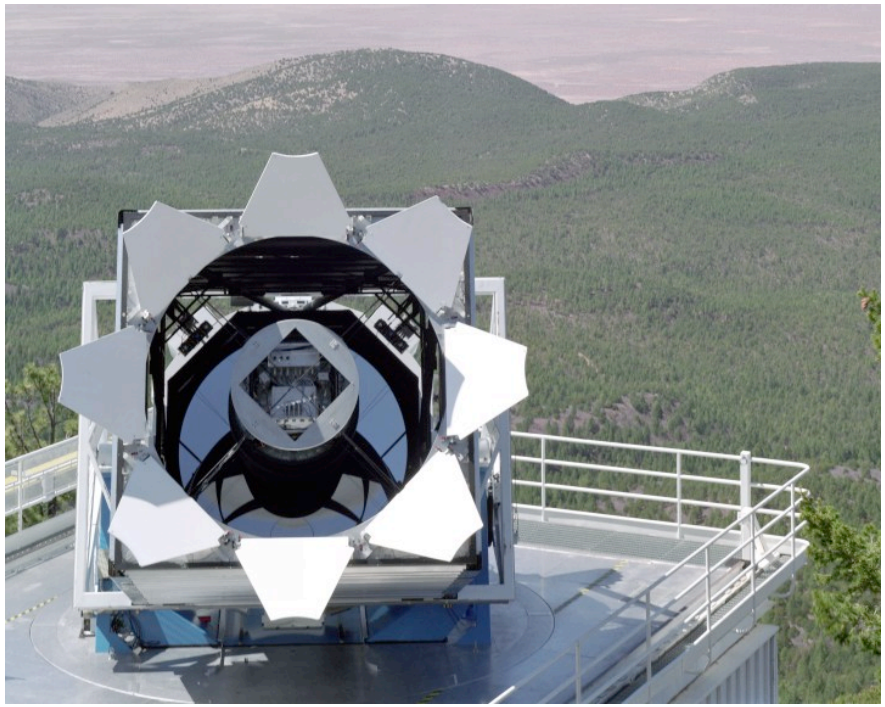
On the (Non)Evolution of HI "Disks" over Cosmic Time

J. Xavier Prochaska

UCO/Lick Observatory

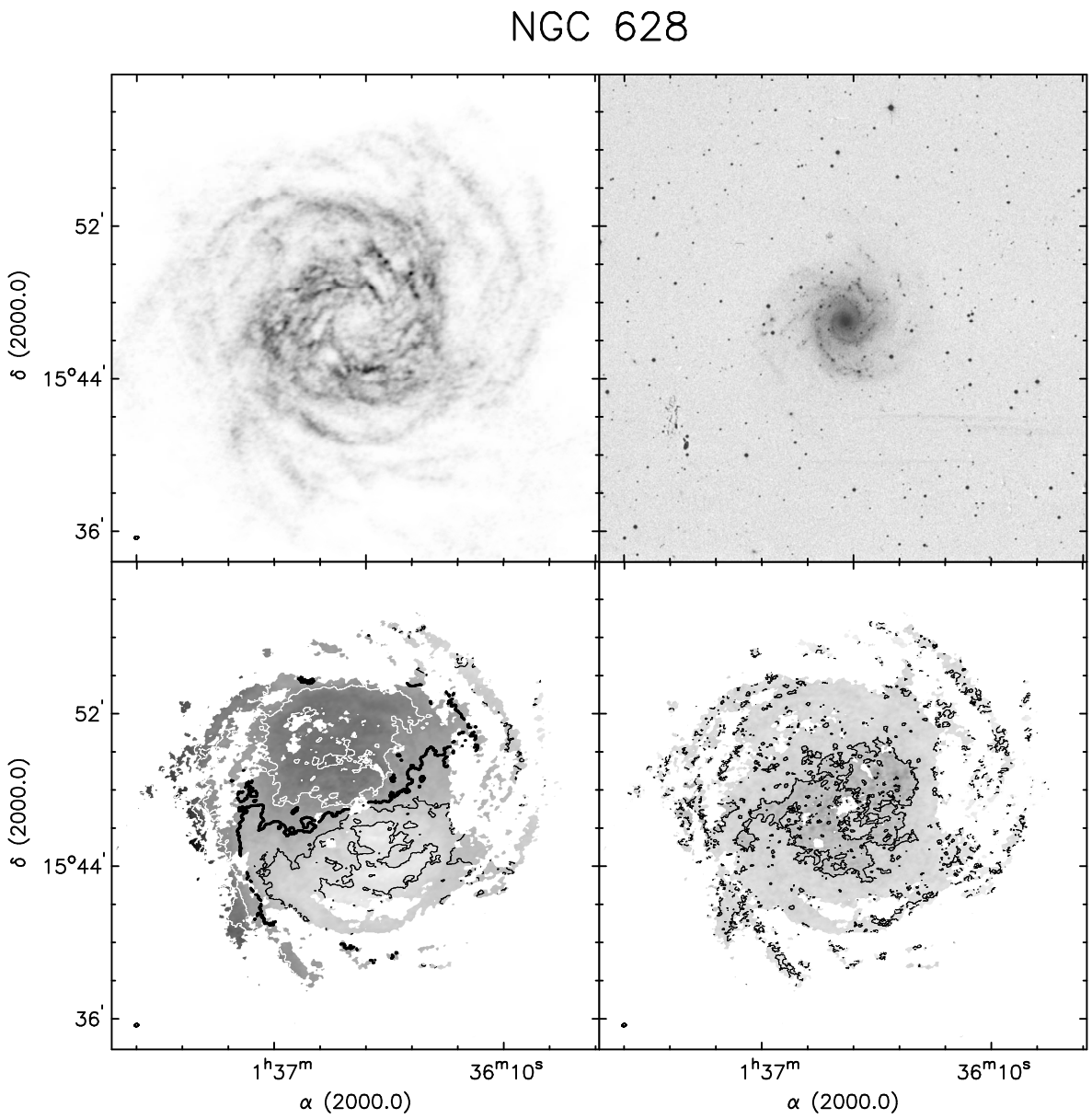
(IMPS: Inter[galactic-stellar] Medium Program of Studies)



A.M. Wolfe (UC San Diego)

S. Herbert-Fort (Arizona)

21cm HI Maps



THINGS: Walter et al. 2008

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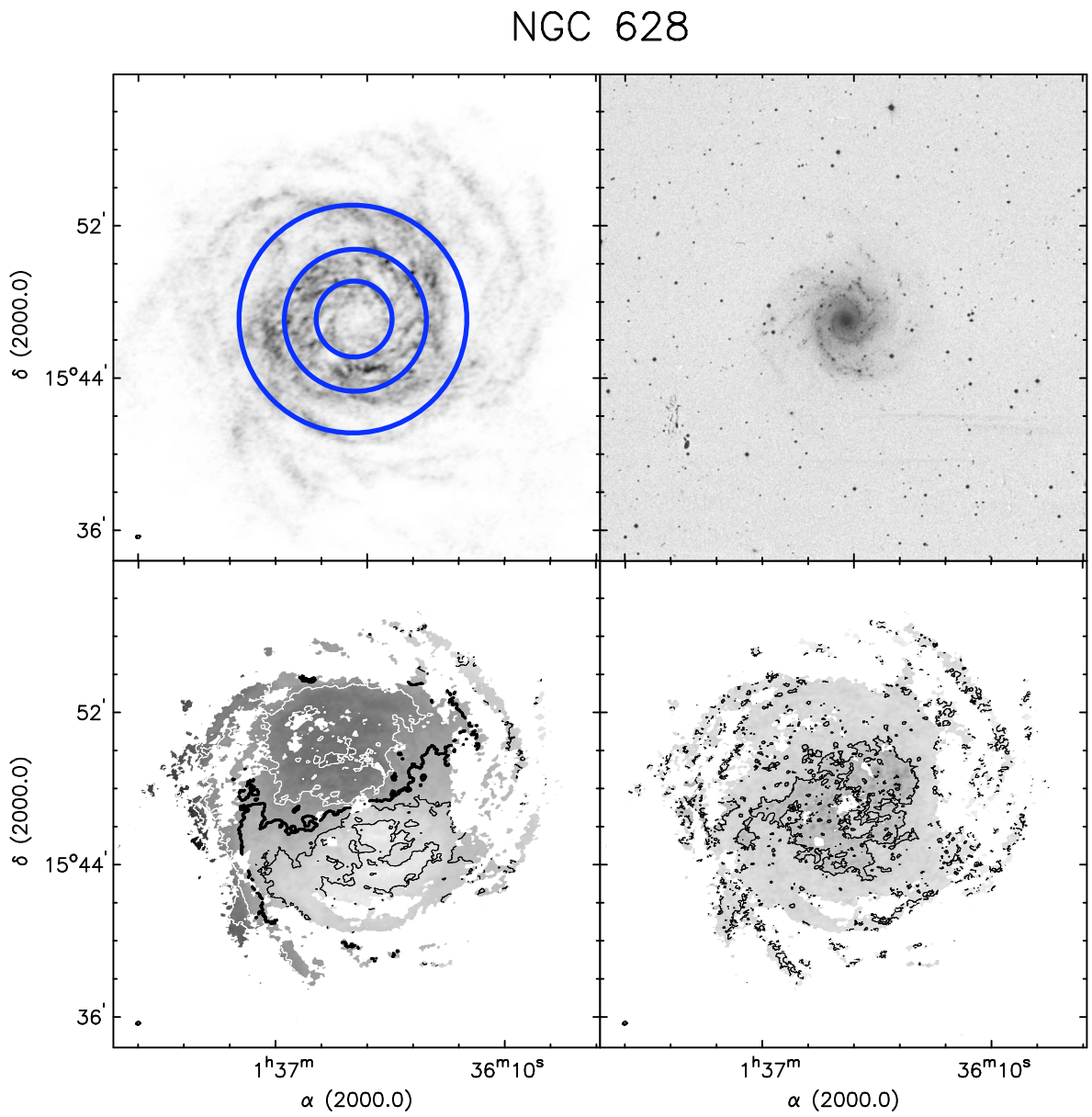
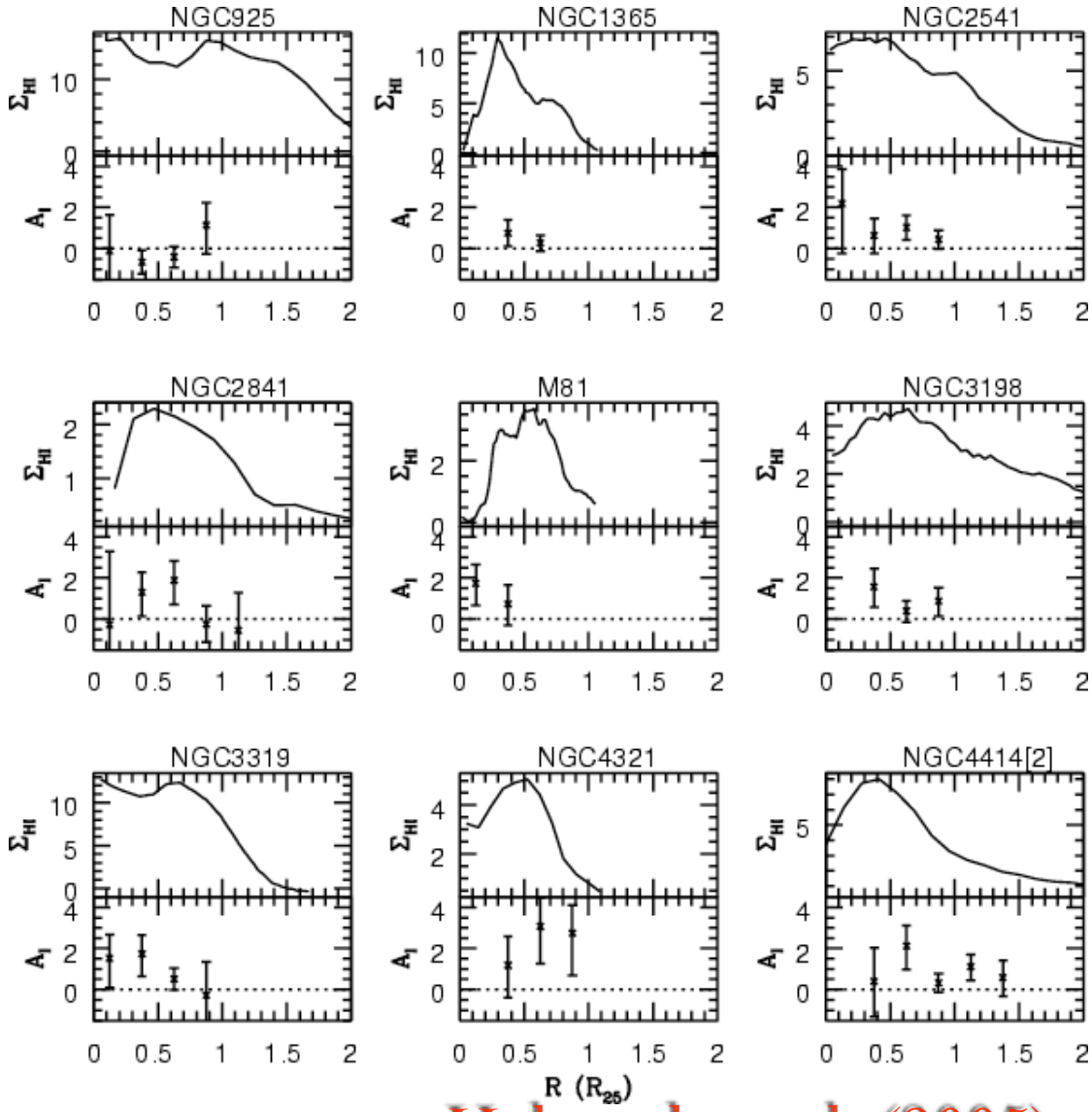


THINGS: Walter et al. 2008

Galactic Σ_{HI} Profiles

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



Holwerda et al. (2005)

