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"

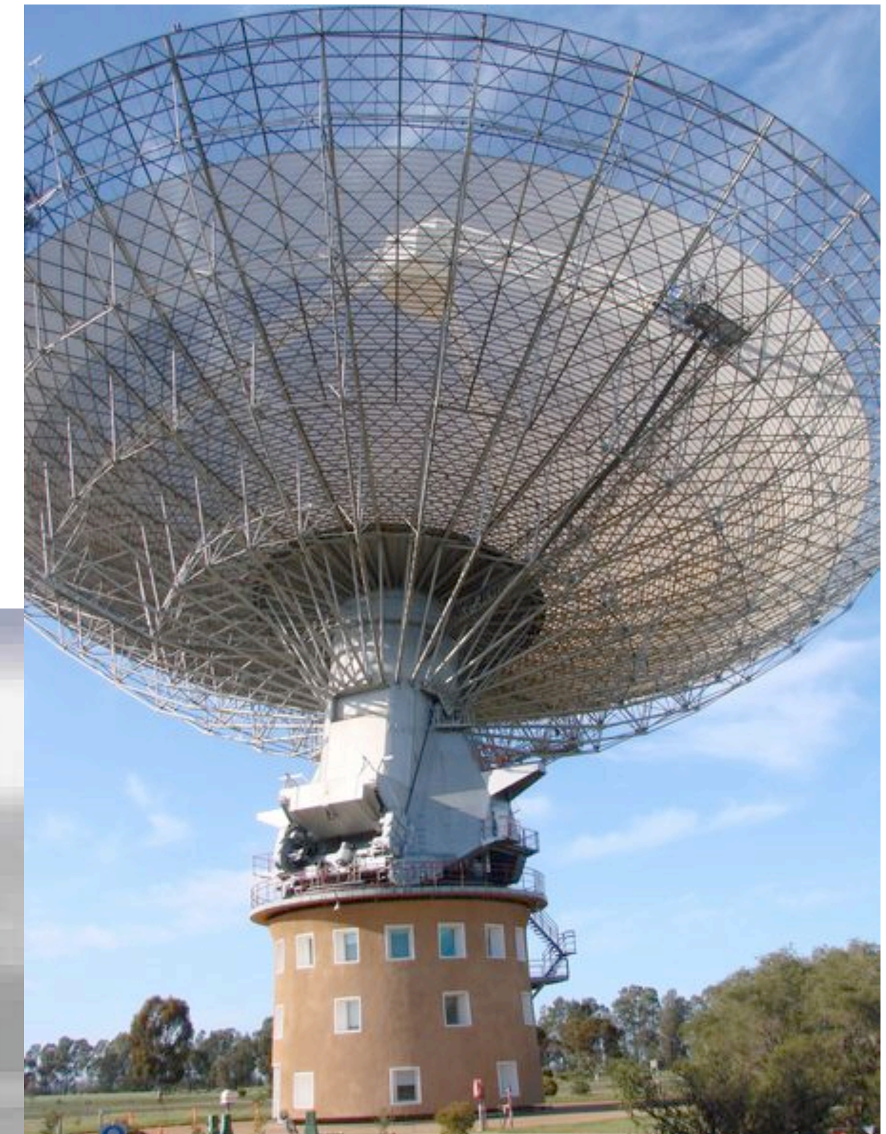
A.M. Wolfe (UC San Diego)

Overview

- Goal: Discuss the global evolution of HI in galaxies across cosmic time

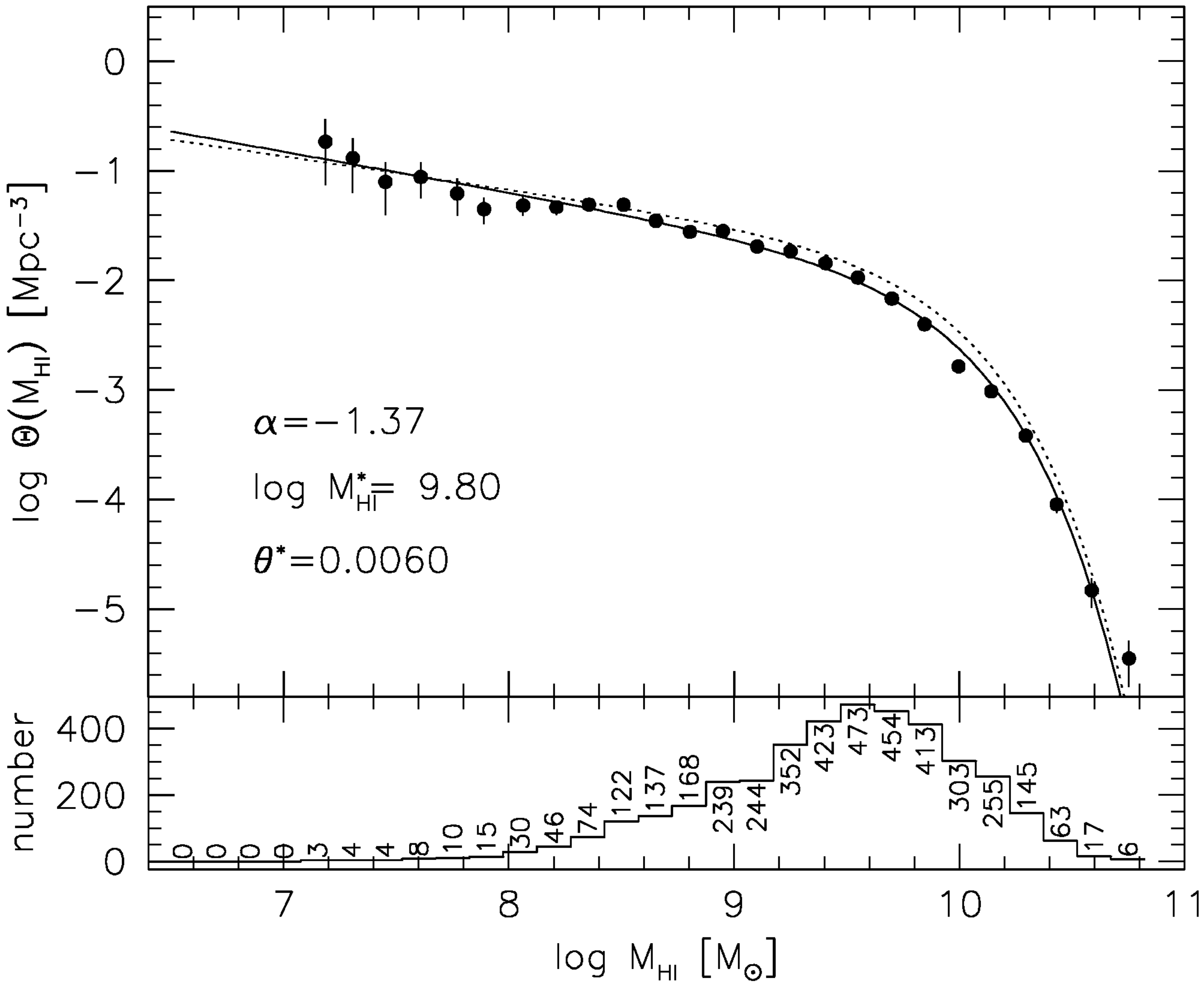
- Motivations
  - HI gas feeds star formation (via H_2)
    - Total HI content is a balance between SF, accretion, and 'feedback'
  - HI is a signpost for recent/current/future SF

HI = 21cm

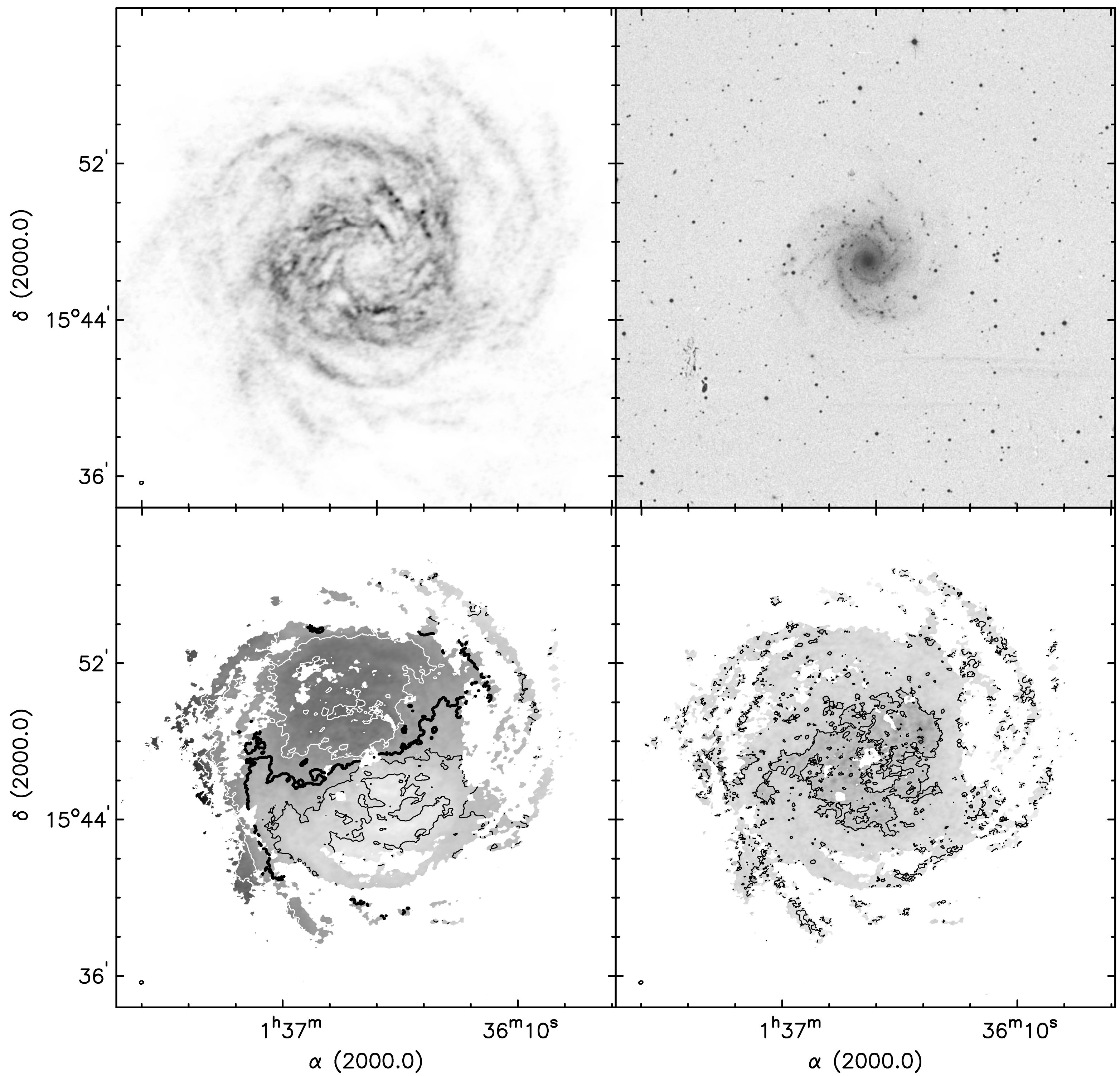


HI at z=0

HIPASS: Zwaan et al. 2005



21cm HI Maps



THINGS: Walter+ 2008

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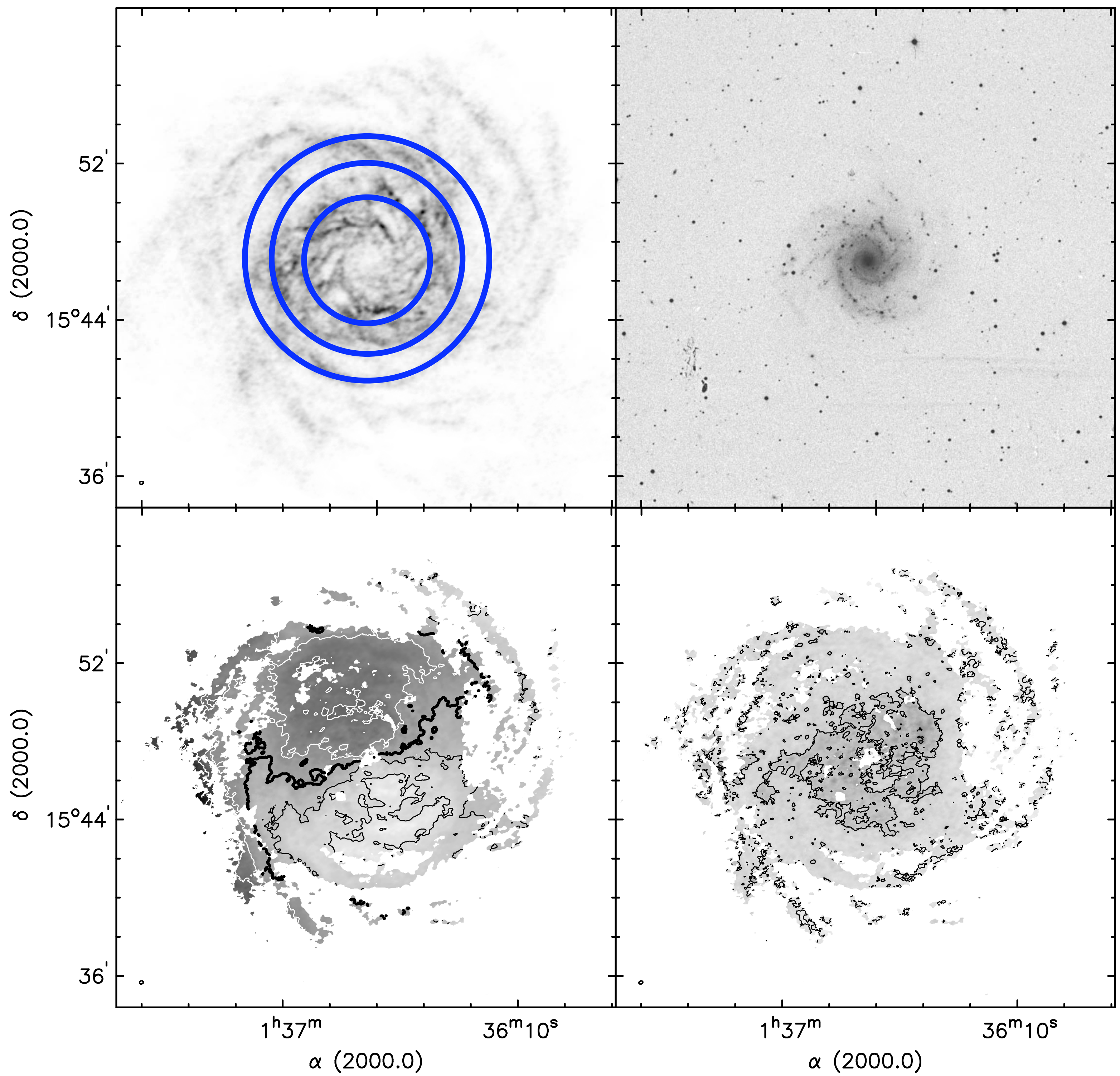
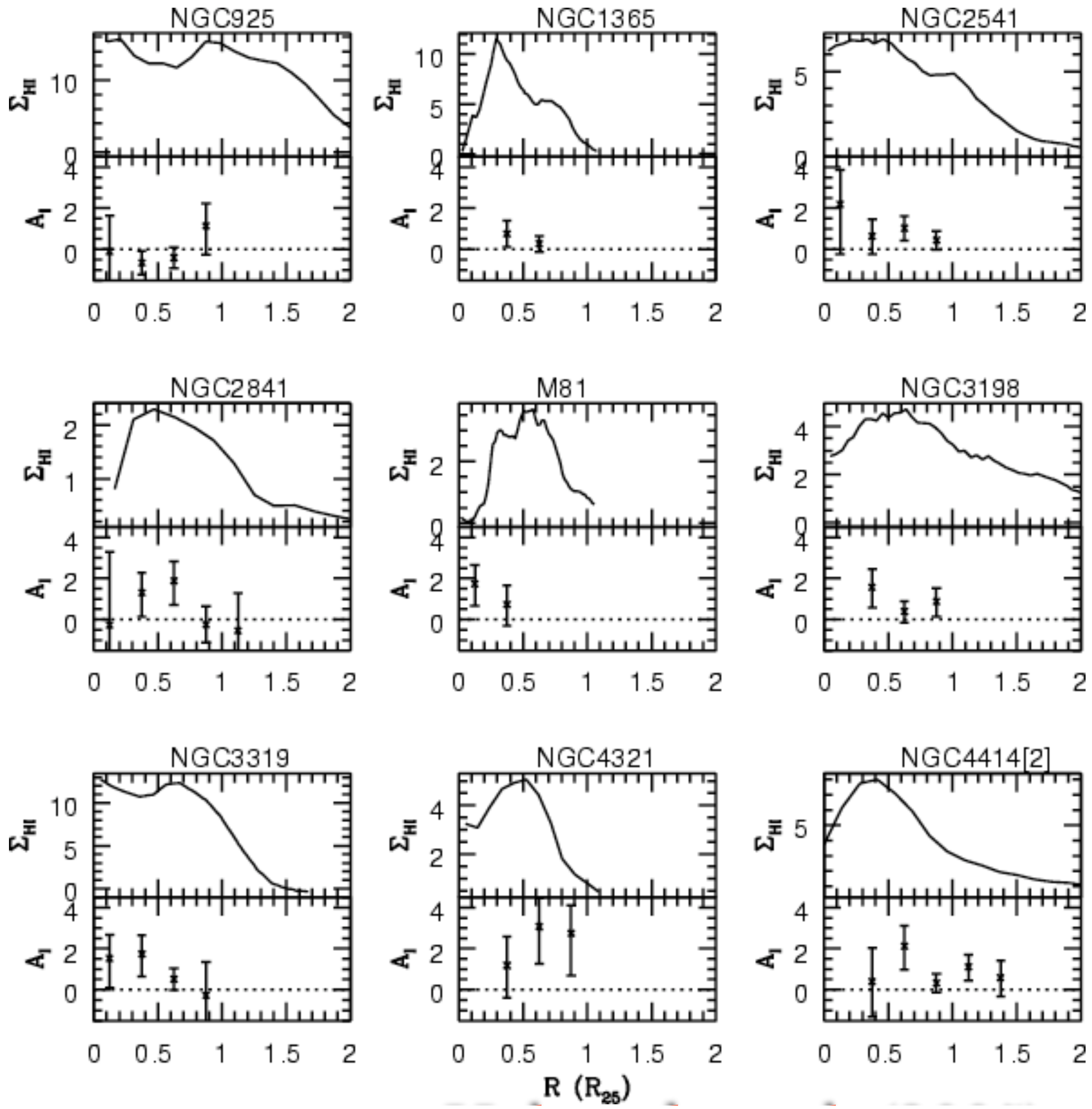


THINGS: Walter+ 2008

Galactic Σ_{HI} Profiles

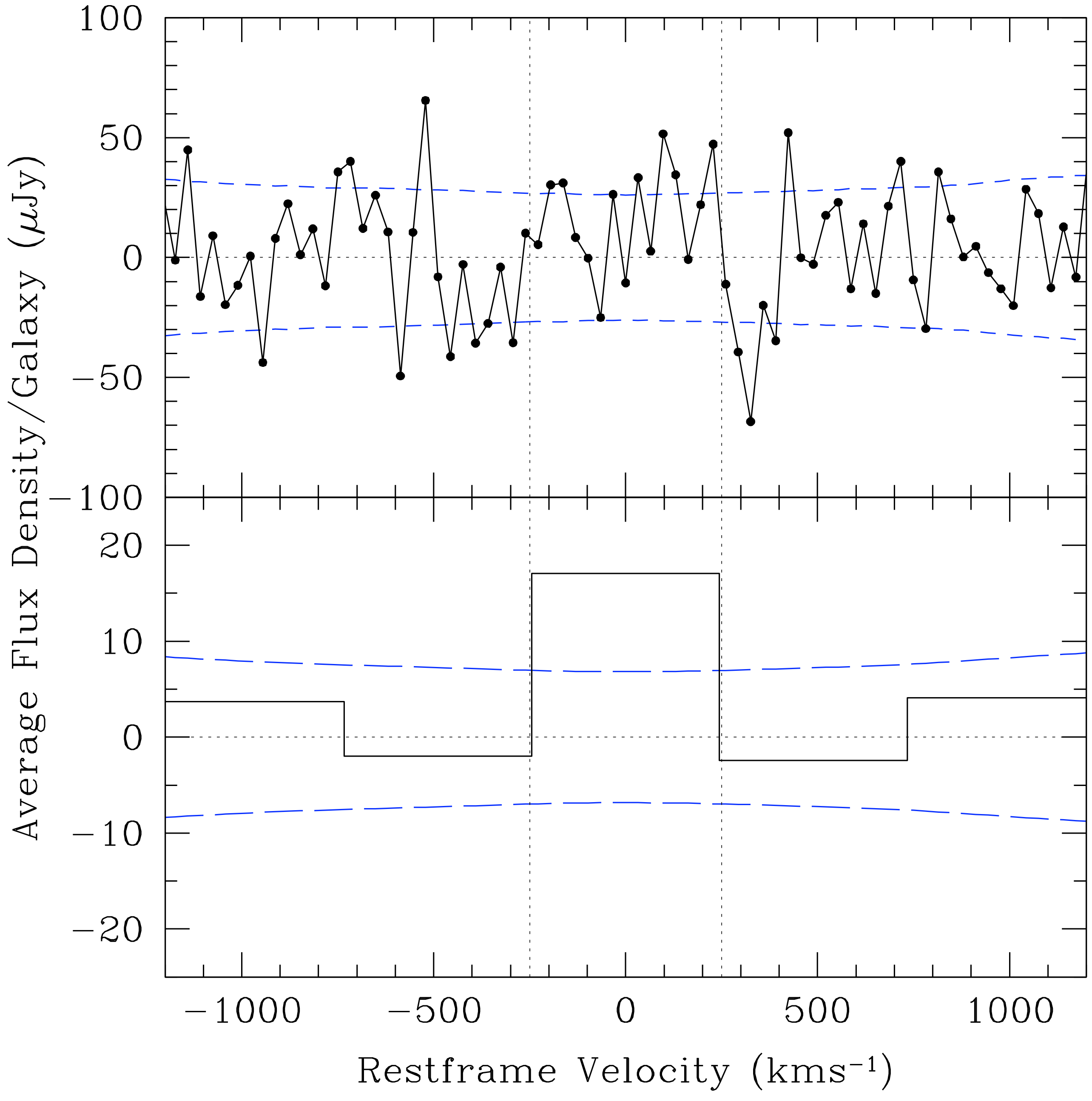
- Analysis
  - De-projection by inclination
  - Average azimuthally
  - Plot
- Common characteristics
  - HI 'holes' at the center
  - Steep decline for $R<R_{25}$
  - Power-law (Metsel) beyond



Holwerda+ 2005

Mapping HI at z>0

Lah+ 2007



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  - Not with today's telescopes
  - SKA (i.e. >2020)

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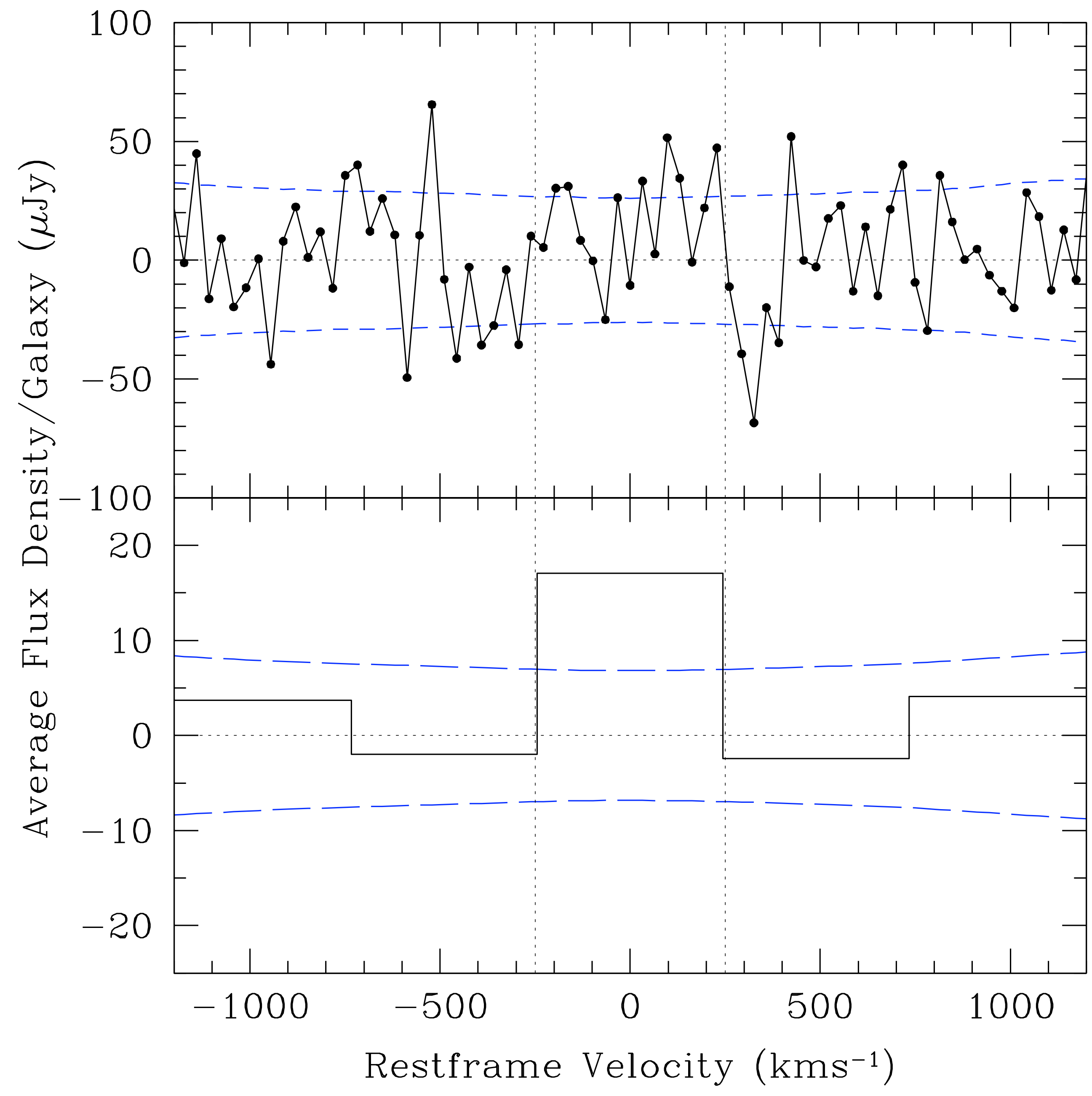

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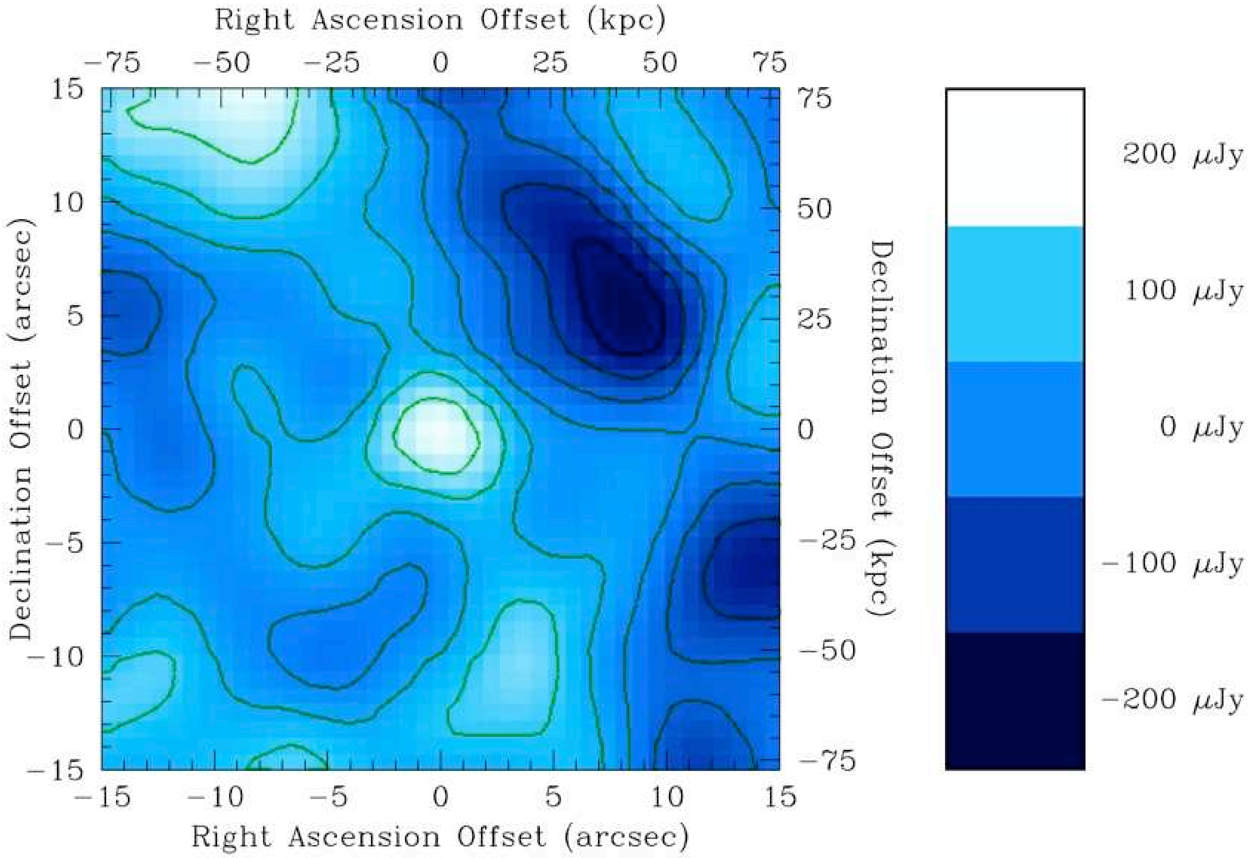

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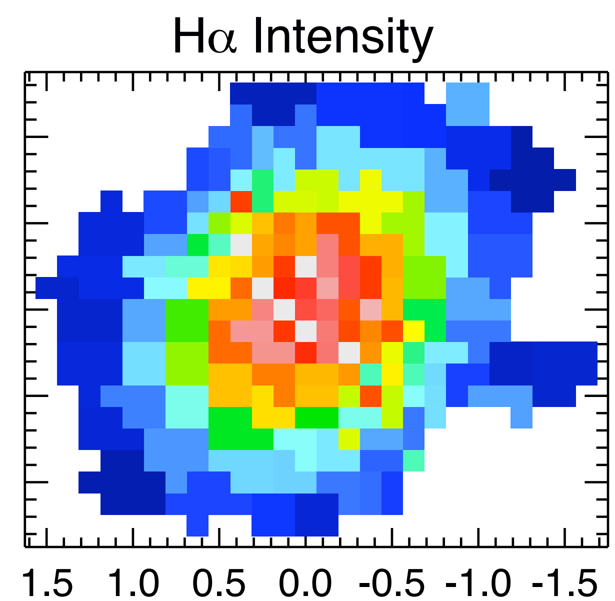
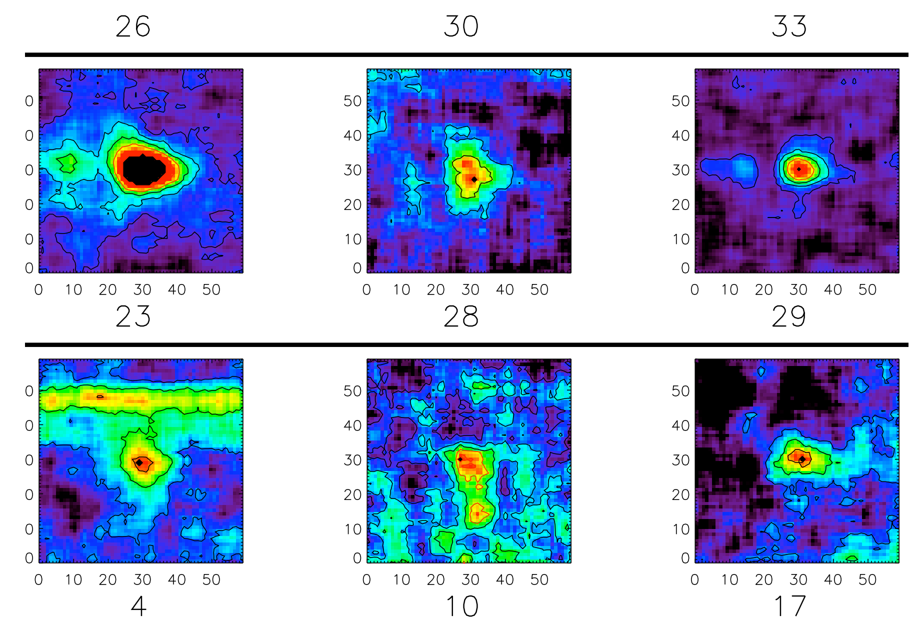
- 21cm?
  - Not with today's telescopes
  - SKA (i.e. >2020)
- Hα, Lyα
  - Difficult observations
  - Primarily trace ionized H gas
    - But connected to atomic/molecular gas

