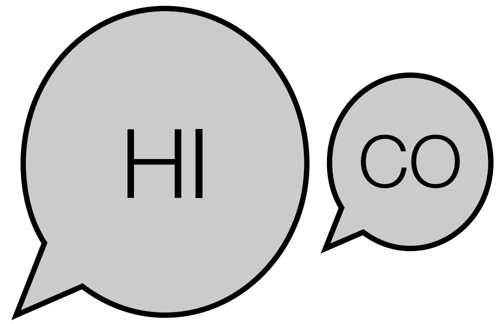
Evolution in the neutral gas

Martin Zwaan
(ESO)



Evolution in the neutral gas

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Evolution in the neutral gas

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Evolution in the cold gas

Martin Zwaan
(ESO)

Topics

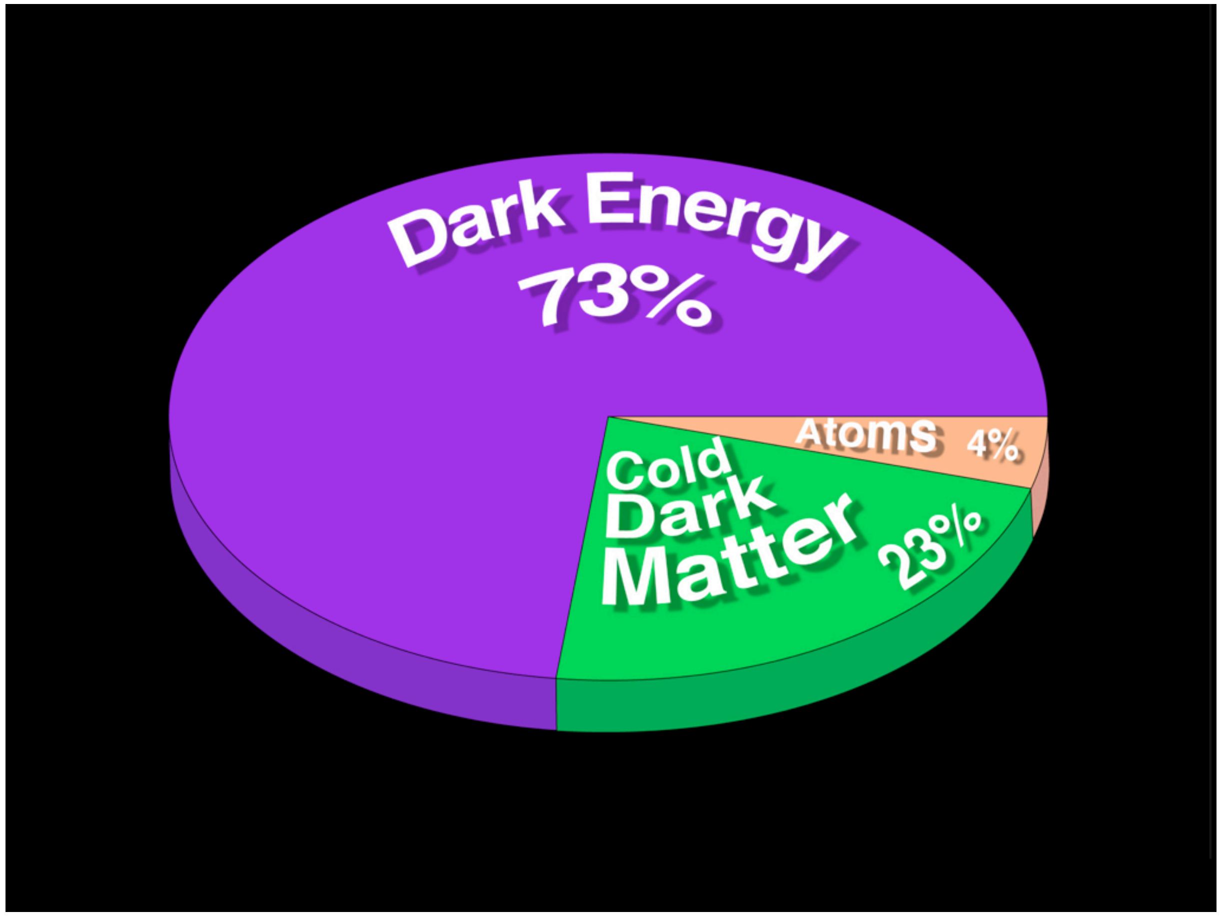
- Why study neutral gas?
- Nearby HI surveys
- Cold gas at higher *z*: QSO absorption lines
- Comparing absorption - emission
- Possible SKA HI surveys at high z
- Possible SKA HI surveys at low z

Who cares about neutral gas?

Cold gas takes up only 1% of baryon mass

but:

- H is the most **abundant** element...
- **Fuel** for star formation (via H_2 ...)
- **Tracer** of galaxy dynamics
- **Search tool** for missing satellites
- **Indicator** of galaxy interactions



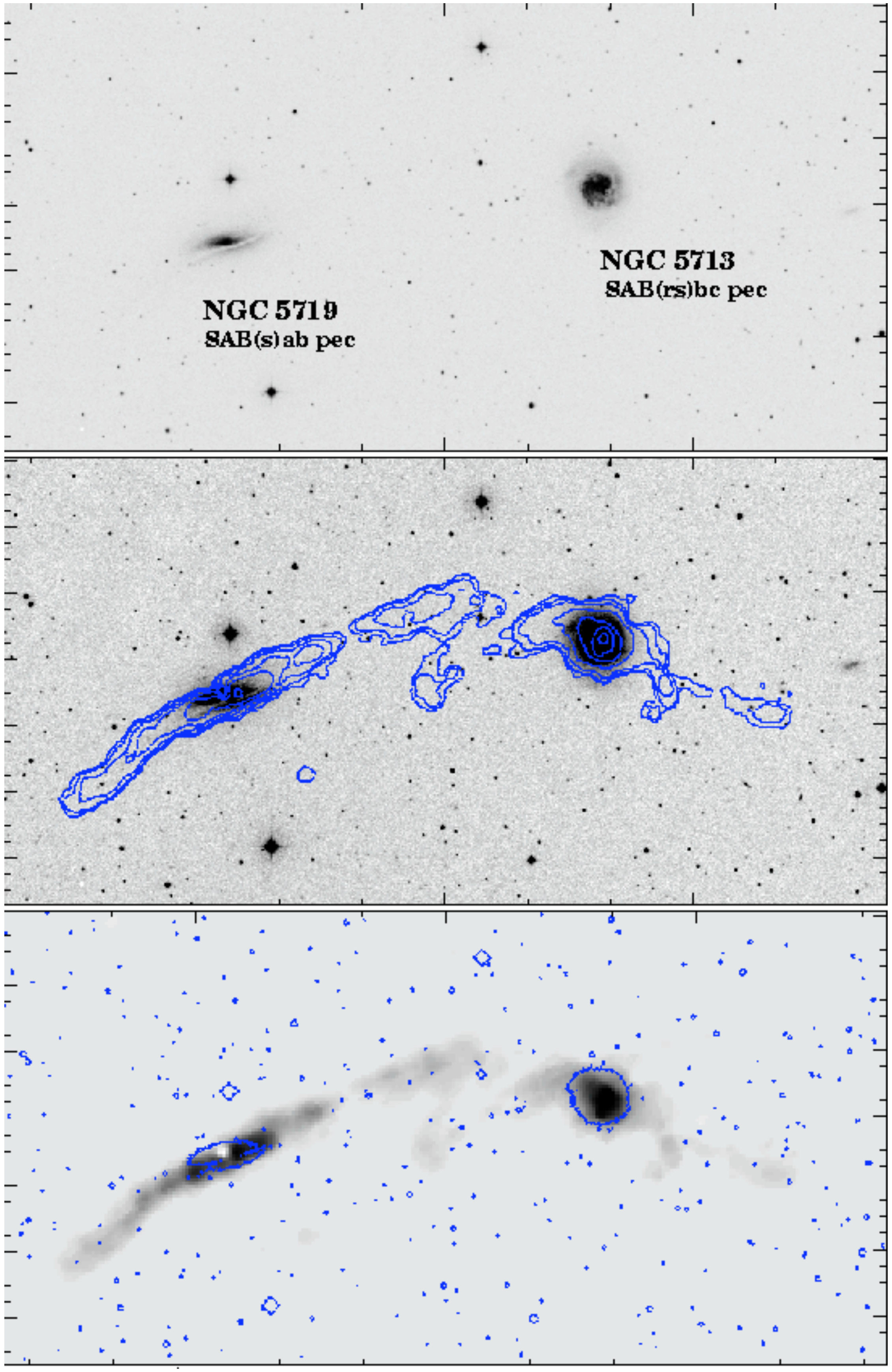


Figure 62: **The NGC 5713/5719 System**.
HI: VLA C-array, 30" resolution, contours= cm.
Optical: DSS, FOV=.
Reference: Langston & Teuben, these proceedings, p. 8

HI rogues gallery (Hibbard)

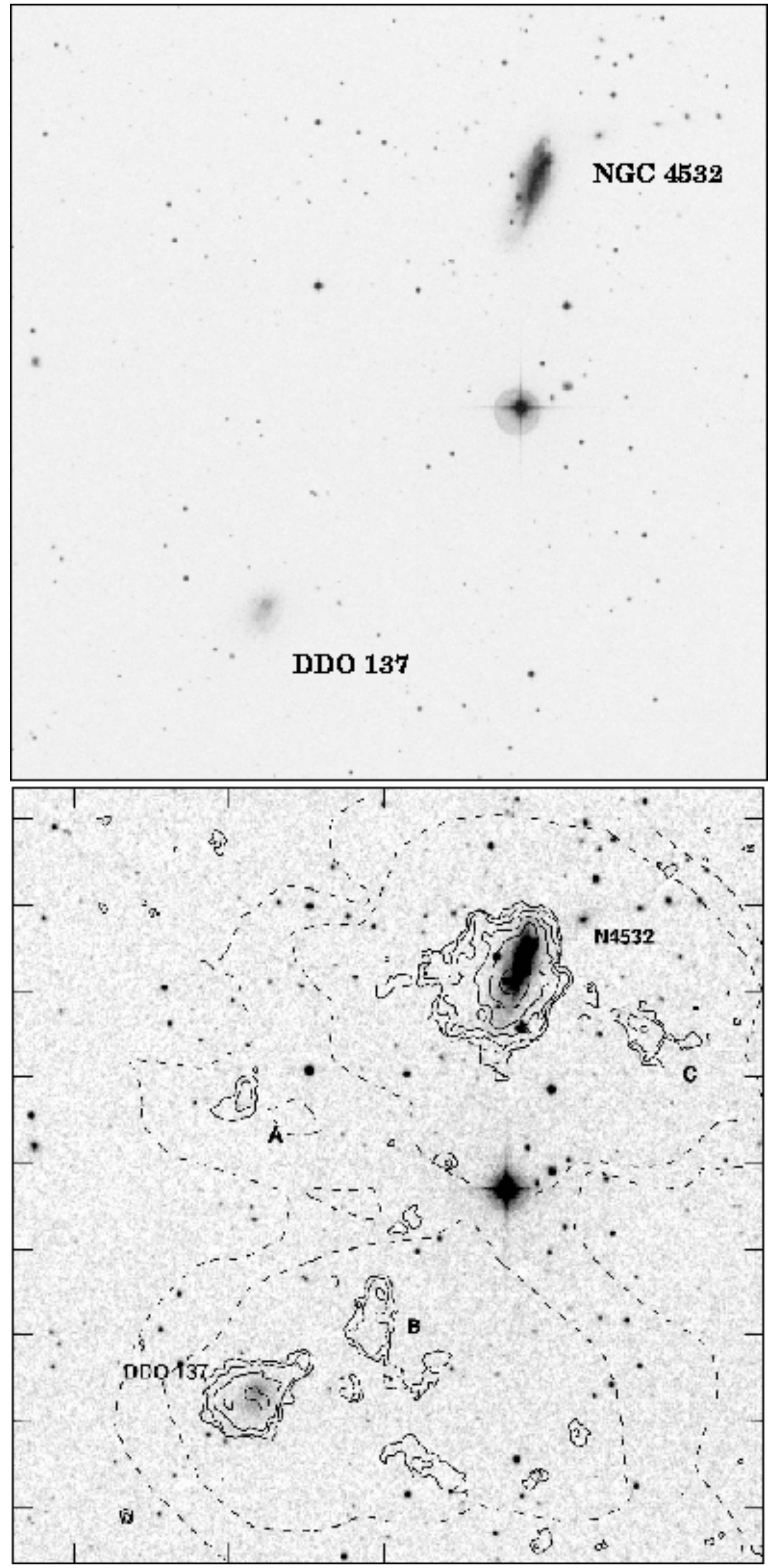


Figure 143: **The NGC4532 System**.

HI: Dotted contours: Arecibo single dish mapping, contours at cm. Solid contours: VLA C+D-array, resolution, contours= cm.

Optical: DSS, FOV=.

Reference: Hoffman, G. L., Lu, N. Y., Salpeter, E. E., & Connell, B. M. 1999, AJ, 117, 811.

What do we know about cold gas evolution?

Not much...

Shockingly little is know about the evolution of cold gas

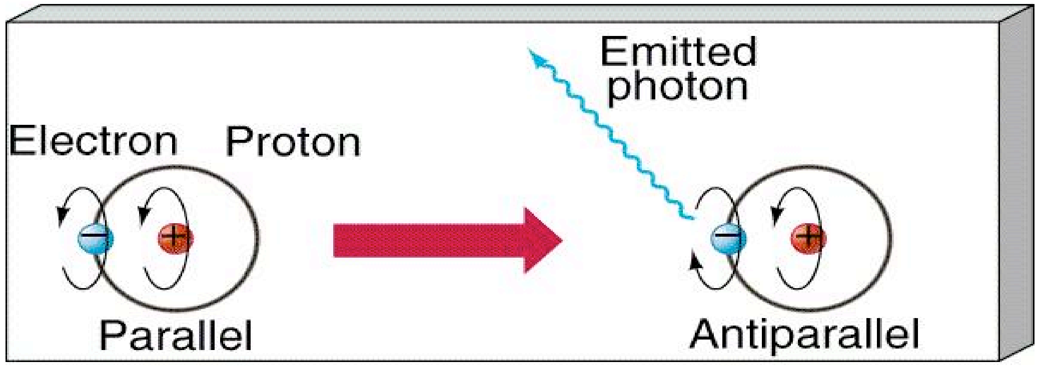
- How much? (mass function, $f(N_H)$)
- Role of gas content in galaxy evolution
- Infall, blow-out?

Understanding galaxy evolution requires knowledge of

$$\Omega_{gas}(z, N_H, M_{halo}, \mathrm{Type}, \rho_{gal}, \ldots)$$

We like the physics of the HI 21-cm line

because it's simple



- Level population determined by collisions
- 21-cm emission independent of temperature and density
- 21-cm flux → column density or mass

Ned. T. Natuurk. 11, December 1945.

Radiogolven uit het wereldruim *)

door C. J. Bakker en H. C. van der Hulst

RADIO WAVES FROM SPACE, SUMMARY

1. *Reception*, by C. J. Bakker.

A short introduction mentions the sources of „noise" in a radio set and the current fluctuations of an antenna immersed in a black body radiation field. Observations at wavelengths smaller than ca 20 m show that radiation of extraterrestrial origin is received by the antenna.

By directional records taken by Jansky and others the source of this radiation is located in the Milky Way, the greatest response being obtained when the antenna points towards the centre of the galactic system. Data of maximum intensities observed at four different wave lengths are given.

2. *Origin*, by H. C. van de Hulst.

Radio waves, received from any celestial object — they being the far infra red portion of its spectrum — deserve attention. Observations of small objects are prevented by diffraction. The sun may be a measurable object for future instruments.

The radiation observed from our galaxy must be due to the interstellar gas, the stars being outruled by their small angular dimensions and the solid smoke particles being outruled by their low temperature.

The spectral emission of a homogeneous layer of ionised hydrogen is computed. The continuous spectrum arising from free-free transitions has the intensity of black body radiation at wavelengths larger than 6 m and has a nearly constant intensity at wavelengths smaller than 2 m, corresponding to a large and to a small optical thickness respectively. These intensities, shown in figure 2, agree with those computed by Henyey and Greenstein and tally fairly well with the observations. No better accordance is to be expected, owing to the unknown electron density and extension of the interstellar gas and to unsatisfactory data about the directional sensibility of the antenna.

Discrete lines of hydrogen are proved to escape observation. The 2.12 cm line, due to transitions between hyperfinestructure components of the hydrogen ground level, might be observable if the life time of the upper level does not exceed 4.10^8 year, which, however, is improbable.

Reber's observation of the Andromeda nebula suggests a rather high electron density. A cosmological remark concludes the article. The low background intensity due to remote nebulae contradicts the Hubble—Tolman static model.

I. Ontvangst der radiogolven

door C. J. Bakker

Inleiding. Het „geruisch" van een radio-ontvanger.

Het is bekend, dat de luidspreker van een radio-ontvanger een geruisch kan laten hooren. Bijzonder duidelijk is dit waar te nemen,

*) Naar aanleiding van voordrachten voor het colloquium van de Ned. Astr. Club op 15 April 1944 te Leiden.

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The telescopes today...

Interferometers:

- large f.o.v. (0.5 degree)
- high spatial resolution (1-60 arcsec)
- not sensitive to extended emission
- R≈10.000, Δz=0.02-0.1

single dish:

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- high sensitivity
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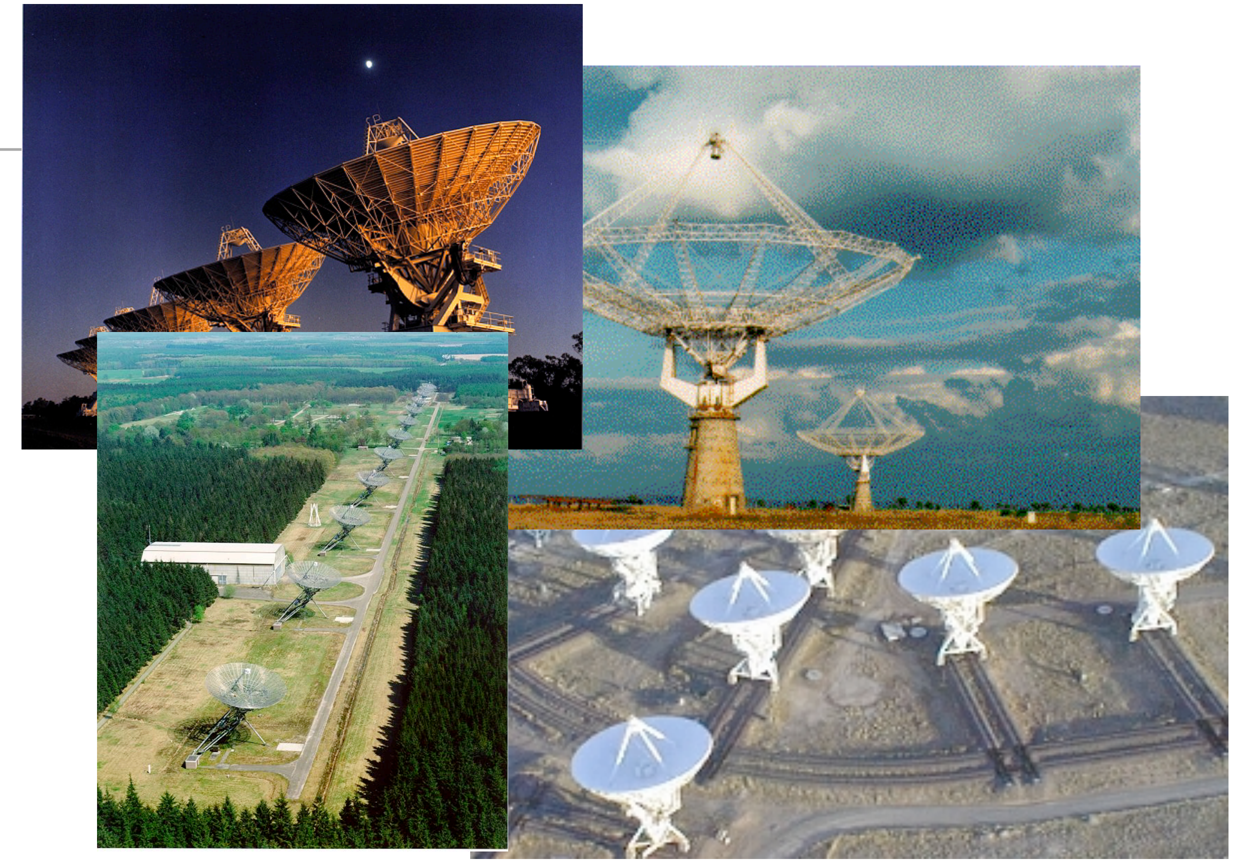

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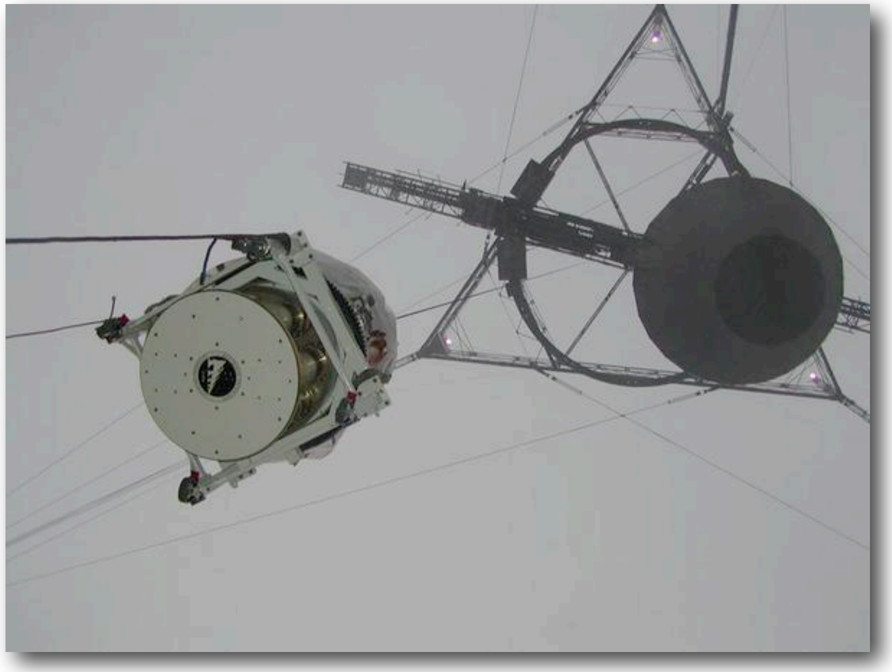
- high sensitivity
- R≈100.000, Δz=0.1

HI surveys today

Singe dish surveys with Parkes and Arecibo

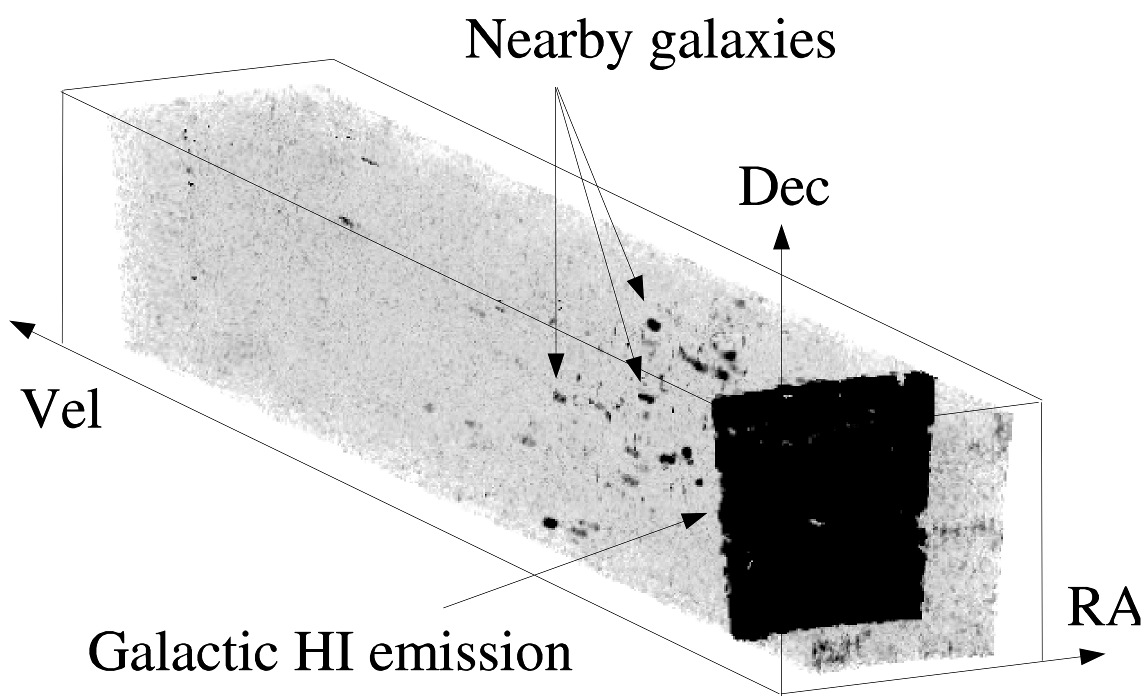
- ‘blind’ surveys (now with ‘multibeams’)
- Good surface brightness sensitivity
- column density limits of ~10^{18} cm^{-2} (for gas that fills the beam!)
- Detect thousand of galaxies
- Get HI masses, velocity widths and redshifts
- Appraise completeness of optical surveys
- Good for measuring Ω_{HI} at z=0



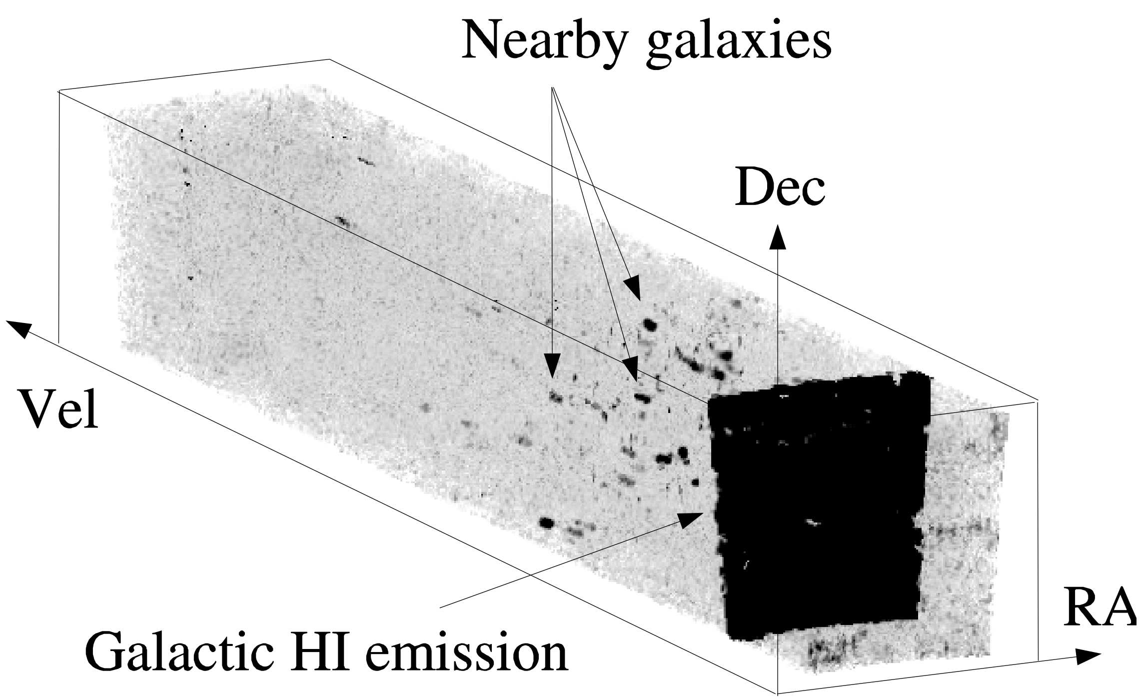
Blind HI surveys coming of age

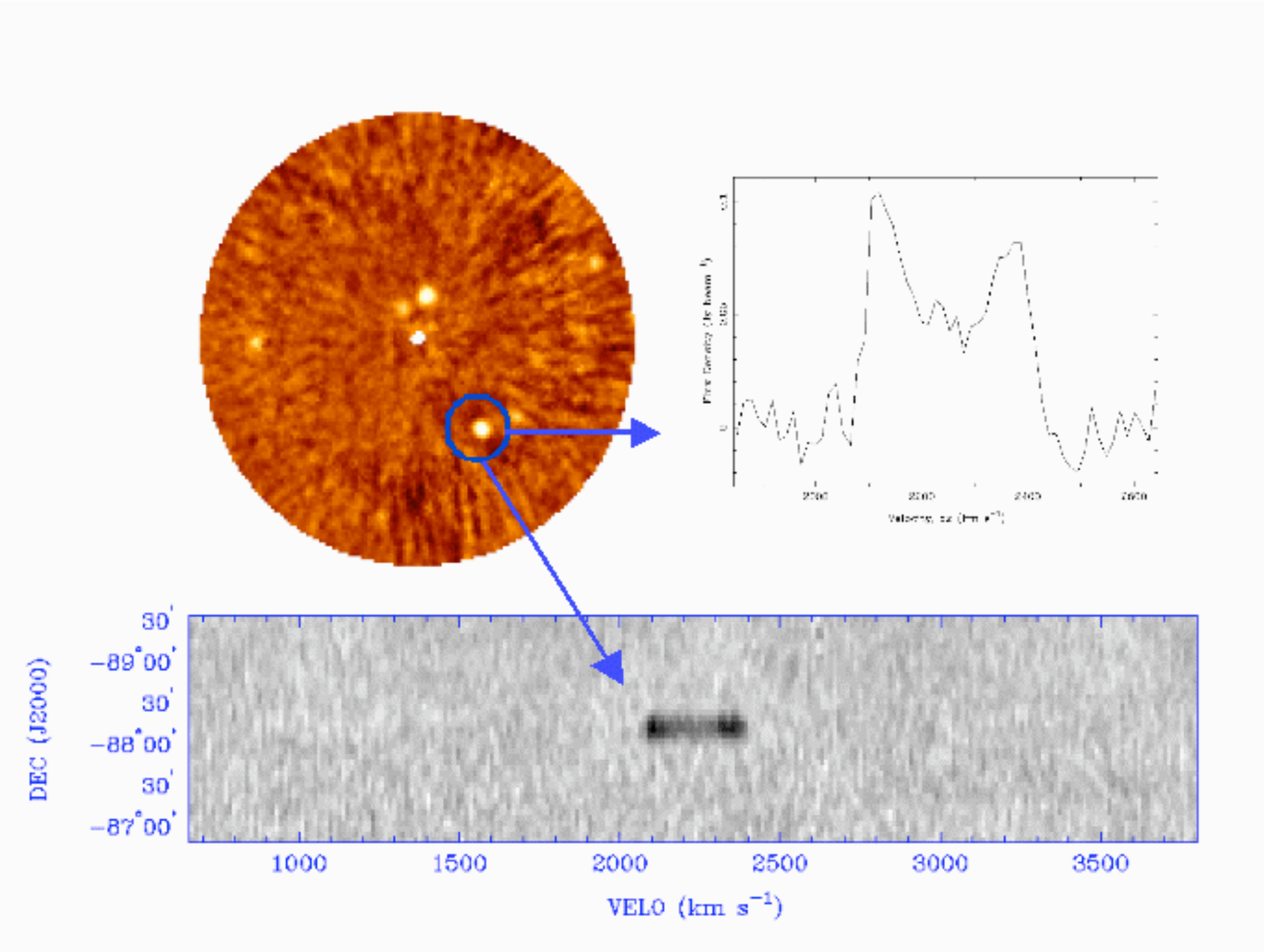
- **AHISS**: HI strip Survey *(Zwaan et al 1997)* **66**
- **AS**: Arecibo Slice *(Spitzak & Schneider 1998)* **75**
- **ADBS**: Arecibo Dual Beam Survey *(Rosenberg & Schneider 2000)* **265**
- **HIPASS**: HI Parkes All Sky Survey *(Zwaan, Meyer et al 2003/2004/2005)* **5317**
- **ALFALFA**: Arecibo Legacy Fast ALFA Survey *(Giovanelli et al 2005) ONGOING...* **15000?**

