Intensity Mapping with SKA: BAOs and neutrinos

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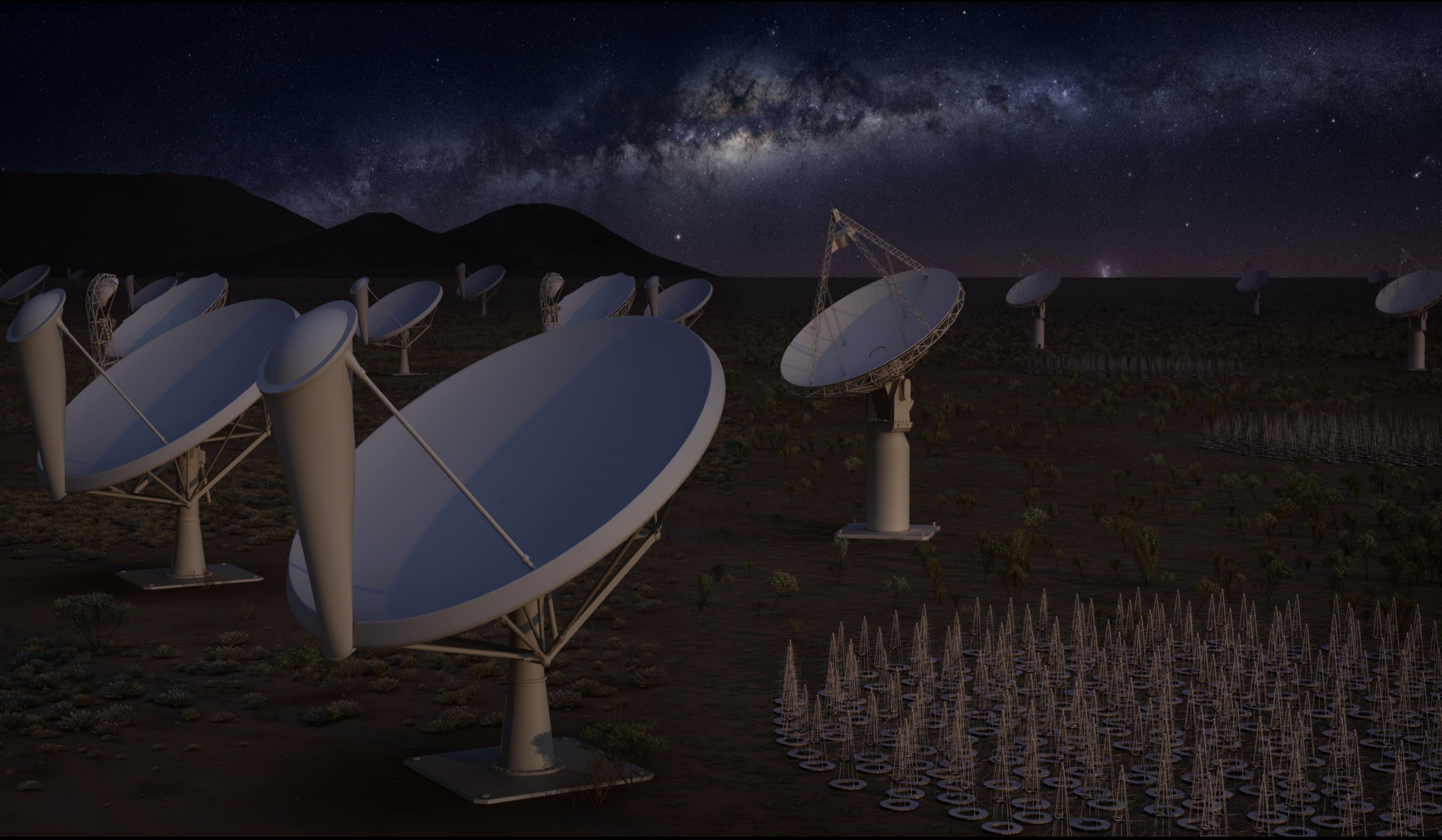
INAF/OATS



ICTP Workshop on Cosmology with Next Generation Radio Surverys – 23/06/2016

OUTLINE

- ✓ Modelling the Intensity Mapping signal
- ✓ Cross-correlation of IM with galaxies
- ✓ Neutrinos
- ✓ BAOs with IM and BAO reconstruction

Francisco Villaescusa-Navarro - Postdoc now moving to CCA in New York: IM and neutrinos

Phil Bull
Caltech and JPL
Neutrinos and IM

Andrej Obuljen - SISSA
PhD student
BAO reconstruction

David Alonso
Oxford Univ.
BAO with IM

Isabella Carucci – SISSA
PhD student
Small scale IM power spectrum

Tirth Roy Choudury
NCRA Pune

Modelling the IM signal at high redshift - I

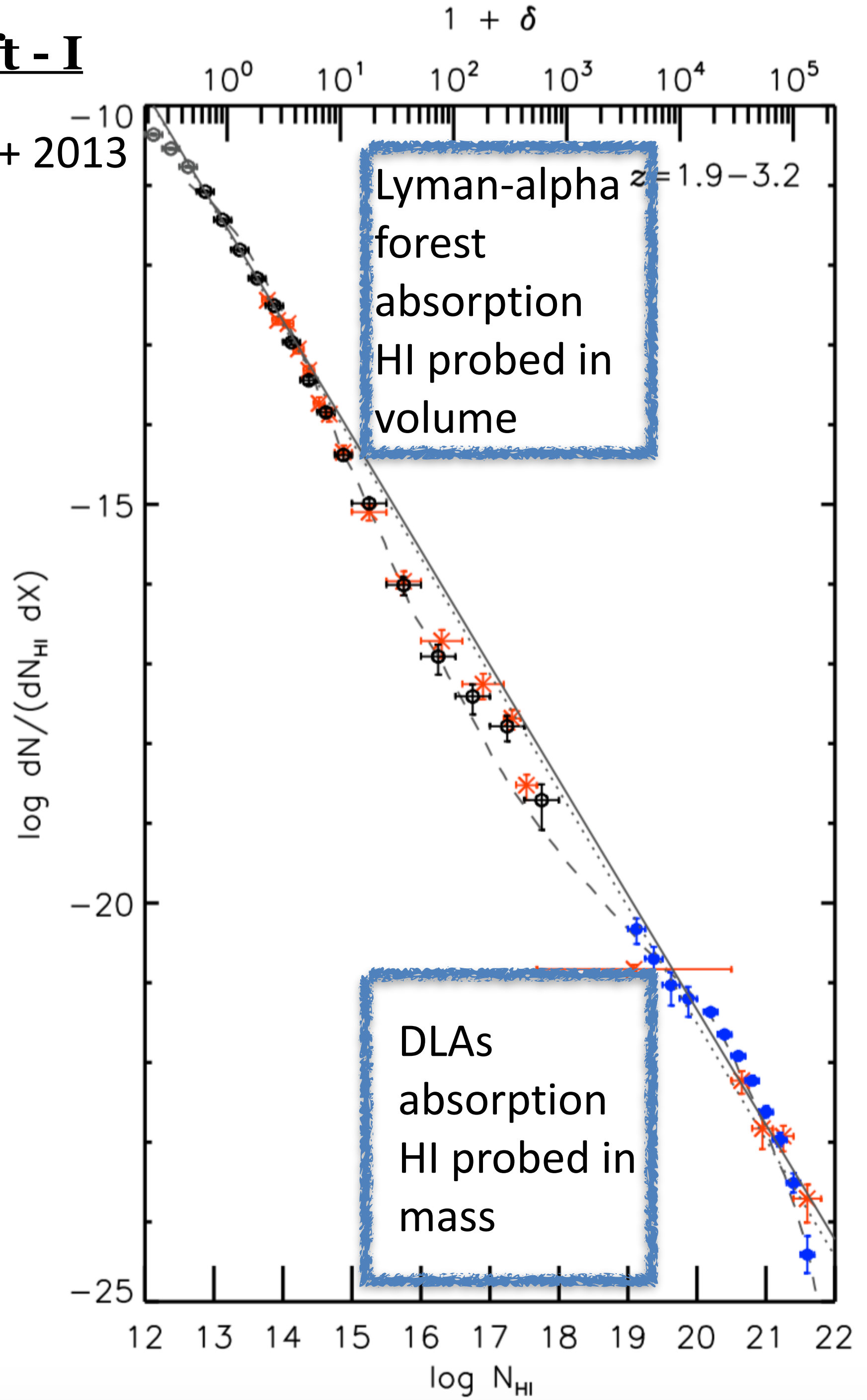
✓ We want to model the bulk of the neutral hydrogen: mostly HI in haloes not filaments (unlike Lyman-alpha forest)

✓ High redshift HI observational constraints come from absorption lines

✓ Any modeling attempt should aim at reproducing observational properties of high column density systems

Absorption lines data provide tight constraints on Ω_{HI}

Kim+ 2013

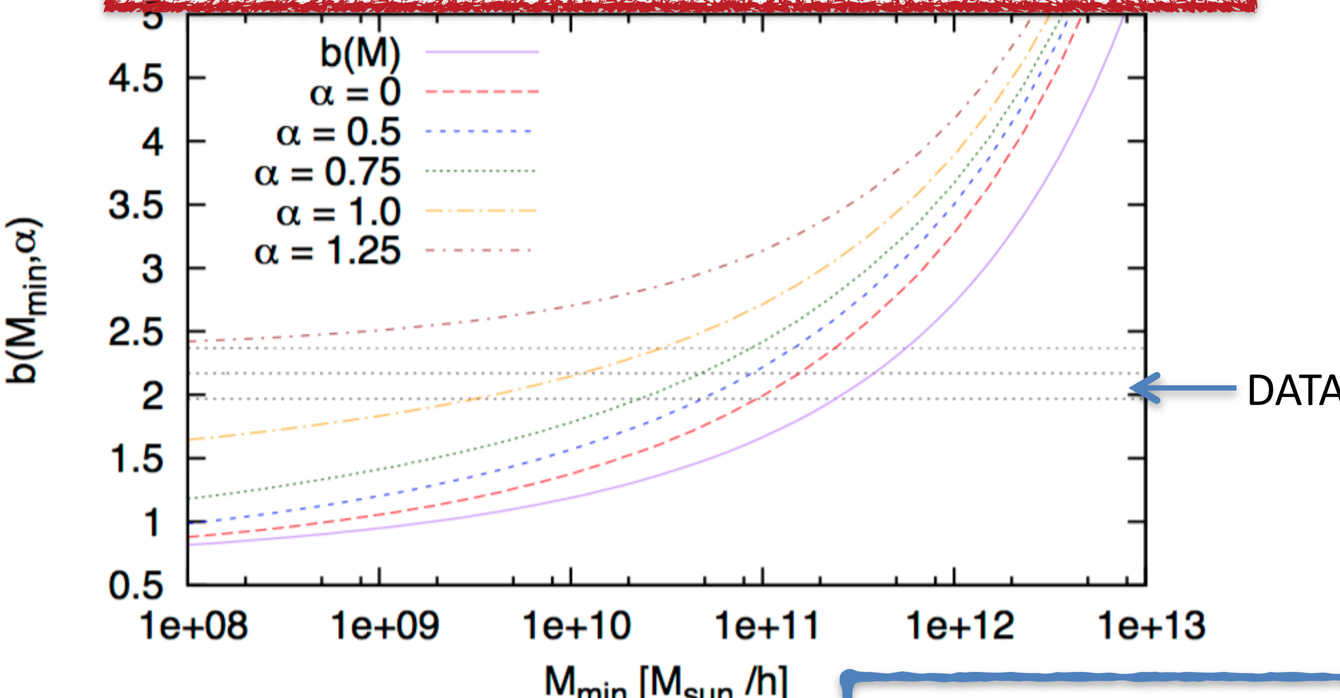


Modelling the IM signal at high redshift - II

✓ New science from BOSS/SDSS-III low res. Low S/N data: modeling of the cross-correlation signal between Lyalpha and DLAs

