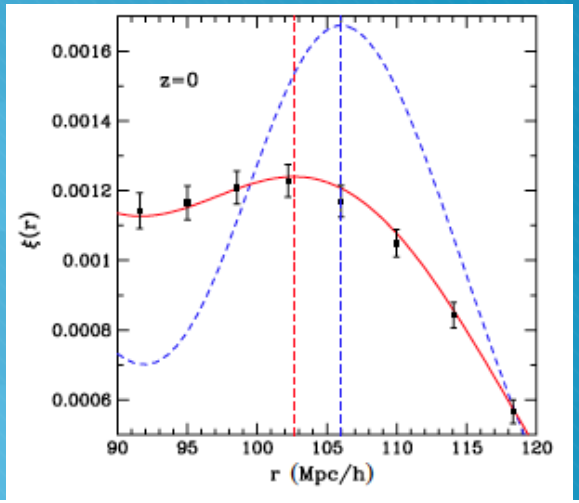
Neutral Hydrogen

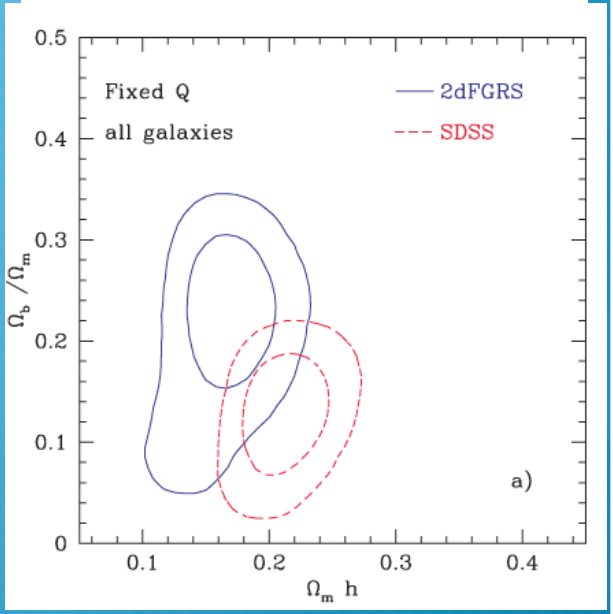
Xin Wang (JHU)

HI introduction

- Cosmology:
  - LSS mapping: DE(BAO, genus), gravity(RS, genus), primordial non-gaussianity, etc.
- Galaxy formation:
  - Star formation, SN feedback, AGN feedback, Other cooling etc.

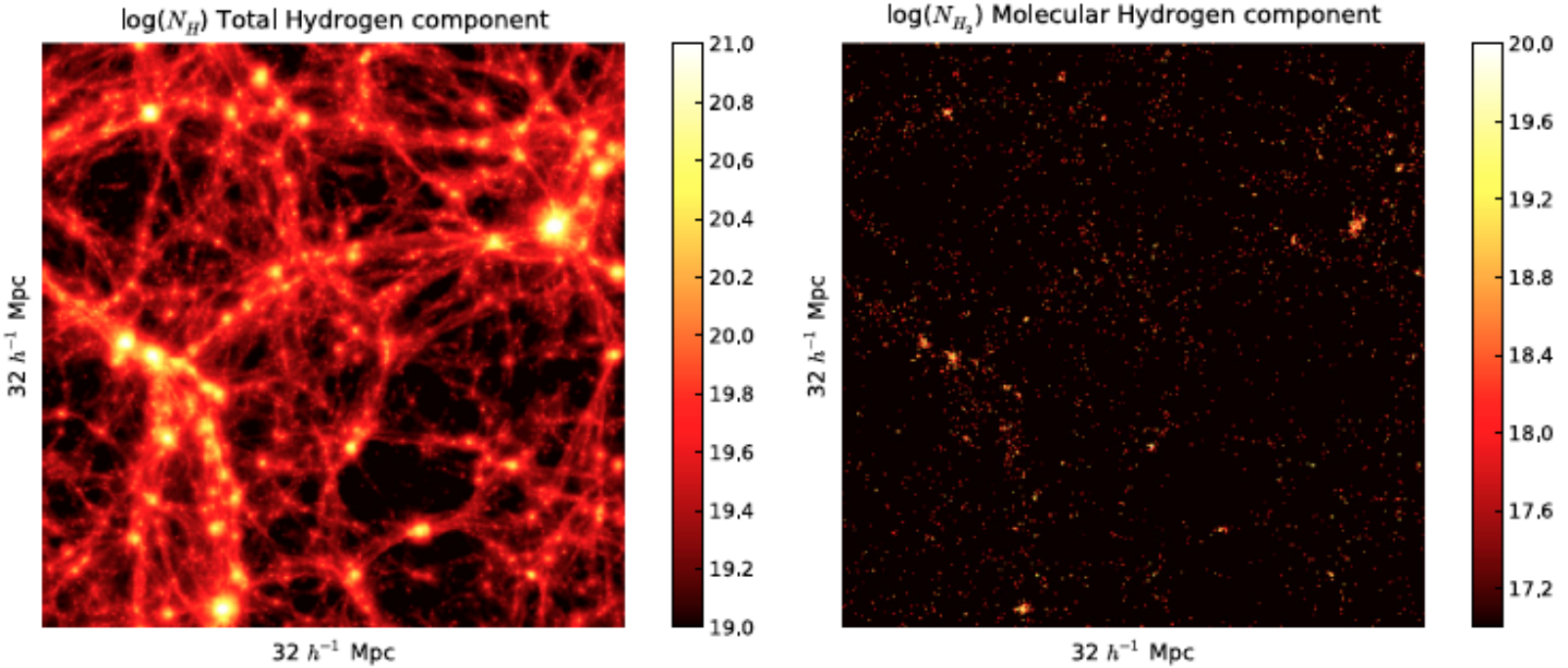
- Small scale baryonic physics → large scale
  - Large-scale bias (scale-dependence, redshift evolution), robustness of BAO:
  - Other measurements (topology, genus), other science (gravity, neutrino…)
- LSS of HI
  - NL effects: BAO peak shift
  - Large-scale bias (scale-dependence)
  - Redshift evolution

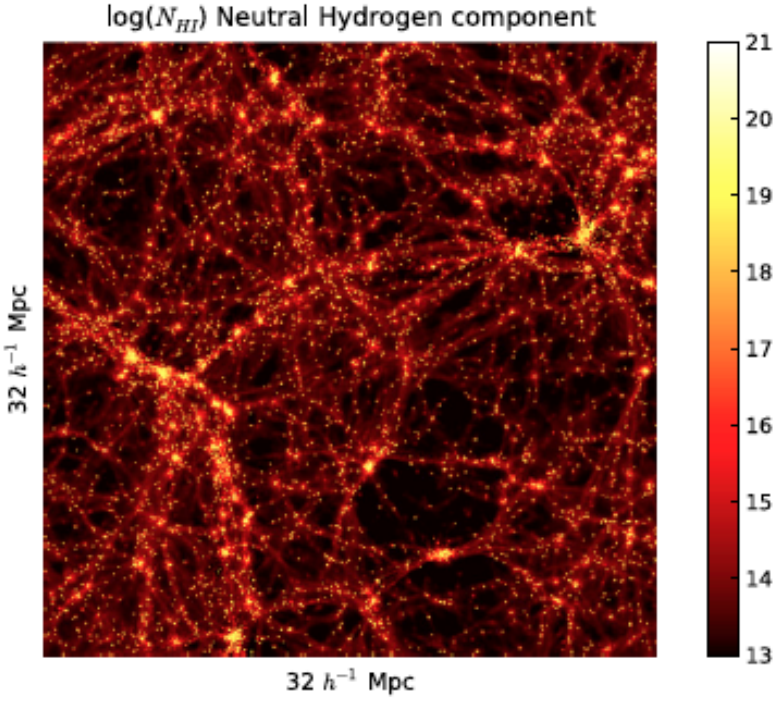




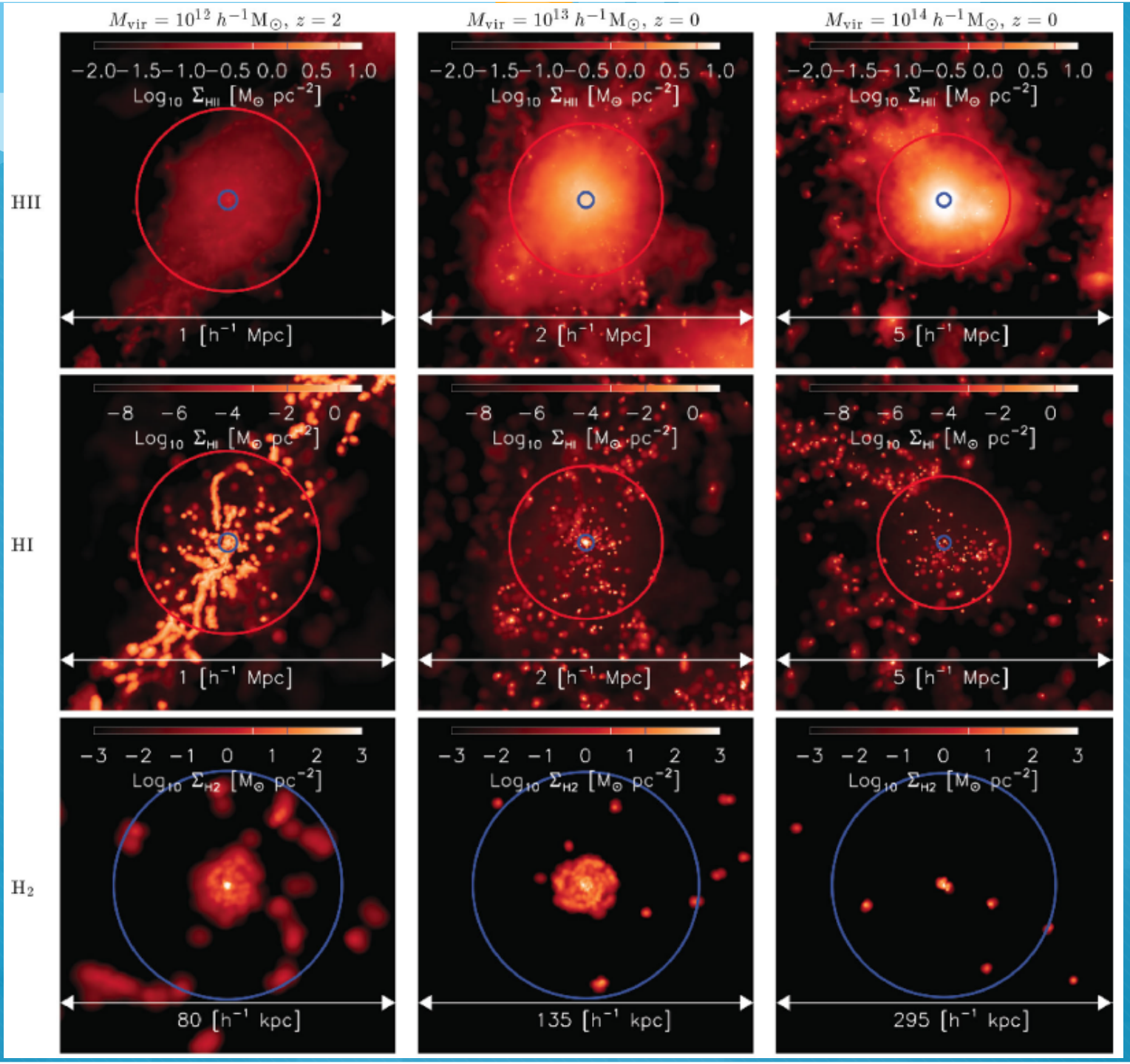
HI Life Circle

- DM potential → gas accumulation → luminous obj
  - Cooling: thermal, non-thermal
- UV background: ionization (low-density region, HII)
- High-density region:
  - self-shielding → cold, neutral
  - → molecule (center, denser) → star formation
- Self-regulation:
  - star photon destroy H_2, HI
  - SN feedback, stellar wind
  - AGN feedback