The data



The data

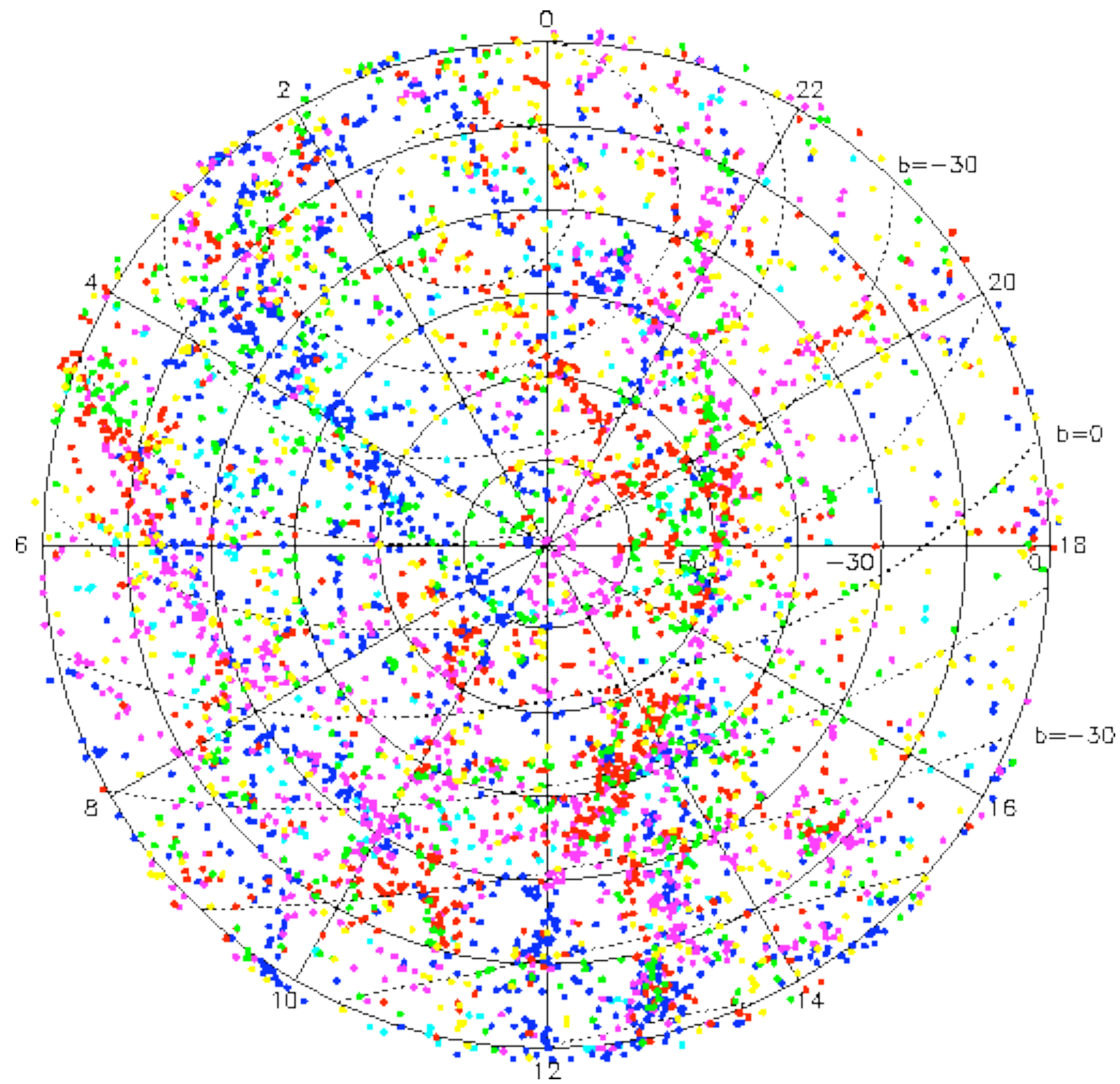


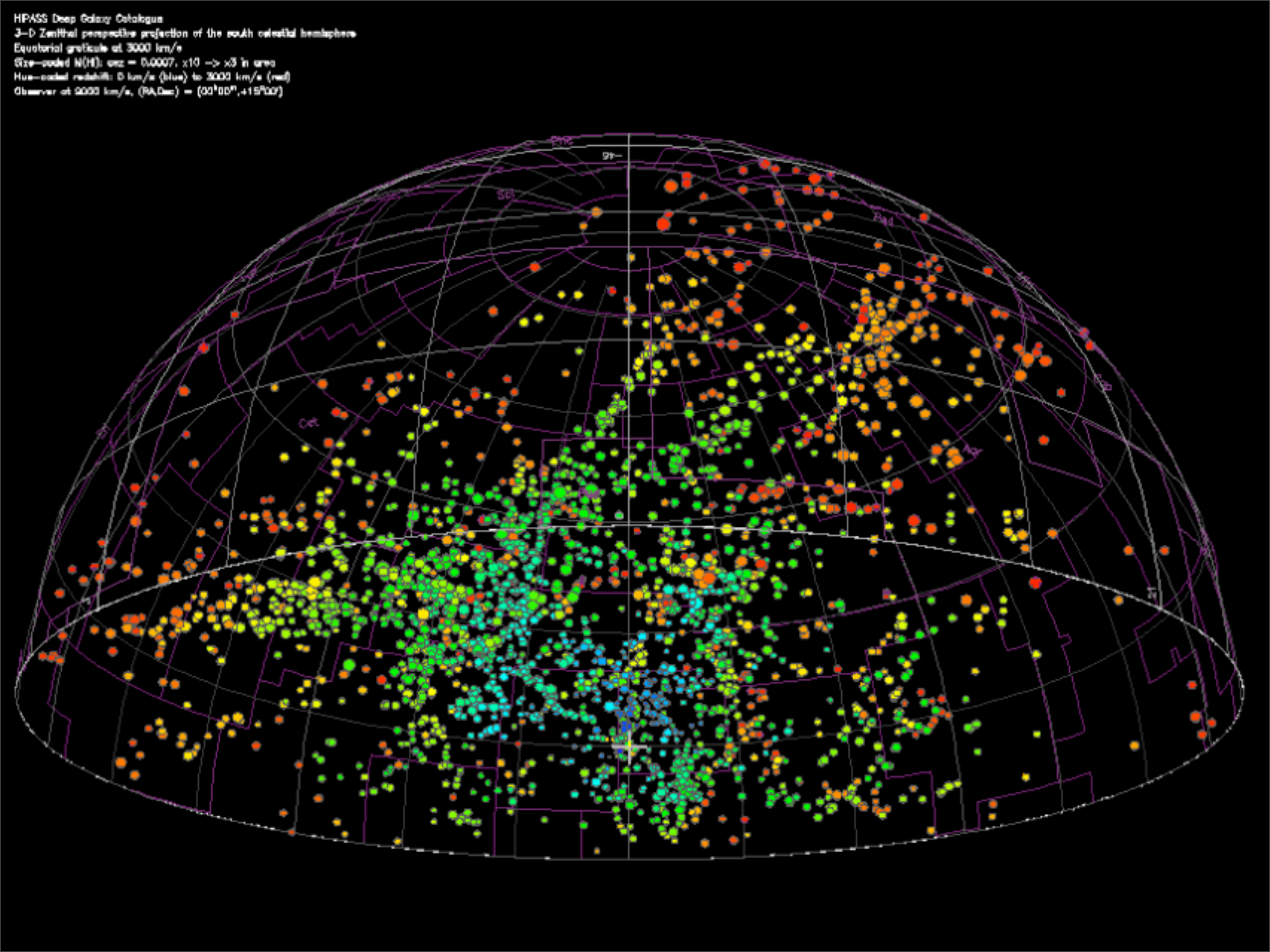


Flux and distance simultaneously

HIPASS

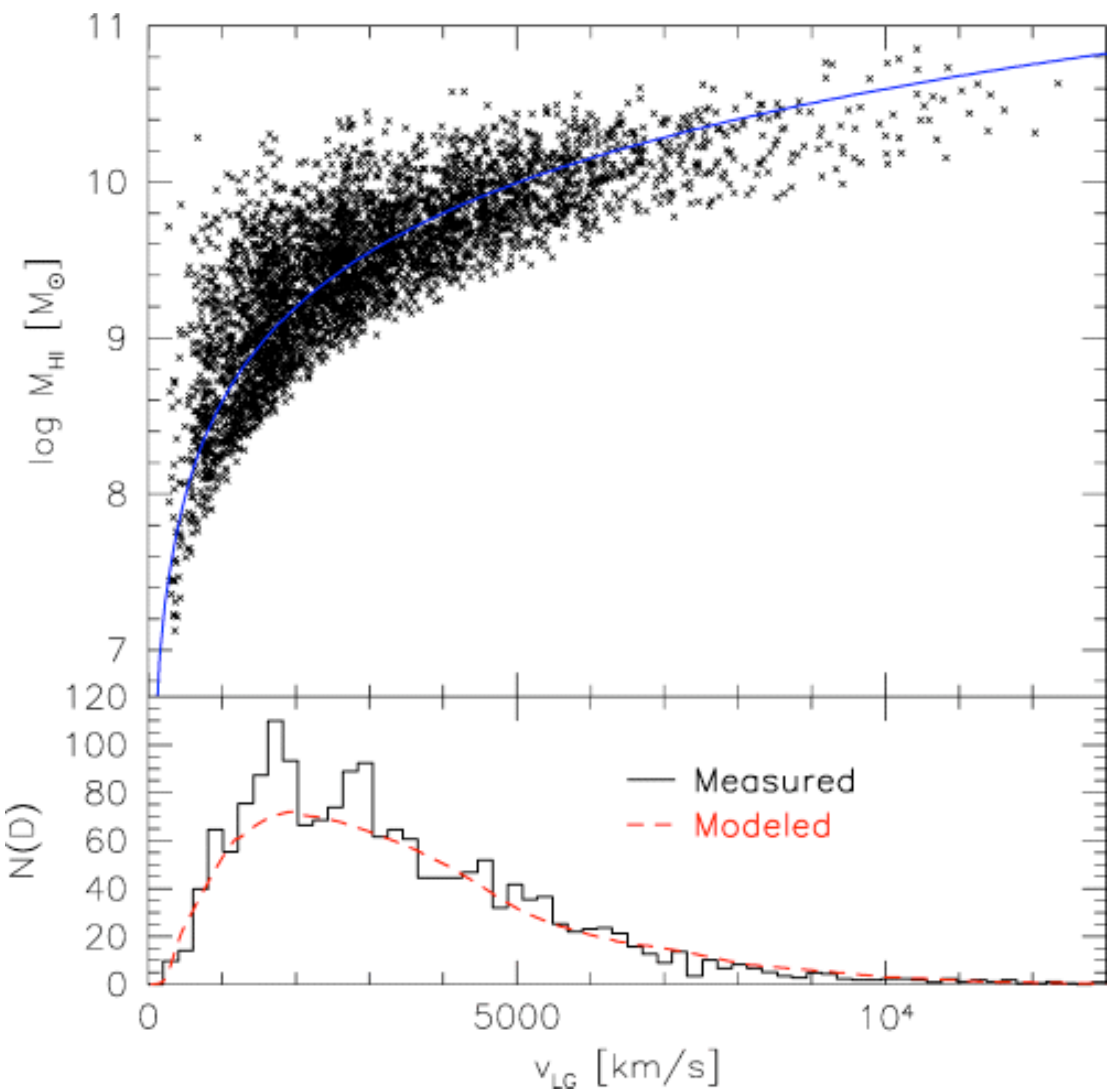
- HI Parkes All Sky Survey
  - blind 21-cm survey of southern sky south of dec=25°
  - 5317 galaxies *(Meyer et al 2004, Zwaan et al 2004, Wong et al 2006)*
  - Catalogue publically available
  - best measurement of HI mass function to date





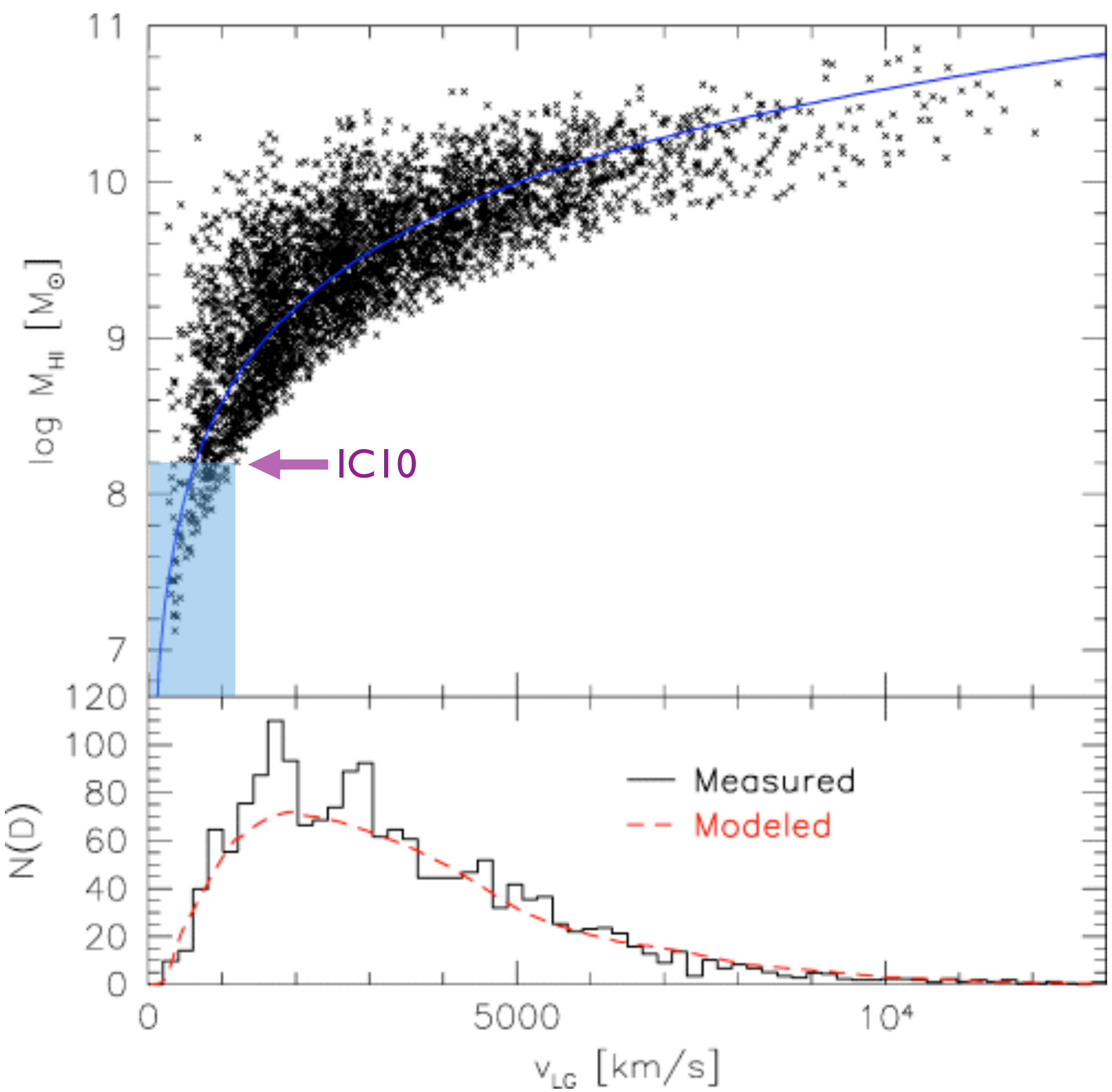
HIPASS Deep Galaxy Catalogue
3-D Zenithal perspective projection of the south celestial hemisphere
Equatorial graticule at 3000 km/s
Hue-coded redshift: 0 km/s (blue) to 3000 km/s (red)
Observer at 9000 km/s, (RA,Dec) = (00h00m,+15°00')

HIPASS results



- $M_{HI} \propto S_{int} D^2$
- $M_{HI}=10^8$ M_o out to ~12 Mpc
- peak at ~25 Mpc
- No sharp flux limit → *complicated completeness corrections*

HIPASS results



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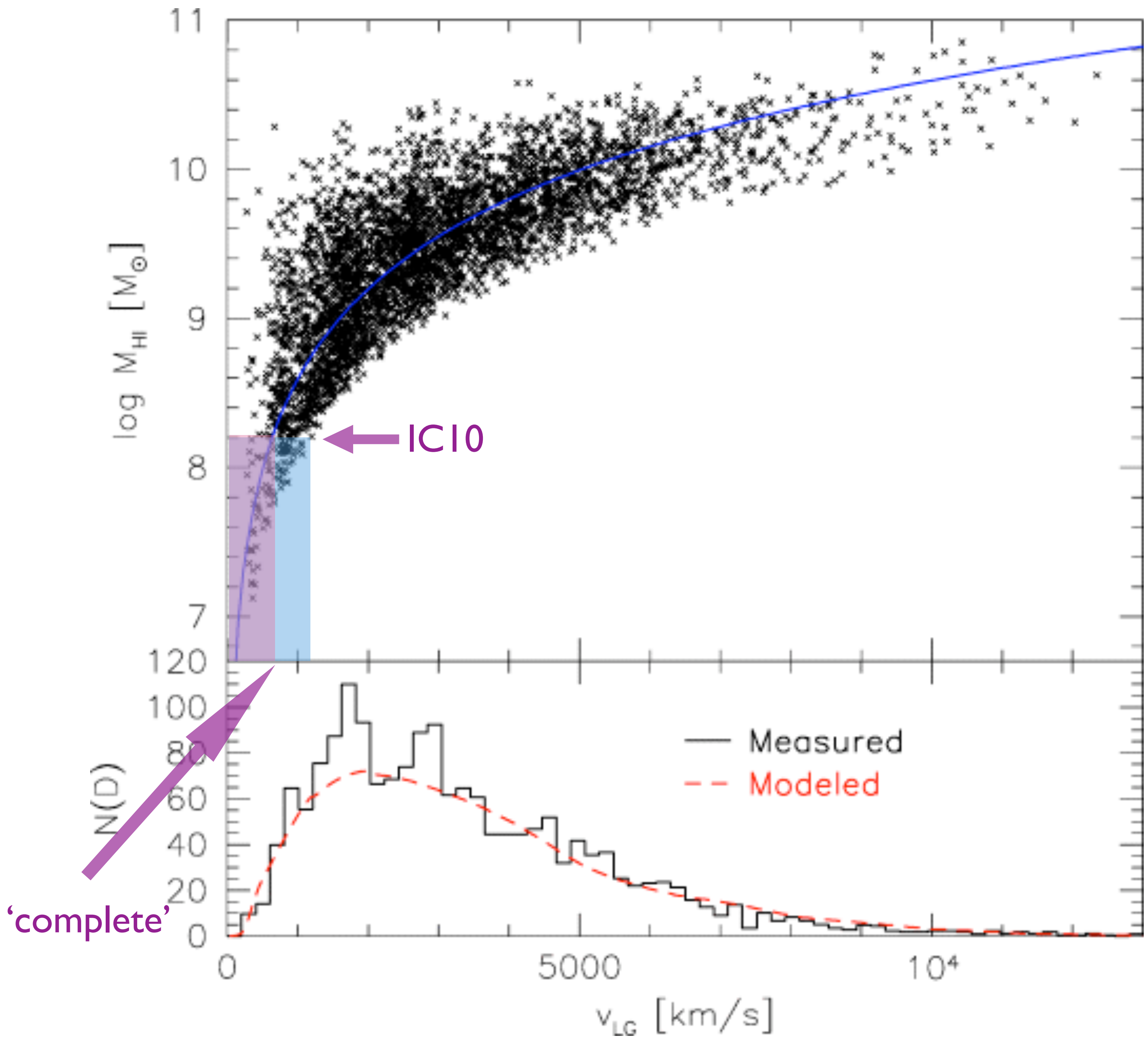

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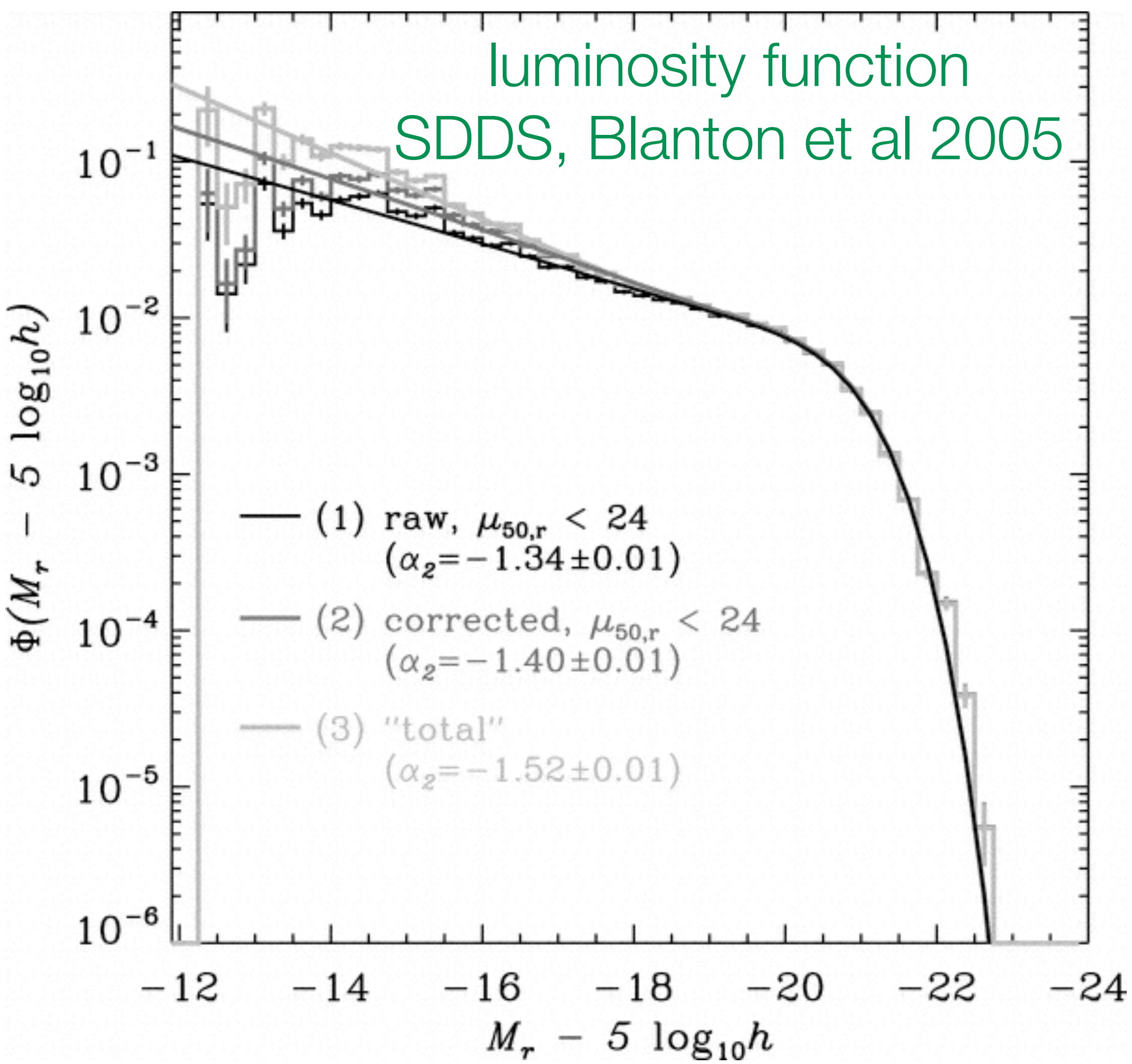
The HI mass function

is the cold gas equivalent of the optical luminosity function



Relevance:

- Theories of galaxy formation and evolution
- Luminosity density
- ...

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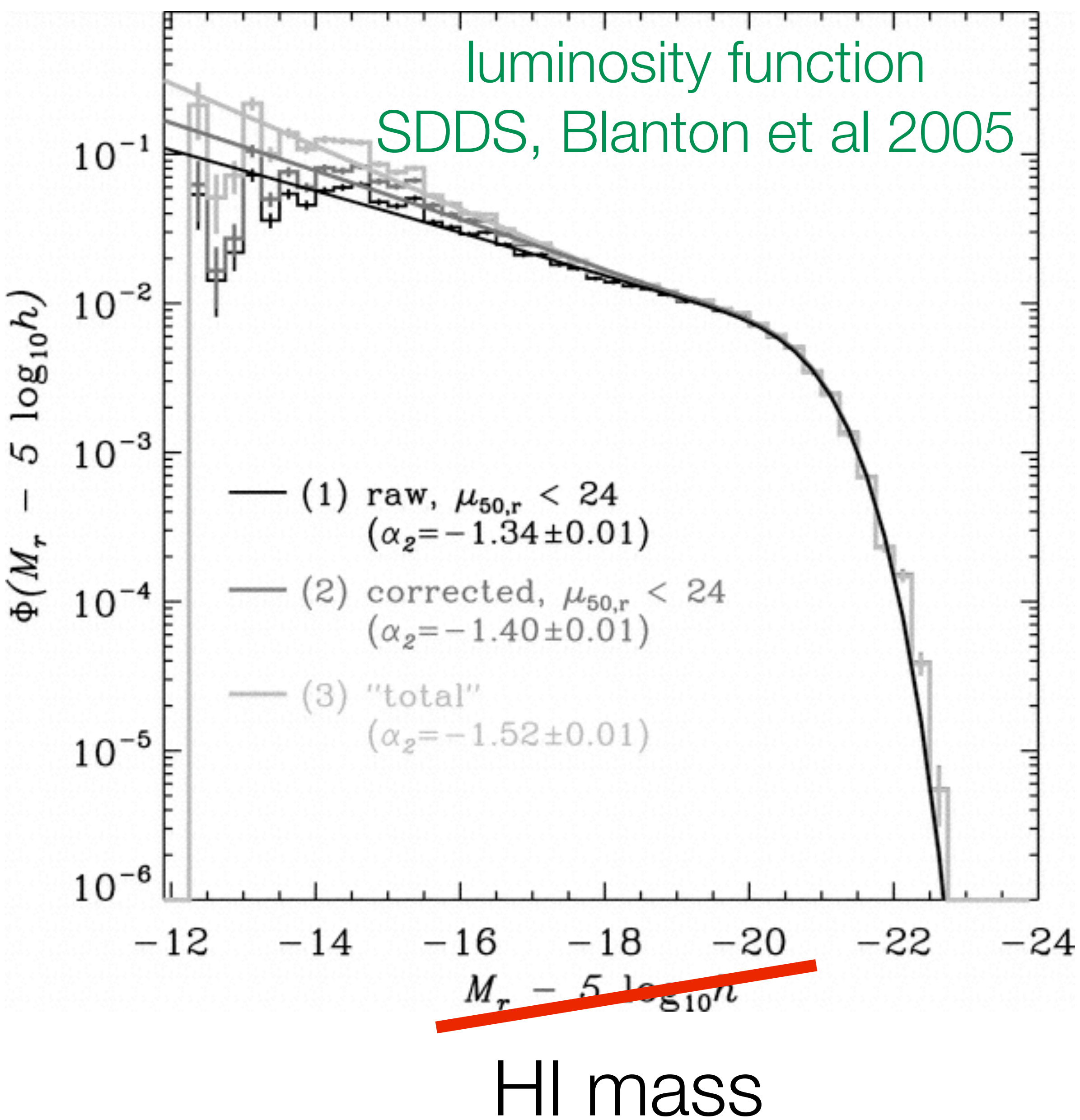

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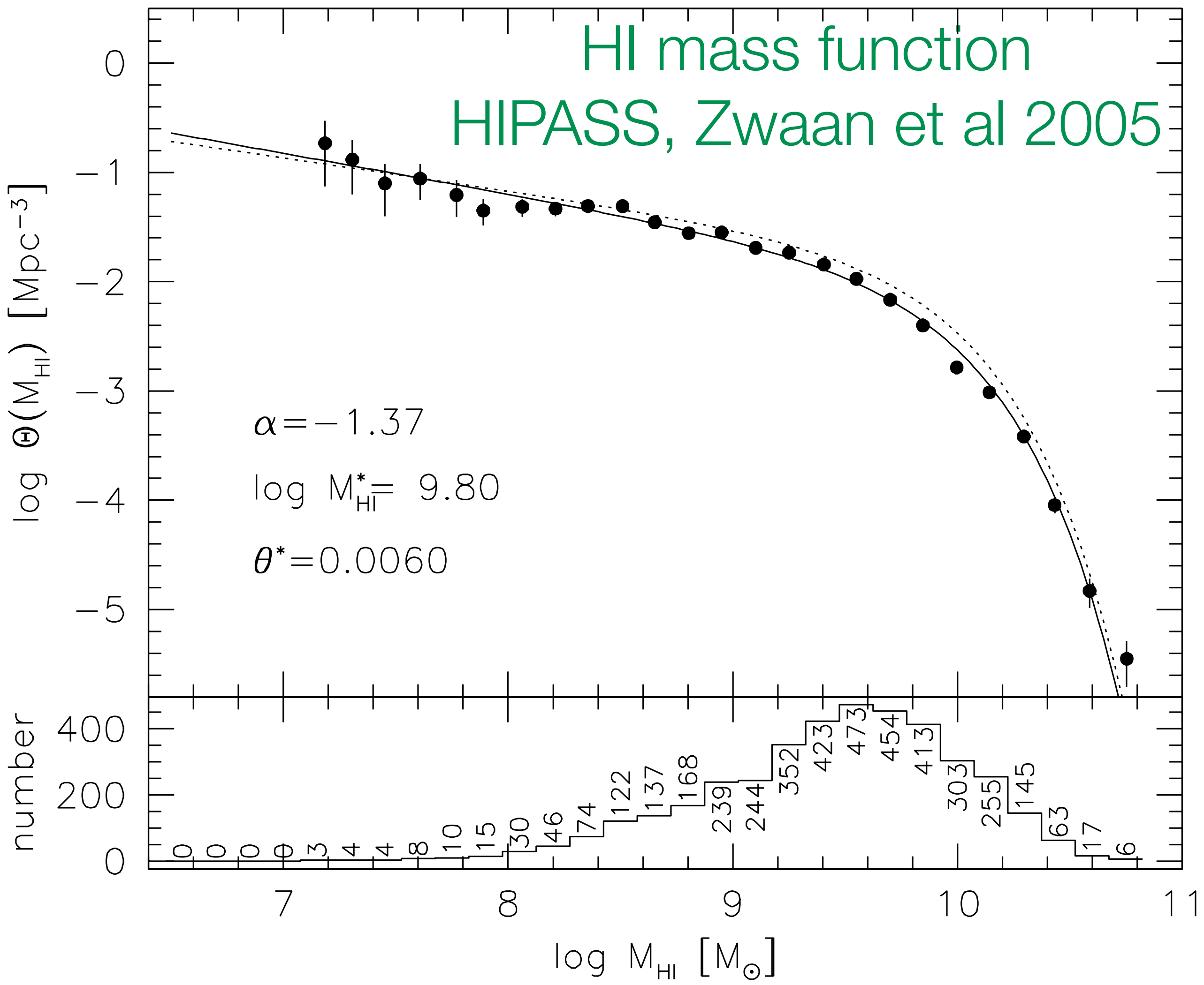

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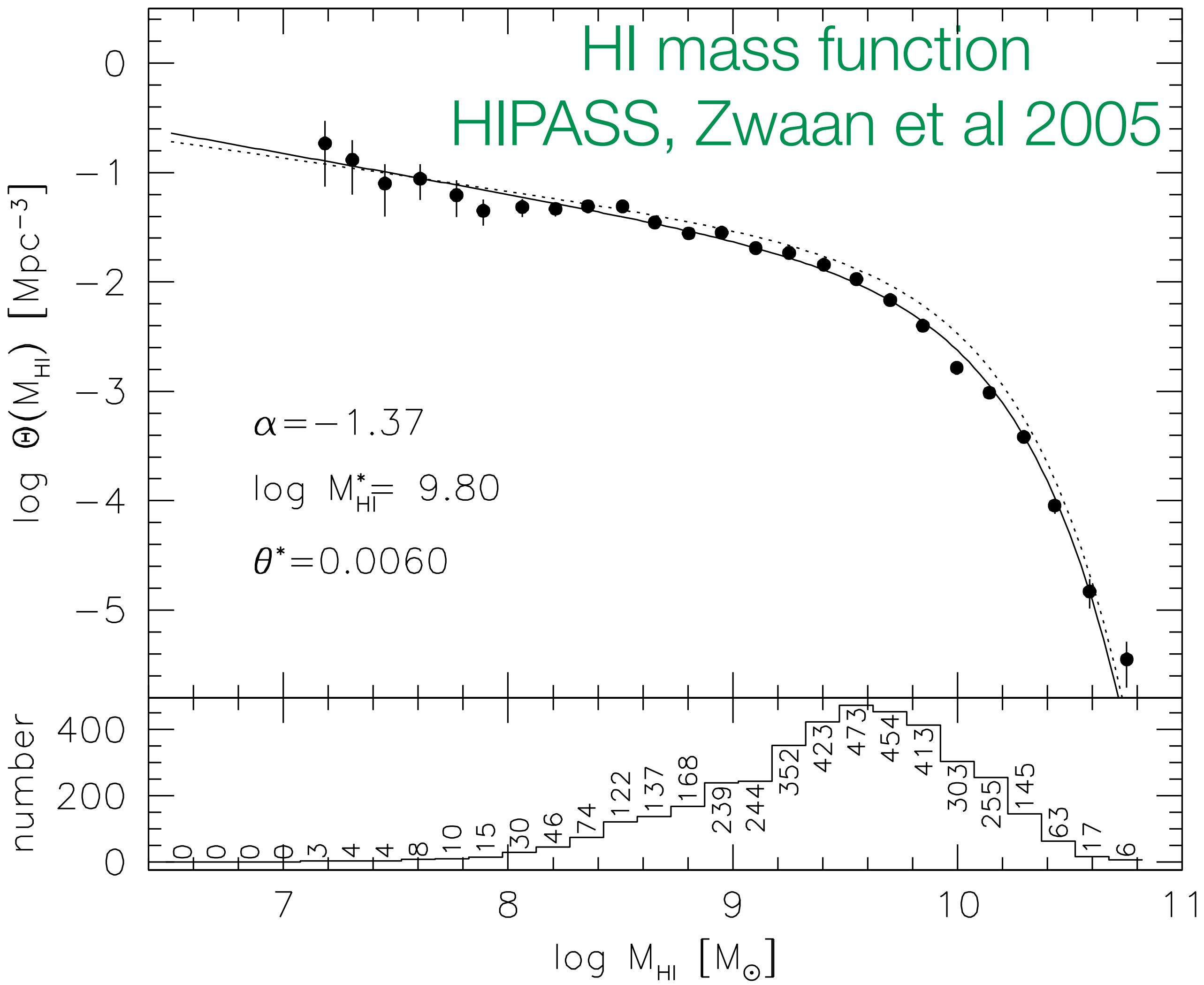

HI mass

Relevance:

- Theories of galaxy formation and evolution
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Why need an HI mass function (HIMF)?

nearby

- constraints on models:
  - low-mass end of mass function
  - missing satellites
- local cosmic cold gas mass density

at higher z

- constraints on models:
  - evolution of gas fractions, gas in blue cloud vs red sequence, etc
- evolution of cosmic cold gas mass density

Why need an HI mass function (HIMF)?

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- constraints on models:
  - low-mass end of mass function
  - missing satellites
- local cosmic cold gas mass density

SKA goal:

measure HIMF down to lowest HI masses

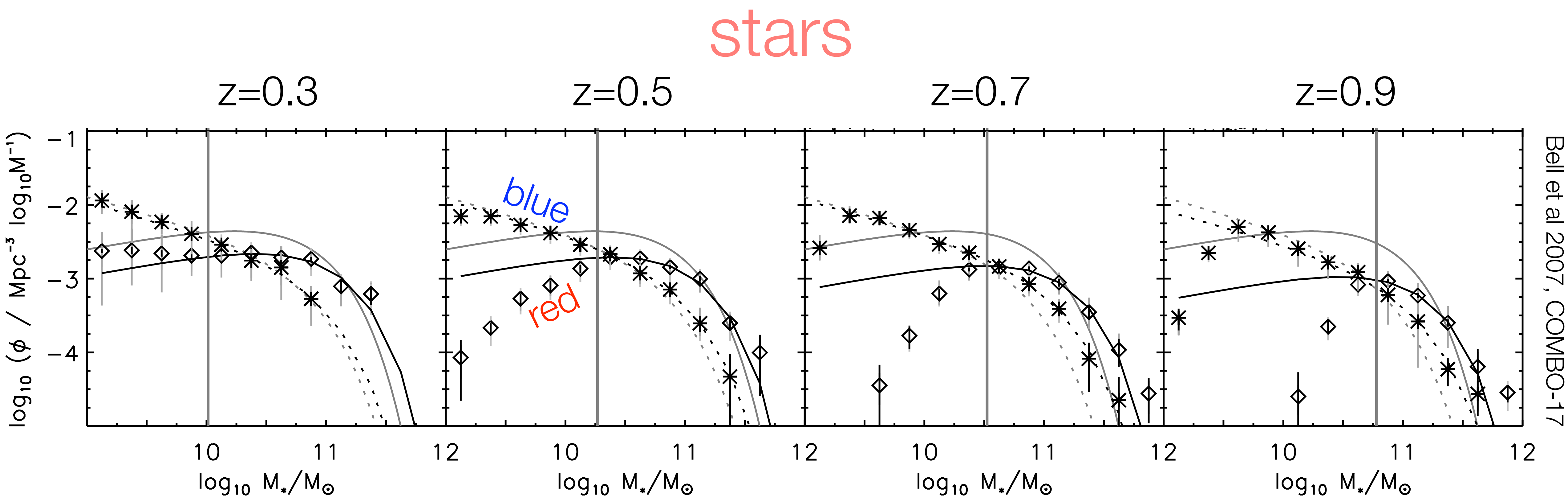
at higher z

- constraints on models:
  - evolution of gas fractions, gas in blue cloud vs red sequence, etc
- evolution of cosmic cold gas mass density

SKA goal:

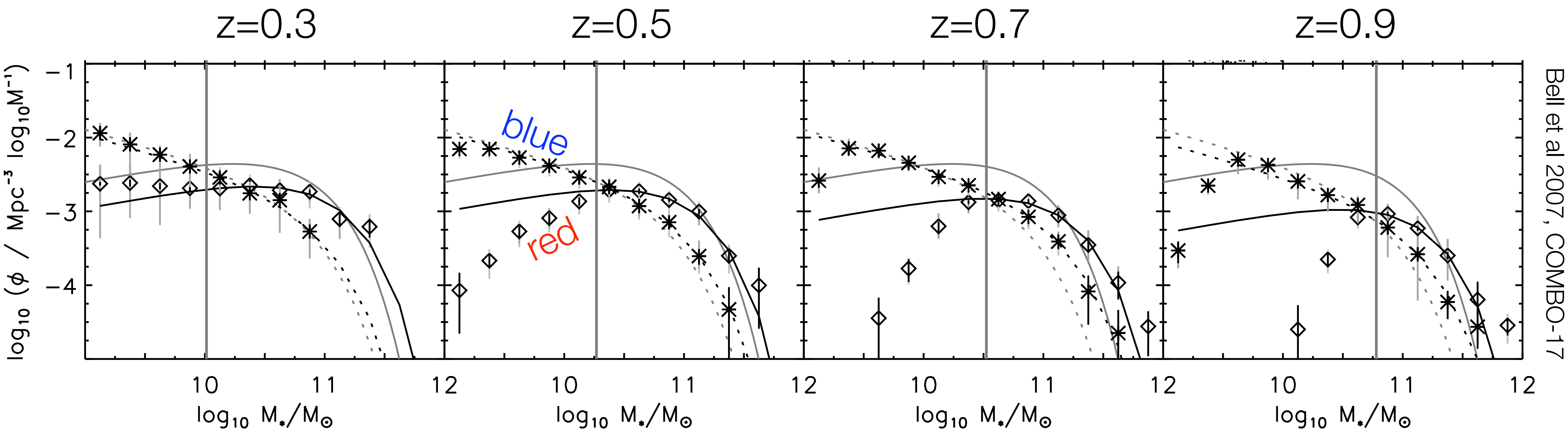
measure HIMF at highest redshift possible

