ASTRO-TS

High-redshift post-reionisation cosmology with 21cm intensity mapping

arXiv:1709.07893

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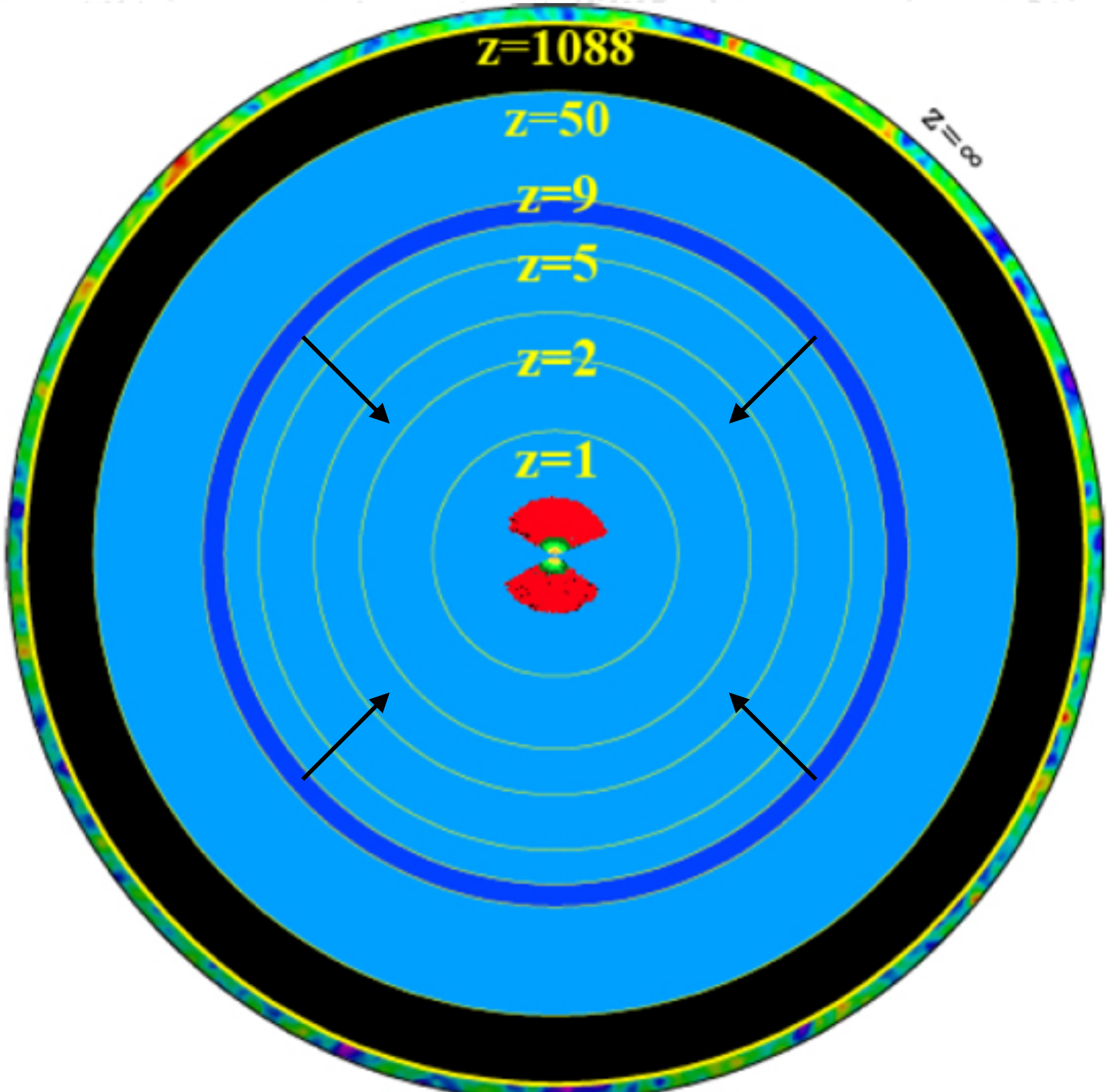
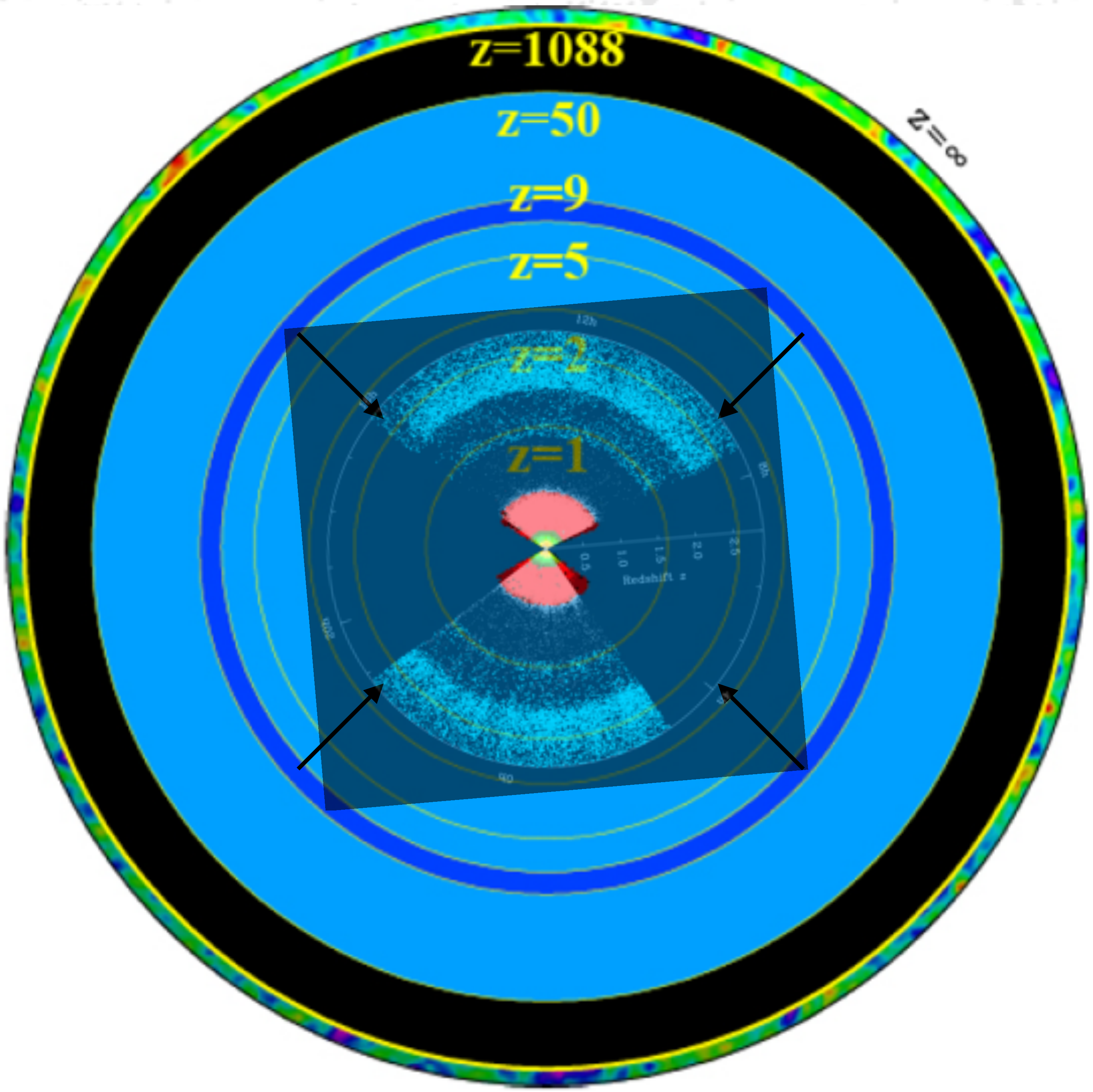
26. September 2017.

