On the (Non)Evolution of HI "Disks" over Cosmic Time

J. Xavier Prochaska

UCO/Lick Observatory

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

"The Swimming Pool Theory of Galaxy Formation"

A.M. Wolfe (UC San Diego)

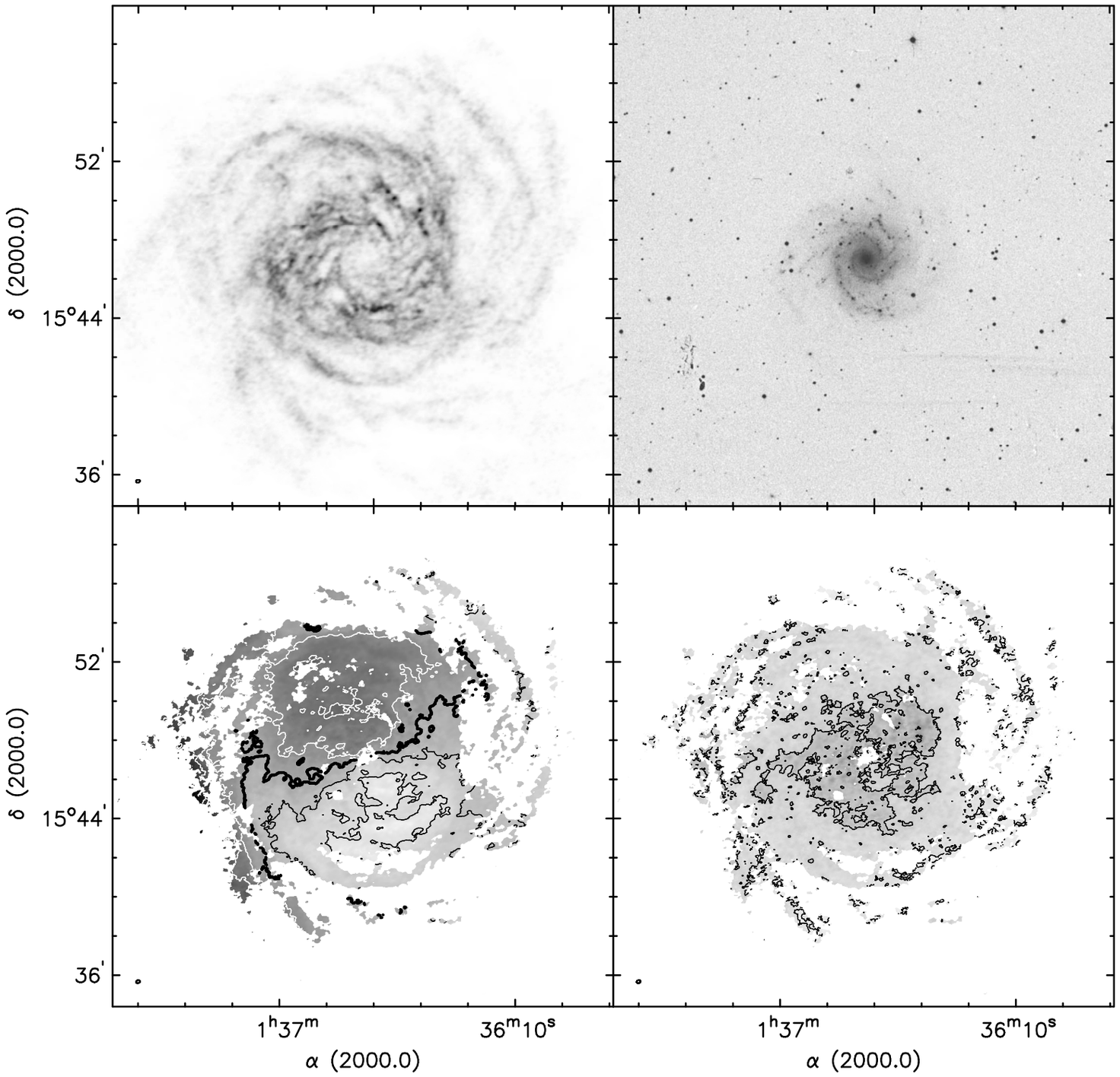
S. Herbert-Fort (Arizona)

Overview

- Goal: Discuss the global evolution of HI in galaxies across cosmic time
  - Secondary: Provide introduction for talks that follow

- Motivation
  - HI gas feeds star formation (via H_2)
    - ✦ Total HI content is a balance between SF, accretion, and 'feedback'
  - HI is a signpost for recent/current/future SF
  - The 'Cosmic' Schmidt Law

21cm HI Maps



THINGS: Walter+ 2008

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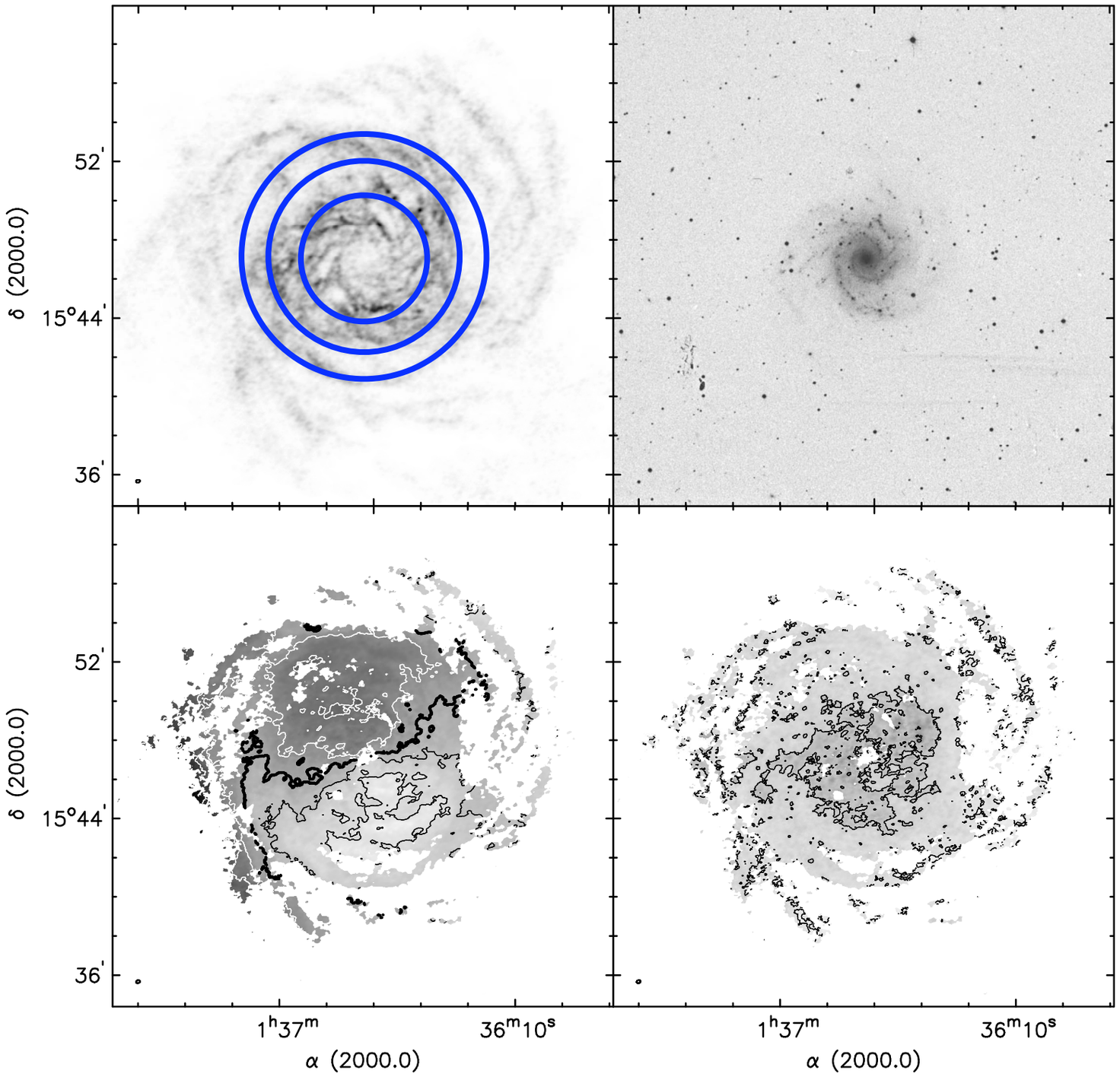
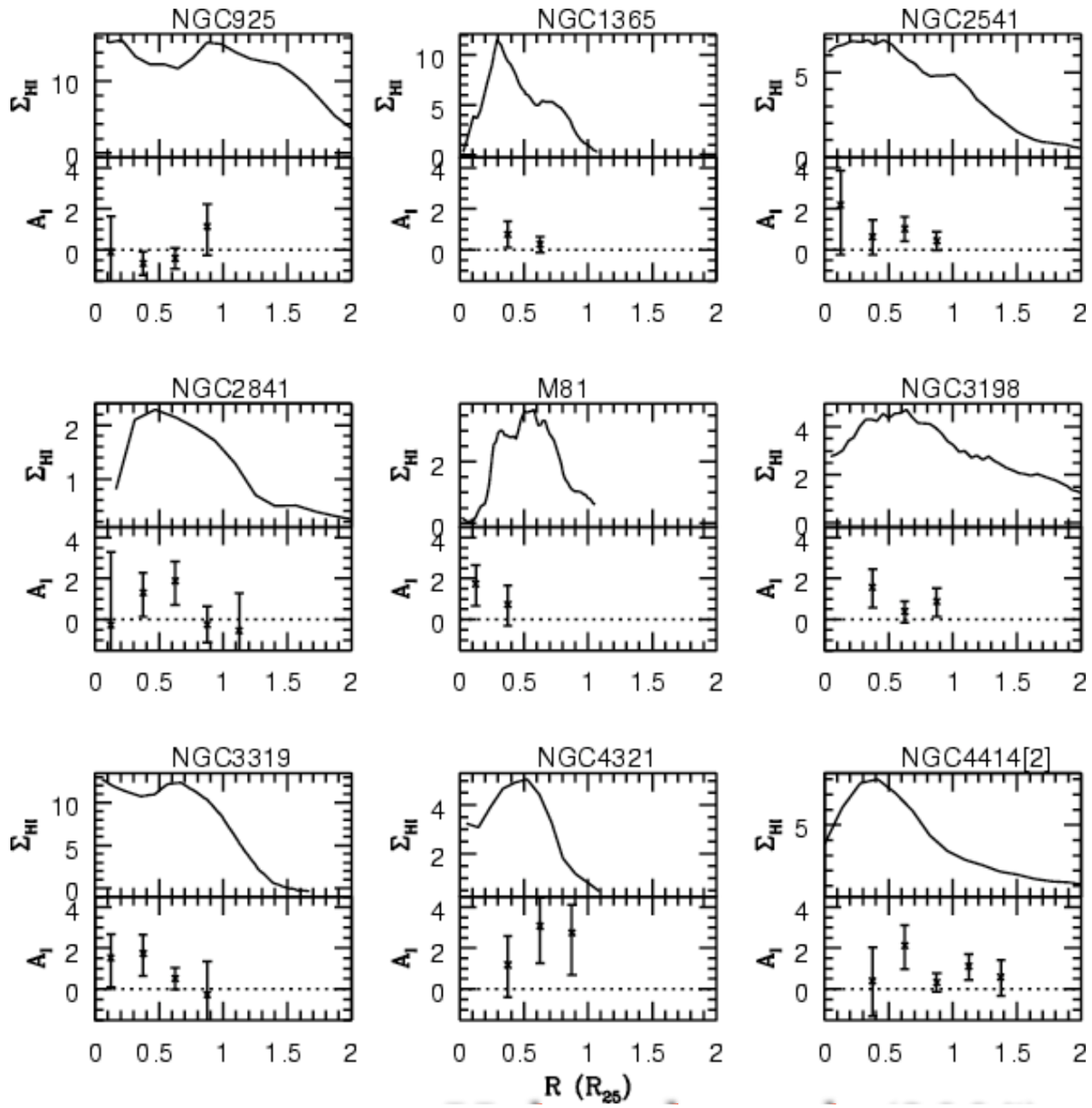


THINGS: Walter+ 2008

Galactic Σ_{HI} Profiles

- Analysis
  - De-projection by inclination
  - Average azimuthally
  - Plot
- Common characteristics
  - HI 'holes' at the center
  - Steep decline for $R<R_{25}$
  - Power-law (Metsel) beyond

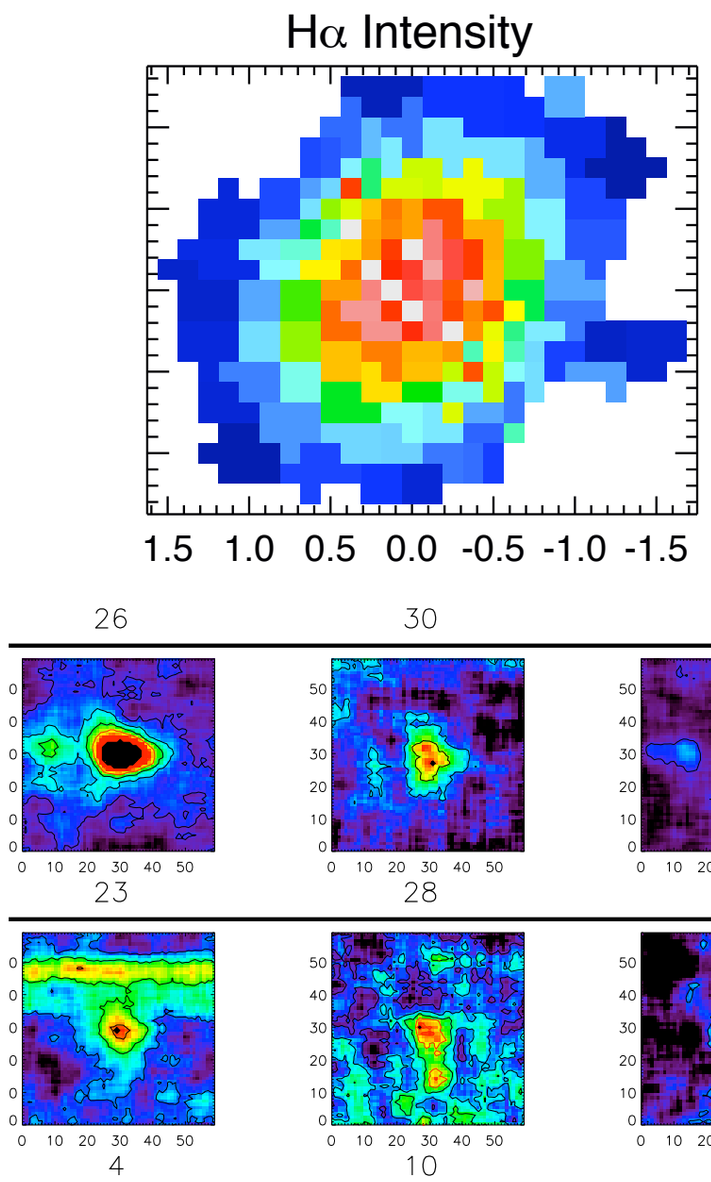


HOLWERDA+ 2005

Mapping HI at z>0

- 21cm?
  - Not with today's telescopes
  - SKA (i.e. >2020)
- Hα, Lyα
  - Difficult observations
  - Primarily trace ionized H gas
    - But connected to atomic/molecular gas
- HI?
  - Lyα absorption

SHAPIRO+ 2008



RAUCH+ 2008

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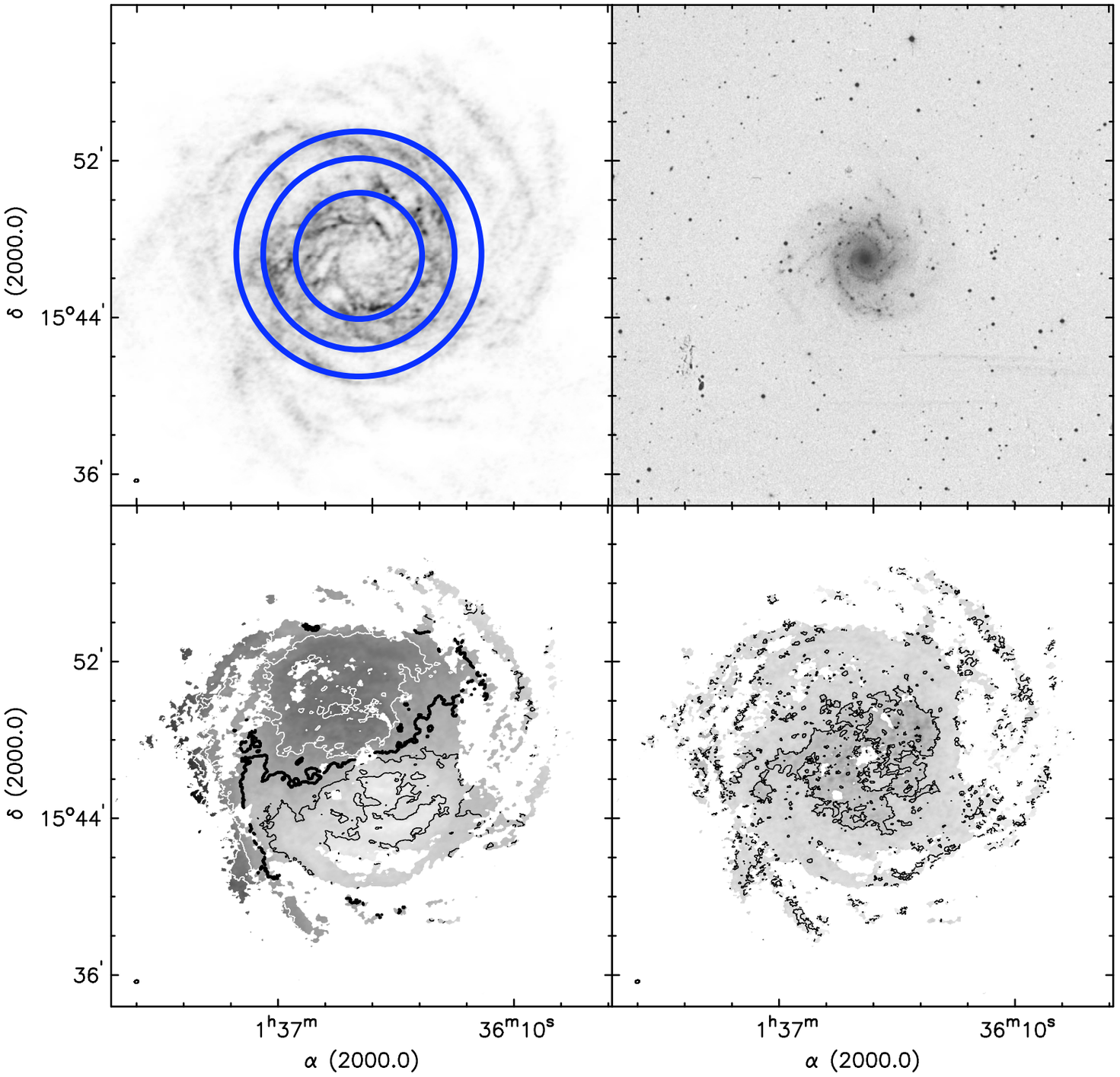
52'
15°44'
36'
δ (2000.0)
1h37m
36m10s
α (2000.0)
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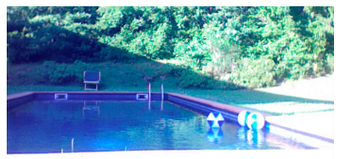

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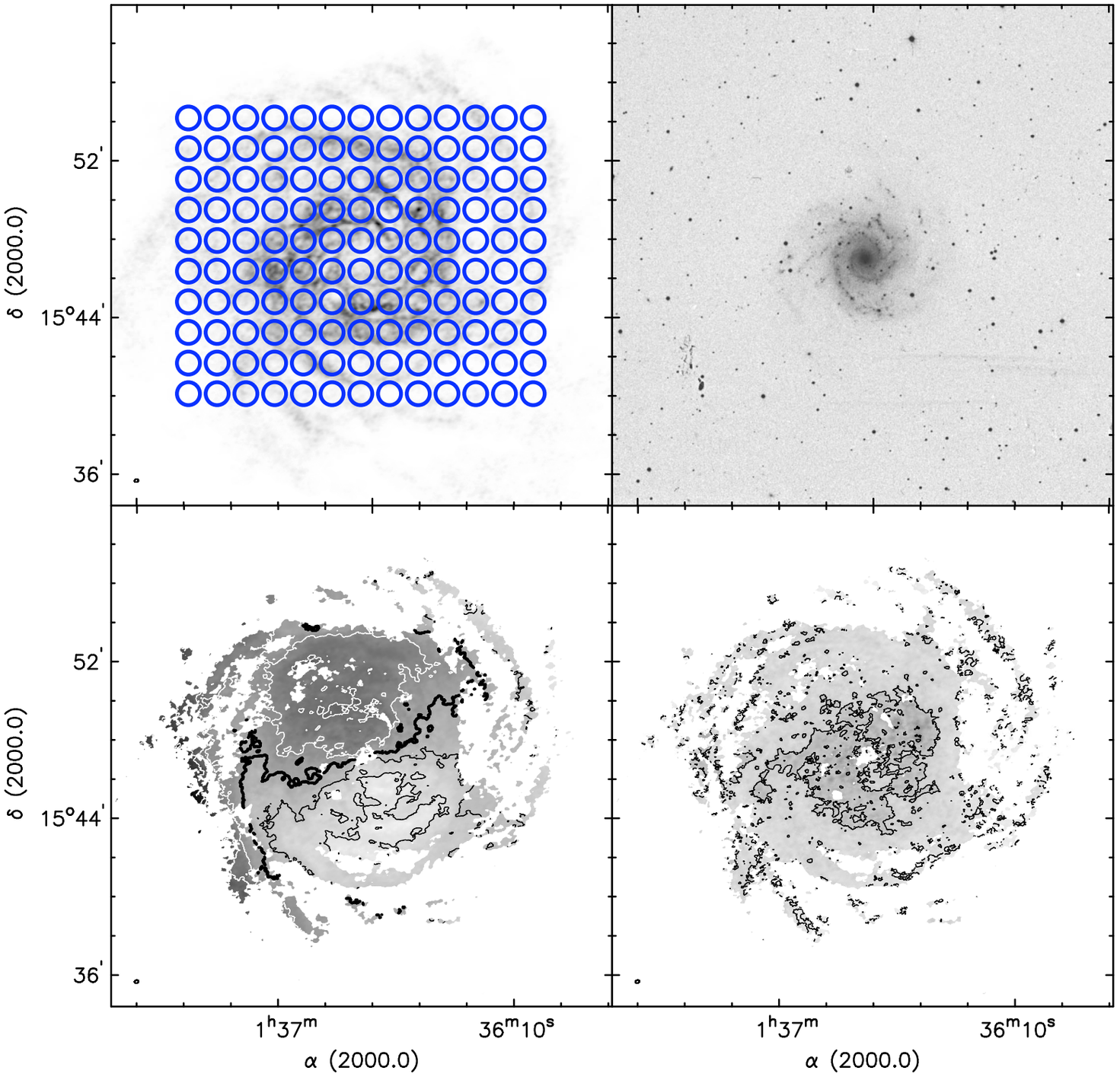
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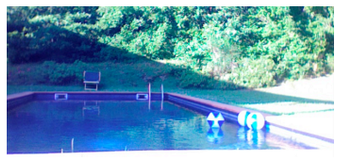