Evolution of stellar mass and cold gas mass

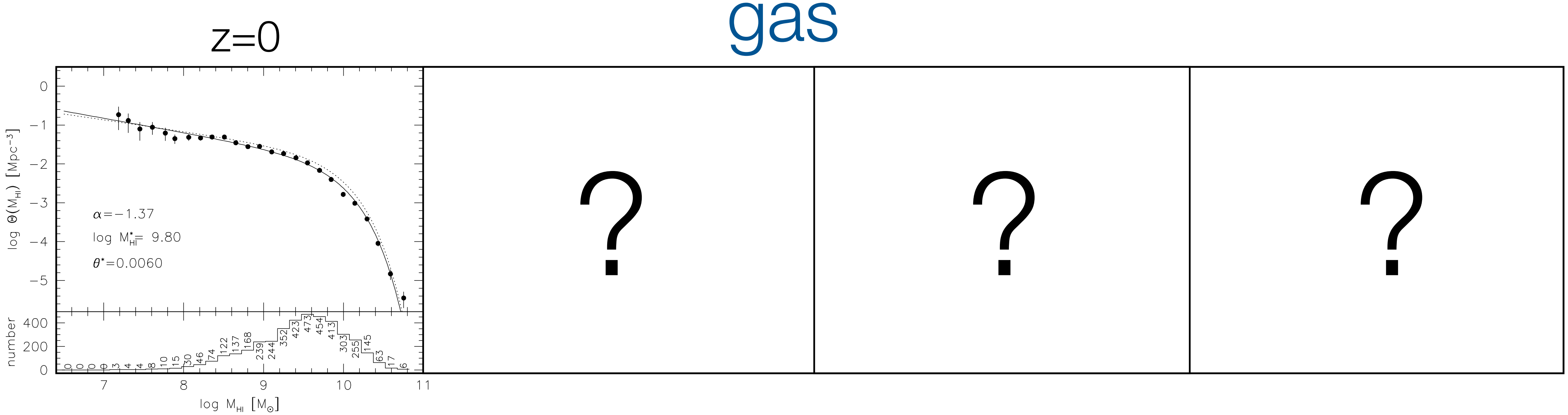


Evolution of stellar mass and cold gas mass

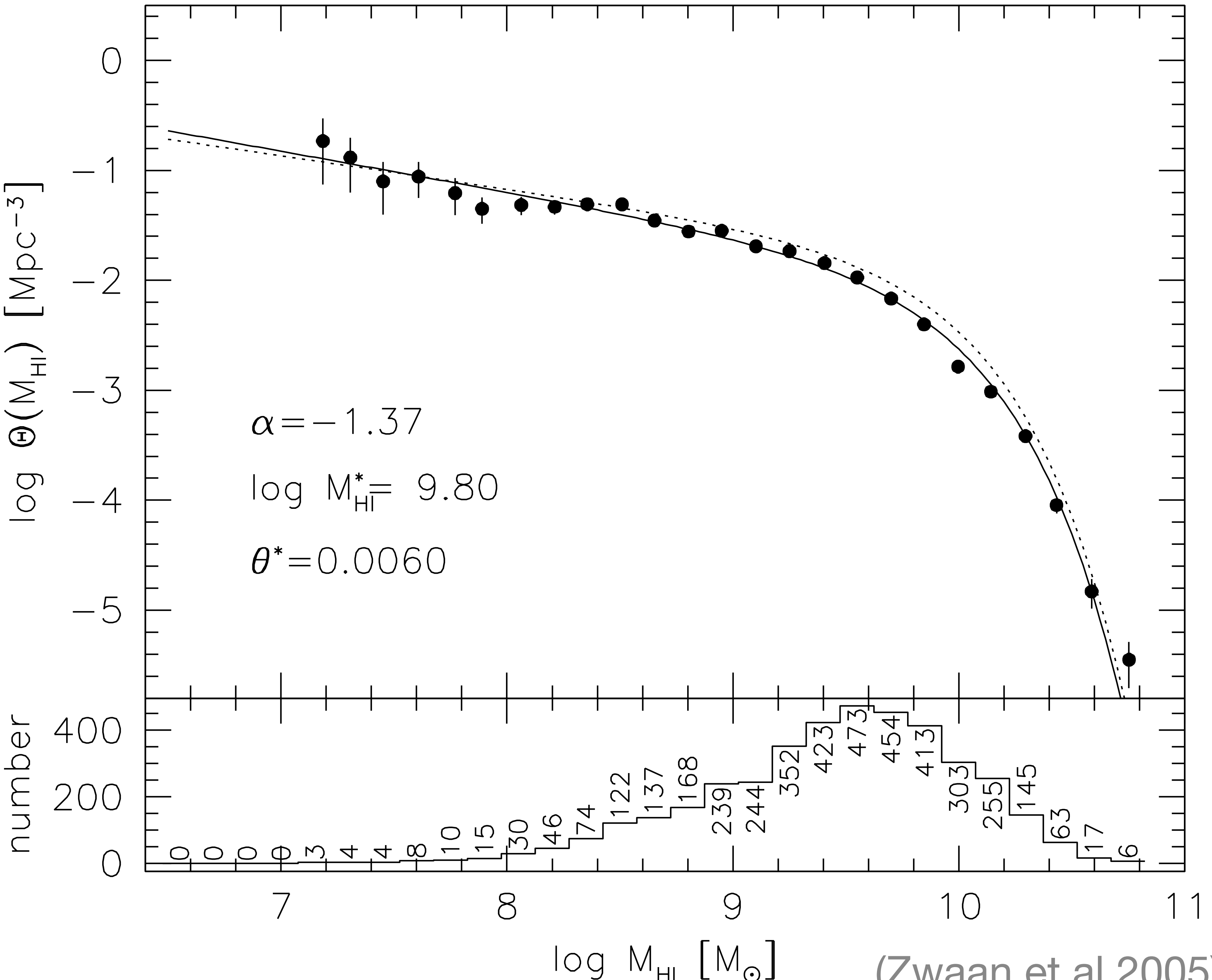
stars



gas



The HI mass function at z=0



(Zwaan et al 2005)

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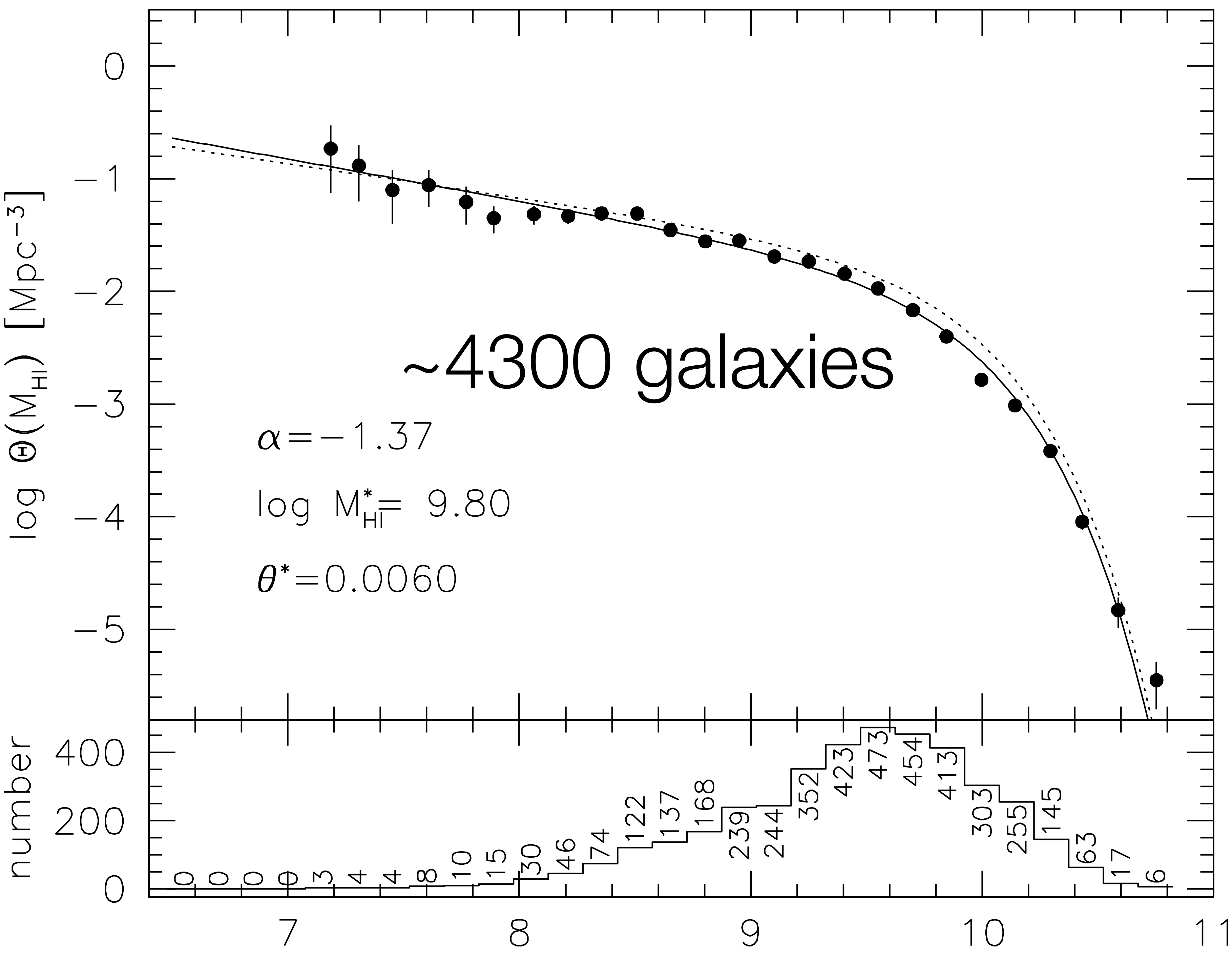

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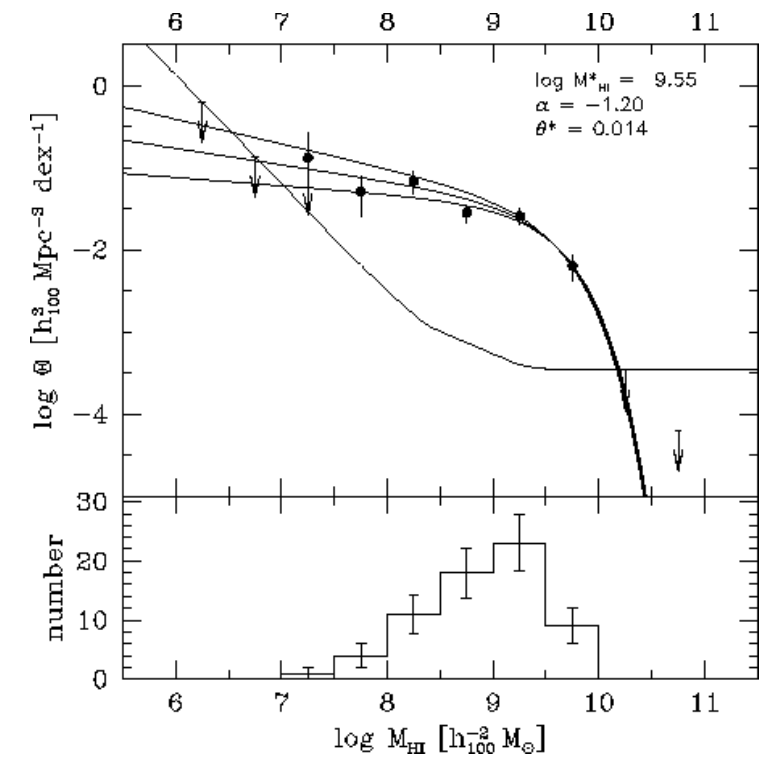
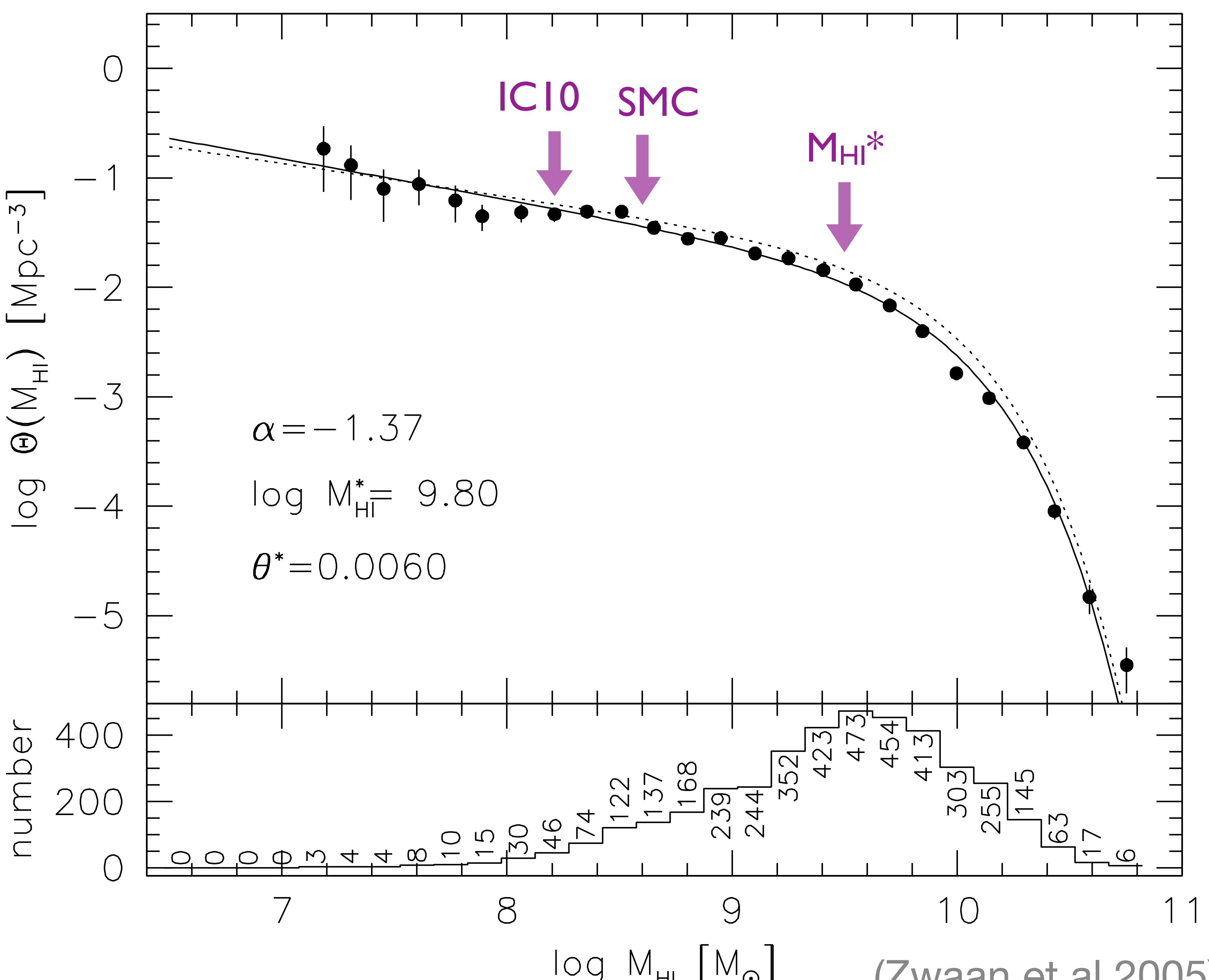


AHISS
(Zwaan et al 1997)

~66 galaxies

The HI mass function at z=0



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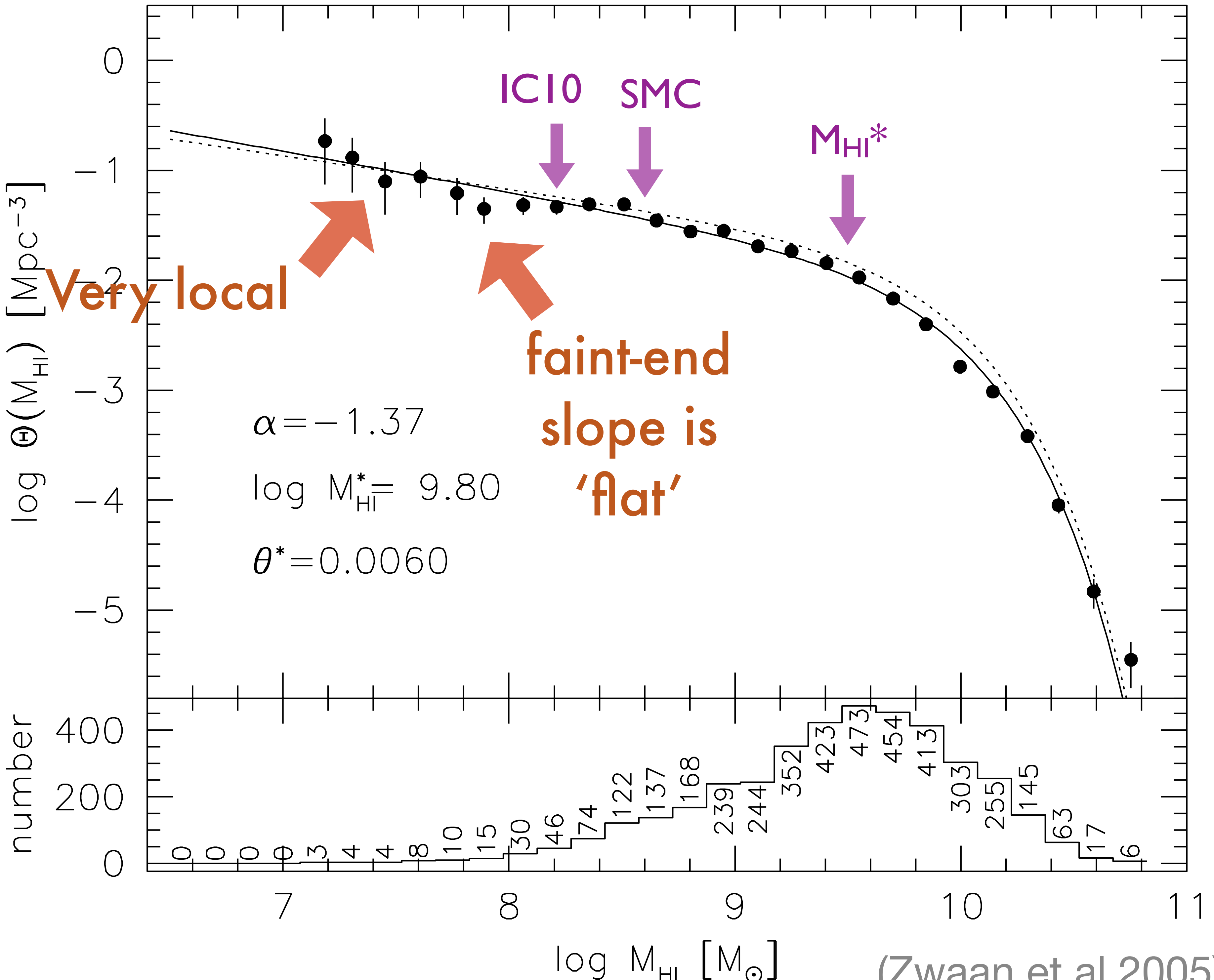

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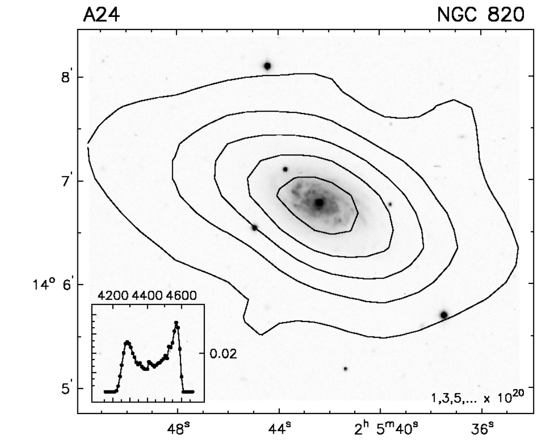

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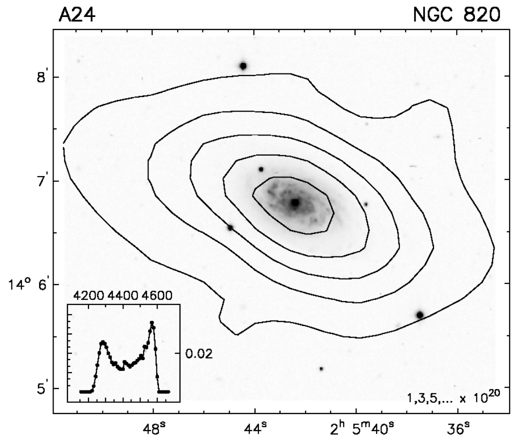

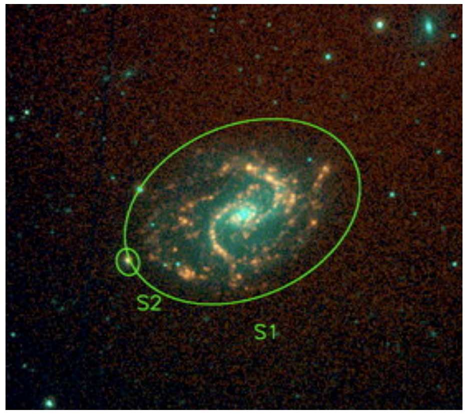

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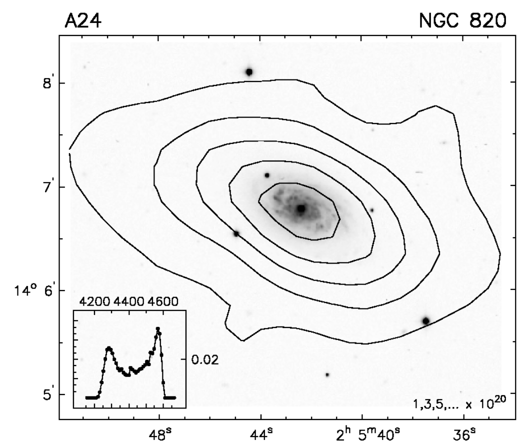

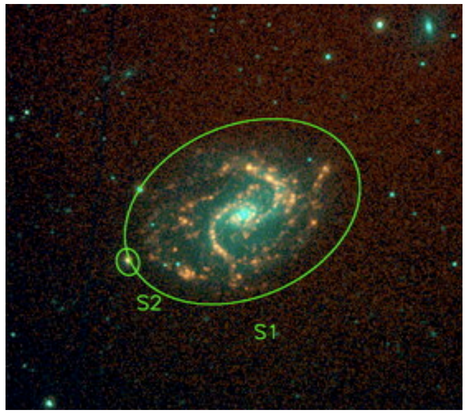

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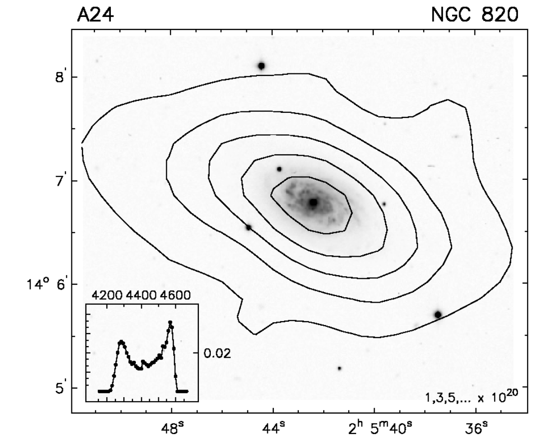
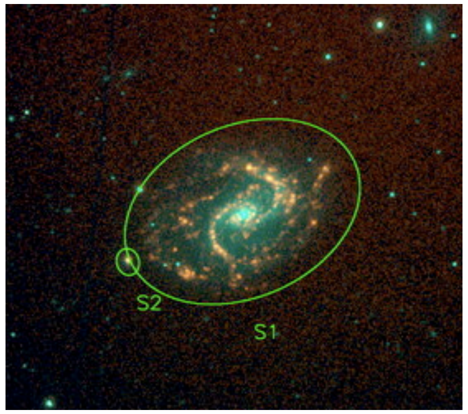
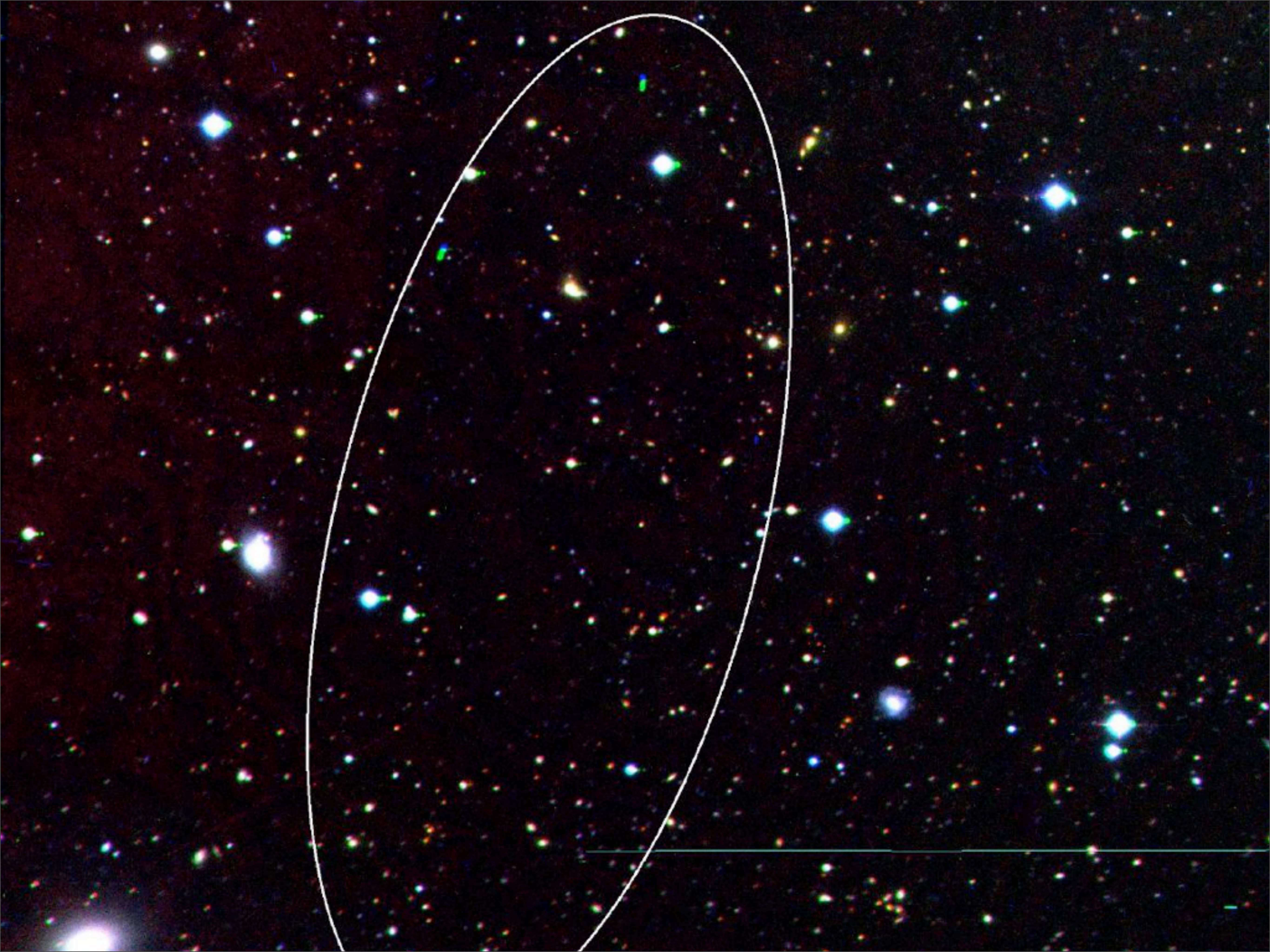
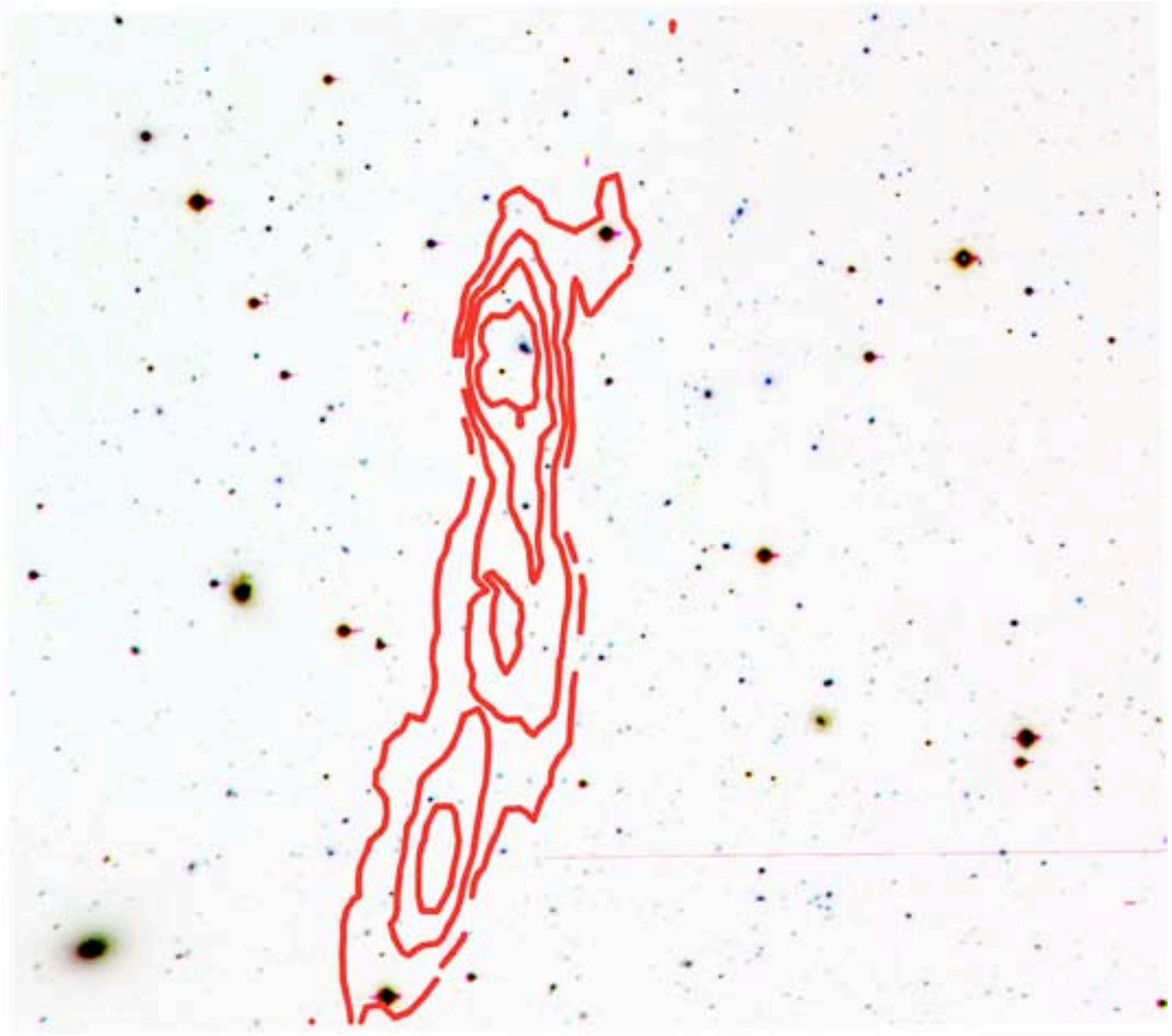
- Virgo HI21? (Minchin et al 2007)...

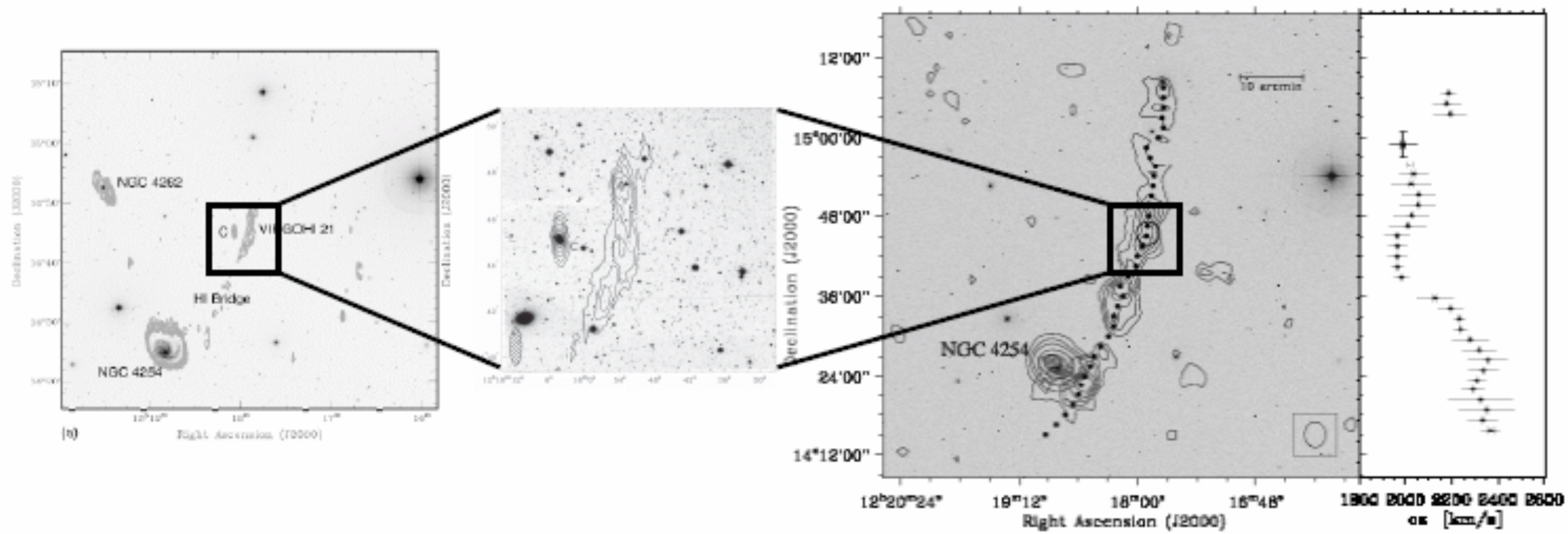






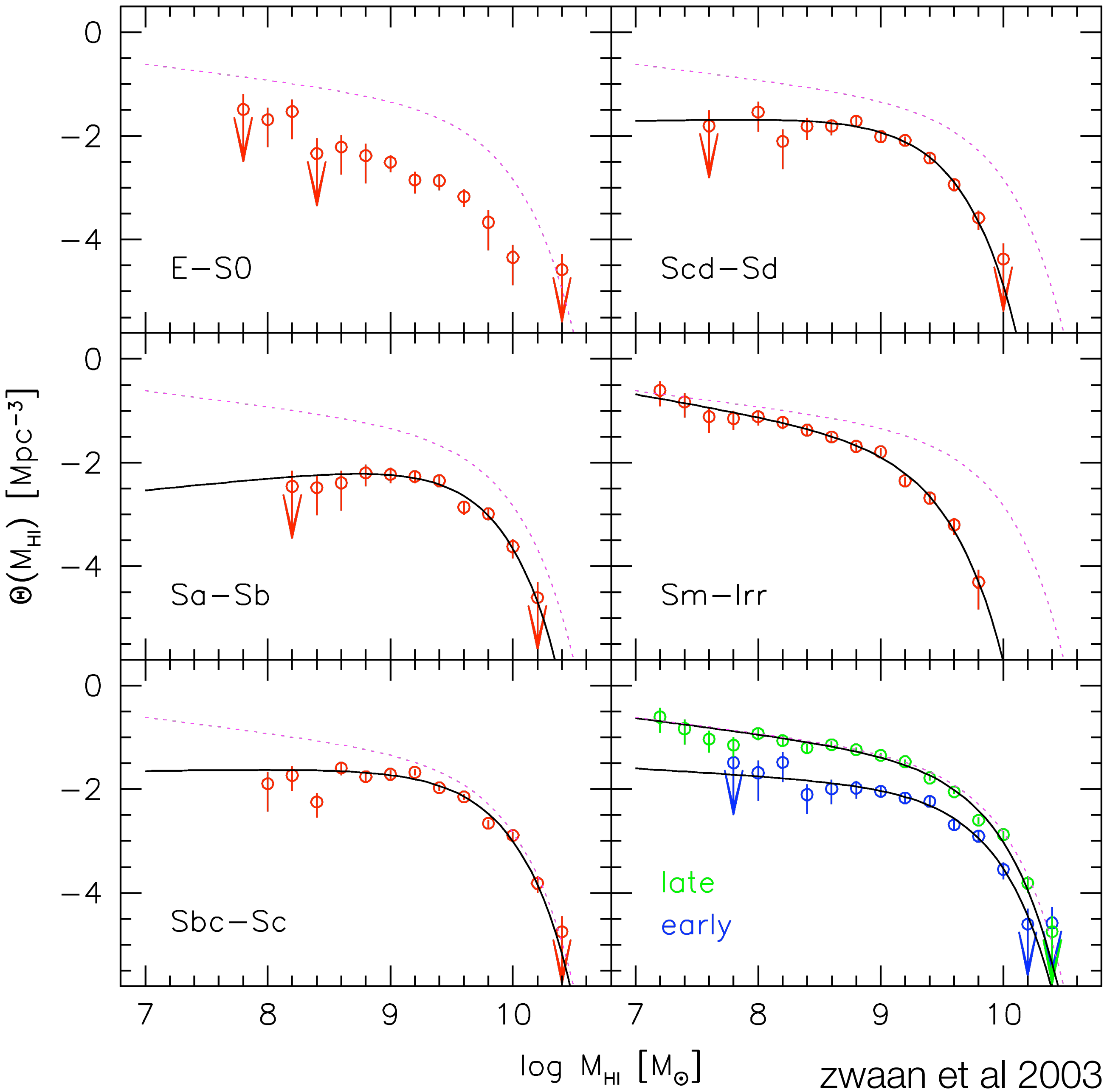


VirgoHI21 is not a galaxy after all...



