21-cm Cosmology
from the Largest to the Smallest Scales

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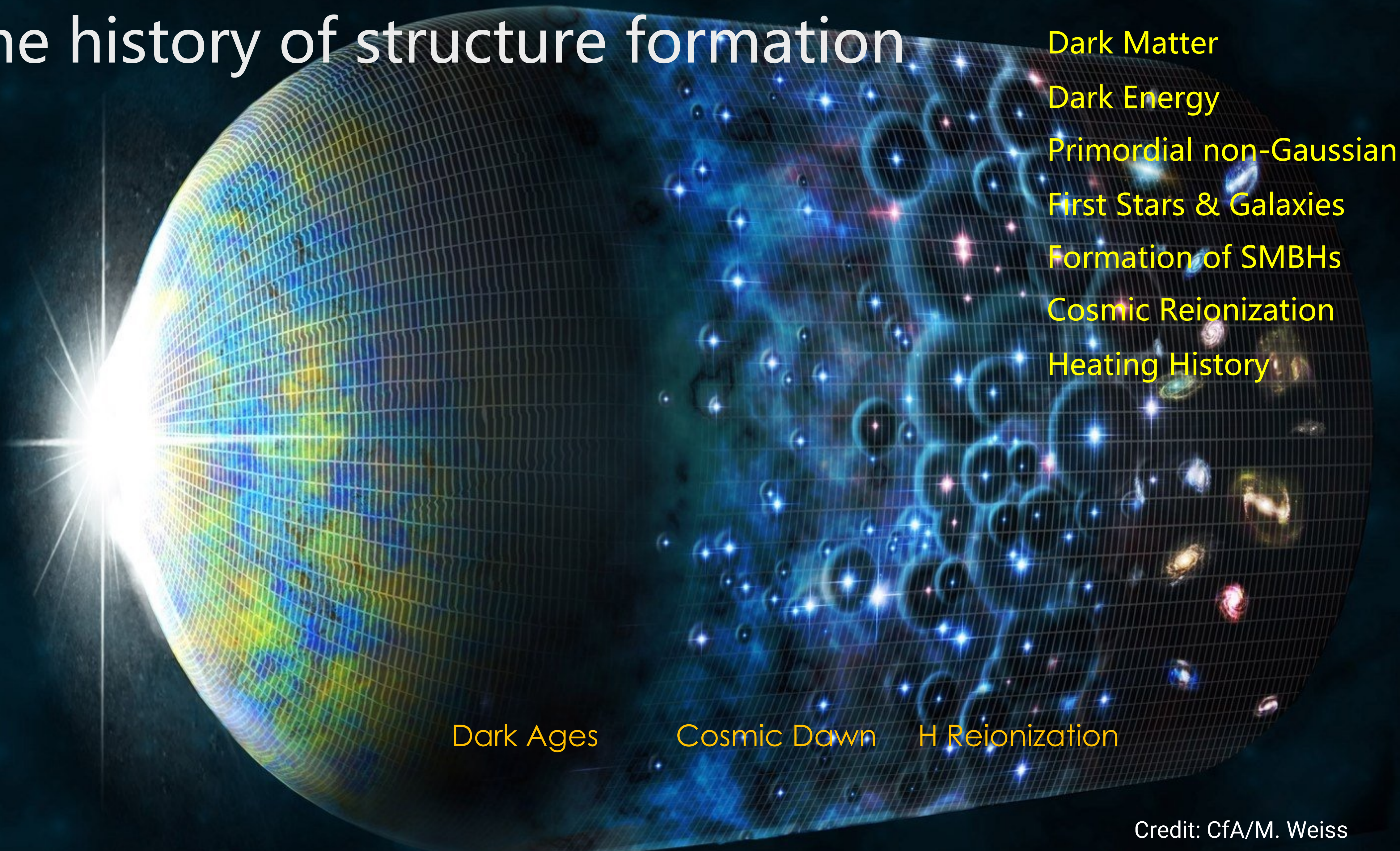
National Astronomical Observatory of China (NAOC)

- The Tianlai collaboration
- The SKA collaboration
- The DSL collaboration

2024.7.22 21 cm Cosmology Workshop @ Hangzhou

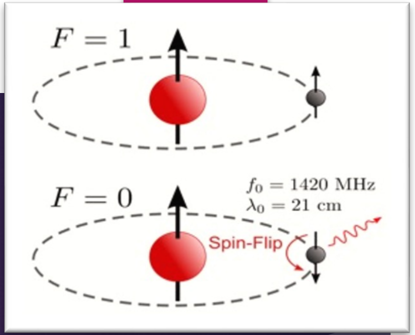
The history of structure formation

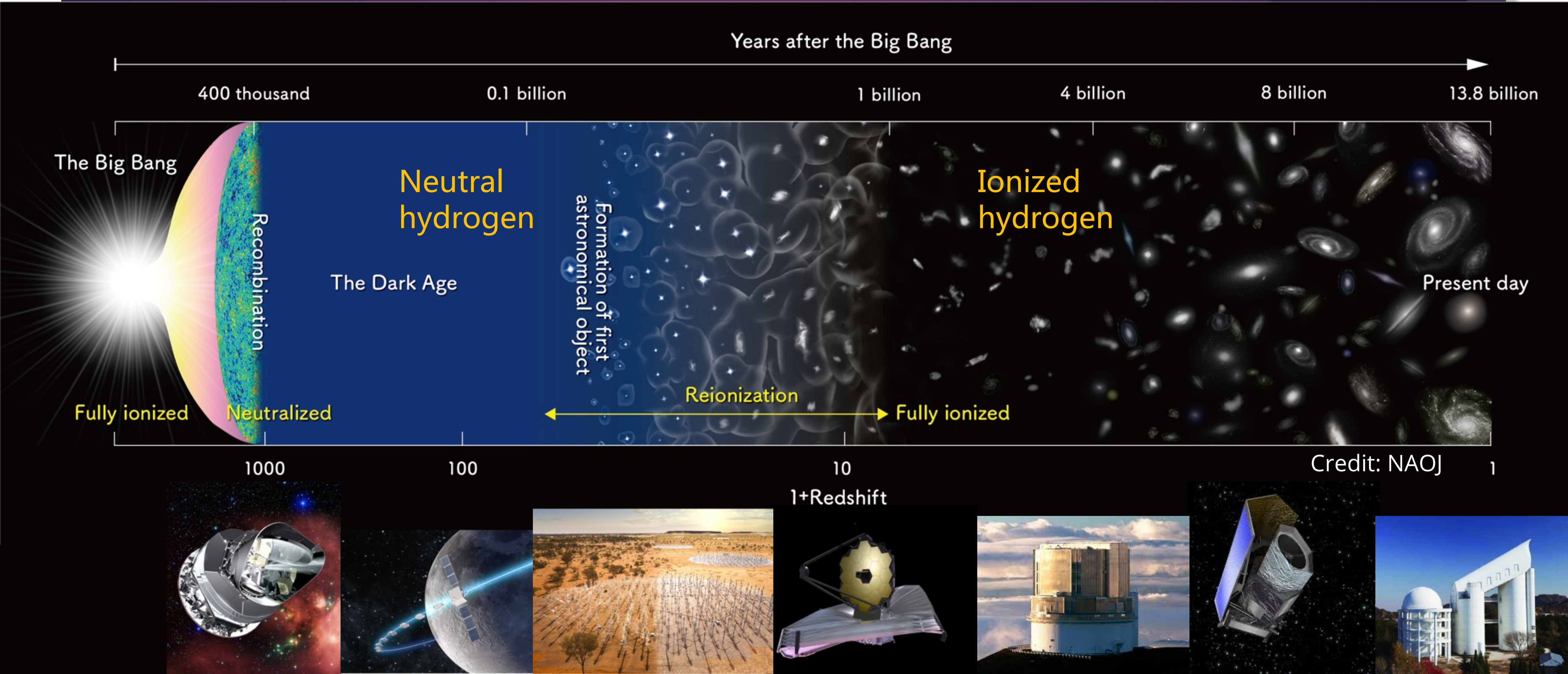
- Dark Matter
- Dark Energy
- Primordial non-Gaussianity
- First Stars & Galaxies
- Formation of SMBHs
- Cosmic Reionization
- Heating History



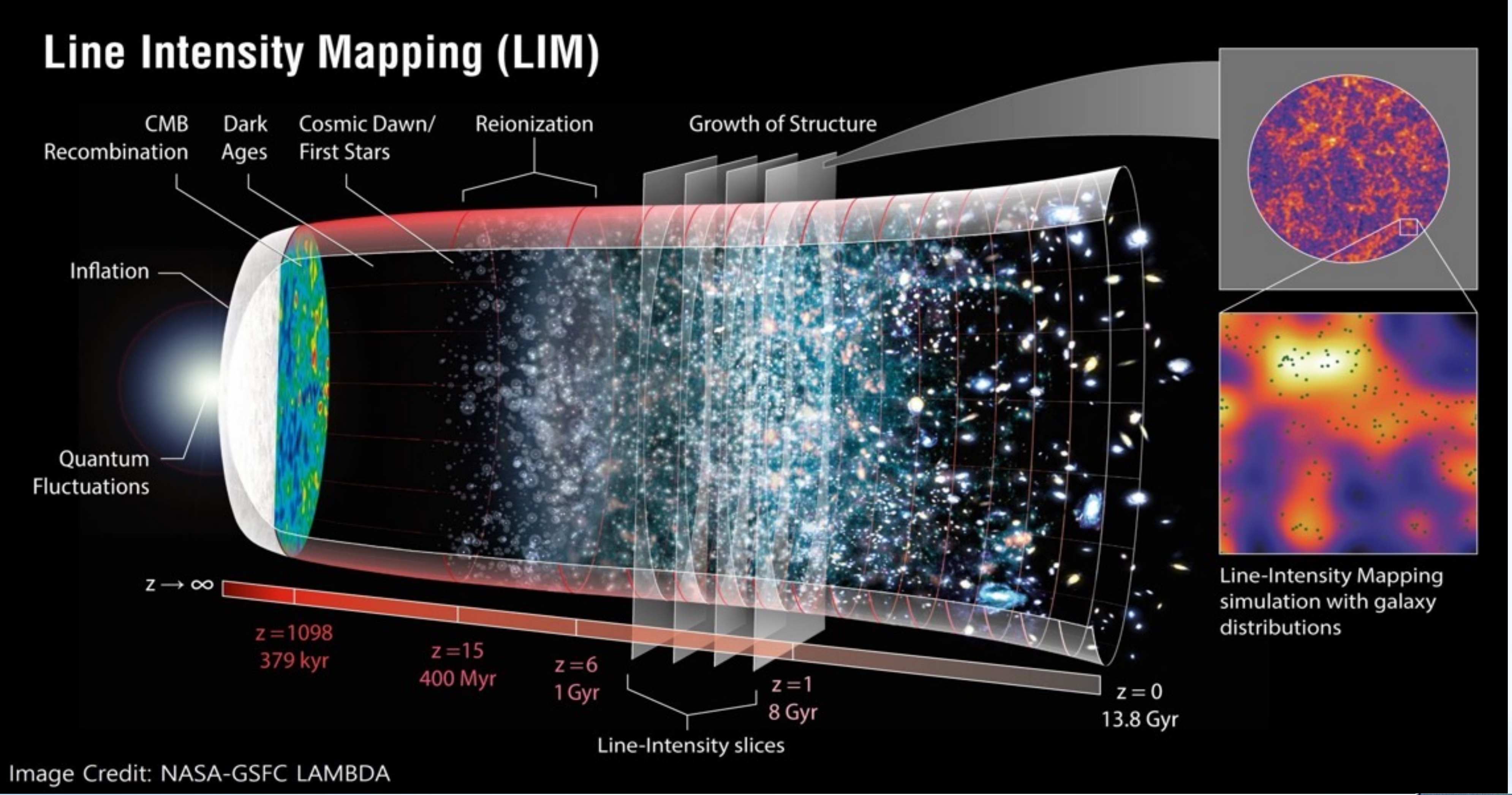
Credit: CfA/M. Weiss

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

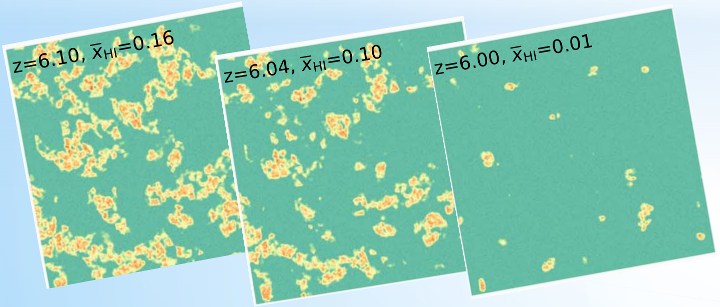




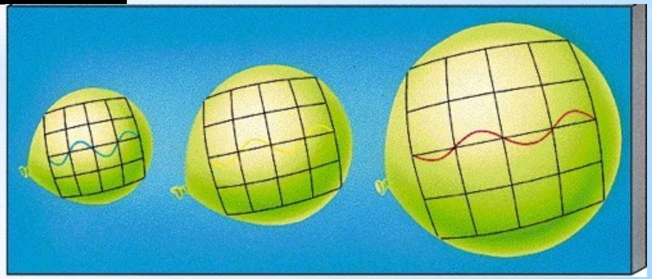
Credit: NAOJ



21cm from post-EoR
→ HI in halos
→ Large-scale structure in 3D



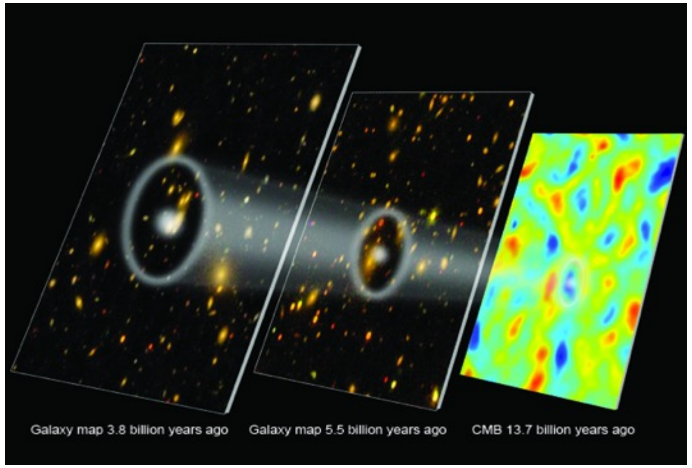
21cm from Dark Ages, Cosmic Dawn, & EoR
→ HI in the IGM
→ Reionization & first galxies



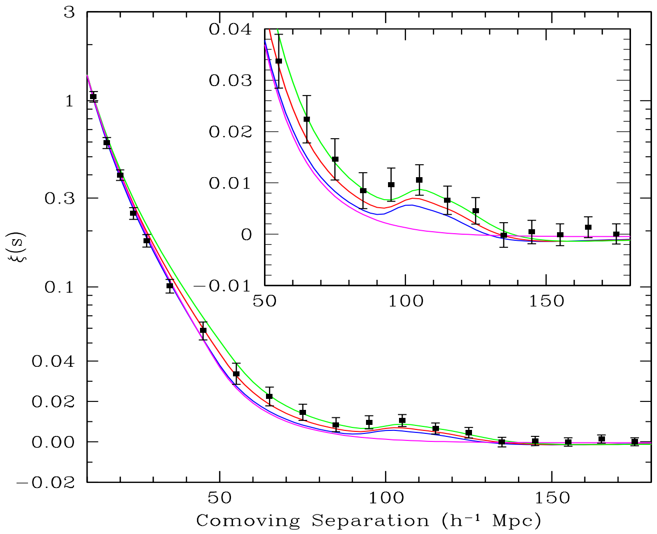
21cm ⟶ 21cm*(1+z)