Cross spectrum $$P_{DF}(\mathbf{k},z) = b_D(z)\left[1+\beta_D(z)\mu_k^2\right] b_F(z)\left[1+\beta_F(z)\mu_k^2\right] P_L(k,z)$$

$$\Sigma(M) = \Sigma_0 (M/M_{min})^{\alpha} \qquad (M > M_{min})$$



Absorption lines data provide tight constraints on bias of DLAs=b_{HI} - somewhat higher values than previously used

Modelling the IM signal - III: key quantities

astrophysical key quantity

$$\Omega_{\rm HI}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{\rm HI}(M,z)dM$$

fixed to obs.

$$b_{\rm HI}(z) = \frac{1}{\rho_c^0\Omega_{\rm HI}(z)}\int_0^\infty b(M,z)n(M,z)M_{\rm HI}(M,z)dM$$

fixed to obs.

$$P_{\rm HI}(k,z) = b_{\rm HI}^2(z)P_{\rm m}(k,z)$$

HI power spectrum real space (not observable)

$$\overline{\delta T_b}(z) = 189\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{\rm HI}(z)h \text{ mK}$$

21cm redshift space power spectrum (observable)

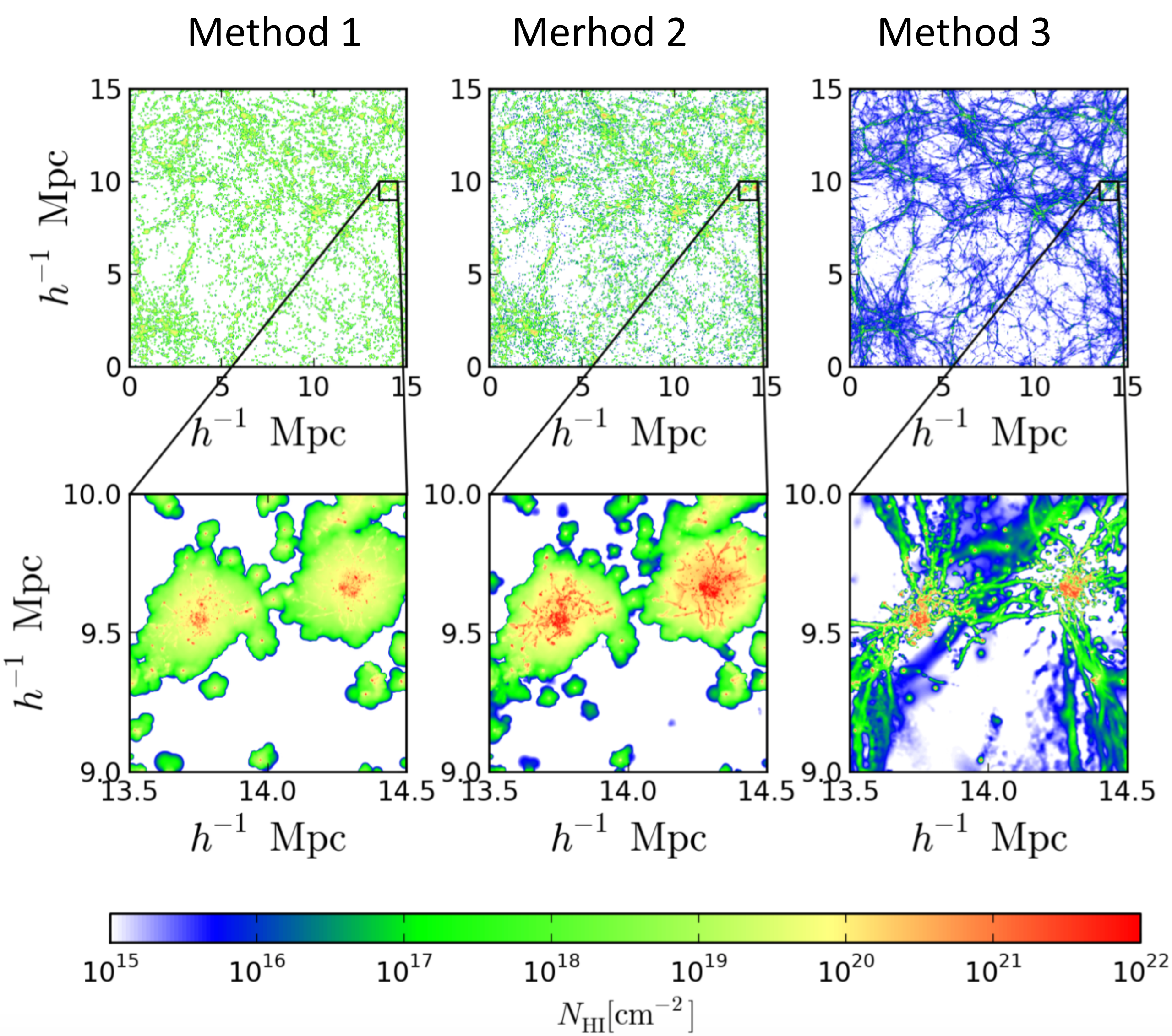
$$P_{\rm 21cm}(k,z) = \overline{\delta T_b}^2(z)b_{\rm HI}^2(z)\left(1+\frac{2}{3}\beta(z)+\frac{1}{5}\beta^2(z)\right)P_{\rm m}(k,z)$$

$$\Omega_{HI}b_{HI}$$

sets the amplitude of the signal

Villaescusa-Navarro, MV, Alonso, Datta, Bull, Santos 2015

Modelling the IM signal at high redshift - IV



Method 1: to fit a low b_{DLA} bias (Bagla et al.)

Method 2: to fit the BOSS observations (high b_{DLA})

Method 3: hydro simulation with self-shielding (no free parameters) - as in Dave'+13

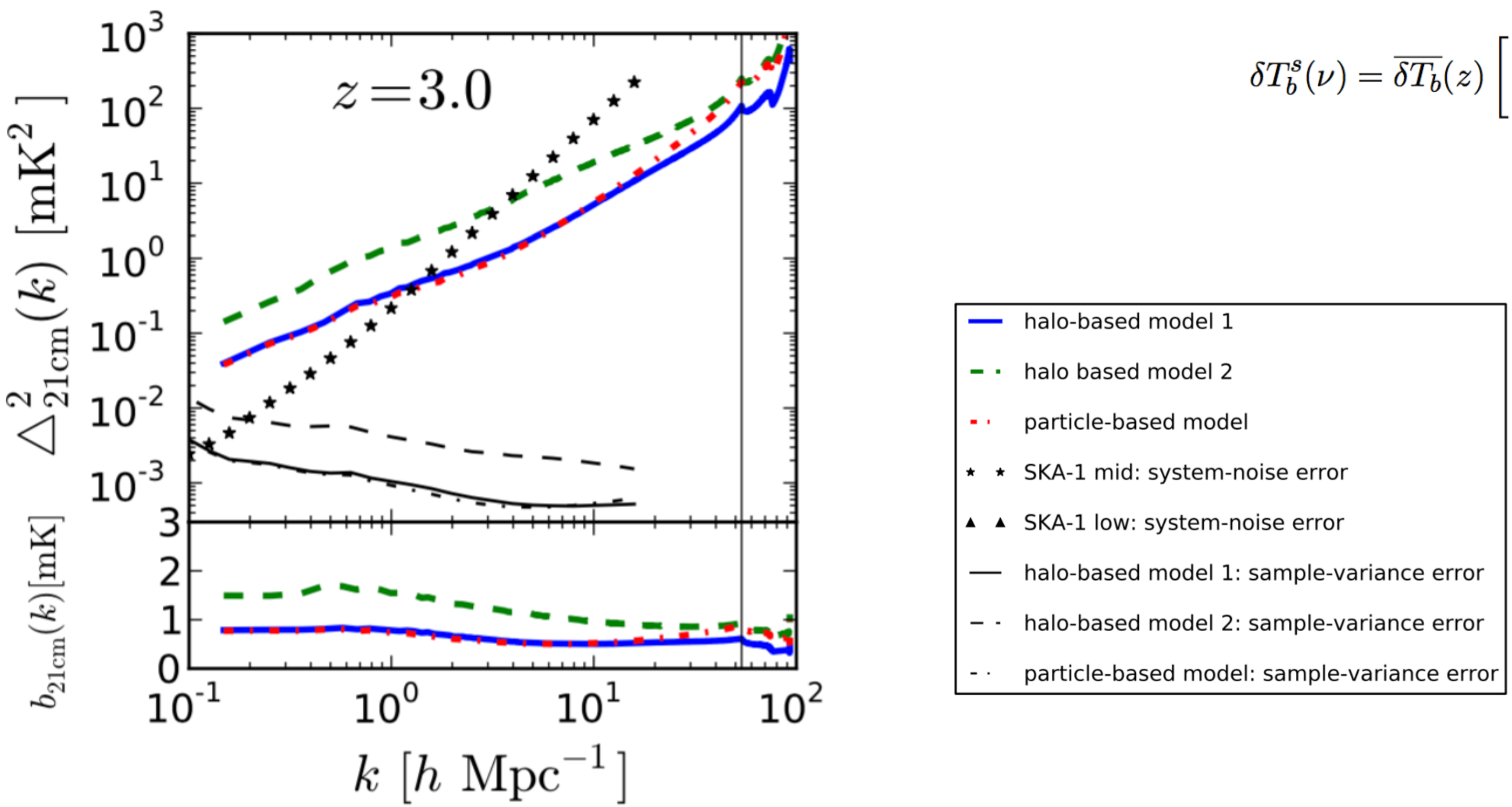
Villaescusa-Navarro, MV, Datta, Roy Choudhury 2014

Modelling the IM signal at high redshift - V

$$\delta T_b(\nu) = \overline{\delta T_b}(z)\left(\frac{\rho_{\rm HI}(\vec{r})}{\bar{\rho}_{\rm HI}}\right)\left[1-\frac{T_\gamma(z)}{T_s(\vec{r})}\right]$$

$$\overline{\delta T_b}(z) = 23.88\,\bar{x}_{\rm HI}\left(\frac{\Omega_{\rm b}h^2}{0.02}\right)\sqrt{\frac{0.15}{\Omega_{\rm m}h^2}\frac{(1+z)}{10}}\ {\rm mK},$$