Kent et al 2007

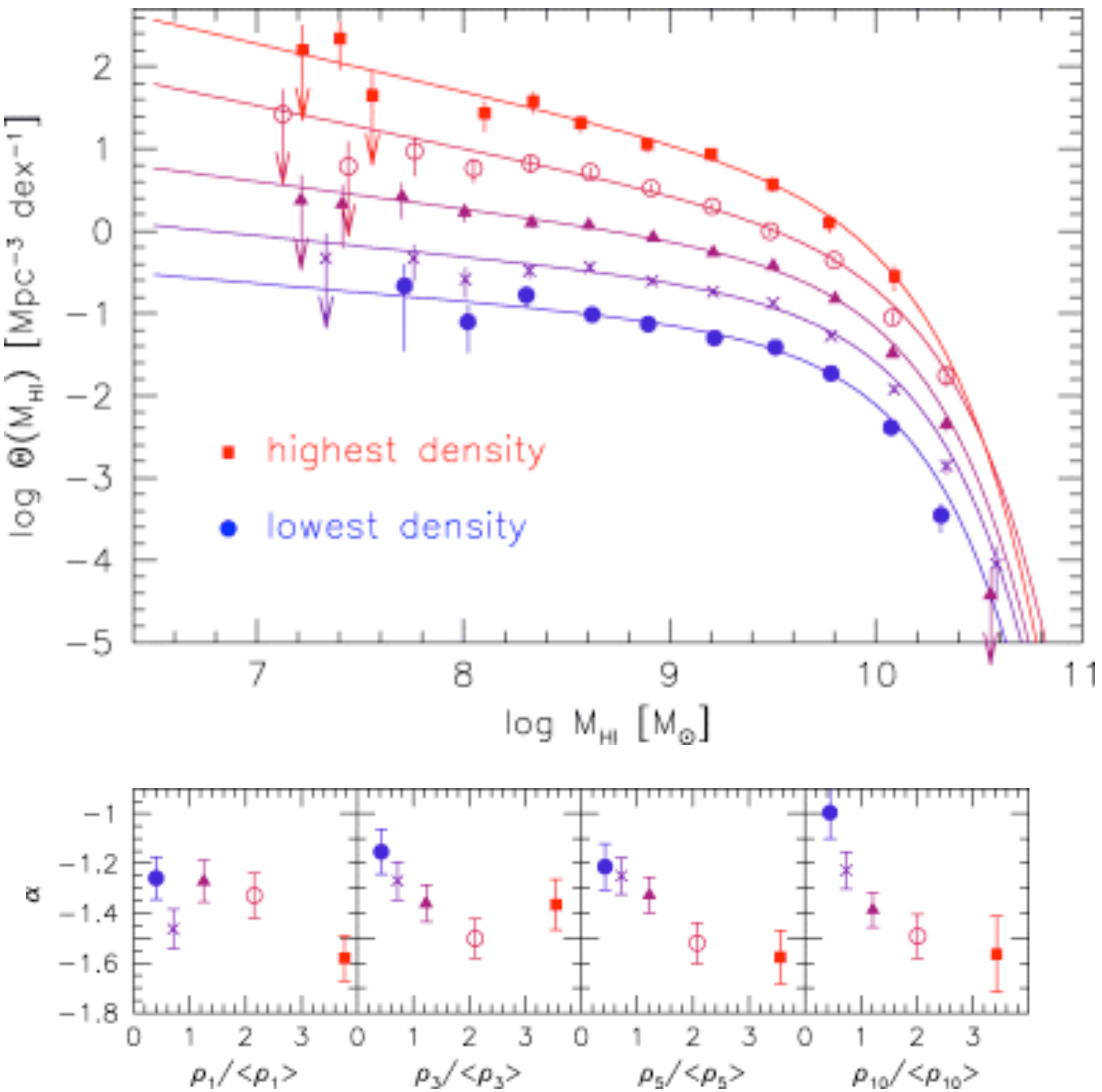
HIMF dependence on galaxy type



zwaan et al 2003

- Low mass end of HIMF dominated by Sm-Irr
- High mass end of HIMF dominated by Sbc-Sc
- Trend consistent with optical luminosity function
- What happens at higher *z*?

Environmental effects on HIMF?

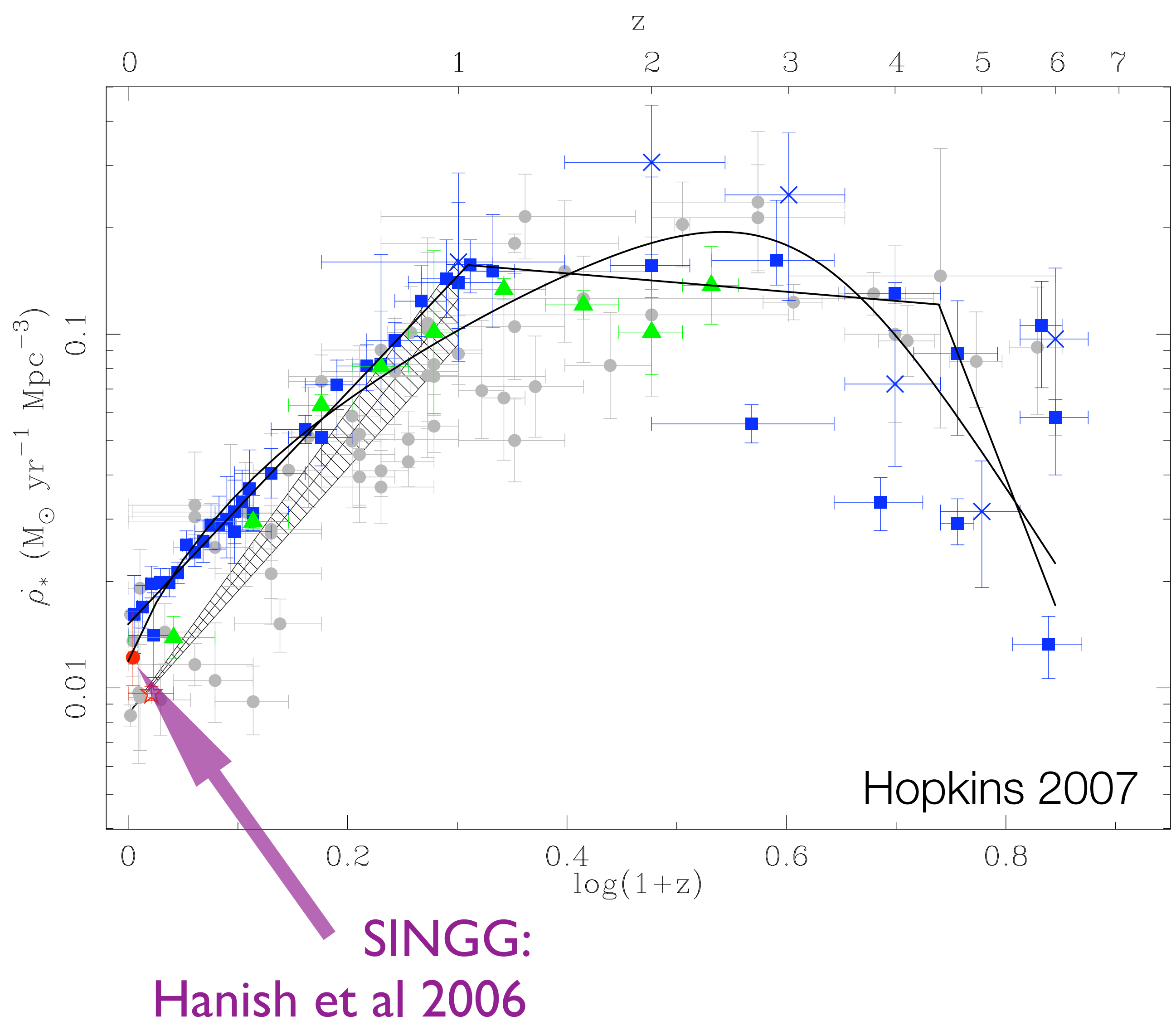


zwaan et al 2005

- Steeper toward higher densities?
- Density contrast lower in HI samples than in optical samples
- Opposite effect seen by Springob et al (2004), based on optically selected galaxies
- Better constraints expected from ALFALFA

SINGG - local star formation rate density

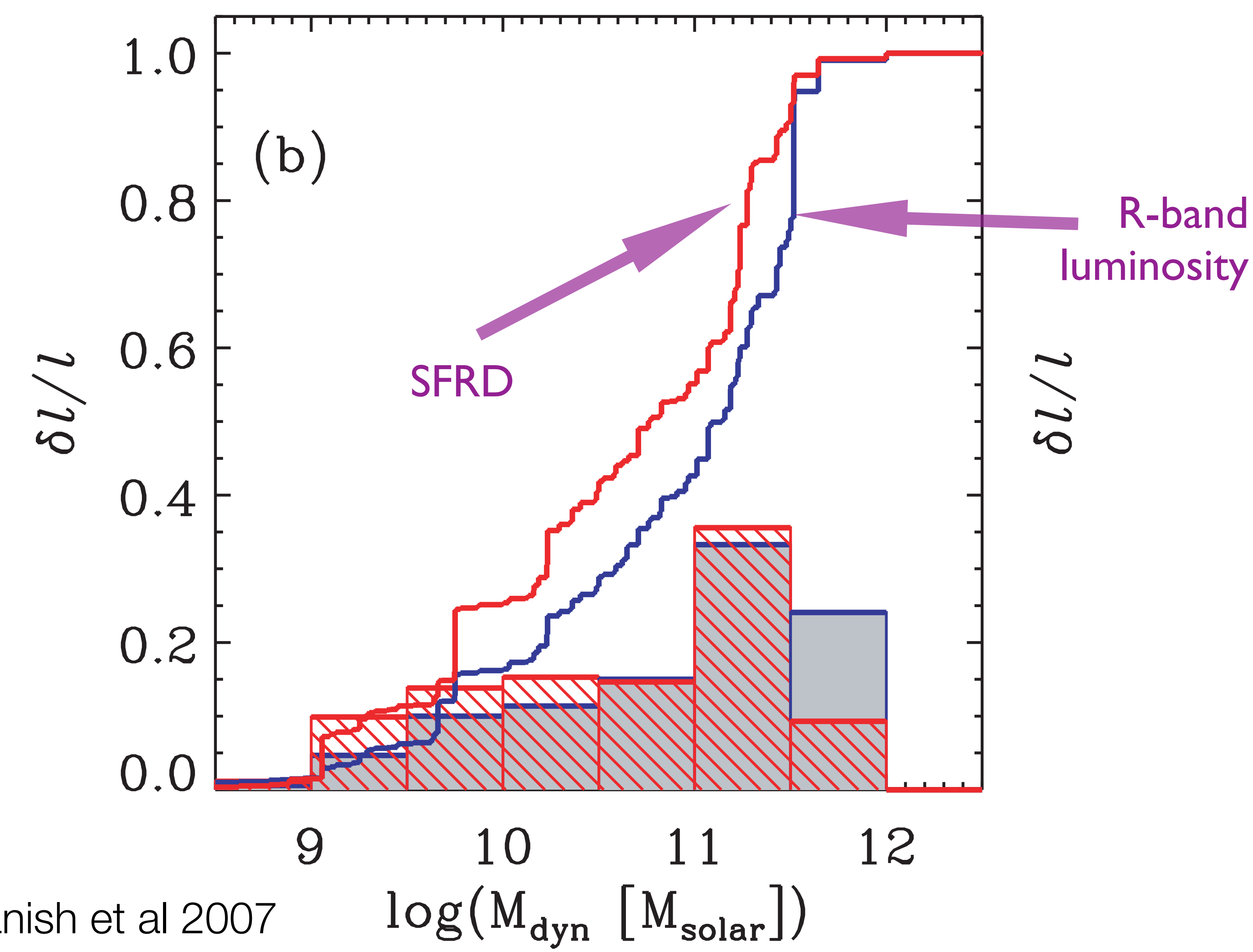
- **S**urvey for **I**onization in **N**eutral **G**as **G**alaxies (PI: Meurer)
    - Hα mapping of 468 galaxies from HIPASS
    - GALEX NUV and FUV observations of ~170 SINGG sources
- Estimates of star formation rate density normally plagued by selection effects:
    - UV-selection, optical selection, FIR-selection,...
- HIPASS selects galaxies by their fuel for star formation (Kennicutt-Schmidt law)



- SFRD(z=0) based on UV will follow shortly

SINGG - local star formation rate density

- Test how star formation rate density is distributed over galaxies of different mass



Hanish et al 2007

- Low mass galaxies contribute more to SFRD than to luminosity density: "Downsizing"

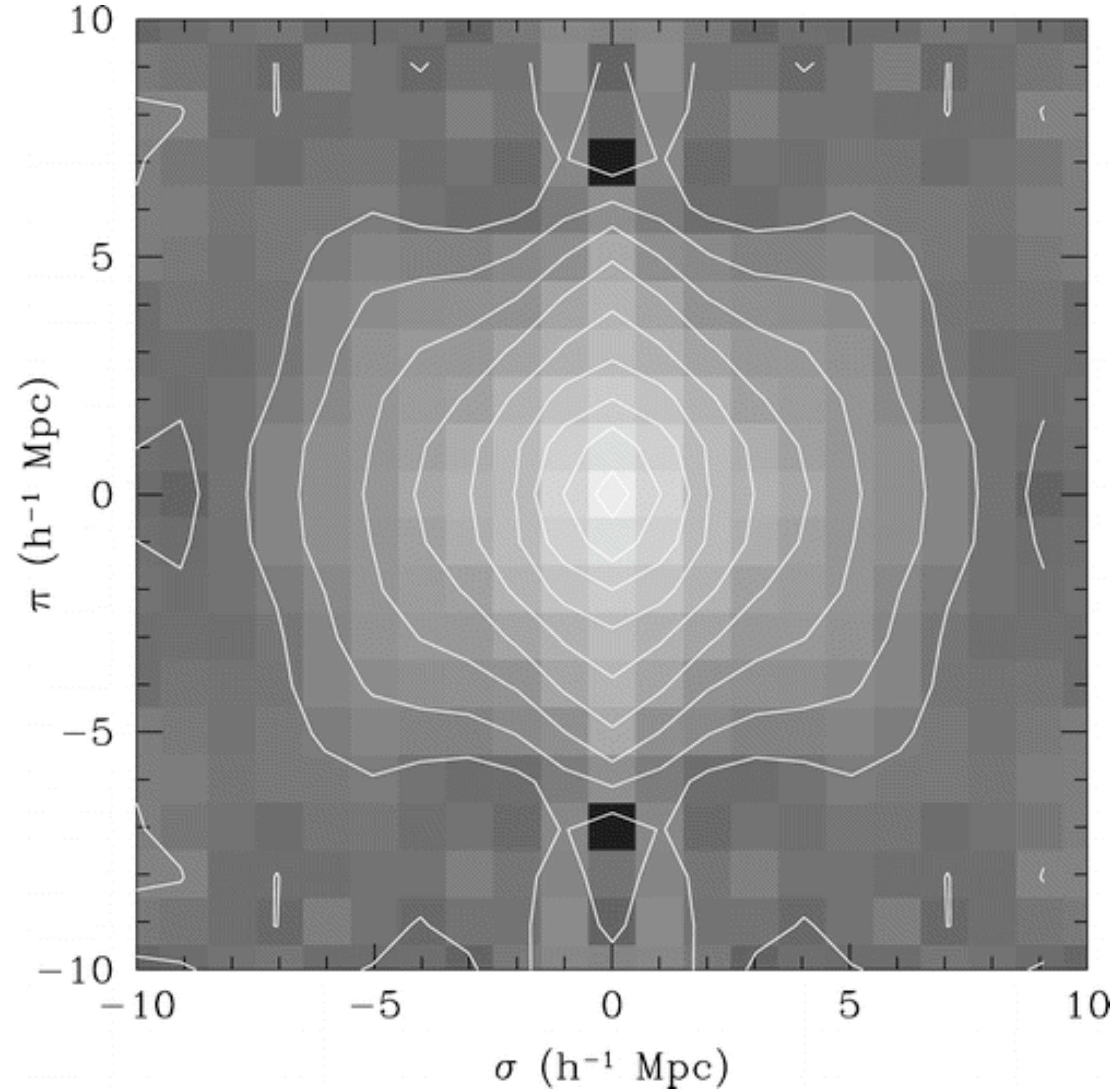
Weak clustering of gas-rich galaxies

(Meyer, Zwaan, et al, 2007)

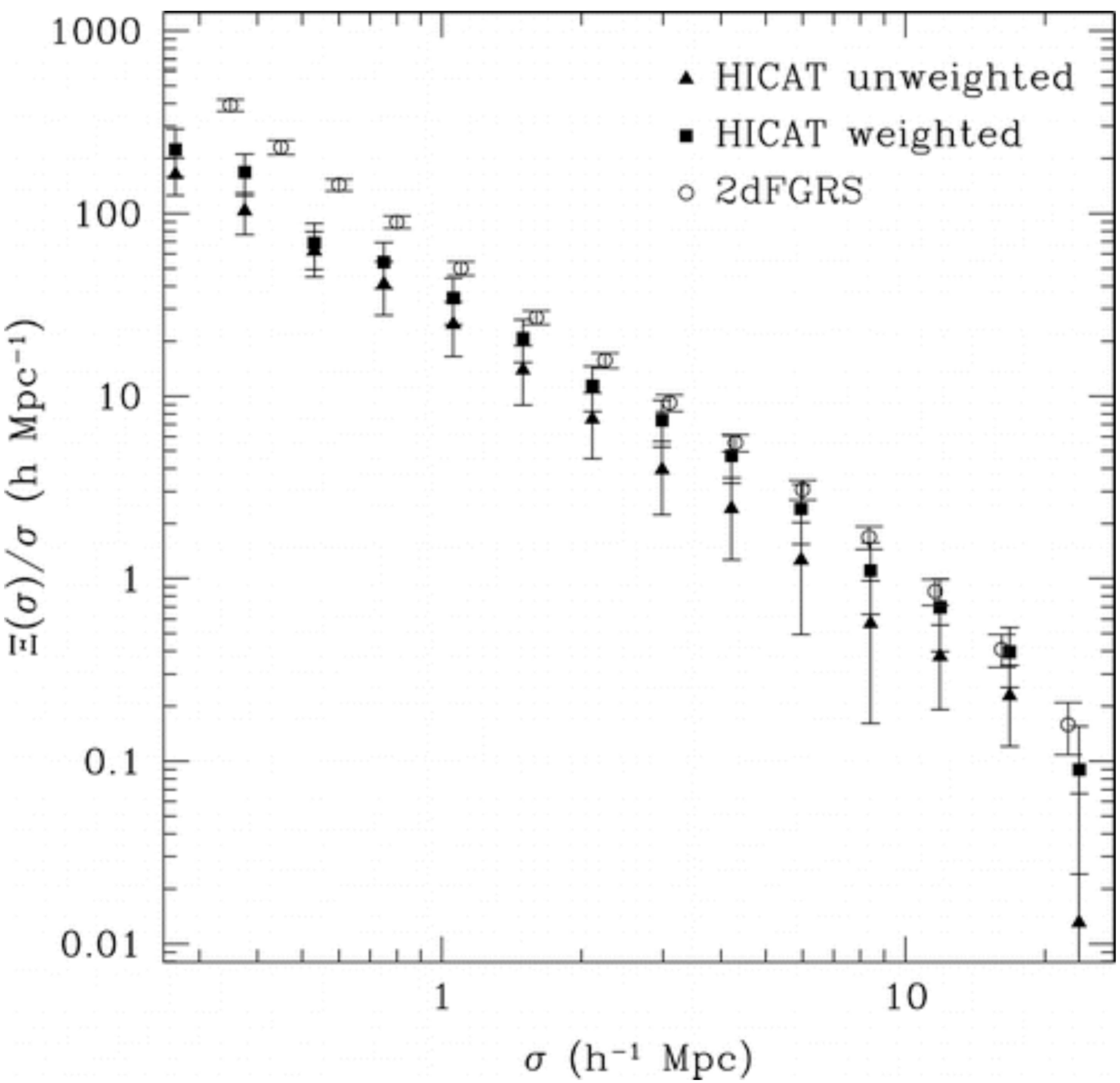
- 2-pt correlation function
  - measures excess number of galaxy pairs at given separation
- Well-studied in the optical (2dFGRS, SDSS)
  - bright vs faint (Norberg et al., 2002, 2001)
  - by spectral type (Norberg et al., 2002)
  - by colour (Zehavi et al.,2002)
  - by star-formation activity (Madgwick et al. 2003)
- What is the HI story?

2-pt correlation function

- “finger-of-God” effect
  - line-of-sight velocity dispersion
- Large scale flattening
  - coherent infall of galaxies



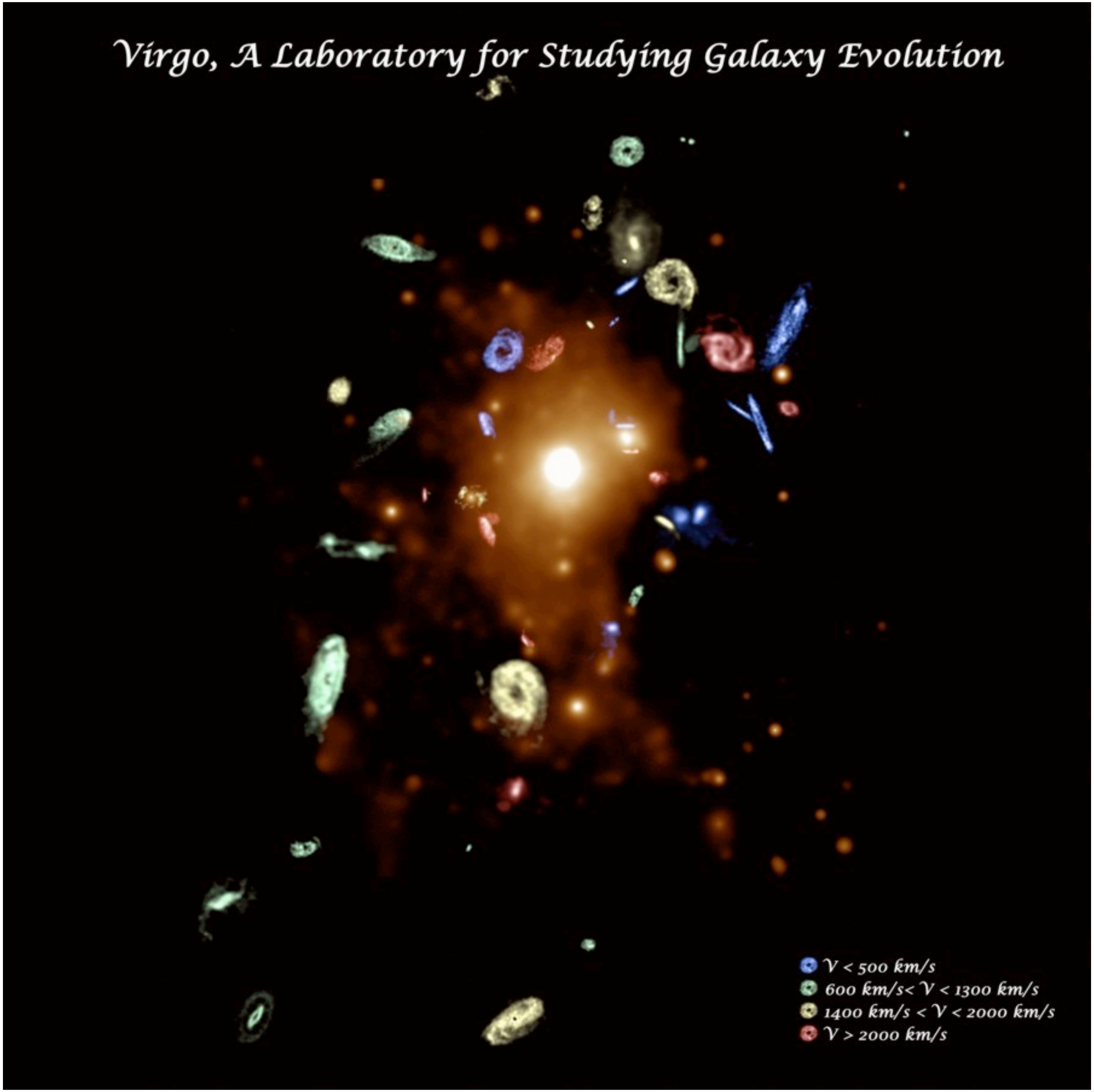
2-pt correlation function



- Projected two-point correlation function
- Gas-rich galaxies clearly more weakly clustered
  - R_0=3.2 Mpc
- This can be done at high-z with the SKA

2-pt correlation function

- Gas-selected galaxies are the most weakly clustered galaxies known
- Clustering strength depends on luminosity and rotational velocity (halo mass), not on HI mass
- Nature or nurture?
  - Environmental effects (tidal stripping, ram pressure stripping, strangulation,...)



Chung et al 2008

2-pt correlation function

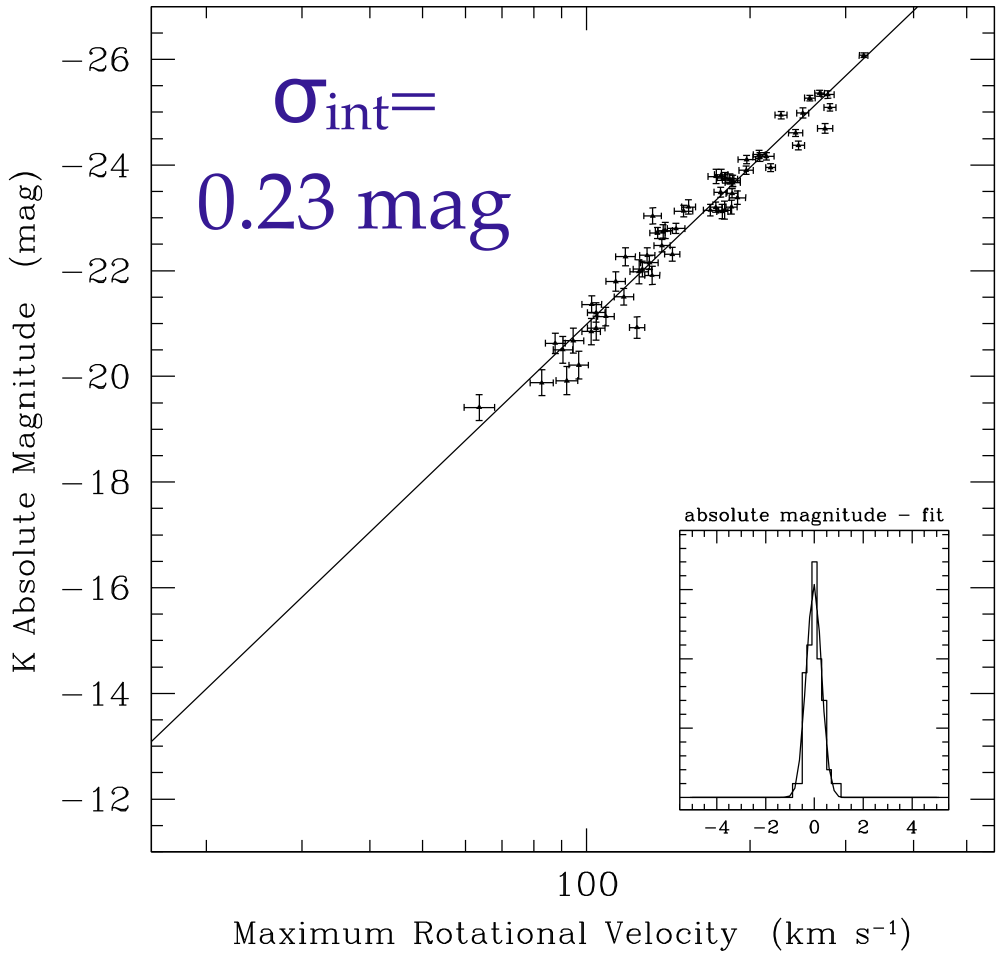
- Gas-selected galaxies are the most weakly clustered galaxies known
- Clustering strength depends on luminosity and rotational velocity (halo mass), not on HI mass
- Nature or nurture?
  - Environmental effects (tidal stripping, ram pressure stripping, strangulation,...)
  - Or, gas-rich galaxies form in intrinsically less clustered dark matter halos.
    - CDM simulations: the brightest galaxies form in the most clustered and massive dark matter halos
    - HI–rich galaxies only forming in the low-medium peaks of the initial density field

Tully-Fisher relation for HI-selected galaxies

- HI-selected galaxy sample unique. No pre-selection of candidates. All velocity widths derived from survey data.
- Cross-correlate HIPASS with 2MASS (J, H, K magnitudes), and ESO-LV (B)
- Use all standard corrections for
  - inclination
  - velocity widths
  - extinction

Tully-Fisher relation for HI-selected galaxies

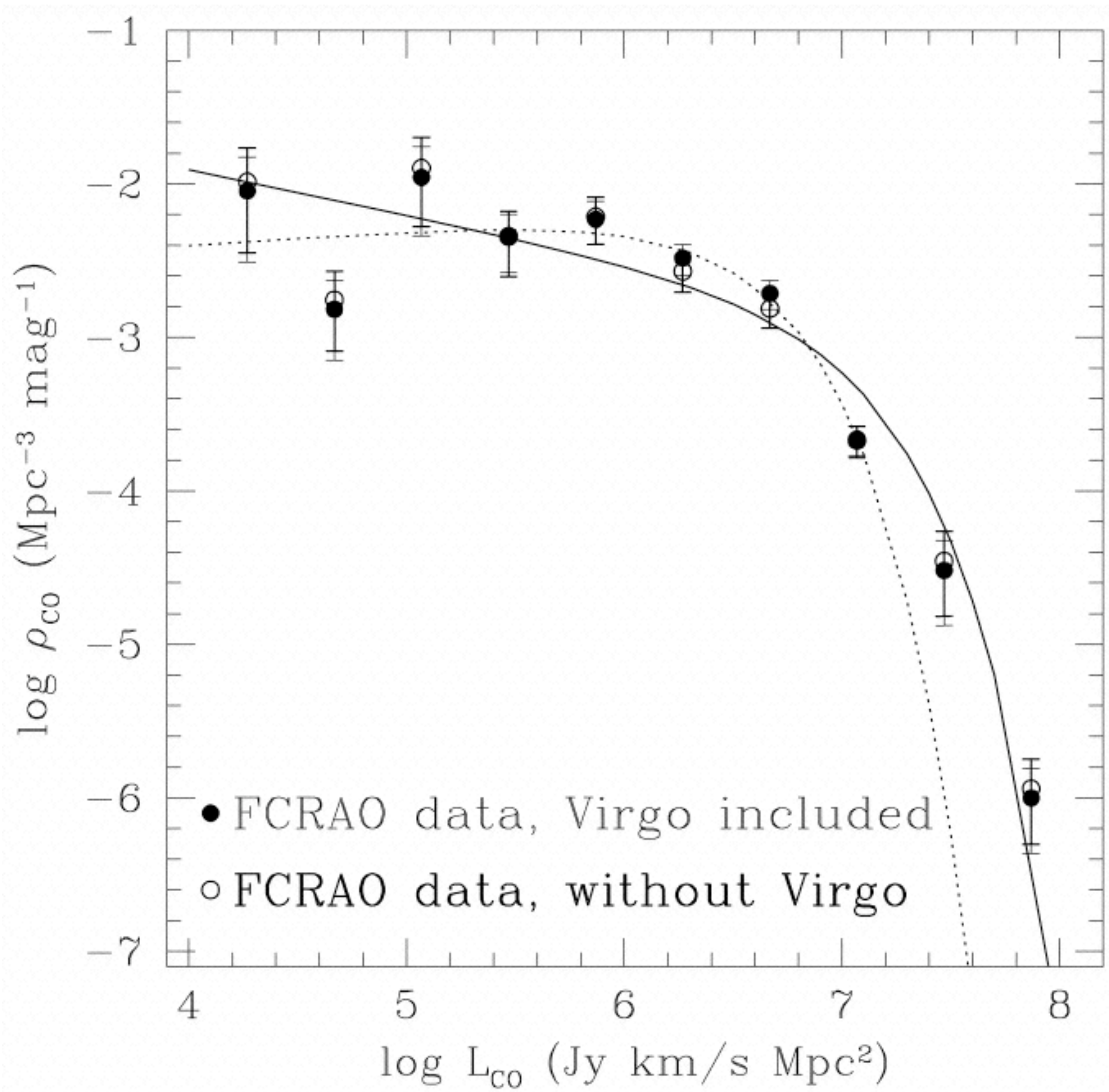
- Minimize observational errors by applying cuts:
  - inclination > 75º
  - size > 30”
  - angle from CMB dipole equator < 20º
  - velocity > 1000 km/s



- with SKA do this at redshifts z=1 to z=2

back to evolution of gas...

