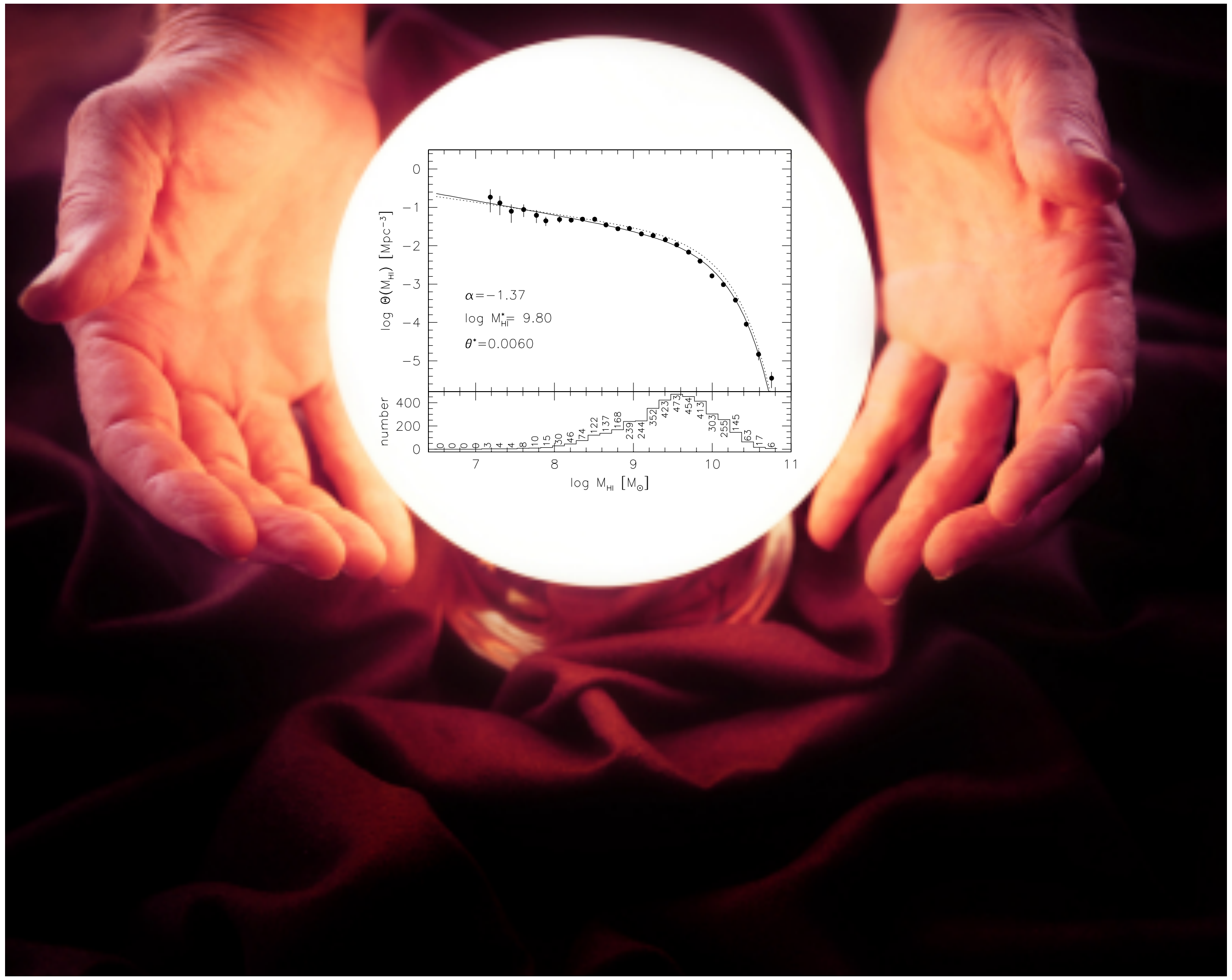
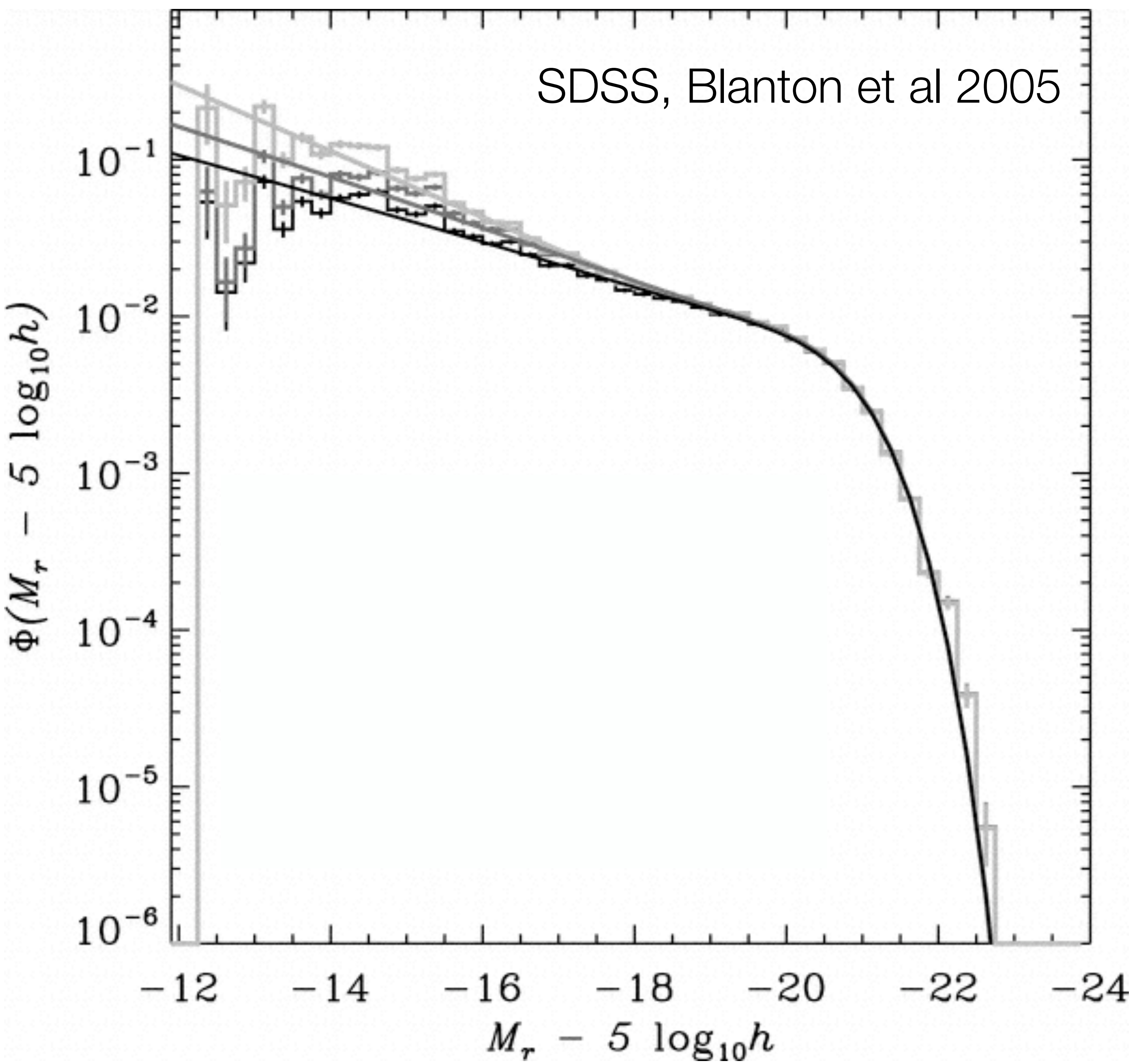
The future of the
HI mass function

Martin Zwaan (ESO)



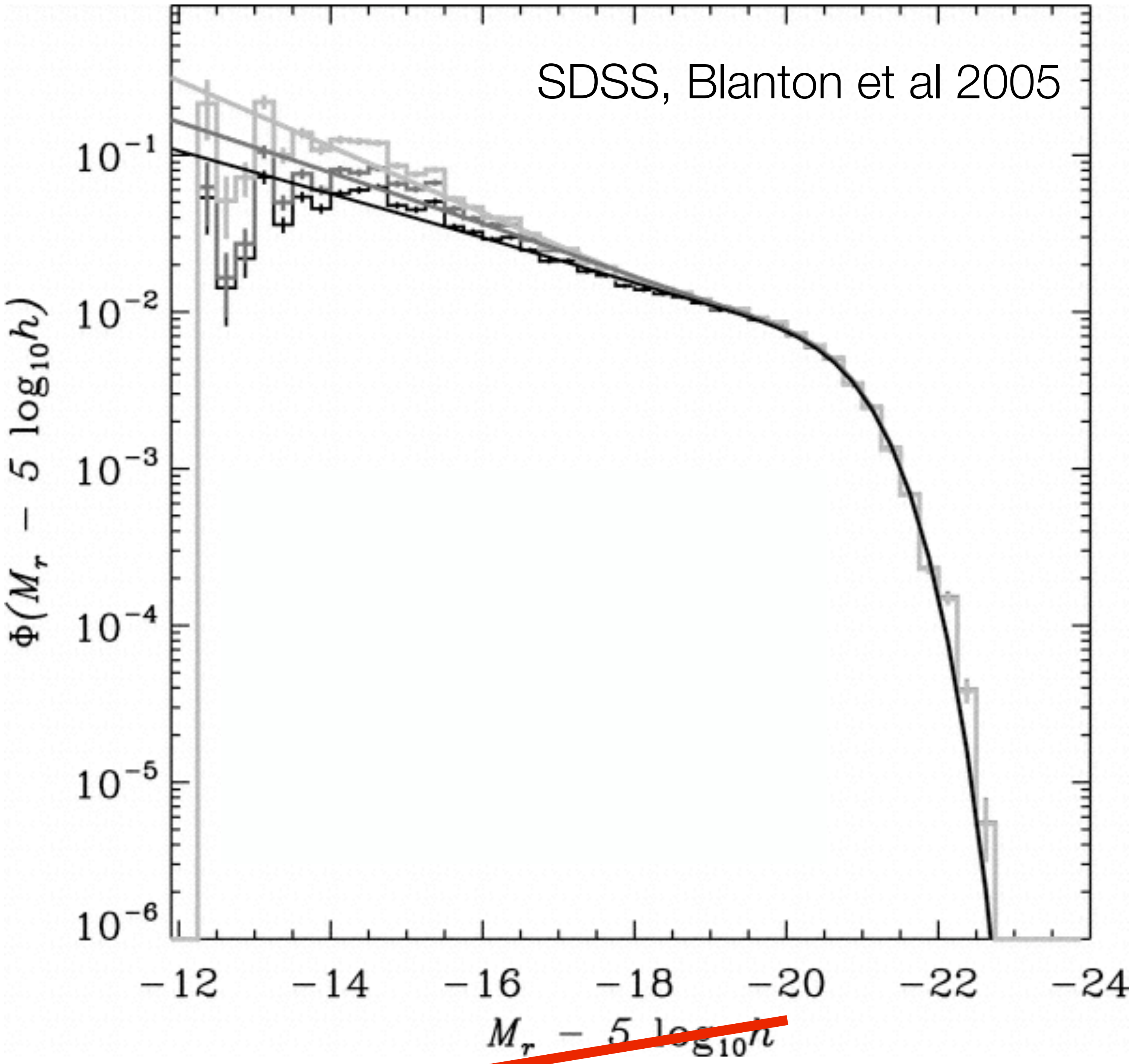
Luminosity function



Relevance:

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

Luminosity function

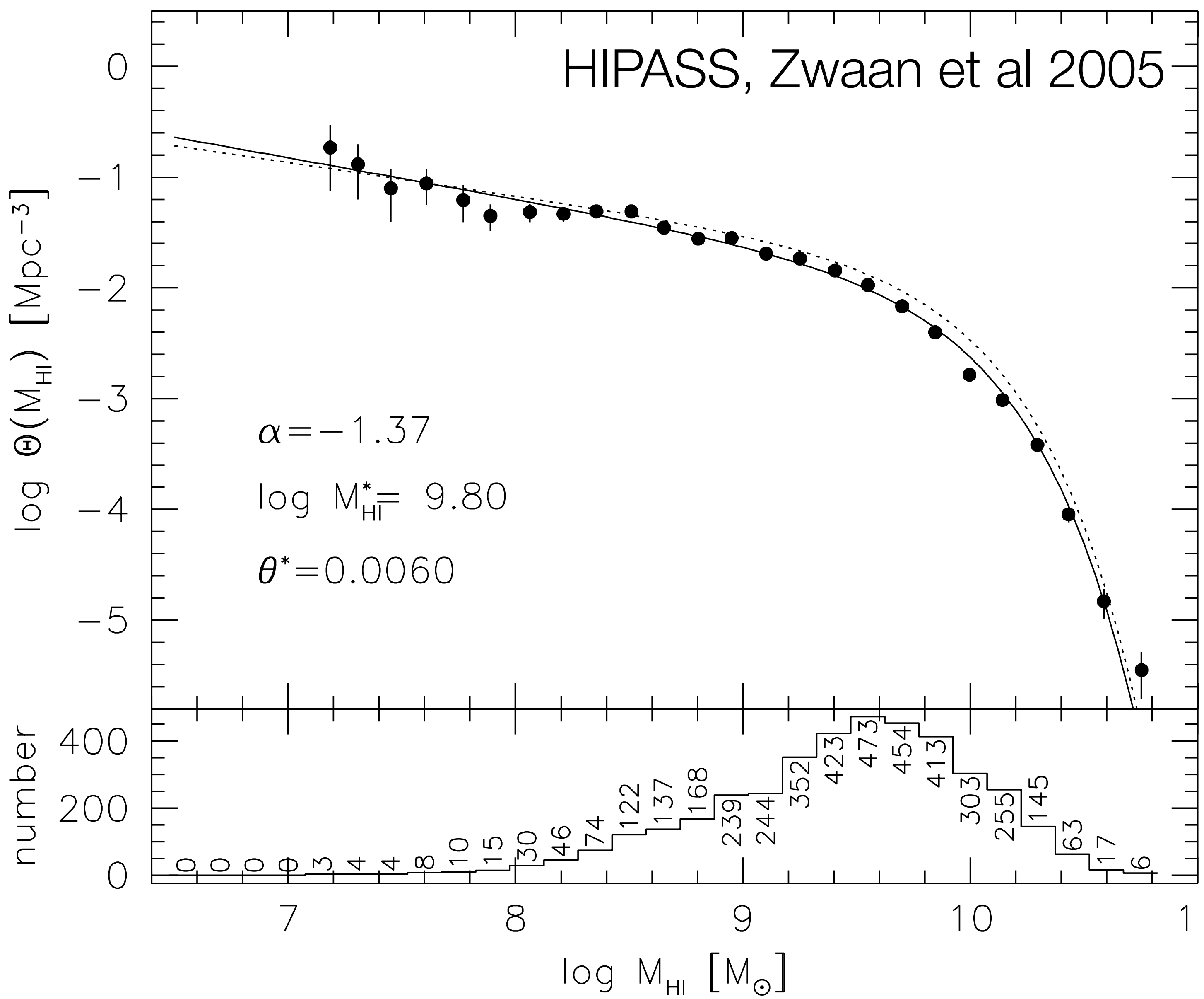


HI mass

Relevance:

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

HI mass function

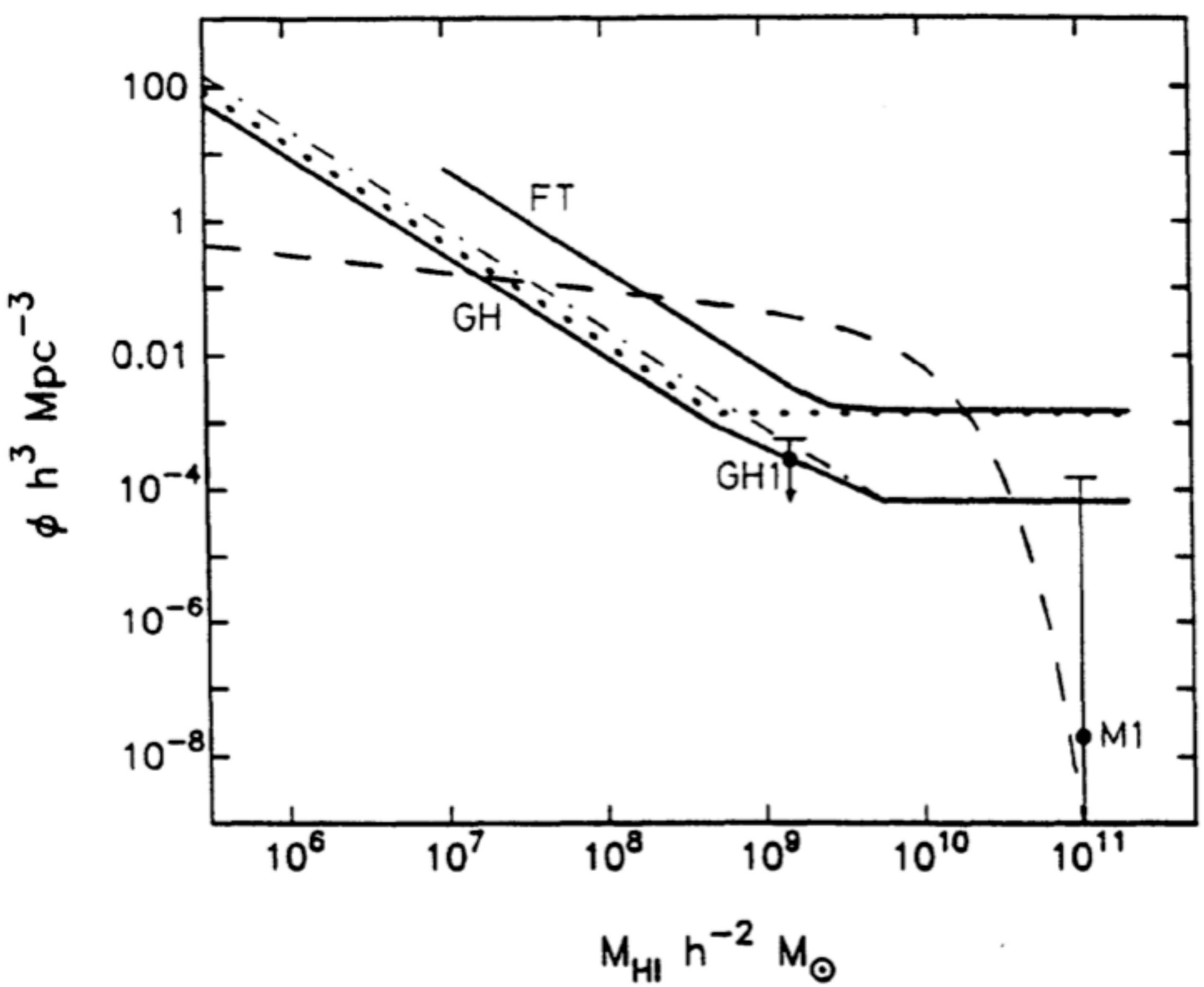


Relevance:

- Theories of galaxy formation and evolution
- Neutral hydrogen gas mass density
- Missing satellites
- Baryon mass functions

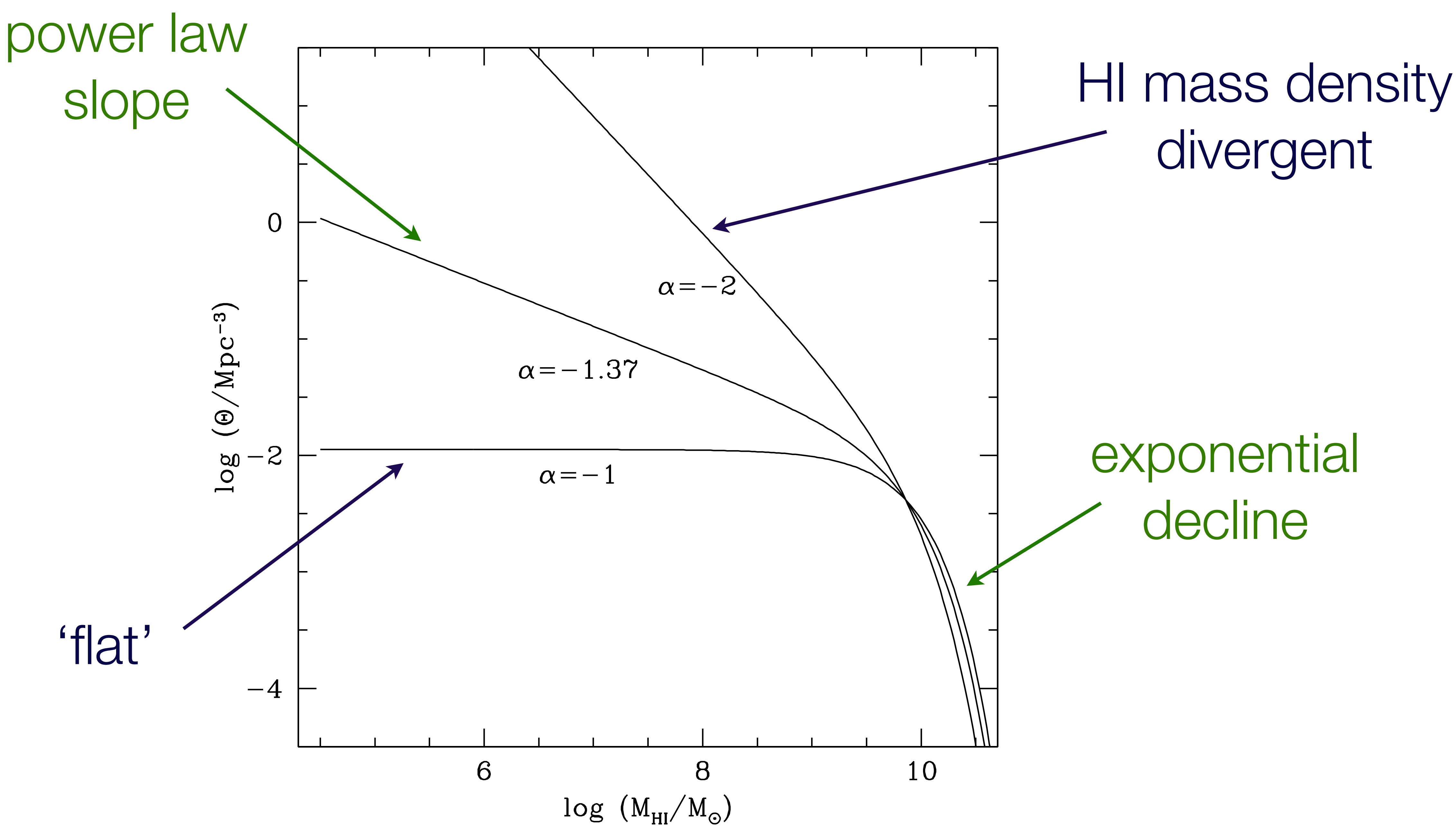
First HI mass functions

- Based on optical catalogues and assumptions on gas richness (Briggs 1990)



Compare with observations:
Is the Universe filled with dark galaxies?
Low surface brightness galaxies?