Shapiro+ 2008





Rauch+ 2008

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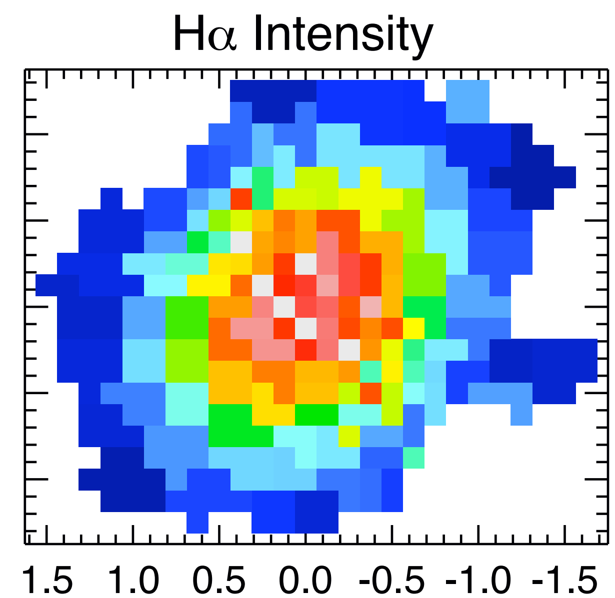

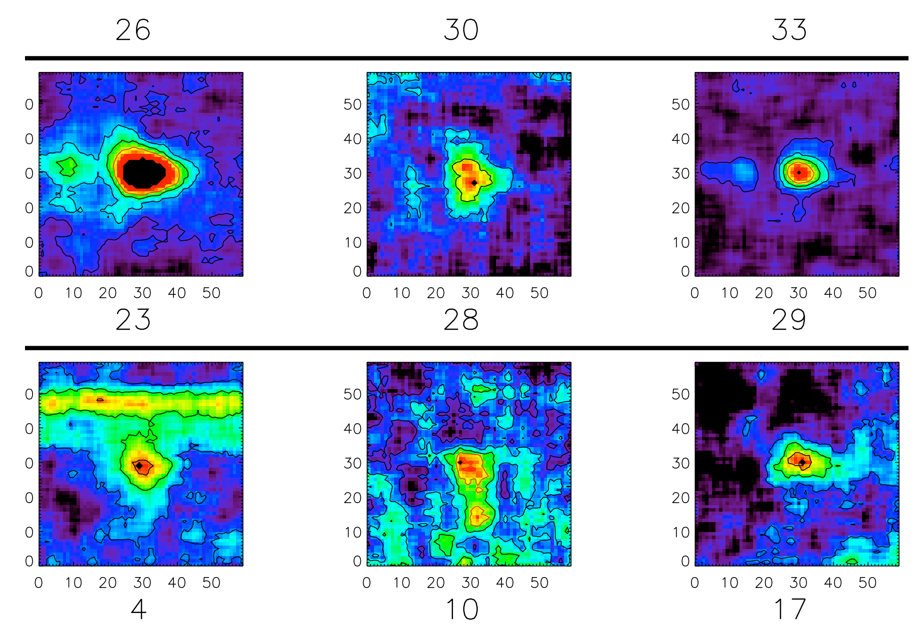

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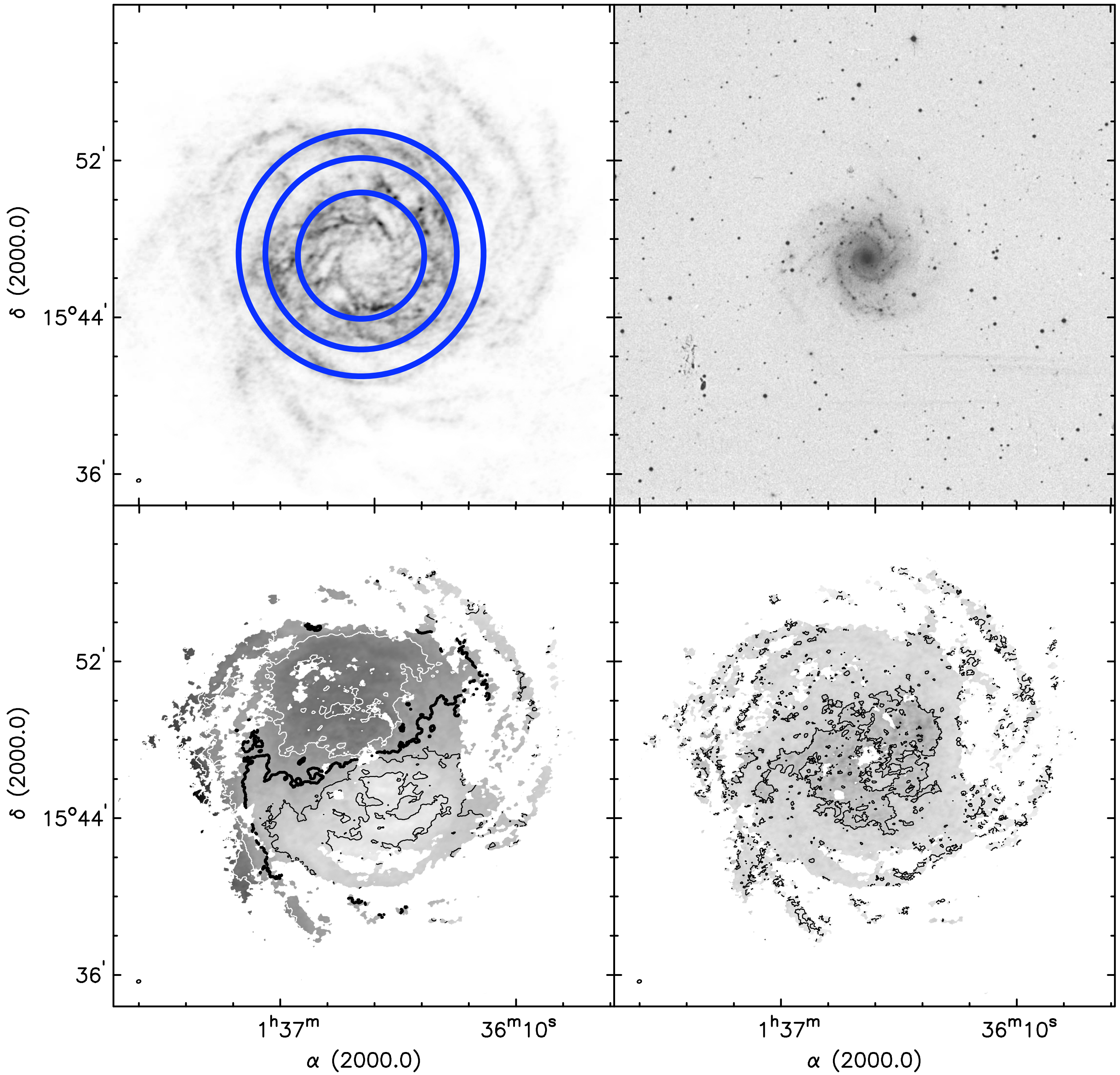
- HI?
  - Lyα absorption
    - via Quasars, GRBs, etc.

21cm HI Maps



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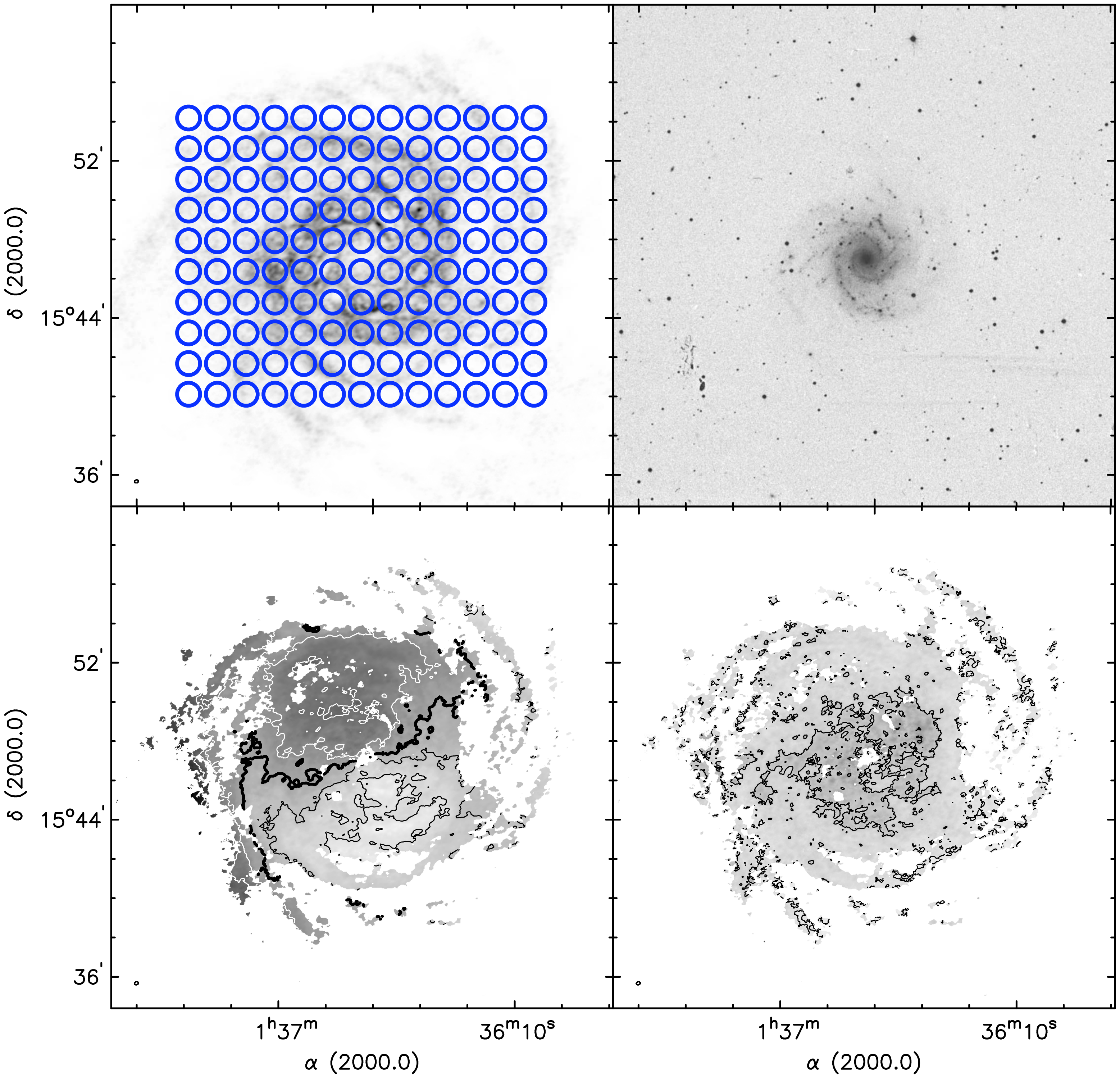

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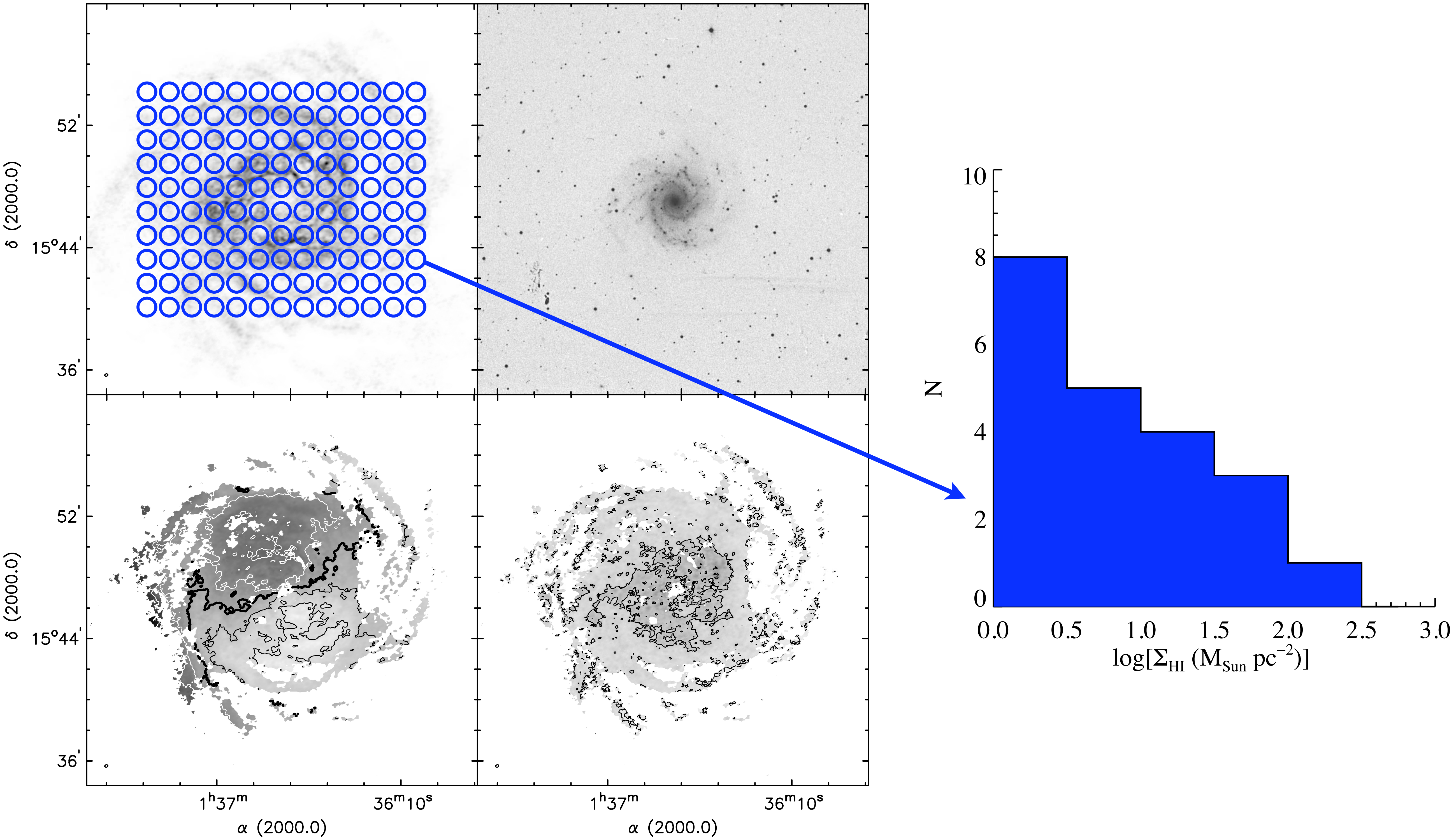
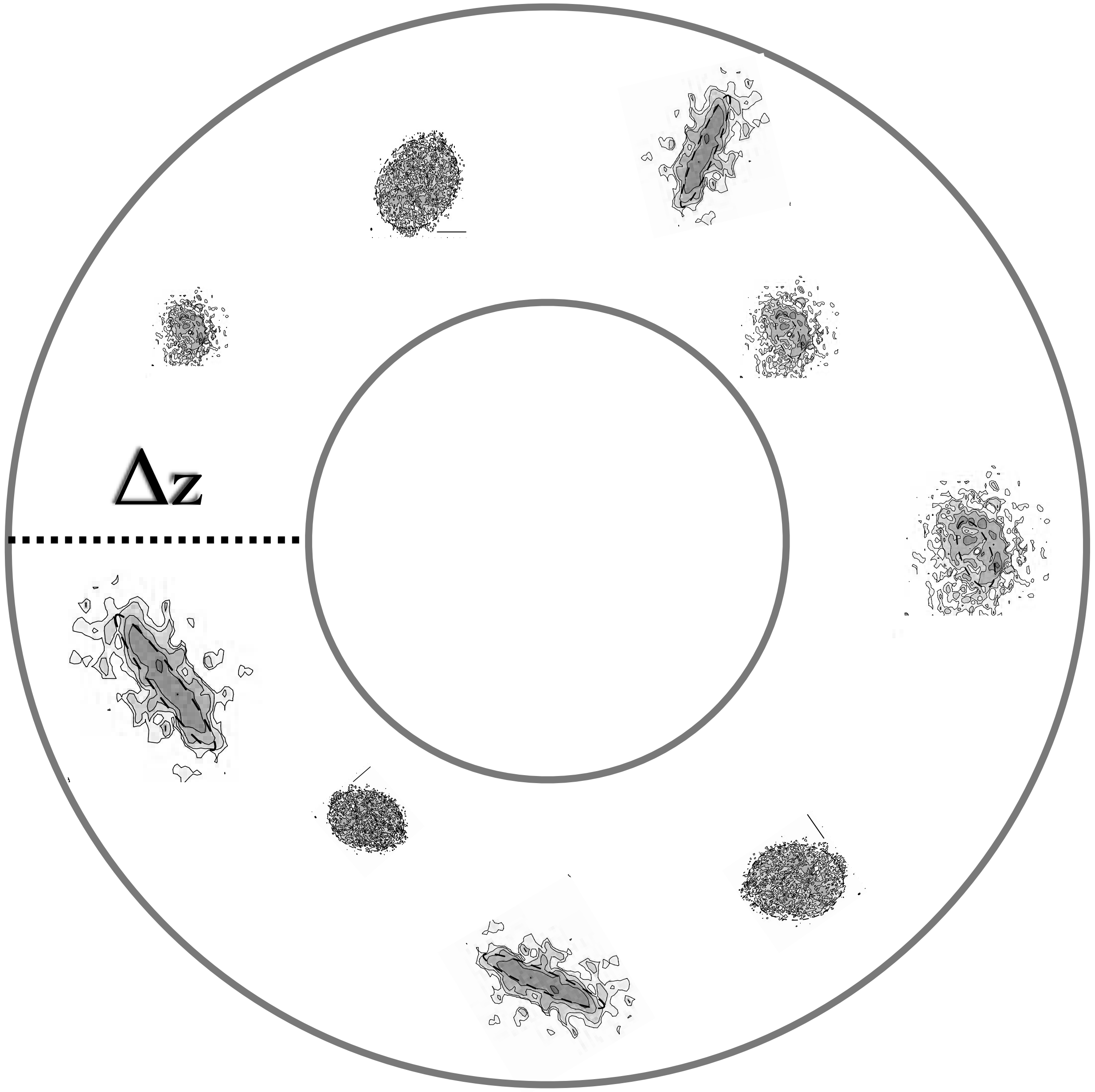


52'
δ (2000.0)
15°44'
36'
1h37m
36m10s
α (2000.0)
10
8
6
4
2
0
N
0.0
0.5
1.0
1.5
2.0
2.5
3.0
log[Σ_HI (M_Sun pc^-2)]

$f(N_{HI})$: Definition

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



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- N_{HI} frequency distribution
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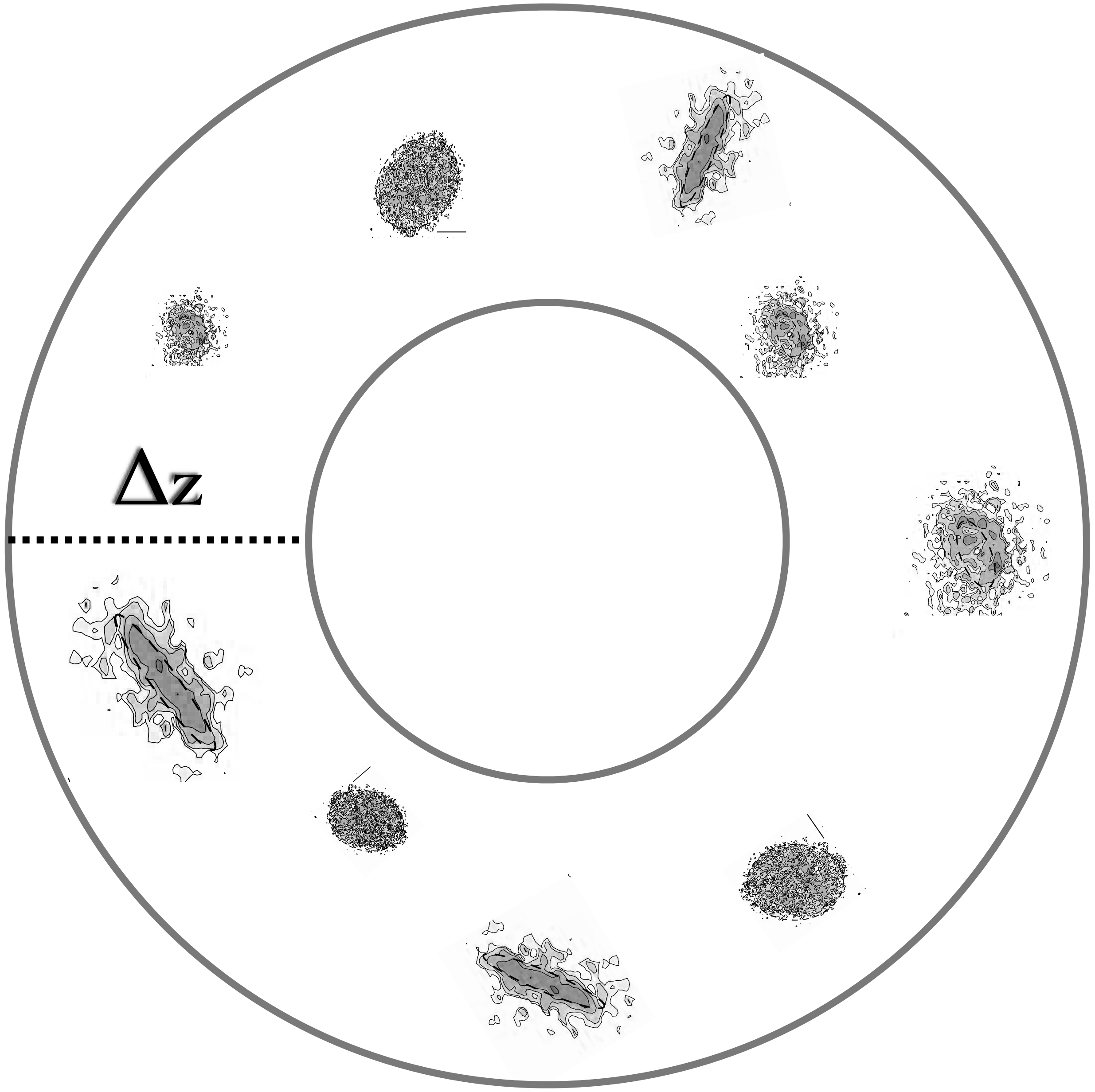

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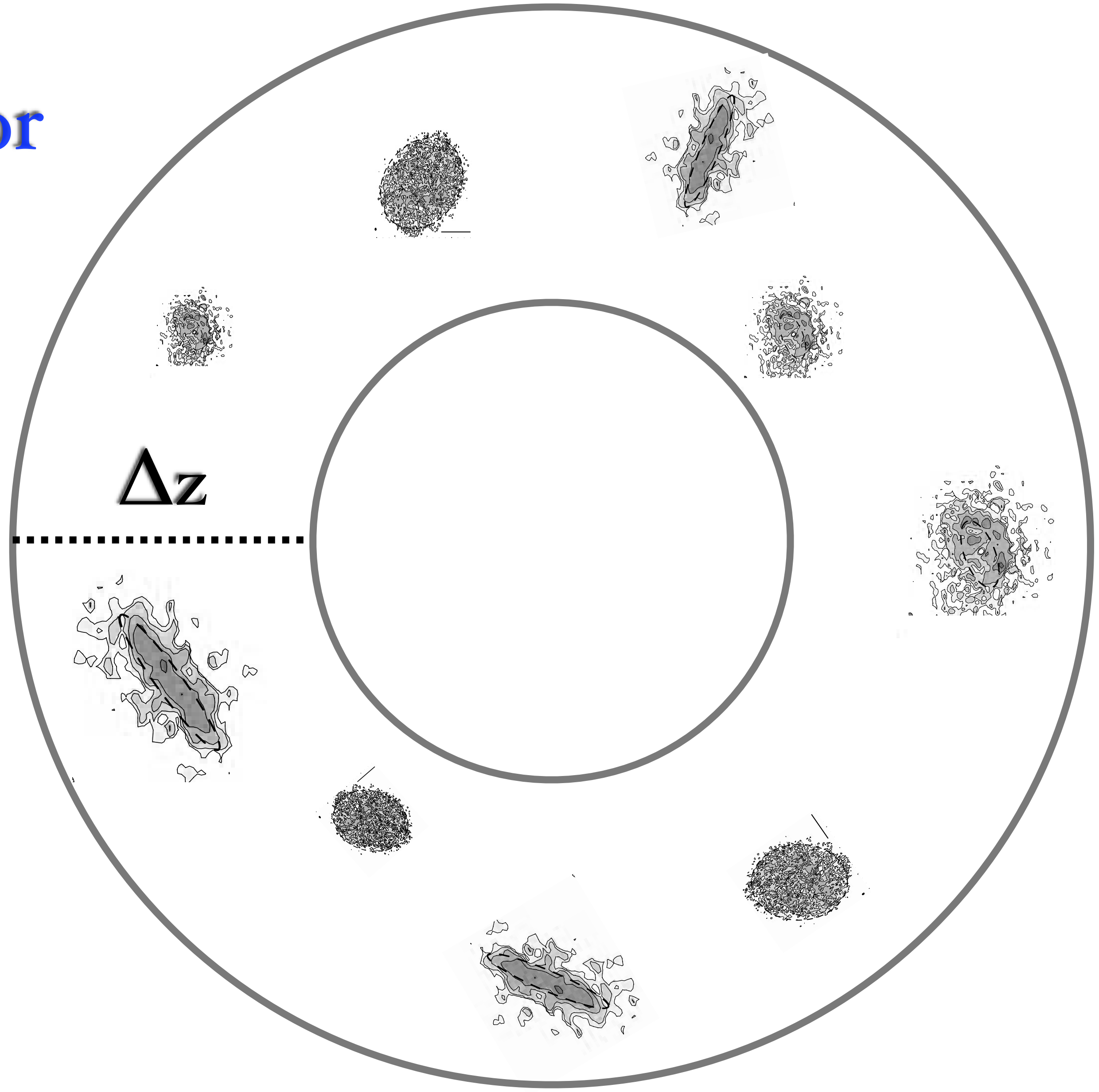
  - Shell has width Δz (e.g. 1Gpc)
  - Projected surface densities



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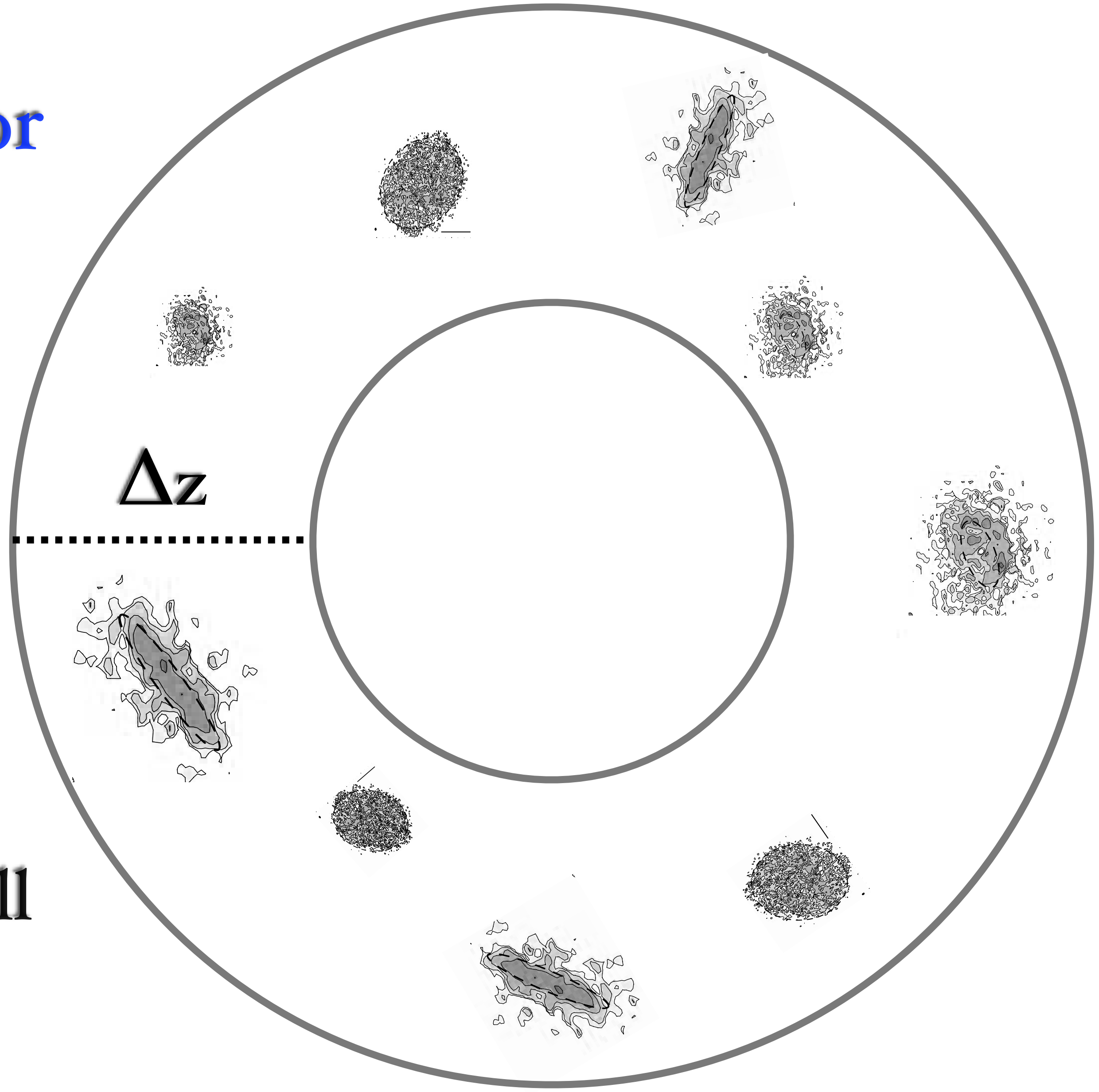
- $f(N_{HI})$
  - # of cells with N_{HI} per dN_{HI} per comoving absorption length (dX)
    - $f(N_{HI})$ is akin to a luminosity function
  - Distribution of projected Σ_{HI} for all galaxies in a shell of the sky
    - (in a finite volume)



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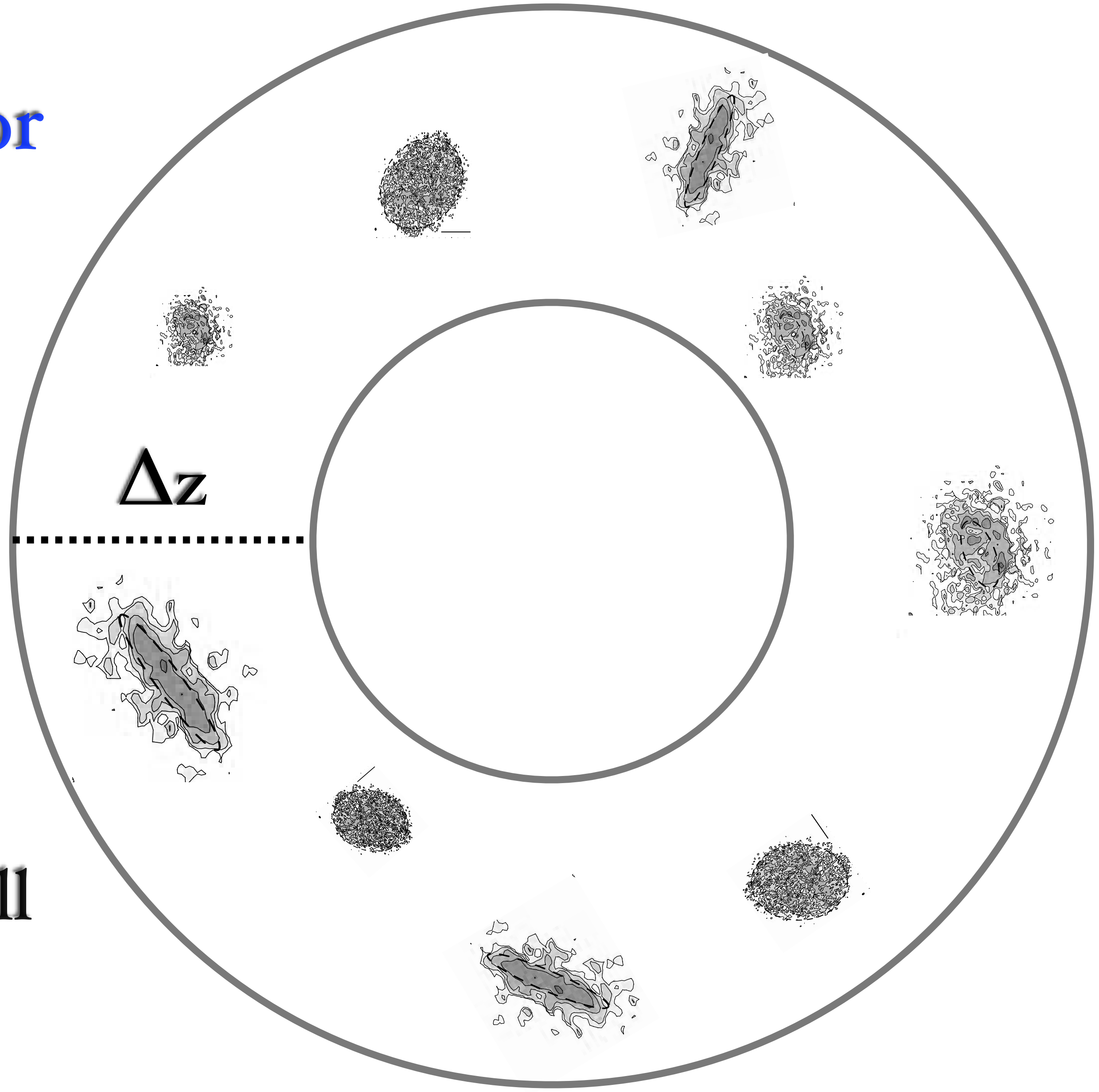
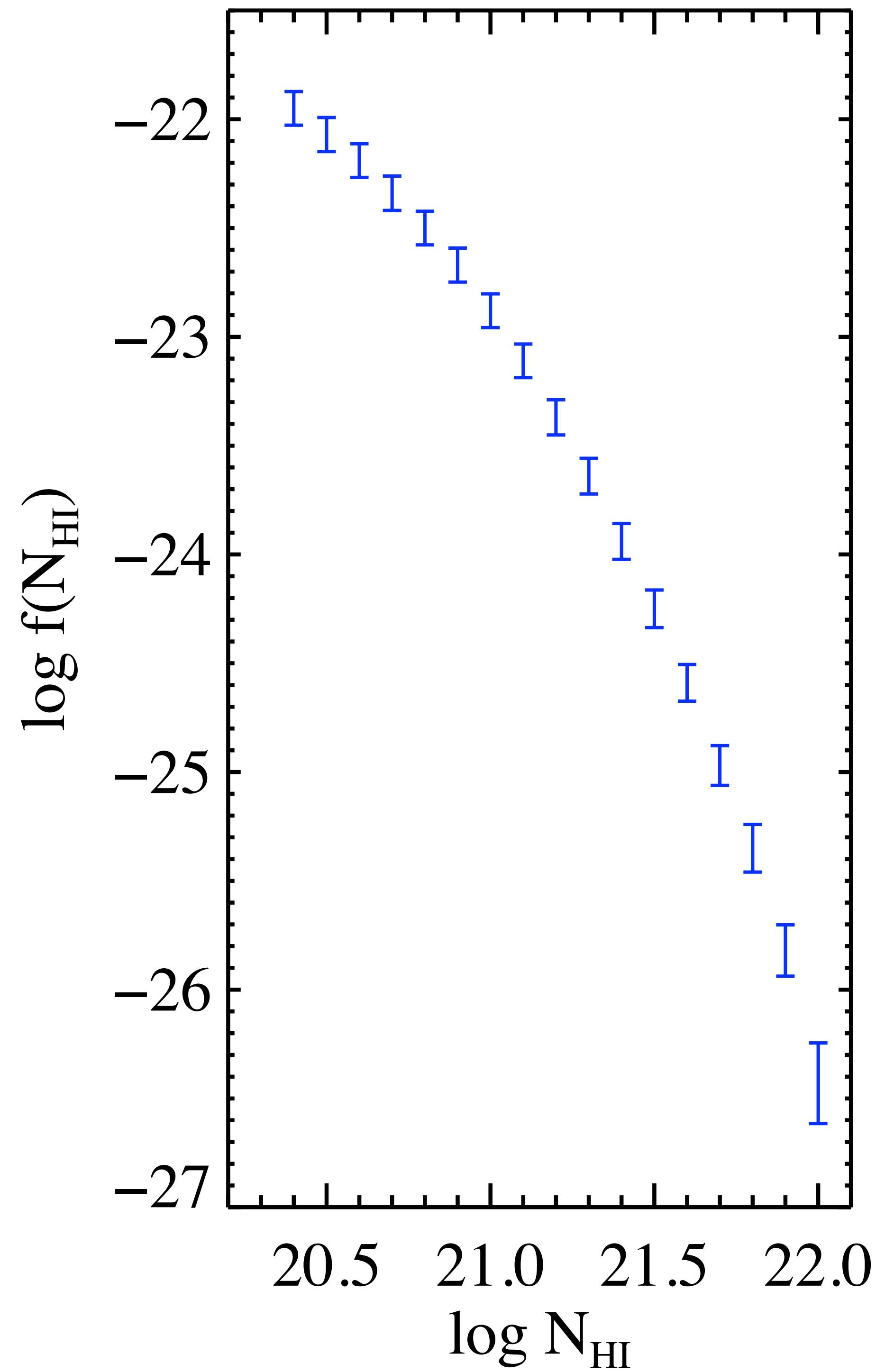