Measuring the large-scale structure with 21cm IM

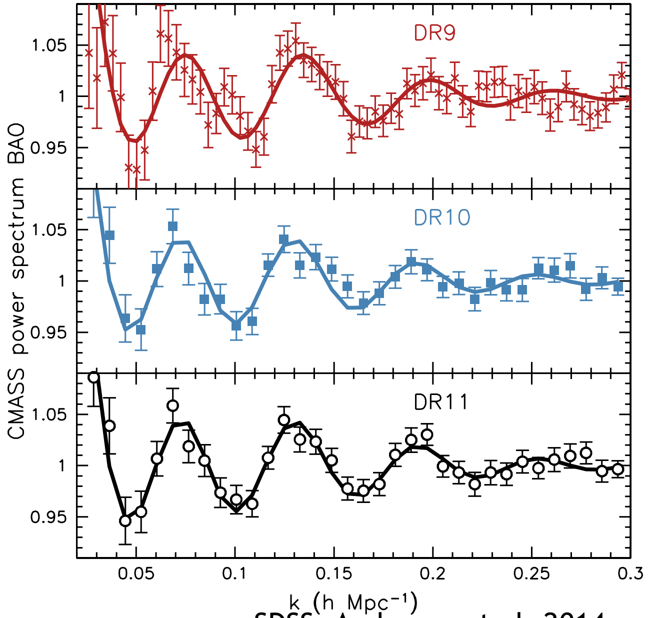
- Baryon Acoustic Oscillations – the cosmological standard ruler
- The standard ruler of the sound horizon at the last scattering surface
  - $r_s(z_d) = 153.3 \pm 2.0$ Mpc (Komatsu et al. 2009)



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

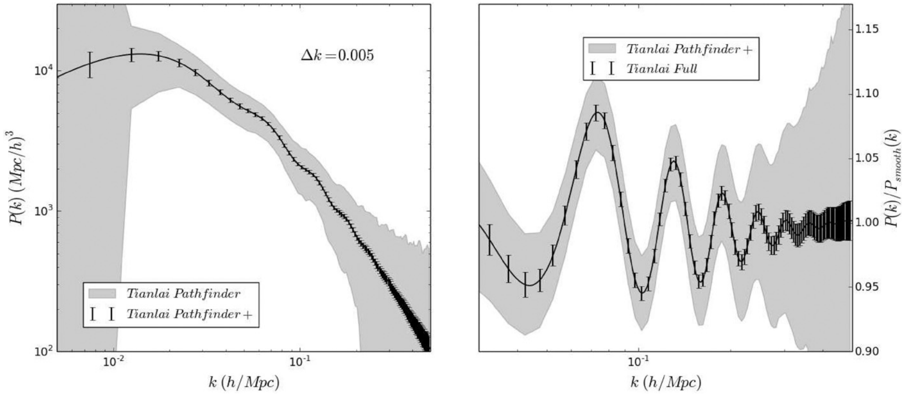


BAP in the clustering of the SDSS LRG galaxy sample (Eisenstein et al. 2005)

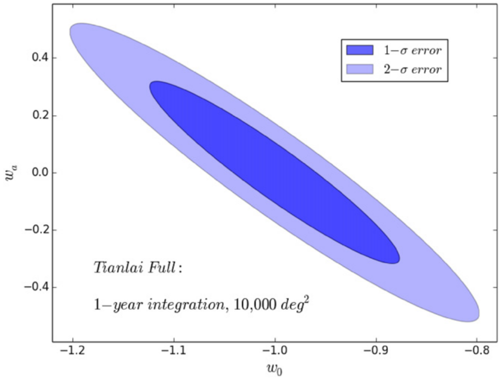


SDSS: Anderson et al. 2014

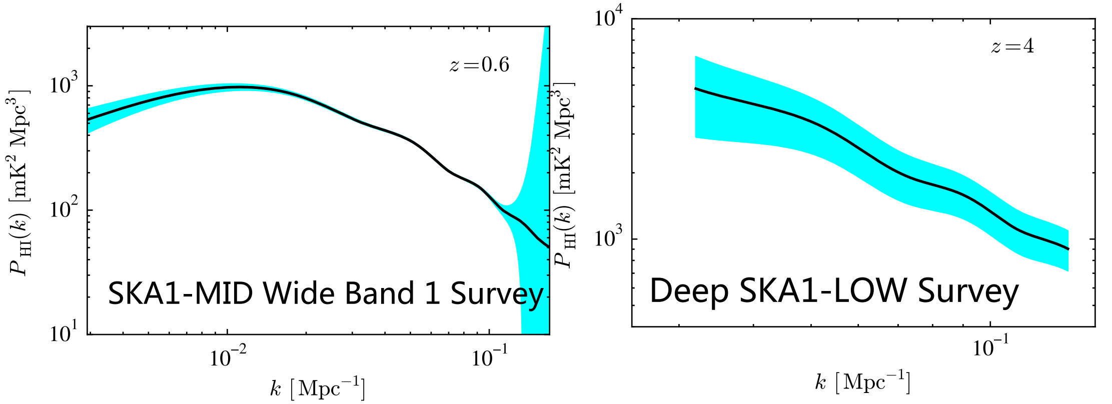
Constraining the Dark Energy EoS with 21cm BAO measurements



survey area: 10,000 deg^2, integration time: 1 year.



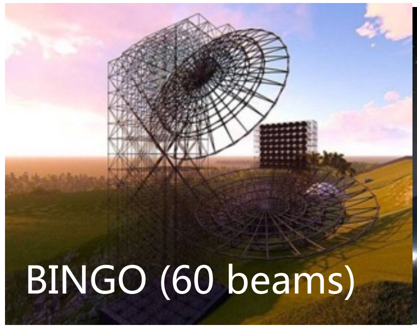
Xu et al. 2015



SKA1-MID Wide Band 1 Survey

Deep SKA1-LOW Survey

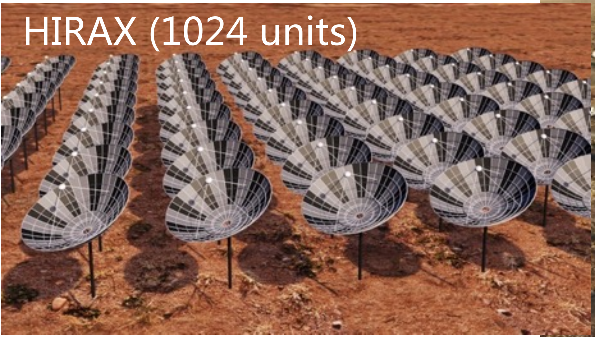
SKA1 Cosmology Red Book 2018
(arXiv:1811.02743)



BINGO (60 beams)

CHIME (1024 units)

Tianlai (96 units)



HIRAX (1024 units)

SKA-Mid (197

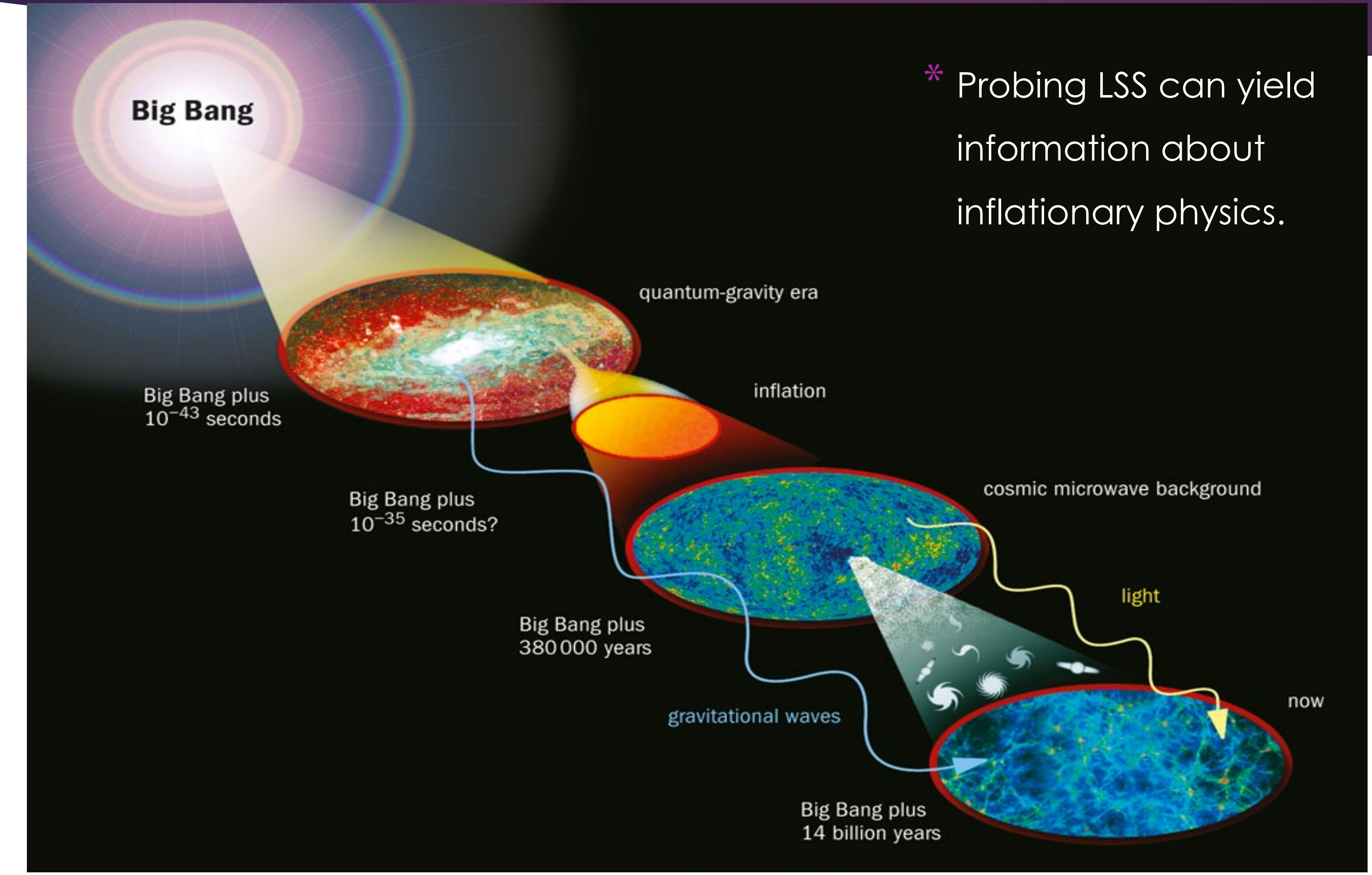
21 cm Cosmology – to avoid/distinguish from astrophysical uncertainties!

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

✓ The cosmological standard ruler – 21 cm BAO ➔ Dark Energy

✓ Go to ultra-large scales ➔ primordial non-Gaussianity (PNG) & Inflation physics

21 cm cosmology – the Primordial Non-Gaussianity

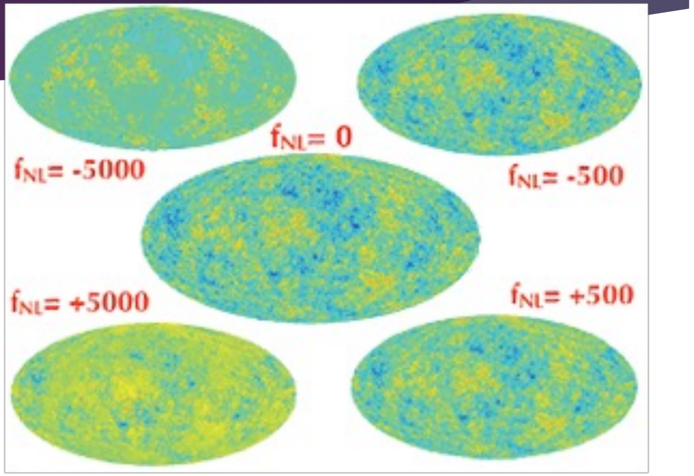


- Probing LSS can yield information about inflationary physics.

- Inflation → Initial density perturbations → Structure Formation → LSS today

(Courtesy: NASA)

The LSS as a Probe of the Primordial Non-Gaussianity



- PNG imprint on the CMB:
  - Angular bispectrum measurement

$$\begin{pmatrix} f_{\rm NL}^{\rm loc} = 2.5 \pm 5.7 \\ f_{\rm NL}^{\rm eq} = -16 \pm 70 \\ f_{\rm NL}^{\rm orth} = -34 \pm 33 \end{pmatrix} (68\,\%\,{\rm CL}, T) \qquad \begin{pmatrix} f_{\rm NL}^{\rm loc} = 0.8 \pm 5.0 \\ f_{\rm NL}^{\rm eq} = -4 \pm 43 \\ f_{\rm NL}^{\rm orth} = -26 \pm 21 \end{pmatrix} (68\,\%\,{\rm CL}, T+E)$$

- PNG effects on LSS:
  - High-order correlations of galaxy distribution – bispectrum, trispectrum (e.g. Sefusatti & Komatsu 2007)
  - Abundance of rare objects – cluster number density (e.g. Afshordi & Tolley 2008; Dalal *et al*. 2008)
  - The large-scale clustering of halos – scale-dependent bias (e.g. Dalal et al. 2008; Desjacques et al. 2011)

Constraints on f_{NL} from the HI Power Spectrum

- For the standard local type PNG, the scale-dependent non-Gaussian correction to the linear halo bias:

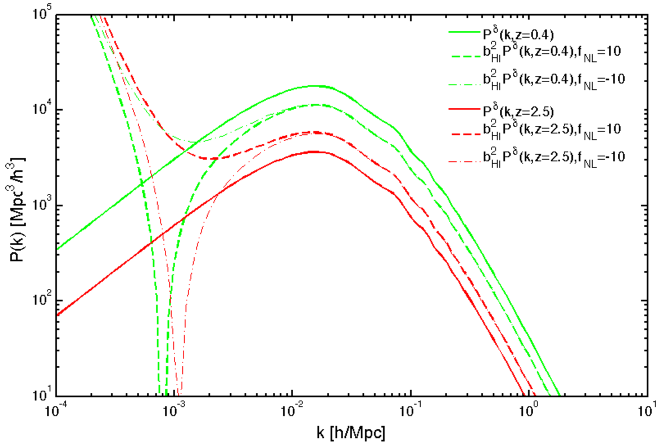
$$\Delta b^d(k, z) = \frac{2\, f_{\rm NL}\, (b_1^{\rm G} - 1)\, \delta_c}{\mathcal{M}(k, z)}$$

→ halo bias →

- **The HI bias factors:**

$$b_i^{\rm HI}(z) = \frac{\int_{M_{\rm min}}^{M_{\rm max}} dM\, n(M, z)\, M_{\rm HI}(M)\, b_i(M, z)}{\rho_{\rm HI}}$$

↓



- The observed HI power spectrum:

$$P_{\rm s}(k, z) = a_0^{\rm P}(\beta)\, P_{\rm H\,I}(k, z).$$

$$P_{\rm HI}(k, z) = \left[b_1^{\rm HI}(k, z)\right]^2 P_{\rm L}(k, z)$$

- Most prominent on very large scale – suitable for intensity mapping
- Camera et al. (2013): a small but compact array working at ~ 400 MHz could possibly achieve $\sigma_{\rm fNL} \sim 1$.

Constraints on f_{NL} from the HI Power Spectrum

- Tianlai cylinder array (Xu et al. 2015):

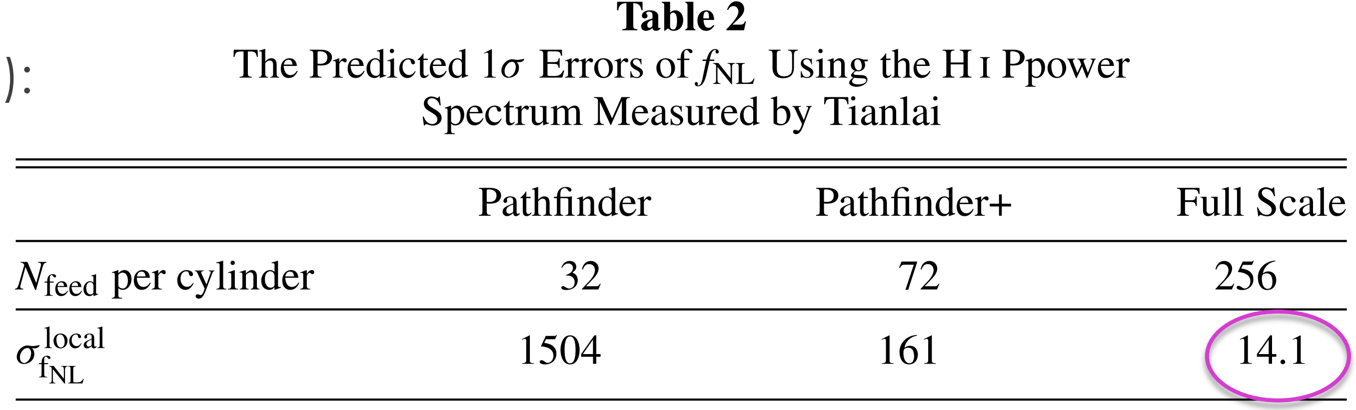


Table 2
The Predicted 1σ Errors of $f_{\rm NL}$ Using the H I Ppower Spectrum Measured by Tianlai

	Pathfinder	Pathfinder+	Full Scale
$N_{\rm feed}$ per cylinder	32	72	256
$\sigma_{\rm f_{NL}}^{\rm local}$	1504	161	14.1

survey area = 10000 deg², integration time = 1 year.

