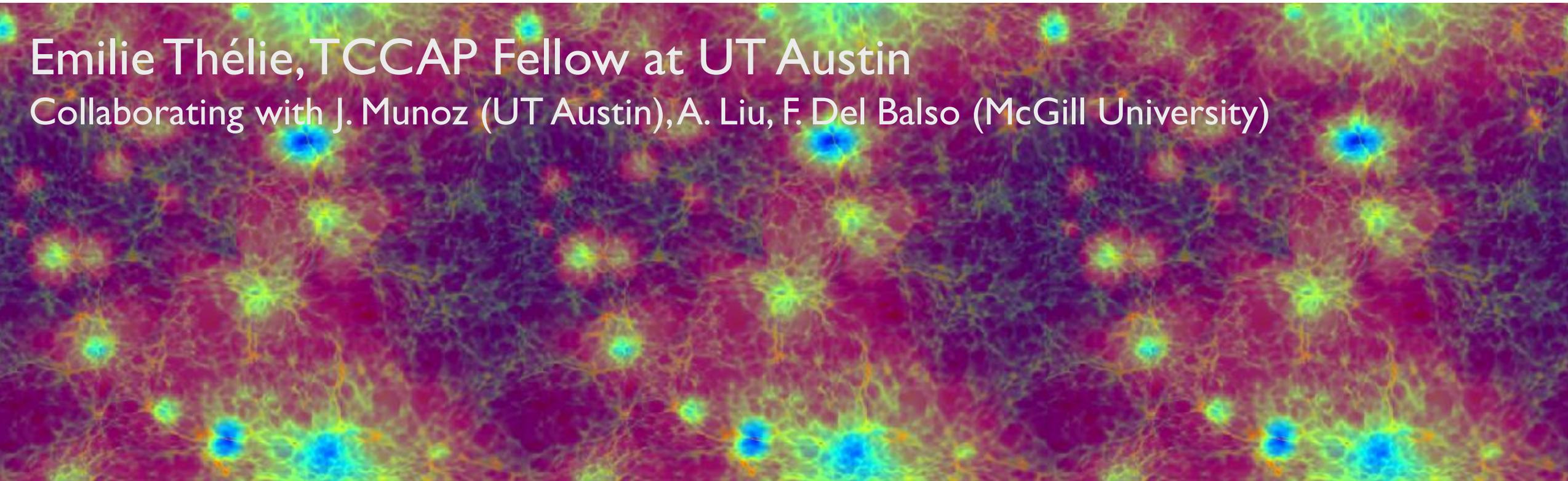


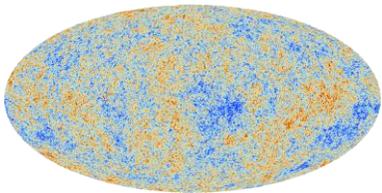
# Constraining cosmology from reionisation bubbles using an Alcock-Paczynski test

Emilie Th  lie, TCCAP Fellow at UT Austin

Collaborating with J. Munoz (UT Austin), A. Liu, F. Del Balso (McGill University)

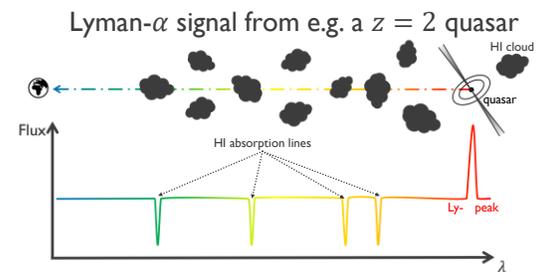
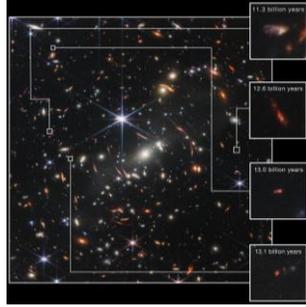


# The Epoch of Reionisation (EoR)

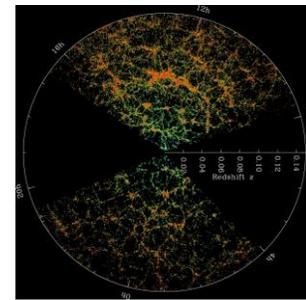
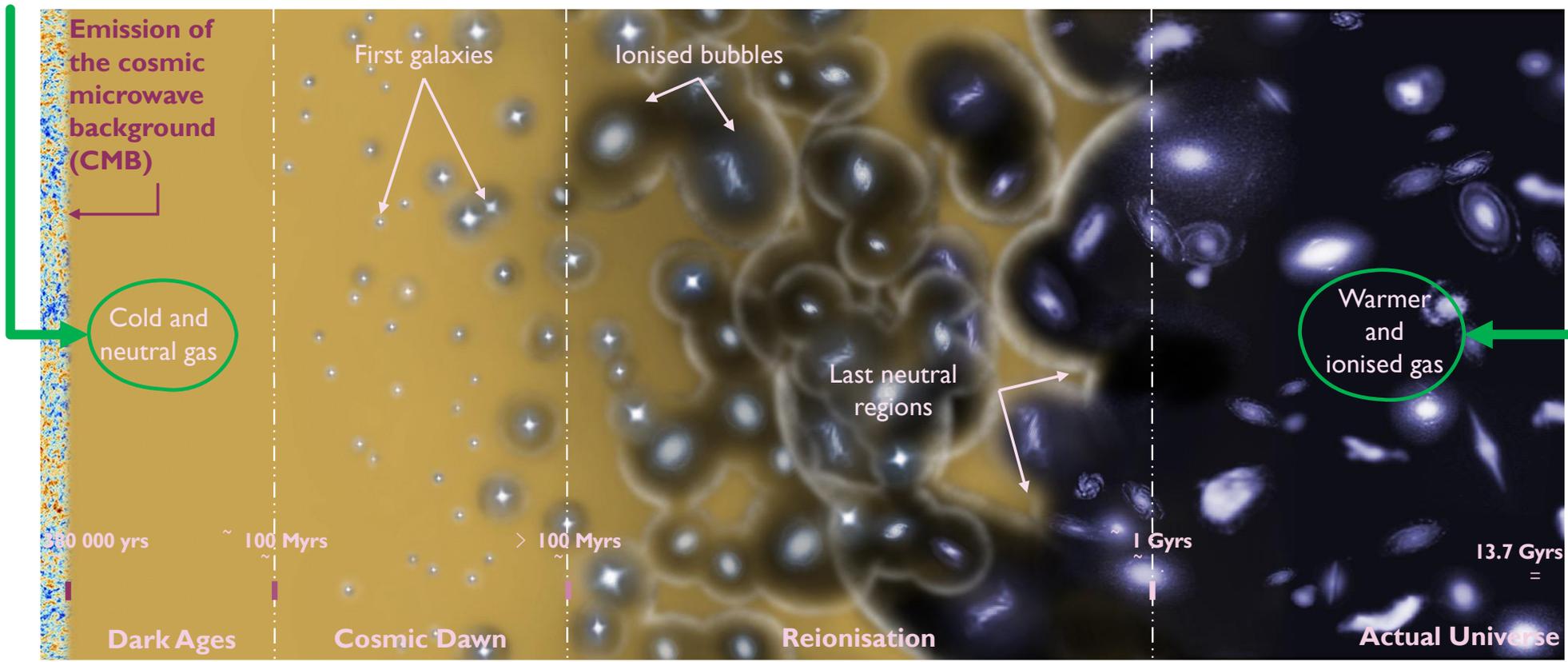


After the emission of the **CMB**, all the gas of the Universe is **neutral**.

**Epoch of Reionisation**  
 Last big transition of our Universe: the intergalactic gas goes from **totally neutral** to **totally ionised**



We know that **today** the gas of the Universe is **ionised**.