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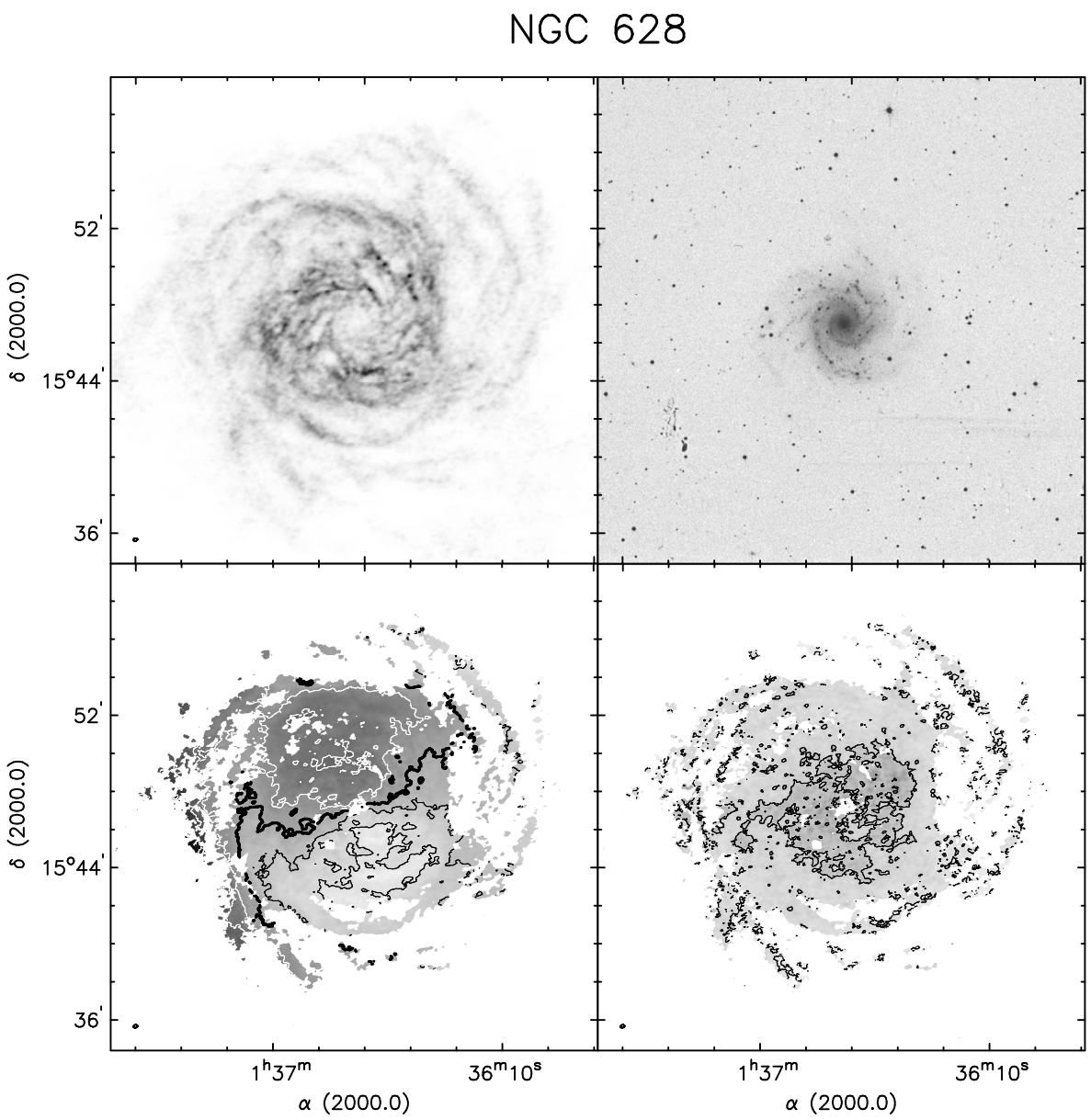

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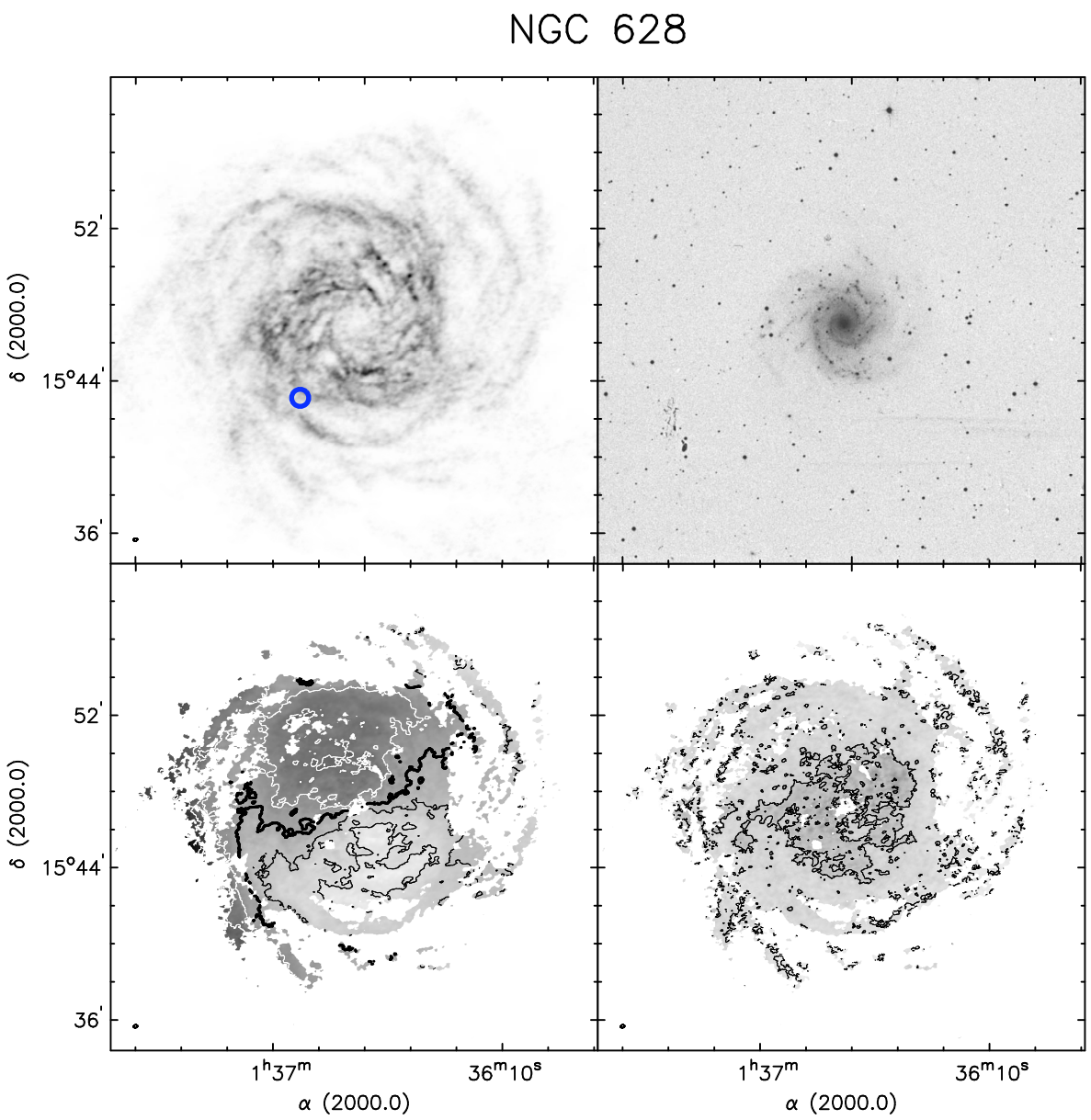

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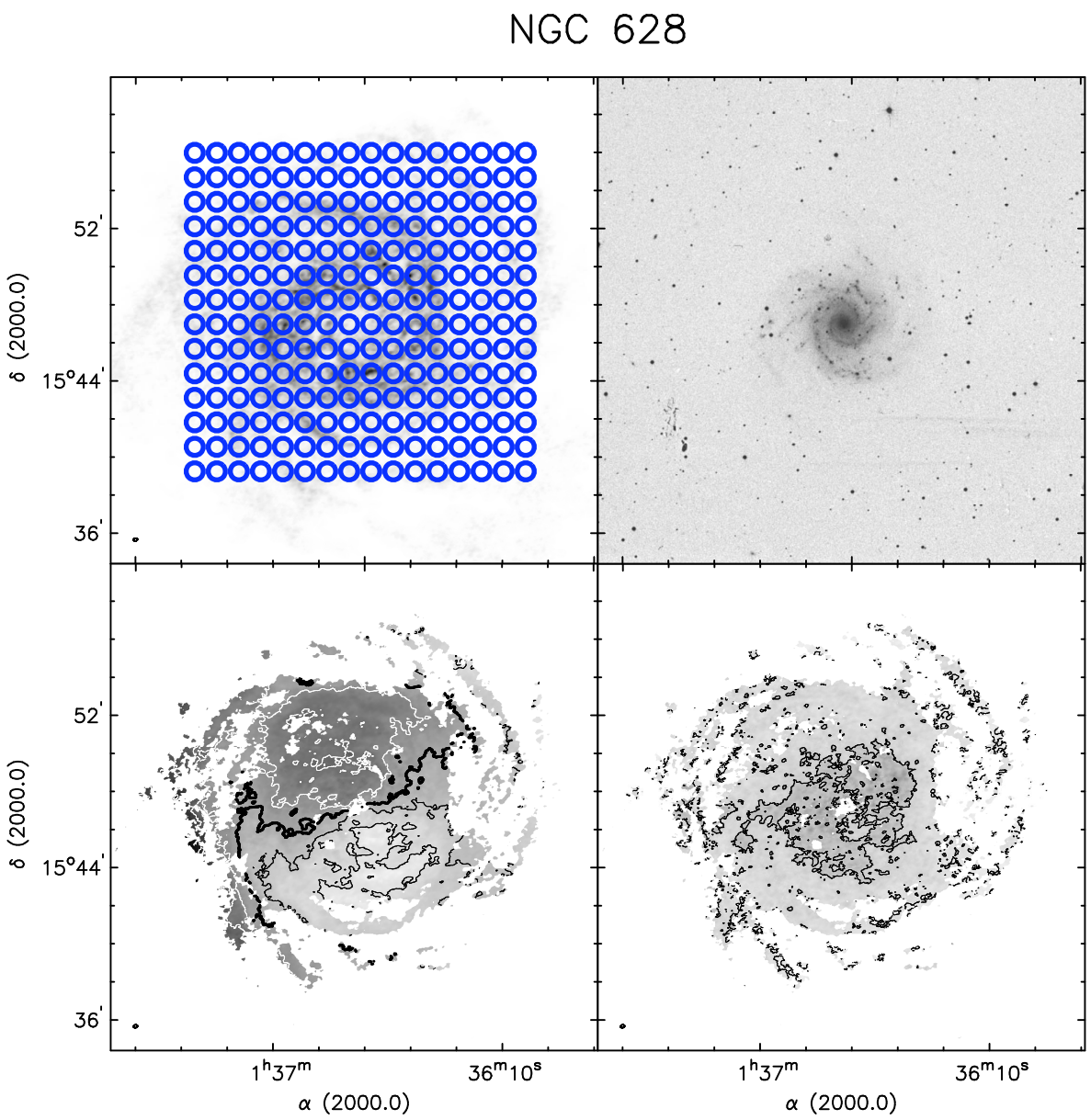
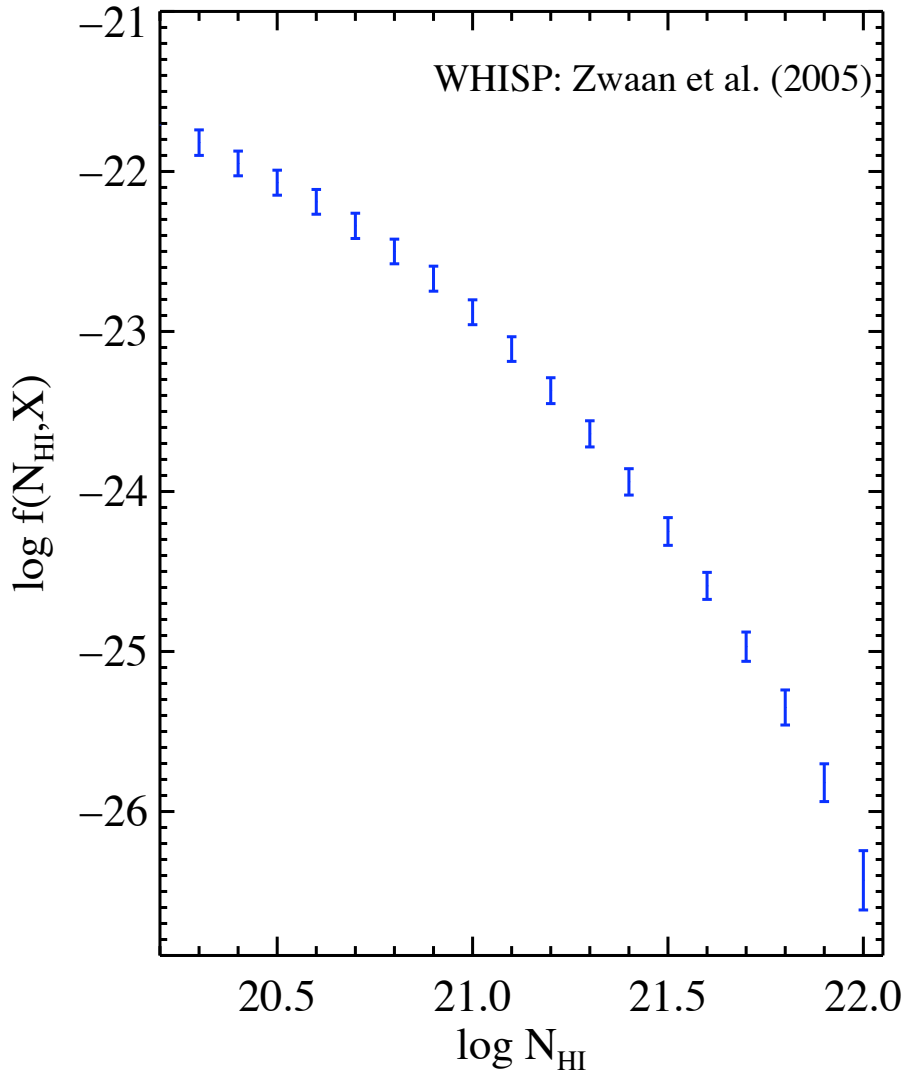


THINGS: Walter et al. 2008

$f(N_{HI})$: Frequency Distribution

- **Observations/Analysis**
  - High spatial resolution, 21cm maps of individual galaxies
  - Recover one N_{HI} value for each spatial resolution element
  - No de-projection
- **Extrapolate to "all galaxies"**
  - Convolve with Φ(L)
  - Normalize by the co-moving volume of Φ(L)
    - Actually, normalize to the co-moving mass density of HI at z=0

