

## 21-cm Cosmology from the Largest to the Smallest Scales

Yidong Xu/徐怡冬

National Astronomical Observatory of China (NAOC)

• The Tianlai collaboration **The SKA collaboration** 

The DSL collaboration

**2024.7.22 21 cm Cosmology Workshop @ Hangzhou**

### Dark Matter The history of structure formation

Dark Energy

Primordial non-Gaussianity

First Stars & Galaxies

Formation of SMBHs

Cosmic Reionization

Heating History<sup>(1)</sup>

Dark Ages Cosmic Dawn H Reionization

Credit: CfA/M. Weiss

## The 21cm line of HI: Exploring the last desert in the observational universe



 $F=1$ 

 $F=0$ 



#### 21cm from post-EoR  $\rightarrow$  HI in halos  $\rightarrow$  Large-scale structure in 3D

Image Credit: NASA-GSFC LAMBDA



21cm from Dark Ages, Cosmic Dawn, & EoR  $\rightarrow$  HI in the IGM  $\rightarrow$  Reionization & first galxies





#### Measuring the large-scale structure with 21cm IM deviation of 0.15). The diagonal elements within this covariance matrix  $\blacksquare$  .  $\blacksquare$  reflecting the smaller variance varian

- ▶ Baryon Acoustic Oscillations the cosmological standard ruler
- $\blacktriangleright$  The standard ruler of the sound horizon at the last scattering surface Extracting the BAO scale from the matter power spectrum remains a thriving area
	- **•**  $r_s(z_d) = 153.3 \pm 2.0$  Mpc (Komatsu et al. 2009)



(E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian.)





matrix is 0.28 (with a standard deviation of 0.06). When the *P*(*k*) measurements are divided by the best-fitting smooth model, *P*sm(*k*), they are, generally, even less correlated. We determine *P*(*k*)*/P*sm(*k*) for each mock sample and construct a revised 'BAO' covariance matrix from this. We do not use this covariance matrix to perform any fits – our fits are to the full *P*(*k*) and use the original covariance matrix. For the revised covariance matrix, the mean first off-diagonal

BAO; the data when presented as *P*(*k*)*/P*sm(*k*) are more independent and provide a more accurate visualization of the measurements. Fig. 16 displays the measured post-reconstruction values of *P*(*k*)*/P*sm(*k*), for the BOSS CMASS sample in DR9, DR10, and

**Figure 17.** The BAO feature in the measured power spectrum of the DR11

#### Constraining the Dark Energy EoS with 21cm BAO measurements !HI assuming the SKA1-MID *Wide Band 1 Survey* and following  $\mathbf{M} \cap \mathbf{M}$  in  $\mathbf{M} \cap \mathbf{M}$  in  $\mathbf{M}$  in straints, we utilise the full HI power spectrum with RSDs. Note that the assumed redshift bin width is "*z* = 0.1, but we show the results for half of the bins for brevity. The cosmological constraints are reported in Figures 11 and 12. *z* σ(!HI*b*HI)*/*(!HI*b*HI) σ(!HI)*/*!HI



**Figure 3.** Measurement errors on the angular diameter distance *D*<sup>A</sup> (left panel), the Hubble expansion rate *H* (central panel), and the growth rate *f* (*z*) = *d* ln *G/d* ln *a* (right panel). The integration time is assumed to be one year. Note here that the number of redshift bins is larger than the one we used for forecasting the constraint on

**Table 10.** Forecasted fractional uncertainties on !HI*b*HI, and

20 David J. Bacon *et al.*

### **21 cm Cosmology – to avoid/distinguish from astrophysical uncertainties!**

**Strategy 1** -- Looking for features not/less affected by later baryonic physics

- $\checkmark$  The cosmological standard ruler 21 cm BAO  $\rightarrow$  Dark Energy
- $\checkmark$  Go to ultra-large scales  $\Rightarrow$  primordial non-Gaussianity (PNG) & Inflation physics

### 21 cm cosmology – the Primordial Non-Gaussianity



 $\blacktriangleright$  Inflation  $\rightarrow$  Initial density perturbations  $\rightarrow$  Structure Formation  $\rightarrow$  LSS today