Timeline from CMB  
 Credit: ESA

# Constraining cosmology with Alcock-Paczynski tests

## Introduction

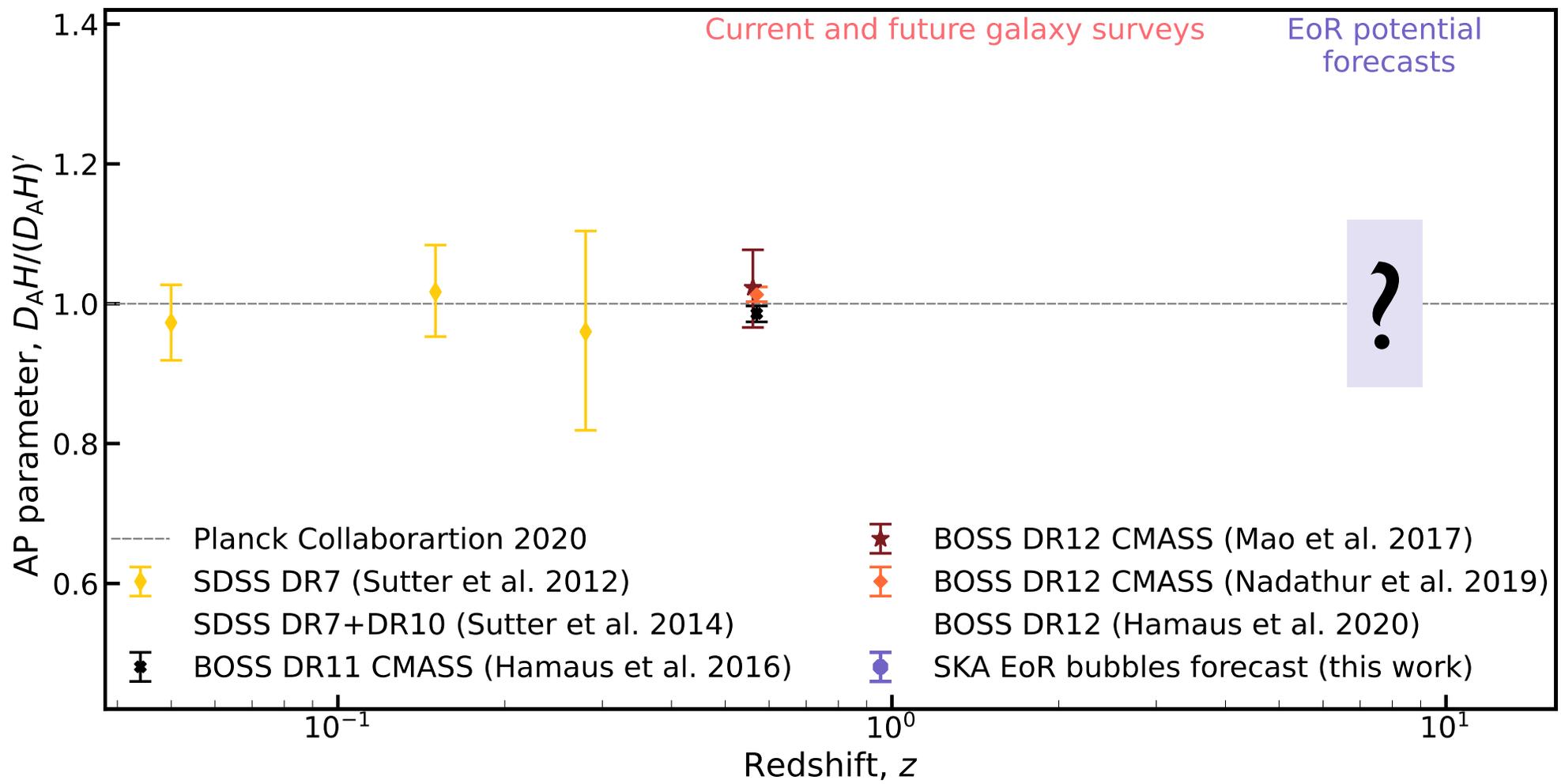
Thelie+25

**MY AIM: put constraints on the product  $D_A H$  at reionisation redshifts**

$D_A$ : comoving angular diameter distance  
 $H$ : Hubble rate

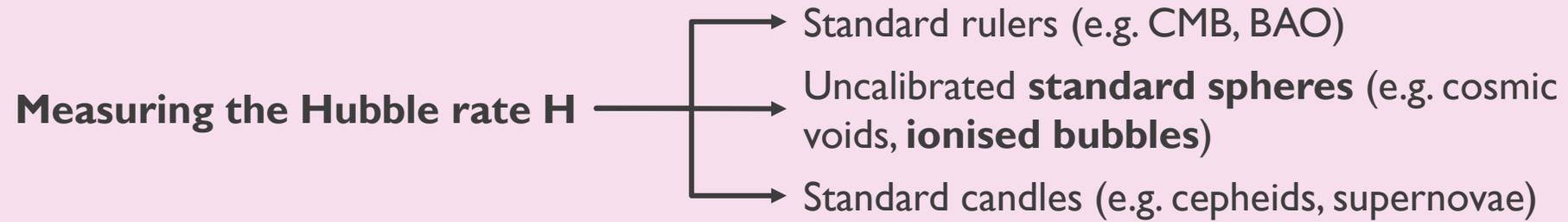
Current constraints:

- As compared to Planck+20 results ( $D'_A H'$ )
- Obtained from **cosmic voids**
- At **redshifts  $< 0.6$**



# Constraining cosmology with Alcock-Paczynski tests

## Introduction



# Constraining cosmology with Alcock-Paczynski tests

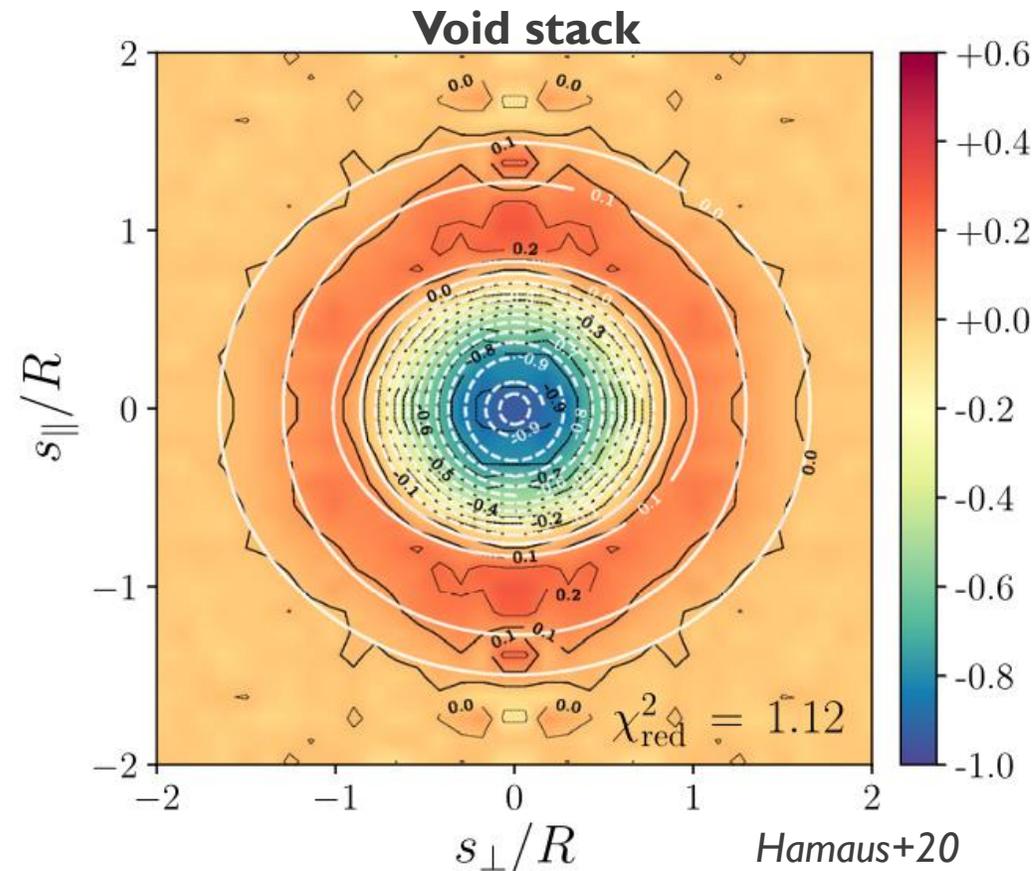
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Measuring the Hubble rate  $H$

Standard rulers (e.g. CMB, BAO)

Uncalibrated **standard spheres** (e.g. cosmic voids, ionised bubbles)

Standard candles (e.g. cepheids, supernovae)



Example with **cosmic voids (Hamaus+20)**:

- **Cosmic voids** = uncalibrated standard spheres (size unknown)
- **Identification of voids** using galaxy surveys
- **Stacking of voids**
- **Alcock-Paczynski (AP) test** to constrain  $D_A H$  among other parameters

# Constraining cosmology with Alcock-Paczynski tests

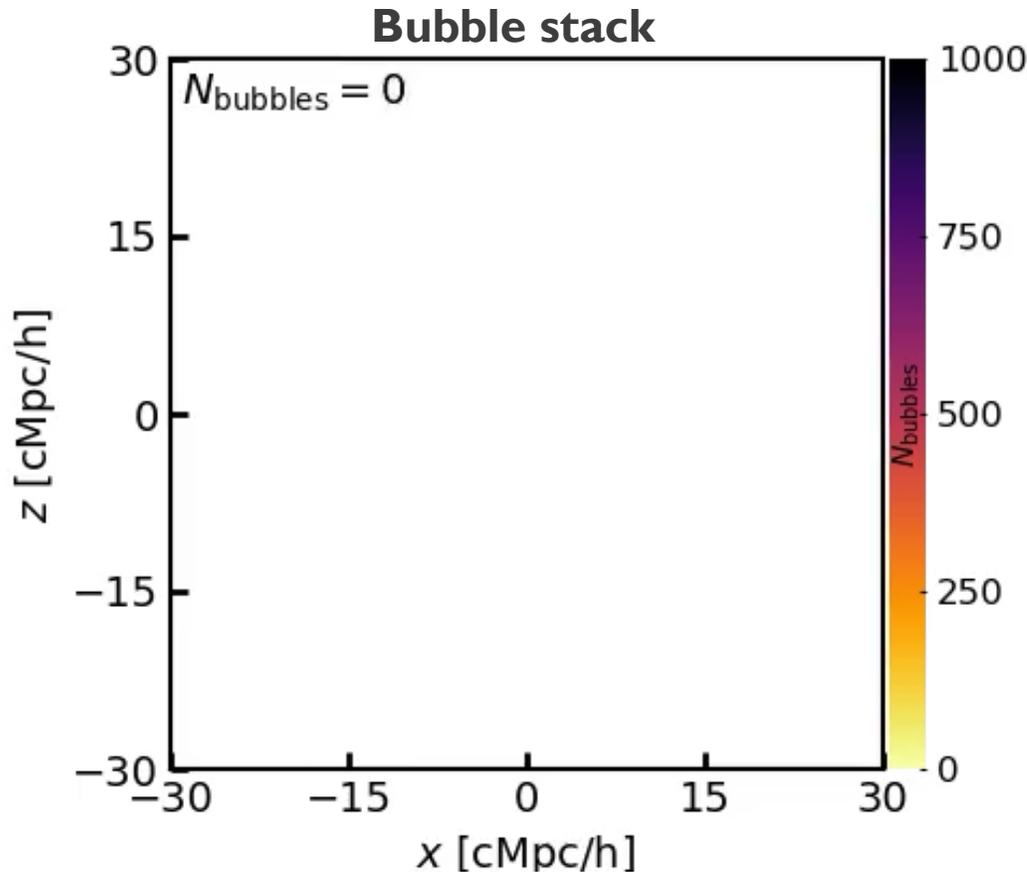
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### In this work:

- **Ionised bubbles** = uncalibrated standard spheres (size unknown)
- **Identification** of **bubbles** using reionisation observations
- **Stacking** of **bubbles**
- **AP test** to constrain  $D_A H$

