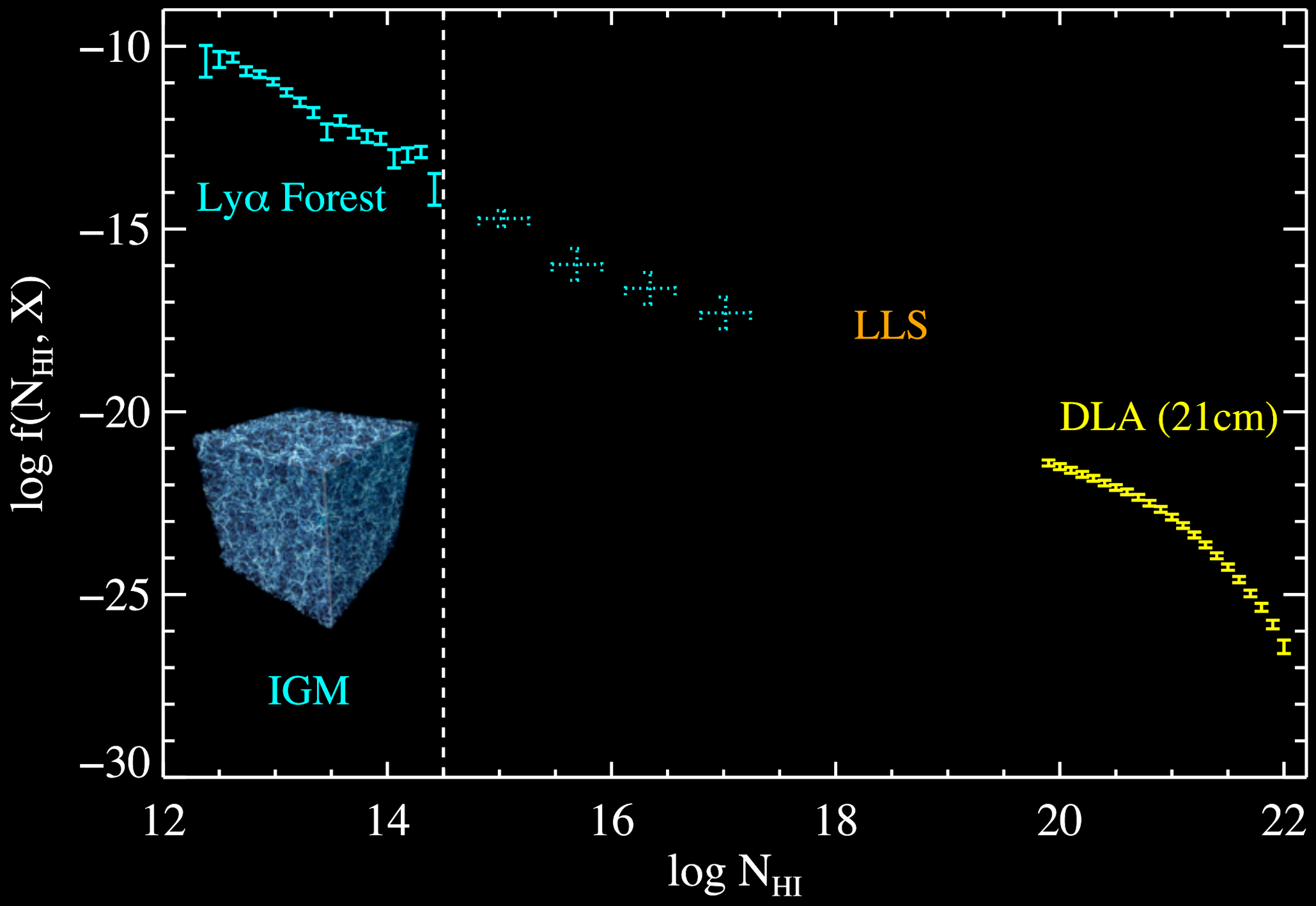

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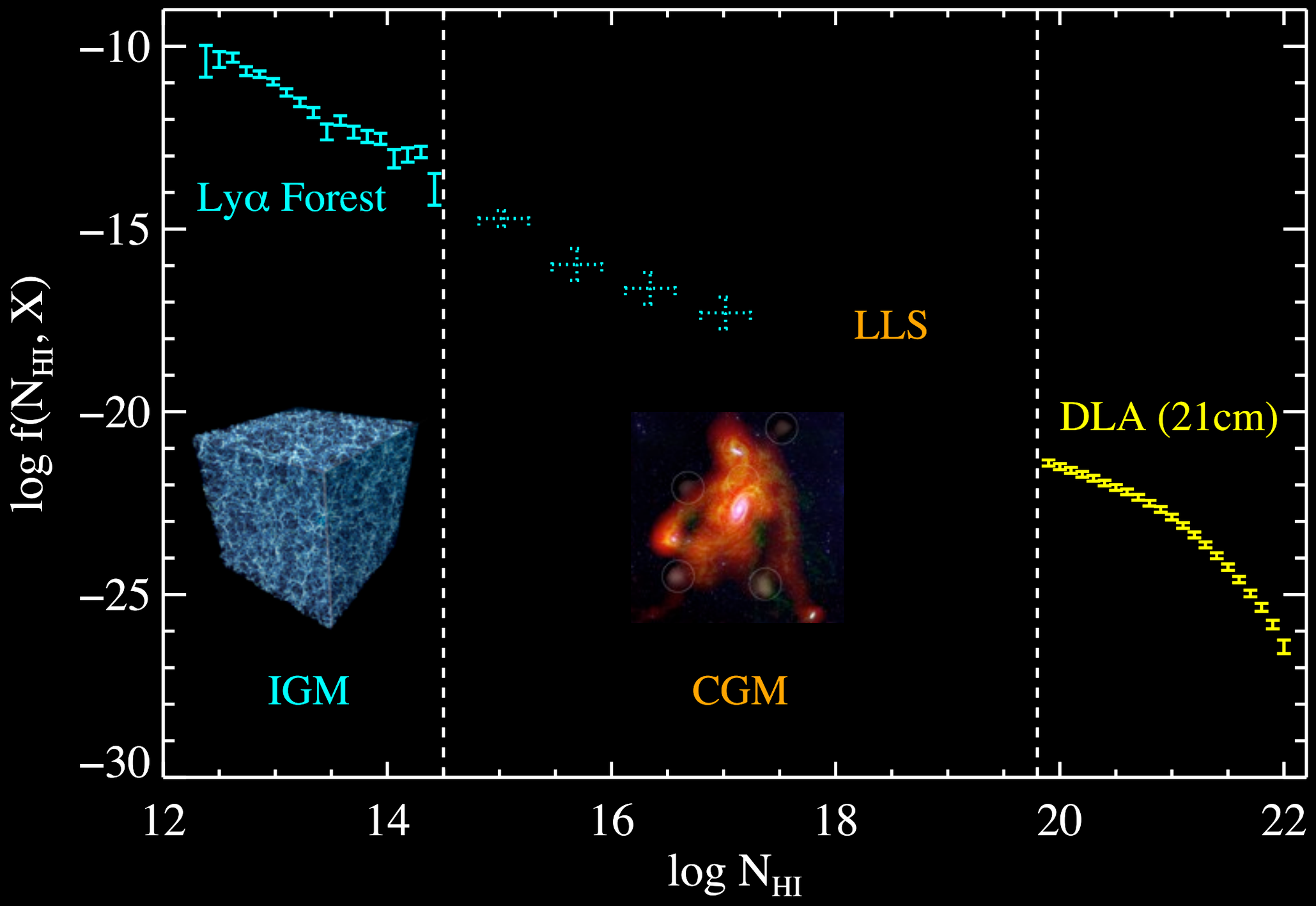

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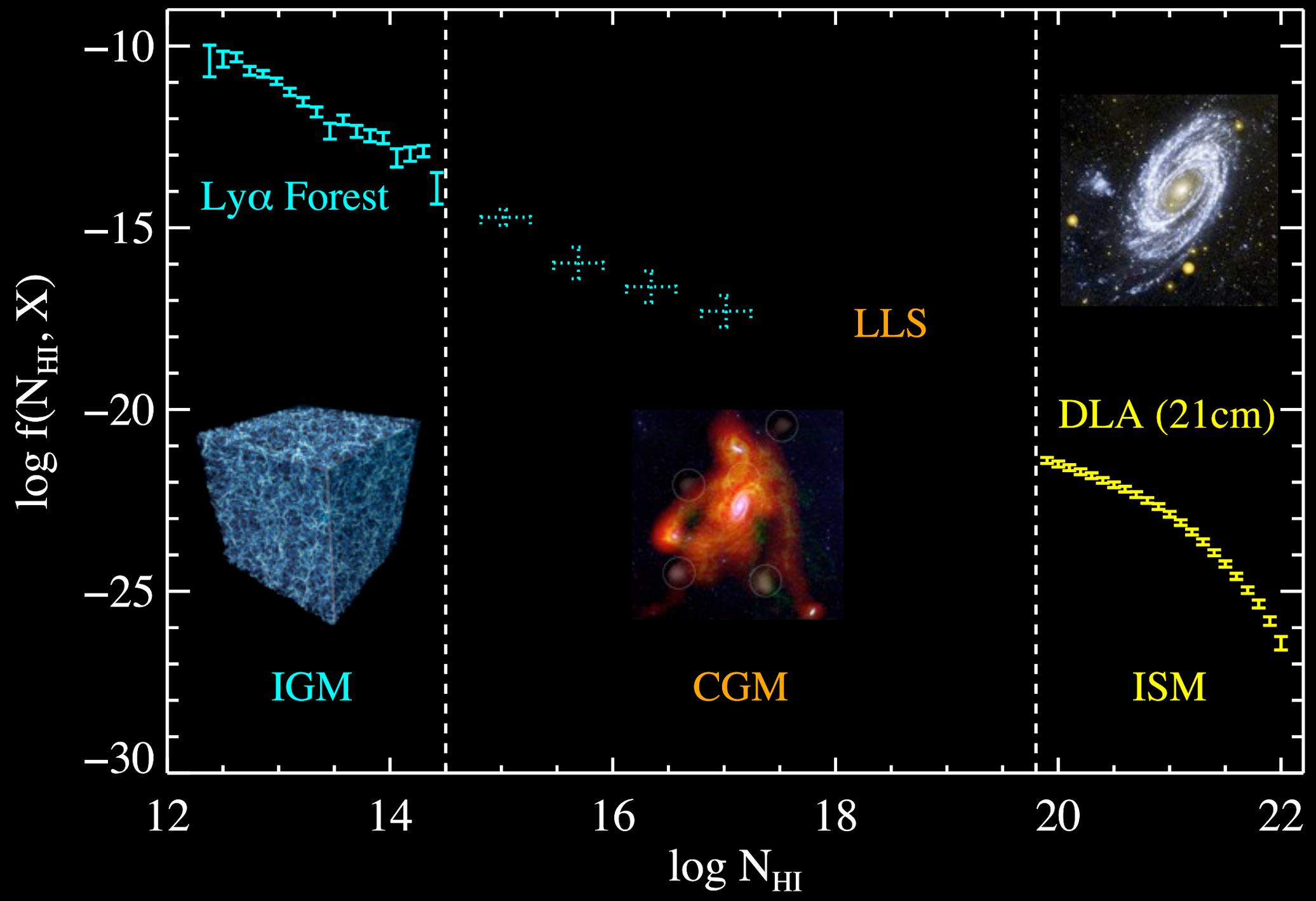

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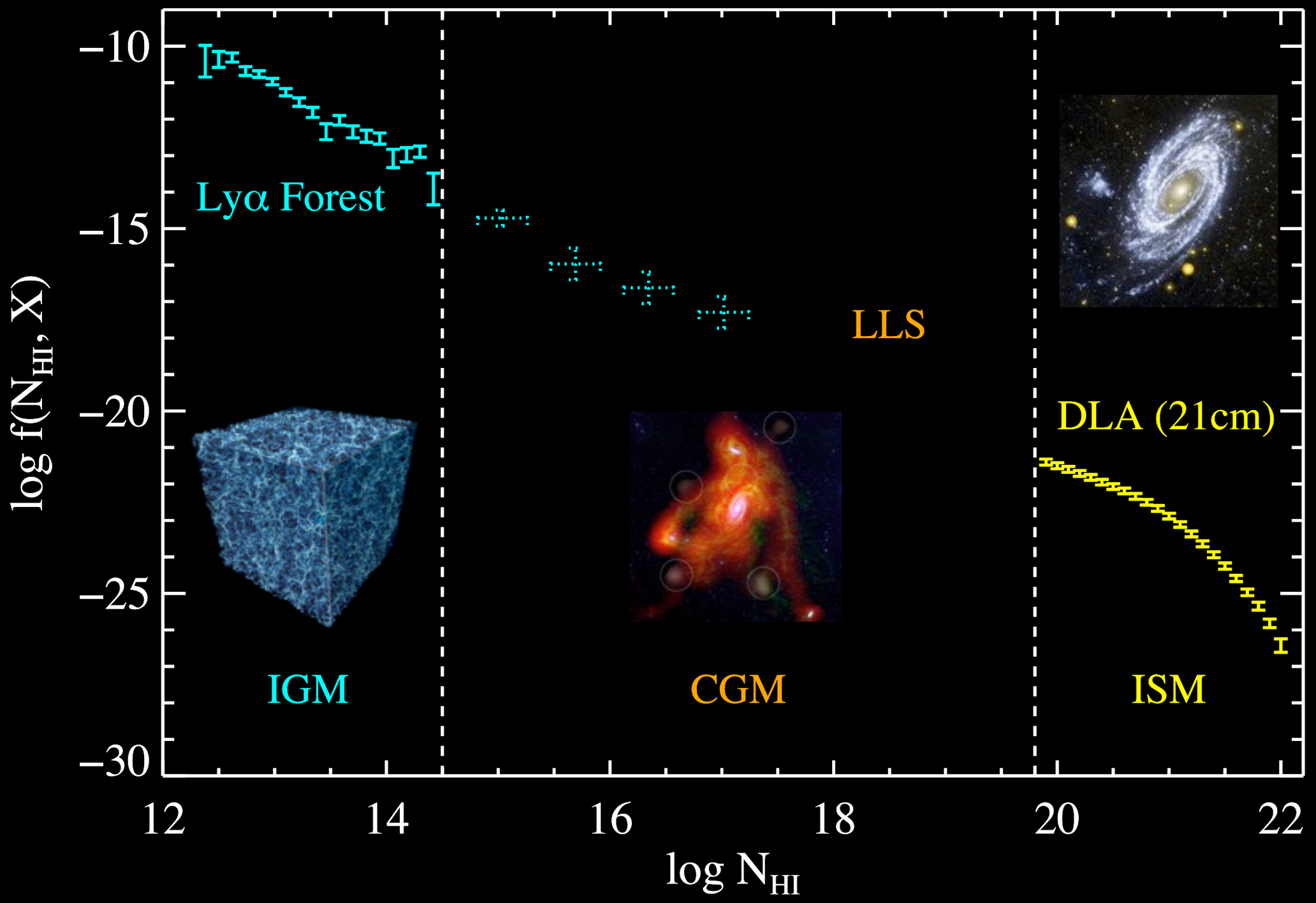
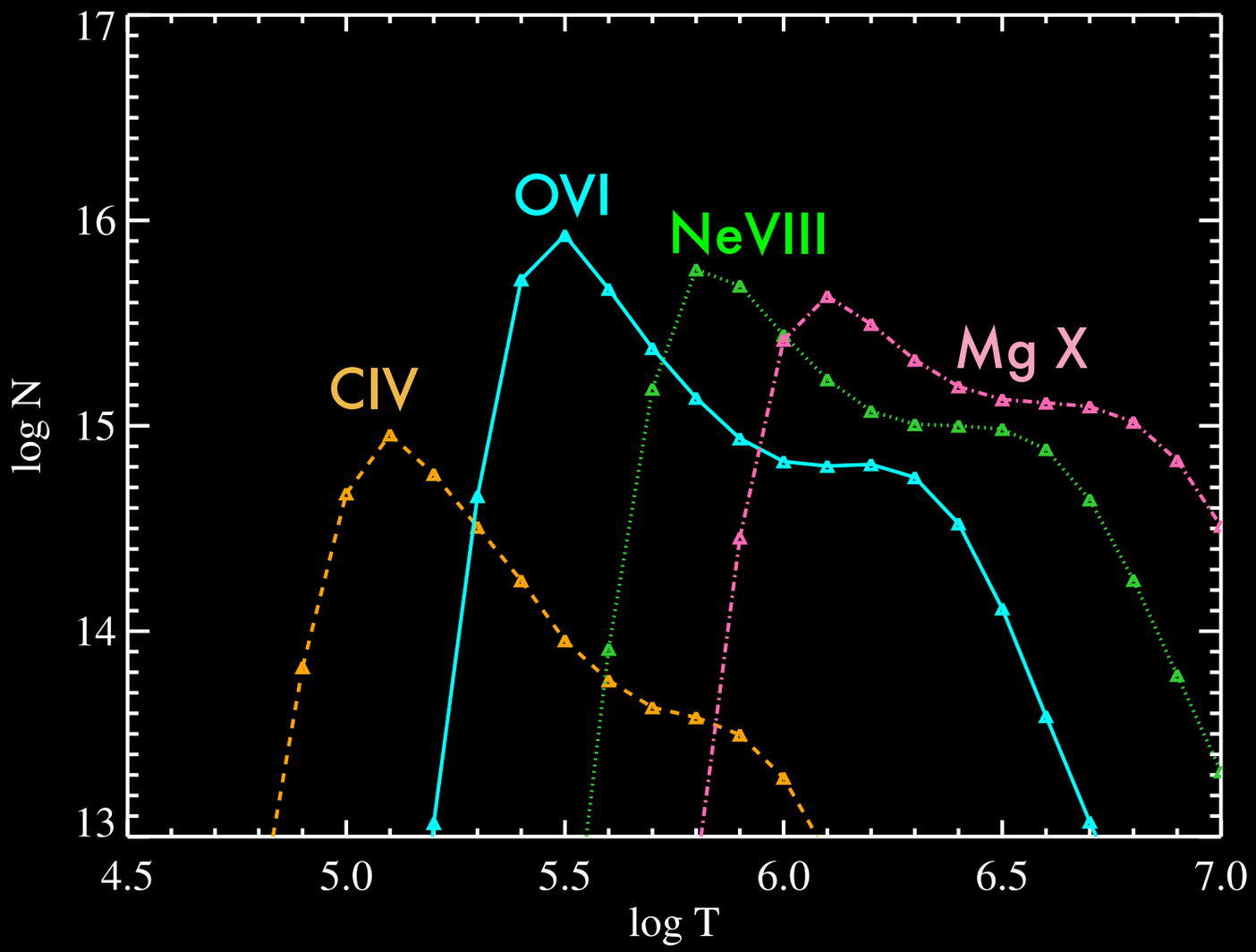


What about metals? How does this picture evolve at high z? And what about outflows?!

‘IGM’ Metals: O VI



O VI has also been widely used to count hot gas (WHIM) or “missing baryons”, so general IGM samples are well characterized.

Tripp+08, Thom+Chen08, Danforth+Shull08

Advantages:

- highest T probe available in FUV
- strong doublet, easily detected
- Most common metal system
- IGM samples for comparison
- peak ionization fraction at T = 300,000K, still significant at 10^6 K
- *catches gas heating and/or cooling through coronal regime.*

Disadvantages:

- must be redshifted to detect w/ HST (mirror absorbs at < 1150A)
- peak abundance lies where rad cooling is efficient, so there are significant non-equilibrium issues

See: H.-W. Chen for MgII, CIV

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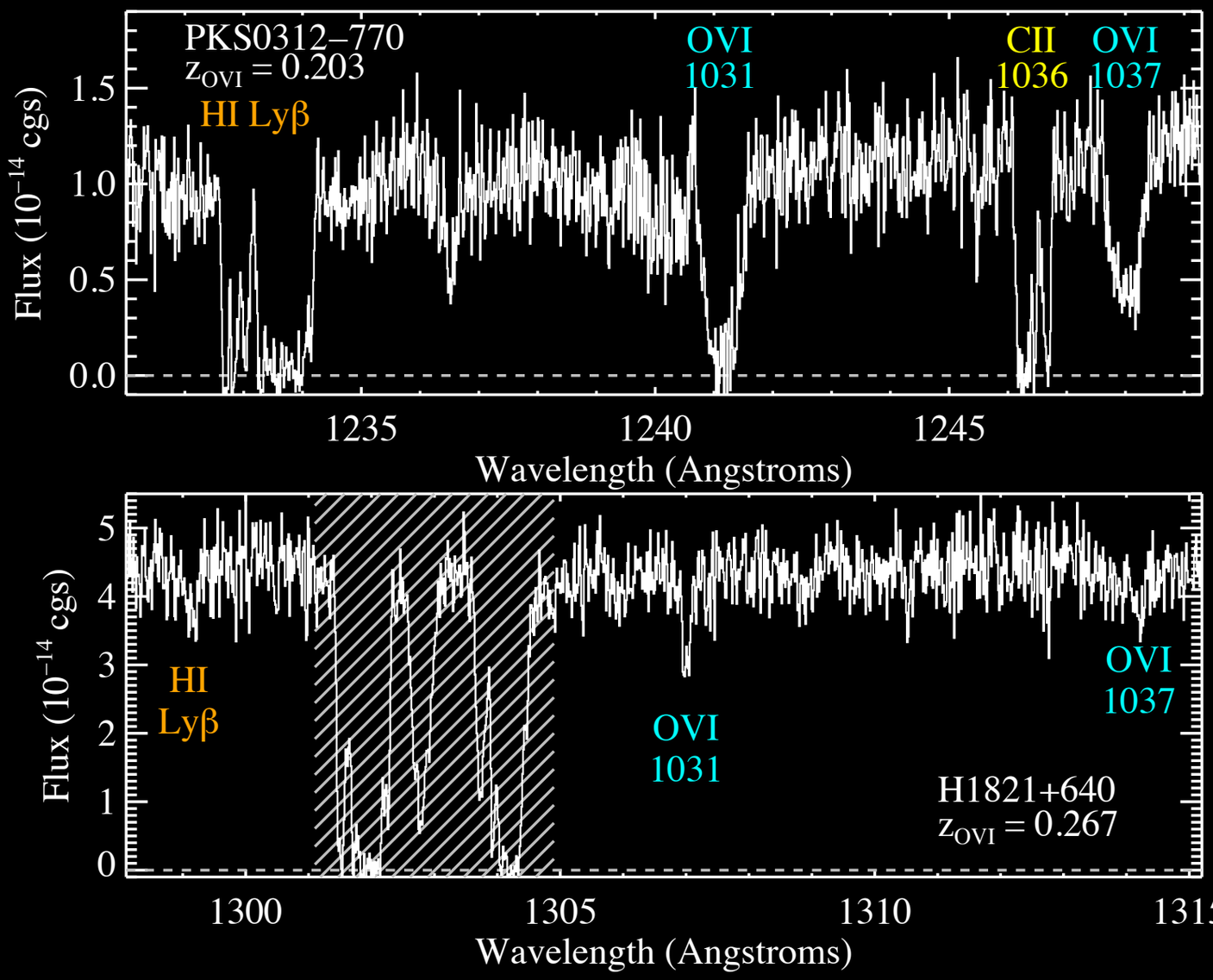

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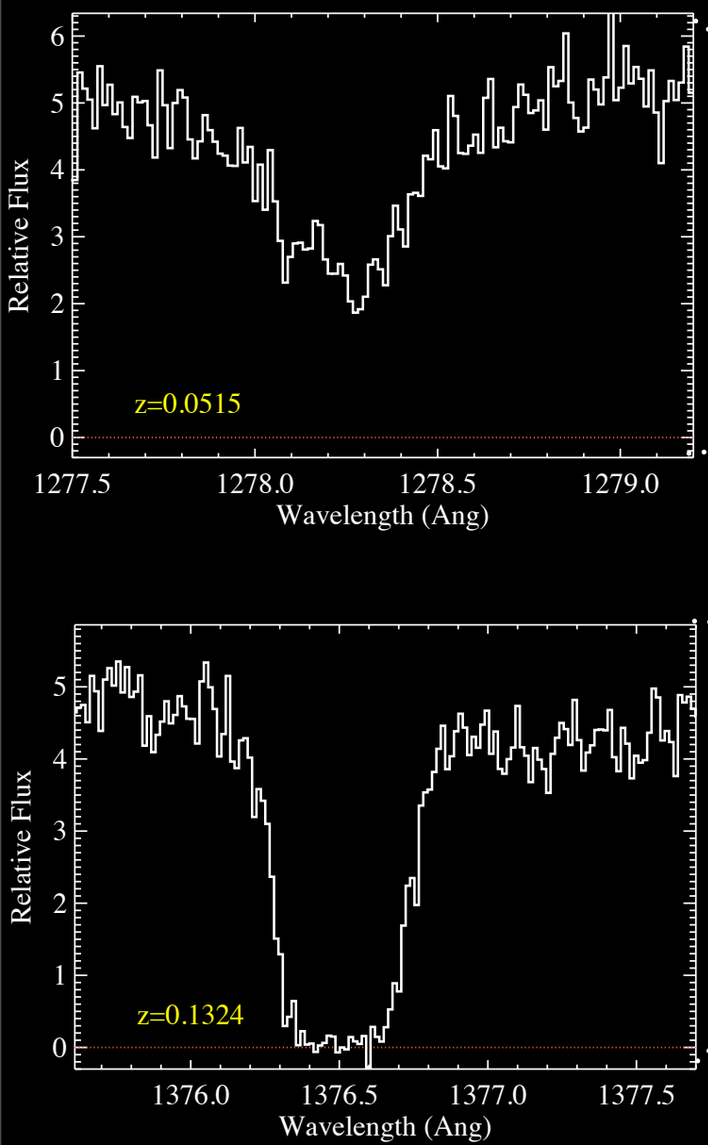
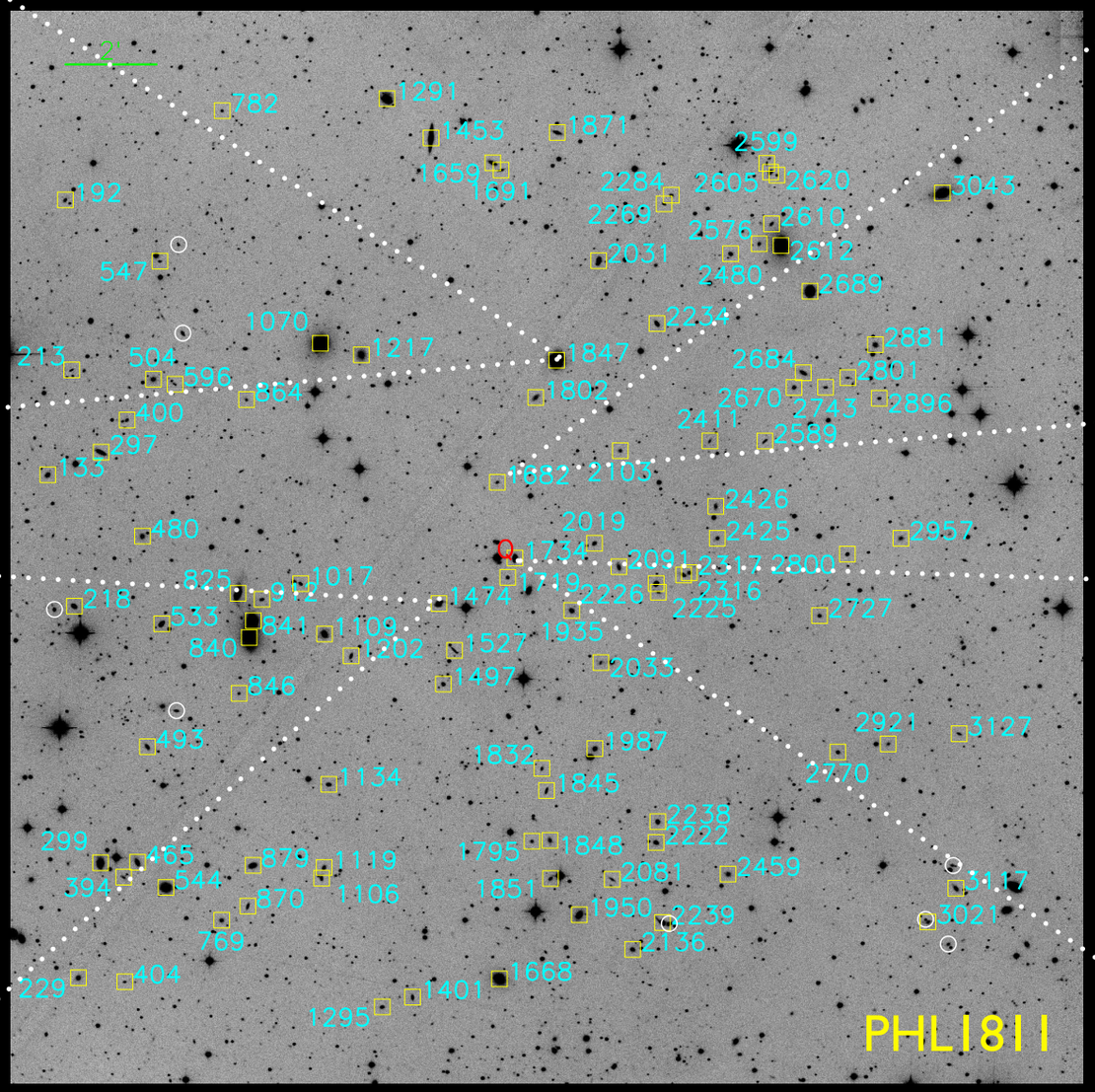
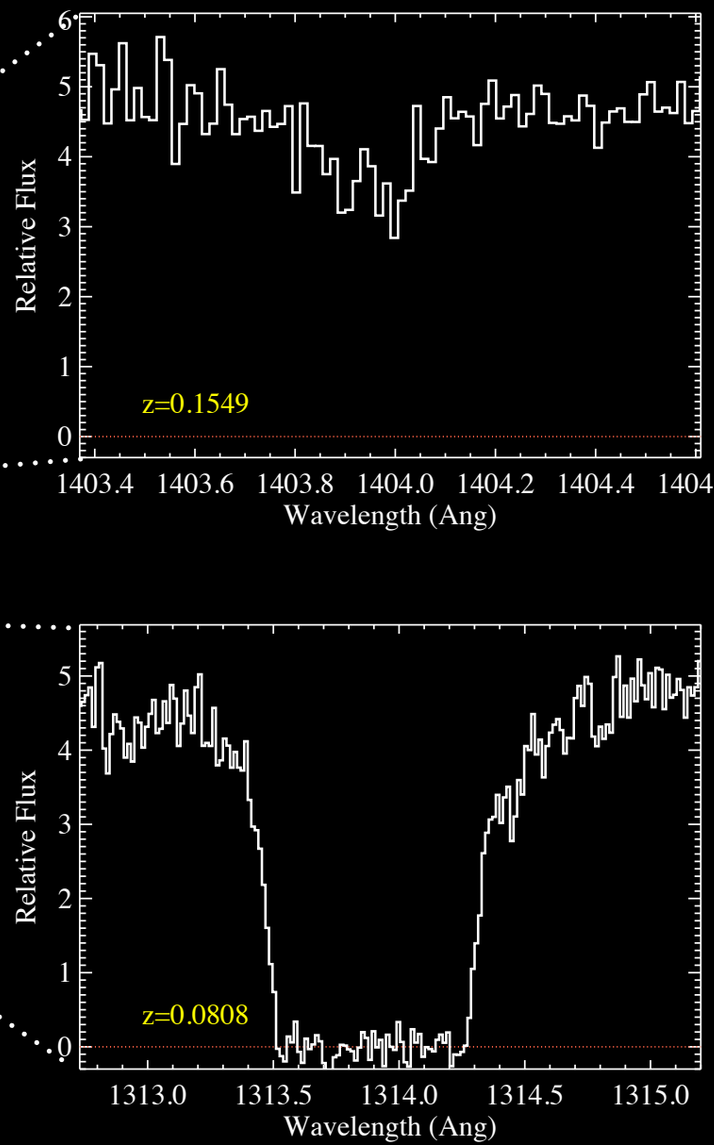
Experiment: Probe Galactic Halos (CGM)