- **FIGURE 1. PNG imprint on the CMB:** several density contours [132].
	- Angular bispectrum measurement

$$
\begin{pmatrix}\nf_{\text{NL}}^{\text{loc}} = 2.5 \pm 5.7 \\
f_{\text{NL}}^{\text{eq}} = -16 \pm 70 \\
f_{\text{NL}}^{\text{orth}} = -34 \pm 33\n\end{pmatrix}\n\begin{pmatrix}\n68\% \text{CL}, T\n\end{pmatrix}\n\qquad\n\begin{pmatrix}\nf_{\text{NL}}^{\text{loc}} = 0.8 \pm 5.0 \\
f_{\text{NL}}^{\text{eq}} = -4 \pm 43 \\
f_{\text{NL}}^{\text{orth}} = -26 \pm 21\n\end{pmatrix}\n\begin{pmatrix}\n68\% \text{CL}, T + E\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\nf_{\text{NL}} = +5000 \\
f_{\text{NL}}^{\text{orth}} = -34 \pm 33\n\end{pmatrix}
$$



- ▶ PNG effects on LSS: *f*eq  $\overline{\mathcal{C}}$ systematics and the (*T* + *E*) constraints should hence be considered as *preliminary*.
	- High-order correlations of galaxy distribution bispectrum, trispectrum (e.g. Sefusatti & Komatsu 2007) of the original the ones mentioned in the ones mentioned in the original term that  $\mu$
- Abundance of rare objects cluster number density (e.g. Afshordi & Tolley 2008; Dalal *et al.* 2008) - Abundance of rare objects - cluster number density no evidence for primordial non-Gaussianities, the 'hints' of NG reported in the *Planck* 2013 rare objects - cluster number aerisity (e.g. Arshorar a rolley zood,
	- The large-scale clustering of halos scale-dependent bias (e.g. Dalal et al. 2008; Desjacques et al. 2011) and be precise, there appears to be no evidence for a positive for any individual feature or resonance for  $r$  $e$  clustering or halos - scale-dependent bias (e.g. balat et al. 2006,  $\,$

#### Constraints on  $f_{NL}$  from the HI Power Spectrum *4.1. Constraints on fNL from the H* <sup>i</sup> *Power Spectrum*  $\frac{1}{2}$   $\bm{m}$  the HI Power Spectrum  $M_{\rm eff}$  ,  $M_{\rm eff}$

2008; Matarrese & Verde 2008). For the standard local type primordial non-Gaussianity, the

ι είναι το linear halo bias for the Gaussian density field, δc = 1.686 is the critical over density field, δc =

u The HI bias factors: by the neutral hydrogen mass hosted by these halos (Gong et al. 2011): <sup>1</sup> (*M,z*) + ∆*b<sup>d</sup>* (*k,M, z*). δk(z) = M(k; z)Φk, (35) \* For the standard local type PNG, the scale-dependent non-Gaussian correction to the linear halo bias: For the standard local type PivG, the scale-dependent  $A_{\rm eff}$  the completion of cosmic reionization, the HI gas in the Universe is mostly distributed in the Universe is most redshift, and *G*(*z*) is the linear growth factor normalized to unity at  $\frac{1}{2}$   $\frac$ for spherical collapse, and M(k, z) relates the density fluctuations in Fourier space,  $\delta$  to the density fluctuations in  $\delta$ ndard local type PNG, the scale-dependent

Gaussianity with *fNL − 1. Here, with a fNL − 1. Here, with a fNL* in bispectrum, with a fNL in bispectrum on the H after reionization and assess the constraint power of the constraint power of the constraint power of the 21 c<br>The 21 cm of the 21

can result in a scale-dependence in the halo bias, which originates from coupling between large- and small-scale modes (Dalal et al. 2008; Matarrese & Verde 2008; Matarrese & Verde 2008; Matarrese & Verde 2008; Matarrese & Verde<br>1980; Matarrese & Verde 2008; Matarrese & Verde 2008; Matarrese & Verde 2008; Matarrese & Verde 2008; Matarre<br>19 dard local-type primordial non-Gaussianity, the scale-dependent

bispectrum measured by the Tianlai experiment.

where begins

$$
\Delta b^{d}(k, z) = \frac{2 f_{NL} (b_1^{G} - 1) \delta_c}{\mathcal{M}(k, z)}
$$
\nholo bias

\nholo bias

\nHolois

\

in which *g*(0) = (1 + *z*i)

As for the relation between the HI gas mass MHI and the host halo mass M, we use the could possibly achieve  $\sigma_{fNL} \sim 1$ . <u>When are the available spectrum in redshift space</u> wavenum- $\frac{1}{\sqrt{N}}$  are not be  $\frac{1}{\sqrt{N}}$  ...