# Constraining cosmology with Alcock-Paczynski tests

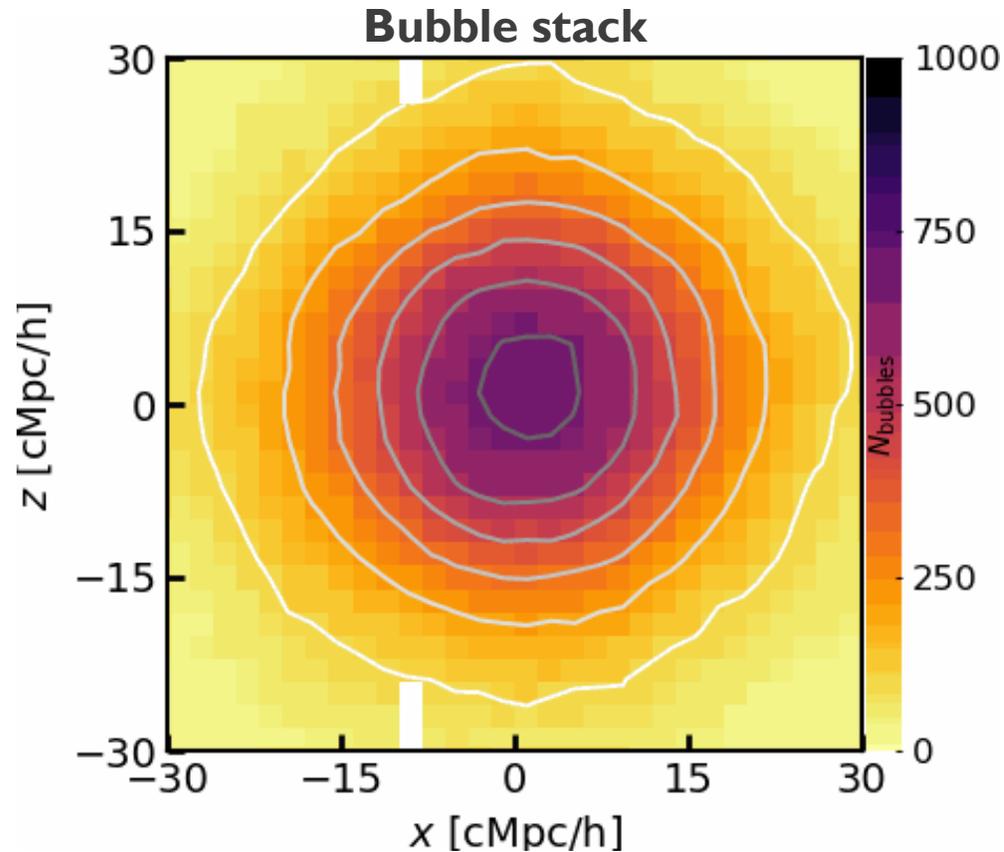
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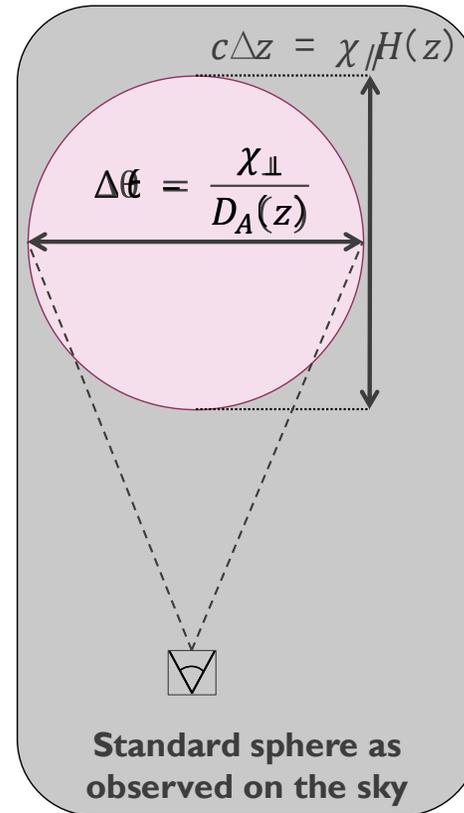
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# Constraining cosmology with Alcock-Paczynski tests

AP test

- Use of observed "standard spheres" (e.g. cosmic voids) to **constrain the expansion history of the Universe**
- Standard spheres in our case: **ionized bubbles** during Reionisation

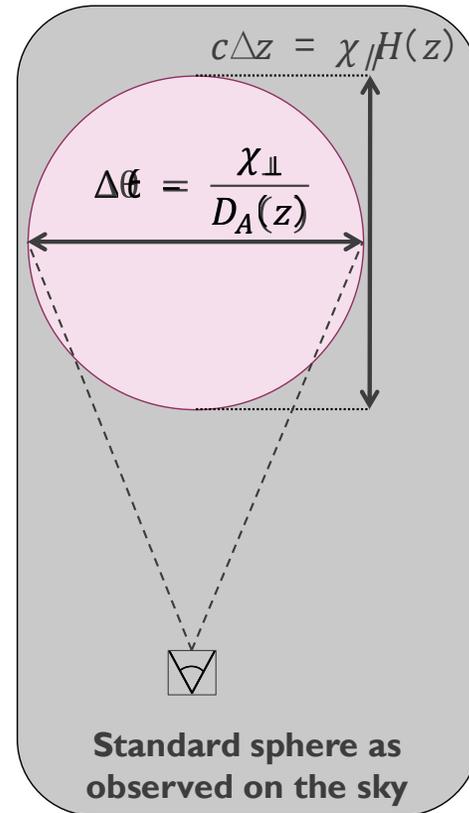


*Thelie+25*

# Constraining cosmology with Alcock-Paczynski tests

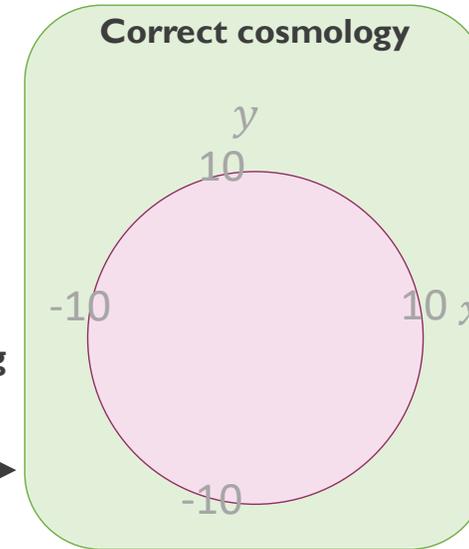
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- **Geometrical distortions** when **converting sky angles to comoving distances**



*Theilie+25*

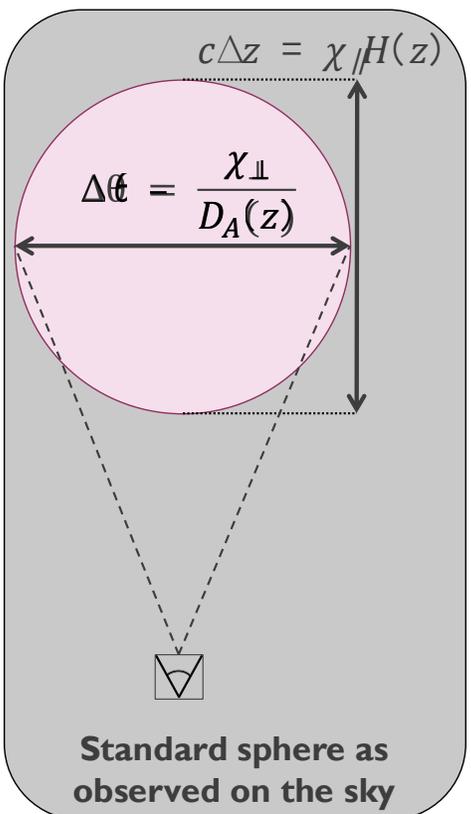
Converting  
angles to  
distances



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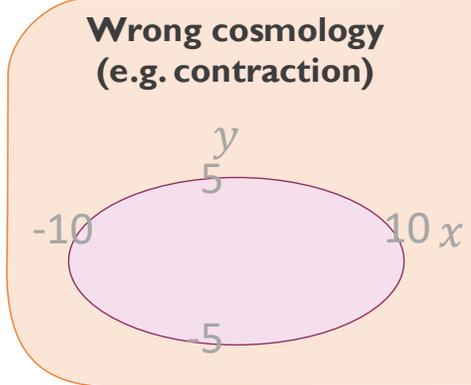
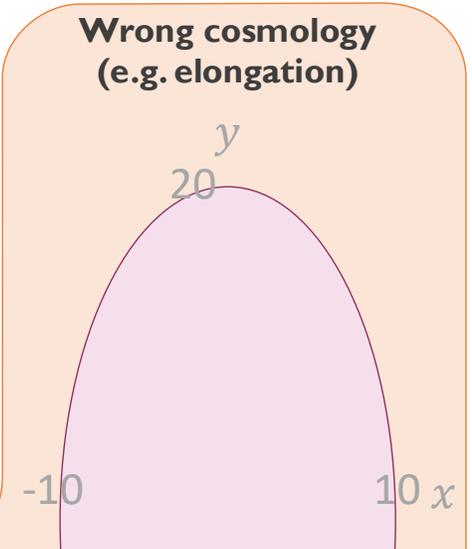
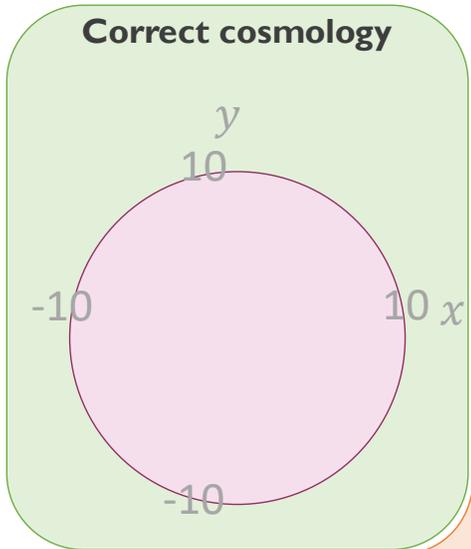
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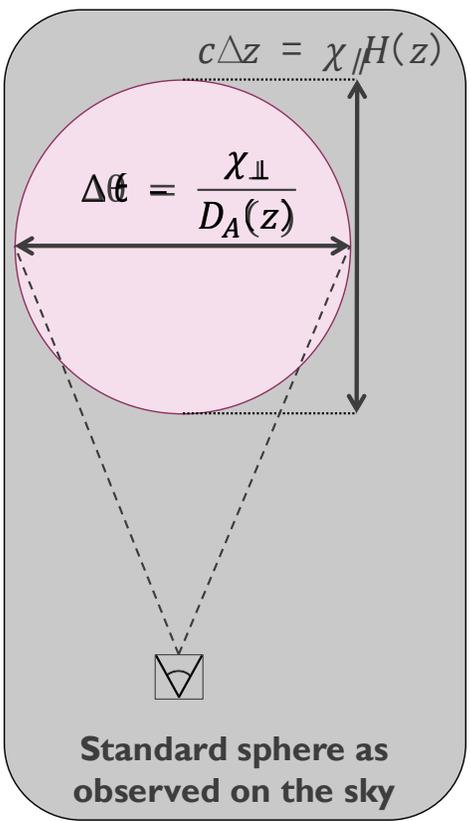
Converting angles to distances