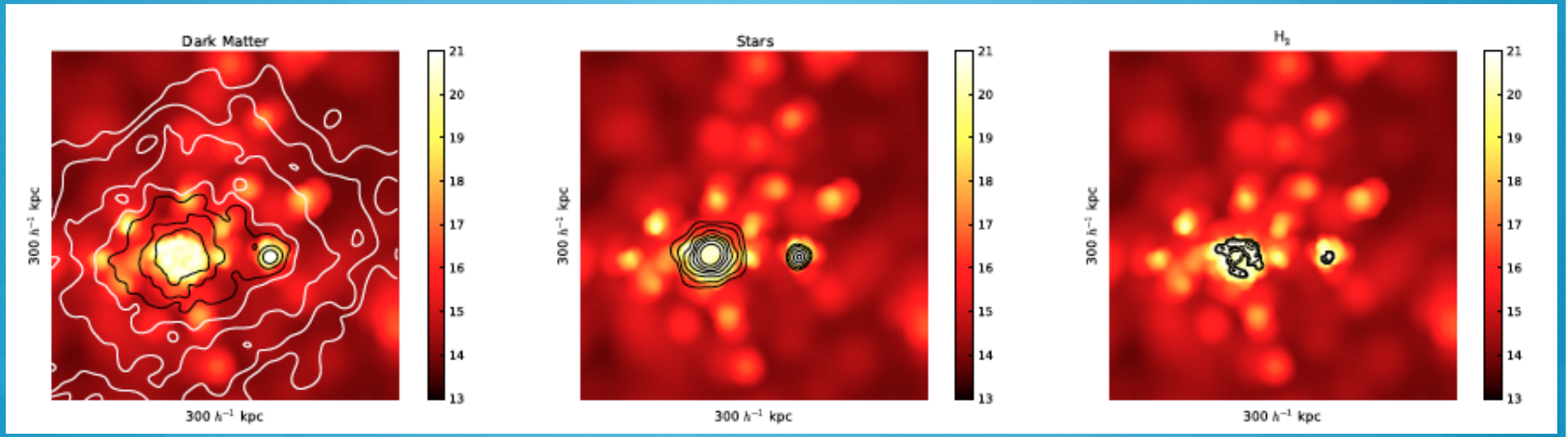




Popping et. al, 2009
A&A 504, 15



Duffy et. al, MNRAS 420, 2799, (2012),



Popping et. al, 2009
A&A 504, 15

HI Modeling

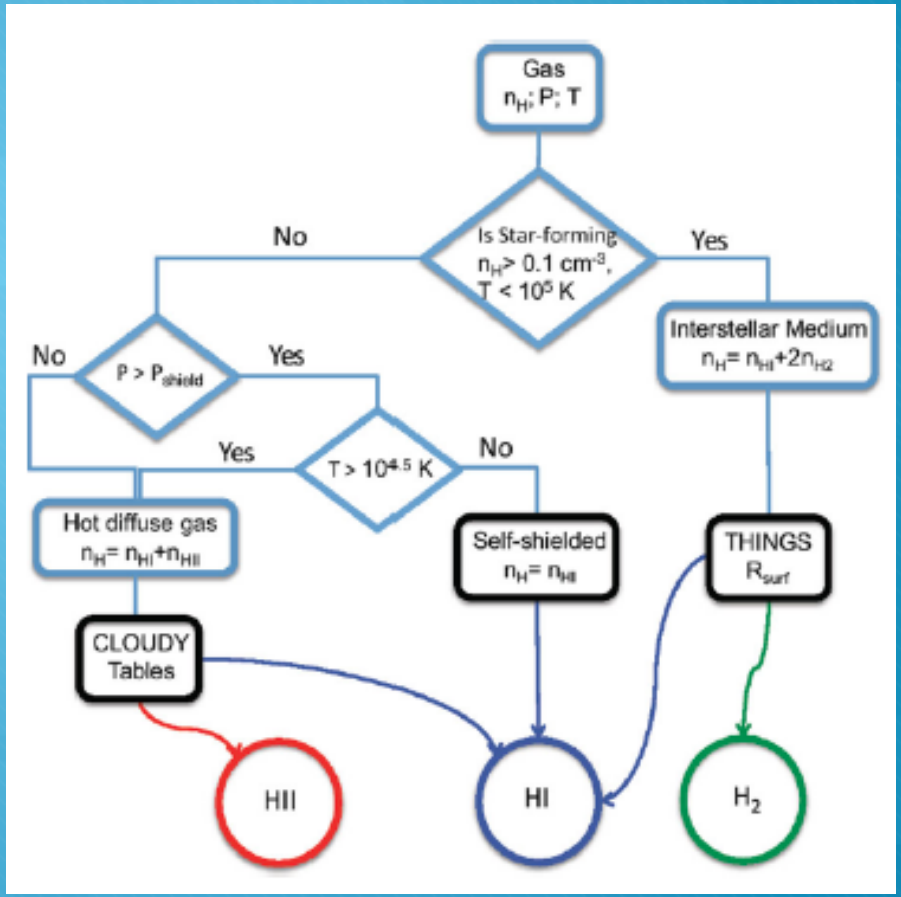
- Optical thin IGM:
  - (nearly-)uniform UV/X-ray background
- Optical thick IGM:
  - Local galactic-UV photon: (young massive stars, quasars)
  - Self-shielding
- ISM:

Invited Review

CLOUDY 90: Numerical Simulation of Plasmas and Their Spectra

G. J. Ferland,[1] K. T. Korista,[1,2] D. A. Verner,[1] J. W. Ferguson,[1,3] J. B. Kingdon,[1,4] and E. M. Verner[1]

Received 1998 January 19; accepted 1998 March 3



Duffy et. al,
MNRAS 420, 2799, (2012),

HI Modeling

- IGM: Self-shielding
  - Surface density threshold
  - Pressure threshold

$$n_{\rm H,\,shield} = 10^{-4}\,{\rm cm}^{-3}(1+\delta)^{-1.5}\Gamma\left(\frac{T}{10^4\,{\rm K}}\right)^{-1} \times \left(\frac{1+z}{4}\right)^{-9/2}\left(\frac{\Omega_{\rm b}h^2}{0.02}\right)^{-3/2}\left(\frac{f_{\rm g}}{0.16}\right)^{-1/2} \times \frac{N_{\rm H\,I}}{2.7\times10^{13}\,{\rm cm}^{-2}},$$

$$\Sigma_{\rm g} \sim \Sigma_{\rm g,J} \equiv \rho_{\rm g} L_{\rm J},$$

$$= \left(\frac{\gamma k}{\mu G X}\right)^{1/2}(f n_{\rm H} T)^{1/2},$$

$$= \left(\frac{\gamma}{G}\right)^{1/2}(f_{\rm g} P_{\rm tot})^{1/2},$$

- Interstellar gas:
  - Self-shielding (H_2)

$$R_{\rm surf} = \left(\frac{P/k}{10^{4.23}\,{\rm K\,cm}^{-3}}\right)^{0.8},$$

$$R_{\rm surf} = \Sigma_{\rm H_2}/\Sigma_{\rm H\,I}$$

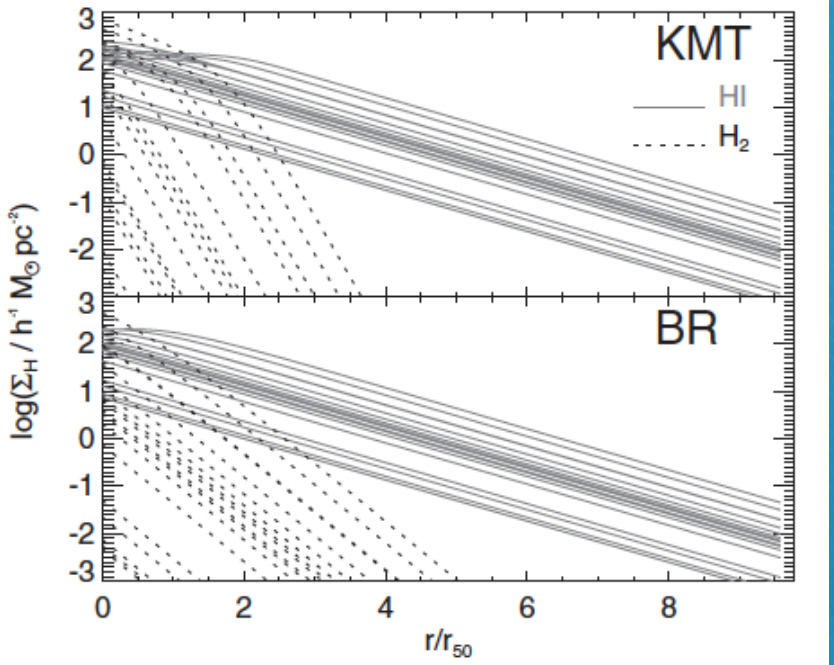
HI Modeling

- Star formation law
  - Complicated, yet some empirical formula
  - BR: empirical

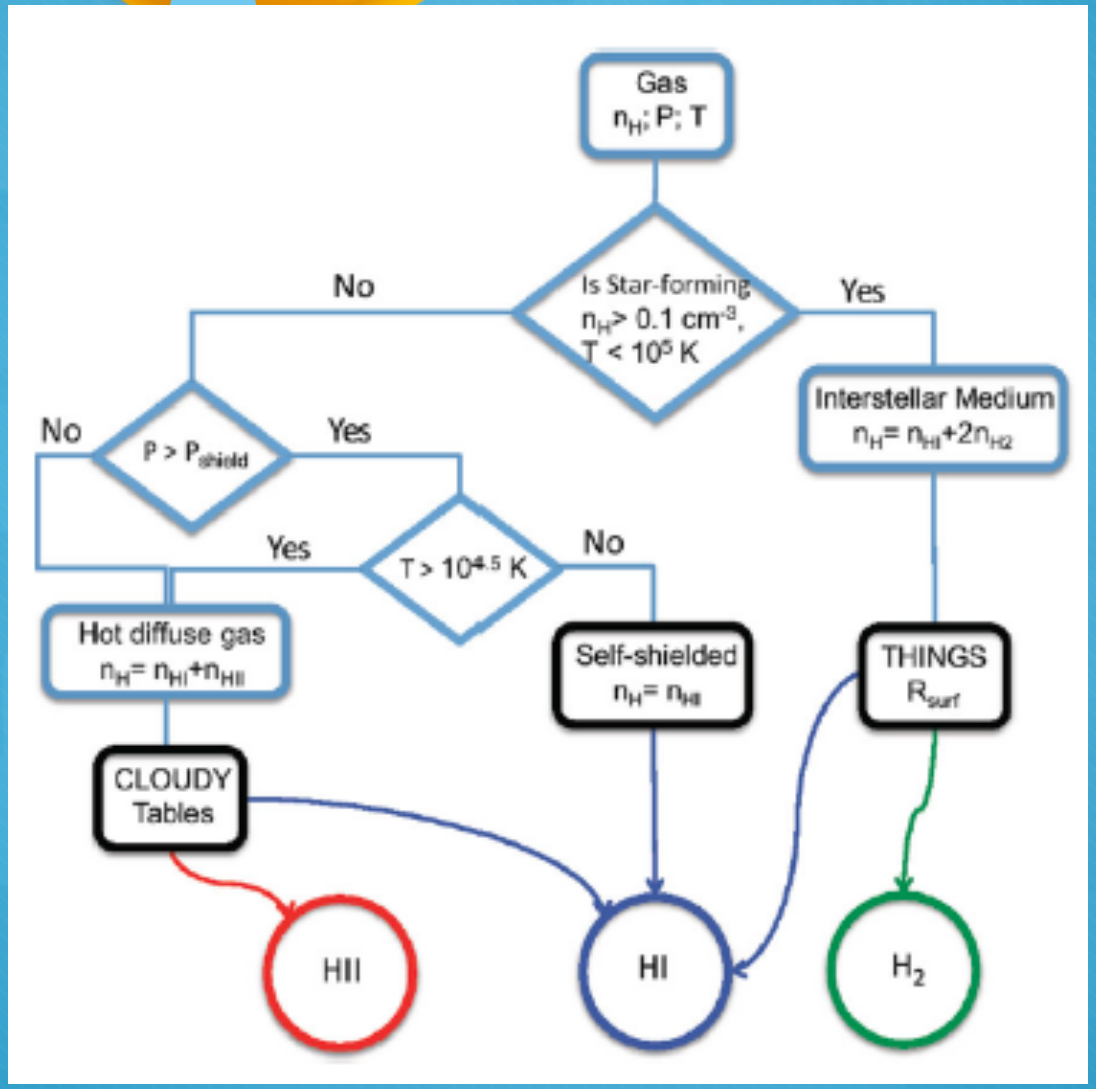
$$\Sigma_{\rm SFR} = \nu_{\rm SF} f_{\rm mol} \Sigma_{\rm gas},$$

  - KMT: theoretical

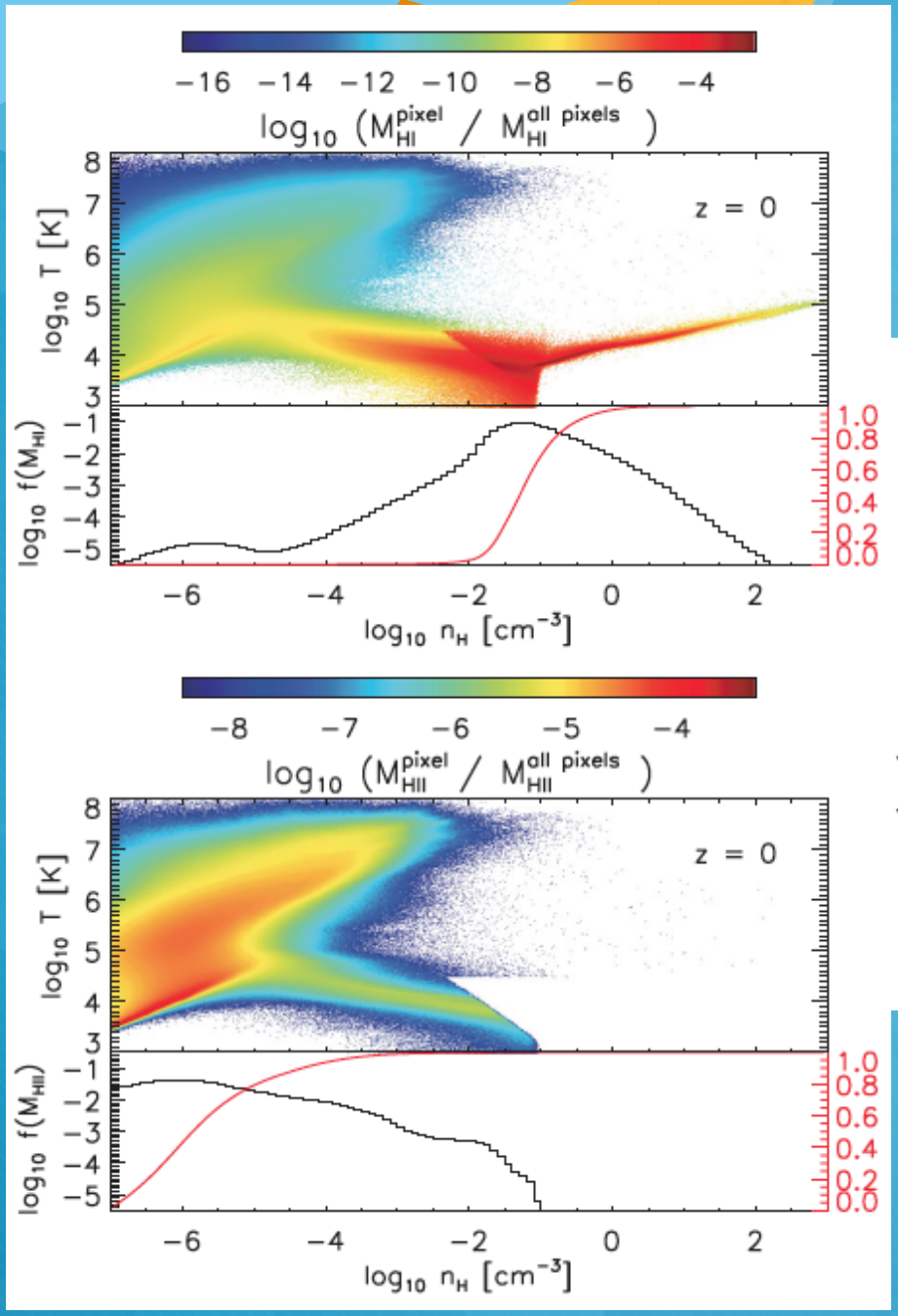
$$\nu_{\rm SF}(\Sigma_{\rm gas}) = \nu_{\rm SF}^0 \times \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{-0.33} \quad \text{for} \quad \Sigma_{\rm gas} < \Sigma_0,$$
$$= \nu_{\rm SF}^0 \times \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{0.33} \quad \text{for} \quad \Sigma_{\rm gas} > \Sigma_0.$$