on large scales, *<sup>c</sup>* is the speed of light, and *<sup>G</sup>*+(*z*) <sup>=</sup> *<sup>g</sup>*(0)*G*(*z*) is the growth factor of the growing mode of density perturbations,

1504 161 14.1

<sup>−</sup><sup>1</sup>*G*−1(*z*i) with *z*<sup>i</sup> being the initial

*.* (36)

Since we are interested in predicting the constraining power of

 $H = \frac{1}{2}$ i.e., the parameter *f*NL, in the following, we will focus on the reduced H i bispectrum, *Q*<sup>H</sup> <sup>i</sup>, which is much less sensitive to other cosmological parameters (Sefusatti & Komatsu 2007). In the real experiments, we always  $\mathcal{L}$ temperature in redshift space. Similar to the tree-level expresion

#### Constraints on  $f_{NL}$  from the HI Power Spectrum  $s_{\text{static}}$   $\sim$   $\epsilon$  from the ULD can free thurs  $\frac{1}{2}$ but annual on  $\frac{1}{2}$  nonnence in rower opeen annual  $\zeta$  can experiment can  $f$  from the  $\frac{1}{2}$  but survey survey survey speed ( $\frac{1}{2}$ ). Such also experience

the constraints on the power spectrum on ultra-large scales

\* Tianlai cylinder array (Xu et al. 2015):  $\text{\textdegree}$  Tianlai cylinder array (Xu et al. 2015): The Predicted I $\sigma$  Errors of  $f_{\rm NL}$  U<br>Spectrum Measured b

the constraints on the power spectrum on  $\mathcal{C}$  ,  $\mathcal$ 

 $\mathcal{L}(\mathcal{D})$  the equality peak). This is an area where a single dished d

ments can provide him to can provide him to can provide him to can provide the can provide that only material

take into account the telescope beams and marginalise beams and marginalise beams and marginalise beams and ma

One example of such an effect is Primordial non-

alise on this ultra-large scales.

**Table 2** The Predicted  $1\sigma$  Errors of  $f_{NL}$  Using the H<sub>I</sub> Ppower Spectrum Measured by Tianlai  $\Box$  Table 2

The Astrophysical Journal, 798:40 (10pp), 2015 January 1 Xu, Wang, & Cheng, & Cheng, & Cheng, & Cheng, & Cheng,



survey area = 10000 deg<sup>2</sup>, integration time = 1 year.

\* SKA1-MID: cast *æ*(*f*NL) *=* 2.8, assuming Band 1 for SKA dishes and UHF  $\Omega$ 

alise on this ultra-large scales. The control of t<br>Alise on the control of the control

*z æ*(≠HI*b*HI)/(≠HI*b*HI) *æ*(≠HI)/≠HI

*M*(*k*; *z*) =  $\sigma(f_{\rm NL}) = 2.8$  (SKA1 Cosmology Red Book 2018)

band for the MeerKaT dishes. Note that our calculations were calculated by the MeerKaT dishes. Note that our c<br>The MeerKaT dishes that our calculations were calculated by the MeerKaT dishest of the MeerKaT dishes that our

<del>d</del><br>2  $L$ ,  $\sim$  1 min mo moin nocen foot ingeb footgak, 2007,  $\overline{\phantom{a}}$ strain dark energy models and the curvature of the Universe Could potentially achieve  $\sigma(f_{\rm NL})$  < 1 with the multi-tracer technique (Seljak, 2009)

#### the reduced HI bispectrum, QHI, which is much less sensitive to other cosmological parameters **Example 1.1 Constraints on**  $f_{NL}$  **from the HI Bispectrum** on the primordial non-Gaussianity, i.e. the parameter function  $\mathcal{N}_{\text{max}}$  is the following, we shall focus on  $\mathcal{N}_{\text{max}}$  $\frac{1}{\sqrt{N}}$ where we have introduced the notation kine is the Dirac delta function  $\mathbb{R}$ To gether with the assumption of statistical homogeneity and isotropy for the primordial perturbations, this implies that  $\alpha$

As we are interested in forecasting the constraining power of HI bispectrum observations

 $\frac{1}{2}$ 

 $\frac{1}{2}$ n for the red  $\mathbf{C} = \mathbf{C} \cdot \mathbf{R}$ rum: , (38)  $\overline{38}$   $\blacktriangleright$  The tree-level expression for the reduced HI bispectrum: trum (Sefusatti & Komatsu 2007), the reduced HI bispectrum in redshift space after a veraging overaging overagi  $\blacktriangleright$  in the lite of the space is ! aP <sup>0</sup> (β) "2 1 <sup>1</sup> )<sup>2</sup> ced HI bispectrum: 3 - non-linear bias