The LCO/WFCCD IGM/Galaxy Survey

Prochaska, Weiner, Chen, Mulchaey, Cooksey 2011







- LCO/WFCCD Survey :: Probing the IGM/Galaxy Connection
  - Magnitude limited (R ~ 19.5) survey for galaxies in UV-bright QSO fields
    - Low-resolution spectra useful for redshifts only
      - ➡ Stay tuned for SFR, metallicities, etc. (Gemini/GMOS via J. Werk)
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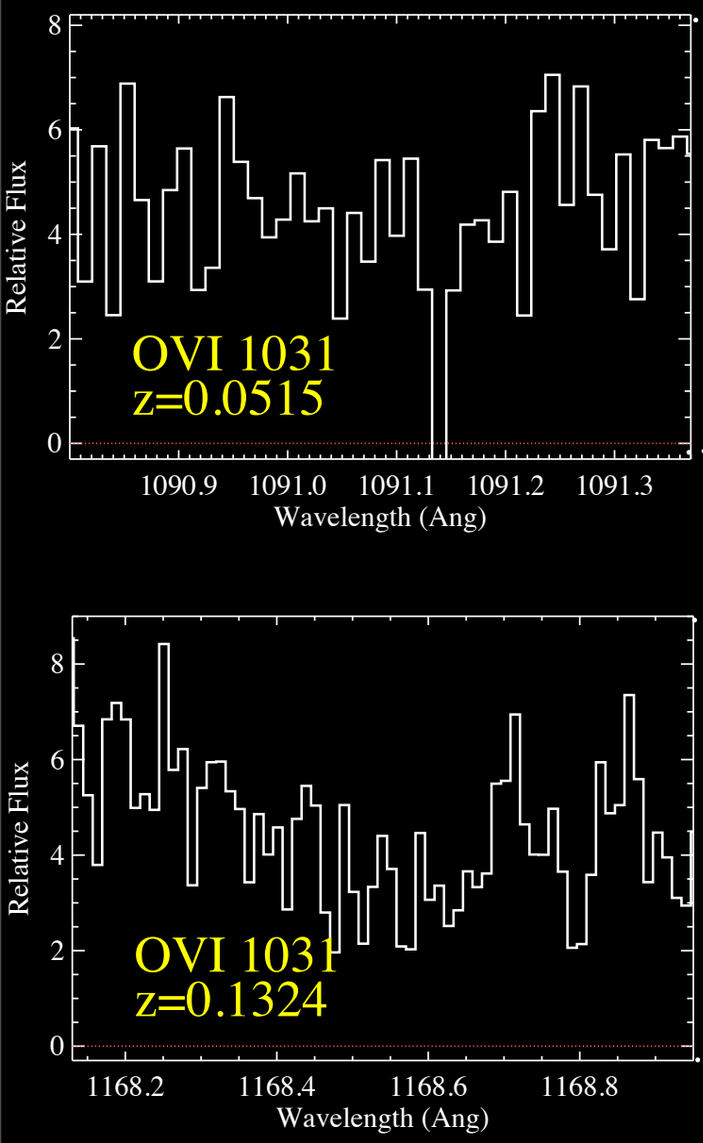

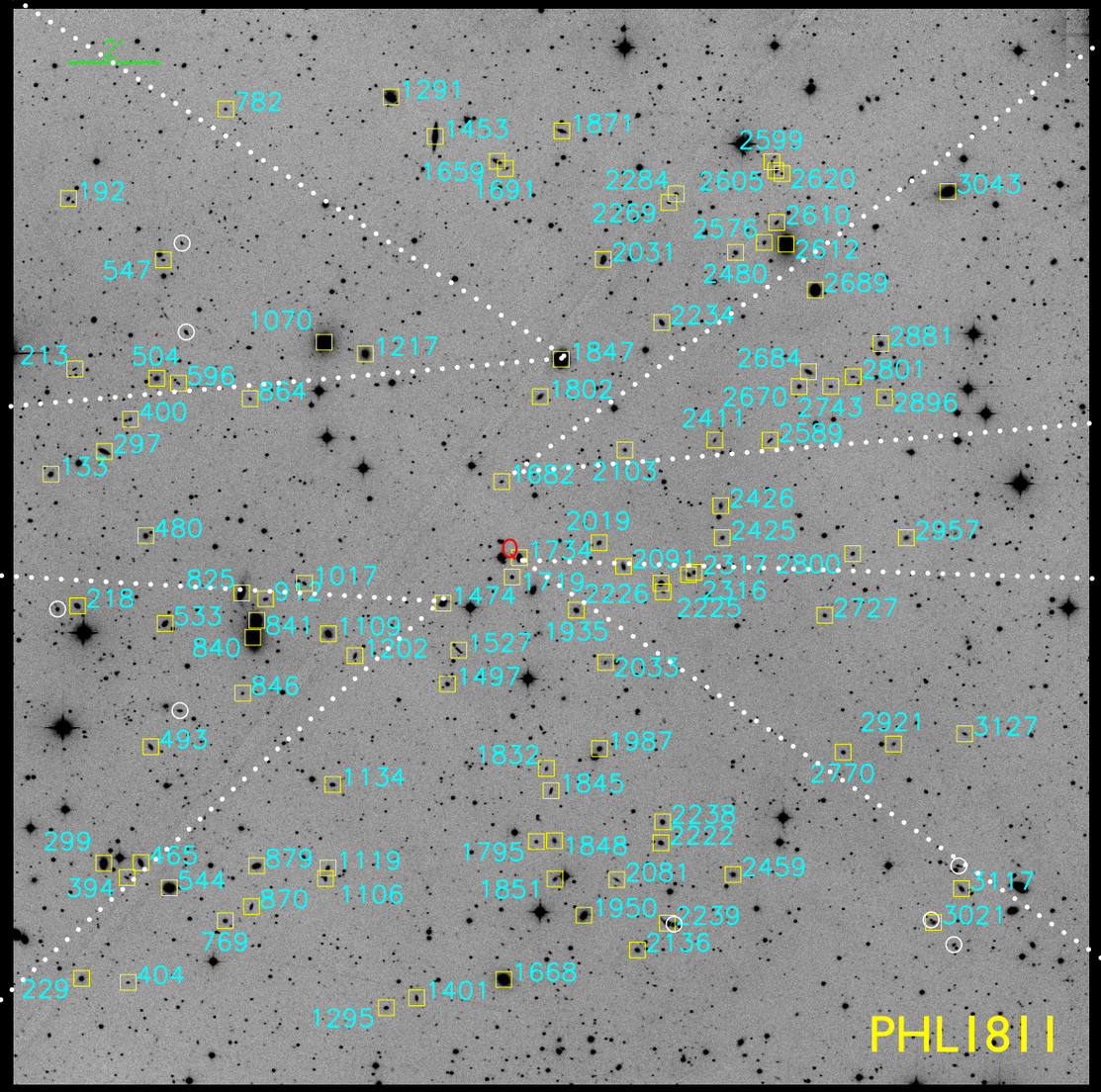

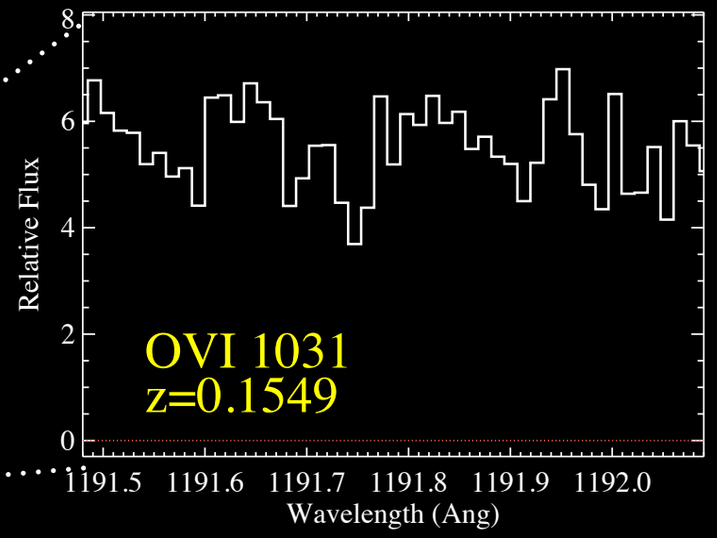

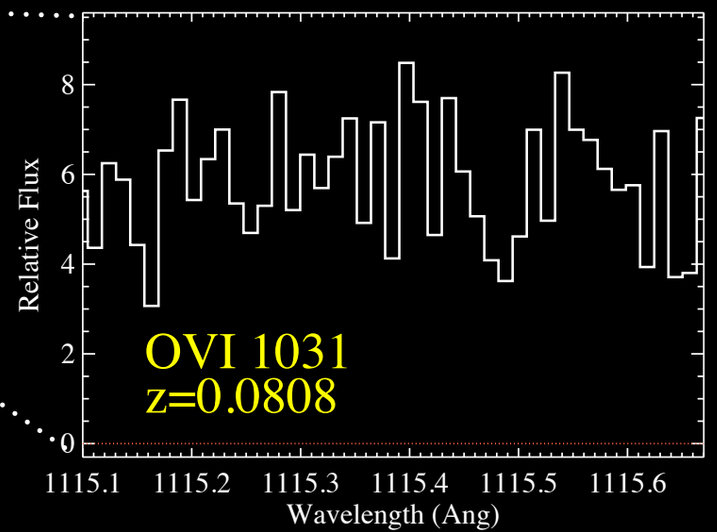

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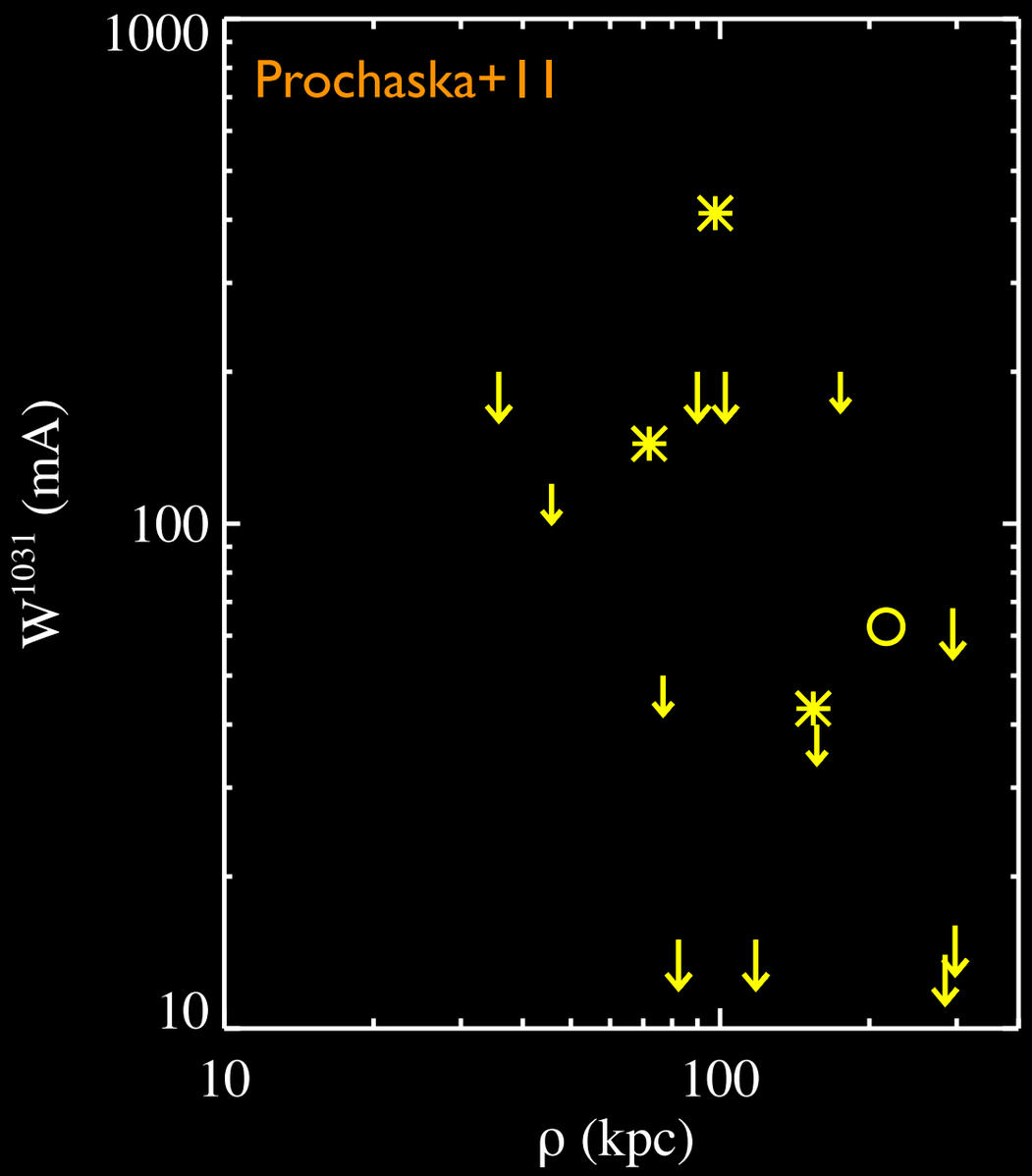
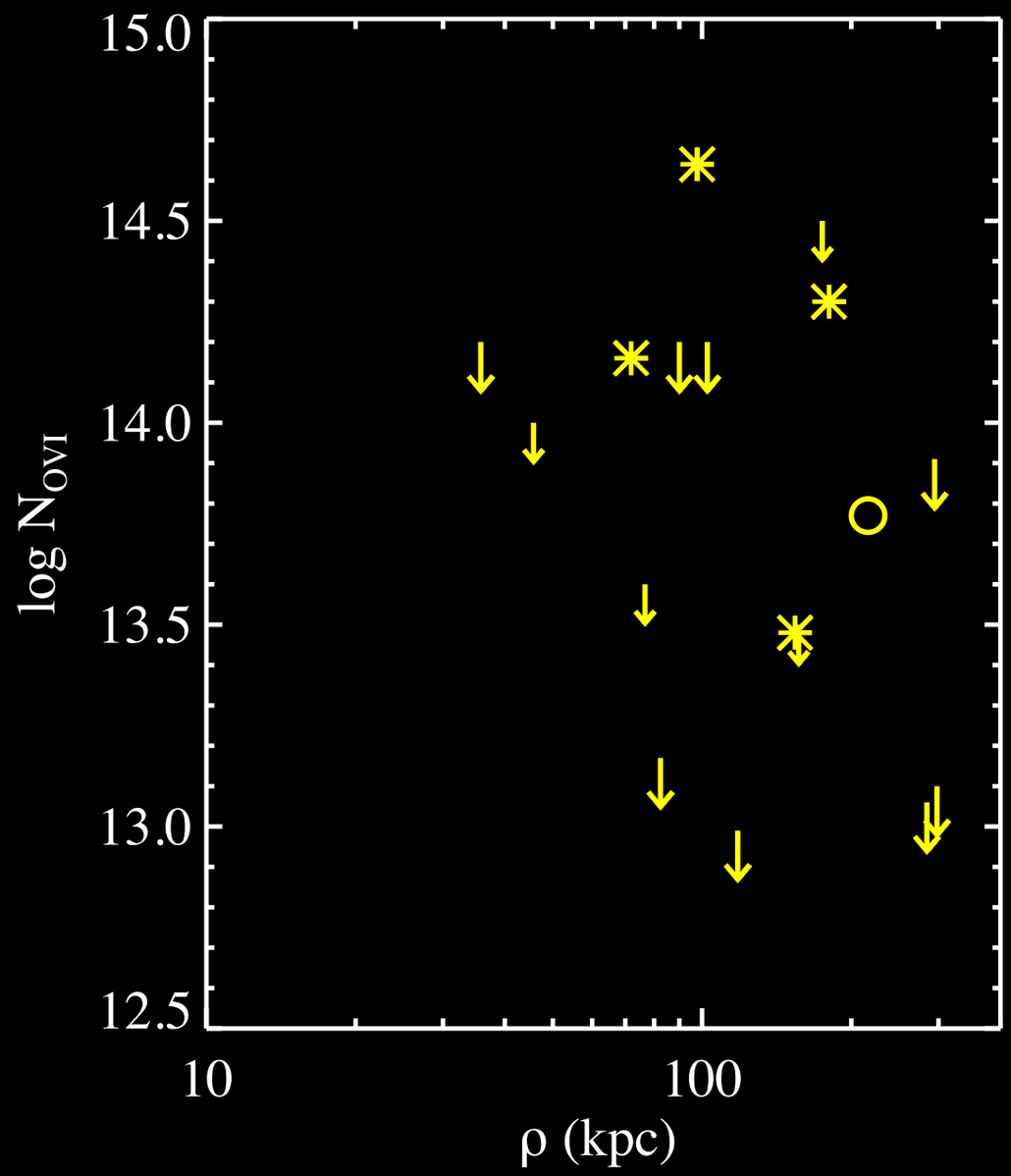
OVI Gas Surrounding z~0 Galaxies





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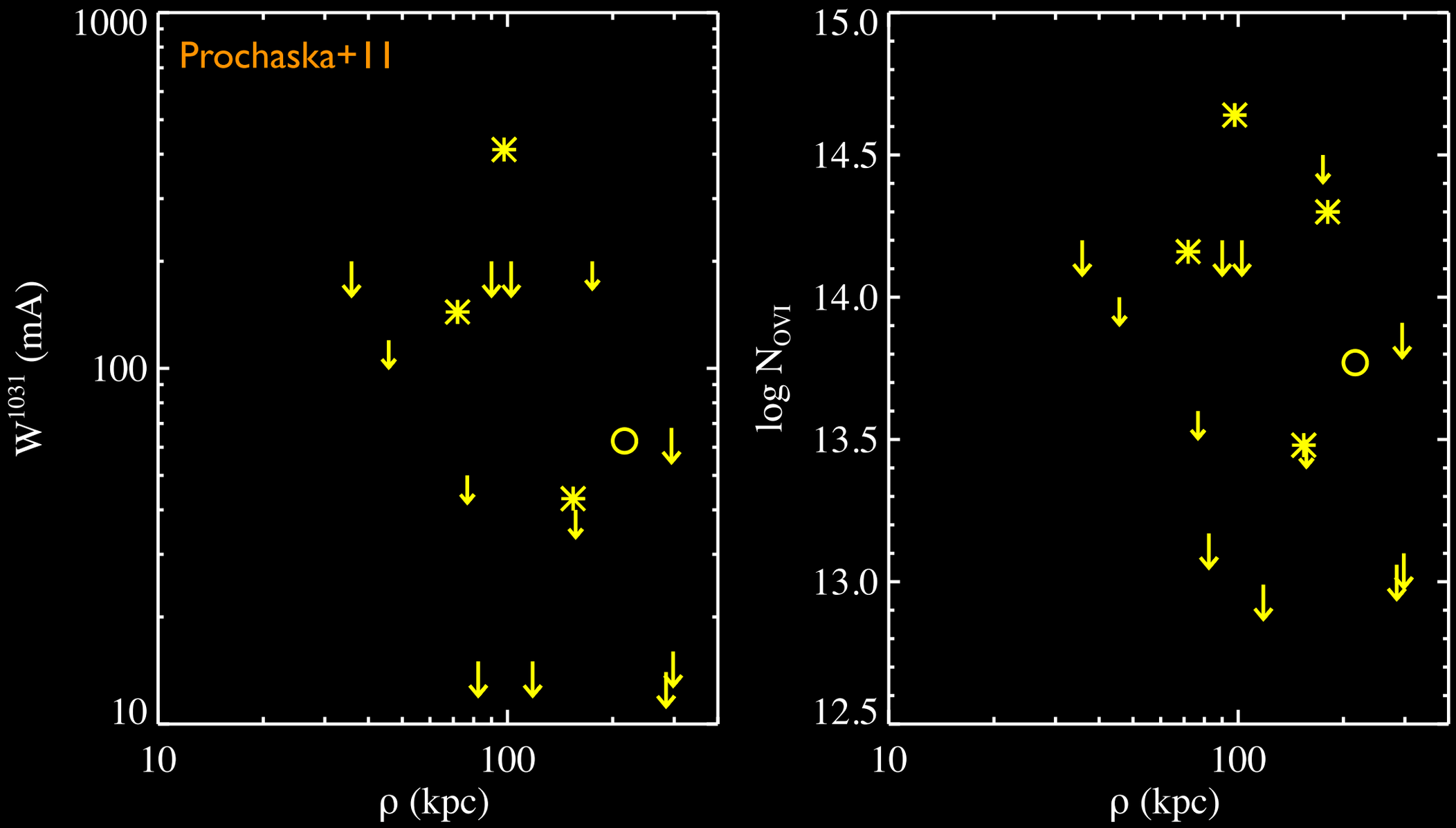

- Dwarf Galaxies (L < 0.1L*)
  - Many fewer positive detections of OVI than Lya

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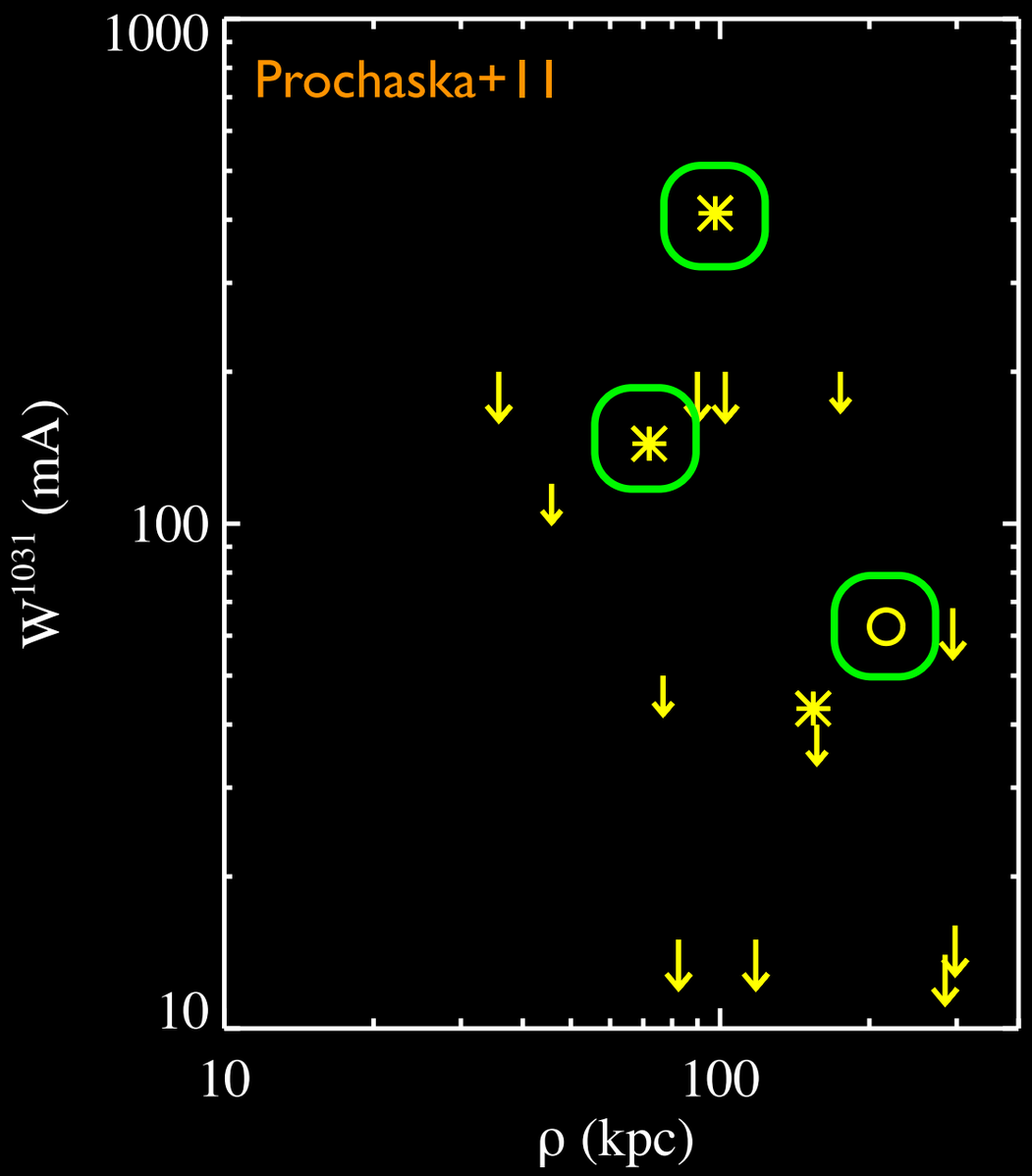

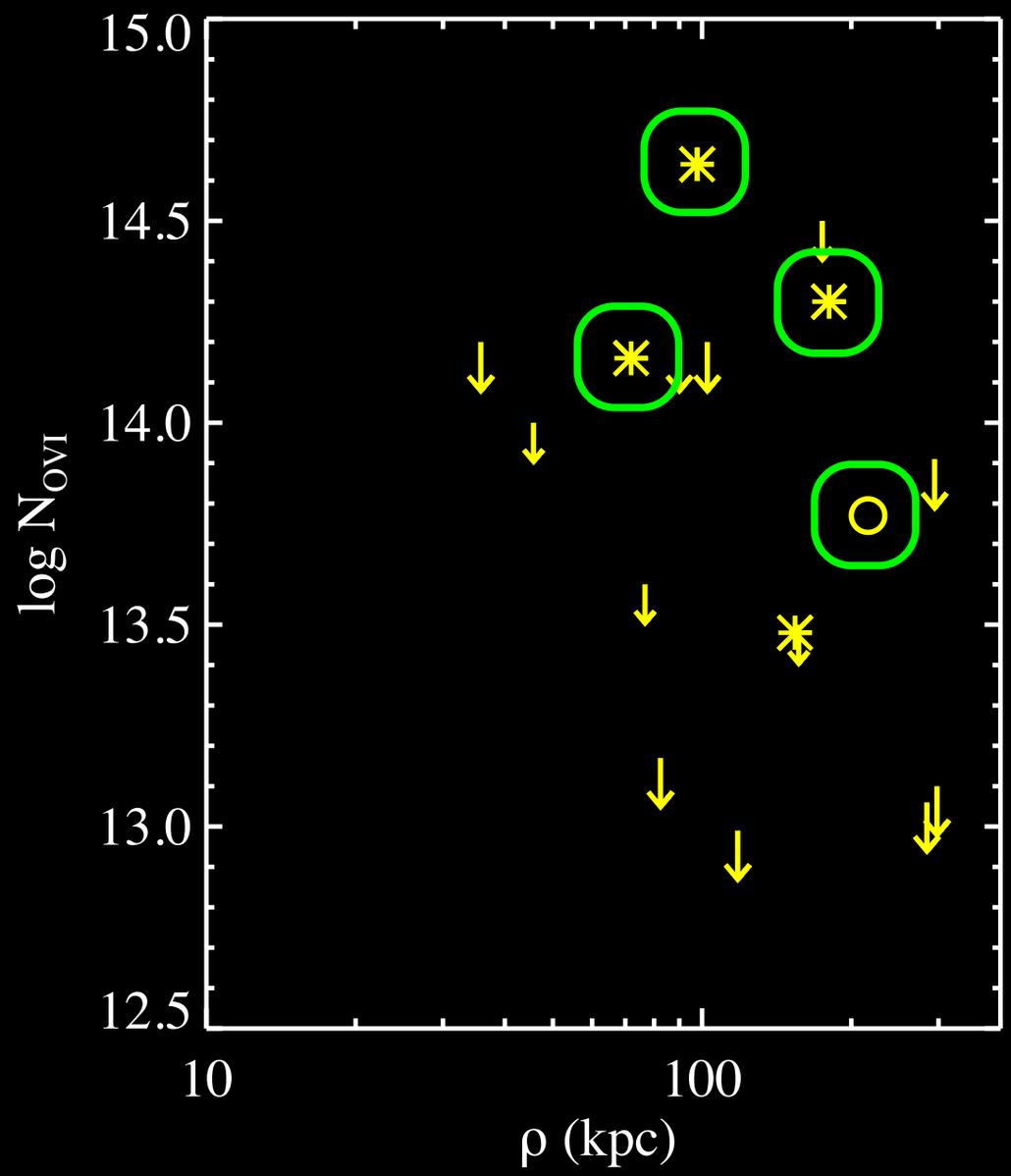

- Dwarf Galaxies (L < 0.1L*)
  - Many fewer positive detections of OVI than Lya
  - Most of the cases where OVI is observed have a second, brighter galaxy nearby