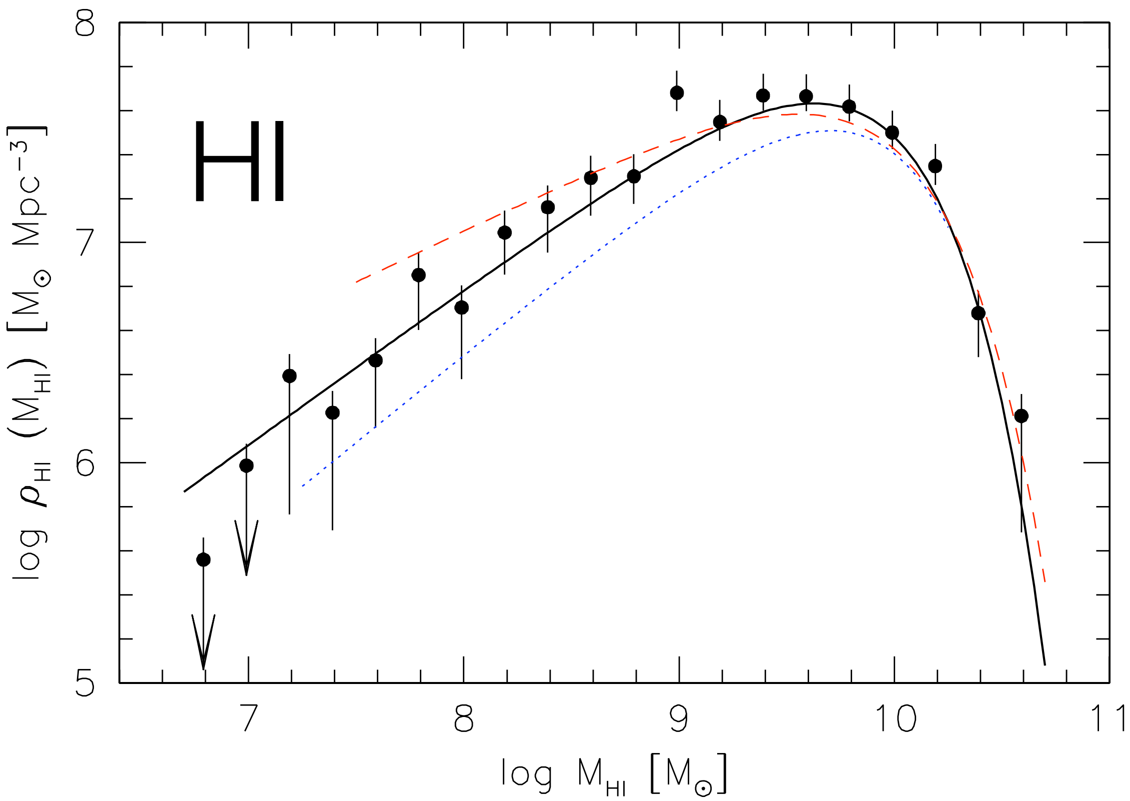
‘H_2’ mass function of galaxies



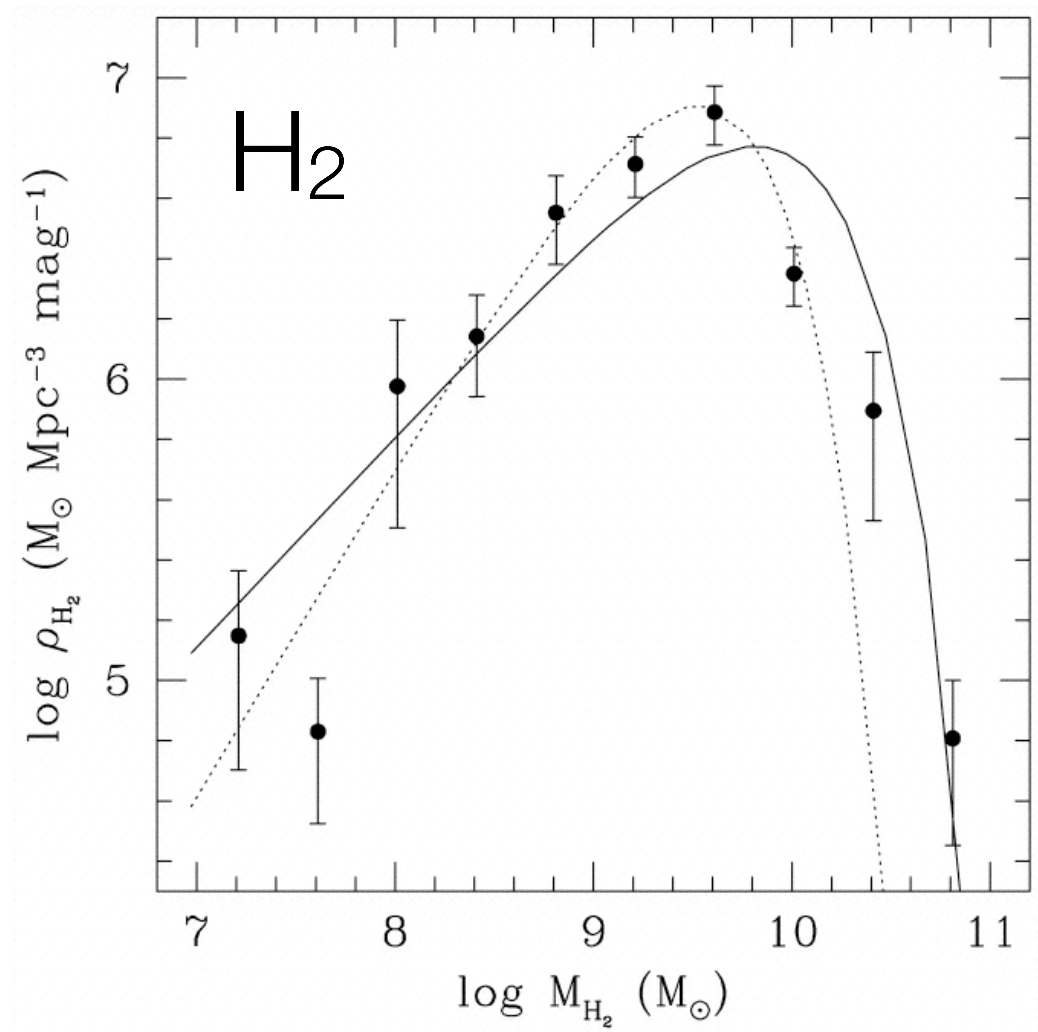
$\Omega_{H2}=0.5\ \Omega_{HI}$

Keres, Yun, Young, 2003, AJ, 582, 659

L* galaxies dominate the gas mass density



Zwaan et al 2003

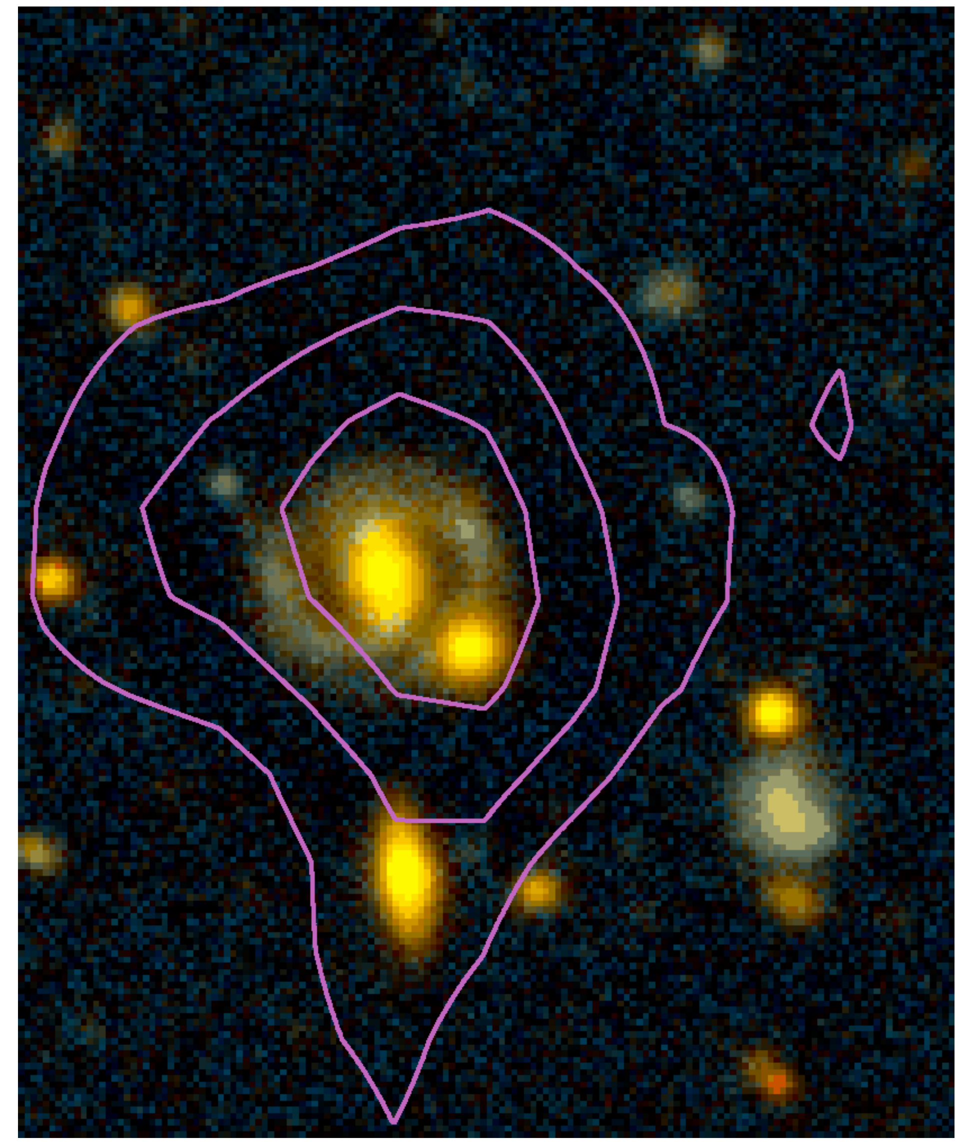


Keres et al 2003

- We need to find at least L* galaxies at high redshift to constrain Ω_{gas}

...but 21-cm line is very weak

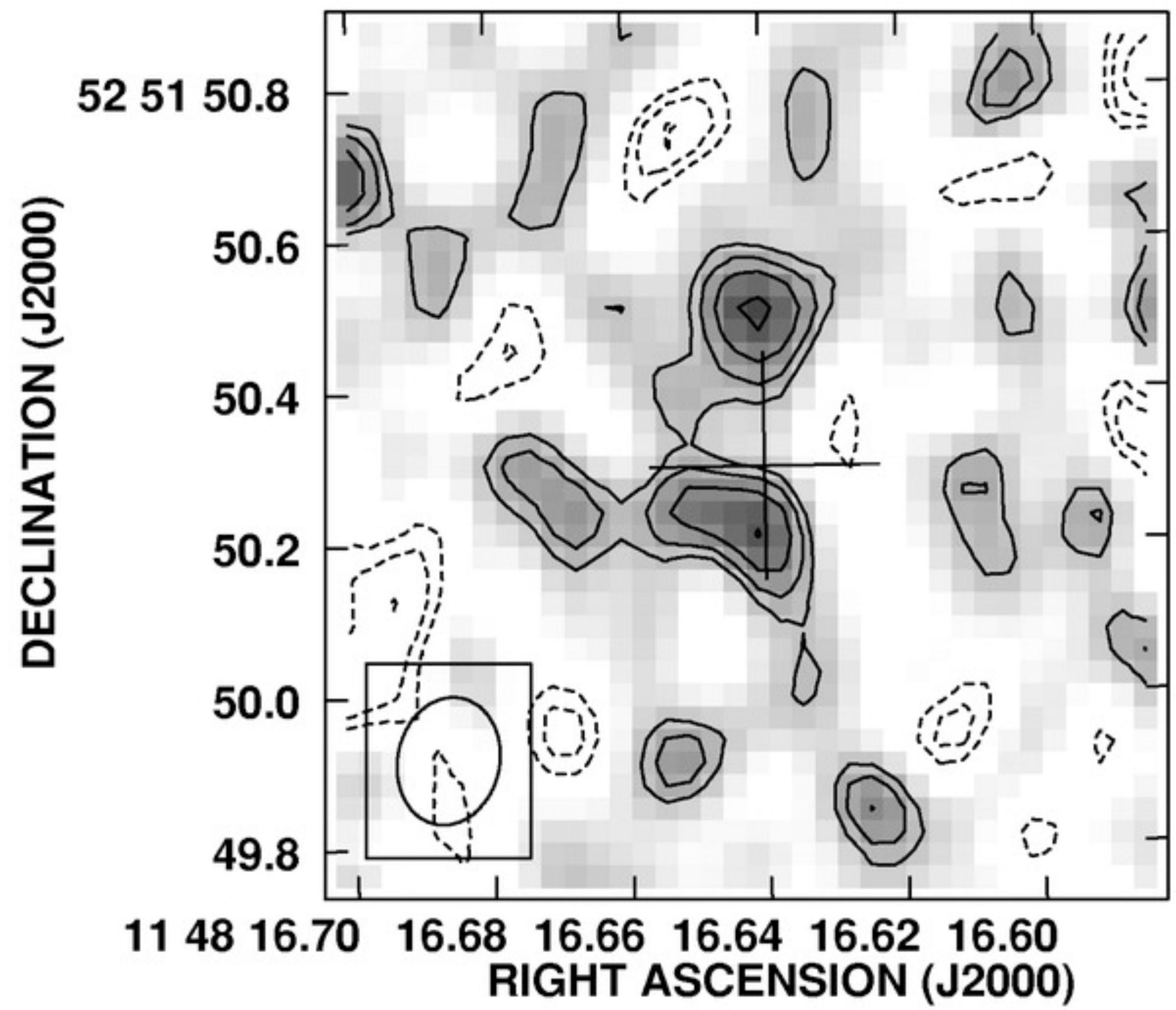
- highest redshift 21-cm emission detection at z=0.2
- HI mass: 2.3 x 109 Mo detected in ~200 hours with Westerbork
- Need SKA for 21-cm emission line surveys at z>0.2



Zwaan, van Dokkum, Verheijen 2001, Science, 293, 1800

...and CO at high z only detected in very massive galaxies

- highest redshift CO emission detection at z=6.4
- H2 mass: ~2 x 1010 Mo detected in ~60 hours with the VLA
- Need ALMA to map CO in regular galaxies at z~3



Walter et al. 2004, ApJ, 615, L17

HI at high redshift: absorption

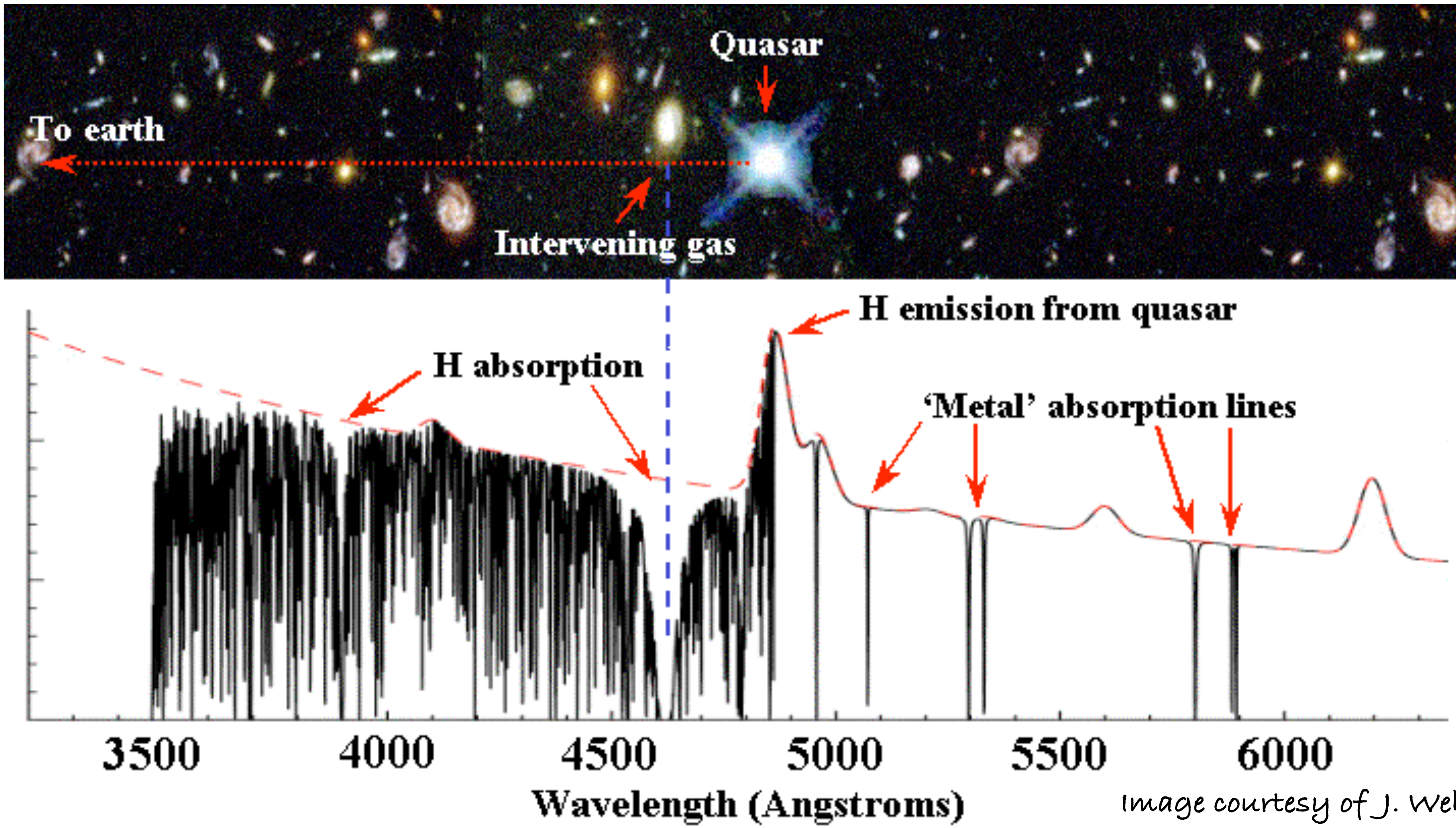


Image courtesy of J. Webb

HI at high (z>0) redshift

- Highest HI column density absorbers: Damped Lyman-α Absorbers (DLAs)
  - Column densities similar to those observed in local galaxies in 21cm
  - Rarest of all HI absorbing systems at all z (~600 known)
  - But contain most of the HI atoms in the universe

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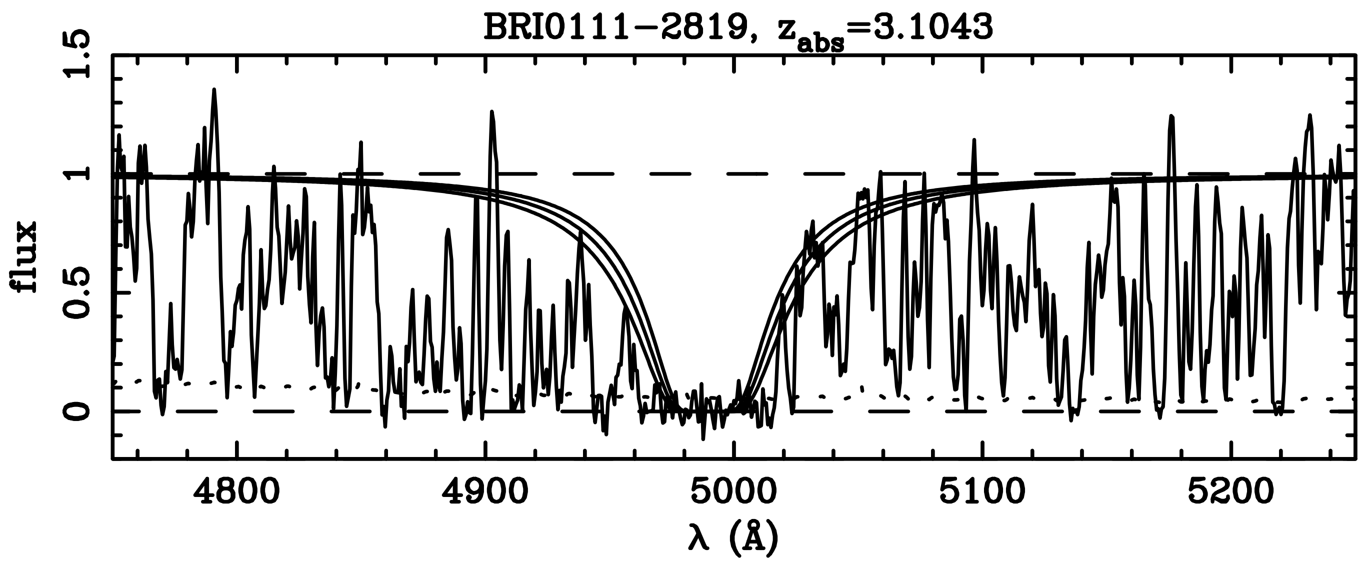


What can we learn from **local galaxies** to understand **DLAs**?

Treat local galaxies as if they were DLAs and calculate “DLA statistics”.

QSO absorption line statistics from local galaxies:

redshift number
density of absorbers

space density
of galaxies

$$dN/dz = c/H_0 \times \text{Area(HI)} \times \mathbf{\Phi}$$

QSO absorption line statistics from local galaxies:

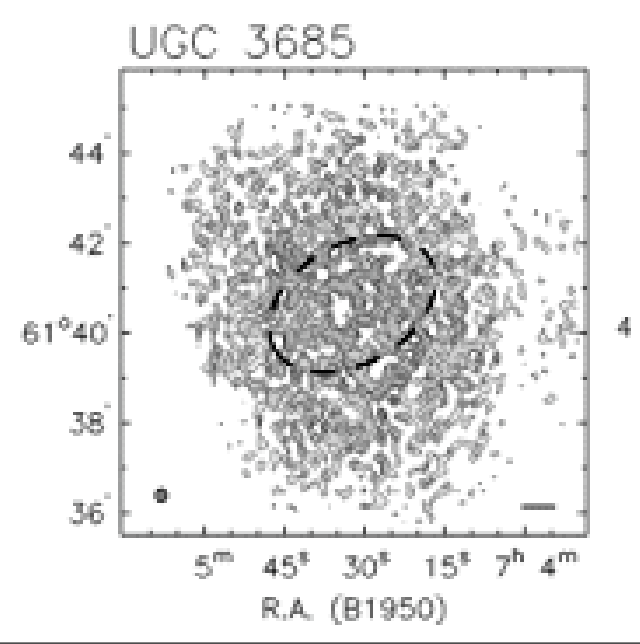
redshift number density of absorbers

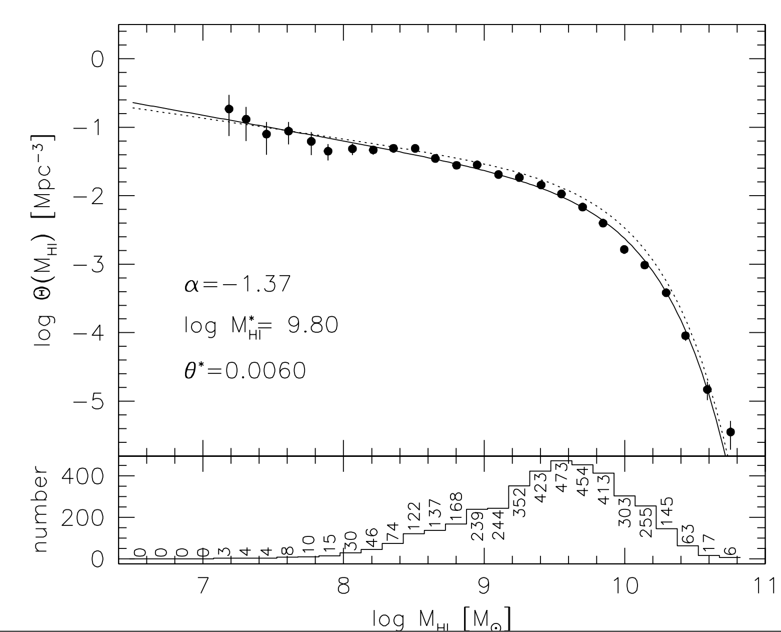
space density of galaxies

$$dN/dz = c/H_0 \times \mathrm{Area(HI)} \times \boldsymbol{\Phi}$$

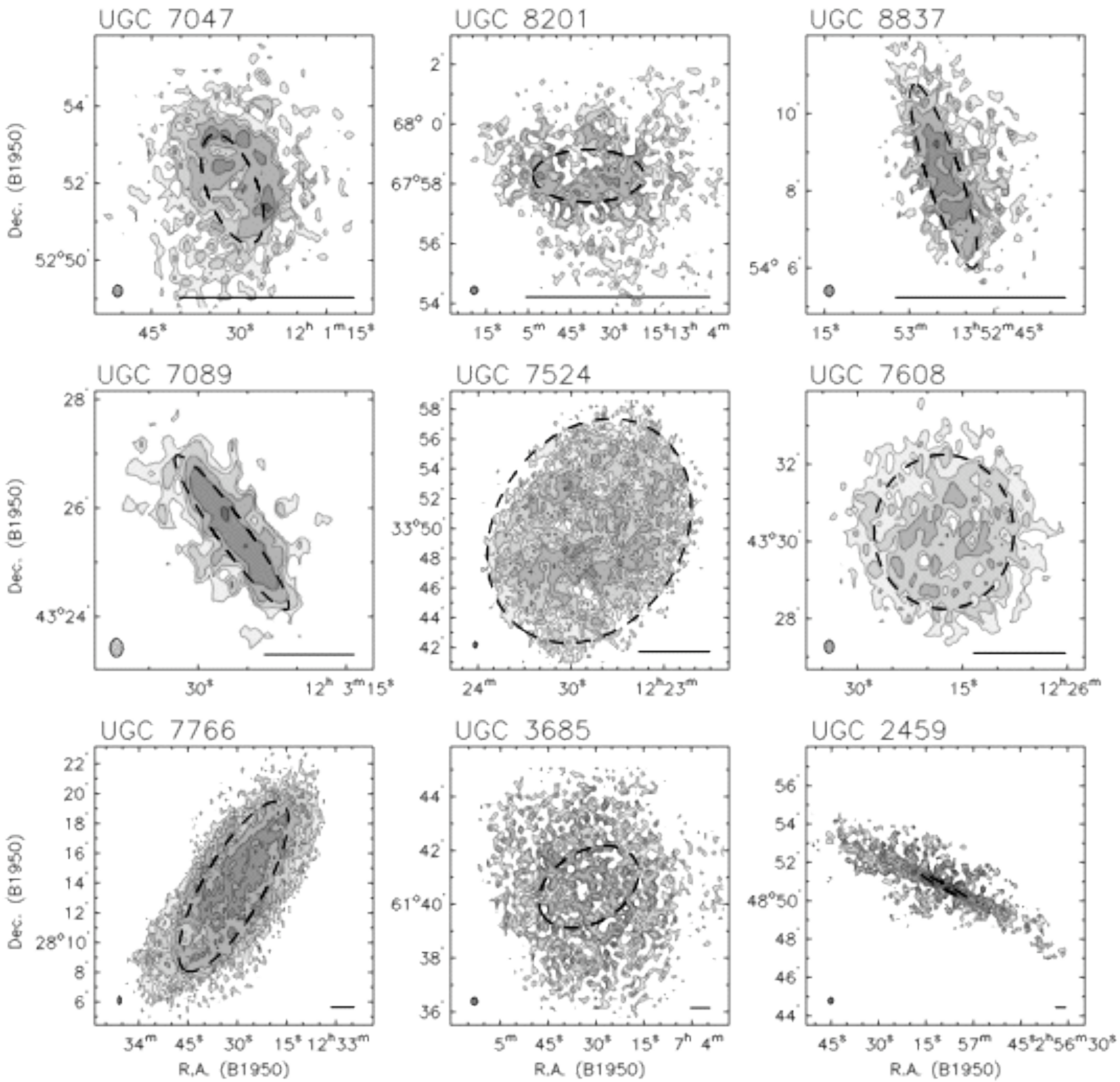
HI imaging

HI mass function





example HI maps

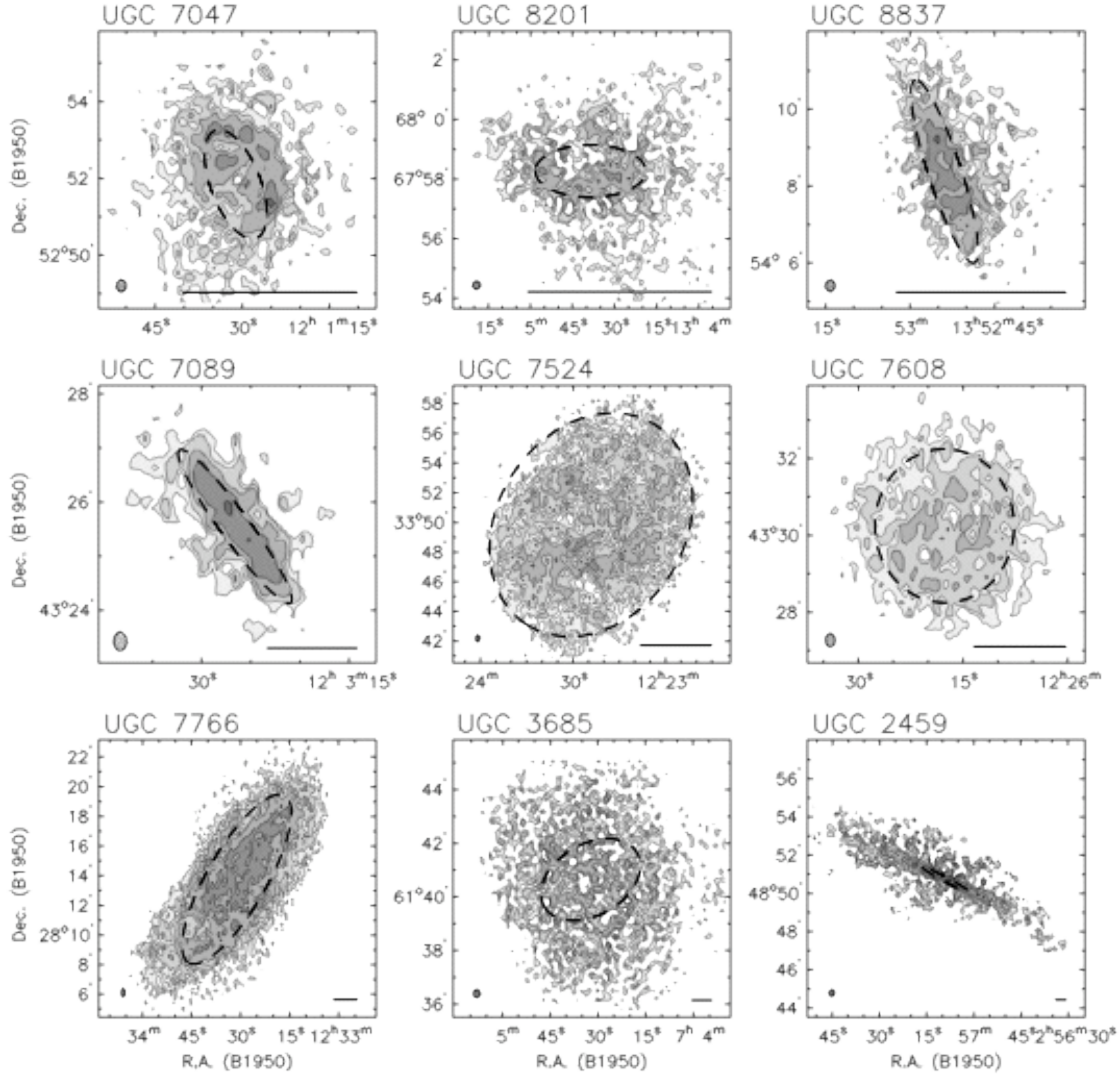


$M_{HI}=10^8\ M_\odot$

$M_{HI}=10^9\ M_\odot$

$M_{HI}=10^{10}\ M_\odot$

example HI maps



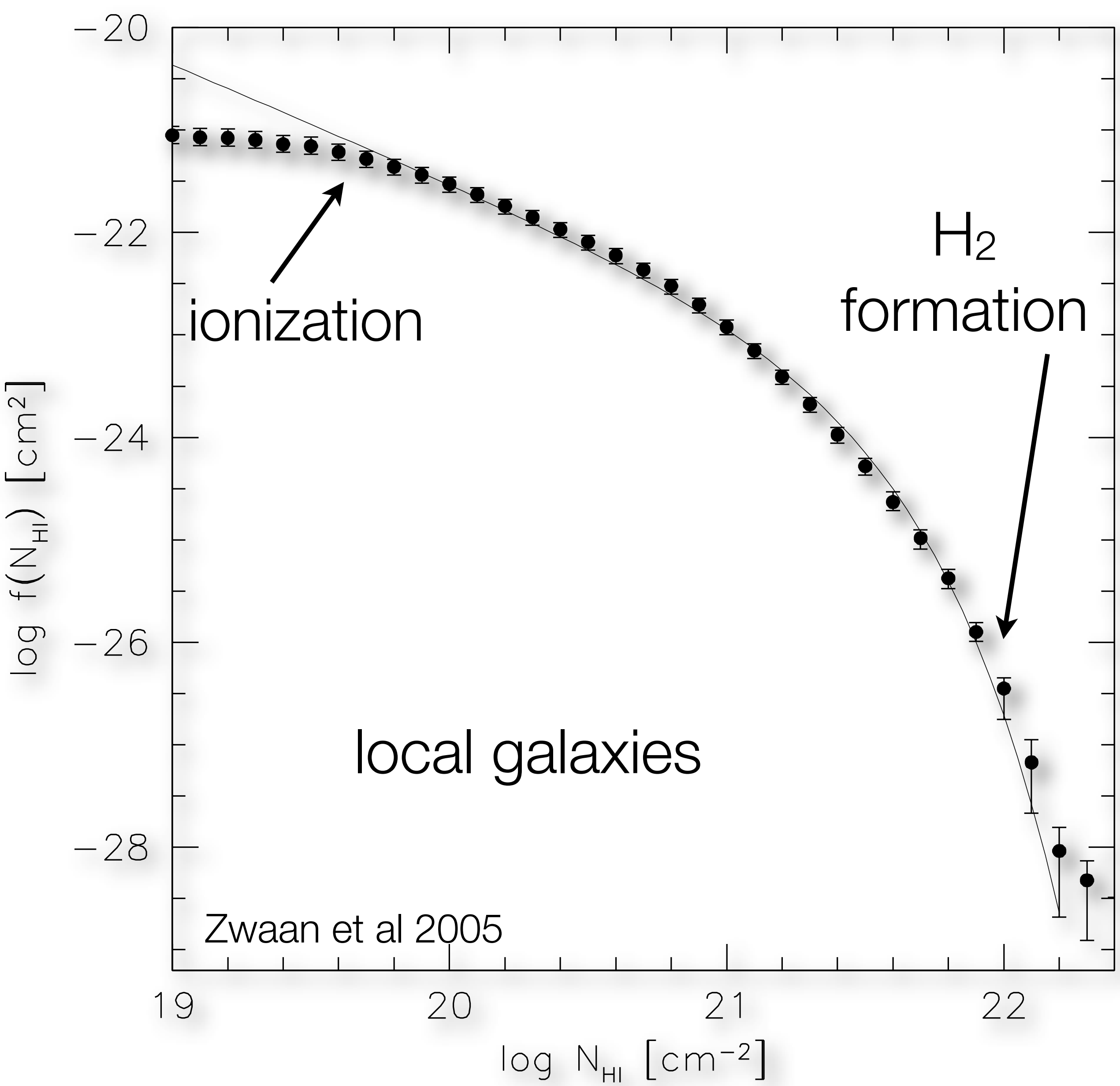
$M_{HI}=10^8\ M_\odot$

$M_{HI}=10^9\ M_\odot$

$M_{HI}=10^{10}\ M_\odot$

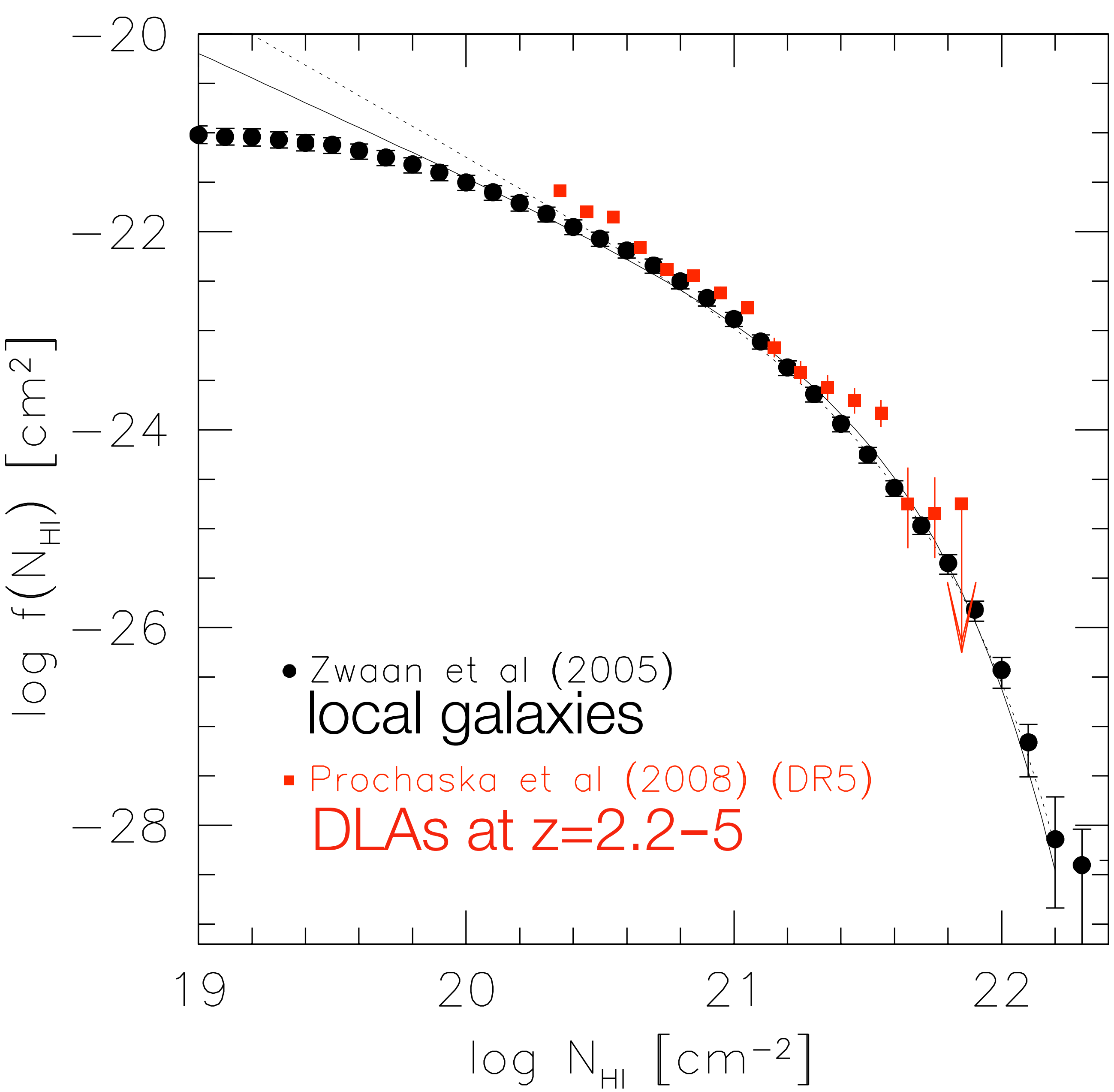
140,000 ‘DLAs’ at z=0

HI column density distribution evolves slowly



- Shape of f(N) is constant in time
- HI distribution in galaxies at z=3 similar to that today?
- Star formation laws similar at higher z?