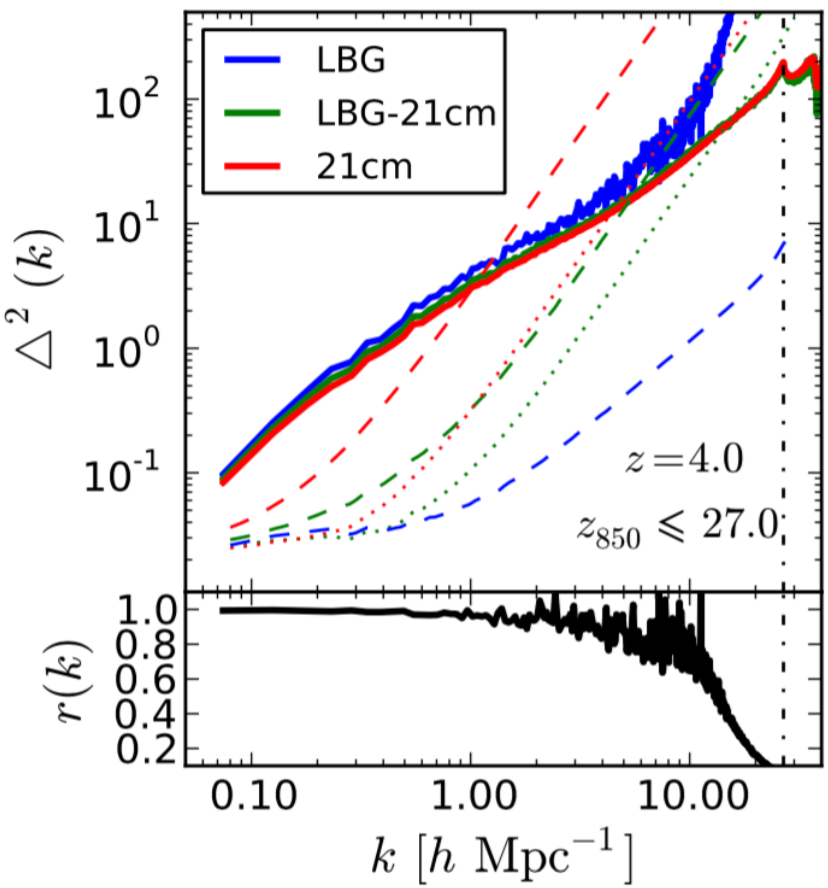
$$\delta T_b^s(\nu) = \overline{\delta T_b}(z)\left[\frac{\rho_{\rm HI}(\vec{s})}{\bar{\rho}_{\rm HI}}\right]$$

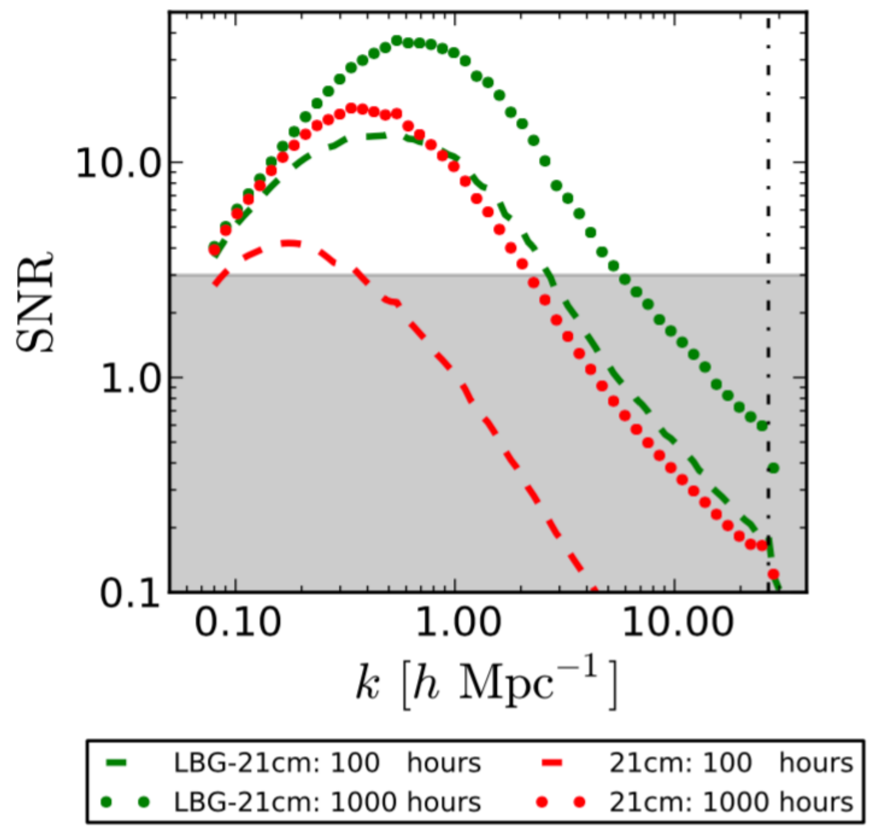


Villaescusa-Navarro, MV, Datta, Roy Choudhury 2014

Modelling the IM signal -VI: at high redshift with cross-correlation

Cross-correlation with a future high redshift SPECTROSCOPIC LBGs survey
allows to probe smaller scales
allows to boost the SNR (Ue Li’s talk)

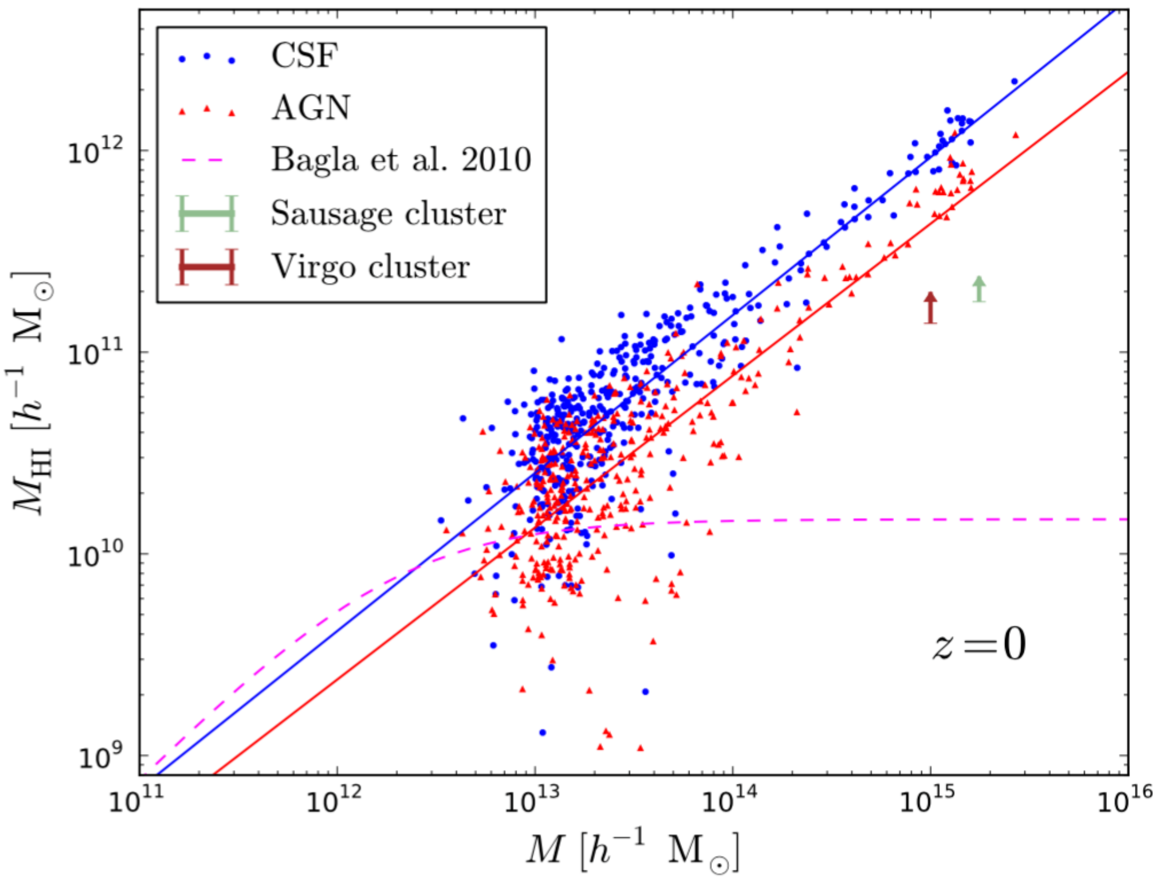




Villaescusa-Navarro, MV, Alonso, Datta, Bull, Santos 2015

Modelling the IM signal - VII: at low redshift in groups and clusters

Caution: astrophysical effects (e.g. AGN feedback) can affect the $M_{HI}(M, z)$ but …. there are other observational constraints independent of absorption lines - AGN reduces the HI content of a halo by 50%



$$M_{\rm HI}(M, z) = \begin{cases} e^{\gamma(z)} M^{\alpha(z)} & \text{if } M_{\min}(z) \leqslant M \\ 0 & \text{otherwise,} \end{cases}$$

Only simulations with AGN matches the observed $\Omega_{HI} b_{HI}$ = 0.0006 value (Chang+10, Masui+13, Switzer+13)

Villaescusa-Navarro+ 16

SUMMARY OF IM MODELING

1) Modelling of 21 cm power spectrum relatively easy in the post-reionization era

2) Key astro quantity is how HI mass is distributed within haloes

3) External observational constraints do not allow total freedom in the model building

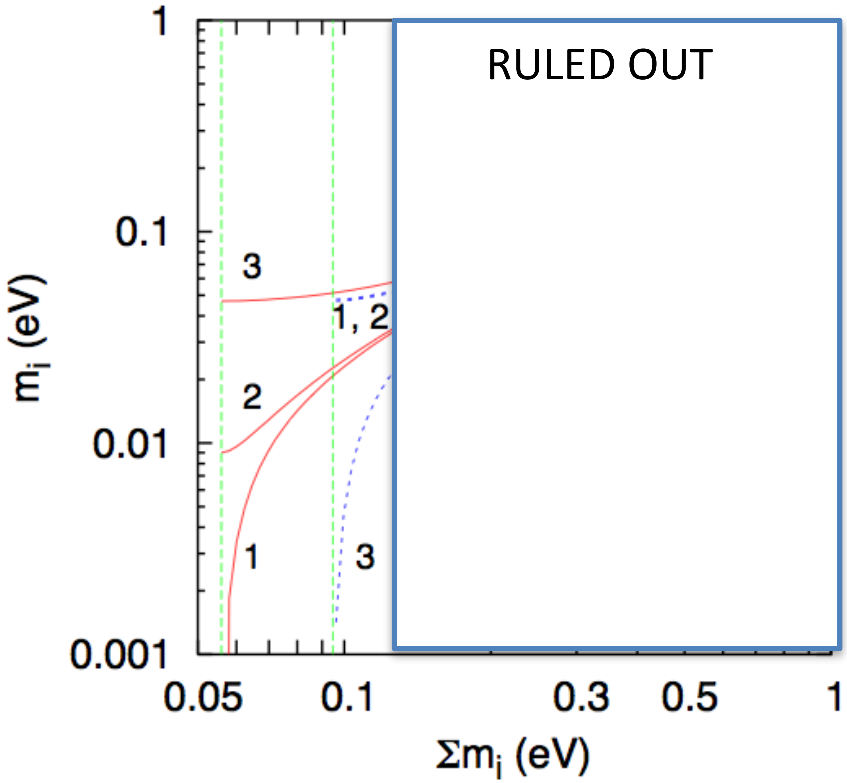
4) Mildly non-linear scales or small scales to be modeled with N-body/hydro or halo models or PT