- SKA1-MID:

$\sigma(f_{\rm NL}) = 2.8$ (SKA1 Cosmology Red Book 2018)

Could potentially achieve $\sigma(f_{\rm NL}) < 1$ with the multi-tracer technique (Seljak, 2009)

Constraints on f_{NL} from the HI Bispectrum

- The tree-level expression for the reduced HI bispectrum:

3 - non-linear bias

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

* The reduced matter bispectrum

2 - non-linear gravitational evolution

$$\begin{aligned} Q^{\rm tree}(k_1, k_2, k_3) &= Q_{\rm I}(k_1, k_2, k_3) \;+\; Q_{\rm G}(k_1, k_2, k_3) \\ &= \frac{B_{\rm I}(k_1, k_2, k_3)}{P_{\rm L}(k_1)\, P_{\rm L}(k_2) \;+\; (2\, perm.)} \;+\; \frac{B_{\rm G}(k_1, k_2, k_3)}{P_{\rm L}(k_1)\, P_{\rm L}(k_2) \;+\; (2\, perm.)} \end{aligned}$$

1 - primordial non-Gaussianity

$$B_{\rm I}(k_1, k_2, k_3) \;=\; \mathcal{M}(k_1; z)\, \mathcal{M}(k_2; z)\, \mathcal{M}(k_3; z)\, \underline{B_\Phi(k_1, k_2, k_3)}$$

Local model

Equilateral model

……

$$B_\Phi(k_1, k_2, k_3) \equiv f_{\rm NL} F(k_1, k_2, k_3)$$

amplitude

shape

(Model-dependent)

Constraints on f_{NL} from the HI Bispectrum

- The PNG from ***Tianlai*** intensity mapping:

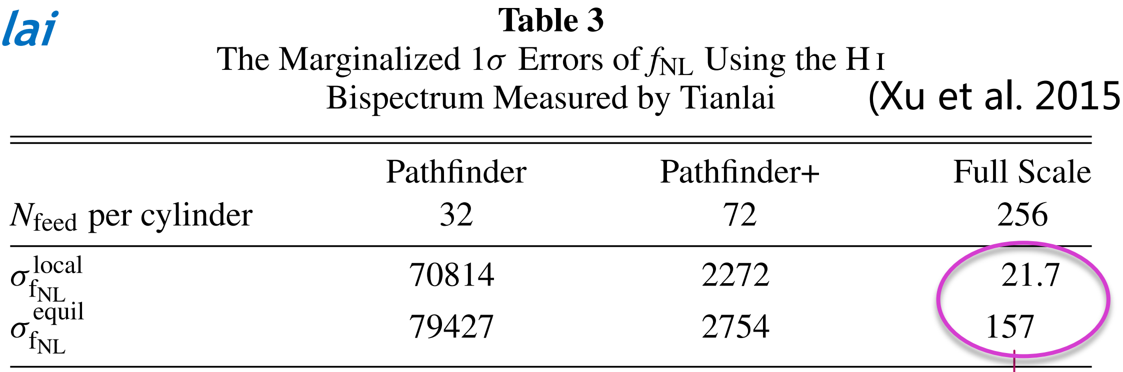


Table 3
The Marginalized 1σ Errors of f_{NL} Using the H I Bispectrum Measured by Tianlai

(Xu et al. 2015)

	Pathfinder	Pathfinder+	Full Scale
N_{feed} per cylinder	32	72	256
$\sigma_{f_{\mathrm{NL}}}^{\mathrm{local}}$	70814	2272	21.7
$\sigma_{f_{\mathrm{NL}}}^{\mathrm{equil}}$	79427	2754	157

survey area = 10000 deg^2,
integration time = 1 year,
system temperature = 50 K.

400 - 1420 MHz

- The PNG from ***SKA*** intensity mapping
  - SKA1-mid (auto-correlation)

$$\sigma(f_{\mathrm{NL}}^{\mathrm{loc}}) = 45.7 \text{ and } \sigma(f_{\mathrm{NL}}^{\mathrm{eq}}) = 214.3$$

  - SKA2-mid (interferometry)

$$\sigma(f_{\mathrm{NL}}^{\mathrm{loc}}) = 6.6 \text{ and } \sigma(f_{\mathrm{NL}}^{\mathrm{eq}}) = 55.4$$

(SKA Science Book 2015)

survey area = 20000 deg^2,
integration time = 5000 hr,
system temperature = 25 K,
350 – 1420 MHz

SKA cosmology – Inflationary Models with Features

- 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)

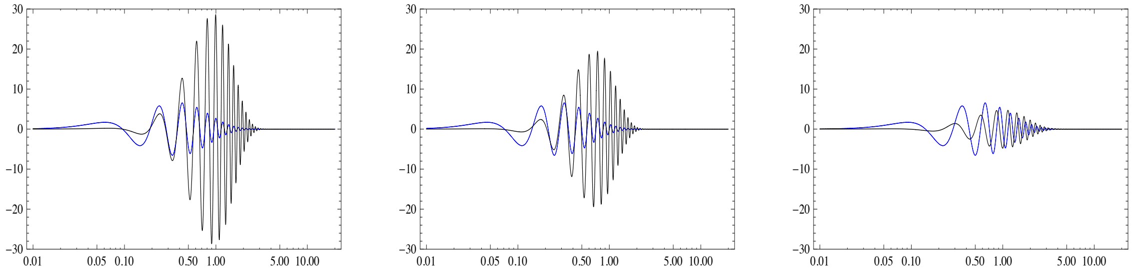


Fig. 4. $f_{\rm NL}/\Delta_{\rm max}$ (Black lines) vs $\frac{\Delta\mathcal{P}}{\mathcal{P}}/\Delta_{\rm max}$ (Blue lines) for the equilateral (right), folded (middle) and squeezed shapes (left) for $\tau_0 k_* = -11$, $c = 0.8$ (top) and $\tau_0 k_* = -11$, $c = 1.5$ (bottom) respectively for the ‘cosh’ drop in the speed of sound, given by $c_s^2 = 1 - \frac{\Delta_{\rm max}}{\cosh[c(\tau-\tau_0)]}$.

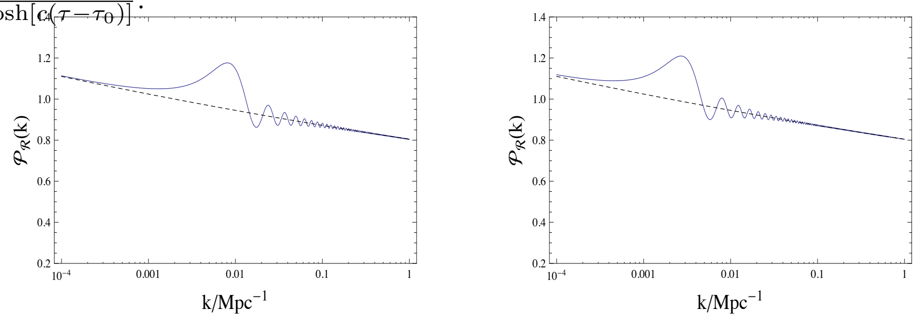
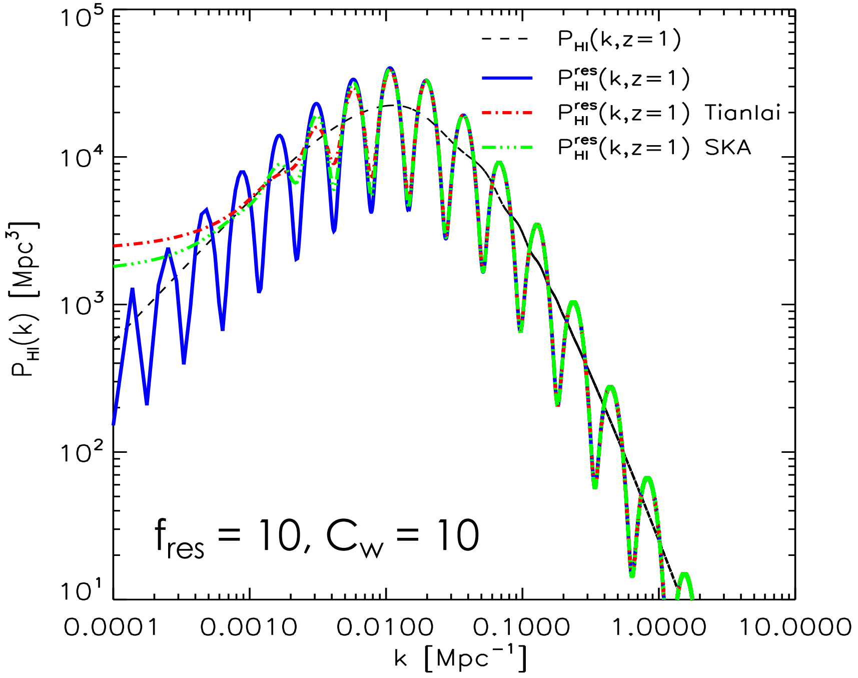


Fig. 6. $\frac{\Delta\mathcal{P}}{\mathcal{P}}$ induced by the particle production for the potential (83), with representative parameters $\Delta := \mu/\dot{\phi}_0 = H^{-1}, \lambda = 0.9, M = 10^{-3}M_{\rm pl}, \epsilon = 0.01$ with $\phi = \phi_*$ approximately 4 and 3 *e*-folds (left and right, respectively) before the current horizon scale exited the Hubble radius during inflation.

Chluba, Hamann & Patil (2015)

The Resonant Model

- Realized in the axion monodromy inflation



The Step Model

- A sudden step in the inflaton potential

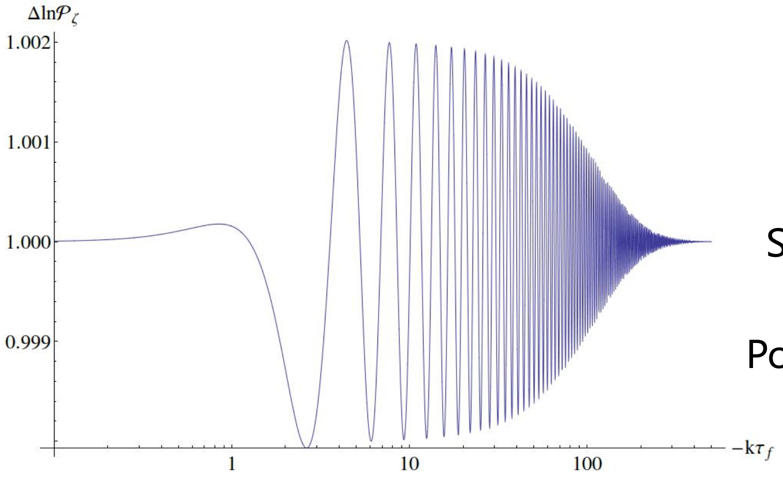


Figure 1. Non-scale invariant part of the power spectrum (3.21) for a hyperbolic tangent st
valuated for $\epsilon_{step} = 0.001$ and $\beta = 43\,\pi$ for illustration purposes.

(Bartolo et al. 2013)

Height -- $\epsilon_{\text{step}} \ll 1$

Sharpness -- $\beta \gg 1$

Position/time -- τ_{f}

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)

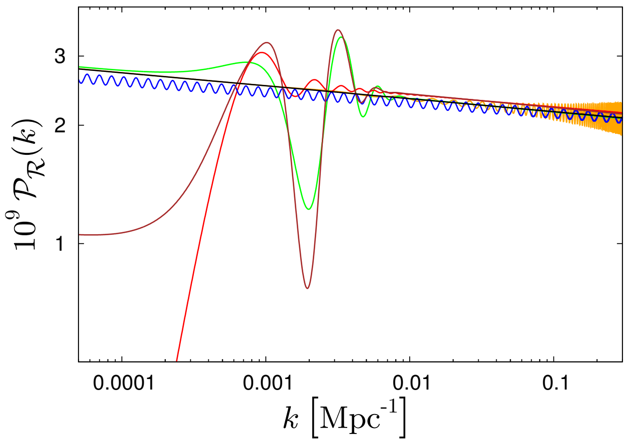
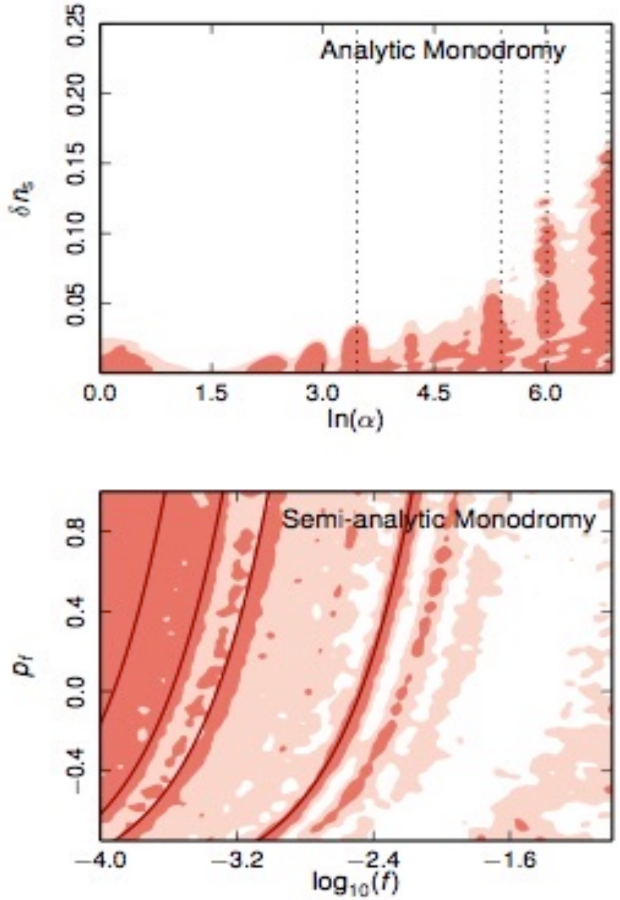


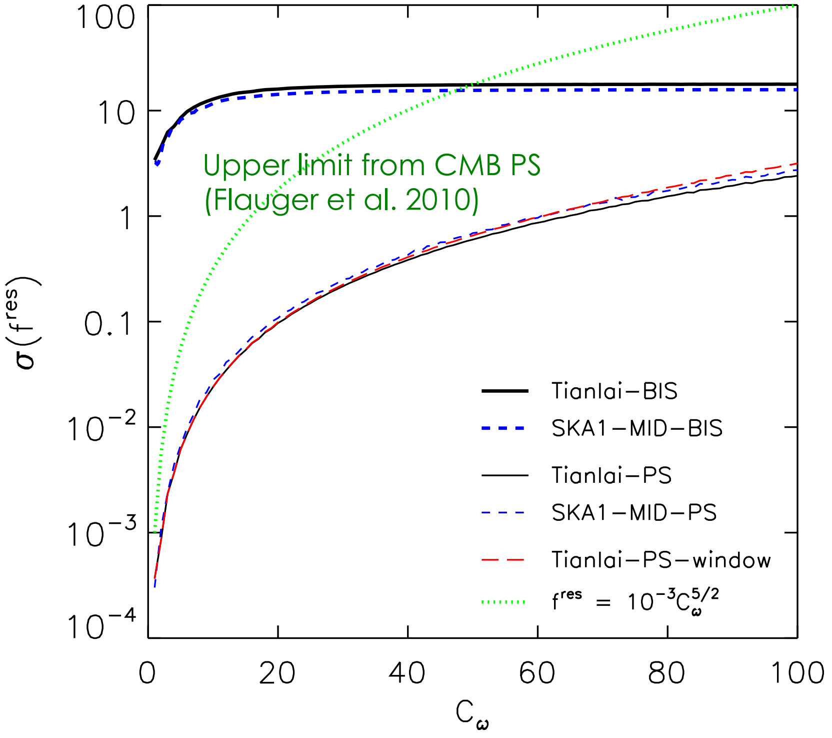
Fig. 34. Best-fit power spectra for the power-law (black curve), step (green), logarithmic oscillation (blue), linear oscillation (orange), and cutoff (red) models using *Planck* TT+lowP data. The brown curve is the best fit for a model with a step in the warp *and* potential (Eqs. (71)–(78)).