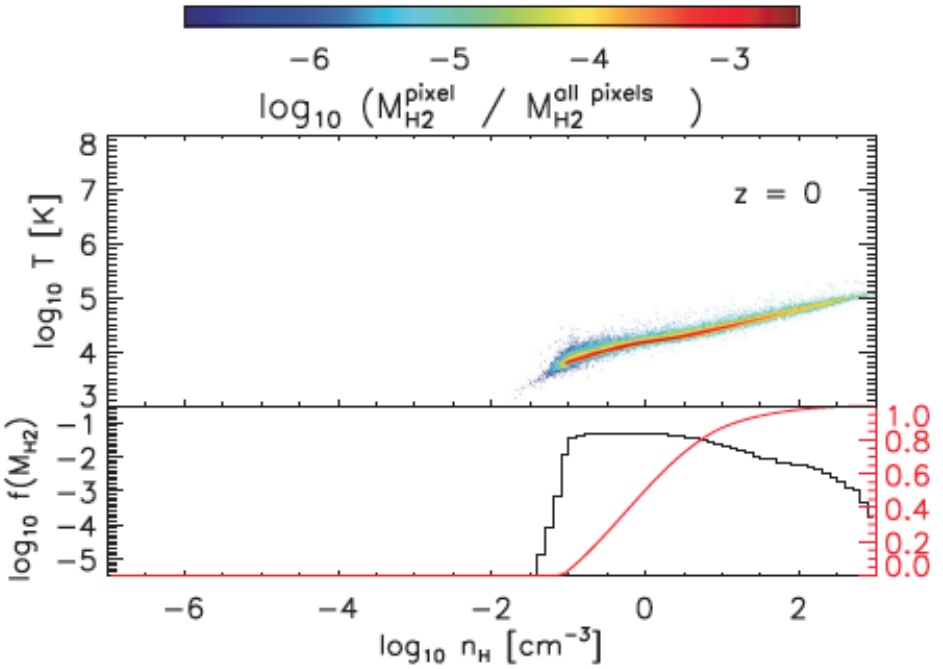


Claudia del P. Lagos et. al, MNRAS, 418, 1649,(2011)



Duffy et. al,
MNRAS 420, 2799, (2012),





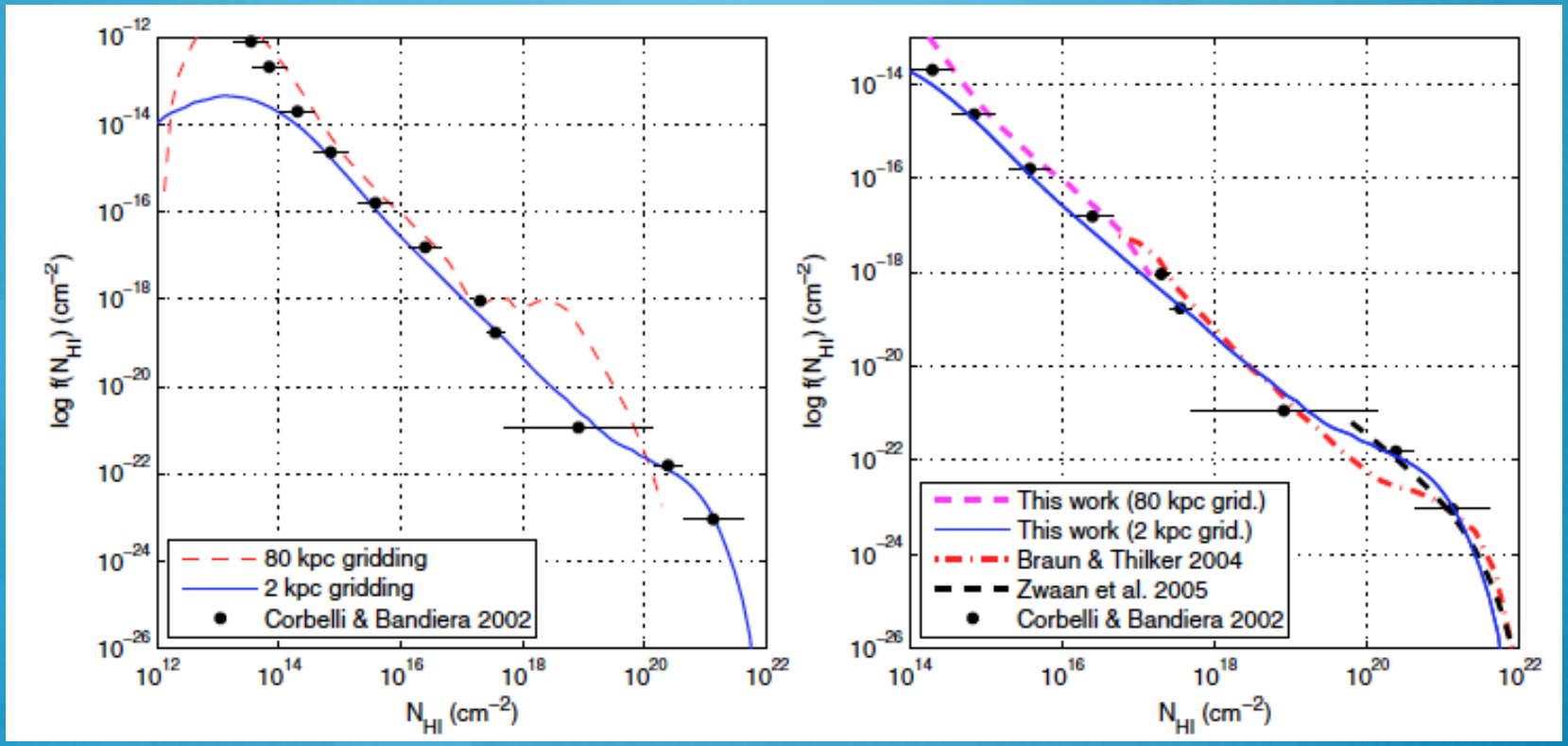
Duffy et. al,
MNRAS 420, 2799, (2012),

HI Modeling

Popping et. al, 2009
A&A 504, 15

- HI distribution function:

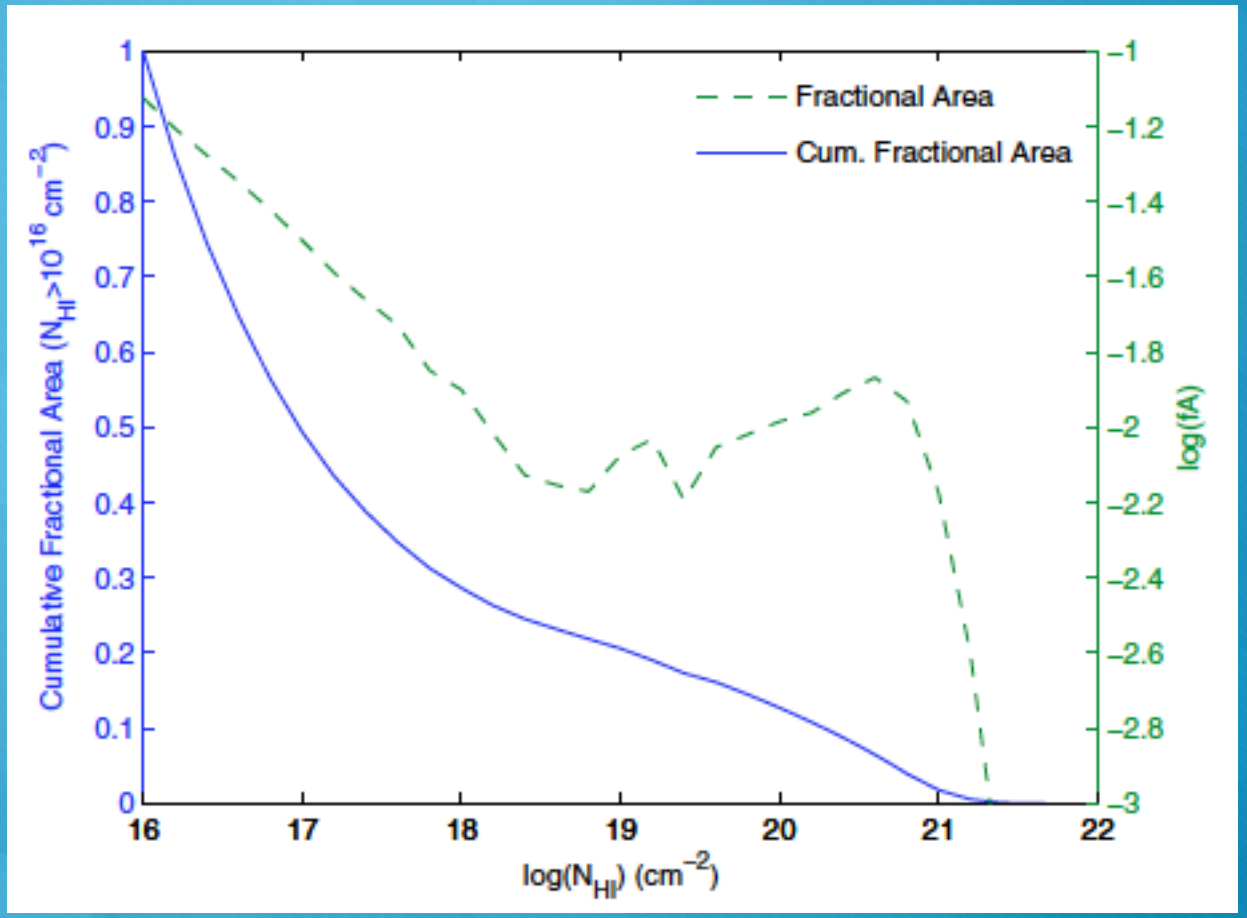
$$f(N_{\rm HI}) = \frac{c}{H_0 {\rm d}z} \frac{A(N_{\rm HI})}{{\rm d}N_{\rm HI}} \ {\rm cm}^2,$$