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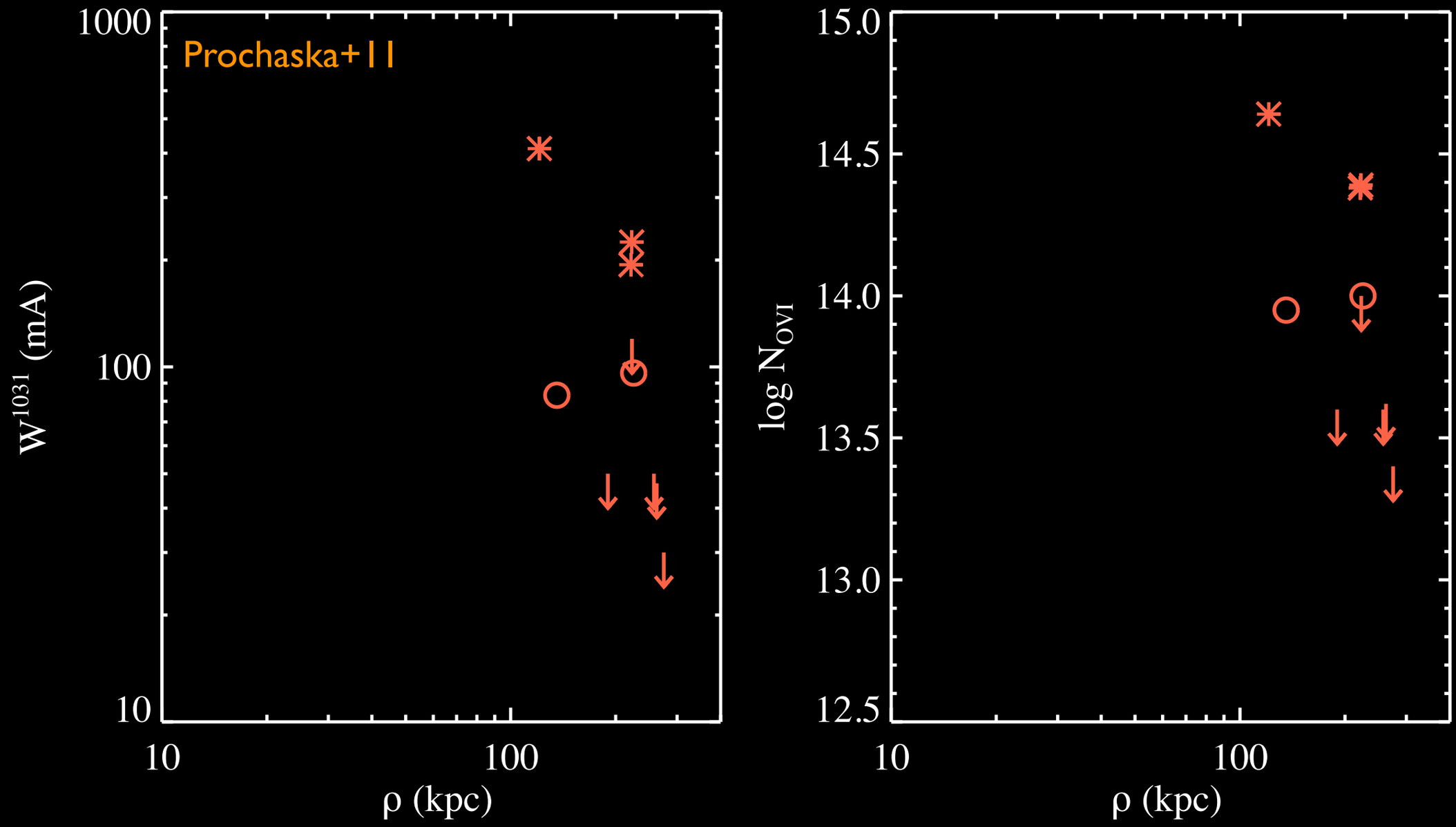

- L* Galaxies (L > L*)
  - Positive detections to ~250 kpc
  - No detections at 250-300 kpc
    - Small sample (stay tuned for HST/COS results)

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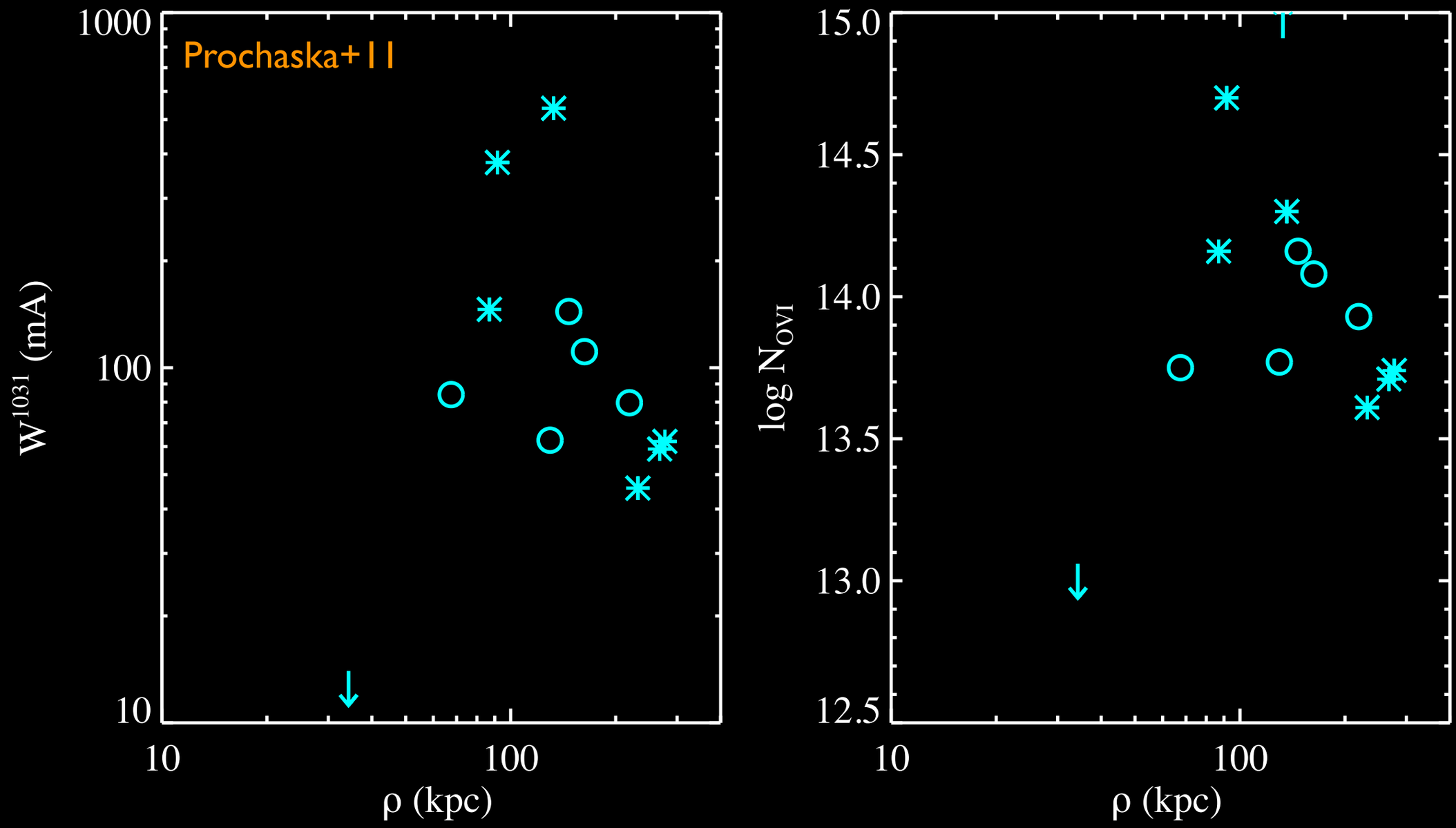

- Sub-L* Galaxies (L* > L > 0.1L*)
  - Almost all positive detections, to 300 kpc
  - Independent of spectral type

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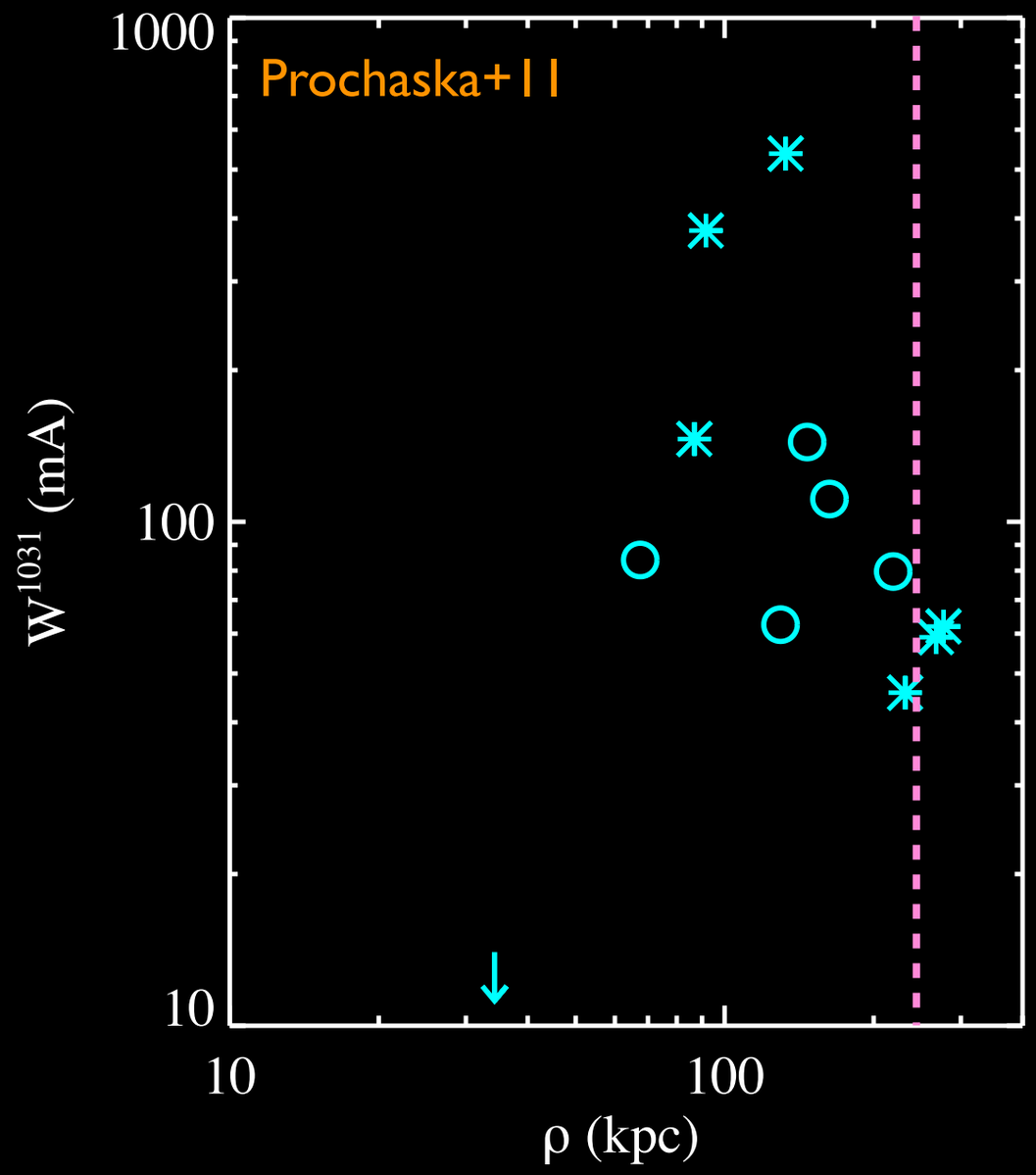

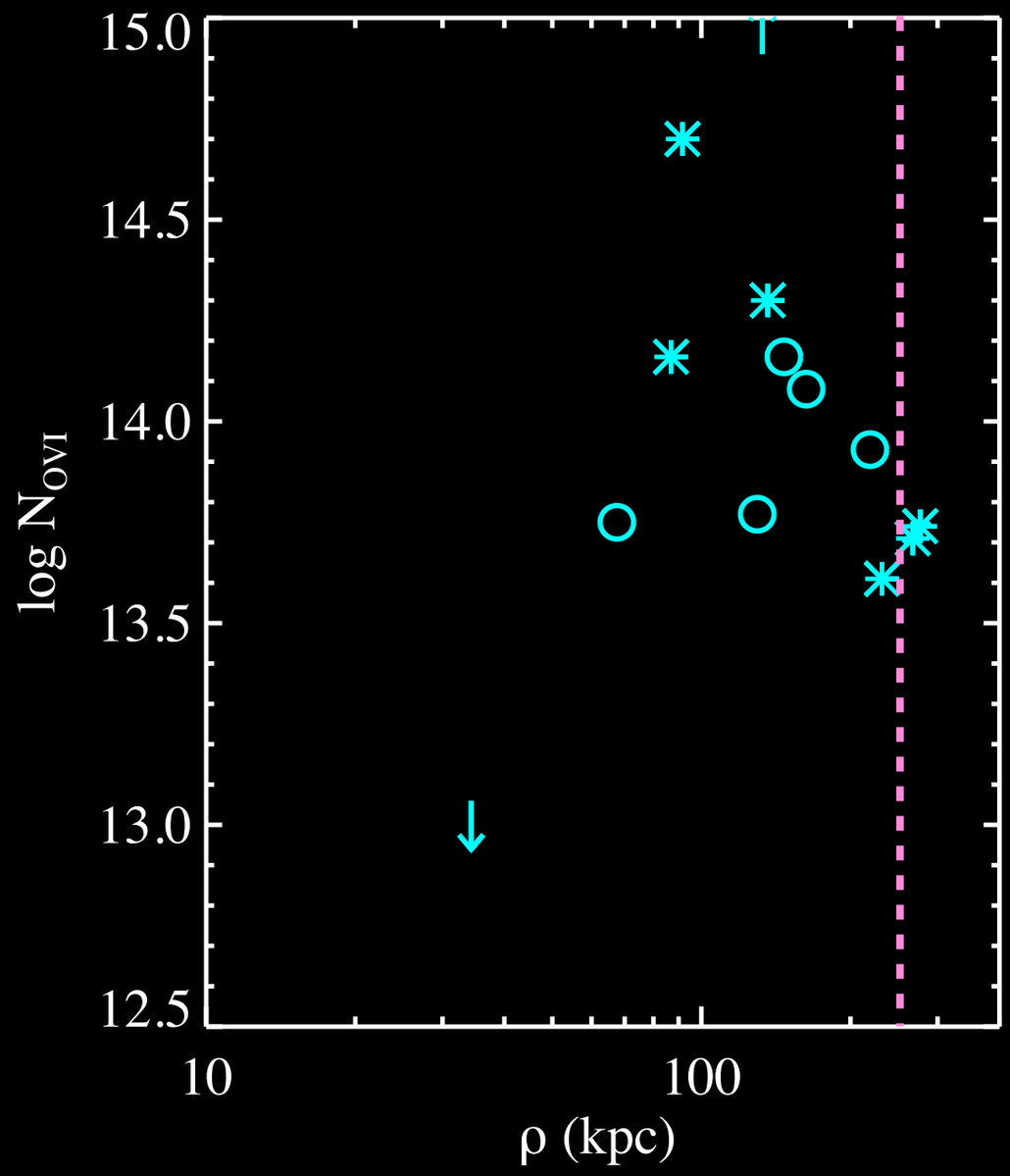

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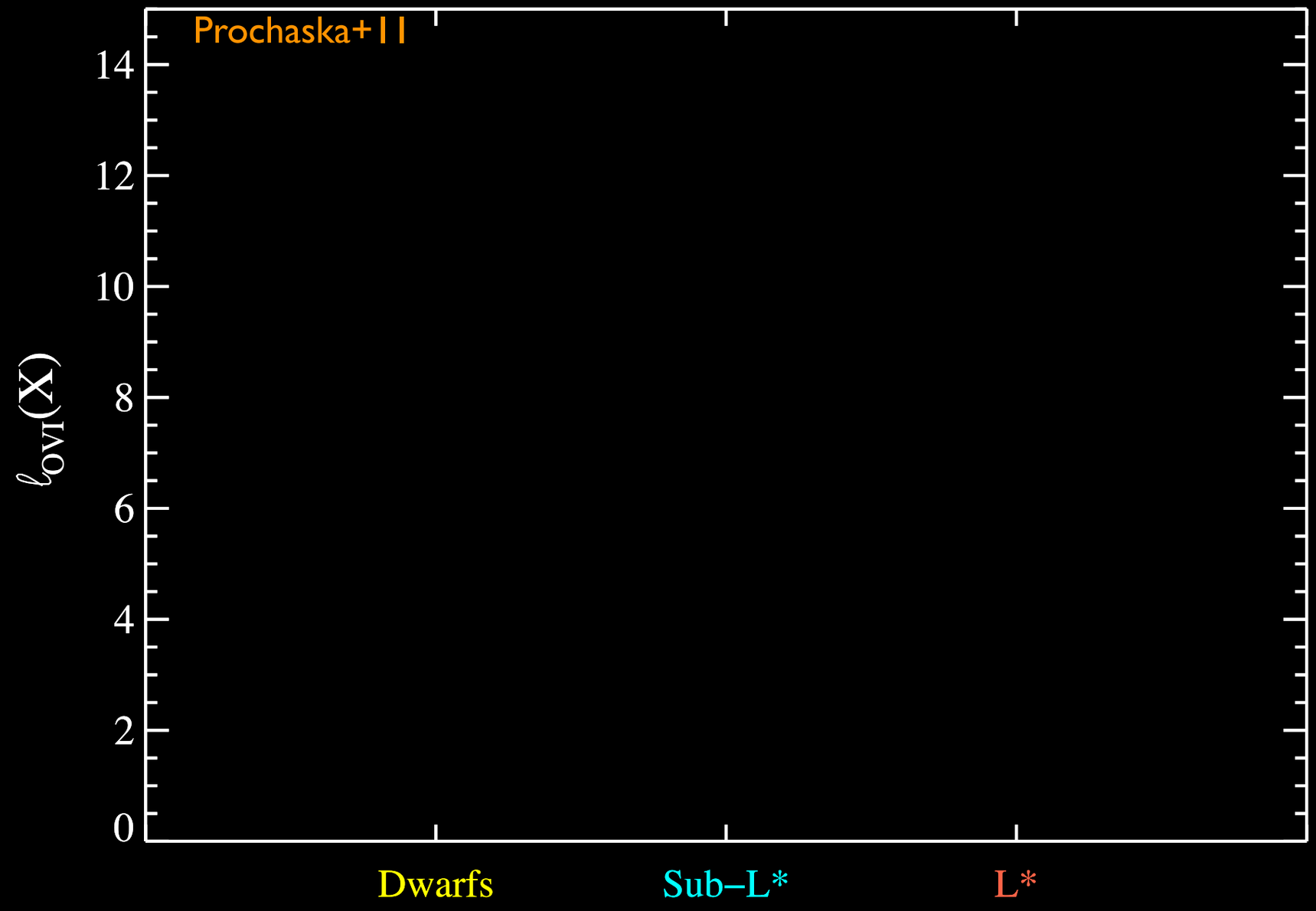
Is the enriched "IGM" simply CGM gas?



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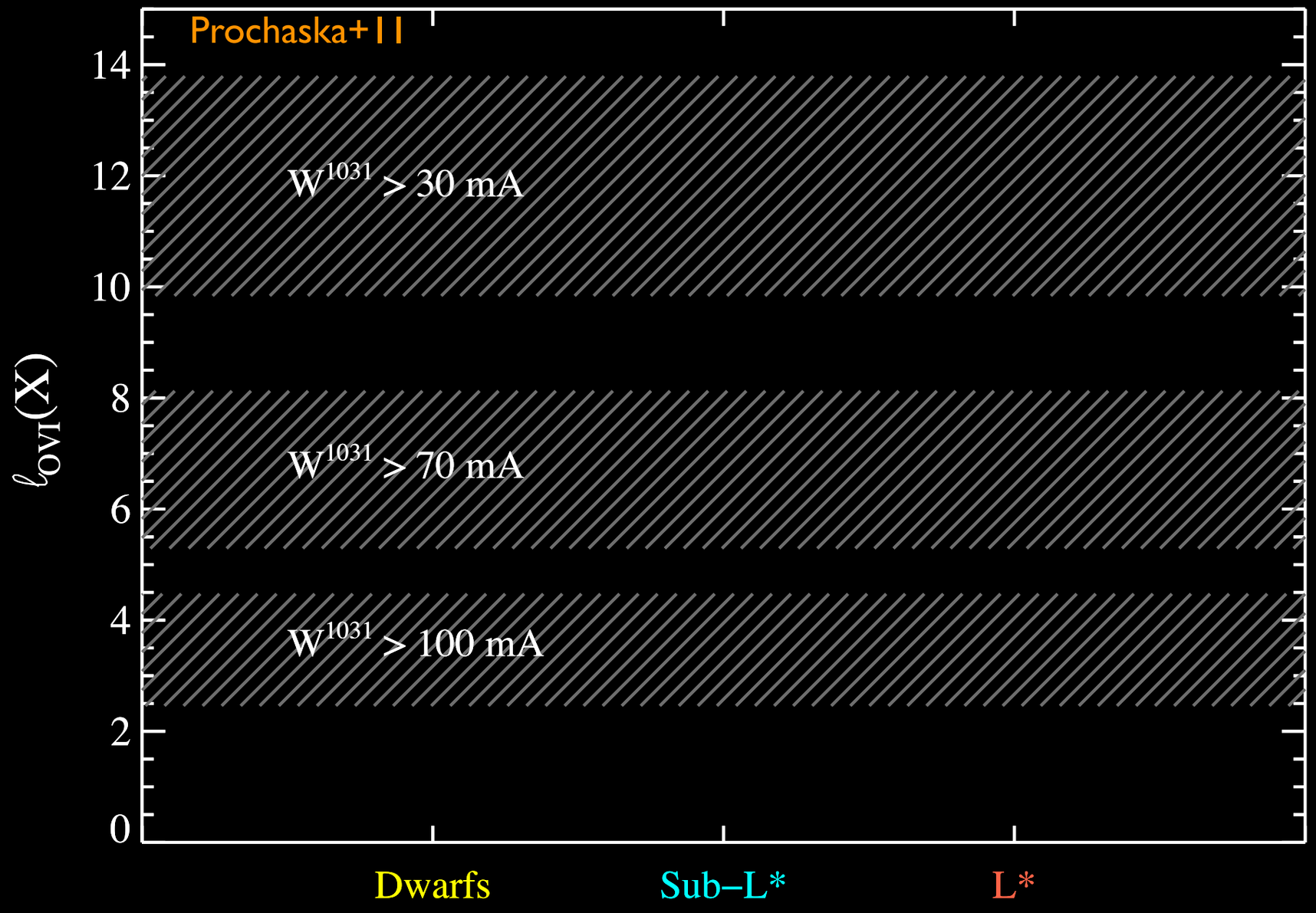

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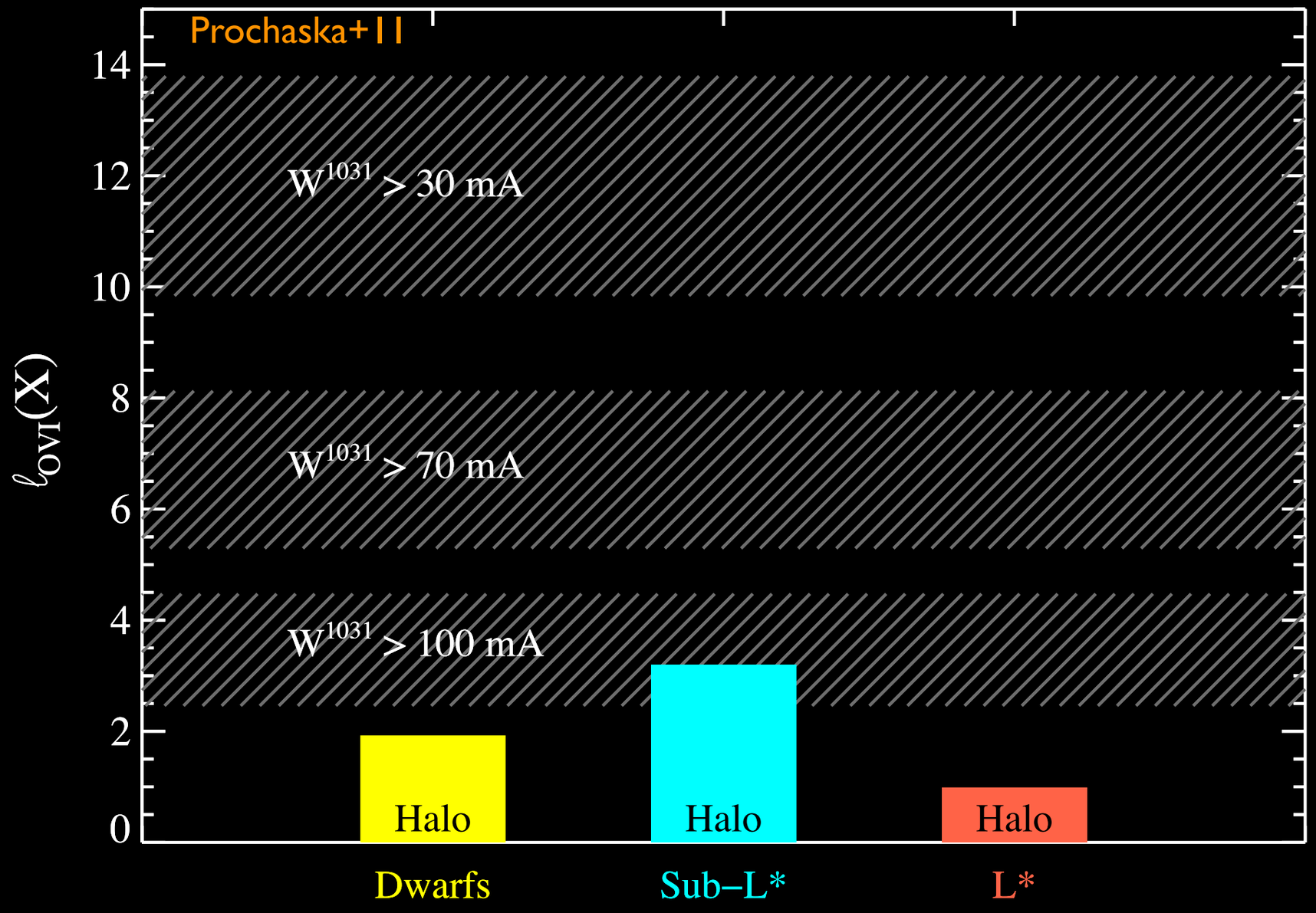

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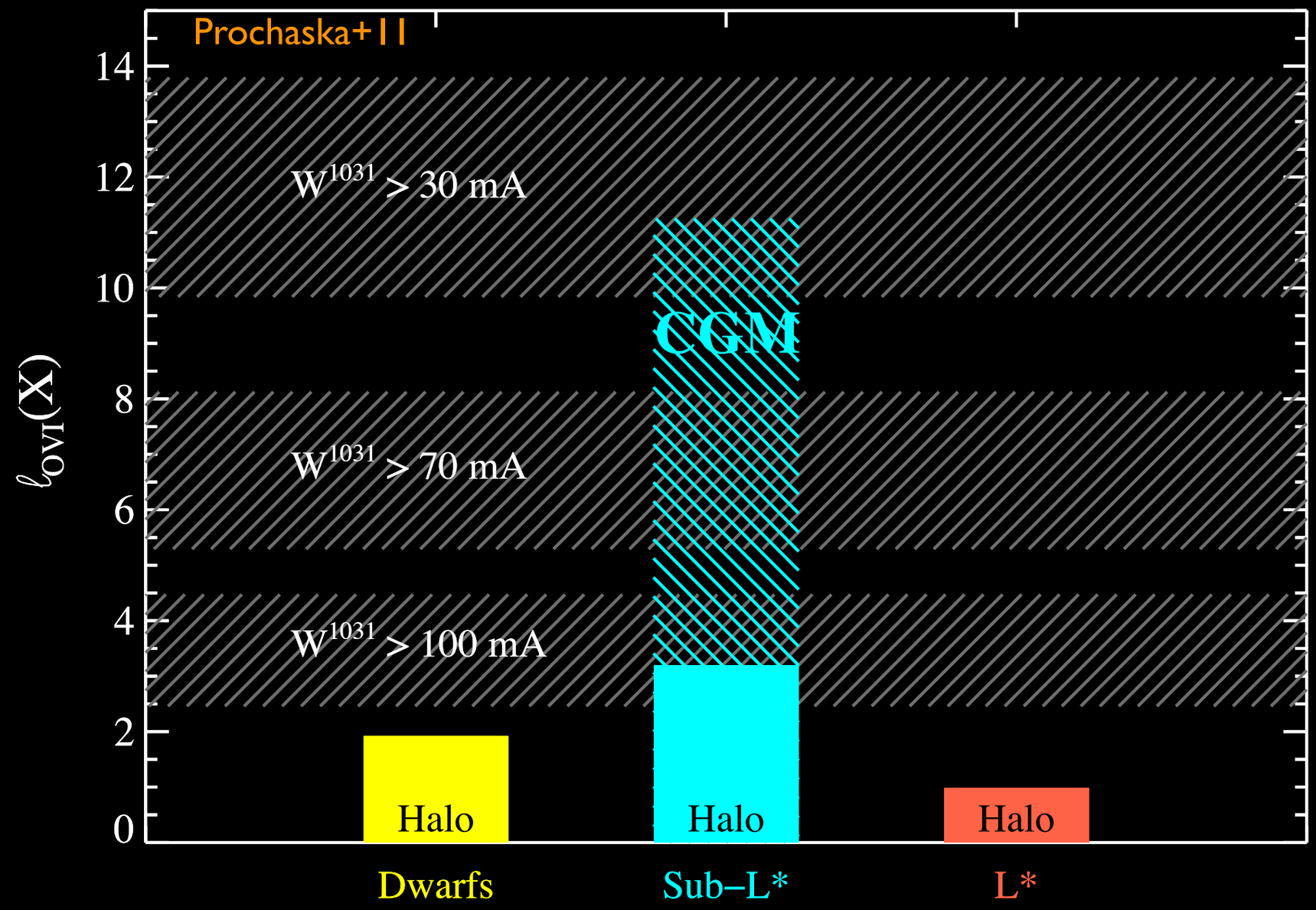

- Yes! The extended CGM of sub-L* gal
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    - ✦ Only for strong OVI

See also
Tumlinson&Fang 05
Stocke+06
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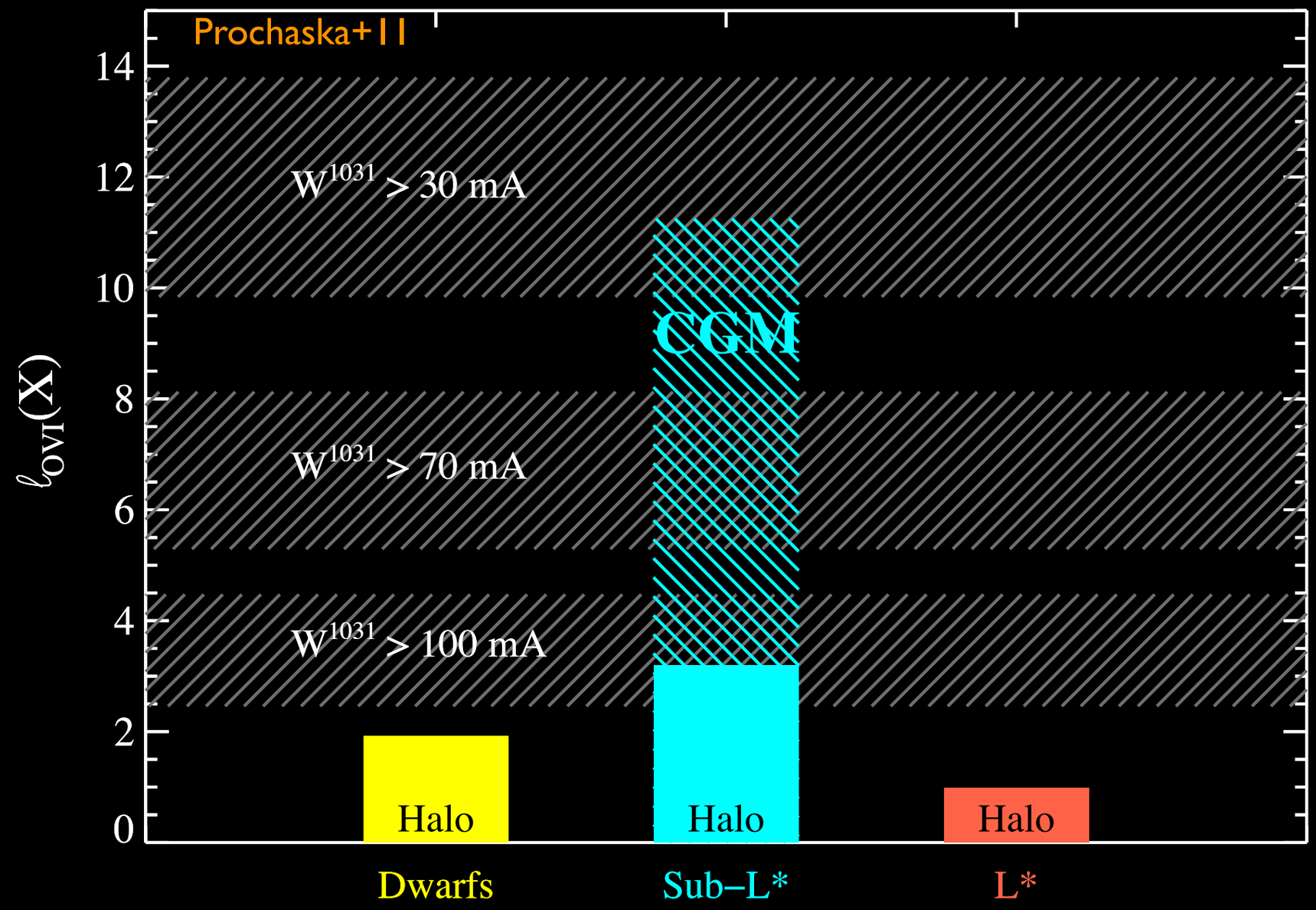