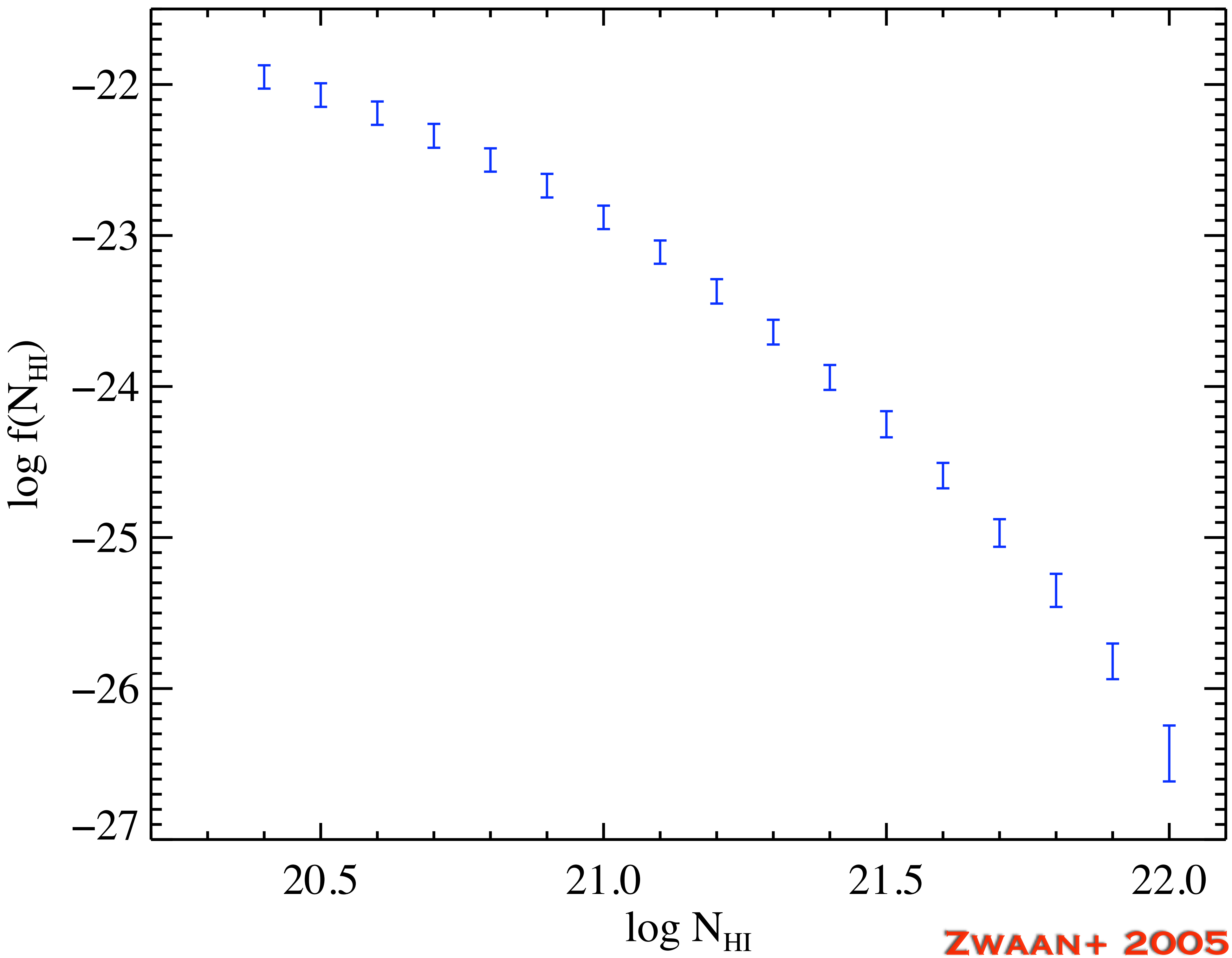
How do we measure this observationally?

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



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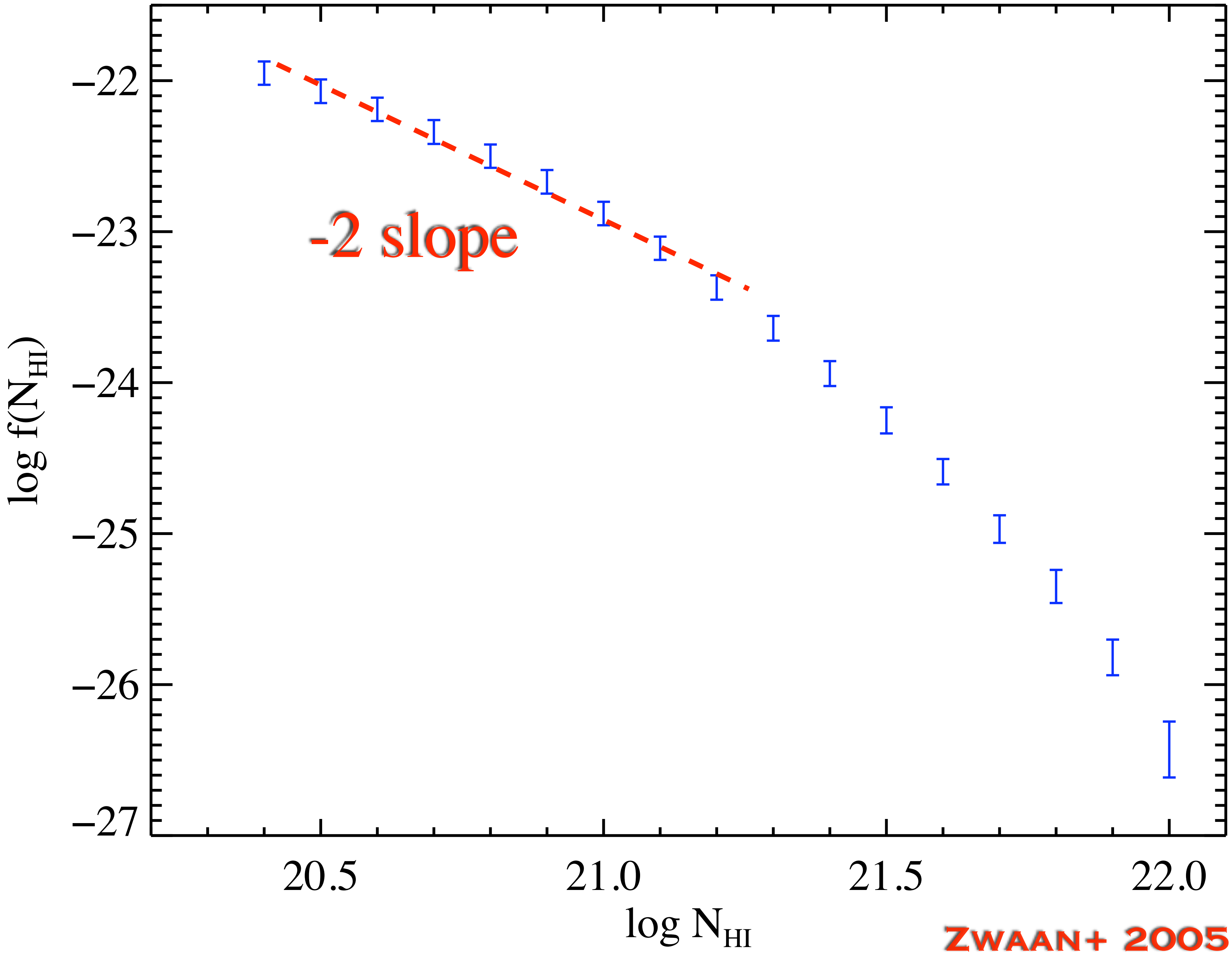

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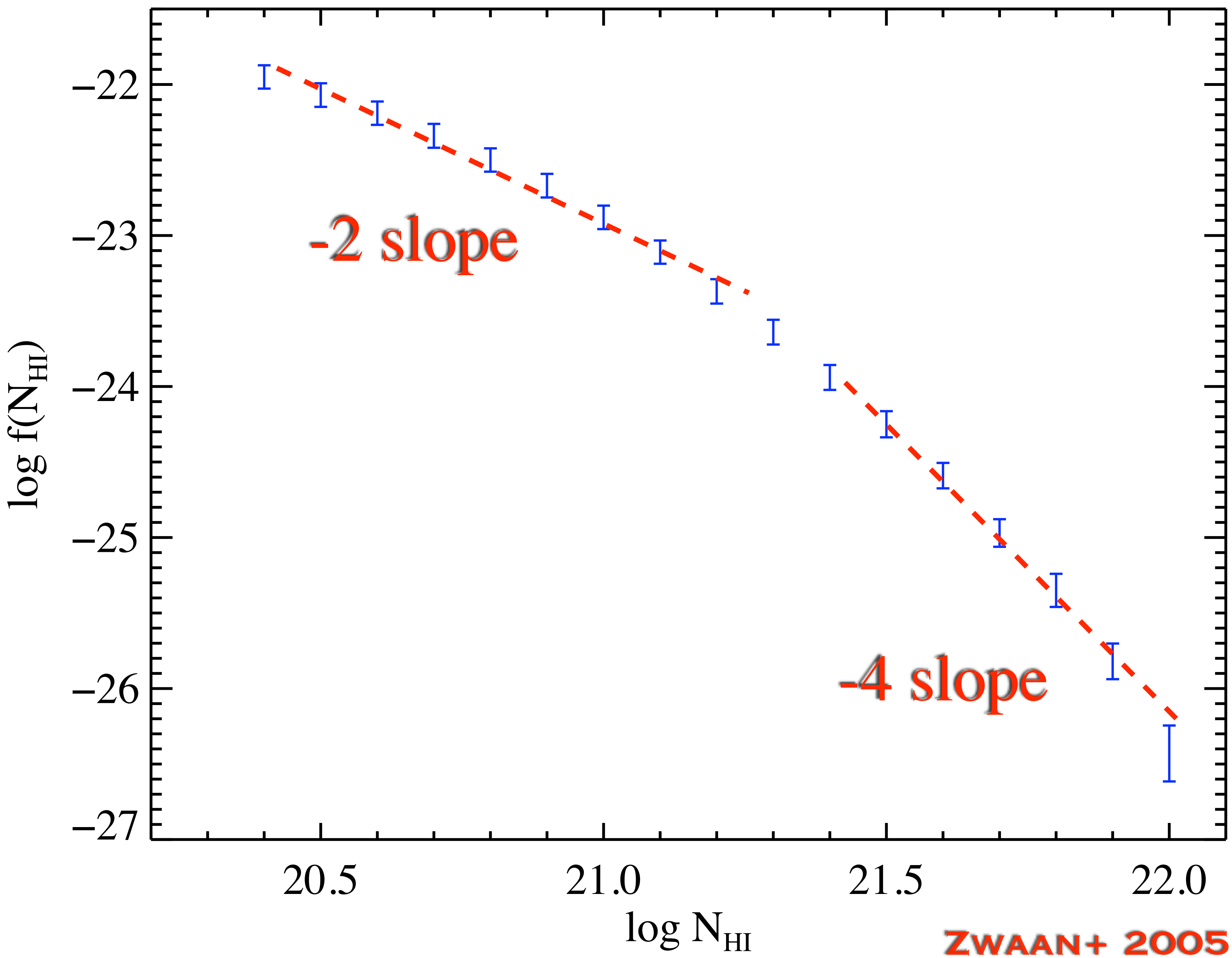

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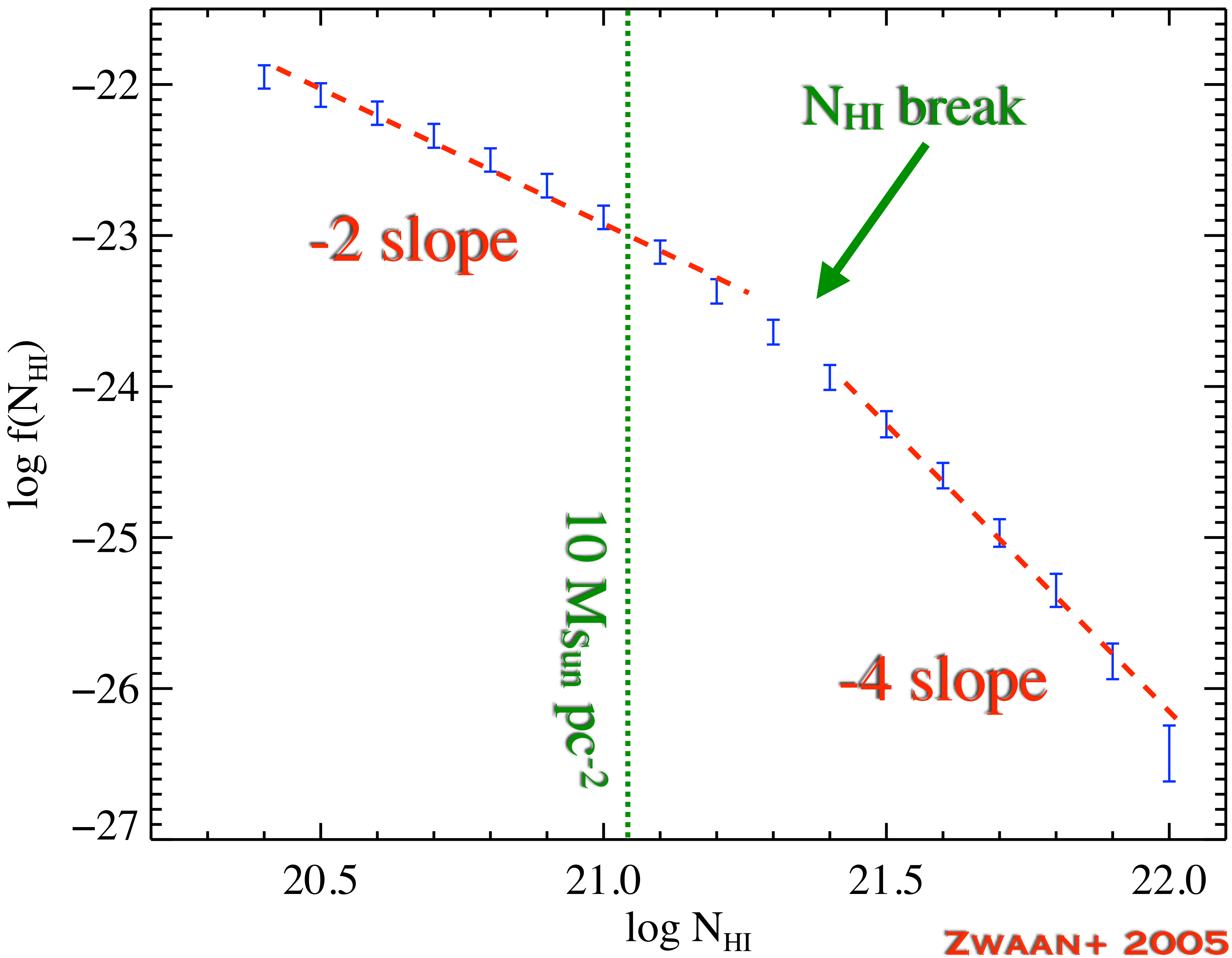

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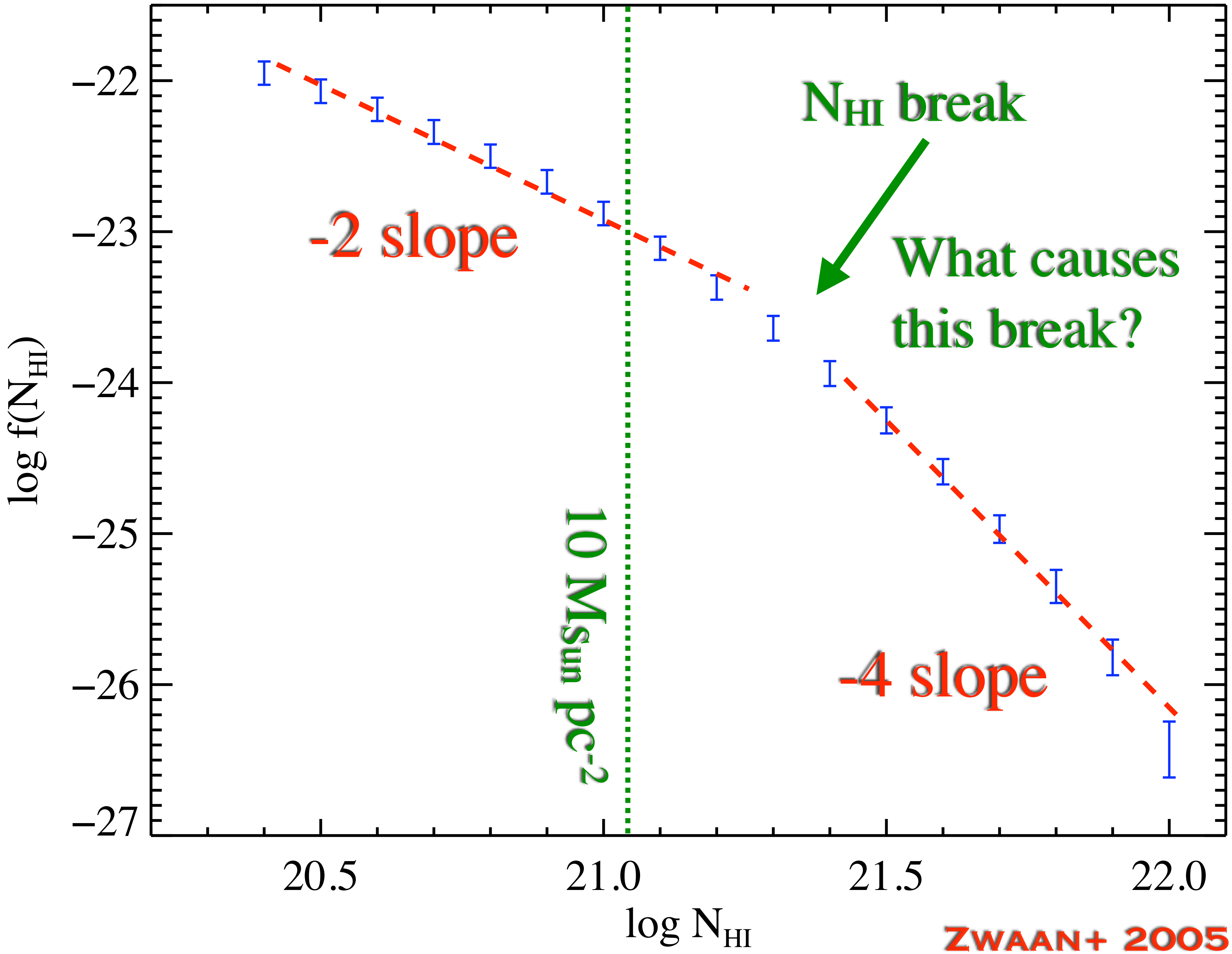
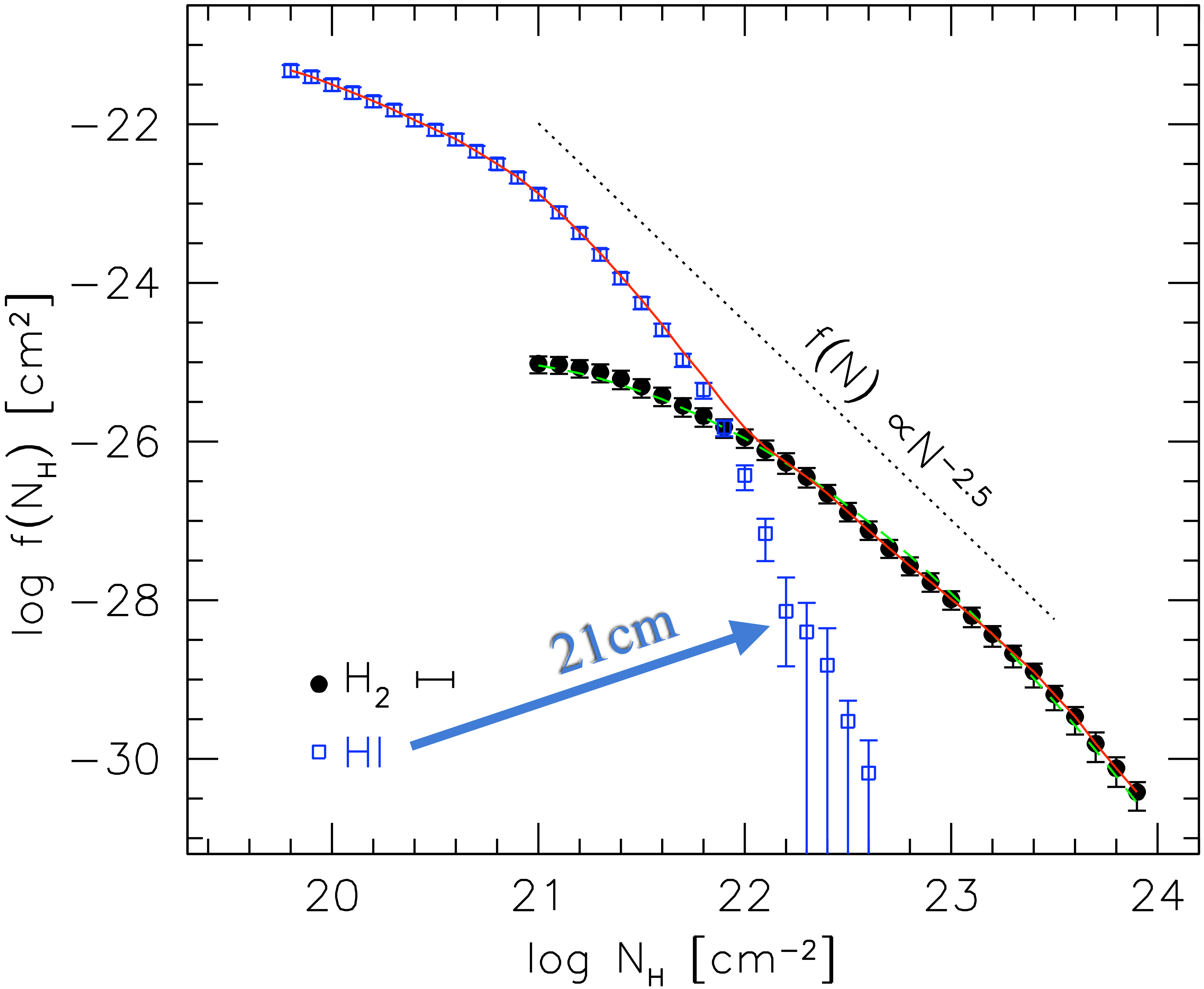


Zwaan+ 2005

$f(N_H)$ at z=0

ZWAAN & PROCHASKA 2006



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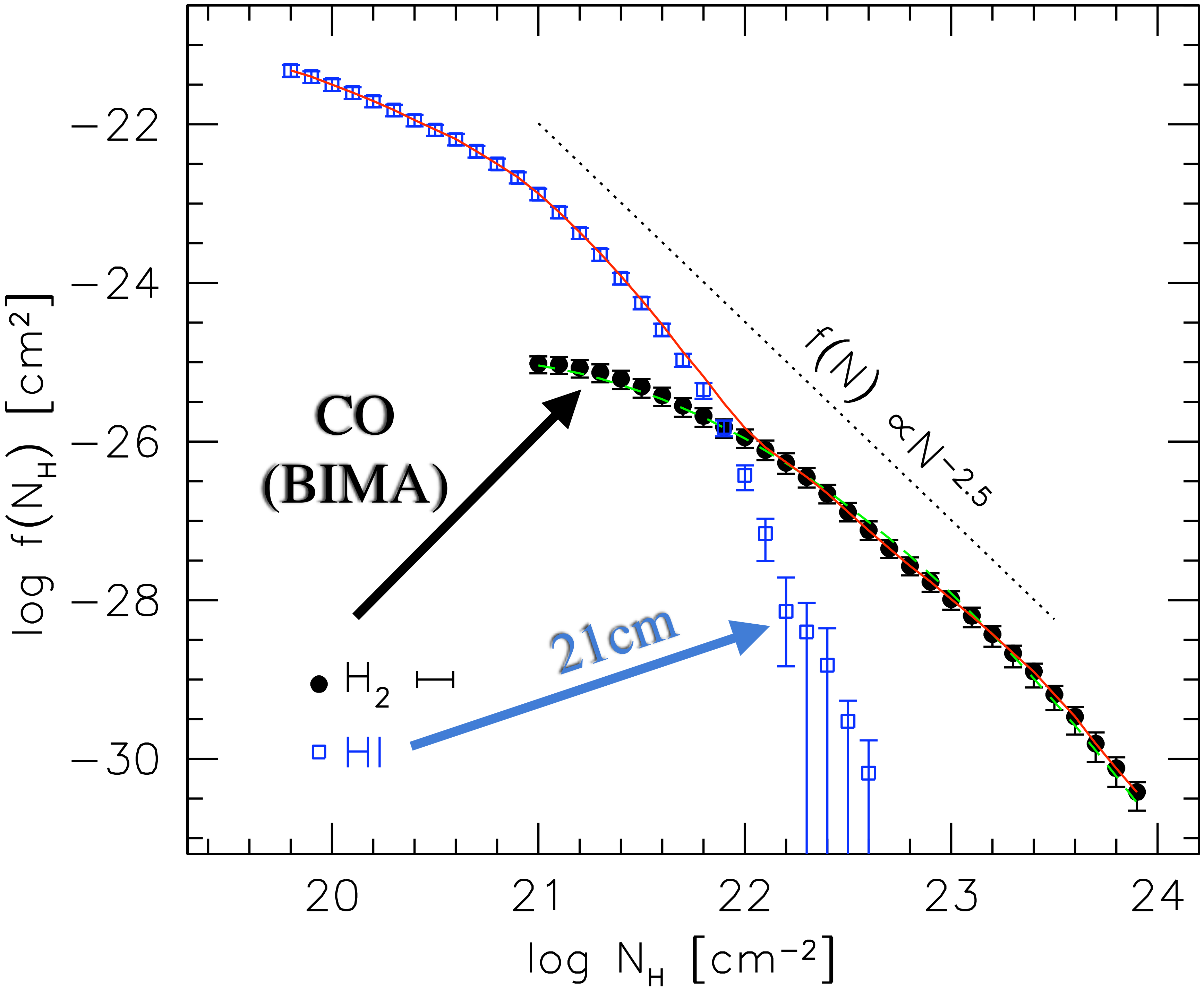

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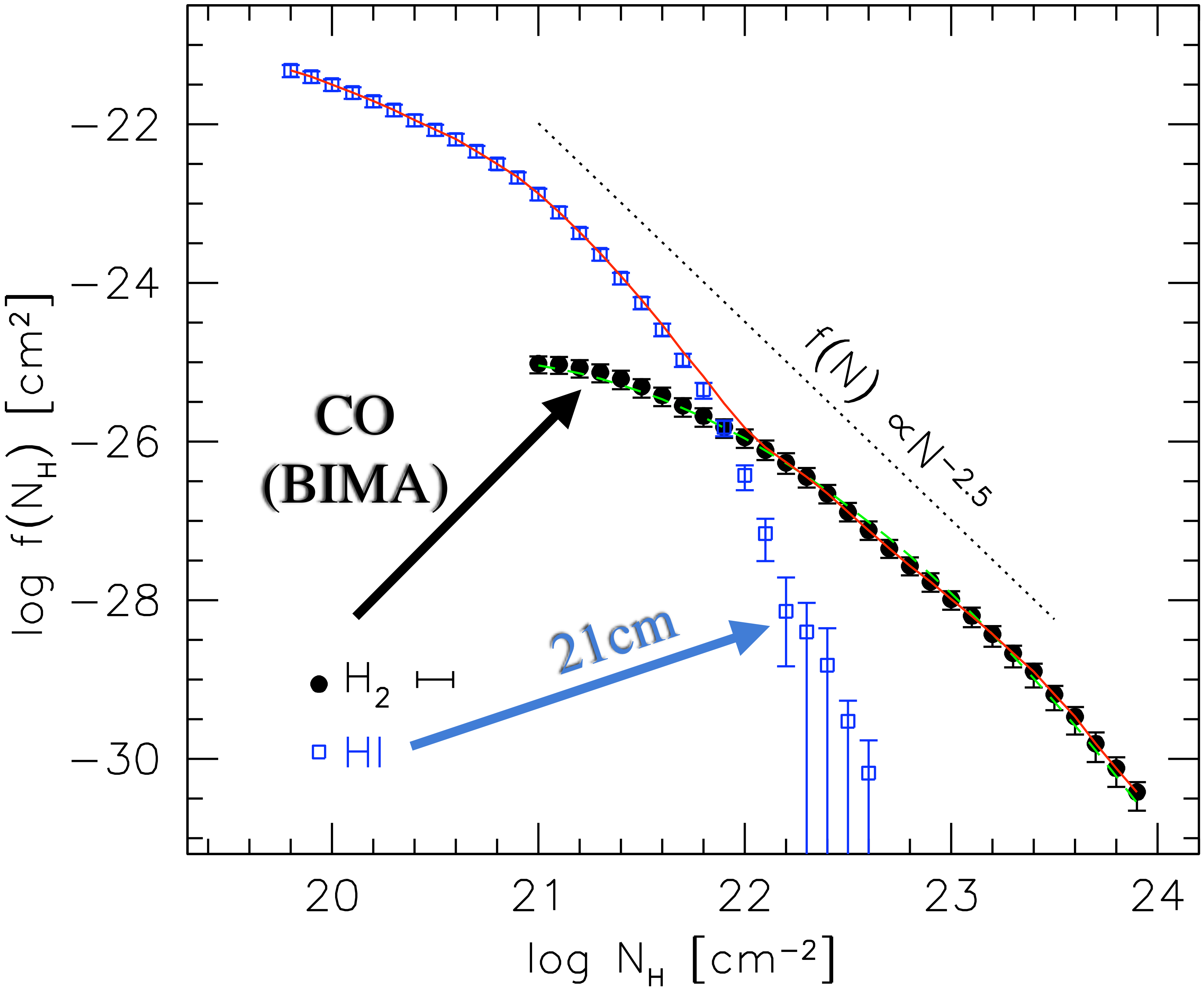