21cm cosmology

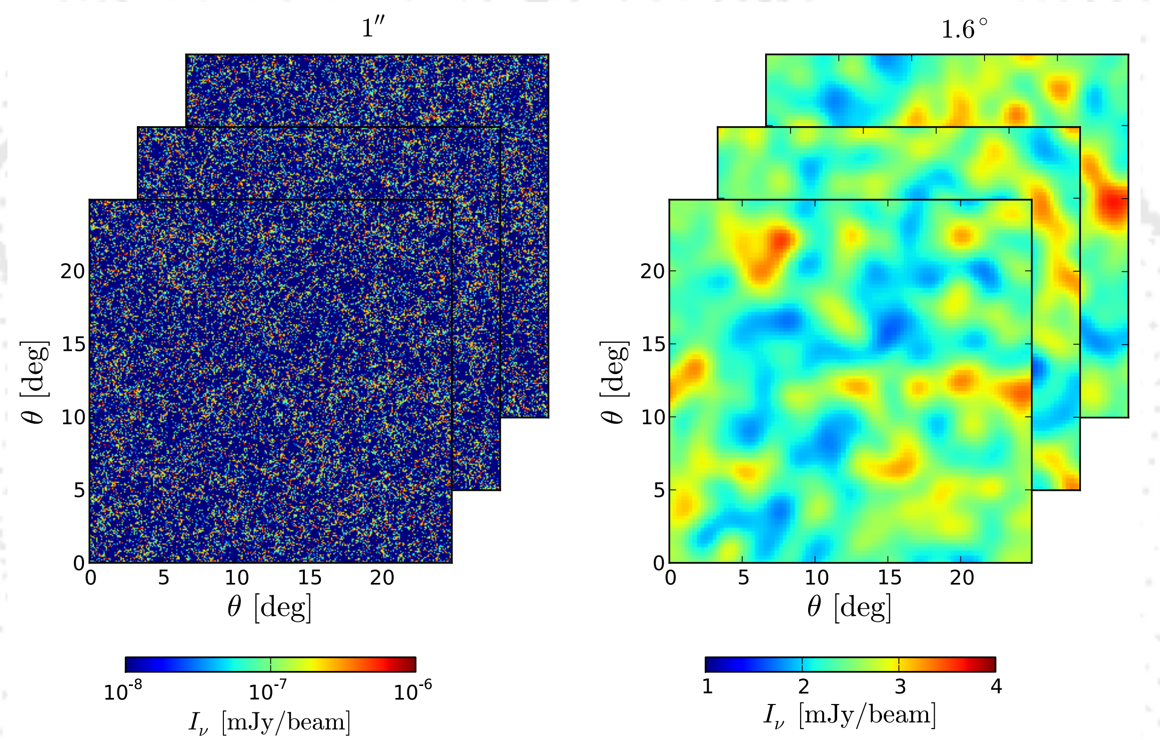


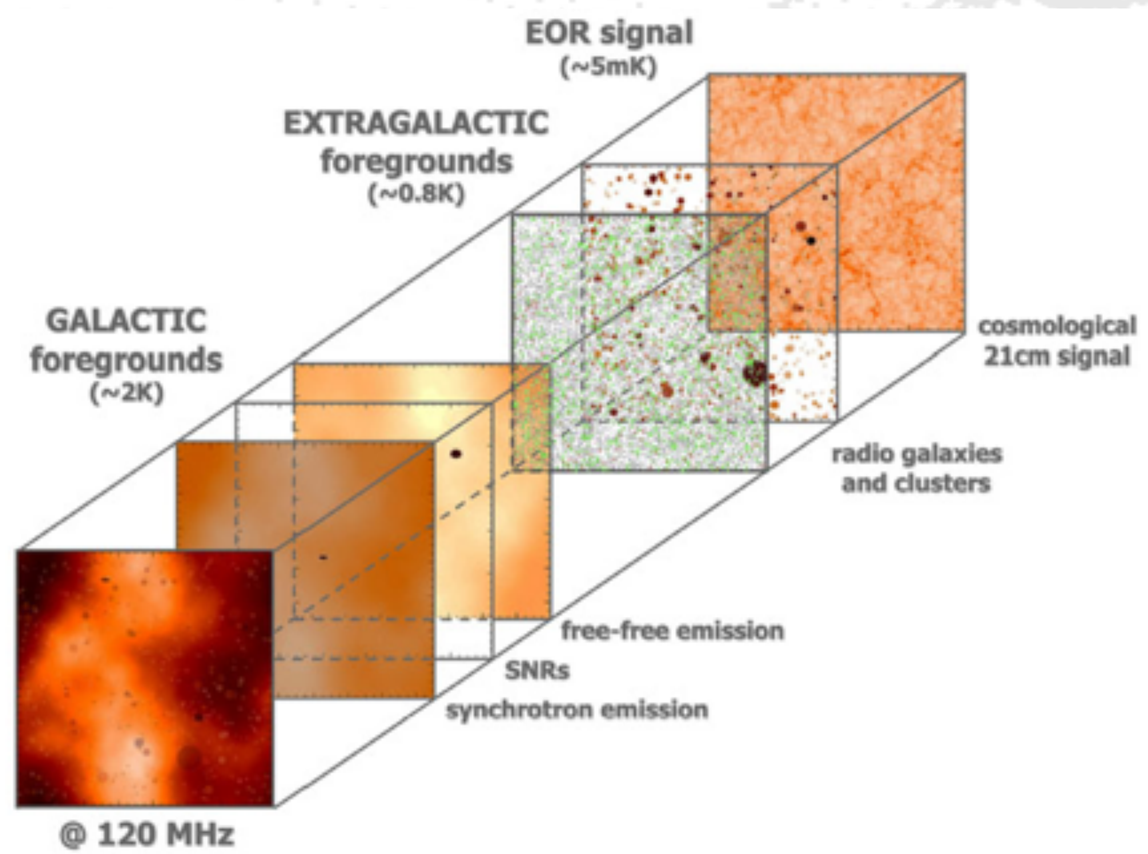
21cm cosmology



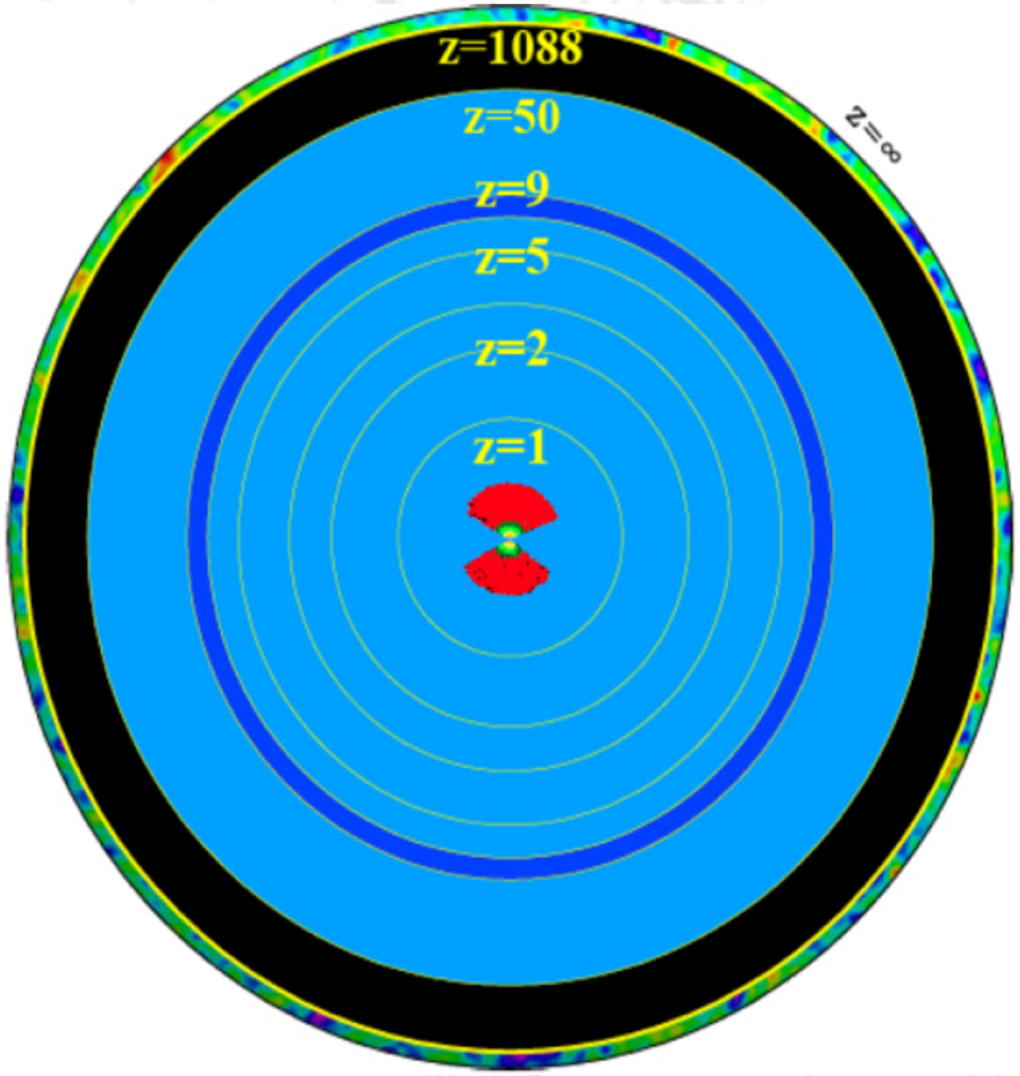
21-cm Cosmology

- Promising probe of LSS
- Intensity mapping (IM) technique
- Foregrounds problem!
- Reionization probes: PAPER, HERA, LOFAR, MWA etc.