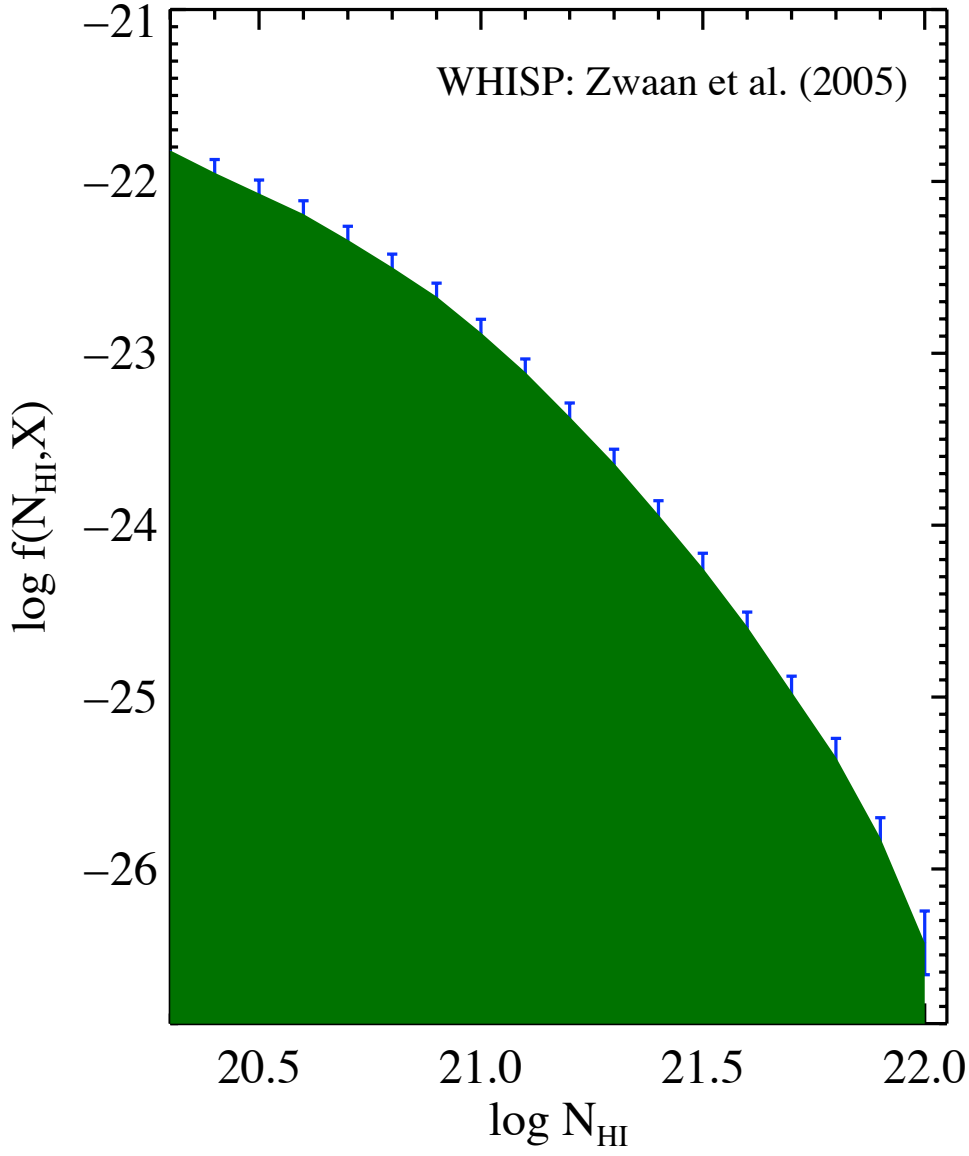


Zeroth Moment of $f(N_{HI})$: l(X)

- **Area under the $f(N_{HI})$ curve**
  - Number of galaxies intersected per pathlength travelled
  - Often denoted dN/dX or dn/dz

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

- **z=0 result**
  - l(X) = 0.046 +/- 0.002
  - One intersects a galaxy with $N_{HI} > 2 \times 10^{20}$ cm^{-2} every 100 Gpc
- **Covering fraction**
  - I view l(X) as how galaxies cover the sky, in projection



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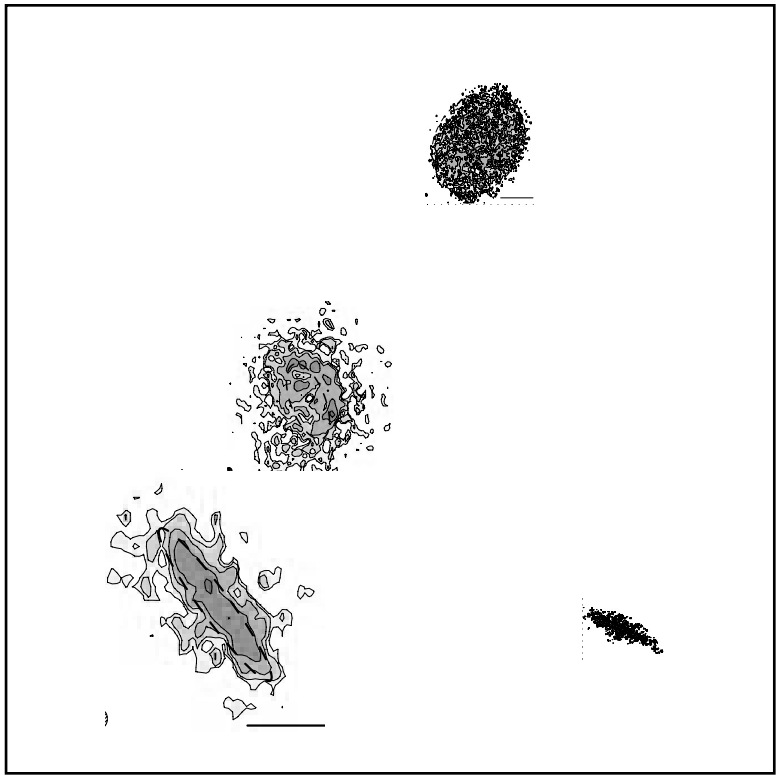

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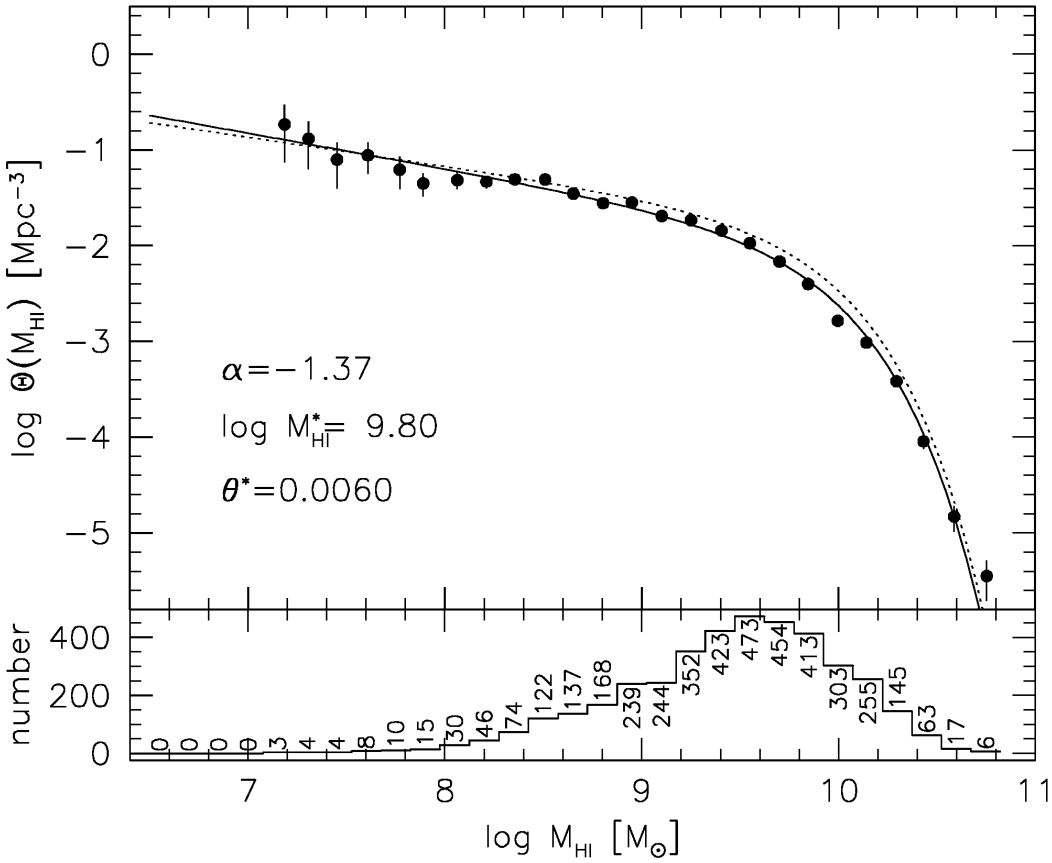
First Moment of $f(N_{HI})$: ρ_{HI}

- Integrate: $N_{HI}\, f(N_{HI})\, dN_{HI}$
  - Comoving HI mass density

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

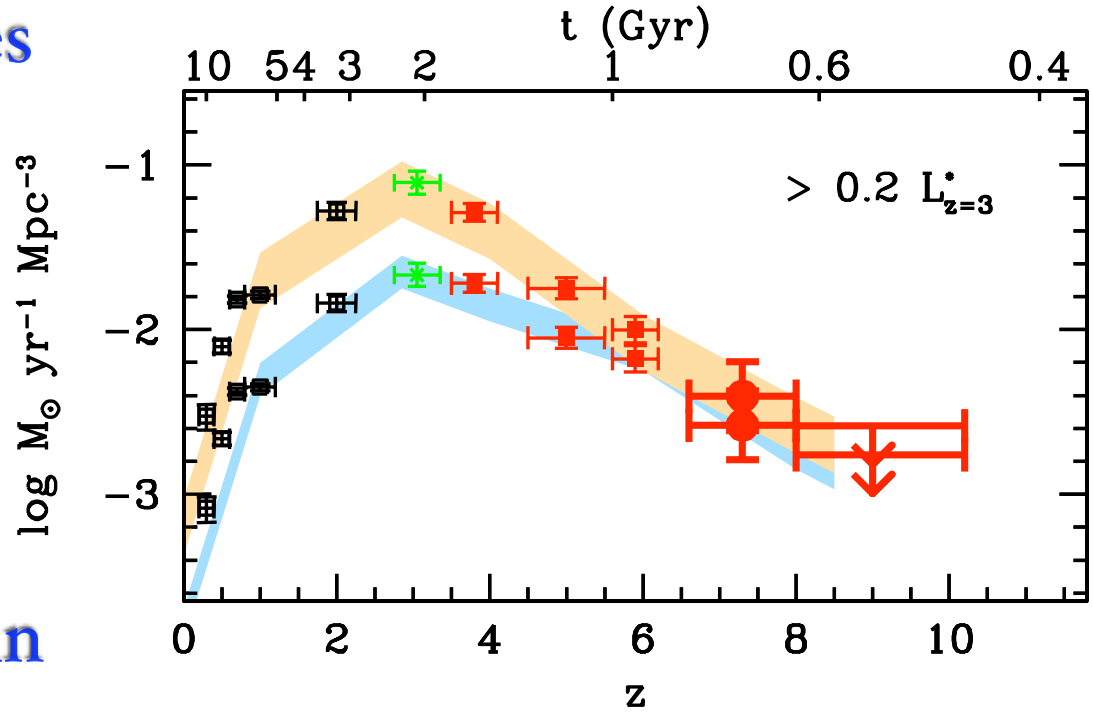
- Actual measurement of ρ_{HI} at z=0 is from the HIMF
  - All sky survey for HI galaxies
  - Construct an HI mass function
  - Integrate
- Value at z=0
  - $\varrho_{HI} = (0.52 +/- 0.07)\ 10^8\ M_{sun}\ Mpc^{-3}$

HIPASS: Zwaan et al. 2005



Cosmic Evolution of HI in Galaxies

- How does HI gas in galaxies evolve with time?
- Are galaxies smaller in the past, e.g. lower l(X)?
- Are galaxies more gas rich in the past, e.g. higher ρ_{HI}?



Bouwens et al. 2008

Probing HI Gas at High z

- 21cm?
  - Not with today's telescopes
  - Limit is z~0.2
  - EVLA?
- Hα, Lyα emission
  - Difficult observations
  - Traces 'special' galactic regions
  - Tough to convert to HI mass
- Lyα absorption
  - Simple counting of atoms
  - Need a background source

Lah et al. 2007

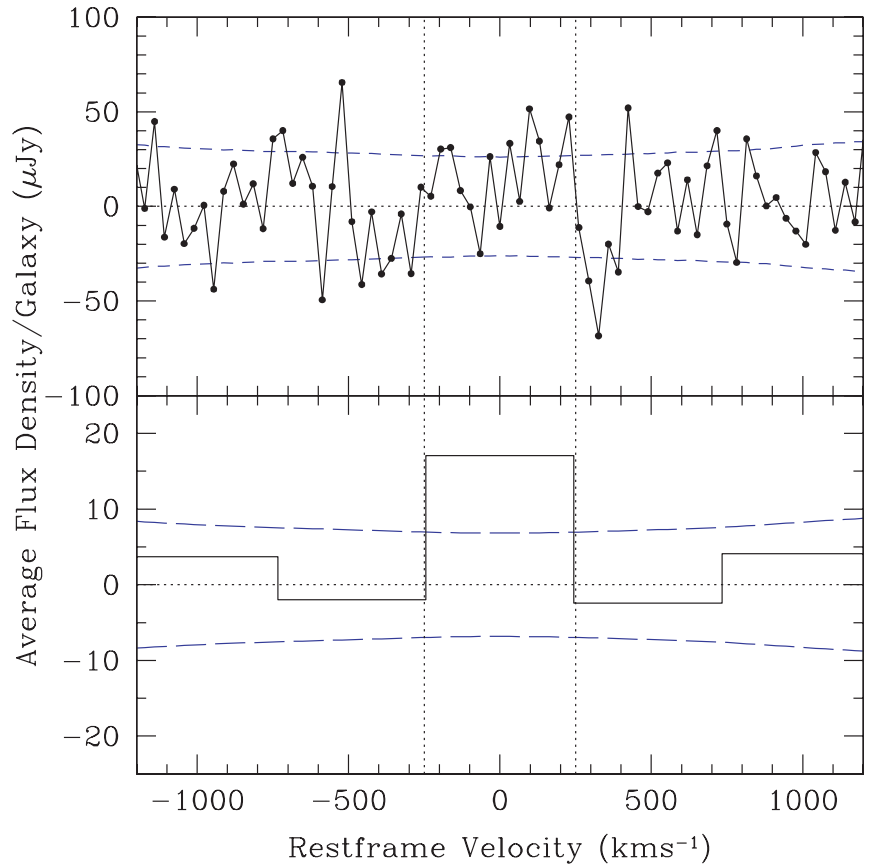


Figure 7. The average H I galaxy spectrum created from co-adding the signal of all 121 galaxies with known optical redshifts. The top spectrum has no smoothing or binning and has a velocity step size of 32.6 km s^{-1}. The bottom spectrum has been binned to ~500 km s^{-1}. This is the velocity width that the combined H I signal of the galaxies is expected to span. For both spectra the 1σ error is shown as dashed lines above and below zero.