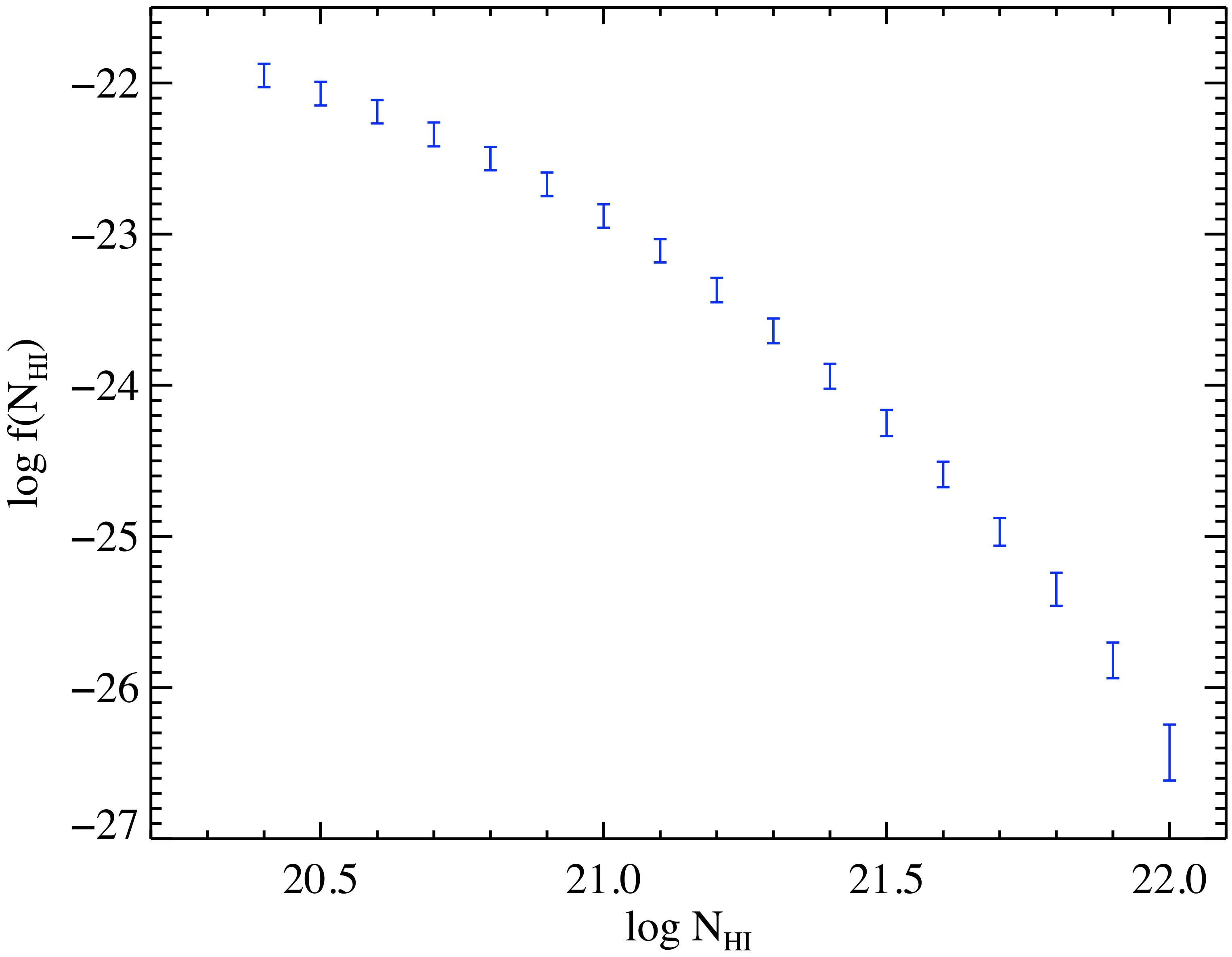
The overlap in the distribution functions seems a remarkable 'coincidence'. (Schaye 2001; Krumholz+ 2009)

Zeroth Moment: "Covering Fraction"

$$\ell(X) = \int_{N_{th}}^{\infty} f(N_{\rm HI}) dN_{\rm HI} \ \sim \ < n_{\rm C} > < \sigma_{\rm ph} >$$

(DLA criterion)

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



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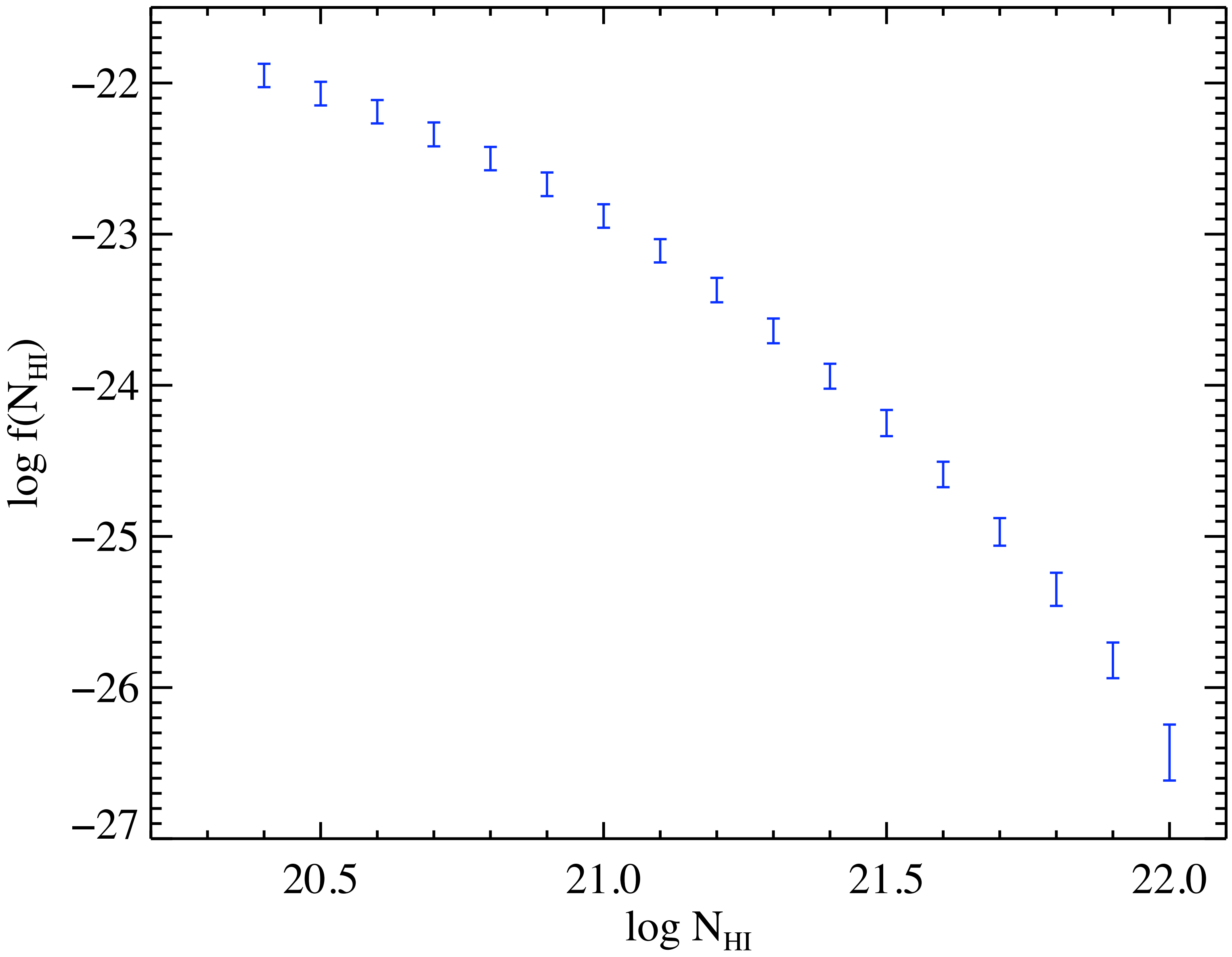

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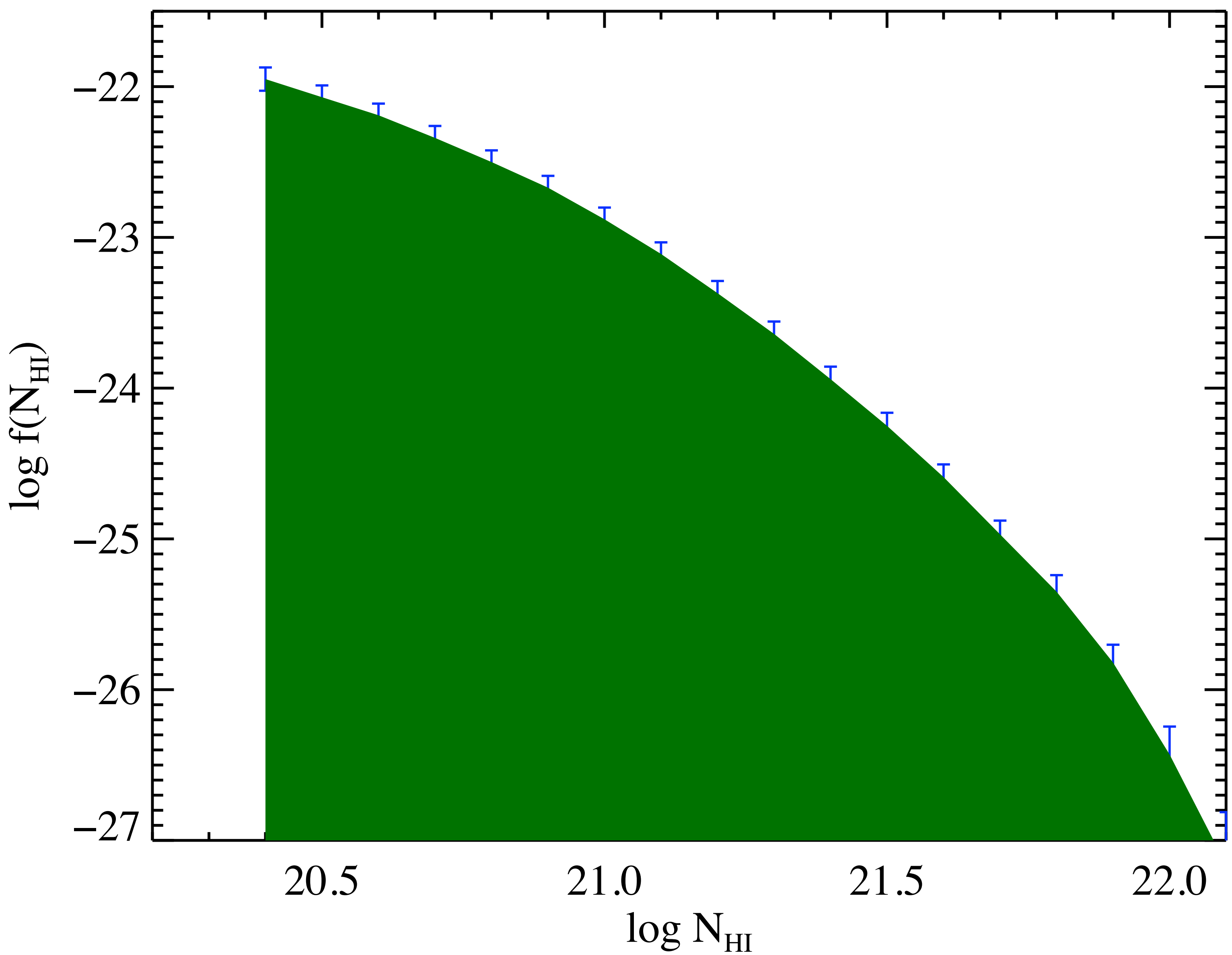

$\ell(X)$ is the number of galaxies intersected per absorption pathlength (ΔX). [opacity]

One intersects 1 galaxy every ~100 Gpc, on average.

<u>Covering fraction</u>:

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

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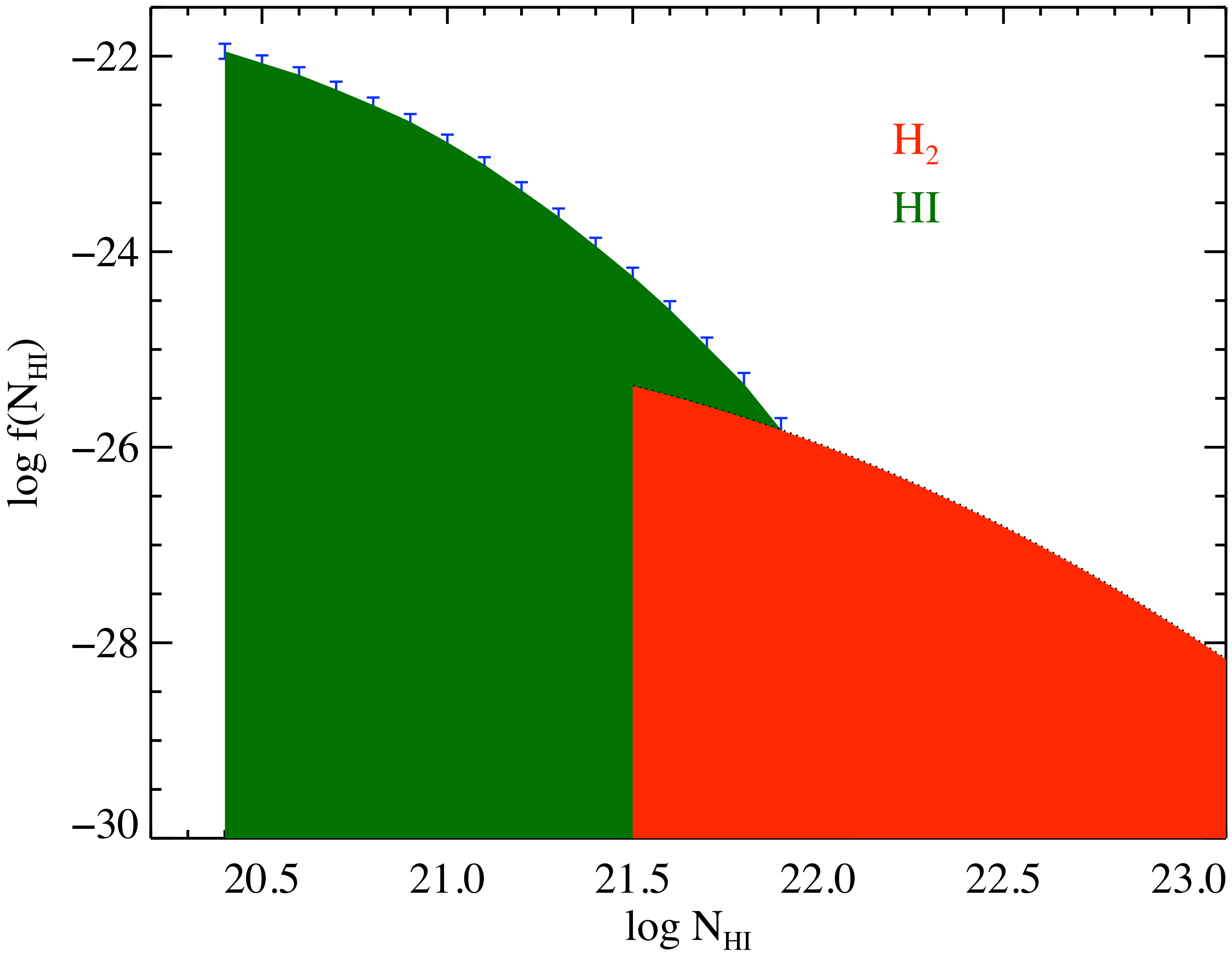

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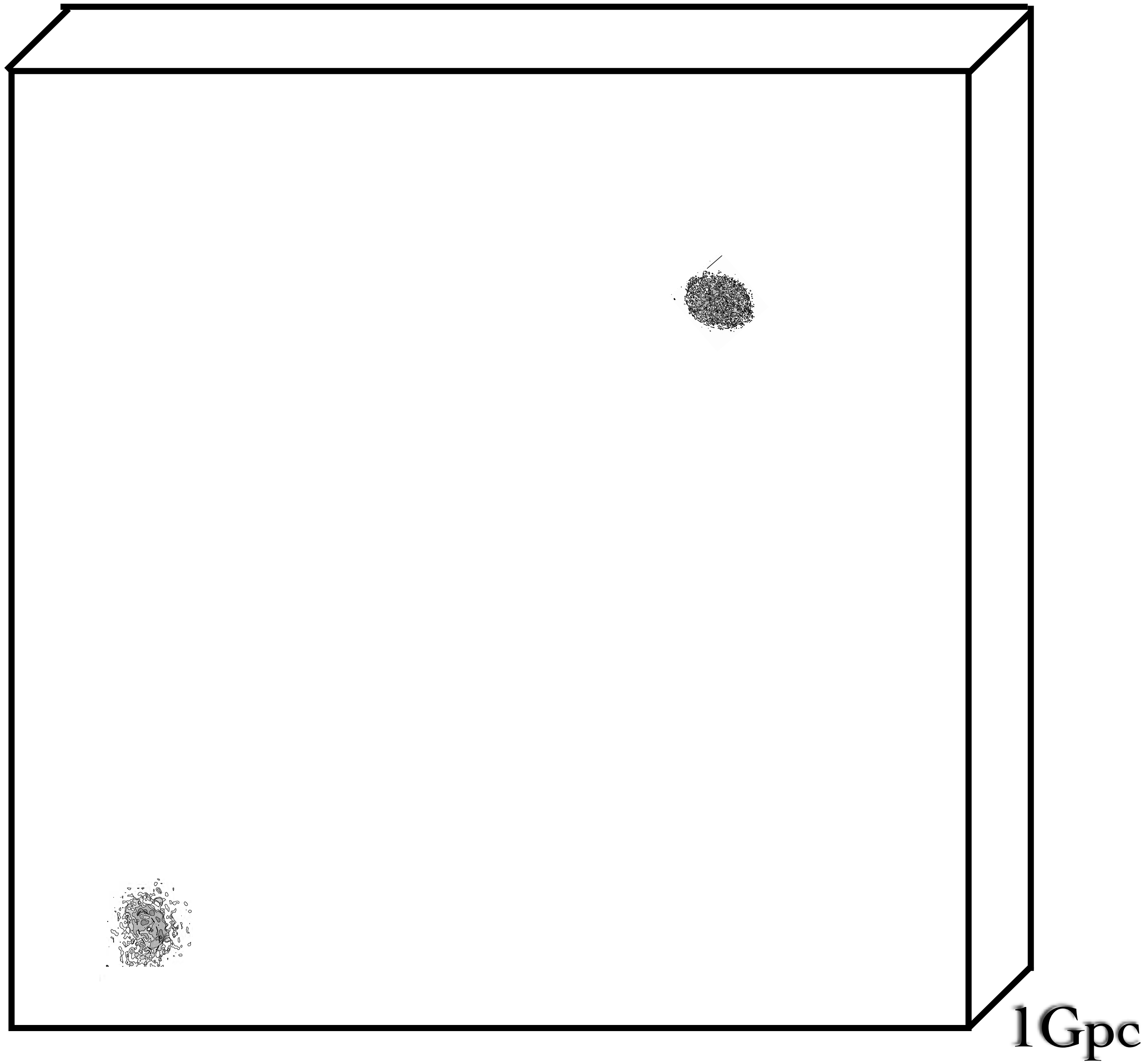
Note: $C_A(H_2)$ = 0.006%

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



First Moment: HI Mass Density

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

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

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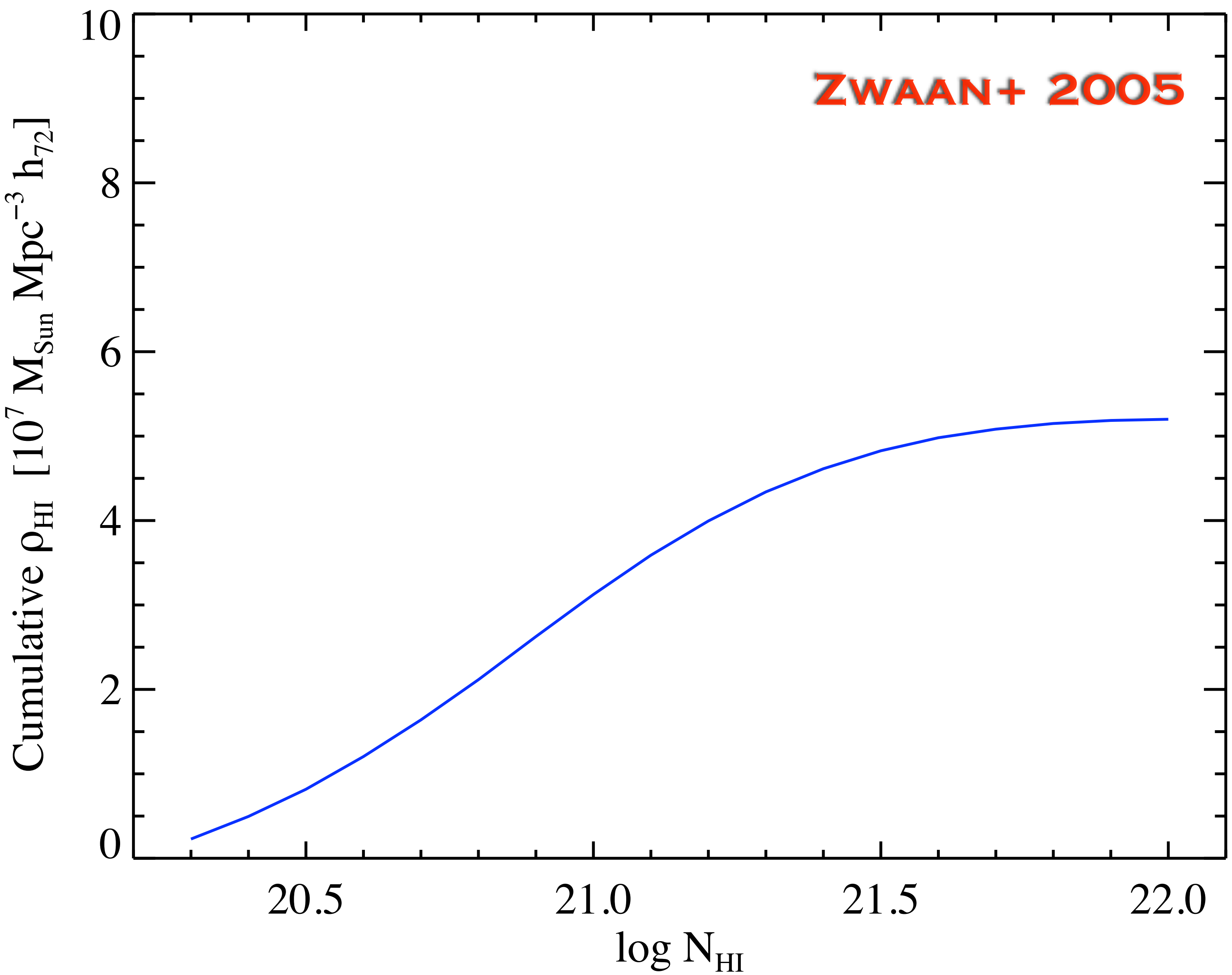

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$\rho_{\rm HI}(z=0) = 5.2 \times 10^7\ M_{\rm Sun}\ {\rm Mpc}^{-3}$

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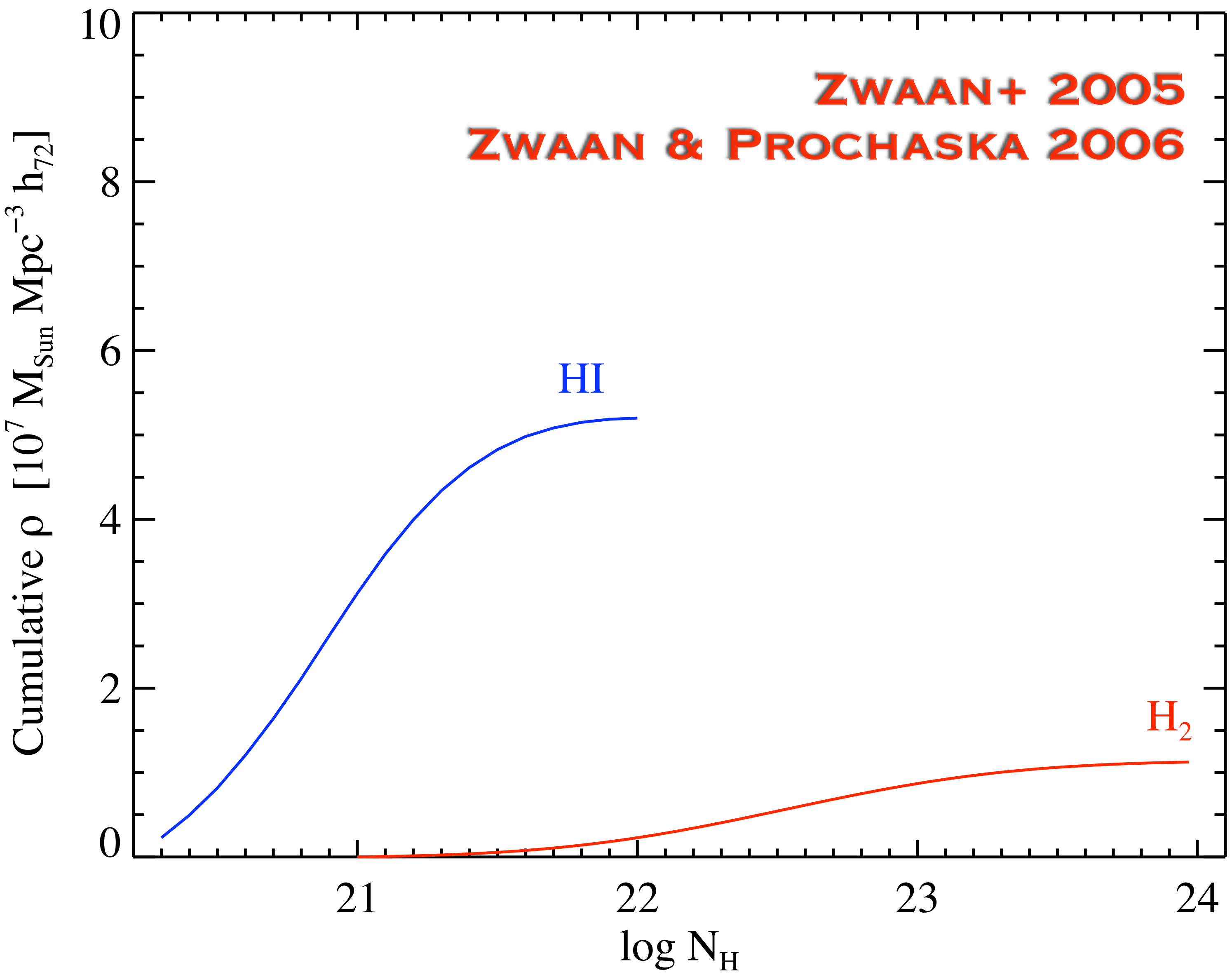

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$\rho_{\rm H2}(z=0) = 1.1 \times 10^7\ M_{\rm Sun}\ {\rm Mpc}^{-3}$

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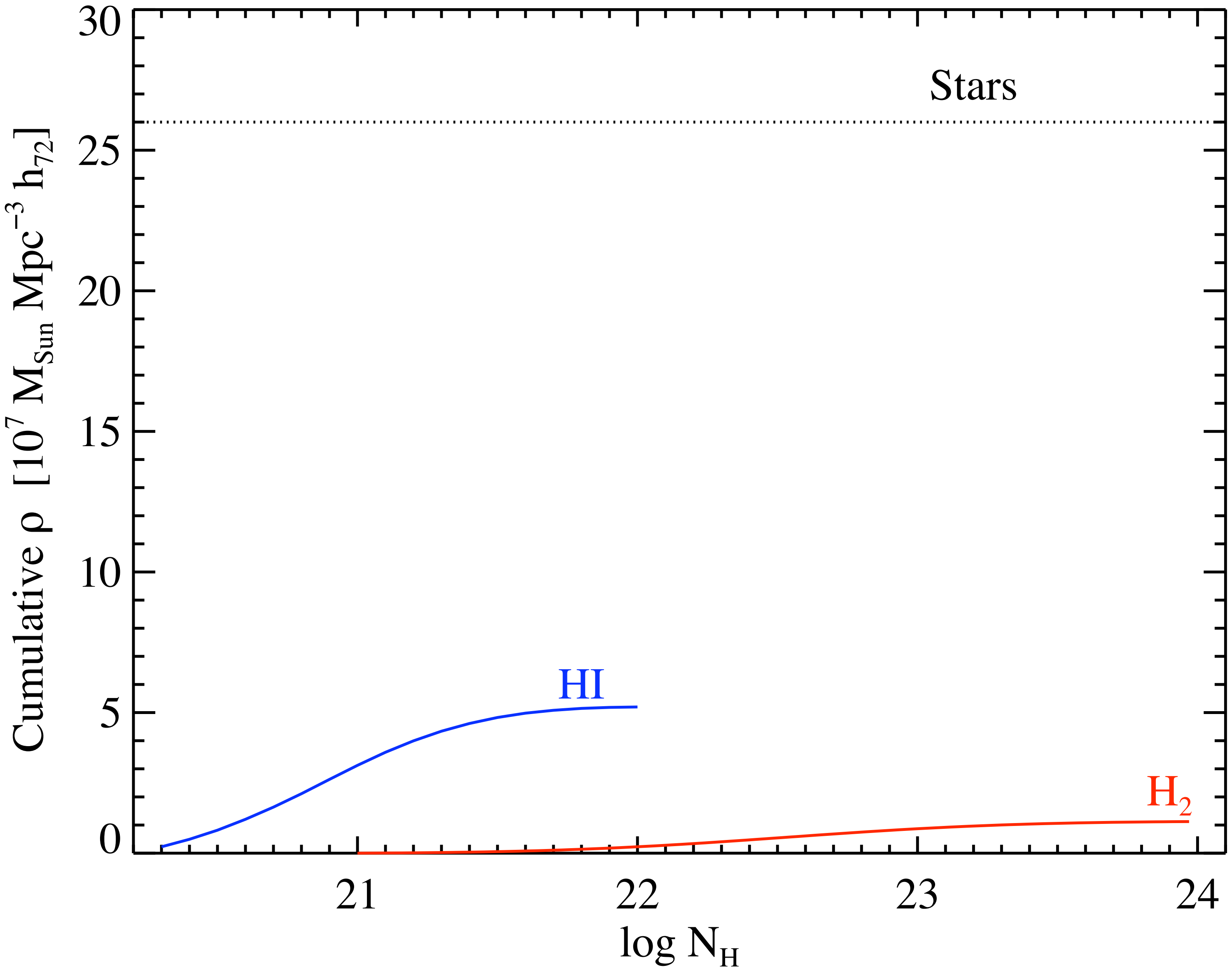

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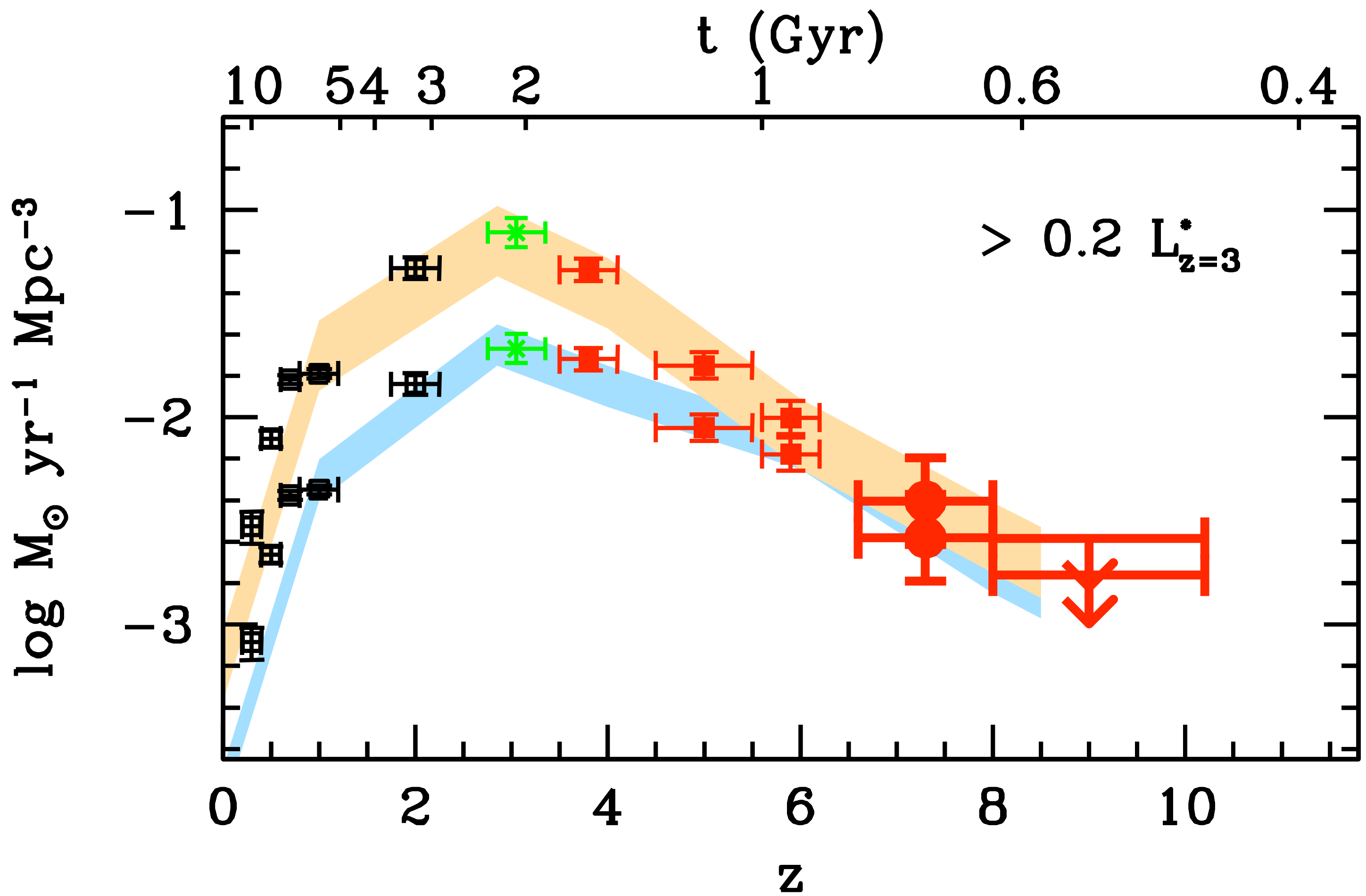
$\rho_{\rm H2}(z=0) = 1.1 \times 10^7\ M_{\rm Sun}\ {\rm Mpc}^{-3}$