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✦ OVI: most common metal-line in the IGM

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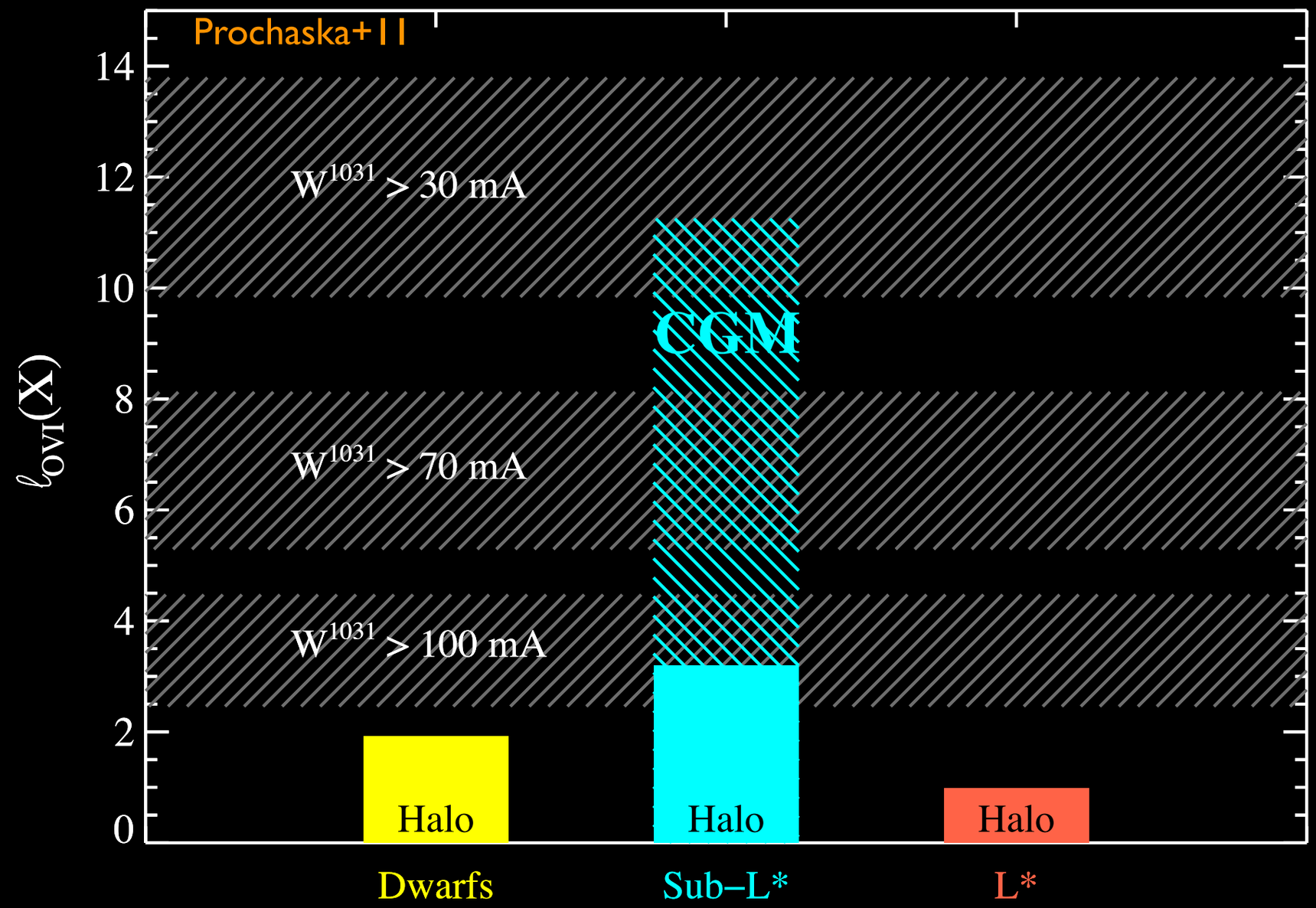

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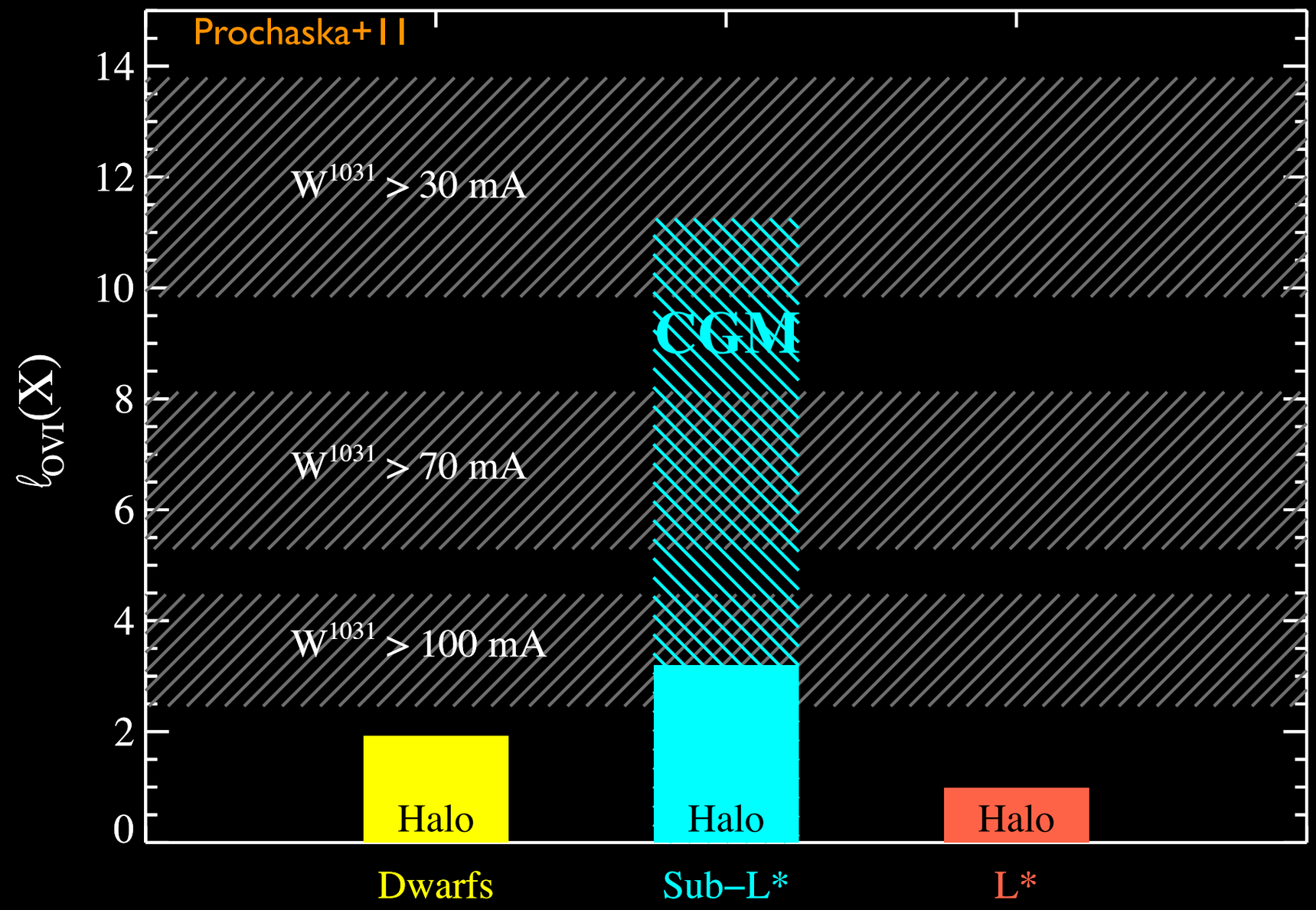

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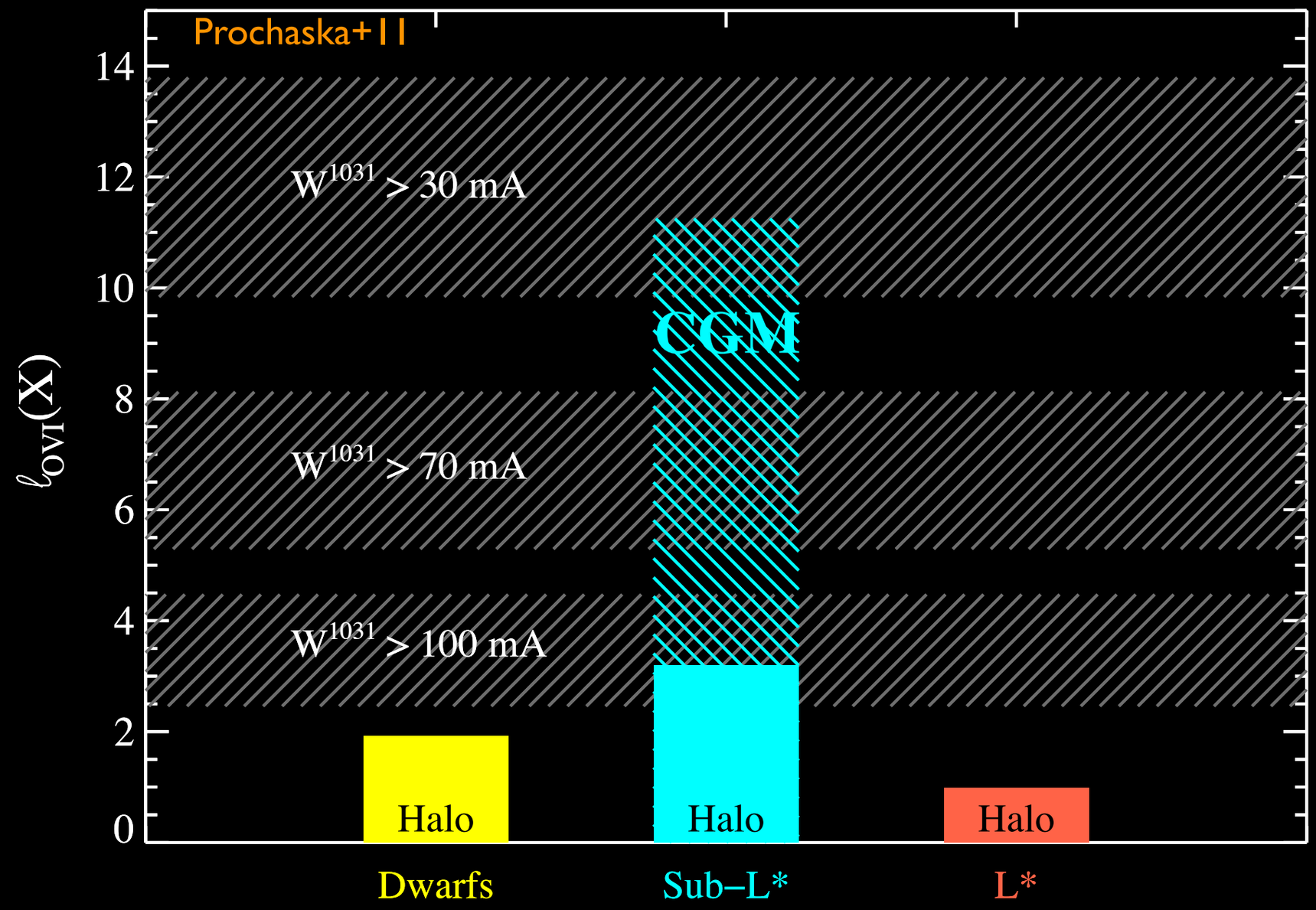

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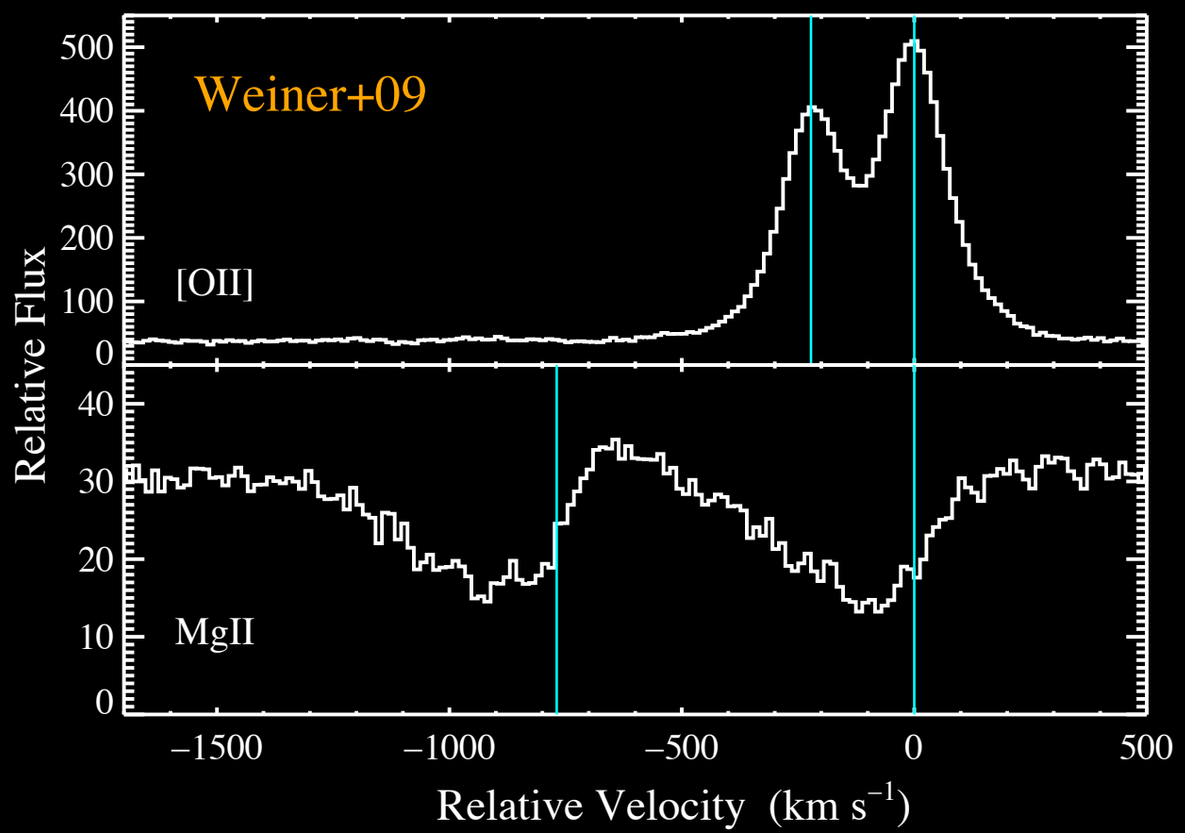
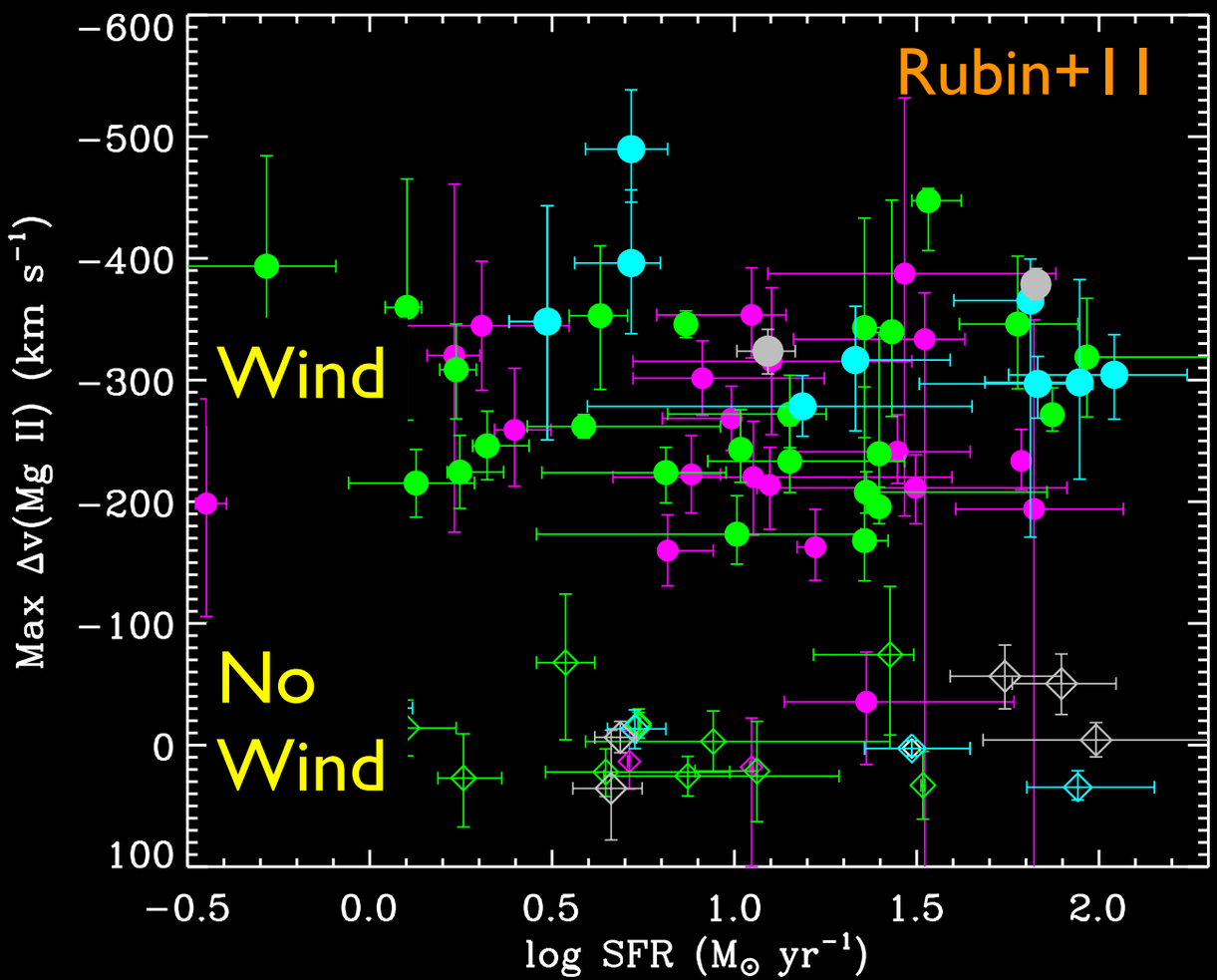
- Key open question
  - Are there many OVI lines with W<30mA?

Metal Transport: Galactic-scale Winds?

Star-forming galaxies at z<1 often exhibit blue-shifted (outflow) absorption by metals.





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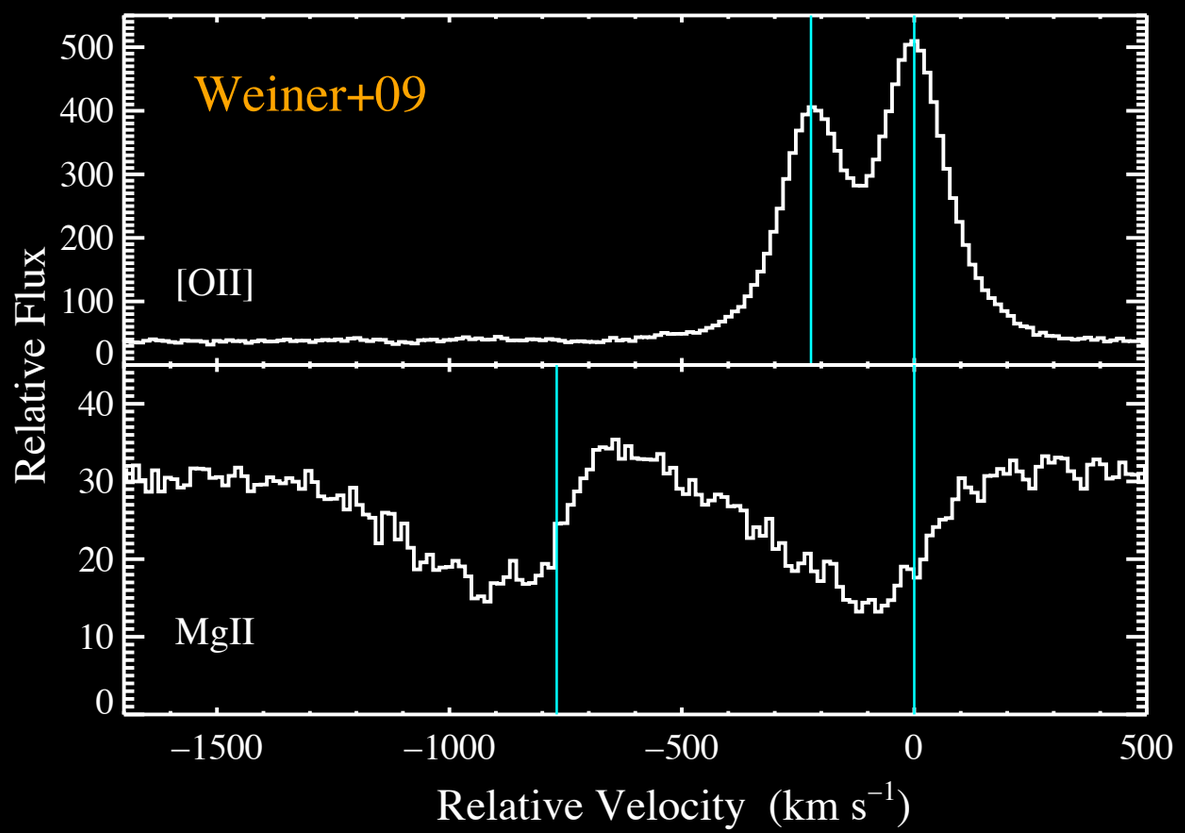

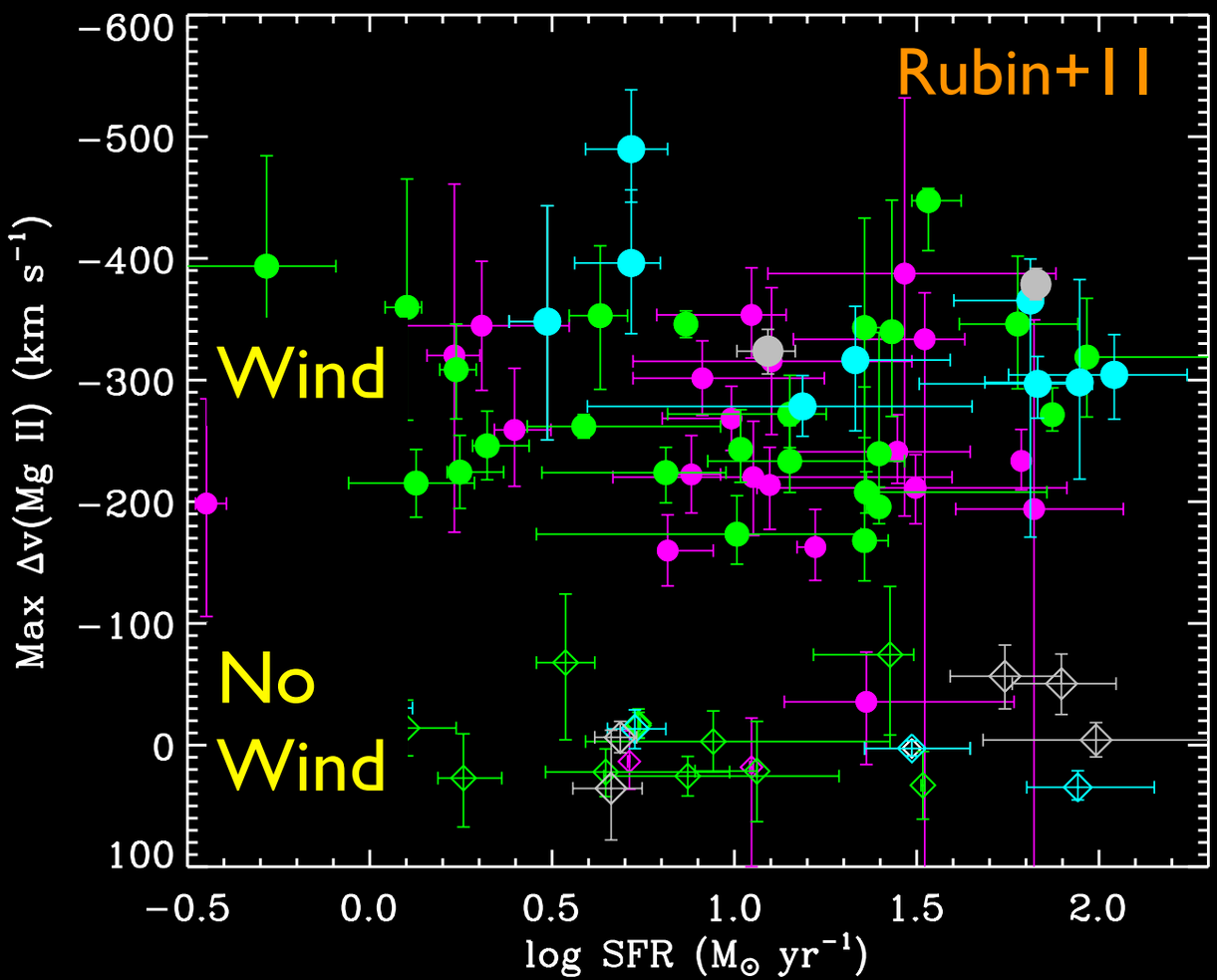

But are these "winds" propagating to 300kpc?
Or were the metals transported long ago?

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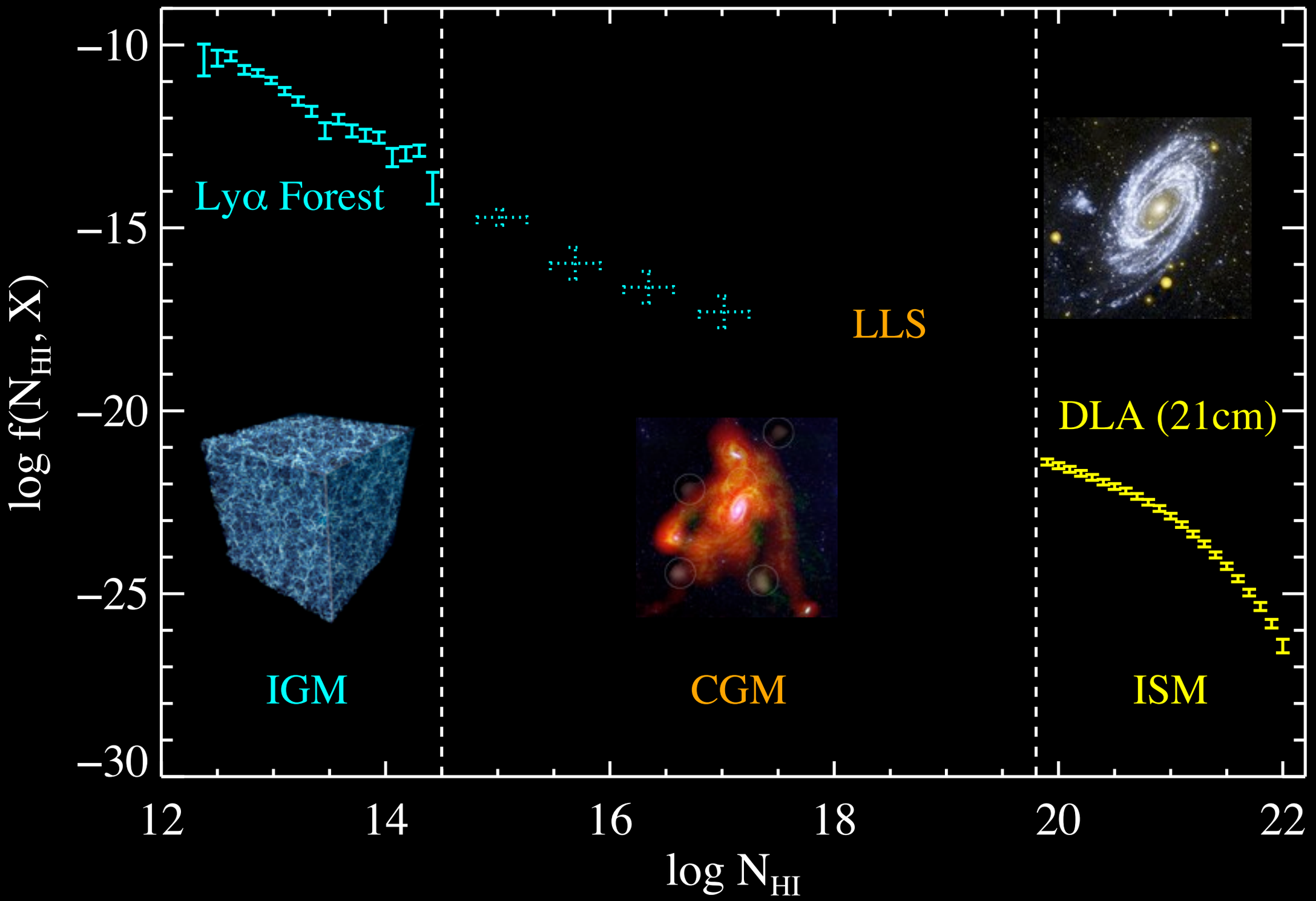

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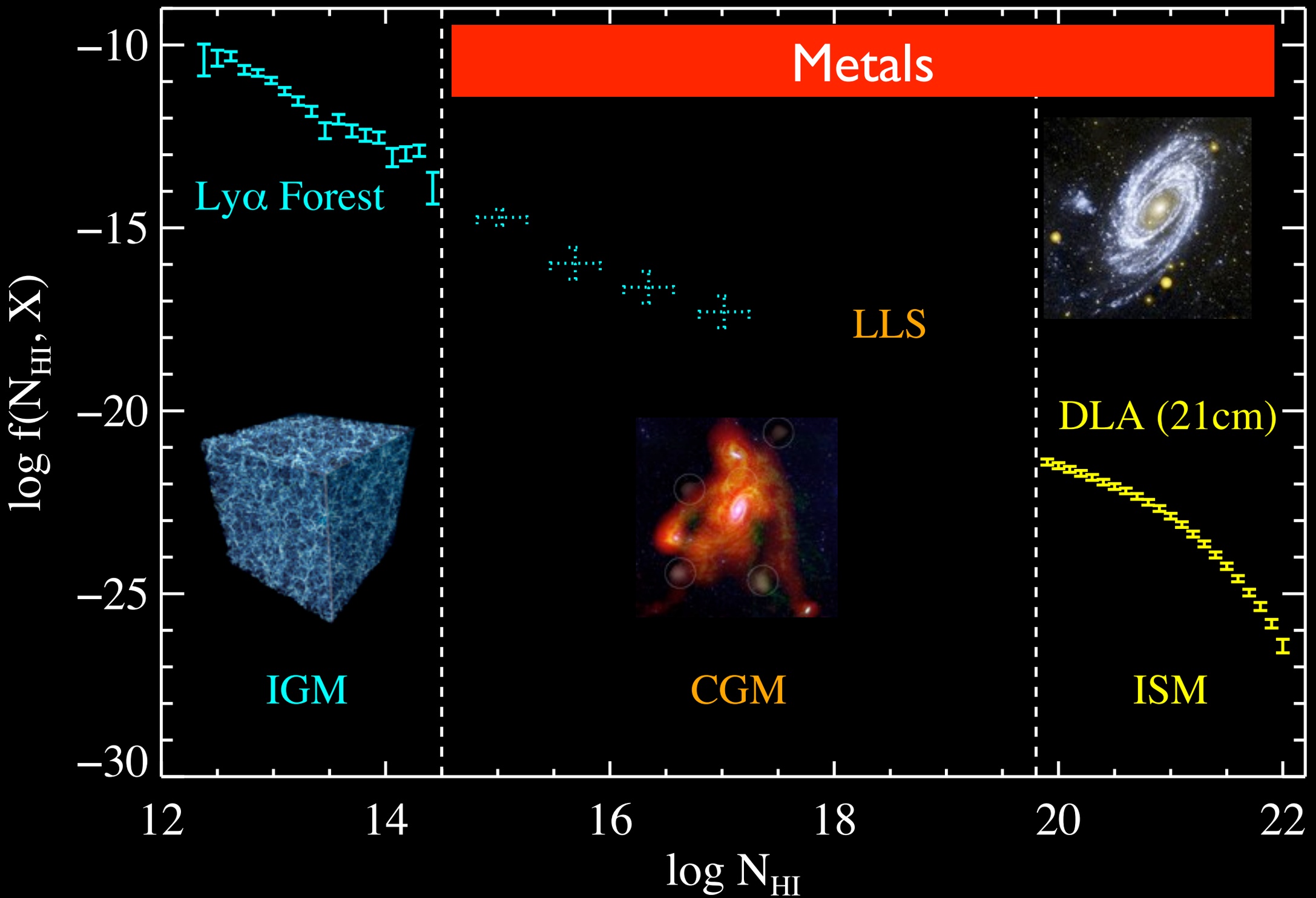

No strong evidence for metals in the IGM (or the WHIM) at z~0.