- We will focus on low-z where HI resides in galaxies
- Many probes are targeting the BAO peak at z<2.5: SKA, CHIME, HIRAX, Tianlai, FAST, BINGO, BAOBAB etc.
- Two approaches: single dish & interferometers





High-redshift cosmology with 21cm IM
2.5<z<5.0



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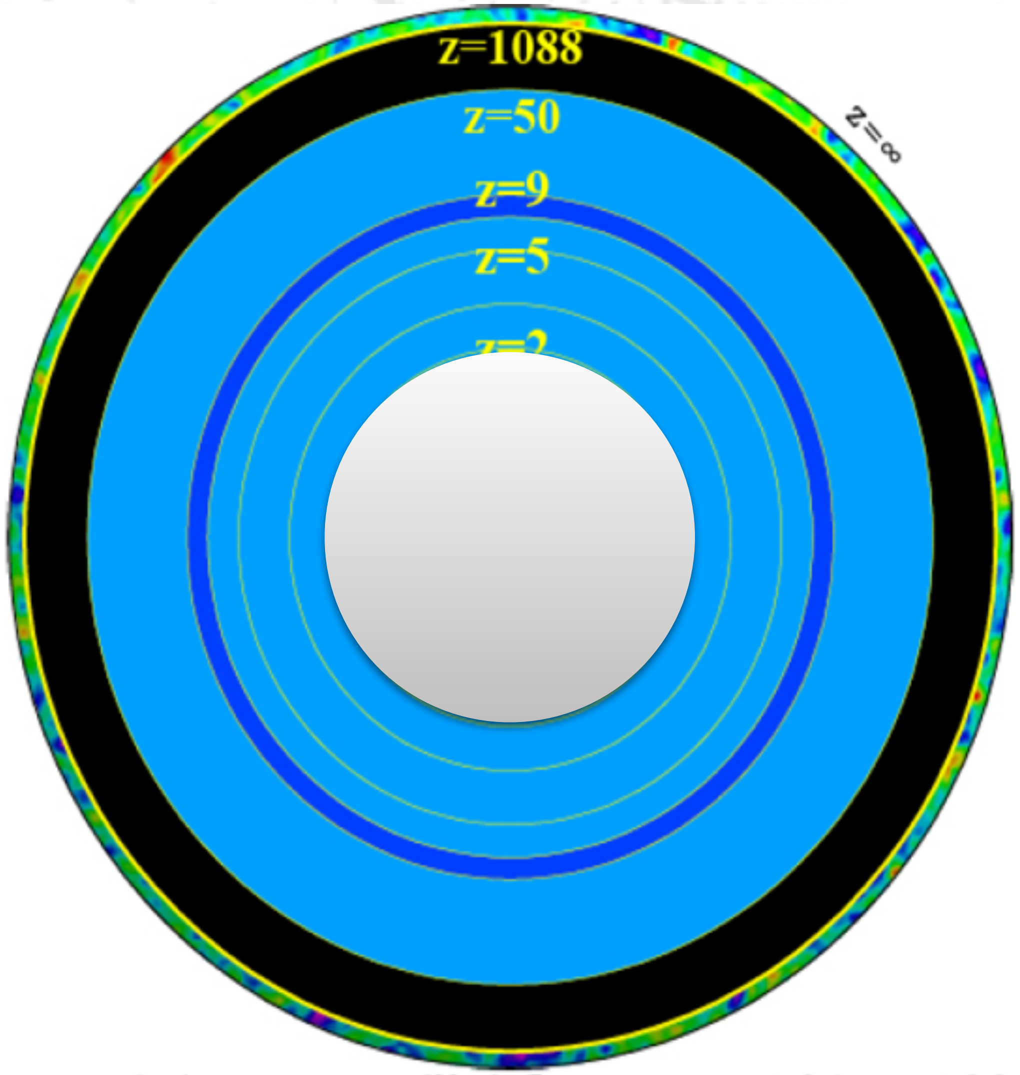