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

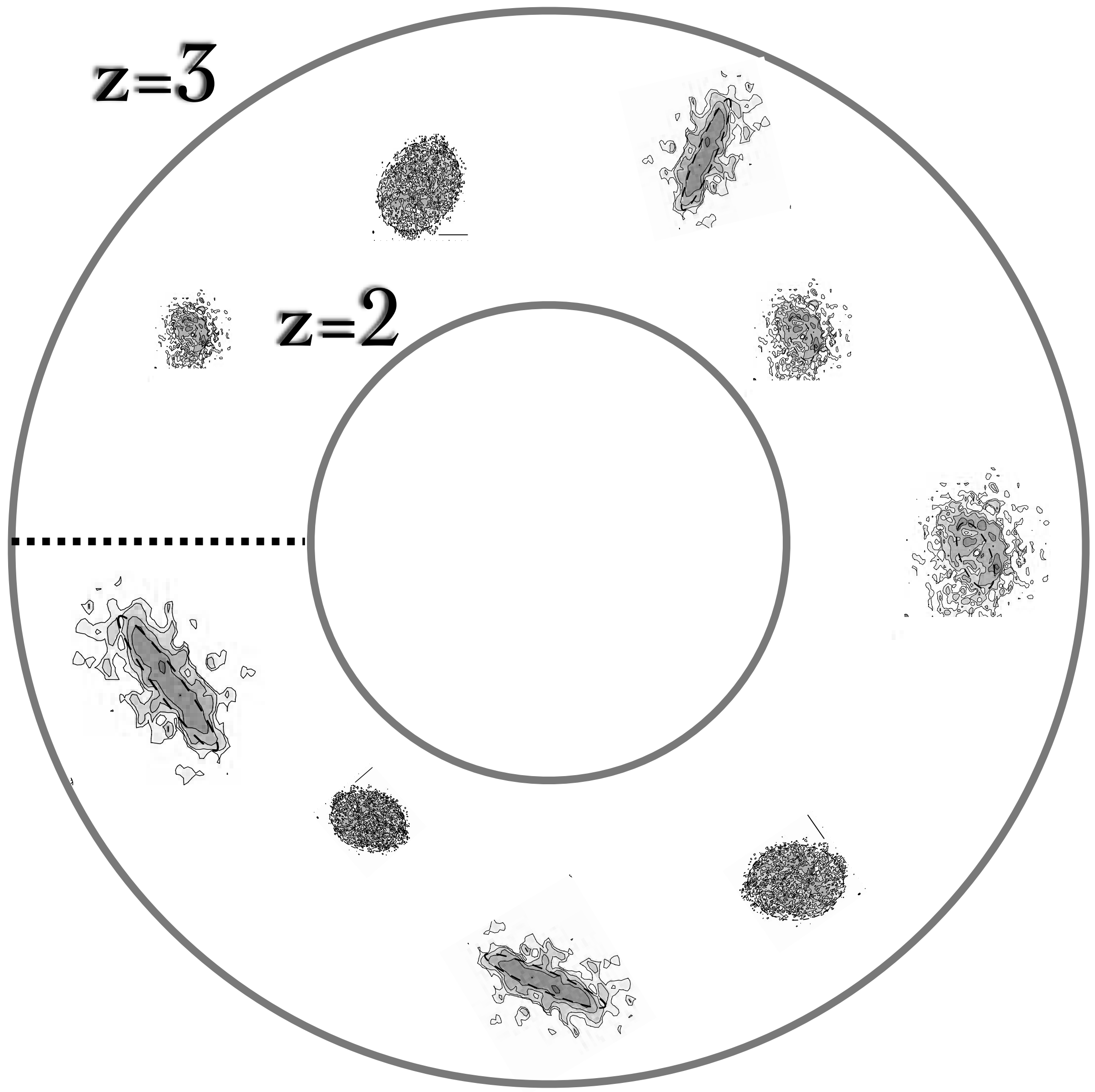
Cosmic Evolution of HI in Galaxies

- 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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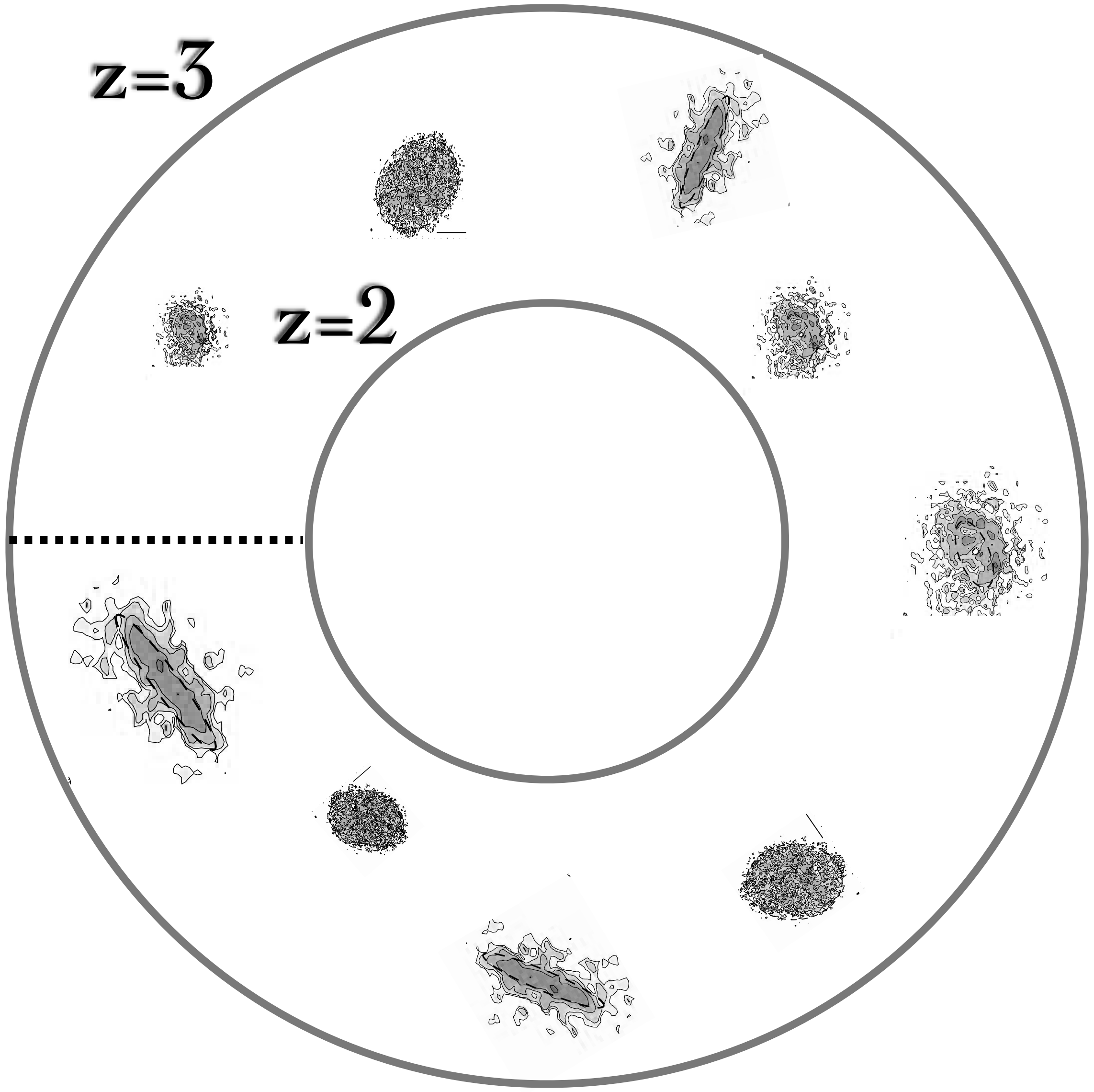

- 21cm emission is 'hopeless'

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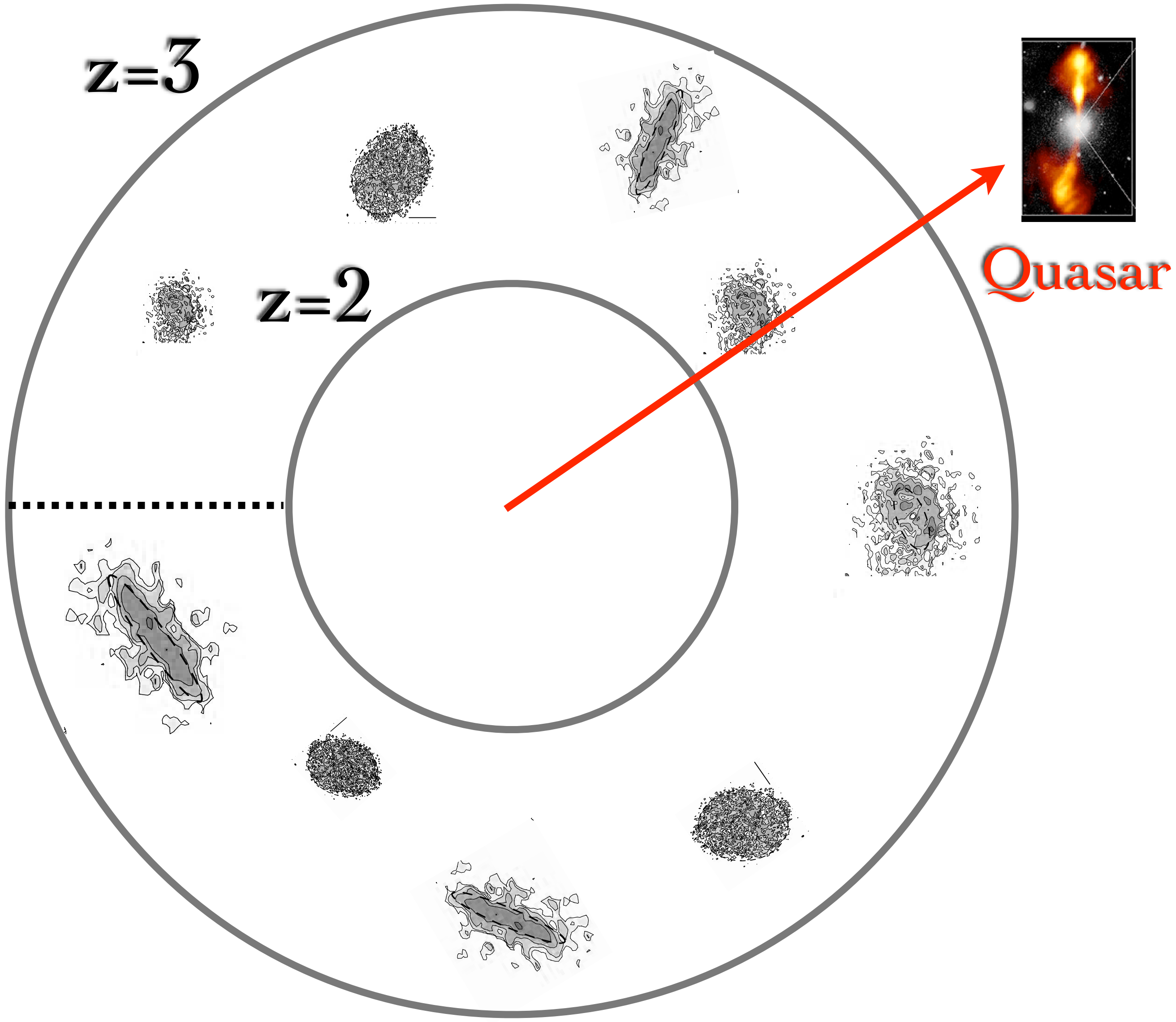

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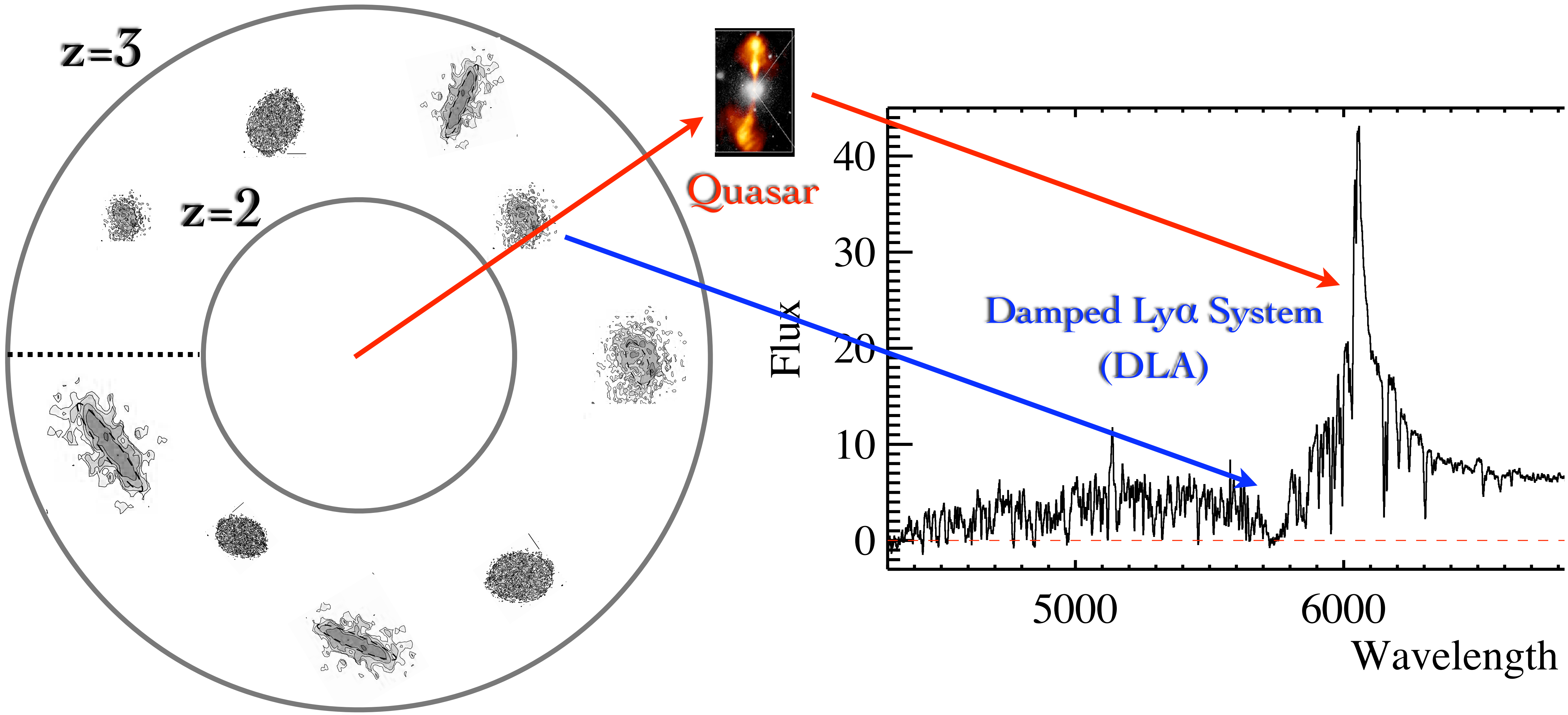
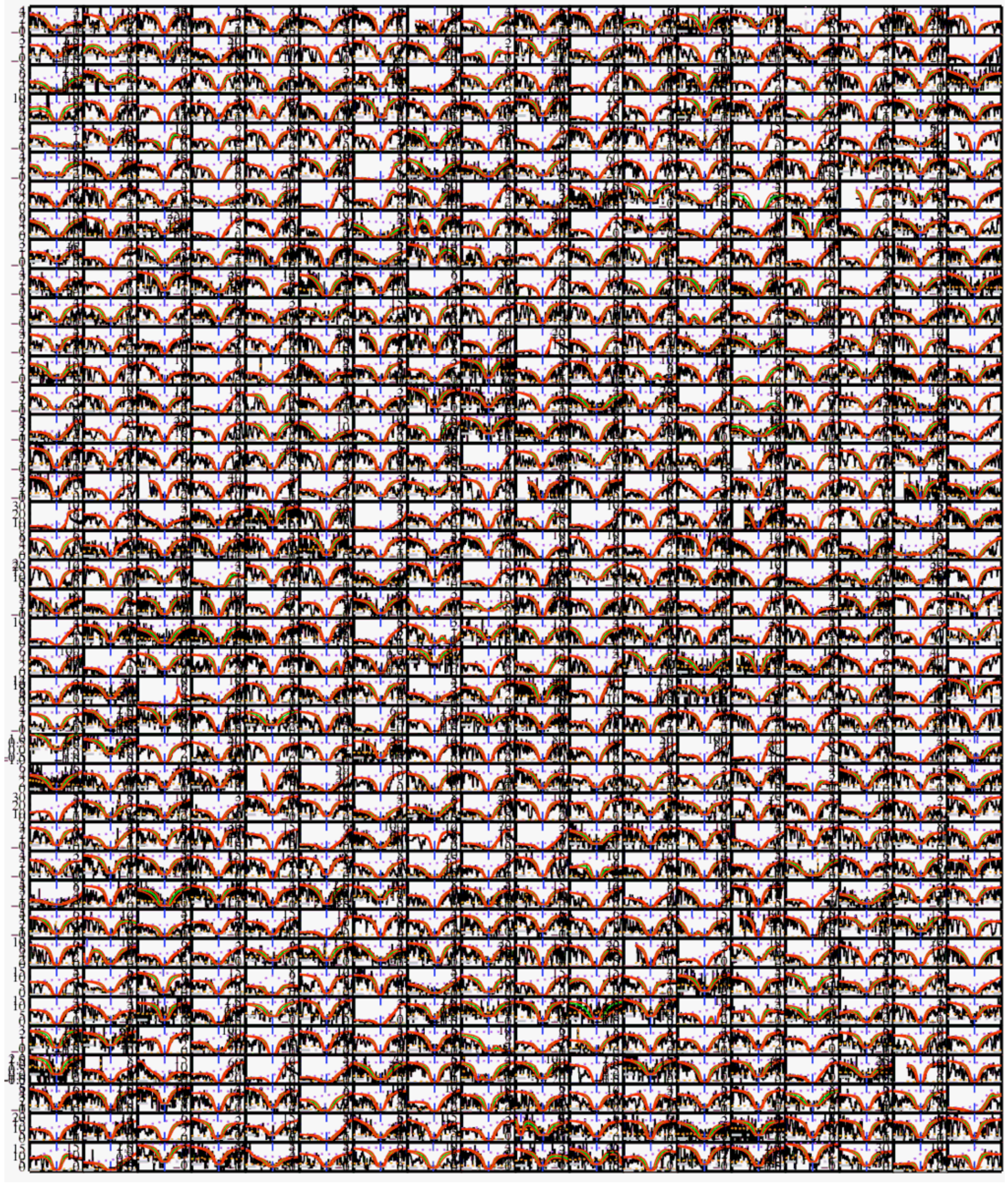


- 21cm emission is 'hopeless'
- Lyα in Absorption
  - Damped portion of the curve-of -growth
  - N_{HI} well measured in modest quality spectra
    - Can use GRBs, galaxies

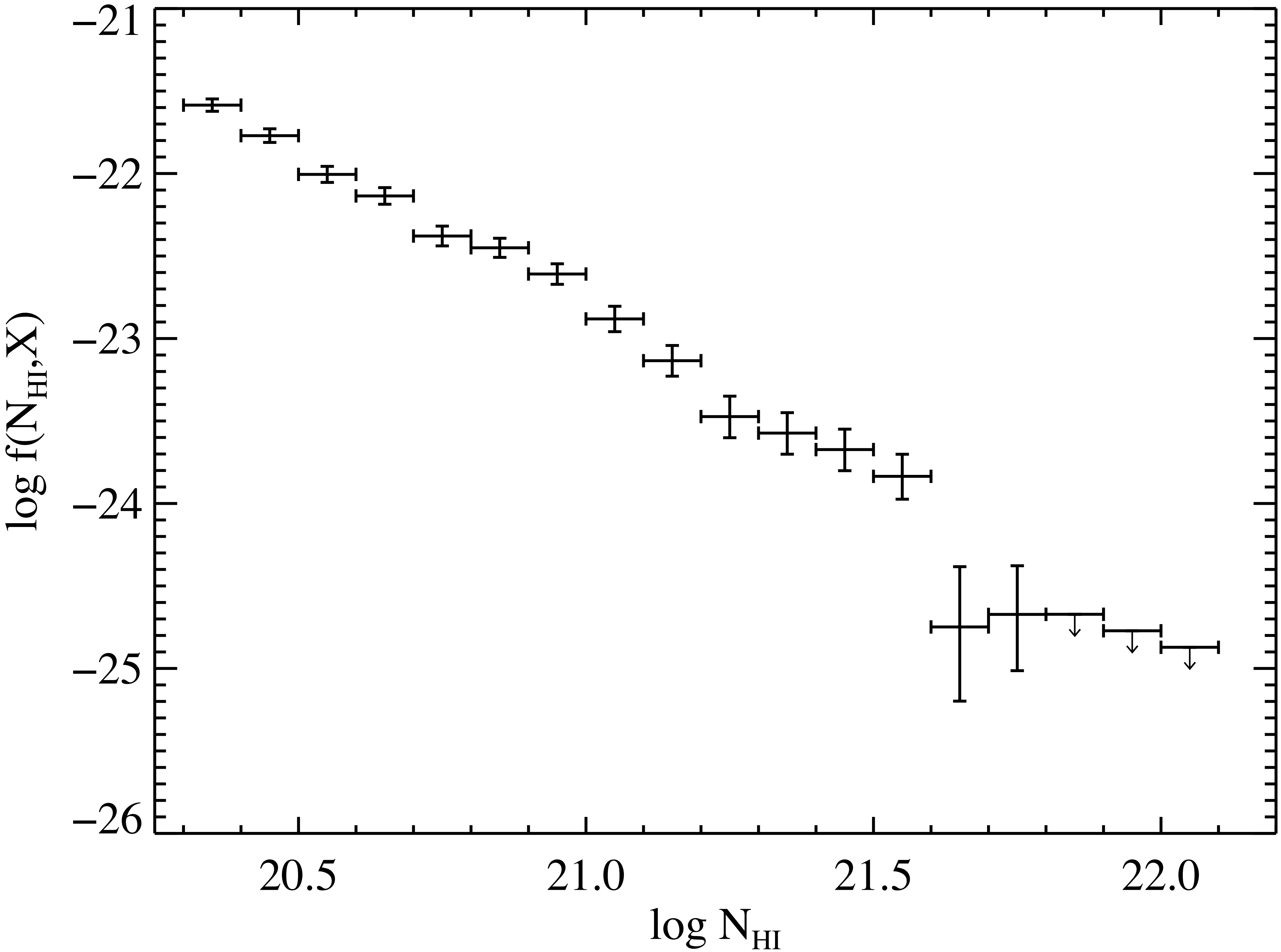
SDSS DR5

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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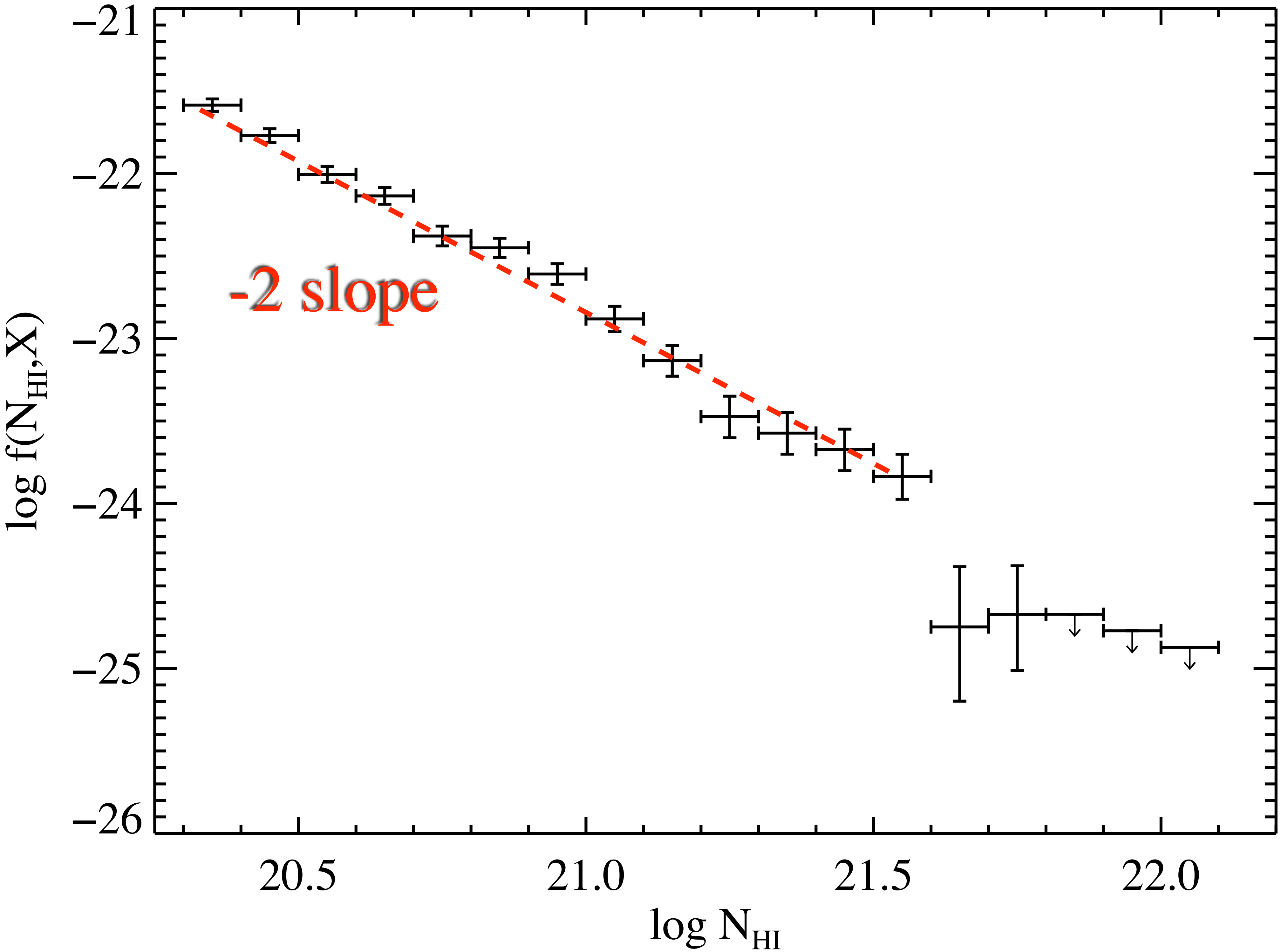

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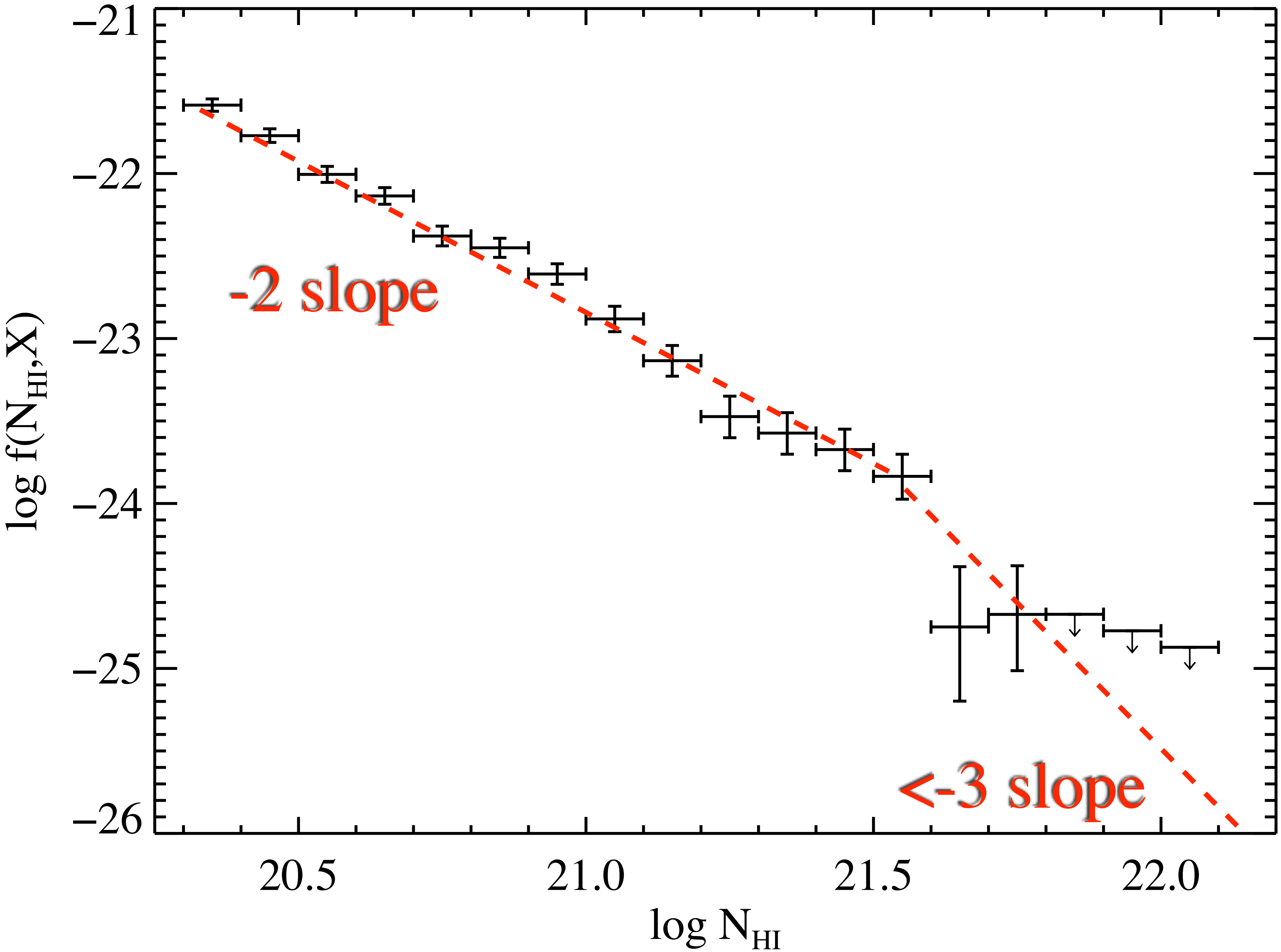