# Constraining cosmology with Alcock-Paczynski tests

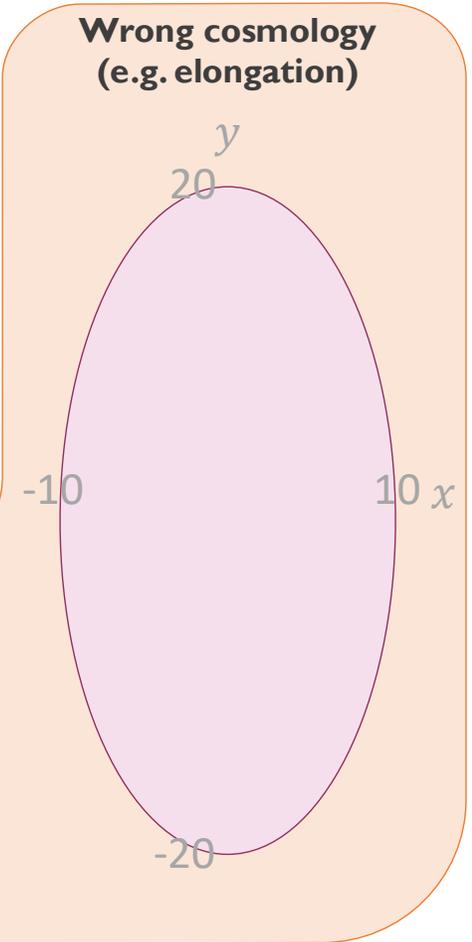
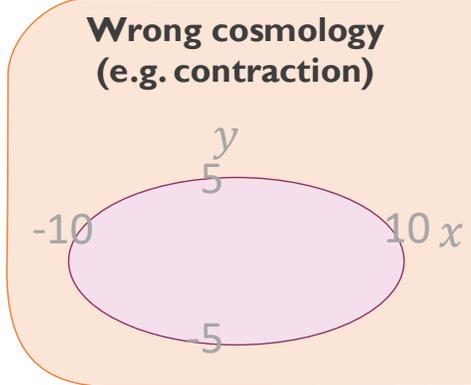
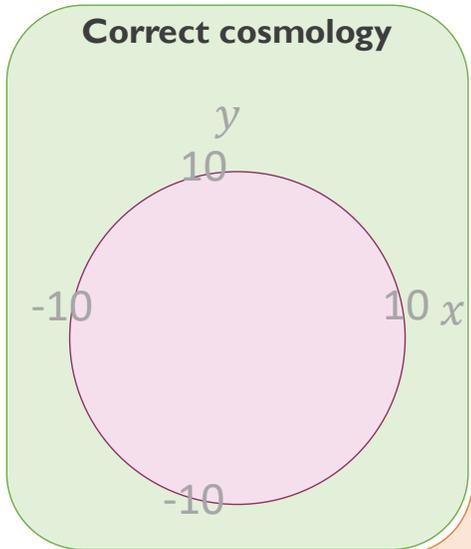
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Converting angles to distances



$$\begin{cases} \chi_{\parallel} = \frac{c}{H(z)} \Delta z \\ \chi_{\perp} = D_A(z) \Delta \theta \end{cases} \Leftrightarrow \begin{cases} \chi'_{\parallel} = \frac{H(z)}{H'(z)} \chi_{\parallel} = q_{\parallel}(z) \chi_{\parallel} \\ \chi'_{\perp} = \frac{D'_A(z)}{D_A(z)} \chi_{\perp} = q_{\perp}(z) \chi_{\perp} \end{cases}$$

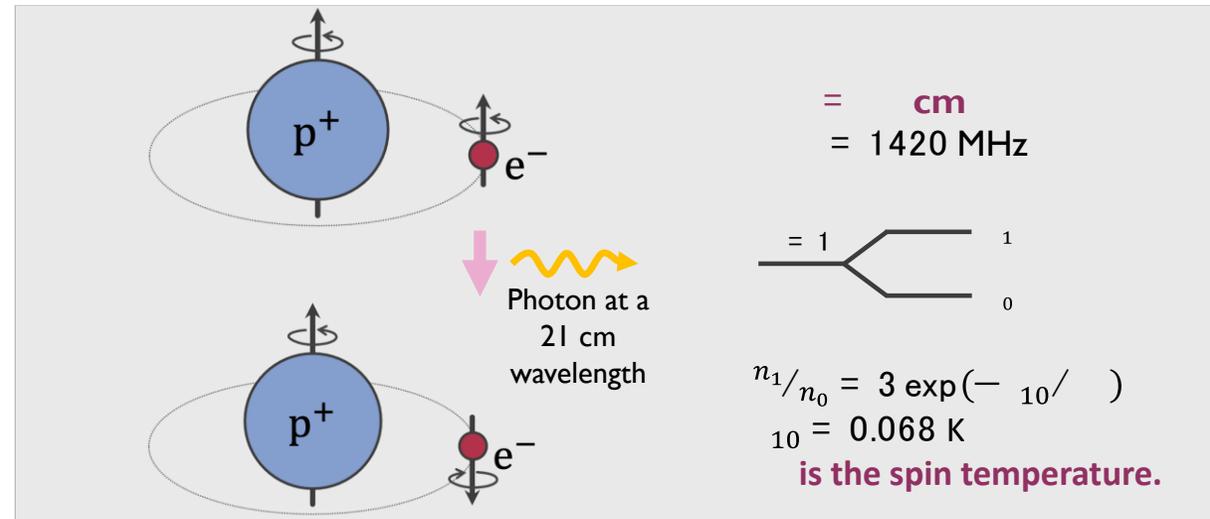


We can probe the following ratio:

$$\alpha = \frac{q_{\parallel}}{q_{\perp}} = \frac{D_A H}{(D_A H)'}$$

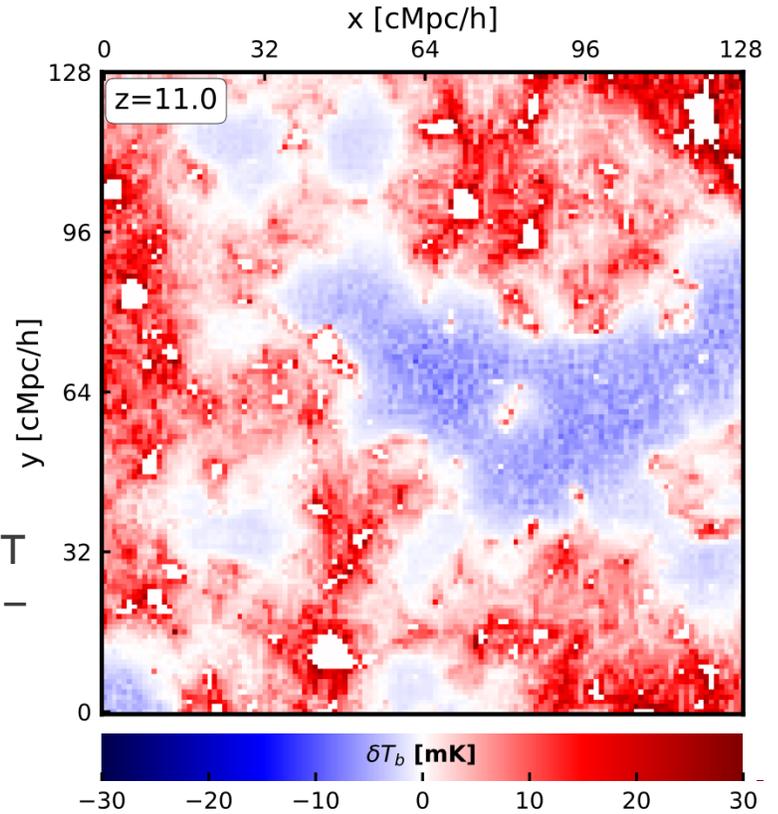
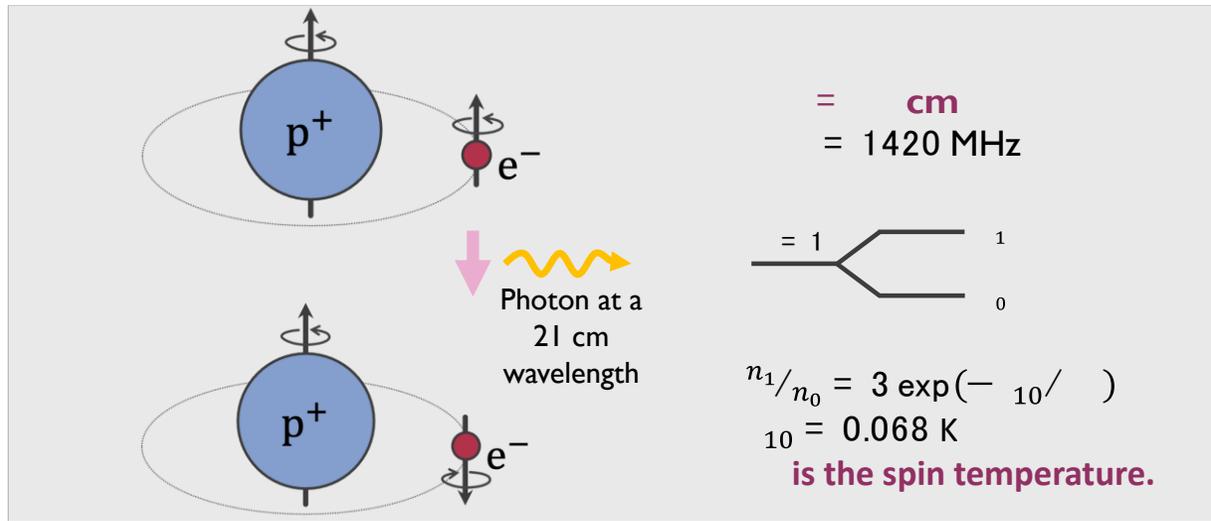
# 21-cm signal

- Mapping the **distribution of neutral hydrogen gas** at **many frequencies**



# 21-cm signal

■ Mapping the **distribution of neutral hydrogen gas** at **many frequencies**



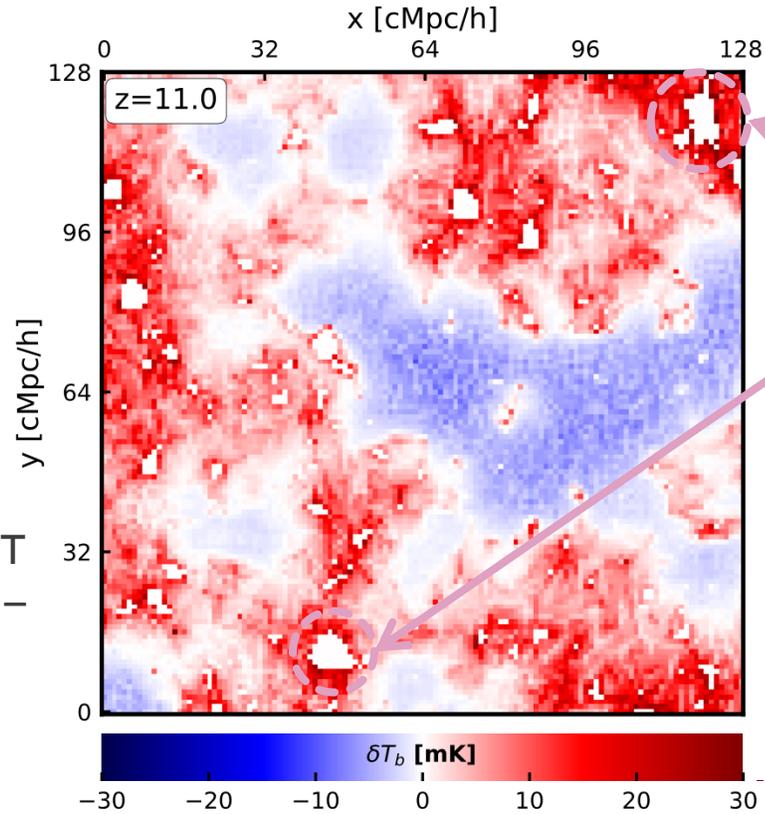
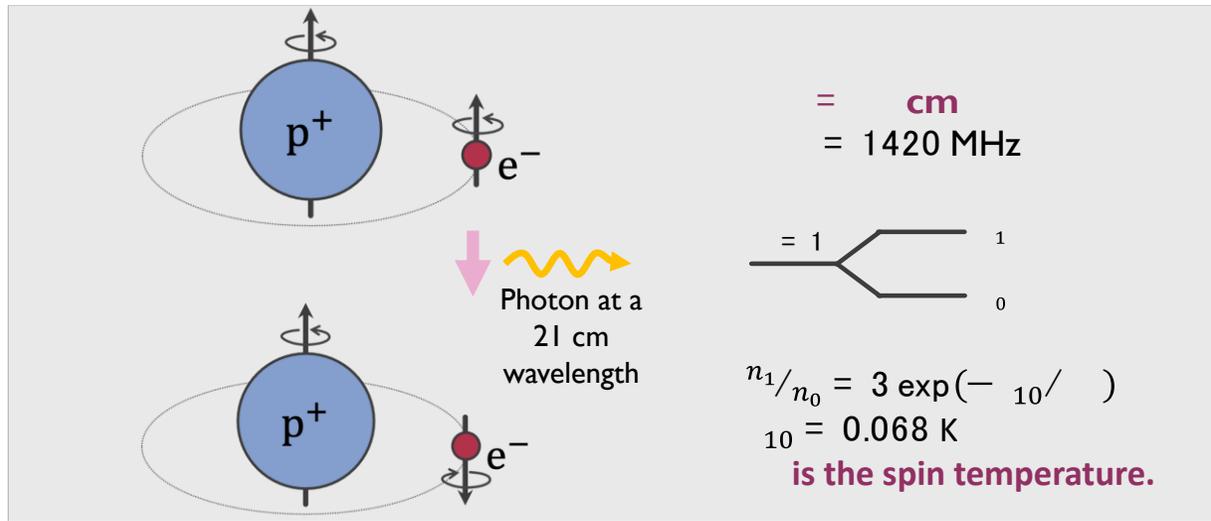
21 cm map (21cmFAST semi-analytical model – 256 cMpc/h)