Probing HI Gas at High z

Shapiro et al. 2008

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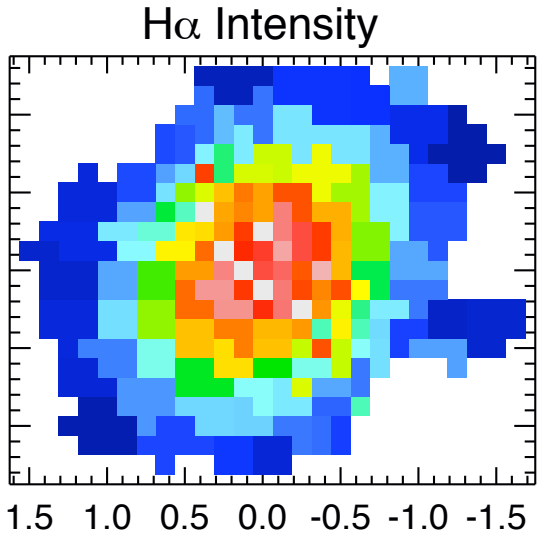
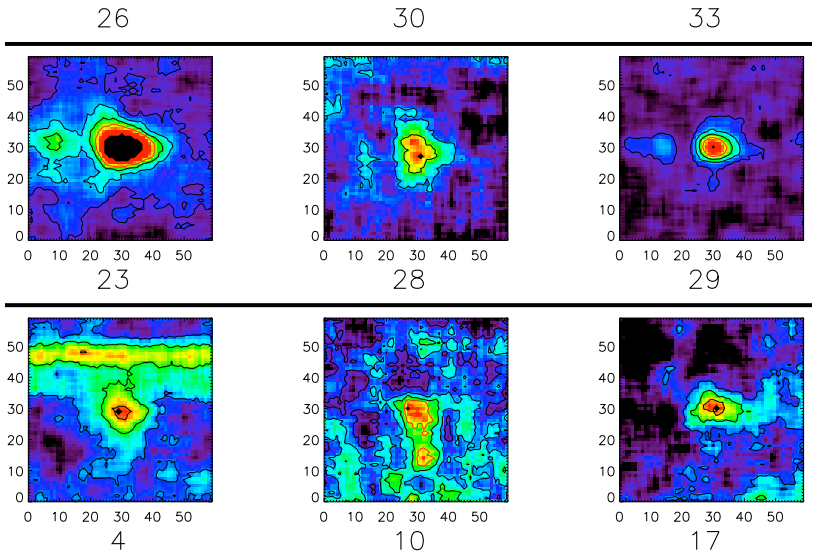
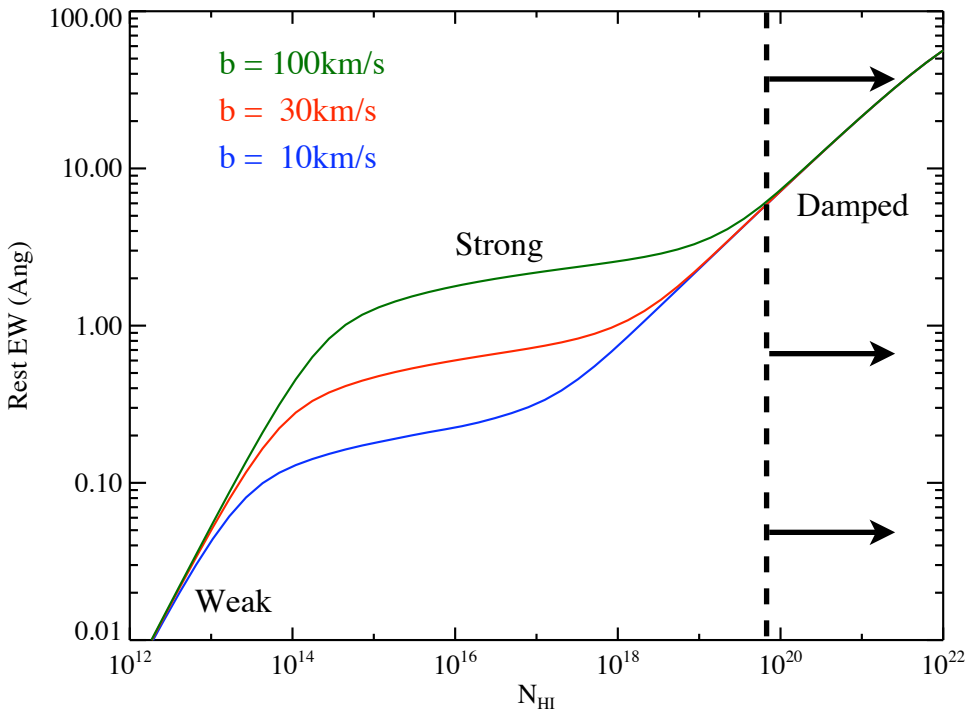




Rauch et al. 2008

Damped Lyα Absorption

- Σ_{HI}=1 M_{sun}/pc^2 is $N_{HI}=10^{20}$ cm^{-2}
  - Optical depth: $\tau^0_{\mathrm{Ly}\alpha} = 7.5 \times 10^6 \frac{N_{\mathrm{HI}}}{10^{20}\ \mathrm{cm}^{-2}}$
  - Damped absorption (Wolfe et al. 1986)
- Experiment: QSO spectroscopy
  - Single shot through one galaxy
  - Repeat experiment to build a sample
  - GRBs work too (e.g. Chen et al. 2005)
- Survey DLAs: SDSS
  - N_{HI} >= 2 x 10^{20} cm^{-2}
    - DR5 -- 1000 DLAs surveyed
    - z=2.2 to 5
  - Hand-fitted Lyα profiles



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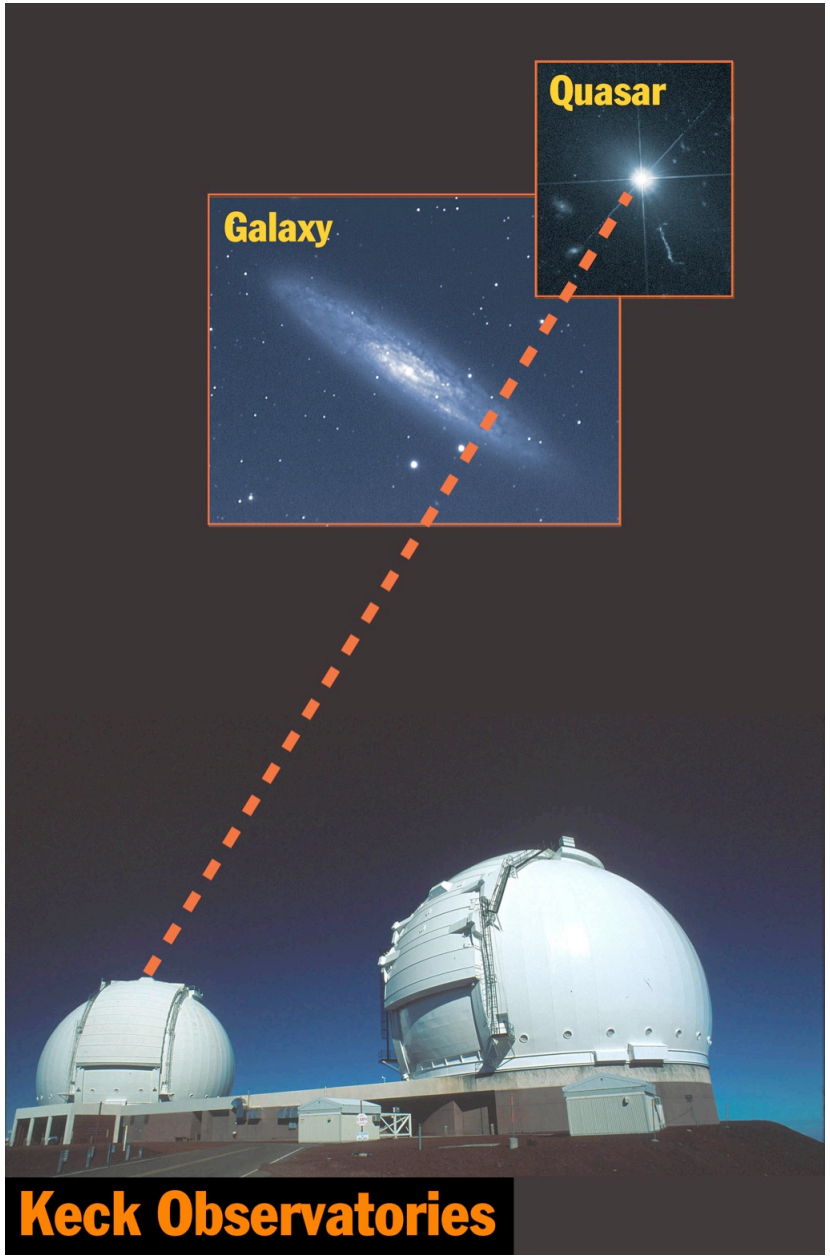

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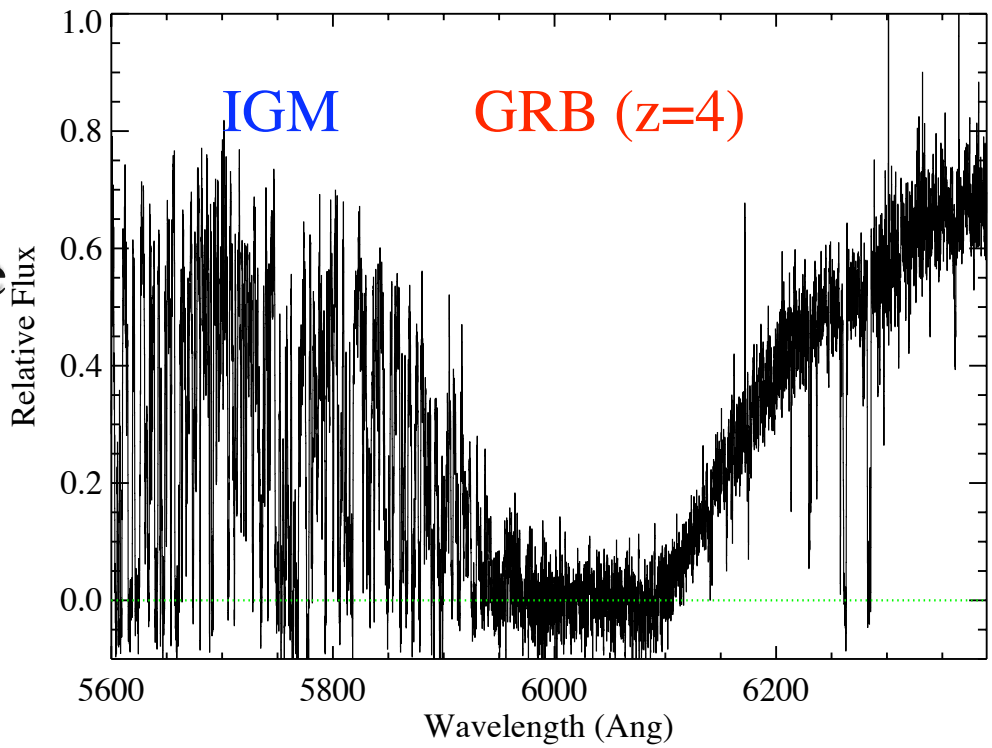

