The neutral hydrogen distribution in the post-reionization era

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21-cm workshop
Orsay, 21-22 Oct 2019

Motivations

- At present HI observations are limited in redshift and resolution but large amount of data will be available
- important implications for cosmology: large scales, evolution of structures, BAO

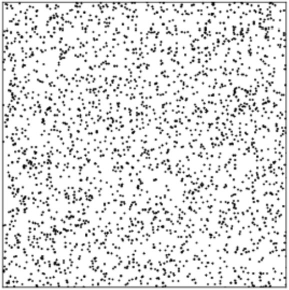
→ 21 cm intensity mapping

- need realistic simulations involving galaxy evolution

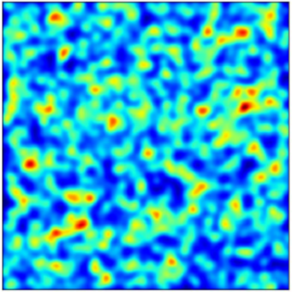
→ e.g. semi-analytic models

21 cm Intensity Mapping

- Look at the total intensity of the 21 cm emission line in a large 3d pixel (angle and frequency)
- Pixel will have joint emission from multiple galaxies
- Cheap for large volume



galaxies

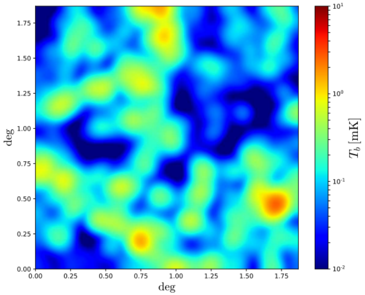


Intensity map

Mock 21 cm maps for IM

(non exhaustive) list of methods:

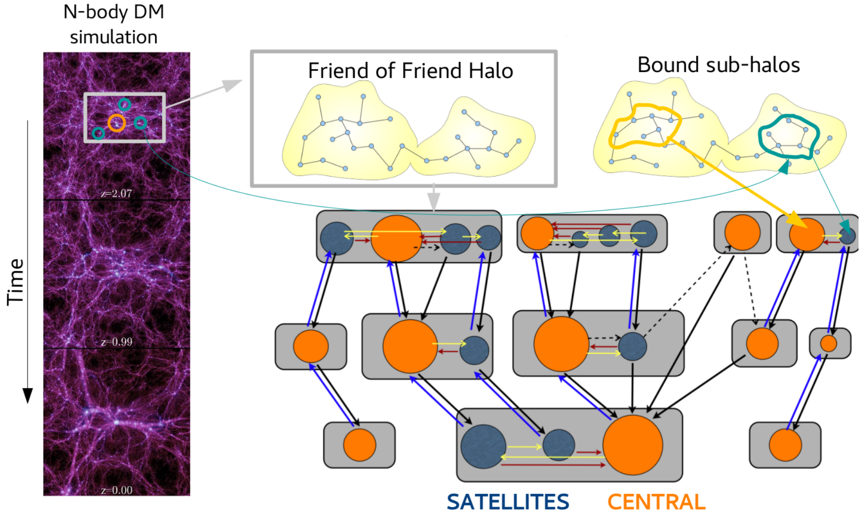
- hydro-dynamical simulations + HI in post processing
  e.g. Villaescusa-Navarro et al. 2014,2018