Hiegal, Th  lie+23

$$\delta T_b(z) \propto x_{HI}(z) (1 + \delta_b(z)) \left( 1 - \frac{T_{CMB}(z)}{T_s(z)} \right) \text{ mK}$$

# 21-cm signal

■ Mapping the **distribution of neutral hydrogen gas at many frequencies**



Ionisation state of the hydrogen gas

$$\delta T_b(z) \propto x_{HI}(z) (1 + \delta_b(z)) \left( 1 - \frac{T_{CMB}(z)}{T_s(z)} \right) \text{ mK}$$

21 cm map (21cmFAST semi-analytical model – 256 cMpc/h)

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# 21-cm signal

## SKA light cones

- Mapping the **distribution of neutral hydrogen gas** at **many frequencies**

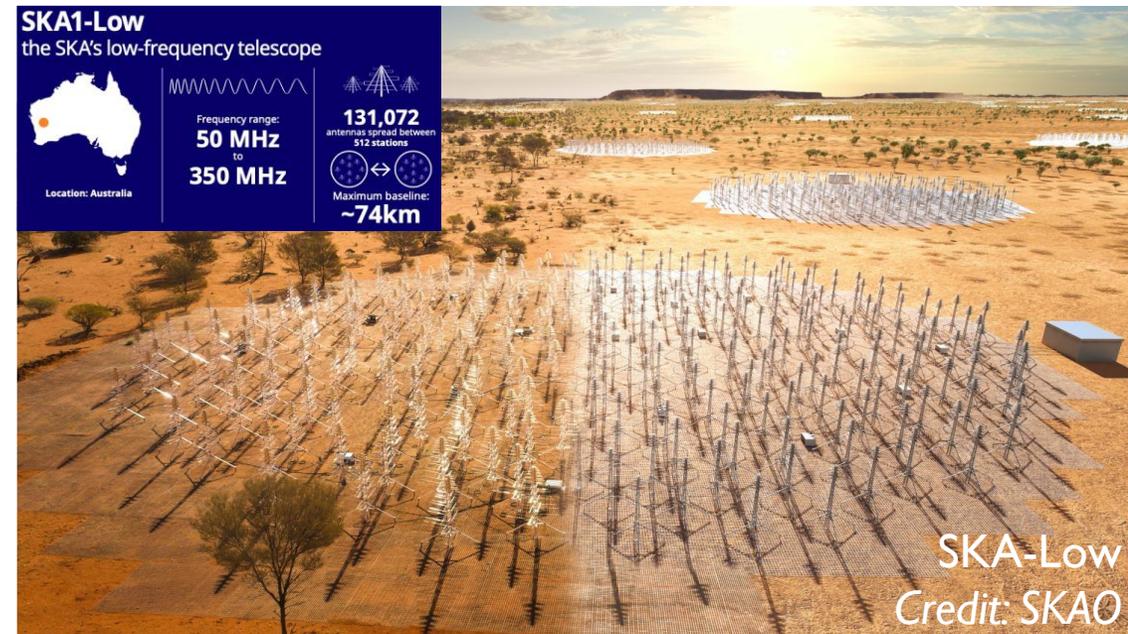
- $\delta T_b(z) \propto x_{HI}(z)(1 + \delta_b(z))F(T)$

### SKA-Low characteristics:

- 50 – 350 MHz  $\sim z \in [6, 25]$
- 200 square degrees ( $> 1$  cGpc)

**Resolution** (see Giri+18):

- $> 7$  cMpc for  $z > 6.5$  on the sky
- $> 1$  cMpc in the line of sight



**SKA-Low:** Observations of the **redshifted 21 cm signal** via **tomography imaging**.

**NB.** Scanning frequencies is equivalent to scanning time/redshift.

# 21-cm signal

## SKA light cones

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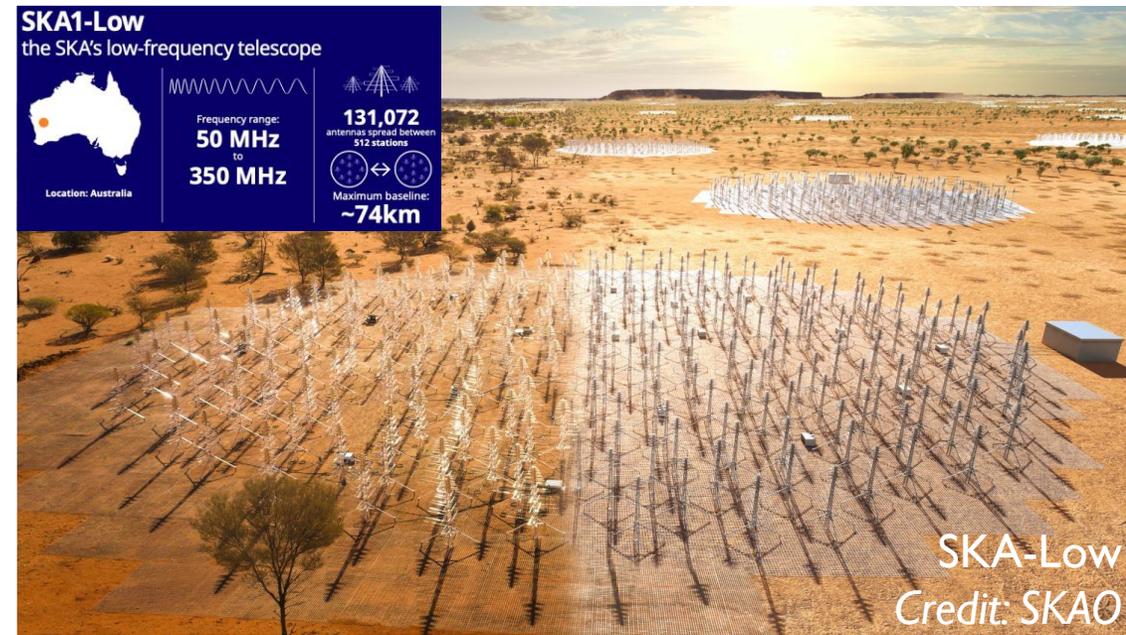
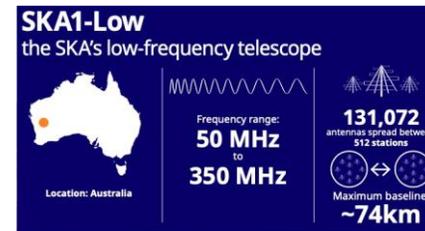
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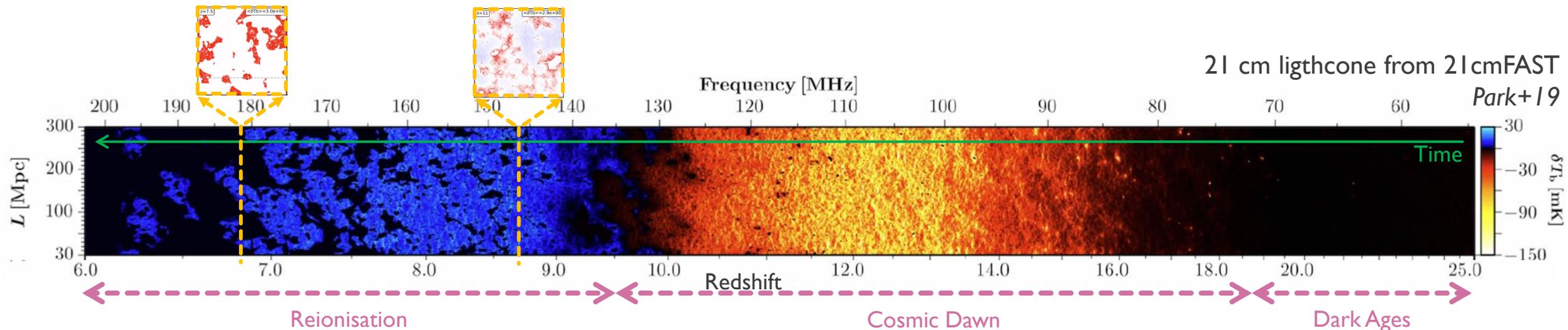
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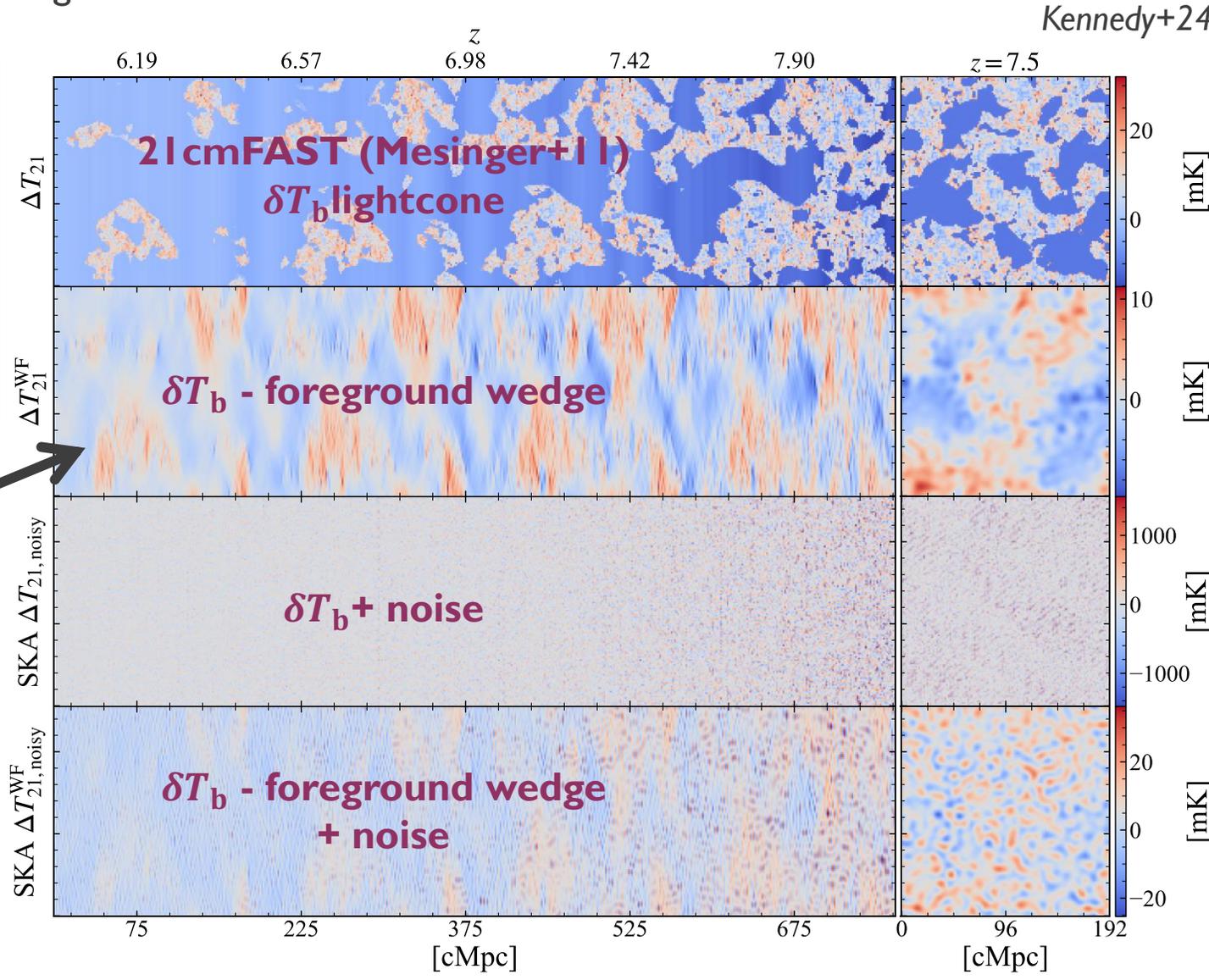
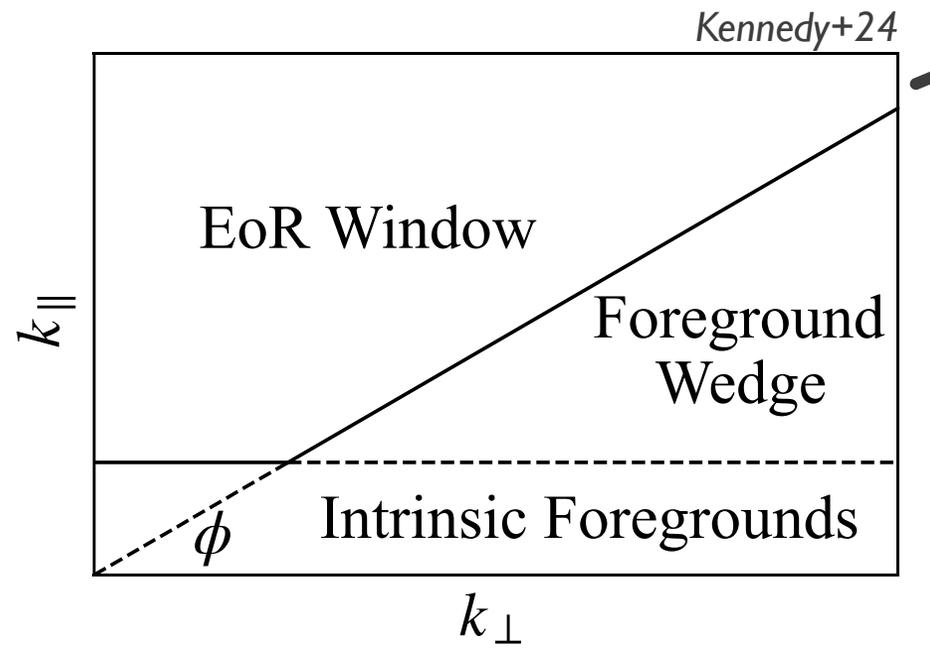
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# Constraining cosmology with Alcock-Paczynski tests