COSMOLOGICAL NEUTRINOS

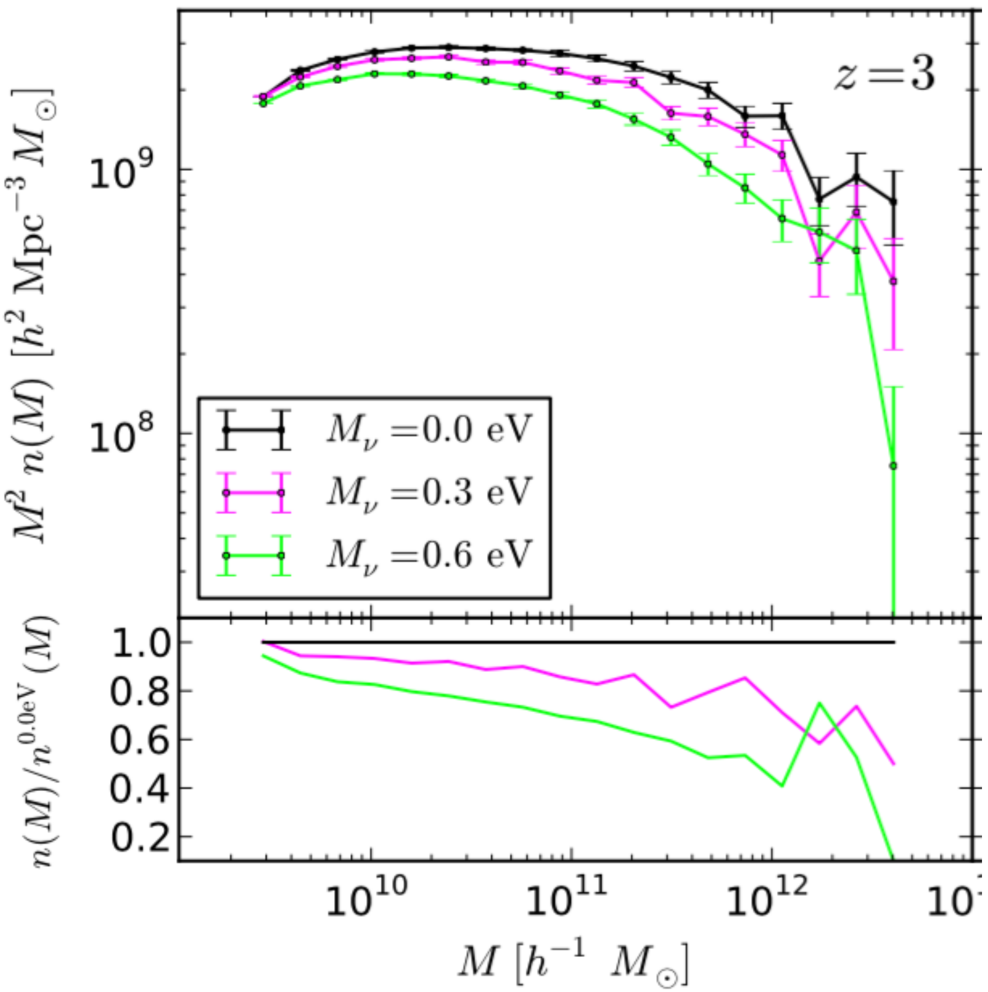
Villaescusa-Navarro, Bull, MV, 2015

COSMOLOGICAL NEUTRINOS: STATUS

- Cosmological neutrino background energy density already detected via Neff (10-17 sigma level)
- Cosmological neutrino free streaming scale much more difficult and not detected yet
- Claims have been made but these appear to reconcile tensions between data sets at the expenses of breaking some internal consistency of the CMB data
- Improvement/progress on the cosmological side has profound implications for particle physics experiments (neutrinoless double beta decay, tritium experiments, etc.)