 $\mathcal{L}$ 

 $\mathcal{S}(\mathcal{S})$  . In the real experiments, we always measure the  $21$  cm brightness measure the  $21$ temperature in redshift space. Similar to the tree-level expression for the observed galaxy bispec-level  $\alpha$ 

# 1

 $\mathcal{L}(\mathcal{L})$ 

<sup>0</sup> (β)

As we are interested in forecasting the constraining power of HI bispectrum observations

on the primordial non-Gaussianity, i.e. the parameter f $\mathcal{N}_{\text{L}}$  is the following, we shall focus on  $\mathcal{N}_{\text{L}}$ the reduced HI bispectrum,  $\mu$  bispectrum,  $\mu$  and  $\mu$  is much less sensitive to other cosmological parameters sensitive to other cosmological parameters  $\mu$ 

trum (Sefusatti & Komatsu 2007), the reduced HI bispectrum in redshift space after averaging over

# 1

<sup>0</sup> (β)

angles in k space is not be a space is a spa<br>Angles is a space is a

 $\mathcal{L}(\mathcal{L})$  , abbreved in the absolution of  $\mathcal{L}(\mathcal{L})$ 

angles in k space is

$$
Q_s(k_1, k_2, k_3) = \frac{a_0^{\rm B}(\beta)}{\left[a_0^{\rm P}(\beta)\right]^2} \left[\frac{1}{b_1^{\rm HI}} Q^{\rm tree}(k_1, k_2, k_3) + \frac{b_2^{\rm HI}}{(b_1^{\rm HI})^2}\right]
$$

\* The reduced matter bispectrum evolution  $Q^{\text{tree}}(k_1, k_2, k_3) = Q_1(k_1, k_2, k_3) + Q_G(k_1, k_2, k_3)$  $=\frac{B_{\rm I}(k_1,k_2,k_3)}{B_{\rm I}(l_1,k_2,k_3)}$  $\frac{P_1(k_1), k_2, k_3}{P_L(k_1)/P_L(k_2) + (2 \text{ perm.})}$  +  $B_{\rm G} (k_1, k_2, k_3)$  $= \frac{1}{P_L(k_1)P_L(k_2) + (2 \text{ perm.})} + \frac{1}{P_L(k_1)P_L(k_2) + (2 \text{ perm.})}$ where  $\mu$  is the sum of n additional terms permuting known permuting k1, and k3. The matrix  $\mu$ 1 - primordial non-Gaussianity | Local model 1984; Bernardeau et al. 2002), and the the matter bispectrum contributed from primordial non- $B_1(k_1,k_2,k_3) = \mathcal{M}(k_1;z) \mathcal{M}(k_2;z) \mathcal{M}(k_3;z) B_{\Phi}(k_1,k_2,k_3)$   $\longrightarrow$  Equilateral model  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  $\begin{array}{|l|} \hline \end{array}$  2 - non-linear gravitational evolution ……  $\sigma^*$  the reduced matter bispectrum and underlying matter. The first term in term in  $\sigma$ from primordial non-linear gravitation, and non-linear gravitation, and the second represents  $\mathcal{P}$  $\overline{\phantom{a}}$  $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$   $\begin{bmatrix} 2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$  Local model Local model  $\frac{1}{2}$  (1, 2, 3) standards for the sum of  $\frac{1}{2}$  (1, 2, 2, 3) ter bispectrum due to gravity alone,  $B_{\rm{max}}$  is given by the second order perturbation theory (Fry $\sim$  $\frac{1}{2}$  $P(B_1, k_2, k_3) = Q_1(k_1, k_2, k_3) + Q_3(k_1, k_2, k_3)$ <br> $P_B(k_1, k_2, k_3)$  $/$  $P_{\rm L}(k_1)/P_{\rm L}(k_2)\, +\, (2\, perm.)\qquad P_{\rm L}(k_1)\, P_{\rm L}(k_2)\, +\, (3\, perm.)$  $\mathcal{L}_{\text{max}}$  $\frac{1}{200}$  et al. 2003), and the the matter bispectrum contributed from primordial non- $\Gamma$  - primorulation-vaussianity  $B_1(k_1, k_2, k_3) = \mathcal{M}(k_1; z) \mathcal{M}(k_2; z) \mathcal{M}(k_3; z) \frac{B_{\Phi}(k_1, k_2, k_3)}{2}$  **Equilateral model** We consider two models of primordial non-Gaussianity here, i.e. the local model and the local model a  $\left| \begin{array}{c} L$  bioff-uncar gravitational bispectrum are usually primordial bispectrum, the primordial bispectrum, the primordial bis periodic service  $\mathbb{R}$  are usually primordial bis periodic service, and usually period characterized by constraints on a single *amplitude parameter*, denoted by *f*NL, once a specific model for *B*⇥ is assumed.  $\mathcal{S}_1, k_2, k_3$  $\frac{B_{\rm G}'(k_1, k_2, k_3)}{B_{\rm G}(k_1, k_2, k_3)}$  $d(n, r) = P_L(k_1) P_L(k_2) + (2 \, perm.)$  $B_{\Phi}(k_1, k_2, k_3) \equiv f_{\text{NL}} F(k_1, k_2, k_3)$ urations. For brevitarian bispectrum is characteristic shape-dependence of a given bispectrum is often referred to simply as the characteristic shape**bispectrum shape function of the bispectrum shape function of the bispectrum shape function of the bispectrum shape function**  $\mathcal{L}(\mathcal{M})$ amplitude  $\vert \vert$  shape