Villaescusa-Navarro et al 2018

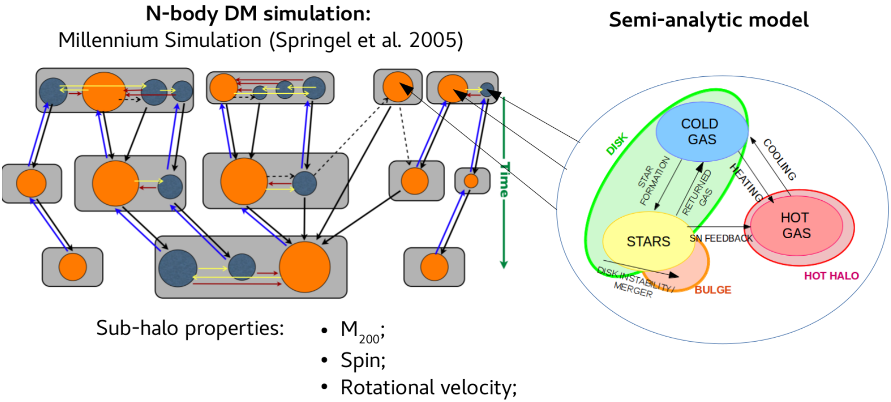
- Gaussian realization of $P_m(k)$ at $z = 0$ (need to assume $x_{\rm HI}$ and bias)
  e.g. Alonso et al. 2014
- HOD techniques on mock halo catalogues:
  - simplistic assumption on HI in halos
  - HI models from hydro-dynamical simulations or Semi-analytic models
    e.g. Baugh et al. 2019, this work

SAMs: from N-body to merger trees



credit: A.Zoldan

From dark matter to baryons



credit: A. Zoldan

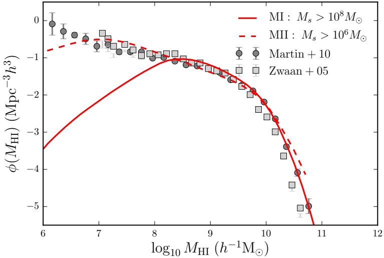
The GAlaxy Evolution and Assembly (GAEA)

- both on Millennium I and II
  more "cosmological" *vs.*
  better resolution
  (500 h^{-1} Mpc, 100 h^{-1} Mpc)

- Tested and upgraded during the years: e.g. De Lucia &. Blaizot 2007, De Lucia et al. 2014, Hirschmann et al. 2016, Xie et al. 2017, Zoldan et al. 2017

- explicit treatment of cold gas partition in atomic (HI) and molecular (H2)
  (Xie et al. 2017)

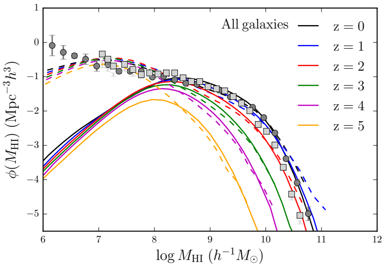
SF efficiency tuned to match the HI mass function at $z = 0$

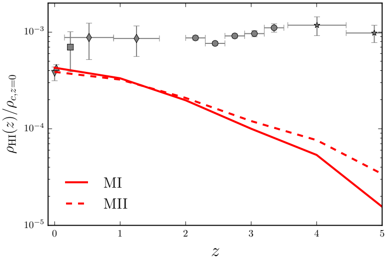


Redshift evolution

How does the HI content evolve with redshift?

- hierarchical growth of structures, switch between $z = 0$ and $z = 1$ due to AGN feedback
- tuned to match $\Omega_{\rm HI}$ in the local universe
- SAMs often predict decrease with redshift

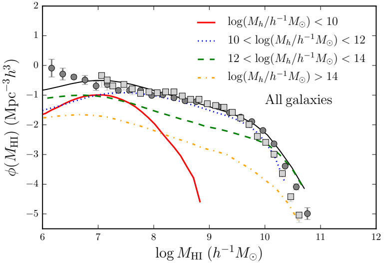


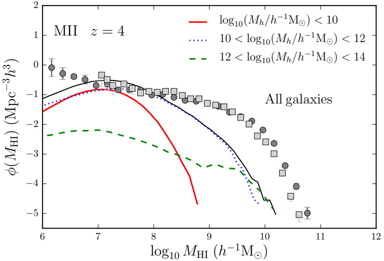


HI mass function and halos

In which halos do HI galaxies live?