Schechter functions



HI mass function from **blind HI Surveys**

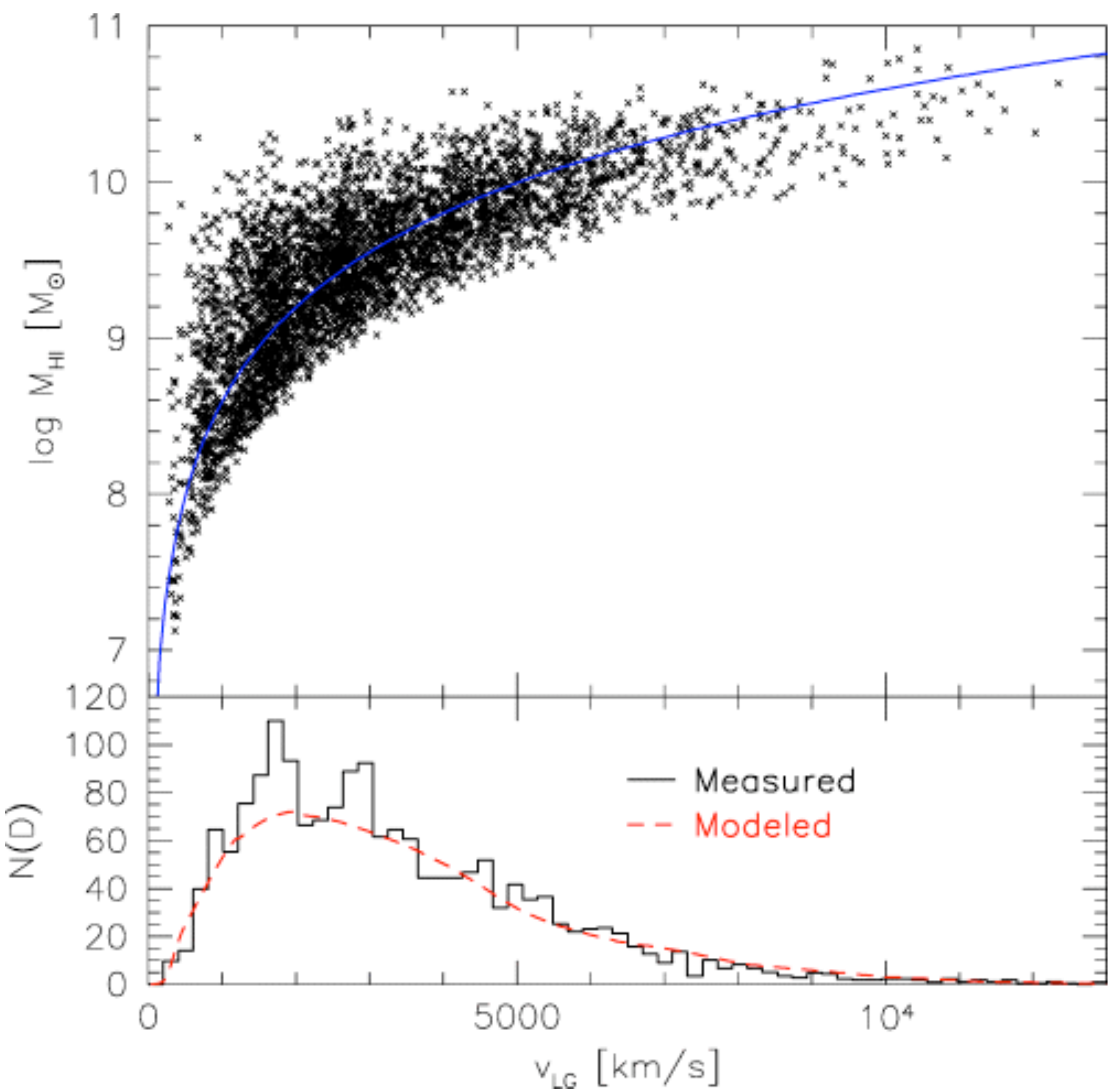
- HIMF measured from blind 21-cm surveys:
  - **AHISS**: HI strip Survey *(Zwaan et al 1997)*
  - **AS**: Arecibo Slice *(Spitzak & Schneider 1998)*
  - **ADBS**: Arecibo Dual Beam Survey *(Rosenberg & Schneider 2000)*
  - **HIPASS**: HI Parkes All Sky Survey *(Zwaan, Meyer et al 2003/2004/2005)*
  - **ALFALFA**: Arecibo Legacy Fast ALFA Survey *(Giovanelli et al 2005)*
  - **SKA pathfinders...**

HI mass function from **blind HI Surveys**

- HIMF measured from blind 21-cm surveys:
  - **AHISS**: HI strip Survey *(Zwaan et al 1997)*
  - **AS**: Arecibo Slice *(Spitzak & Schneider 1998)*
  - **ADBS**: Arecibo Dual Beam Survey *(Rosenberg & Schneider 2000)*
  - **HIPASS**: HI Parkes All Sky Survey *(Zwaan, Meyer et al 2003/2004/2005)*
  - **ALFALFA**: Arecibo Legacy Fast ALFA Survey *(Giovanelli et al 2005)*
  - **SKA pathfinders...**

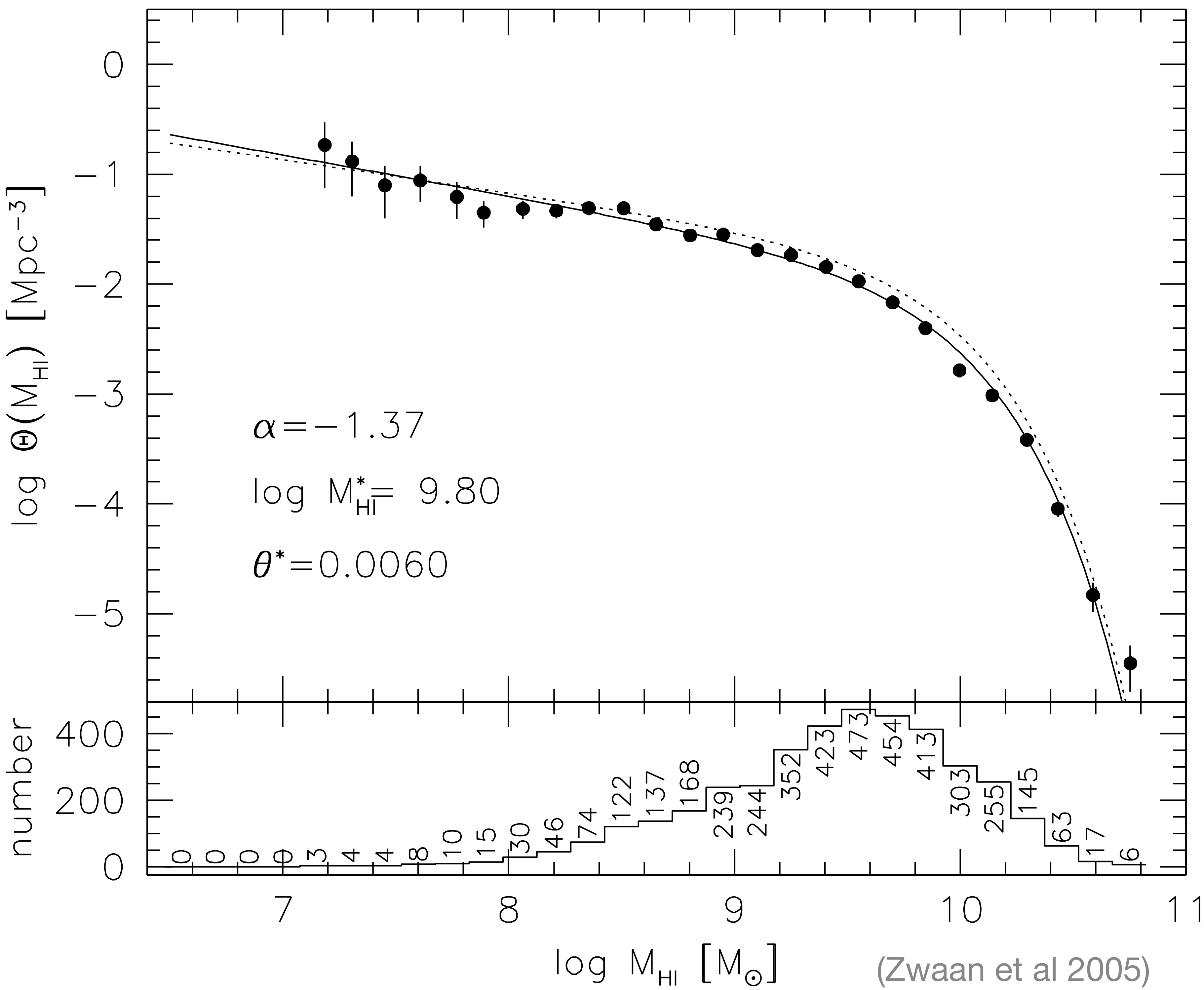
Blind survey covering whole southern sky up to dec=+25°. 5300 detections

HIPASS results



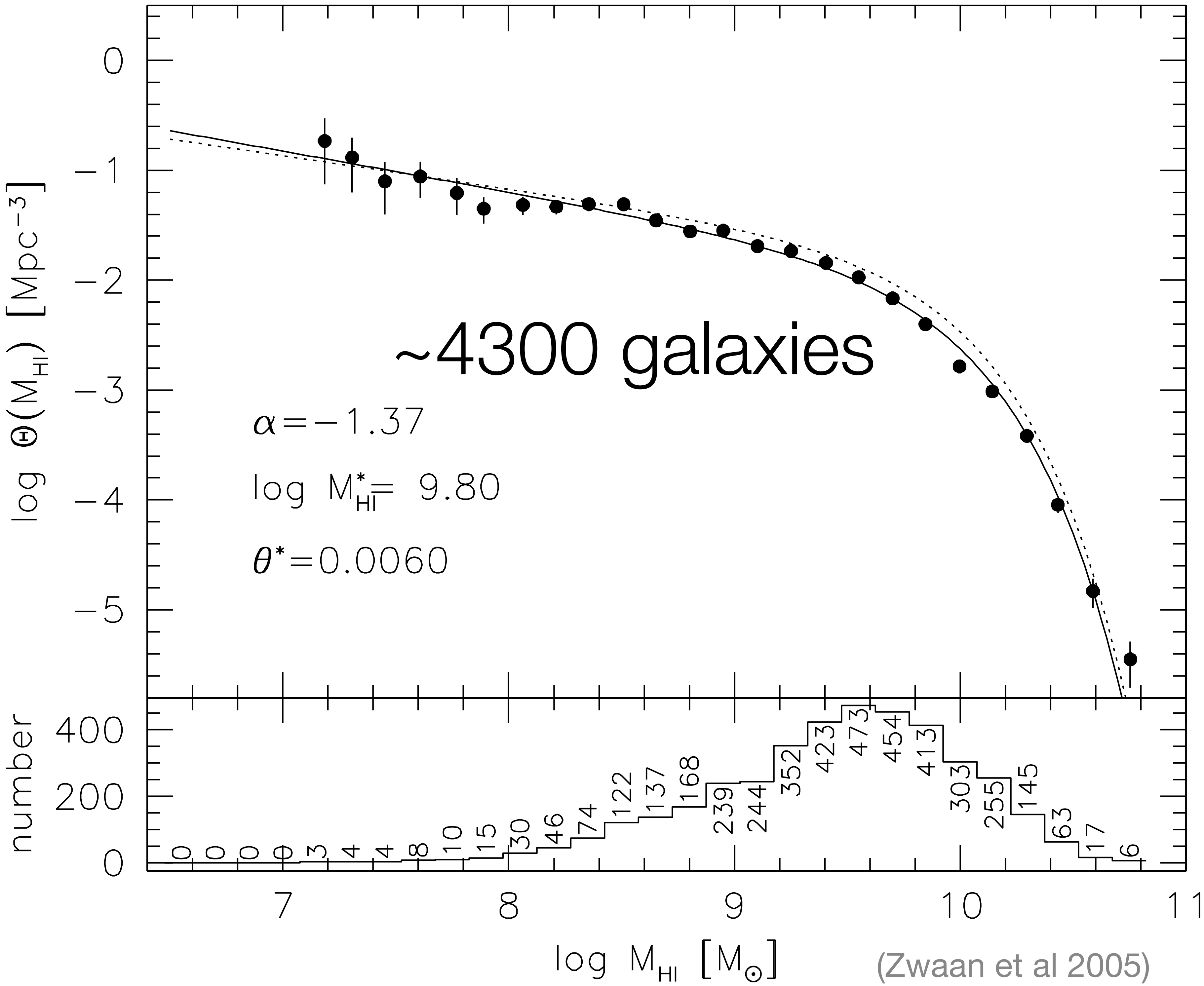
- $M_{HI} \propto S_{int} D^2$
- $M_{HI} = 10^8$ M_o out to ~12 Mpc
- peak at ~25 Mpc
- No sharp flux limit → *complicated completeness corrections*

The **HI mass function**

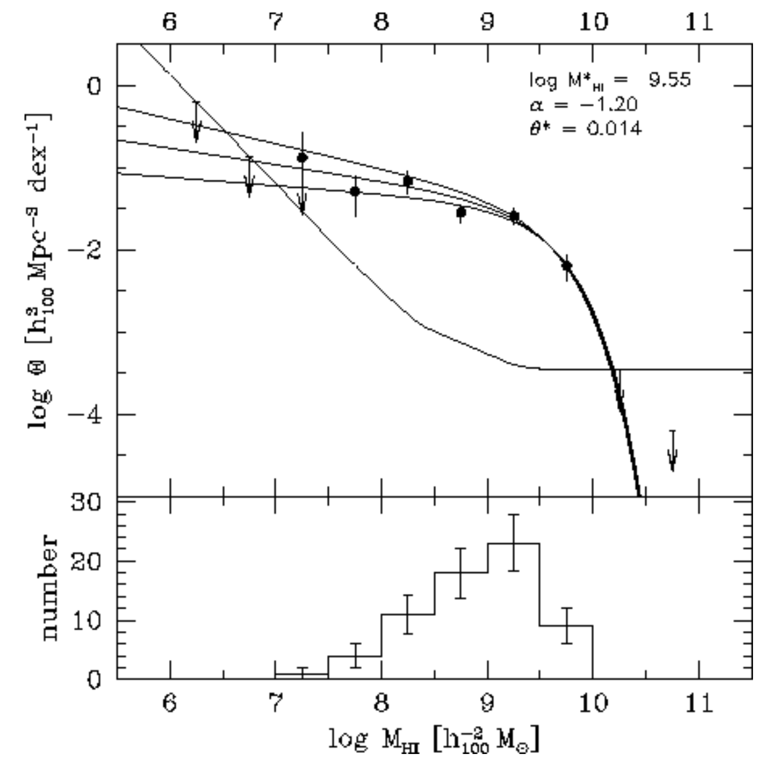


(Zwaan et al 2005)

The **HI mass function**



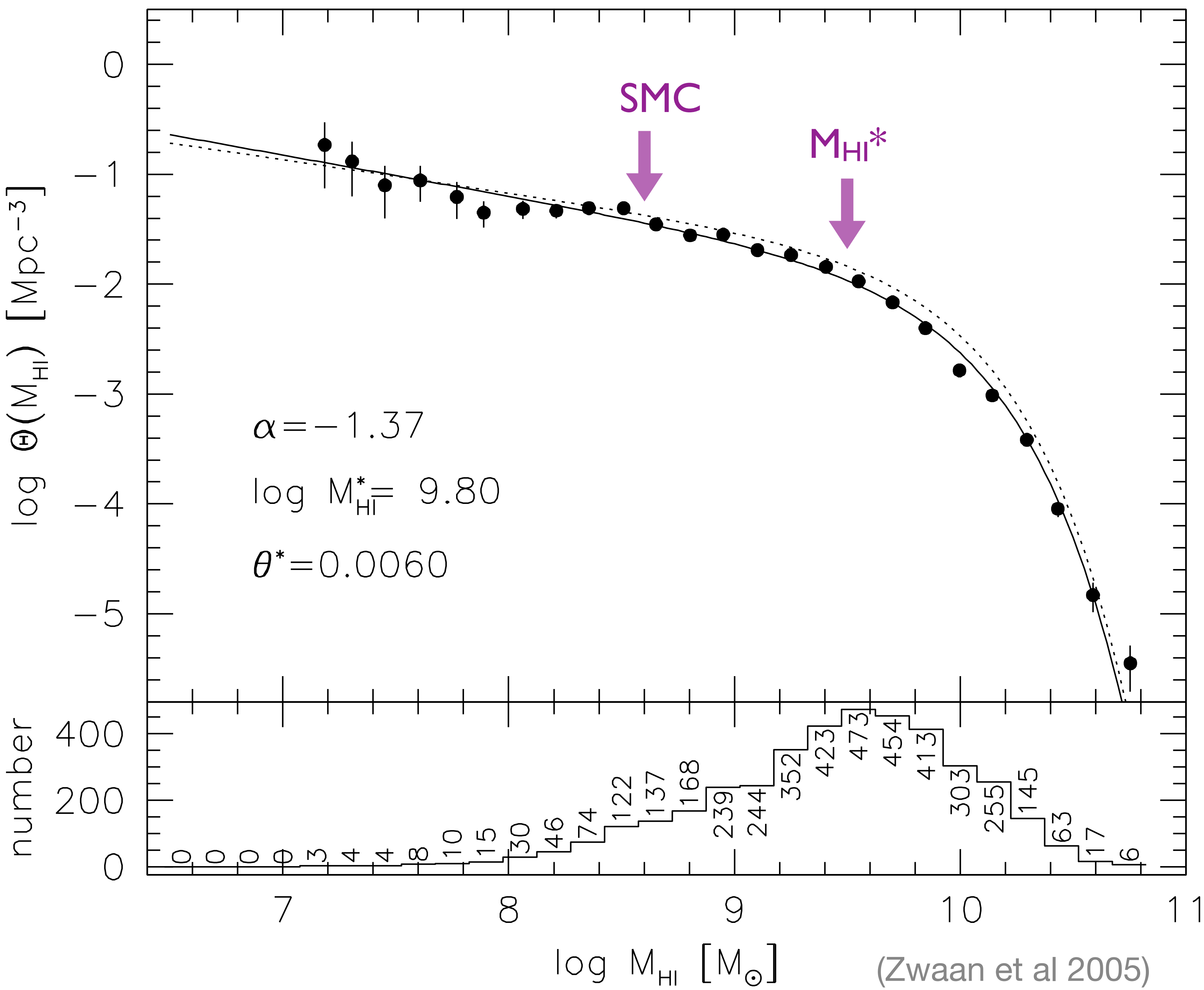
(Zwaan et al 2005)



AHISS
(Zwaan et al 1997)