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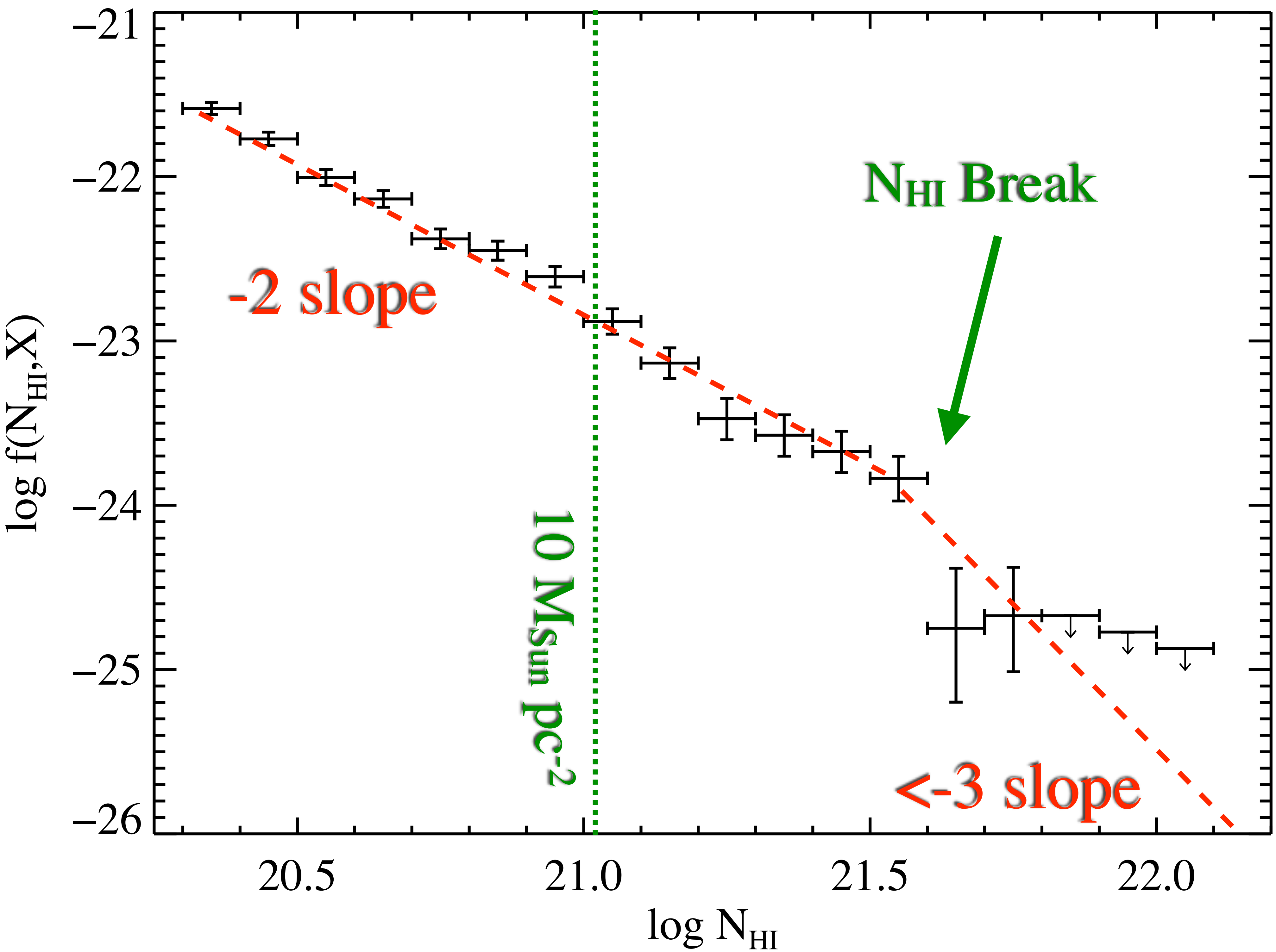
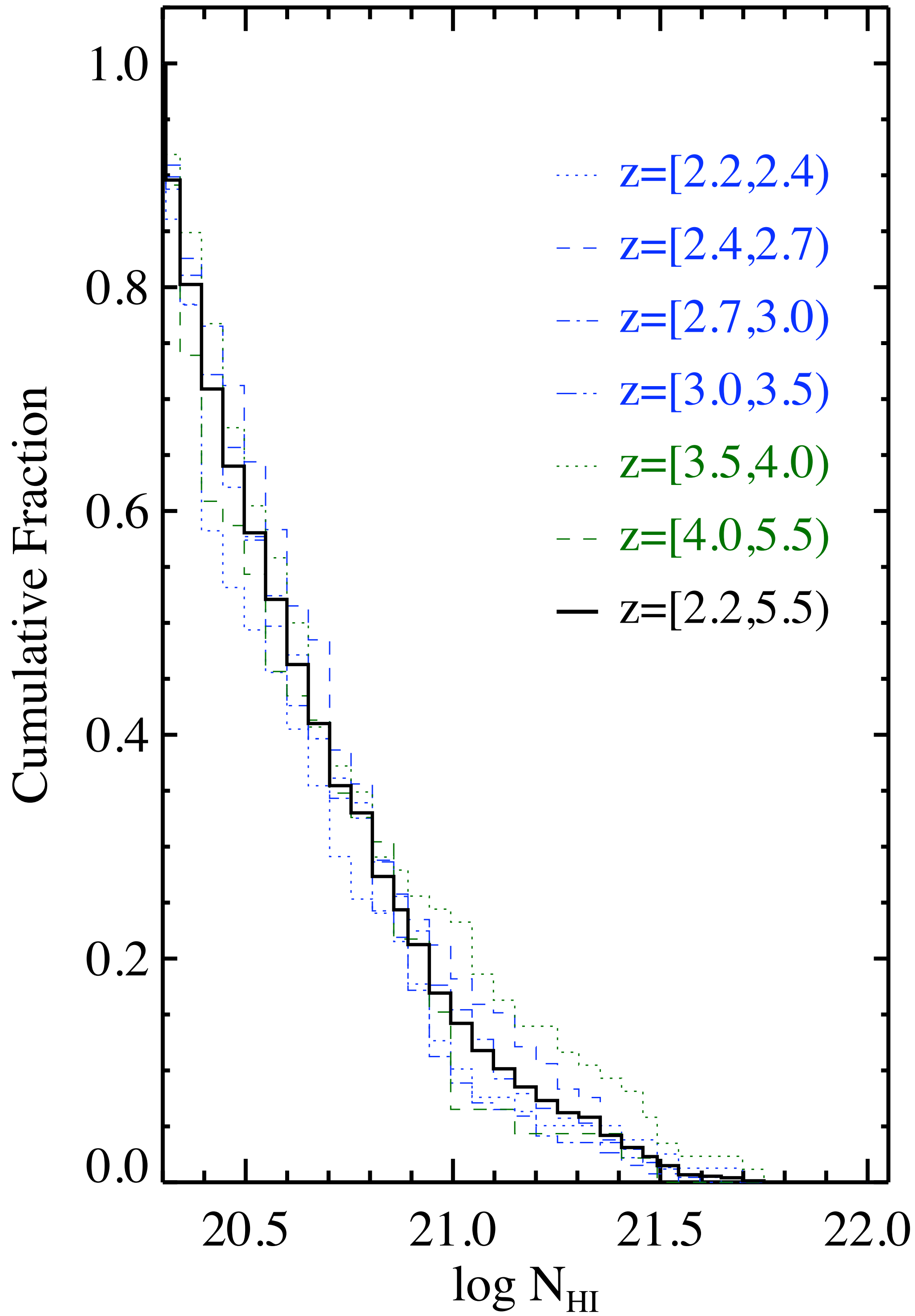


Prochaska & Wolfe 2009

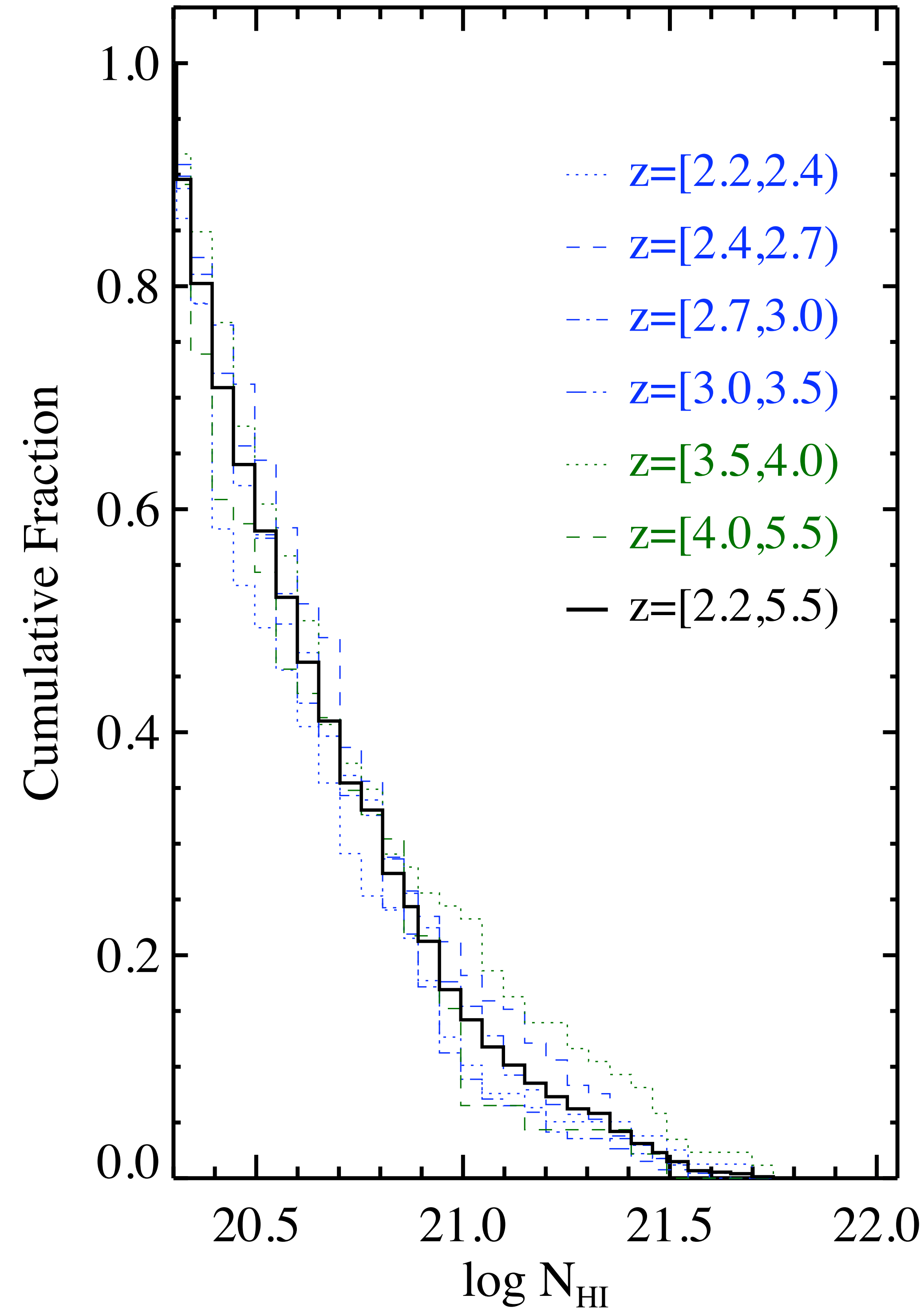
Non-Evolution in the Shape of $f(N_{HI})$



P&W 2009

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

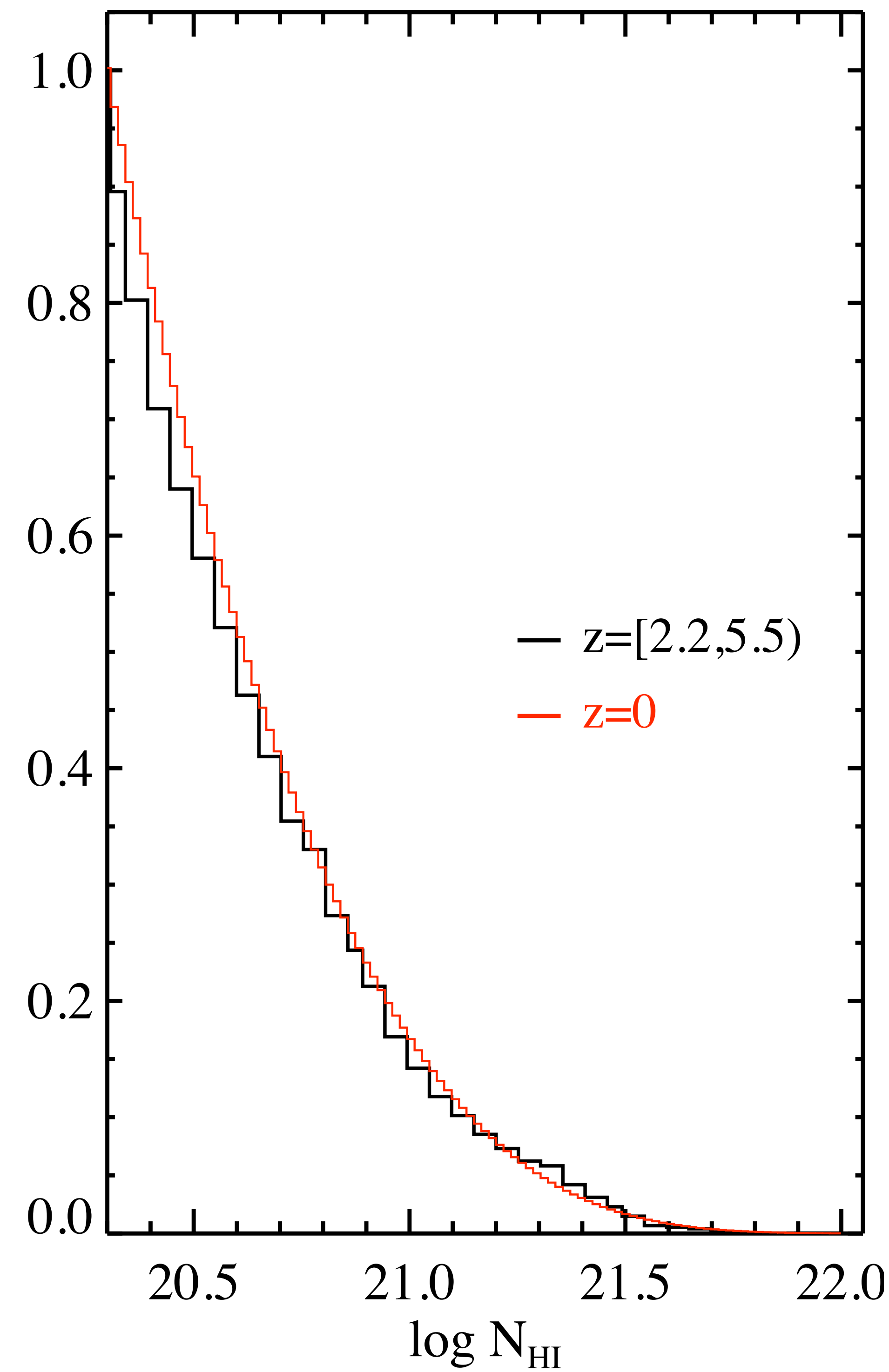
- No evolution from z=2 to 4
  - Gas remains distributed in a self-similar fashion during this 1Gyr



P&W 2009

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

- No evolution from z=2 to 4
  - Gas remains distributed in a self-similar fashion during this 1Gyr
- 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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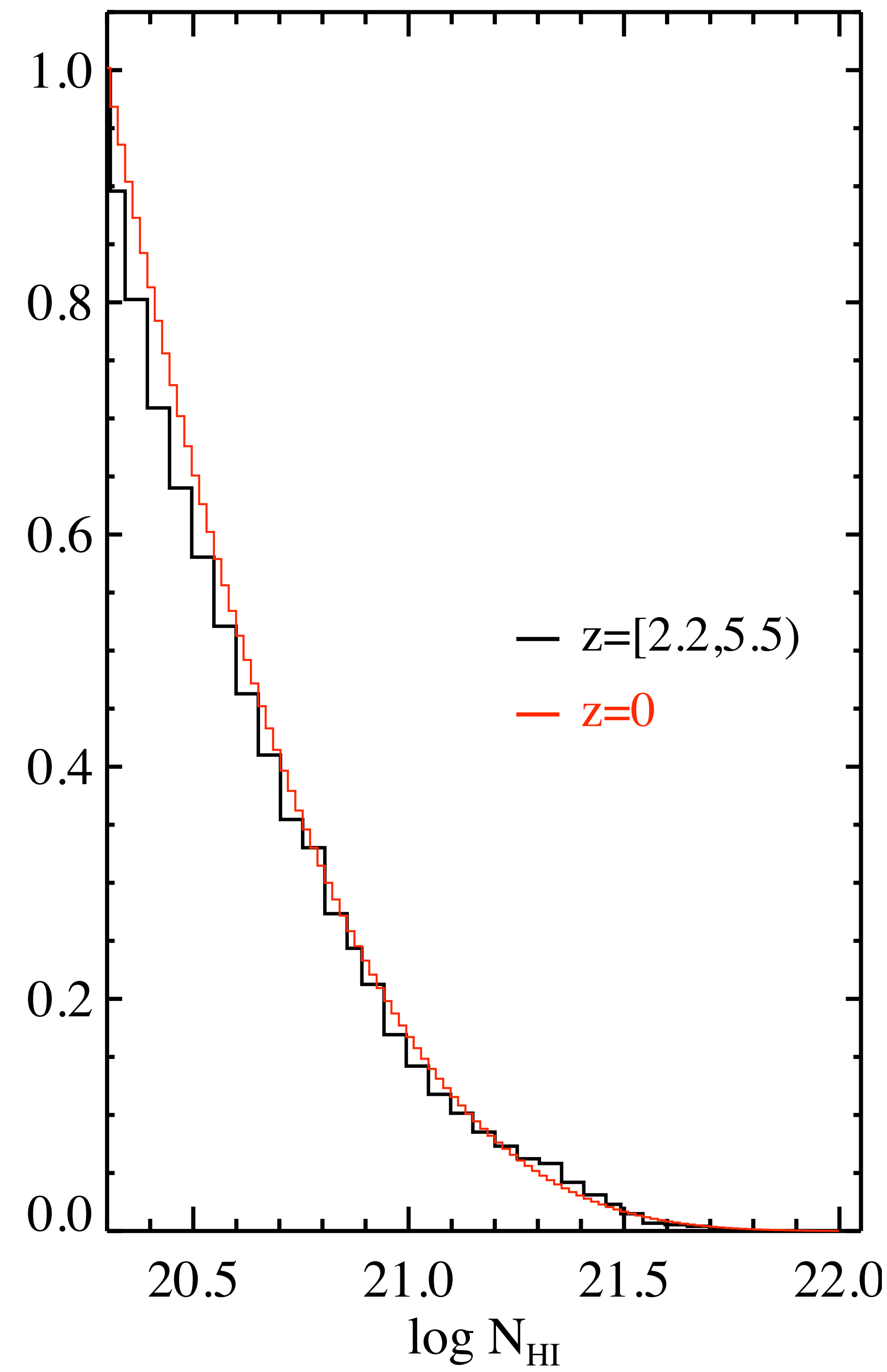
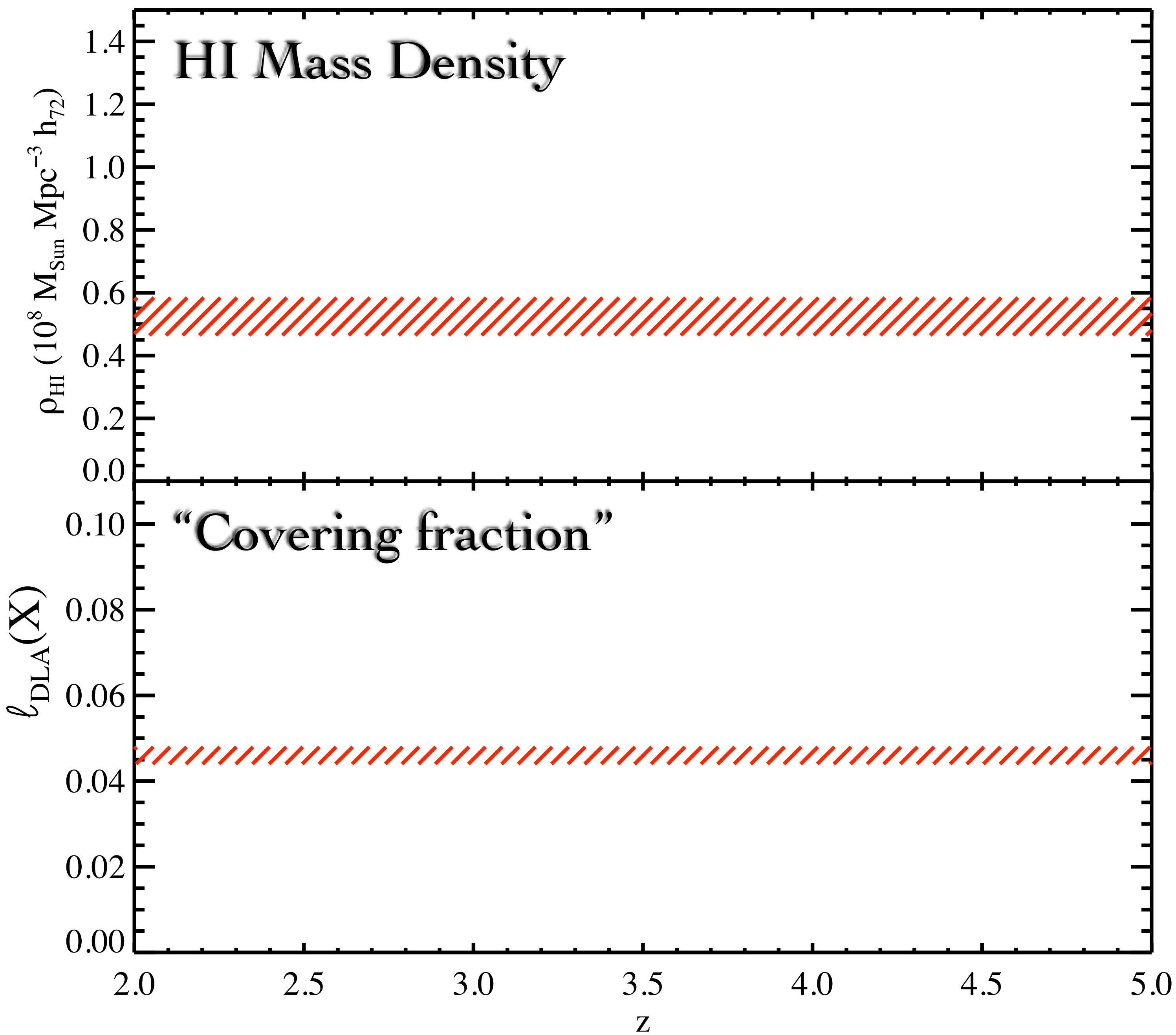
  - At all cosmic time, galaxies (as a population) have the same relative distribution of projected Σ_{HI}
    - On pc scales
- No shift in the N_{HI} break with z
  - To within a factor of ~2
  - Consistent with H_2 physics



P&W 2009

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



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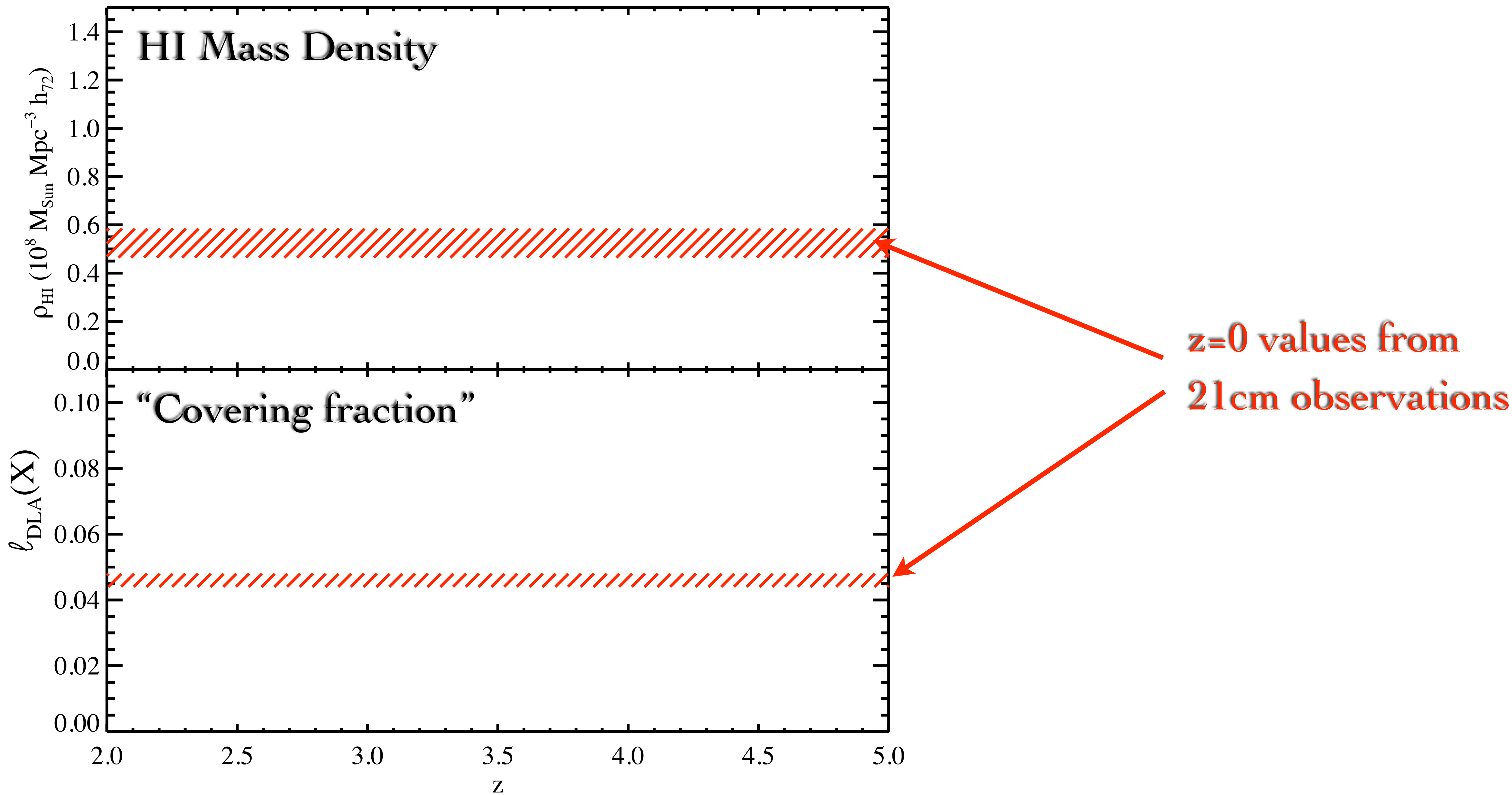

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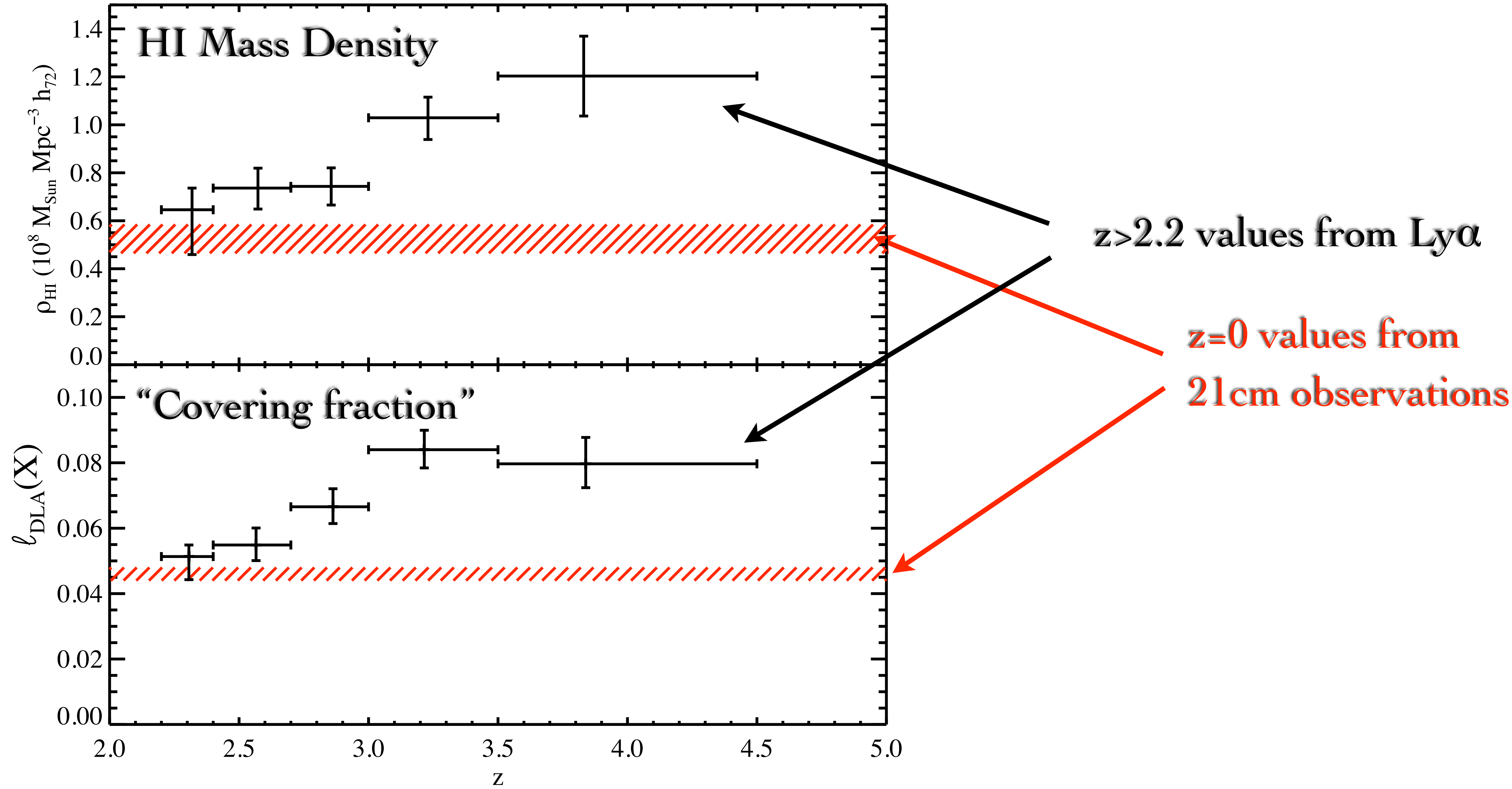

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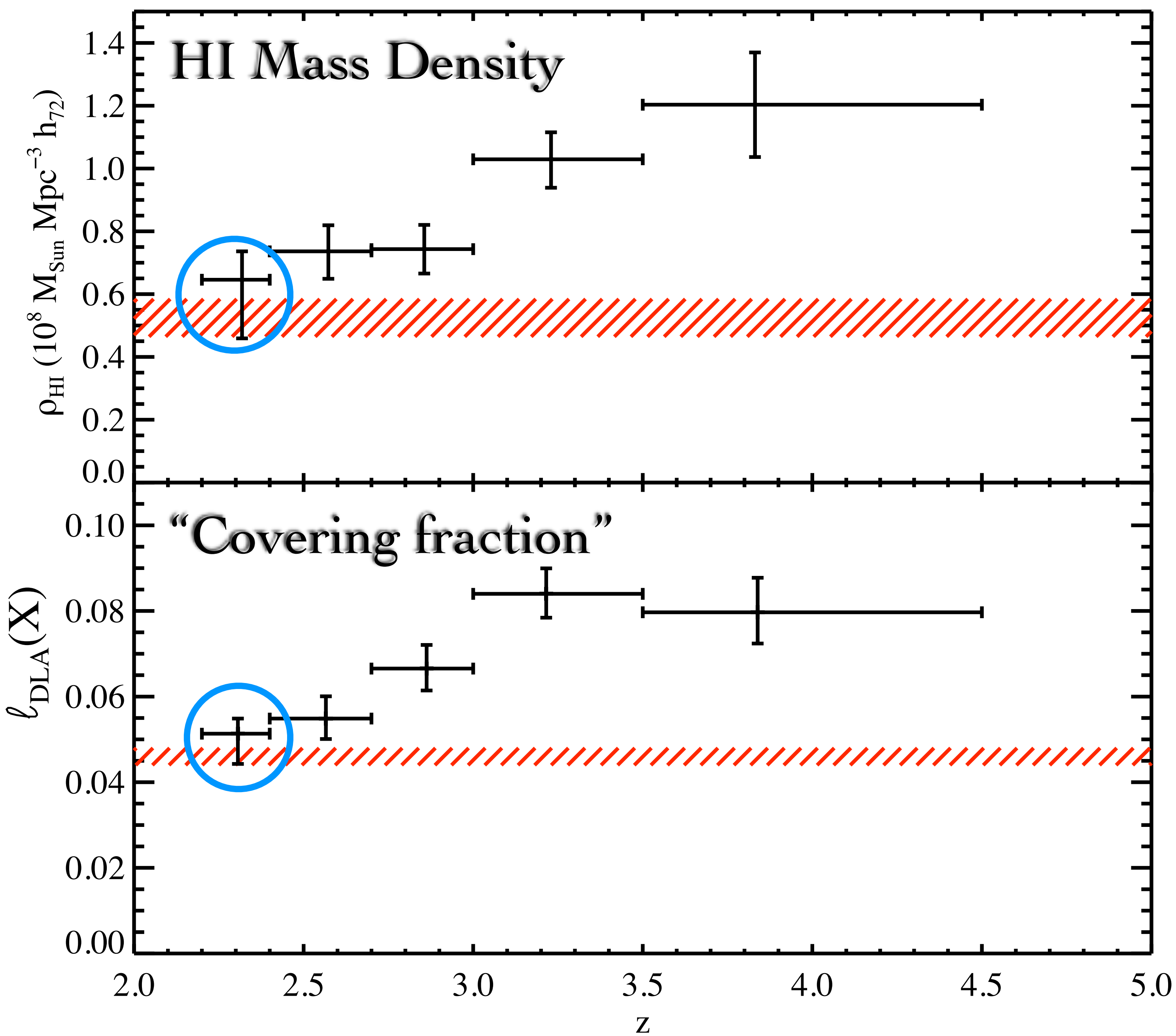


- Galaxies today have nearly the same size* and total HI mass as 10 Gyr ago
  - Am willing to interpolate
    - i.e. constant since z~2
- But, we know stars have formed since z~2
  - Driven by gas accretion
    - (See other talks)
  - 'Disks' at large N_{HI} are critically unstable (Q~1) to SF at all times

*For a constant comoving number density

DLA Systematic Biases

- **Dust** (Ellison+01,Jorgenson+06)
  - Obscures background quasar
  - Likely a ~10% effect
- **Color selection** (Prochaska+09)
  - SDSS is biased toward DLAs at z~3
    - Possibly a 20% effect
  - Not important at z>3.5
- **Survey path** (Notredaeme+09)
  - DLAs affect the S/N of their spectra
  - Boosts statistics at z~2 by ~30%