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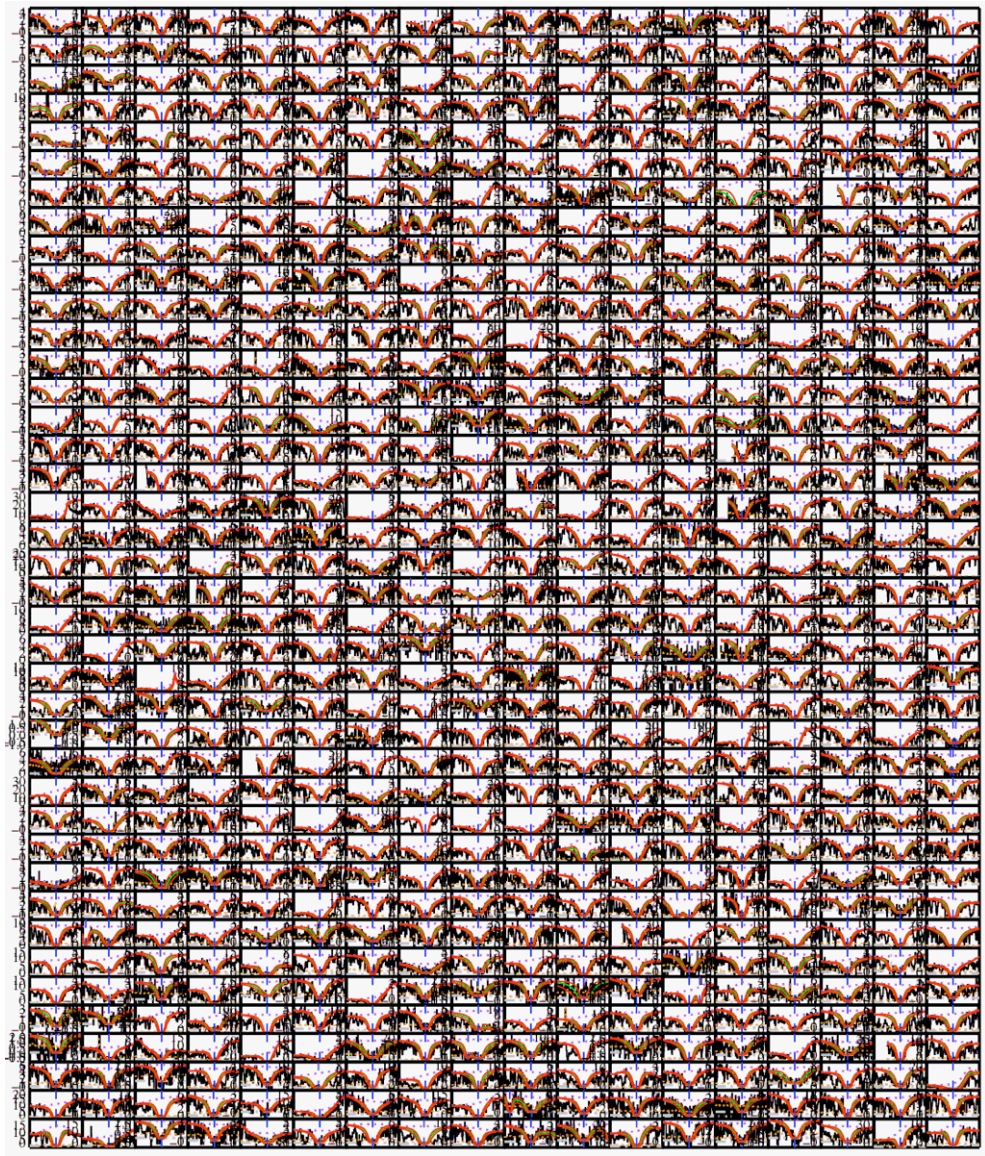
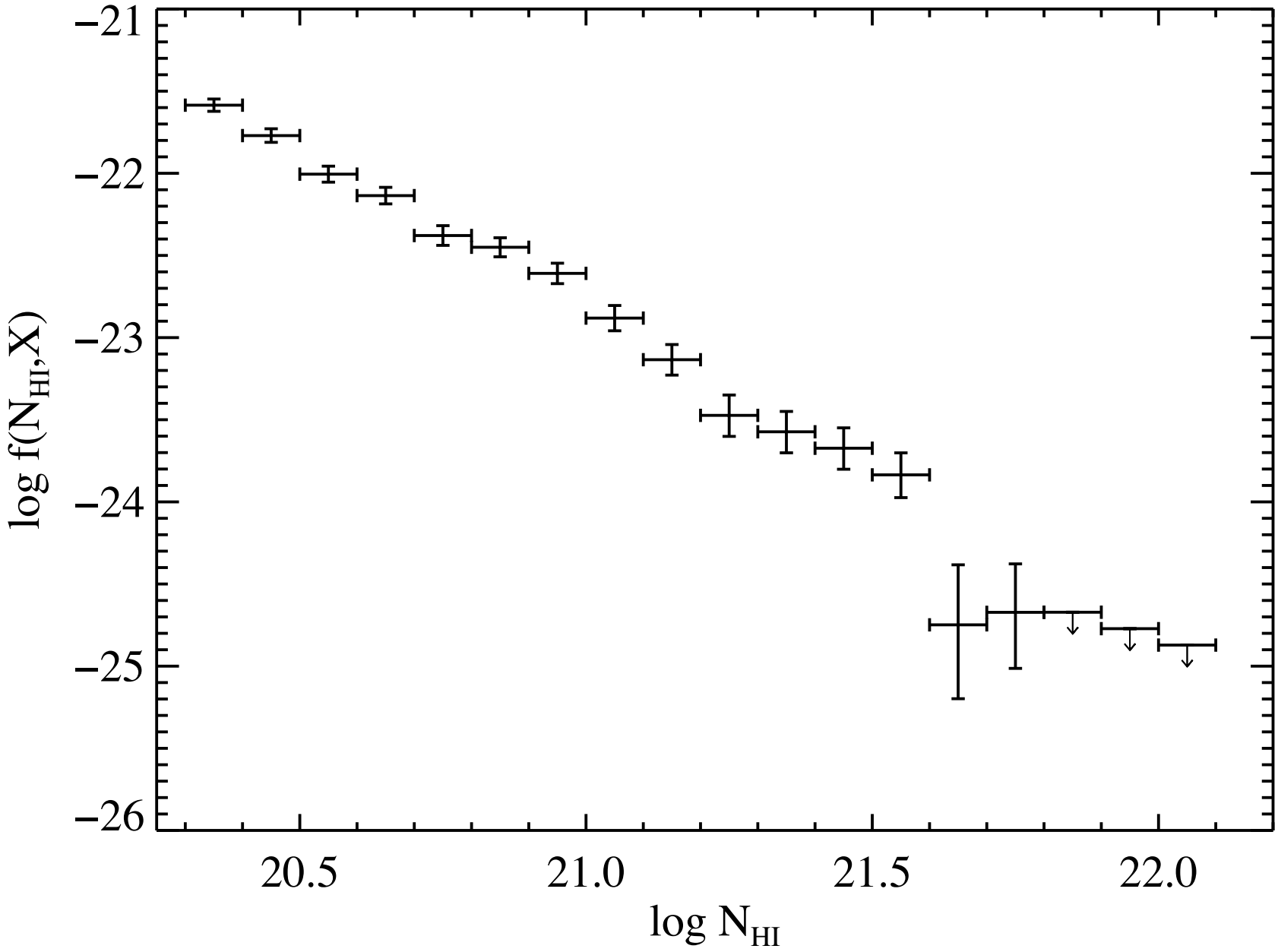


$f(N_{HI})$ at z~3



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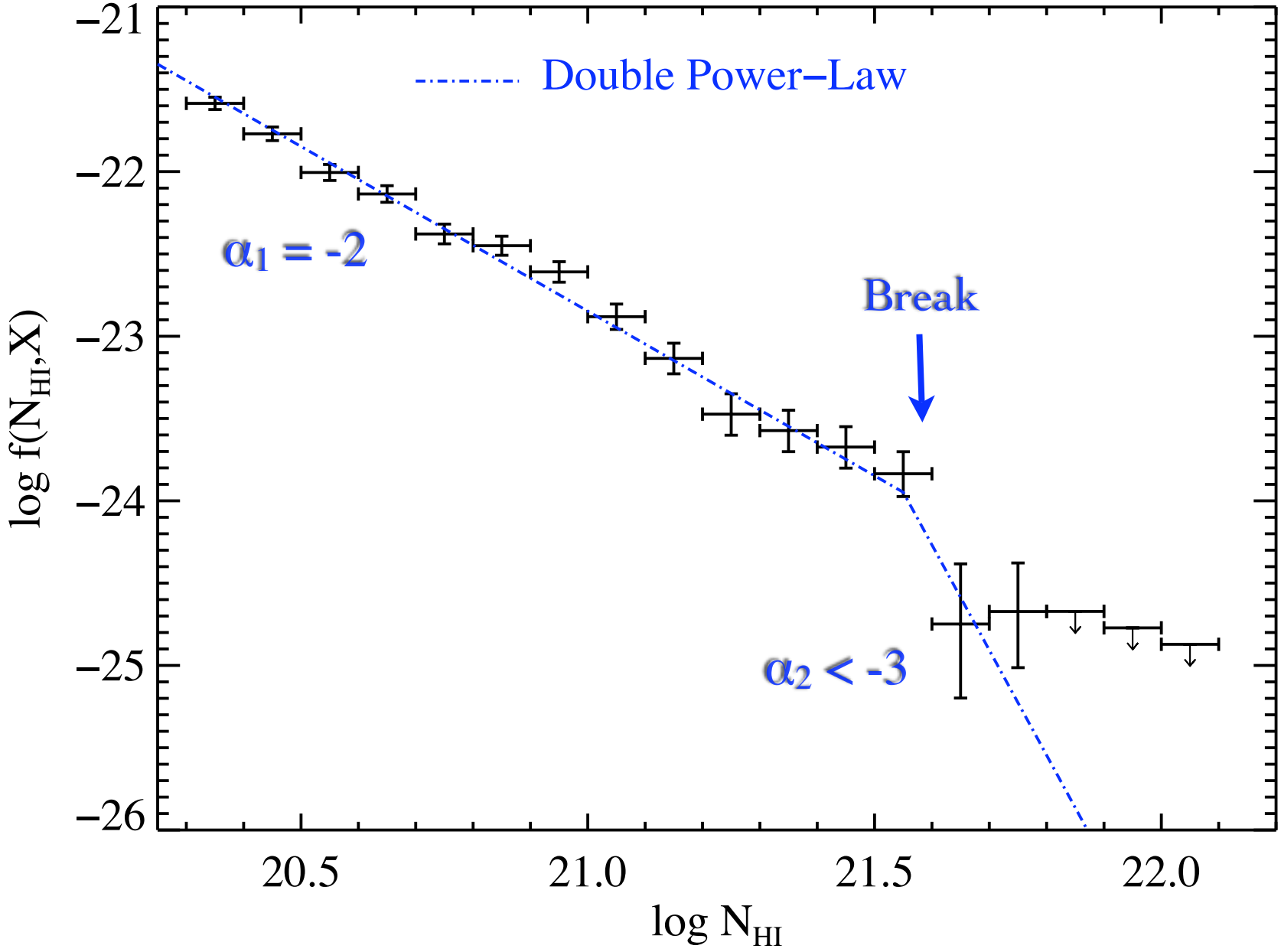
Double Power–Law
$\alpha_1 = -2$
Break
$\alpha_2 < -3$
log f(N_HI,X)
log N_HI
−21
−22
−23
−24
−25
−26
20.5
21.0
21.5
22.0

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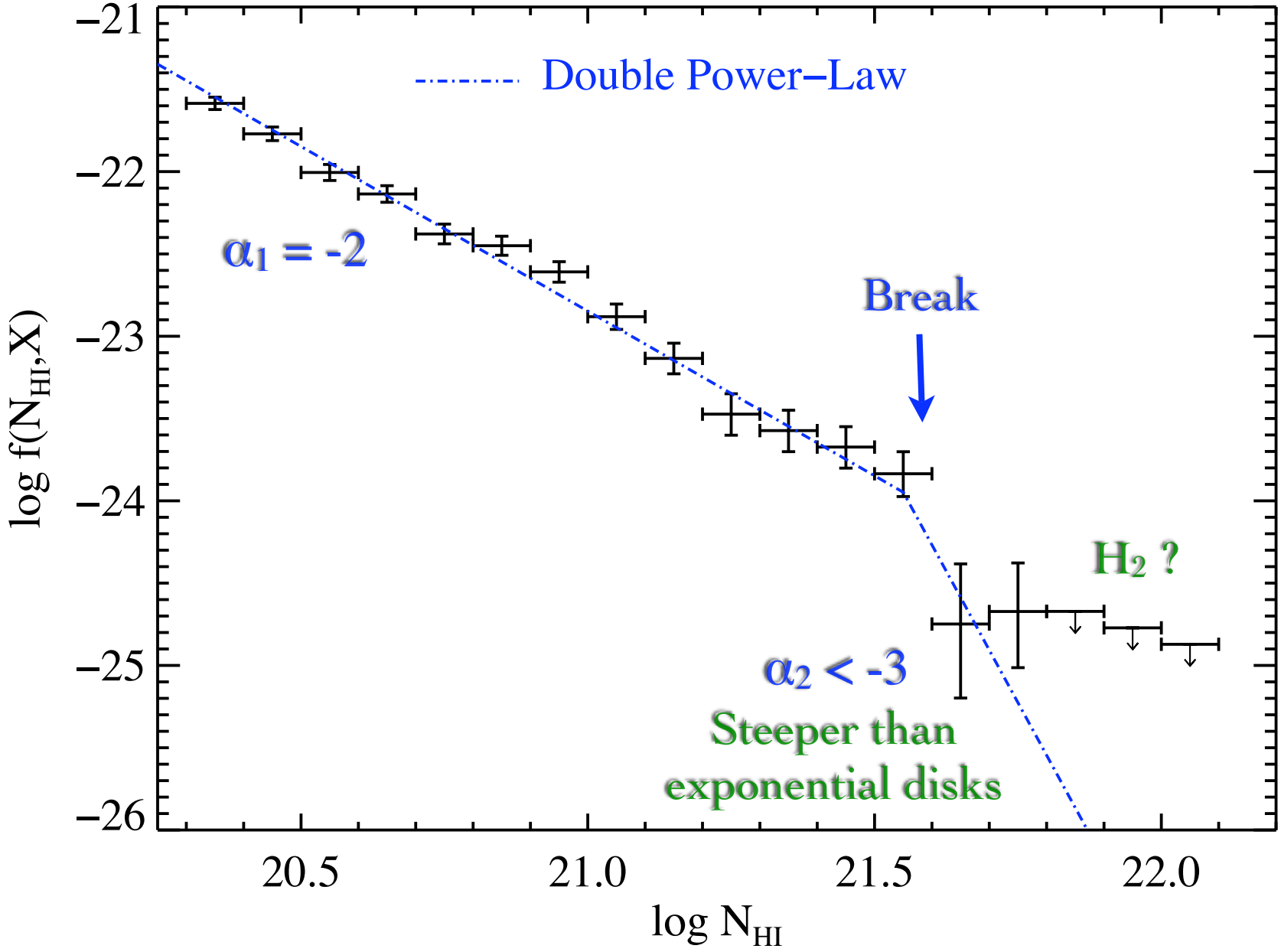
Double Power–Law
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Break
H_2 ?
$\alpha_2 < -3$
Steeper than
exponential disks
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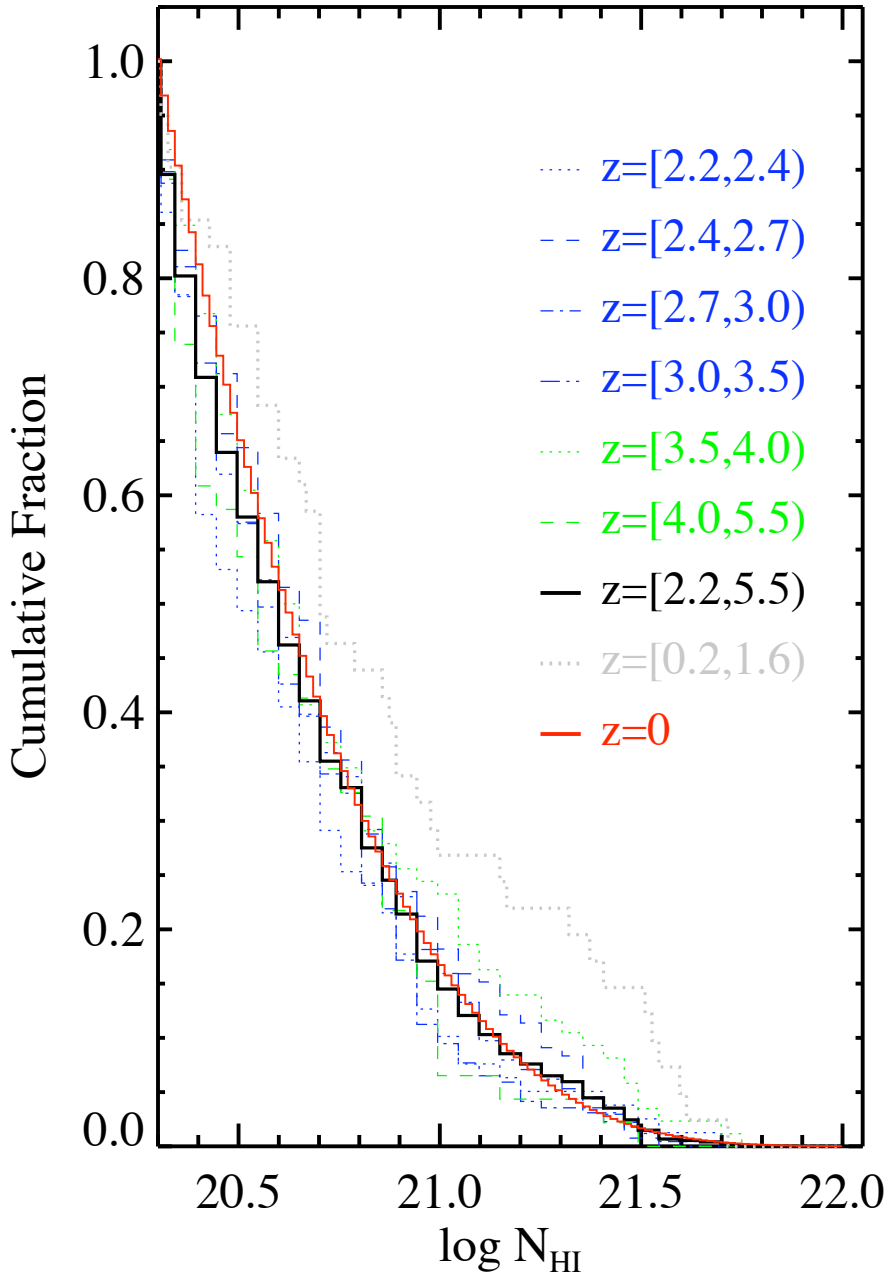
Non-Evolution in the Shape of $f(N_{HI})$