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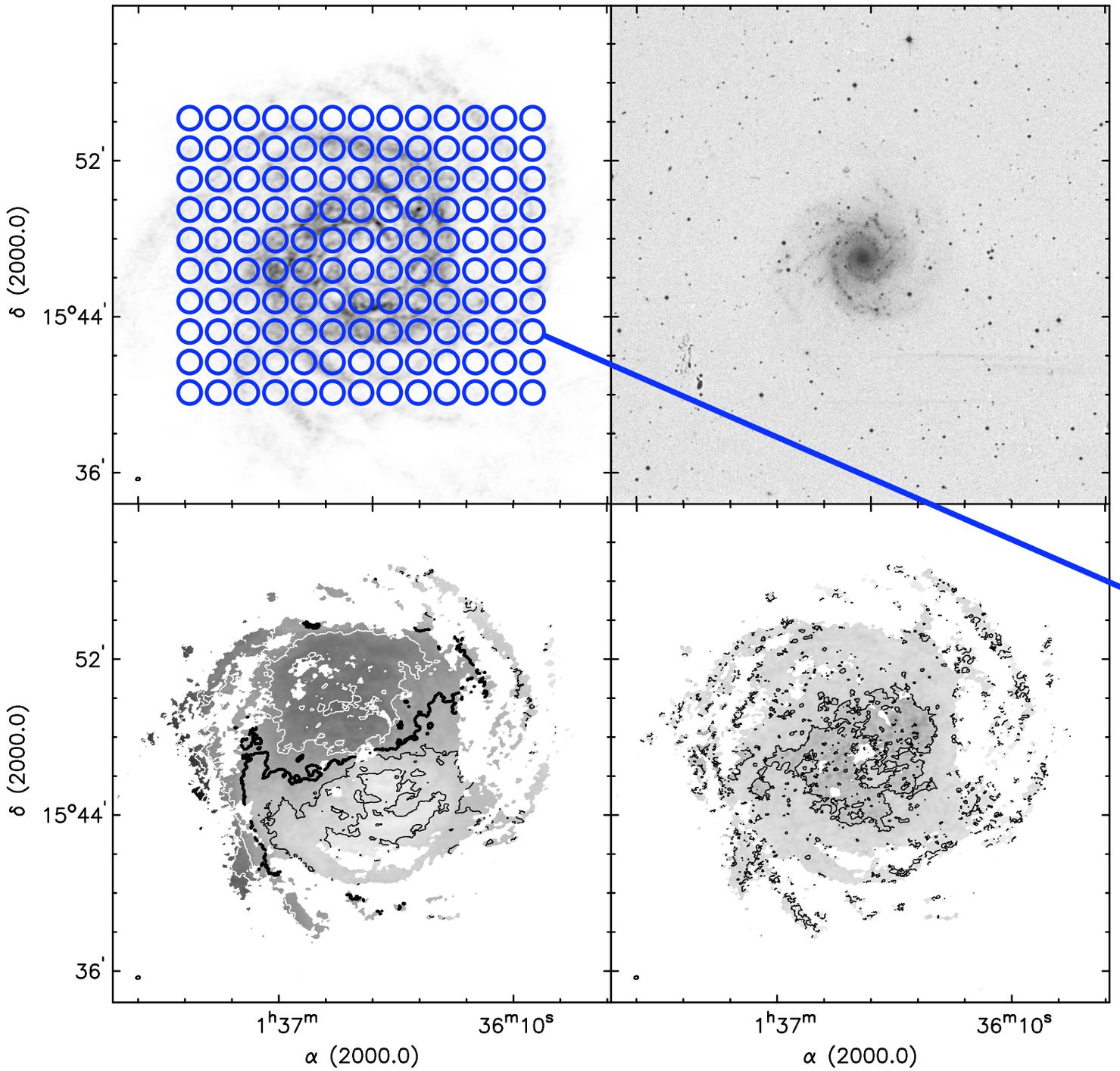
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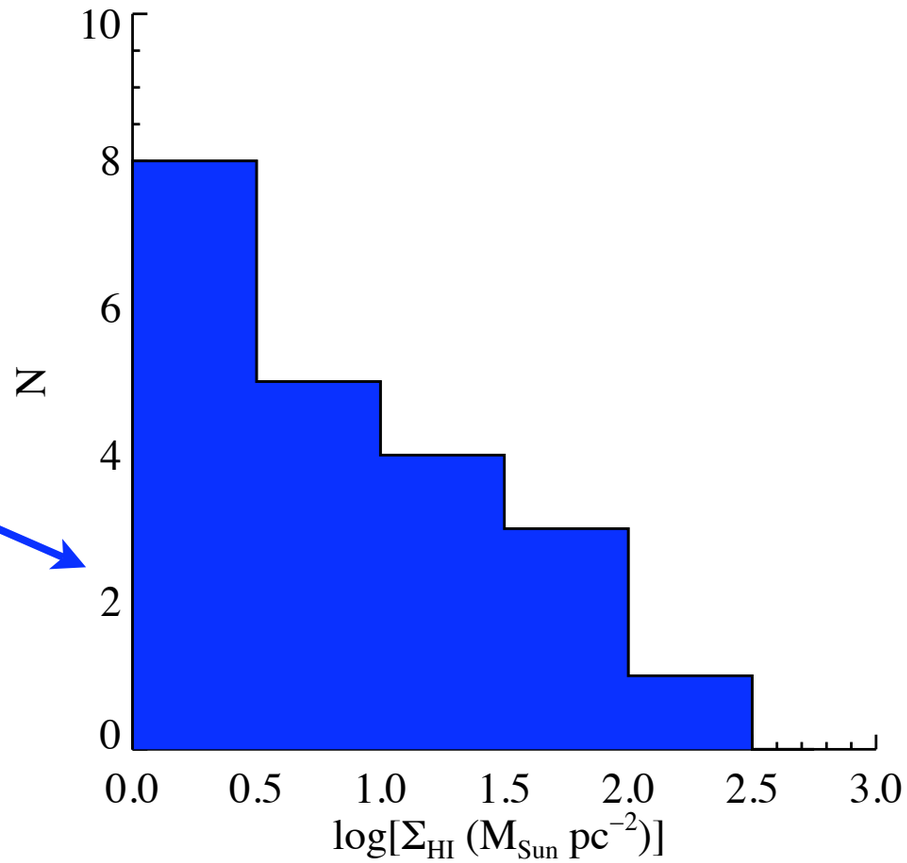
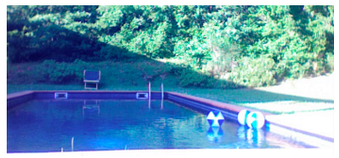
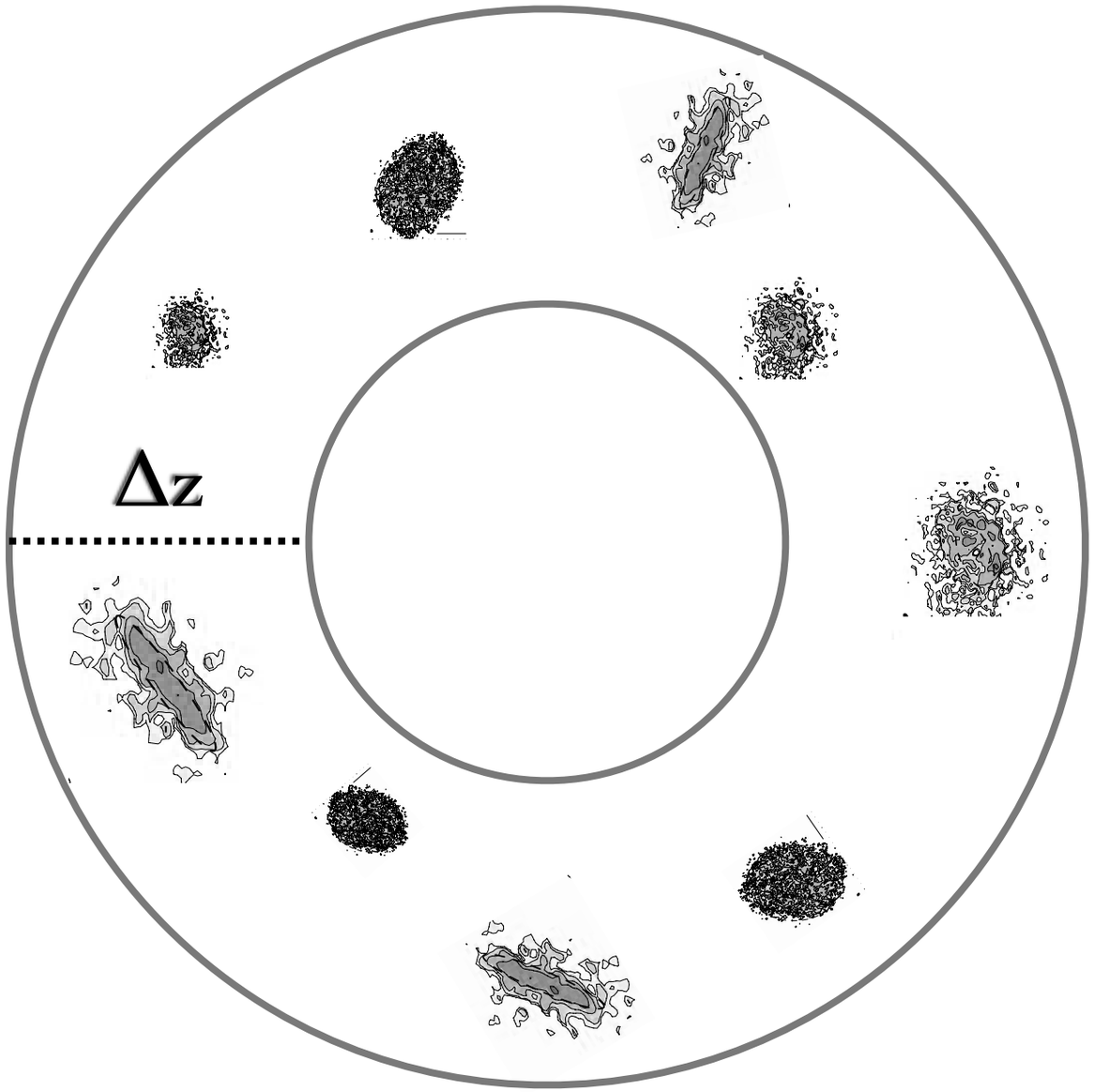

N
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
log[Σ_HI (M_Sun pc^-2)]



$f(N_{HI})$: Definition

10^{21} cm^{-2} = 8 M_{Sun} pc^{-2}



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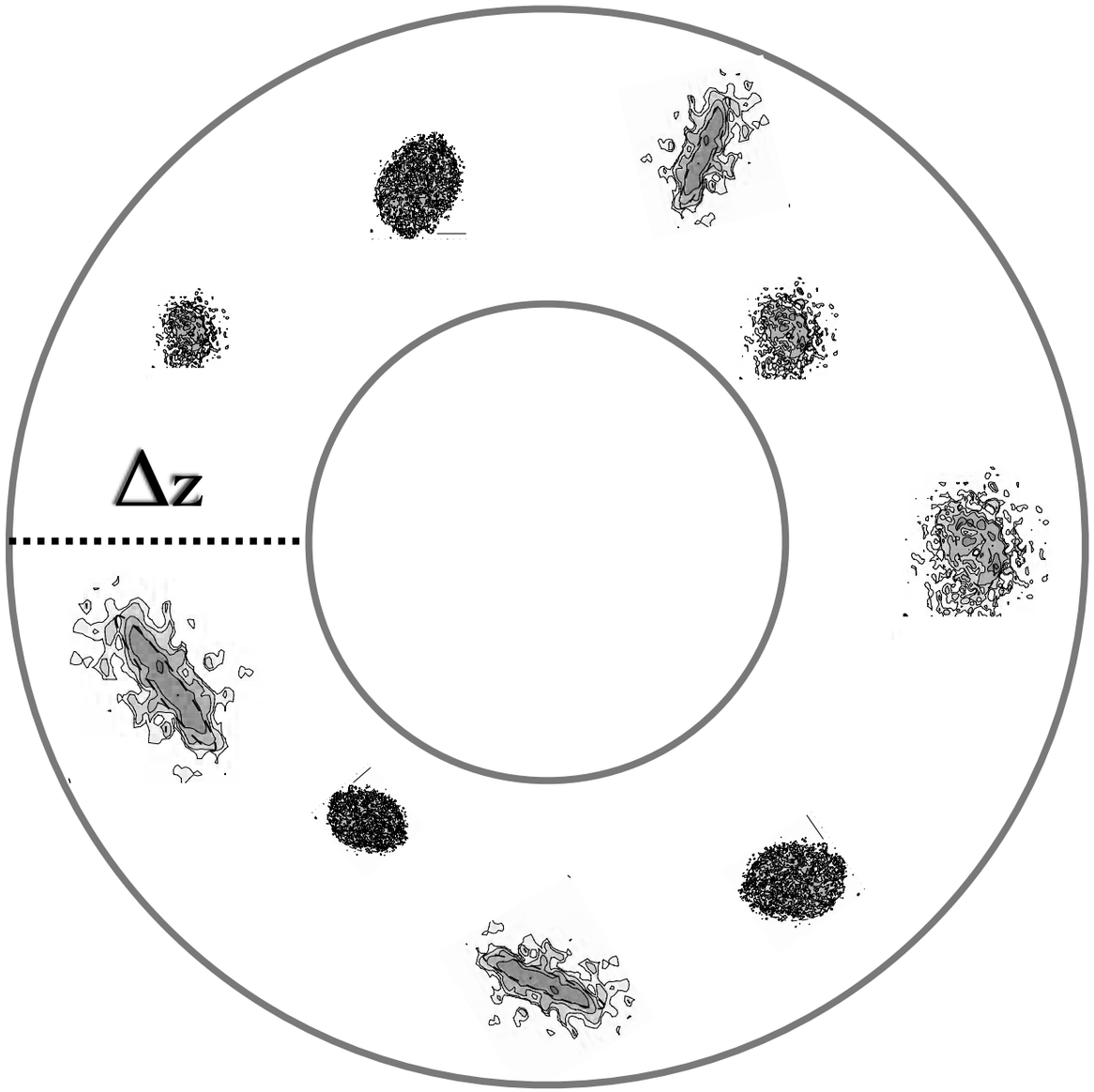

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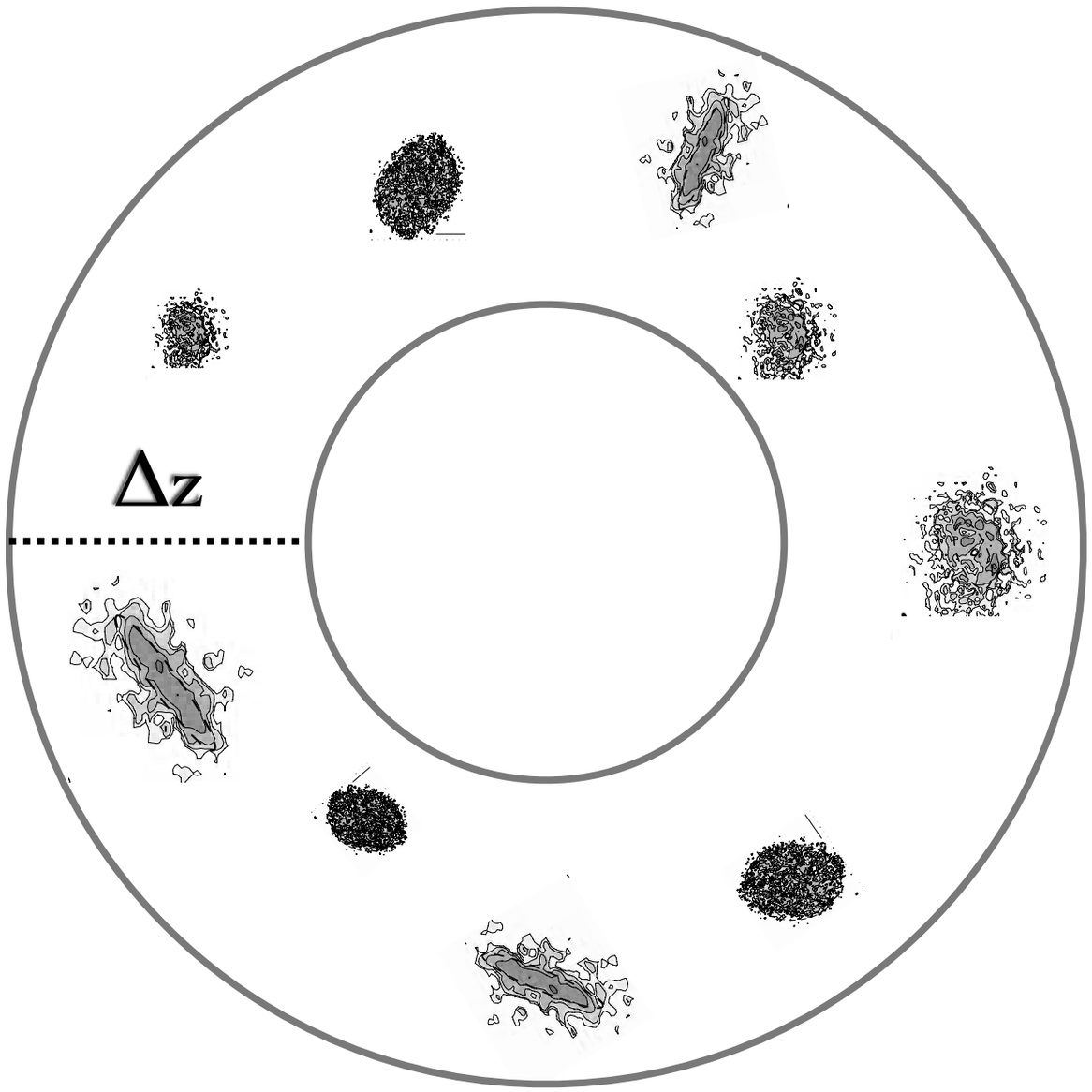
  - Shell has width Δz (e.g. 1Gpc)
  - Projected surface densities



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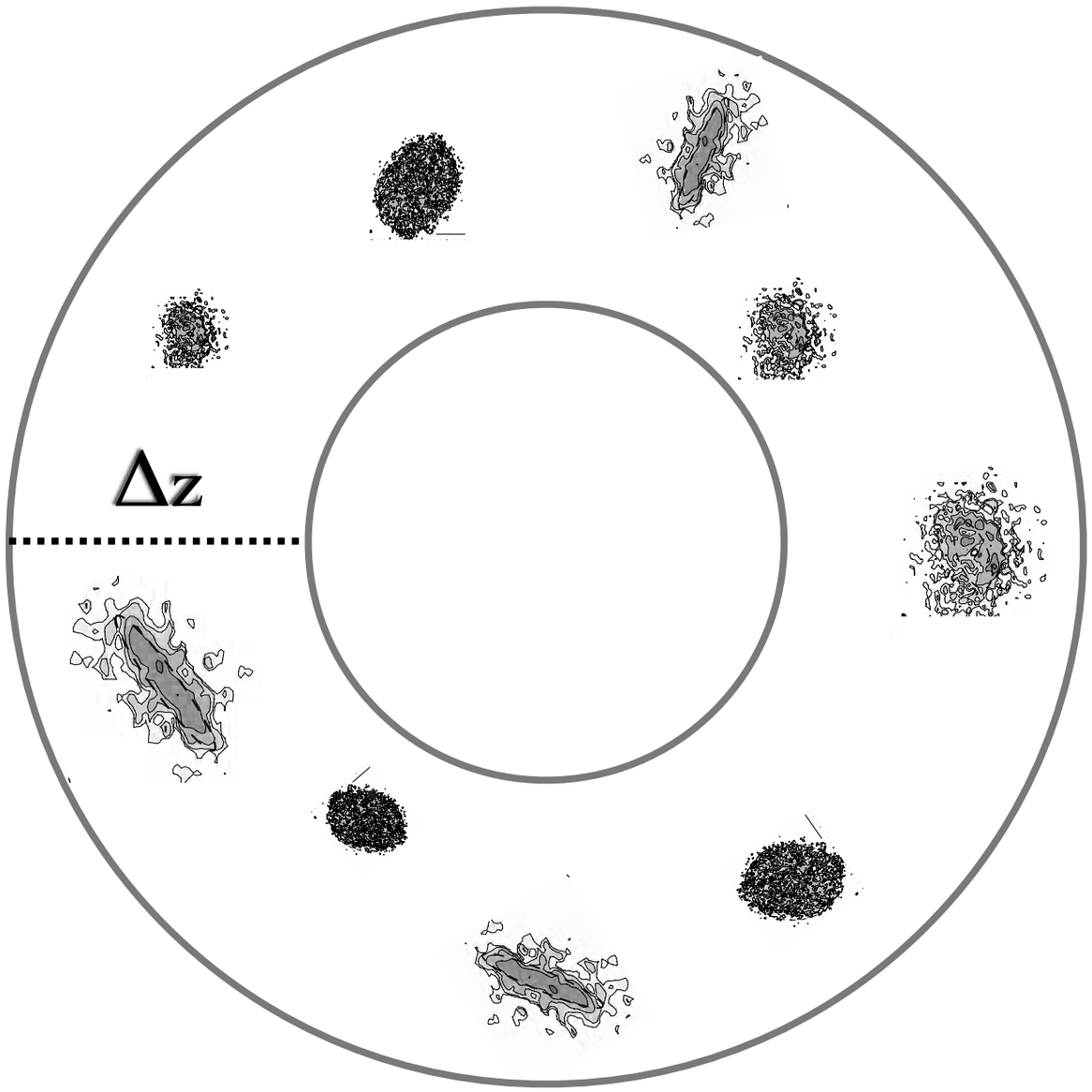
- $f(N_{HI})$
  - # of cells with N_{HI} per dN_{HI} per comoving path length
    - $f(N_{HI})$ is akin to a luminosity function
  - Distribution of projected Σ_{HI} for all galaxies in a shell of the sky
    - (in a finite volume)



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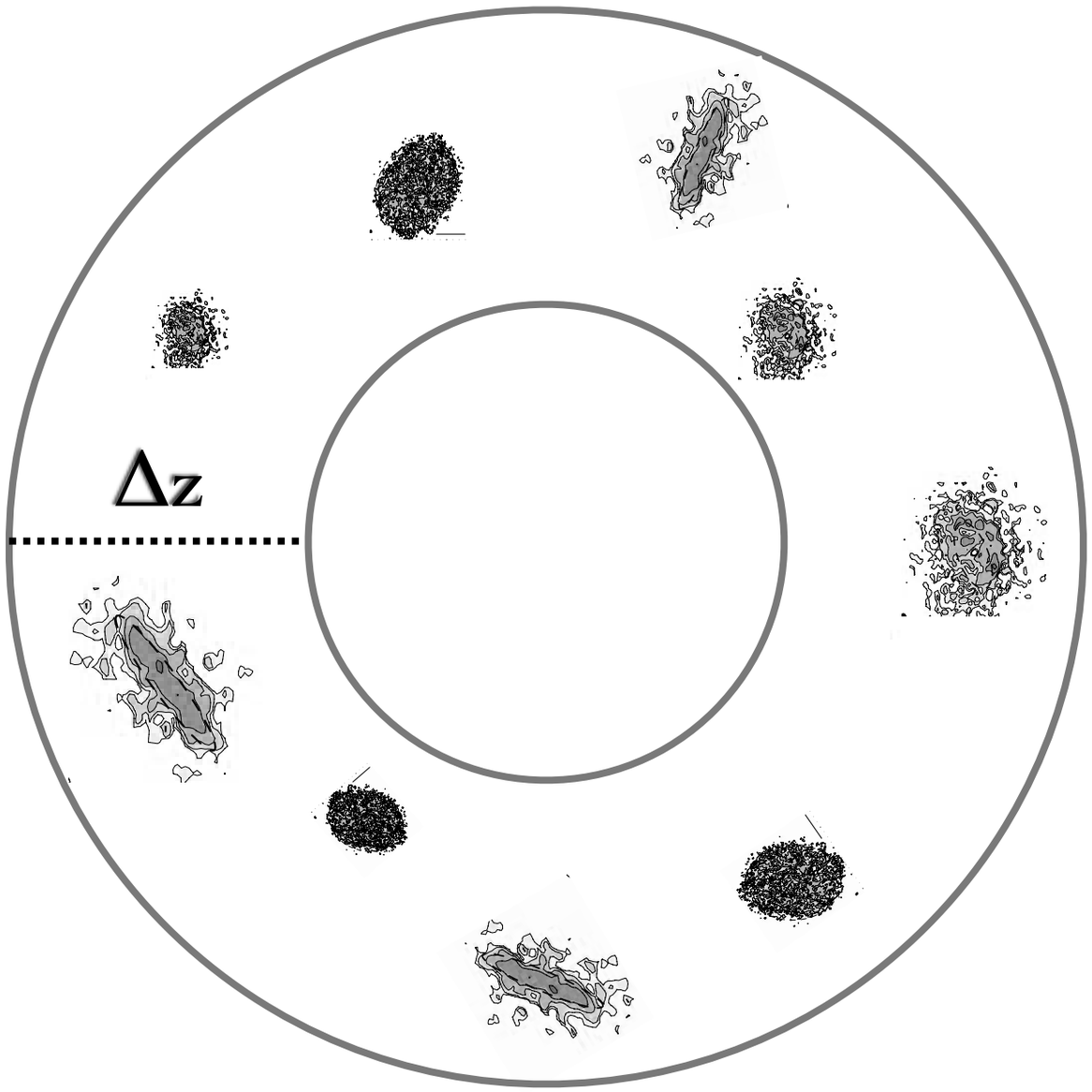


How do we measure this observationally?

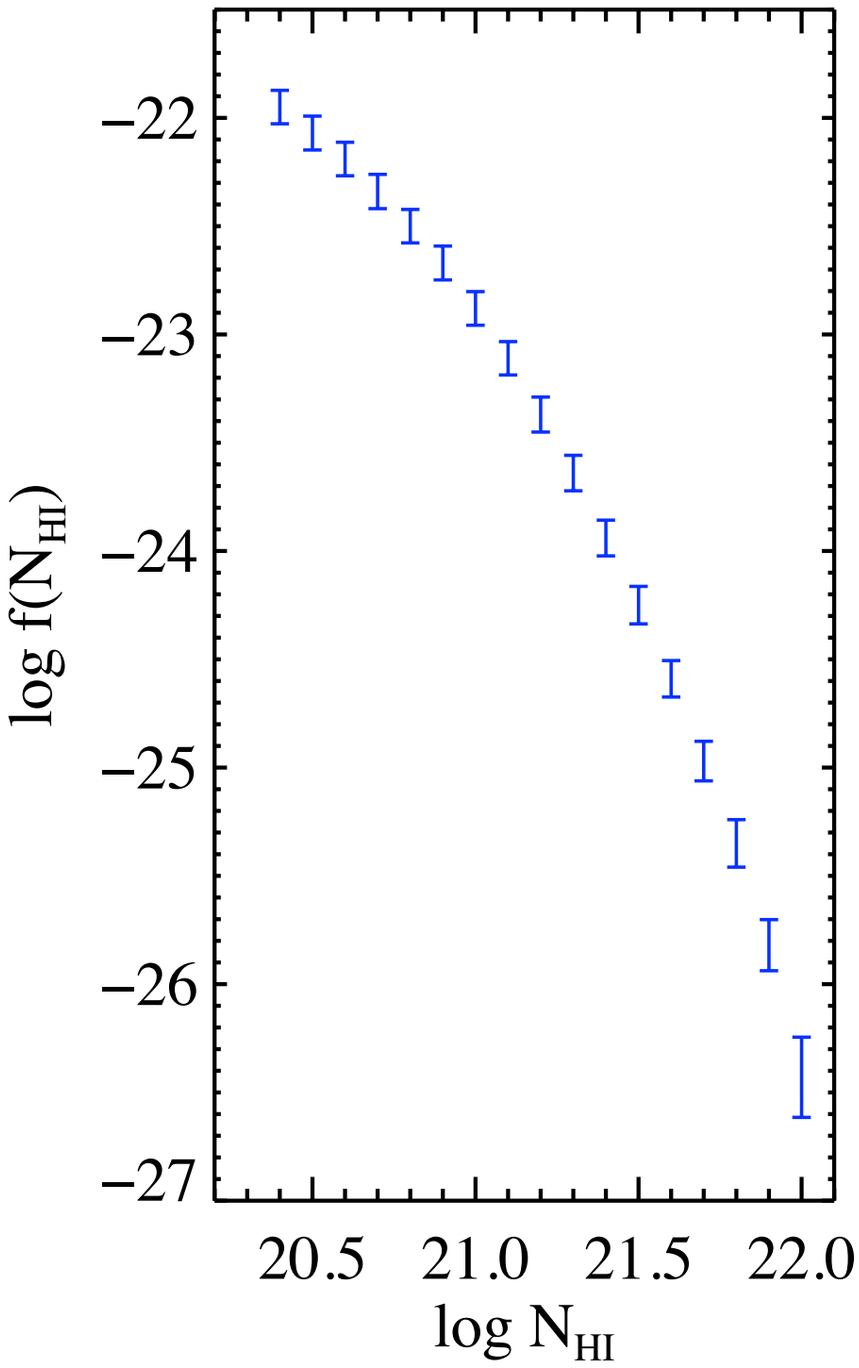
Measuring $f(N_{HI})$ at z=0

- Ideally
  - Analyze an all-sky 21cm map at high spatial resolution
- Alternate approach

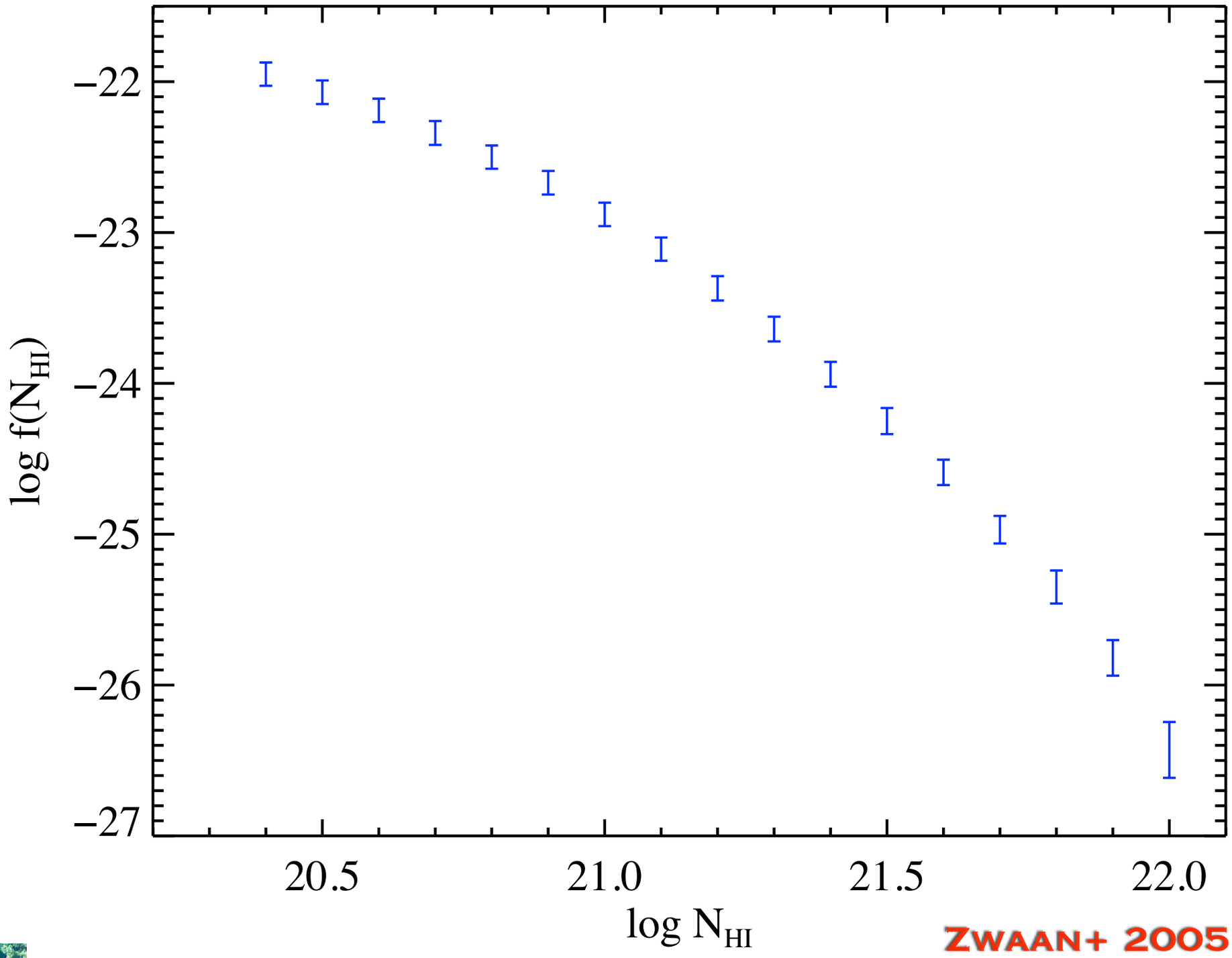
  i) Choose a sample of galaxies with a wide range of luminosity: L

  ii) Map in 21cm at high spatial res.

  iii) Weight+normalize the results by the luminosity function $\Phi(L)$
- WHISP
  - Zwaan+ 2005
  - Beam size of ~1kpc diameter