2

,  $\frac{1}{2}$  ,  $\frac$ 

\$

3

the bispectrum is a function of the triplet defined by the magnitude of the wavenumbers *k*1, *k*<sup>2</sup> and *k*<sup>3</sup> forming a closed

triangular configuration. The current constraints that we are able to derive on the bispectrum *B*⇥(*k*1, *k*2, *k*3) provide

additional information about the early Universe; the possible detection of a non-vanishing primordial bispectrum  $\mathcal{L}$ 

⌅*D*(k123) *B*⇥(*k*1, *k*2, *k*3) , (I.1)

dictions for amplitude  $f(x) = \frac{1}{2\pi} \int_{0}^{1} f(x) \, dx$  that are strongly model-dependent. Notice that the subscription of  $f(x)$ 

### Constraints on  $f_{NL}$  from the HI Bispectrum

The Astrophysical Journal, 798:40 (10pp), 2015 January 1 Xu, Wang, & Cheng, & Cheng, & Cheng, & Cheng, & Cheng,

*Cosmology on the Largest Scales* Stefano Camera



*<sup>s</sup>* given by Equation (45). (SKA Science Book 2015)

### SKA cosmology – Inflationary Models with Features

30

- Large non-Gaussianities could have been produced (Nearly orthogonal to all commonly studied shapes)
- Significant local deviations from scale invariance
	- 'Cosh' drop in the speed of sound
	- Particle production (before the current horizon scale exited the Hubble radius during inflation)



0.01 0.05 0.10 0.50 1.00 5.00 10.00 -<sup>30</sup>

folded (middle) and squeezed shapes (left) for  $\tau_0 k_* = -11$ ,  $c = 0.8$  (top) and  $\tau_0 k_* = -11$ , Fig. 4.  $f_{\text{NL}}/\Delta_{\text{max}}$  (Black lines) vs  $\frac{\Delta \mathcal{P}}{\mathcal{P}}/\Delta_{\text{max}}$  (Blue lines) for the equilateral (right),  $c = 1.5$  (bottom) respectively for the 'cosh' drop in the speed of sound, given by  $c_s^2 =$ 



Fig. 6. *<sup>P</sup>* Fig. 6.  $\frac{\Delta P}{P}$  induced by the particle production for the potential (83), with representative parameters  $\Delta := \mu/\dot{\phi}_0 = H^{-1}, \lambda = 0.9, M = 10^{-3} M_{\text{pl}}, \epsilon = 0.01$  with  $\phi = \phi_*$  approxiparameters  $\Delta := \mu/\varphi_0 = H$ ,  $\lambda = 0.9, M = 10^{-7}M_{pl}, \epsilon = 0.01$  with  $\varphi = \varphi_*$  approximately 4 and 3 *e*-folds (left and right, respectively) before the current horizon scale exited the Hubble radius during inflation. the Hubble radius during inflation. Chluba, Hamann & Patil (2015)

the time being, postponing a discussion of more appropriate estimators for  $\mathbf{f}$ 