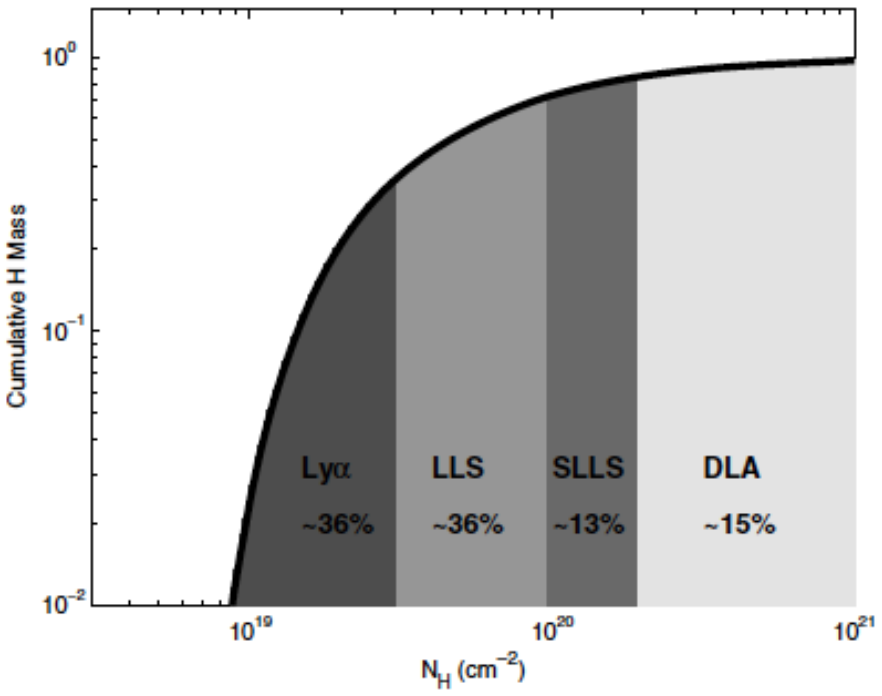


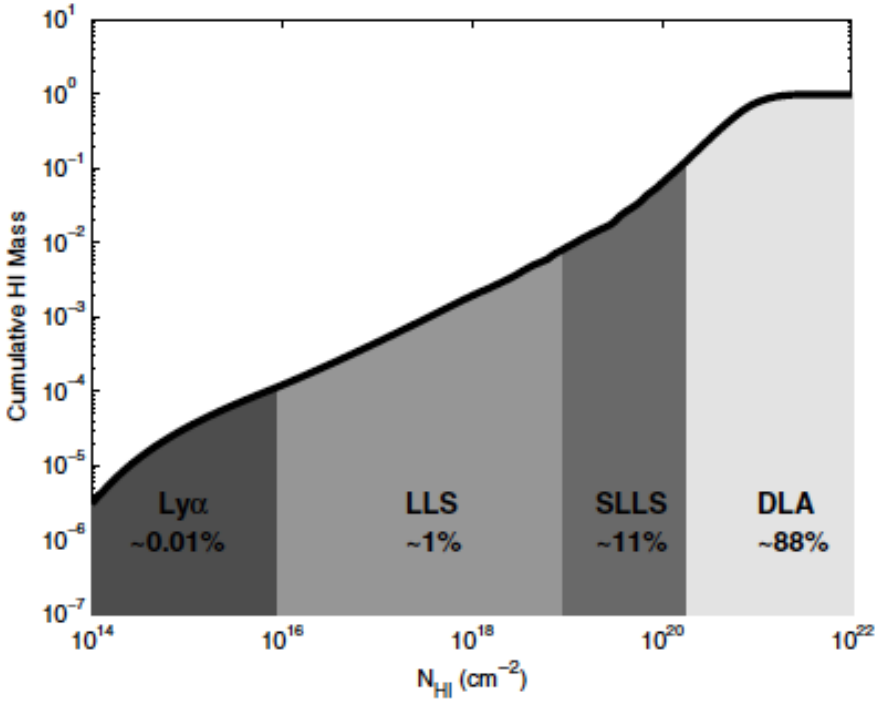
HI Modeling

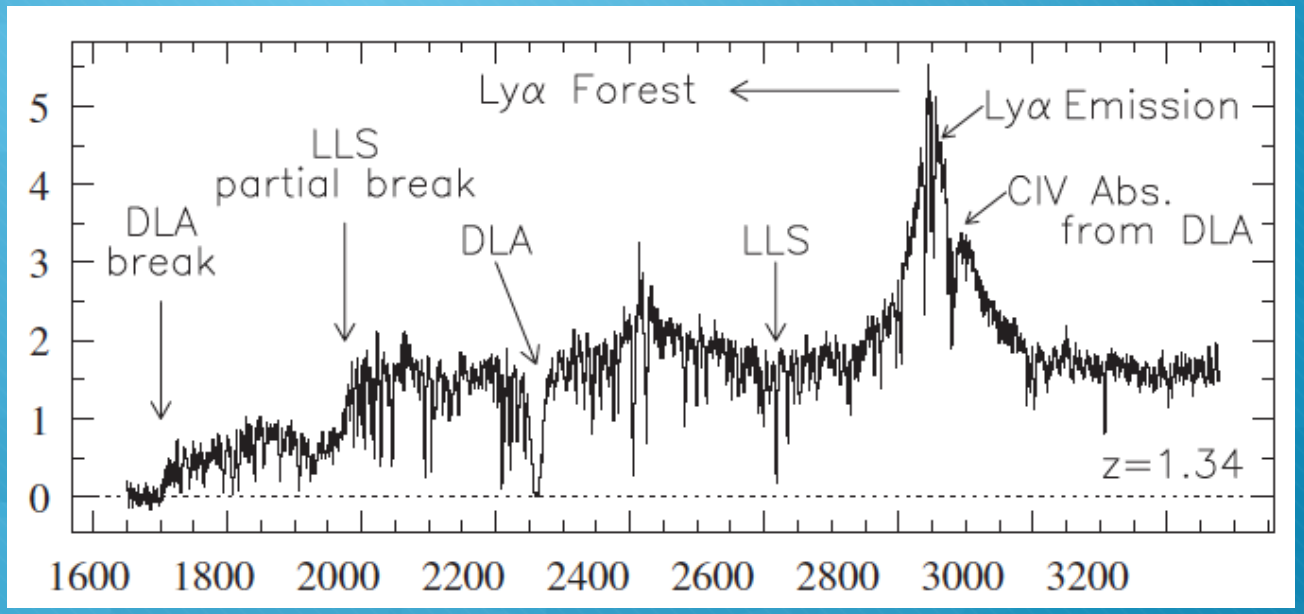
Popping et. al, 2009
A&A 504, 15

$$fA = \frac{A(N_{\rm HI})}{{\rm d}\log(N_{\rm HI})} \cdot$$









Popping et. al, 2009
A&A 504, 15

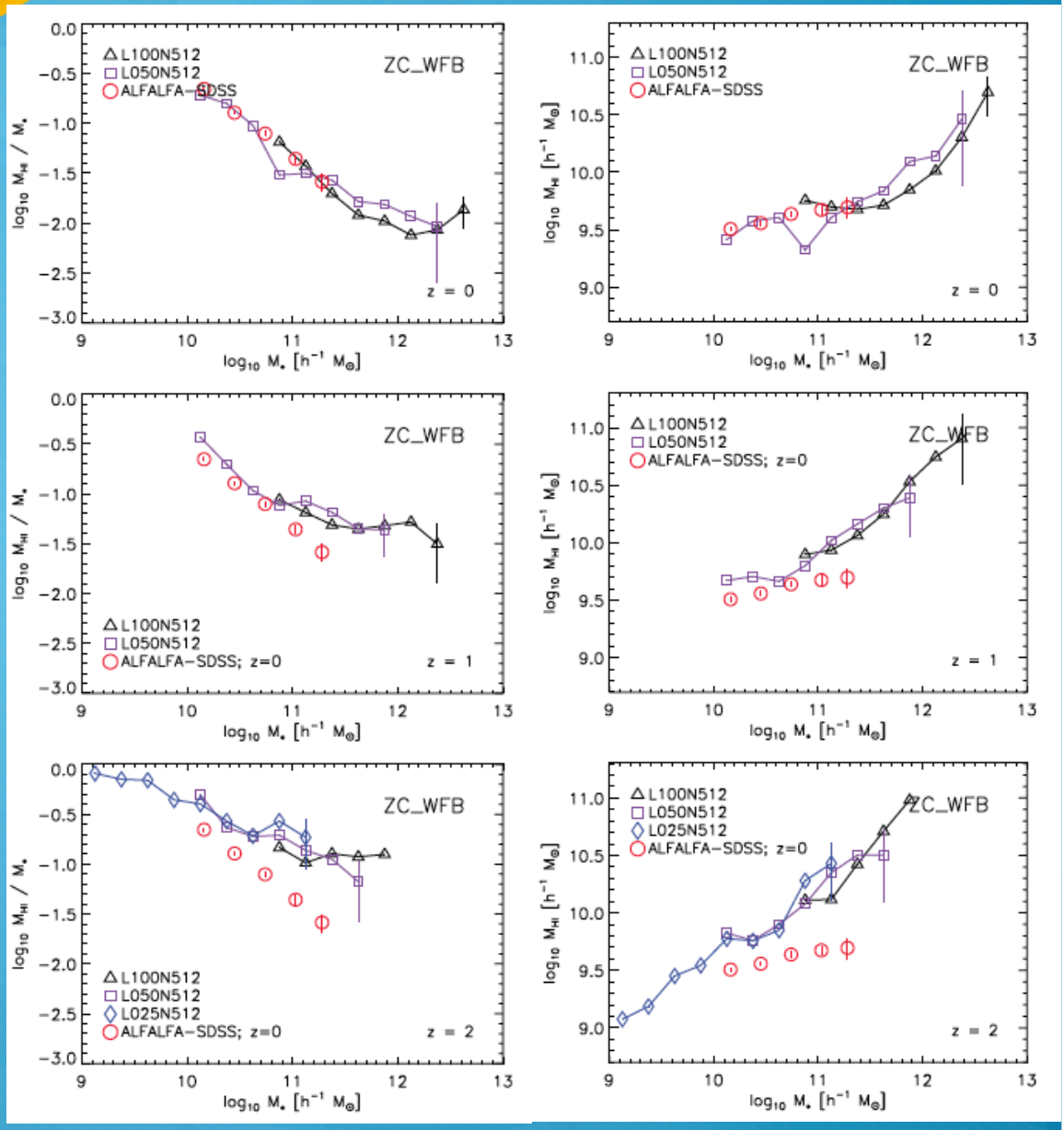
HI and galaxy formation

- Various processes can affect HI/H_2 contents
  - SN feedback, mass ejection rate (SFR)
  - AGN feedback, suppress gas cooling
  - Metal cooling

HI & stars

- Positive correlation
  - Larger stellar mass, more HI
- M_{HI}/M_{st}
  - Decrease with mass: Massive galaxies, relatively deficient in HI
  - Increase with redshift: cold gas accretion slow down
- AGN (?)

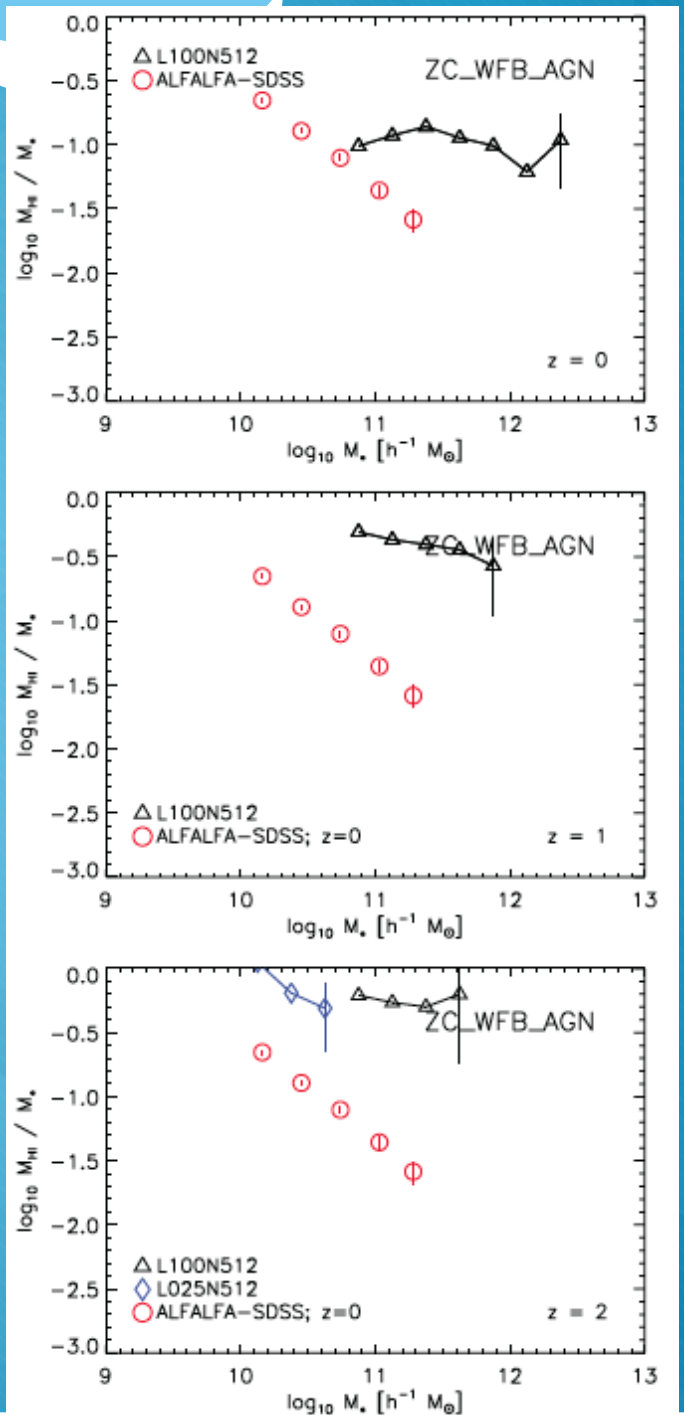
Duffy et. al,
MNRAS 420, 2799, (2012),



HI & stars

- Positive correlation
  - Larger stellar mass, more HI
- M_{HI}/M_{st}
  - Decrease with mass: Massive galaxies, relatively deficient in HI
  - Increase with redshift: cold gas accretion slow down
- AGN (?)

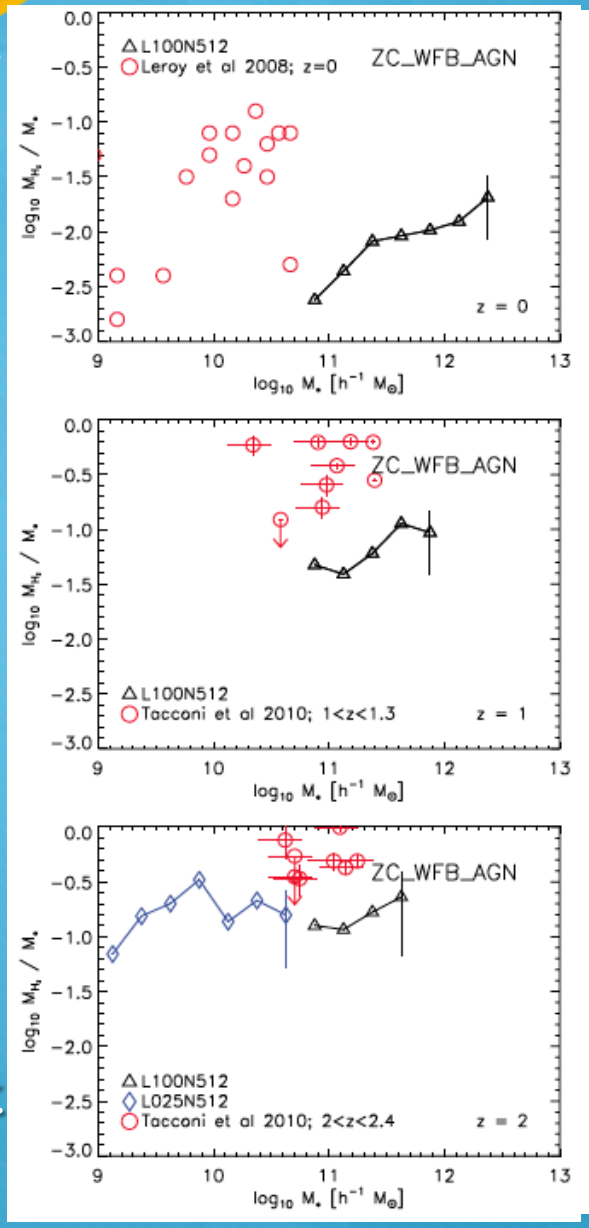
Duffy et. al,
MNRAS 420, 2799, (2012),

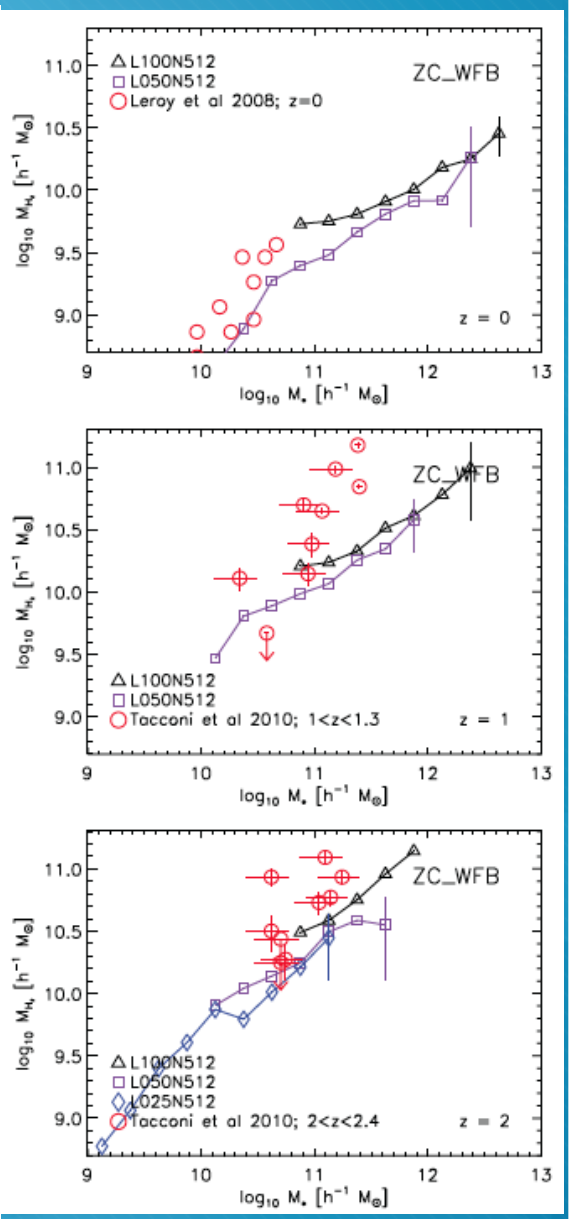


H_2 & stars

Duffy et. al,
MNRAS 420, 2799, (2012),

- Positive correlation
  - Match obs @ z=0
  - High-z: less H_2
- AGN feedback
  - Suppress gas-> star
  - (worse)
- M_{H2}/M_{st}
  - Decrease with mass
  - Increase with redshift