The 3-D information matters!

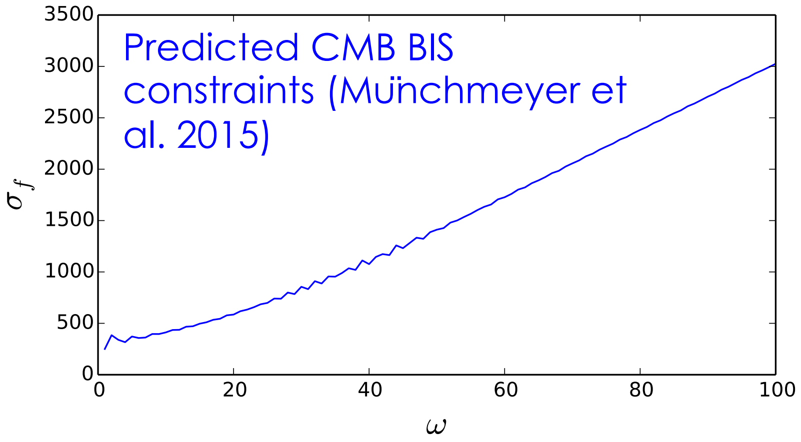
Constraint on resonant model with 21 cm IM

- Both Tianlai and SKA1-MID can make excellent measurement on the relevant redshift range and scales.

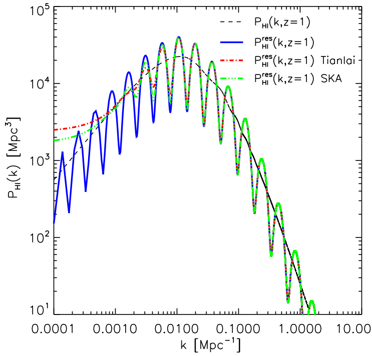


Upper limit from CMB PS (Flauger et al. 2010)

Xu et al. 2016



Predicted CMB BIS constraints (Münchmeyer et al. 2015)



- The HI power spectrum observations have better sensitivity than the bispectrum.
- Bispectrum: $\sigma_{fres} \lesssim 18$ for Tianlai and $\sigma_{fres} \lesssim 16$ for the SKA1-MID
- Power spectrum (for $C_\omega \lesssim 100$): $\sigma_{fres} \lesssim 2.5$ for Tianlai and $\sigma_{fres} \lesssim 2.8$ for the SKA1-MID.

Constraint on step model with 21 cm IM

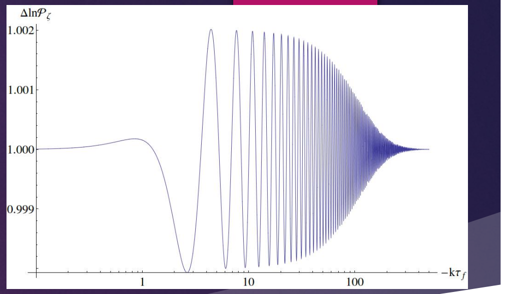
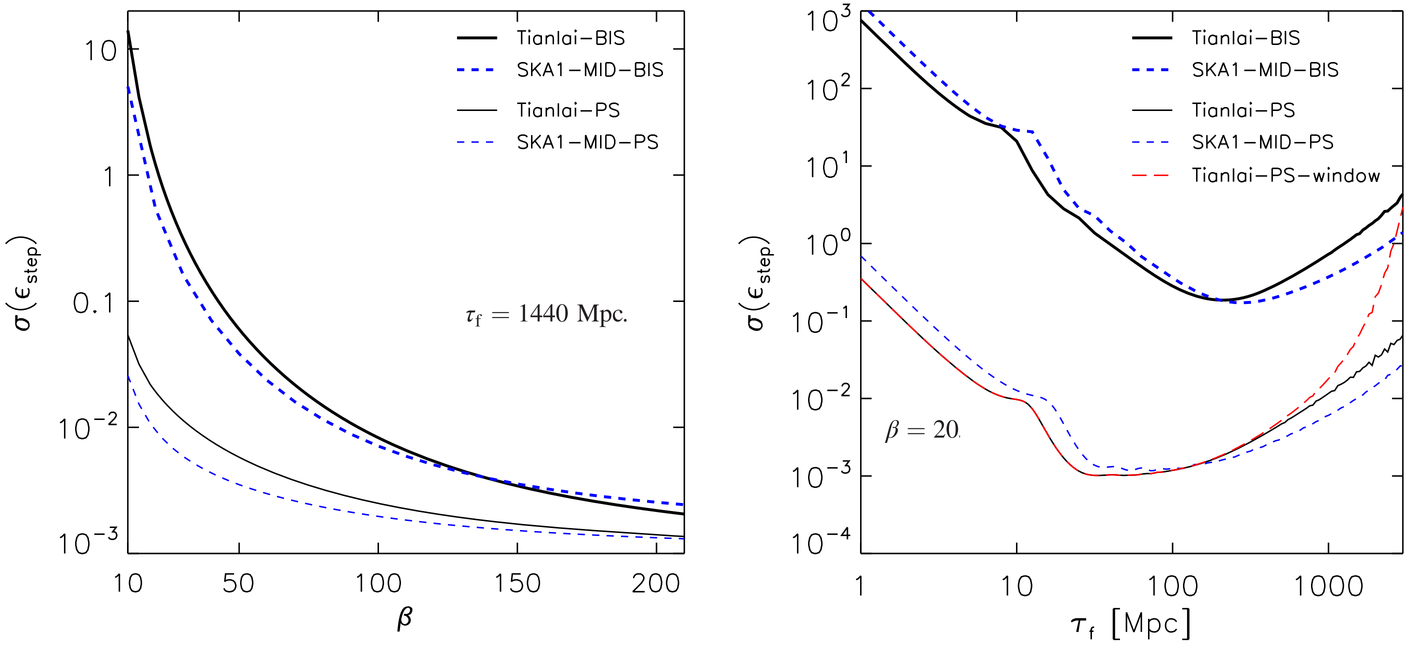


Figure 1. Non-scale invariant part of the power spectrum (3.21) for a hyperbolic tangent ste
evaluated for $\epsilon_{step} = 0.001$ and $\beta = 43\pi$ for illustration purposes.

- For $\beta \gtrsim 10$, the HI bispectrum measurements could achieve $\sigma_{\varepsilon step} \lesssim 14$ for Tianlai and $\sigma_{\varepsilon step} \lesssim 5.0$ for SKA1-MID;
- The HI power spectrum measurements could achieve $\sigma_{\varepsilon step} \lesssim 0.054$ for Tianlai and $\sigma_{\varepsilon step} \lesssim 0.026$ for SKA1-MID.



- The sensitivity increases with larger β.

Xu et al. 2016

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

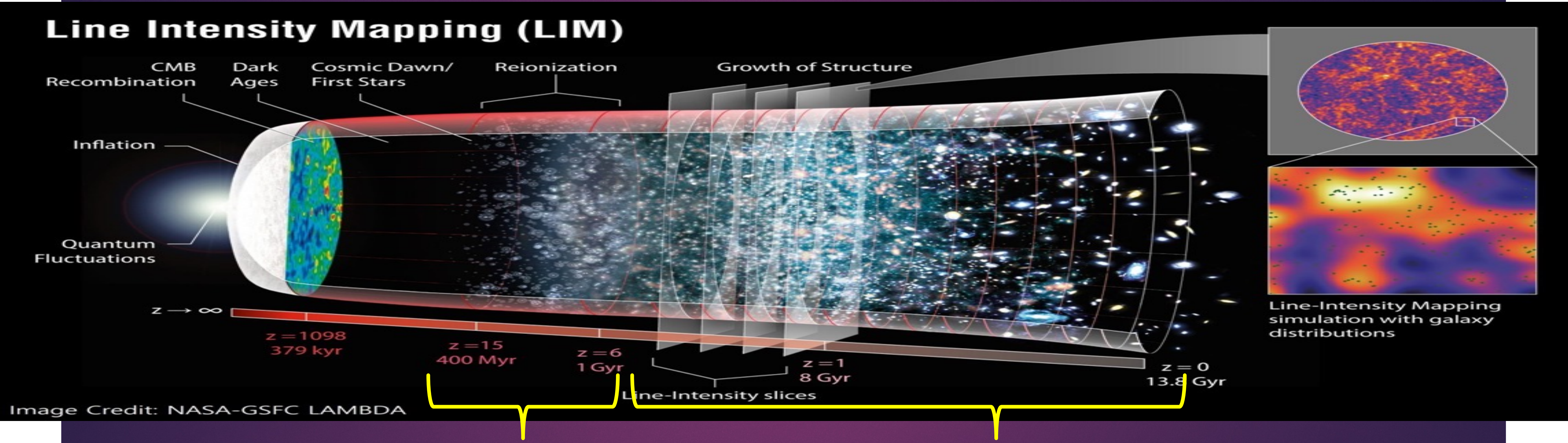


Image Credit: NASA-GSFC LAMBDA

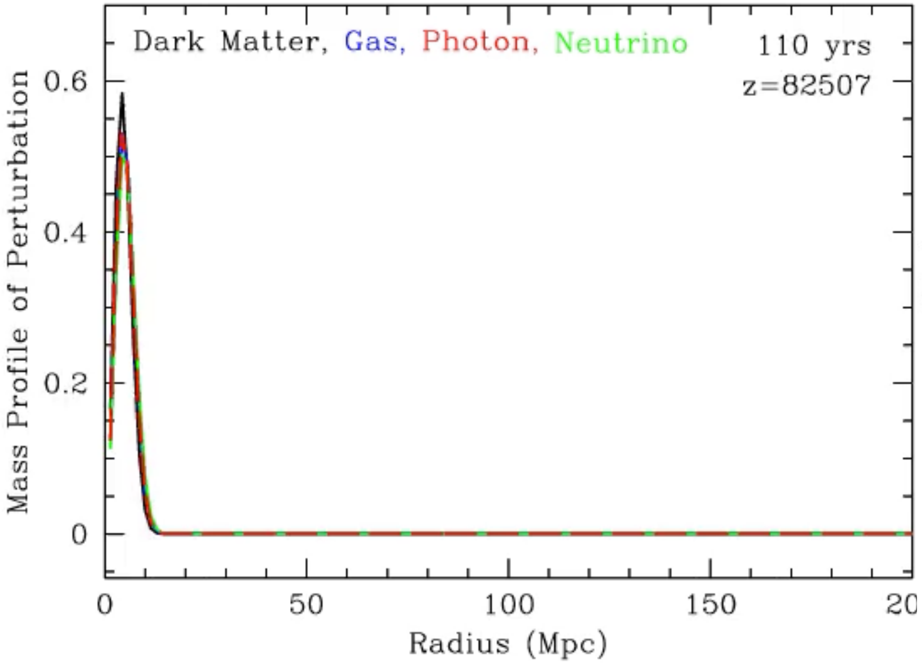
Strategy 2 -- Looking for features less vulnerable to unknown astrophysics

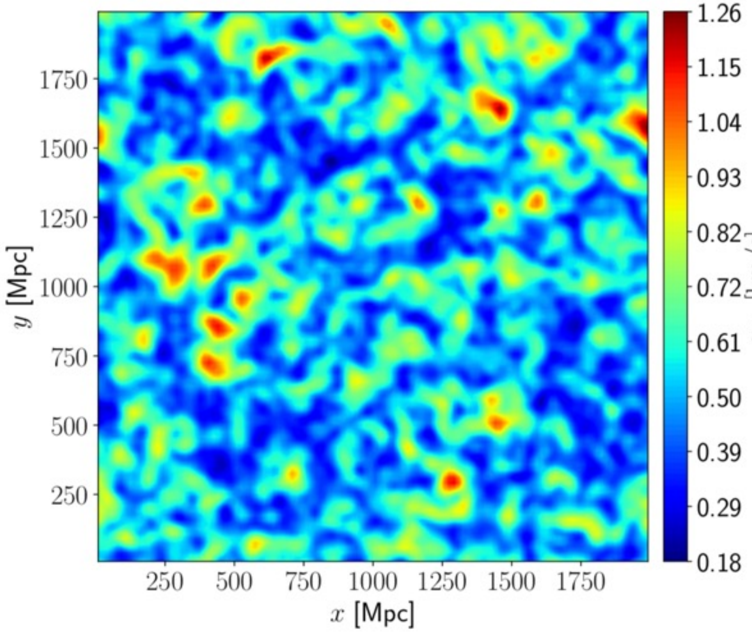
- ✓ Velocity Acoustic Oscillations (VAO) -- probe the small-scale structures with large-scale 21cm signals ➔ Dark Matter properties

- ✓ Standard ruler ➔ Dark Energy
- ✓ Go to ultra-large scales ➔ PNG, GR effects

Velocity Acoustic Oscillations (VAO) = streaming velocity + BAO

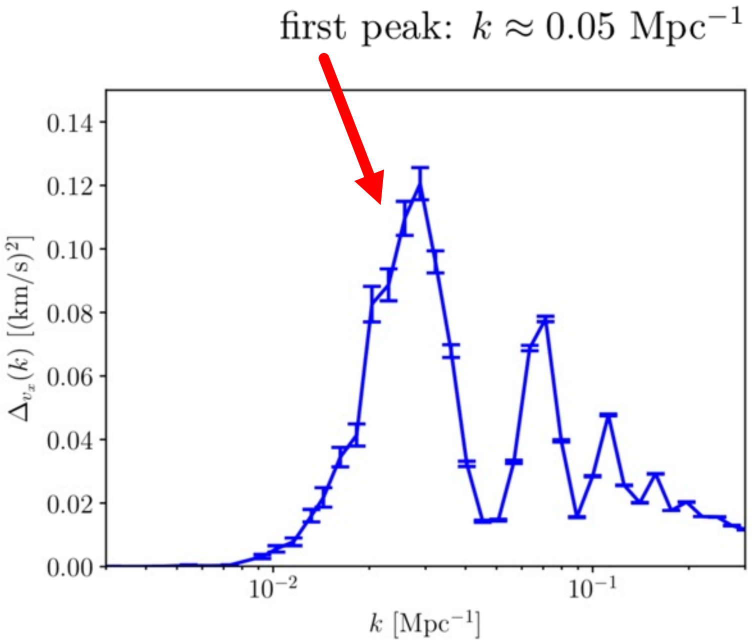
(e.g., Tseliakhovich et al. 2011)





z = 20

v_{db} field



v_{db} power spectrum

Credit:http://burro.case.edu/Academics/Astr328/Notes/StructForm/bao_1d_anim.gif

VAO features on 21 cm power spectrum

relative streaming velocity field

prevent gas collapse into DM halos with $v_c <\sim v_{db}$

suppress PopIII star formation in minihalos

Large-scale VAO features in Lyα, X-ray, and ionizing fields

Features on the large-scale distribution of the 21 cm signal

$$\sigma_{\rm rms} = \langle v_{\rm db}^2 \rangle^{1/2} \approx 30(1+z)/(1+z_{\rm rec})\ {\rm km\,s^{-1}}$$