Bubbles from the future SKA observations of the 21-cm signal?

- Observations:  $\delta T_b$  lightcones, which will include foregrounds and noise



Kennedy+24

Kennedy+24

# Constraining cosmology with Alcock-Paczynski tests

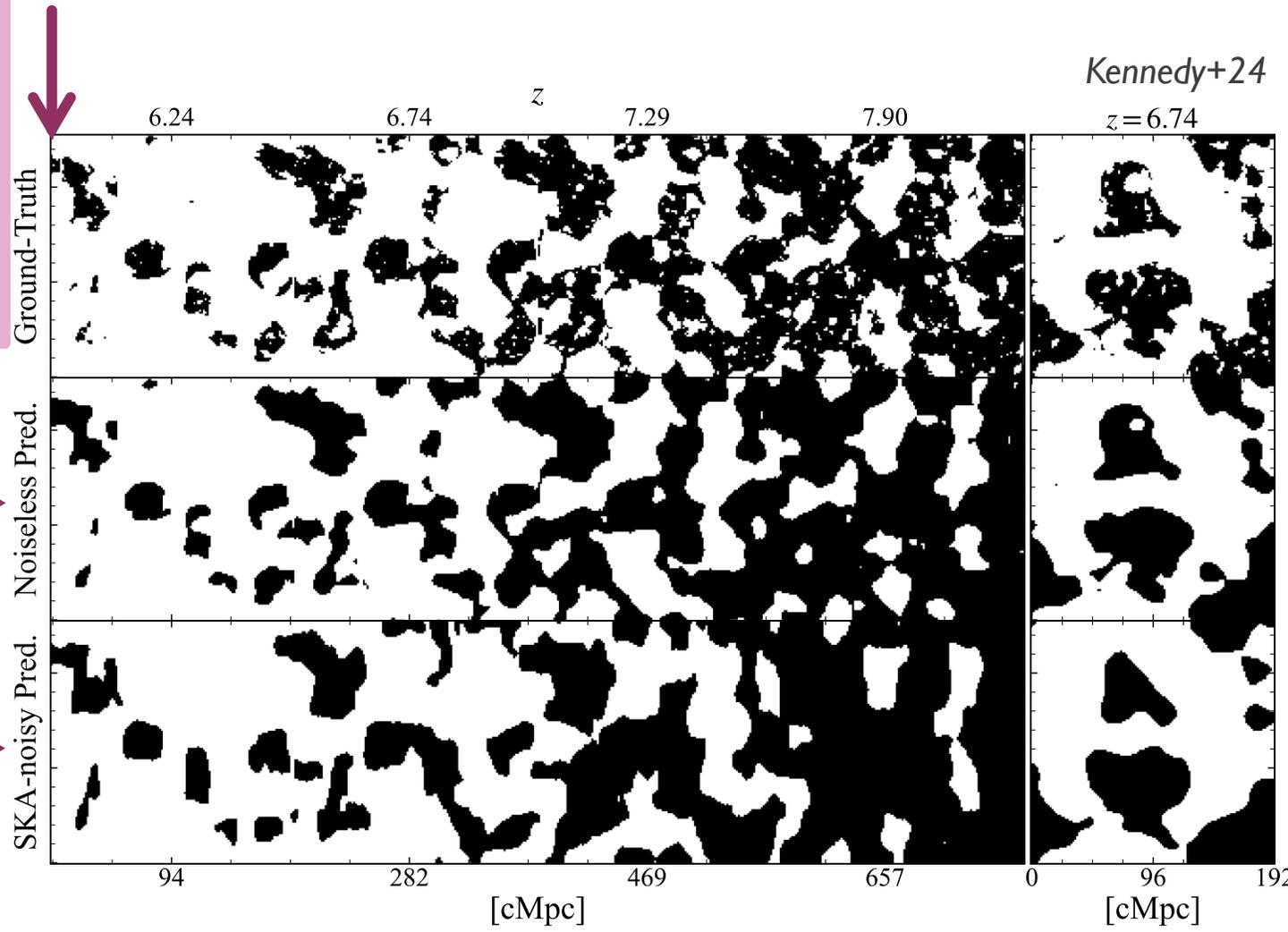
Bubbles from the future SKA observations of the 21-cm signal?

- Observations:  $\delta T_b$  lightcones, which will include foregrounds and noise
- Trained Unet on  $\delta T_b$  lightcones/coeval boxes to recover the binarized  $x_{HI}$
- Extraction of the bubbles via a watershed algorithm (Lin+16)