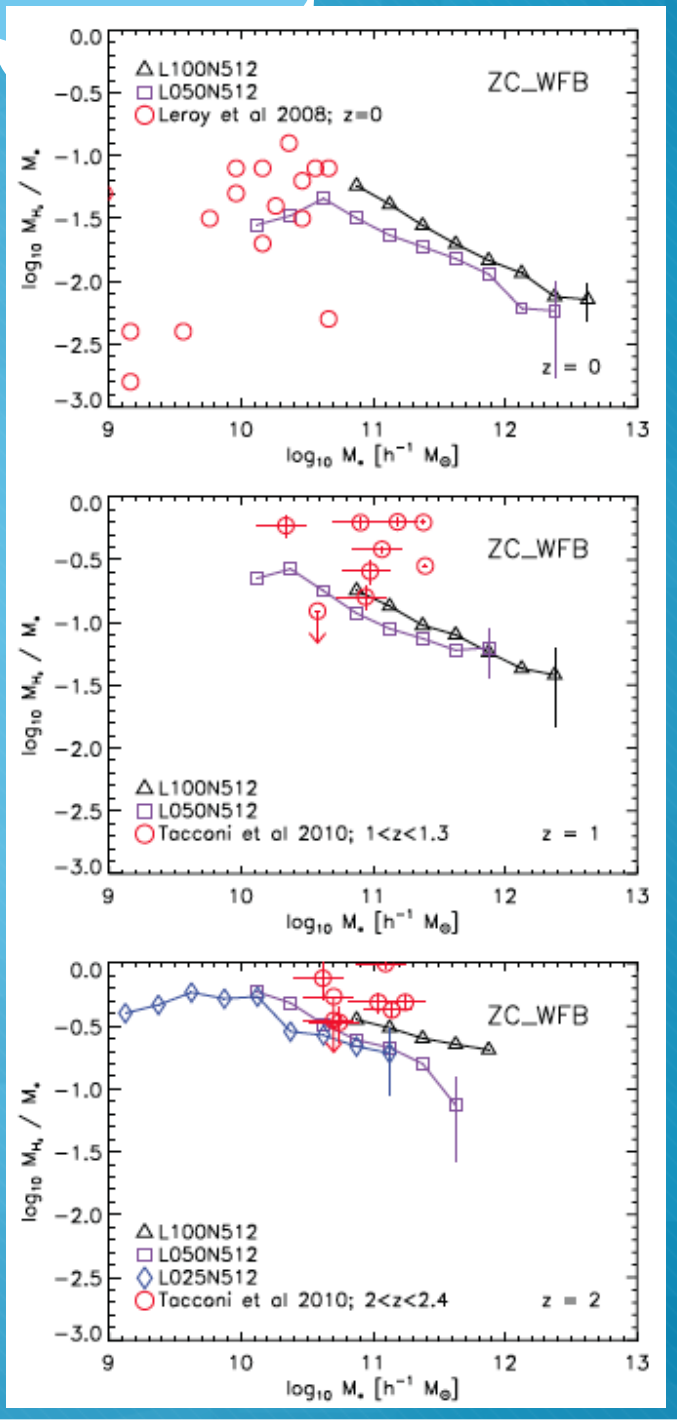


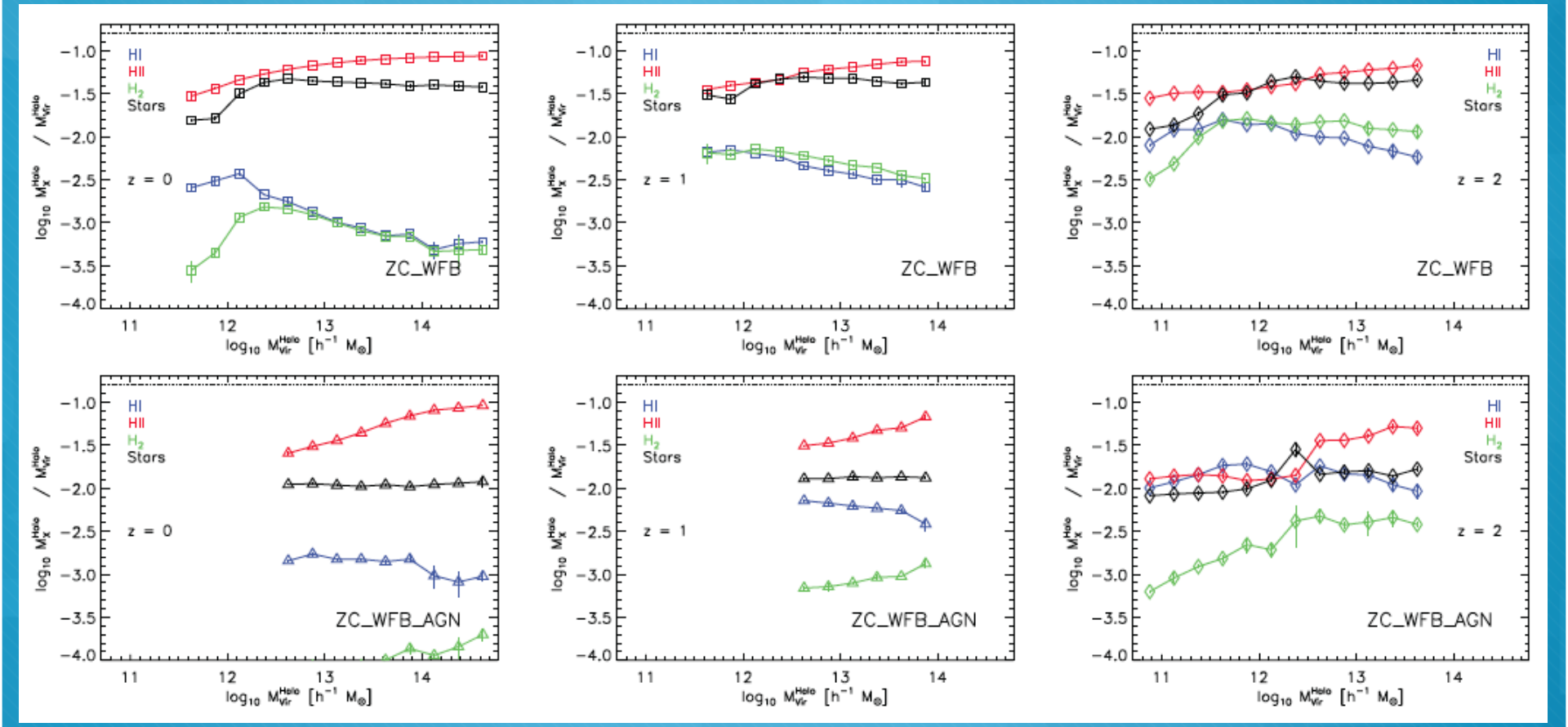


H_2 & stars

- Positive correlation
  - Match obs @ z=0
  - High-z: less H_2
- AGN feedback
  - Suppress gas-> star
  - (worse)
- M_{H2}/M_{st}
  - Decrease with mass
  - Increase with redshift

Duffy et. al,
MNRAS 420, 2799, (2012),

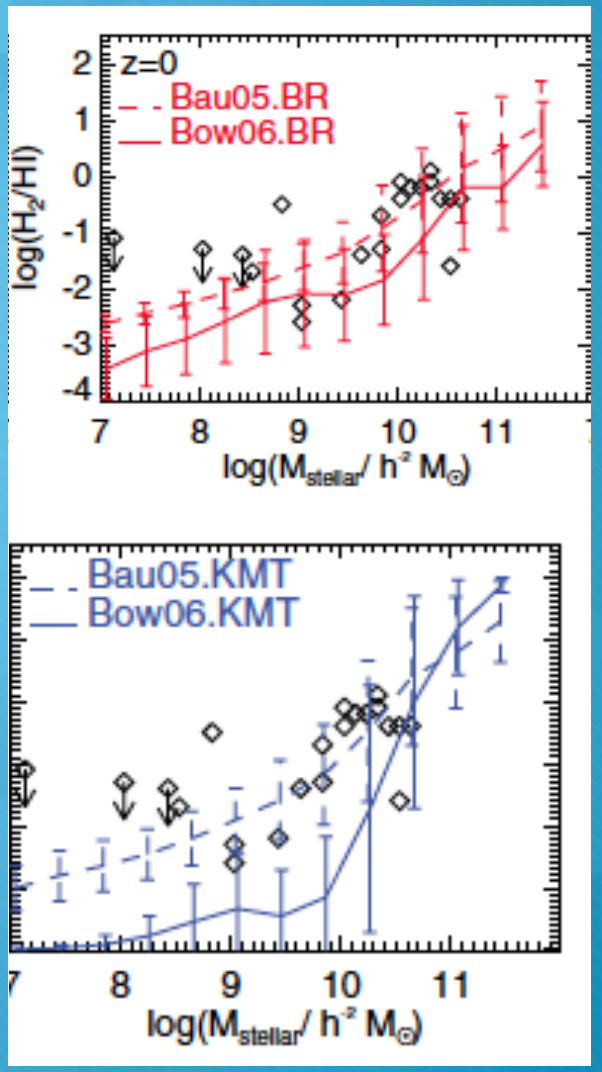




Duffy et. al,
MNRAS 420, 2799, (2012),

HI/H_2 and stars

- H_2/HI ratio
  - BR (empirical SF law) + Bow06 (AGN feedback)
  - BR/KMT + Bau05(SN feedback)



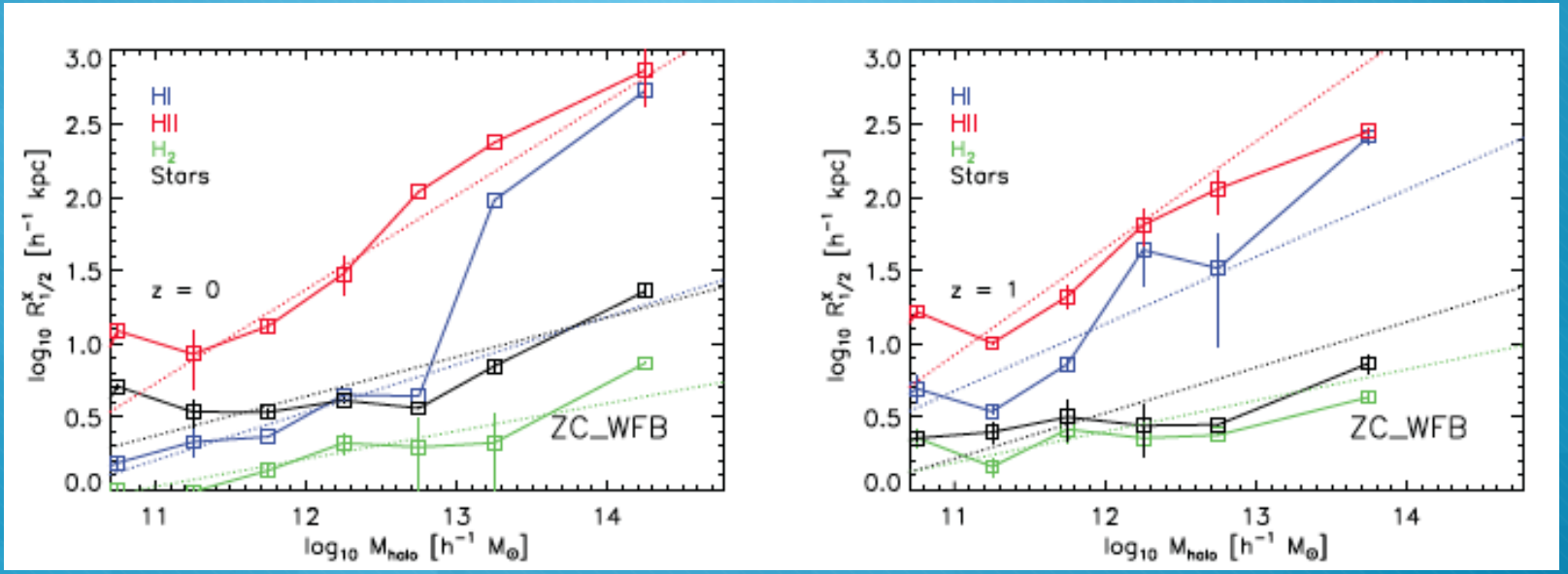
Claudia del P. Lagos et. al, MNRAS, 418, 1649,(2011)

Spatial distribution

- Half-mass radii distribution

Duffy et. al,
MNRAS 420, 2799, (2012),

  - HI: M>10^{13}, extended than star/H_2
  - Star ~~ H_2 @ high-z (z=0, diffusive stellar component)