- at $z = 0$: high mass end dominated by galaxies in big halos, at low masses small halos important
- at $z = 4$: similar behaviour
- smallest halos mass function do not evolve much with redshift

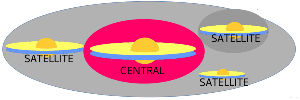




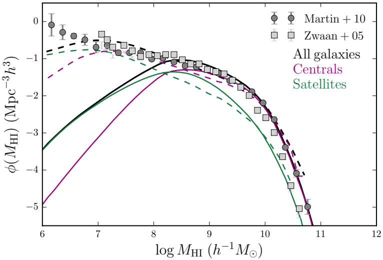
Role of centrals and satellites

Centrals dominate from intermediate to high HI masses

Satellites dominate for low HI masses



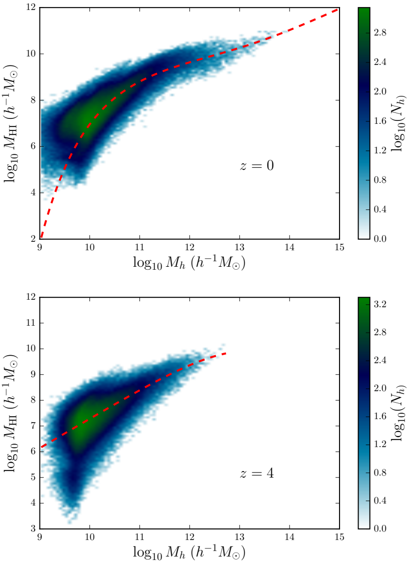
— MI – – MII



HI halo mass function

Total HI content $M_{\rm HI}$ of a halo of mass M_h: $M_{\rm HI}(M_h)$

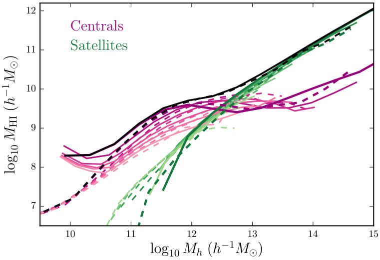
- a fundamental ingredient of the halo model and to build mock 21 cm maps
- $z = 0$: fit a functional form with: low mass cut-off + power law with an inflection point
(due to AGN feedback: Baugh et al. 2019)

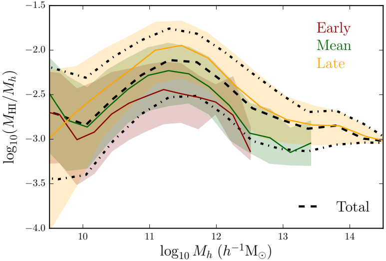


HI halo mass function

SAMs allows to investigate further:

- role of centrals and satellites also as function of redshift
- role of assembly history dividing in bins wrt redhift at which halo acquired 50% of its mass

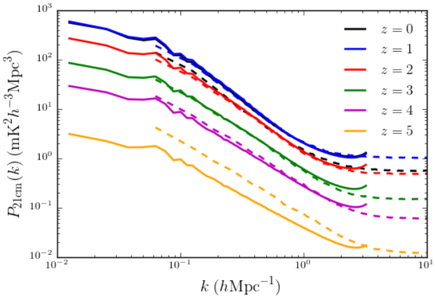




21cm Power Spectrum

$$P_{21\mathrm{cm}}(z,k) = \bar{T}_b^2 x_{\mathrm{HI}}^2 \left[b_{\mathrm{HI}}^2 \left(1 + \beta^2\mu^2\right)^2 P_m(z,k) + P_{\mathrm{SN}} \right]$$

e.g. Kaiser (1987), Bacon et al (2019)



— MI – – MII

x_{HI}: abundance of neutral hydrogen

b_{HI}: HI bias

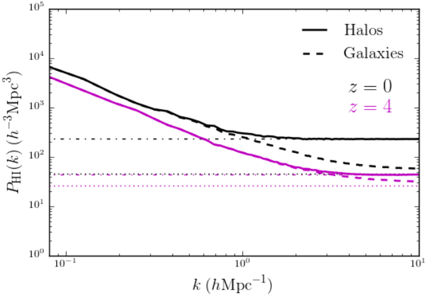
$\beta^2\mu^2$, with $\beta \equiv f/b_{\mathrm{HI}}$
Redshift Space Distortions