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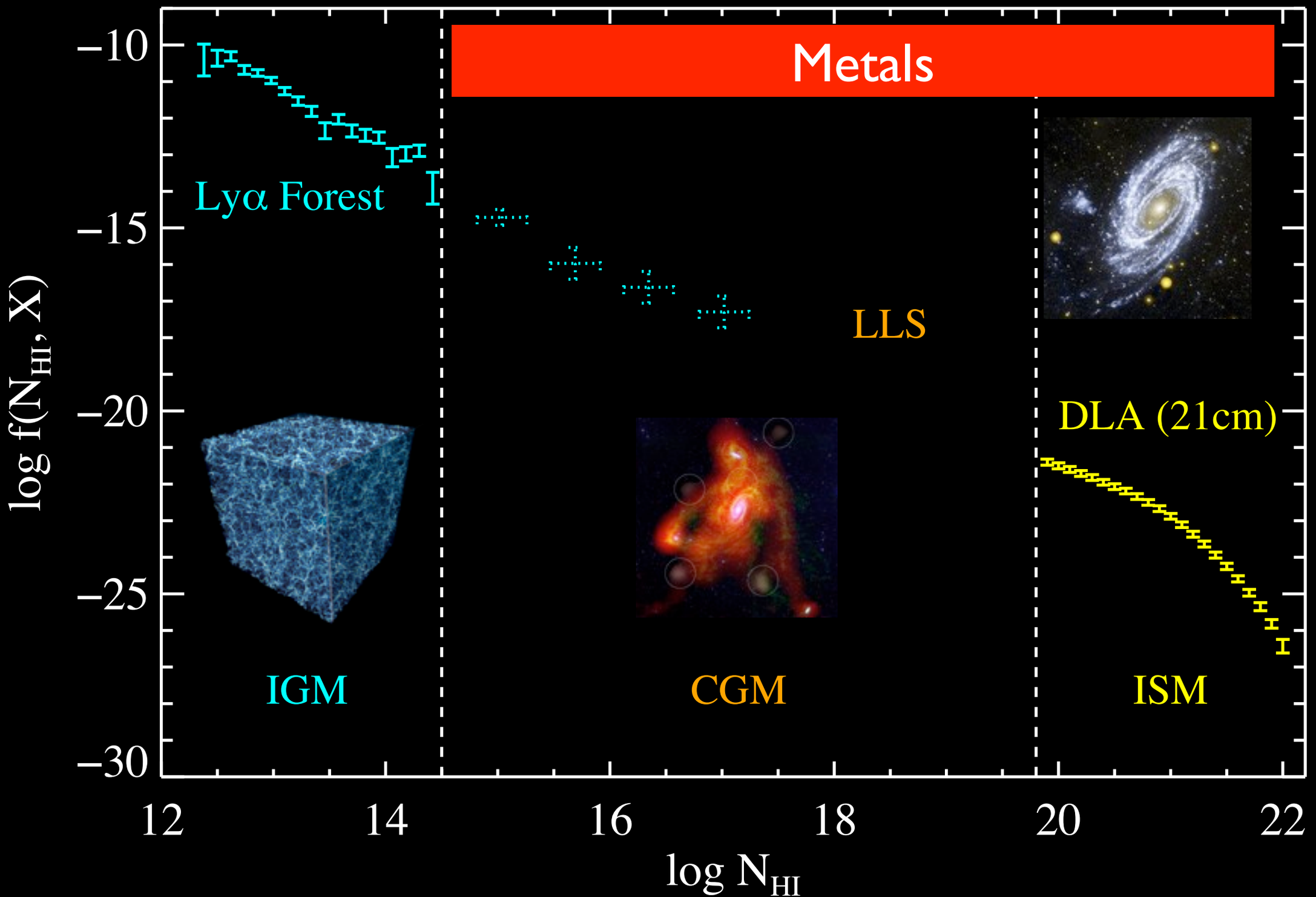

Statistically, the picture is well developed. But the precise relationship of gas to galaxies requires further research.

Hubble Space Telescope Cycle 17 GO Proposal <ID>

How Galaxies Acquire their Gas: A Map of Multiphase Accretion and Feedback in Gaseous Galaxy Halos

Principal Investigator: Dr. Jason Tumlinson

Institution: ~~Yale University~~ STScI

"COS-Halos"

Data Division

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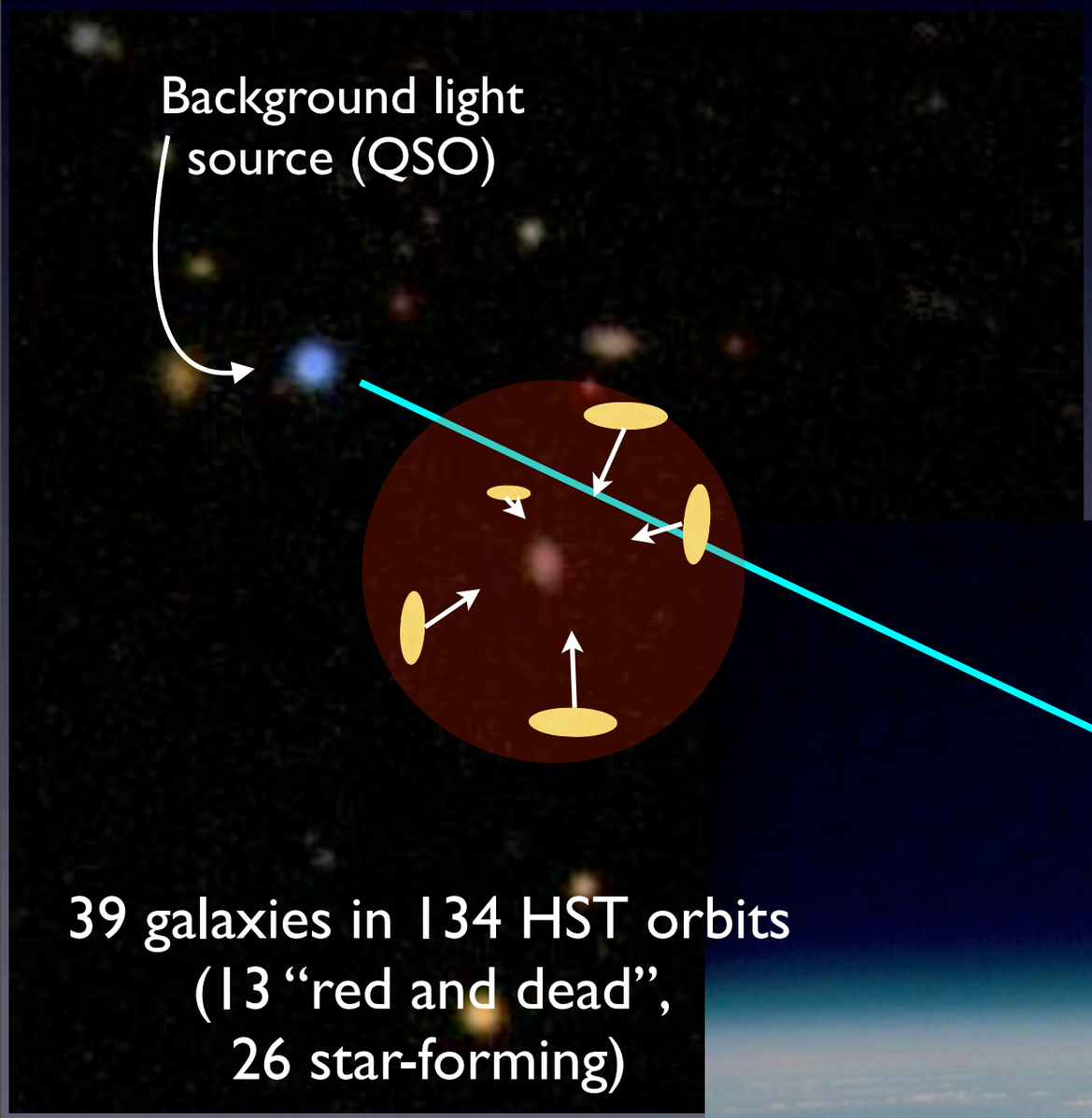
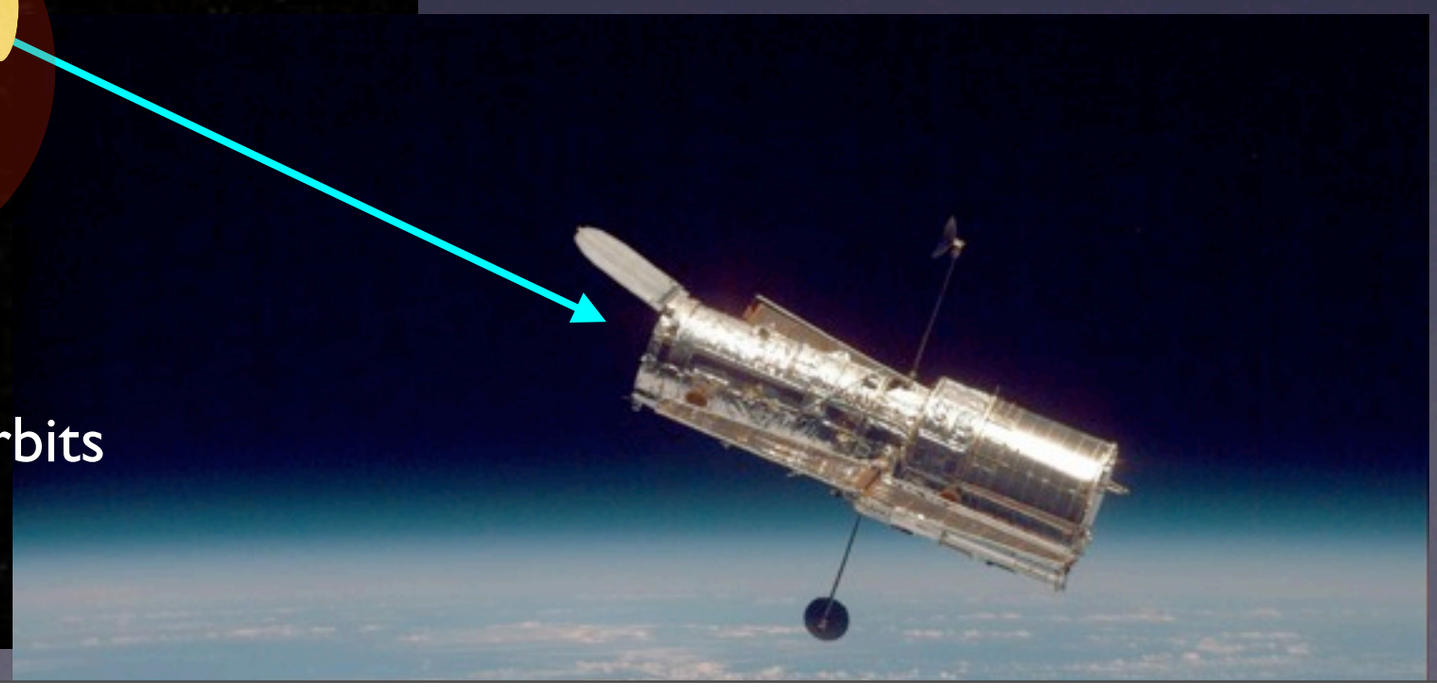


39 galaxies in 134 HST orbits
(13 "red and dead",
26 star-forming)



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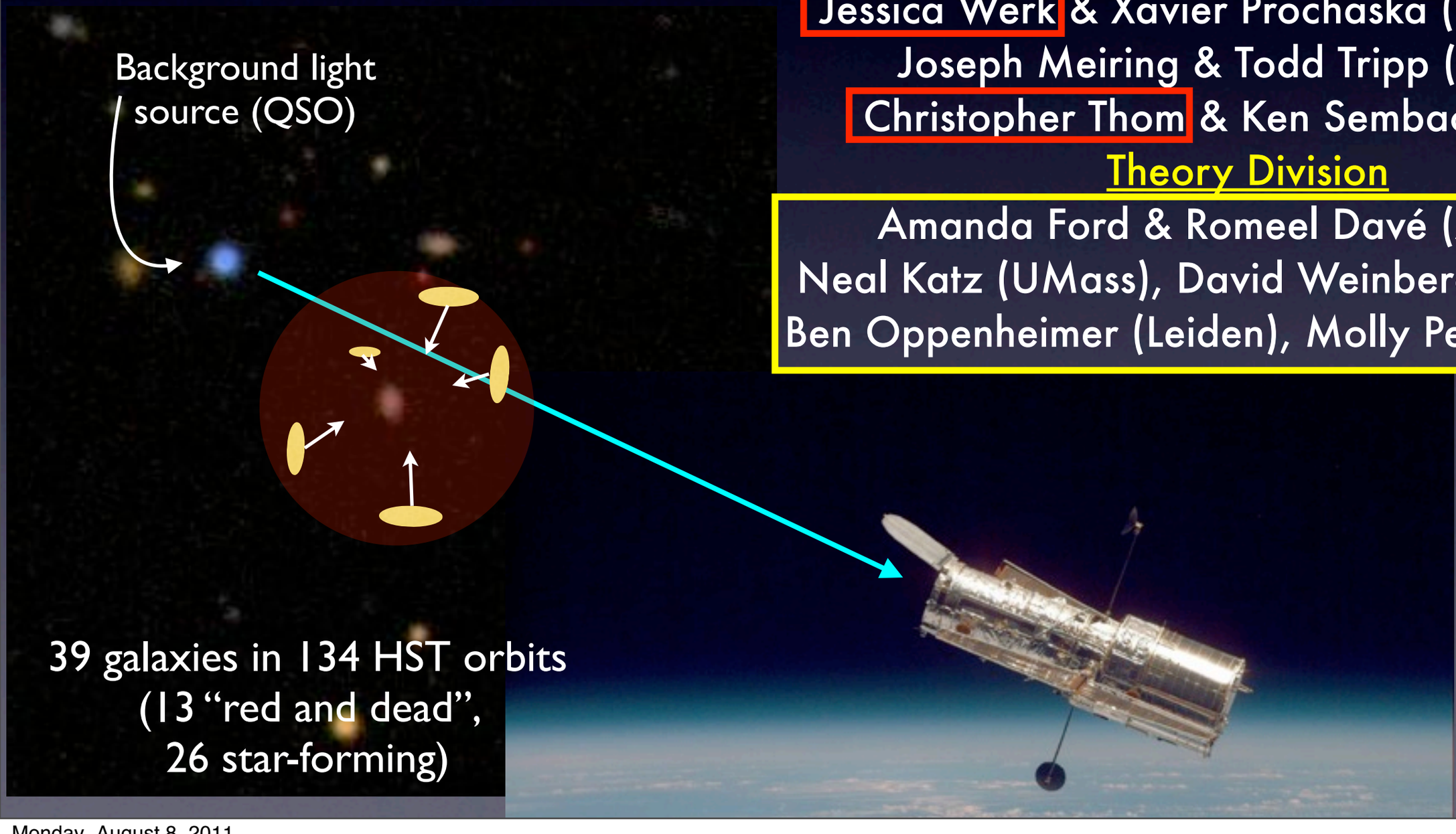
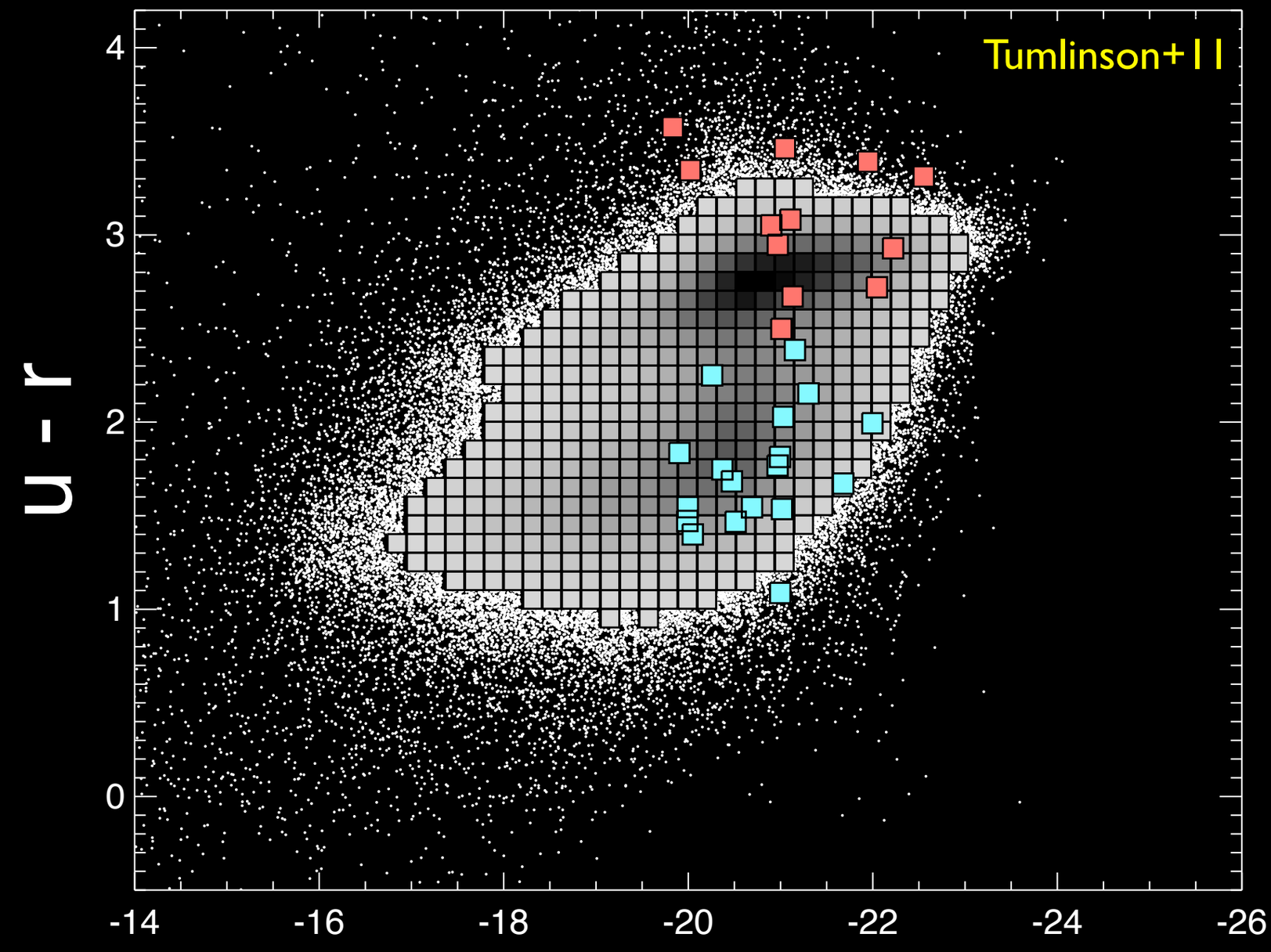
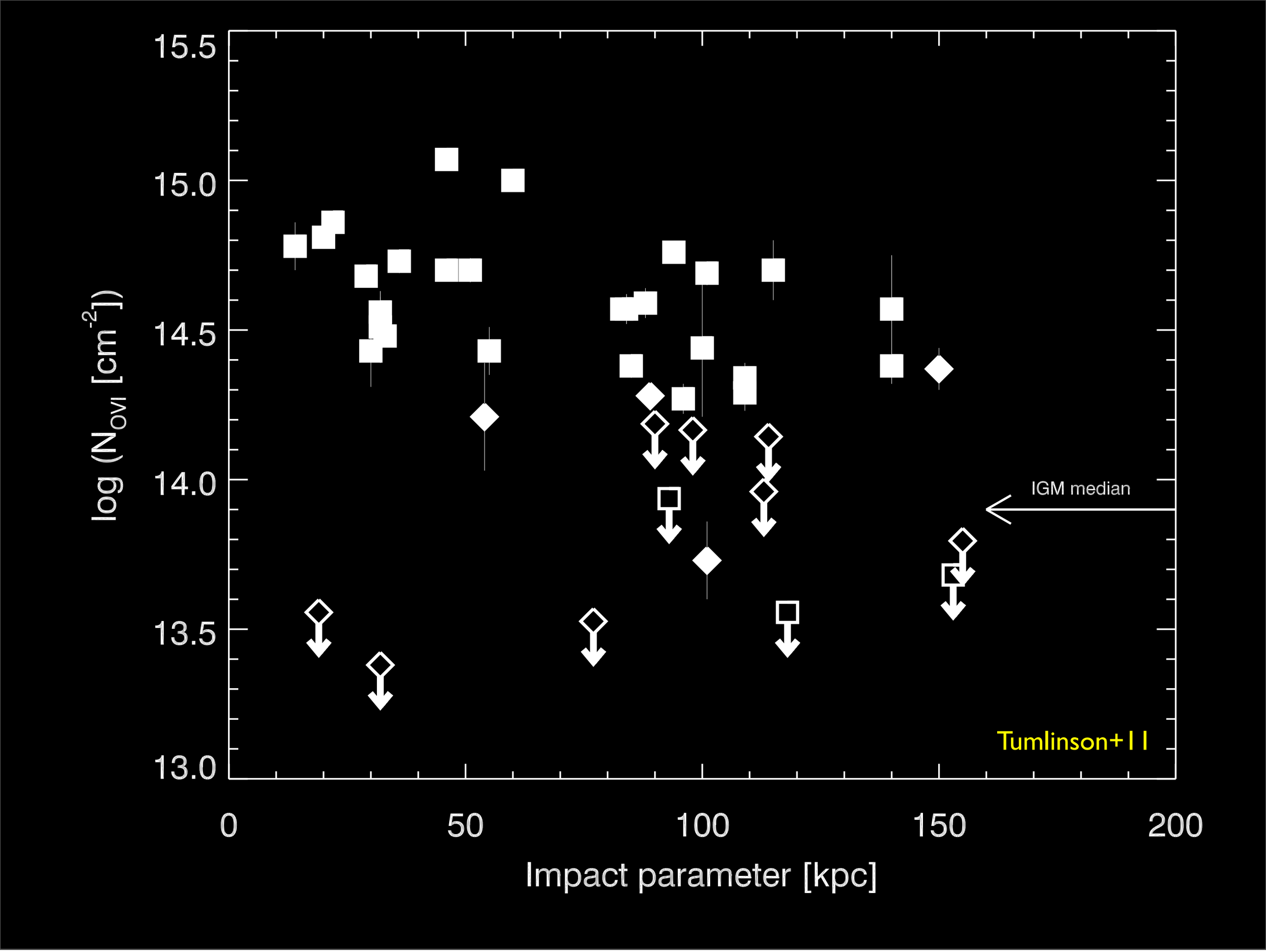
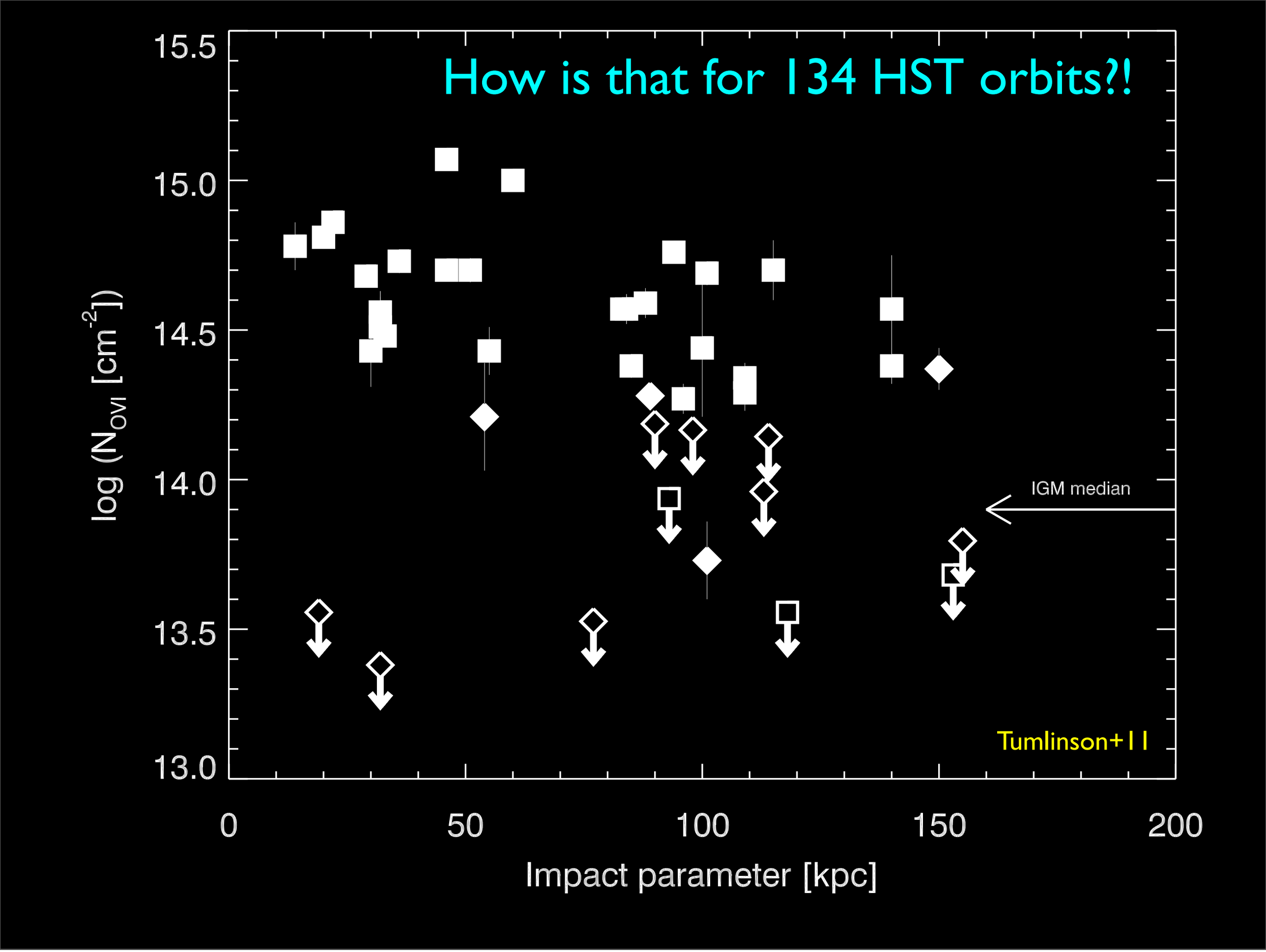


COS-Halos Survey Design:



Blue and red, L~L* galaxies at impact parameters of 20-150kpc. (Much easier at z~0)


15.5
15.0
14.5
14.0
13.5
13.0
log (N_{OVI} [cm^{-2}])
0
50
100
150
200
Impact parameter [kpc]
IGM median
Tumlinson+11