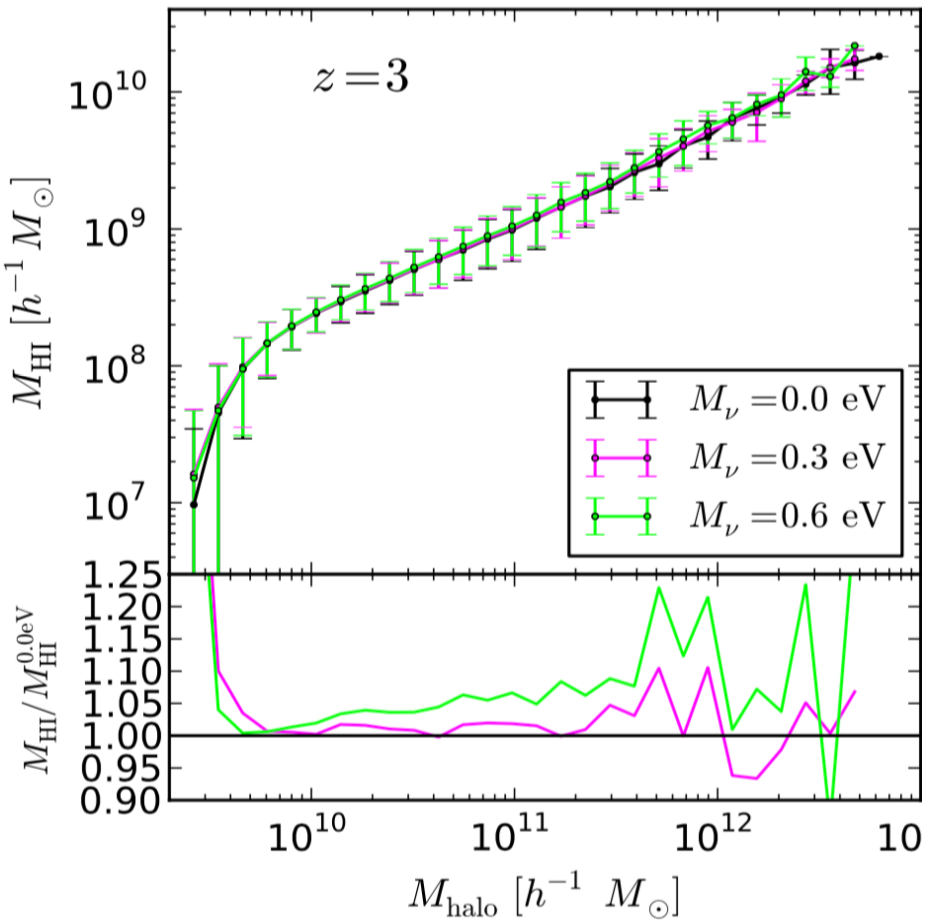


Neutrinos and IM - I: effect on cosmology

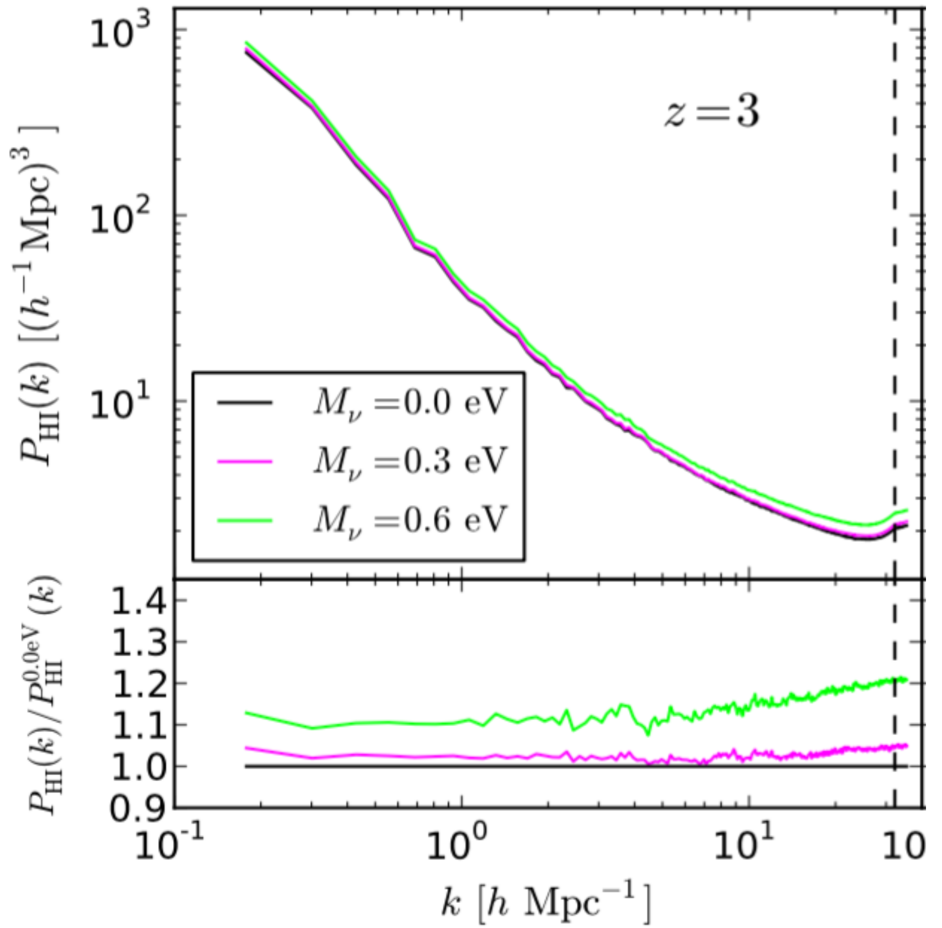


Effect of neutrino free streaming on halo mass function

Neutrinos and IM - II: HI modeling

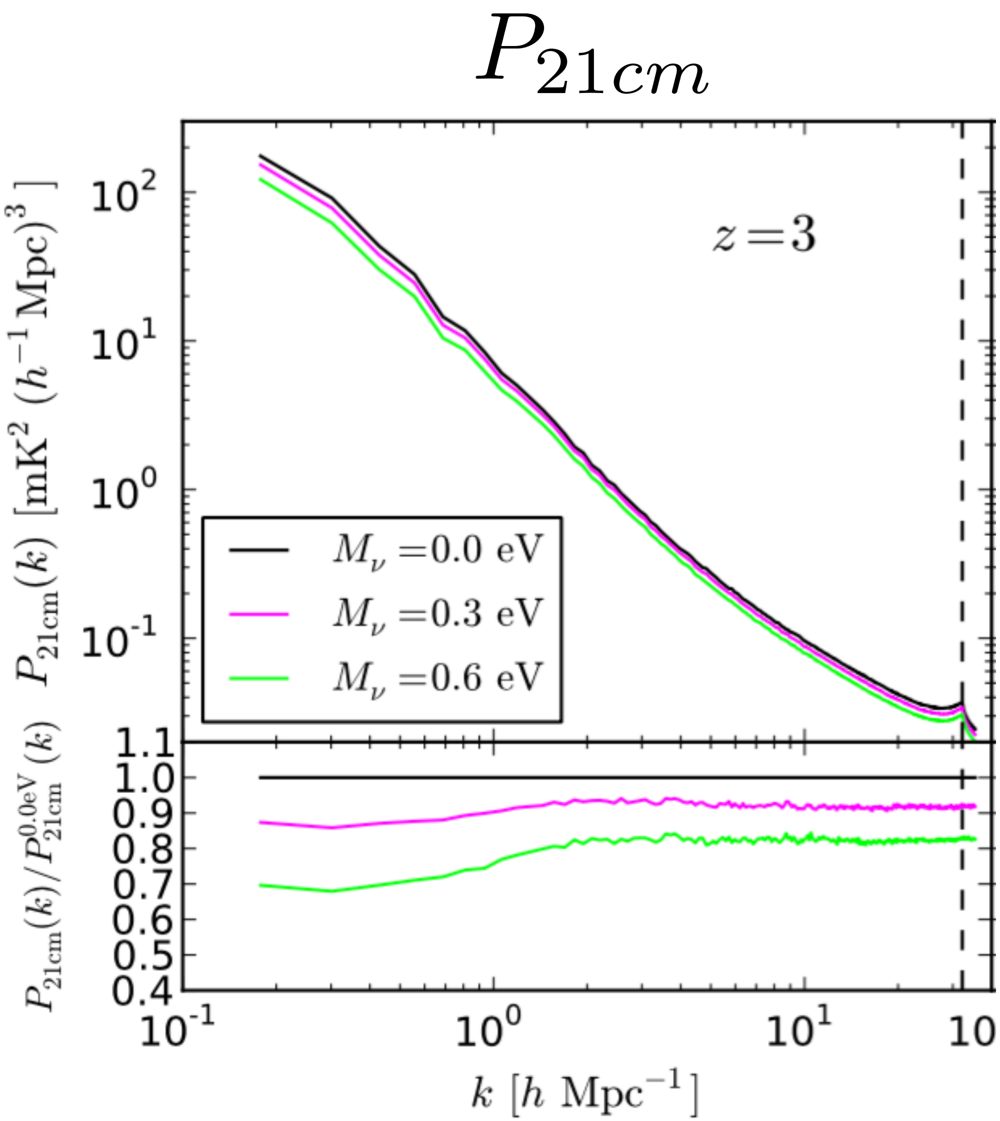


$$M_{HI}(M, z)$$



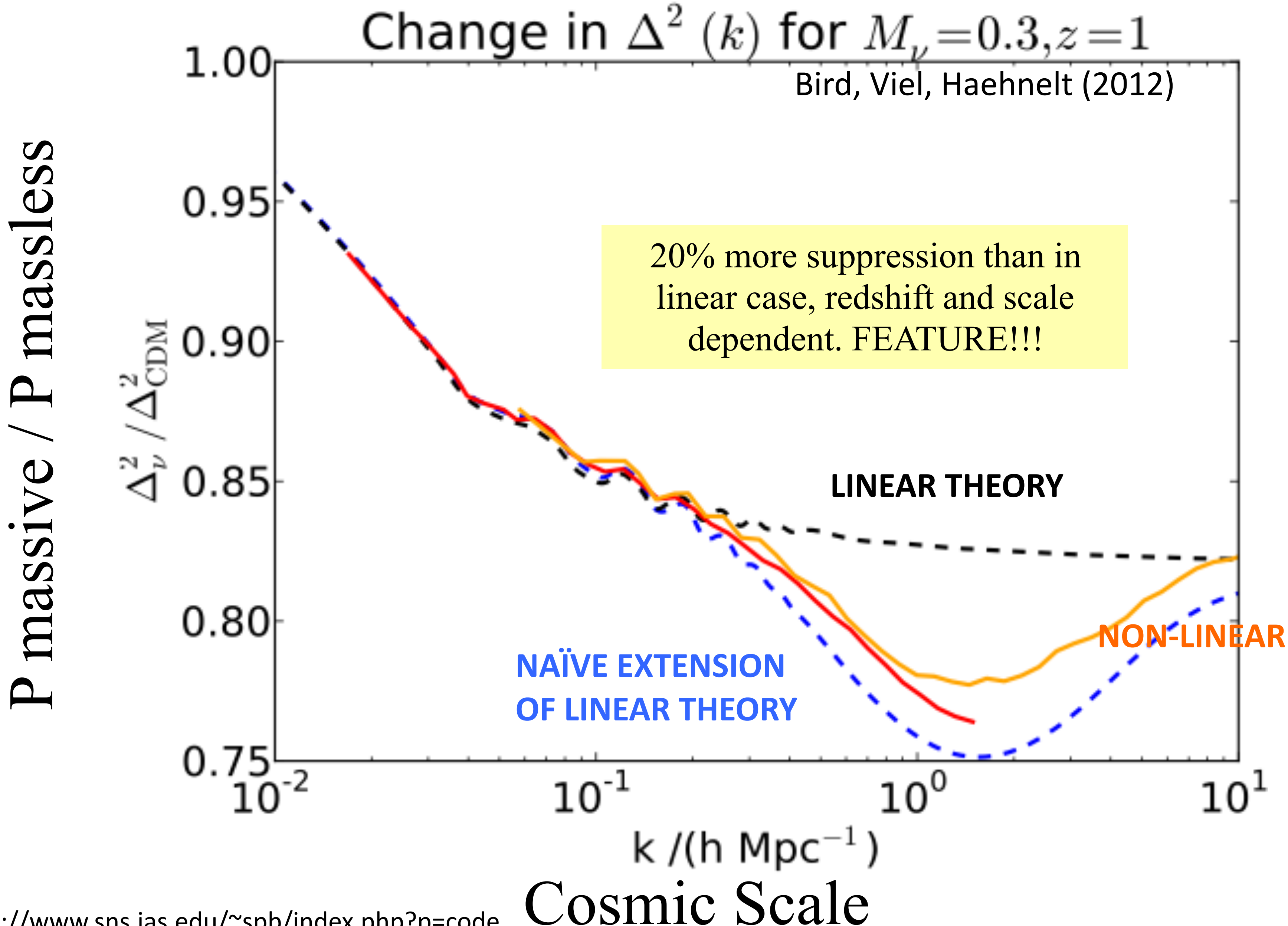
$$P_{HI}$$

Neutrinos and IM - III: 21 cm power spectrum



Effect induced by neutrino free streaming to be compared with…..

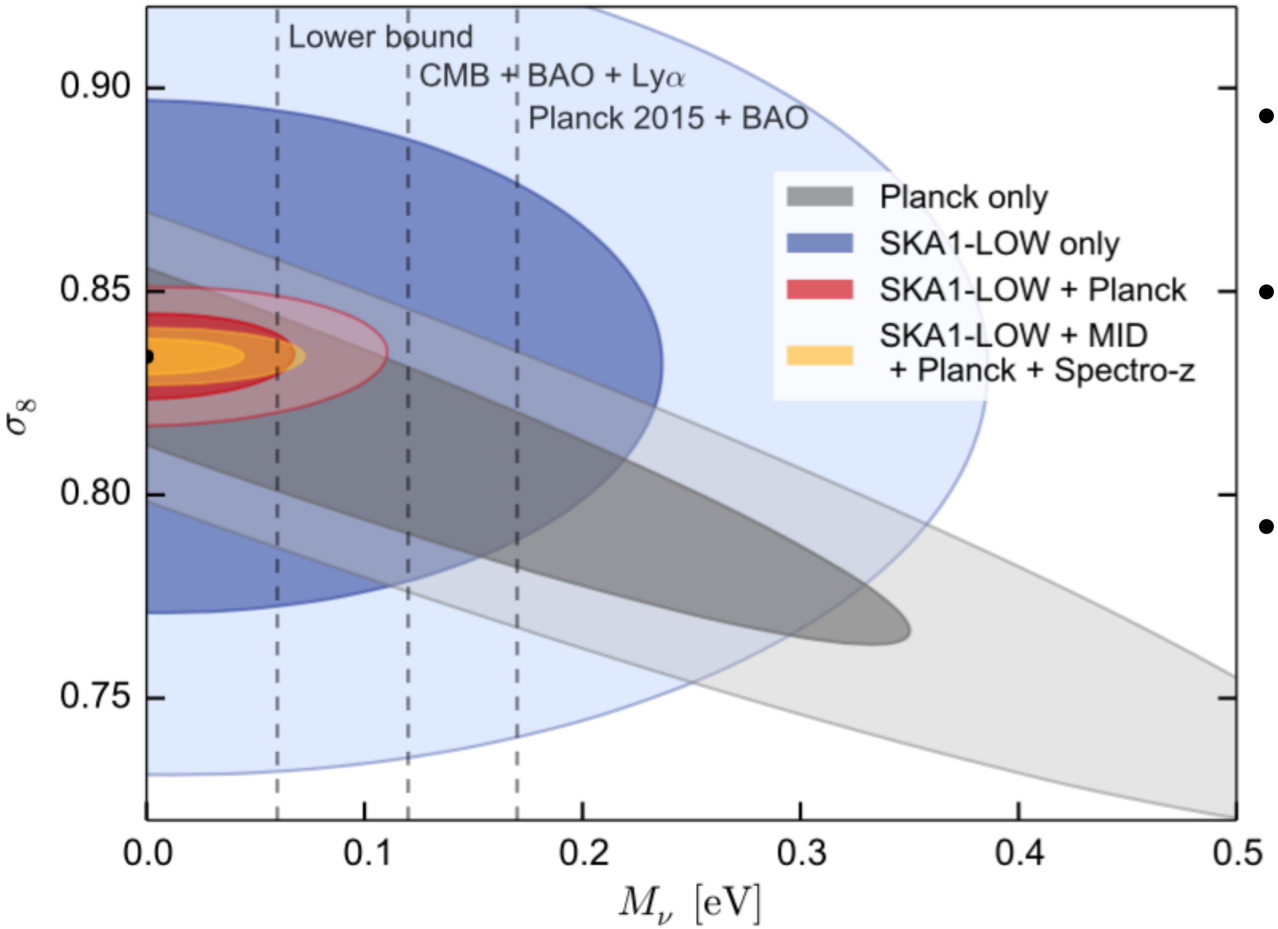
COSMOLOGICAL NEUTRINOS: NON-LINEAR MATTER POWER



http://www.sns.ias.edu/~spb/index.php?p=code

Neutrinos and IM - III

Fisher matrix analysis



- Different degeneracy contours between CMB and IM
- Results do not depend on the IM modeling (4 methods used)
- Wide redshift range (i.e. z=0-4) and spectro-z complementarity quite crucial to get competitive constraints

Neutrinos and IM - IV: constraints

	SKA1-LOW	SKA1-MID
$T_{\rm inst}$ [K]	$40 + 0.1T_{\rm sky}$	28
$N_d \times N_b$	911×3	190×1
$\nu_{\rm min}$ [MHz]	210	375
$\nu_{\rm max}$ [MHz]	375	1420
$A_{\rm eff}(\nu_{\rm crit})$ [m^2]	925	140
$S_{\rm area}$ [deg^2]	20	25,000
$t_{\rm tot}$ [hrs]	10,000	10,000
z bin edges	2.75, 3.25, 3.75, 4.25, 4.75, 5.25, 5.75	0, 0.125, 0.375, 0.625, 0.875, 1.125, 1.375, 1.625, 1.875, 2.2, 2.8

30 meV realistic conservative 1sigma error bar
DESI, Euclid quote errors that are usually around 20 meV

Possibly firm detection of non-zero mass
Hierarchy more difficult

Massive neutrino datasets	$\sigma(M_\nu)$ / eV (95% CL)		
		+ Planck CMB	+ Planck CMB + Spectro-z
Planck M_ν	—	0.461	0.094
SKA1-LOW	0.311	0.208	0.118
SKA1-MID	0.268	0.190	0.104
SKA1-LOW + SKA1-MID	0.183	0.145	0.082
SKA1-LOW + Planck M_ν	—	0.089	0.076
SKA1-MID + Planck M_ν	—	0.071	0.065
SKA1-LOW + SKA1-MID + Planck M_ν	—	0.067	0.058