Shot Noise from small scales

Shot Noise

- intrinsic discrete nature of the measurement
- SN computed from the value of PS at small scales
- in the halo model: associated to 1-halo term e.g. Villaescusa-Navarro et al. 2018
- low values: good for BAO studies

$$P_{\rm SN} = \ell_{box}^3 \frac{\sum M_{{\rm HI},i}^2}{(\sum M_{{\rm HI},i})^2}$$



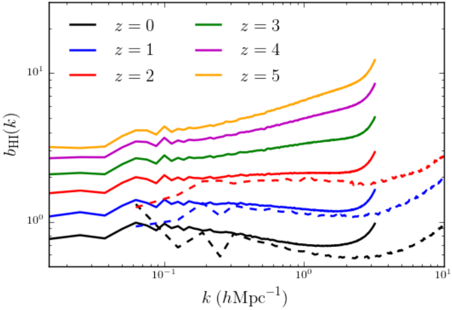
Bias

How do HI sources trace dark matter?
(cosmology is in $P_m(k)$)

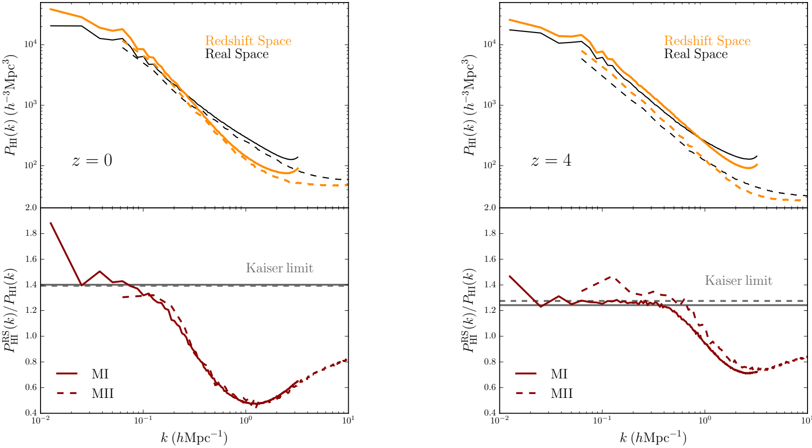
$$b_{\rm HI}(k) = \sqrt{\frac{(P_{\rm HI}(k) - P_{\rm SN})}{P_m(k)}}$$

- *constant* at large scales, then scale dependence
- dip around $k \sim 1h\text{Mpc}^{-1}$ at $\mathbf{z=0}$ (also in observations Anderson et al. 2018)
- bias grows with redshift (good news for IM!)

— MI – – MII



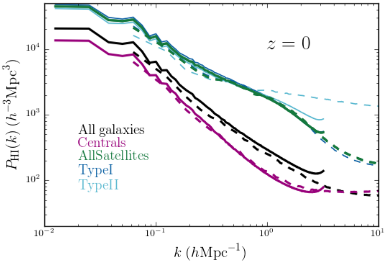
Redshift Space Distortion

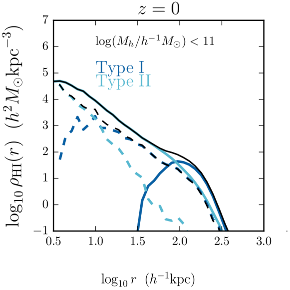


The role of satellites

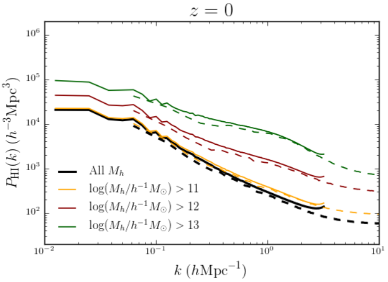
Satellites and centrals different HI power spectrum

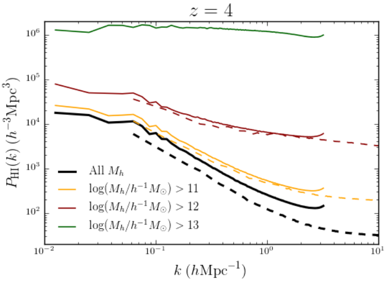
- satellites in big halos
- centrals in low and intermediate mass halos
- satellites: Type I (normal) and Type II (orphans) different role in HI profiles of halos
- can see this difference in the $P_{\rm HI}$