0.01 0.05 0.10 0.50 1.00 5.00 10.00 -<sup>30</sup>

### The Resonant Model

### The Step Model

the damping function DðyÞ ¼ πy= sinhðπyÞ for a hyperbolic tangent step in the inflaton potential. The correspond-

 $\frac{1}{\sqrt{2}}$ bolic tangent step in the inflaton potential. The correspond-

ing bispectrum is  $\frac{1}{3}$ 

 $\mathbf{1}_{\mathbf{1}_{\mathbf{2}}}$ 

**D** 

<sup>Φ</sup> ðk1; k2; k3Þ

12 m

Bstep

5

¼

the damping function  $\mathcal{L}_\mathcal{A}$  function  $\mathcal{L}_\mathcal{A}$  for a hyper-function  $\mathcal{L}_\mathcal{A}$  for a hyper-function  $\mathcal{L}_\mathcal{A}$ 

bolic tangent step in the inflaton potential. The correspond-

Φ

# <sup>ð</sup>2πÞ<sup>4</sup>Δ<sup>2</sup>

 $\blacktriangleright$  Realized in the axion monodromy inflation



 $\blacktriangleright$  A sudden step in the inflaton potential 12 Sudden step in the infl  $\overline{v}$ d tential <sup>2</sup> <sup>þ</sup> <sup>k</sup><sup>2</sup>



evaluated for  $\epsilon_{step} = 0.001$  and  $\beta = 43 \pi$  for illustration purposes.  $\epsilon_{step} = 0.001$  and  $\rho = 43\pi$  for interaction purposes.<br>(Bartolo et al. 2013)

¼

### Searching for Inflationary Features in the CMB

• No evidence for such features in the power spectrum or bispectrum with a statistical significance higher than 3σ (Planck 2015 results) spectrum or pispectrum  $T$  internal as well as a well as a set of the probability to expect as  $\alpha$ <sup>e</sup>↵ (*p*-value), constructed from simulated *Planck* 2015 results ence for the power-





Fig. 34. Best-fit power spectra for the power-law (black curve), step (green), logarithmic oscillation (blue), linear oscillation (orange), and cutoff (red) models using *Planck* TT+lowP data. The brown curve is the best fit for a model with a step in the warp *and* potential (Eqs. (71)–(78)).



### Constraint on resonant model with 21 cm IM

\* Both Tianlai and SKA1-MID can make excellent measurement





 $- - P_{\text{m}}(k, z = 1)$  $P_{m}^{res}(k, z=1)$ 

- $\triangleright$  The HI power spectrum observations have  $\begin{array}{ccc} \text{\color{red}{\text{I}}}& \text{\color{red$ 
	- $\triangleright$  Bispectrum: σ<sub>fres</sub> ≤18 for Tianlai and σ<sub>fres</sub> ≲ 16 for the SKA1-MID
- Power spectrum (for  $C_{\omega} \lesssim 100$ ):  $\sigma_{\text{fres}} \lesssim 2.5$  $T_{\text{TOO}}$  for Tianlai and  $\sigma_{\text{fres}} \lesssim 2.8$  for the SKA1-MID. parameters can be obtained the Figure of  $\epsilon$  and the approximation of  $\epsilon$



#### $\approx 10$  the HI bispectrum measurements cou  $\sim$  10, me m pspectrom measure  $\frac{1}{2}$ power spectrum measurements could ac  $\bullet$  For β  $\geq$  10, the HI bispectrum measurements could achieve  $\sigma_{\rm cstep} \leq 14$  for Tianlai and  $\sigma_{\rm cstep} \leq 5.0$  for SKA1-MID;  $\frac{a}{2}$  $*$  The HI power spectrum measurements could achieve  $\sigma_{\rm \tiny{step}}$   $\lesssim$ 0.054 for Tianlai and  $\sigma_{\rm \tiny{step}}$   $\lesssim$  0.026 for SKA1-MID.