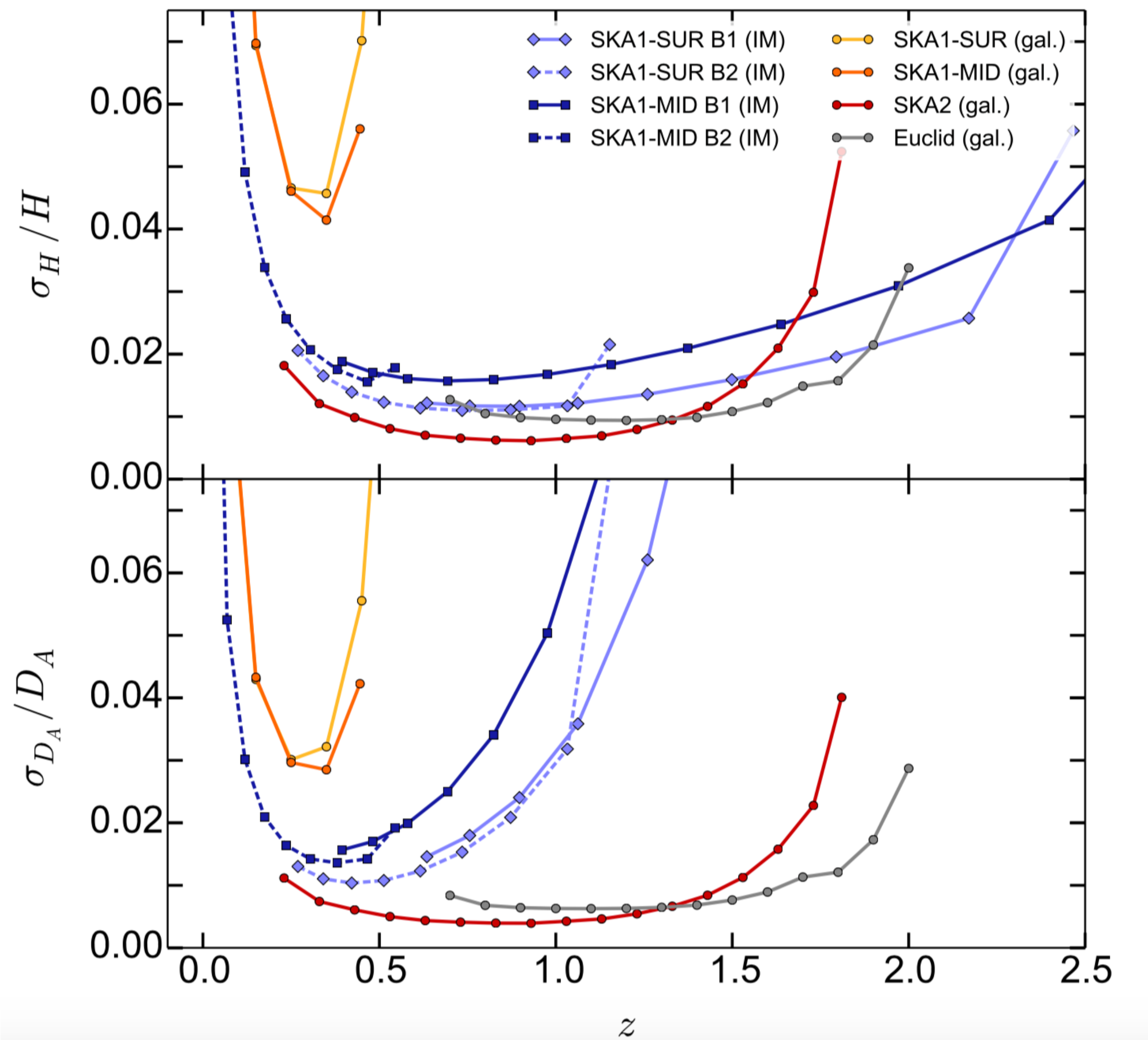
TABLE 5
MARGINAL 2σ (95% CL) CONSTRAINTS ON THE NEUTRINO MASS, FOR VARIOUS COMBINATIONS OF SURVEYS AND PRIOR INFORMATION.

BAOs in IM

Villaescusa-Navarro, Alonso, MV in prep.

BAOs in IM - I

Bull, Camera, Raccanelli+ 2015

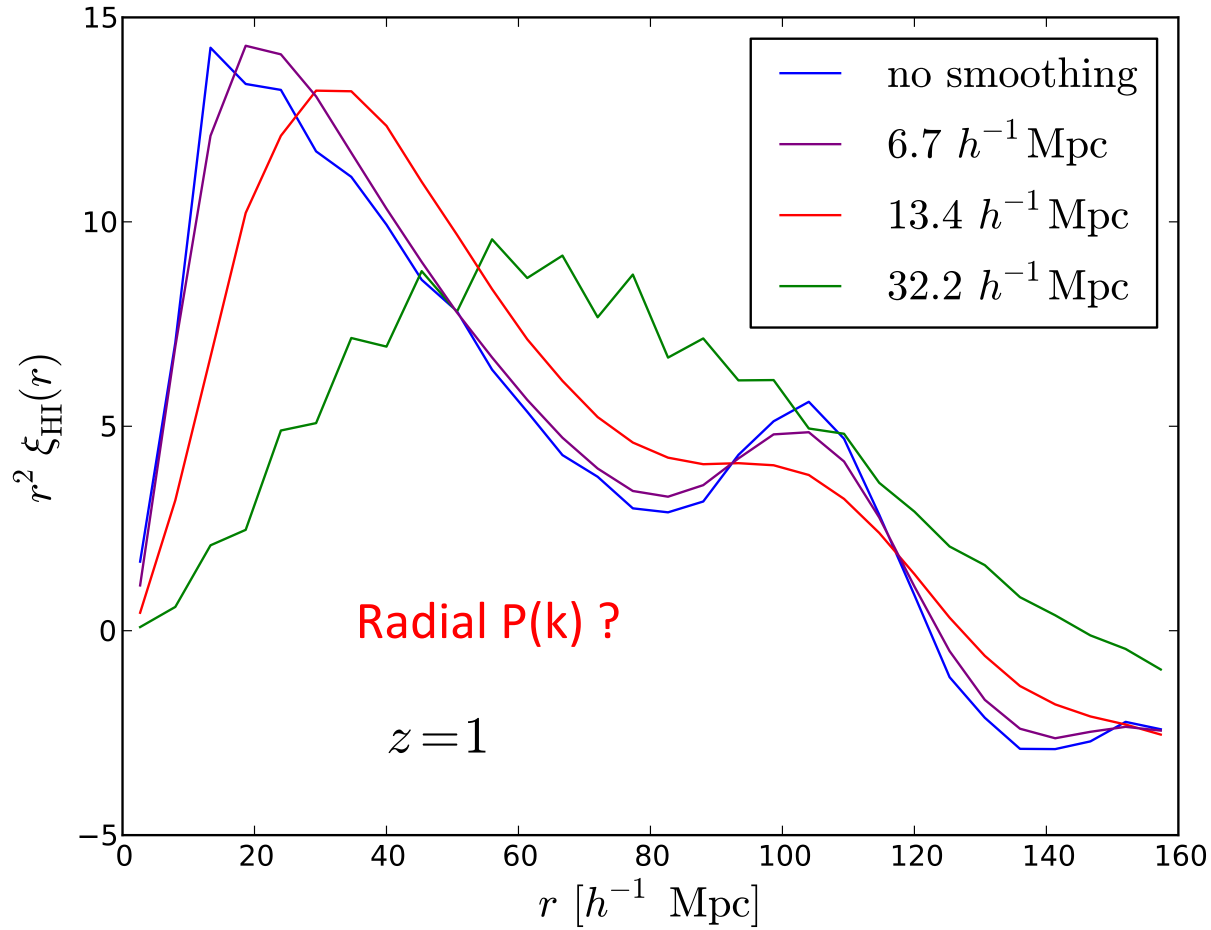


Radial BAO

Transverse BAO

BAOs in IM - II

Angular resolution too poor 1.6 deg



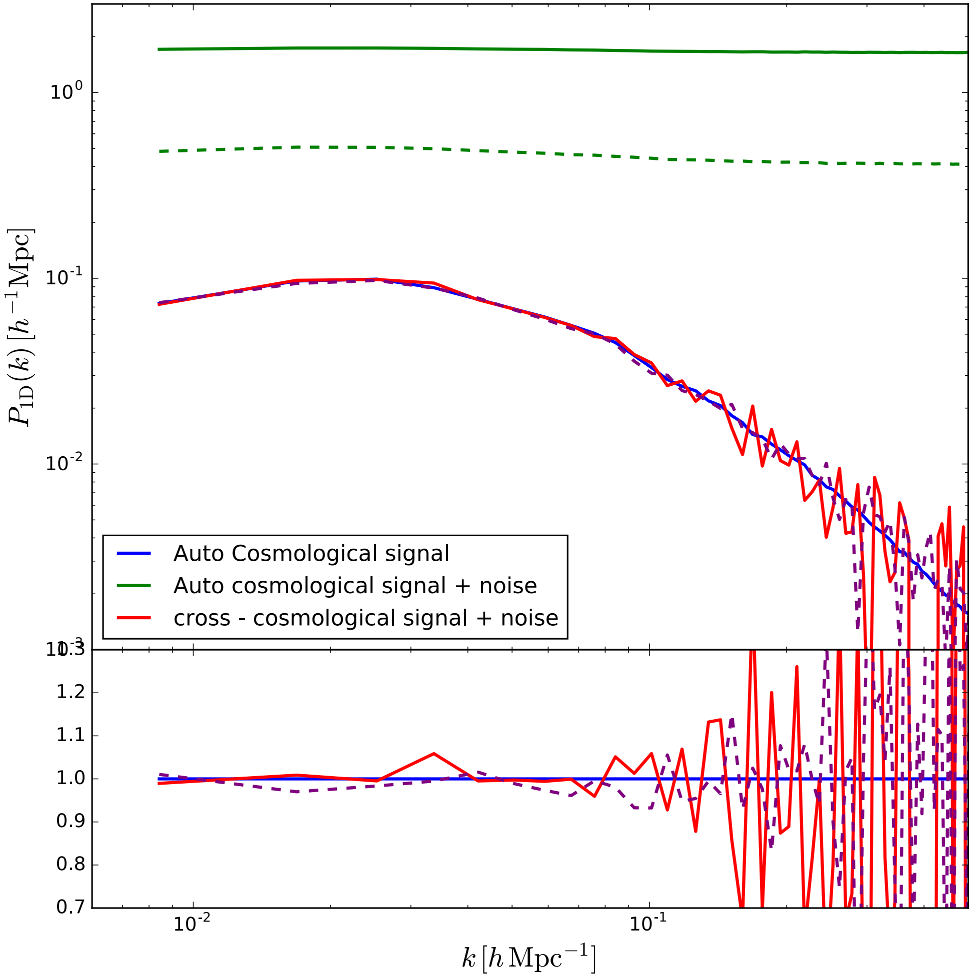
This motivates the use of 1D power only…….

$$P_{\mathrm{i,1D}}(k_\parallel) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2} P_{\mathrm{i,3D}}(k_\parallel, \boldsymbol{k}_\perp)$$

BAOs in IM - III

$$P_{21\mathrm{cm}}(k_\parallel, \boldsymbol{k}_\perp, z) = b^2_{21\mathrm{cm}}(z)\left(1+\beta\mu^2\right)^2 e^{-(k_\perp R)^2} P_\mathrm{m}(k,z)$$

$$P_\mathrm{model}(k_\parallel, z|\boldsymbol{\Theta}) \quad = \quad \left[P_\mathrm{lin,1D}(k_\parallel/\alpha, z) - P_\mathrm{nw,1D}(k_\parallel/\alpha, z)\right] e^{-k_\parallel^2\Sigma^2} + P_\mathrm{nw,1D}(k_\parallel, z) + A(k_\parallel)$$