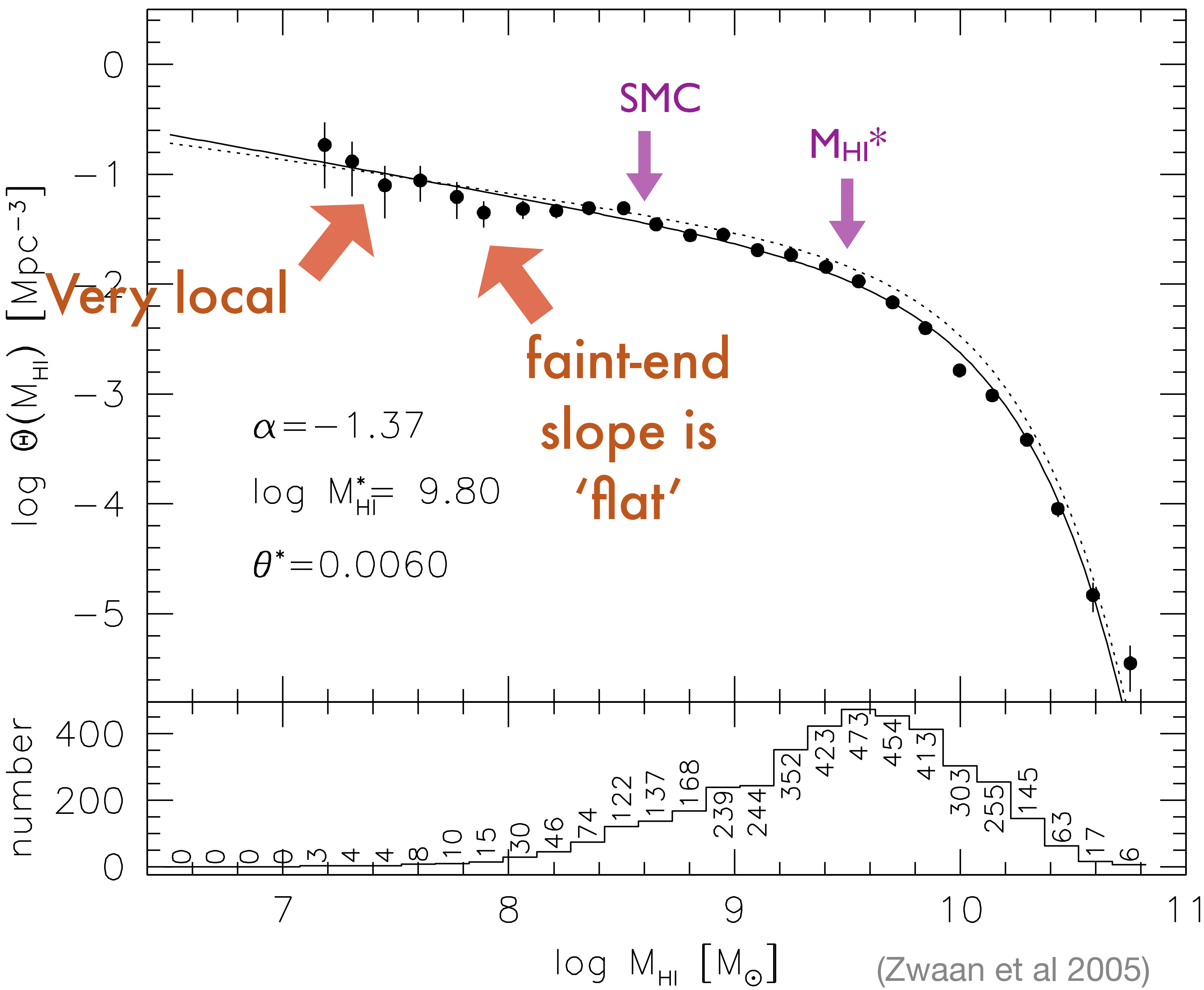
~66 galaxies

The **HI mass function**



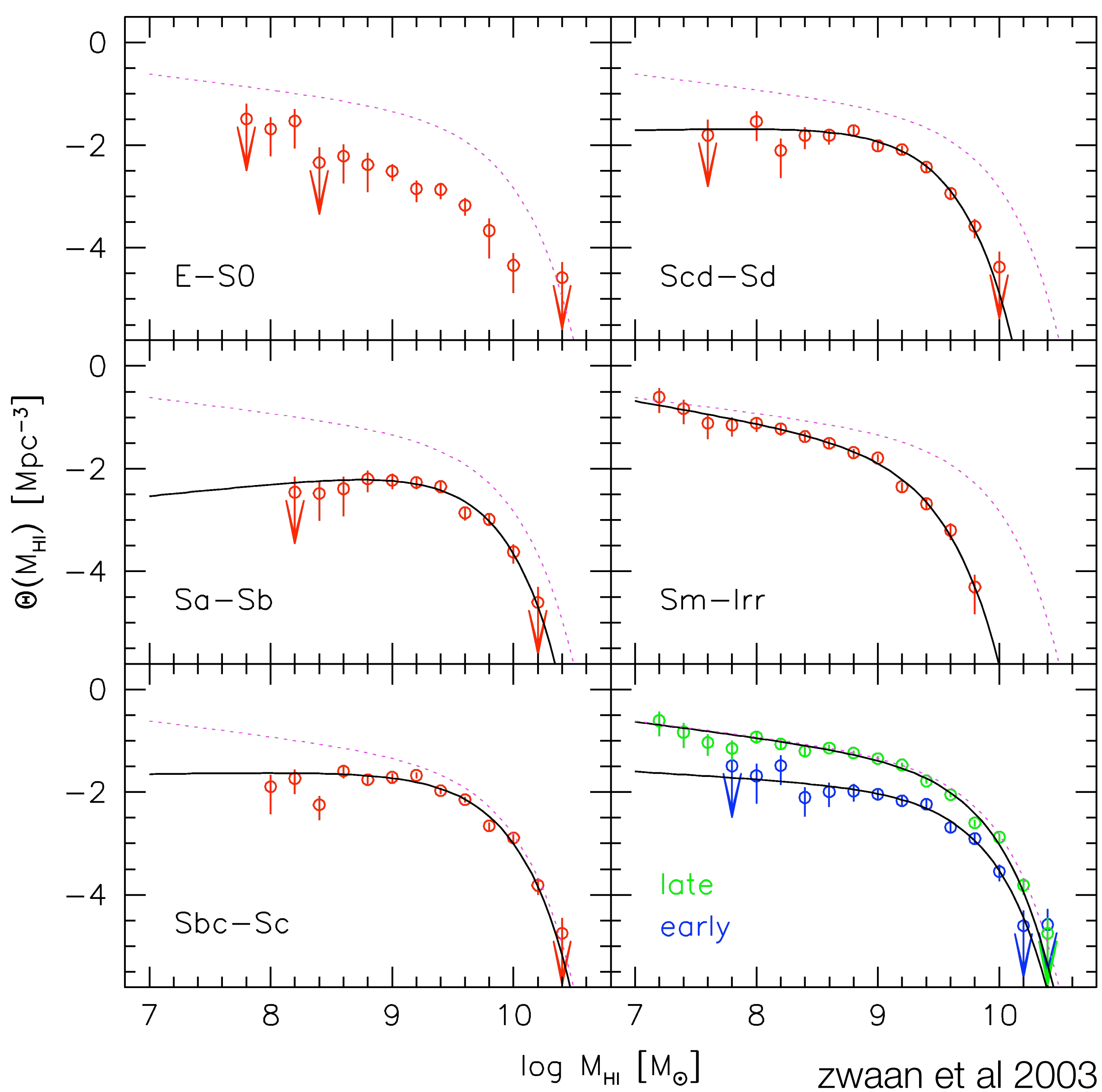
(Zwaan et al 2005)

The **HI mass function**



(Zwaan et al 2005)

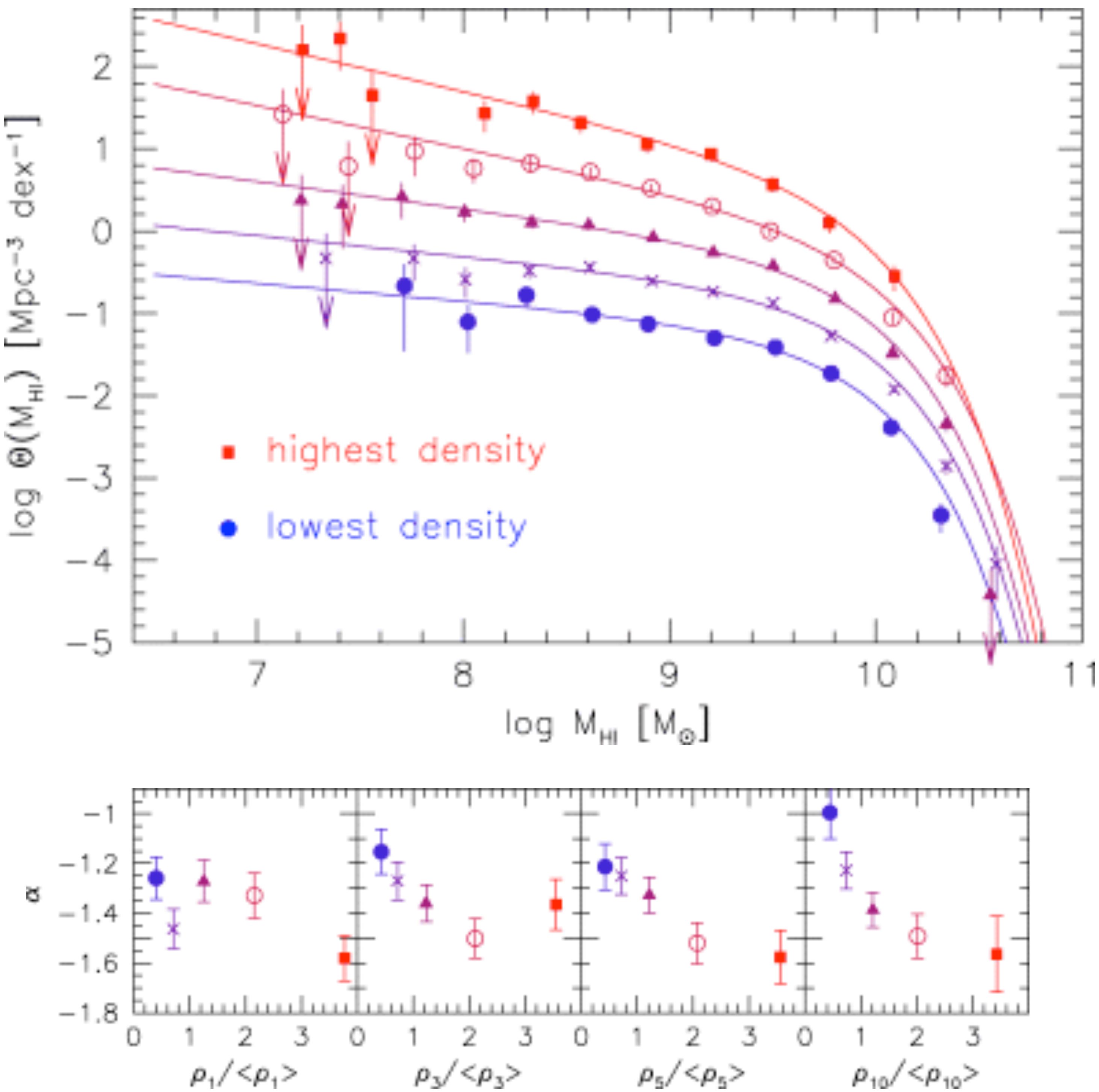
HIMF dependence on **galaxy type**



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

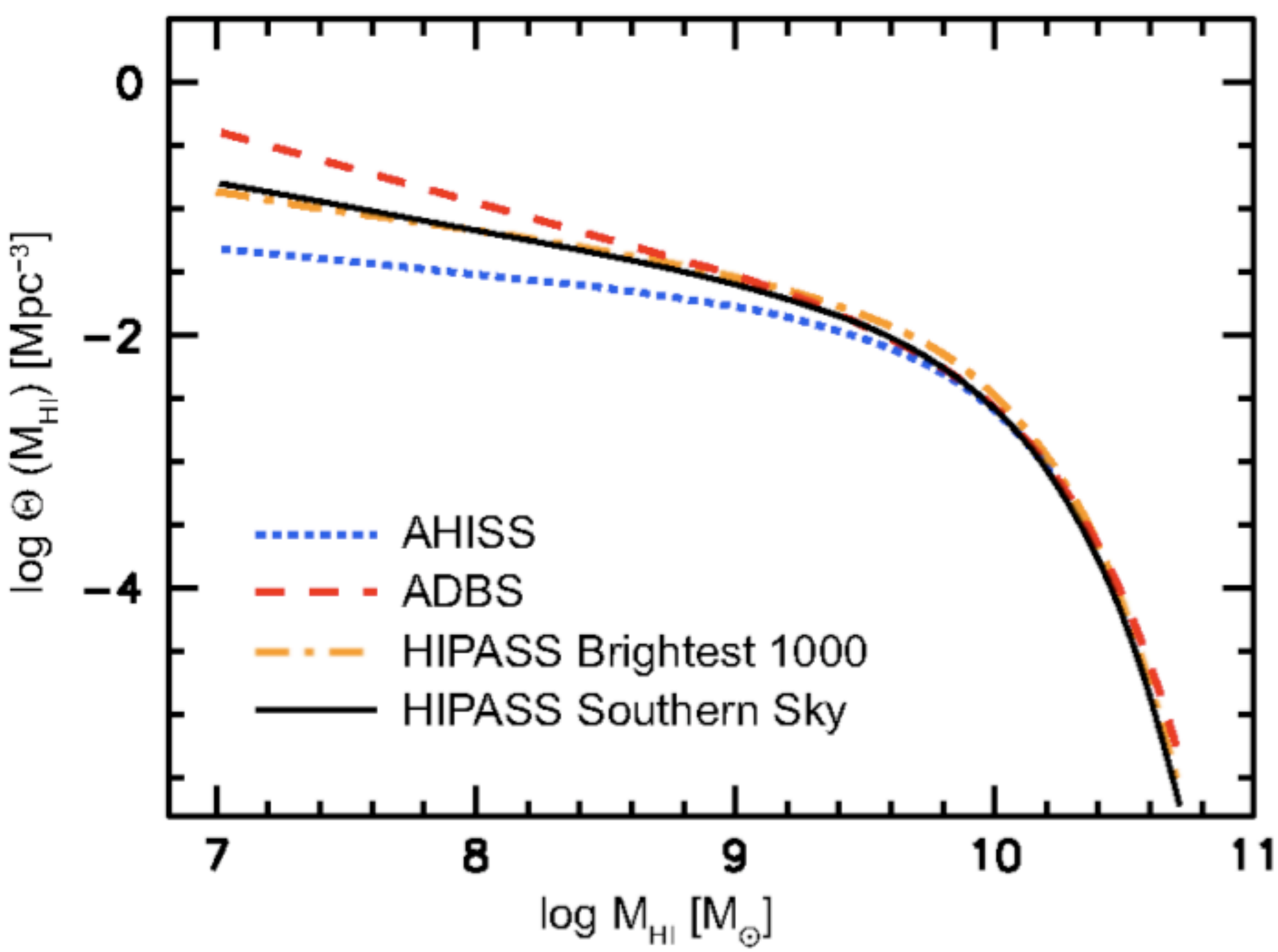
Environmental effects on HIMF?



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

HIMF **variations**



From Schneider et al 2008

Different surveys probe different depths

Large scale structure causes variations in HIMF?

Or is it differences in analysis?

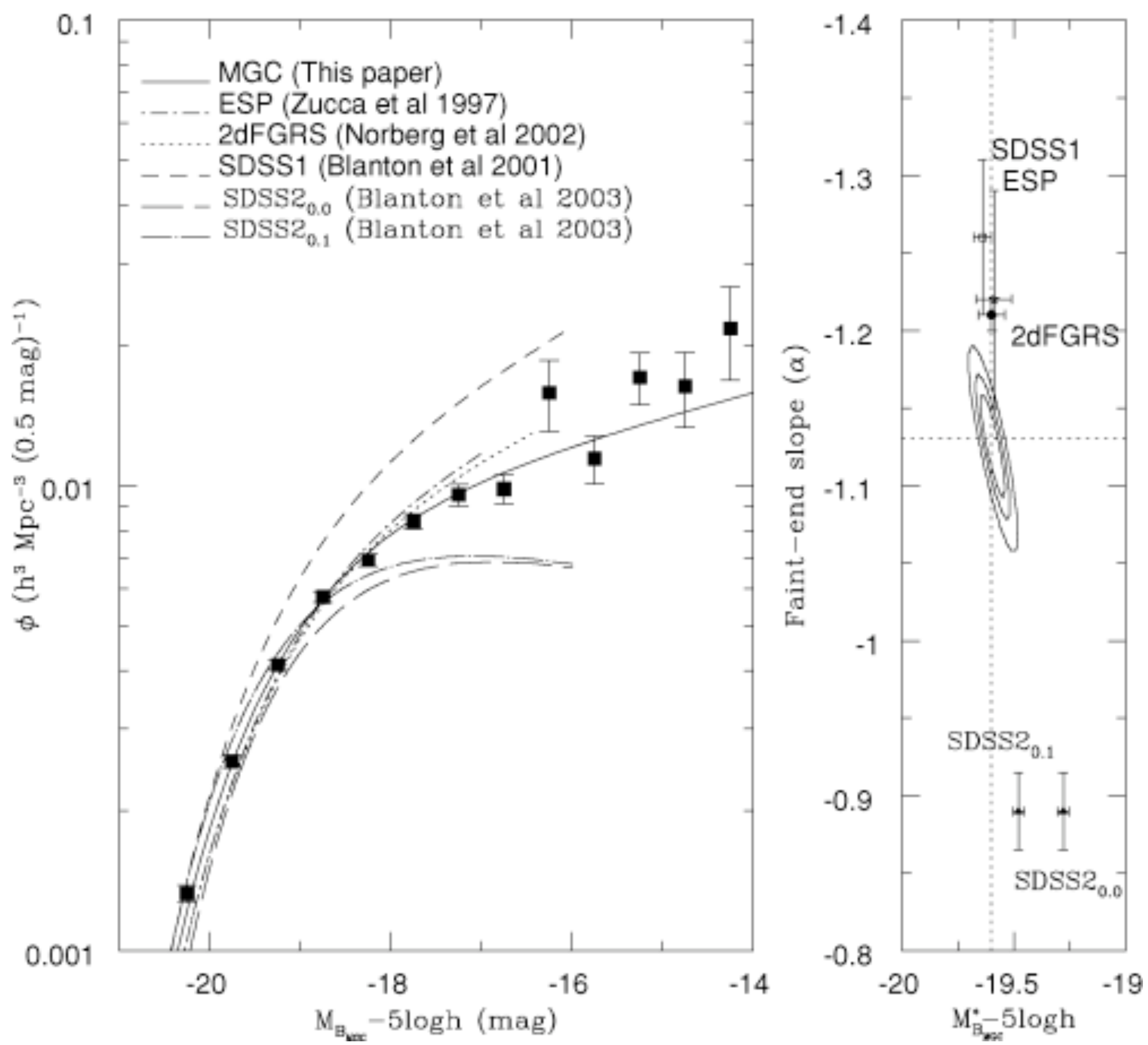
Do **larger surveys** help?

Do **larger surveys** help?

- Uncertainties in HI mass function dominated by **systematic** errors

Do **larger surveys** help?

- Uncertainties in HI mass function dominated by **systematic** errors
- Compare optical luminosity function →



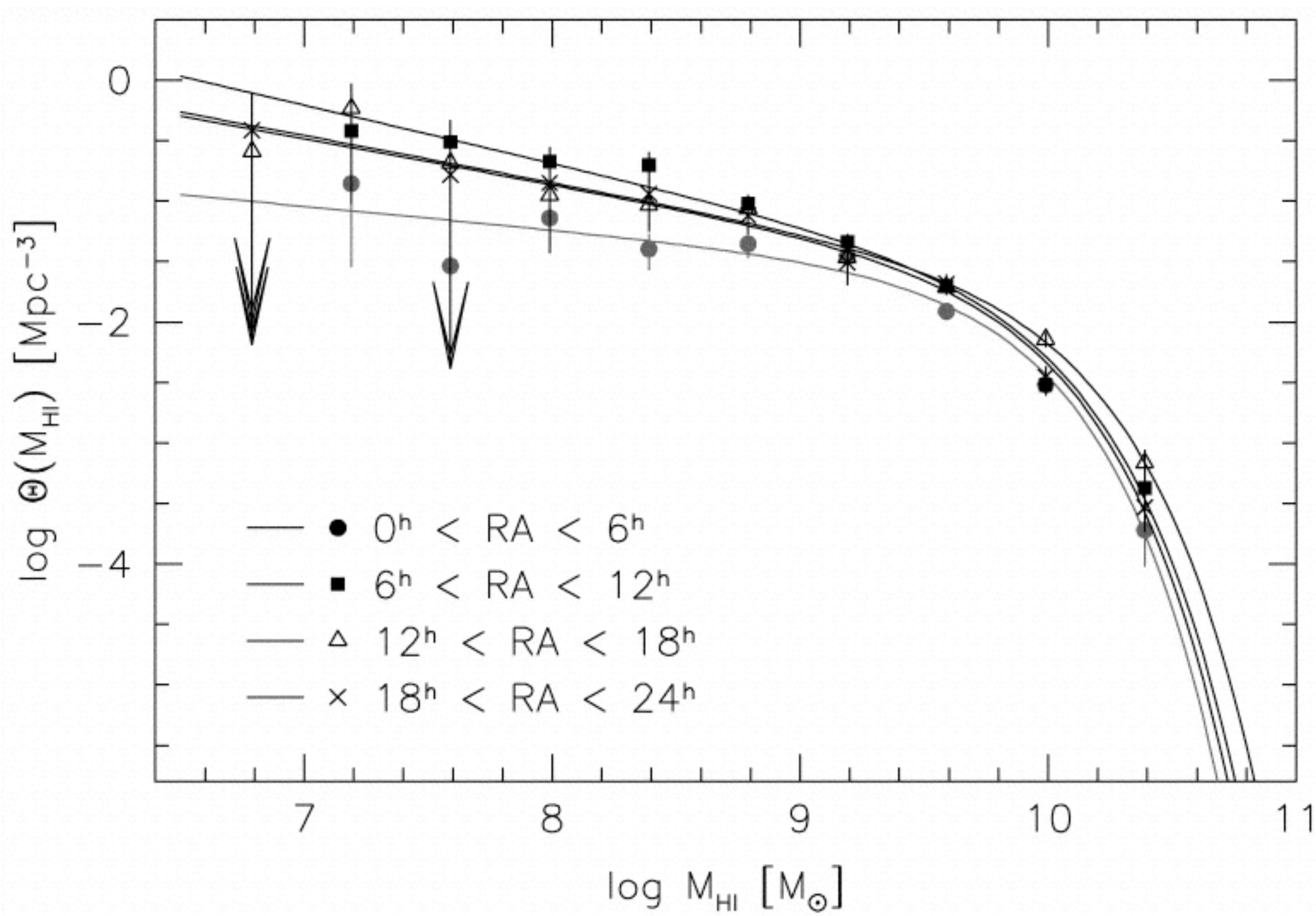
Driver et al 2005

Analysis techniques

Completeness ⟷ **Reliability**

- Most detection very close to the noise...
- Put fake sources in your data!