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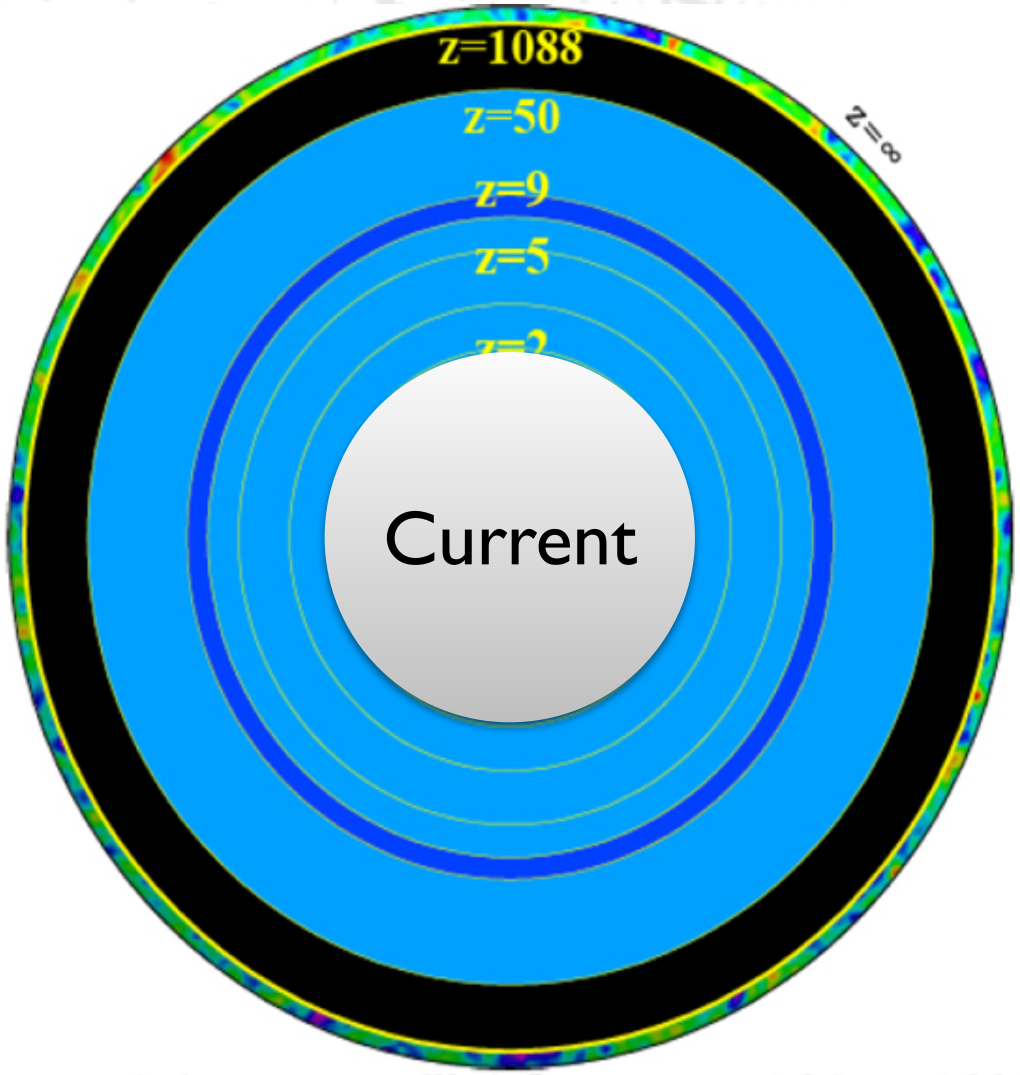