How is that for 134 HST orbits?!
15.5
15.0
14.5
14.0
13.5
13.0
log (N_{OVI} [cm^{-2}])
IGM median
Tumlinson+11
0
50
100
150
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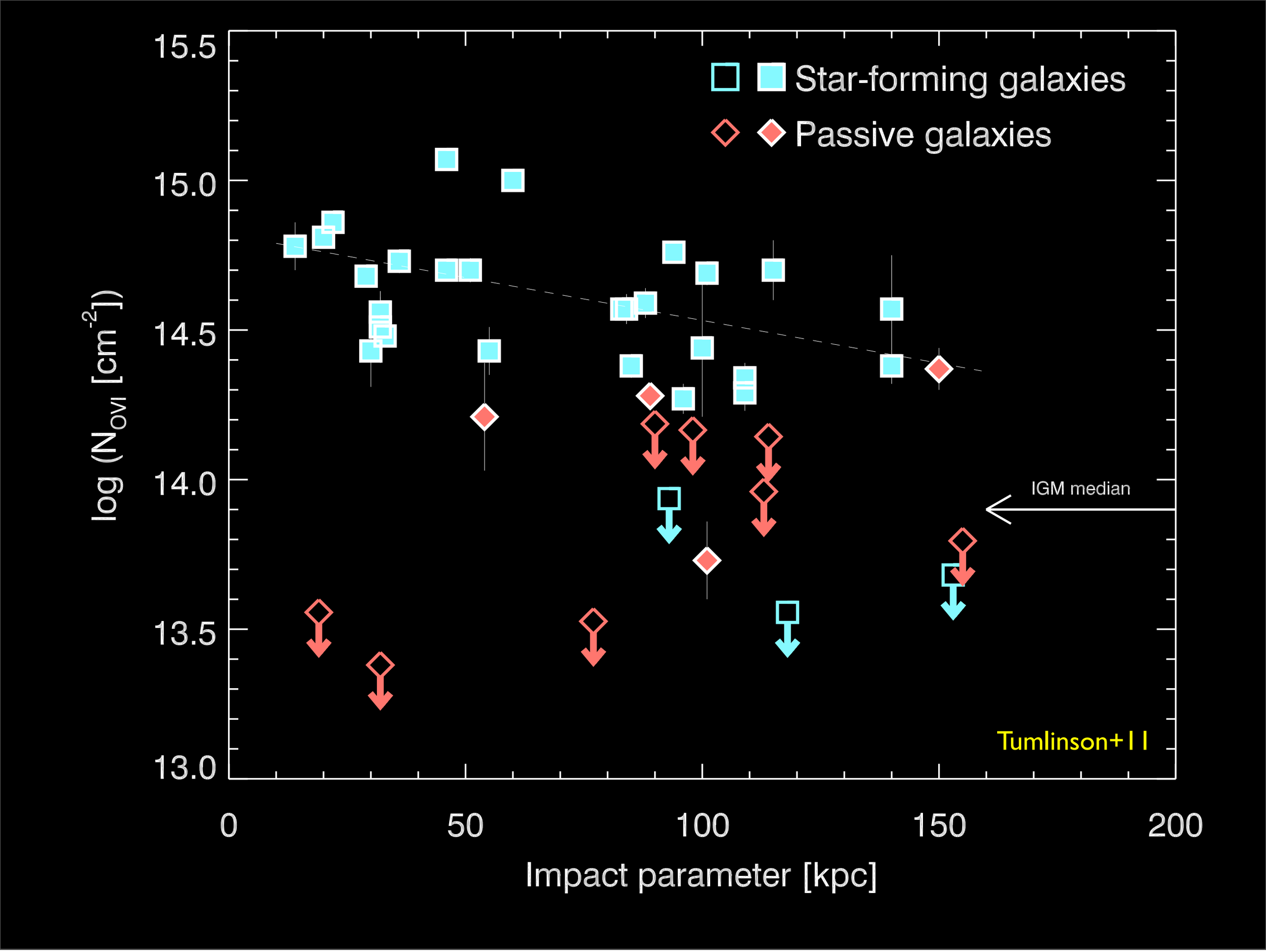
Impact parameter [kpc]


Star-forming galaxies
Passive galaxies
IGM median
Tumlinson+11
log (N_{OVI} [cm^{-2}])
15.5
15.0
14.5
14.0
13.5
13.0
0
50
100
150
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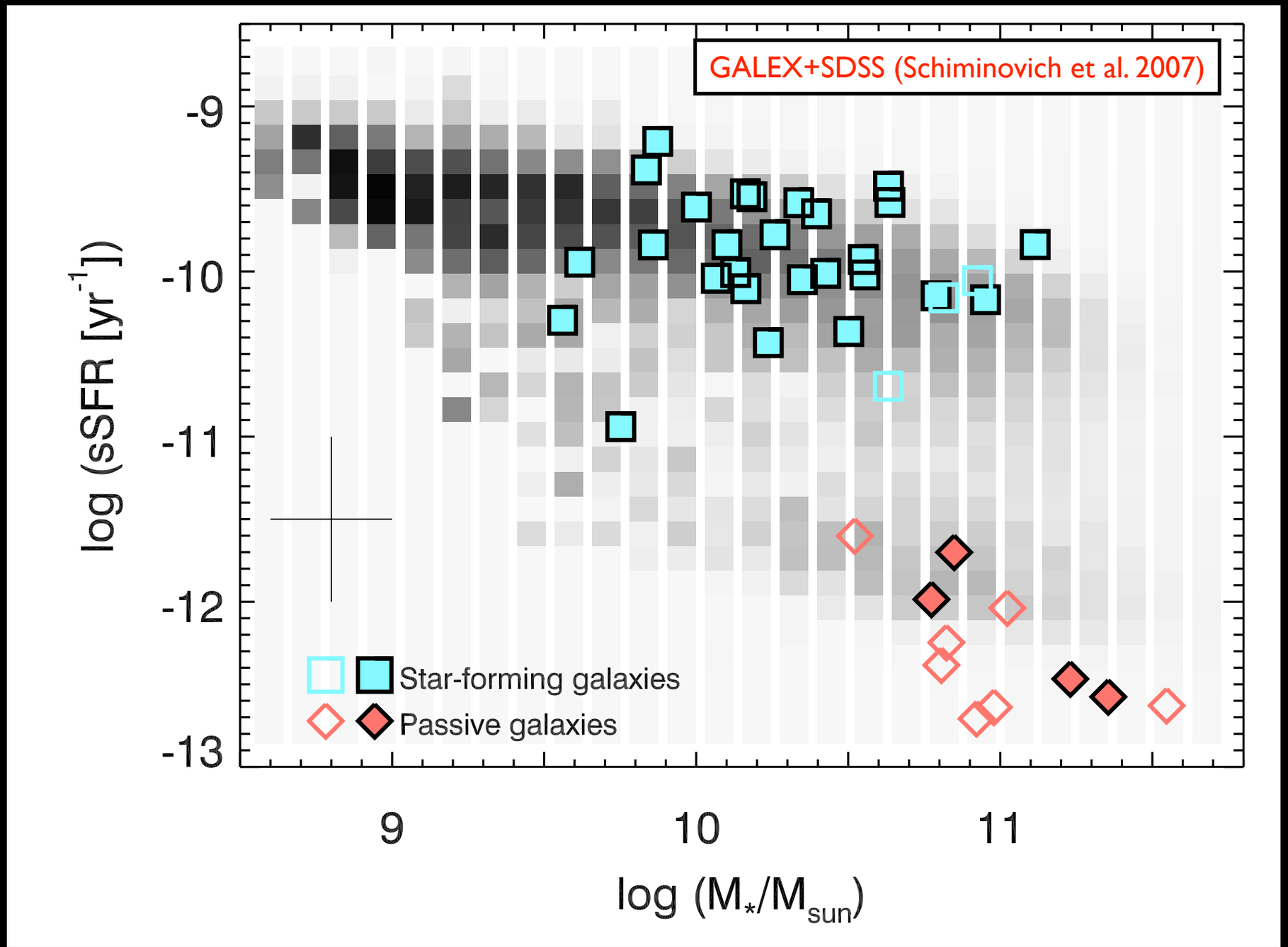
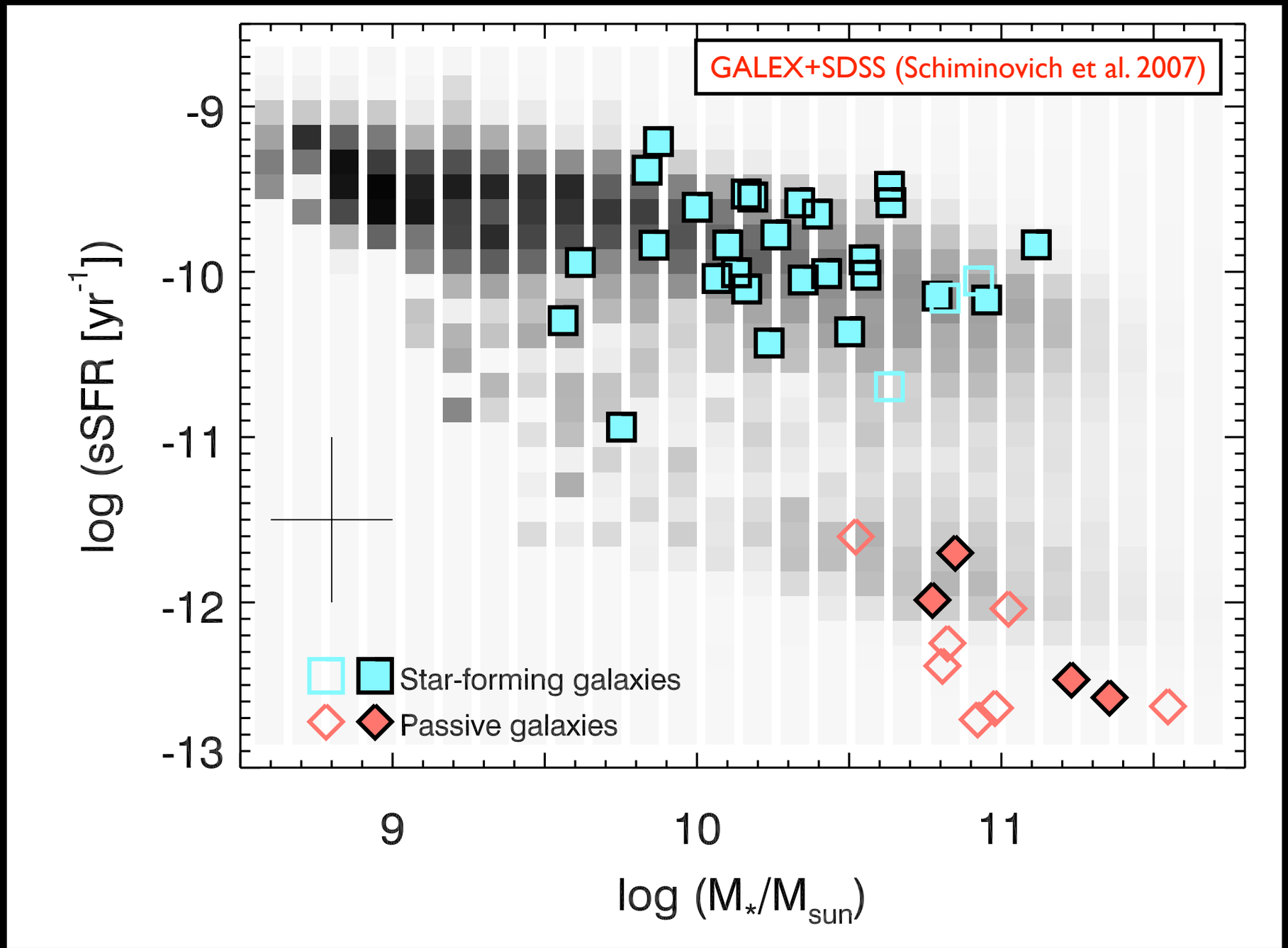
Impact parameter [kpc]

Gas Halos and Galaxy Bimodality

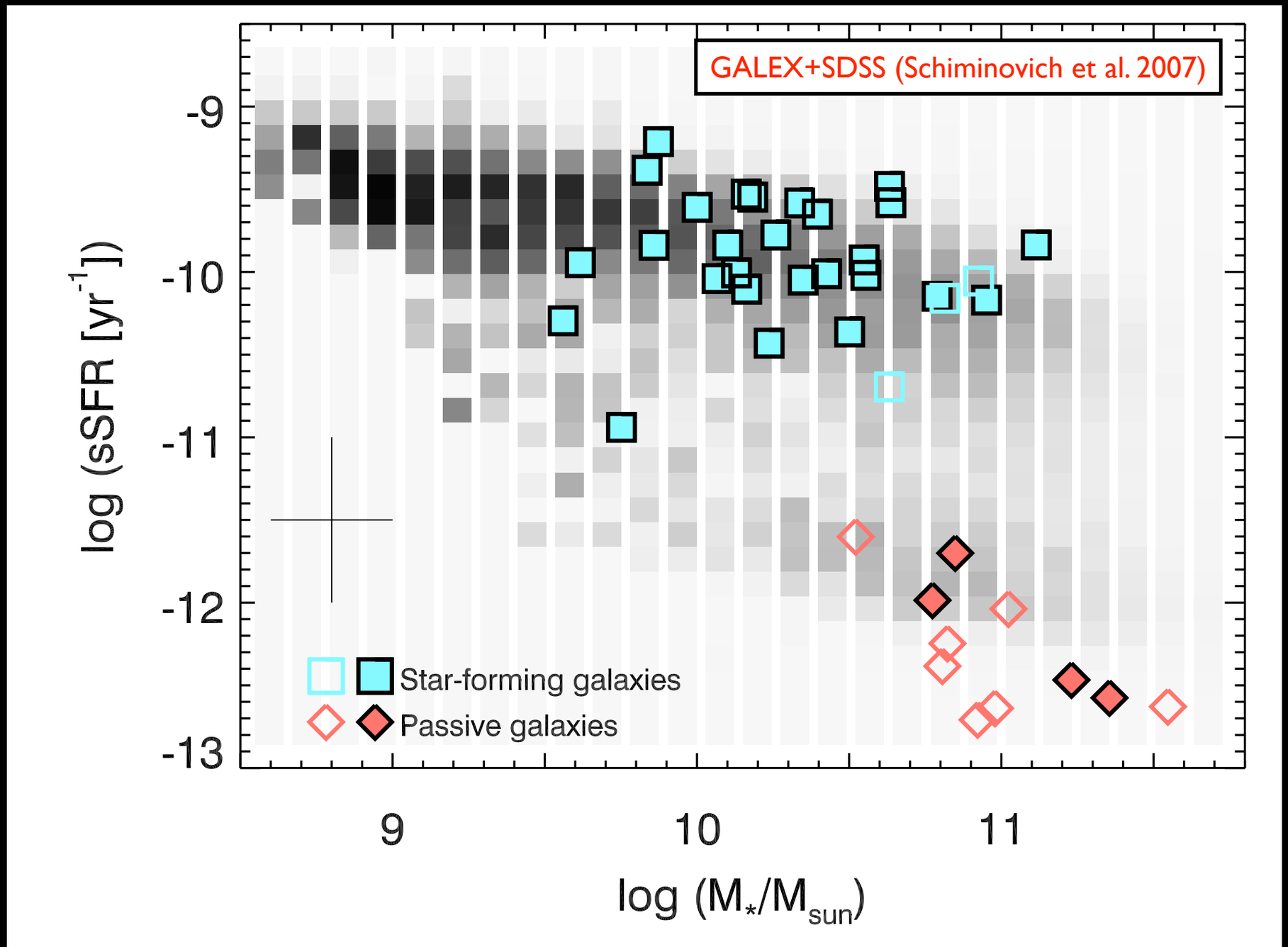


Gas Halos and Galaxy Bimodality



"Blue cloud" galaxies have 92% detection rate (100% inside 90 kpc)

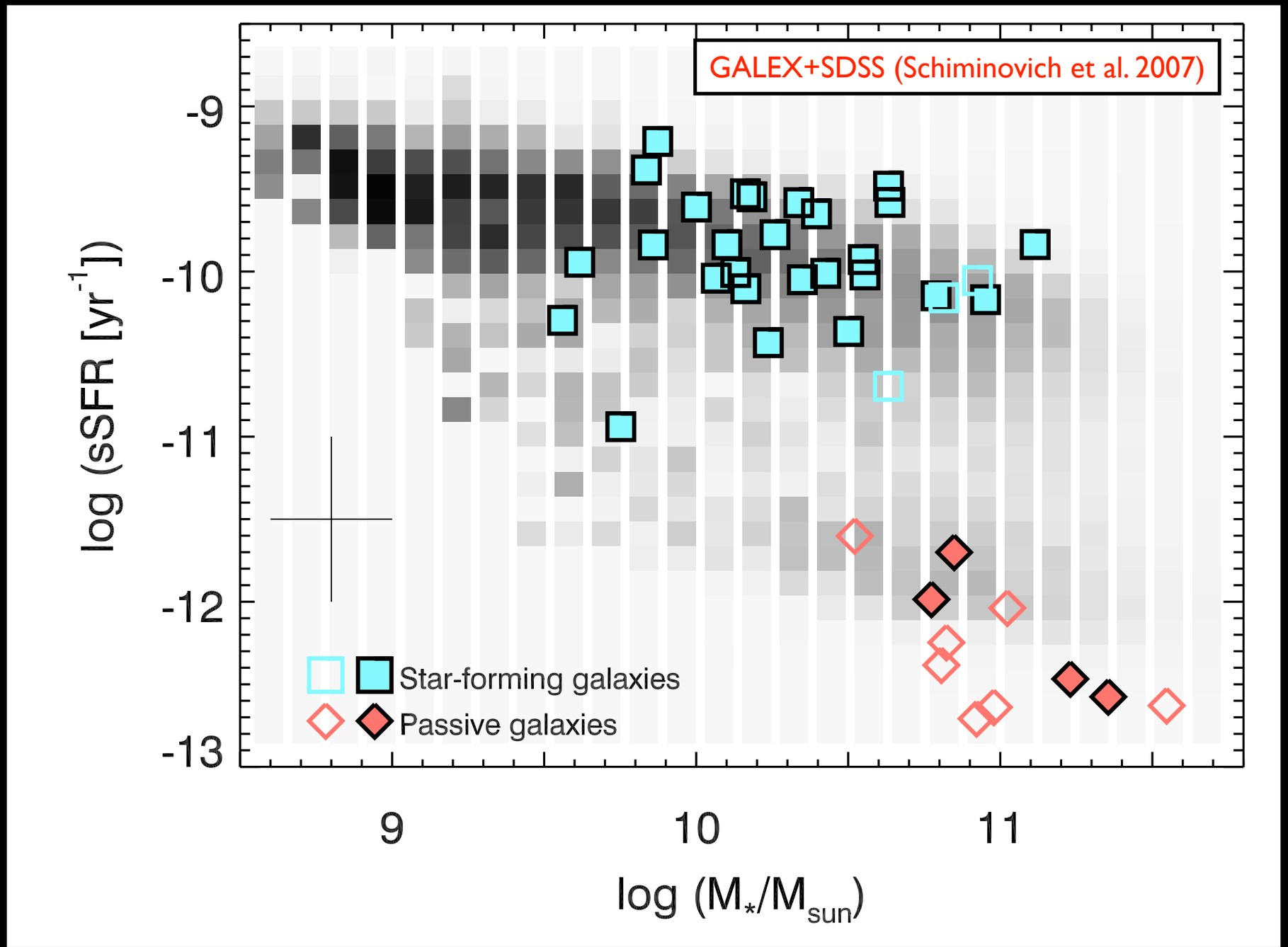
Gas Halos and Galaxy Bimodality



"Blue cloud" galaxies have 92% detection rate (100% inside 90 kpc)

"Red sequence" galaxies have 44% detection rate.

Gas Halos and Galaxy Bimodality

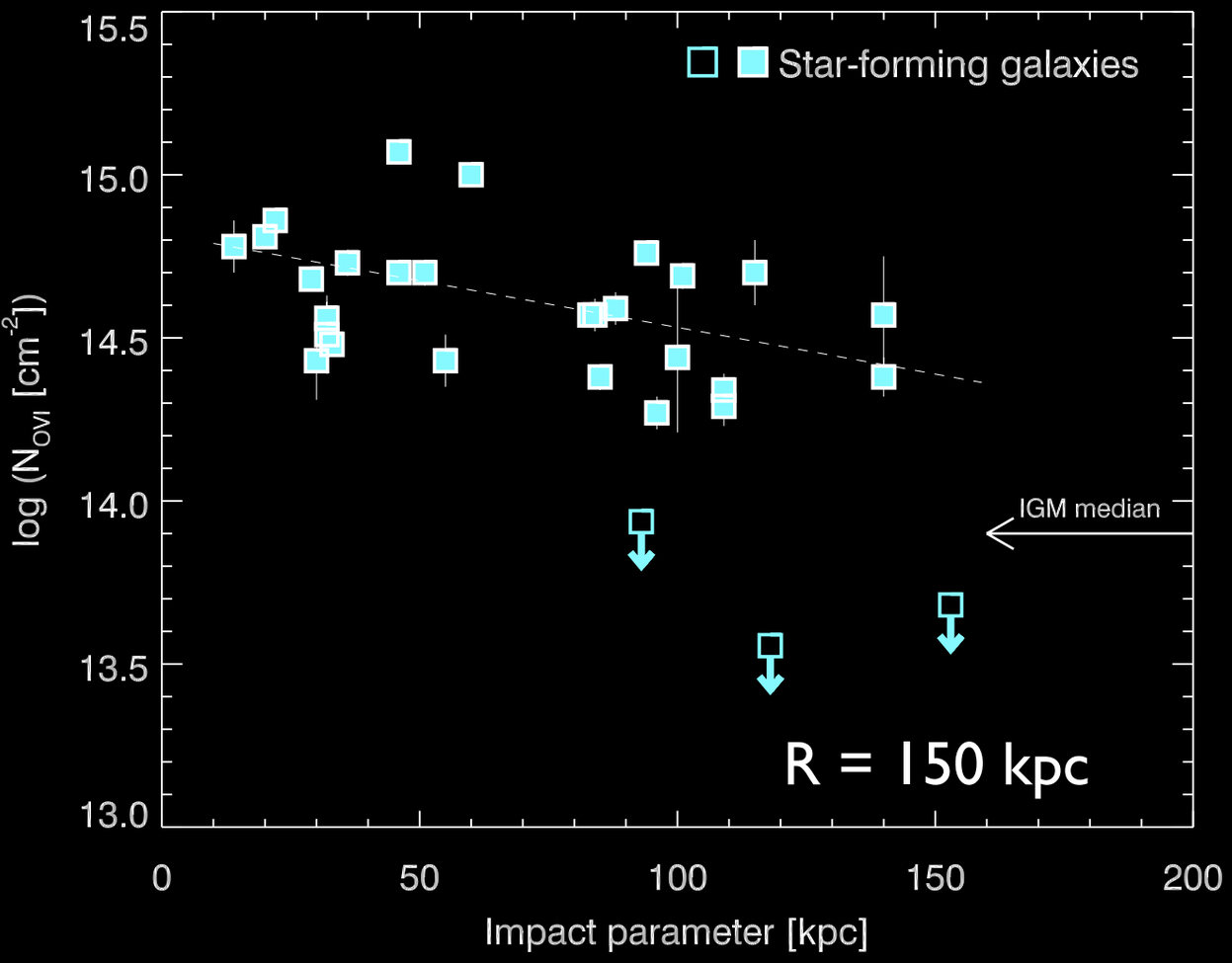


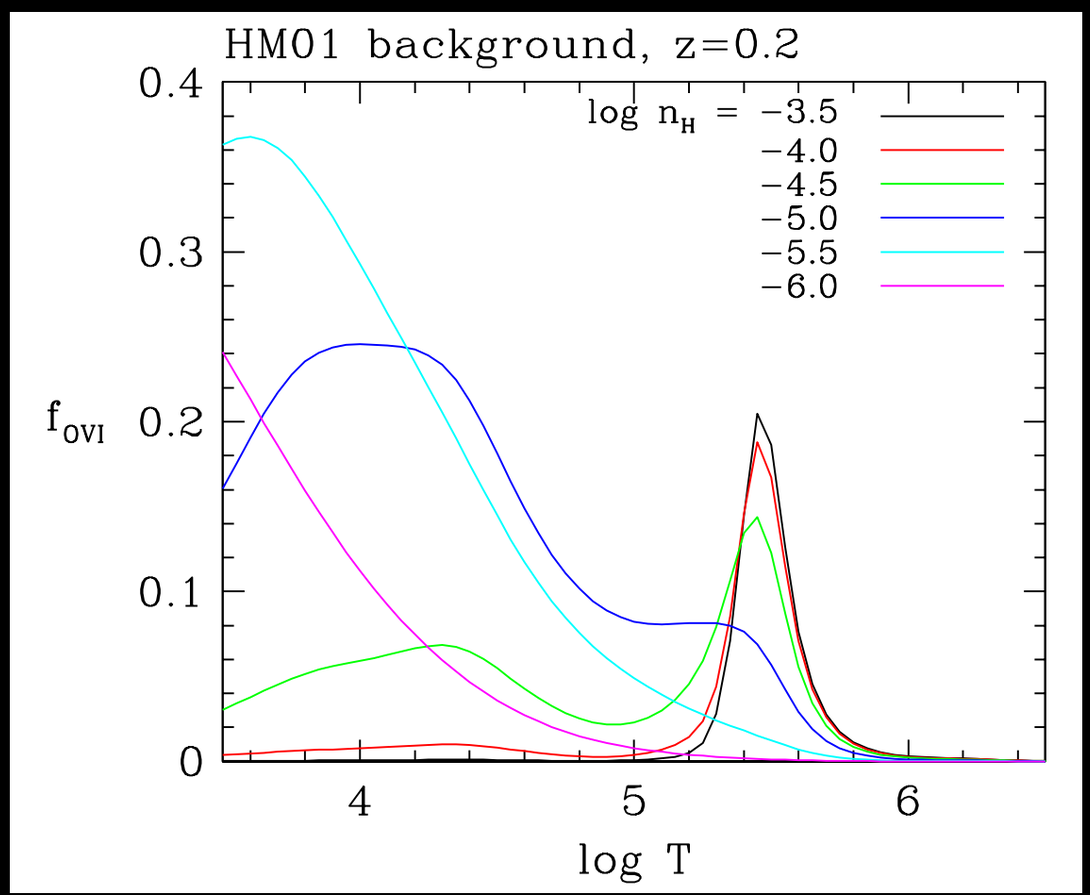
"Blue cloud" galaxies have 92% detection rate (100% inside 90 kpc)

"Red sequence" galaxies have 44% detection rate.

And much of this gas may be the extended CGM of neighbors.

Star Forming Galaxy Halos: Lots of Oxygen Mass!

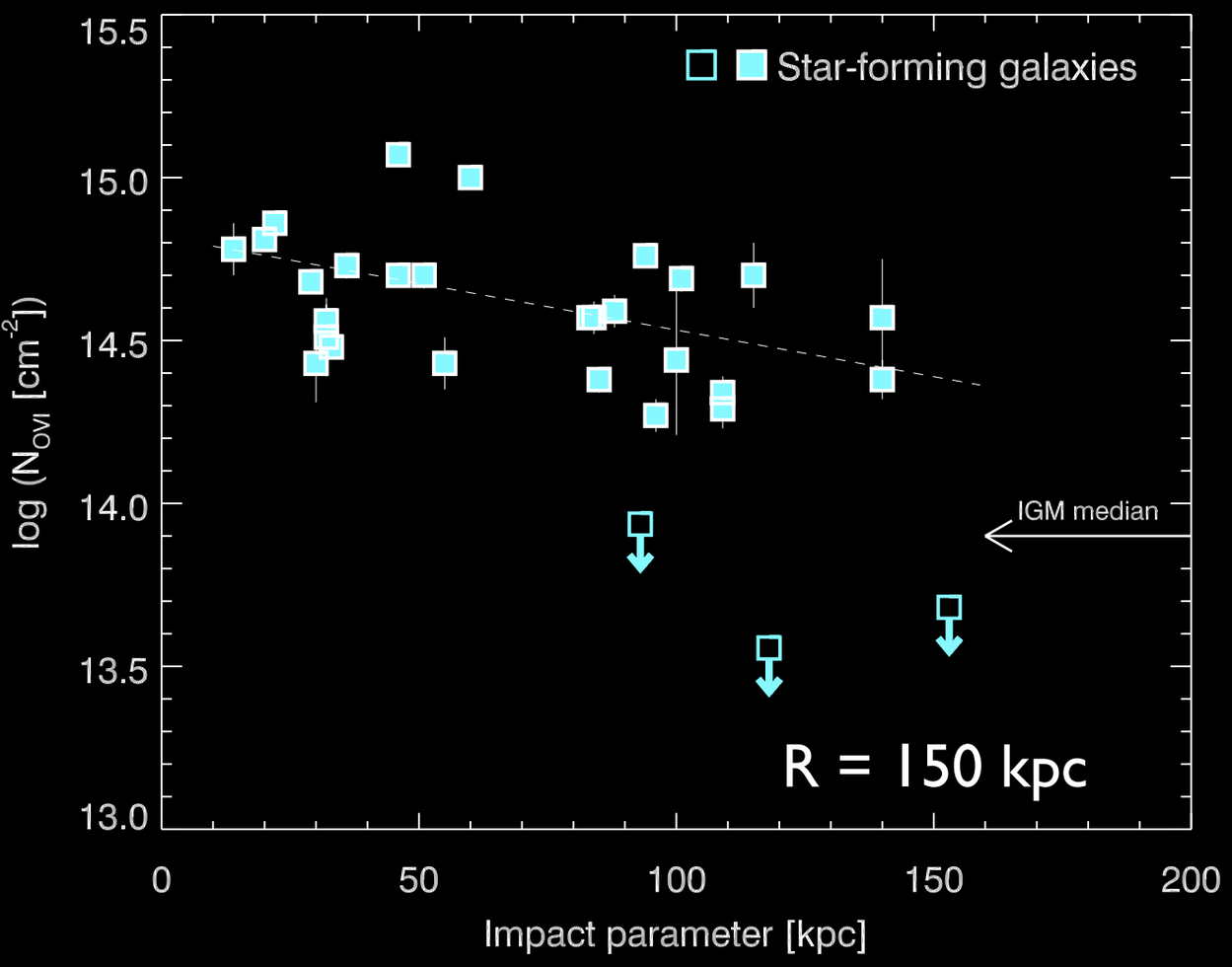


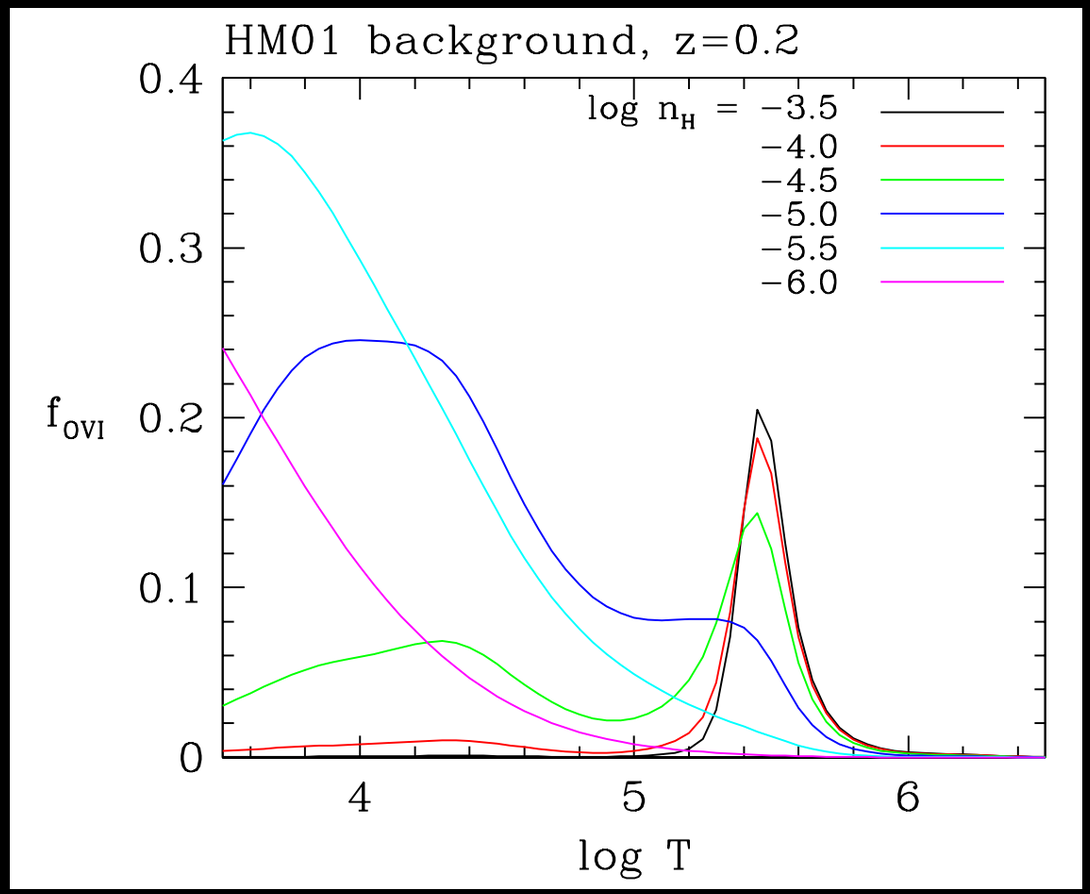


Star Forming Galaxy Halos: Lots of Oxygen Mass!

$$M_{OVI} = \pi R^2 \, N_{OVI} \, 16 m_H \, M_\odot$$

. . . then apply ionization correction f_{OVI}. . .