$f(N_{HI})$ at z=0



ZWAAN+ 2005

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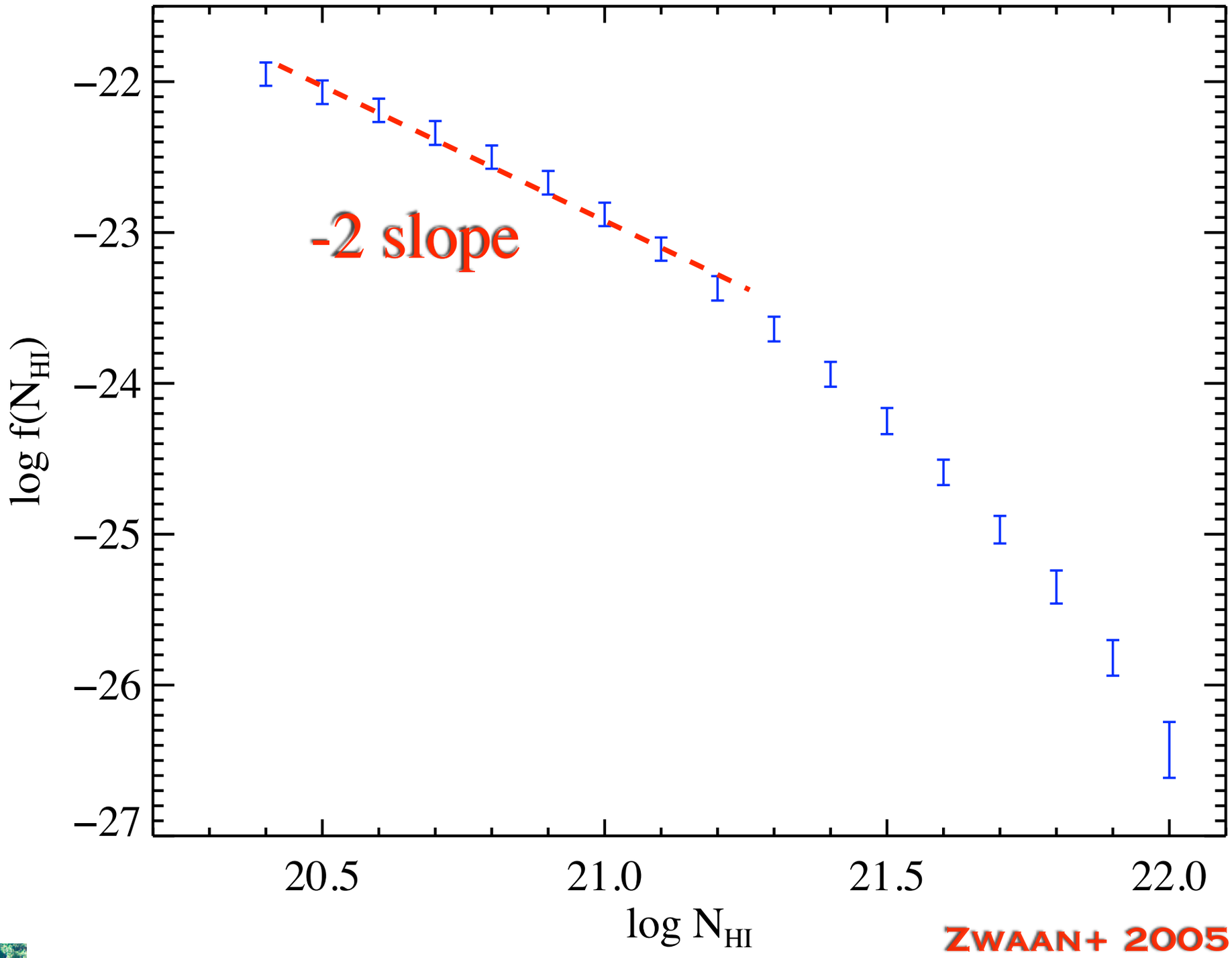

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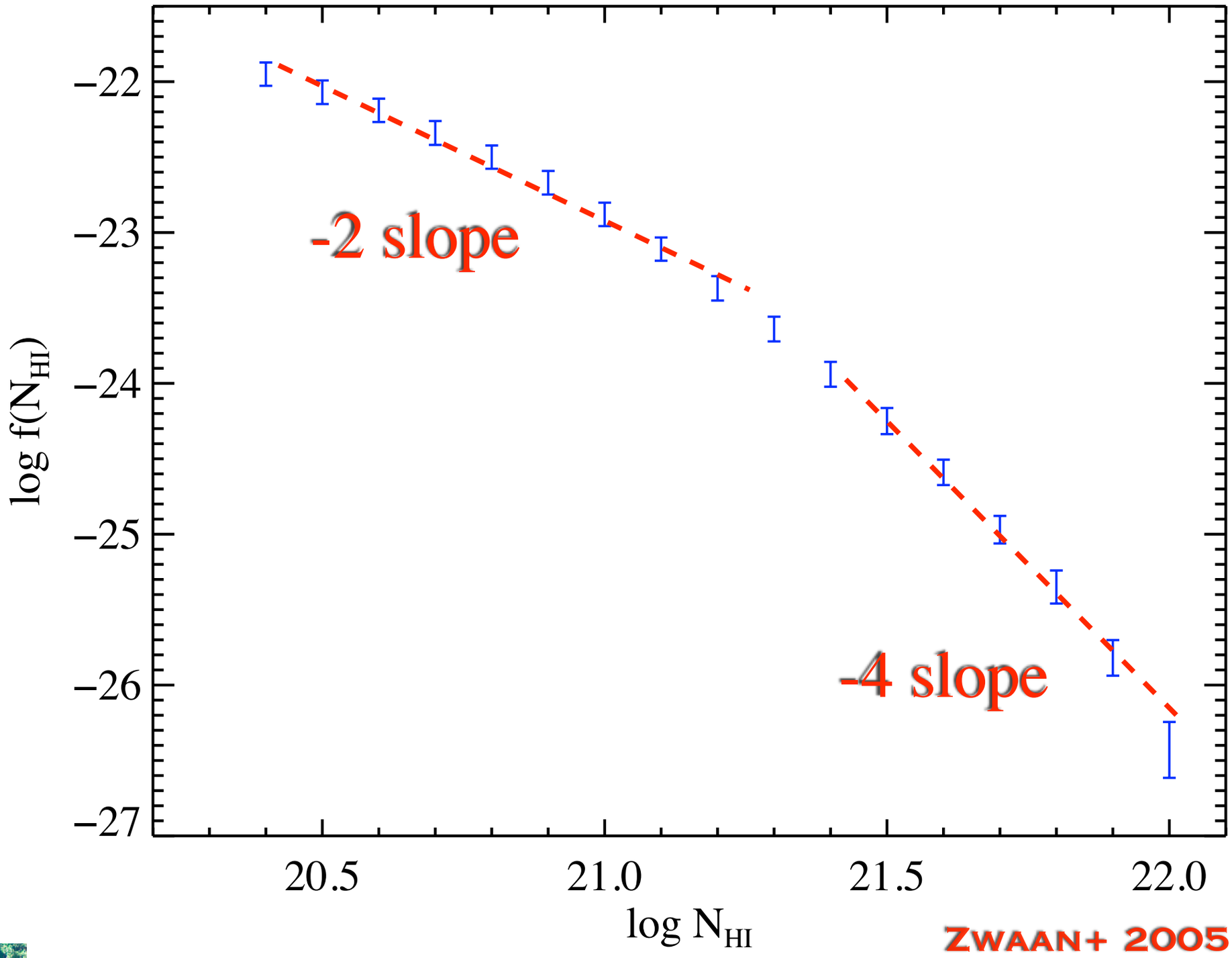
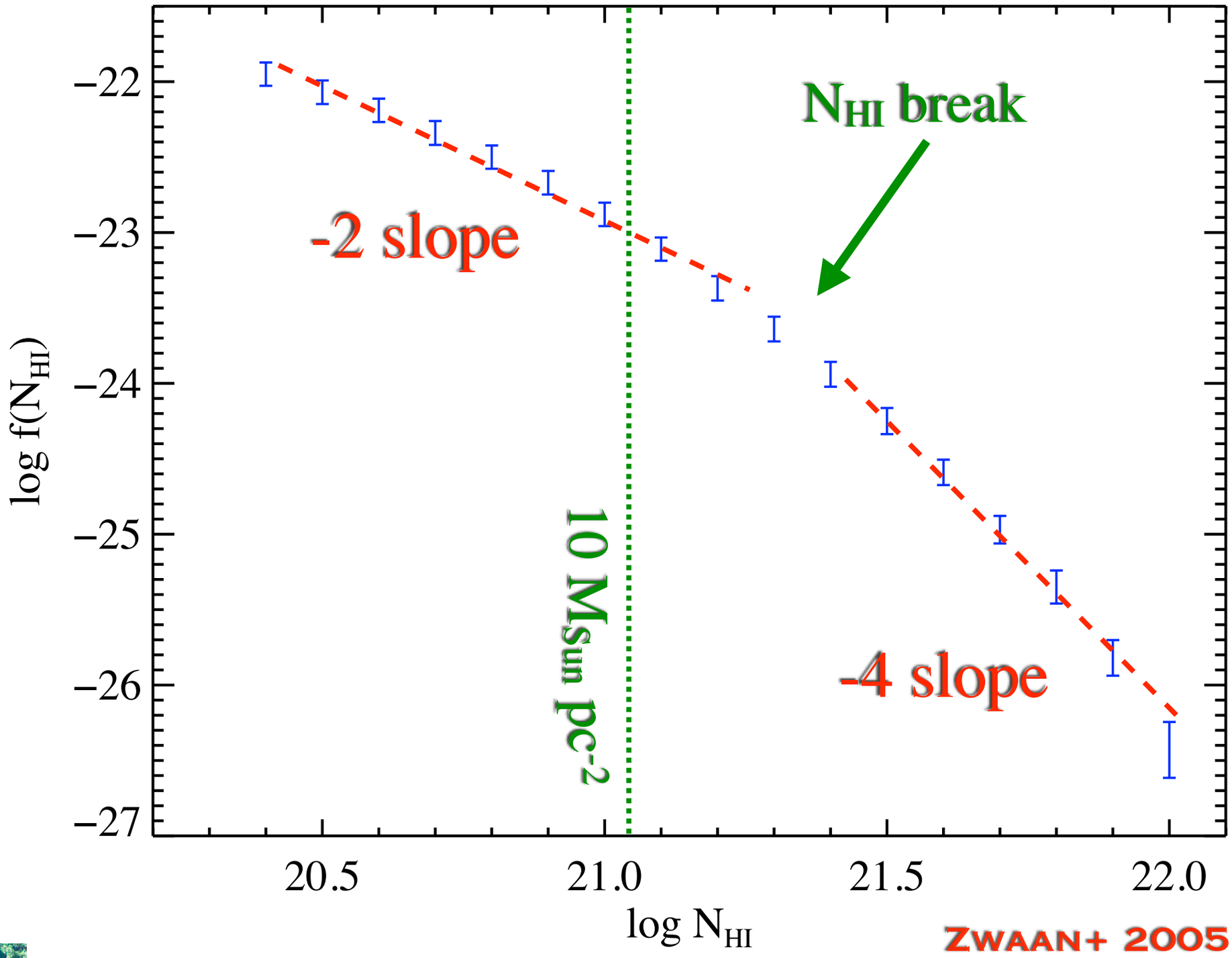

−22
−23
−24
−25
−26
−27
log f(N_HI)
20.5
21.0
21.5
22.0
log N_HI
-2 slope
-4 slope
ZWAAN+ 2005

$f(N_{HI})$ at z=0


N_HI break
-2 slope
-4 slope
10 M_sun pc^-2
log f(N_HI)
log N_HI
−22
−23
−24
−25
−26
−27
20.5
21.0
21.5
22.0
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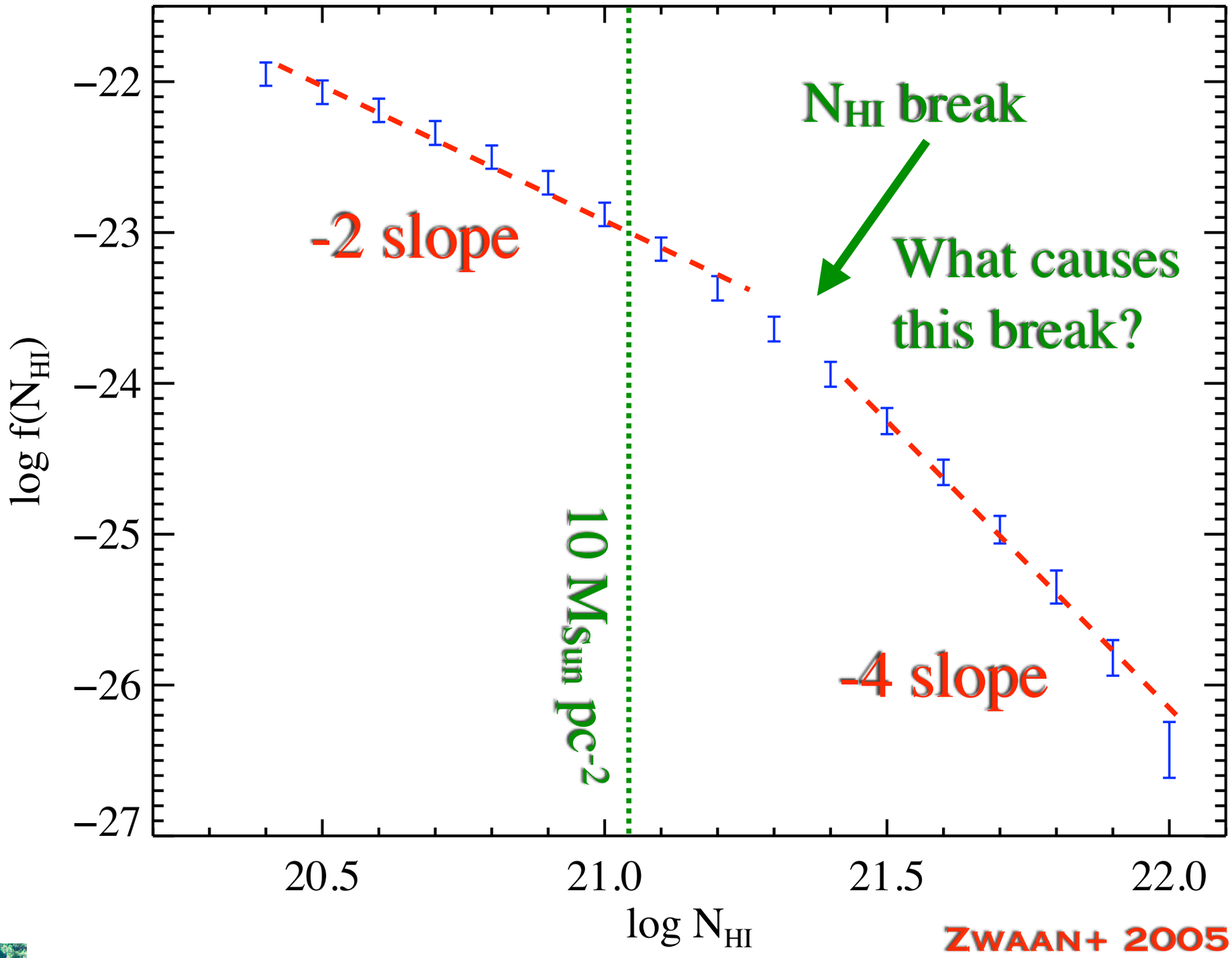
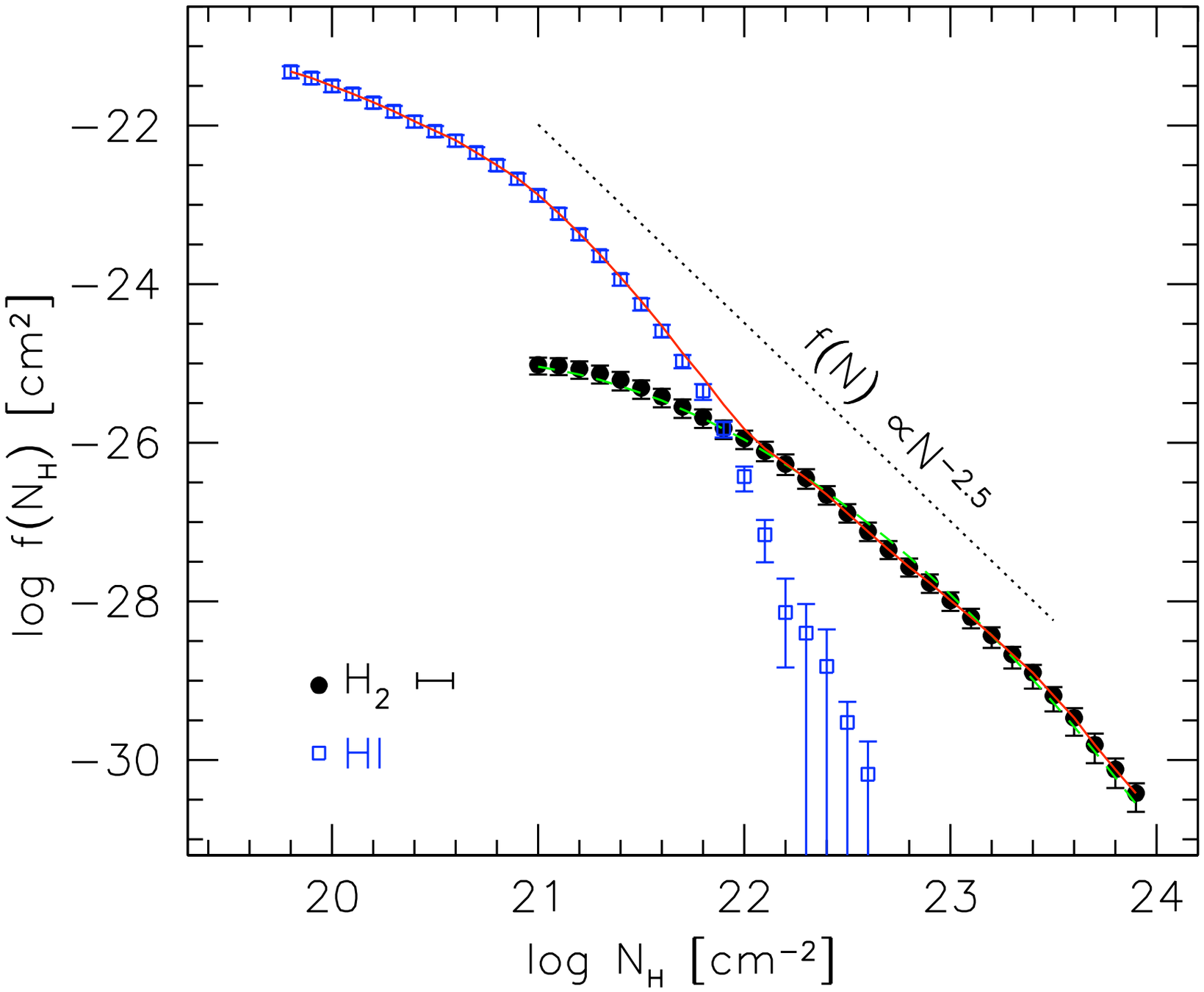

N_HI break
What causes this break?
-2 slope
-4 slope
10 M_sun pc^-2
log f(N_HI)
log N_HI
−22
−23
−24
−25
−26
−27
20.5
21.0
21.5
22.0
ZWAAN+ 2005

$f(N_H)$ at z=0

Zwaan & Prochaska 2006



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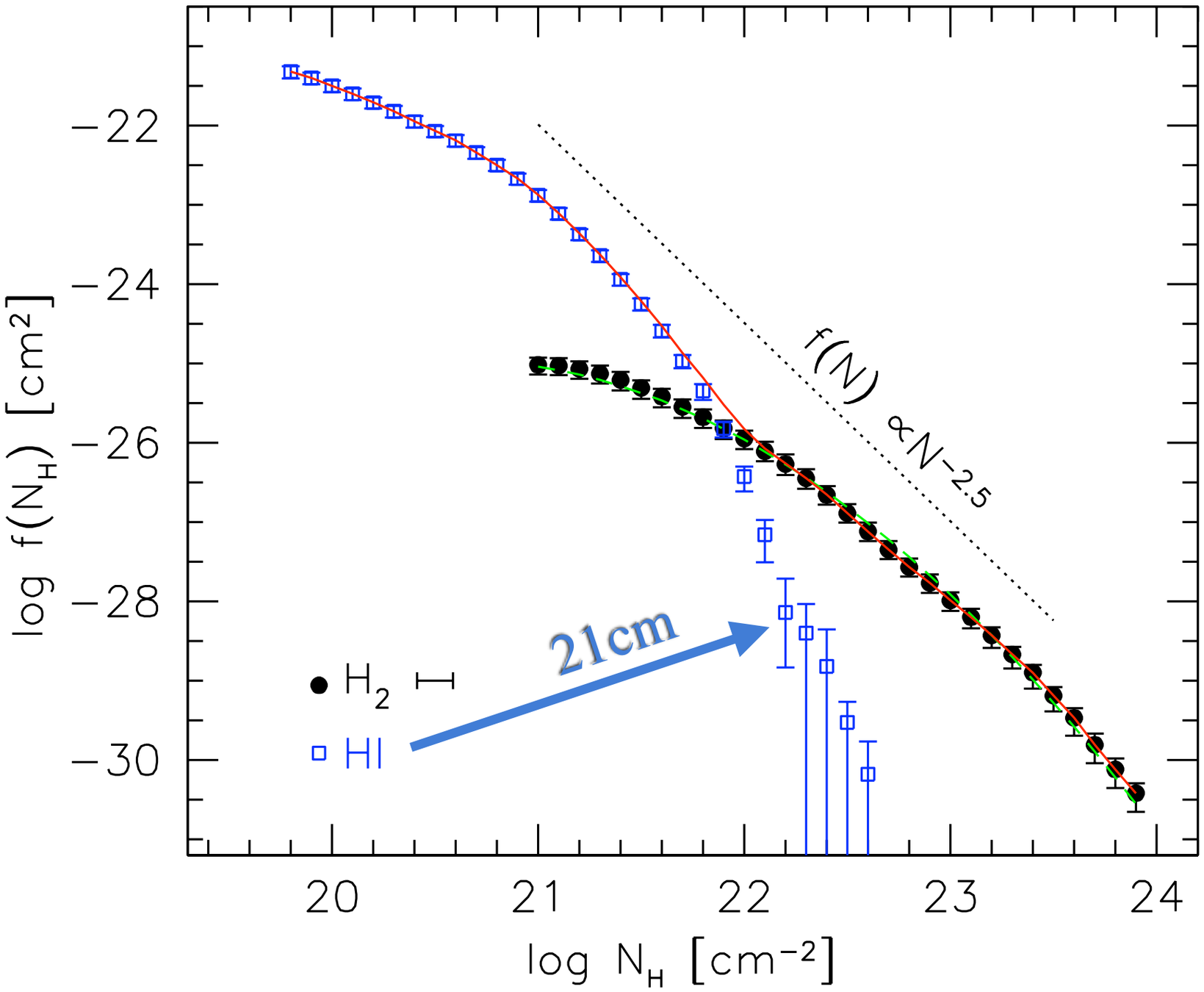
Zwaan & Prochaska 2006



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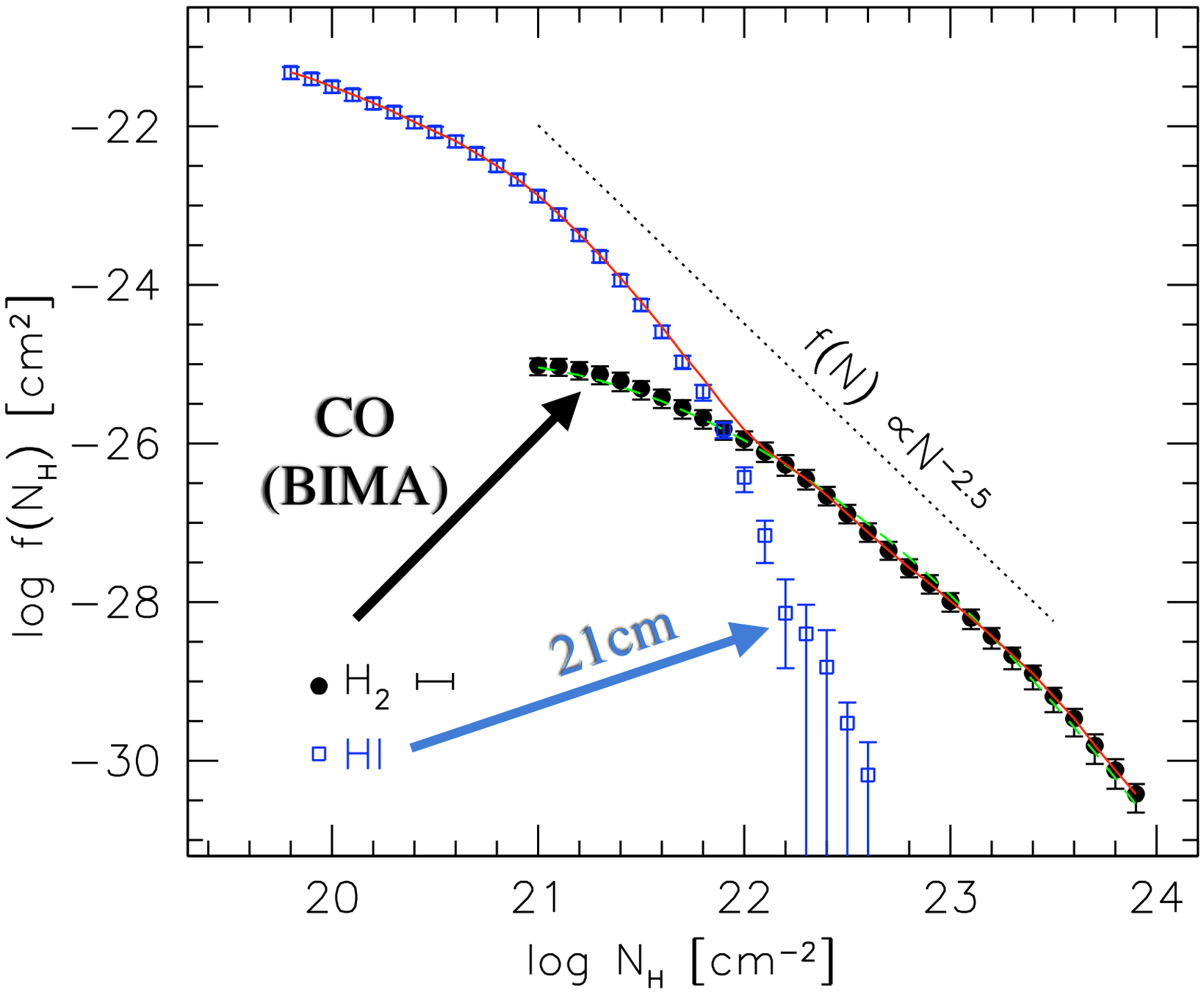