The HIMF and **cosmic variance**



HIPASS 1000 brightest galaxies

four different quadrants of the southern sky

Future challenges for HI mass function

low mass end

environment

evolution

Future challenges for HI mass function

low mass end

environment

evolution

Future challenges for HI mass function

low mass end
deep & wide

environment
wide

evolution
deep

How to **measure space densities**

- **Traditionally: $1/V_{max}$ method** (Schmidt 1968)
  - Summing volumes accessible to objects
  - Sensitive to large scale structure
- **Maximum likelihood methods** (Efstathiou et al 1988, Sandage et al 1979)
  - Find θ that yields maximal joint probability of detecting all sources in sample

How to **measure space densities**

- **Traditionally: 1/V_{max} method** (Schmidt 1968)
  - Summing volumes accessible to objects
  - Sensitive to large scale structure
- **Maximum likelihood methods** (Efstathiou et al 1988, Sandage et al 1979)
  - Find θ that yields maximal joint probability of detecting all sources in sample

$$p(M_{\mathrm{HI},i}|D_i) = \frac{\theta(M_{\mathrm{HI},i})}{\int_{M_{\mathrm{HI,min}(D_i)}}^{\infty} \theta(M_{\mathrm{HI}}) dM_{\mathrm{HI}}}$$

How to **measure space densities**

- **Traditionally: $1/V_{max}$ method** (Schmidt 1968)
  - Summing volumes accessible to objects
  - Sensitive to large scale structure
- **Maximum likelihood methods** (Efstathiou et al 1988, Sandage et al 1979)
  - Find θ that yields maximal joint probability of detecting all sources in sample

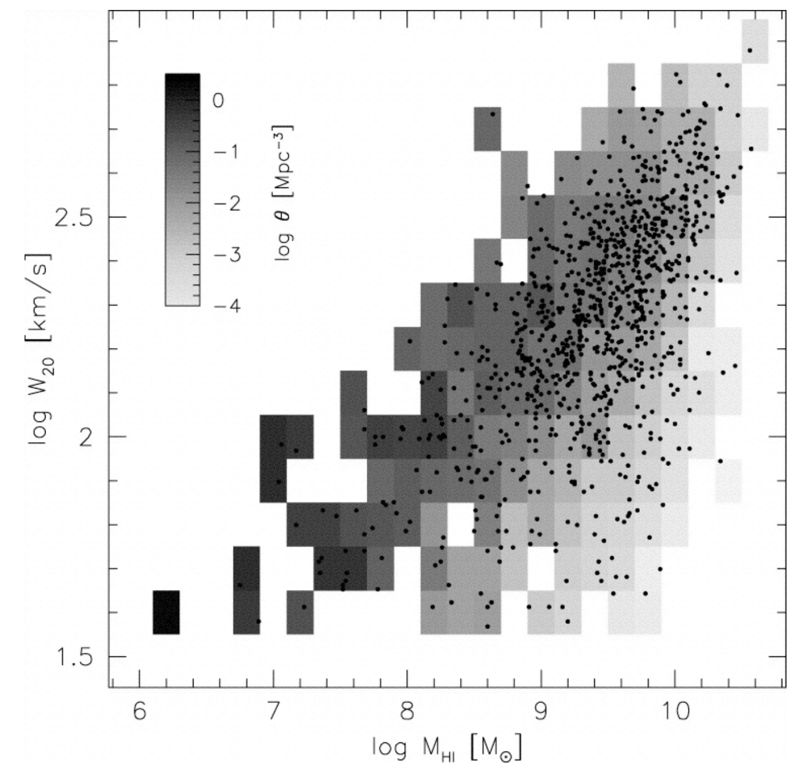
$$p(M_{\mathrm{HI},i}|D_i) = \frac{\theta(M_{\mathrm{HI},i})}{\int_{M_{\mathrm{HI,min}(D_i)}}^{\infty} \theta(M_{\mathrm{HI}}) dM_{\mathrm{HI}}}$$

minimal detectable HI mass at distance D_i

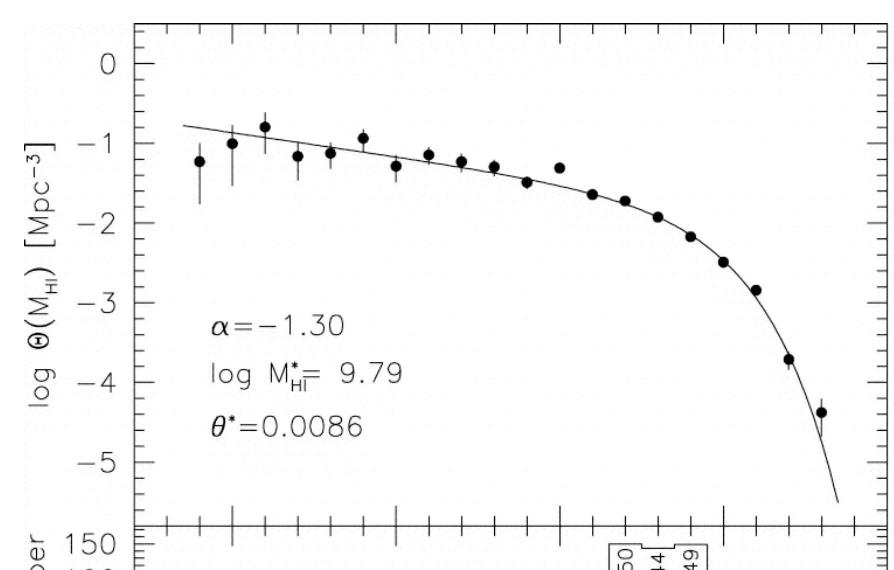
generally **not defined** for HI selected samples

How to **measure space densities**

- solution: multi-dimensional stepwise maximum likelihood methods
- Find $\theta(M_{HI},W)$
- Collapse to find HIMF
- Or, find ML-based effective volume accessible to each galaxy individually



$\Sigma 1/V_{max}$



Biases in HI mass determination

Biases in HI mass determination

Eddington effect

cosmic variance

noise bias

confusion

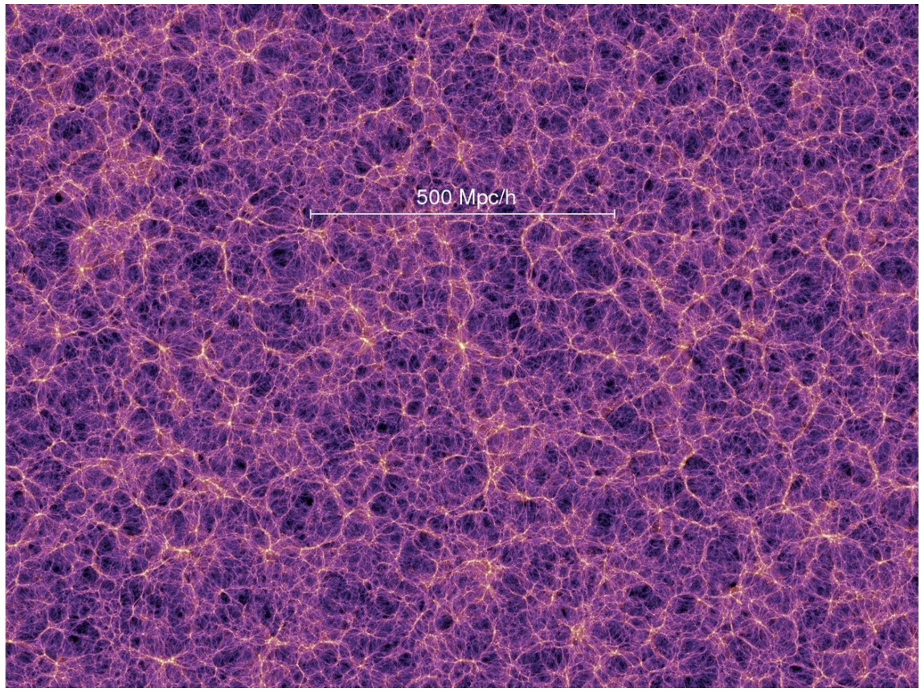
HI self-absorption

inclination bias

resolve large galaxies

Simulations to test HIMF recovery

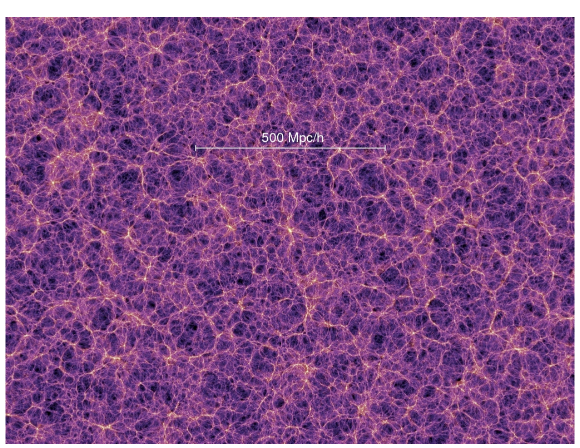
- Millennium Simulation (Springel et al 2005)
- 9 million galaxies in the full simulation box (500 Mpc/h on a side)
- Stich several cubes together
- Assume a HIPASS HI mass function
- Low mass (log M_{HI}<8.5) cluster around larger ones



Simulations

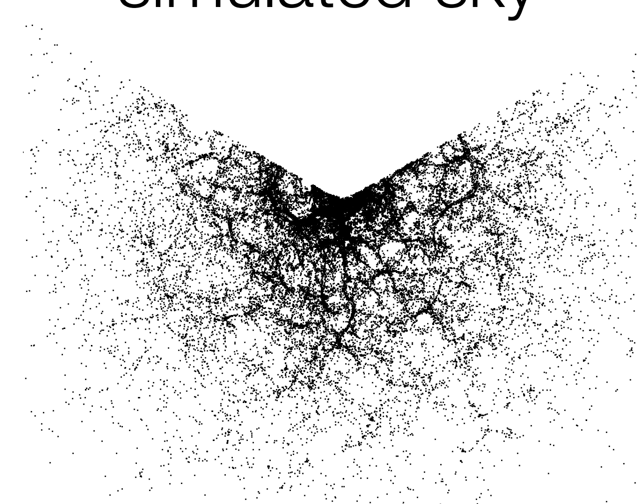
- Rotational velocity - HI mass relation from Obreschkow & Rawlings (2009)
- Random inclinations -> velocity widths
- Realistic scatter on all parameters
- Select galaxies from simulated boxes, assuming ‘**optimal smoothing**’