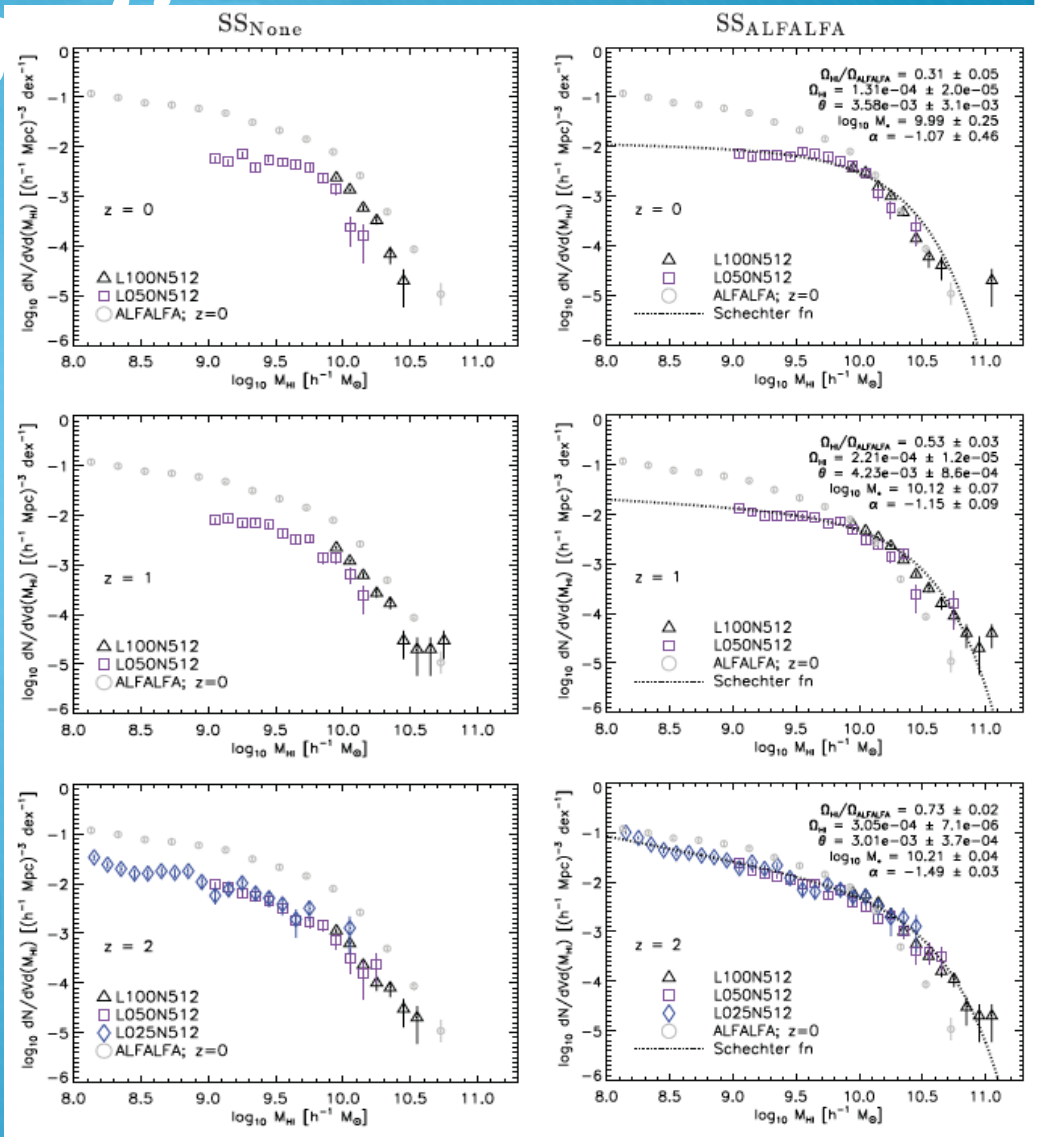


HI / H_2 Mass Function

and the redshift evolution

HI Mass Fun

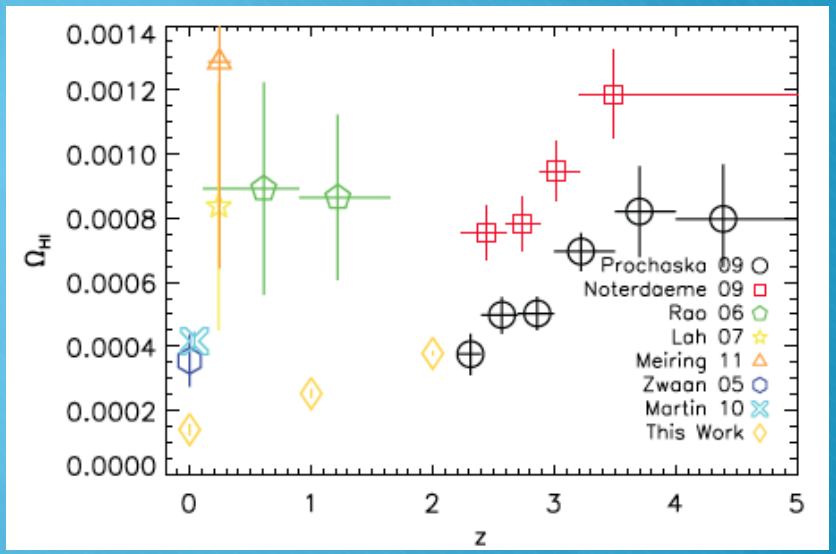
- Self-shielding:
  - No SS: underestimate, little evolution
  - SS(const P_{th}):
  - SS(z-dep P_{th}): similar
  - Little evolution of P_{th} ?
- Galaxy formation
  - Evolution of low-mass tail



Duffy et. al,
MNRAS 420, 2799, (2012),

HI Mass Function

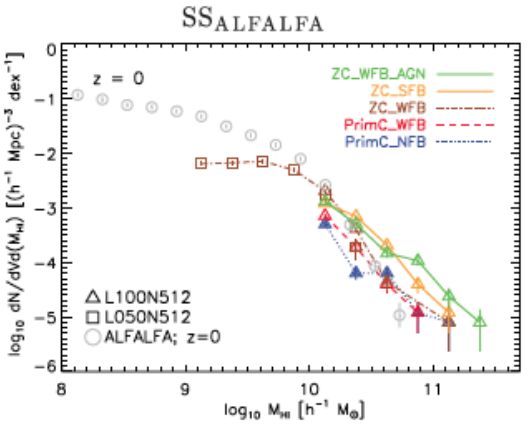
- Self-shielding:
  - No SS: underestimate, little evolution
  - SS(const P_{th}):
  - SS(z-dep P_{th}): similar
  - Little evolution of P_{th} ?
- Galaxy formation
  - Evolution of low-mass tail

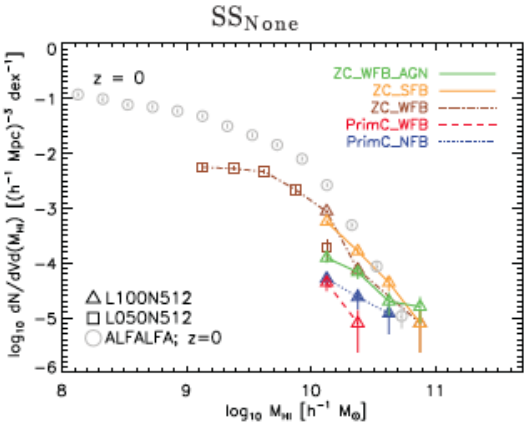


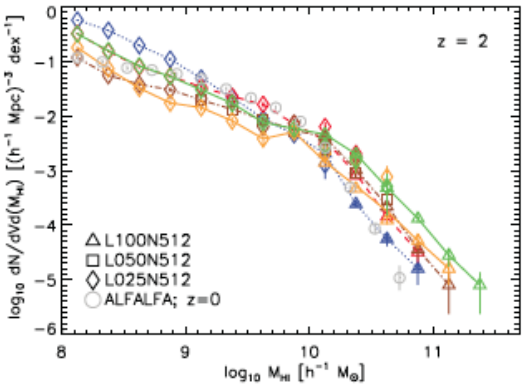
Duffy et. al,
MNRAS 420, 2799, (2012),

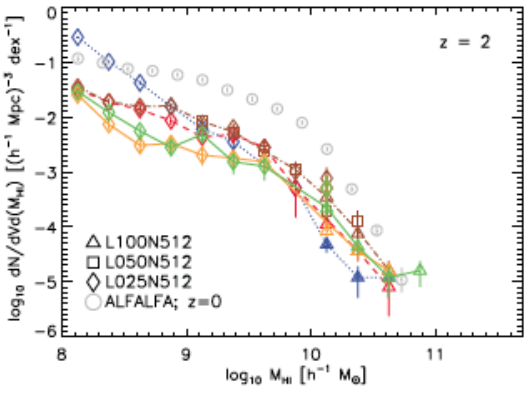
HI Mass Function

- Feedback:
  - No SS: Strong FB → more HI (less cold gas → stars
  - SS: differences reduced (fine-tuned P_{th})
- Therefore, HI mass function are **sensitive** to Feedback, self-shielding







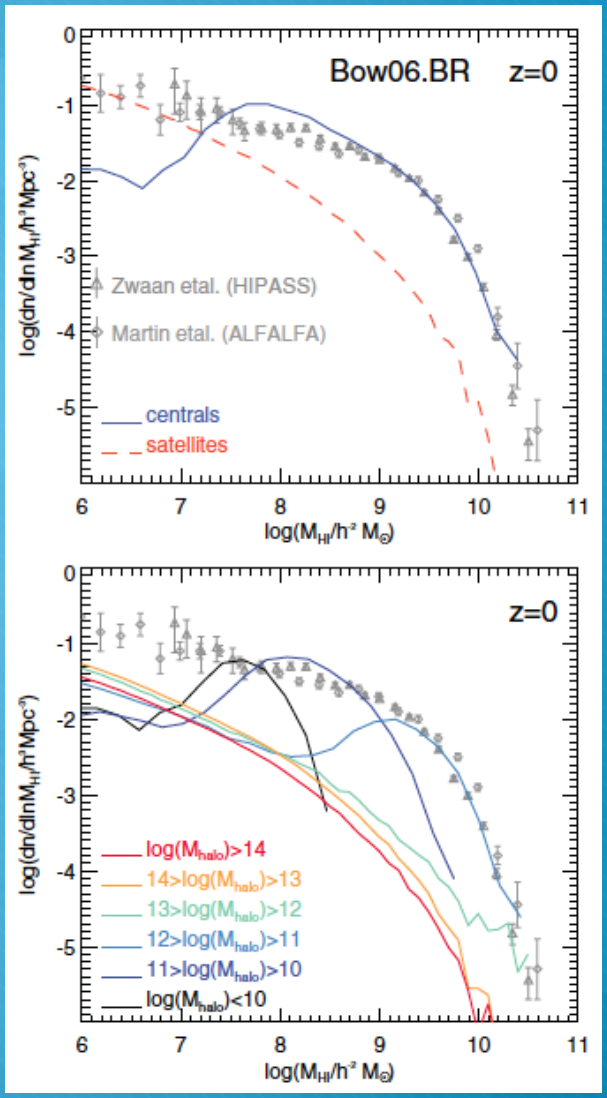


Duffy et. al,
MNRAS 420, 2799, (2012),

HI Mass Function

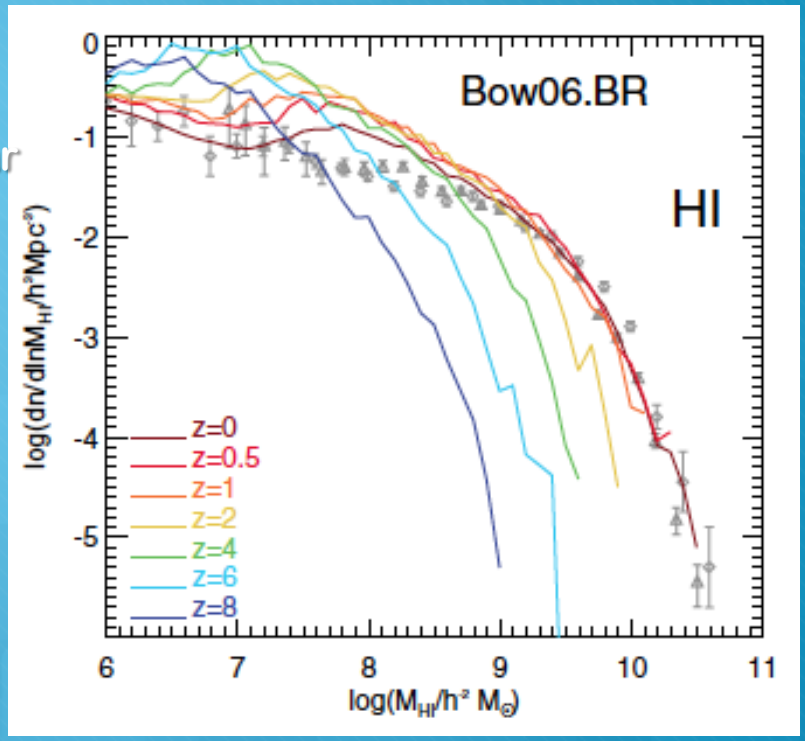
- Galaxy formation model
  - Empirical SF model (BR) works well, SN feedback important
- Centrals – satellites
  - Satellites dominates low-mass end (< 10^7): reionization
- M_{HI} -- M_{halo}:
  - Intermediate/high HI galaxies: hosted by low/interm mass halos
  - Low HI galaxies: satellites in high mass halos
    - AGN feedback

Claudia del P. Lagos et. al, MNRAS, 418, 1649,(2011)