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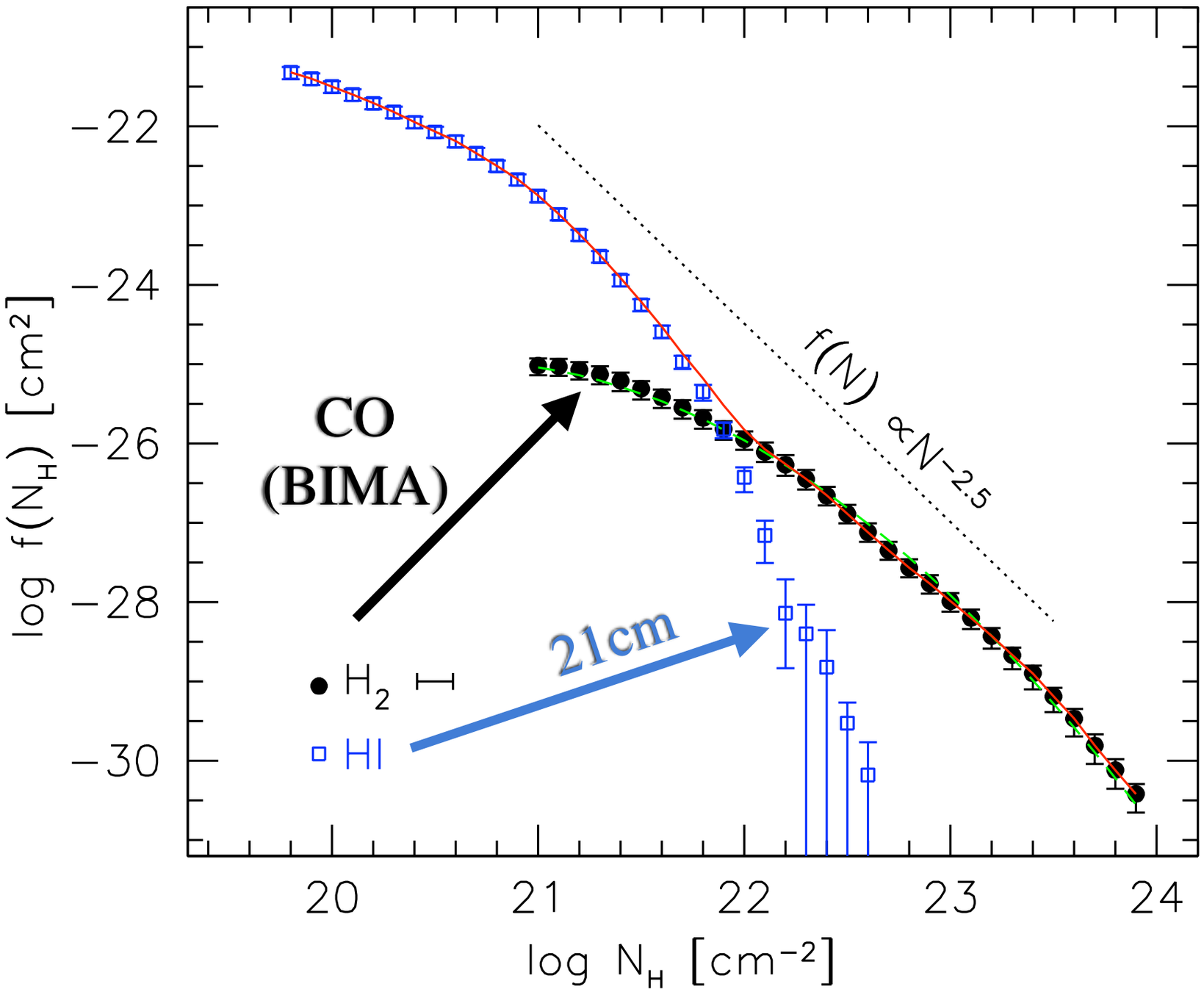


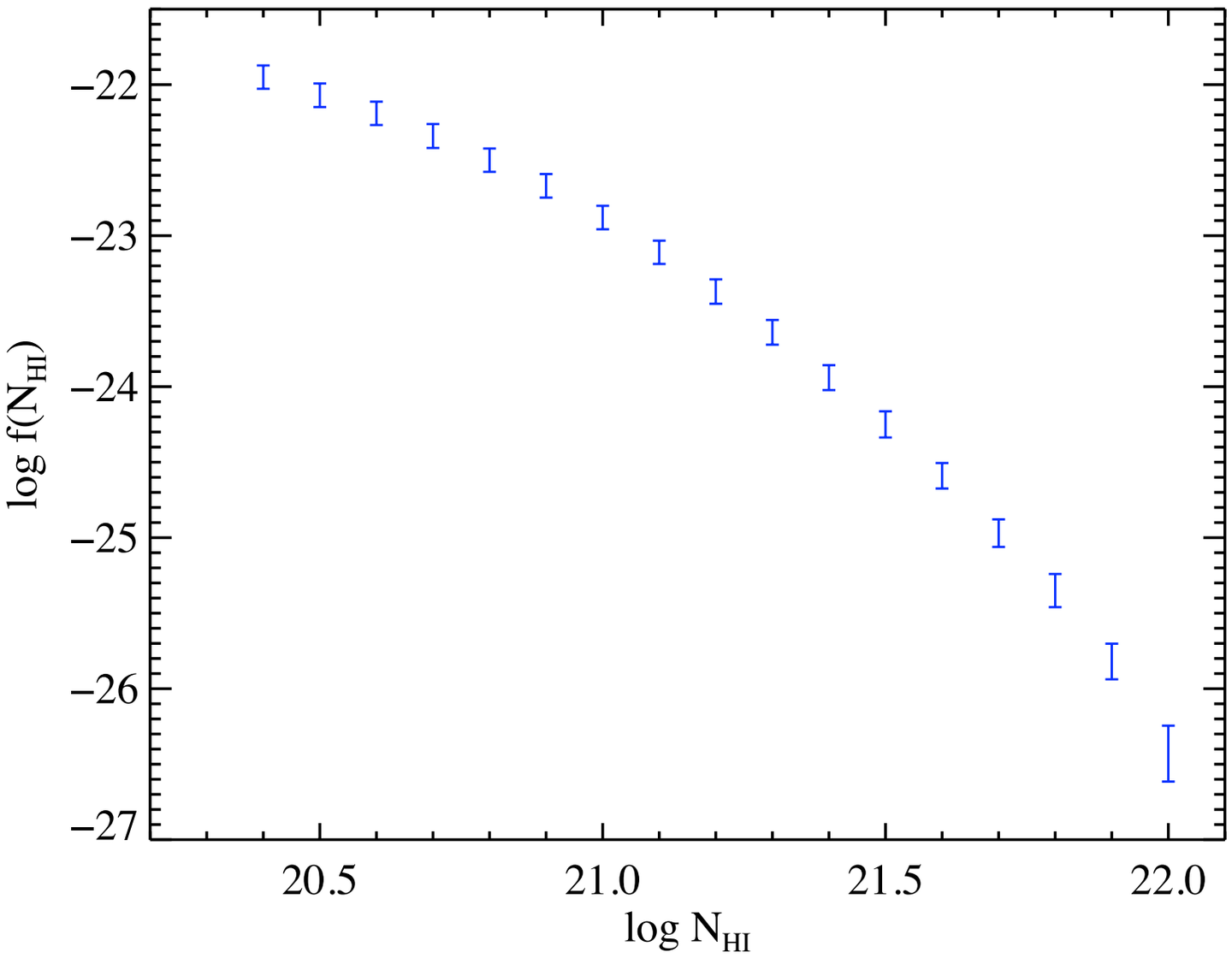
The overlap in the distribution functions seems a remarkable 'coincidence'. (Schaye 2001; Krumholz+ 2009)

Zeroth Moment: "Covering Fraction"

$$\ell(X) = \int_{N_{th}}^{\infty} f(N_{\rm HI}) dN_{\rm HI}$$

(DLA CRITERION)

$N_{th} = 2 \times 10^{20}\,{\rm cm}^{-2} \quad (1.6 M_\odot\ {\rm pc}^{-2})$



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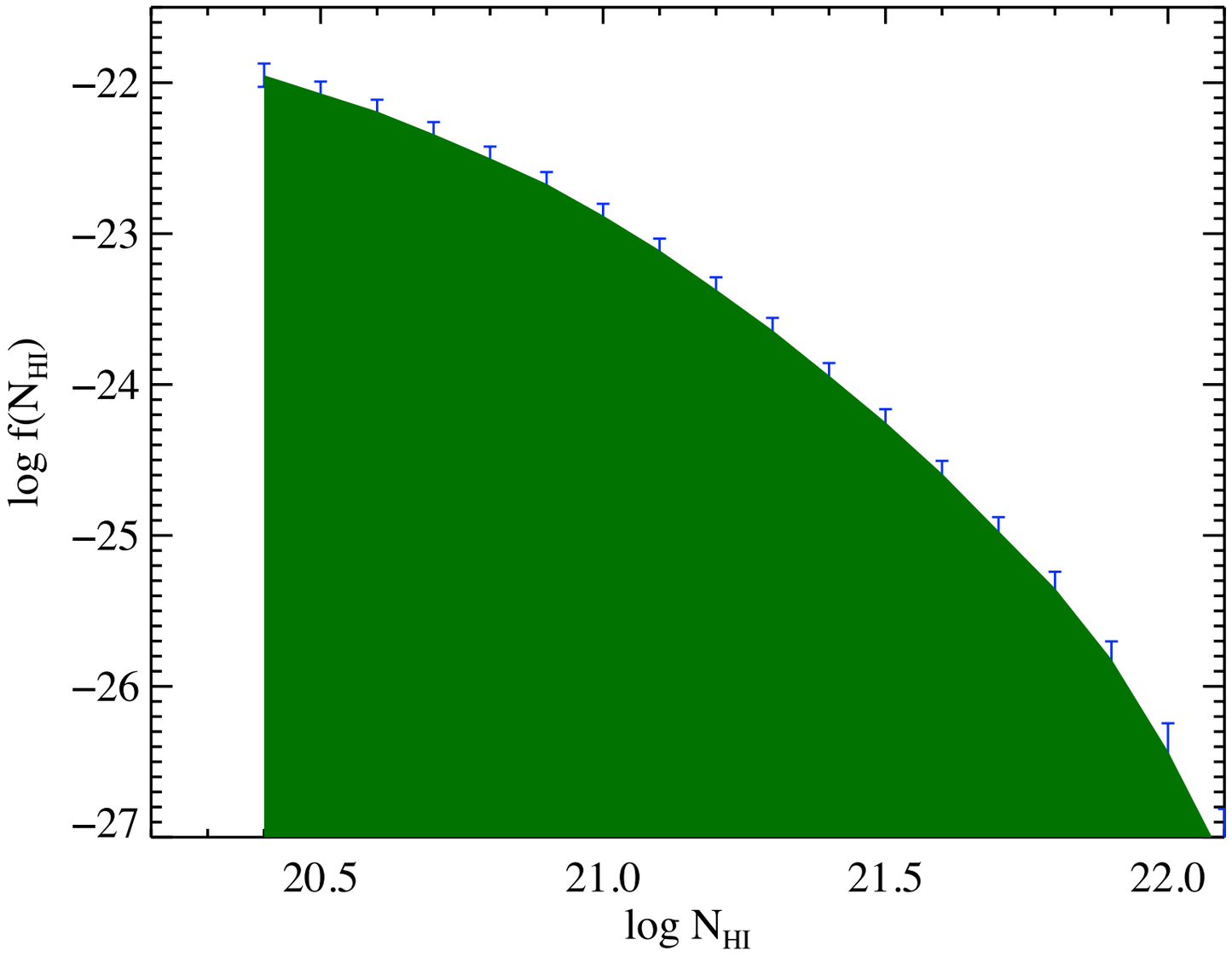

$\ell(X)$ is the number of galaxies intersected per comoving pathlength (ΔX).

For ΔX = 1Gpc, one intersects 0.01 galaxies on average.

<u>Covering fraction</u>:

C_A = 1% for a 1Gpc shell at z=0

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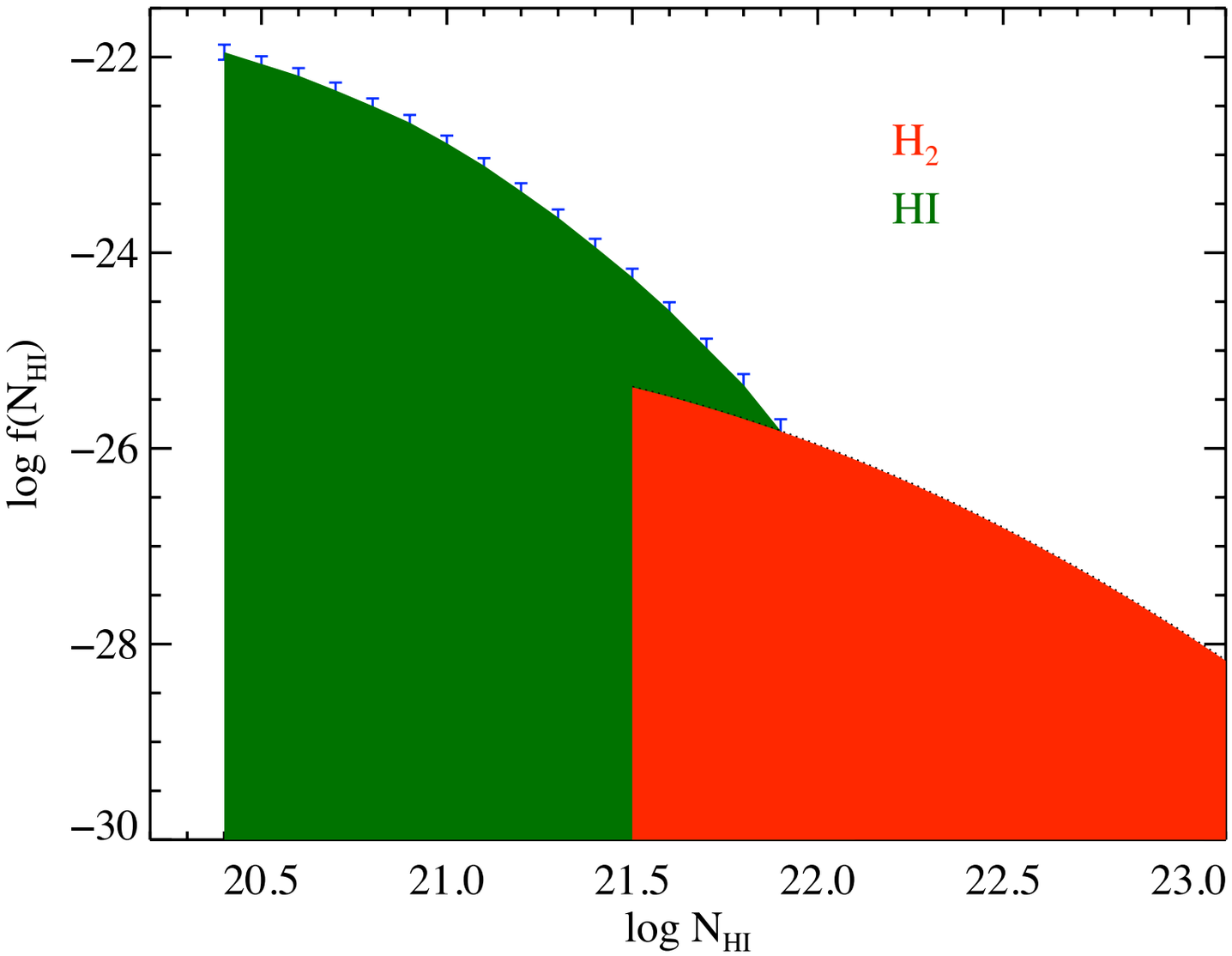

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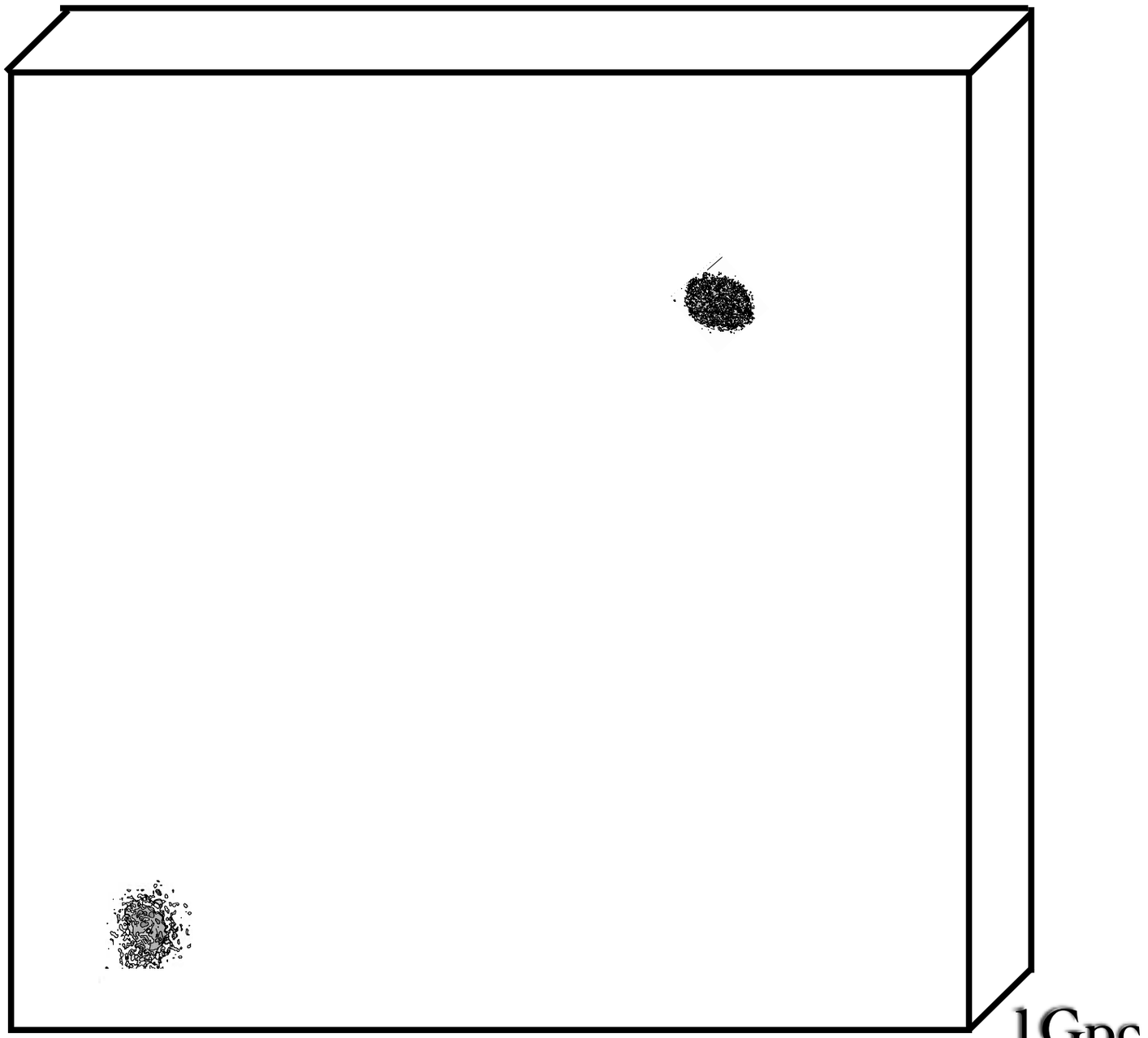
Note: $C_A(H_2)$ = 0.006%

1% Covering Fraction to 1.6 M_{Sun} pc^{-2}



First Moment: HI Mass Density

$$\rho_{\rm HI} = \frac{m_p H_0}{c} \int_{N_{th}}^{\infty} N_{\rm HI}\, f(N_{\rm HI})\, dN_{\rm HI}$$

Aside: In practice, $\varrho_{\rm HI}$ is derived from all-sky surveys of HI galaxies

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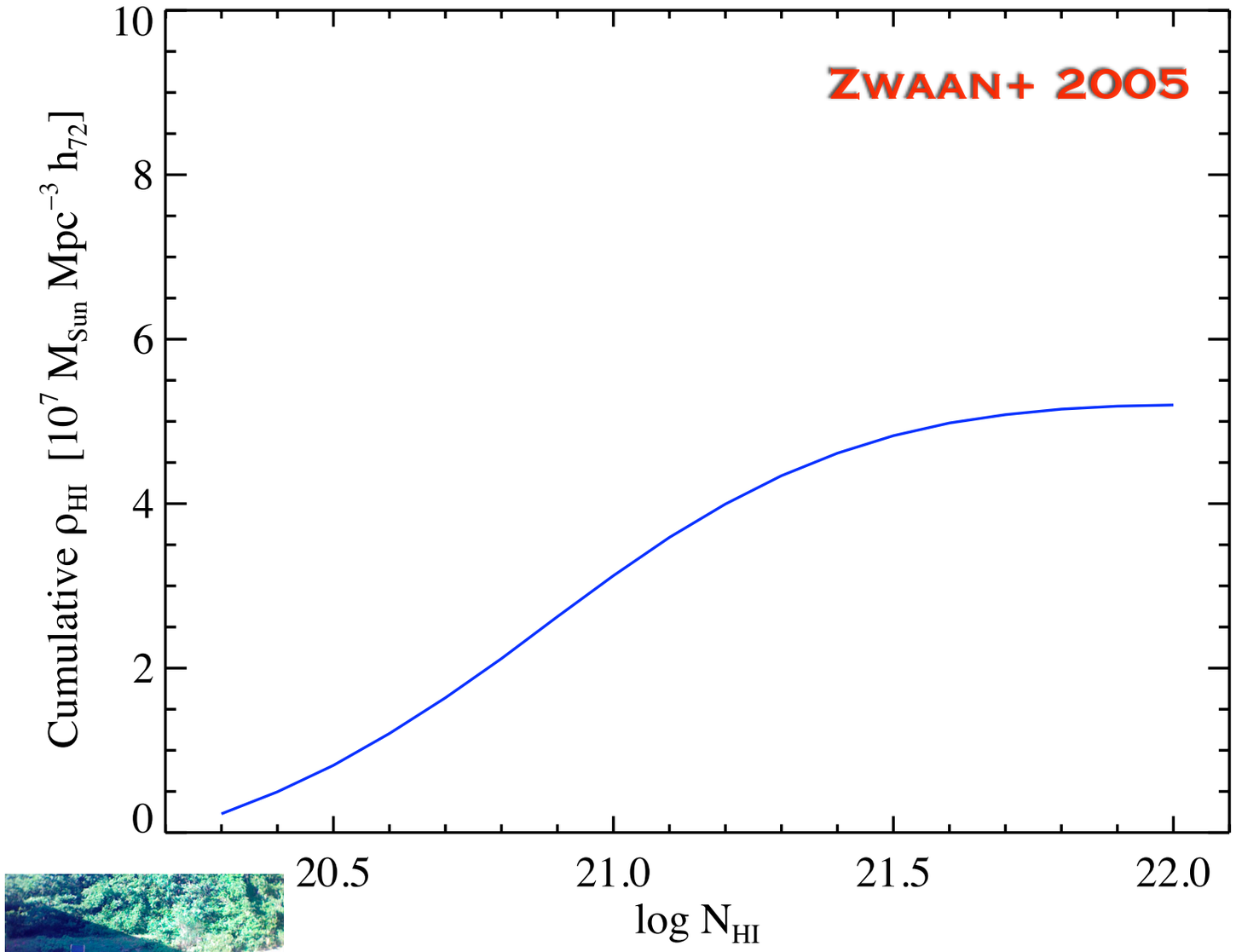

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$\varrho_{\rm HI}(z=0) = 5.2 \times 10^7\ M_{\rm Sun}\ {\rm Mpc}^{-3}$

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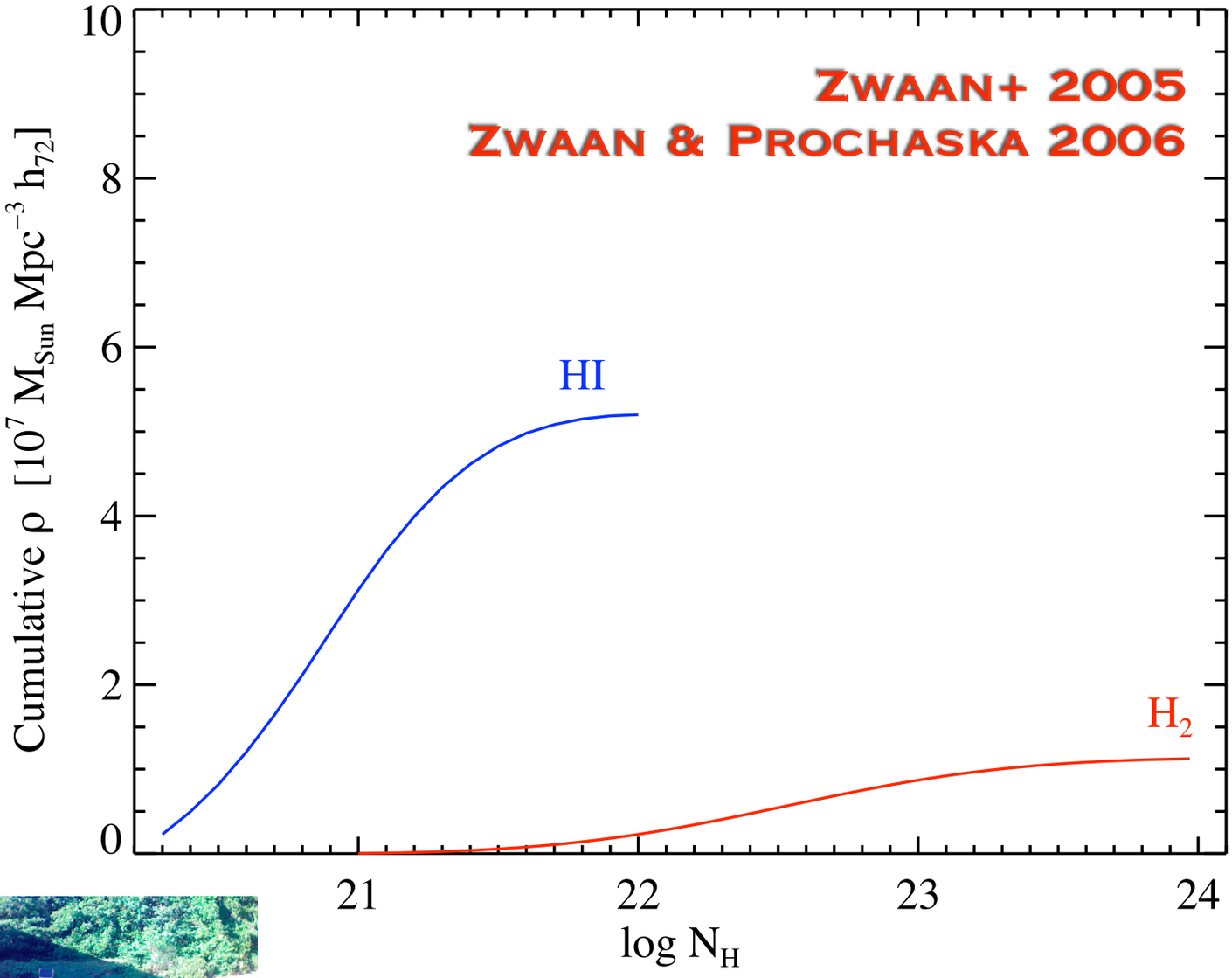

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$\varrho_{H2}(z=0) = 1.1 \times 10^7\ M_{Sun}\ Mpc^{-3}$

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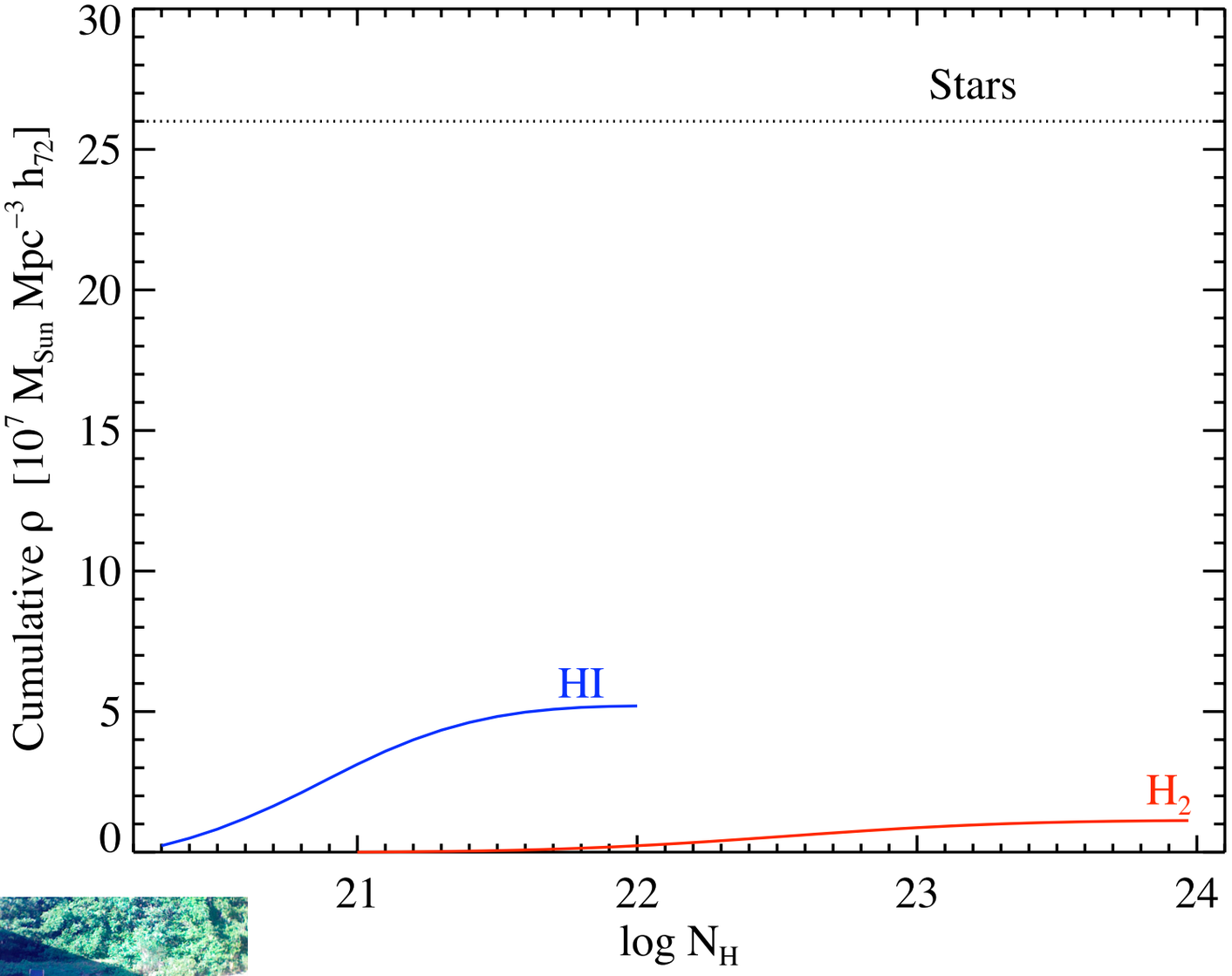