input catalogue



selection method

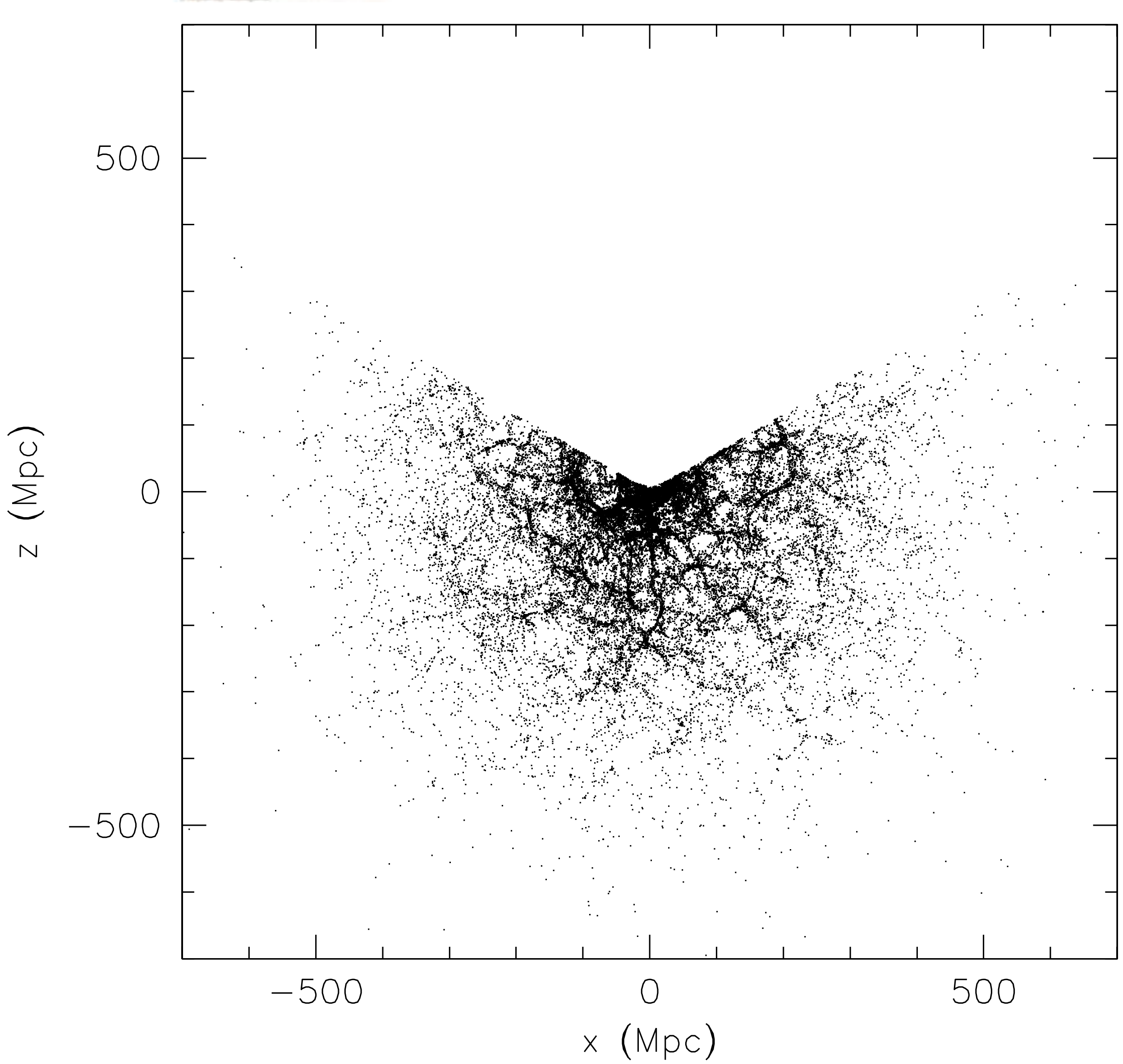
simulated sky

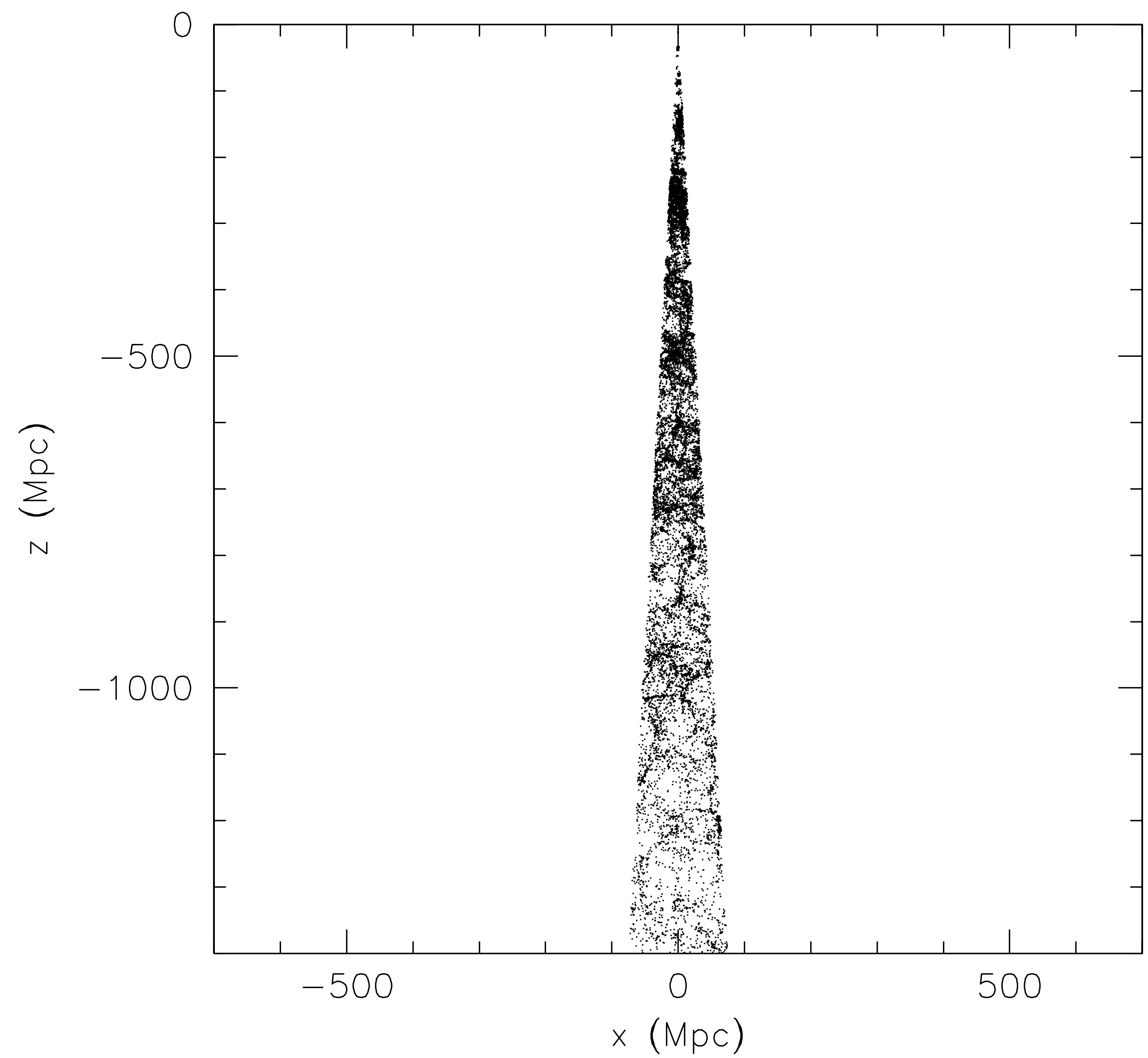


Simulated HI skies

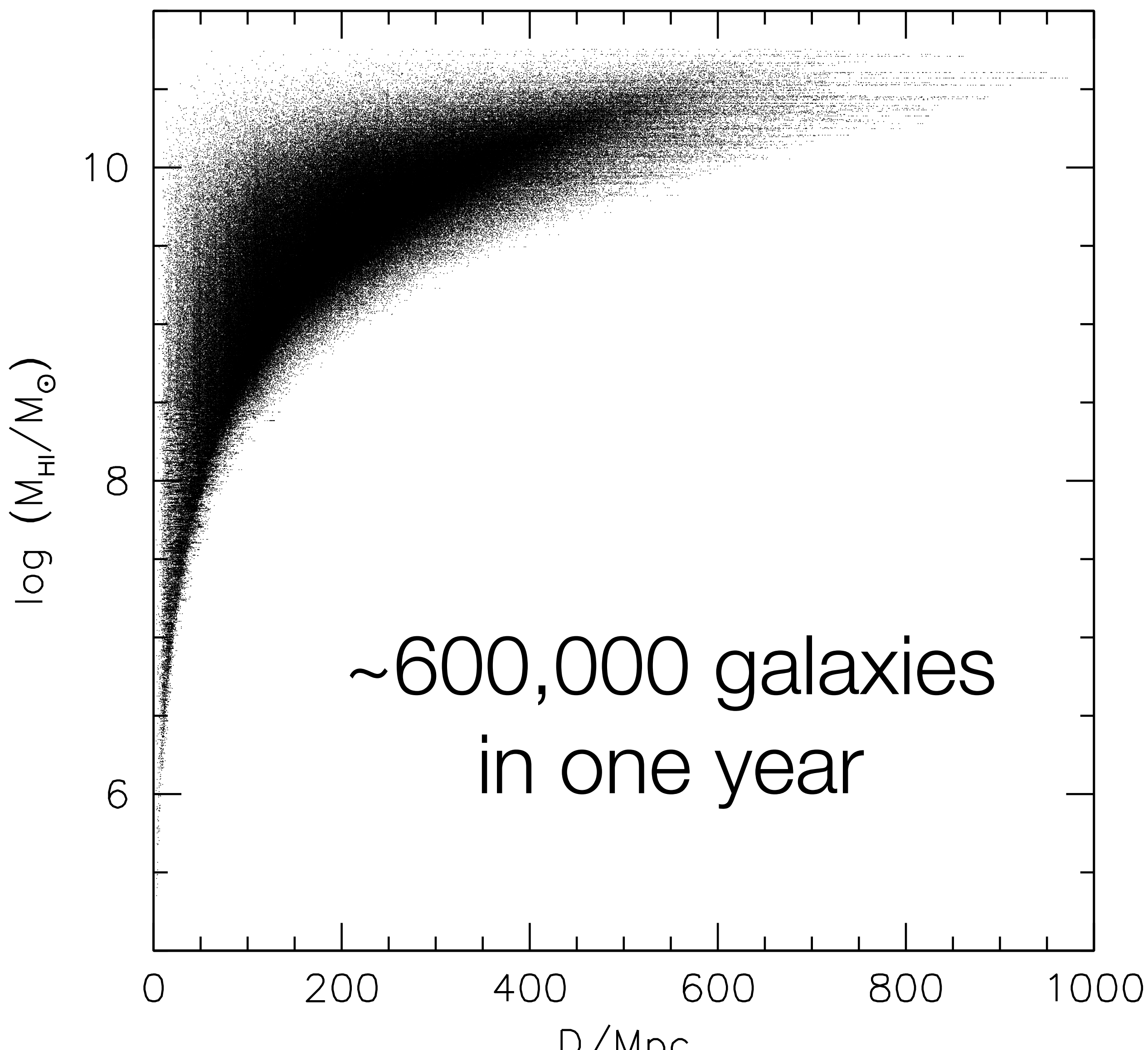
“Wallaby”
all sky shallow

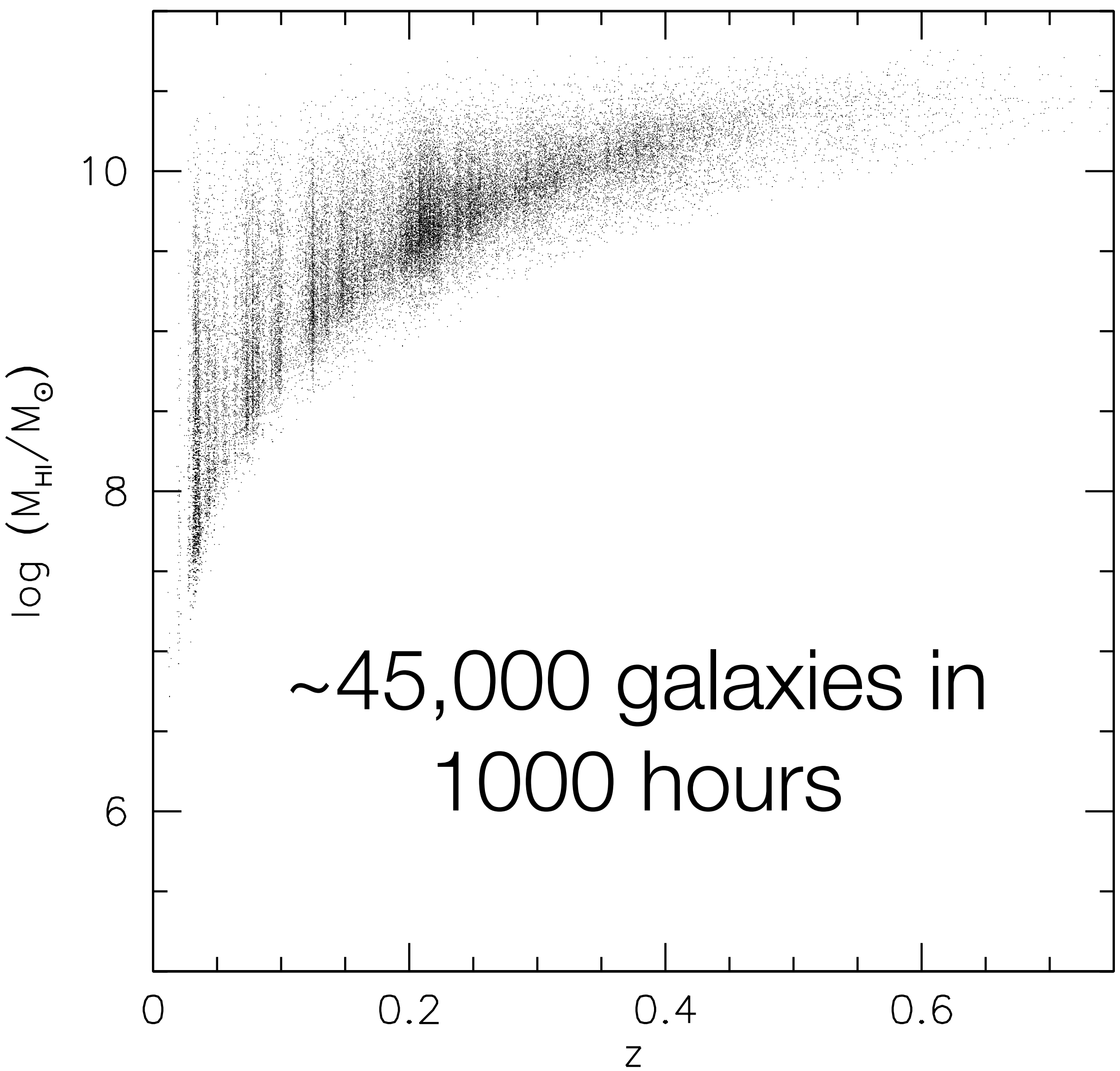
“Dingo”
30deg^2 deep



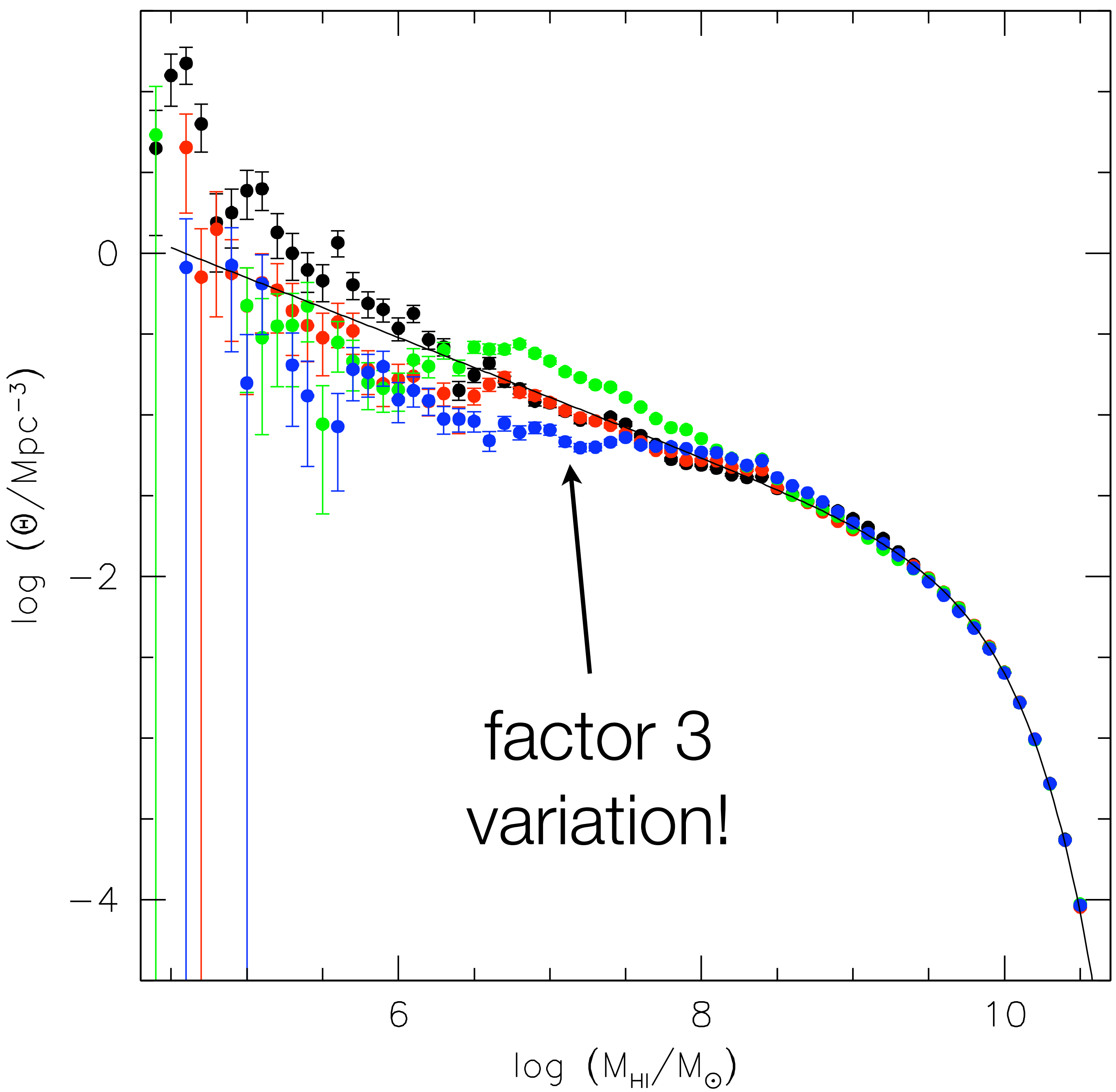


Simulated HI catalogues



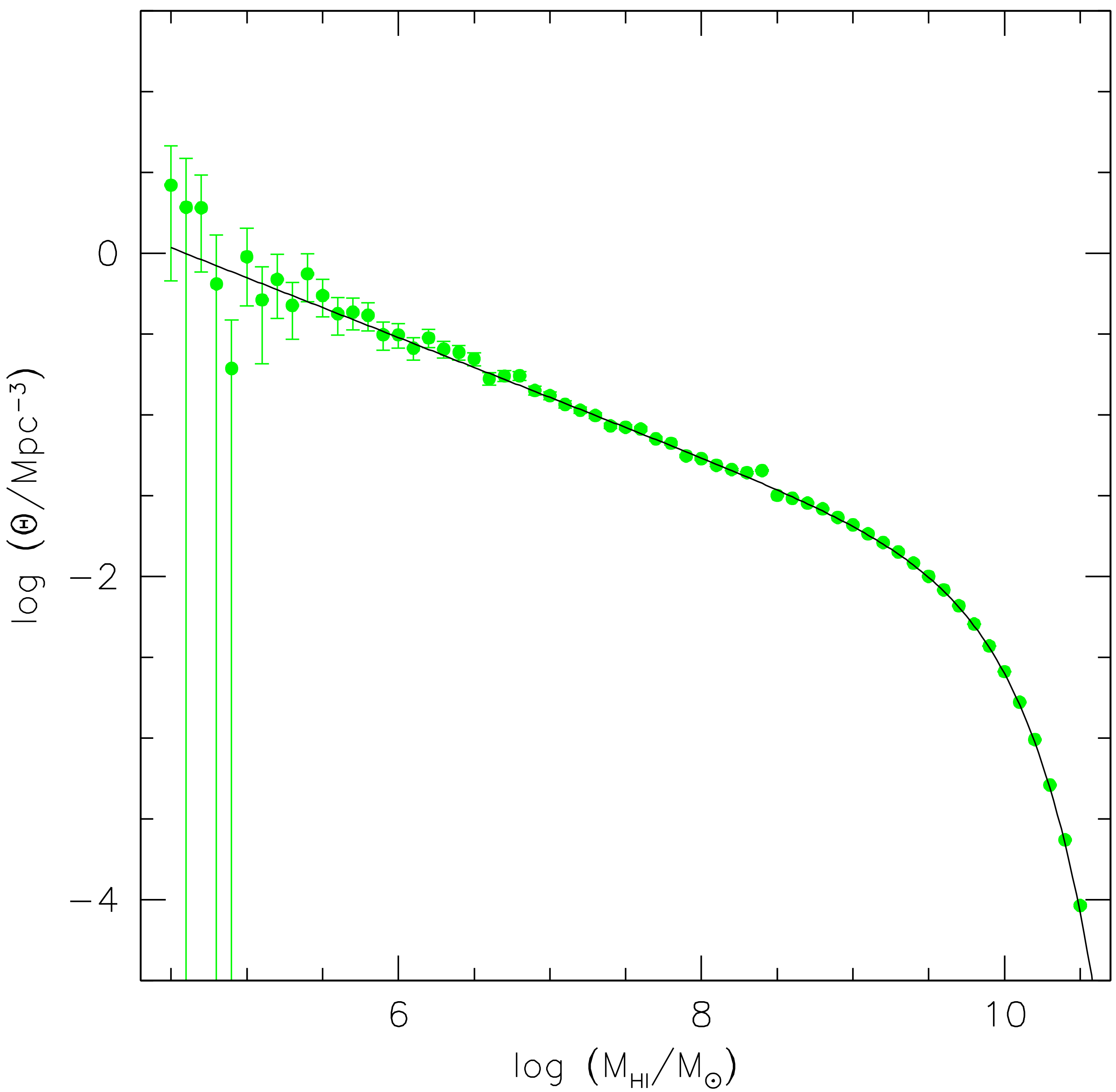


Wide field HIMFs



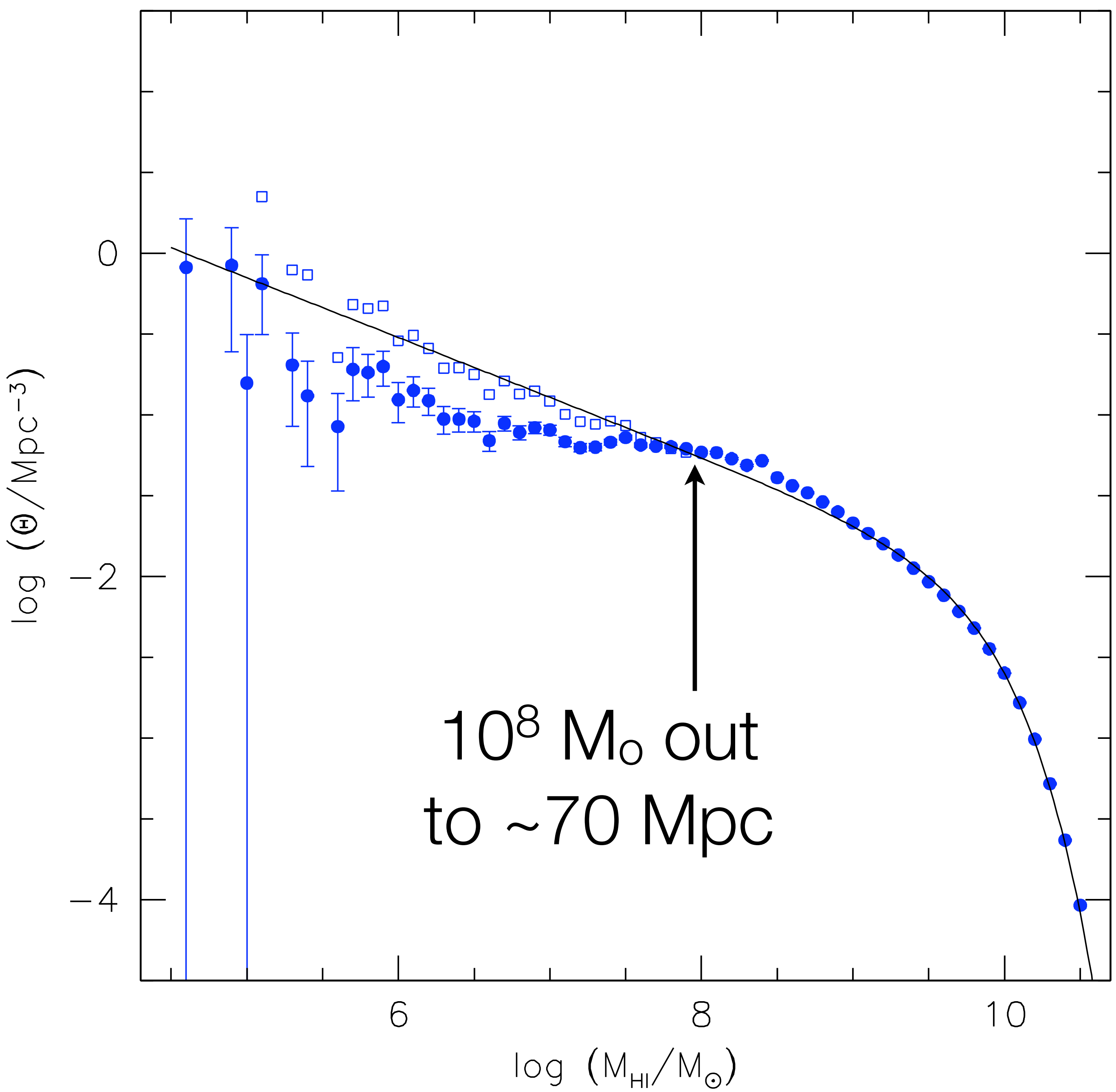
Four different realizations of Wallaby:
huge variations in HIMF based on $1/V_{max}$ method

Without **large scale structure**...



but with scatter in M-W relation

The magic of **stepwise maximum likelihood**



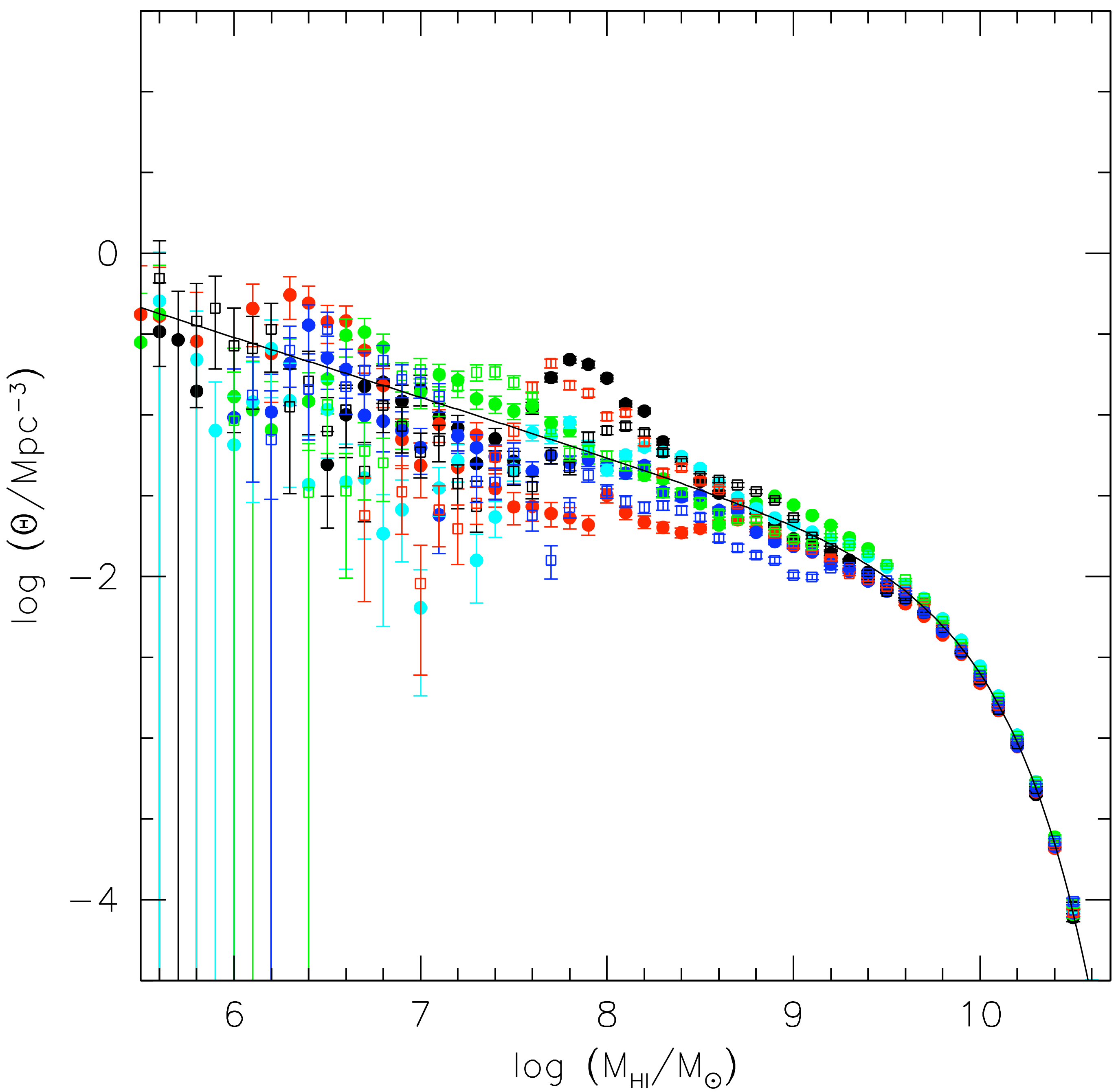
Solid: $1/V_{max}$ method
Open: 2DSWML

(ran 2DSWML only on galaxies $M_{HI} < 10^8\ M_o$)