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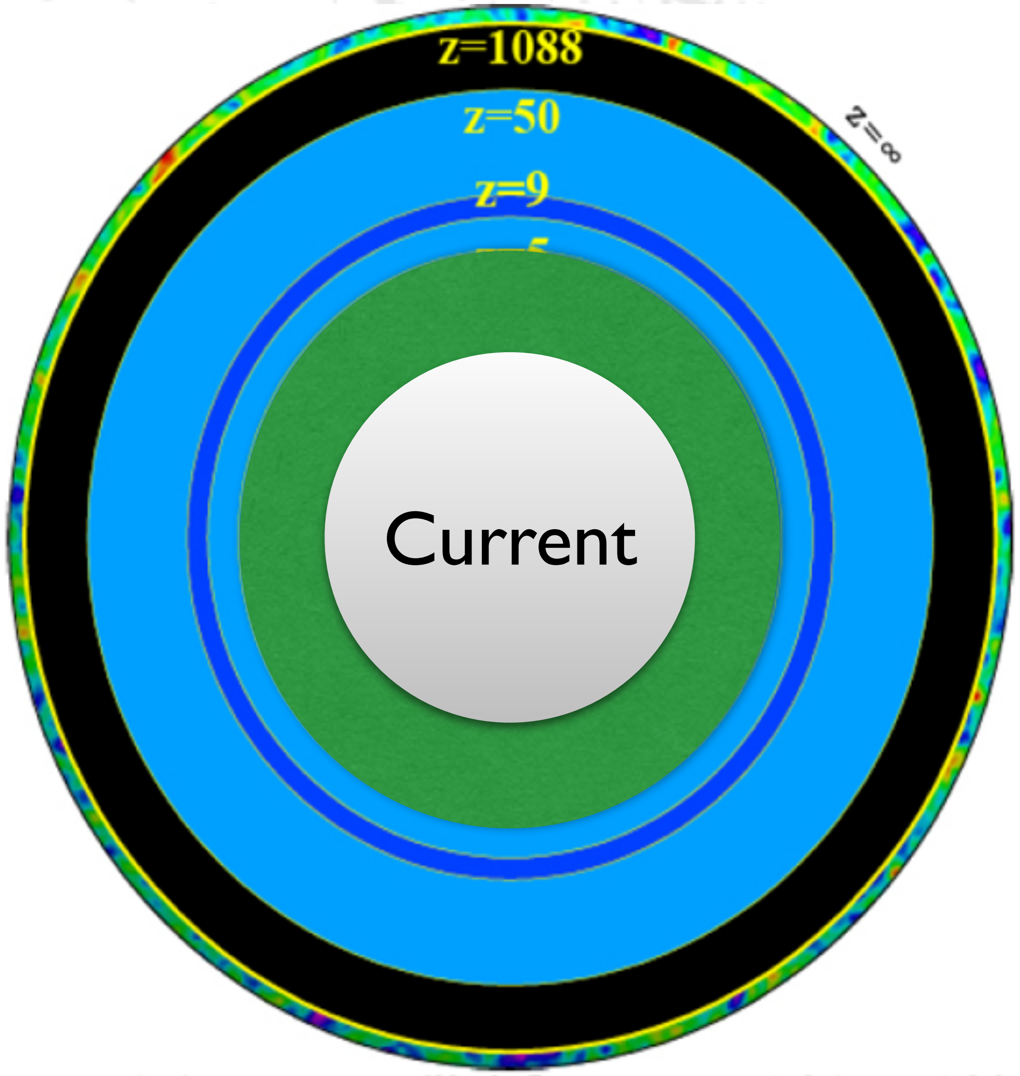

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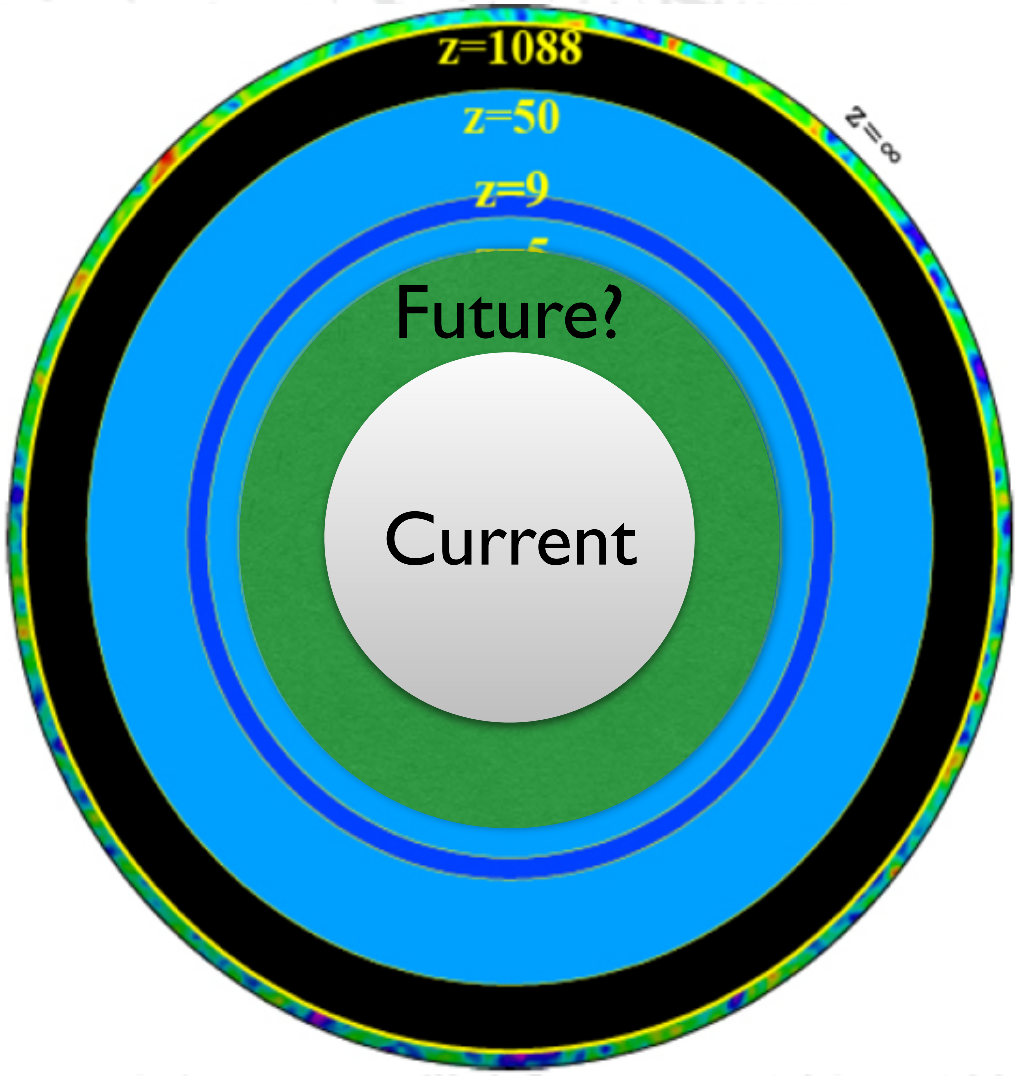
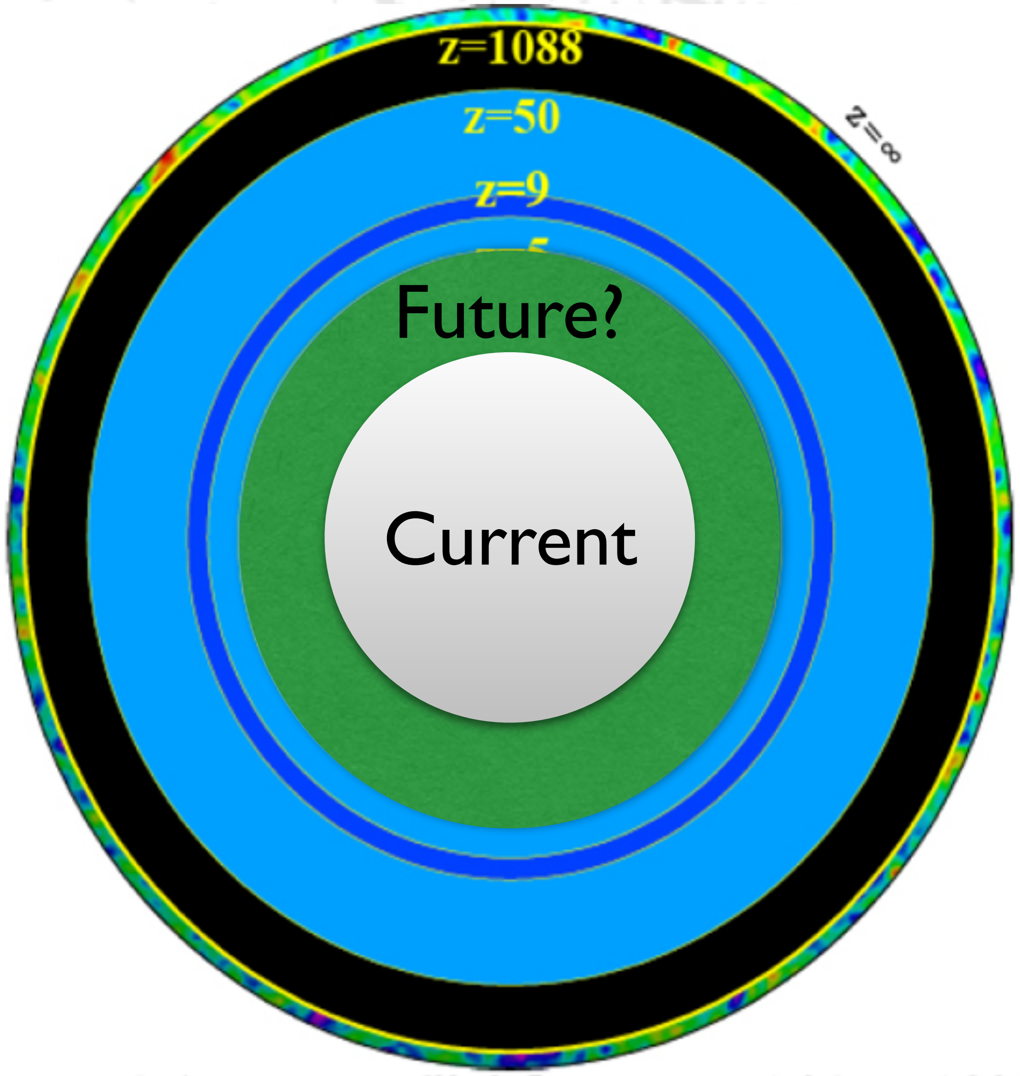