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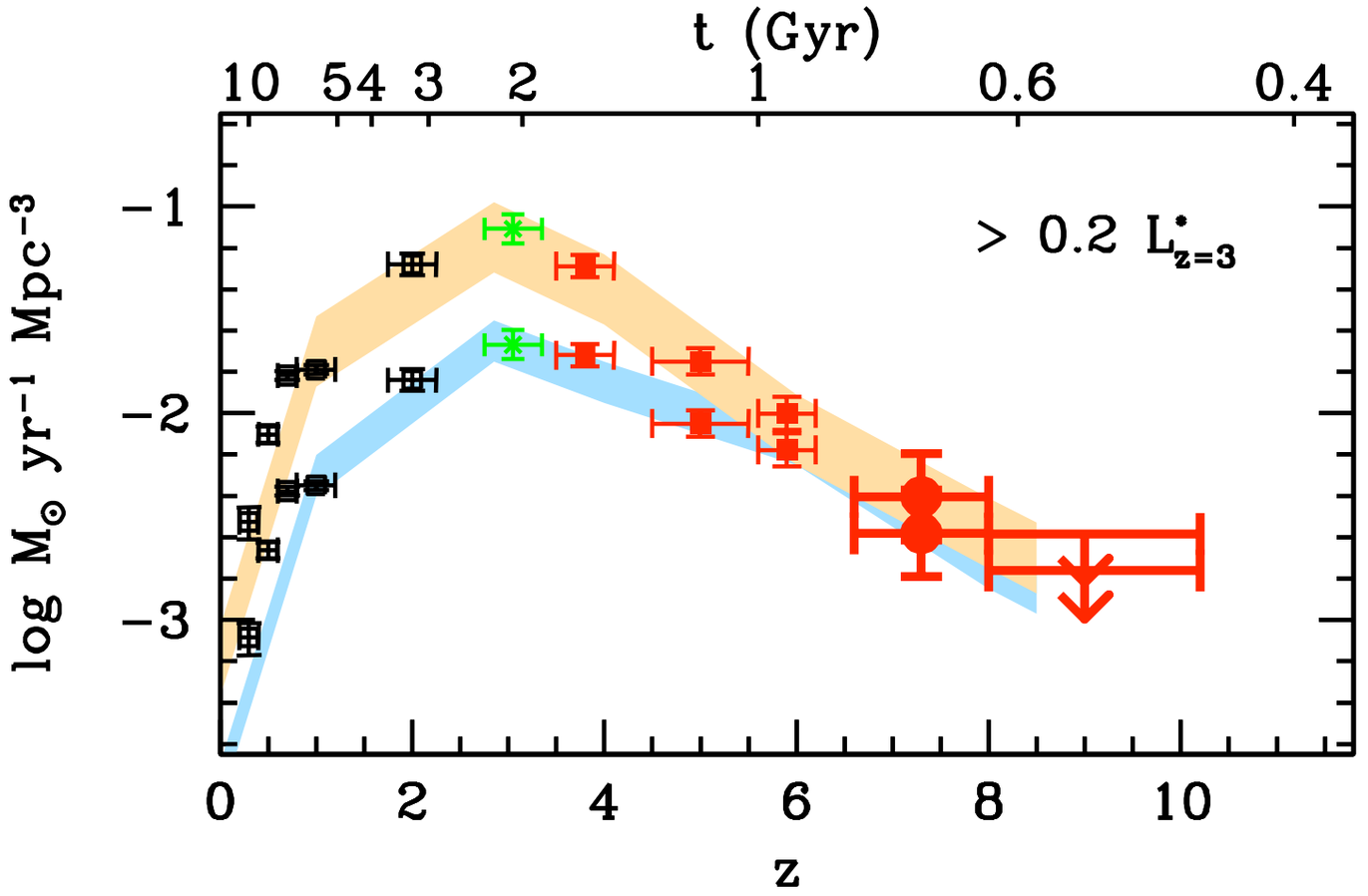
$\varrho_{H2}(z=0) = 1.1 \times 10^7\ M_{Sun}\ Mpc^{-3}$

$\varrho_{Stars}(z=0) = 26 \times 10^7\ M_{Sun}\ Mpc^{-3}$

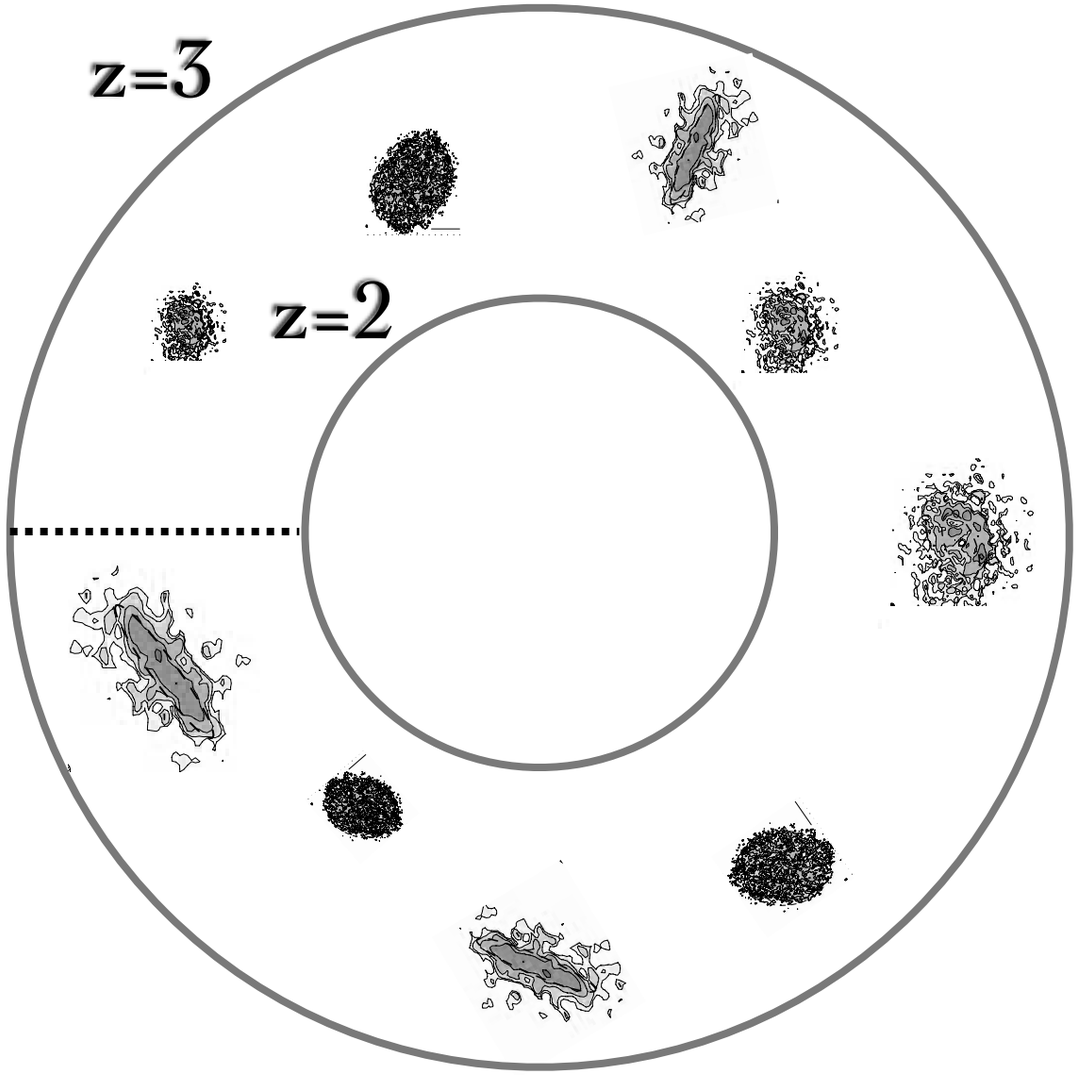
Cosmic Evolution of HI in Galaxies

- How does HI evolve in galaxies in time?
- Are galaxies smaller in the past, e.g. lower C_A?
- Are galaxies more gas rich in the past?



BOUWENS+ 2008

Heading to the High z Universe



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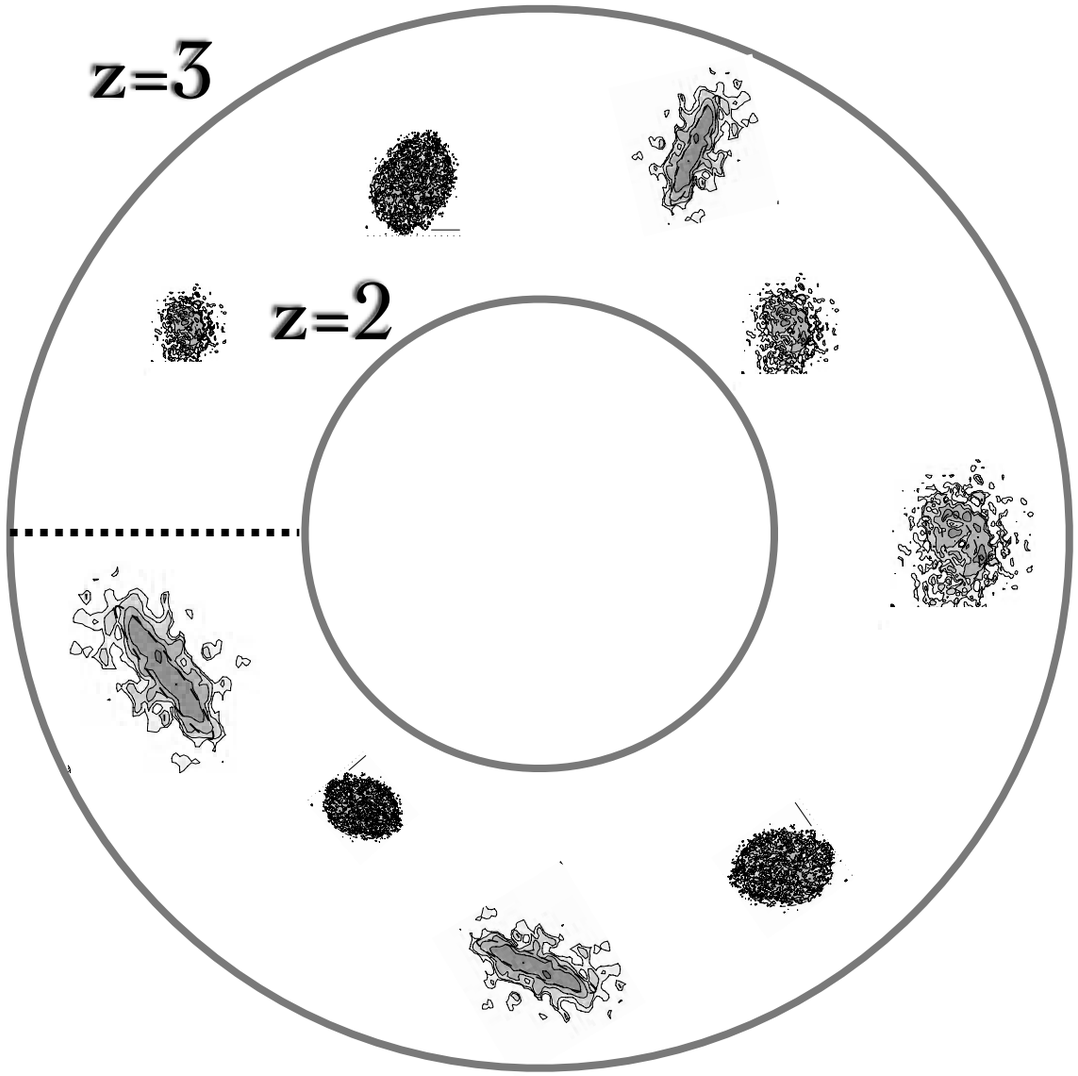
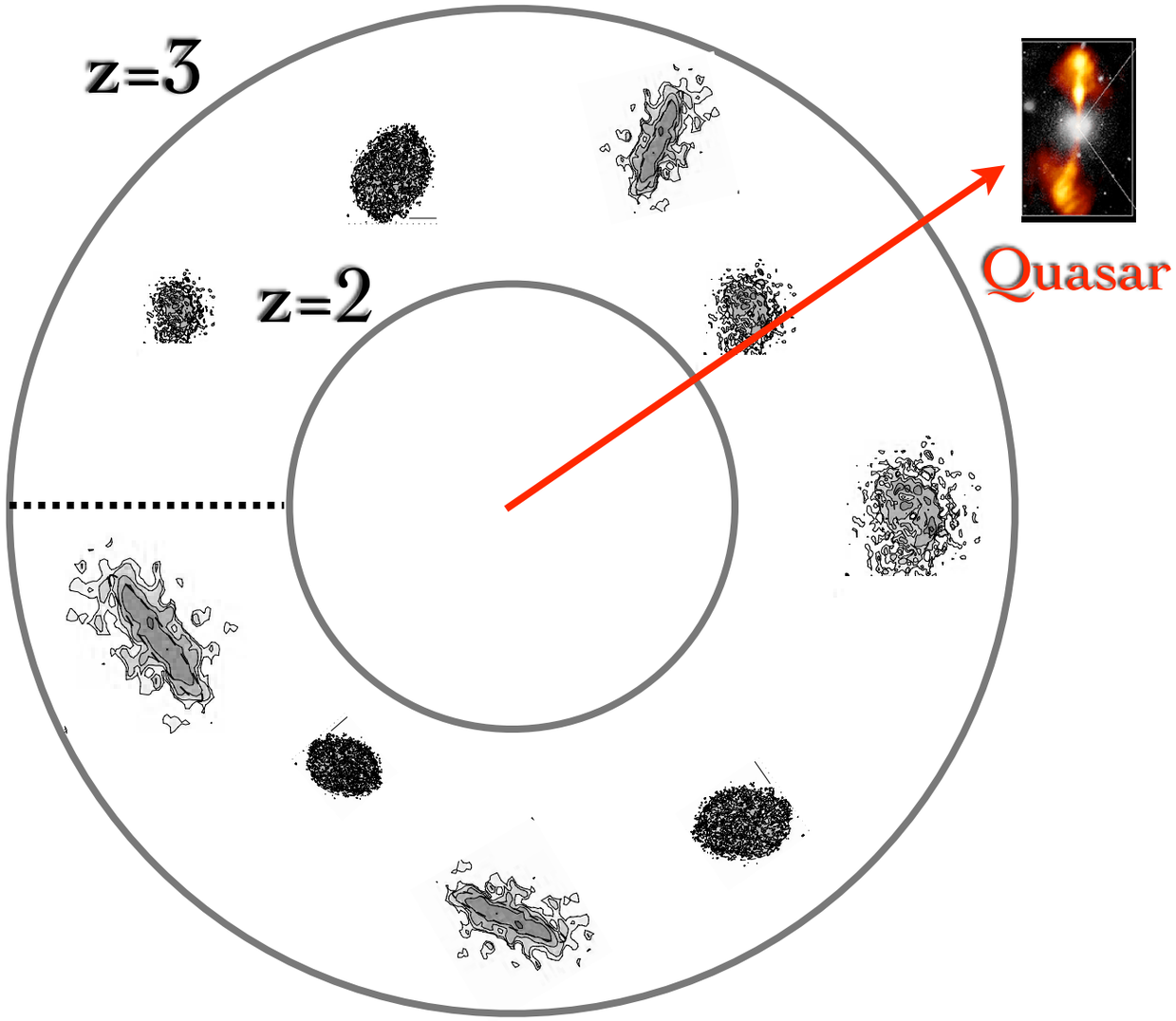


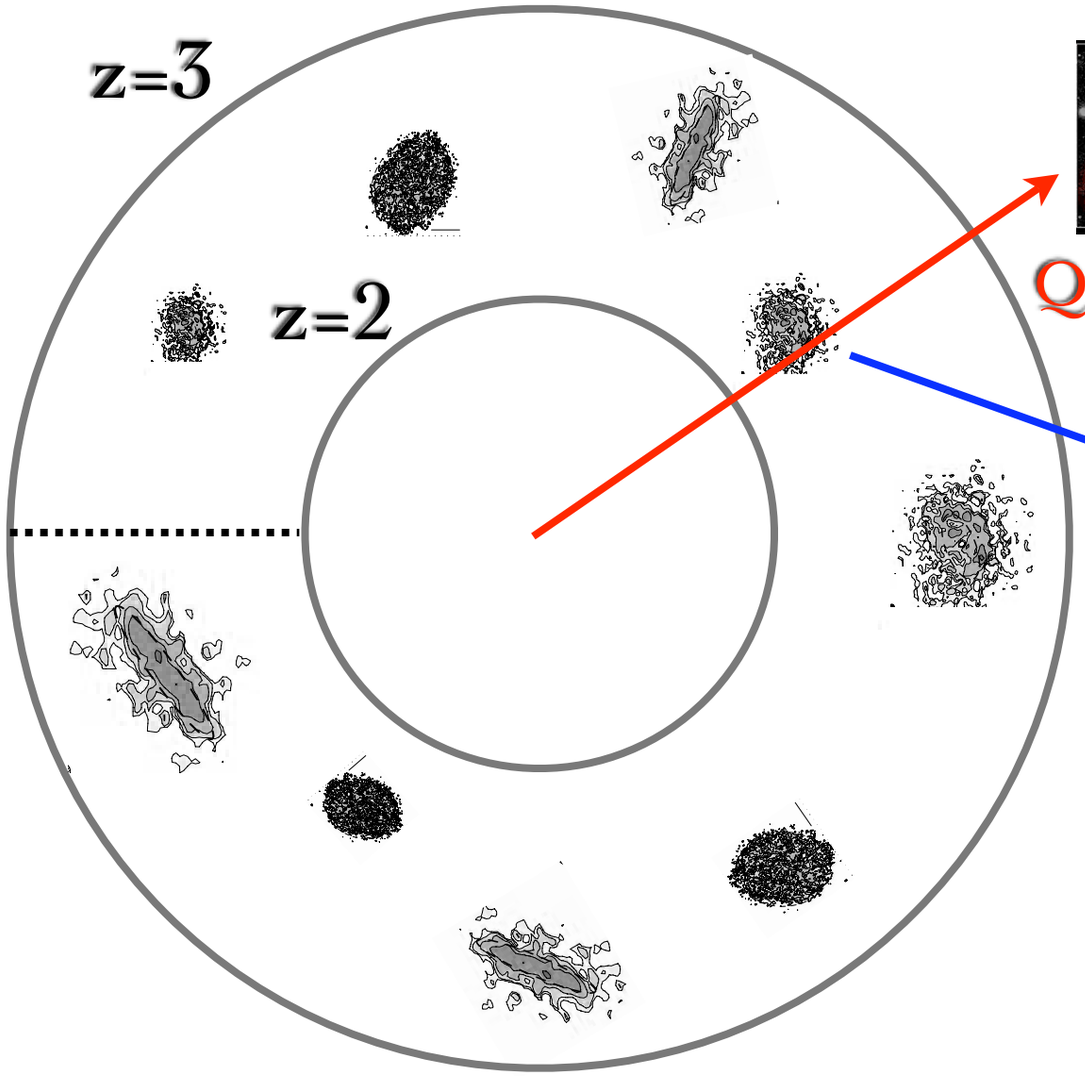
- 21cm emission is ‘hopeless’

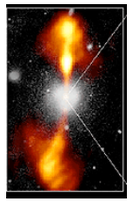
Heading to the High z Universe



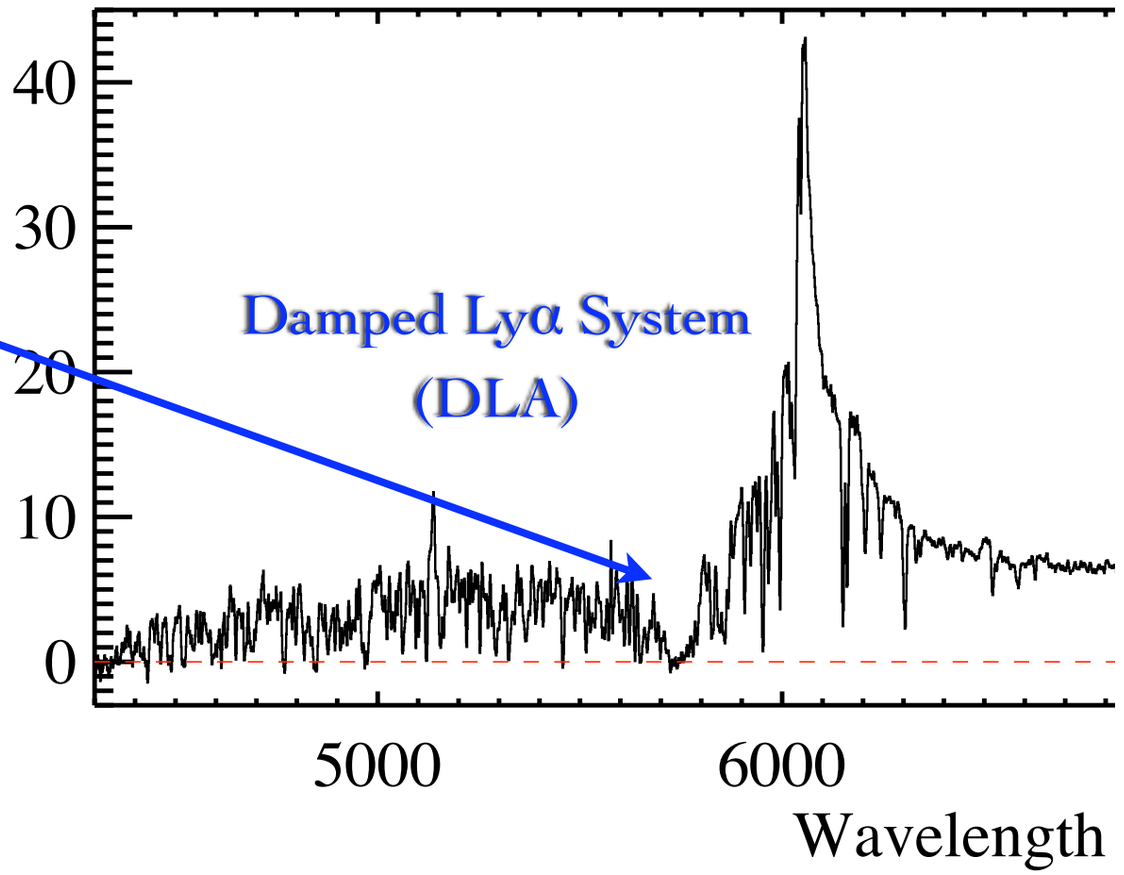
- 21cm emission is 'hopeless'
- Lyα in Absorption
  - Damped portion of the curve-of -growth
  - N_{HI} well measured in modest quality spectra
    - Can use GRBs, galaxies

Heading to the High z Universe





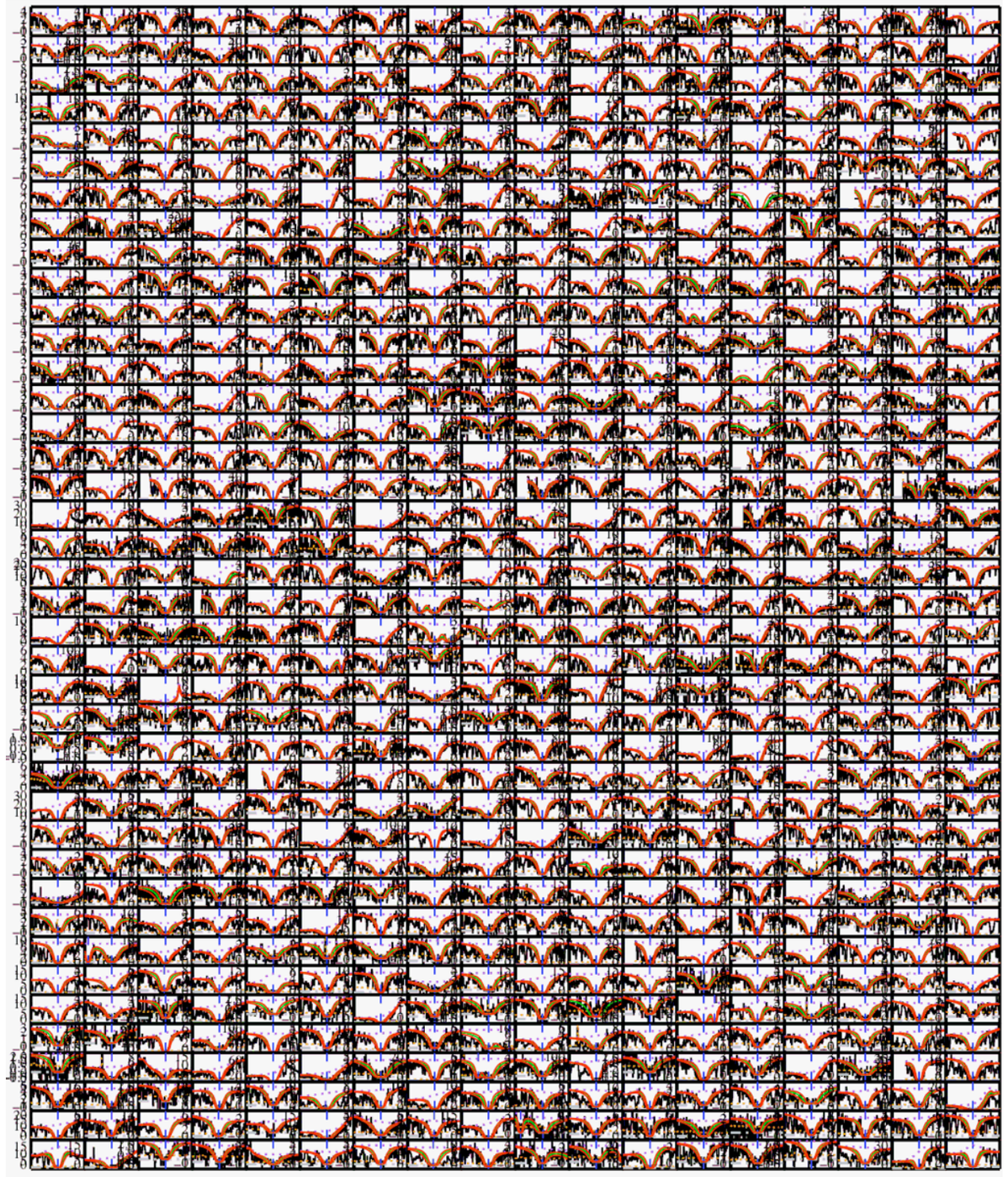
Quasar



- 21cm emission is 'hopeless'
- Lyα in Absorption
  - Damped portion of the curve-of -growth
  - N_{HI} well measured in modest quality spectra
    - Can use GRBs, galaxies