 $\mathcal{L}_{\mathcal{D}}$  at the dependence on  $\mathcal{L}_{\mathcal{D}}$  and  $\mathcal{L}_{\mathcal{D}}$  at the understood by looking at the actual amplitude of the modulations in the modulations in the modulations in the power and  $\alpha$ 

solid and dashed lines are for Tianlai and SKA1-MID, respec-

taken into account. actual amplitude of the modulations in the power and

 $\epsilon$  increases with  $\epsilon$  indicating the current that the that that the that the that the that the that the that the theorem test will be more to more that the money in the money of the money of the money in the model in the money in the  $\sim$ The dependence on Cuba by looking at the understood by looking at the understood by looking at the understood

tively. The thin long-dashed line shows the HI power spectrum

 $\mathcal{L}(\mathcal{L})$  is dominated by the cosine term at low frequencies term at low frequencies  $\mathcal{L}(\mathcal{L})$ 

pt on sten model with  $\sum_{i=1}^n$ 



## **21 cm Cosmology – to avoid/distinguish from astrophysical uncertainties!**

#### **Line Intensity Mapping (LIM)**



**Strategy 2** -- Looking for features less vulnerable to unknown astrophysics

- $V$  Velocity Acoustic Oscillations (VAO)
	- -- probe the small-scale structures with large-scale
	- $21$ cm signals  $\rightarrow$  Dark Matter properties
- $\checkmark$  Standard ruler  $\Rightarrow$  Dark Energy
- $\checkmark$  Go to ultra-large scales  $\Rightarrow$  PNG, GR effects

### Velocity Acoustic Oscillations (VAO) = streaming velocity + BAO (e.g., Tseliakhovich et al. 2011)



Credit:http://burro.case.edu/Academics/Astr328/Notes/StructForm/bao\_1d\_anim.gif

### VAO features on 21 cm power spectrum



### VAO features on 21 cm power spectrum

 $v_{db}$  field

### collapse fraction 21 cm field



### VAO features on 21 cm power spectrum -- a standard ruler at Cosmic Dawn



See also: Dalal+10, Visbal+12, Fialkov+12, McQuinn+12 Munoz 19, Park+19, Cain+20, Sarkar+22 Zhang et al. 2024ApJ...964...62Z

(arXiv:2401.14234)

### 21cm VAO features modulated by small scale structures



- 1. In FDM model, the lack of small-scale structure (minihalo) leads to the lack of Pop III & VAO signal;
- 2. The VAO effect makes it possible to detect small-scale via 21 cm at large-scale;
- 3. Minihalo is less influenced by baryon;
- 4. At Cosmic Dawn, X-ray heating is positive factor for VAO signal。

## **CDM vs. axion** 21cm VAO features modulated by small scale structures



See also Hotinli et al. (2022), Sarkar et al. (2022), Flitter & Kovetz (2022), Vanzan et al. (2024)





### **The VAO signal in mixed-DM models**





Zhang et al. 2024ApJ...964...62Z (arXiv:2401.14234)

## 21 cm power spectrum -- probing large-scale imprints from DM



LOFAR

### **21 cm Cosmology – to avoid/distinguish from astrophysical uncertainties!**

**Strategy 3** – Breaking the degeneracy with unknown astrophysics

ü**21 cm Forest**

**-- probing the smallest structures at cosmic dawn**

 $→$  **Dark Matter properties** 

21 cm Forest -- absorption lines against high-z radio point sources (e.g. Carilli et al. 2002; YX et al. 2009, 2010, 2011)

ر<br>ساب

129.2

129.4

 $v_{obs}$  [MHz]

129.6

129.8

 $\bigcap$ 

### 21 cm Forest



 $\blacktriangleright$  Unique probe to small –scale structures at cosmic dawn  $(CD) \rightarrow$  Dark Matter properties at CD



### 21-cm Forest: observational challenges

Grant FIRSTLIGHT - 258942.

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e<sup>d:</sup> T=e<sup>d:</sup><br>Oo Oooo Oooo

 $\mathbb{H}^n$ 1 11 1<br>100 EIL ग्न

 $\mathbf{1}$ 10-4

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 $\frac{8}{11}$  0.99

 $\frac{1}{20}$ 

 $\blacktriangleright$  Probing thermal history  $\Leftrightarrow$  easily **Probing thermal history**  $\Leftrightarrow$  **easily suppressed (weak)** 



Figure 13. Upper panel: Spectrum of a source positioned at  $z = 14$  (i.e.  $\nu \sim 95$  MHz), with an index of the power-law  $\alpha = 1.05$  and a flux density  $S_{\text{in}}(z_s) = 50$  mJy. The lines are the same as those in Figure 10. Here we have assumed the noise  $\sigma_n$  given in eq. 3, a bandwidth  $\Delta \nu = 20$  kHz, smoothing over a scale  $s = 20$  kHz, and an integration time  $t_{int} = 1000$  h. The IGM absorption is calculated from the reference simulation  $\mathcal{L}4.39$ .