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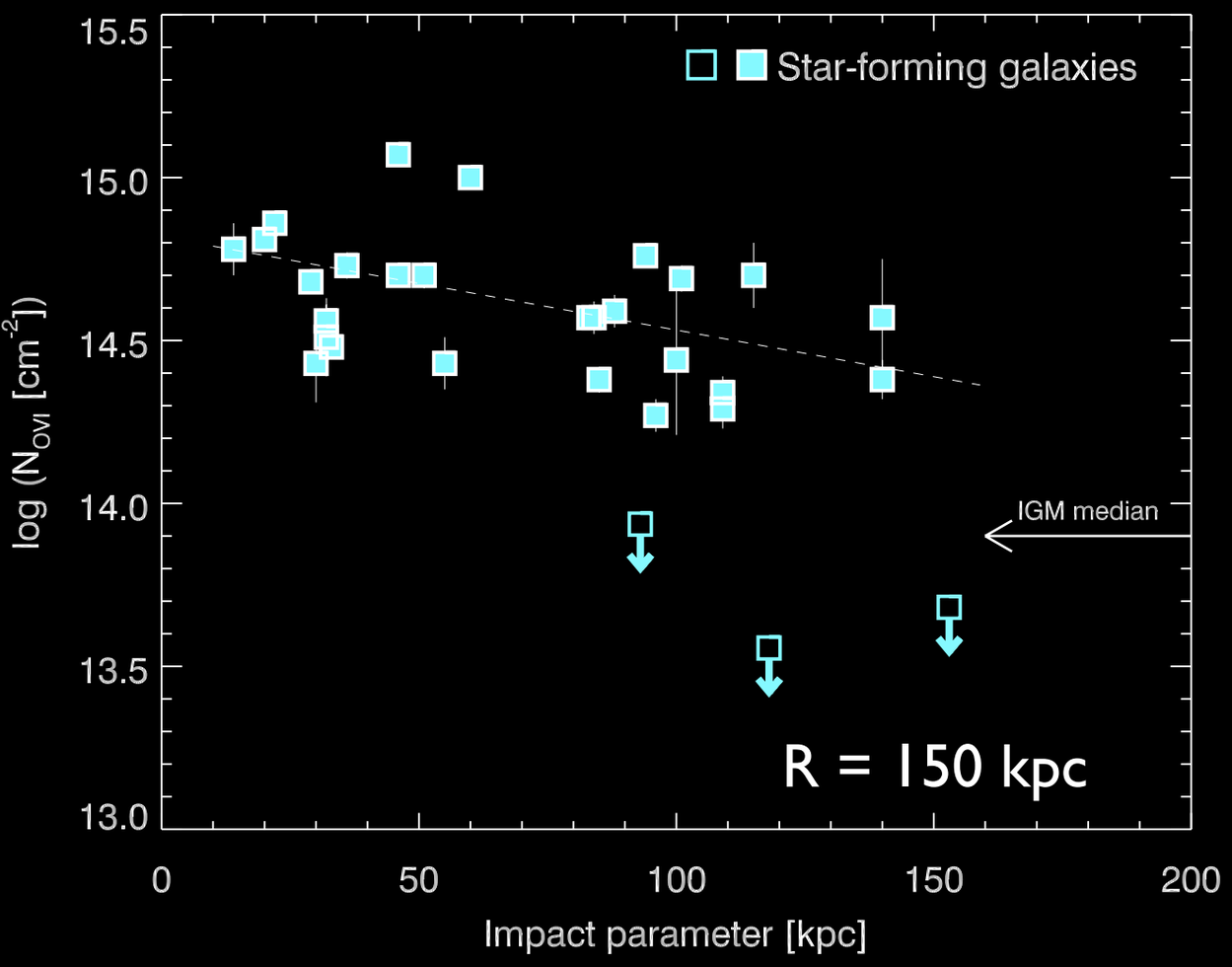
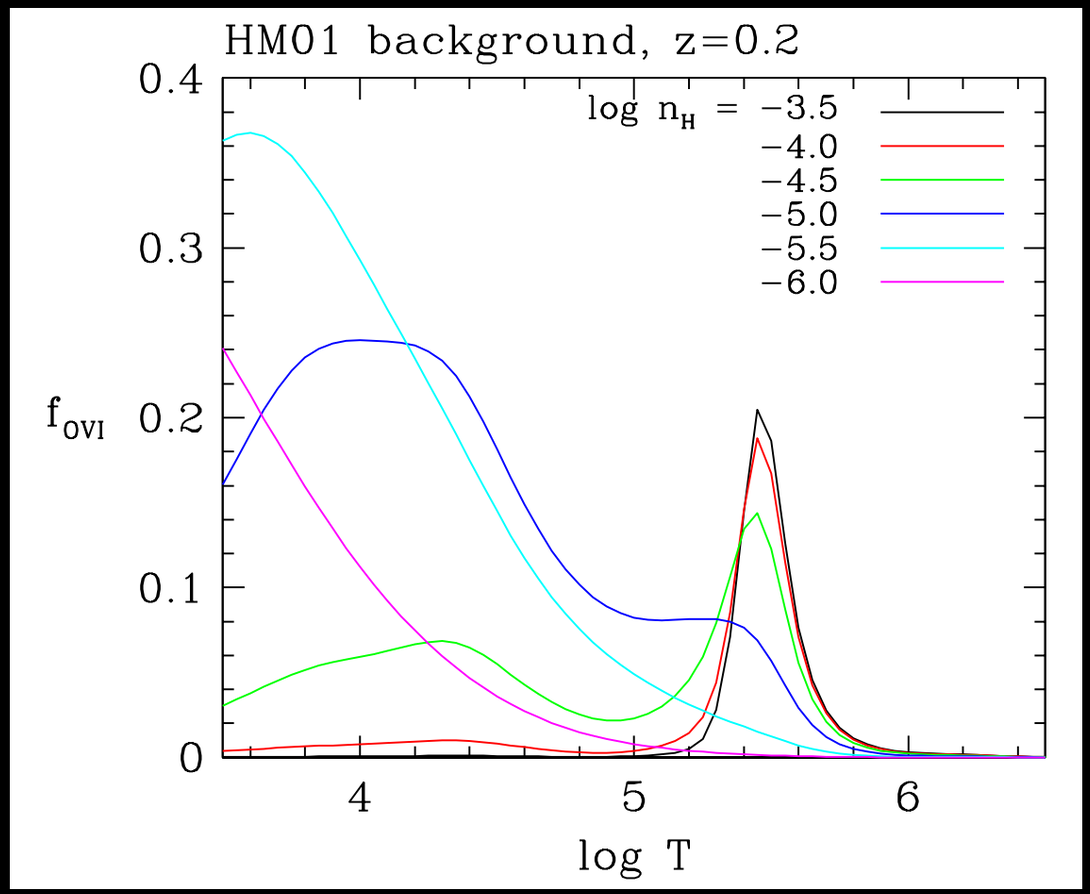
$$M_{Oxygen} = 1.2 \times 10^7\ (0.2/f_{OVI})\ M_\odot$$





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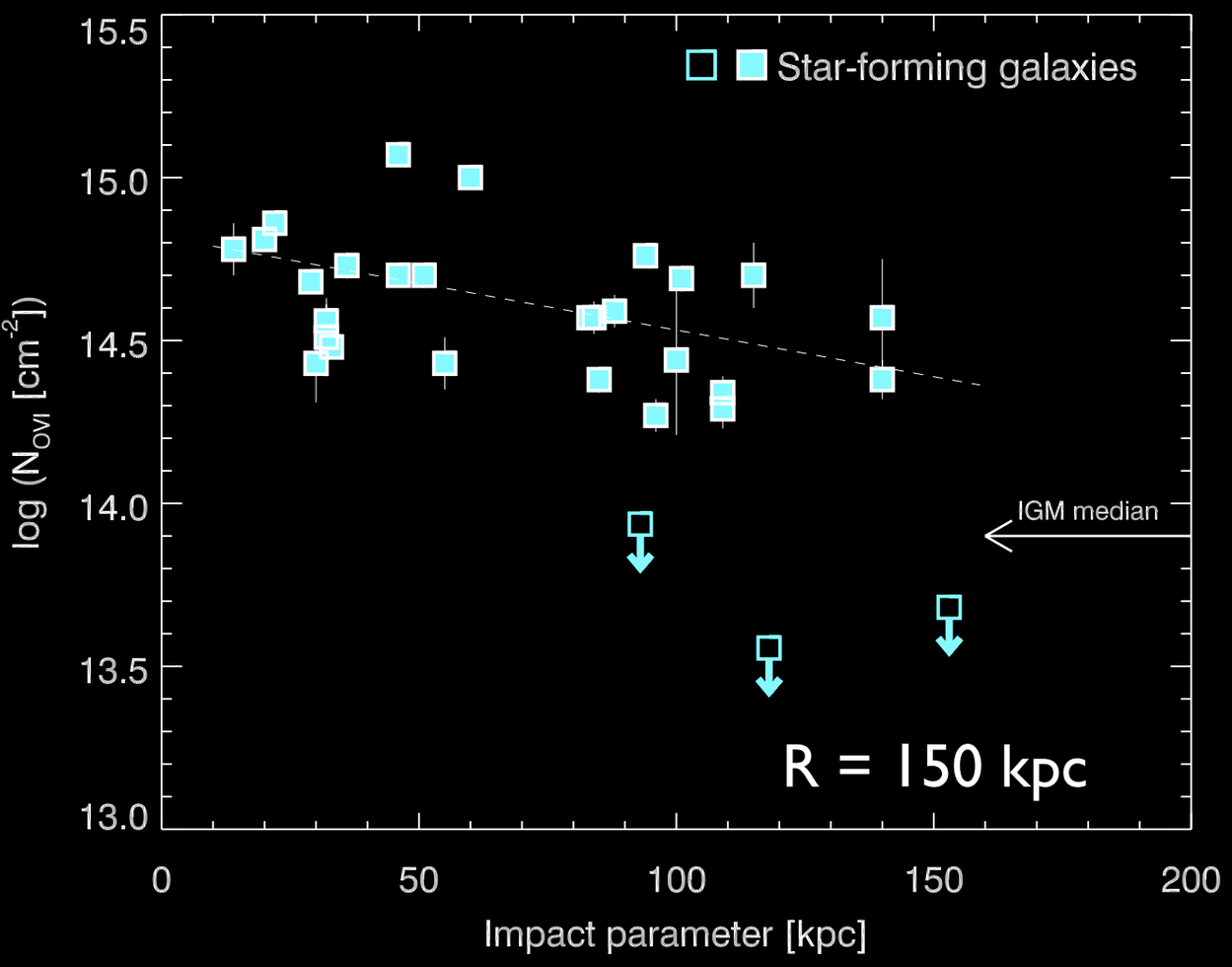

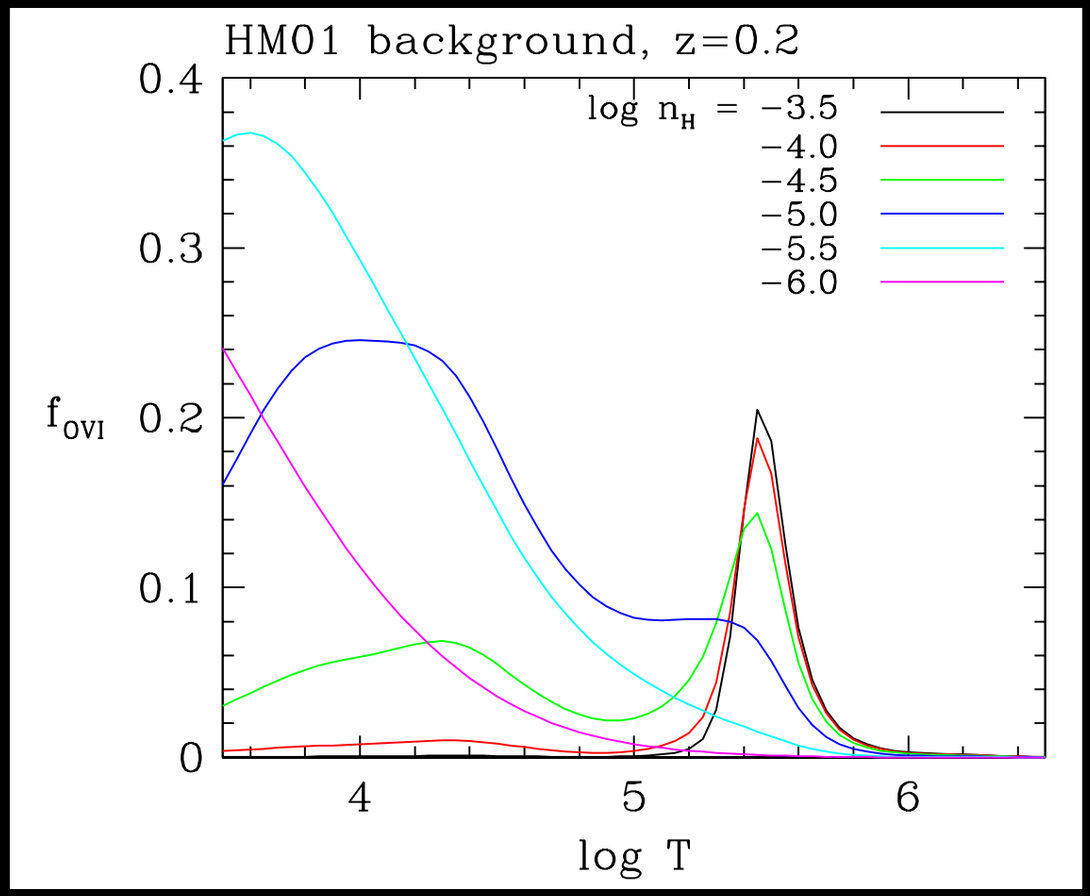

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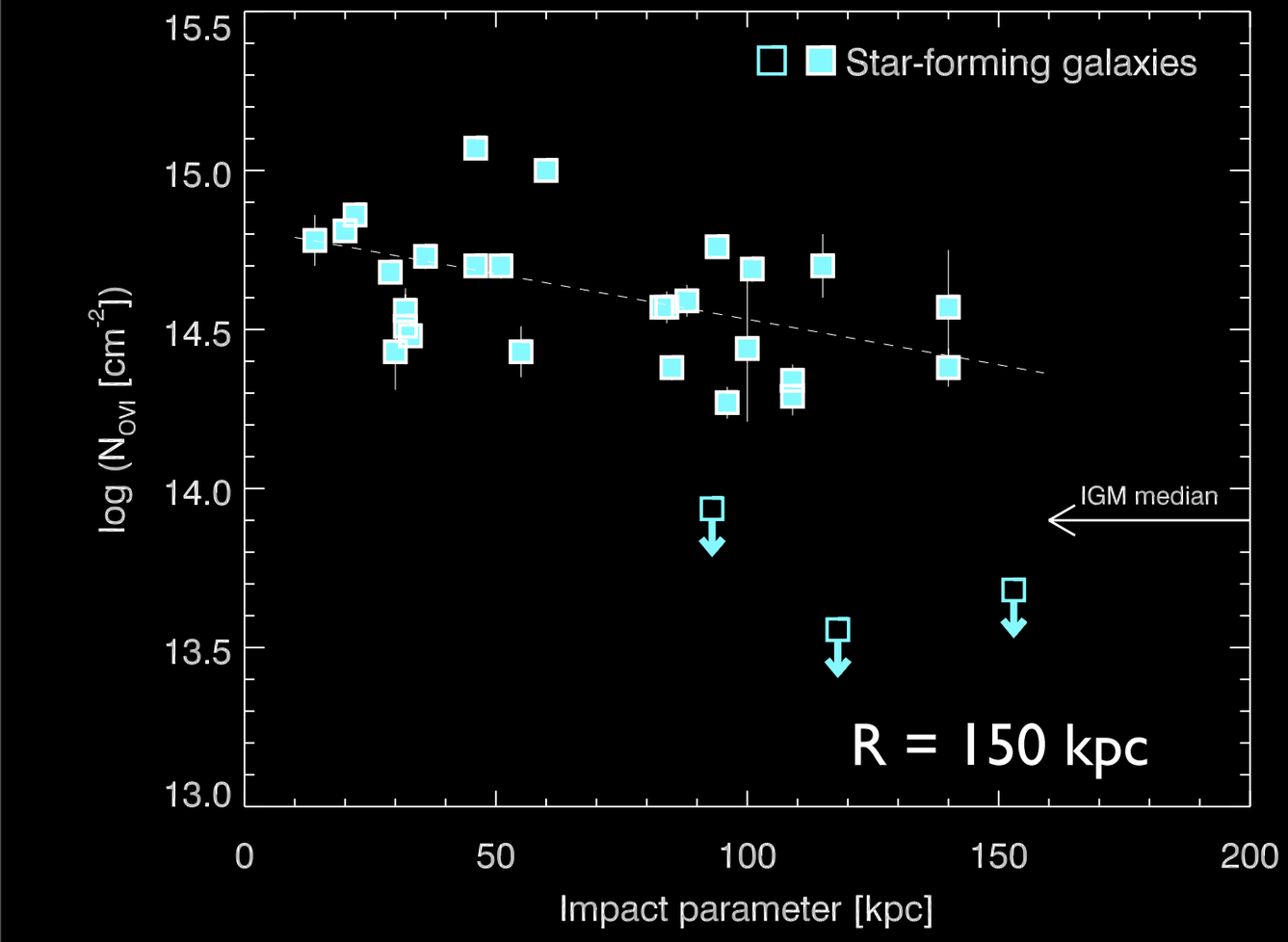
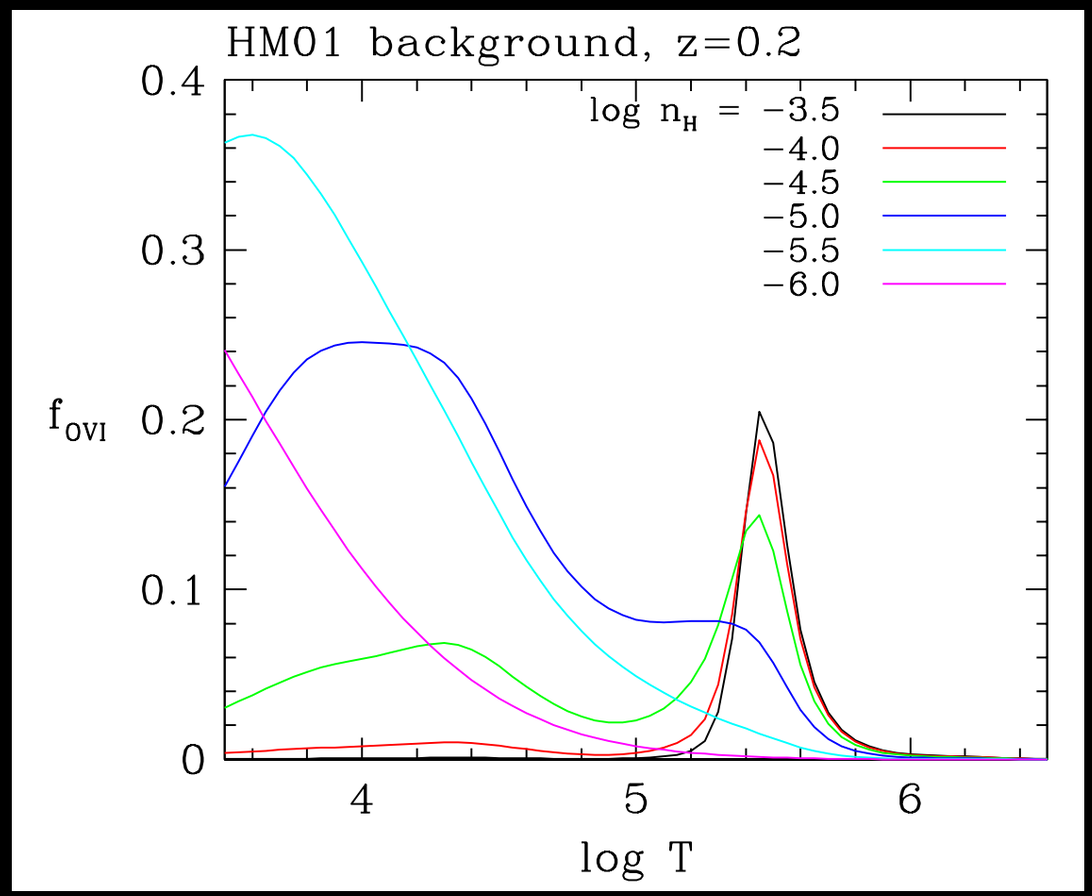
An ISM worth of metals at r~100 kpc!!

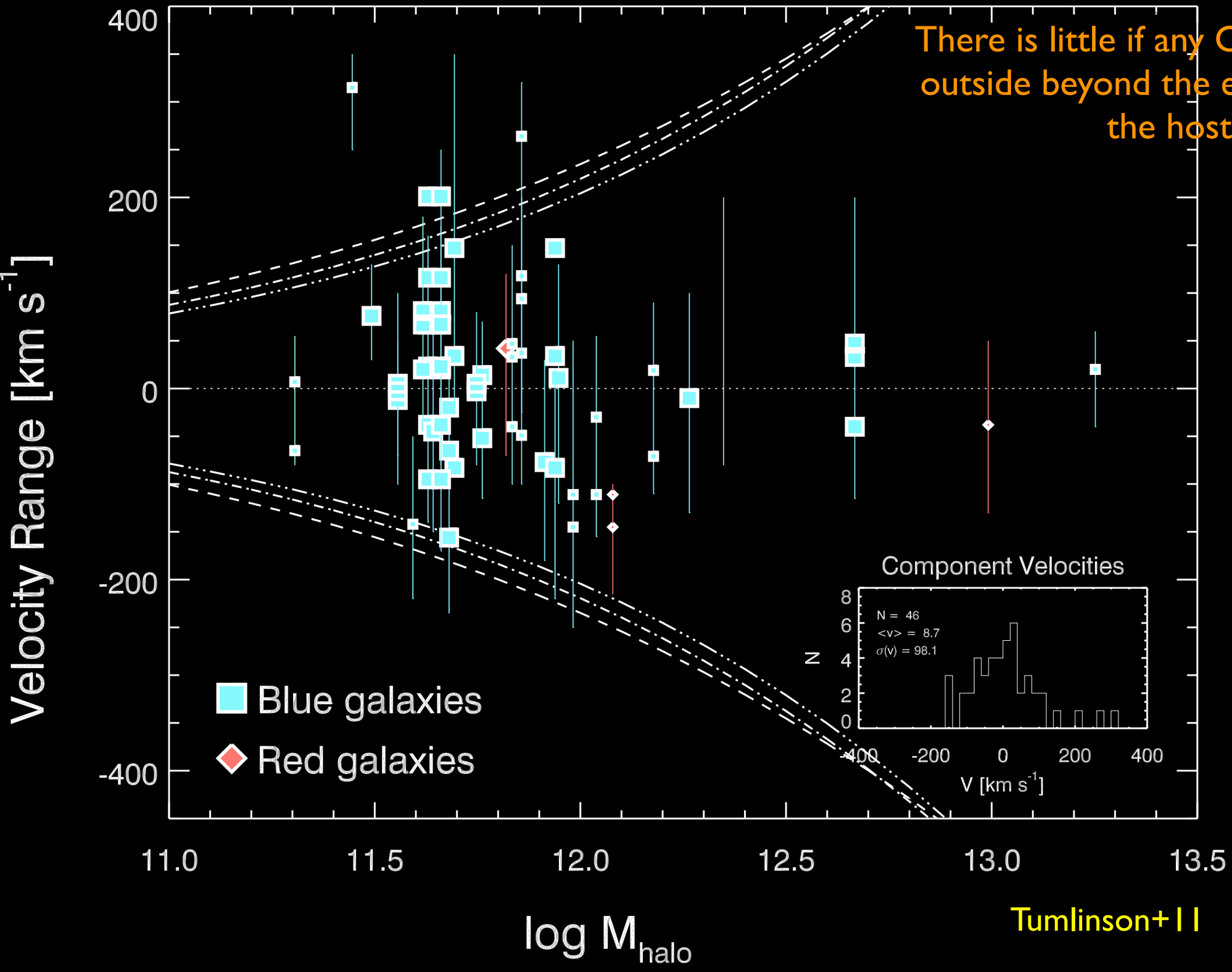




O VI Kinematics

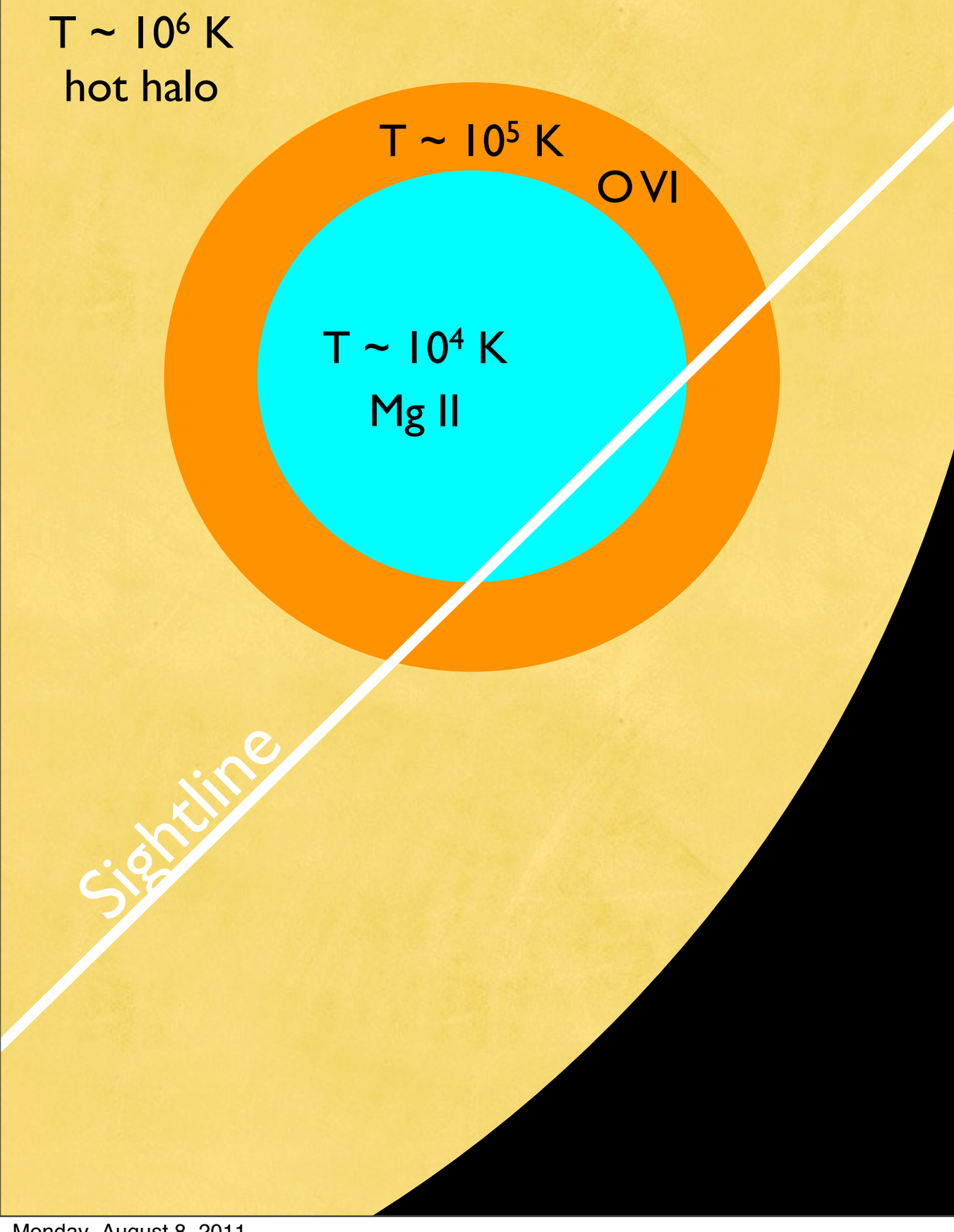
O VI gets stronger by getting broader (not by getting optically thick and saturated).

There is little if any O VI-traced material outside beyond the escape velocities of the host halos.



Tumlinson+11

Accretion Scenario for O VI?