Clustering and halo mass

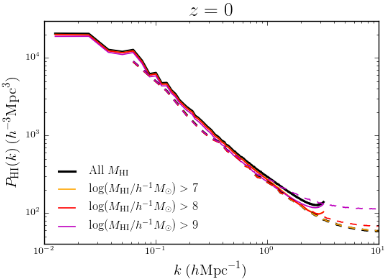


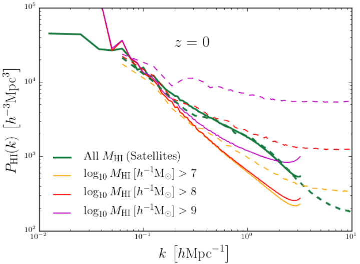


- progressively selecting bigger halos: P_k rises for halo bias
- highest halo masss cut: enough satellites to appreciate the 1-halo term

- at higher redshift not enough big halos: shot noise
- the smallest halos drive the difference between MI and MII

The role of low HI galaxies



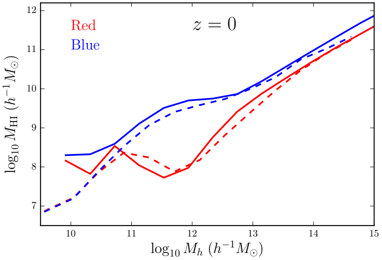


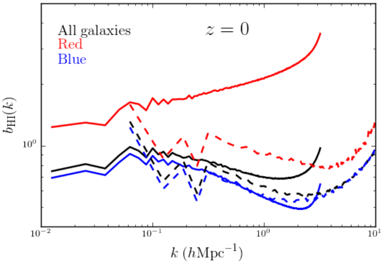
- HI masses quite evenly distributed in halos
- SN rises only for highest HI mass cut

looking only at satellites: lowest HI masses fundamental for the 1-halo term

Red and Blue clustering

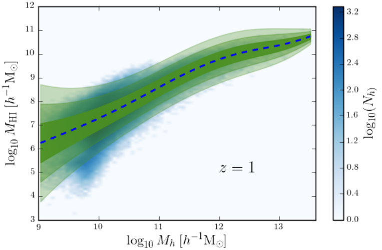
- Red vs Blue with a cut in sSFR
- Red in massive haloes with high halo bias: most satellites in massive haloes are red galaxies
- Blue star forming dominates HI content of medium mass haloes driving the clustering properties of all HI
- agreement with Anderson et al. (2018)

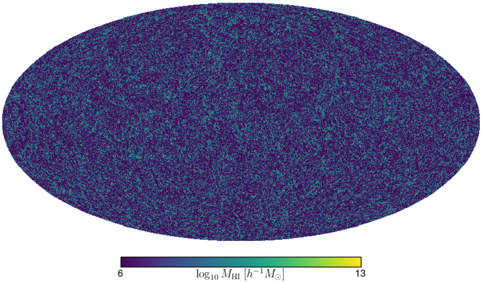




HI Probe-POPulator (HIP-POP)

- extract from SAM analytic prescriptions for $M_{\mathrm{HI}}(M_h)$
- use fast halo catalogues from LPT e.g. *Pinocchio* Monaco et al. (2002)





- full sky maps maps to be used for testing foreground cleaning in both auto and cross correlation

WORK IN PROGRESS

Conclusions

- Semi-analytic models are a powerful (predictive!) tool to investigate the connection between the signal and the details of galaxy evolution:
  - HI halo mass function $M_{\rm HI}(M_h)$
  - investigate HI bias, Shot Noise and the effect of RSD
  - investigate HI clustering and its dependence on a variety of parameters (satellites and centrals but also halo mass, HI minimal mass, color)
- 21 cm Intensity Mapping analysis will need to control instrumental systematics and foreground emissions, but also to understand/simulate properly the signal
- generate fast, realistic, mock 21 cm maps (for example in combination with LPT halo catalogues)

an important bridge between cosmology and galaxy evolution