Constraining DM: **degenerate** with astrophysics





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 $\text{CDM}_{\text{WDM}}$ =30keV  $m_{\text{WDM}}^{\text{WDM}}$ =20keV .......  $m_{\text{WDM}}^{\text{WDM}}$ =10keV  $m_{WDM}$ =6keV

## Key strategy #1: multi-scale hybrid modeling



**radii of halos at** *z* **= 9 with an un-heated IGM (***f*<sup>X</sup> **= 0).** The green, yellow and red lines

## The mock 21 cm signals



## Key strategy #2: 1-D cross-power spectrum

 $\triangleright$  Cross-correlate two measurements to suppress the noise **Eing the small structure we are a**  $\Gamma$  from correlate two measurements to suppress the holse for the total integration times  $\sim$ 

<sup>b</sup> (*s*ˆ*, rz*) *eik*k*r<sup>z</sup>* d*rz.* (17)

I

est include the thermal noise, the sample variance, the contaminating spectral structures from

foreground sources in the chromatic sidelobes, and the bandpass calibration error. The bandpass

plitude of the continuum, so we expect that it has a negligible effect on the small-scale features

densities from = 0*.*7 to = +1*.*5.

we are interested in the contamination spectral structures from foregrounds are not likely affect-

Z

*T*<sup>0</sup>

ments of 1-D power spectra from segments of spectra, each collection spectra, each contrading to a comoving le<br>In the comoving length of spectra, each comoving length of spectra, each comoving length of the comoving length

of 10 Mpc. We adopt *N<sup>s</sup>* = 100, and *<sup>P</sup>* (*k*) is obtained by simulating 21-cm forest signals from

 $\sim$  10 sources with S<sub>150</sub> = 10 mJy at z = 9



### 1-D cross-power spectrum  $\rightarrow$  Two birds with one stone



### 21 cm forest: a simultaneous probe of **Figure 1944 Figure 10** *PM & first galaxies* **ments of 10 comoving Mpc length in neutral patches of 10 comoving Mpc length in neutral patches along lines of 10 comoving lines of 10 co**

Using  $\sim$  10 sources with  $S_{150}$  = 10 mJy at  $z$  = 9



- $\sigma_{m_{\rm WDM}}^{}=1.3~{\rm keV}$  and  $\sigma_{T_{\rm IGM}}^{}=3.7~{\rm K}$
- **For SKA2-Low:**

$$
\sigma_{m_{\text{WDM}}} = 0.3 \text{ keV and } \sigma_{T_{\text{IGM}}} = 0.6 \text{ K}
$$

 $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$   $\text{max}$  and  $\text{max$ 35.000 DVD:

**Figure 6** *|* **Constraints (68.3**% **and 95.4**% **confidence level) on** *T*<sup>K</sup> **and** *m*WDM **with**



 $\sigma_{m_{\rm WDM}} = 0$ . 6 keV

and  $\sigma_{T_{\rm IGM}} = 88$  K

The dark matter forest at the dawn of time The 21-cm forest - absorption lines of atomic hydrogen against a background highredshift radio source - can be used to probe small-scale structures in the early Universe When observed at scale with the upcoming Square Kilometre Array, statistical analysis of

these lines will be able to constrain the properties of dark matter at that epoch.

#### See Shao et al.

Image: Xin Zhang, Northeastern University, Shenyang, China and Yidong Xu, National Astronomical Observatories, Chinese Academy of Sciences. Cover design: Bethany Vukomanovic.

#### Shao Y., **XuYD**, et al. 2023 **NA**

## 21 cm Cosmology: challenging but intriguing!

- $\blacktriangleright$  Vital to avoid/distinguish from astrophysical uncertainties!
- **Strategy 1** -- Looking for features not affected by later baryonic physics
	- $\checkmark$  The cosmological standard ruler 21 cm BAO  $-$  Dark Energy  $-$  comparable to stage IV
	- ü Go to ultra-large scales -- **PNG & Inflation physics** -- powerful for inflation models with oscillatory features
- **Strategy 2** -- Looking for features less vulnerable to unknown astrophysics
	- $\checkmark$  21cm VAO -- probe the small-scale structures with large-scale 21cm signals  $\hat{\to}$  distinguish DM models
- ▶ Strategy 3 Breaking the degeneracy with unknown astrophysics
	- ü **21 cm Forest** -- probing the smallest structures at cosmic dawn a **simultaneous probe** of DM & first galaxies



# Thank you!