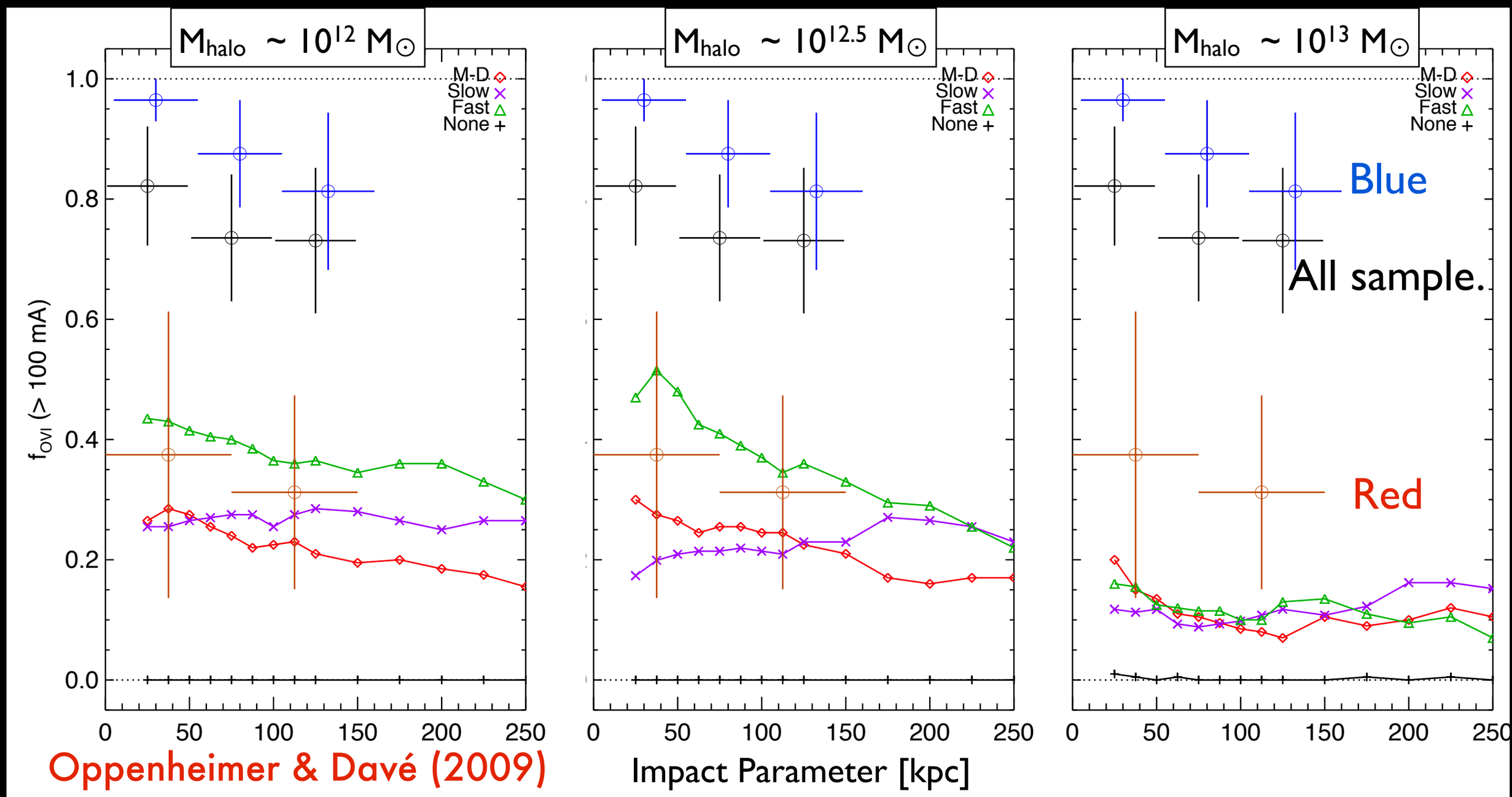


O VI can fit into the "Multiphase Accretion" scenario as the tracer of interface gas between the cooler condensed clouds and the hot coronal halo.

But the covering fraction predicted by "cold mode" or "multiphase" accretion is ~10-20%, not ~100%.

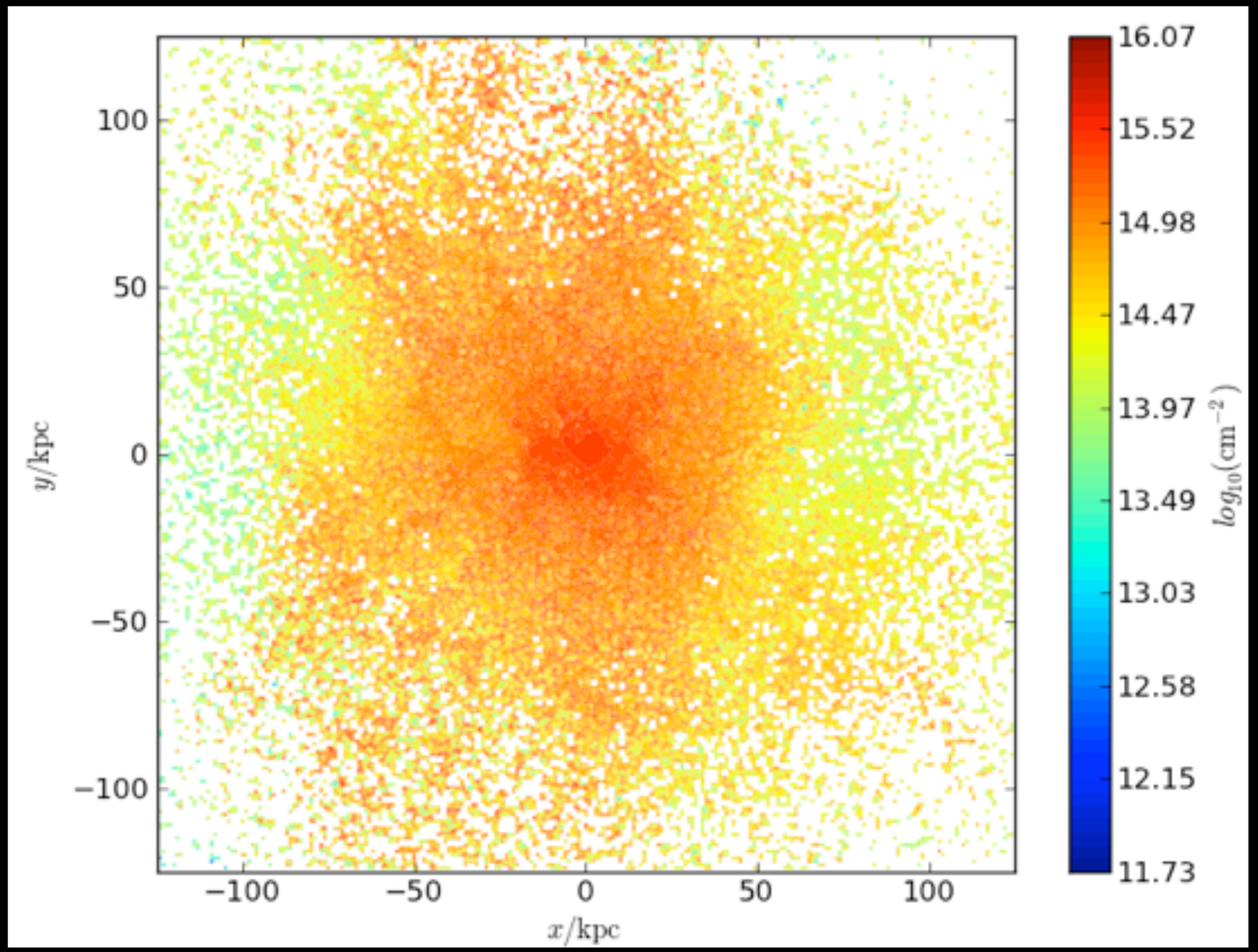
e.g. Keres & Hernquist 2009

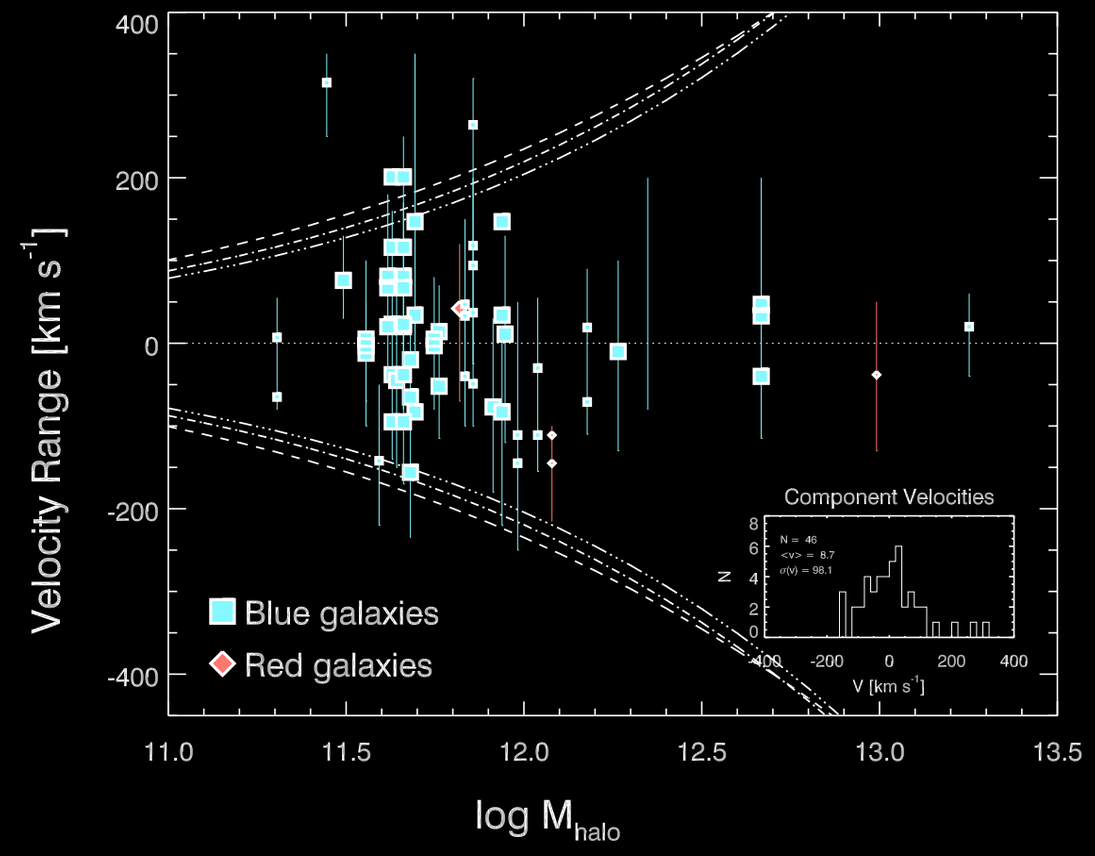
So what about active outflows?



The large oxygen mass in the ionized halos of galaxies implies at least 1 Gyr worth of star formation and oxygen yield, efficiently transported out to > 150 kpc. Current simulations – even those with extreme winds – fail to reproduce these observations.

"Recycled" winds = half of accretion at z < 1?





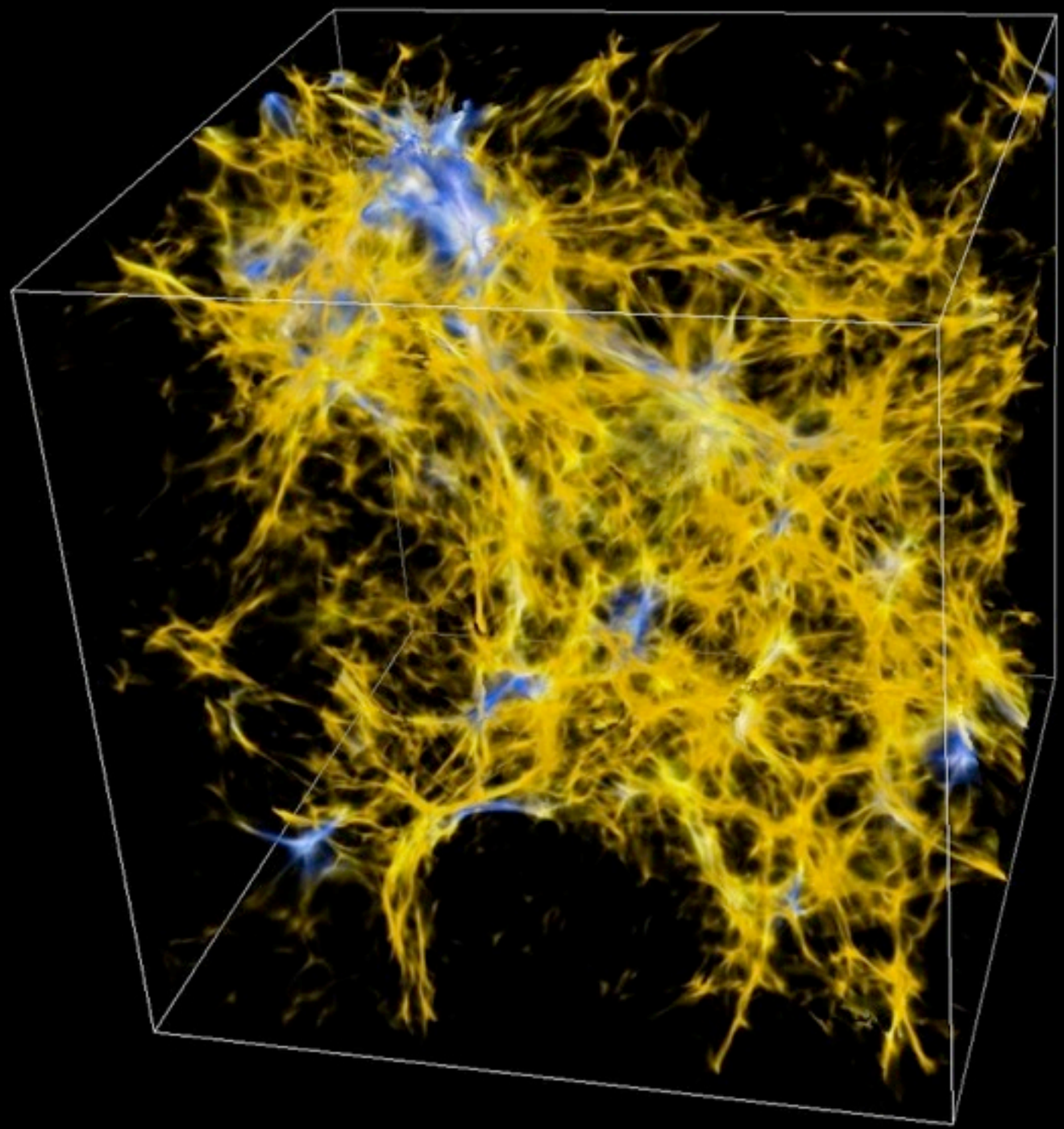
Stinson,Brook+, in prep.

The O VI we represents significant mass and metal outflow from galaxies, yet does not appear to exceed the escape velocity.

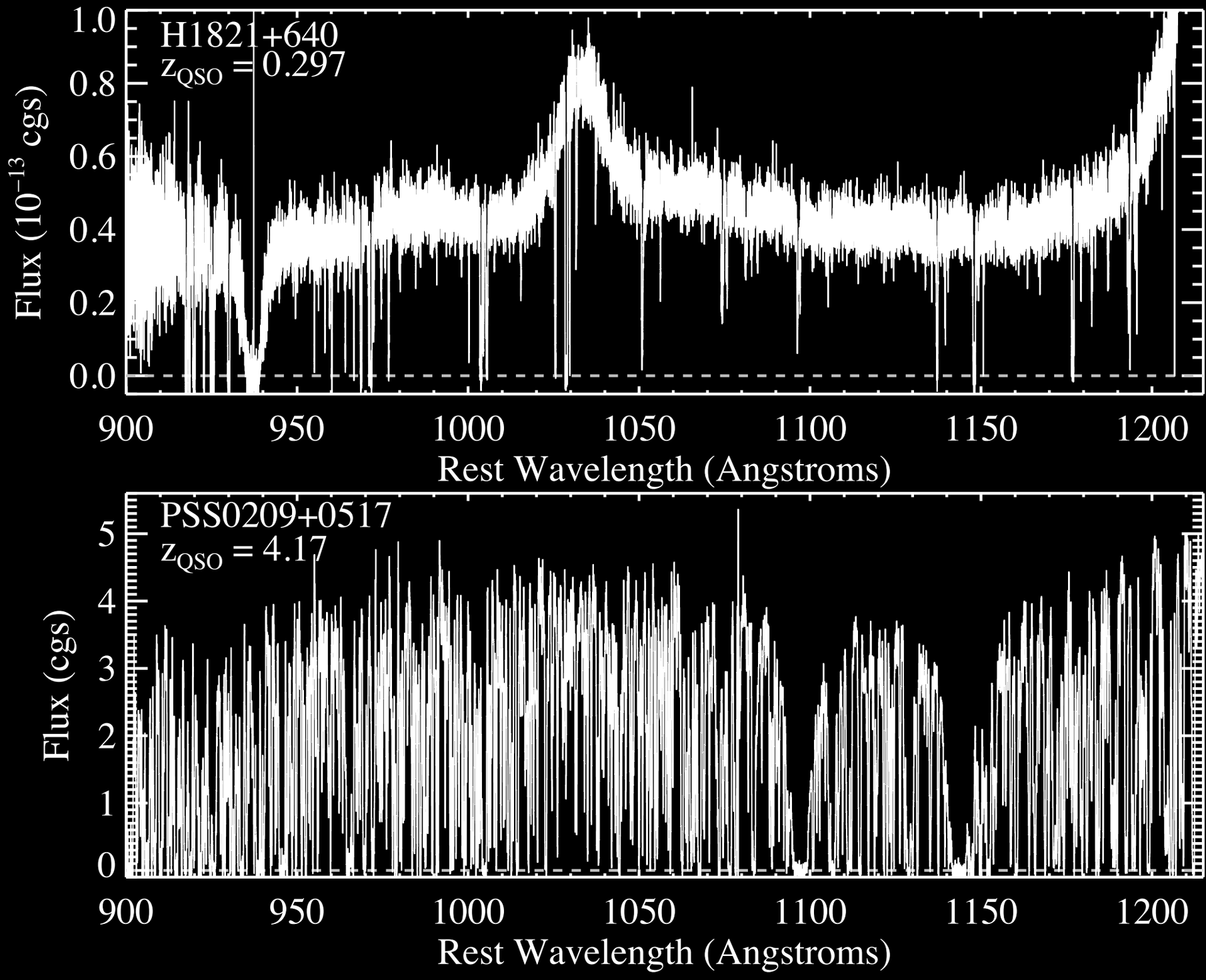
This finding is consistent with the expectation that much of z < 1 accretion is recycled outflows.

Outline: The IGM/Galaxy Connection

- IGM introduction
  - Absorption line systems
  - f(N,X), l(X)
- Exploring the CGM at z~0
  - Extended gaseous halos
  - Origin of the Lya/OVI "IGM"
- The IGM/CGM at z~2
  - Evolution?
- A few contrarian remarks on galactic-scale winds and the CGM
  - If you like..



Do these z~0 IGM/CGM Results Apply at z>1?



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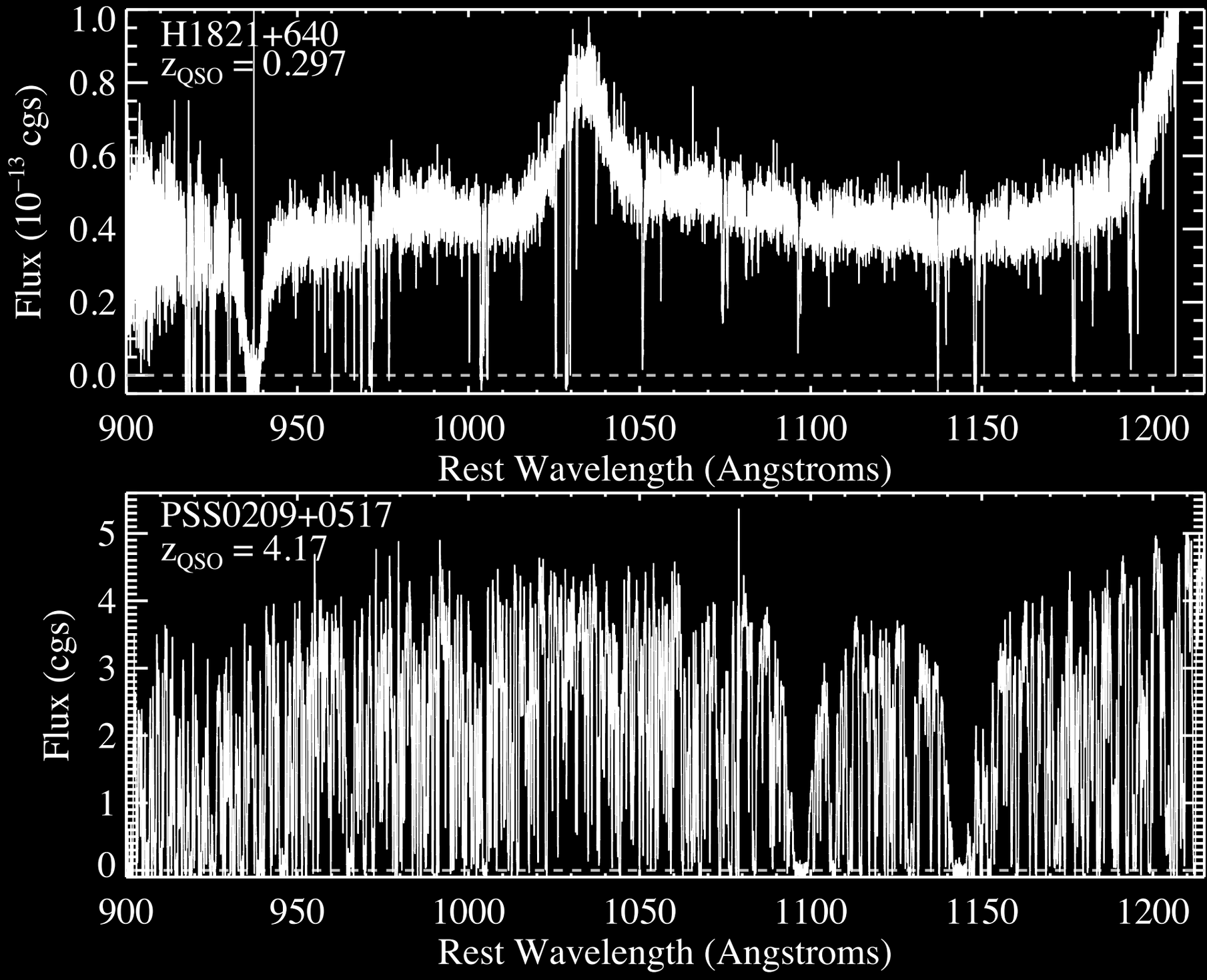
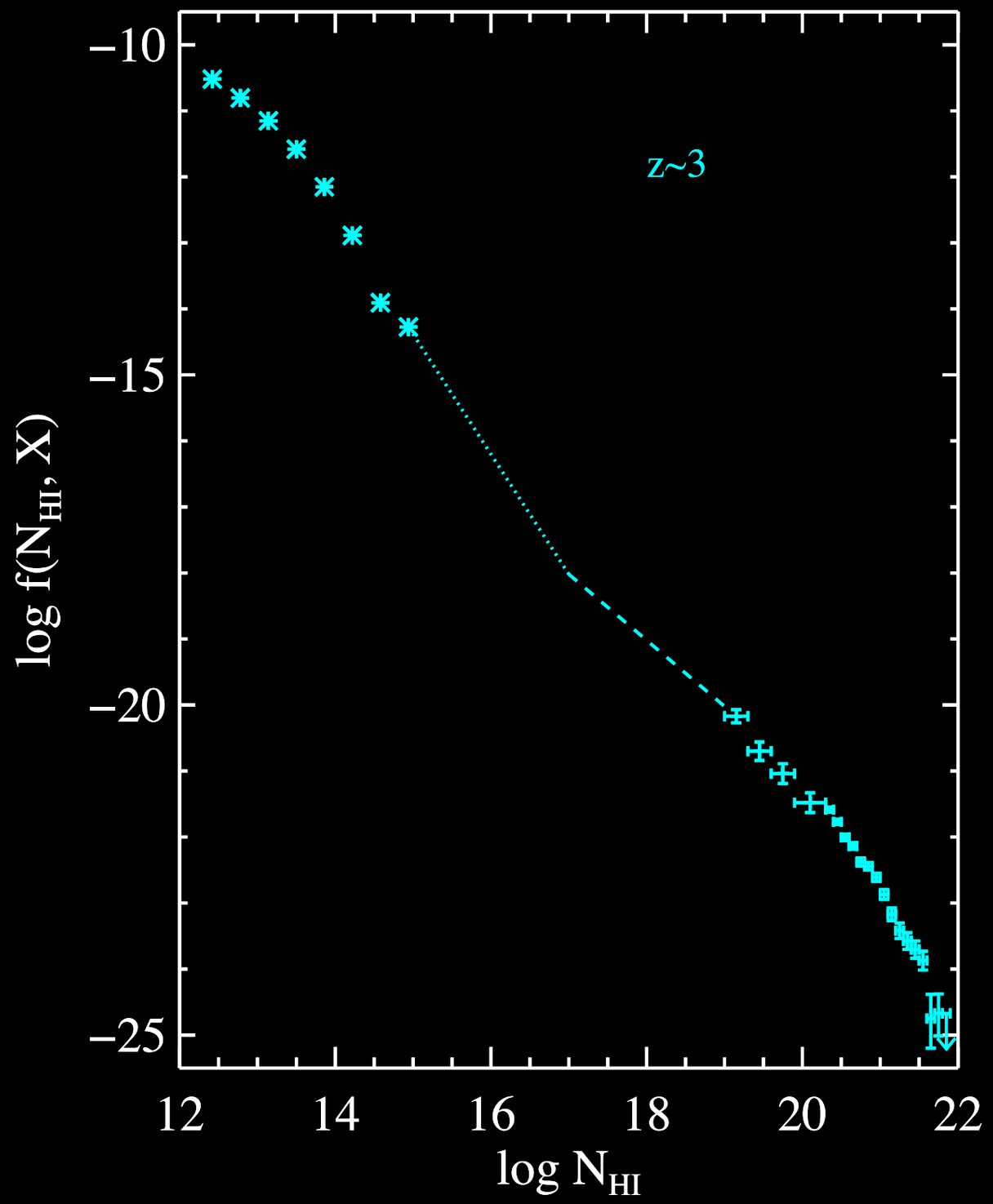


Yes, quite probably... (see Steidel+10, Rudie+11,O'Meara+12)

e.g. Halos of gas and metals around SF galaxies to r~200kpc

The IGM/Galaxy Connection at z~2

- **Lya forest**
  - Very similar f(N)
    - ✦ Mildly steeper at low z
- **ISM**
  - Same $f(N_{HI})$ distribution
    - ✦ Nearly identical HI mass density
- **CGM**
  - SF galaxies surrounded by gas and metals to ~300 kpc
    - ✦ Rudie+11
  - This includes massive galaxies (traced by quasars)
    - ✦ Hennawi+06, PH10
- **Only galaxies are changing!**



Penton+04, Lehner+07, Zwaan+05, Prochaska+05, O'Meara+06, Prochaska+10, O'Meara+11

See Altay+11 for a theoretical perspective

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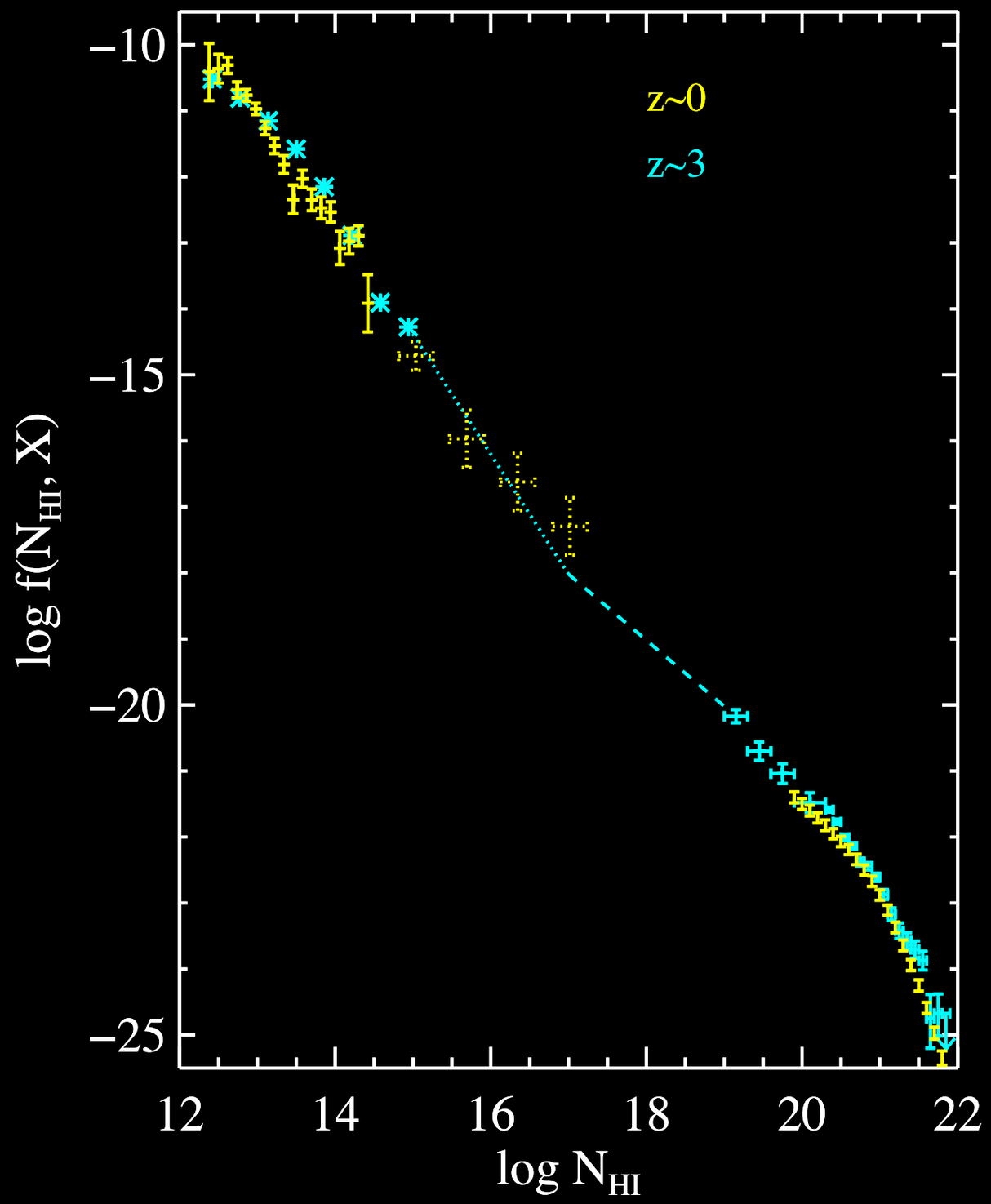

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See Altay+11 for a theoretical perspective

Summary

- "IGM"/Galaxy connection
  - Lya
    - Strong Lya lines = Galaxy CGM
    - Weak Lya lines = The proper IGM
  - OVI
    - Strong OVI lines = Galactic halos
    - Weak OVI = CGM (of sub-L*)
      - ➡ No WHIM component needed (or allowed?!)
- CGM at z~0
  - HI to 300kpc around every galaxy
    - Beyond r_{vir} for most galaxies
    - Width of cosmic web threads?
      - ➡ Less than a 1% volume filling factor
  - Baryonic Mass
    - $>3x10^{10}$ M_{Sun}
    - Most (all) of the 'missing' galactic baryons
  - Metals (L* galaxies)
    - Strong OVI around SF galaxies
      - ➡ Equivalent to an ISM mass
    - Substantial metal transport (recently?)
      - ➡ Stay tuned for more HST/COS results
- IGM/CGM at high z (vs low z)
  - Similar f(N,X) distributions
    - Remarkably little evolution in the IGM over 10 Gyr
  - CGM
    - Also is qualitatively similar
- Key open questions
  - What/when transported the metals?
  - Does the CGM balance the galactic baryon budget?
  - Is there any major evolution outside galaxies (and clusters) from z=3?