Wallaby-type survey: HIMF expectations

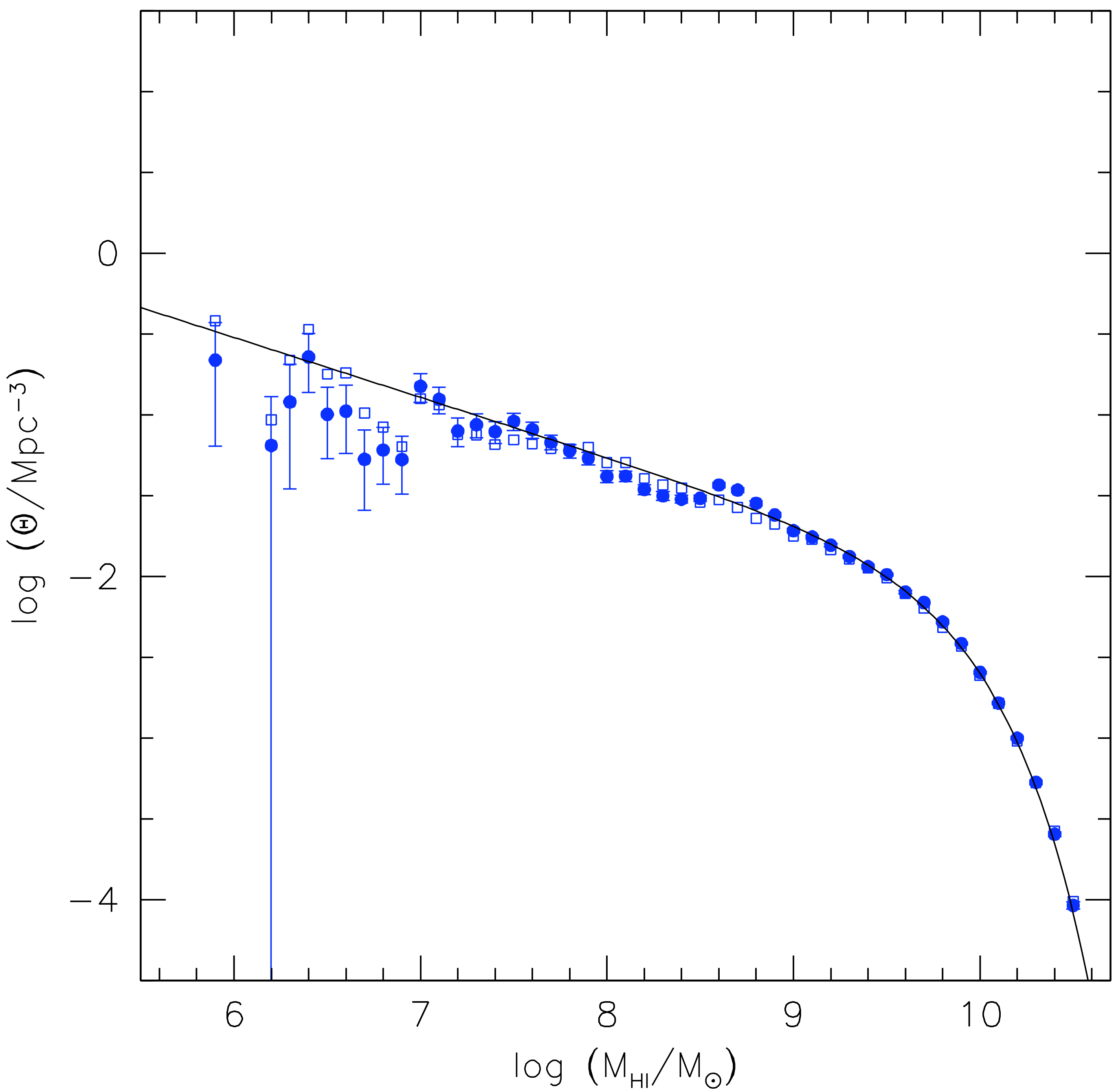
- ~600,000 galaxies (depending on selection technique)
- Can see $M_{HI} = 10^7\ M_\odot$ out to ~30 Mpc
- Can measure HIMF down to $M_{HI} \sim 10^6\ M_\odot$
- Excellent for measuring HI as function of environment

Dingo HI mass functions



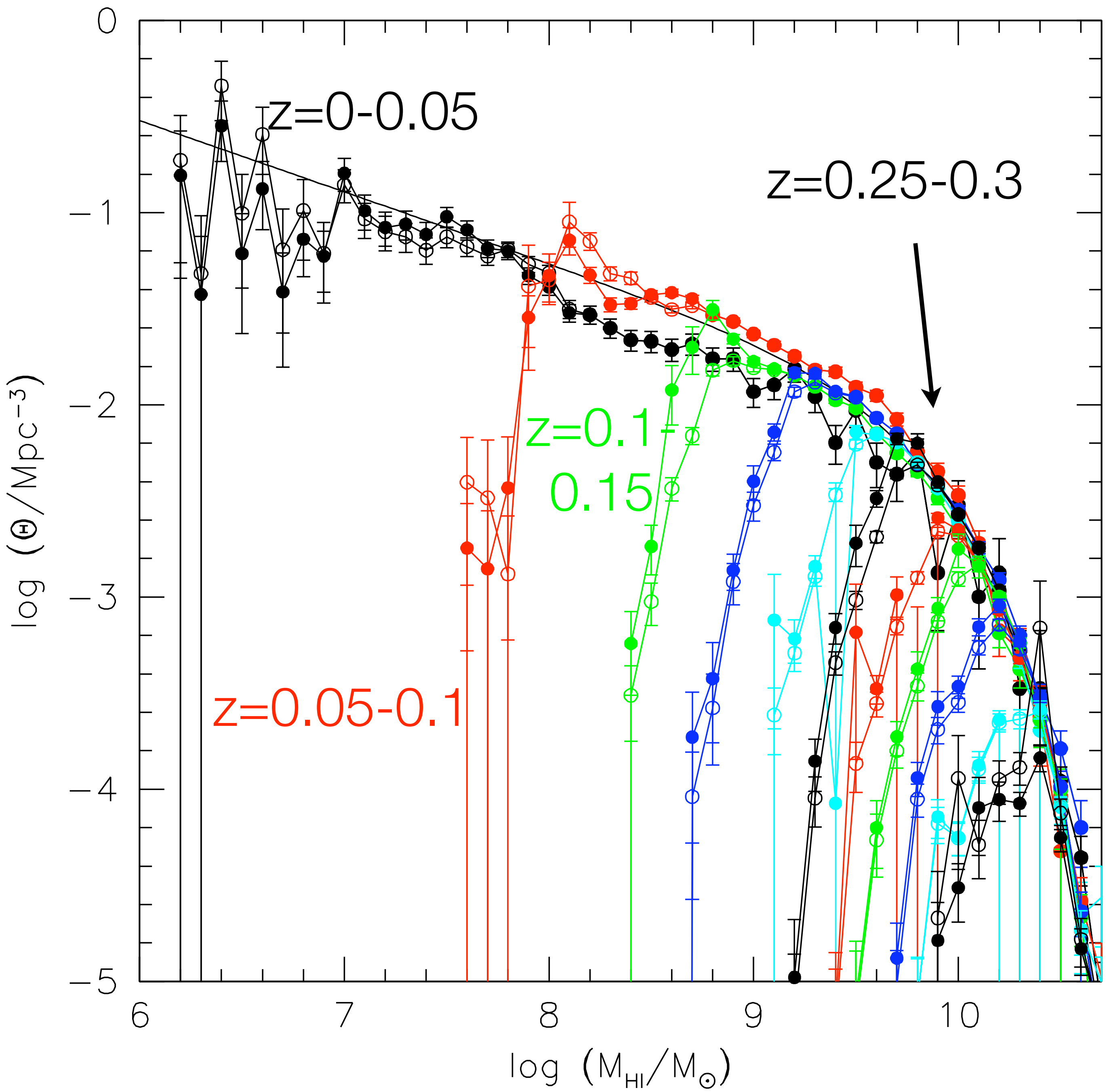
Ten different realizations of Dingo ultradeep: huge variations in HIMF based on $1/V_{max}$ method

The magic of **stepwise maximum likelihood**



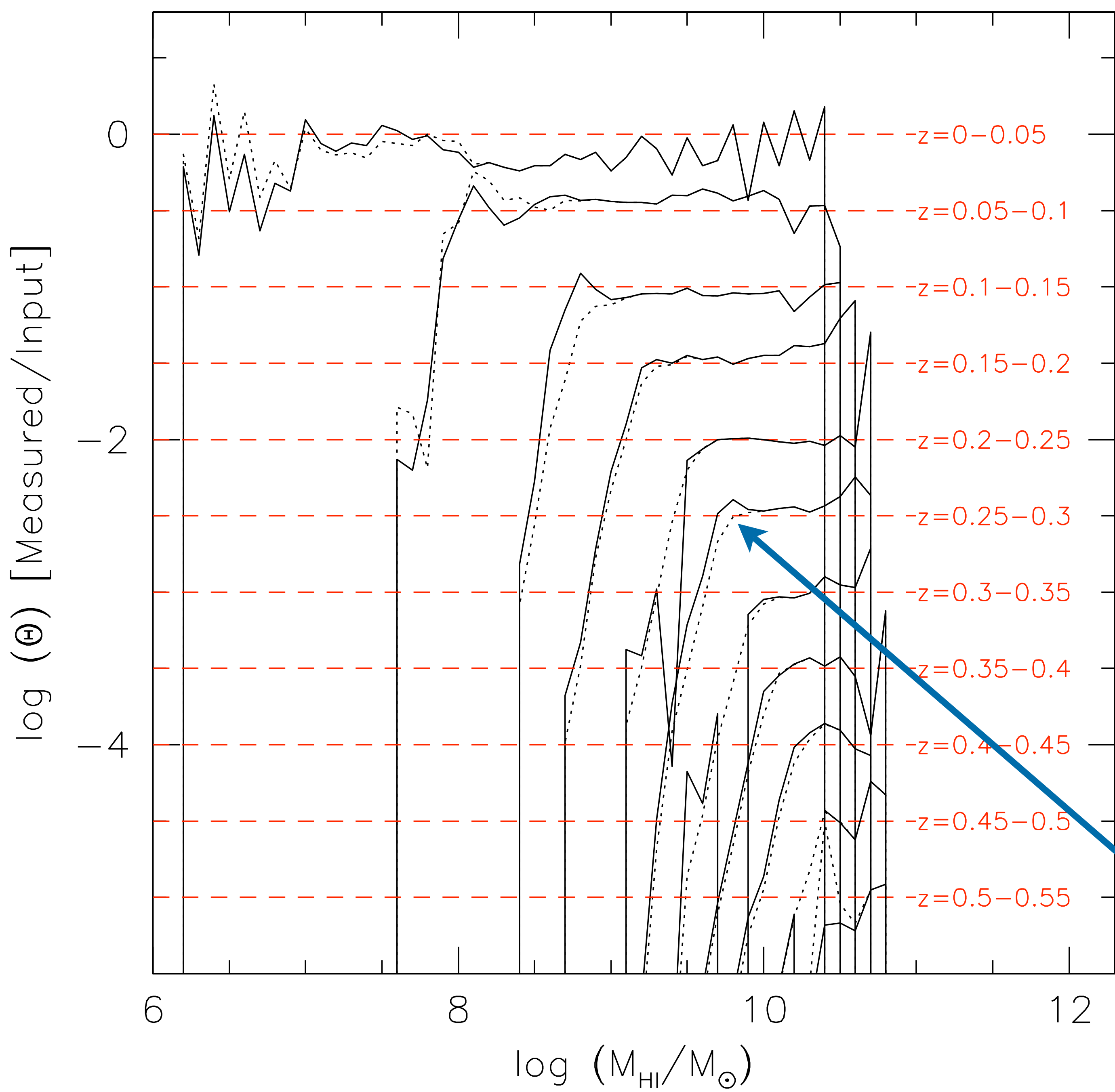
Solid: $1/V_{max}$ method
Open: 2DSWML

with Dingo **to higher redshifts**



Can reliably measure HIMF above M_{HI}^* out to z=0.3

Use Dingo to study **HIMF as function of redshift**



1/V_{max}

Maximum likelihood

Maximum likelihood does not help much

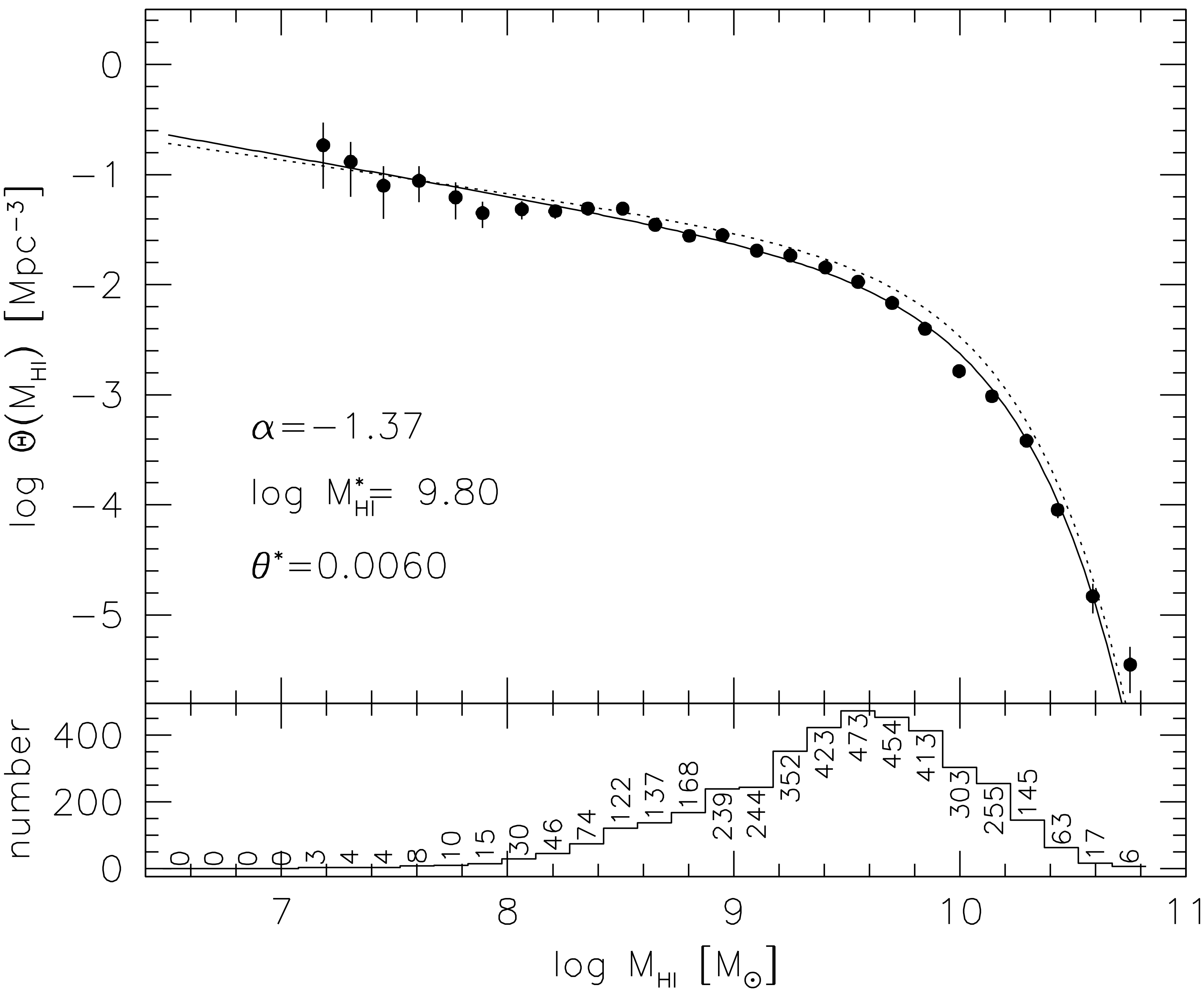
For HIMF evolution, one deep field is dangerous

M_{HI}^* out to z=0.3

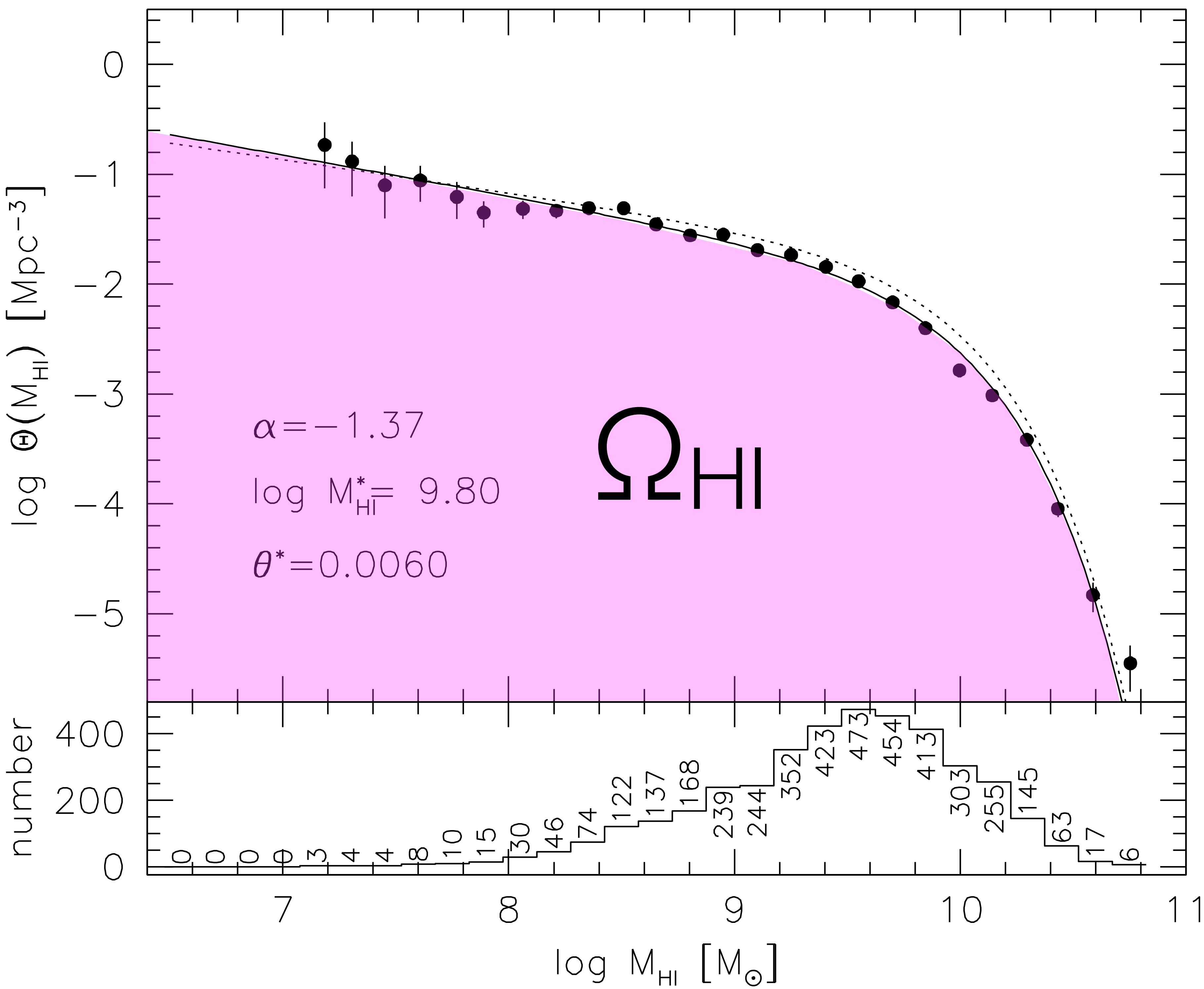
Dingo-type survey: HIMF expectations

- ~45,000 galaxies per 30º ultradeep field (depending on selection technique)
- ~12,000 galaxies per 30º deep field
- Can see $M_{HI} = 10^8\ M_\odot$ out to z~0.07
- Can measure HIMF out to z~0.3
- Can measure evolution of Ω_{HI} out to higher z using some assumptions/tricks