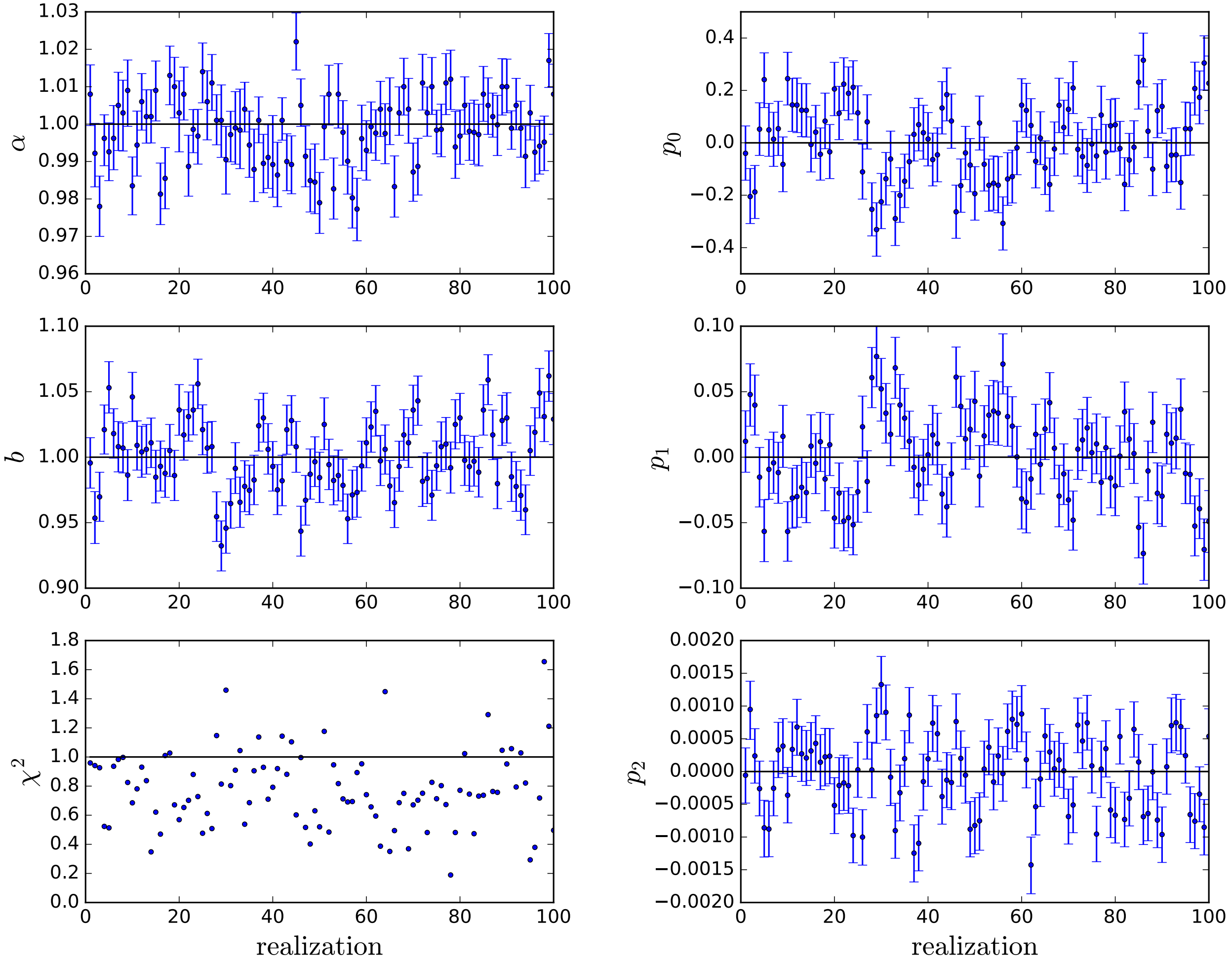


$$\boldsymbol{\Theta} = \{\alpha, b_\mathrm{HI}, R, p_0, p_1, p_2\}$$

$$A(k) = p_0 k + p_1 + p_2/k,$$

BAOs in IM- IV: MCMC fitting

$$\alpha = 0.99853 \pm 0.00928$$

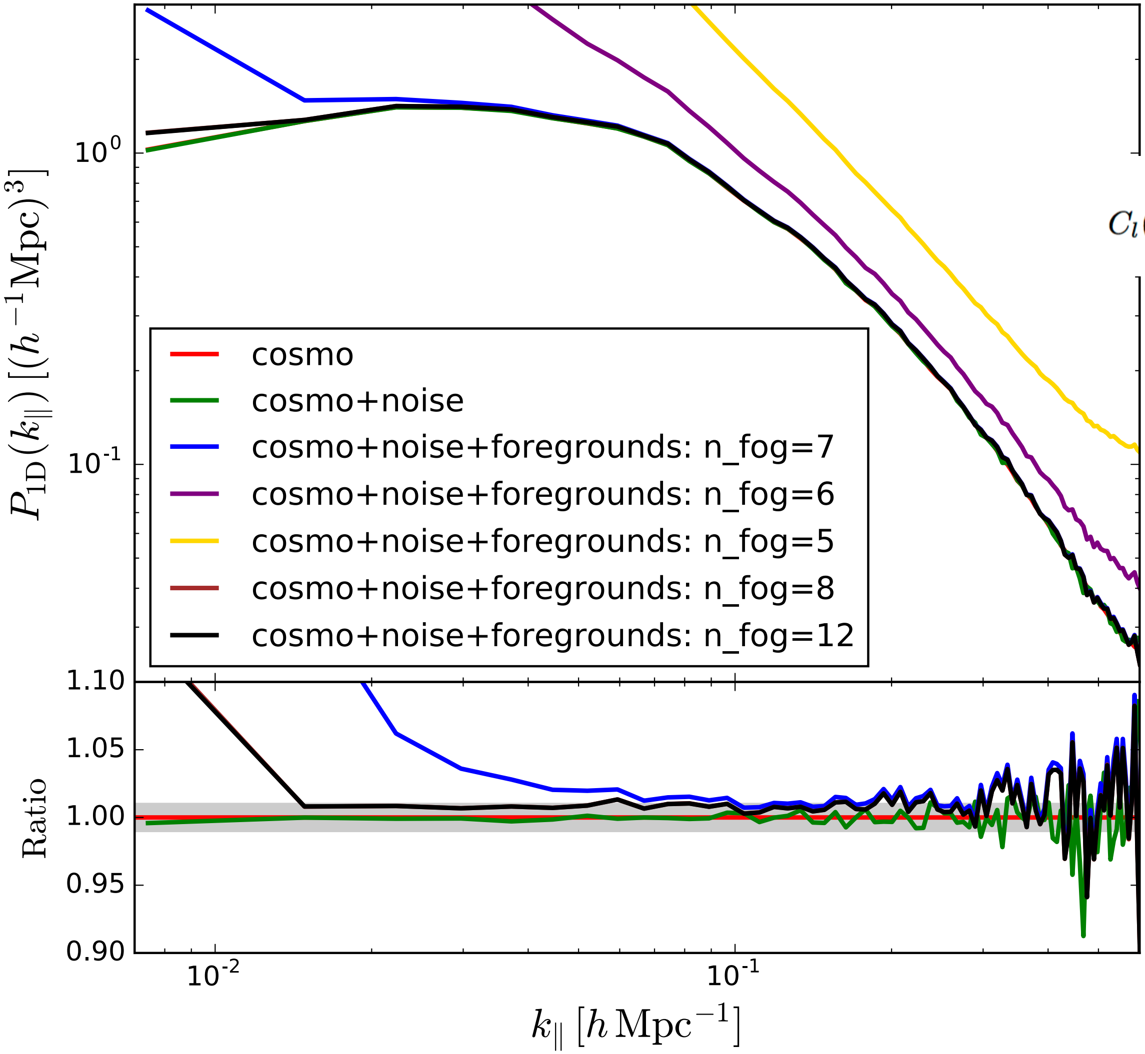


1% accuracy
in alpha determination

This is remarkable

Present constraints
on the radial BAO are
at the level of 3.5% or so

BAOs in IM - V: foregrounds modeling and subtraction



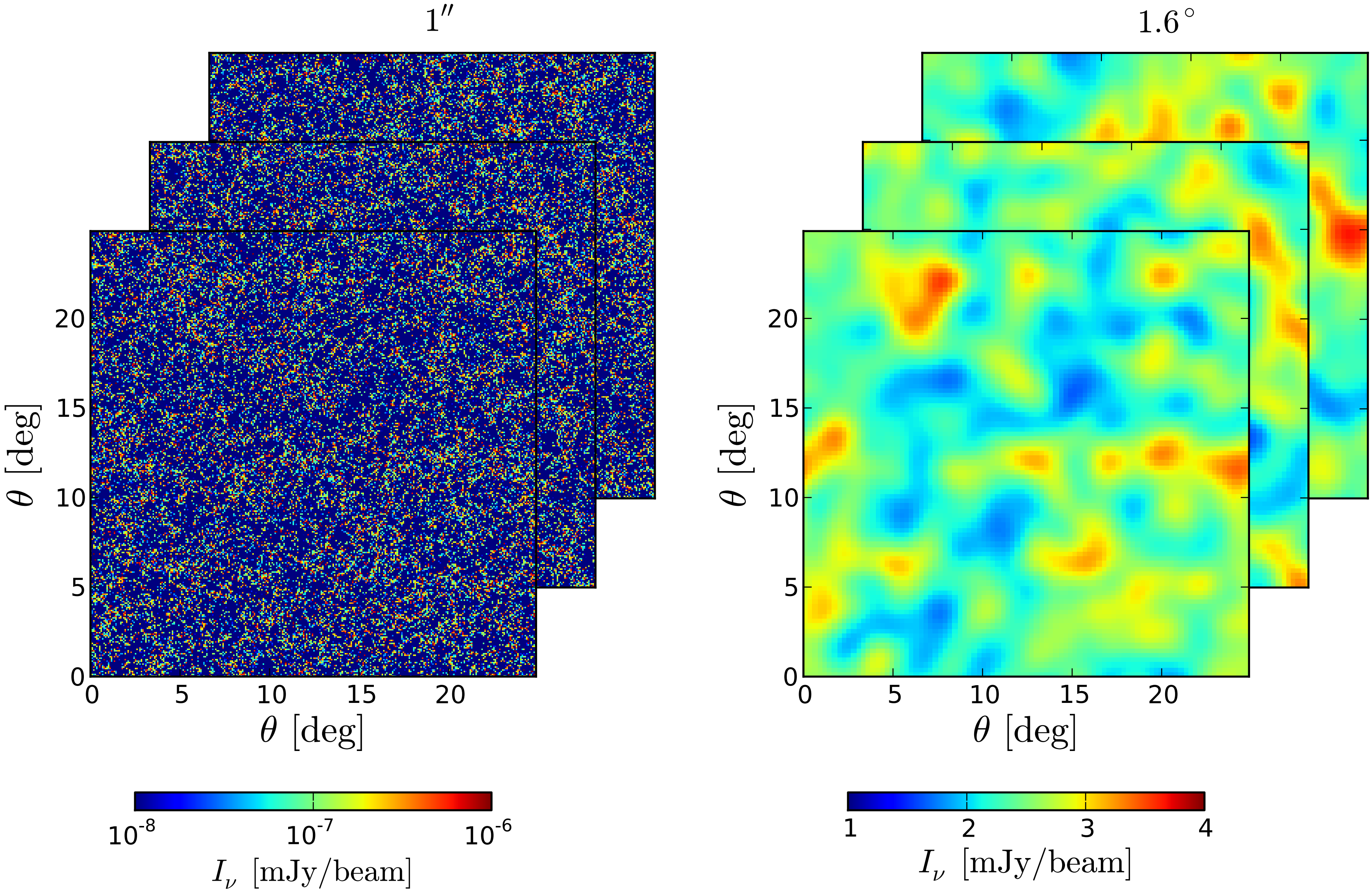
Foreground	A (mK^2)	β	α	ξ
Galactic synchrotron	700	2.4	2.80	4.0
Point sources	57	1.1	2.07	1.0
Galactic free-free	0.088	3.0	2.15	35
Extragalactic free-free	0.014	1.0	2.10	35

$$C_l(\nu_1,\nu_2) = A\left(\frac{l_{\rm ref}}{l}\right)^{\beta}\left(\frac{\nu_{\rm ref}^2}{\nu_1\,\nu_2}\right)^{\alpha}\exp\left(-\frac{\log^2(\nu_1/\nu_2)}{2\,\xi^2}\right)$$

BAOs in IM - VI: reconstruction

- BAO scale is in mildly non-linear regime
- Dominant smoothing from coherent flows, rather than random motions
- Large scale modes, bulk flows, supercluster formation
- Shifts in BAO peak ~ 0.3%
- Reconstruction improves the error on alpha by 50% or so.