$$\sigma_{\rm rms} \approx 0.6\ {\rm km\,s^{-1}}\ {\rm at}\ z = 20.$$

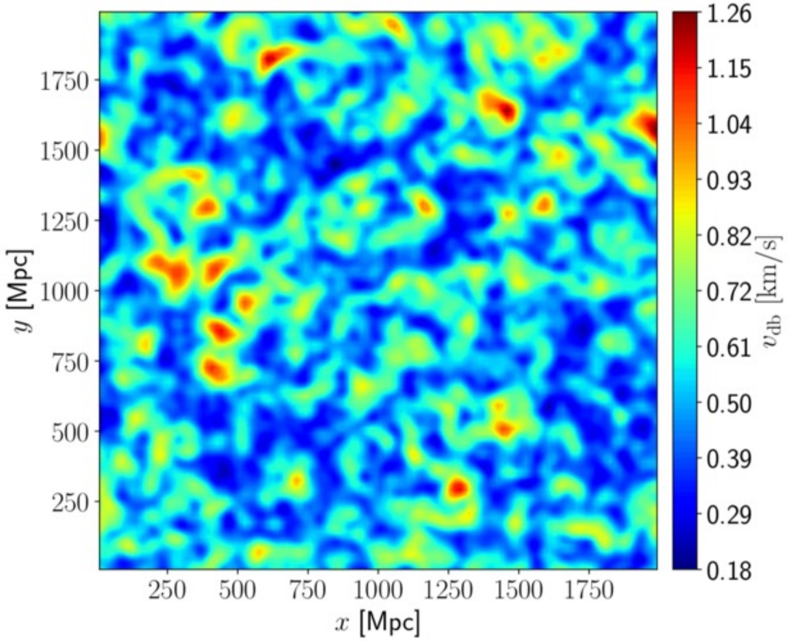
$M \sim 10^5\ M_\odot$

$v_c \sim 3\ {\rm km\,s^{-1}}$

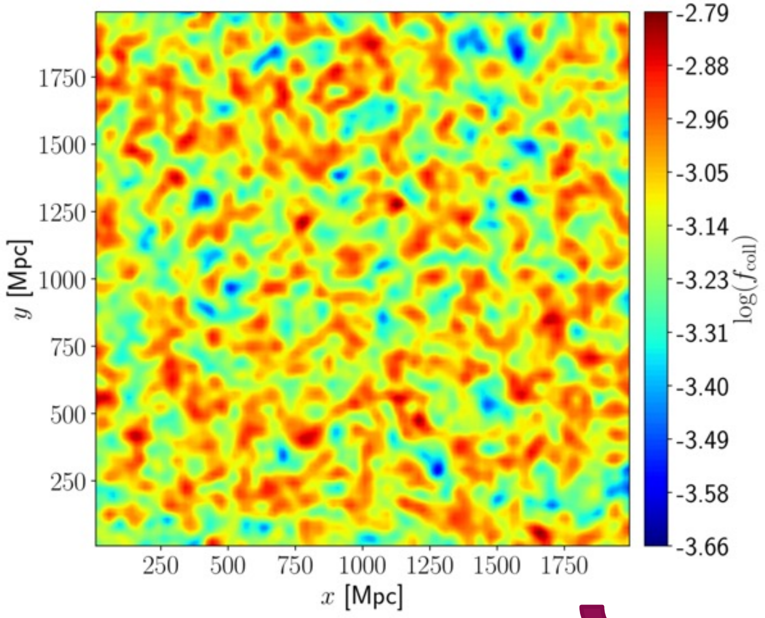
$M_{crit}(V_{db}(x))$

VAO features on 21 cm power spectrum

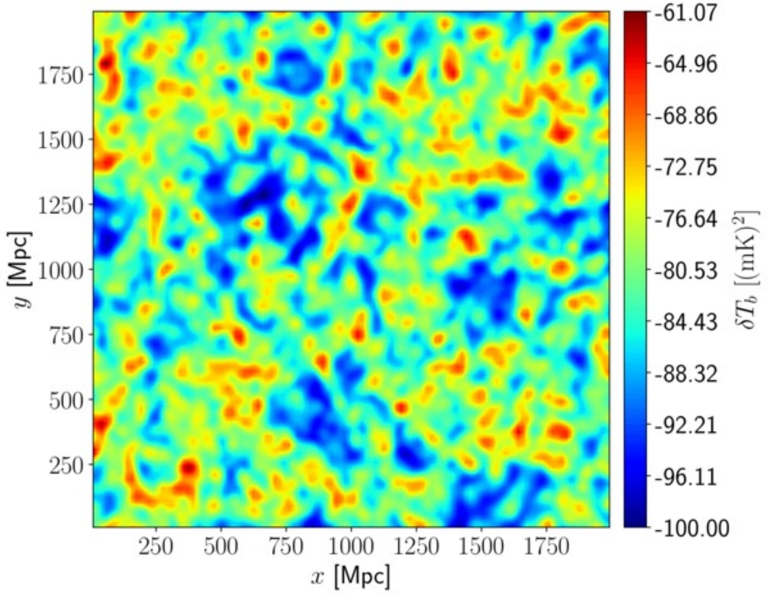
$v_{\rm db}$ field



collapse fraction



21 cm field



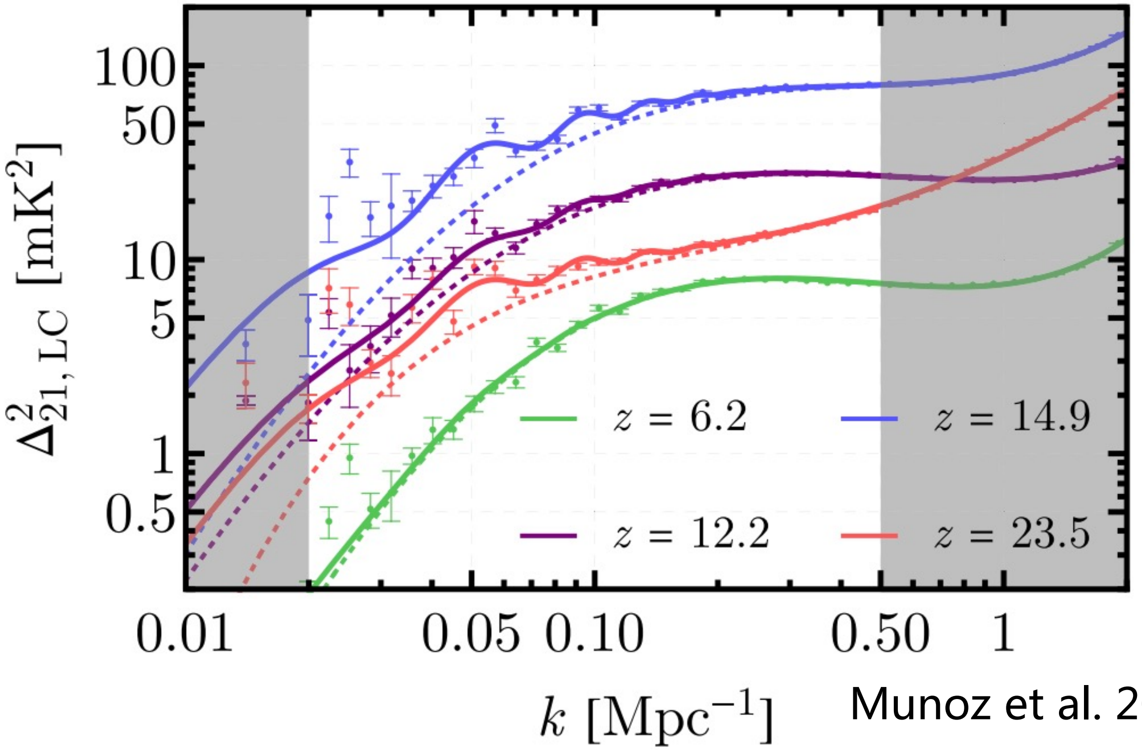
$$f_{\rm coll}(z|\delta_{\rm cell}, M_{\rm cell}, v^{\rm db}_{\rm cell}) = \int_{M_{\rm crit}(z, J^{\rm LW}_{\rm cell}, \underbrace{v^{\rm db}_{\rm cell}}_{\text{VAO}})}^{M_{\rm max}} M \frac{dn}{dM}(z|\underbrace{\delta_{\rm cell}}_{\text{BAO}}, M_{\rm cell})dM$$

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_k^{-1}}{1 + x_\alpha + x_c}$$

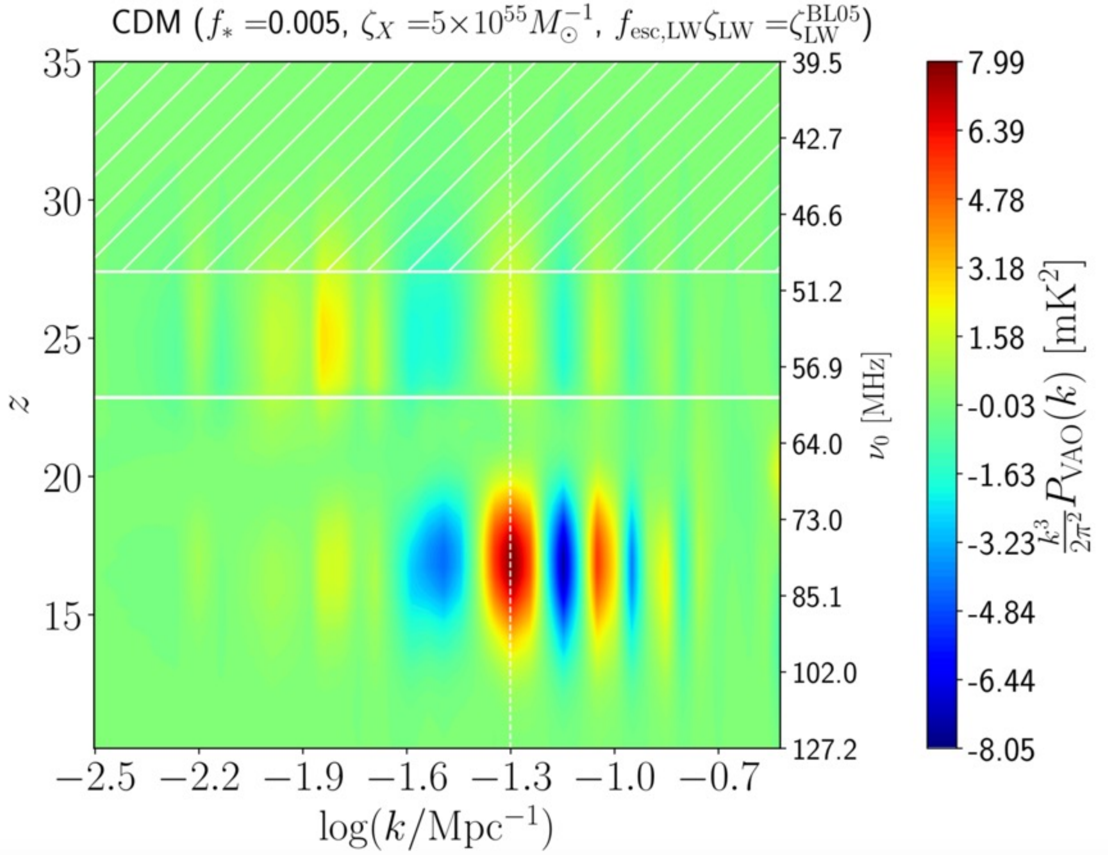
Lyα

X-ray

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



Munoz et al. 2022

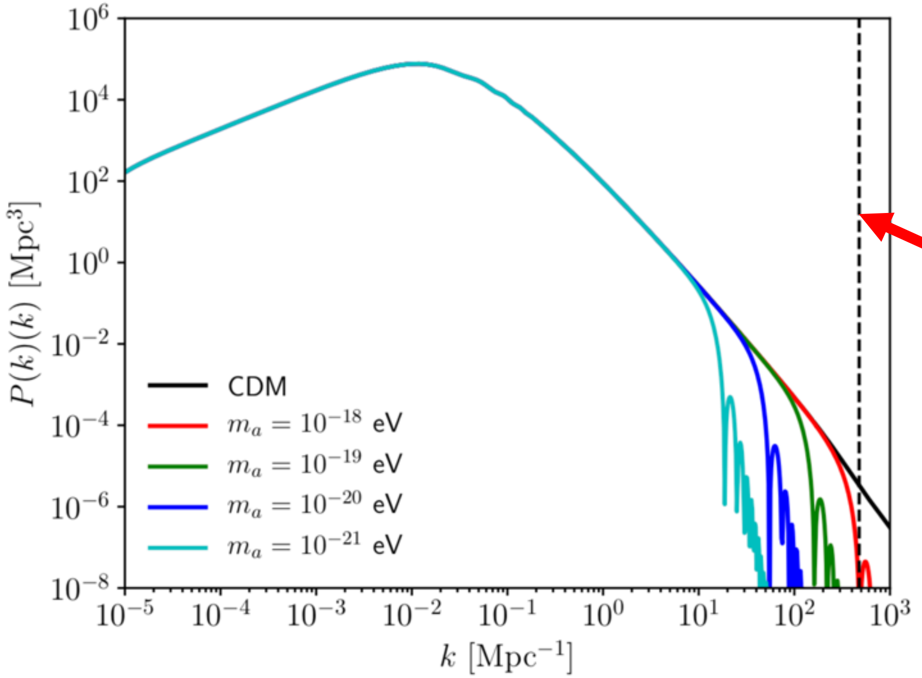


See also: Dalal+10, Visbal+12, Fialkov+12, McQuinn+12
Munoz 19, Park+19, Cain+20, Sarkar+22

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

21cm VAO features modulated by small scale structures

Cold dark matter (CDM) vs. fuzzy dark matter (FDM, e.g. axion)