$x_{HI}$  reconstruction from  $\delta T_b$  - foreground wedge

$x_{HI}$  reconstruction from  $\delta T_b$  - foreground wedge + noise

$x_{HI}$  reconstruction from  $\delta T_b$



# Constraining cosmology with Alcock-Paczynski tests

Mock bubble stacks

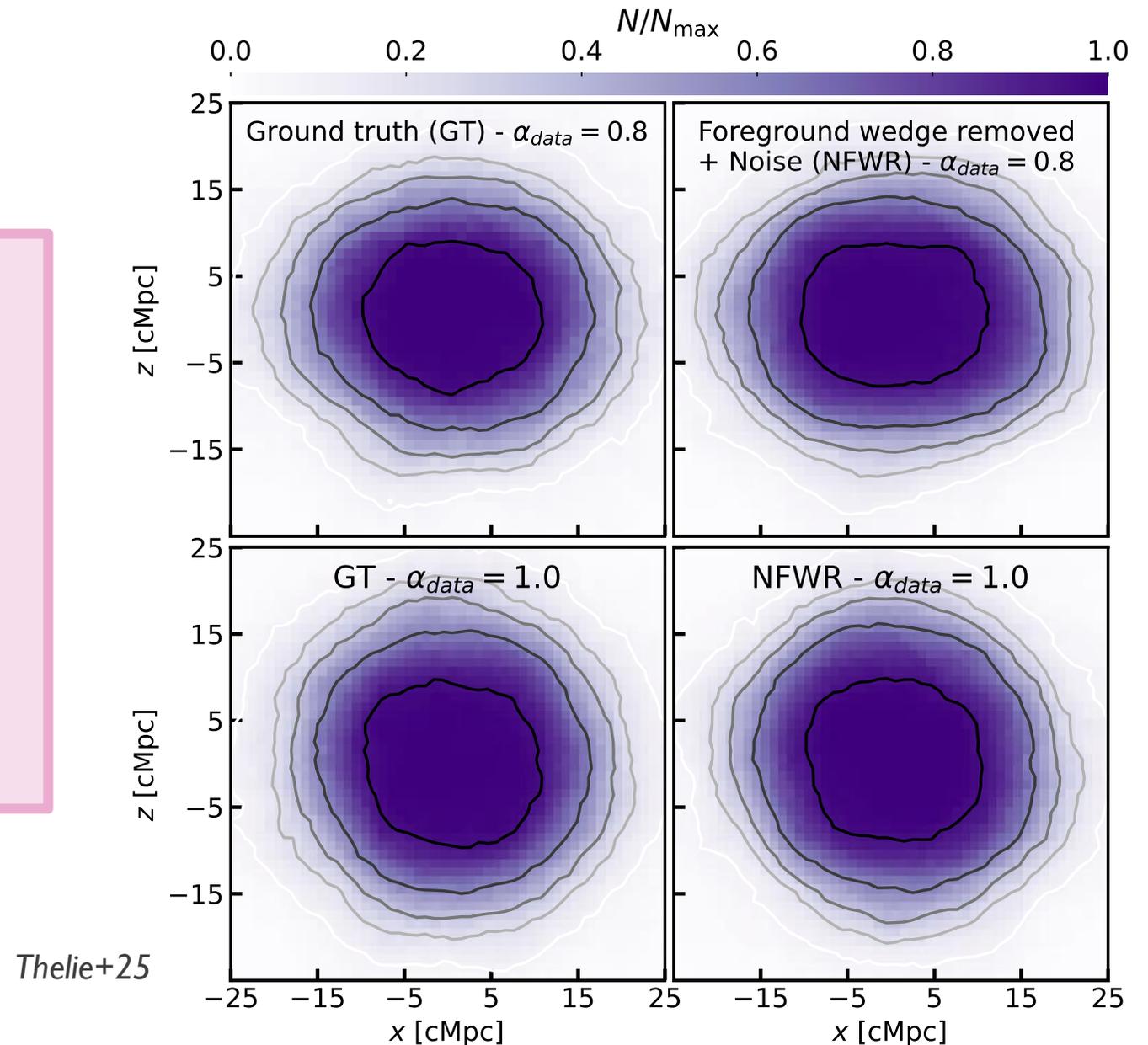
## Mock observation data:

- $25 \times 400$  ground truth  $x_{\text{HI}}$  maps and U-Net recovered  $x_{\text{HI}}$  maps at  $z = 7.5$
- With a **deformation** along the line of sight representing different cosmologies:

$$\alpha_{\text{data}} \in \{0.8, 1\}$$

## Bubble stacks:

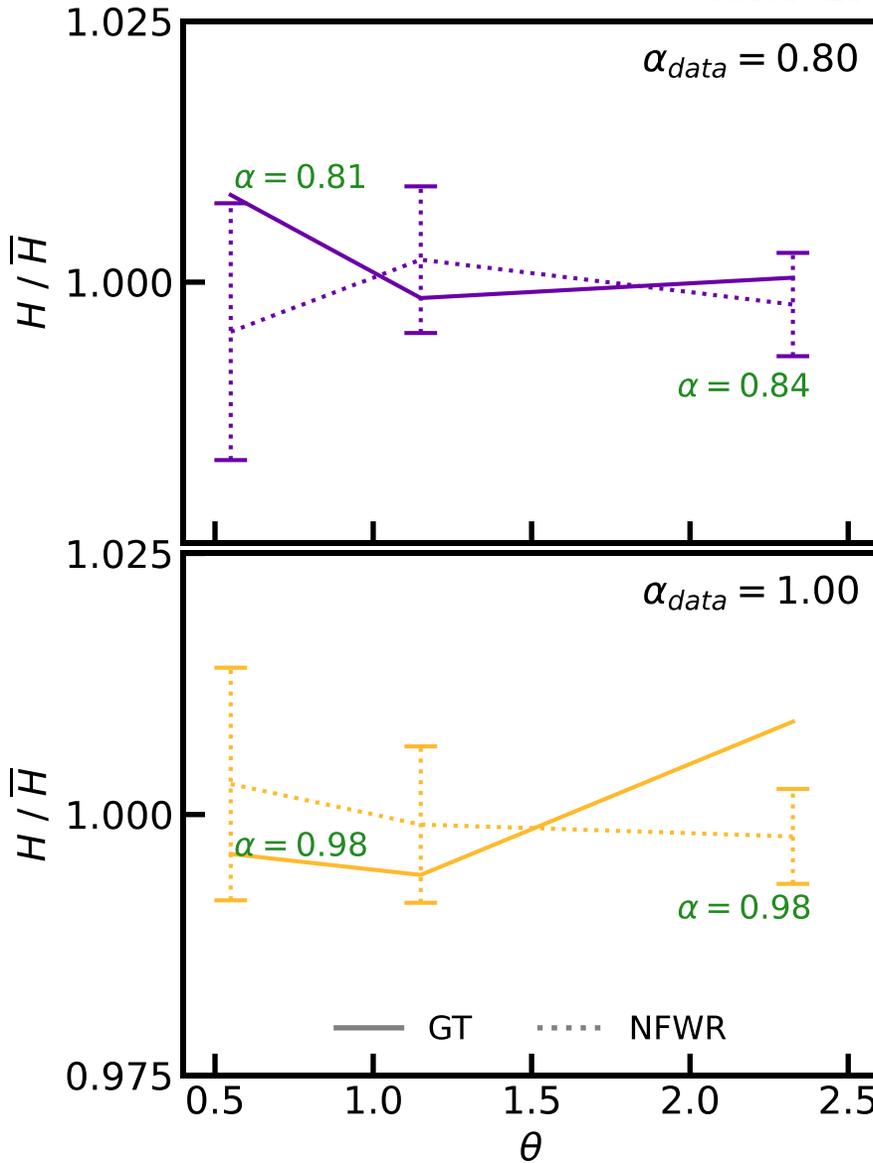
- **400 stacks** from **25 maps** (to represent the total surface that SKA will probe)



# Constraining cosmology with Alcock-Paczynski tests

## Sphericity test

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$N$ : bubble stack

$\bar{N}$ : spherically symmetric stack

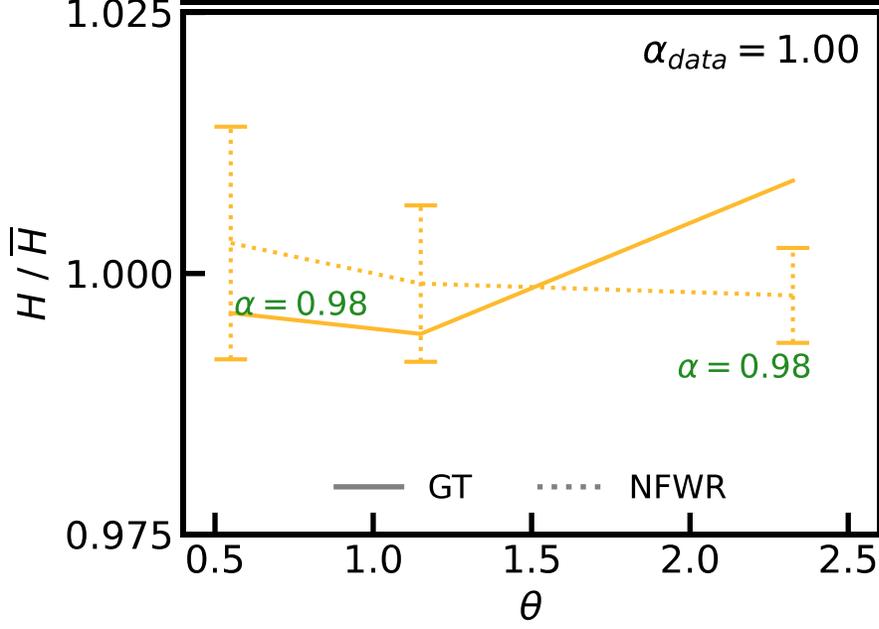
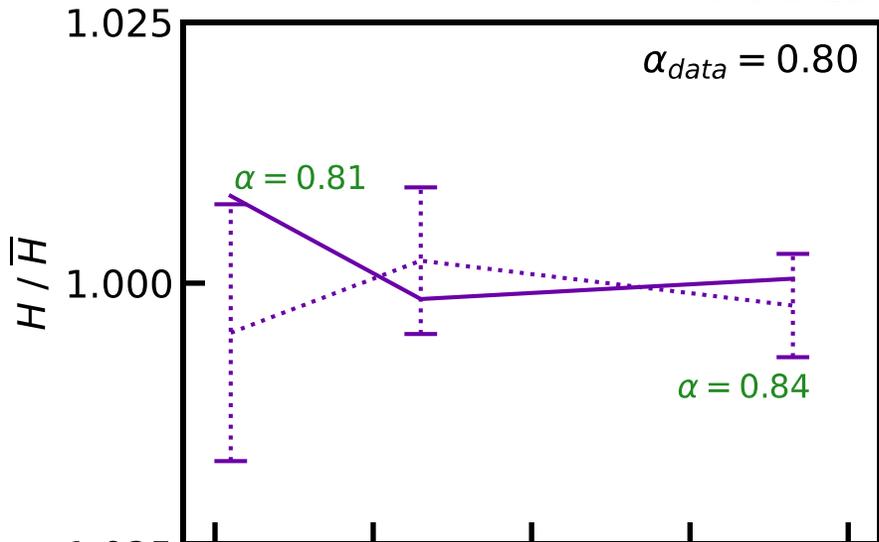
$H, \bar{H}$ : histograms of  $\theta$  weighted by  $N, \bar{N}$