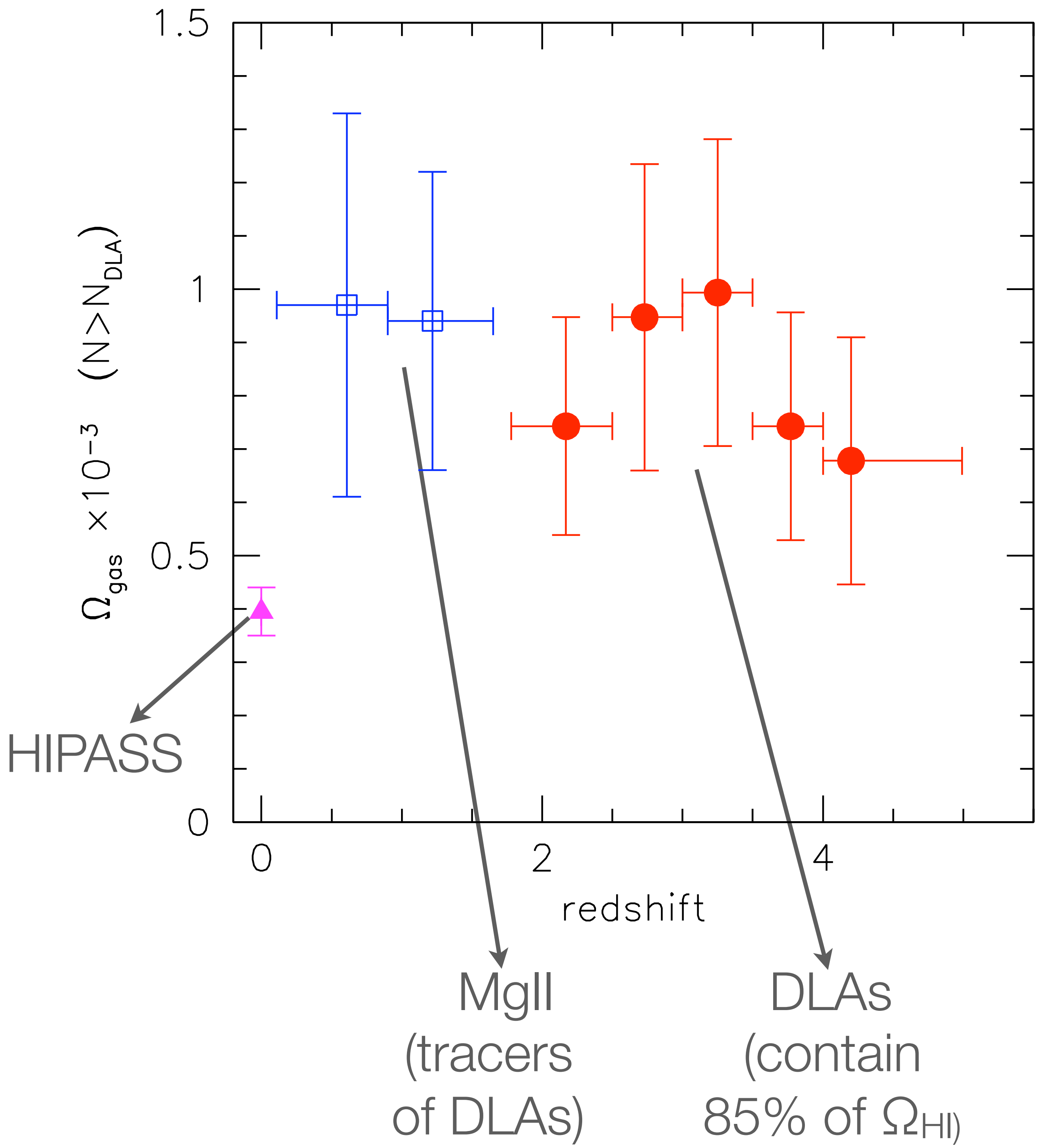
Ω_{HI}: the cosmic **HI mass density**



Ω_{HI}: the cosmic **HI mass density**

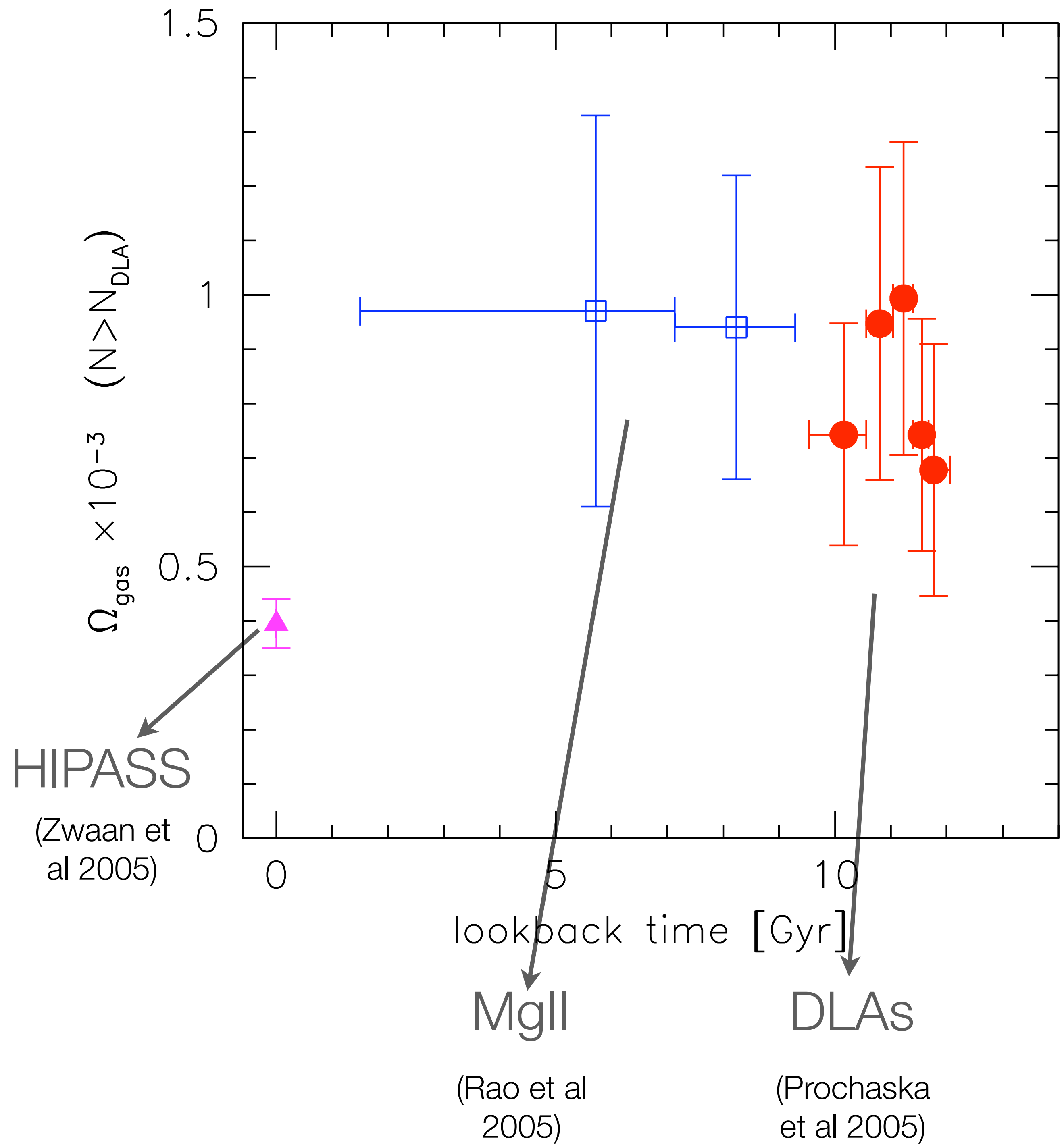


Number of **HI atoms** does **not evolve** much



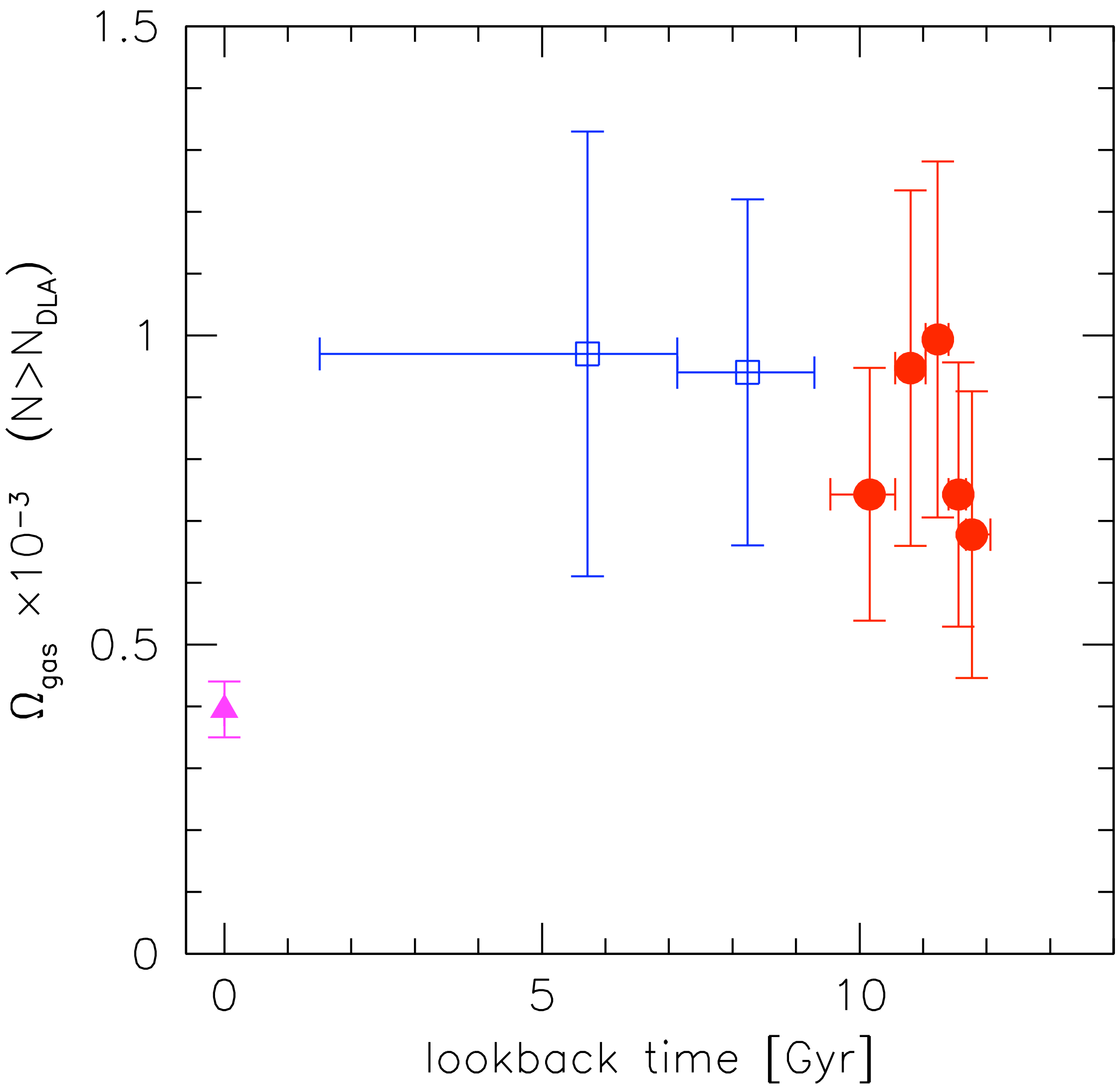
- DLAs are a "phase" not a "reservoir"

Number of **HI atoms** does **not evolve** much



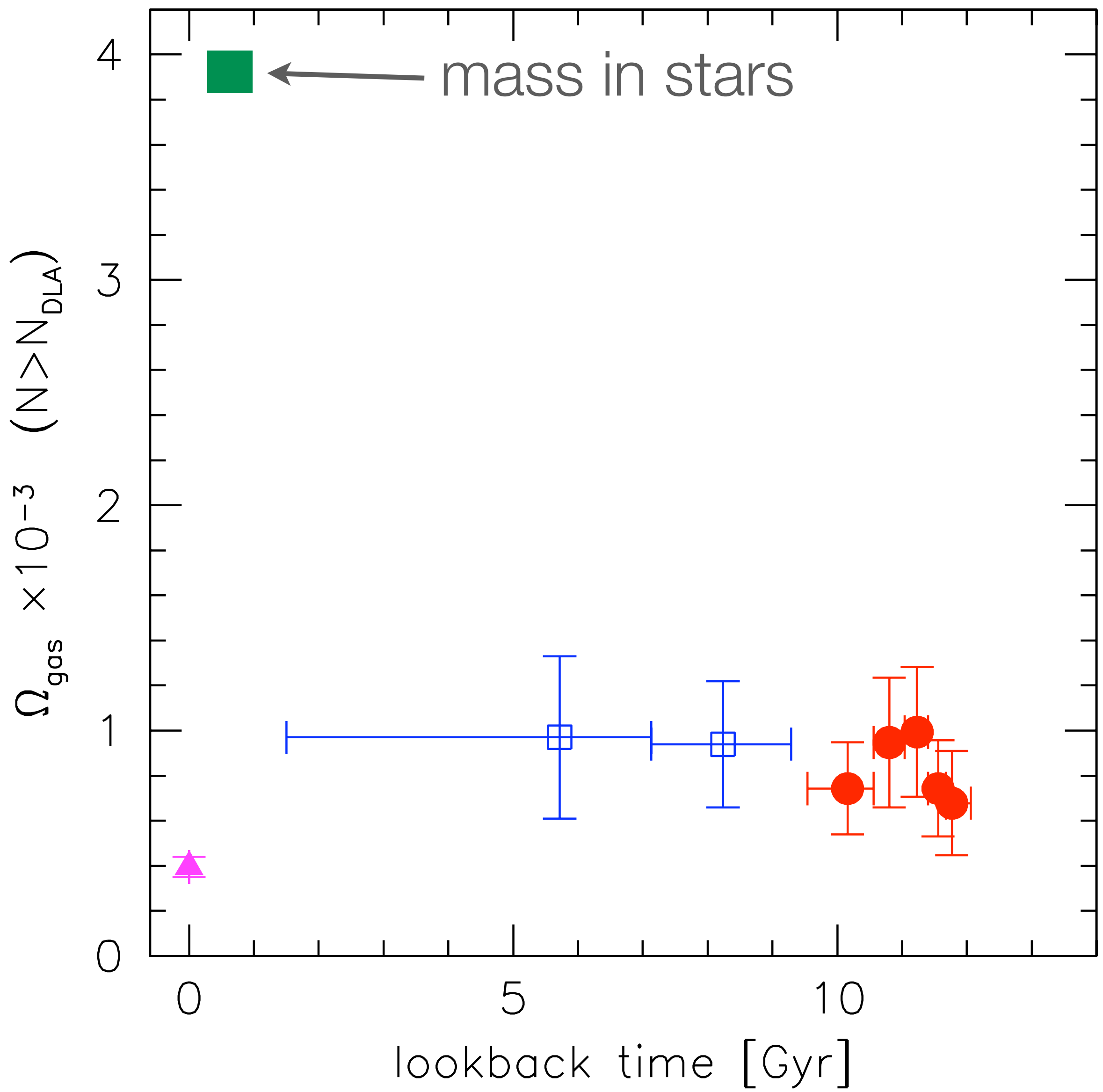
- DLAs are a "phase" not a "reservoir"

Number of **HI atoms** does **not evolve** much



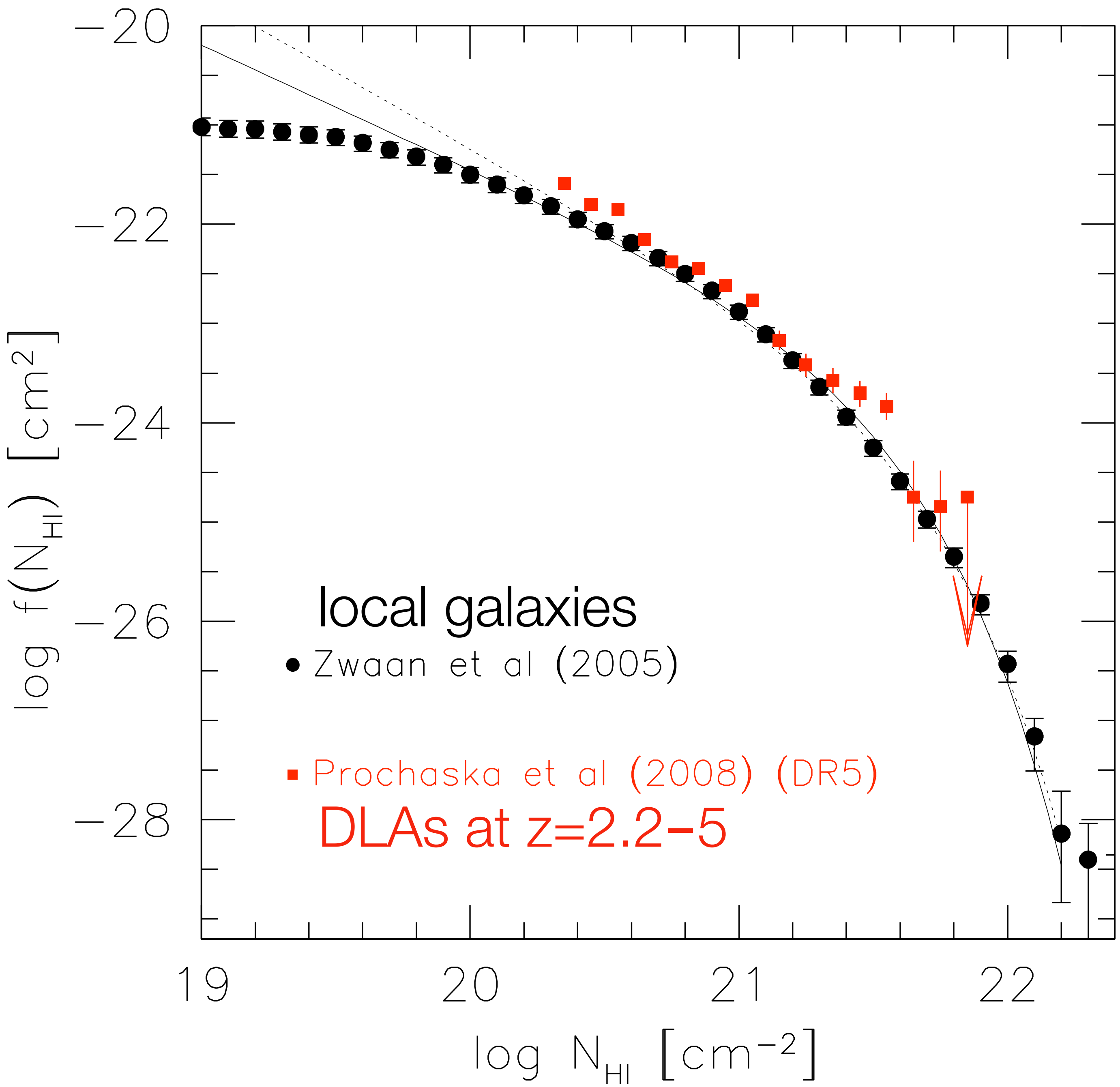
- DLAs are a "phase" not a "reservoir"

Number of **HI atoms** does **not evolve** much

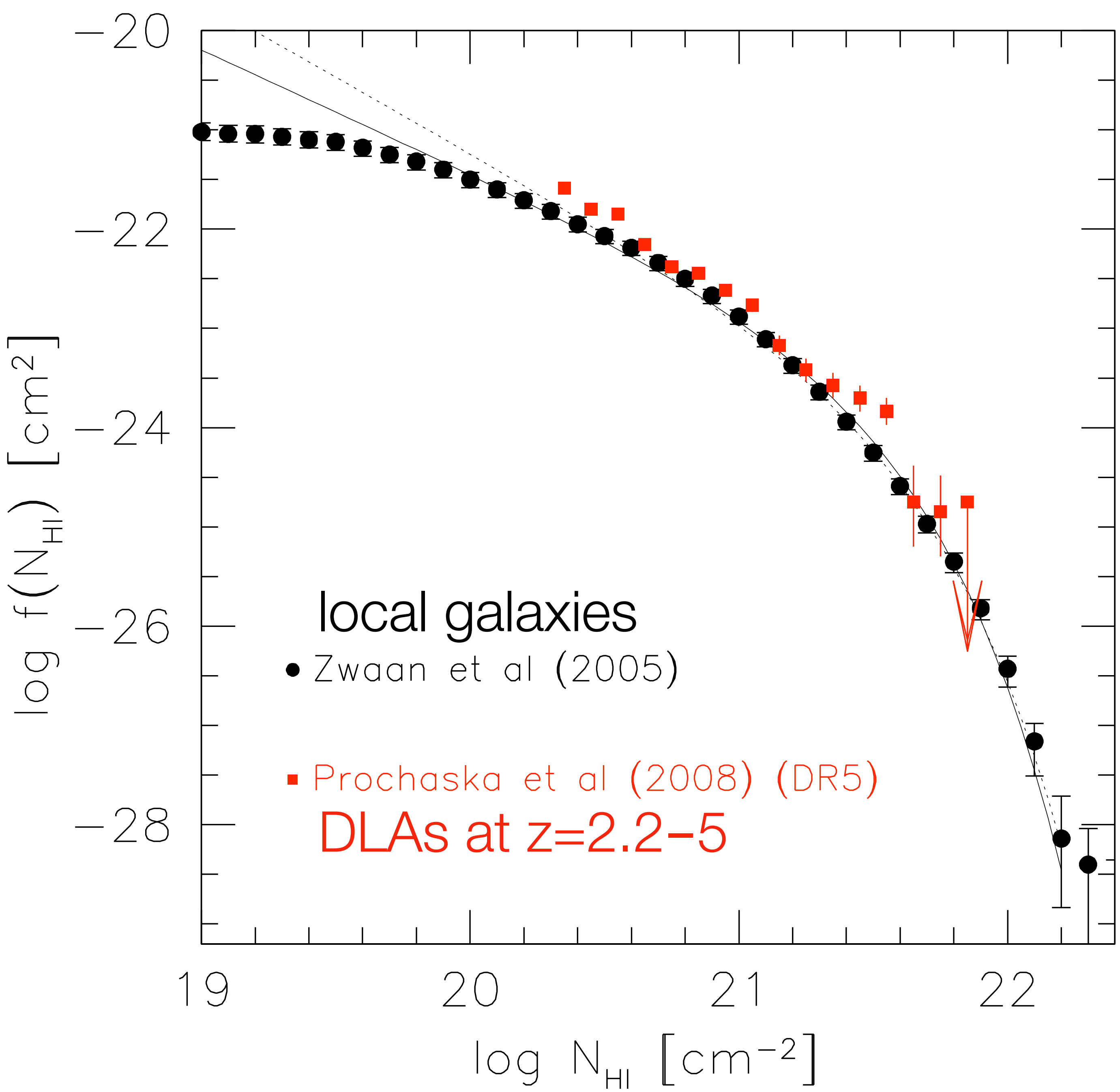


- DLAs are a "phase" not a "reservoir"
- Where is the missing gas?