- **z= 2 to 4**
  - KS test gives $P_{KS} > 10\%$
  - Over these few Gyr, HI gas is distributed in a self-similar fashion
    - Especially at low N_{HI} values
  - l(X) and ρ_{HI} must evolve together
- **z=2 vs. z=0**
  - Nearly identical distributions!
  - HI gas in galaxies at z>2 has the same projected N_{HI} as z=0 disks
    - Is HI at high z in similar disks with similar surface density profiles?
- **Inference**
  - HI has been distributed in a self-similar fashion over <u>all</u> cosmic time



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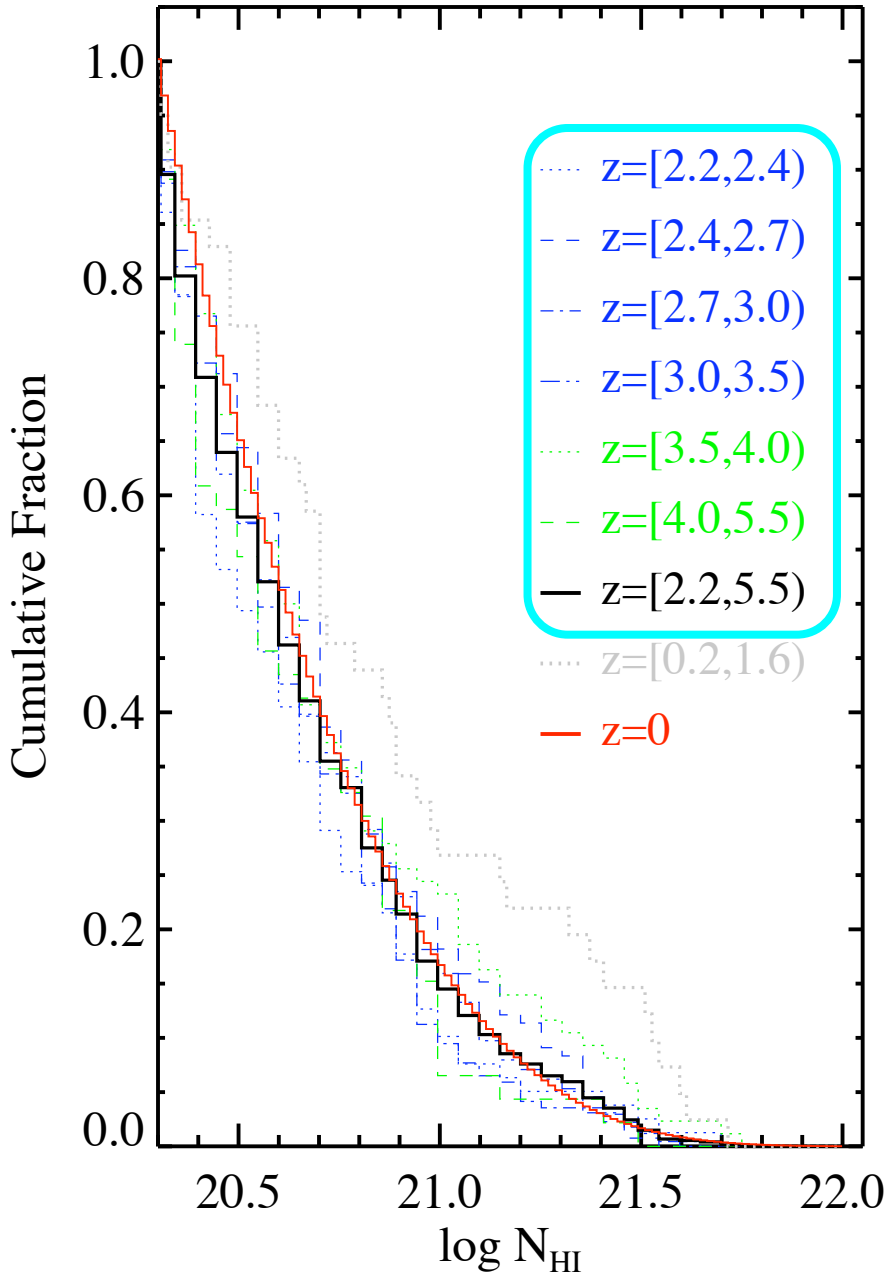

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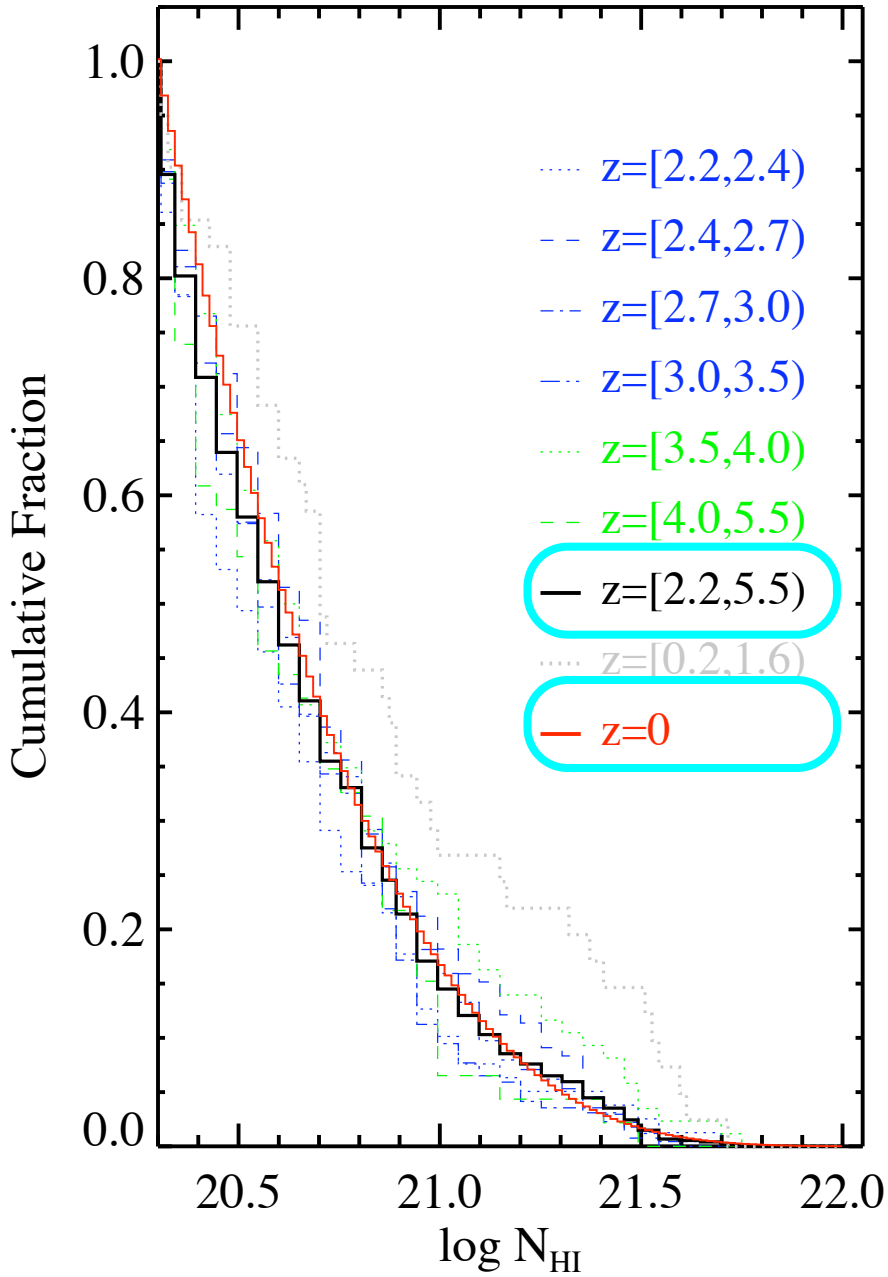

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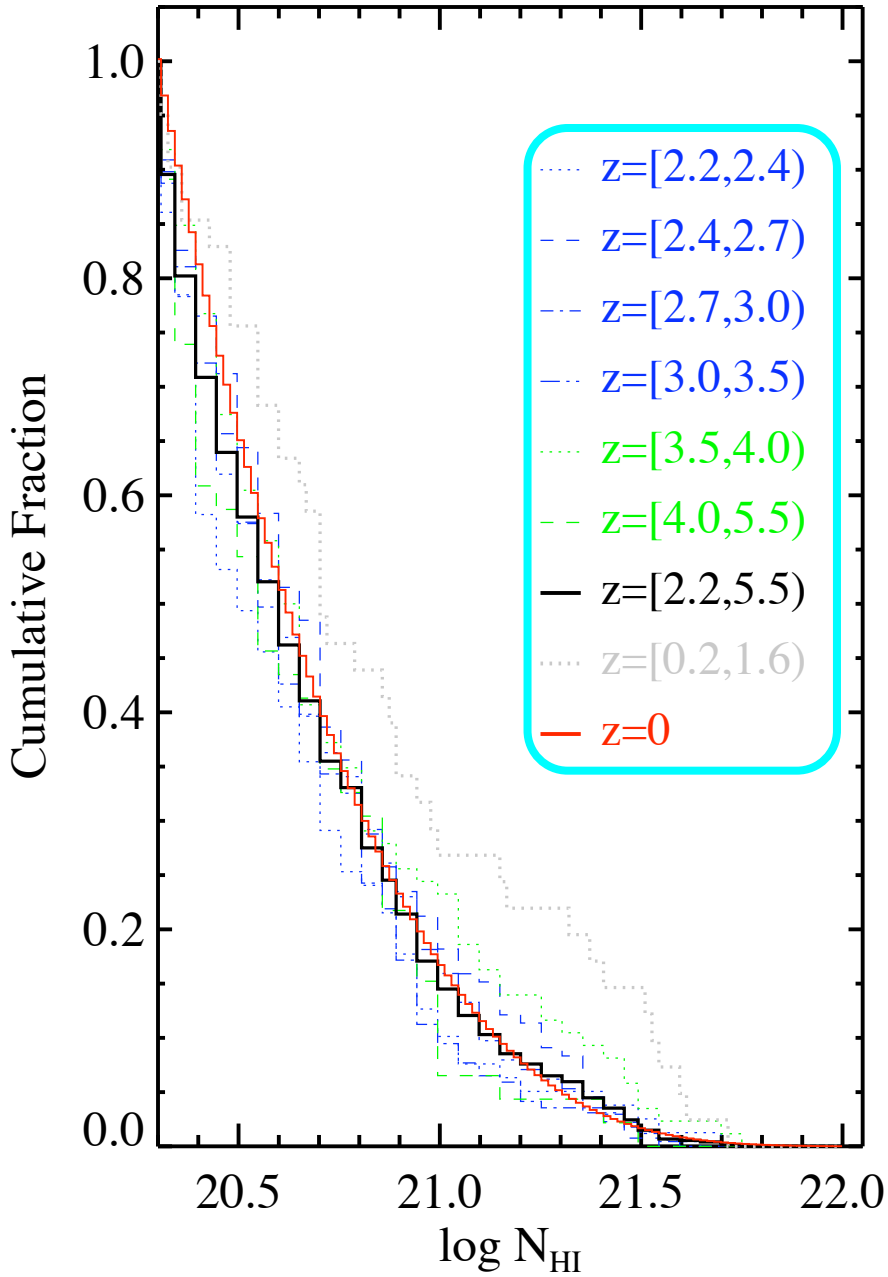

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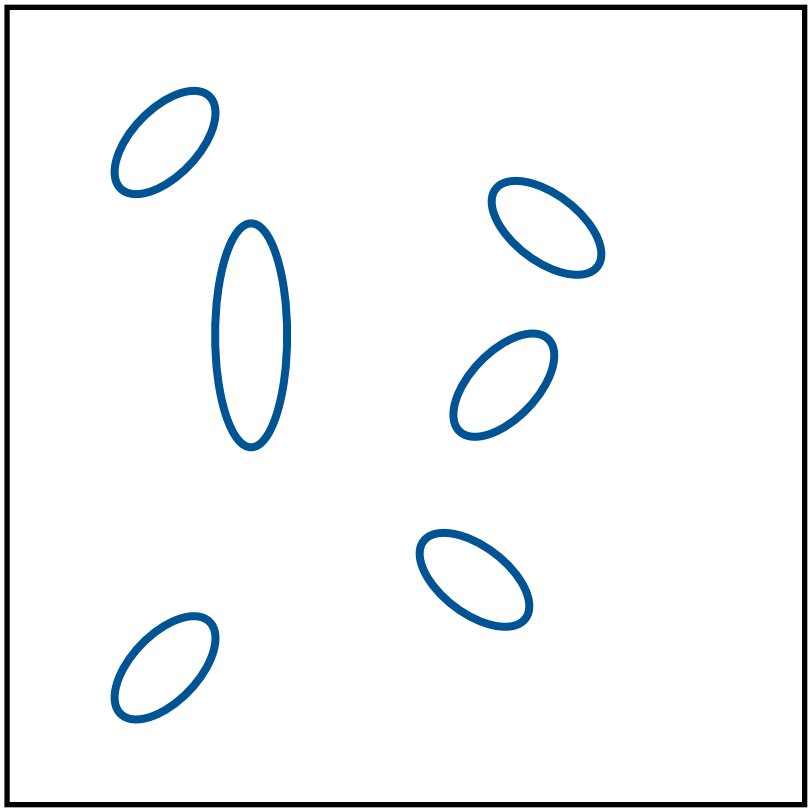
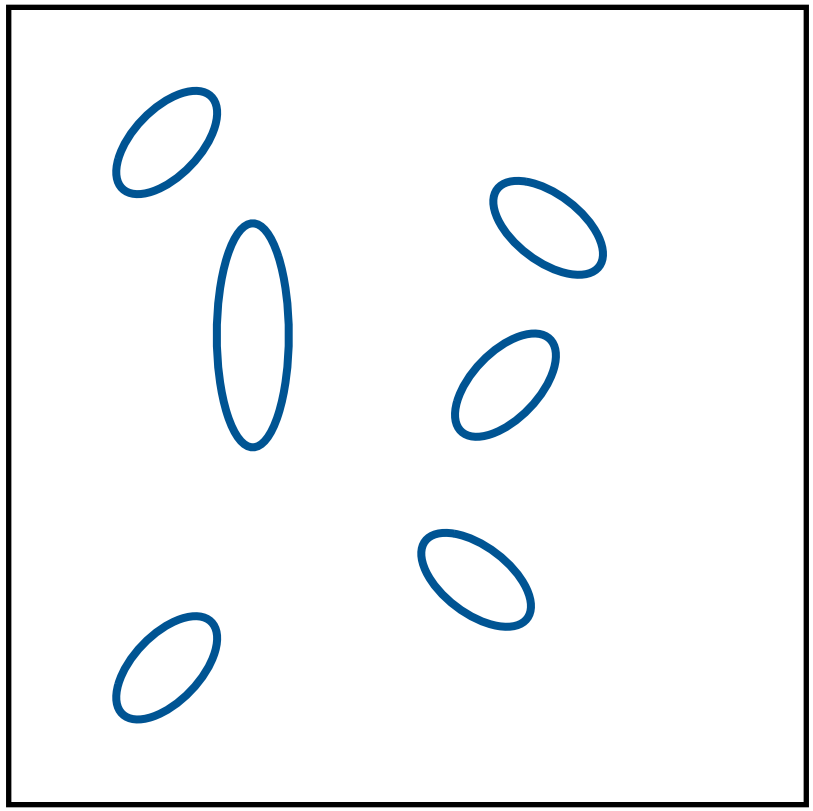


z>2



The shape does not evolve, but the normalization might.