Then  $(H/\bar{H})(\theta_i) = 1 \Leftrightarrow \alpha = \alpha_{data}$

# Constraining cosmology with Alcock-Paczynski tests

Making the forecast

Thelie+25



$N$ : bubble stack  
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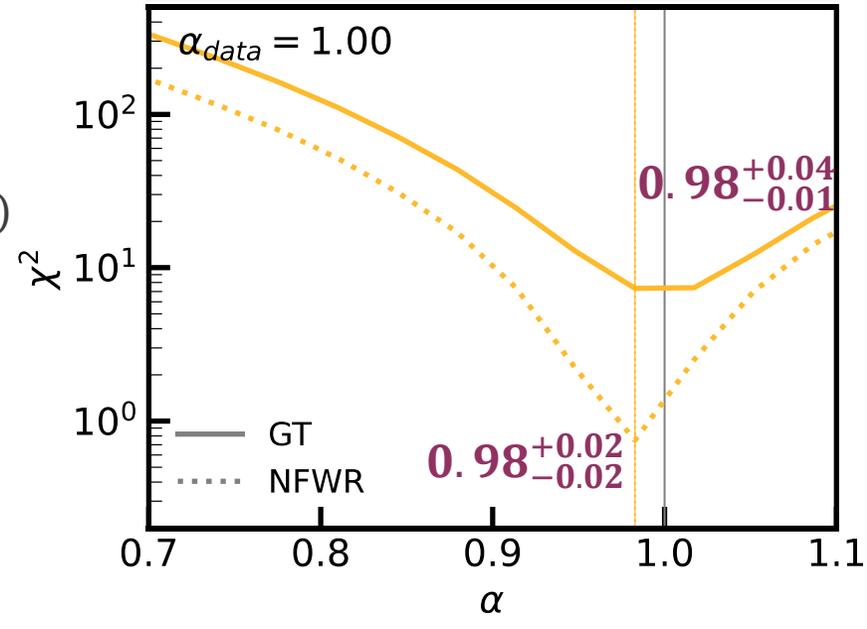
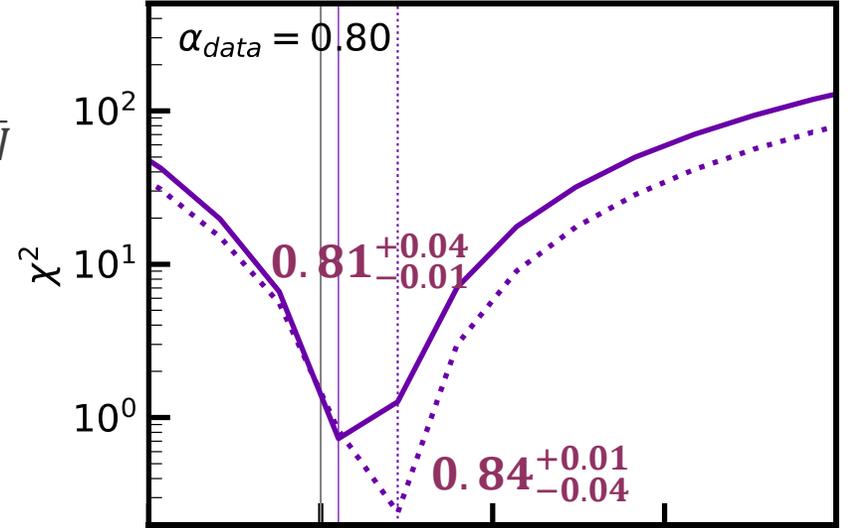
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$$\chi^2(\alpha) = (\mathbf{D} - \mathbf{M})^T \mathbf{C}^{-1} (\mathbf{D} - \mathbf{M})$$

$$= \sum_{i,j} (\mathbf{D}_i - 1) \mathbf{C}_{ij}^{-1} (\mathbf{D}_j - 1)$$

$\mathbf{D}$ : data,  $\mathbf{D}_i = (H/\bar{H})(\theta_i)$   
 $\mathbf{M}$ : model,  $\mathbf{M}_i = 1$   
 $\mathbf{C}$ : covariance matrix, computed from the 400 stacks

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# Constraining cosmology with Alcock-Paczynski tests

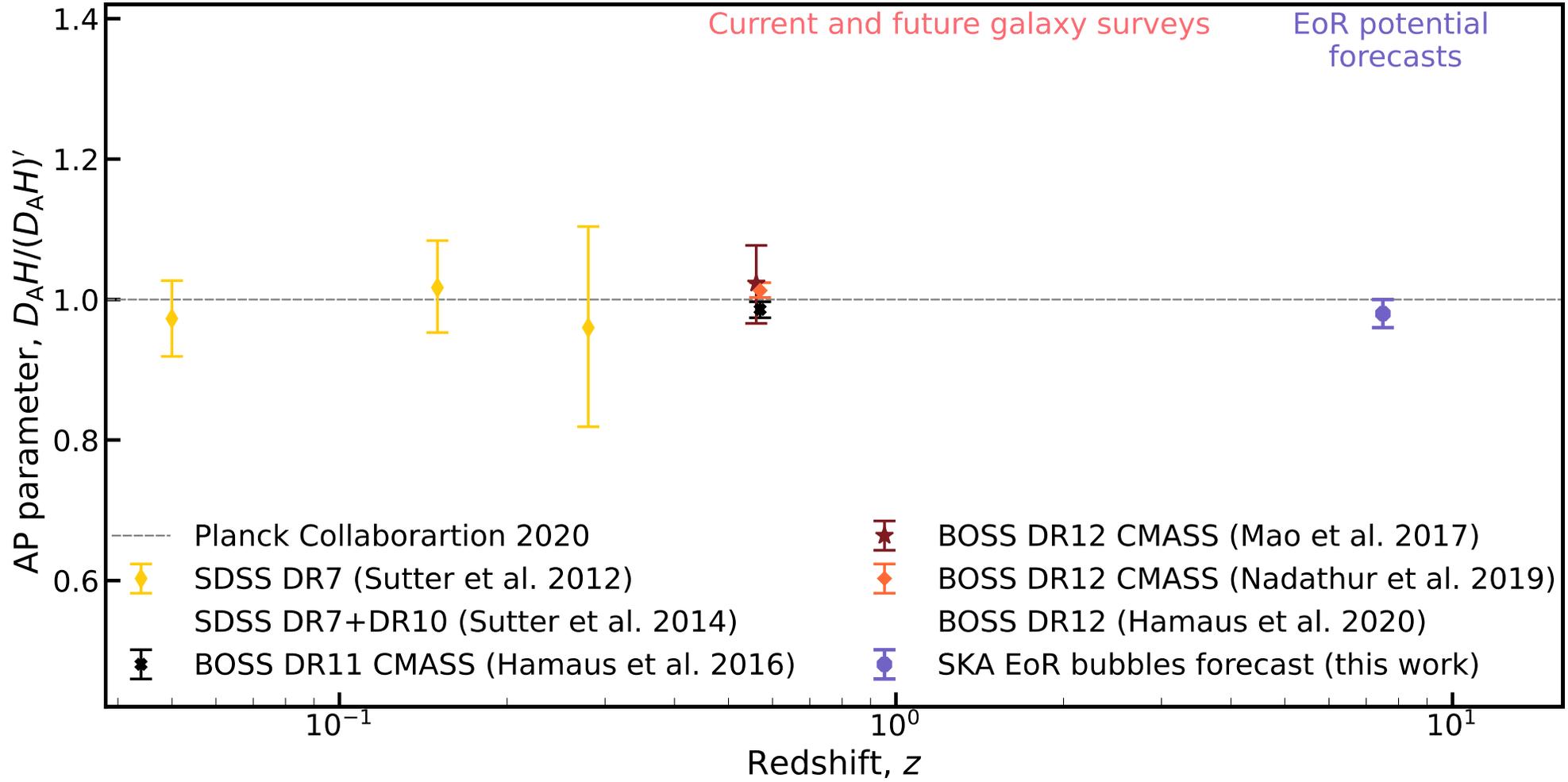
Forecast

Thelie+25

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$D_A$ : comoving angular diameter distance  
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**Forecast:**  
 $\alpha(7.5) = 0.98^{+0.02}_{-0.02}$   
 ~10% precision



# Constraining cosmology with Alcock-Paczynski tests

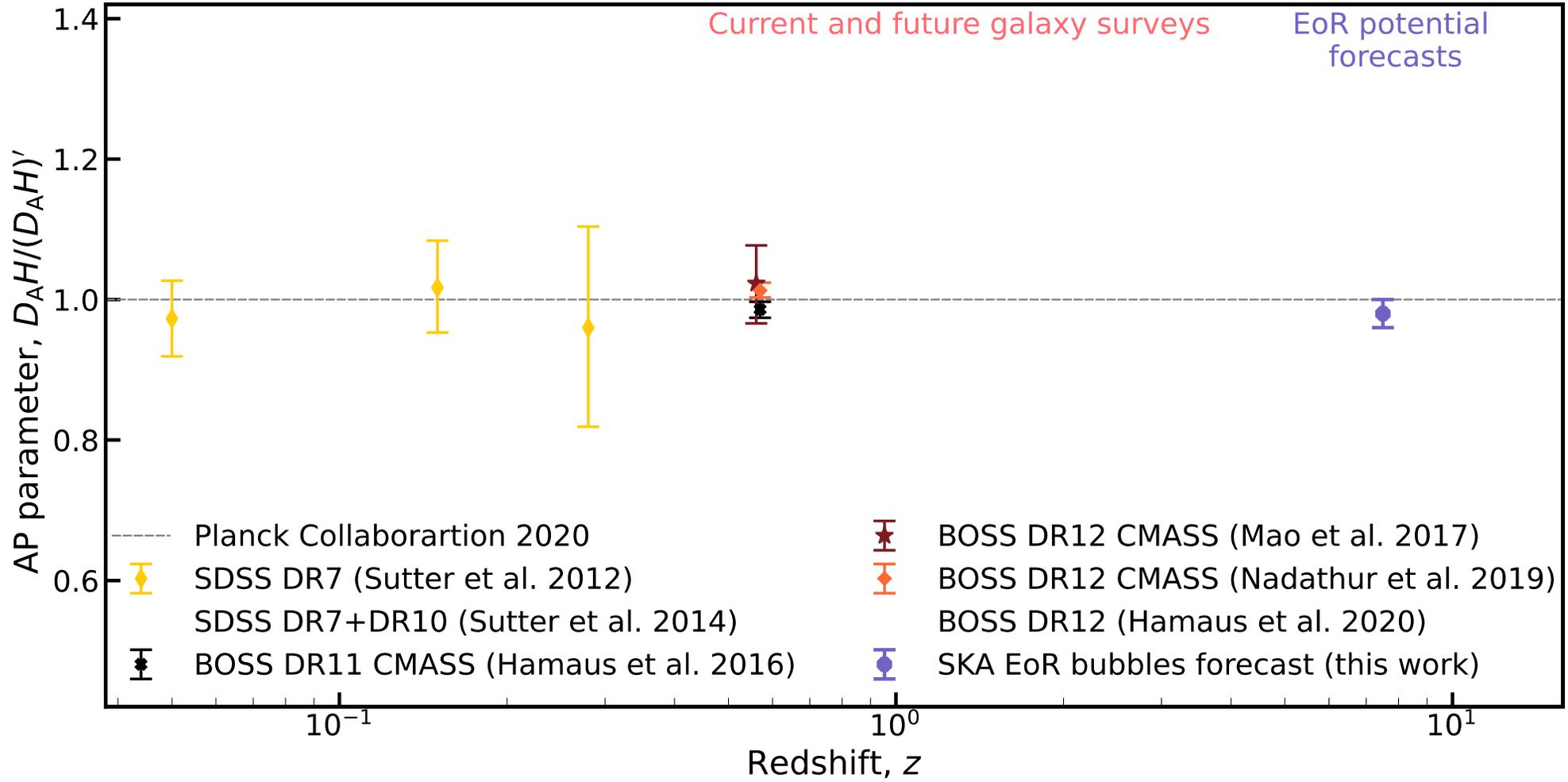
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