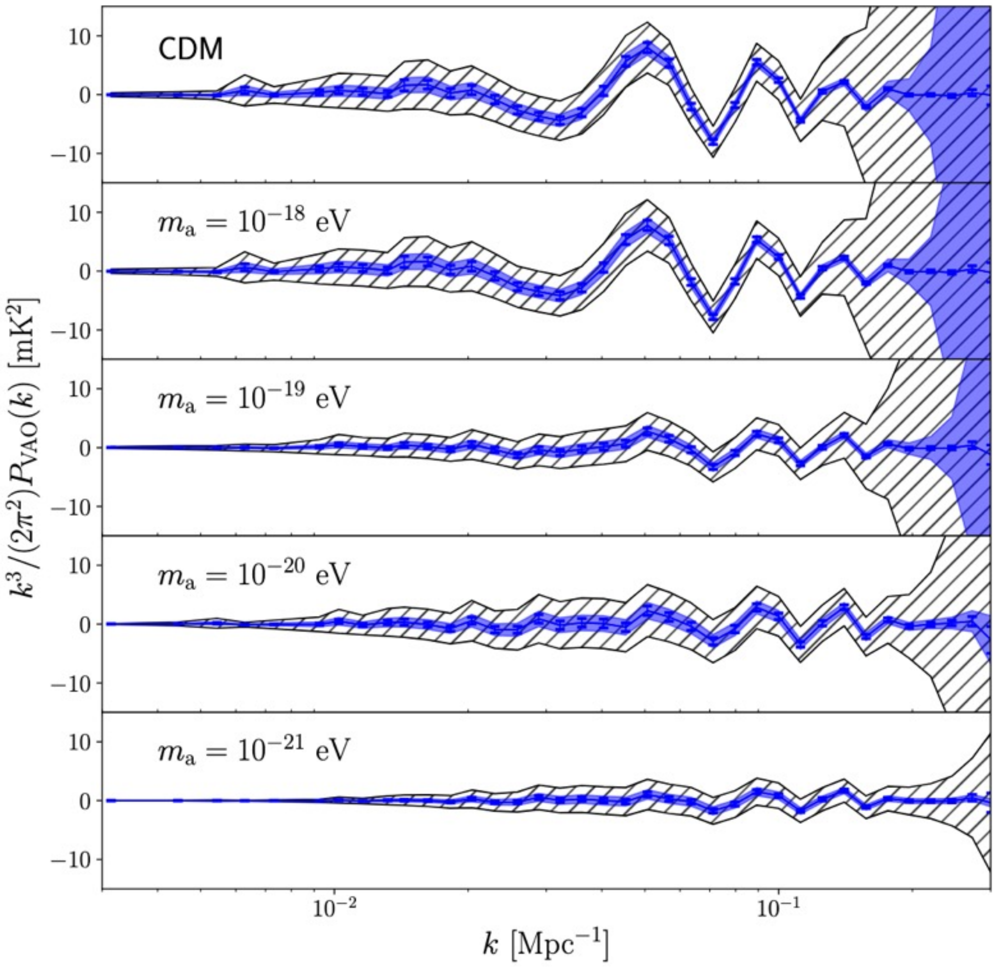


minihalo scale

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。

21cm VAO features modulated by small scale structures

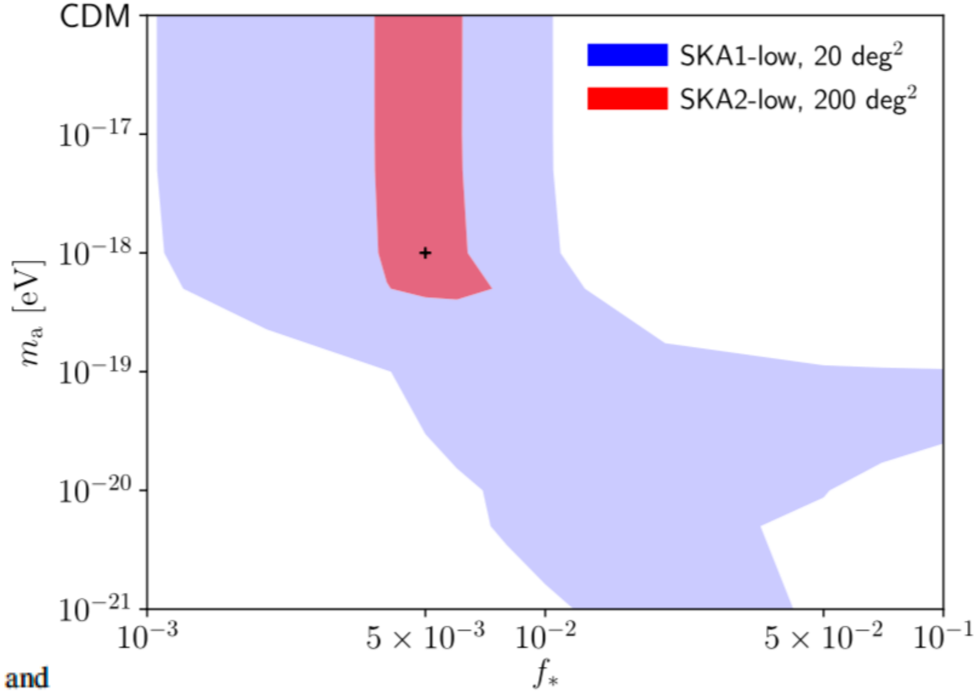
CDM vs. axion



$t_{\rm obs} = 2000$ hr and

$\Delta\nu = 20$ MHz.

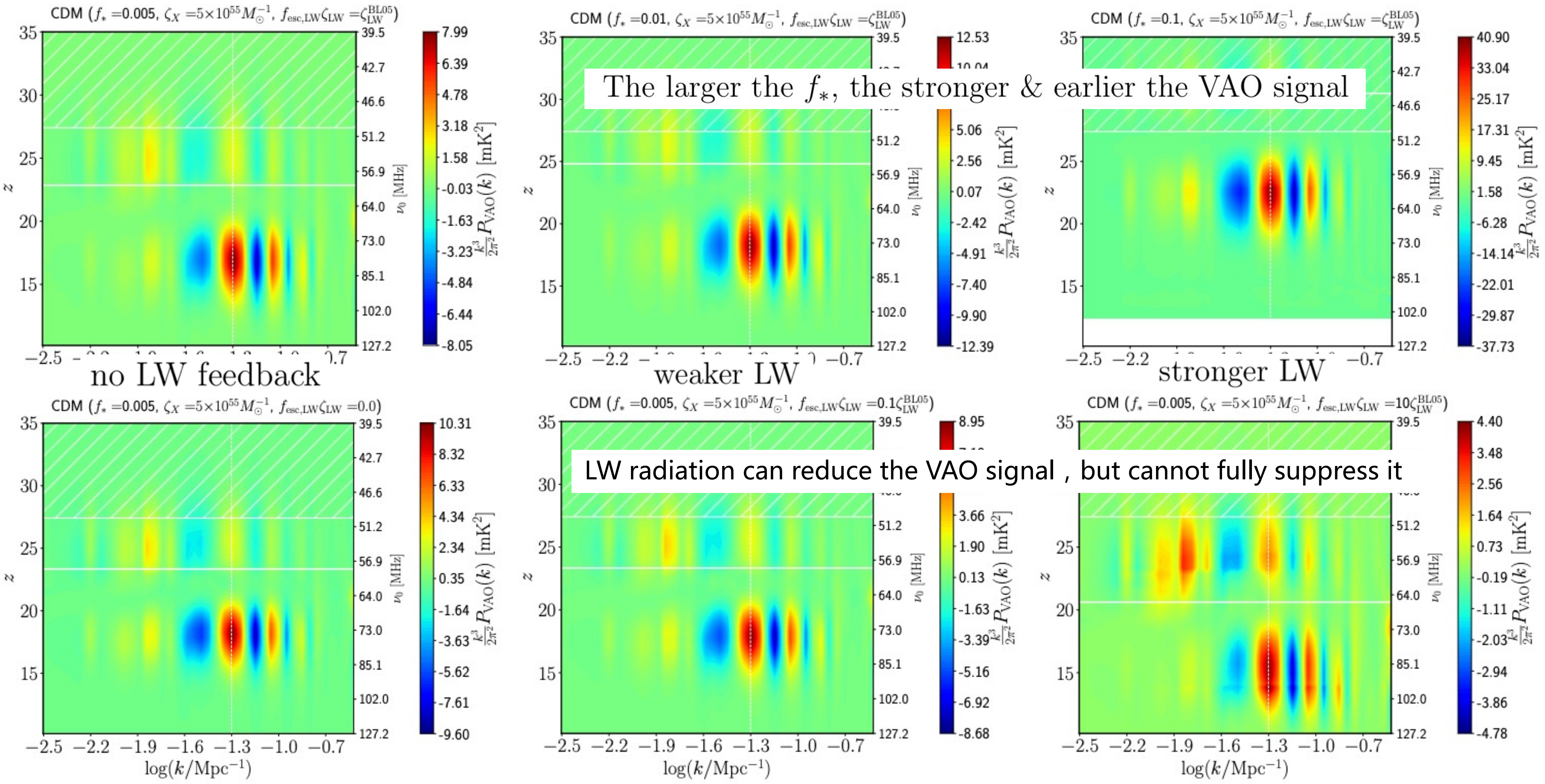
See also Hotinli et al. (2022), Sarkar et al. (2022), Flitter & Kovetz (2022), Vanzan et al. (2024)



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

The star formation efficiency & LW feedback

$f_* = 0.005$ $f_* = 0.01$ $f_* = 0.1$



The larger the f_*, the stronger & earlier the VAO signal

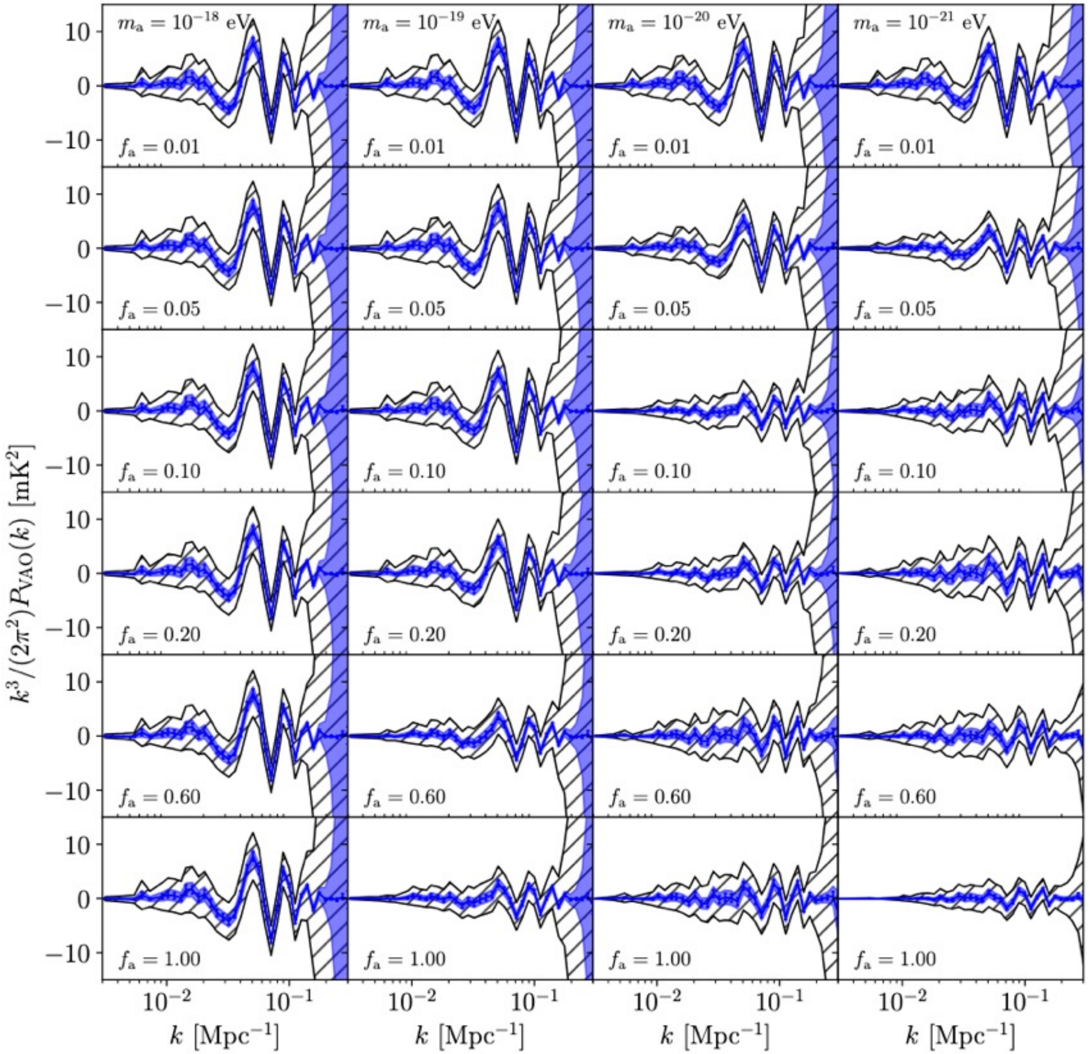
no LW feedback

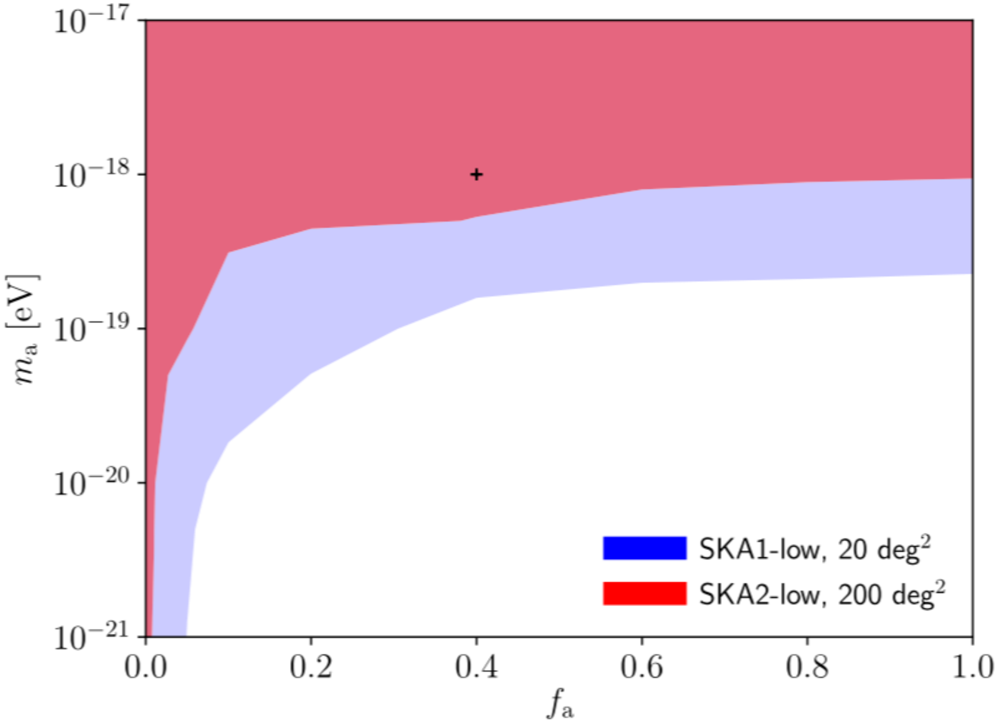
weaker LW

stronger LW

LW radiation can reduce the VAO signal，but cannot fully suppress it

The VAO signal in mixed-DM models



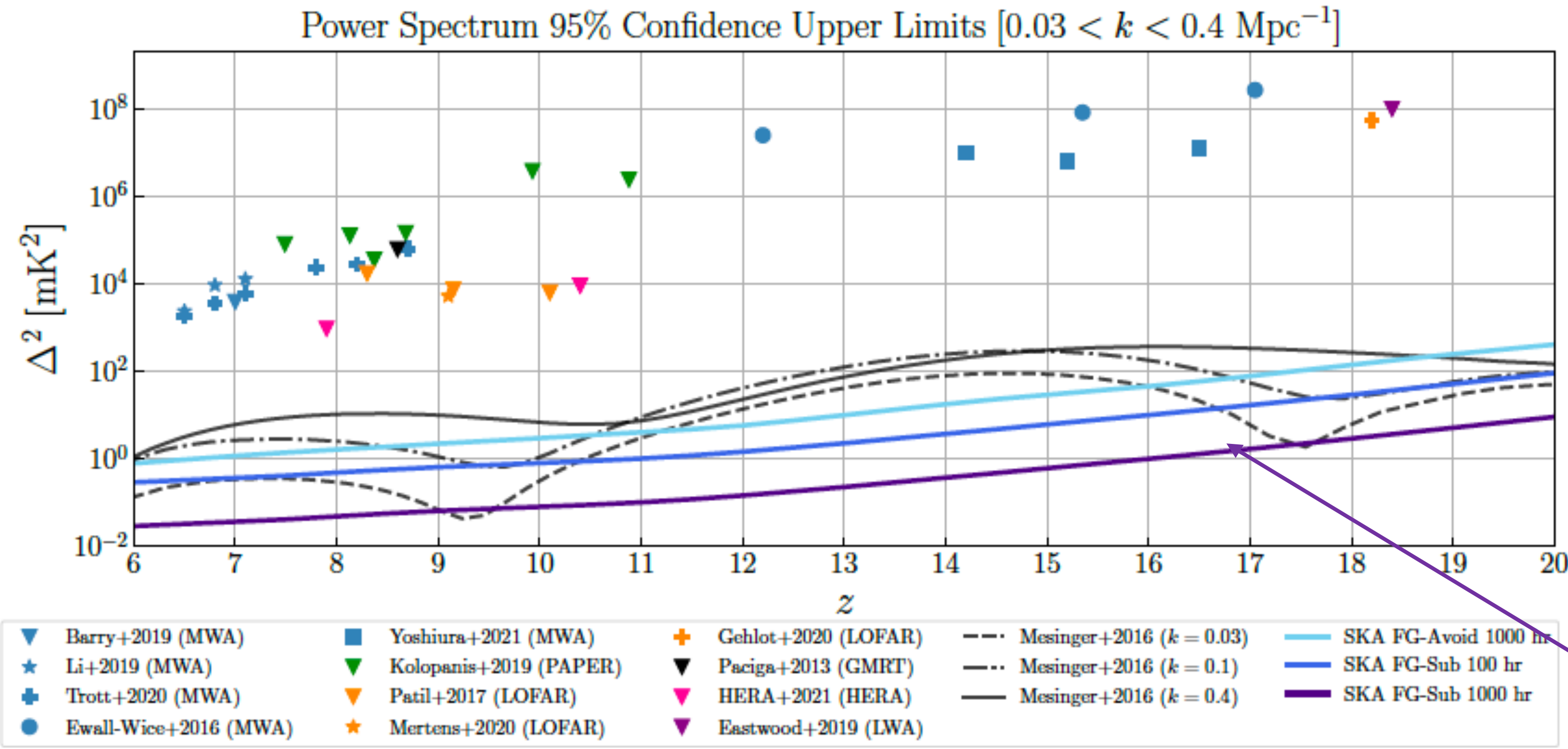


$t_{\rm obs} = 2000$ hr and

$\Delta\nu = 20$ MHz.