Mass Function Evolution

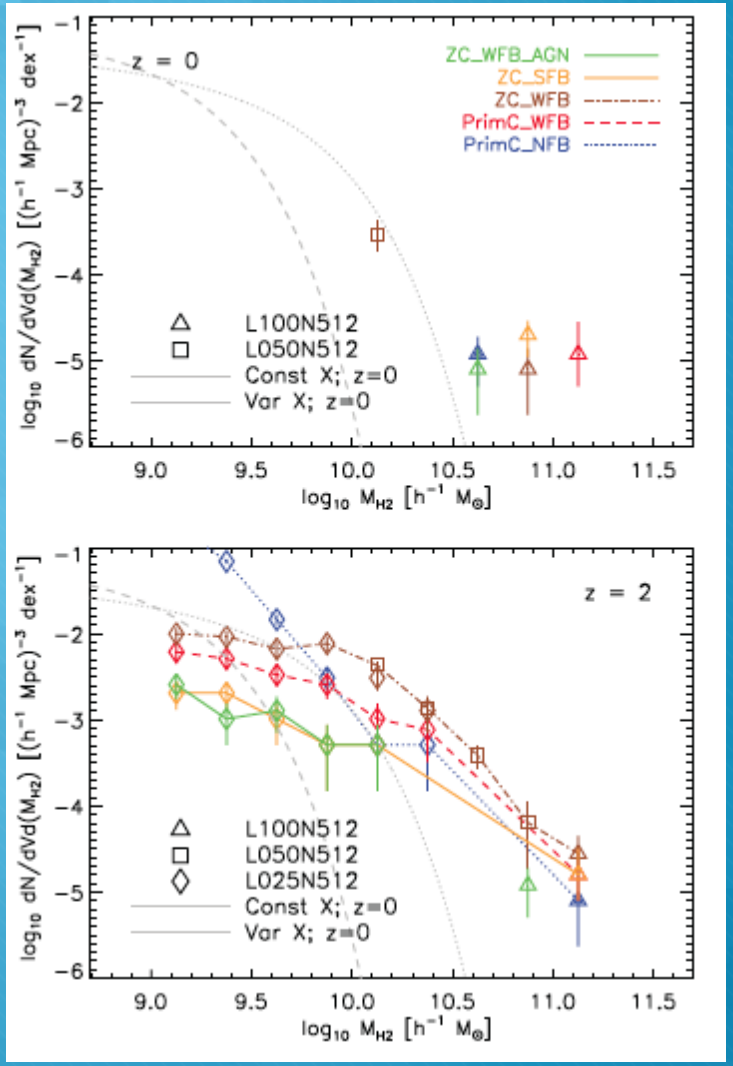
- Low-HI mass galaxies (<10^7)
  - Increase with redshift (8<z<4)
    - Cold gas consuming: quiescent SF, star burst
- 10^7 <M< 10^8:
  - 0<z<1: increase
  - 1<z<4: little evolution
  - z>4: decrease
- M>5*10^8 :
  - 8<z<1: # dens grows hierarchically
  - Until z~1: AGN feedback important
  - z<1: less evolution (intm halos, less AGN)



Claudia del P. Lagos et. al, MNRAS, 418, 1649,(2011)

H_2 Mass Function

- Feedback:
  - Given FB (WFB): metal cooling (ZC) results more H_2
  - Given cooling, strong feedback remove more dense gas

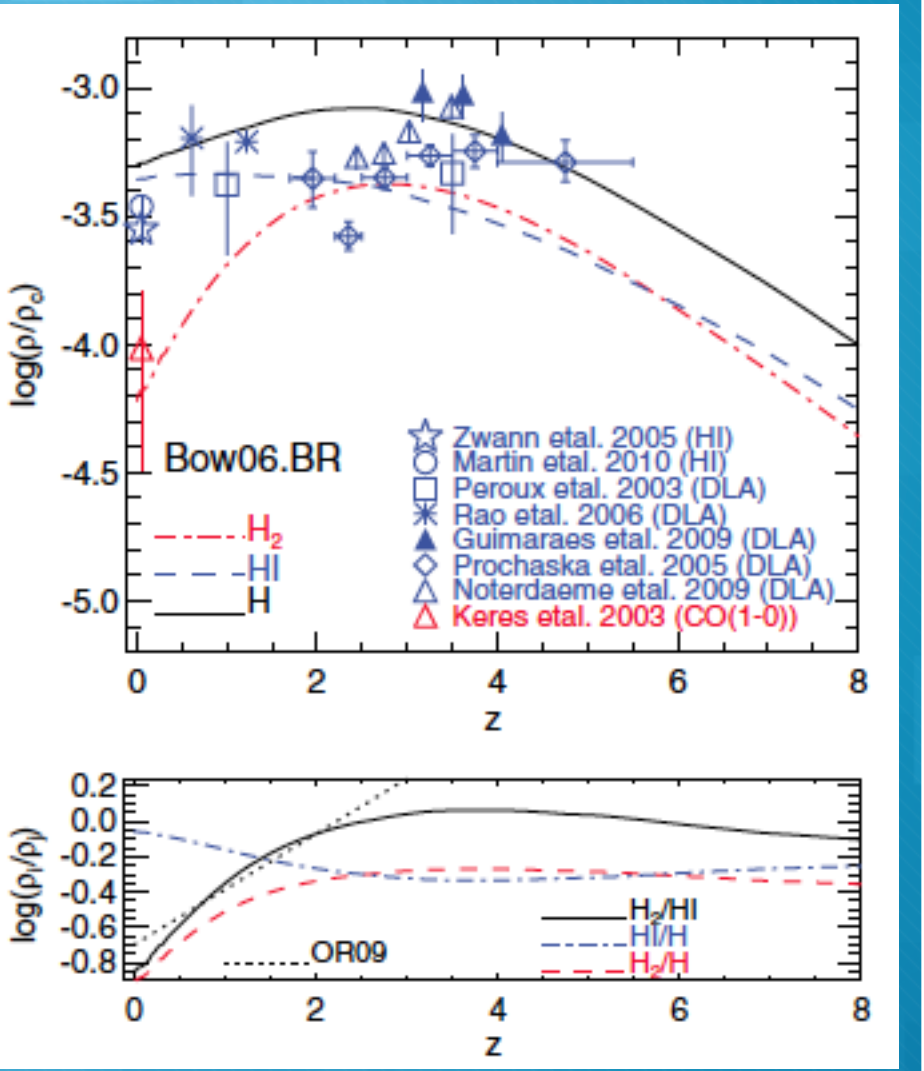


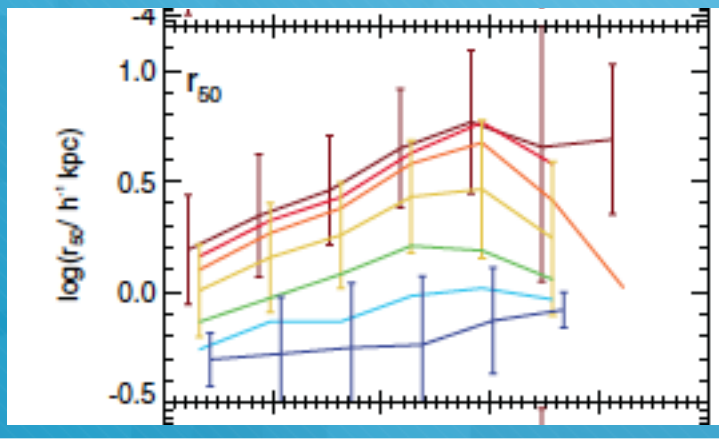
Duffy et. al,
MNRAS 420, 2799, (2012),

density evolution

Claudia del P. Lagos et. al, MNRAS, 418, 1649,(2011)

- Local universe (z~0)
  - Relatively ok (HI & H_2)
  - H_2 << HI: low disc pres
- 2<z<5: more H_2
  - High disc pressure



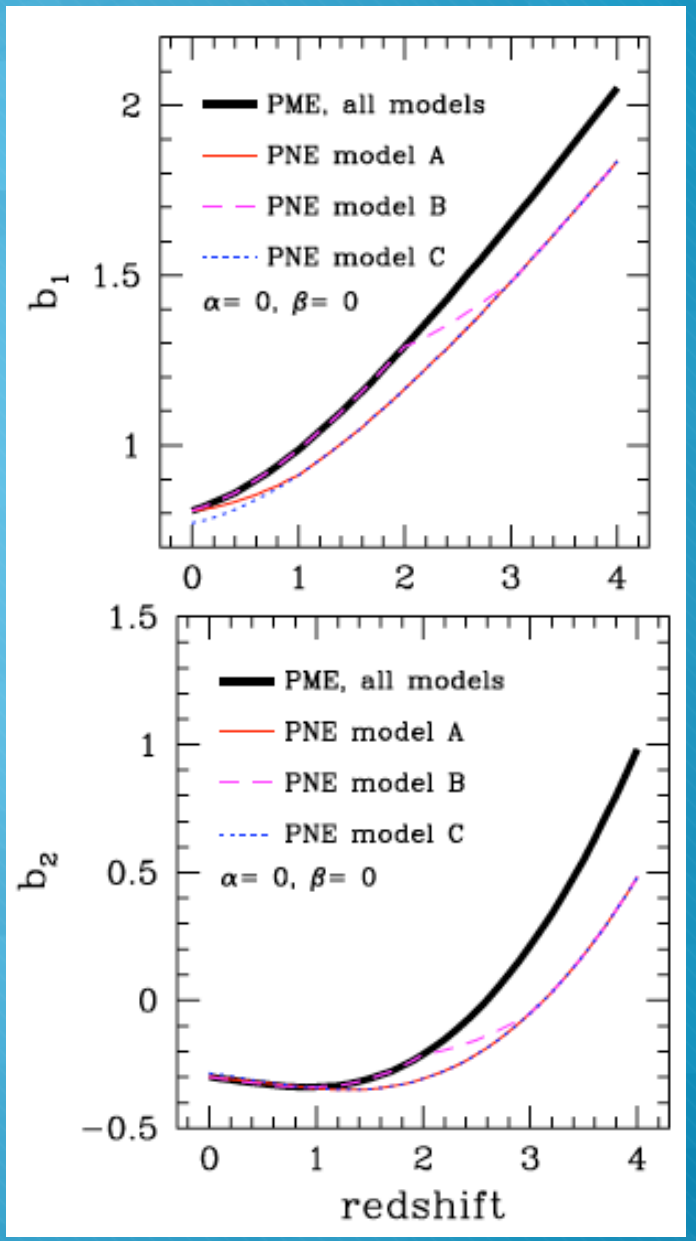


LSS Modeling

- Large-scale bias:
  - noise power, PS shape
  - Halo-based approach:
    - $M_{HI} - M_{halo}$ relation

$$b_{i,\mathrm{H\,I}} = \frac{1}{\rho_{\mathrm{H\,I}}} \int_{M_{\min}}^{\infty} dM n_h(M) b_i^h(M) \langle M_{\mathrm{H\,I}}(M) \rangle ,$$

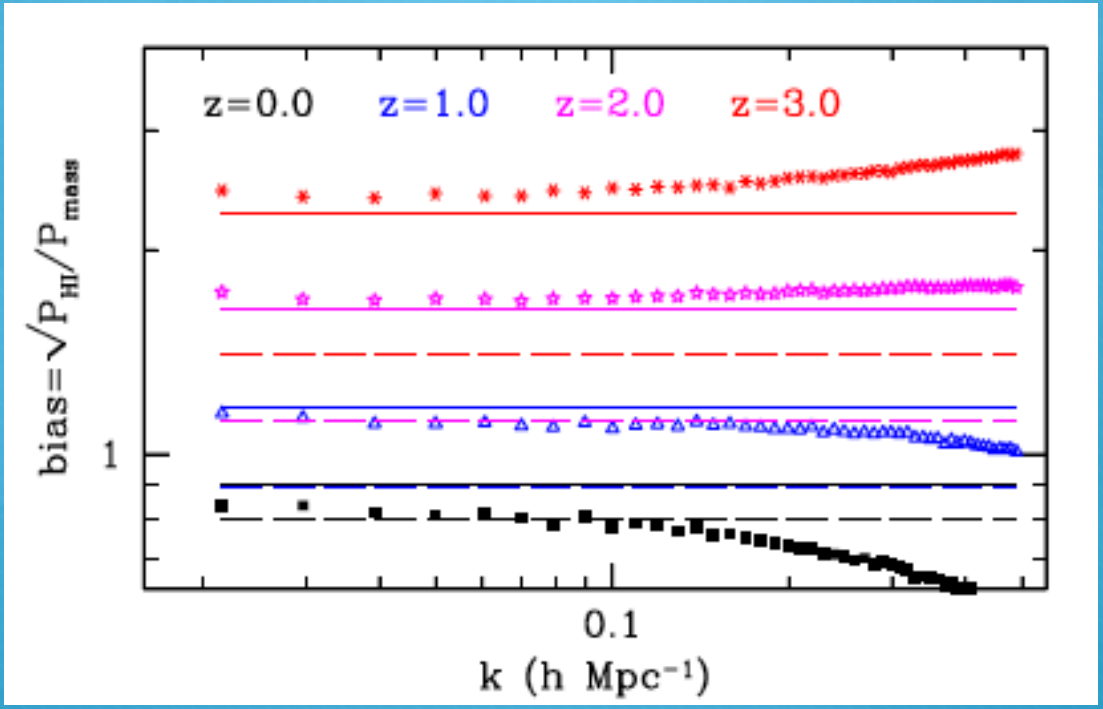
$$\rho_{\mathrm{H\,I}} = \int_{M_{\min}}^{\infty} dM n_h(M) \langle M_{\mathrm{H\,I}}(M) \rangle .$$



Marin et. al, APJ, 718, 972, (2010)