HI column density distribution evolves slowly



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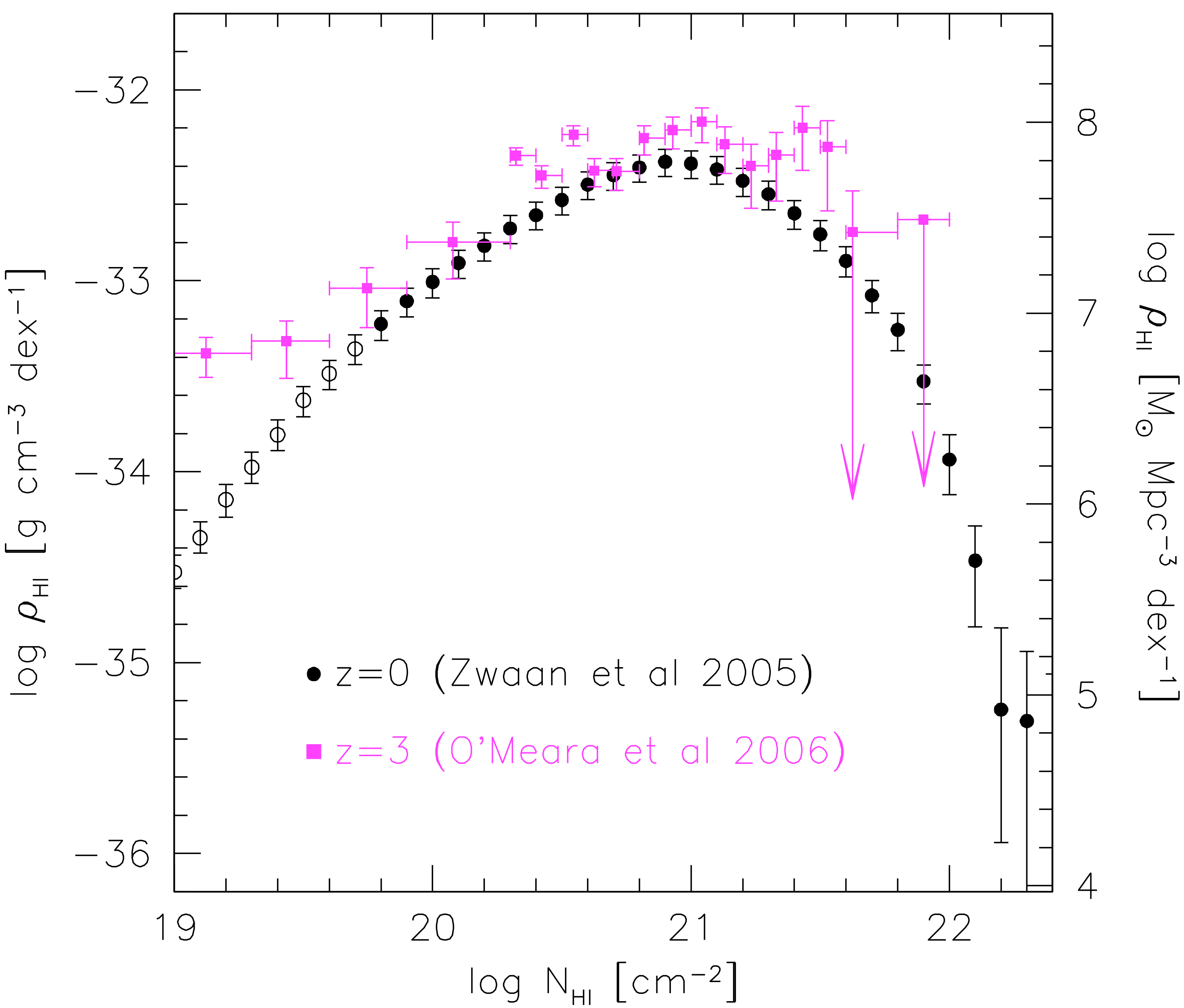
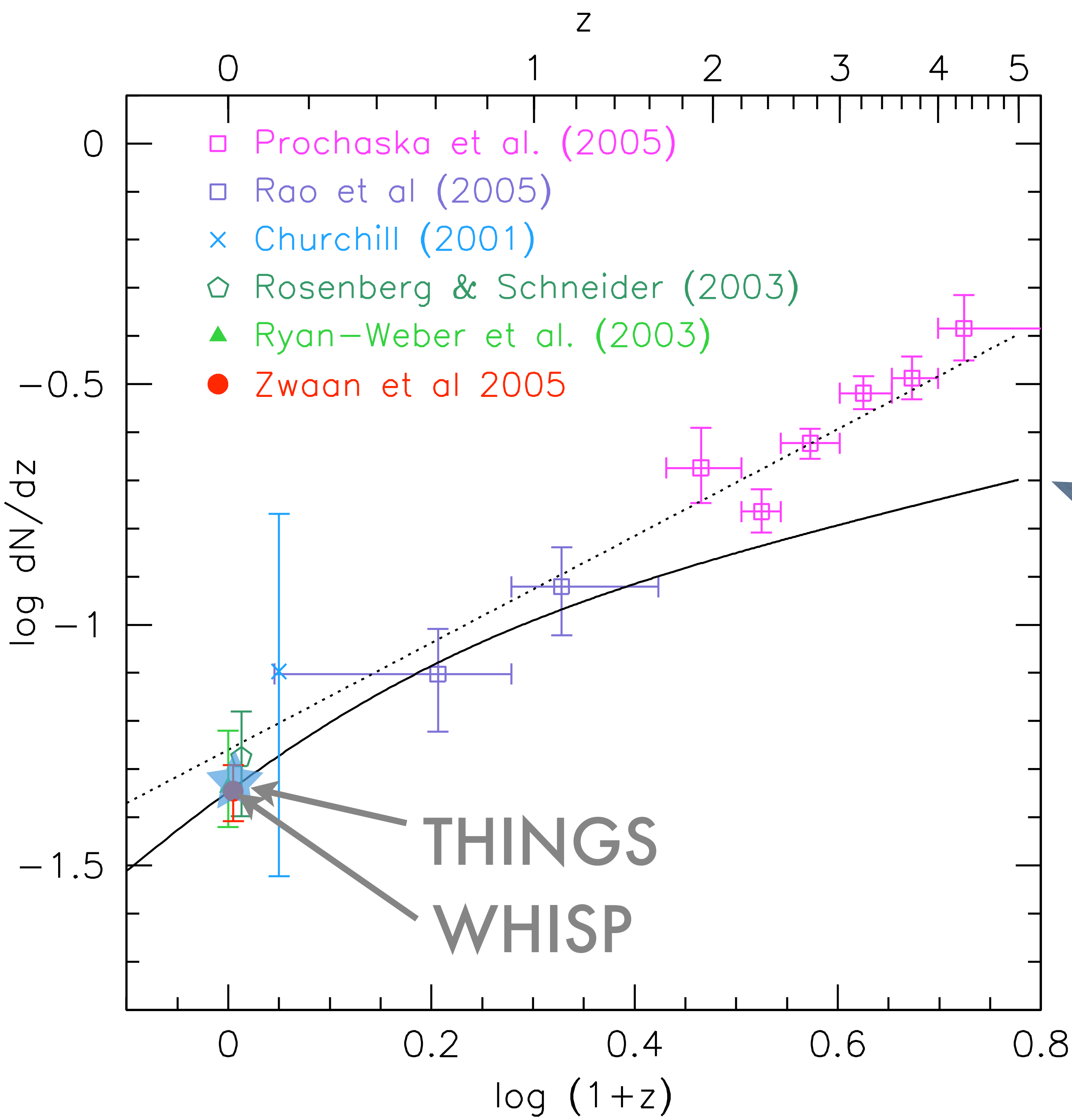


- Most of the HI atoms in column densities around 10^{21} cm^{-2}

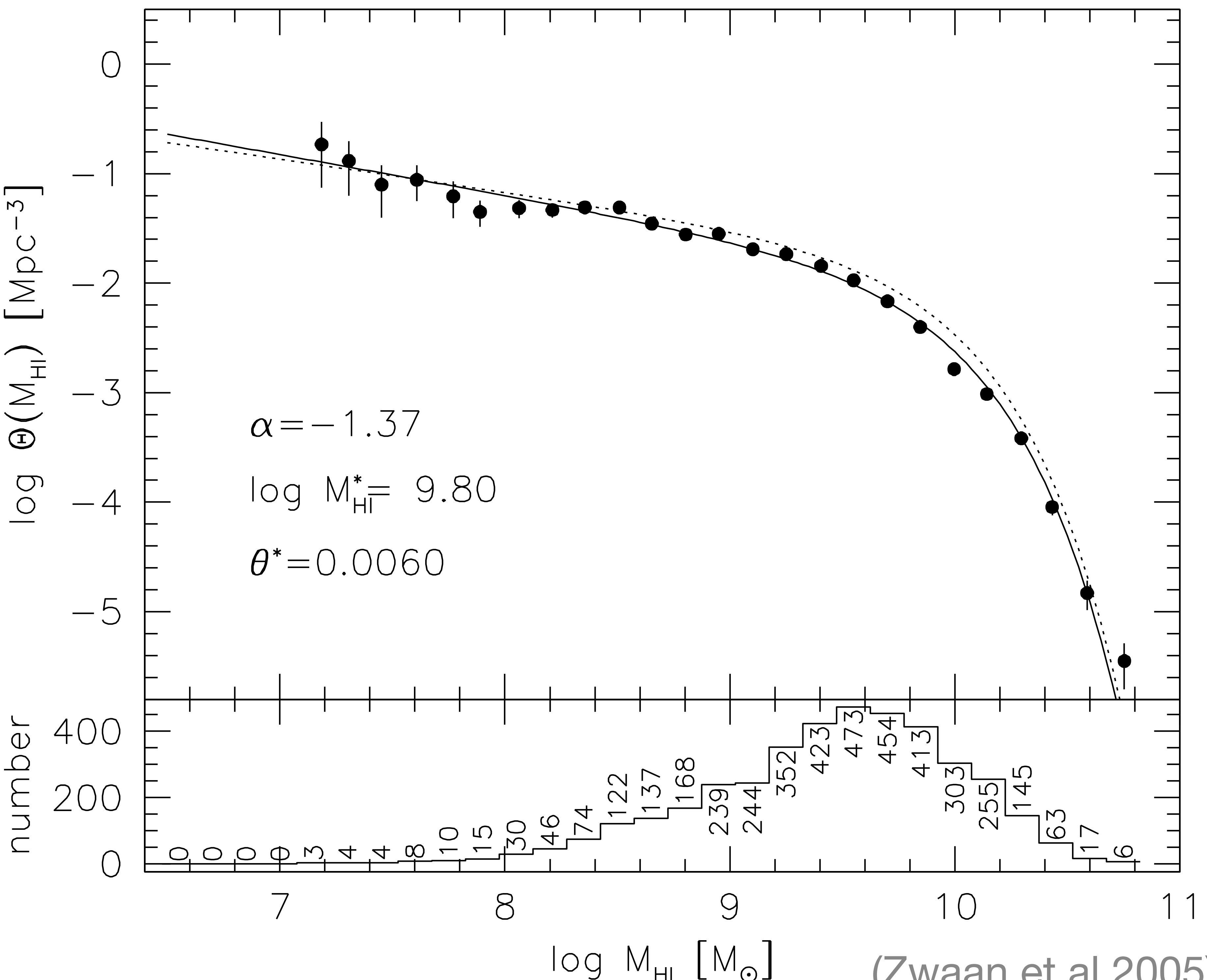
Local galaxies can explain incidence rate



- Local galaxies explain dN/dz of DLAs at z<1.5

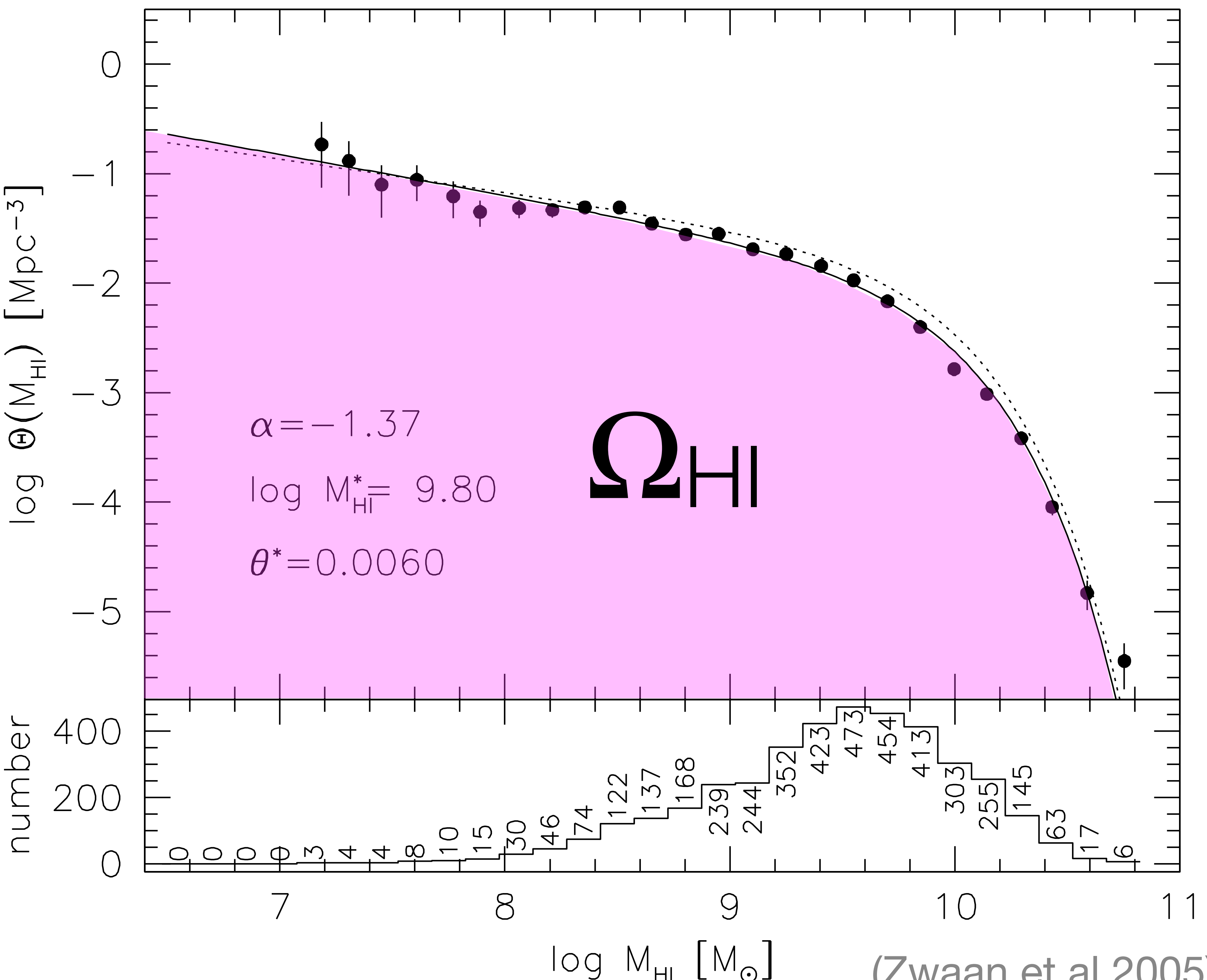
solid line: no evolution in 'number density times cross section'

The HI mass function



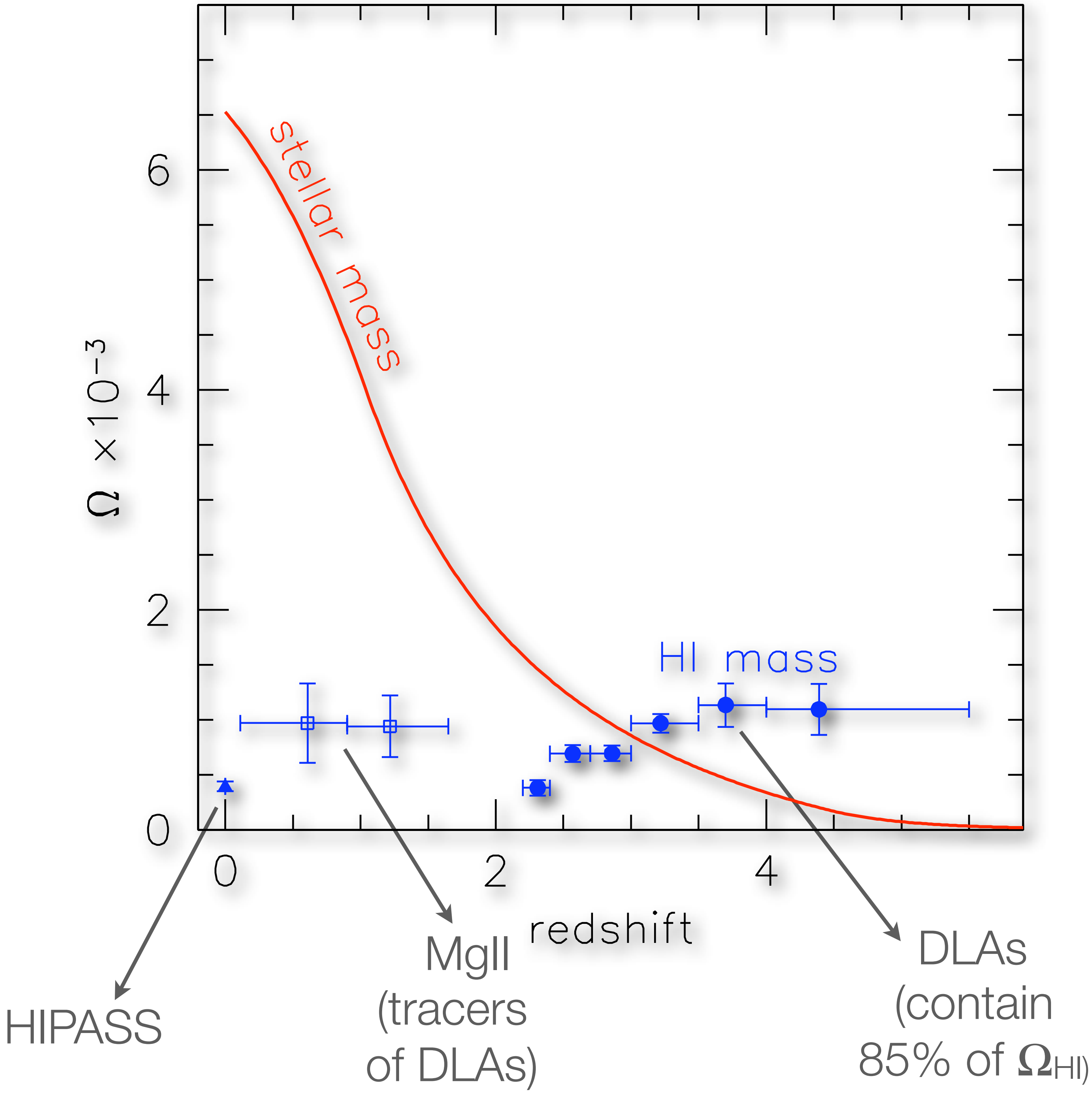
(Zwaan et al 2005)

The HI mass function



(Zwaan et al 2005)

Cosmic HI mass density evolves slowly



- DLAs are a "phase" not a "reservoir"
- Is HI interesting at all?
- Where is the "missing" gas?

What about the molecules?

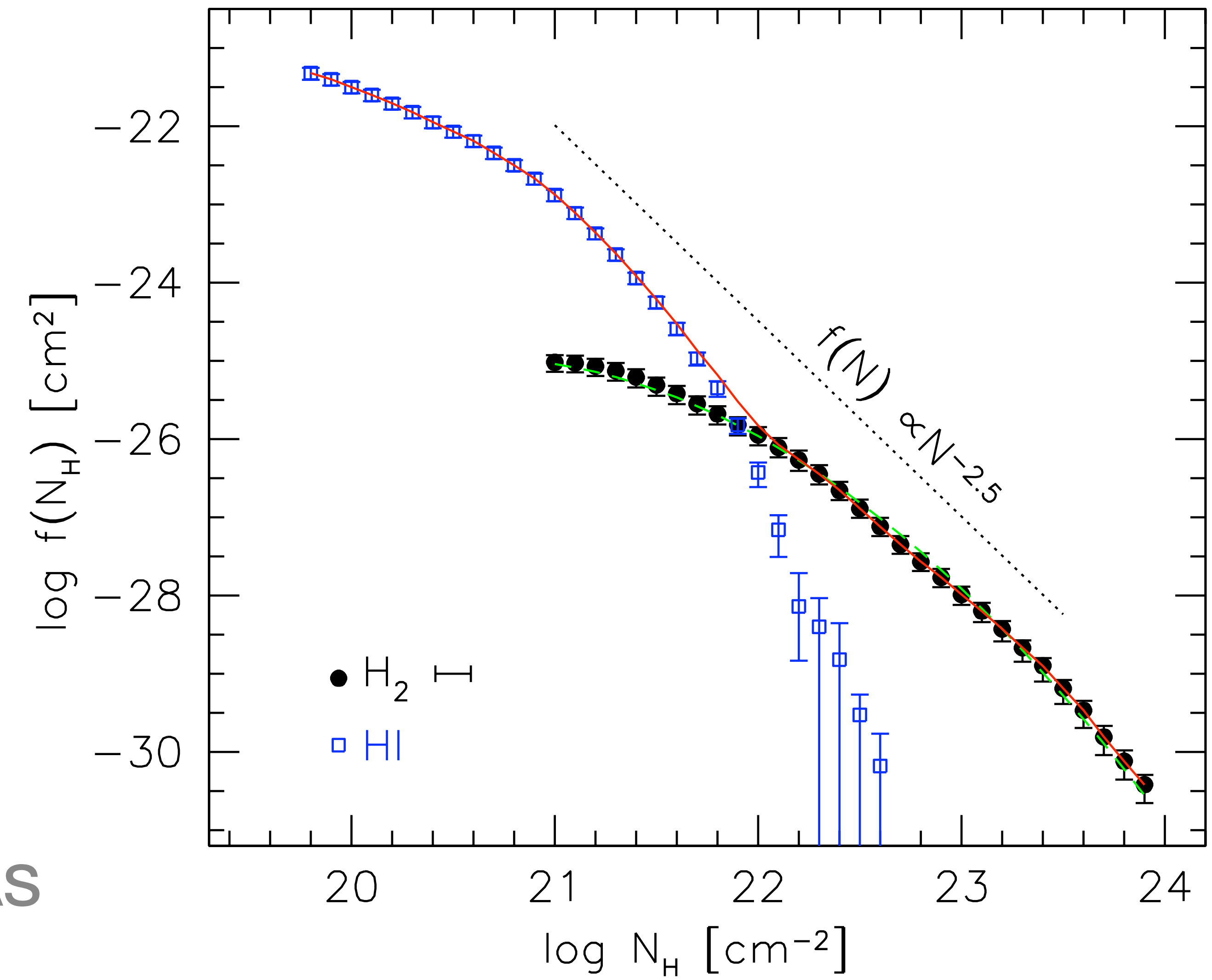
- DLAs contain the **reservoir for star formation**
- Star formation occurs in molecular clouds

→ DLAs **should contain molecules**

- surveys for millimetre molecular absorption have been **unsuccessful** (Curran et al 2004, Wiklind & Combes,...)
- optical/UV surveys for H_2 have **low success rate** and find very **low H_2 fractions** (10^{-3} - 10^{-2}) (e.g., Ledoux et al 2003)

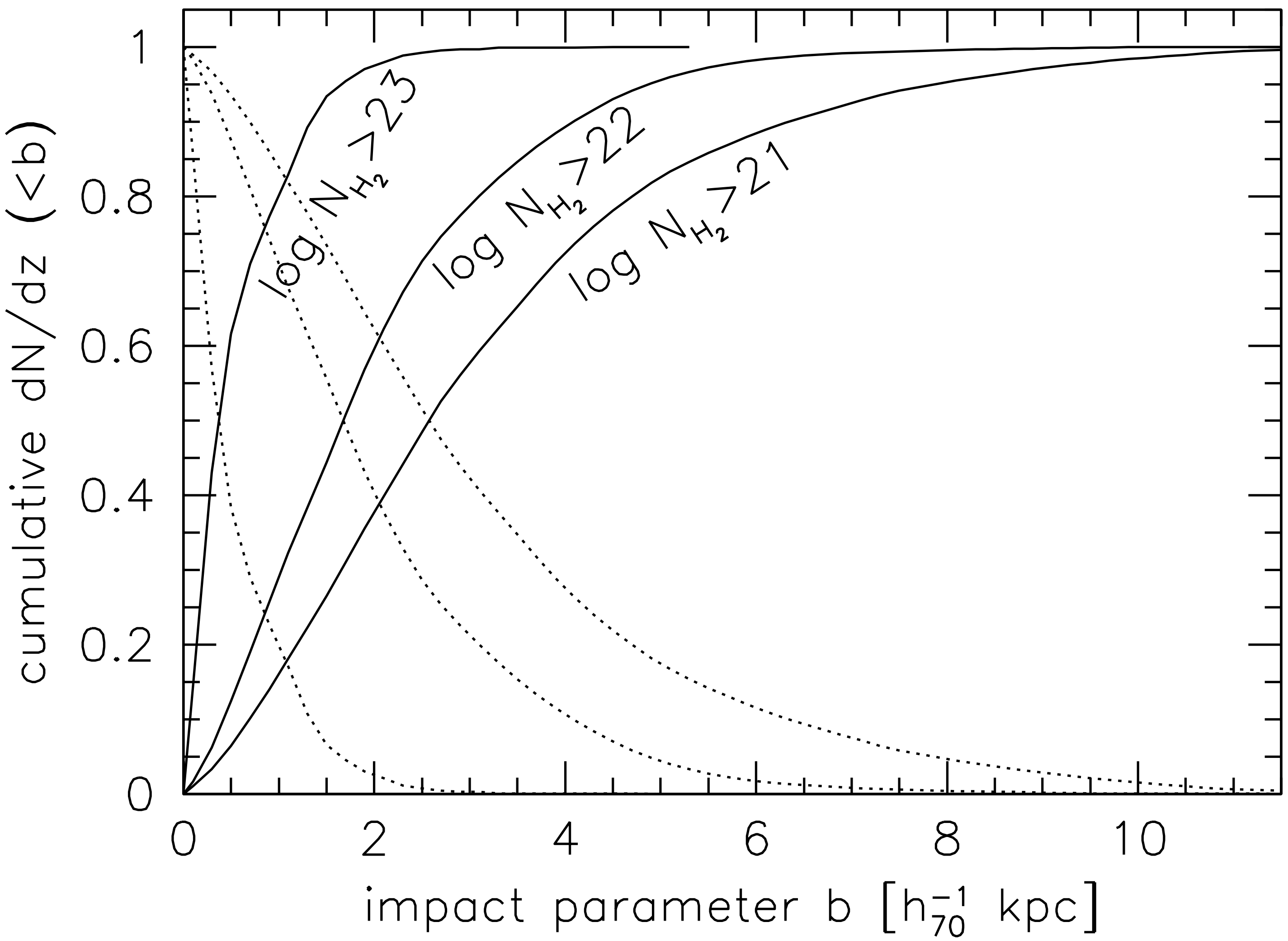
f(N) for molecular gas

- Use CO maps from BIMA-SONG (Helfer et al 2003) to derive $f(N_{H2})$
- $dN/dz\ (N_{H2}>10^{21}) = 3\times10^{-4}$
- >100 times lower than that for HI in DLAs
- ➡ molecular surveys in DLAs unsuccessful



Zwaan & Prochaska 2006

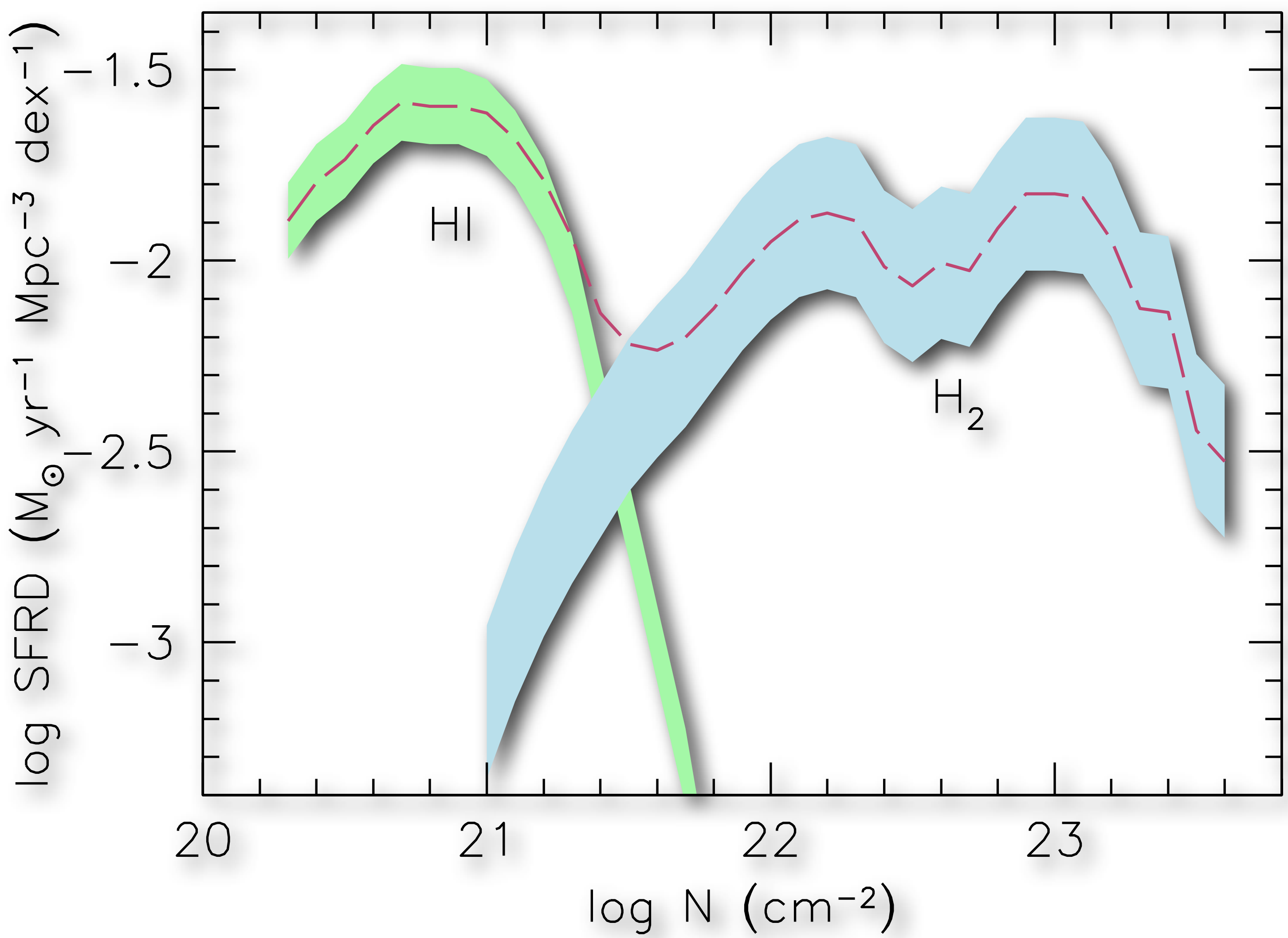
Molecules are at small impact parameters



- 90% of H_2 mass within impact parameters of 6.5 kpc

Implications for cosmic SFR density

SFRD as function of HI and H_2 (at z=0):



Even though H_2 has very small cross section, it contributes significantly to $\mathbf{\Omega}_{gas}$ and the SFRD

Molecular mass density at high z

- Need Ω_{H2} at z>0
    - to reconcile SFRD with DLAs
    - solve ‘missing gas’ problem
    - help to solve ‘missing metals problem’
- Most of Ω_{H2} is in ‘normal’ galaxies, not in supermassive galaxies
- Need ‘blind’ mm absorption line surveys or very deep emission line surveys

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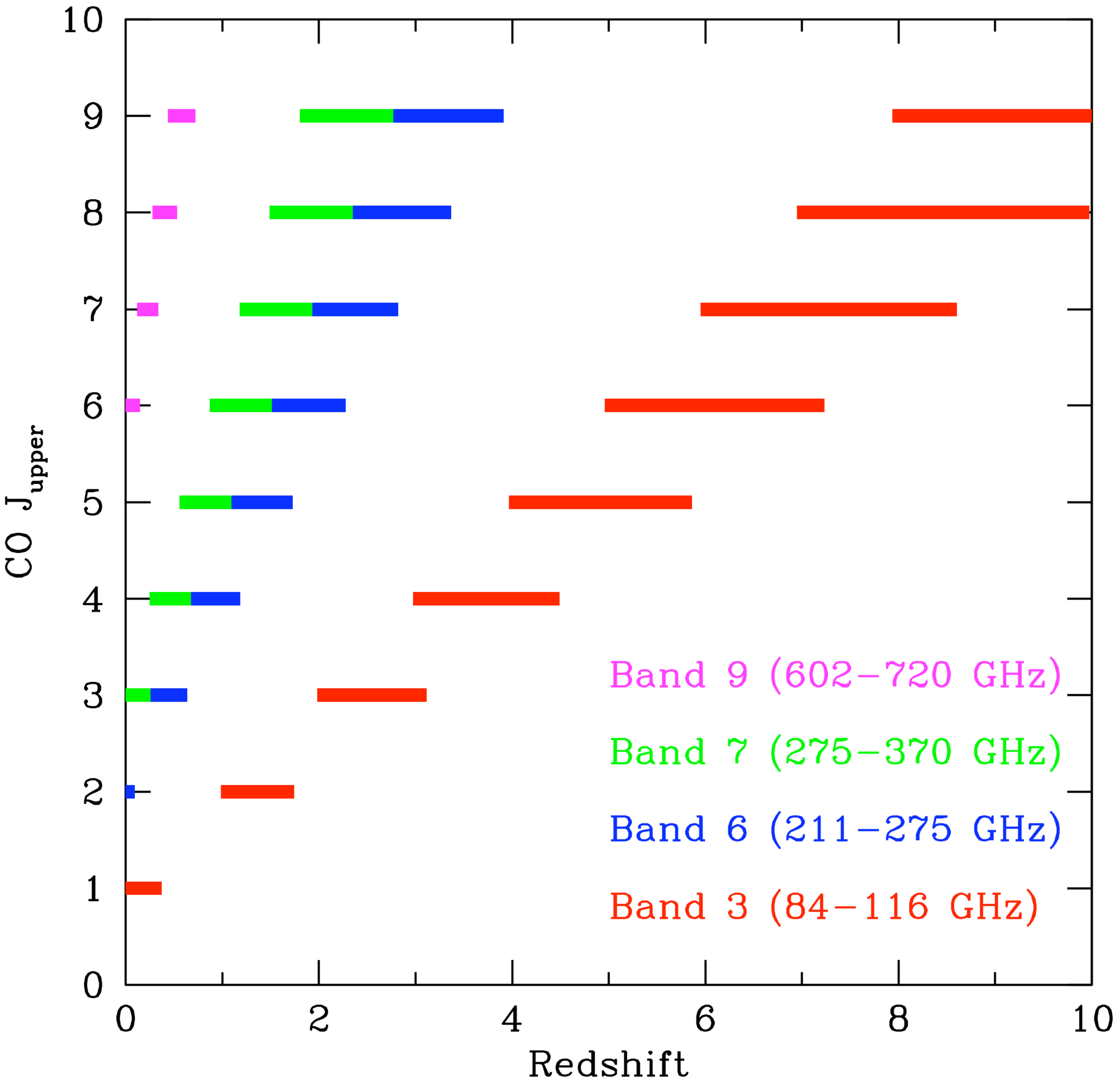
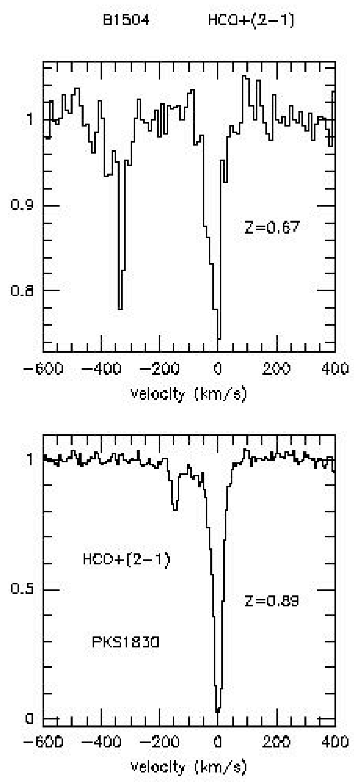
→ALMA & SKA

Observing CO with ALMA



Measure Ω_{H2} with ALMA

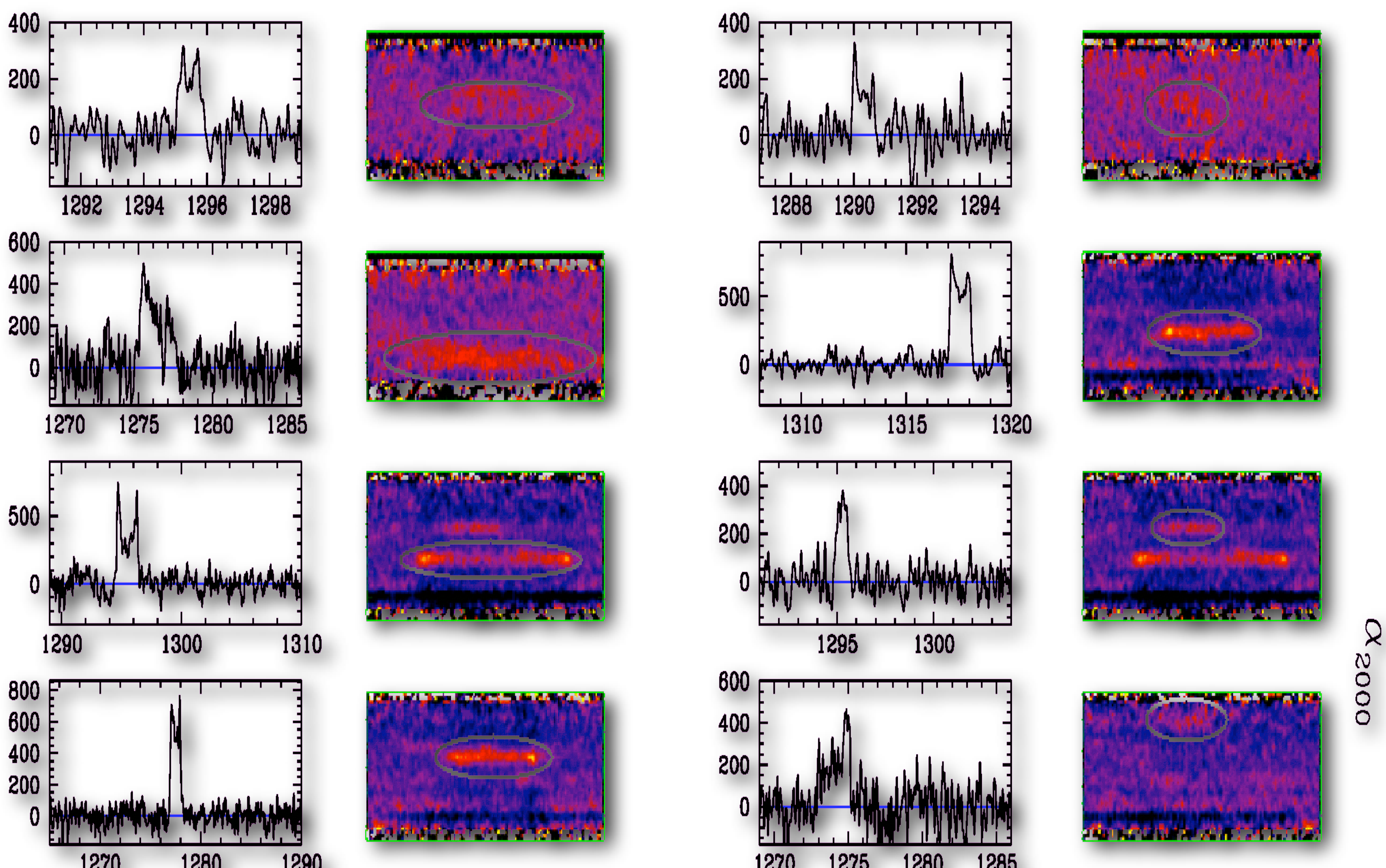
- CO(3–2) line at z=2 to 3 in ALMA band 3
- CO absorption corresponding to log N_{H2} > 21 detectable in ±one minute against a 50 mJy background source.
- 8 GHz bandwidth: Δz~0.08
- Assuming no evolution in Ω_{H2}, ±5 days are required to measure $f(N_{H2})$. In reality, a few days should be sufficient.
- Need follow-up to find other lines



HI at higher redshifts...?