High-redshift cosmology with 21cm IM
2.5<z<5.0

- **Advantages**
- More comoving volume:
- More linear
- You are running out of galaxies anyway



High-redshift cosmology with 21cm IM 2.5<z<5.0

- **Advantages**
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- More linear
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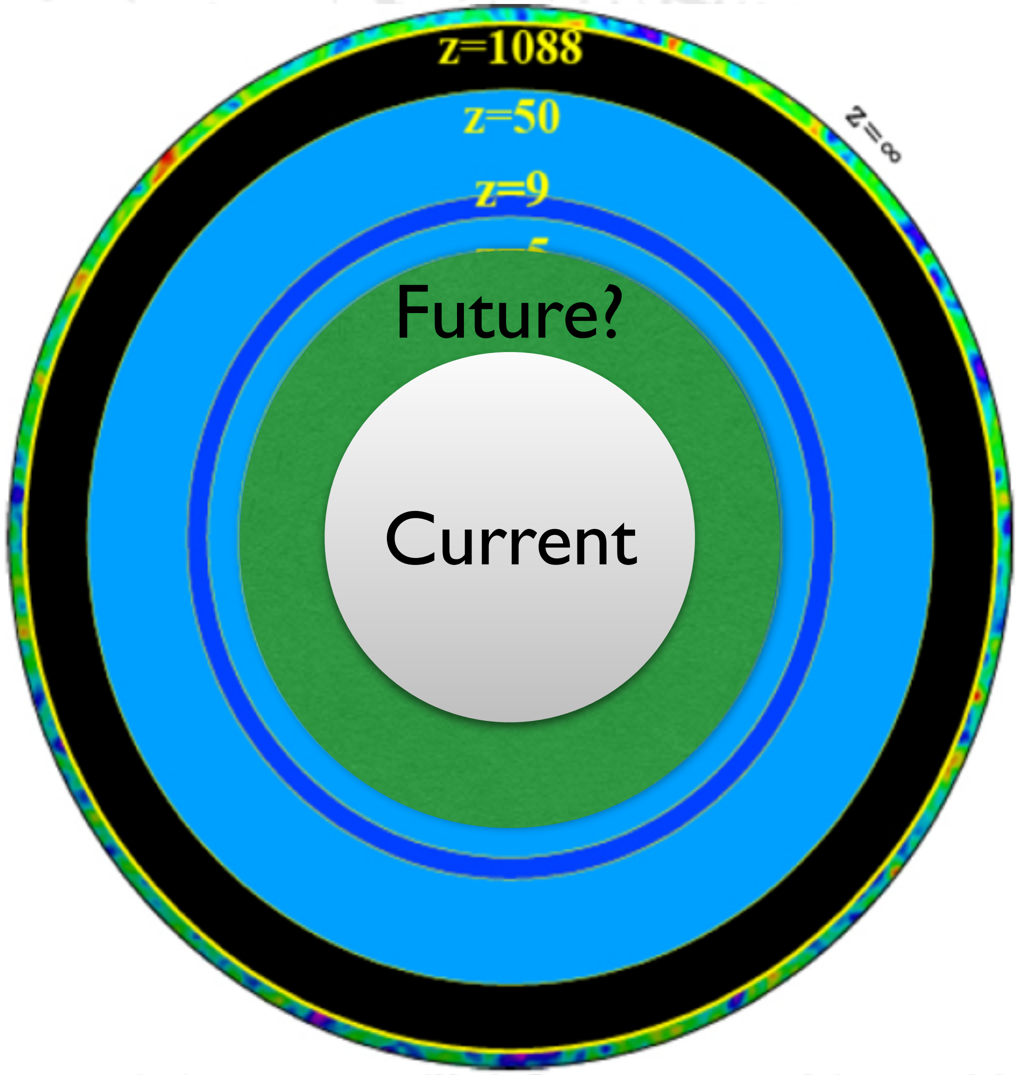