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

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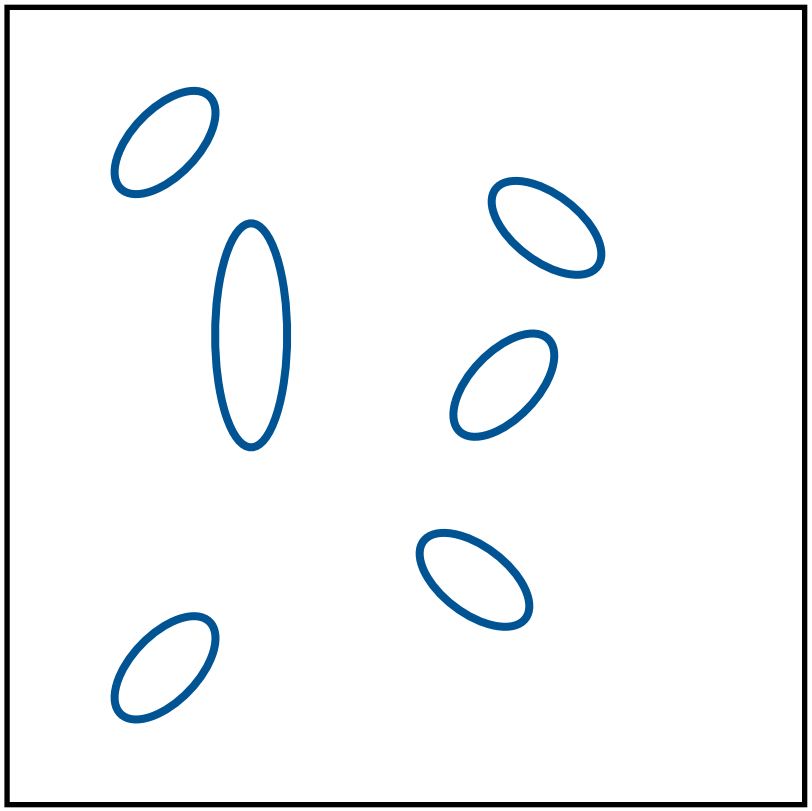

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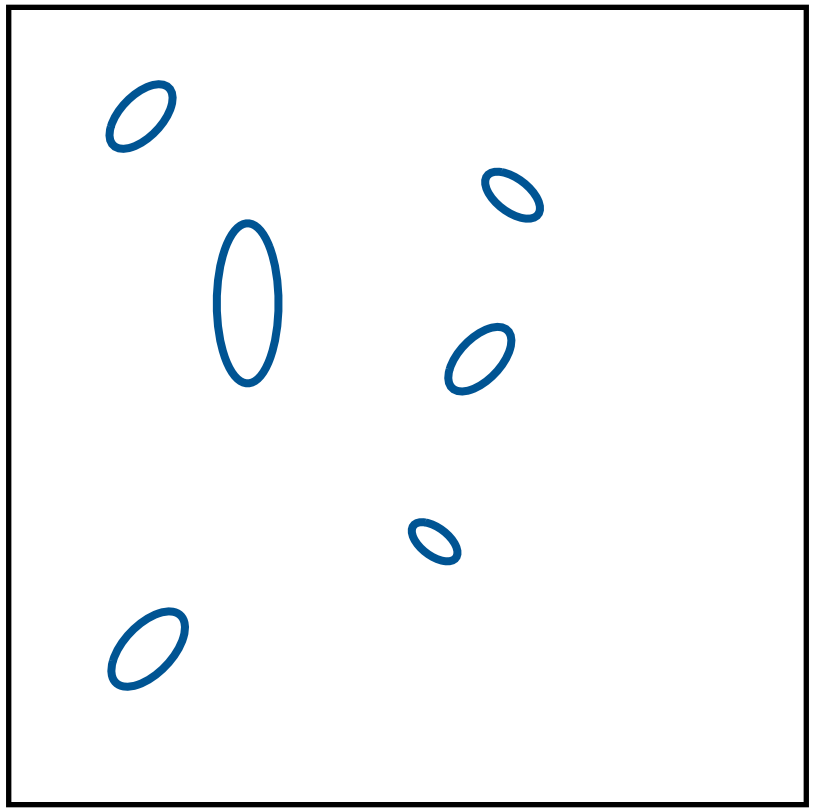

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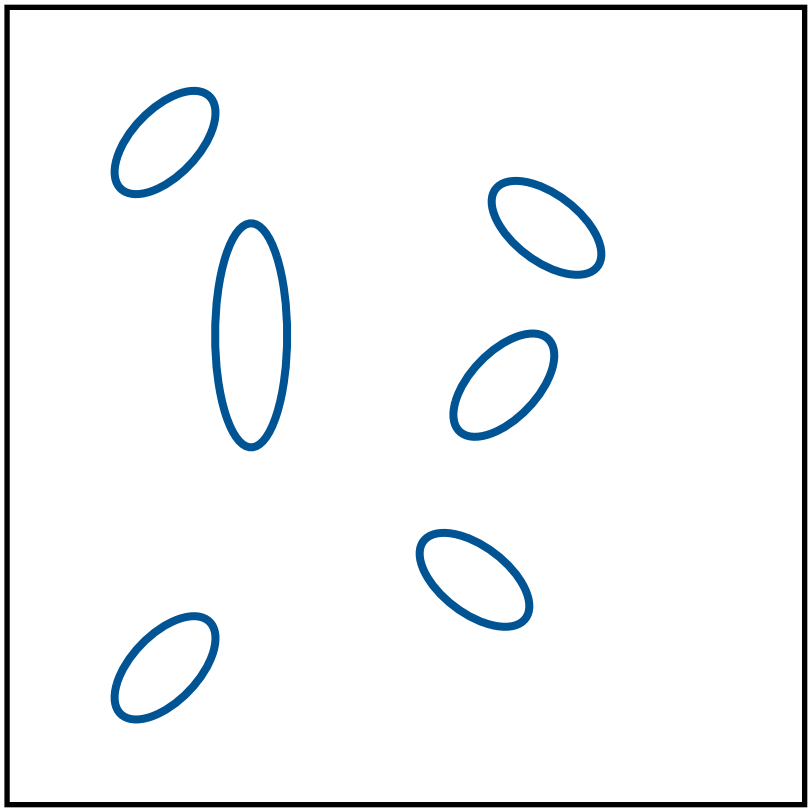

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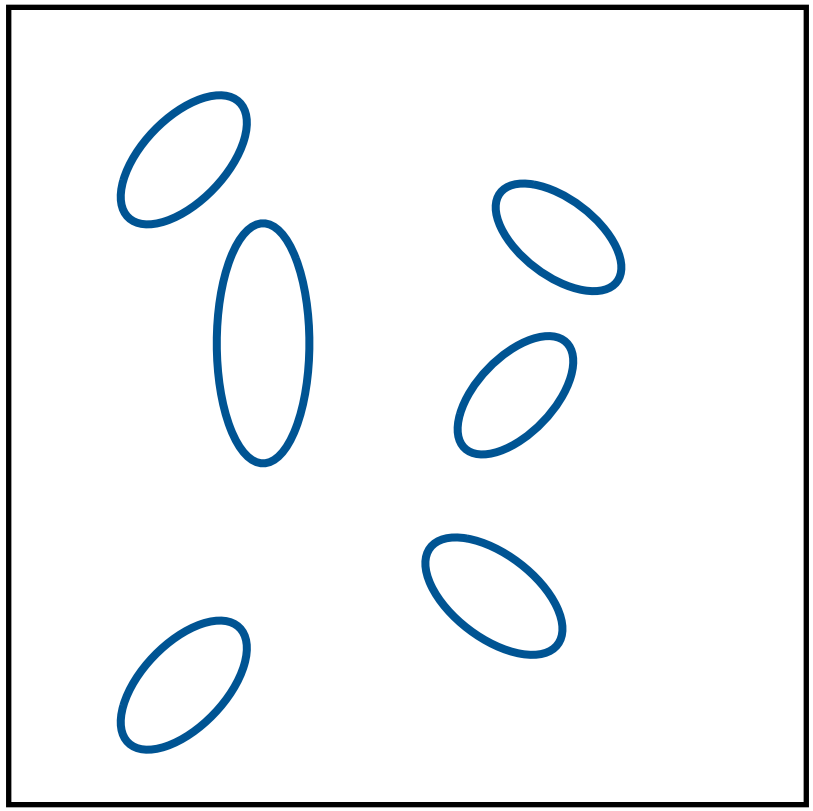

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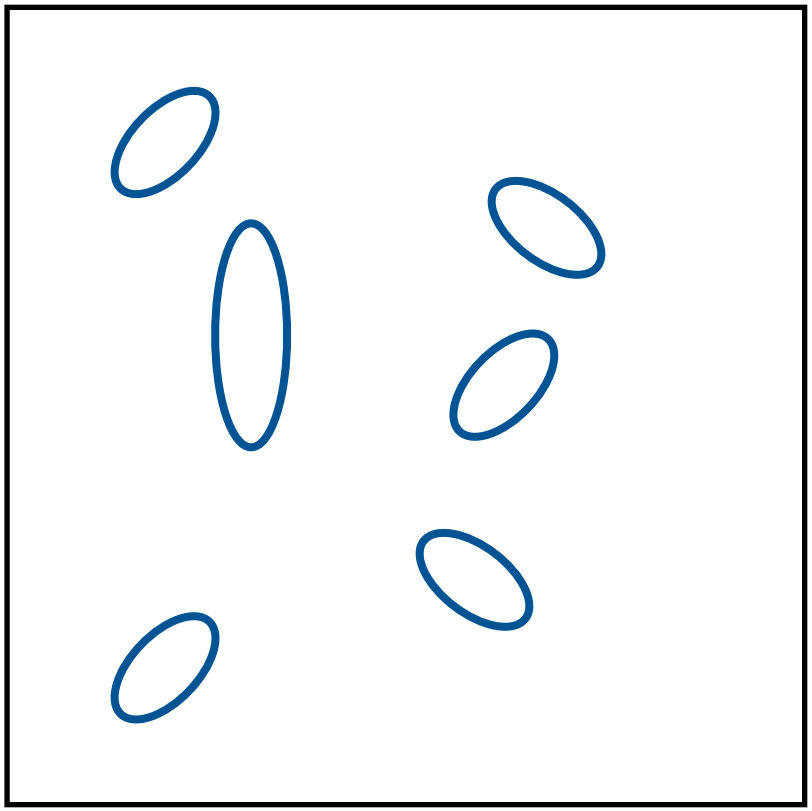

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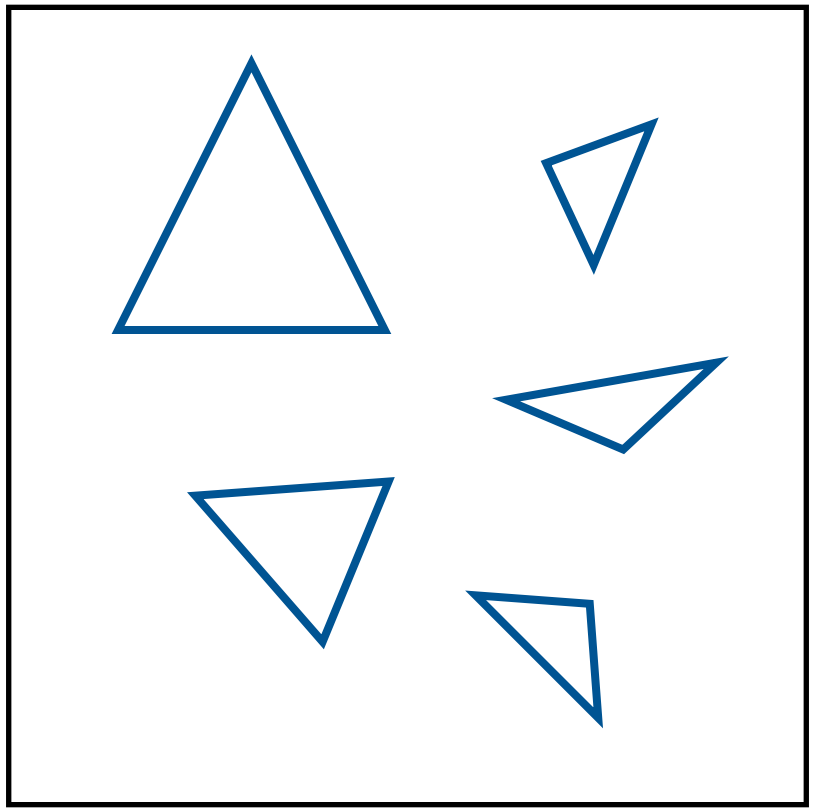