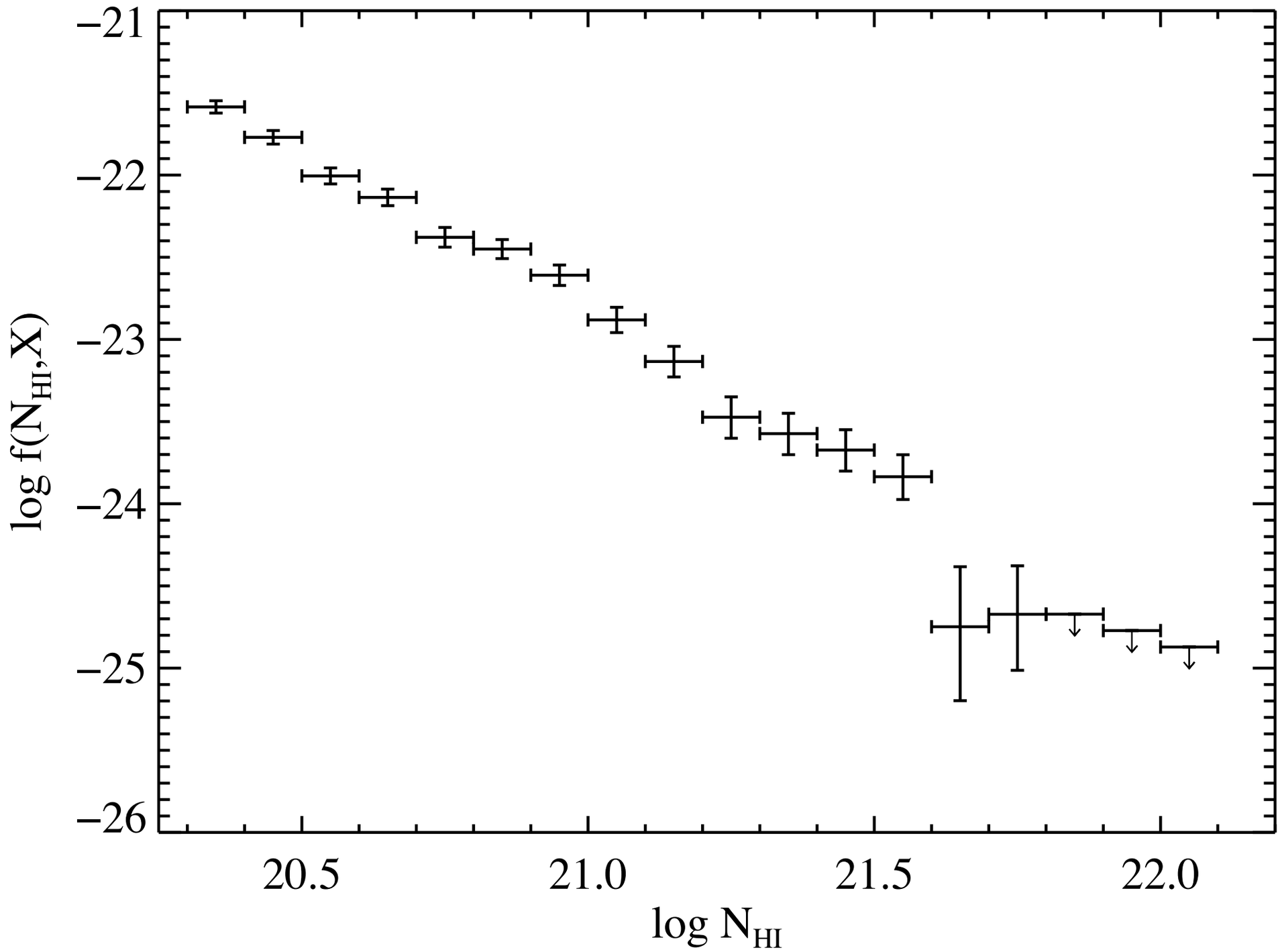
SDSS DR5

Prochaska+ 2005
Prochaska & Wolfe 2009



- ~1000 DLAs
  - Towards several thousand quasars
  - Automated algorithm with refined (by-hand) analysis
- z=2.2 to 5

$f(N_{HI})$ at z~3



Prochaska & Wolfe 2009

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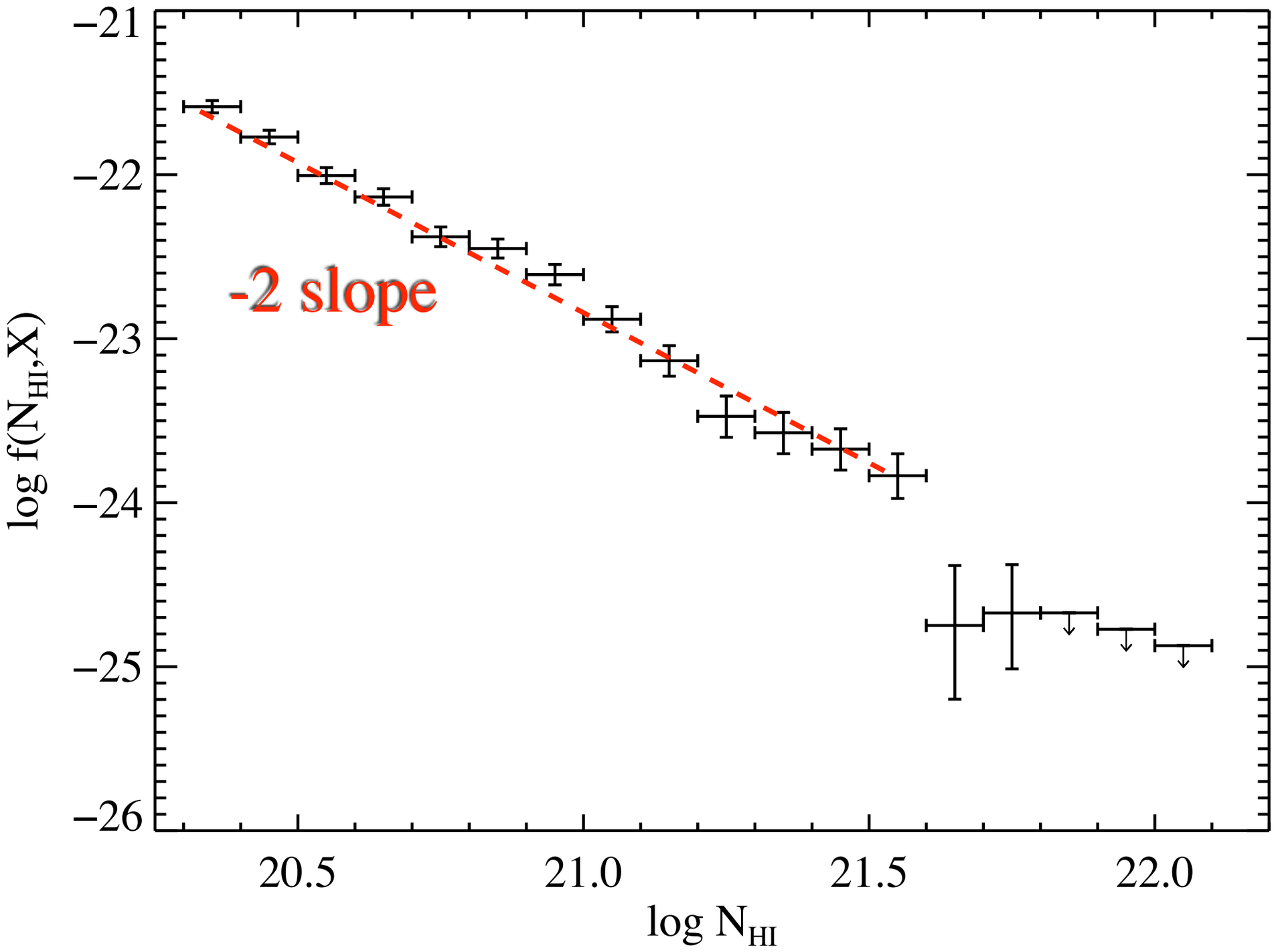

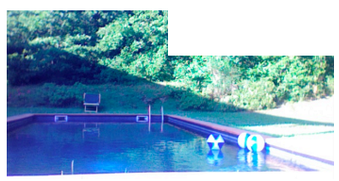

PROCHASKA & WOLFE 2009

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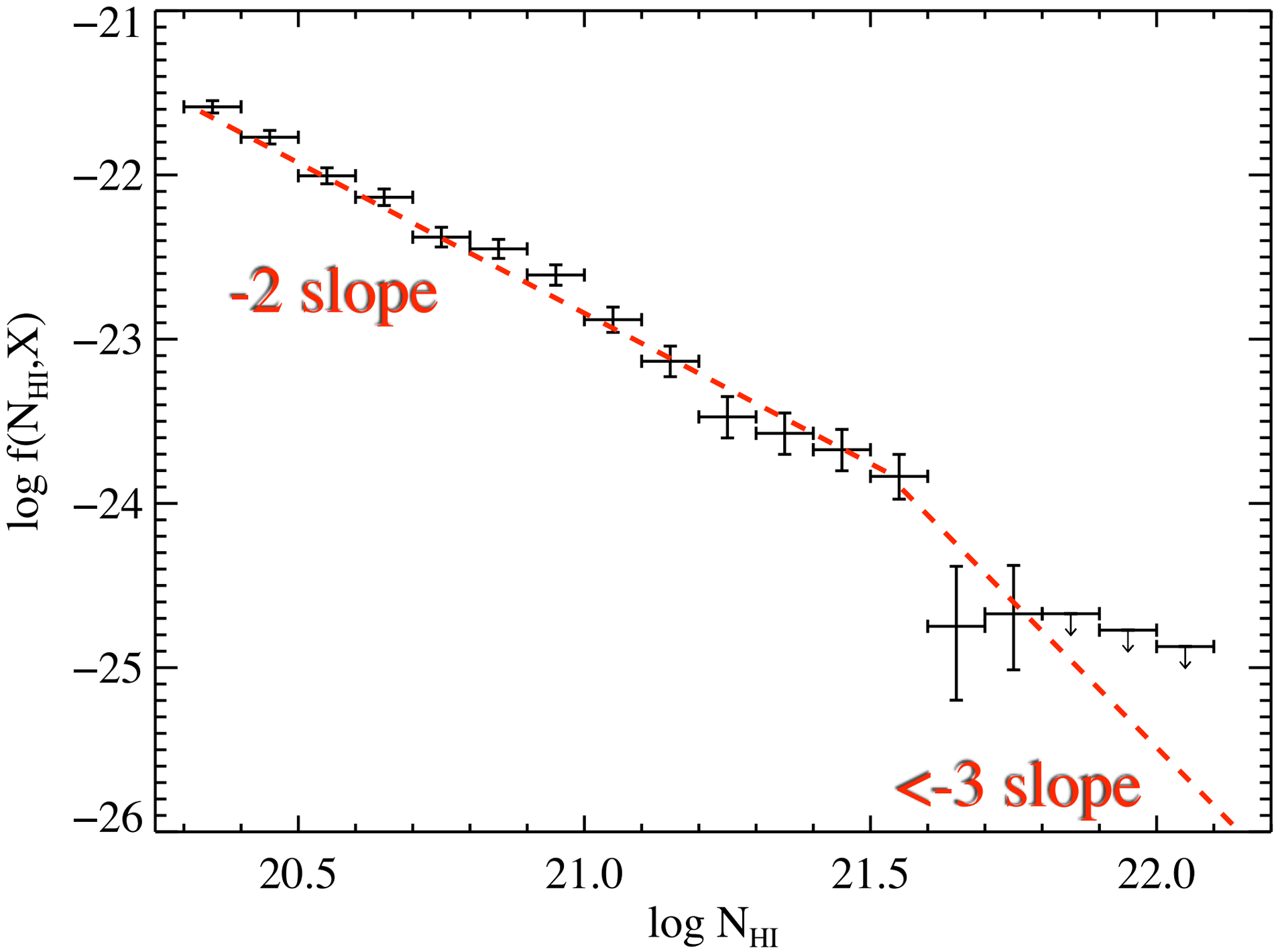

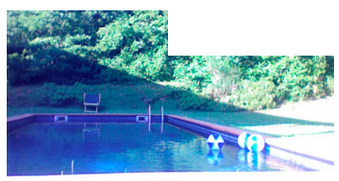

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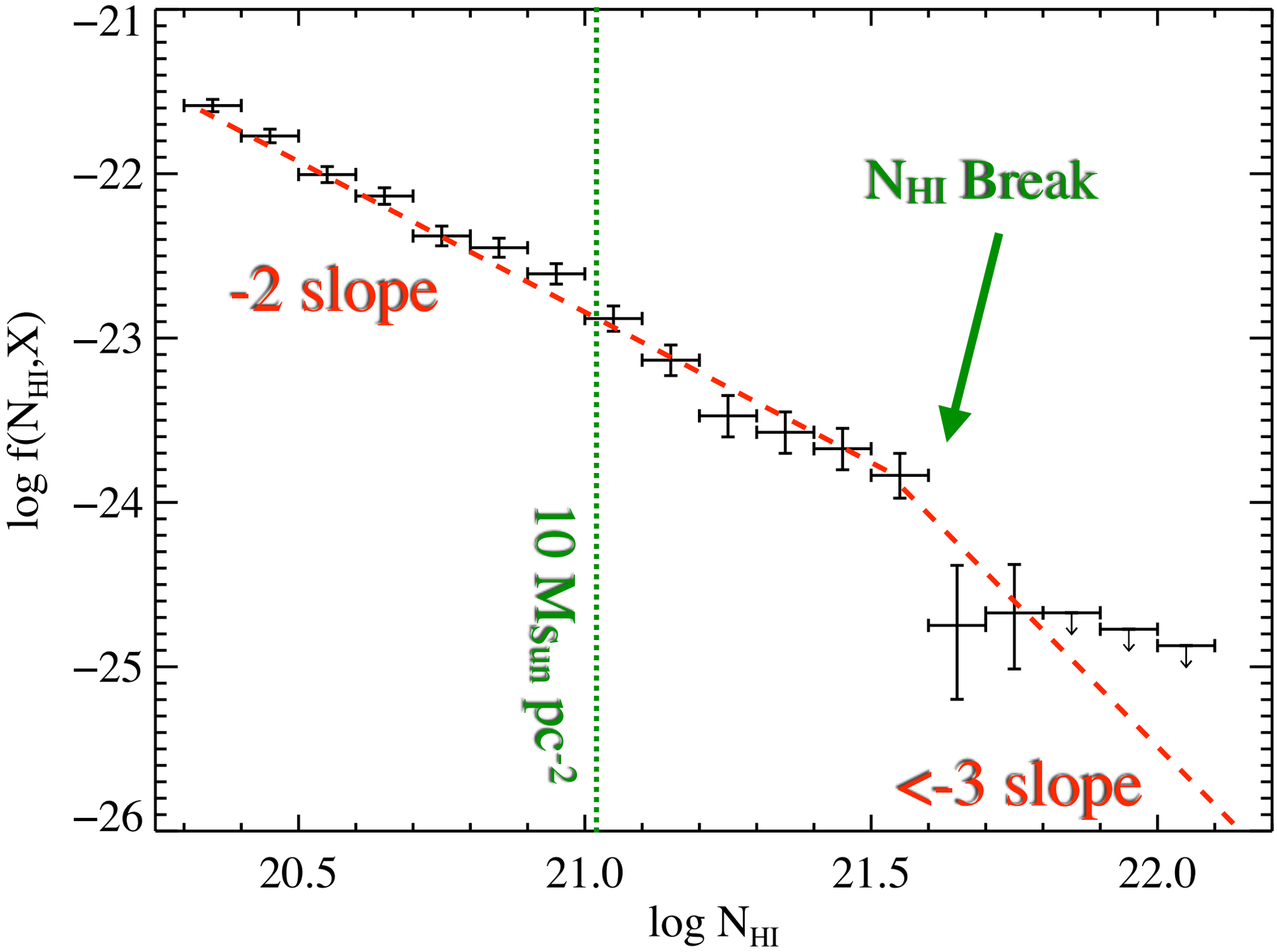
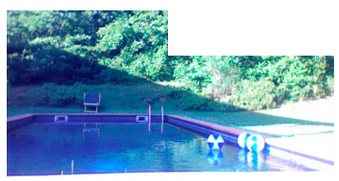
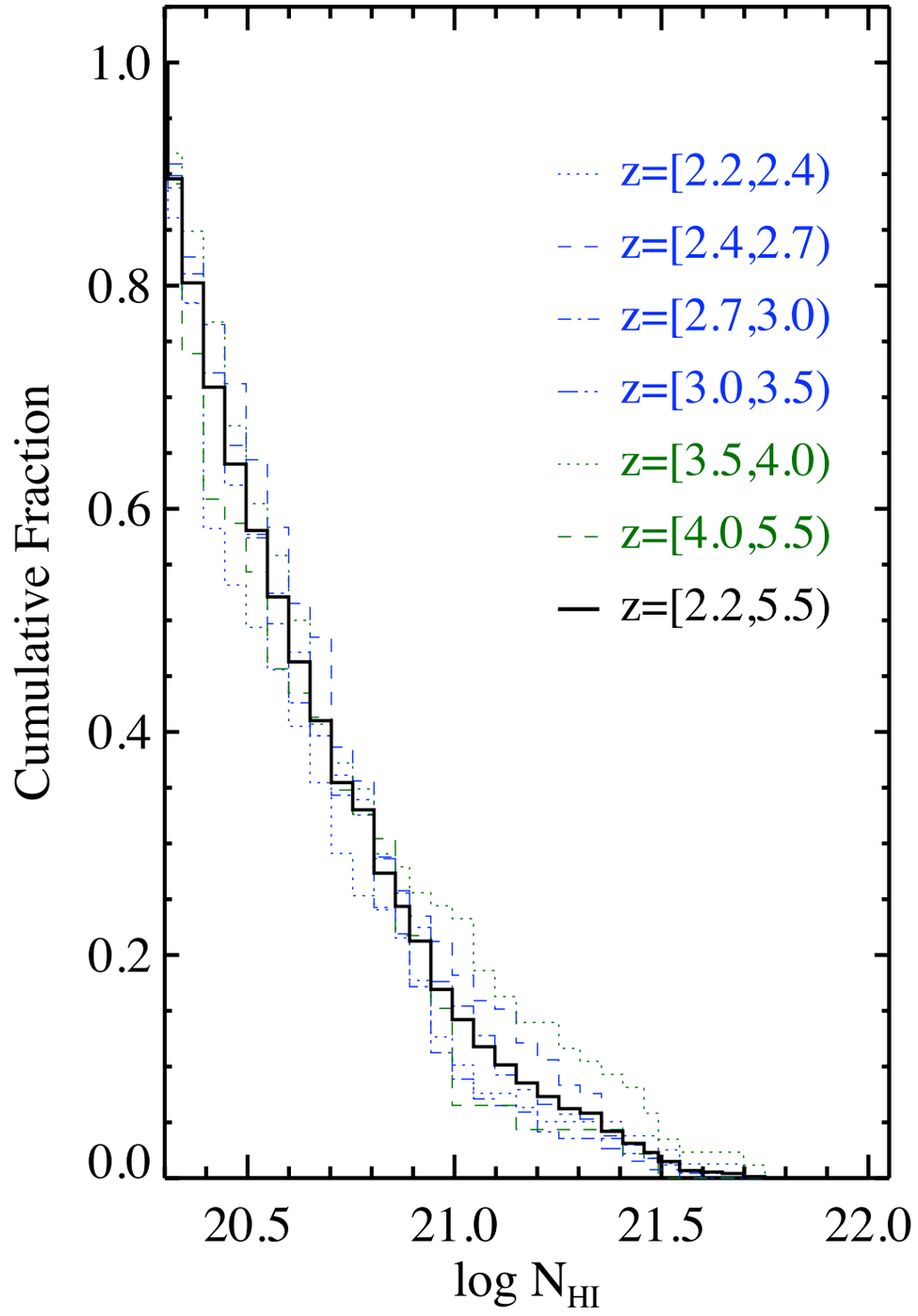




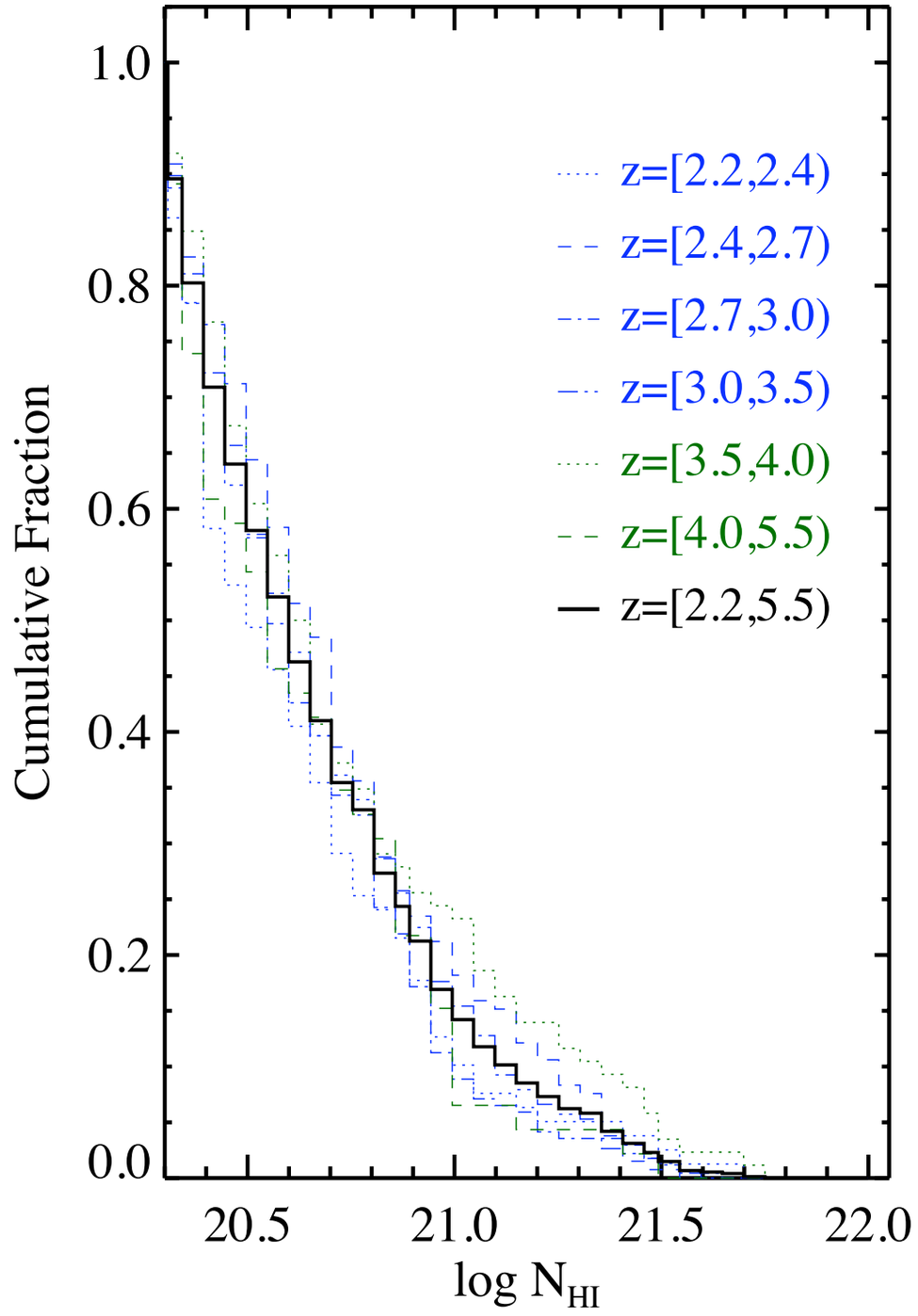
PROCHASKA & WOLFE 2009

Non-Evolution in the Shape of $f(N_{HI})$



Non-Evolution in the Shape of $f(N_{HI})$

- No evolution from z=2 to 4
  - Gas remains distributed in a self-similar fashion across this 1Gyr



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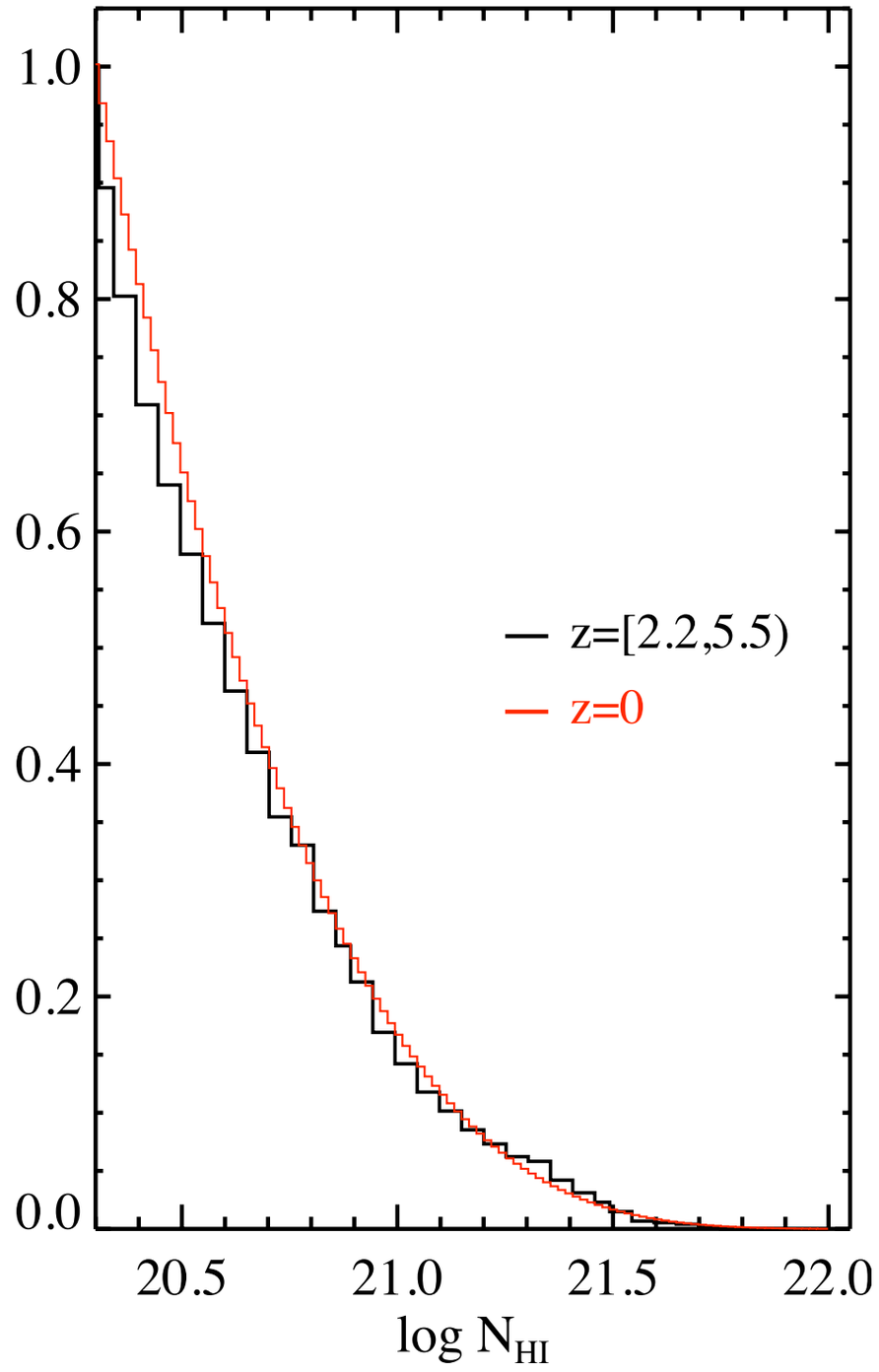
- No evolution from z=2 to 0!!
  - At all cosmic time, galaxies (as a population) have the same relative distribution of projected Σ_{HI}
    - On pc scales