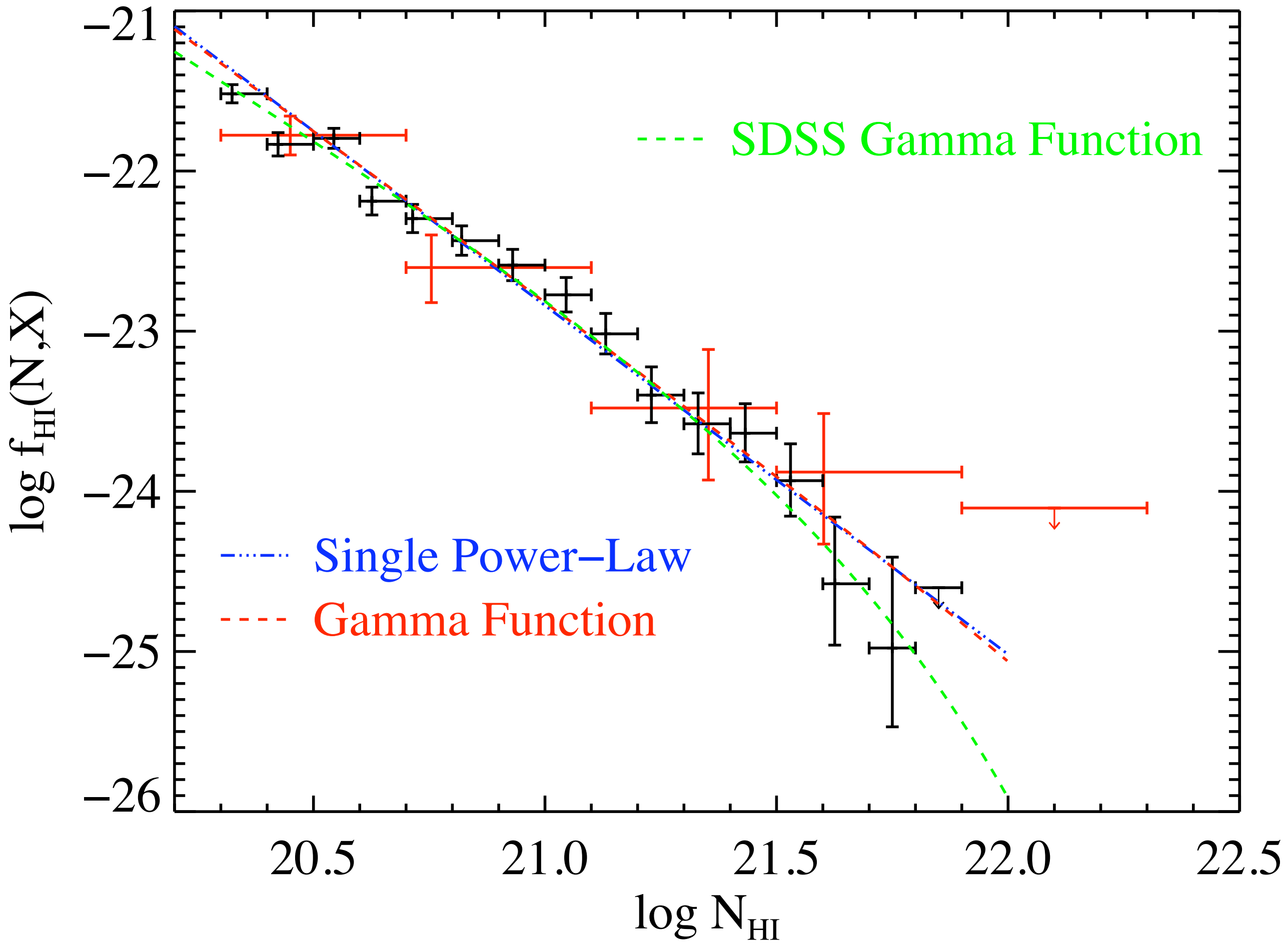
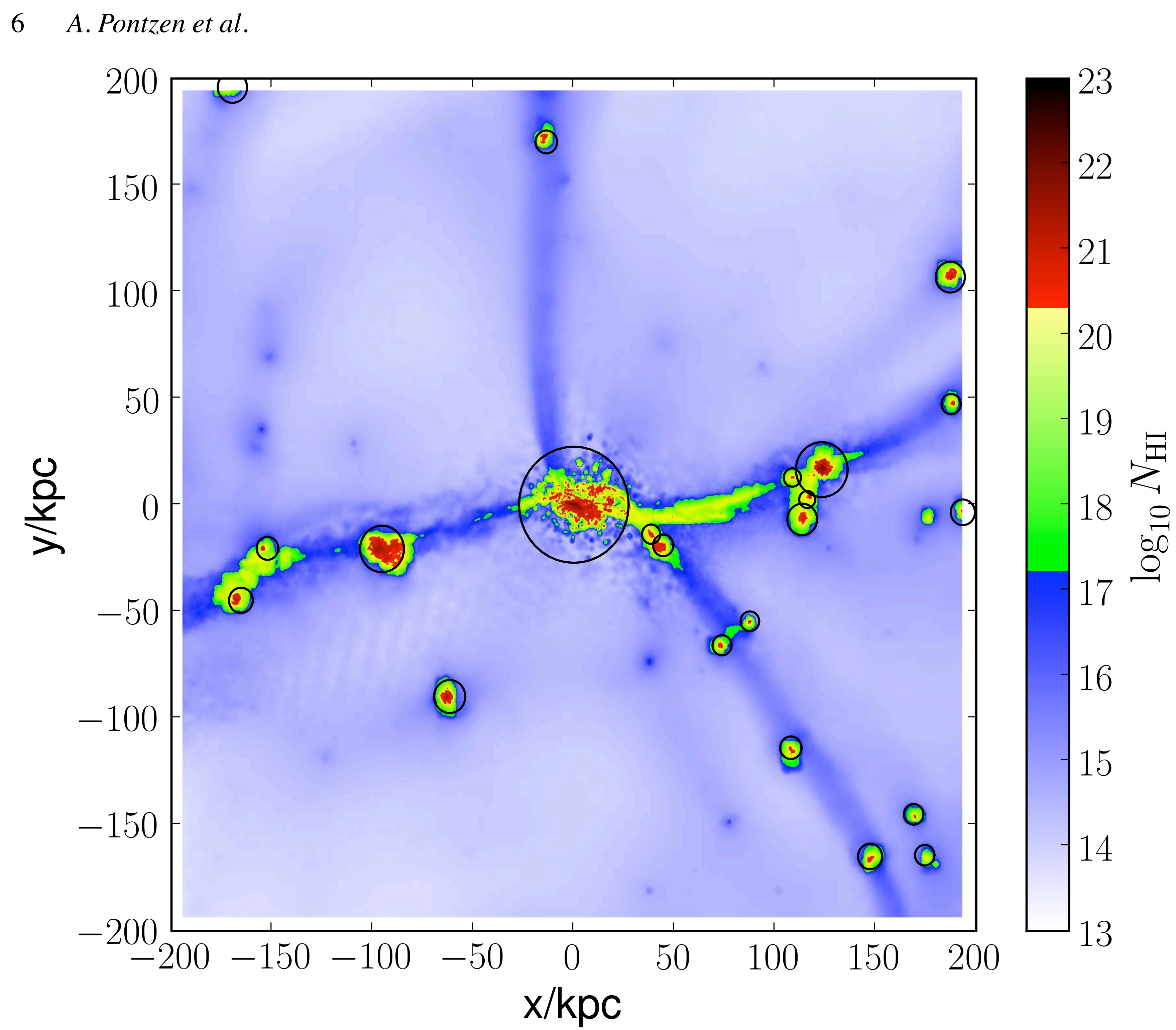
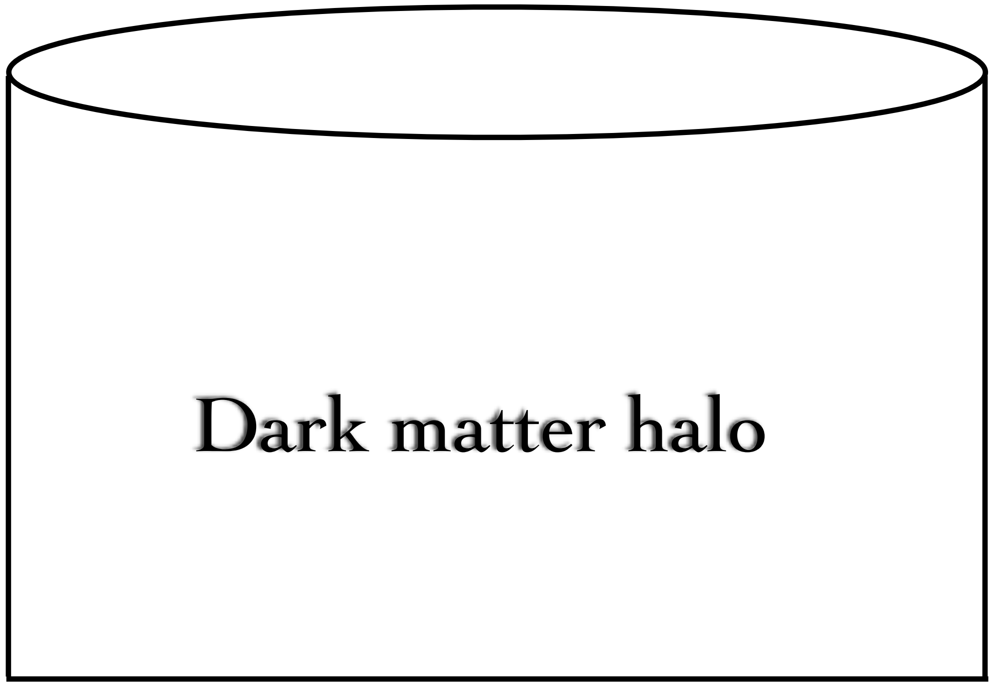


FIG. 3.— The H I frequency distribution $f_{\rm HI}(N,X)$ for the 26 DLAs of the combined sample is plotted in red. Overplotted are the fits of a single power-law, the dot-dashed line in blue, and a Γ-function, the dashed line in red. The last bin contains the 2σ upper limit. Plotted in black is the $f_{\rm HI}(N,X)$ for the optical data from the SDSS-DR3, with the Γ-function fit in green.

Put a theory slide here?



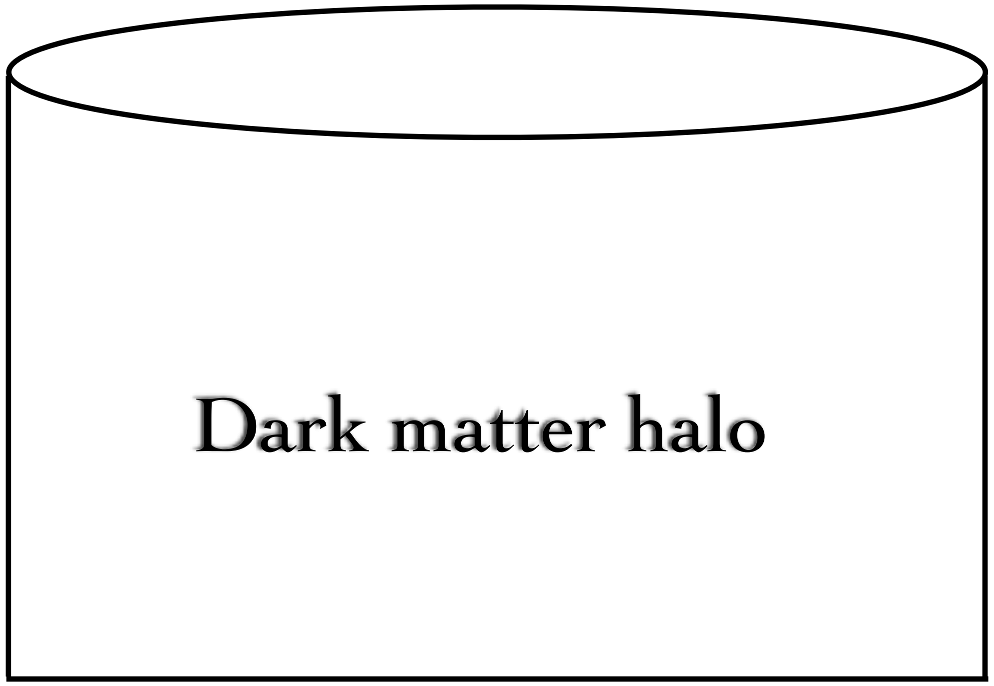
Swimming Pool Theory of Galaxy Formation



See also Bouche & Dekel 2009

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



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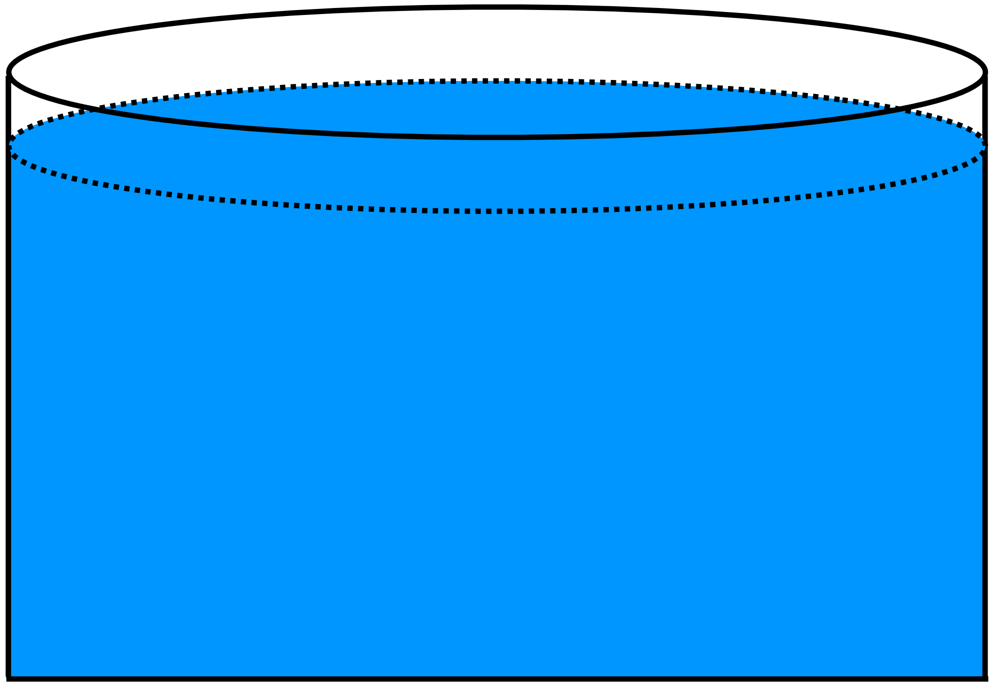

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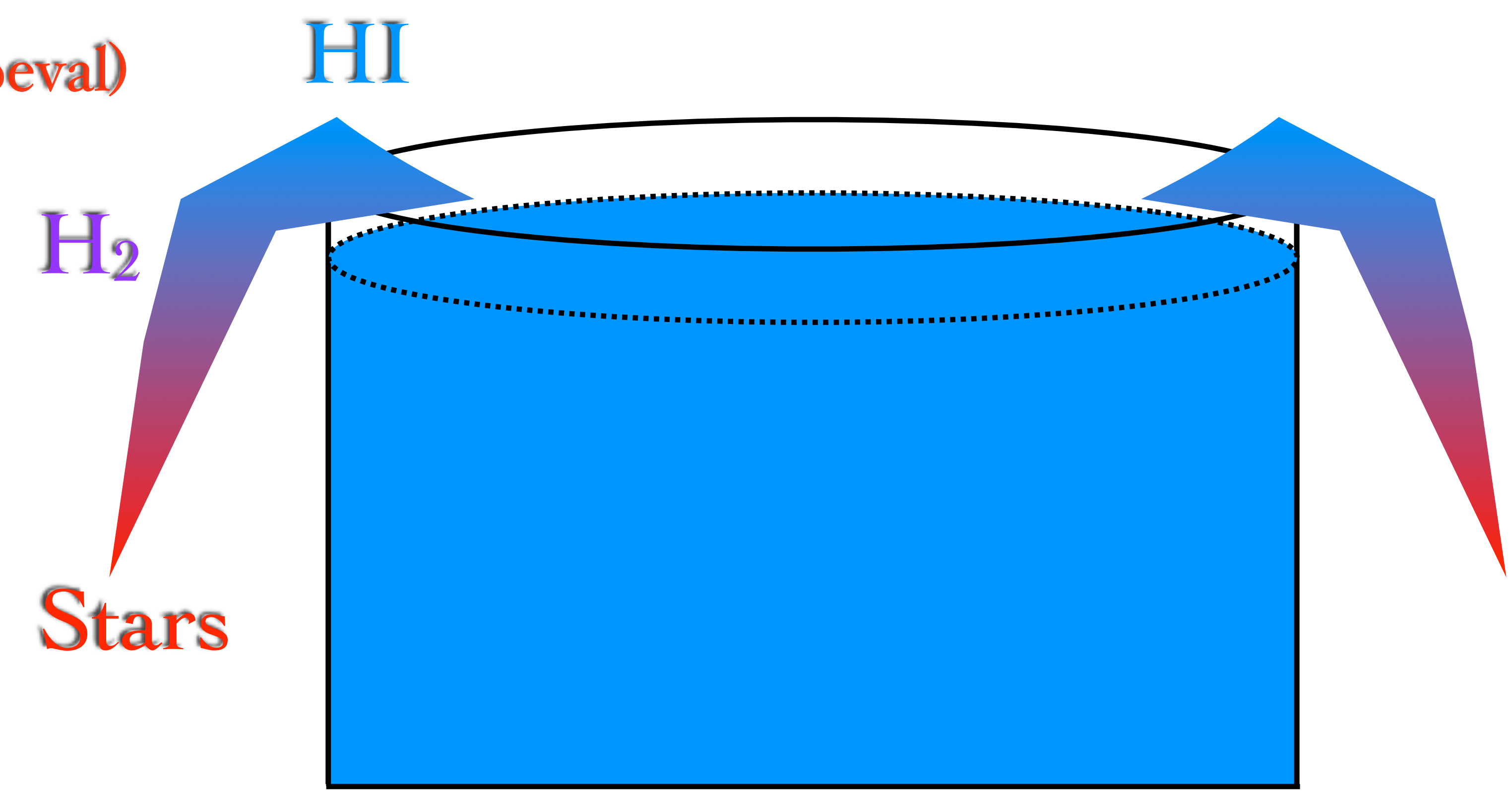
- Excess water spills into H_2
  - H_2 rapidly converted to stars
  - HI level maintained



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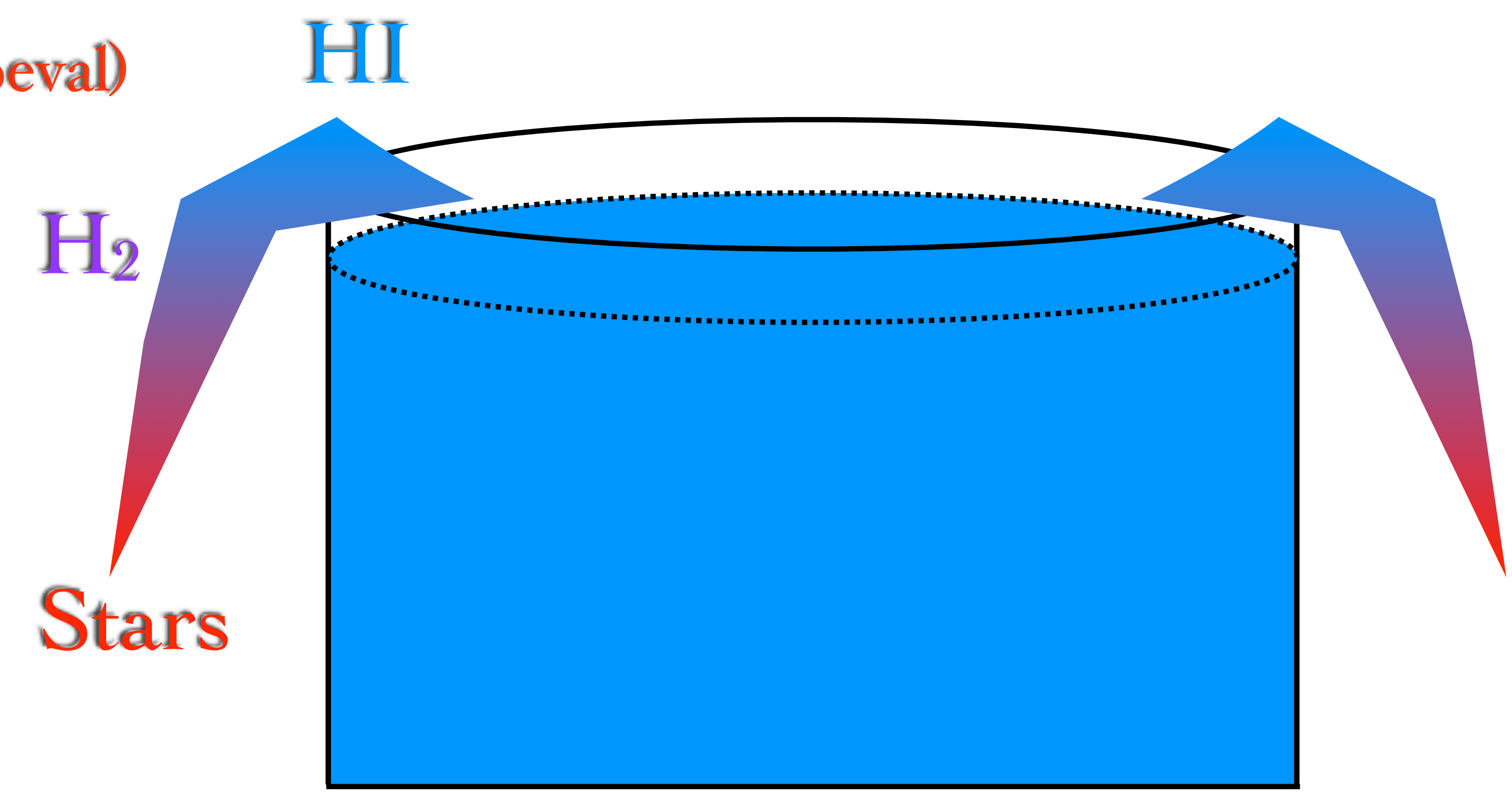
- Excess water spills into H_2
  - H_2 rapidly converted to stars
  - HI level maintained
- Accretion stops/slows
  - SF slows
  - Pool stays full
    - Absent a major (destructive) event



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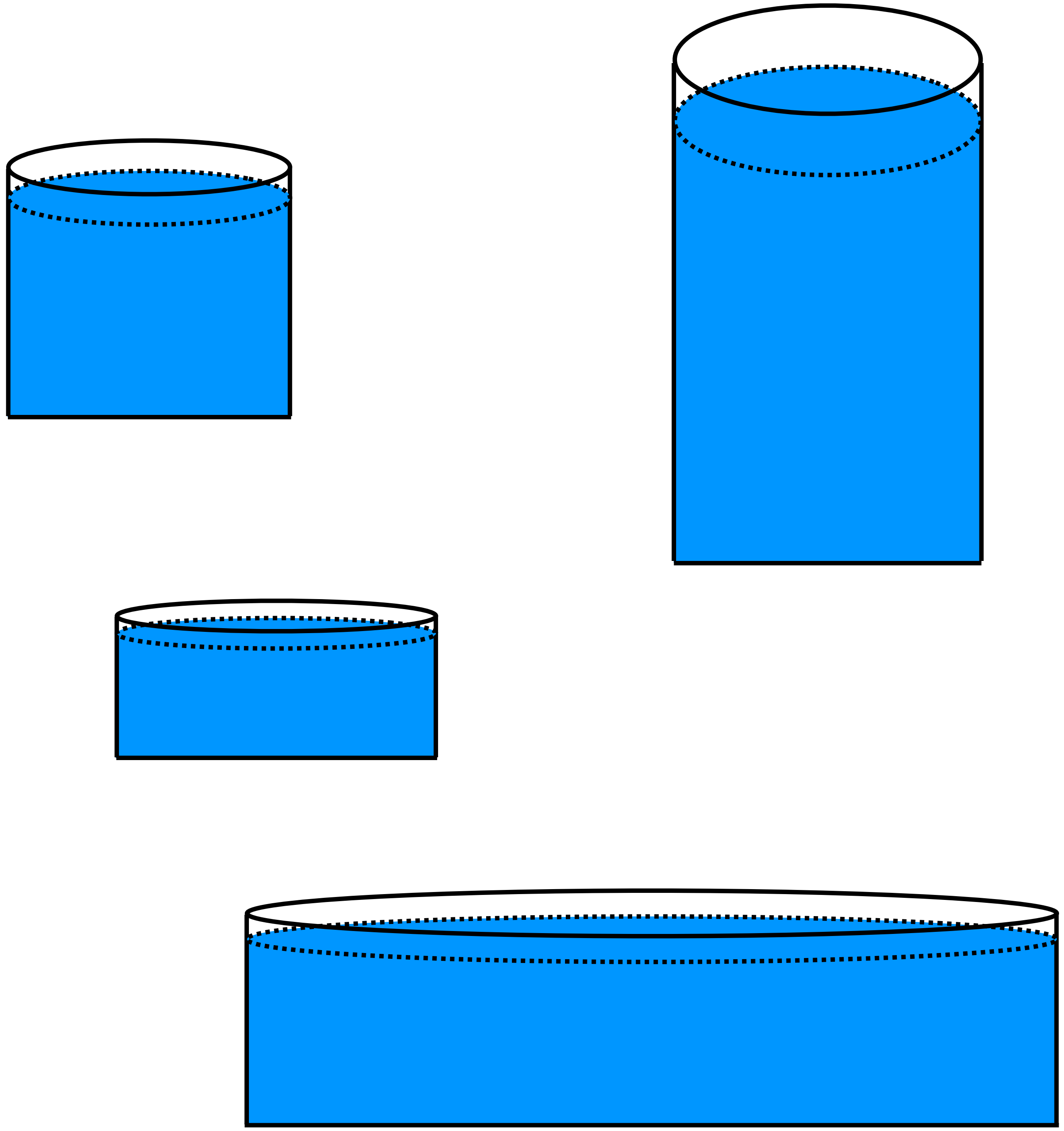
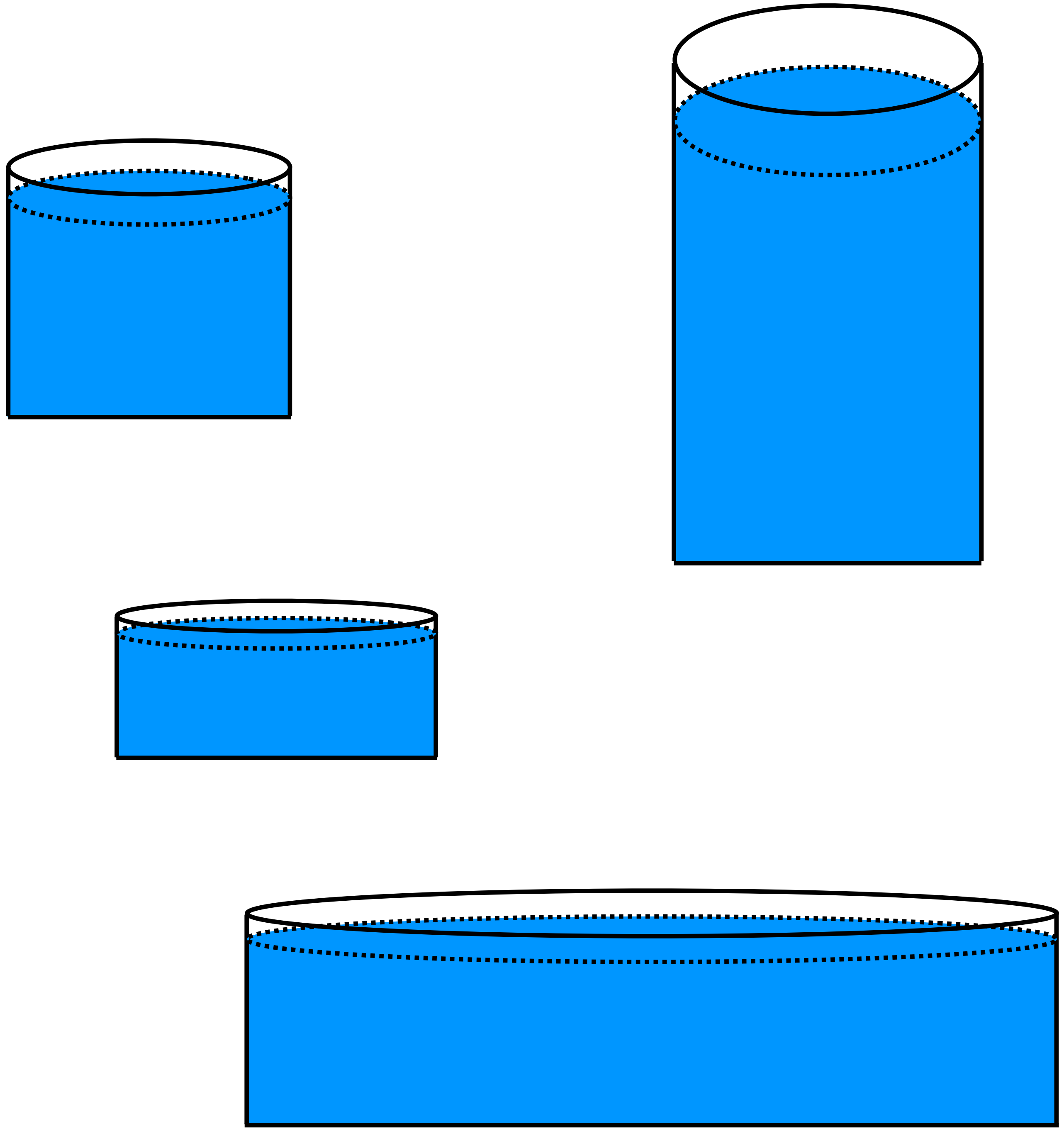


Swimming Pool Theory of Galaxy Formation

- 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



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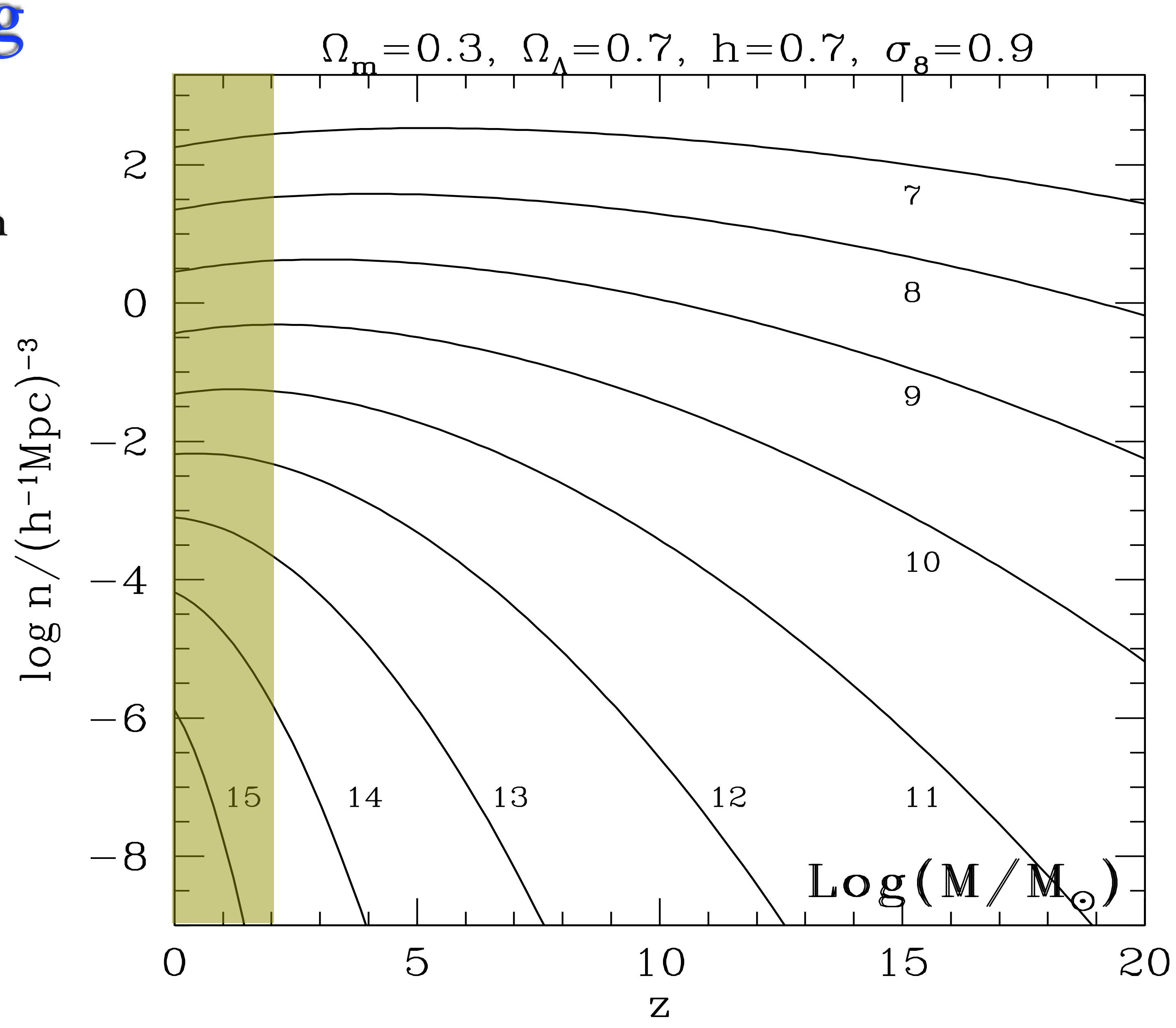
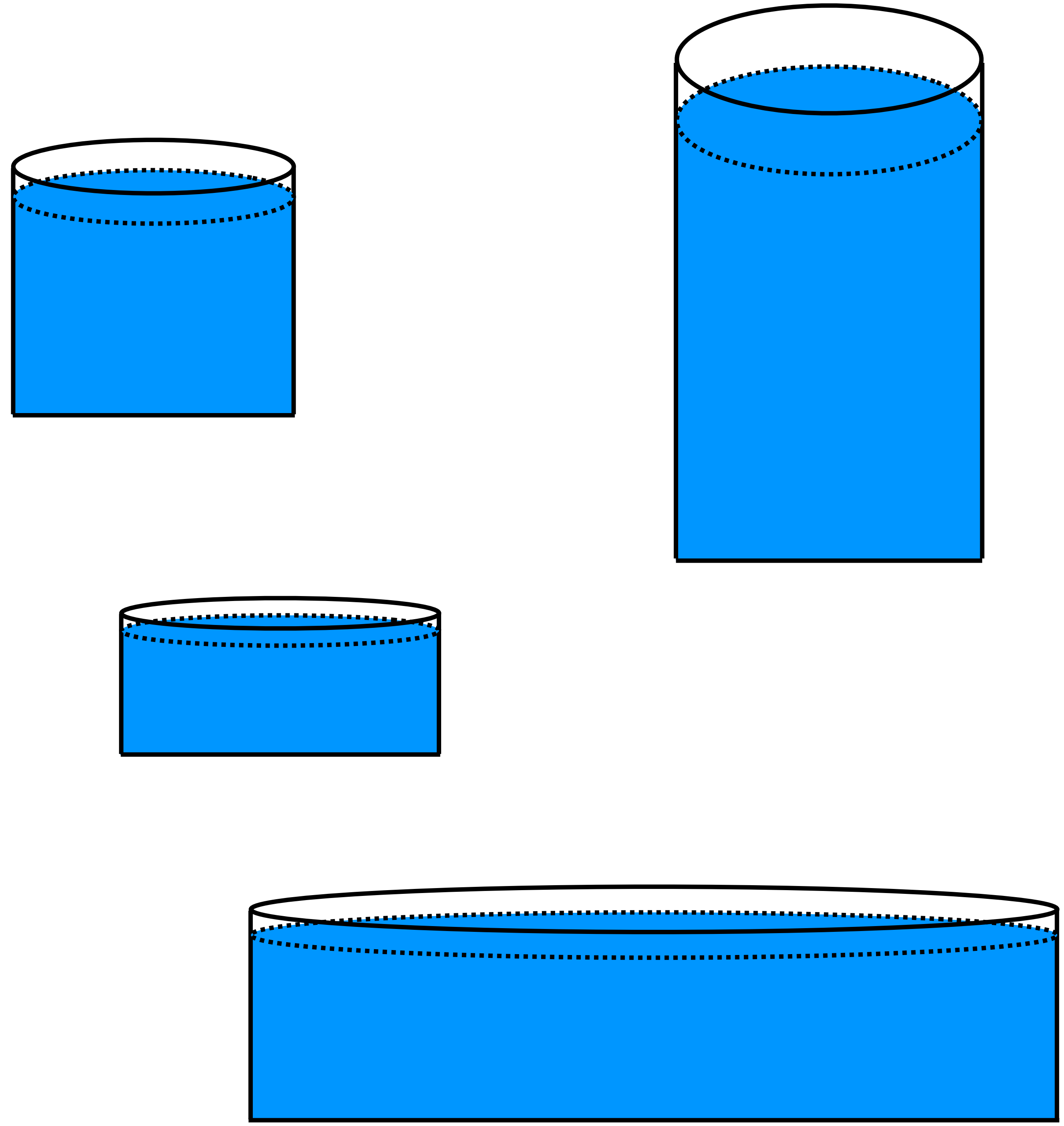
MO & WHITE 2002