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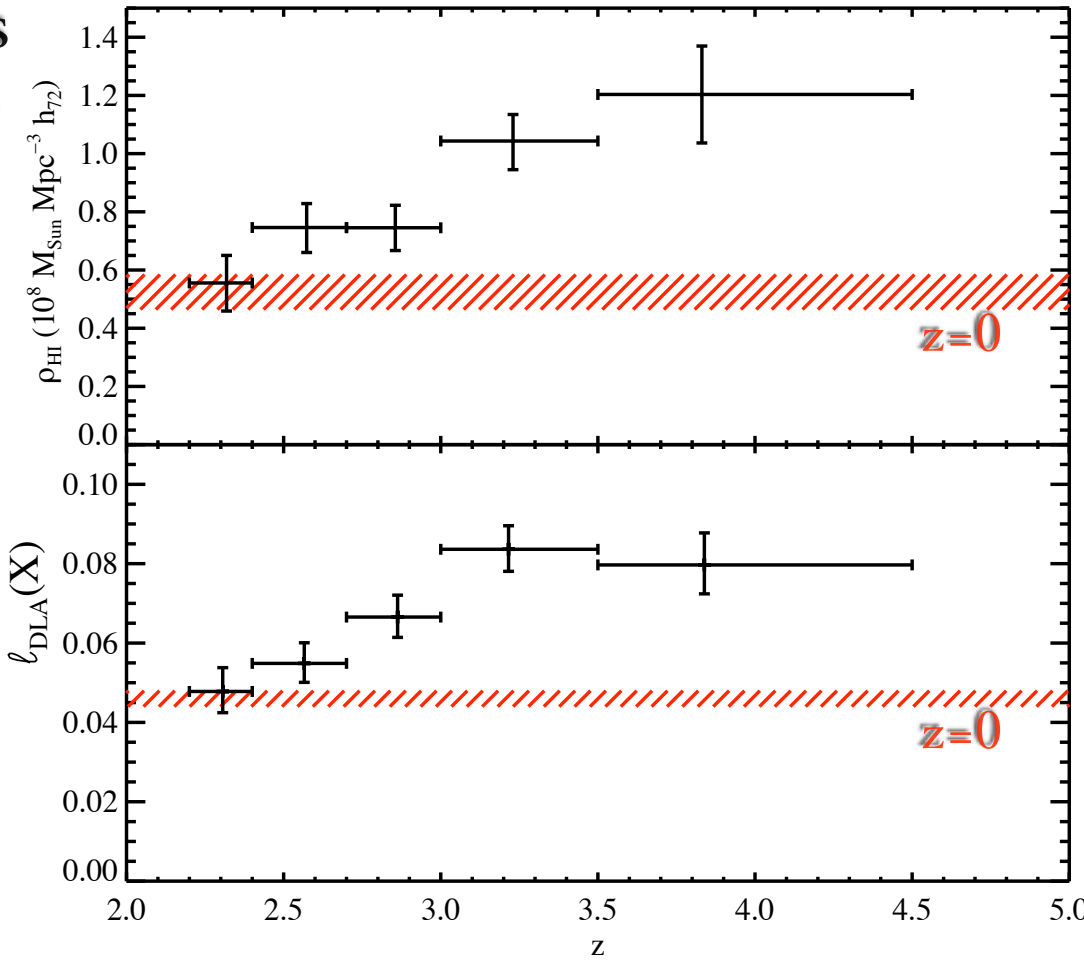
Moments of $f(N_{HI})$: z=2 vs. 0

- **Comparison**
  - $l(X)$ and ρ_{HI} match the z=0 values
  - This suggests that the values have not evolved for 10 Gyr!
- **But, we know stars form..**
  - HI gas in galaxies is a necessary but insufficient condition for SF
    - HI gas acts as a "bias level"
    - Accretion of new gas drives the SFR
- **Don't galaxies evolve?**
  - Yes, but in LCDM galactic-sized halos are 'frozen in' by z=2
  - Galaxies as a population maintain the same HI gas distribution
    - In shape and absolute value



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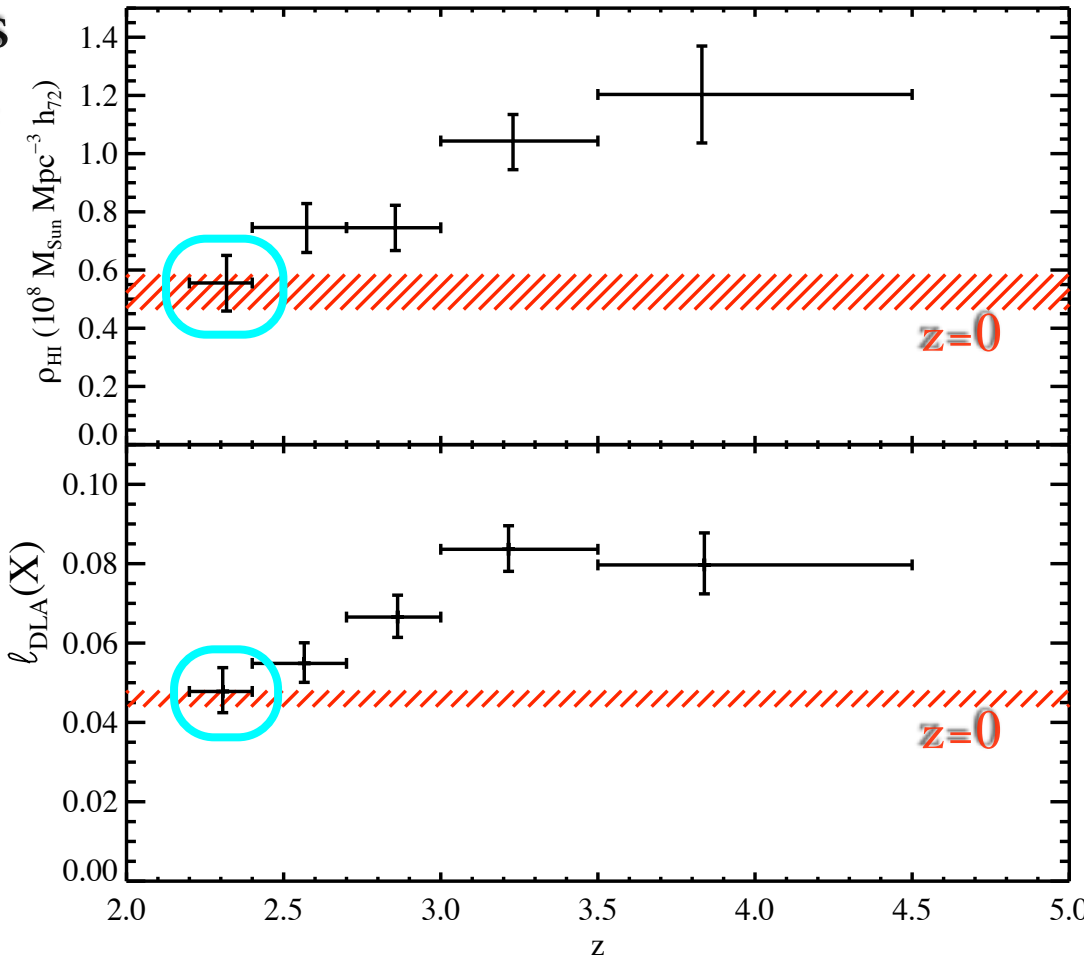
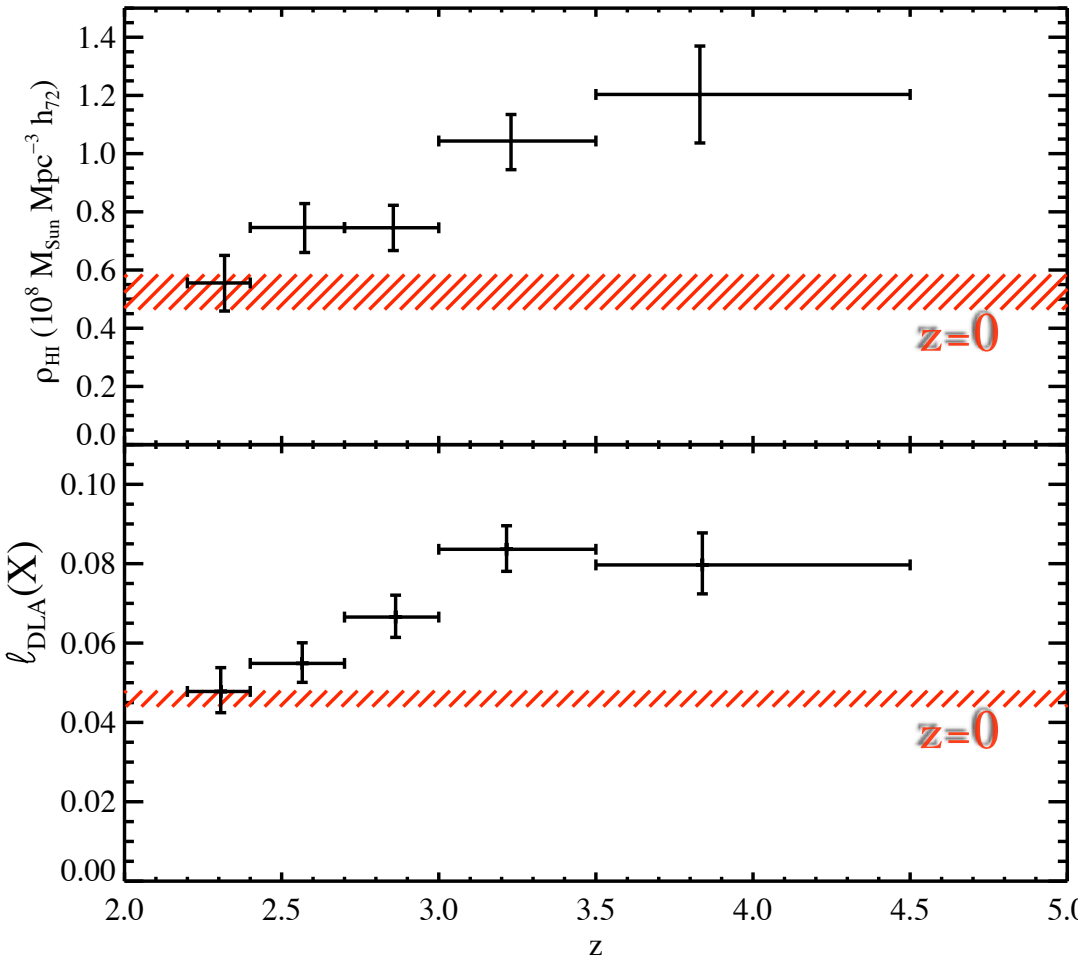
  - Galaxies as a population maintain the same HI gas distribution
    - In shape and absolute value



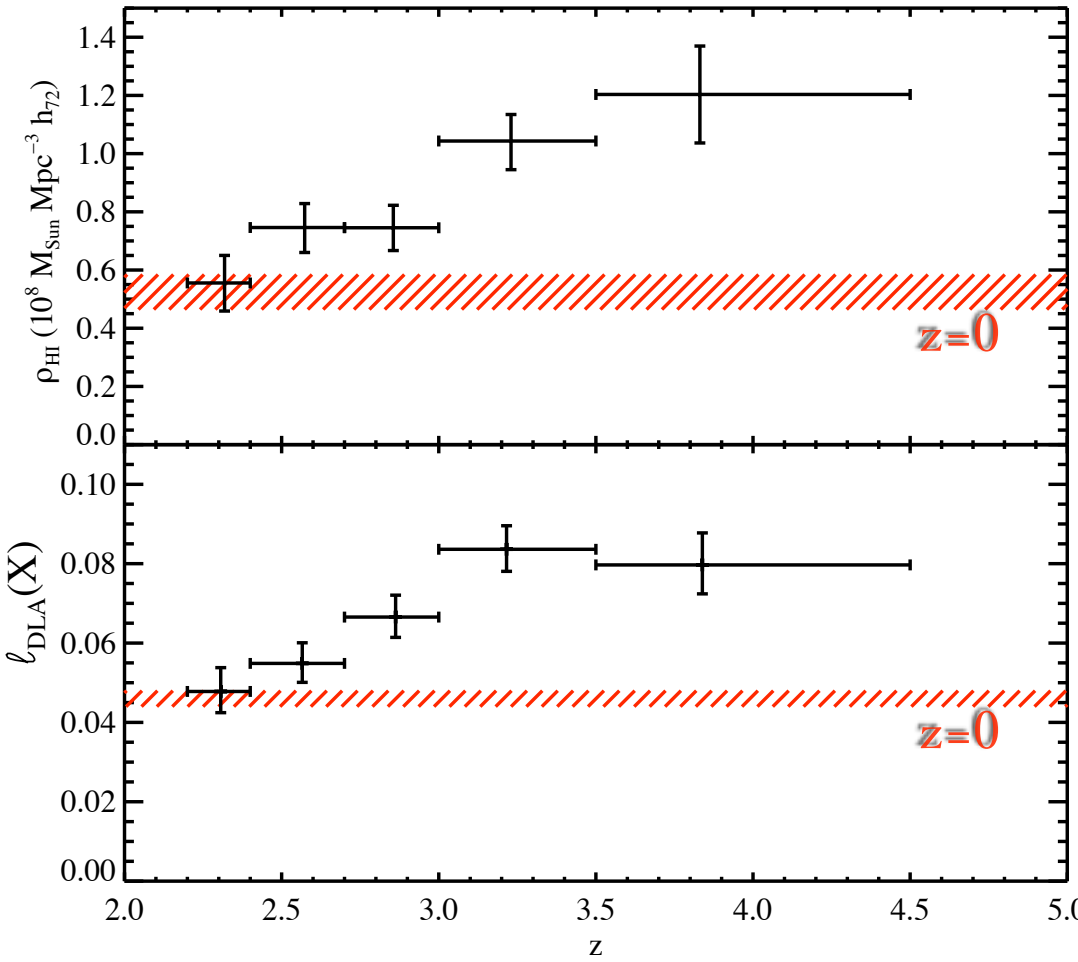
Moments of $f(N_{HI})$: z=4 to 2

- **Evolution**
  - l(X) and ρ_{HI} drop by 50%
    - Both the mass density and the covering fraction
    - Over an interval of ~2 Gyr time
  - What is driving this?
- **Failed hypotheses**
  - In-situ star formation
    - Rates are too low
    - $f(N_{HI})$ would evolve markedly
  - Conversion to H_2
    - Same problems as in-situ SF
  - Secular processes
    - Could reduce l(X), but why ρ_{HI}?



Moments of $f(N_{HI})$: z=4 to 2

- "Violent" removal
  - Remove gas entirely from ~1/2 of the galaxies
    - l(X) and ρ_{HI} will decline in tandem
  - Options (usual suspects)
    - AGN, Galactic winds, mergers
- End state
  - Half of the galaxies have no HI
    - SF halts
    - Progenitors of red+dead galaxies
  - Infer: z~3 is the formation epoch of early-type galaxies
    - Stars are ~10 Gyr old
    - Such populations are observed
      - ➡ (DRGs, EROs)



Open Questions (for the EVLA)

- What is the HIMF at z=0.2 or even z=1?
  - We predict no evolution from z=0
- Have we observed enough faint galaxies at z=0?
- What happens below columns of $N_{HI} = 10^{20}$ cm^{-2}?
- Does the beam difference between 21cm and Lyα matter?
  - Higher spatial resolution 21cm
- Why do the kinematics evolve significantly?
  - Are winds playing a role?