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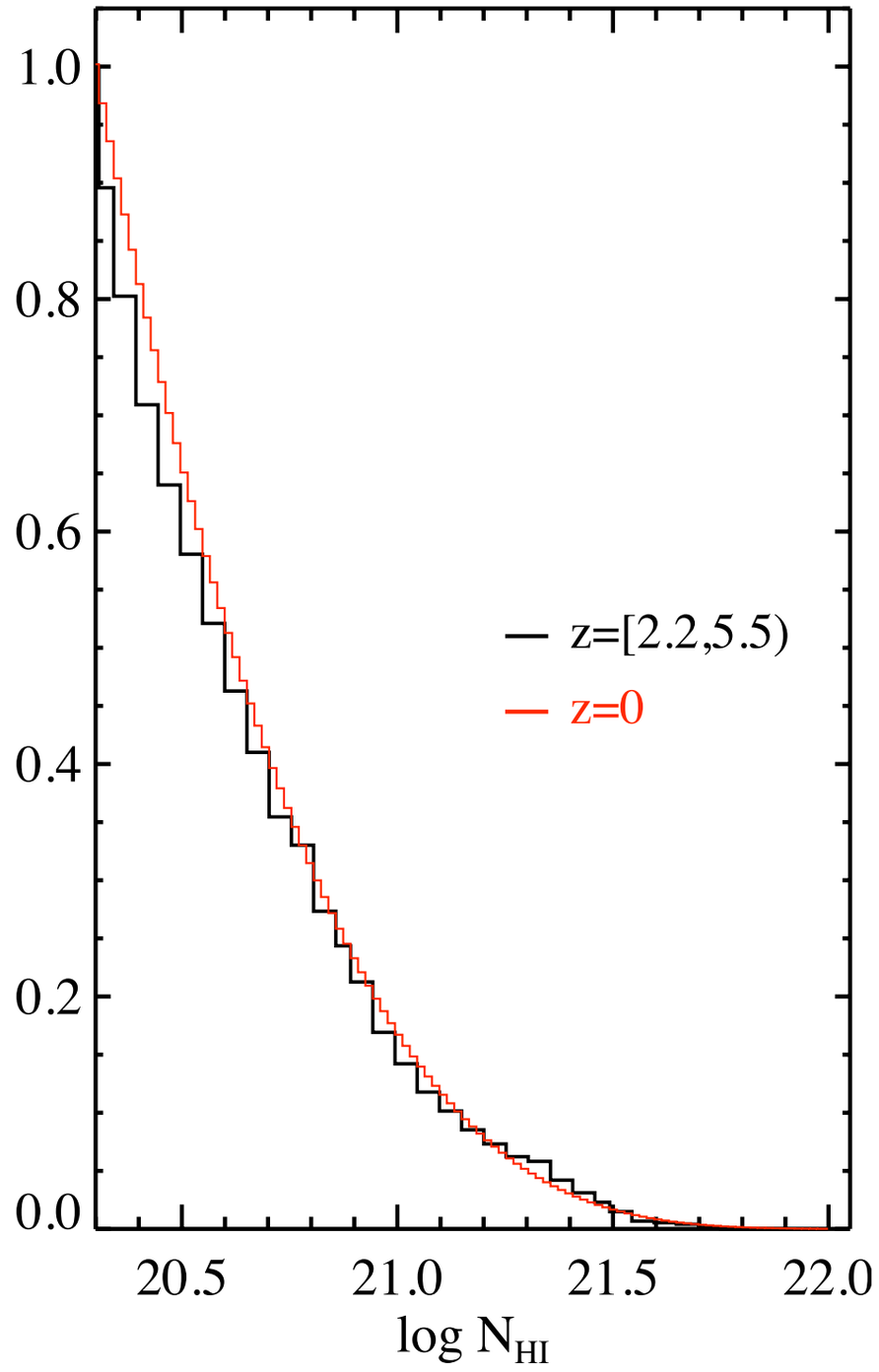
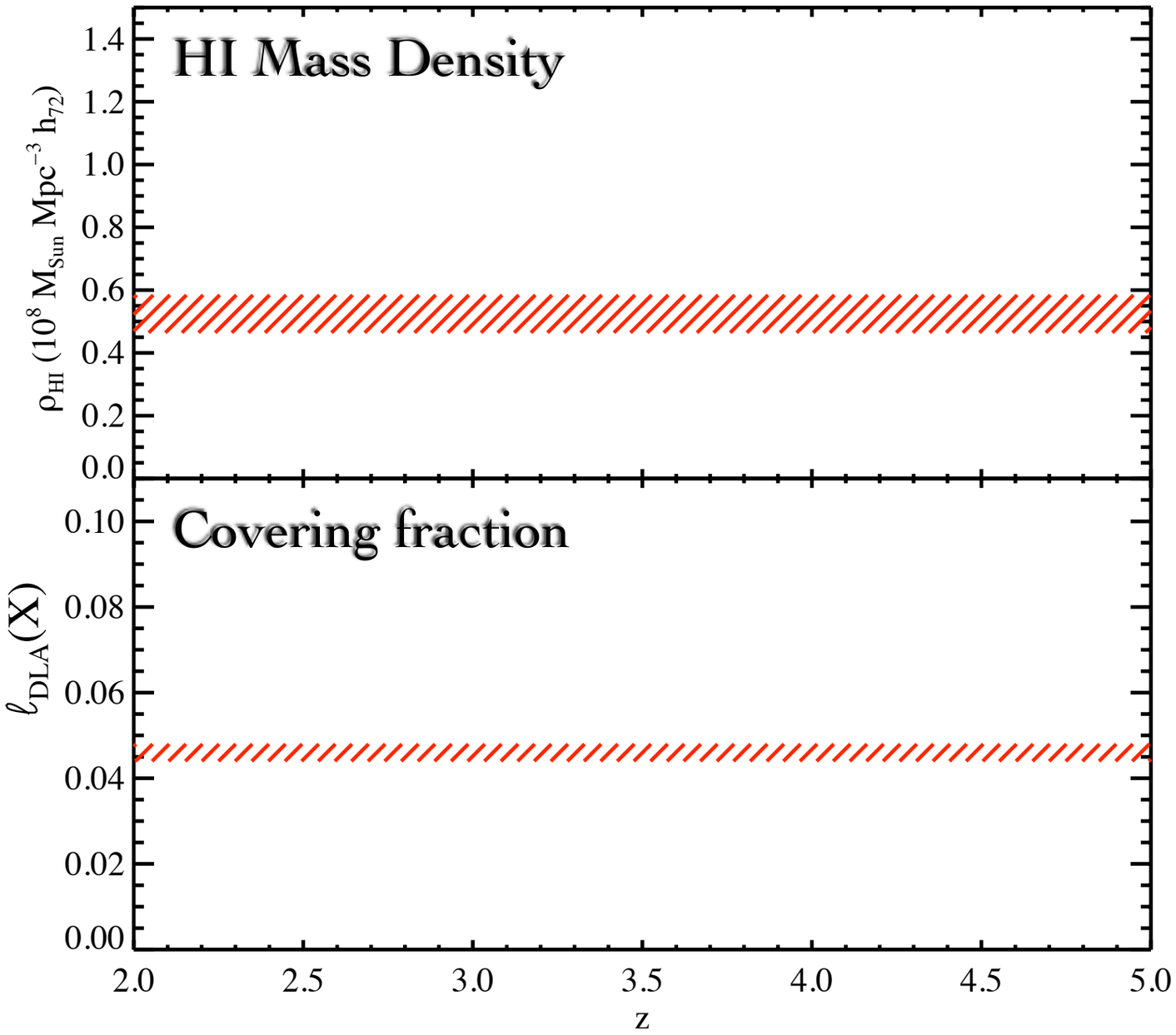
  - At all cosmic time, galaxies (as a population) have the same relative distribution of projected Σ_{HI}
    - On pc scales
- No shift in the N_{HI} break with z
  - To within a factor of ~2
  - Consistent with H_2 physics



(Non)Evolution in the f(N_{HI}) Moments



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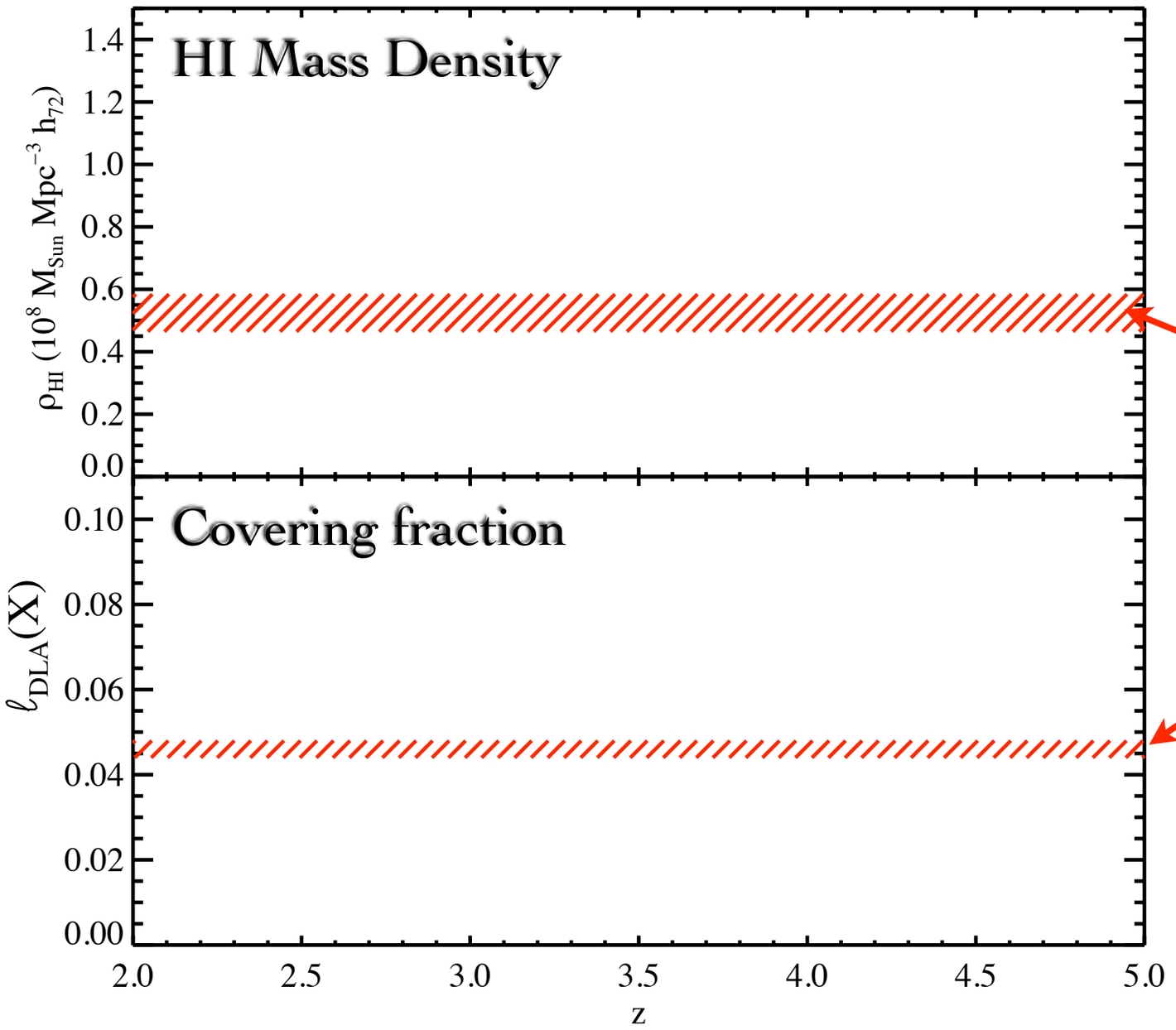

z=0 values from 21cm observations

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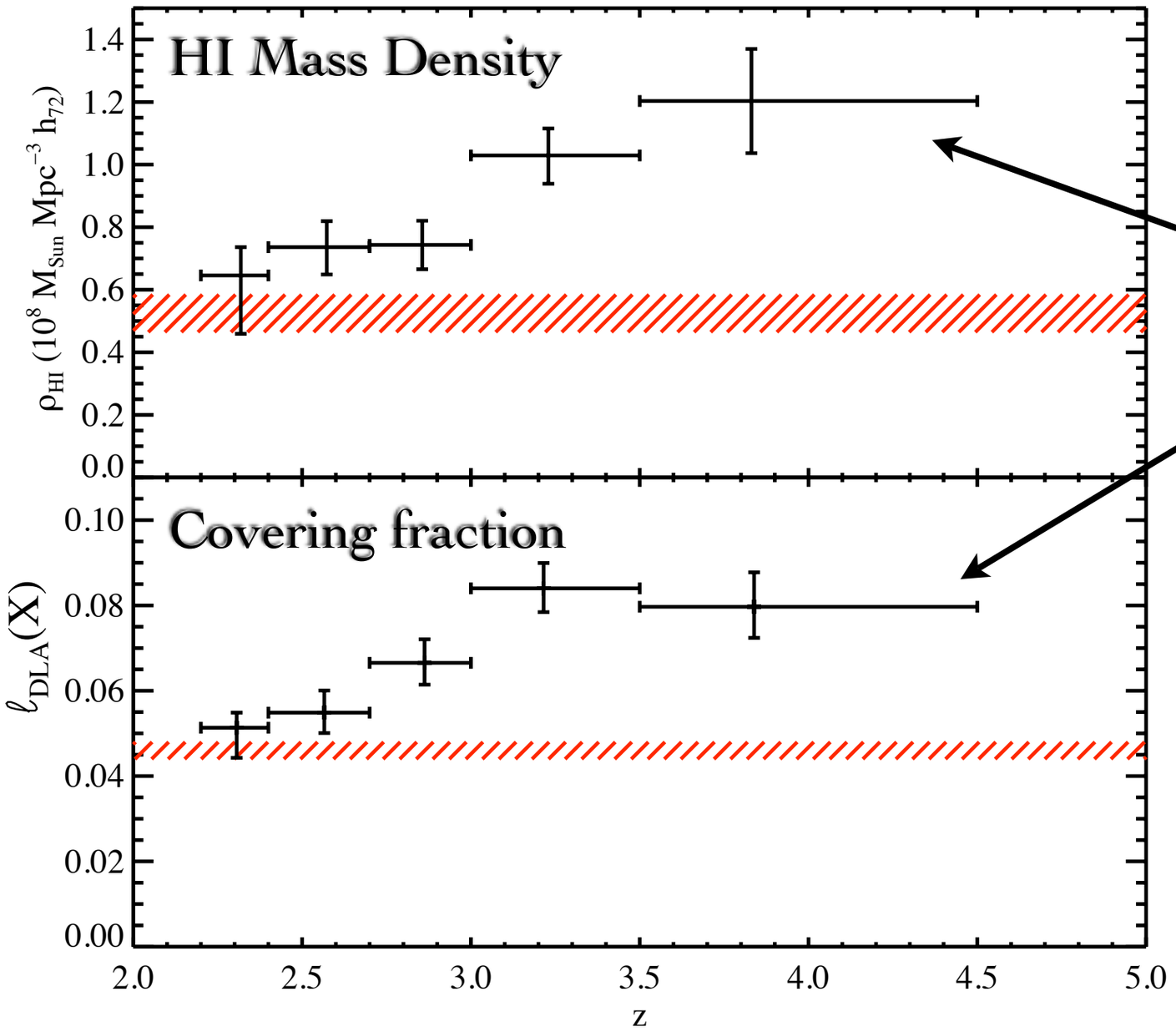
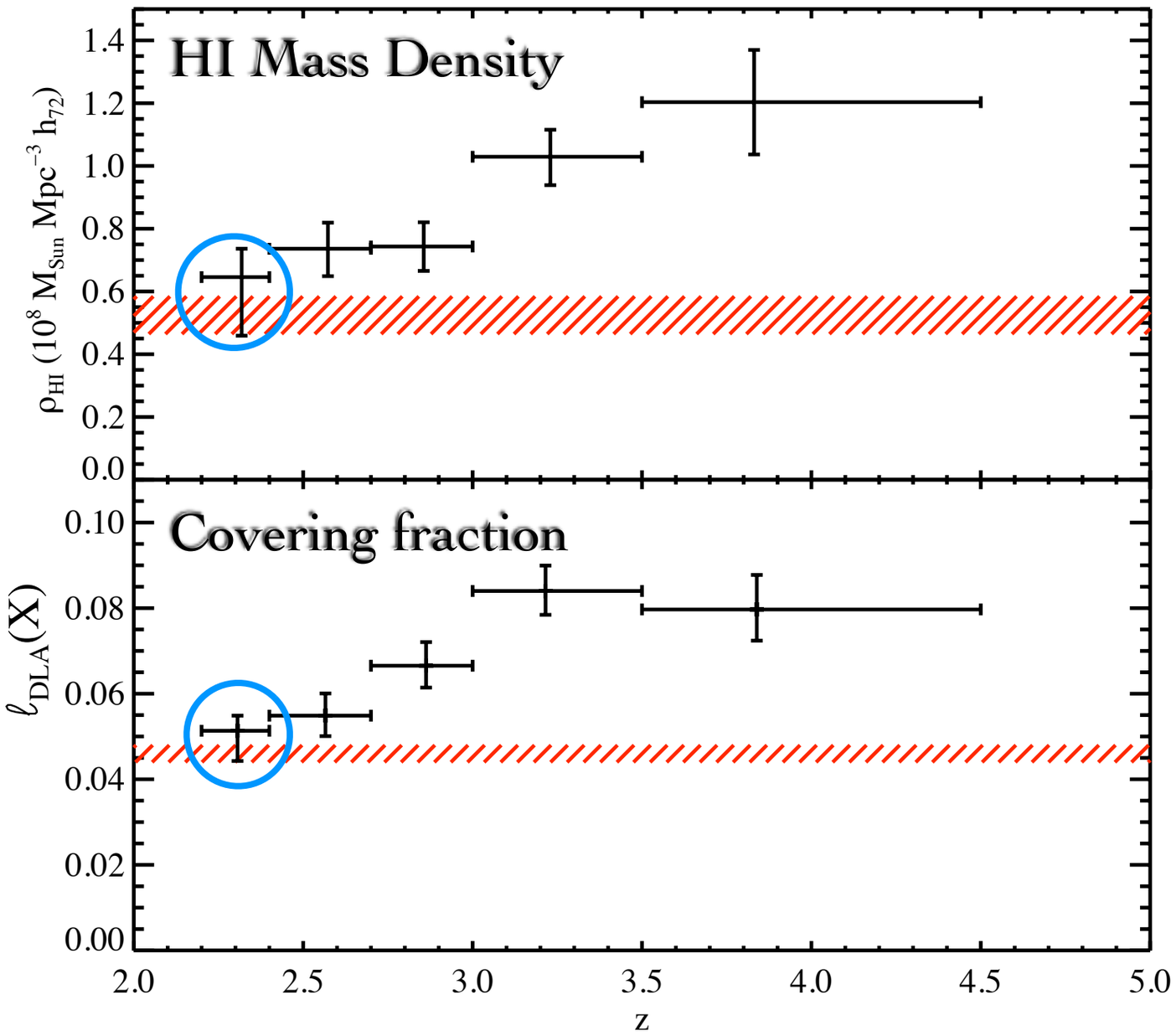


z>2.2 values from Lyα

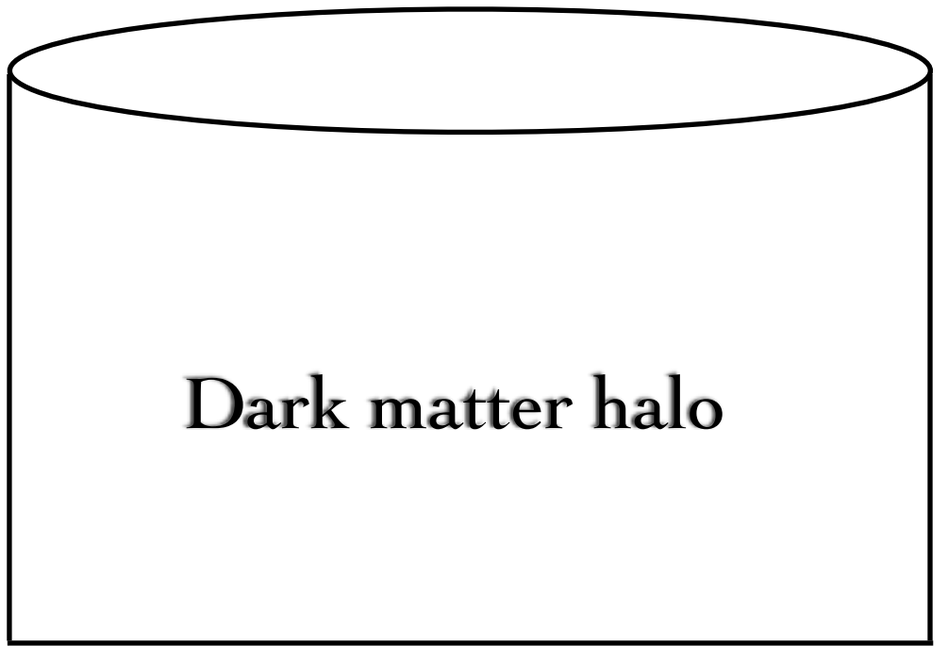
Non-Evolution in the f(N_{HI}) Moments



- Galaxies today have essentially the same total covering fraction and HI mass as 10 Gyr ago
  - Am willing to interpolate
    - i.e. constant since z~2
- But, we know stars have formed since z~2
  - Driven by gas accretion
    - (See Keres)
  - 'Disks' are critically unstable (Q~1) to SF at all times

Swimming Pool Theory of Galaxy Formation

- **Construction**
  - Dark matter halo forms
  - Gas pools in
    - This may occur very rapidly (i.e. coeval)
    - Cools+recombines to form HI
- **Pool fills**
  - Excess water spills into H_2
    - H_2 rapidly converted to stars
    - HI level maintained
- **Accretion stops**
  - SF slows
  - Pool stays full
    - Absent a major (destructive) event



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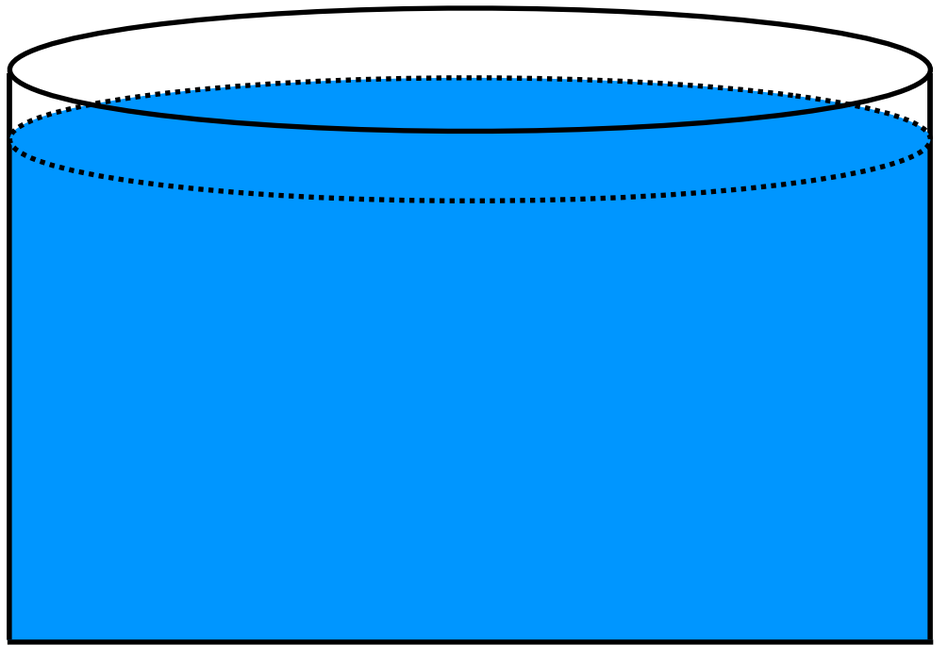

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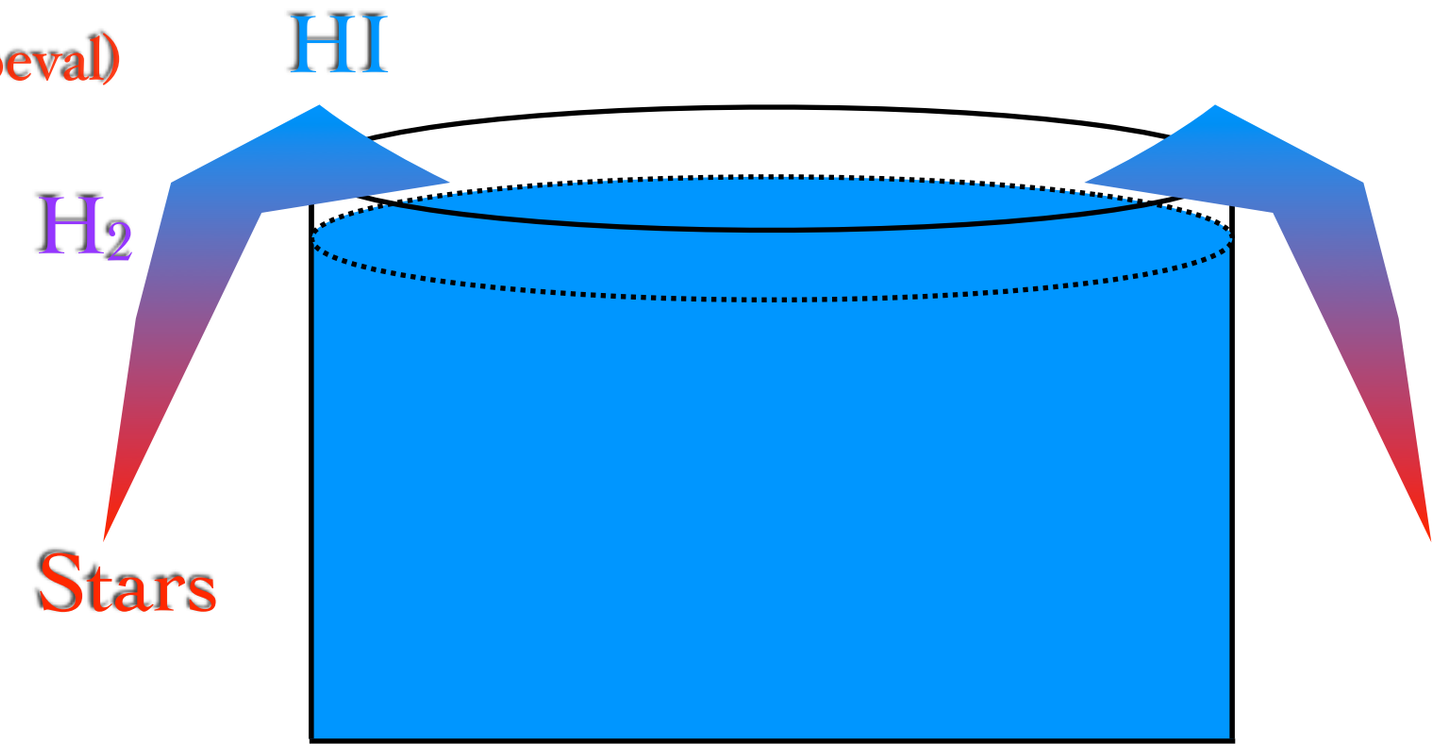
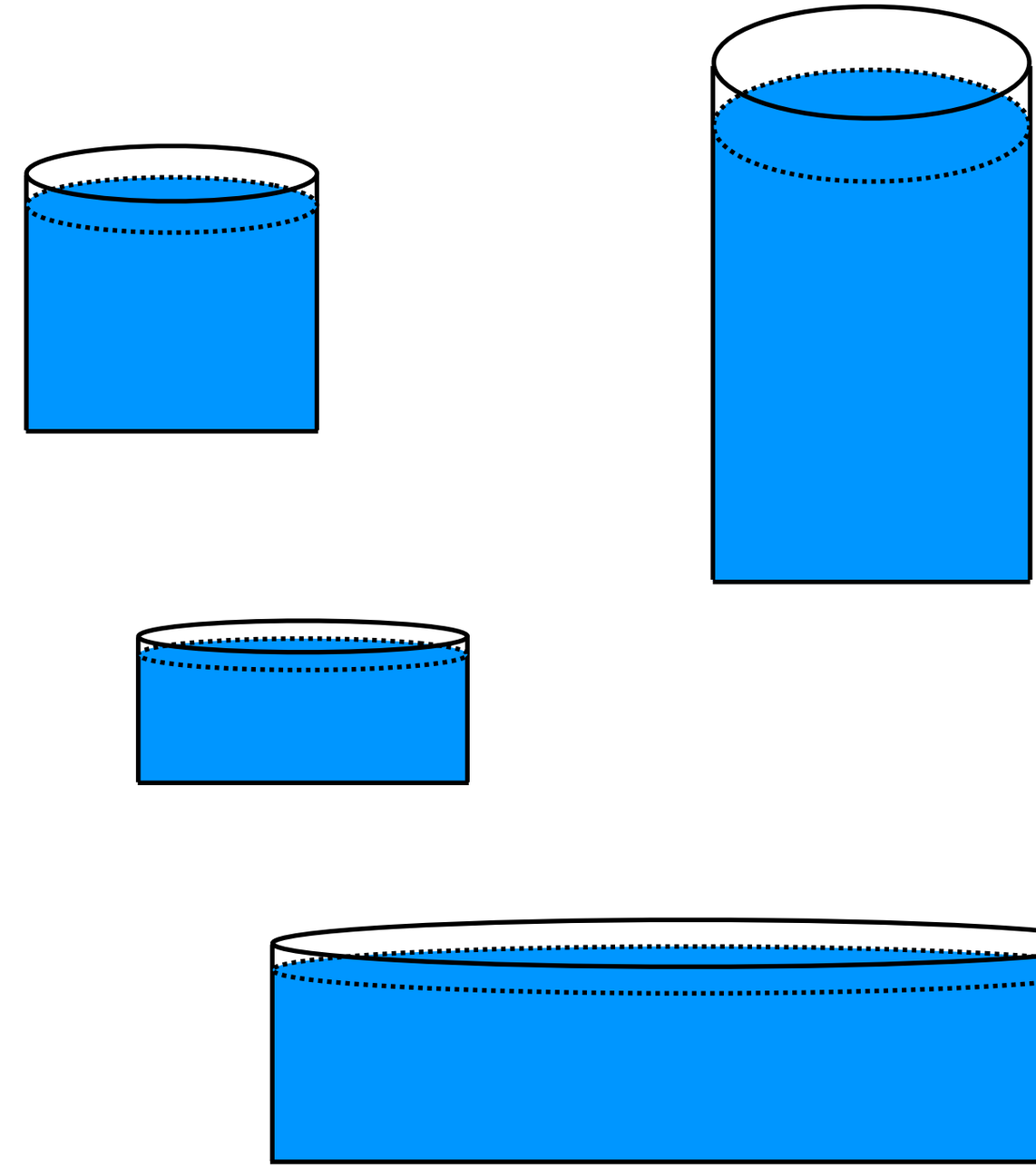
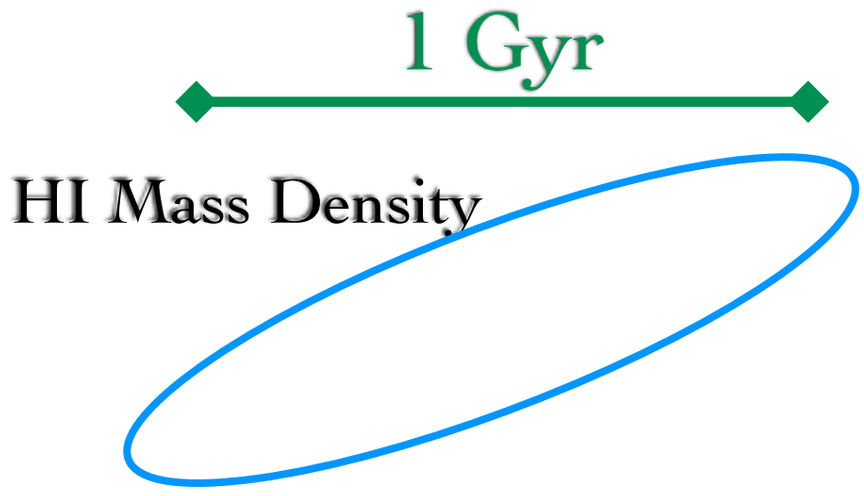