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

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



LOFAR

HERA

Barry et al. arXiv:2110.06173

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

Strategy 3 – Breaking the degeneracy with unknown astrophysics

✓ **21 cm Forest**

-- probing the smallest structures at cosmic dawn

➔ **Dark Matter properties**

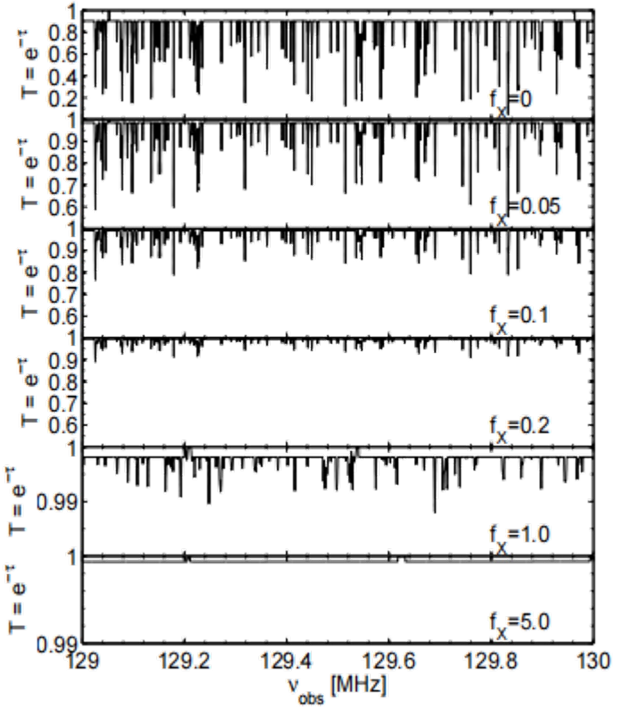
21 cm Forest
-- absorption lines against high-z radio point sources

(e.g. Carilli et al. 2002; YX et al. 2009, 2010, 2011)

21 cm Forest

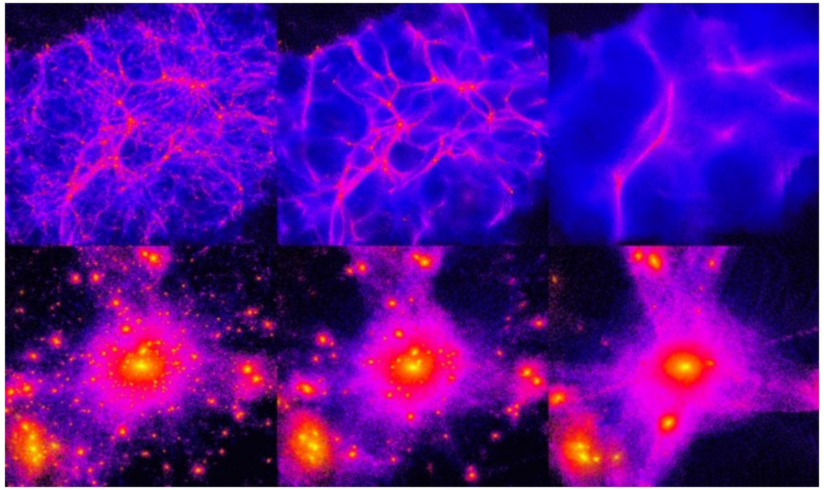
- Sensitive probe to T_{IGM}

$$\tau \propto \frac{1}{T_S}$$



Xu YD et al. 2009, 2010, 2011

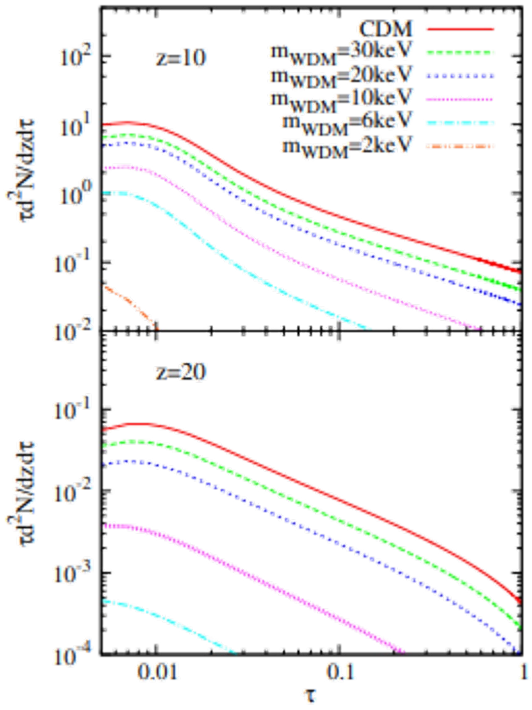
- Unique probe to small –scale structures at cosmic dawn (CD) → Dark Matter properties at CD



CDM
WIMP/AXION

WDM
Sterile
Neutrino

HDW
3 Neutrinos

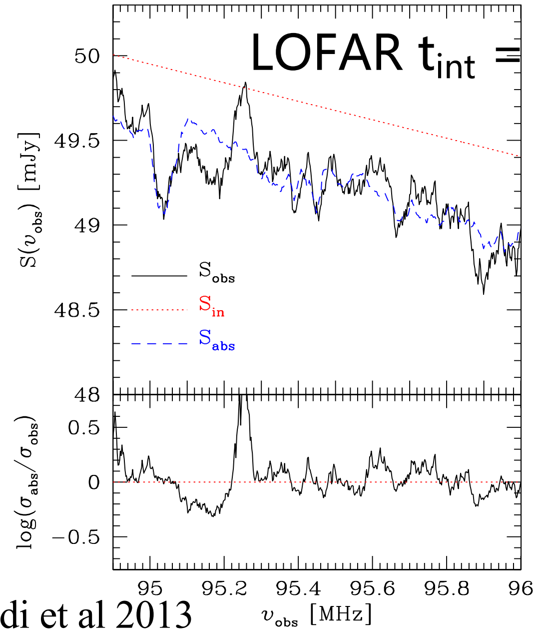


Shimabukuro et al. 2014

21-cm Forest: observational challenges

- Probing thermal history ⇔ easily suppressed (**weak**)

$$\tau \propto \frac{1}{T_S}$$

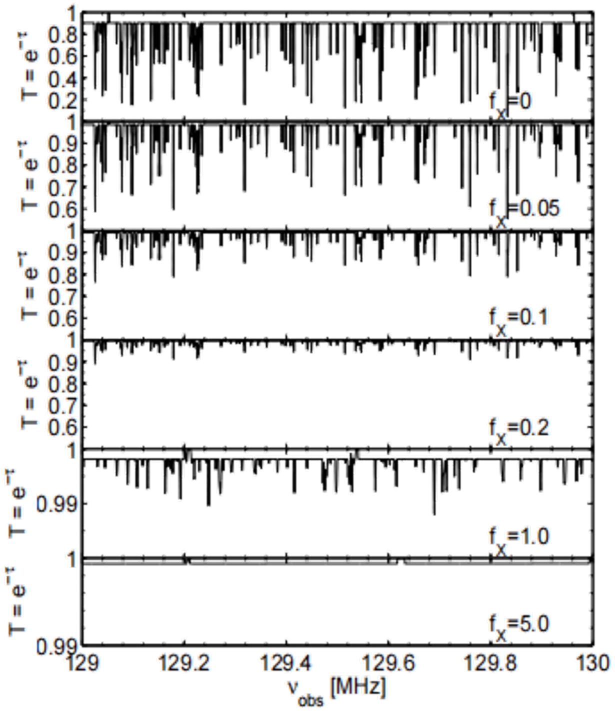


LOFAR t_{int} = 1000 hr

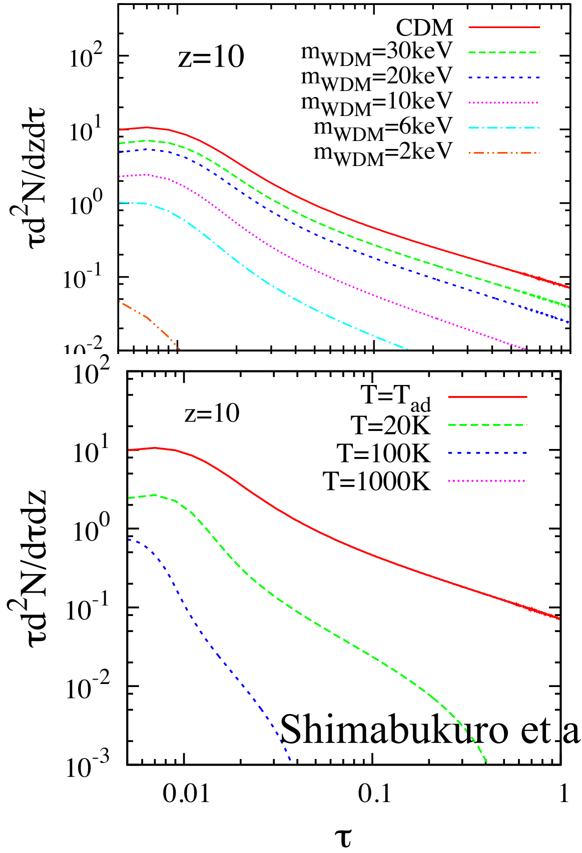
Ciardi et al 2013

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 $S_{\rm in}(z_s) = 50$ mJy. The lines are the same as those in Figure 10. Here we have assumed the noise σ_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



Xu YD et al. 2011



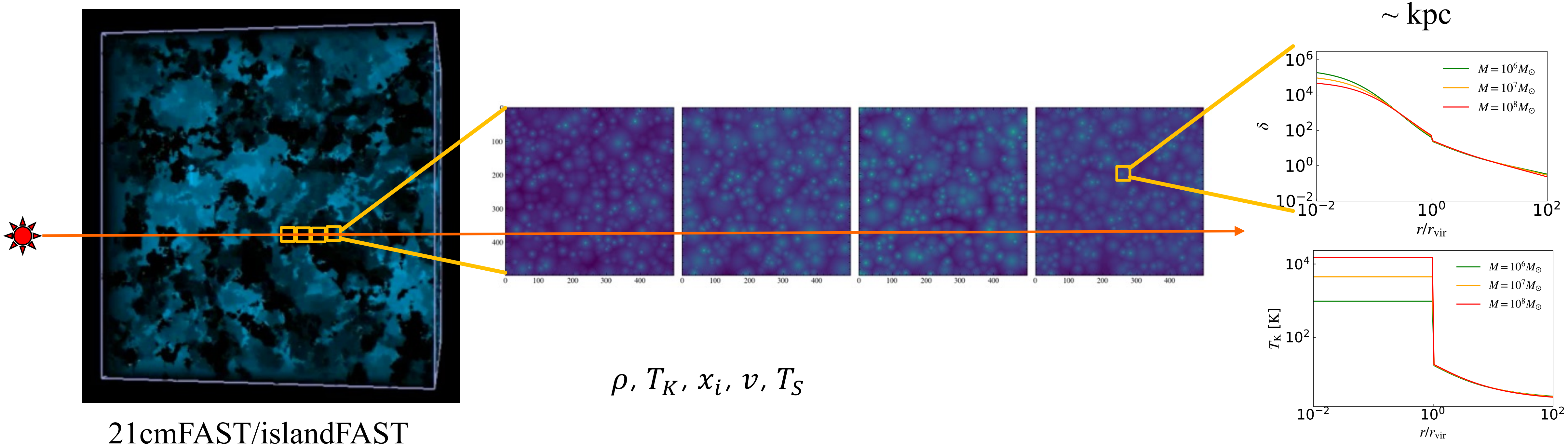
Shimabukuro et al. 2014

Key strategy #1: multi-scale hybrid modeling

- Large scales: semi-numerical simulation
- Small scales: analytic modeling

Box 1 Gpc → 500^3 Grids

2 Mpc → 500^3 Voxels



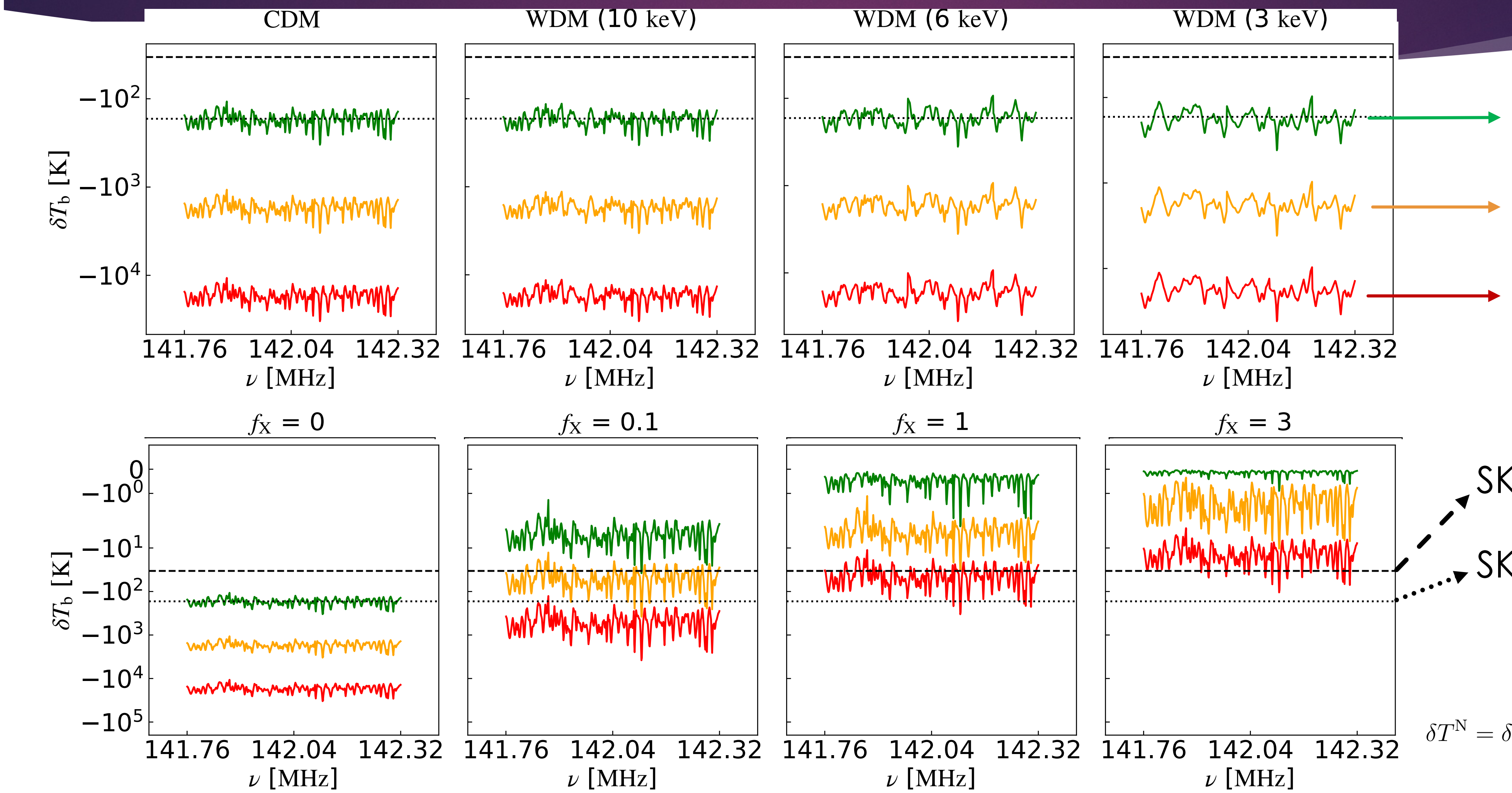
ρ, T_K, x_i, v, T_S

21cmFAST/islandFAST

XuYD et al. 2017

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

The mock 21 cm signals



S_{150} = 1 mJy

S_{150} = 10 mJy

S_{150} = 100 mJy

	$A_{\rm eff}/T_{\rm sys}$ =
SKA2-Low	4000 $\rm m^2\ K^{-1}$
SKA1-Low	800 $\rm m^2\ K^{-1}$