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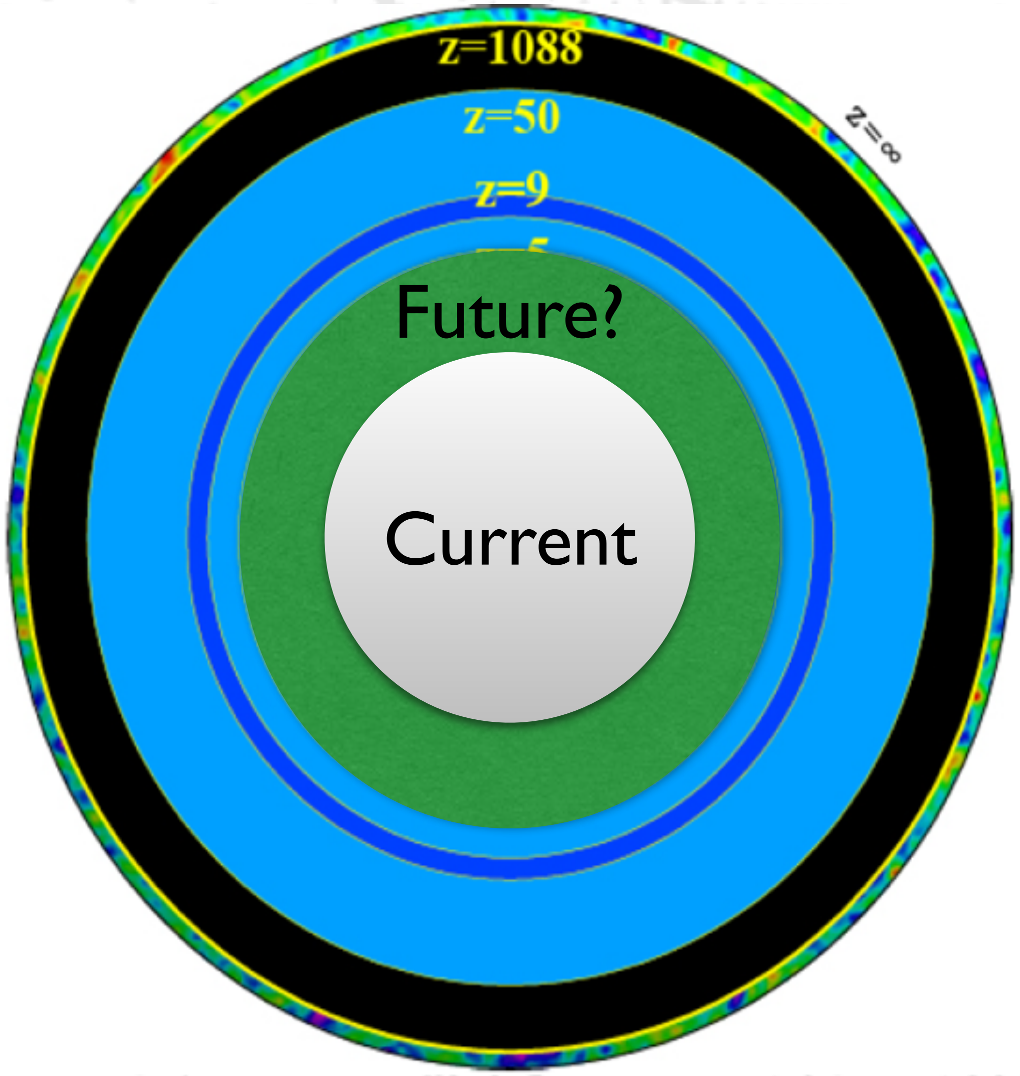
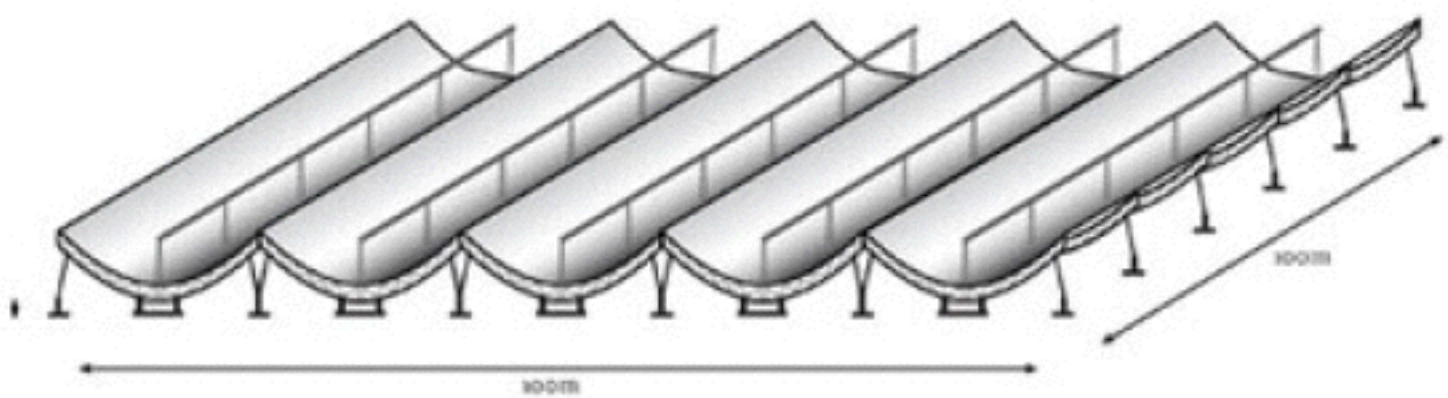


- **Disadvantages**
- Foreground problems
- Sky temperature blows up
- Wedge for interferometers
- Angular resolution for single-dish

Expand current experiments?