HI column density distribution **evolves slowly**

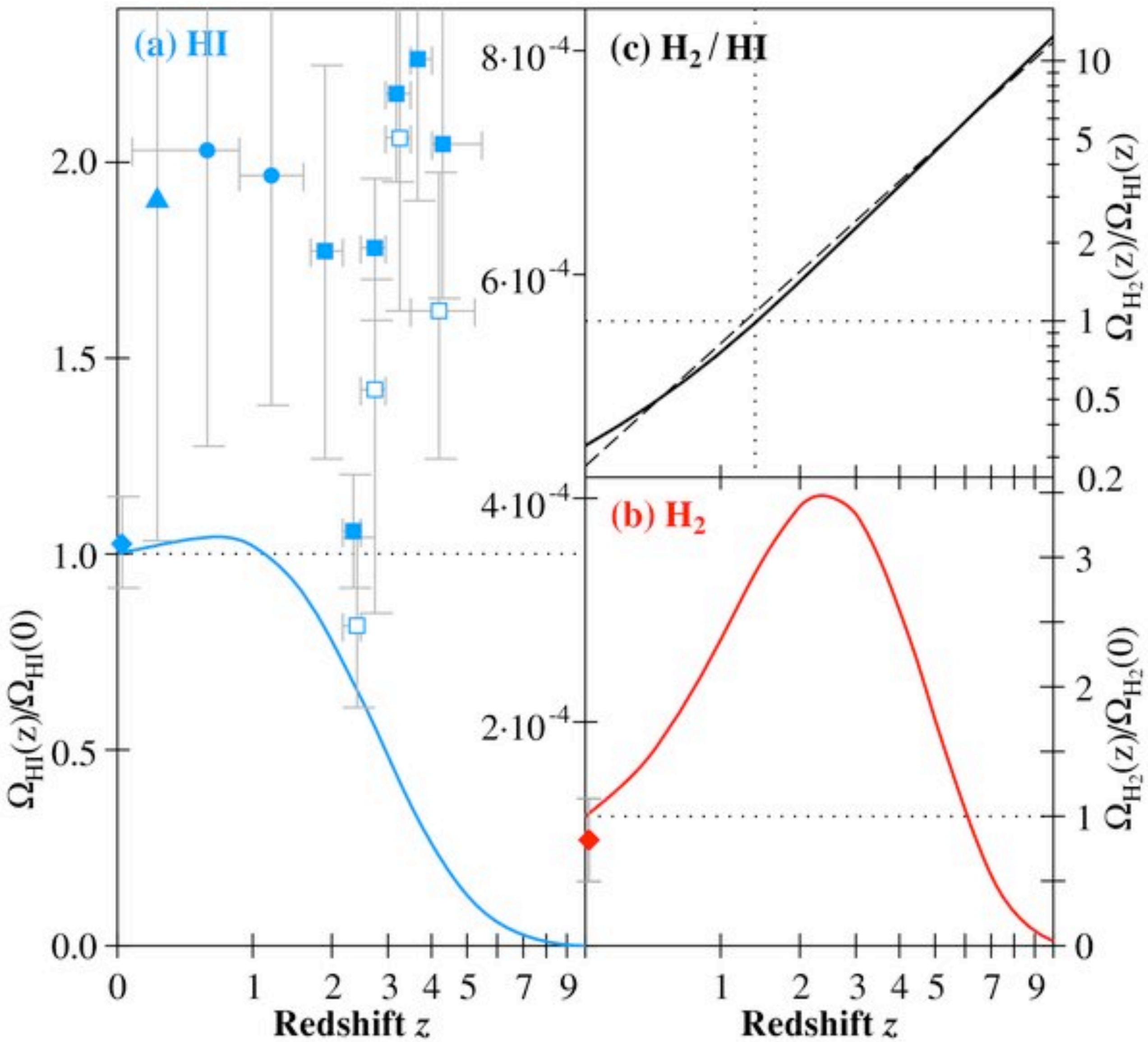


HI column density distribution **evolves slowly**



- HI distribution in galaxies at z=3 similar to that today?
- Star formation laws similar at higher z?

Should we be looking at **HI or H_2**?



Obreschkow & Rawlings 2009

- Obreschkow & Rawlings (2009): pressure-based models predict that H_2 mass density rises quickly
- See also Zwaan & Prochaska (2006)
- Need to follow up part of a deep HIfield with ALMA

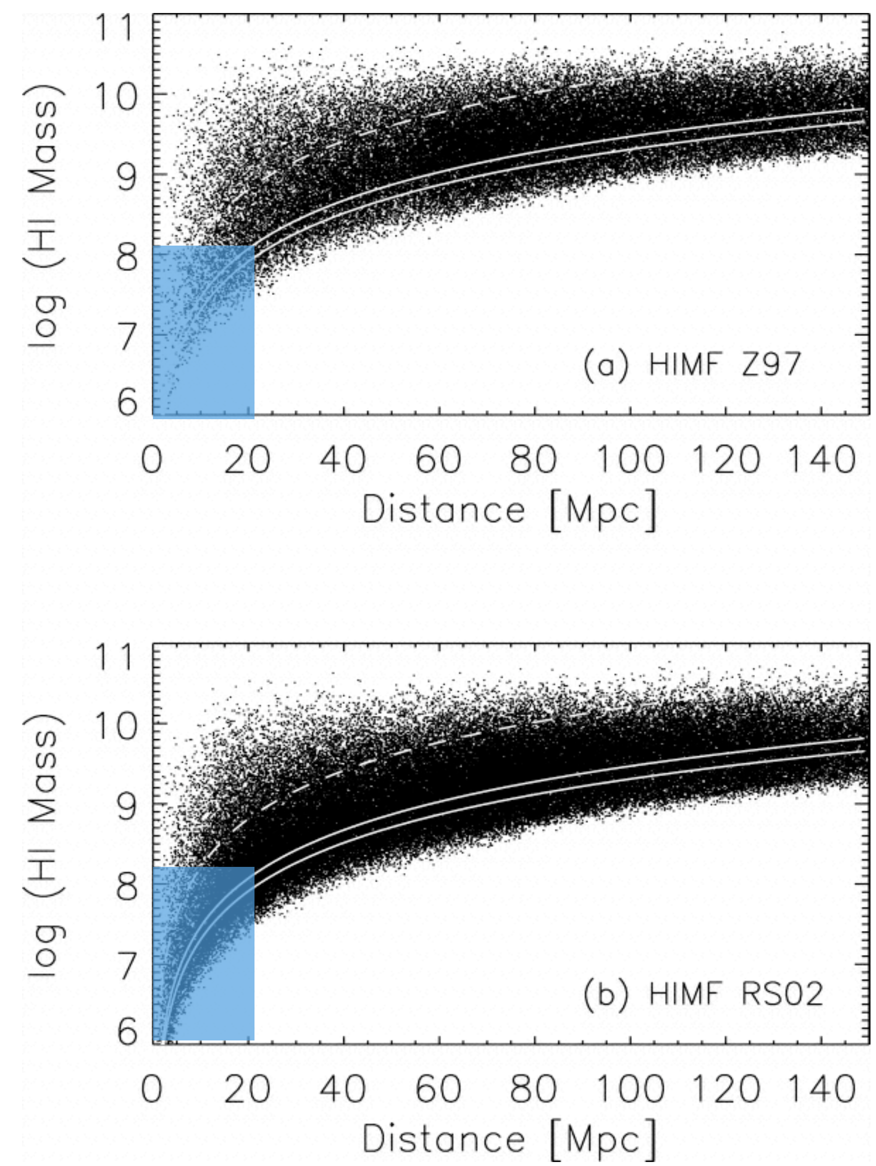
What's next? (Before SKA pathfinders?)

The Arecibo Legacy Fast ALFA Survey

	HIPASS	ALFALFA
sensitivity	13 mJy	1.7 mJy
beam	15'	3.5'
area	30000 deg^2	7000 deg^2
detections	5300	~18000?

- ALFALFA finished~ 2011/2012
- 2 times smaller error bars on HIMF, but uncertainty determined by systematics...

Predicted detections in ALFALFA
(Giovanelli et al 2005)

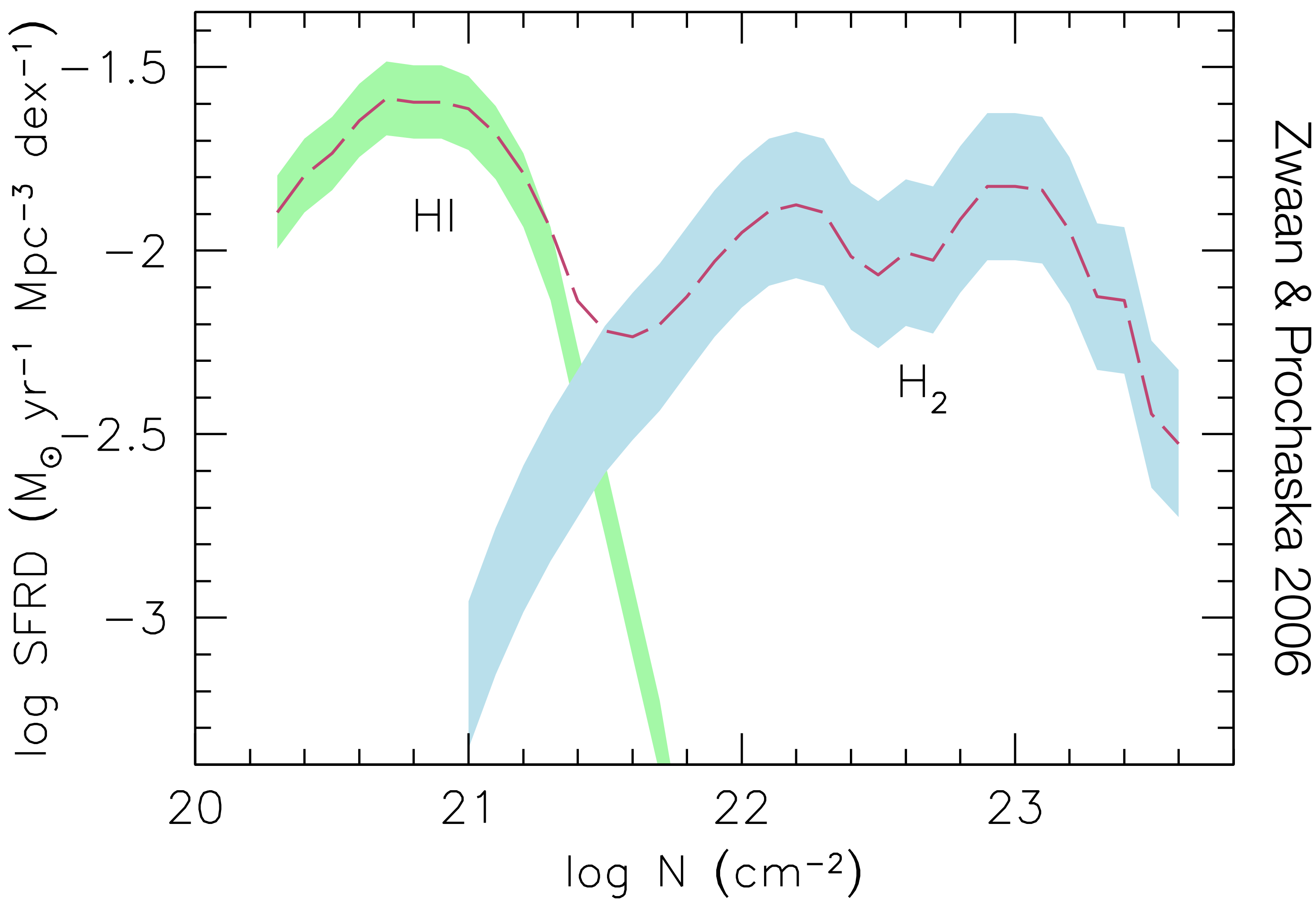


Conclusions

- HI mass function fairly flat (α=-1.3)
  - *but we worry about cosmic variance*
- More sophisticated techniques are essential for volume corrections
  - *but don't help much with deep field evolution*
- Need to know HIMF as function of environment
  - *also to understand 'the' local HIMF*
- Need to know how HI mass function evolves
  - *but all the action is in the molecules?*

Implications for cosmic **SFR density**

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

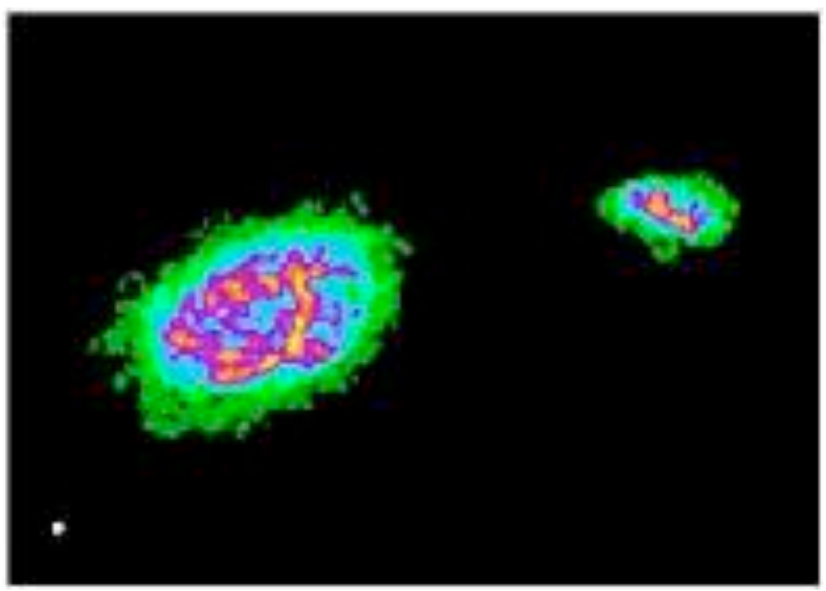


Even though H_2 has very small cross section, it contributes significantly to Ω_{gas} and the SFRD

HI at **high** and **low *z***

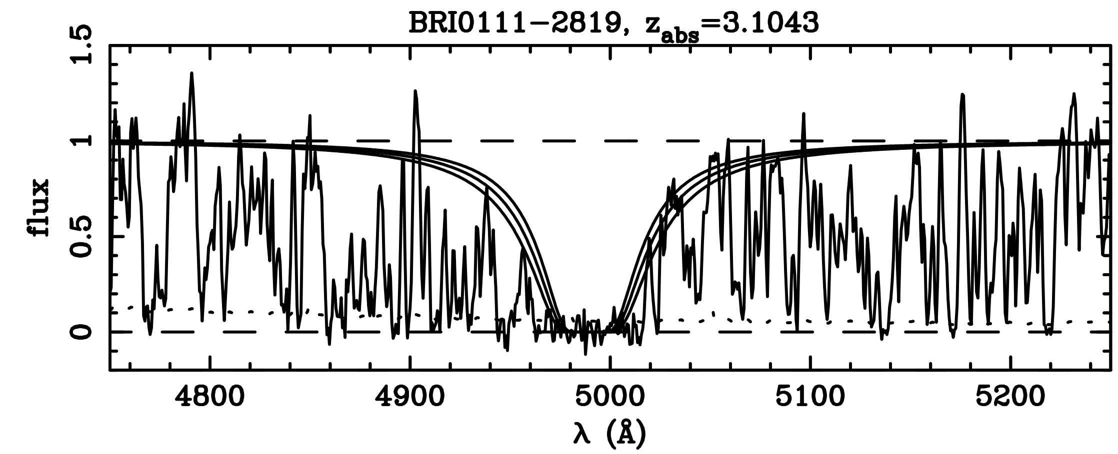
low redshift

- 21-cm emission



high redshift

- Lyα absorption



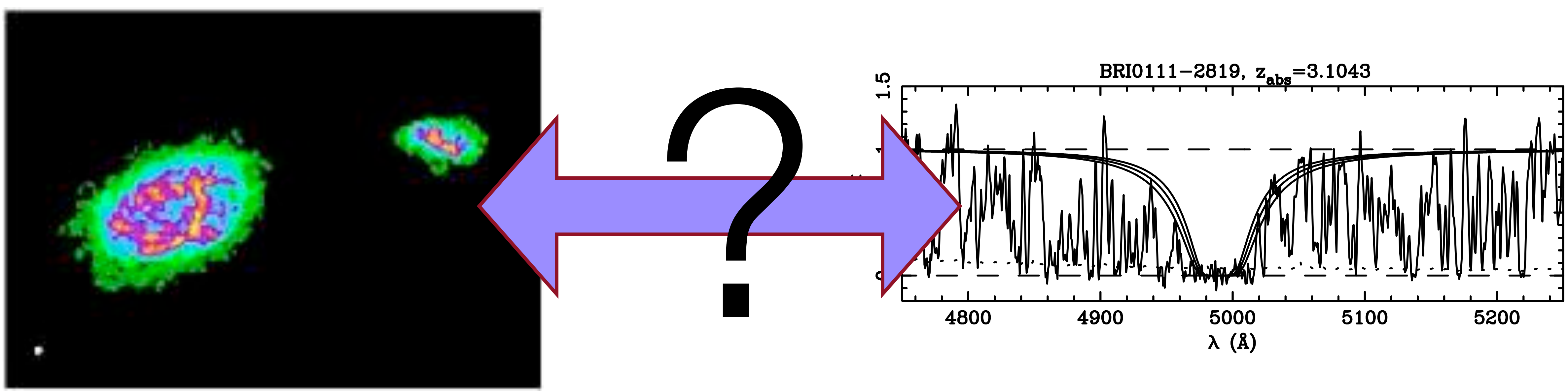
HI at **high** and **low *z***

low redshift

- 21-cm emission

high redshift

- Lyα absorption



QSO absorption line statistics from local galaxies:

redshift number
density of absorbers

space density
of galaxies

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

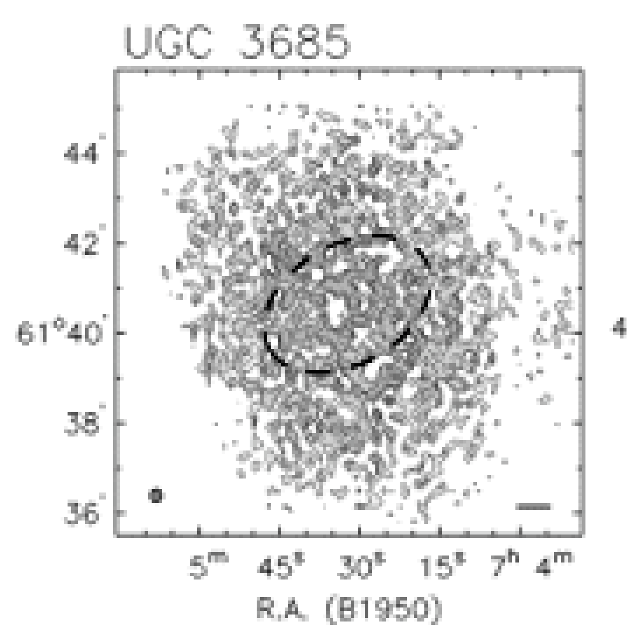
QSO absorption line statistics from local galaxies:

redshift number density of absorbers

space density of galaxies

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

HI imaging



HI mass function