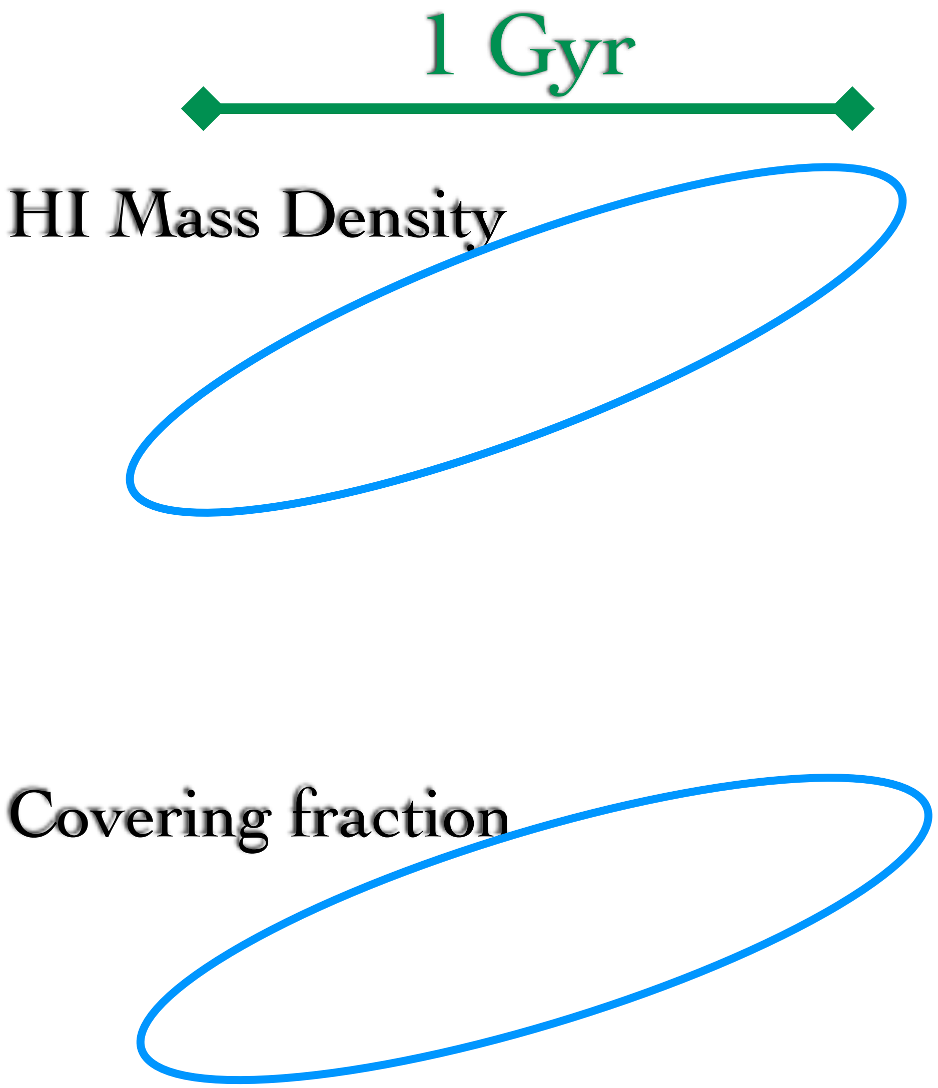


Swimming Pool Theory of Galaxy Formation

- 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
    - ✦ Or existing ones grow



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



- 2x decrease in $\ell(X)$ 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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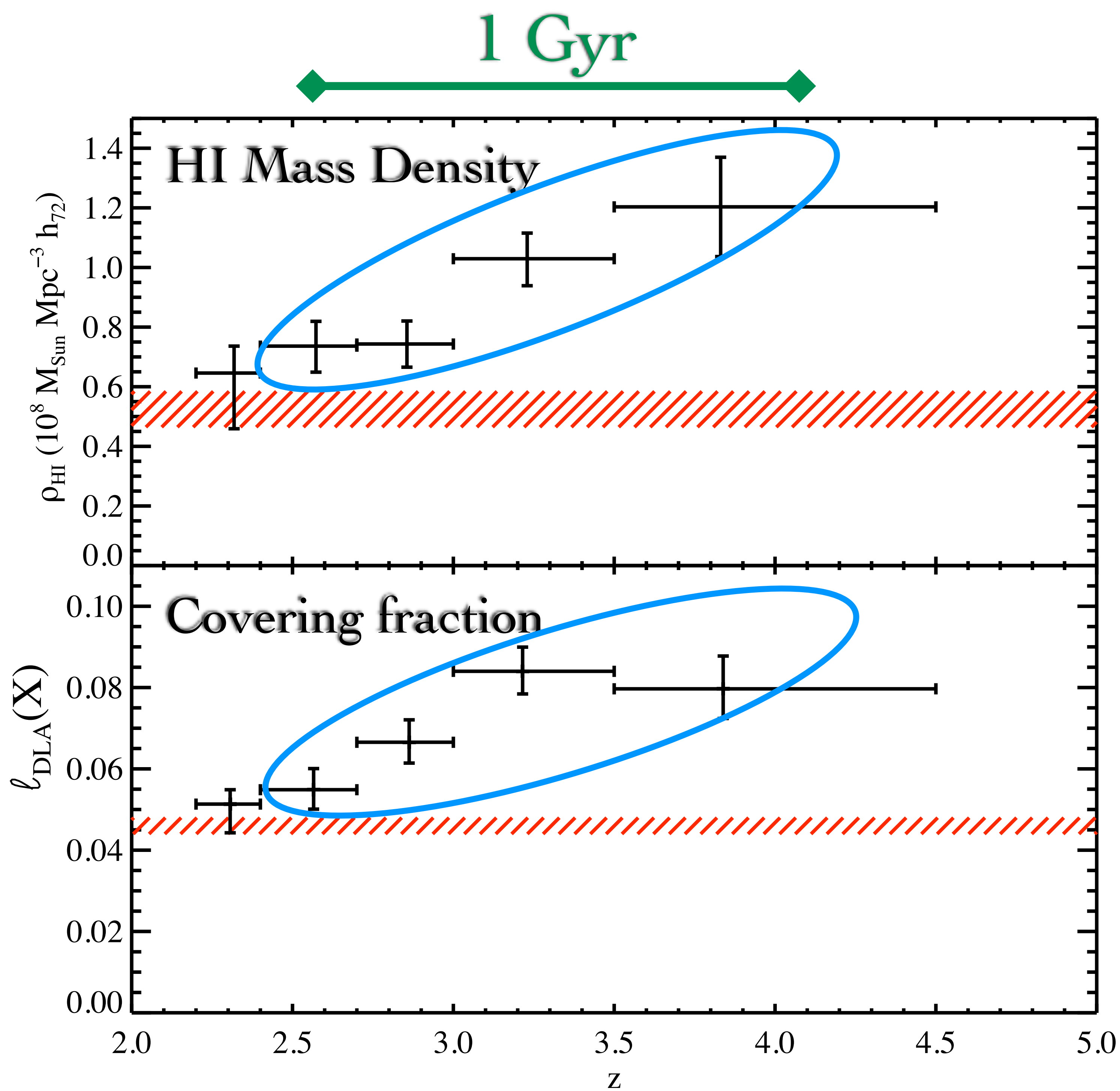

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Swimming Pool Theory of Galaxy Formation

- Evolution in HI 'disks'
  - Not sufficient to empty each pool by 50%
    - This would reduce ρ_{HI}
    - But would minimally change C_A
  - Need to remove 1/2 of the pools
    - While leaving the other 1/2 alone
- What drives this process?
  - SF: Consistent with the SFR
    - But why only 1/2 of the galaxies?
    - And how is the low Σ_{HI} gas removed?
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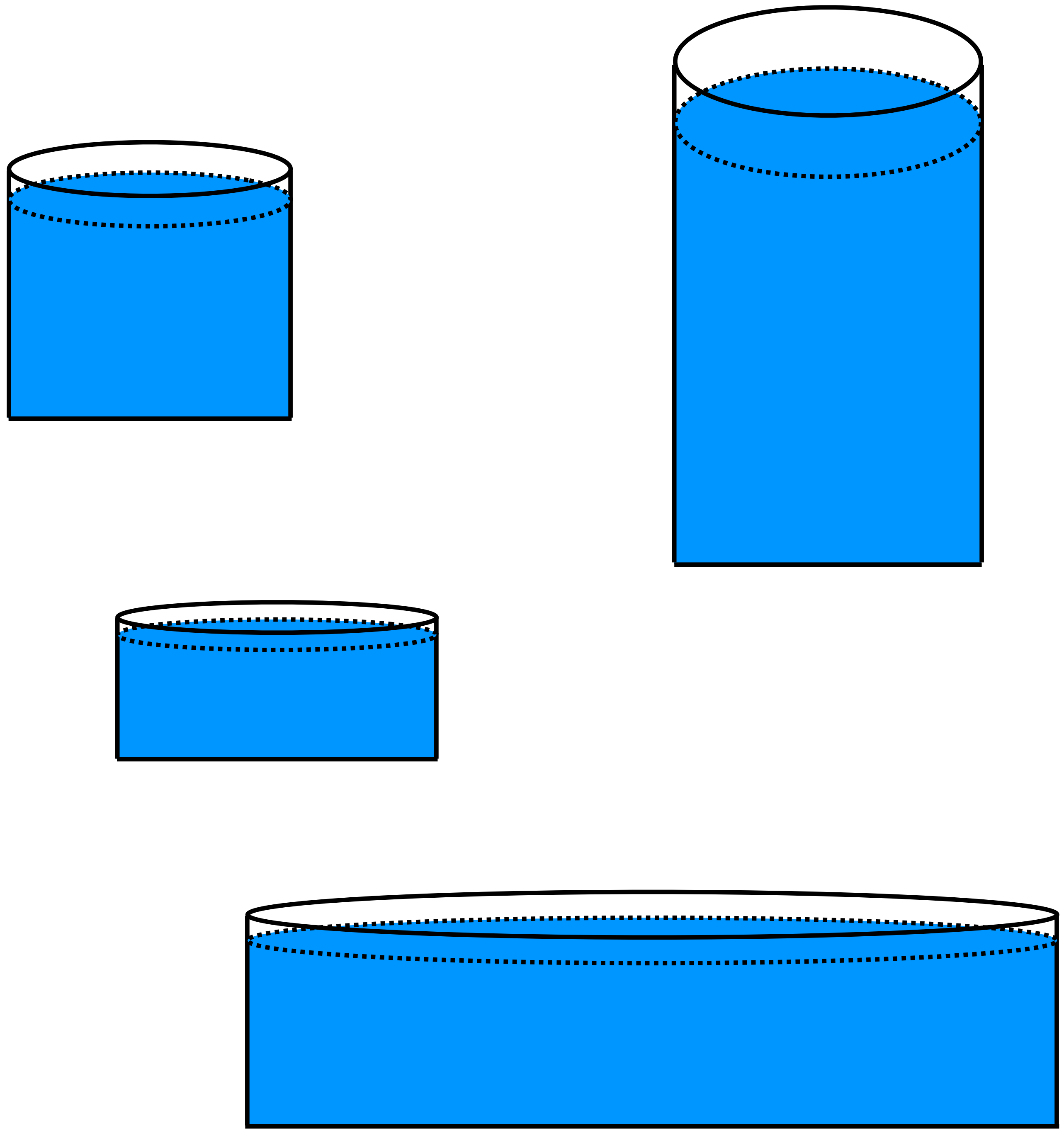

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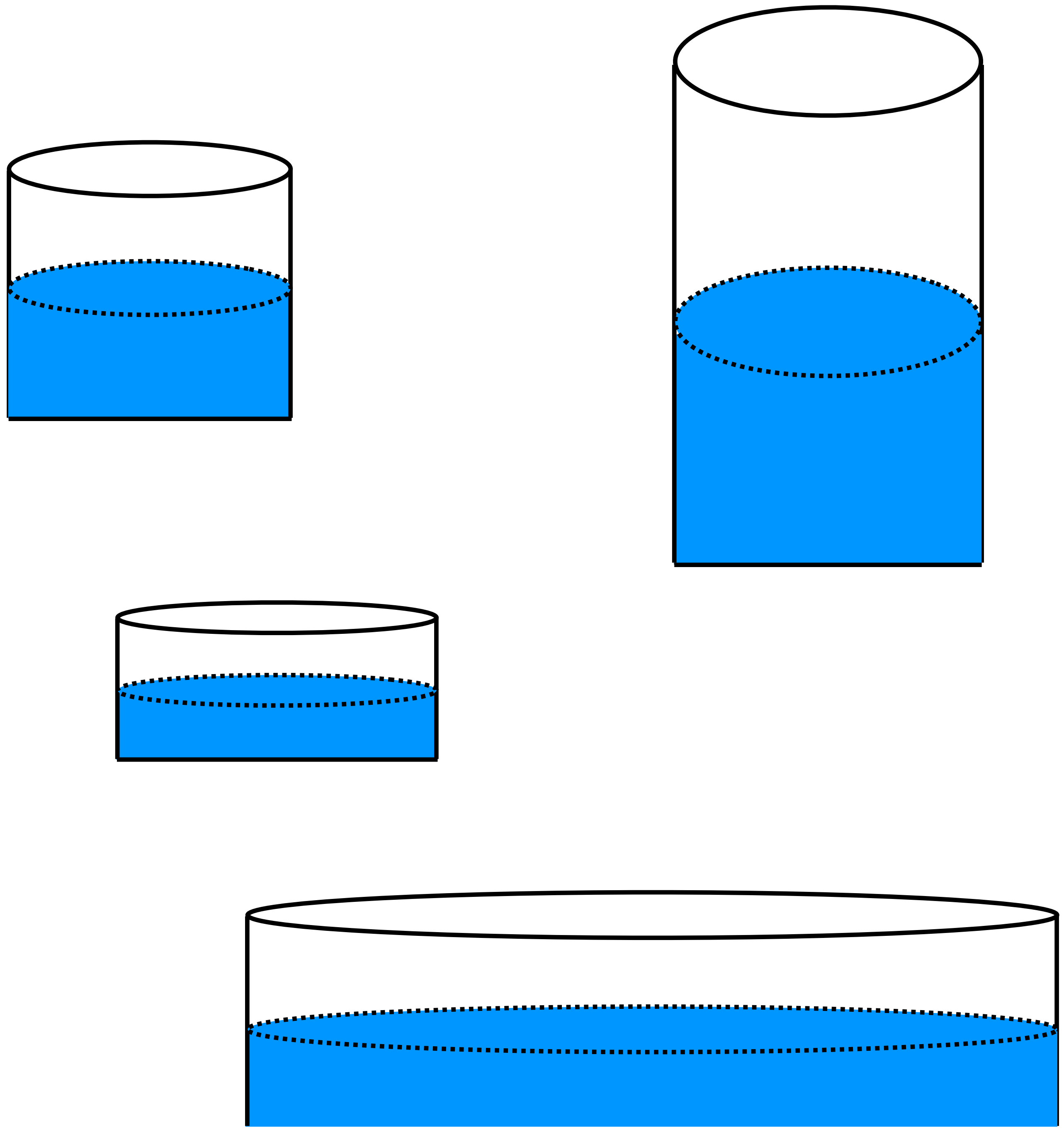

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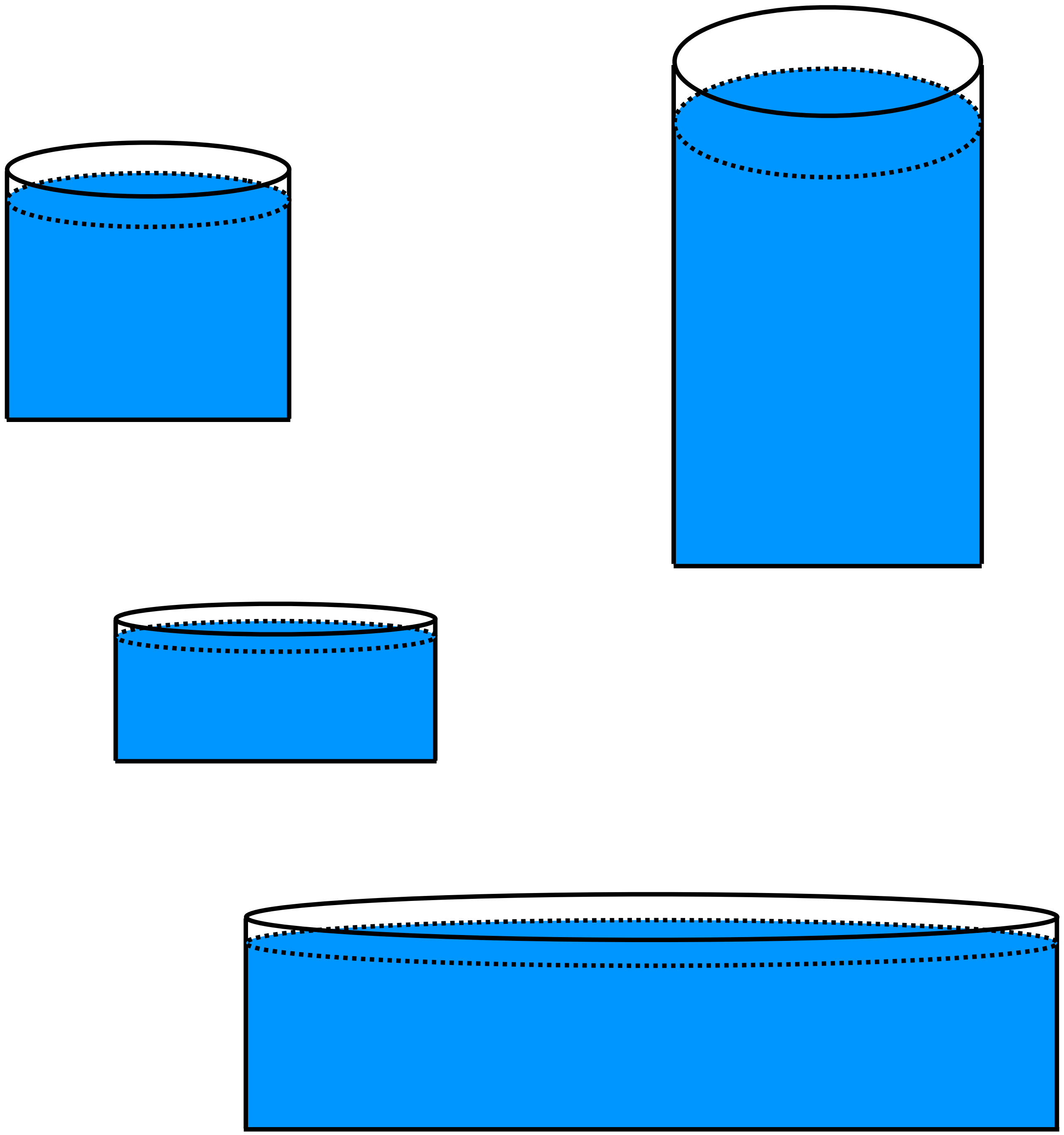

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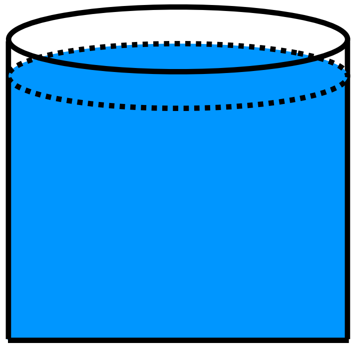
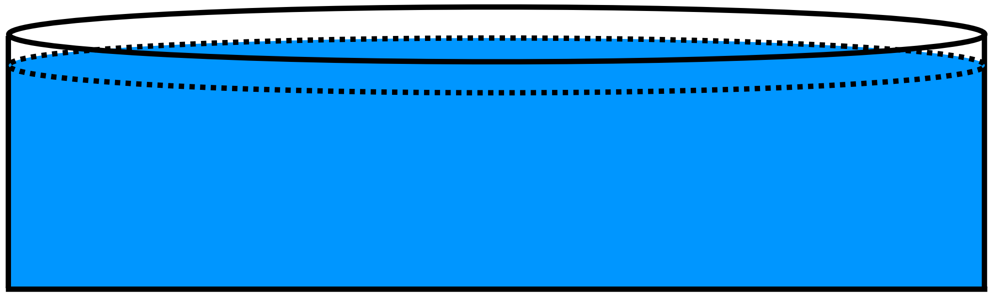
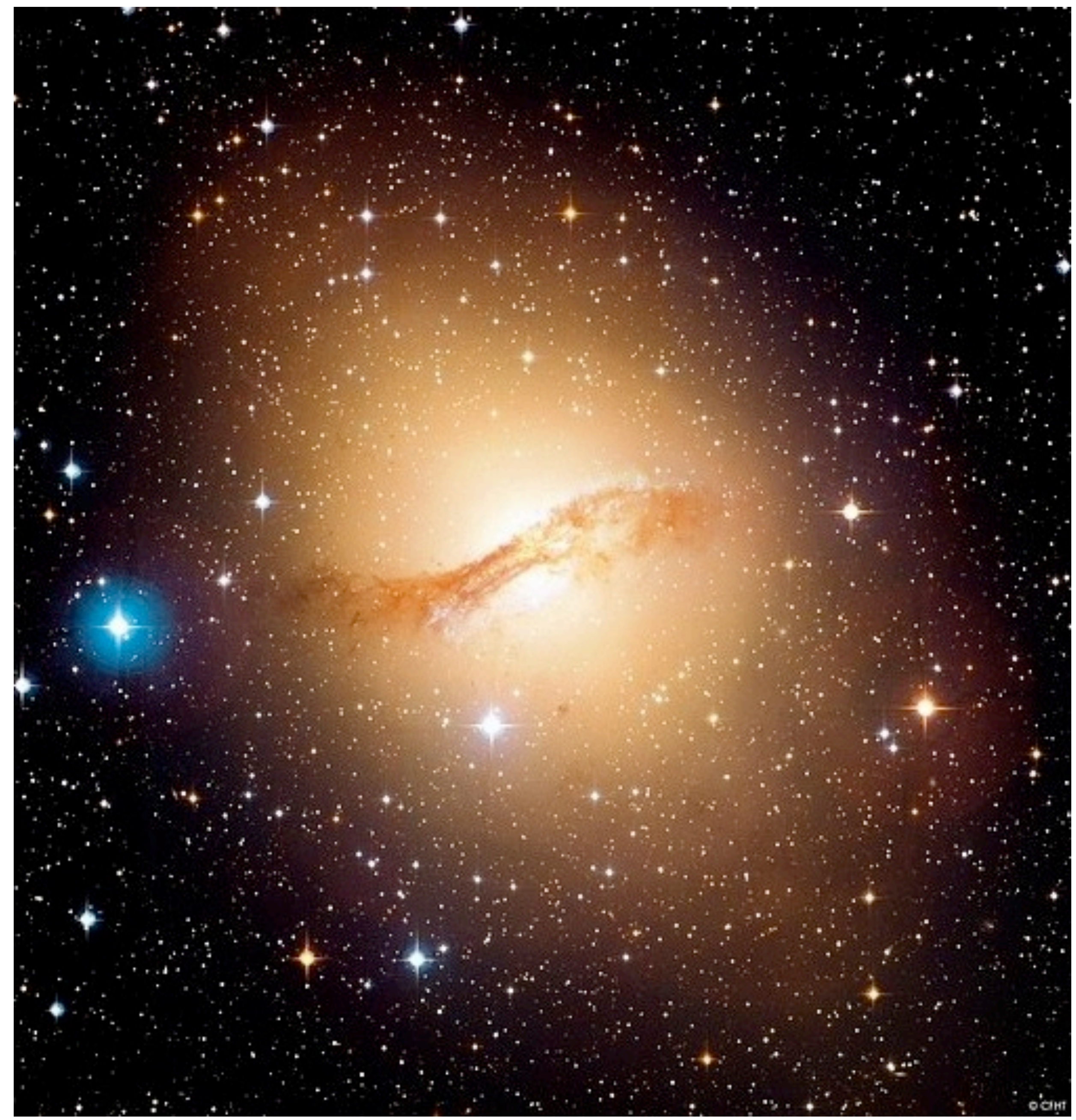




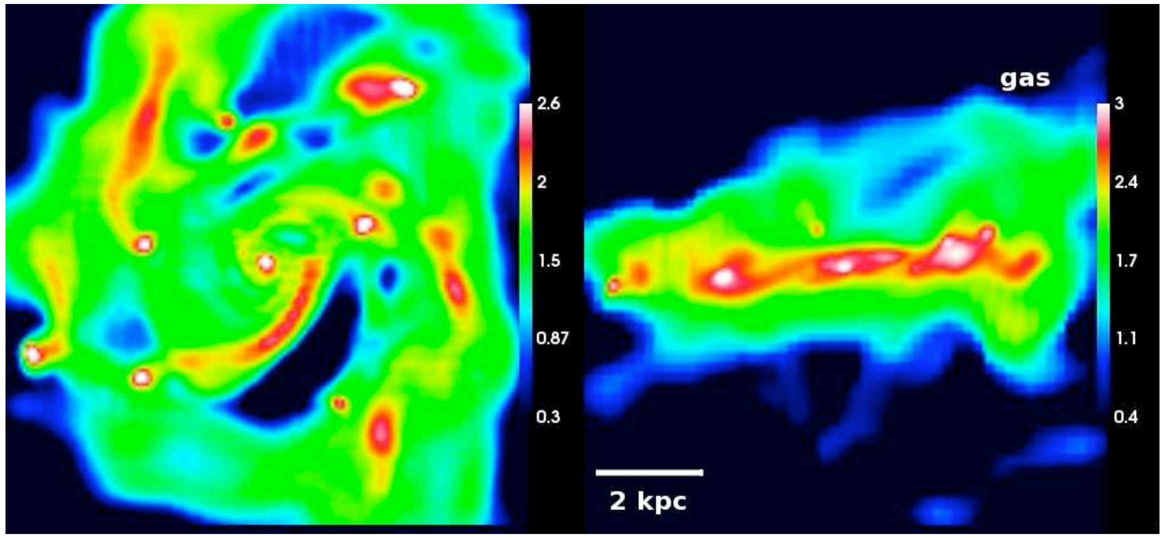
z~3 is the Epoch of Elliptical 'Formation'

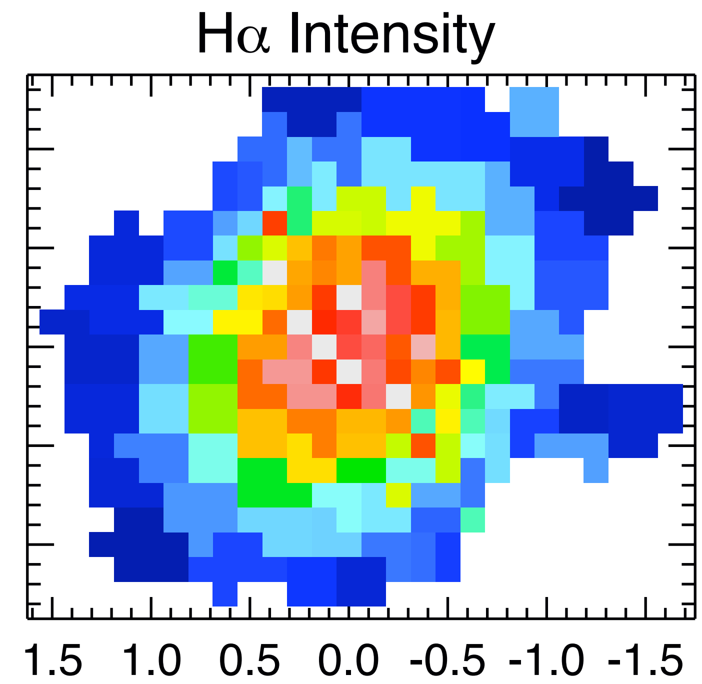
- Red and 'dead' galaxies exist
  - Some mechanism removed the majority of their cold ISM to halt star formation
- Elliptical galaxies have old stellar populations
  - >10 Gyr (z>2)
- Connect:
  - Rapid decline in ρ_{HI} and the covering of C_A



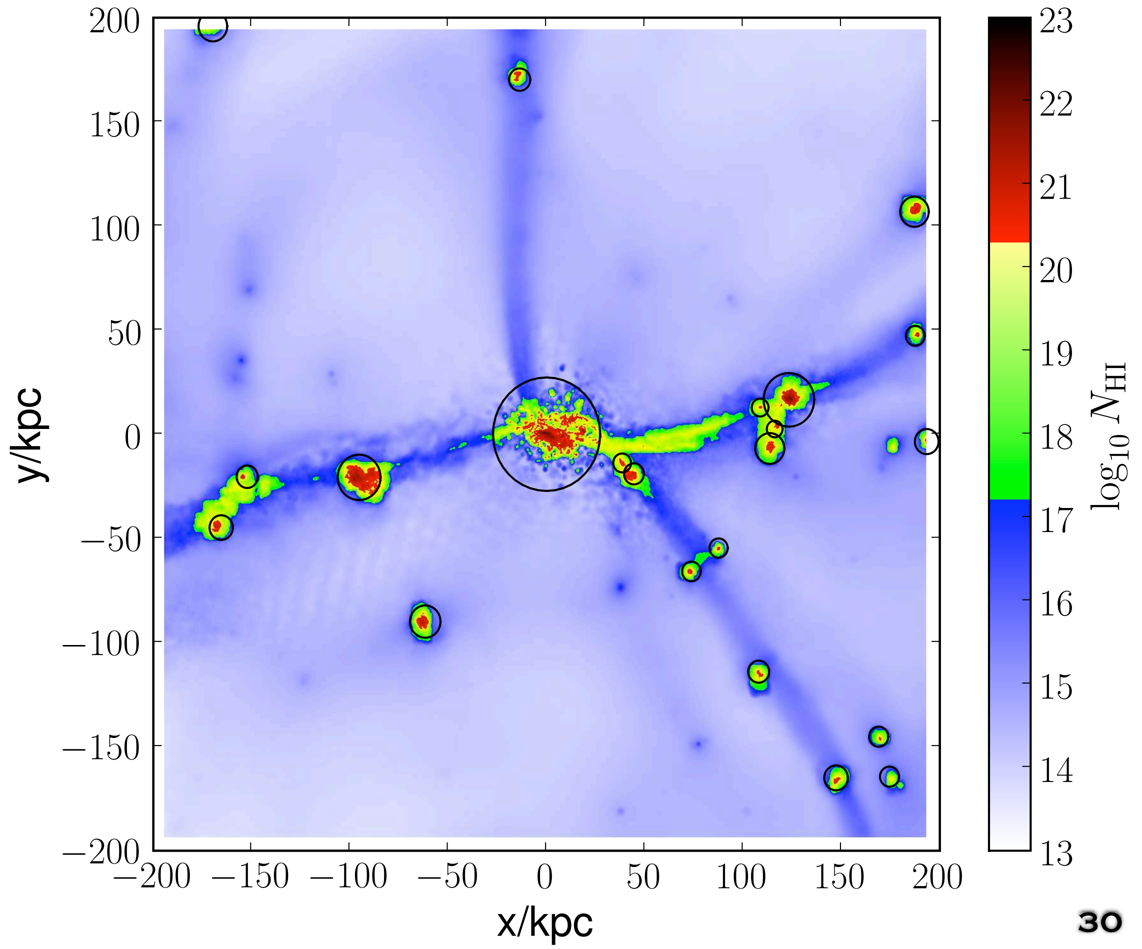
What do these swimming pools look like?

D. Ceverino, A. Dekel & F. Bournaud





6 *A. Pontzen et al.*



ALMA will play a major role here...

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? SF?
- 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
    - SF proceeds only because of new accretion