Arecibo **U**ltra-**D**eep **S**urvey (AUDS) (Freudling et al)

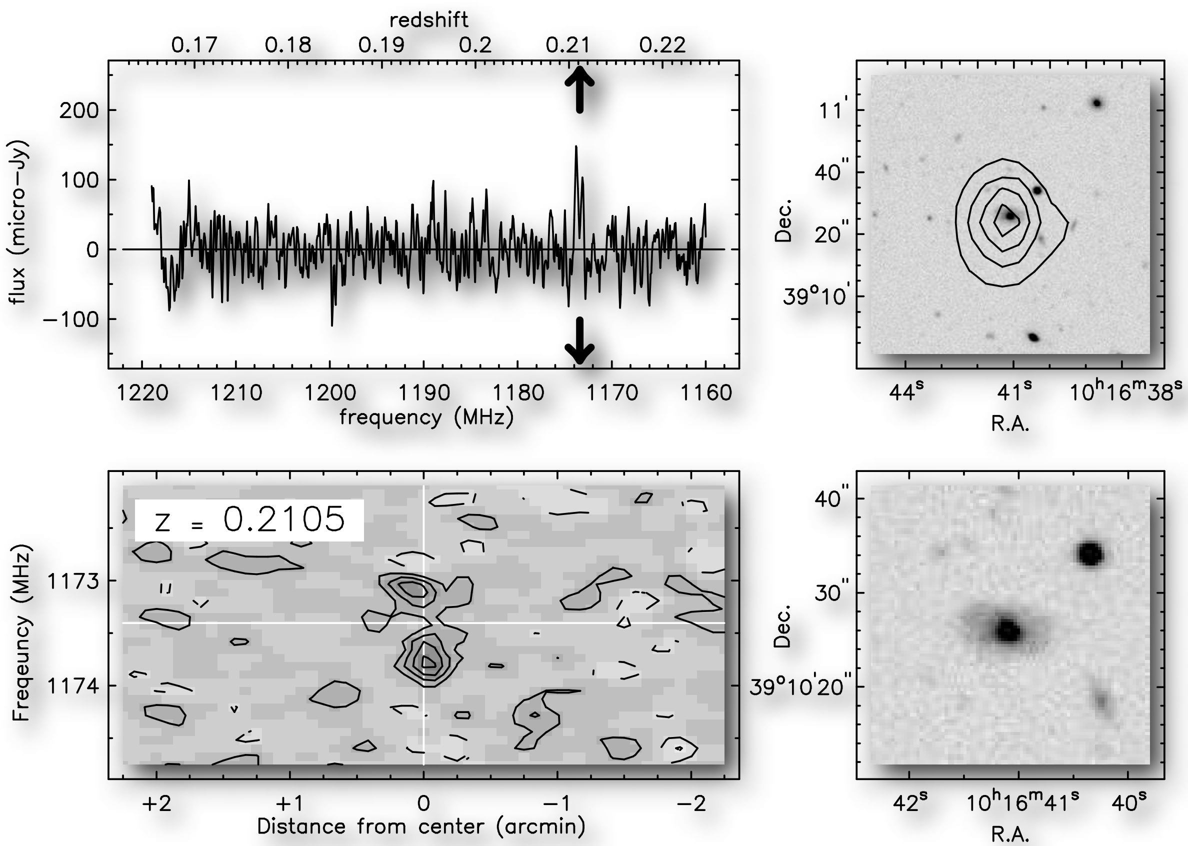
- Deepest blind HI survey: 50 μJy rms, 1000 hours are allocated
- 0.36 degree^2 out to z=0.16
- Two fields in SDSS regions, no bright 20-cm sources



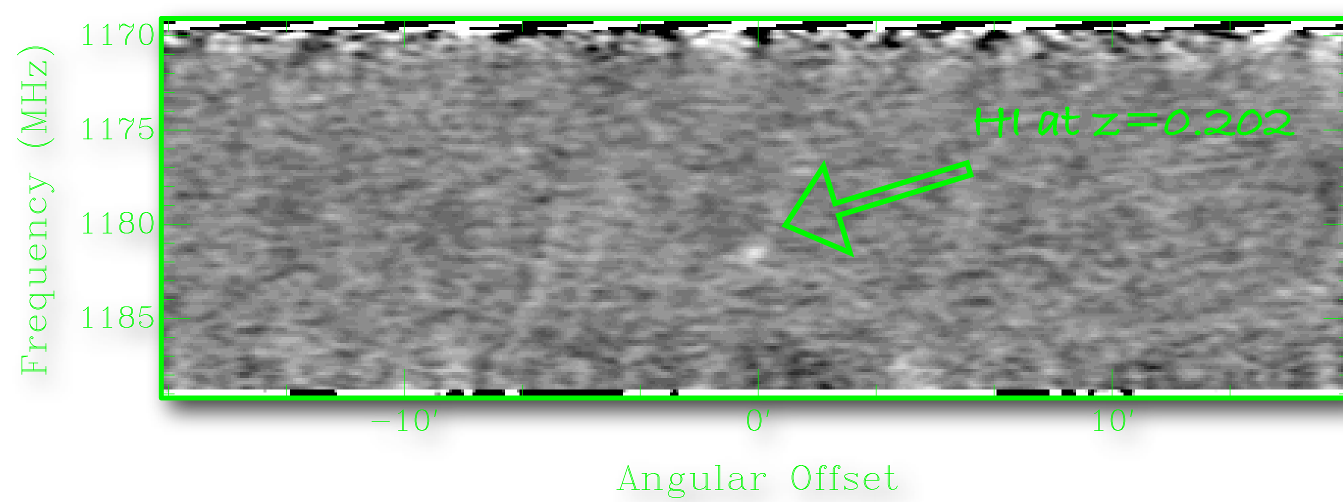
- Precursor observations:
- 53 hours of 'drift-and chase' resulted in 14 detections between z=0.07 and z=0.15
- Detections confirmed with WSRT

HI at higher redshifts...?

- **Westerbork:**



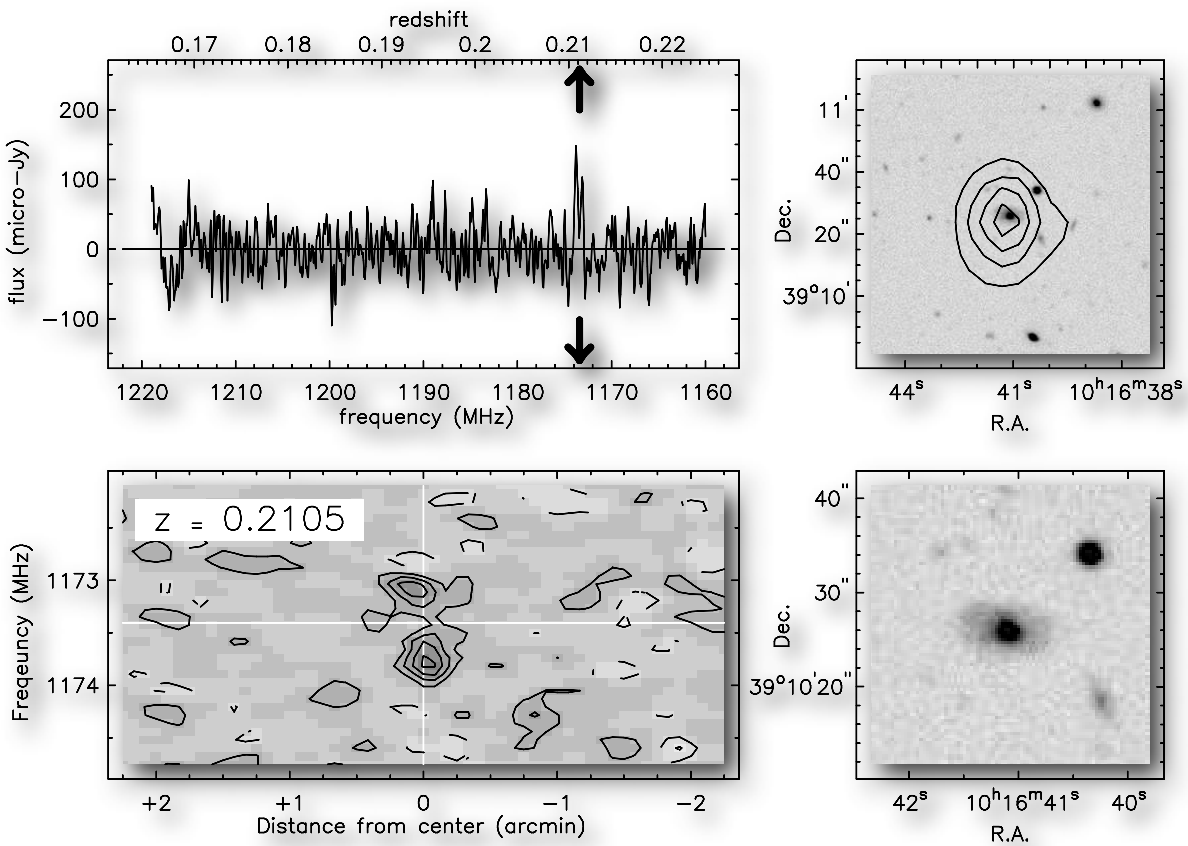
Verheijen et al. 2007



Zwaan et al in prep.

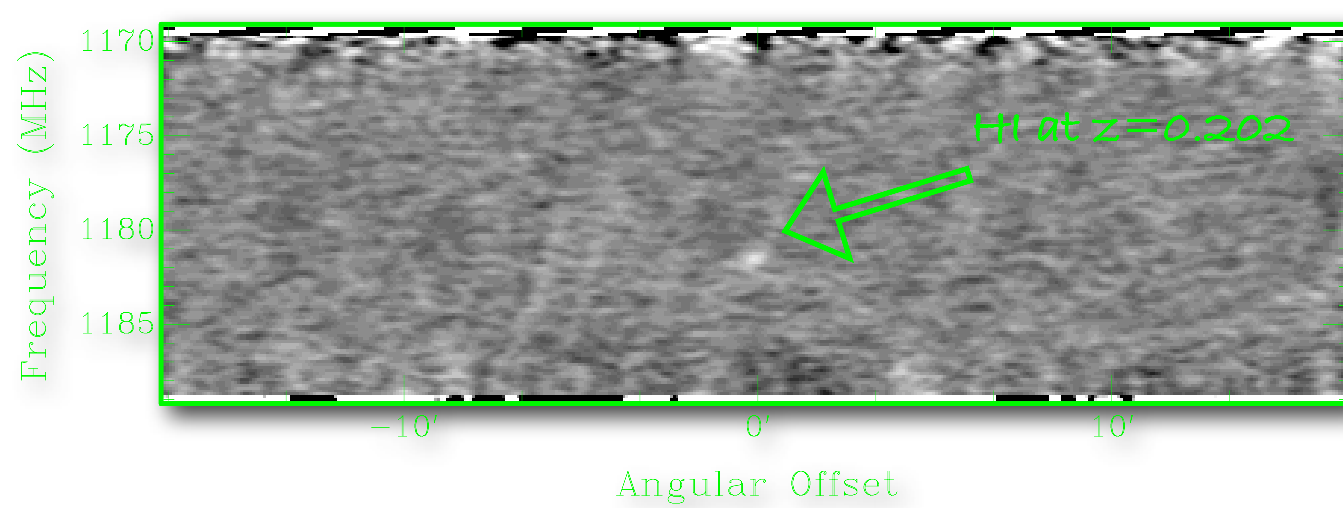
HI at higher redshifts...?

- **Westerbork:**



Verheijen et al. 2007

z=0.2-0.3 is the limit



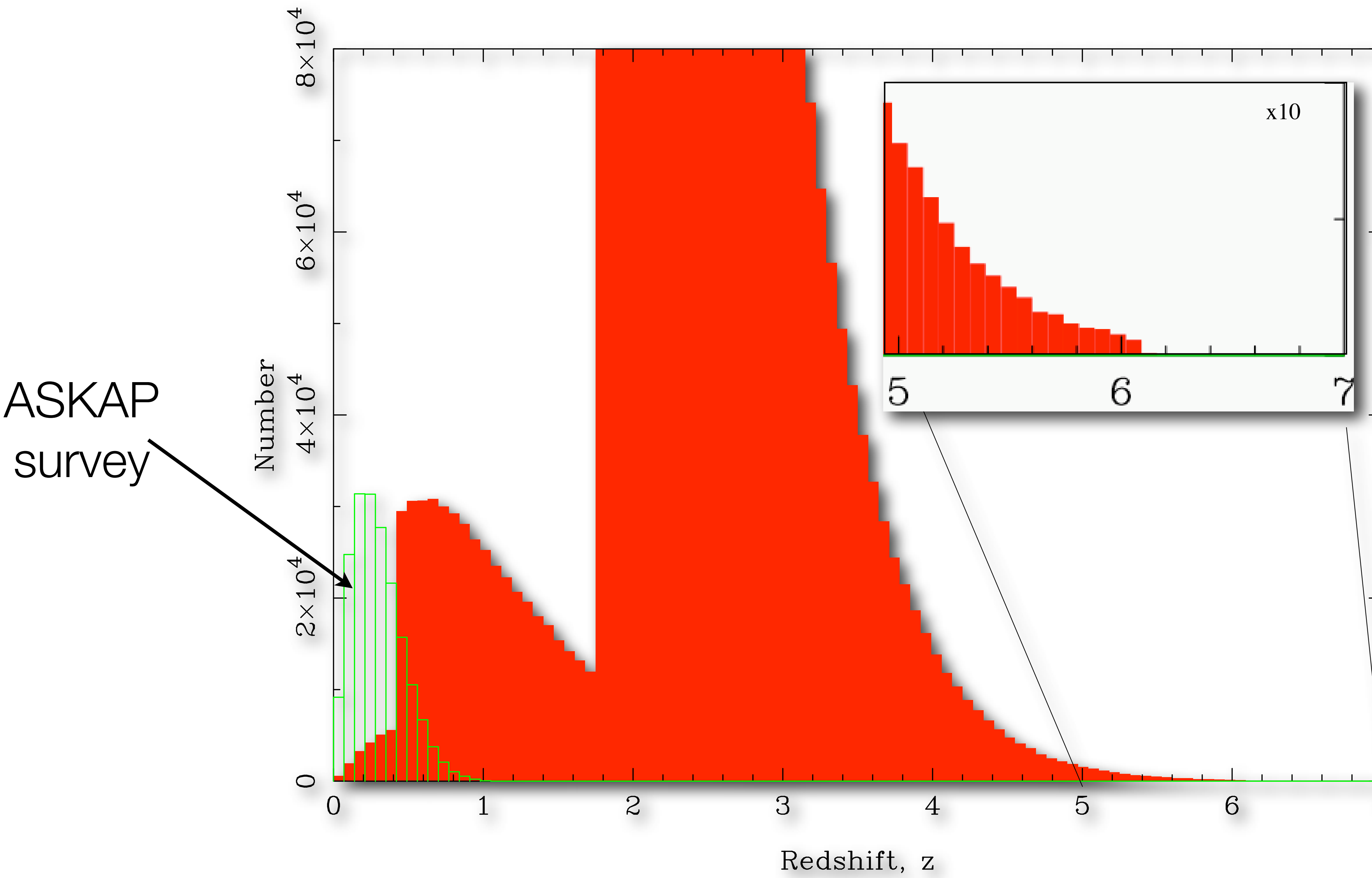
Zwaan et al in prep.

SKA capabilities for deep HI surveys at high *z*

- Expected statistics for 8 Msec deep field with 100% SKA (Staveley-Smith 2007)
  - Based on Schilizzi's (2007) "preliminary specifications"
  - Using inner 75% baselines
  - Assuming non-evolving HIPASS HI mass function

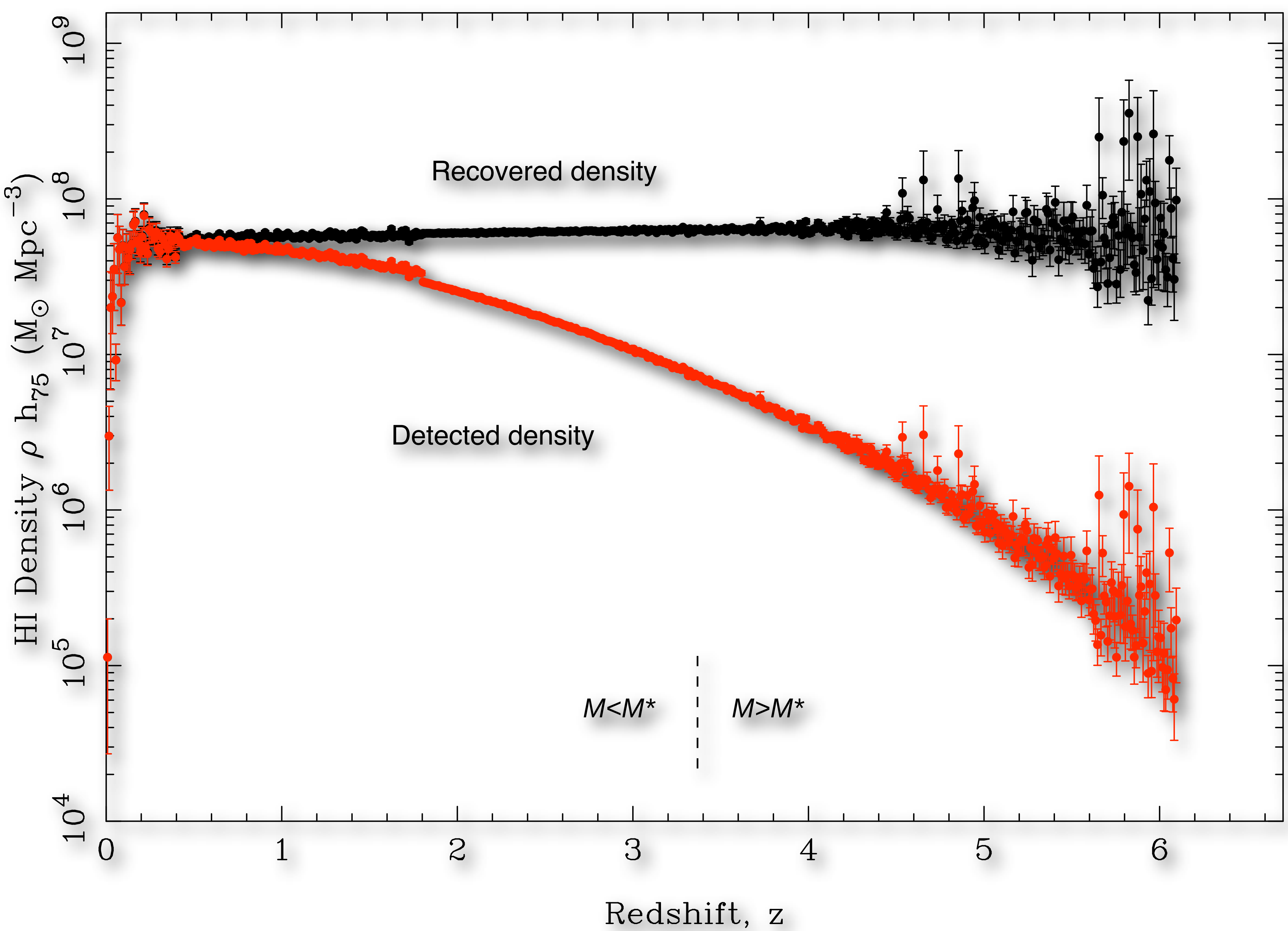
freq range (MHz)	redshift	A/T (m^2/K)	Ω (deg^2)	N
200-500	z=1.8-6.1	7500	200	6.6×10^6
500-1000	z=0.4-1.8	9000	2.0	4.4×10^5
1000-1420	z=0-0.4	9000	0.4	2.1×10^6

8 Msec SKA ‘pencil beam’ detection statistics



Staveley-Smith (2007)

Recovery of HI mass density



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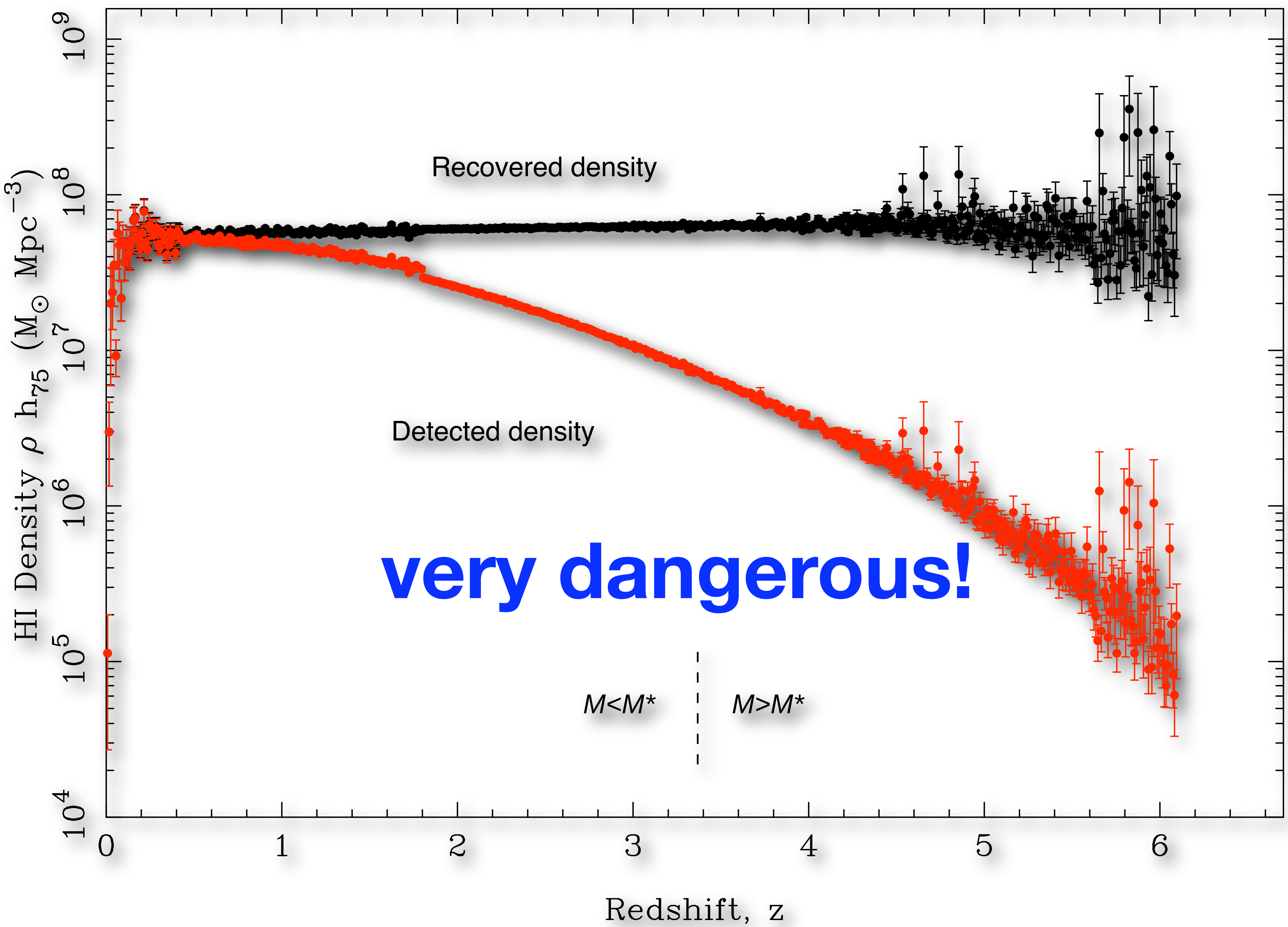
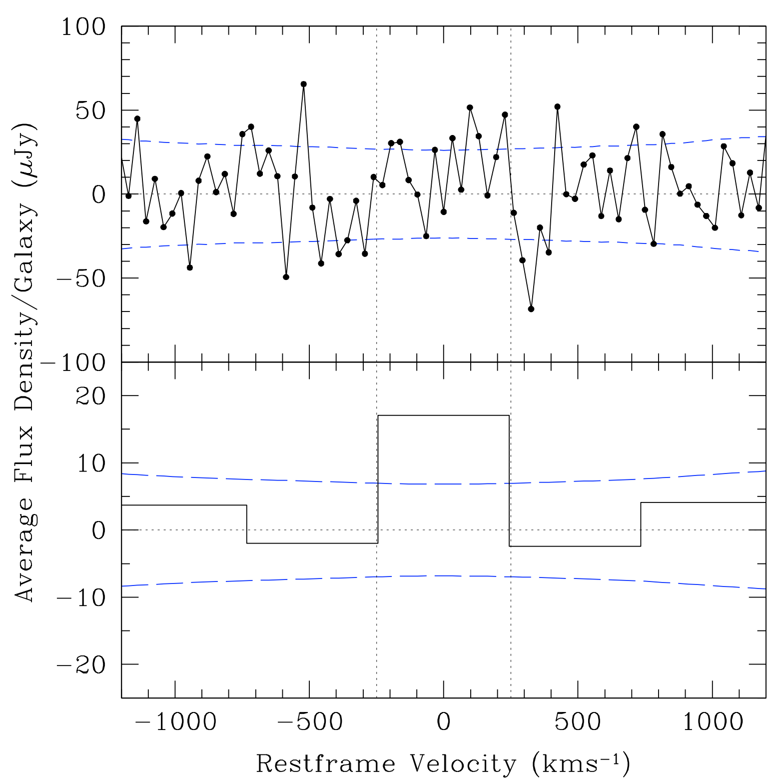


Staveley-Smith (2007)

HI at the very highest redshifts

- Even with deep surveys with the SKA, it will remain difficult to determine HI masses of L* galaxies beyond *z*=3
- Solution: stacking of HI spectra
- Demonstrated by Zwaan (2000), Verheijen et al (2007), Lah et al (2007) at redshifts z~0.2



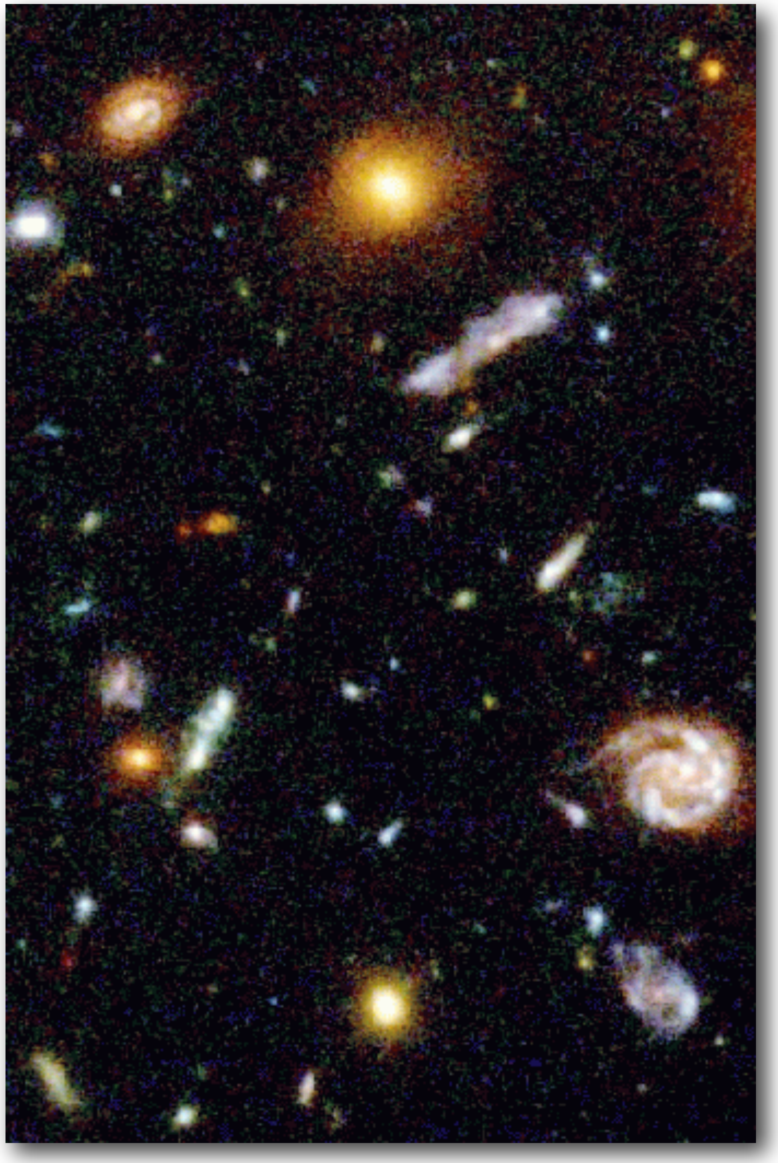
Lah et al: Statistical detection of HI emission of Hα-selected galaxies at z=0.24 with GMRT

Choose SKA deep survey in optical deep field

(Preferably with spectroscopic follow-up...)

- Allows stacking at highest redshifts
- Allows construction of morphological type-specific HI mass functions
- Allows study of HI dependence on galaxy density
- Allows Tully-Fisher
- Allows SFR measurements from SKA continuum

  (get for free, but need high spatial resolution)



From an HI survey to an HI mass function...

- Finding weak signals in the noise...
- Confusion from RFI and radio continuum...
- What is the reliability? *(false positives)*
- What is the completeness? *(false negatives)*
- Are we surveying a representative volume?
- Need multi-variate maximum likelihood methods to calculate space densities

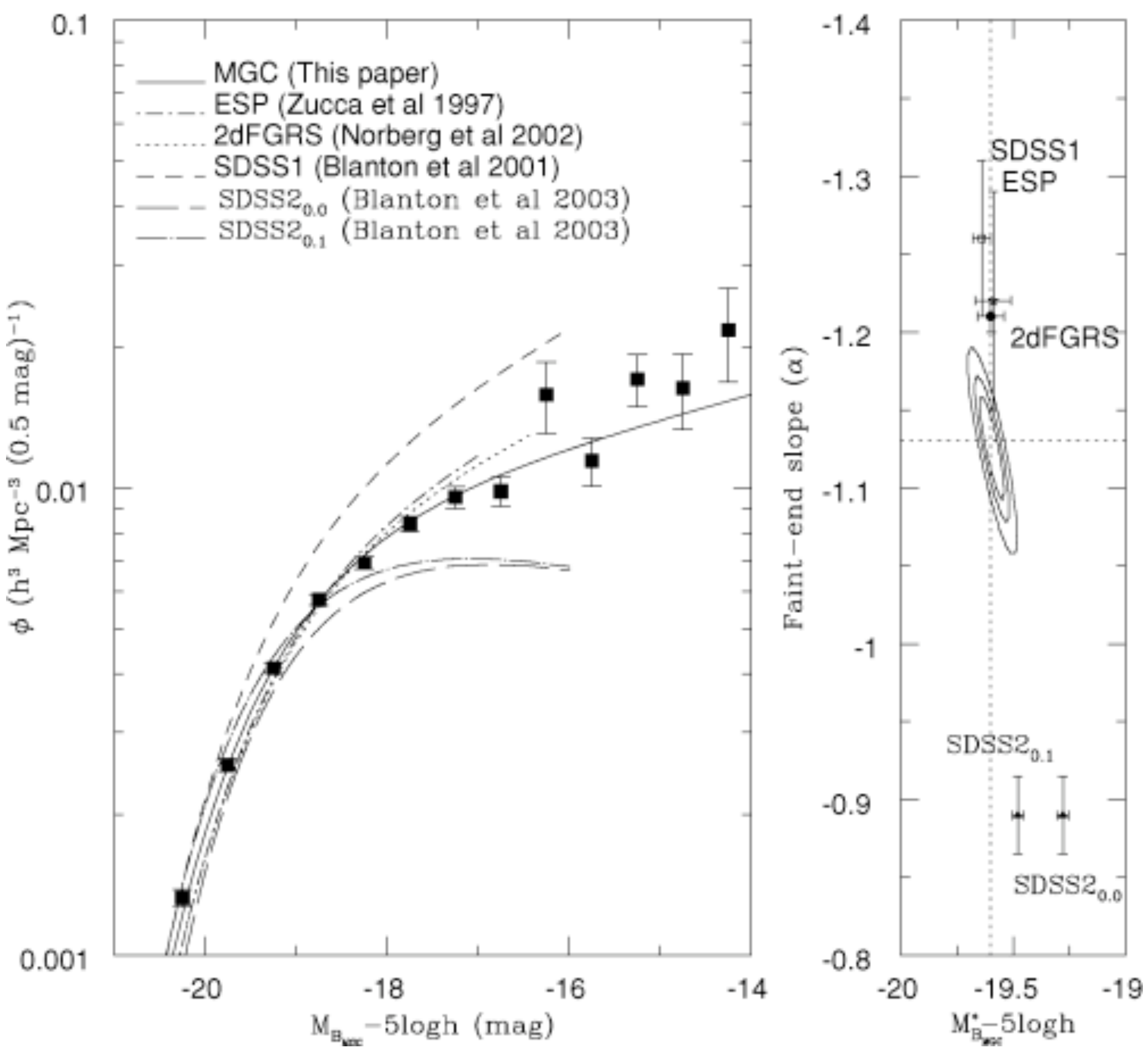
Understand your selection function...

Understand your selection function...

- Uncertainties in HI mass function dominated by systematic errors
  - varying profile shape
  - extended sources
  - RFI
  - distance uncertainties

Understand your selection function...