Swimming Pool Theory of Galaxy Formation

- At z~2, all of the swimming pools are in place (and full)
  - i.e. Halos with M < 10^{12} M_{Sun}
    - ✦ Predicted by LCDM
- Implications
  - HI 'disks' at z~2 are as large as today
    - ✦ True as a population
  - Very few HI disks are destroyed since z~2
    - ✦ Those that are destroyed are replaced



Evolution in the $f(N_{HI})$ Moments



- 2x decrease in C_A and ϱ_{HI} from z=4 to 2.5 (1 Gyr)
  - Eliminate, uniformly, gas at all surface densities
- Star formation?
  - Unlikely to remove gas with low Σ_{HI}
- 'Violent' processes
  - Mergers
  - Feedback

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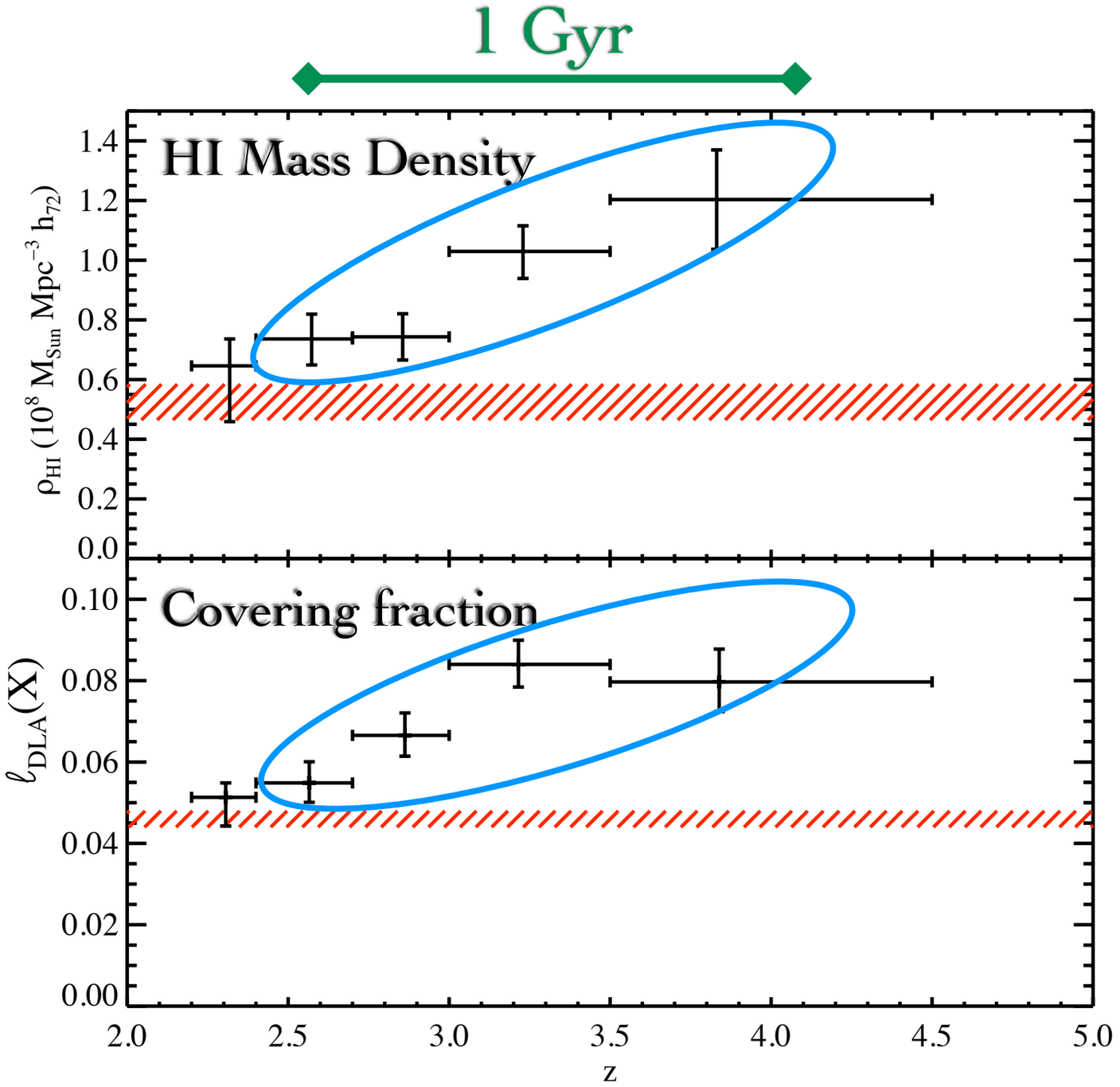

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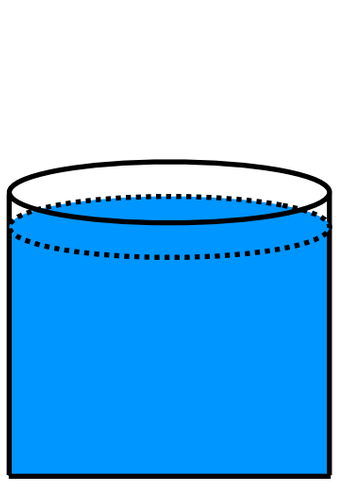

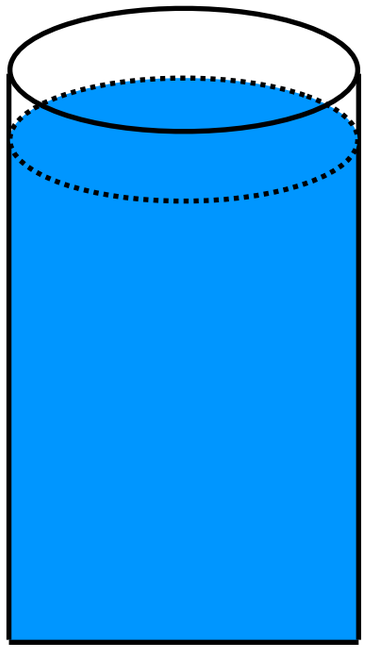

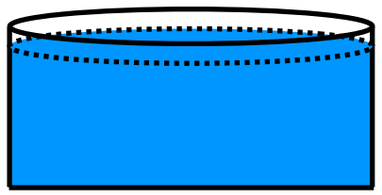

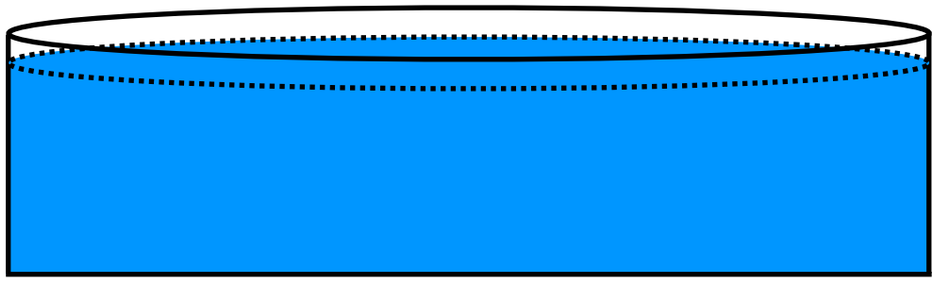

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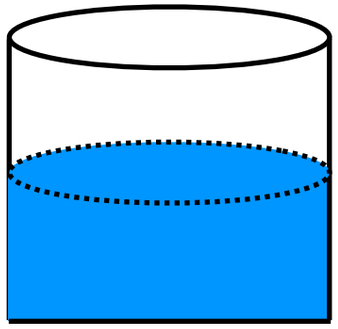

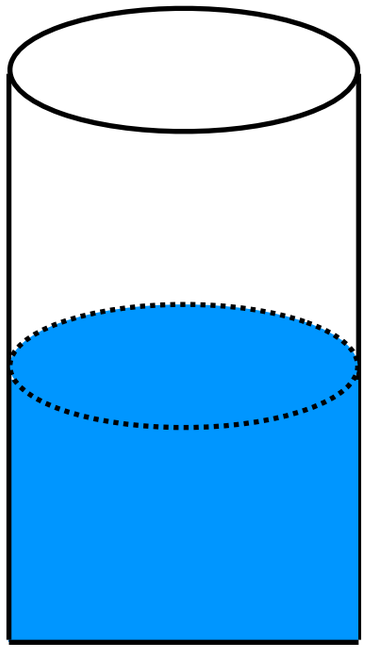

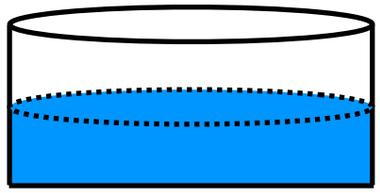

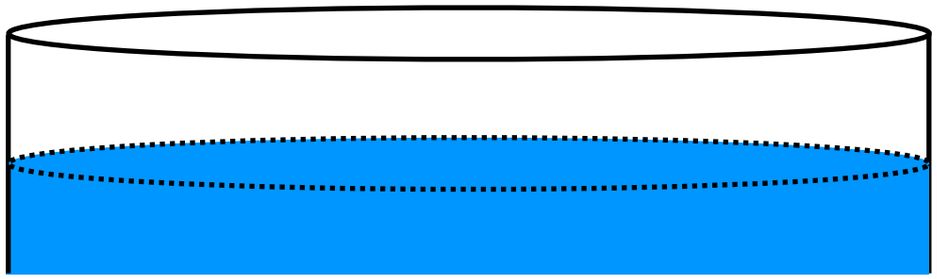

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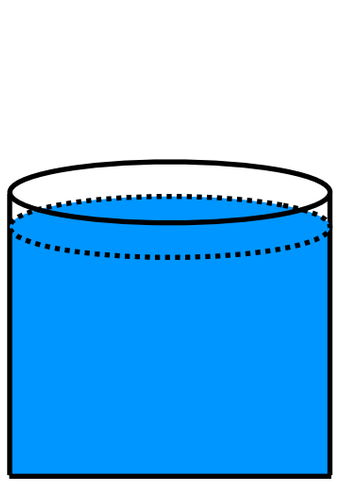

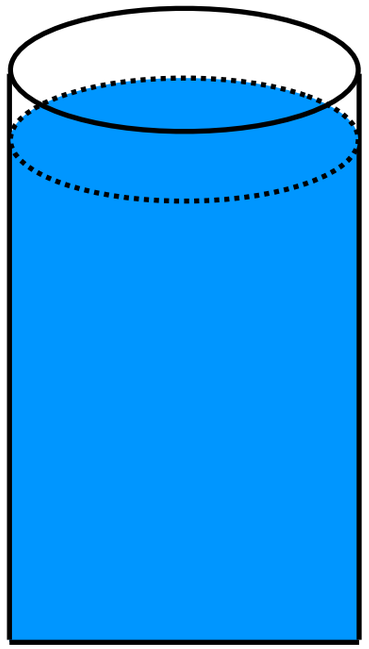

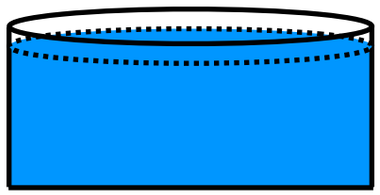

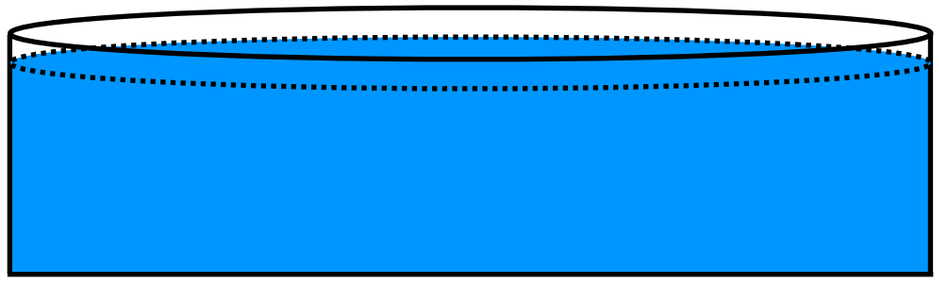

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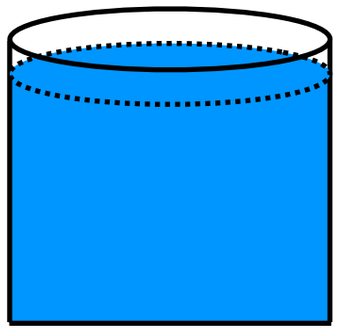

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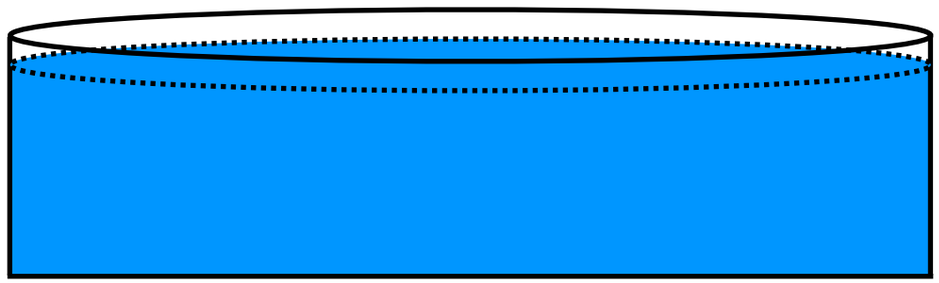
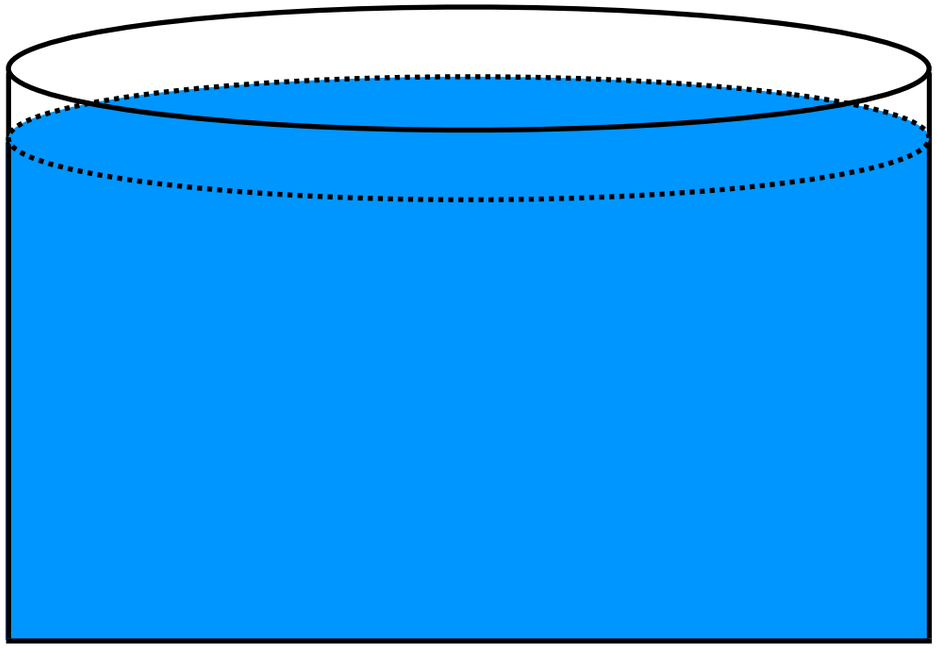
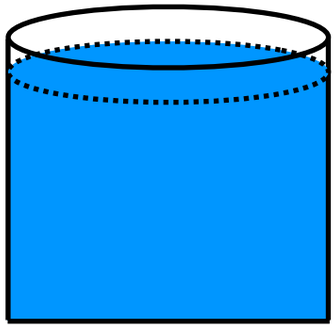
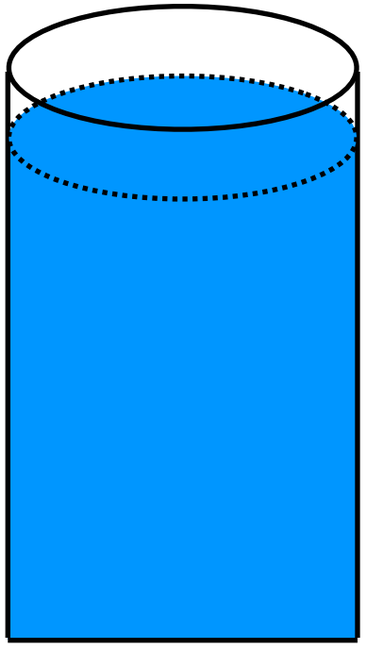
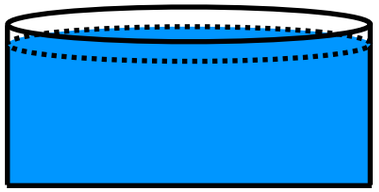
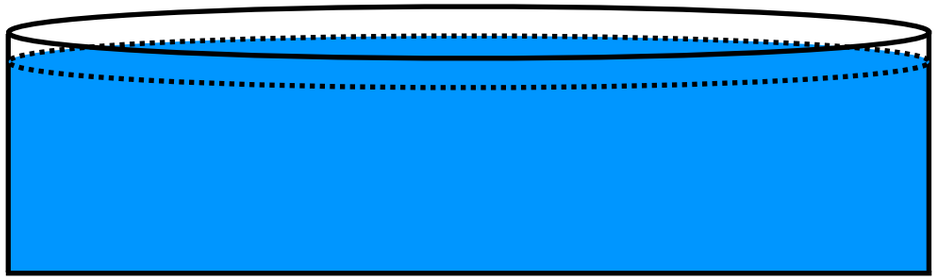
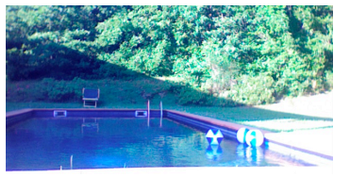
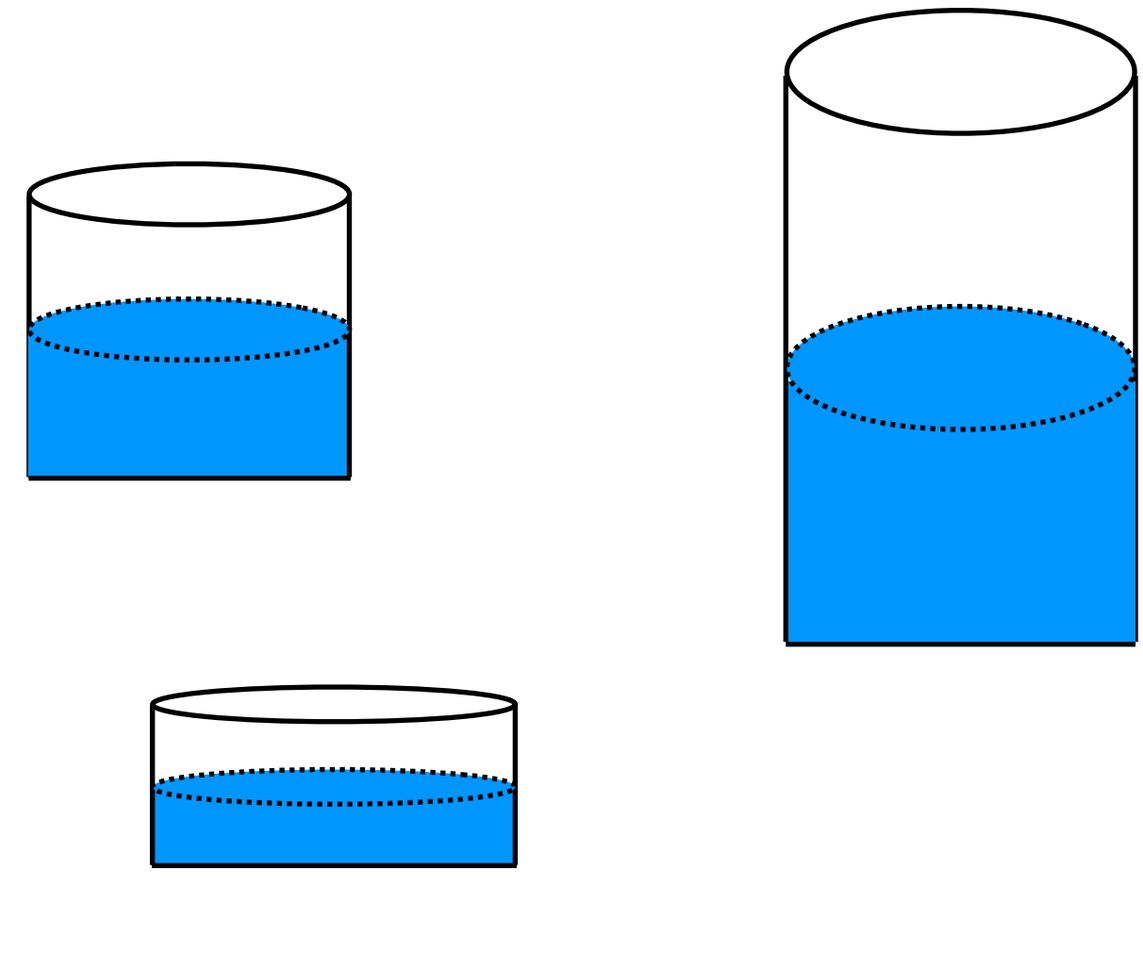
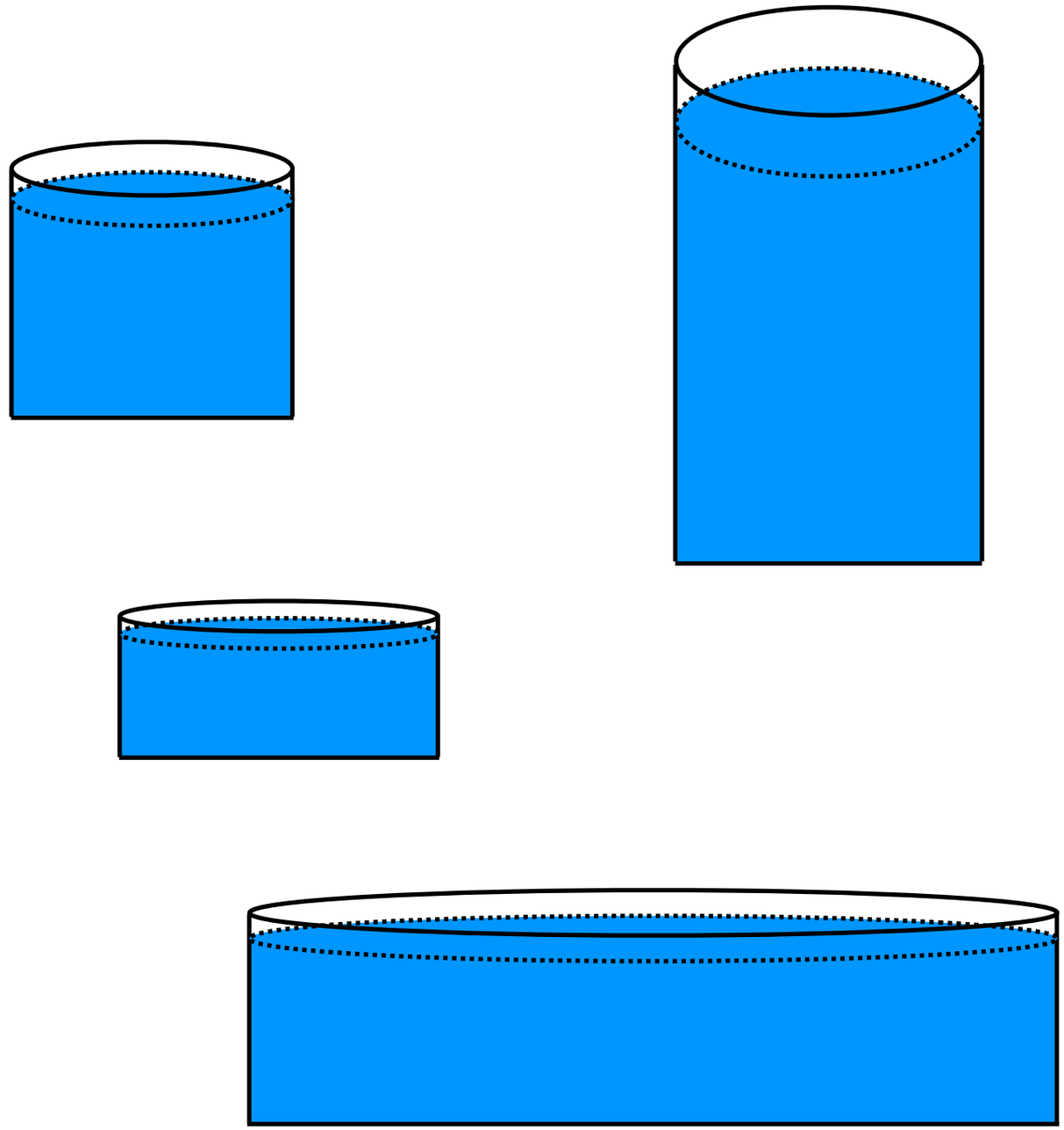


Summary

- Galaxies (as a population) have the same distribution of Σ_{HI} at z=2 and 0
  - And probably at all times in between
  - Shape holds to z>4
- HI mass density and covering fraction decline by 50% in 1 Gyr from z=4 to 2
  - Mergers? Feedback?
- Swimming Pool Theory of GF
  - z=4 to 2
    - 1/2 of the pools are completely emptied
  - z=2 to today
    - The pools are filled and do not evolve