BAOs in IM - VI: reconstruction



Standard reconstruction algorithm

- Smooth the density field
$$\delta(\vec{k}) \rightarrow S(\vec{k})\delta(\vec{k})$$
- Compute negative Zel'dovich displacement field on a grid
$$\vec{s}(\vec{k}) \equiv -i\frac{\vec{k}}{k^2}S(\vec{k})\delta(\vec{k})$$
- Displace original particles by s - "displaced"
$$\delta_d(\vec{k}) = \int d^3q e^{-i\vec{k}\cdot\vec{q}}(e^{-i\vec{k}\cdot\left(\vec{\Psi}(\vec{q})+\vec{s}(\vec{q})\right)} - 1)$$
- Shift spatially uniform grid of particles - "shifted"
$$\delta_s(\vec{k}) = \int d^3q e^{-i\vec{k}\cdot\vec{q}}(e^{-i\vec{k}\cdot\vec{s}(\vec{q})} - 1)$$
- Reconstructed density field
$$\delta_{recon} \equiv \delta_d - \delta_s$$

Padmanabhan et al, 2009.

Reconstruction algorithm

- Smooth the density field

$$\delta(\vec{k}) \to S(\vec{k})\delta(\vec{k})$$

- Compute negative Zel'dovich displacement field on a grid

$$\vec{s}(\vec{k}) \equiv -i\frac{\vec{k}}{k^2}S(\vec{k})\delta(\vec{k})$$

- Displace ~~original particles~~ grid cells by s - "displaced"

$$\delta_d(\vec{k}) = \int d^3q e^{-i\vec{k}\cdot\vec{q}}\left(e^{-i\vec{k}\cdot\left(\vec{\Psi}(\vec{q})+\vec{s}(\vec{q})\right)} - 1\right)$$

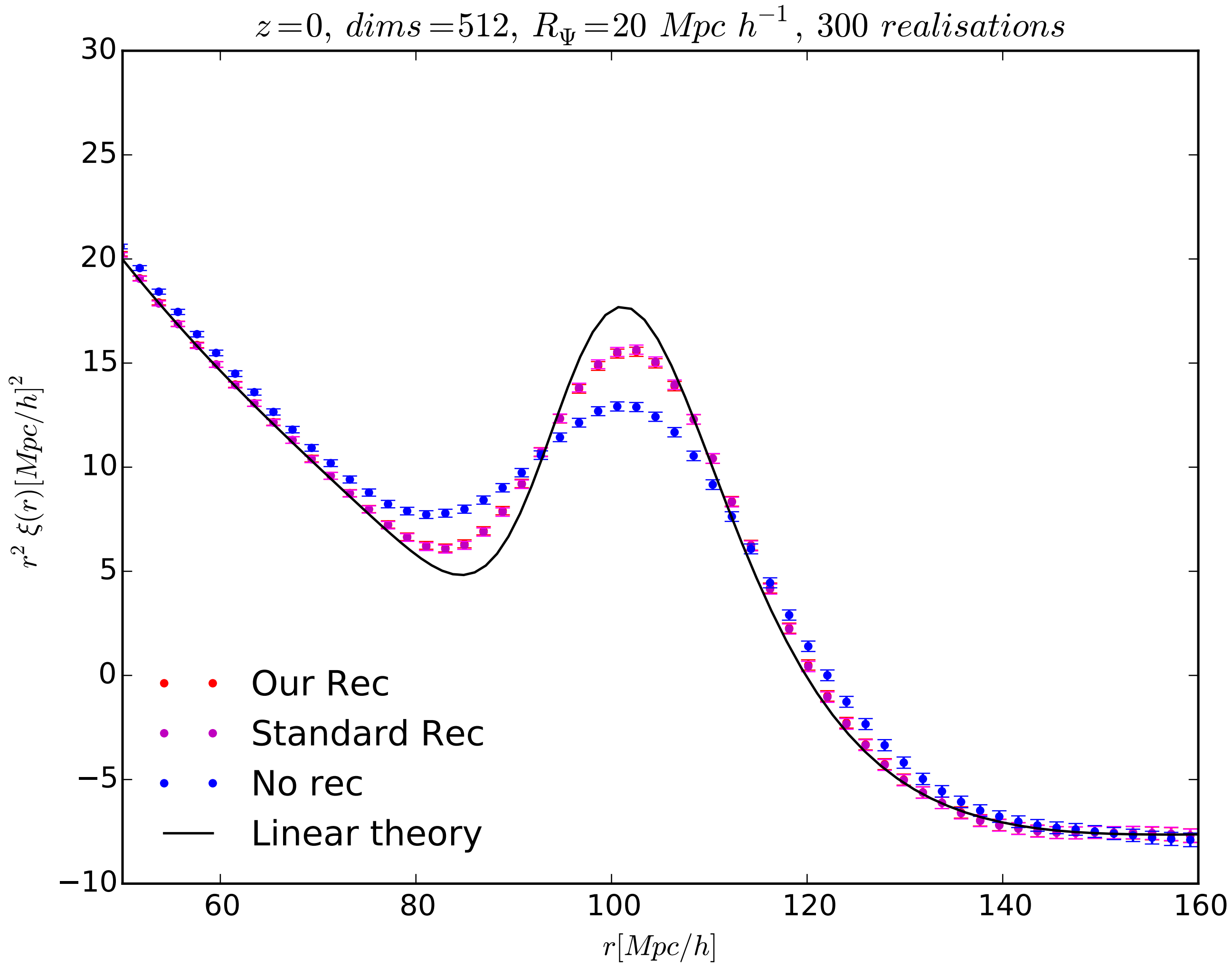
- ~~Shift spatially uniform grid of particles - "shifted"~~ apply uniform weights to displaced grid positions

$$\delta_s(\vec{k}) = \int d^3q e^{-i\vec{k}\cdot\vec{q}}\left(e^{-i\vec{k}\cdot\vec{s}(\vec{q})} - 1\right)$$

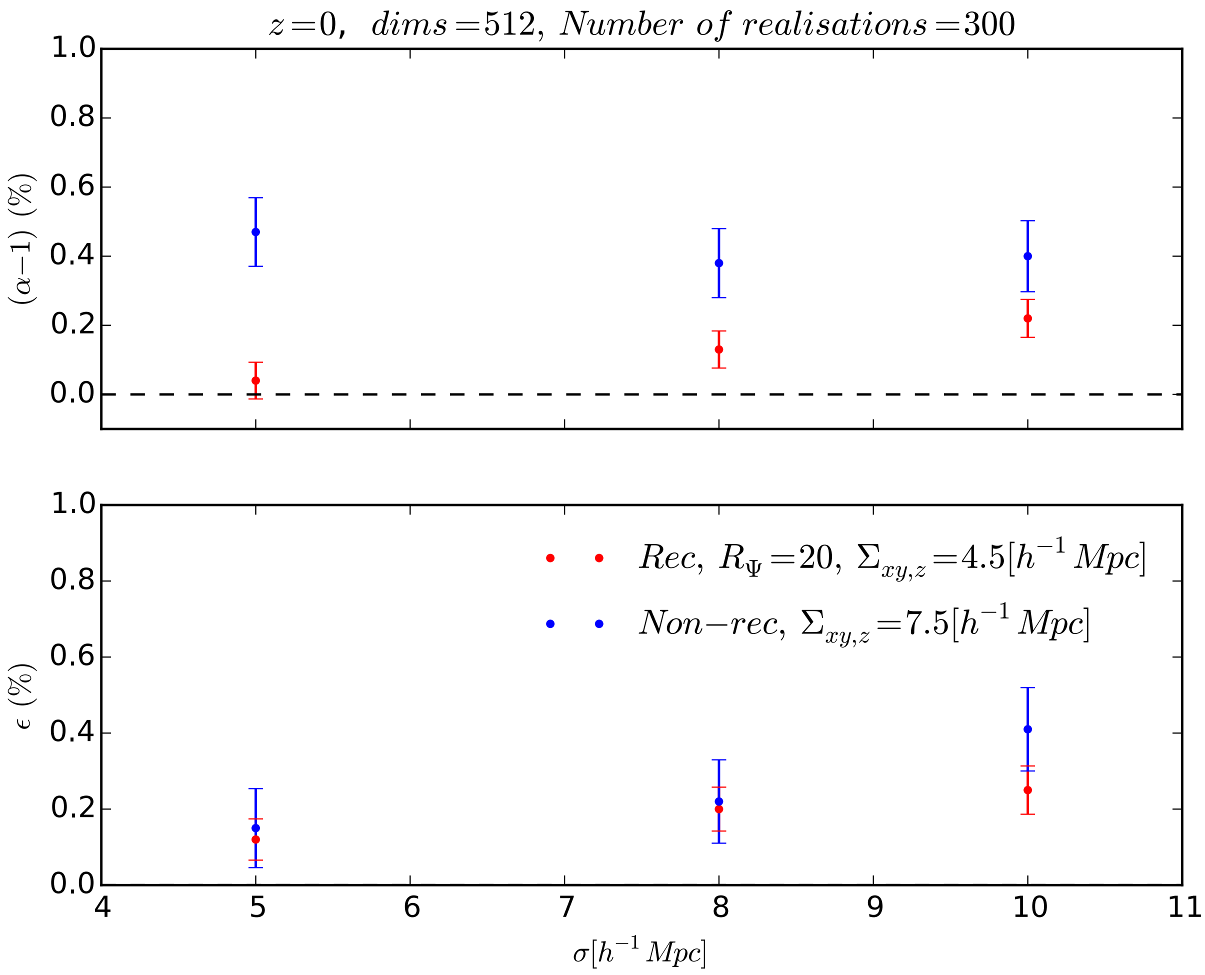
- Reconstructed density field

$$\delta_{recon} \equiv \delta_d - \delta_s$$

BAOs in IM: reconstructed BAO peak in 2+1 dimensions



BAOs in IM: reconstructed BAO peak in 2+1 dimensions



Conclusions

-> Exciting new era for cosmology at high redshift with IM has already started

-> Post reionization Universe is promising: DE evolution, modified gravity?

-> HI modeling inside galaxies is crucial: more physical models and observations will of course improve the knowledge of how HI is distributed within haloes and cosmological constraints could become tighter

-> Neutrino honest bound around 30 meV (present constraints < 0.14 eV at 2sigma)

-> IM BAOs (a new observable) could allow to recover D_H and D_A in the range 0<z<3