- Uncertainties in HI mass function dominated by systematic errors
    - varying profile shape
    - extended sources
    - RFI
    - distance uncertainties
- Compare optical luminosity function →



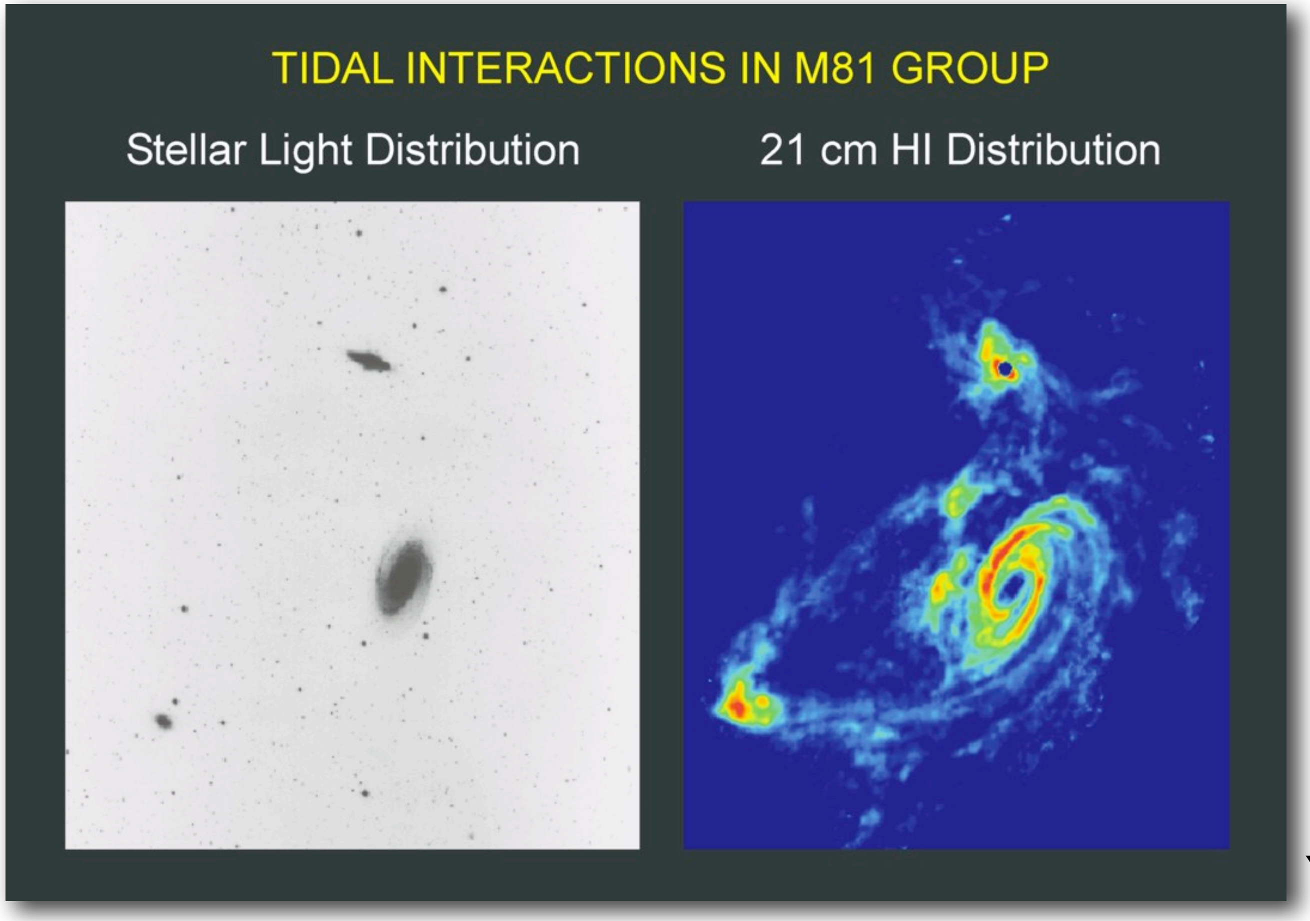
Driver et al 2005

galaxy formation in action

rotation curves

Resolving the high-z galaxies

- For the study of galaxy formation and evolution, resolved images would help
- Need ~100σ detections, at least 10 beams across gas disk
- The 8 Msec pencil-beam survey should find >10^4 galaxies between z=1 and 2

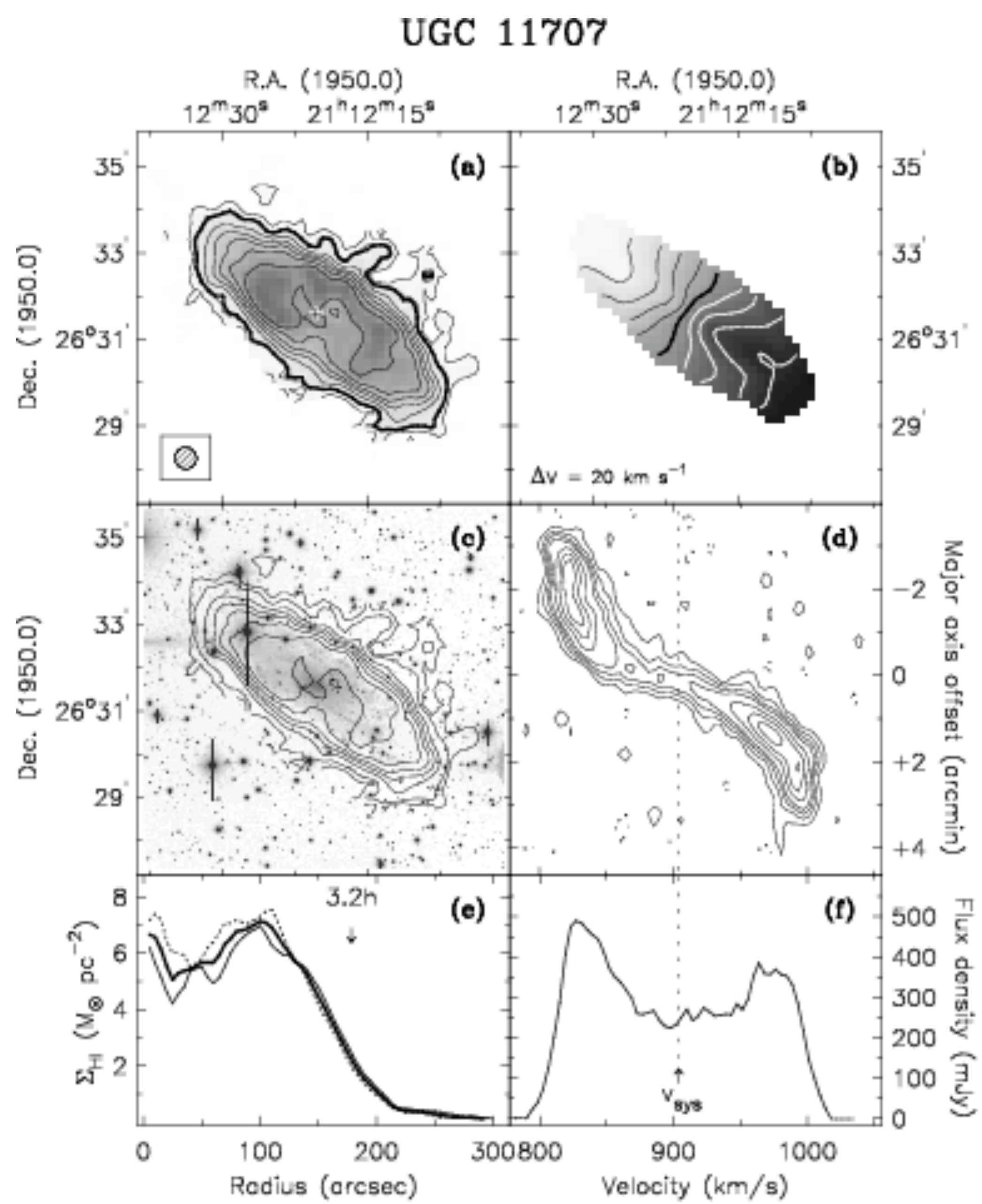


do this at z=1, z=2?

Yun et al

Resolving the high-z galaxies

- rotation curves...
- Synergies with ALMA



Swaters et al

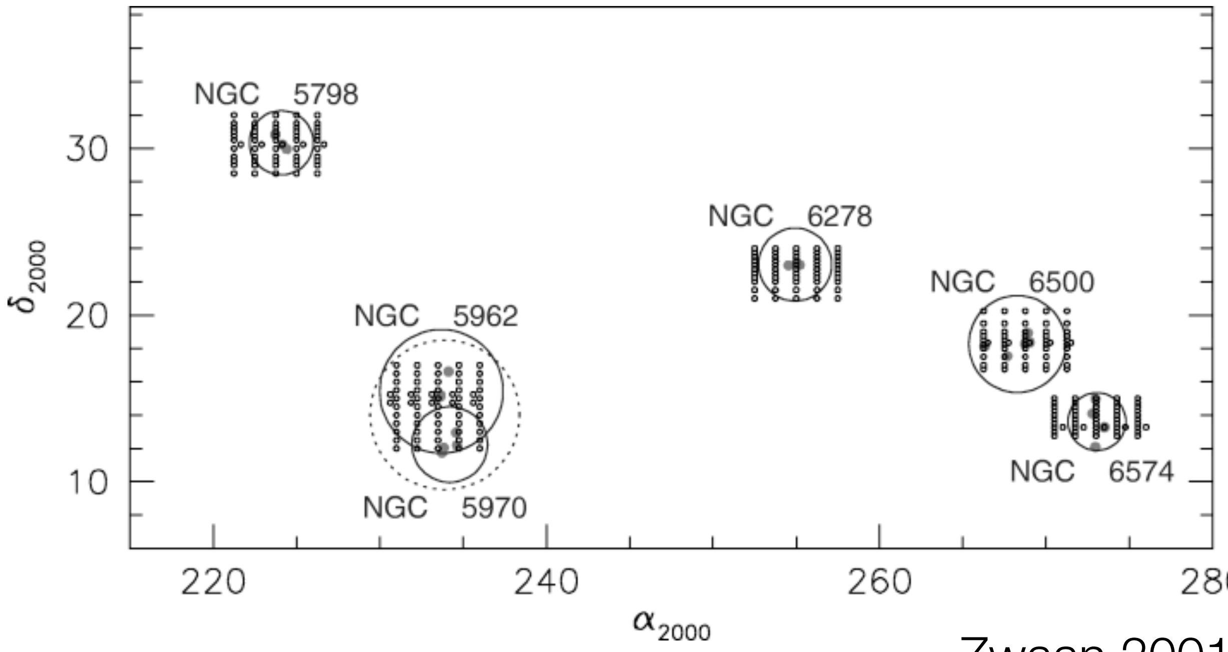
do this at z=1, z=2?

SKA HI surveys at low z

- Galaxy groups, missing satellites
- Low column densities - the “cosmic web”
- High spatial resolution, deep imaging of nearby galaxies
  - gas accretion
  - star-formation law on sub-Jeans scales

HI surveys in groups

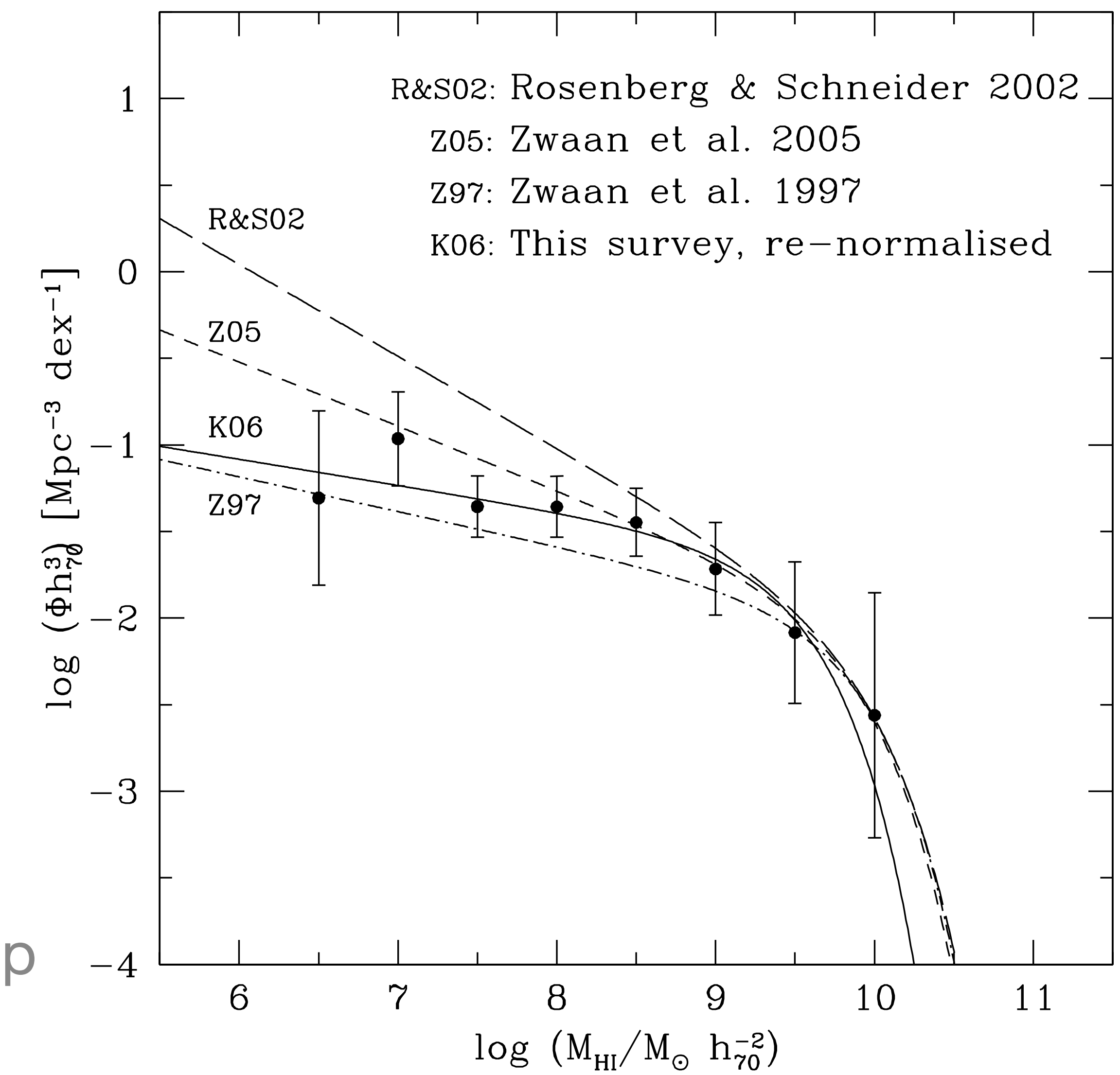
- Looking for HI clouds in groups
  - Low mass dwarfs
  - HVCs as building blocks? (Blitz et al 1999)
  - CDM missing satellites?
- Arecibo pointed observations in groups
  - Sensitive to $M_{HI}=6\times10^6$ Mo
  - A few new detections of HI dwarfs, no HI clouds
  - Similar surveys by Pisano et al, de Blok et al, etc



Zwaan 2001

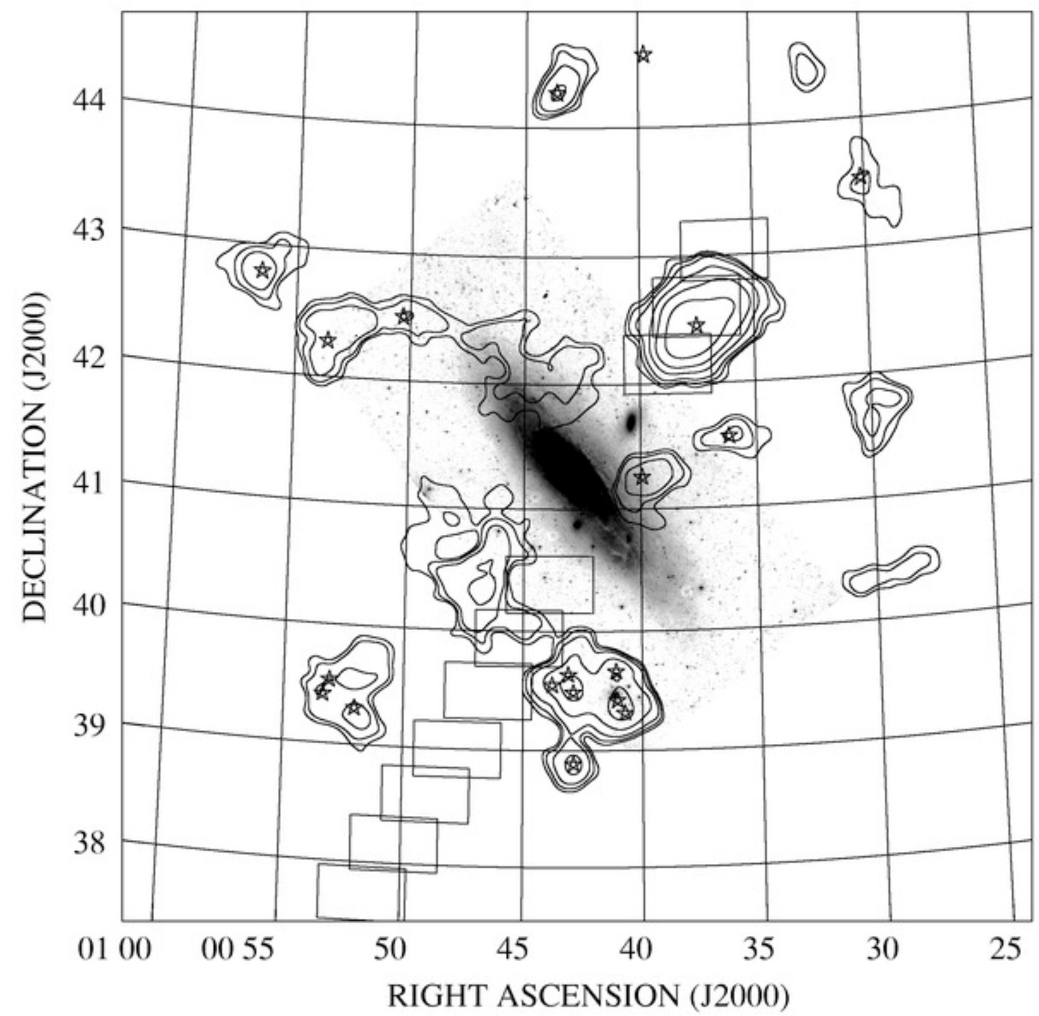
HI mass function in groups

- Very nearby groups
    - WSRT CVn survey (Kovac in prep)
        - 86 deg^2
        - 70 detections
        - HIMF ‘flat’
    - Similar results by Verheijen et al in UMa group

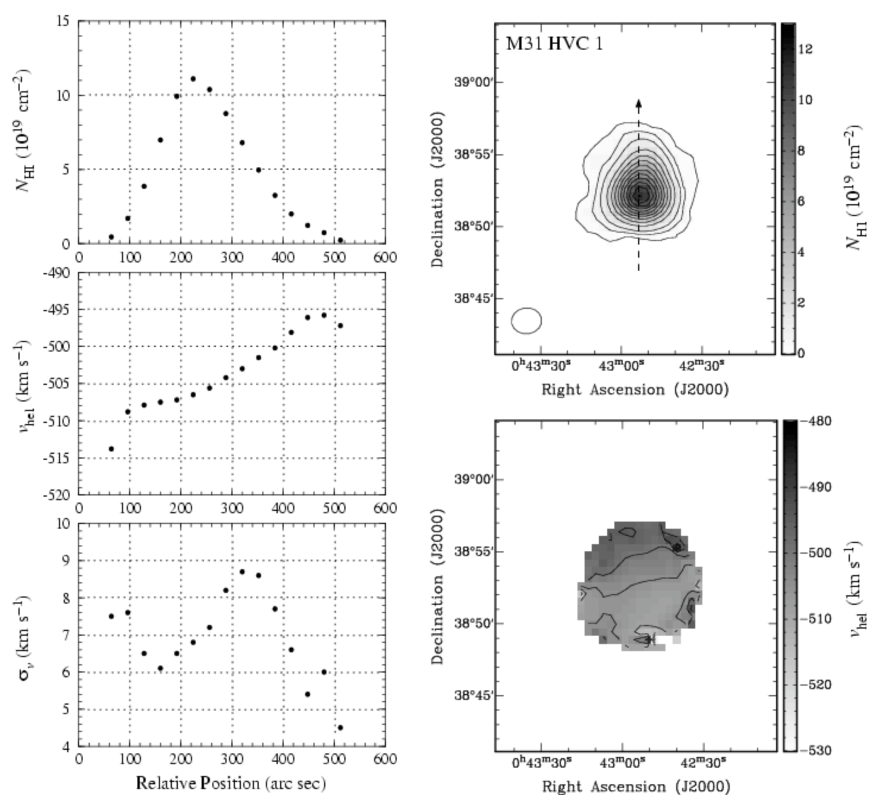


The lowest HI masses

- Thilker et al 2004 found HI clouds near M31
  - 20 clouds within 50 kpc of M31
  - Equivalents of Milky Way HVCs?
  - HI masses ~10^6 $M_{\odot}$
  - sizes ~1 kpc



Thilker et al GBT survey



Westmeier et al WSRT folow-up

- tidal?
- cooling of coronal gas?
- low mass DM halos?

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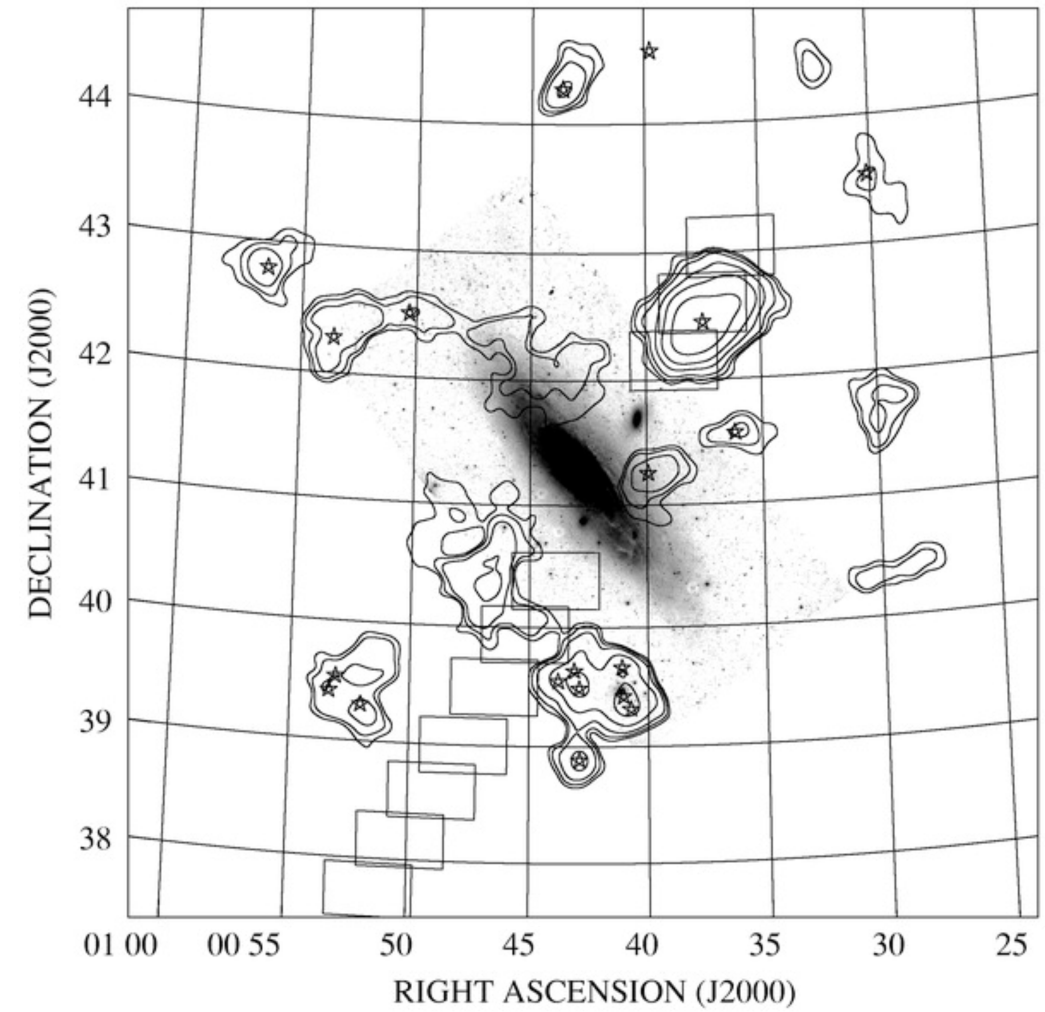

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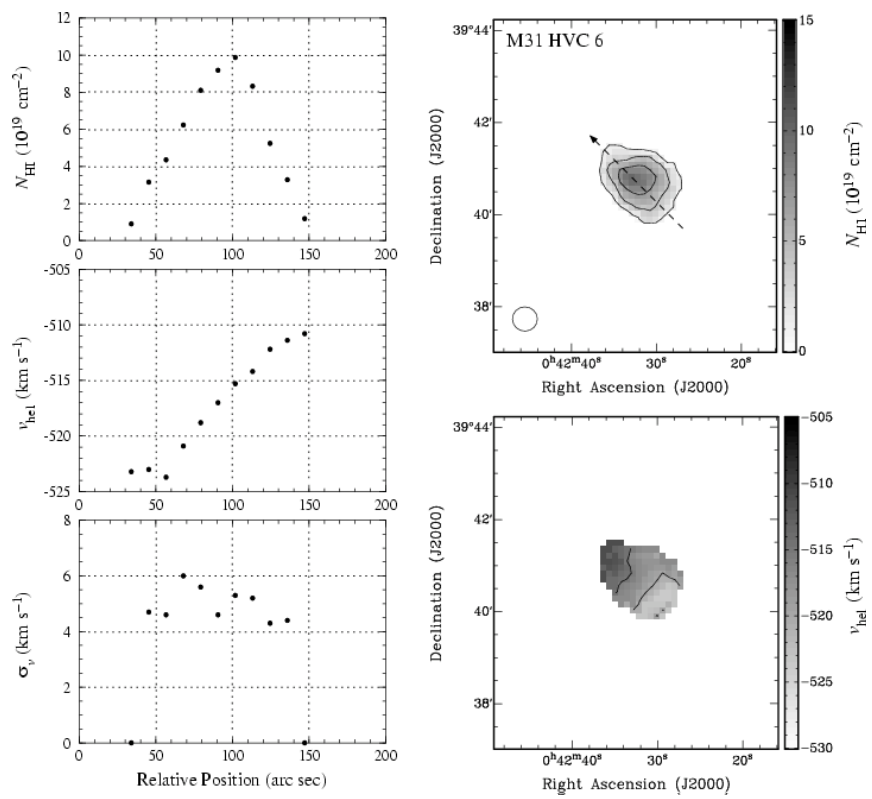

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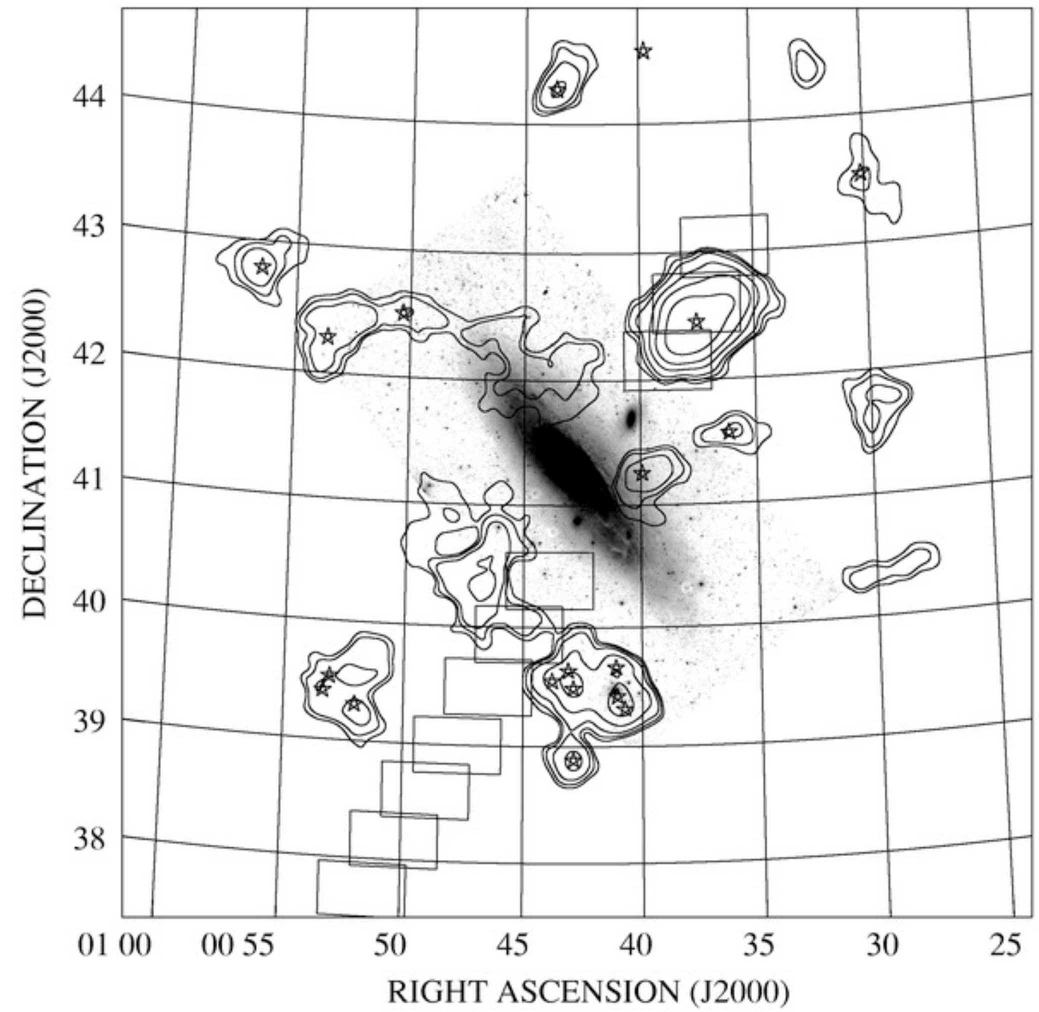

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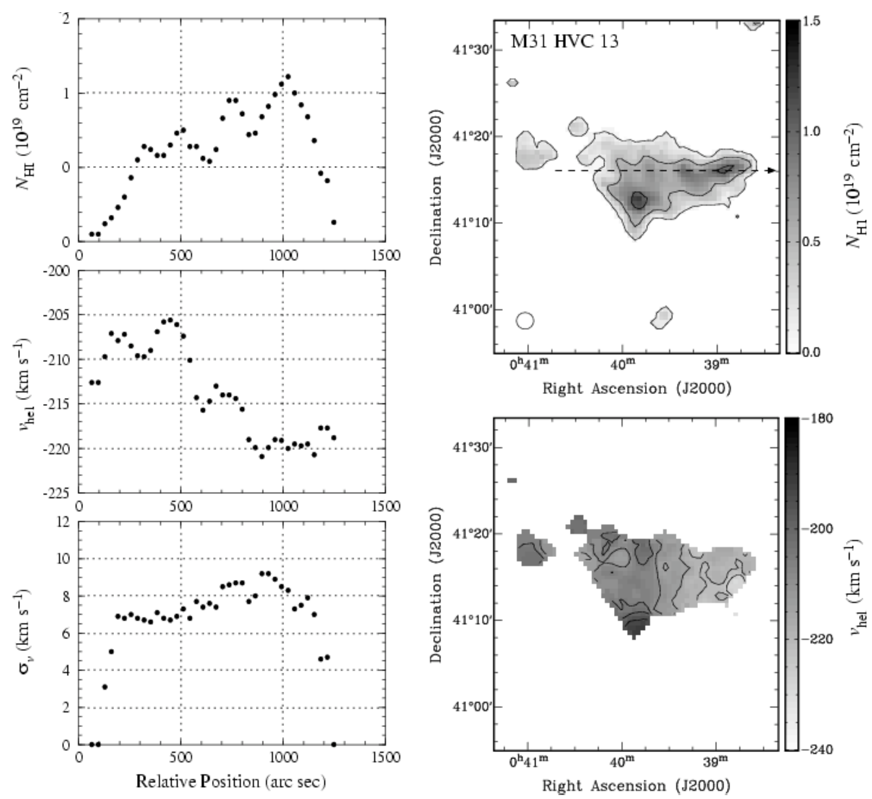

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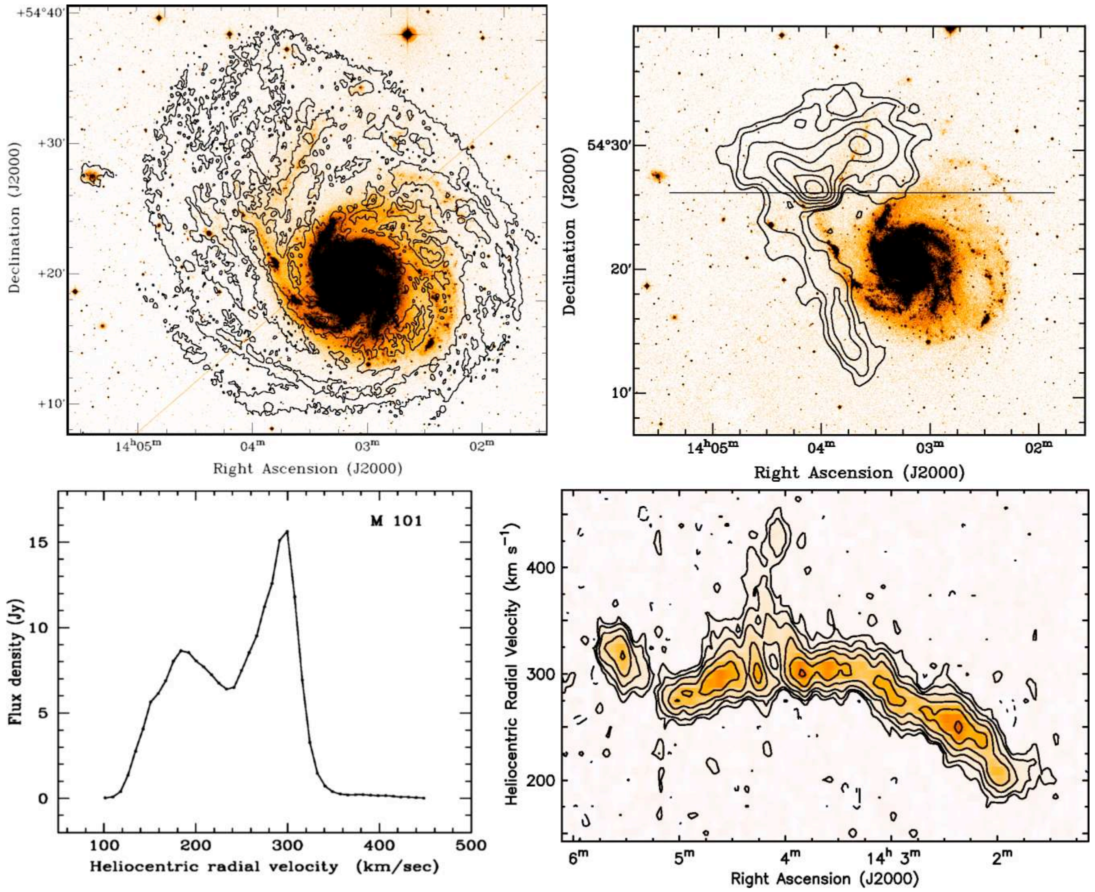
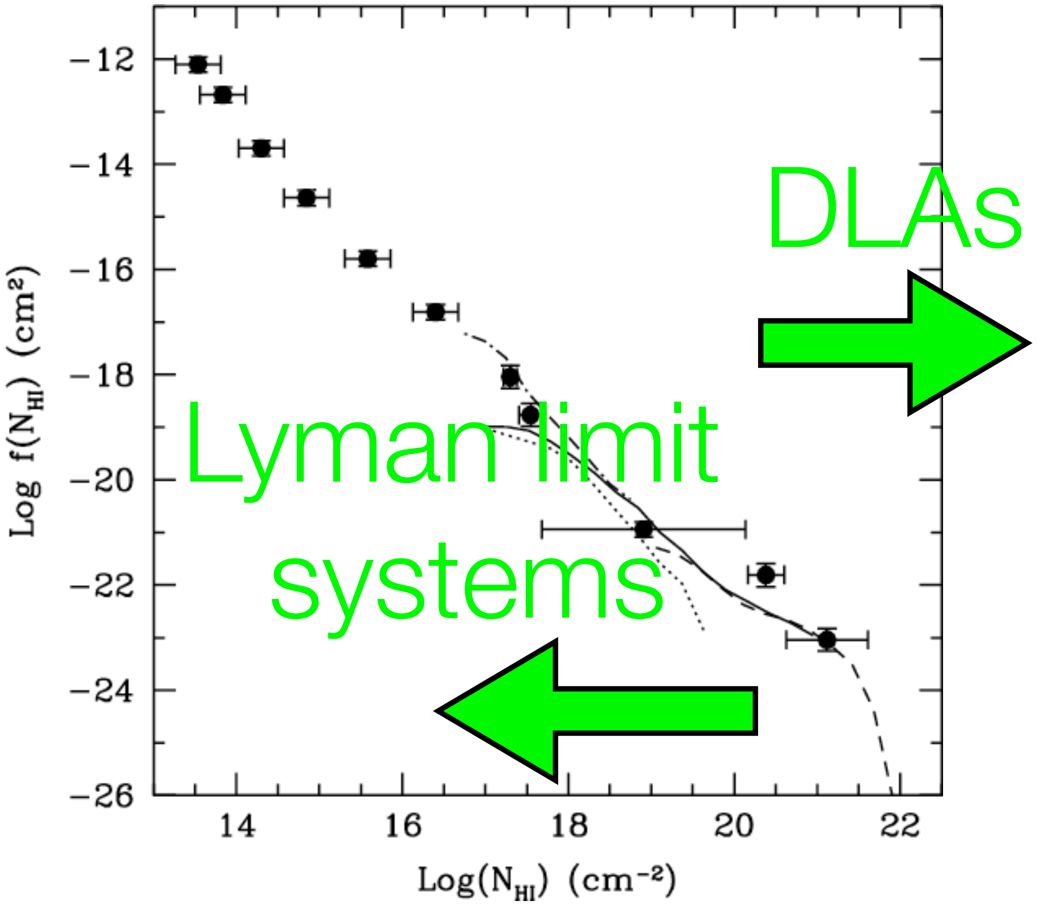
Small HI clouds with the SKA

- 5” beam, 10 km/s:
    - 5 x 10^3 $M_\odot$ in 12 h in M81 (90 pc beam)
    - 1.5 x 10^5 $M_\odot$ in 12 h in Virgo cluster (500 pc beam)
- This is much below what you can see now in nearby galaxies



Low column densities

- Lyman limit systems
- crossing the 'HI desert'
    - from few times 10^{19} to 10^{18} cm^{-2}
- What is distribution and kinematics of this gas?
- With SKA can reach 10^{17} cm^{-2} over 10 km/s per 150" beam in 12h



SKA HI goals

- To **higher redshifts**
  - evolution of HI mass density, gas fractions of galaxies, galaxy formation in action...
- To **lower column densities**
  - image the ‘cosmic web’, Lyman-limit systems, gas accretion/fountain
- To **lower HI masses**
  - missing satellites, HVCs, gas accretion