100 hr, 1 kHz

$$\delta T^{\rm N} = \delta S^{\rm N}\left(\frac{\lambda_z^2}{2k_{\rm B}\Omega}\right) \approx \frac{\lambda_z^2 T_{\rm sys}}{A_{\rm eff}\Omega\sqrt{2\delta\nu\delta t}},$$

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

- Cross-correlate two measurements to suppress the noise

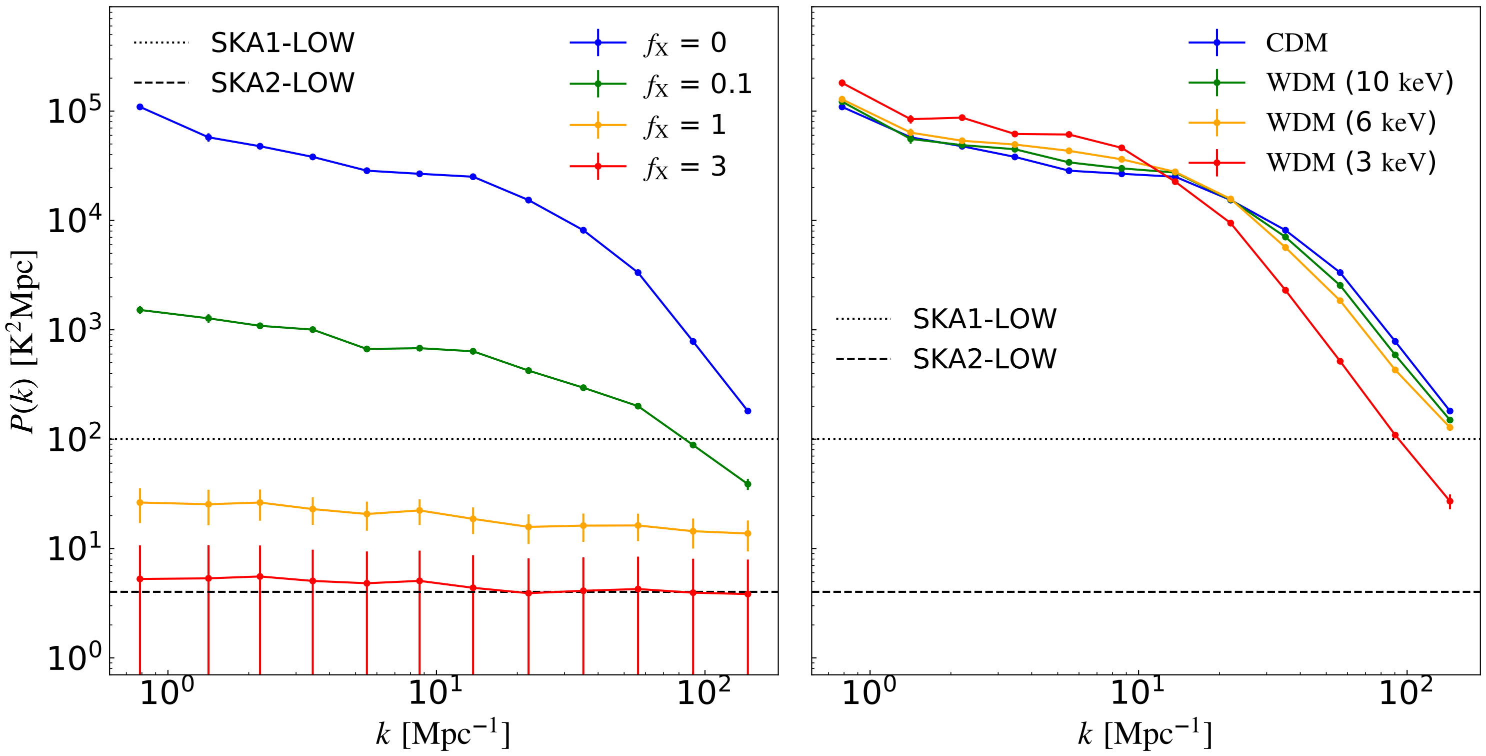
~ 10 sources with S_{150} = 10 mJy at z = 9

$$P\left(\hat{\boldsymbol{s}}, k_{\parallel}\right) = \left|\delta \widetilde{T}'\left(\hat{\boldsymbol{s}}, k_{\parallel}\right)\right|^2 \left(\frac{1}{\Delta r_z}\right)$$

$$P^S = \sigma_P(k)/\sqrt{N_s \cdot N_m}$$

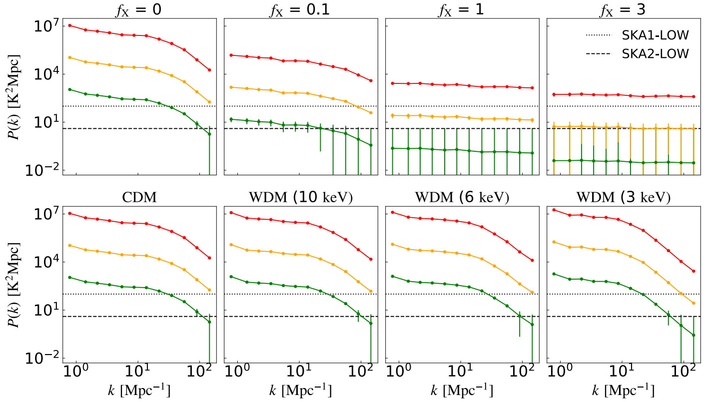
$$P^N = \frac{1}{\sqrt{N_s}} \left(\frac{\lambda_z^2 T_{\rm sys}}{A_{\rm eff}\Omega}\right)^2 \left(\frac{\Delta r_z}{2\Delta\nu_z \delta t_{0.5}}\right)$$

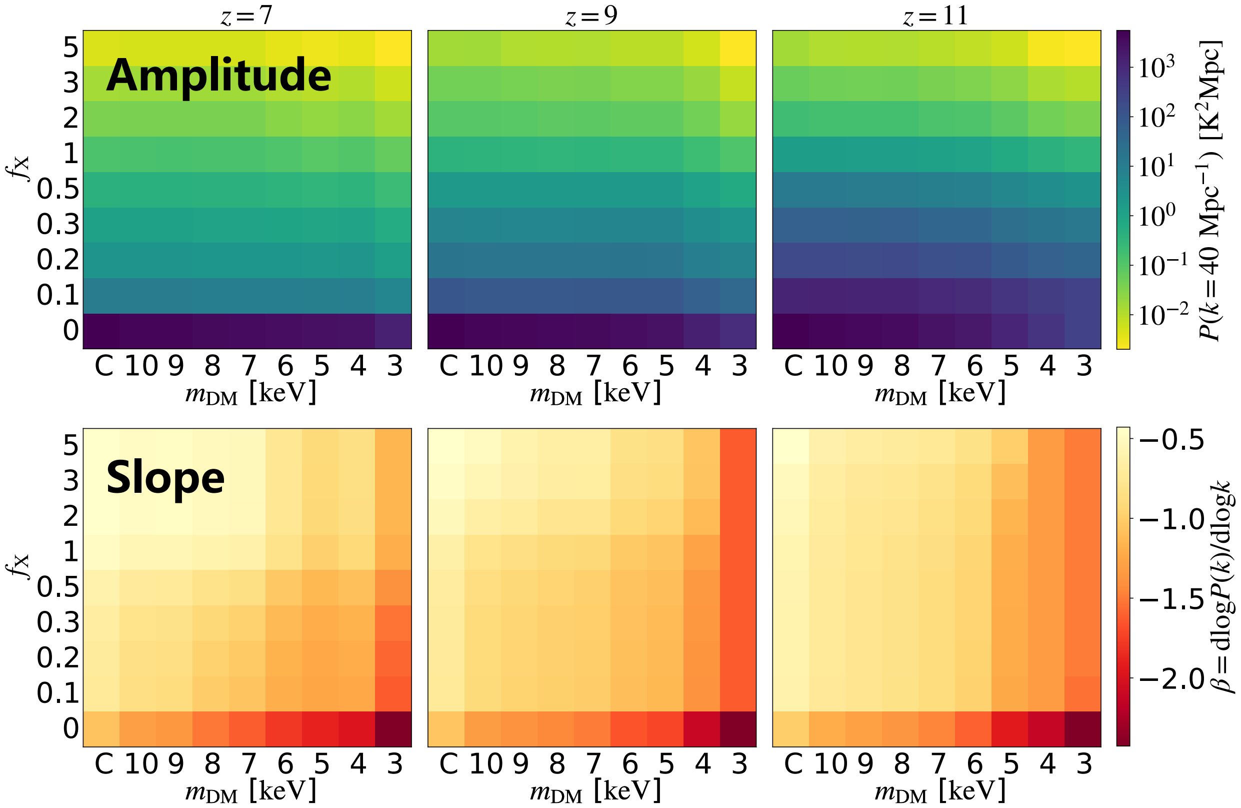
$t_{\rm int}$ = 2 * 50 hr



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

1-D cross-power spectrum ➔ Two birds with one stone





- Scientifically:

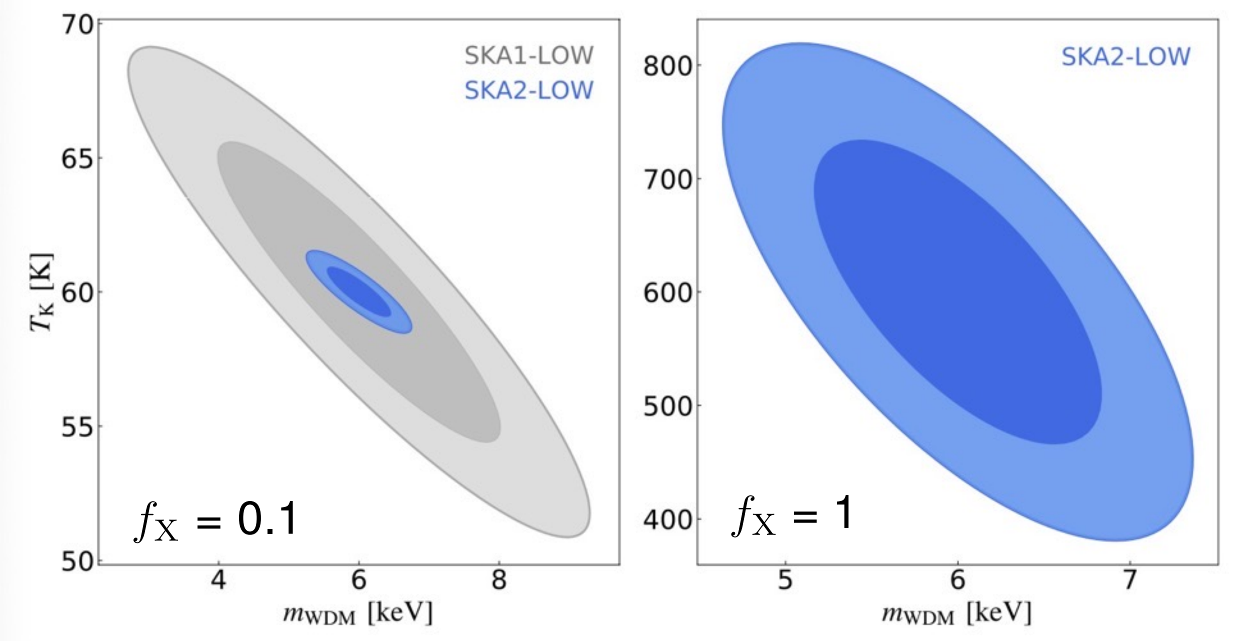
1. DM particle mass
2. Cosmic thermal history

- Technologically:

1. Increase the sensitivity → feasible
2. Breaking the degeneracy → simultaneous constraints

21 cm forest: a simultaneous probe of DM & first galaxies

Using ~ 10 sources with S_{150} = 10 mJy at z = 9



- **For SKA1-Low:**

$$\sigma_{m_{\rm WDM}} = 1.3\ \text{keV and}\ \sigma_{T_{\rm IGM}} = 3.7\ \text{K}$$

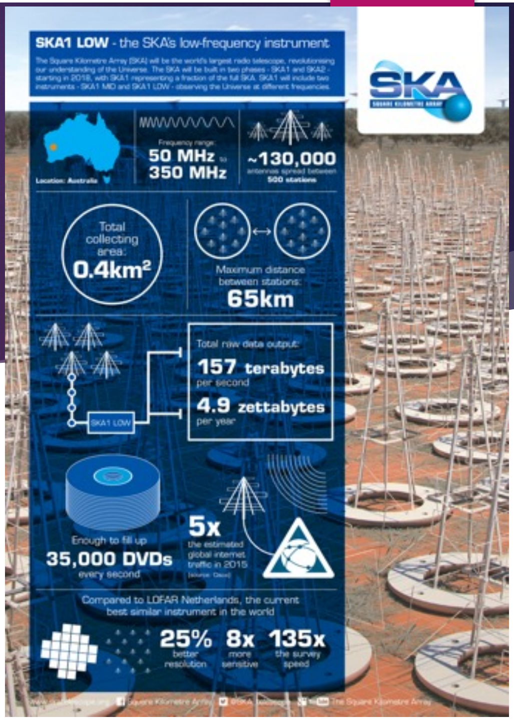
- **For SKA2-Low:**

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

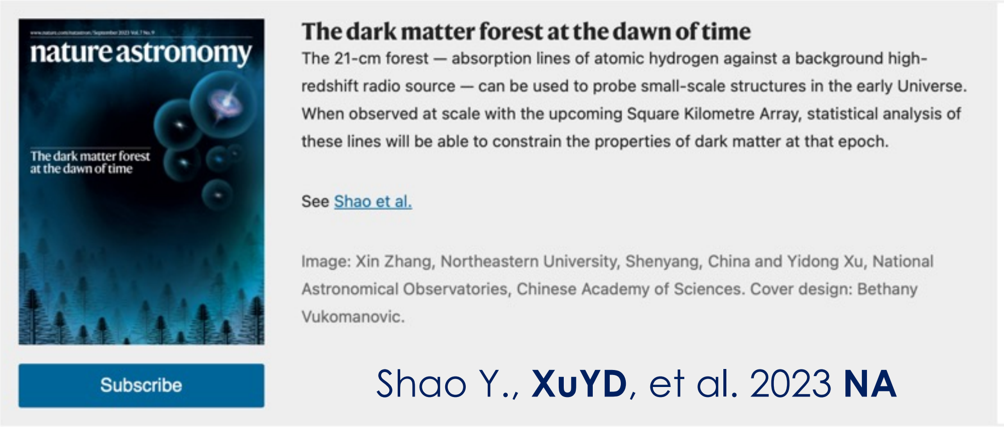
- **For SKA2-Low:**

$$\sigma_{m_{\rm WDM}} = 0.6\ \text{keV}$$

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



Volume 7 Issue 9, September 2023



The dark matter forest at the dawn of time

The 21-cm forest — absorption lines of atomic hydrogen against a background high-redshift 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!

- Vital to avoid/distinguish from astrophysical uncertainties!
- **Strategy 1** -- Looking for features not affected by later baryonic physics
  - ✓ The cosmological standard ruler – **21 cm BAO** -- Dark Energy -- comparable to stage IV
  - ✓ 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
  - ✓ **21cm VAO** -- probe the small-scale structures with large-scale 21cm signals → distinguish DM models
- **Strategy 3** – Breaking the degeneracy with unknown astrophysics
  - ✓ **21 cm Forest** -- probing the smallest structures at cosmic dawn a ***simultaneous probe*** of DM & first galaxies

Thank you!