LSS Modeling

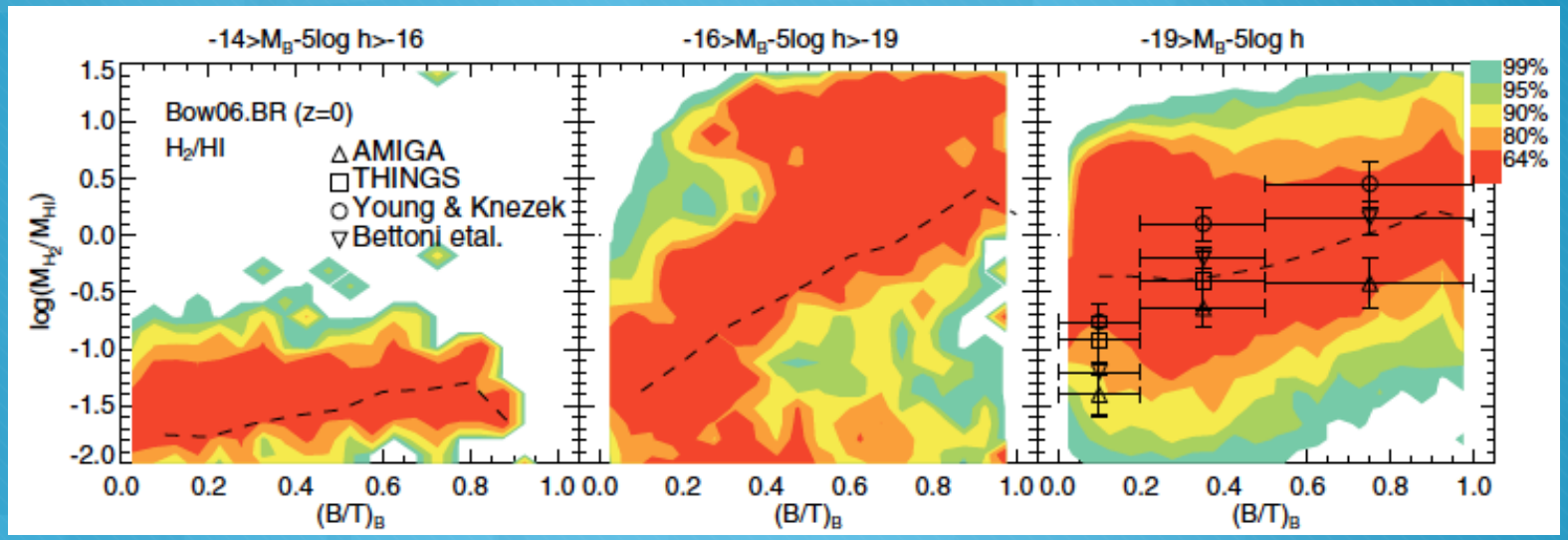
- Bias from Millennium simulation



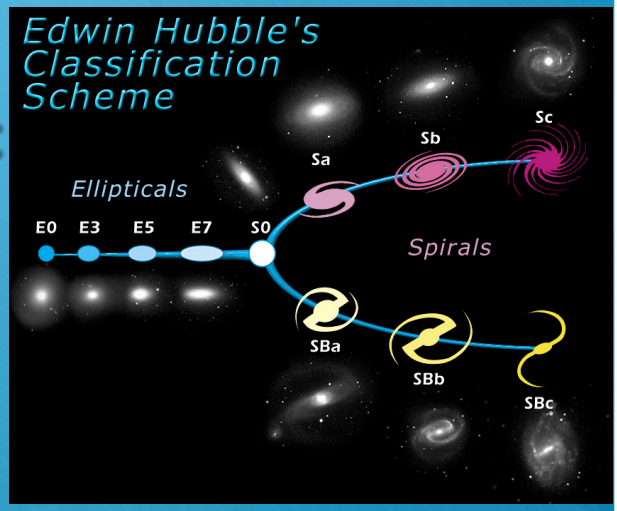
Marin et. al, APJ, 718, 972, (2010)

Claudia del P. Lagos et. al,
MNRAS, 418, 1649,(2011)

HI and galaxy morphology

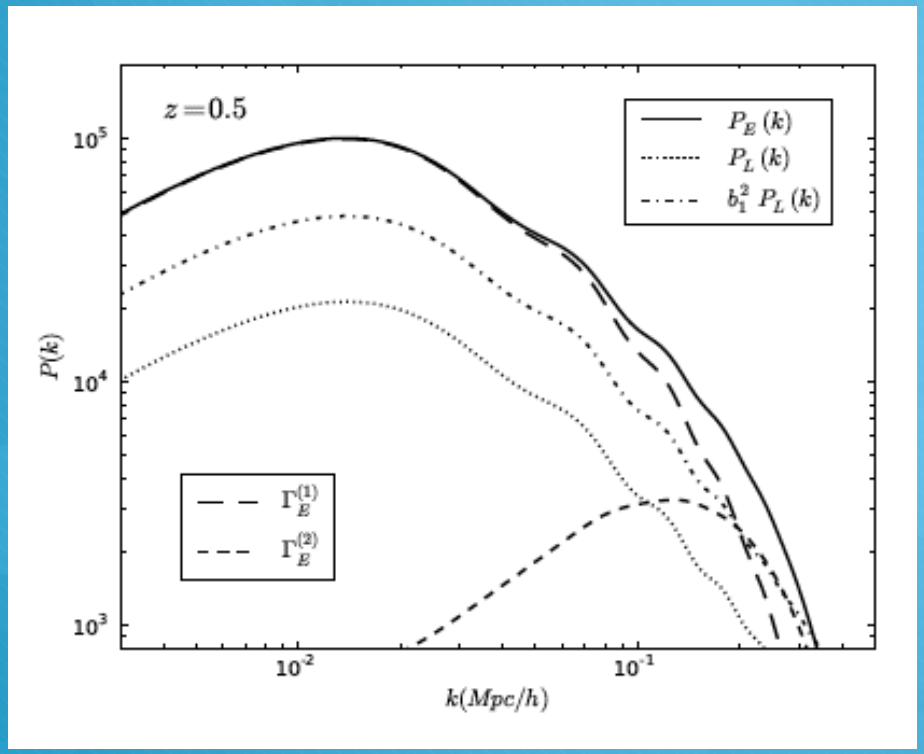


- Bulge-to-total luminosity ratio (B/T):
  - B/T<0.2: Irr, Sm, Sd galaxies
  - 0.2<B/T<0.5: Sc, Sb and Sa galaxies
  - B/T > 0.5: E and S0 galaxies

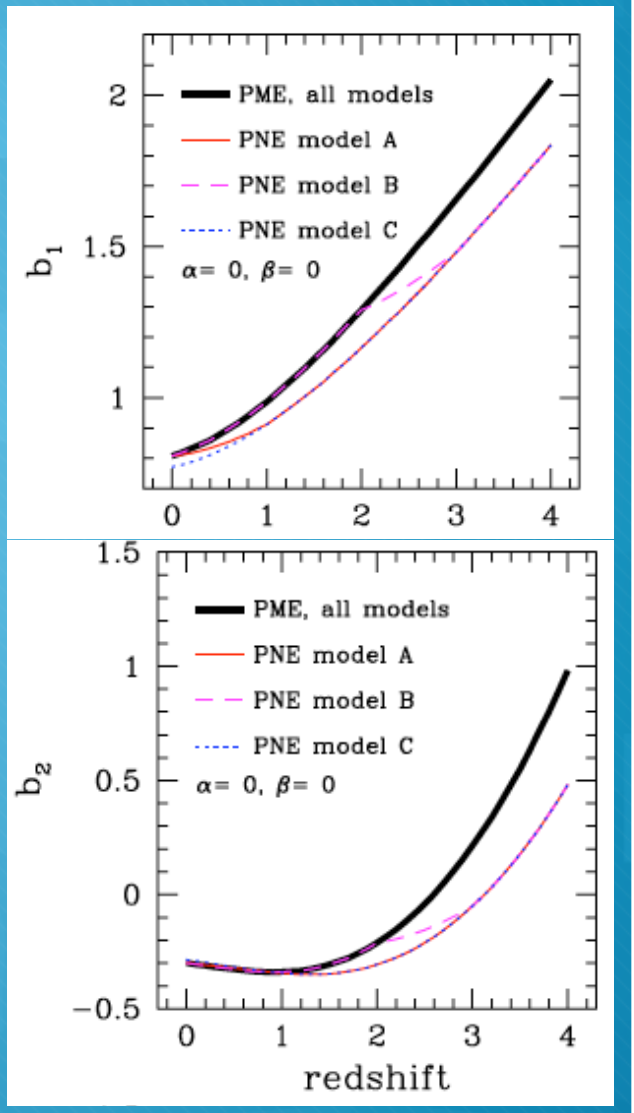


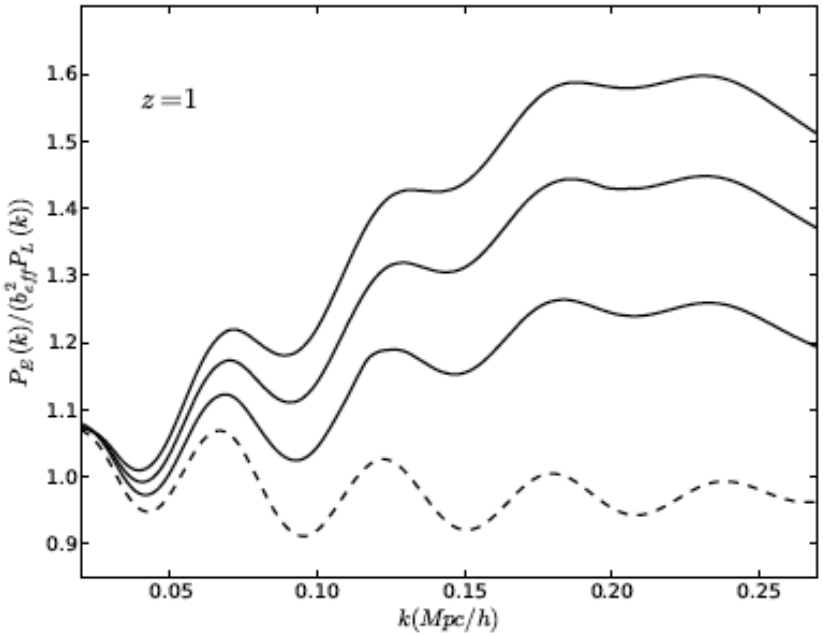
PT Approach

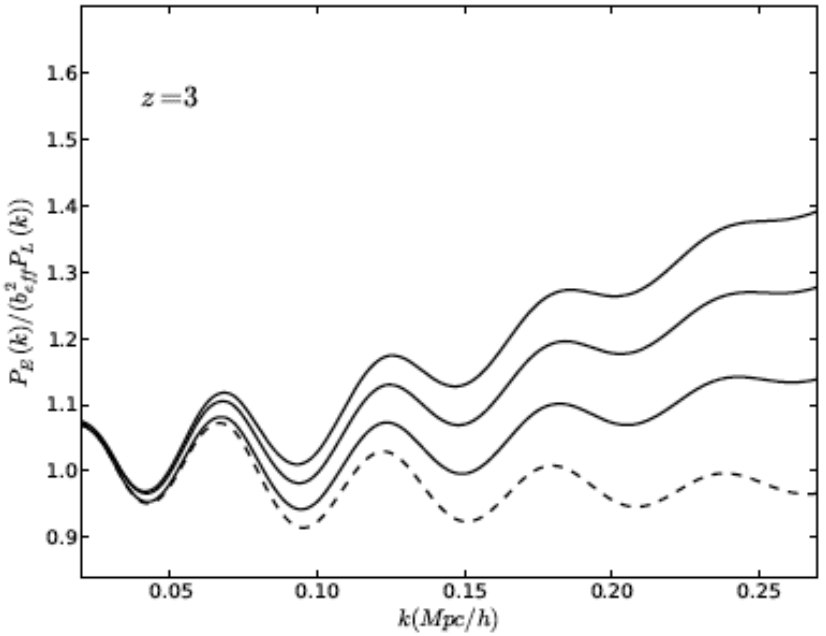
X. Wang (2012), arxiv: 1204.0019



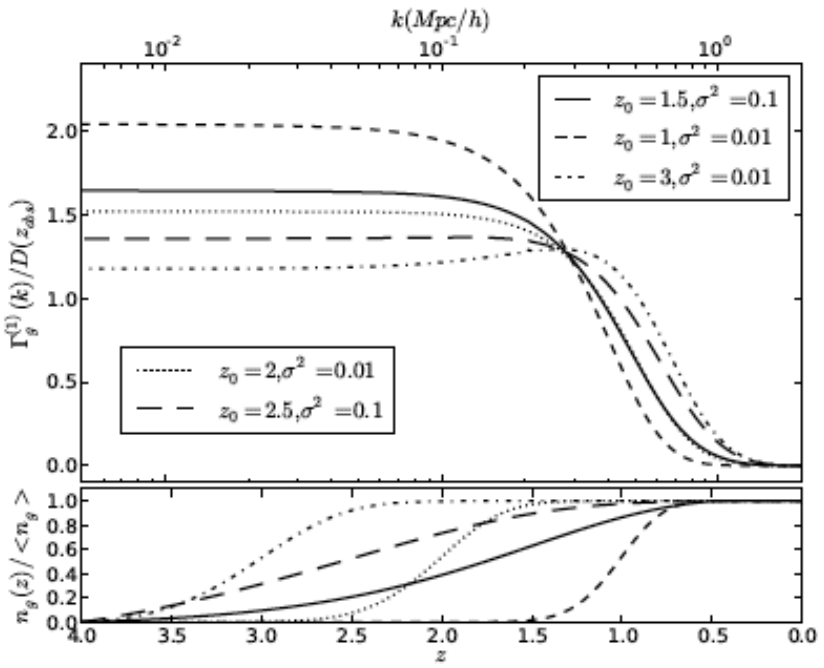
$$\delta_E(\mathbf{x},\eta) = F\left[\delta_m(\mathbf{x},\eta)\right] = \sum_n \frac{b_n}{n!}\left[\delta_m(\mathbf{x},\eta)\right]^n ,$$

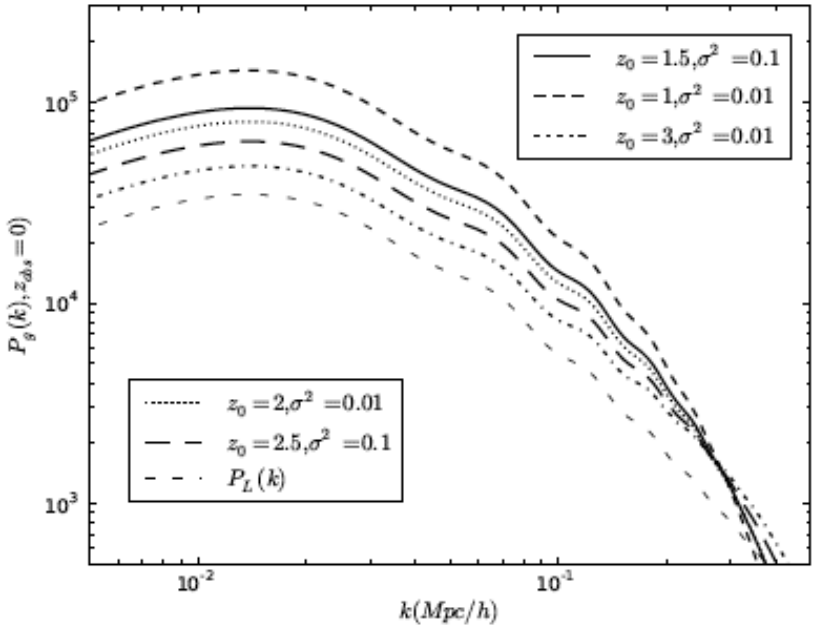






X. Wang (2012), arxiv: 1204.0019





X. Wang (2012), arxiv: 1204.0019

X. Wang (2012), arxiv: 1204.0019