CHIME

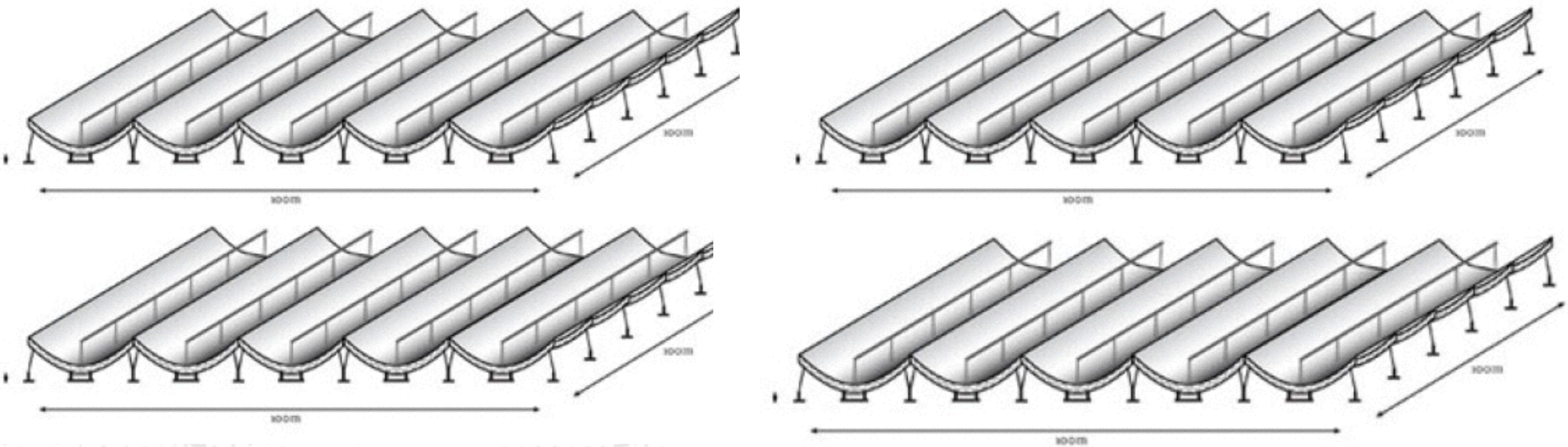


FAST

HIRAX 32x32

Expand current experiments?

2x2xCHIME = Ext-CHIME



highzFAST

HIRAX 64x64 = Ext-HIRAX

High redshift cosmology with 21cm IM
2.5<z<5.0

We are interested in the following quantities:

- Growth of structures — $f\sigma_8$
- BAO Alcock-Paczynski parameters — $H(z)\,\&D_A(z)$
- Sum of the neutrino masses — Σm_ν
- Effective number of the neutrino species — $N_{\rm eff}$

Fisher forecasts

Fisher matrix:

$$F_{ij} = \frac{1}{8\pi^2}\int_{-1}^{1} d\mu \int k^2 dk \frac{\partial \ln P_{21}(k,\mu)}{\partial p_i}\frac{\partial \ln P_{21}(k,\mu)}{\partial p_j} V_{\rm eff}(k,\mu)$$

$$V_{\rm eff}(k,\mu) = V_{\rm sur}\left(\frac{P_{21}(k,\mu)W(k,\mu)}{P_{21}(k,\mu)W(k,\mu)+P_{\rm N}^{\rm tot}(k,\mu)}\right)^2$$

It works under the assumption of Gaussian likelihood and no theoretical uncertainties!

One should be careful about the range of wavenumber considered (kmin, kmax)

HI power spectrum model

$$P_{21}(k, z, \mu) = \overline{T}_b^2(z)(b_{\mathrm{HI}}(z) + f(z)\mu^2)^2 P(k, z)$$

$$\overline{T}_b(z) \propto \Omega_{\mathrm{HI}}(z)$$

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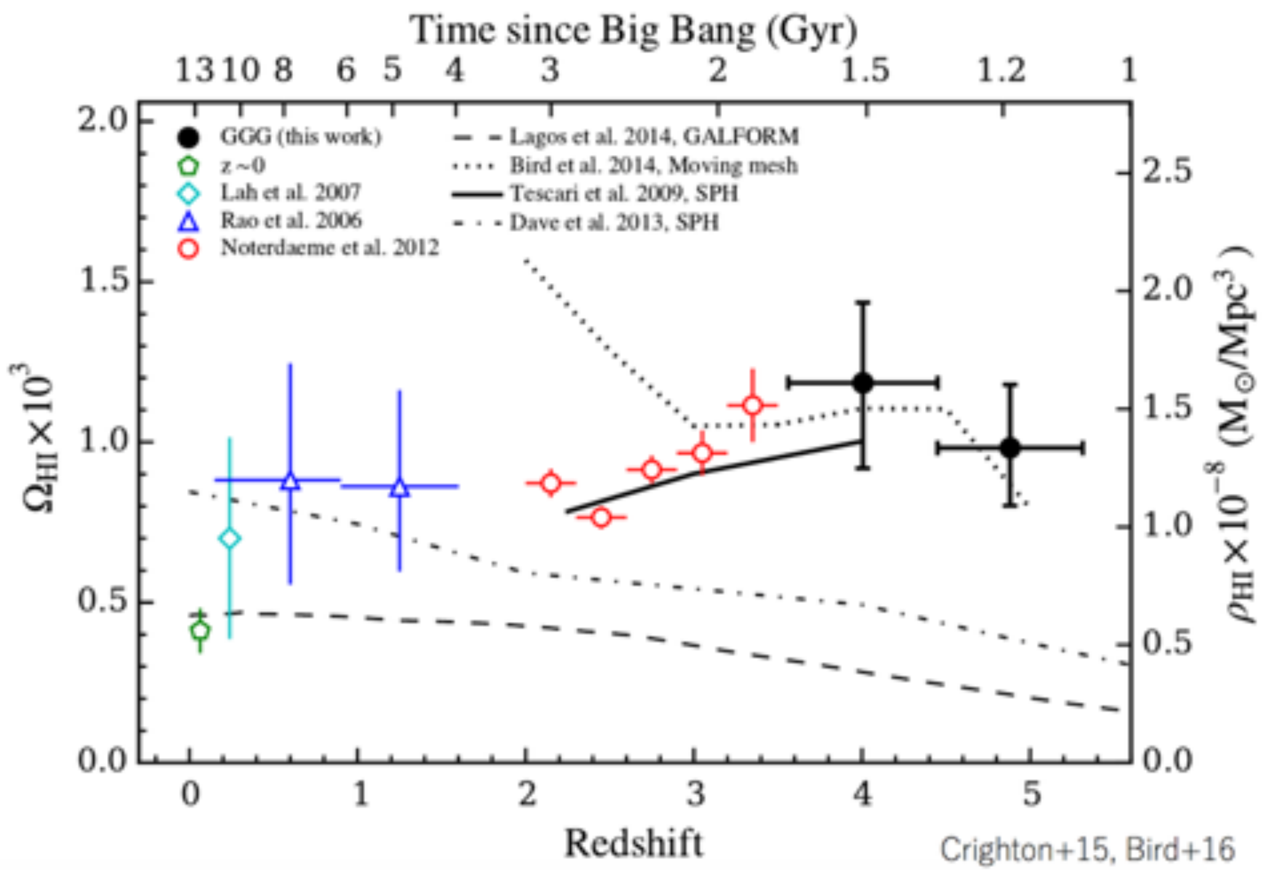

Crighton+15, Bird+16

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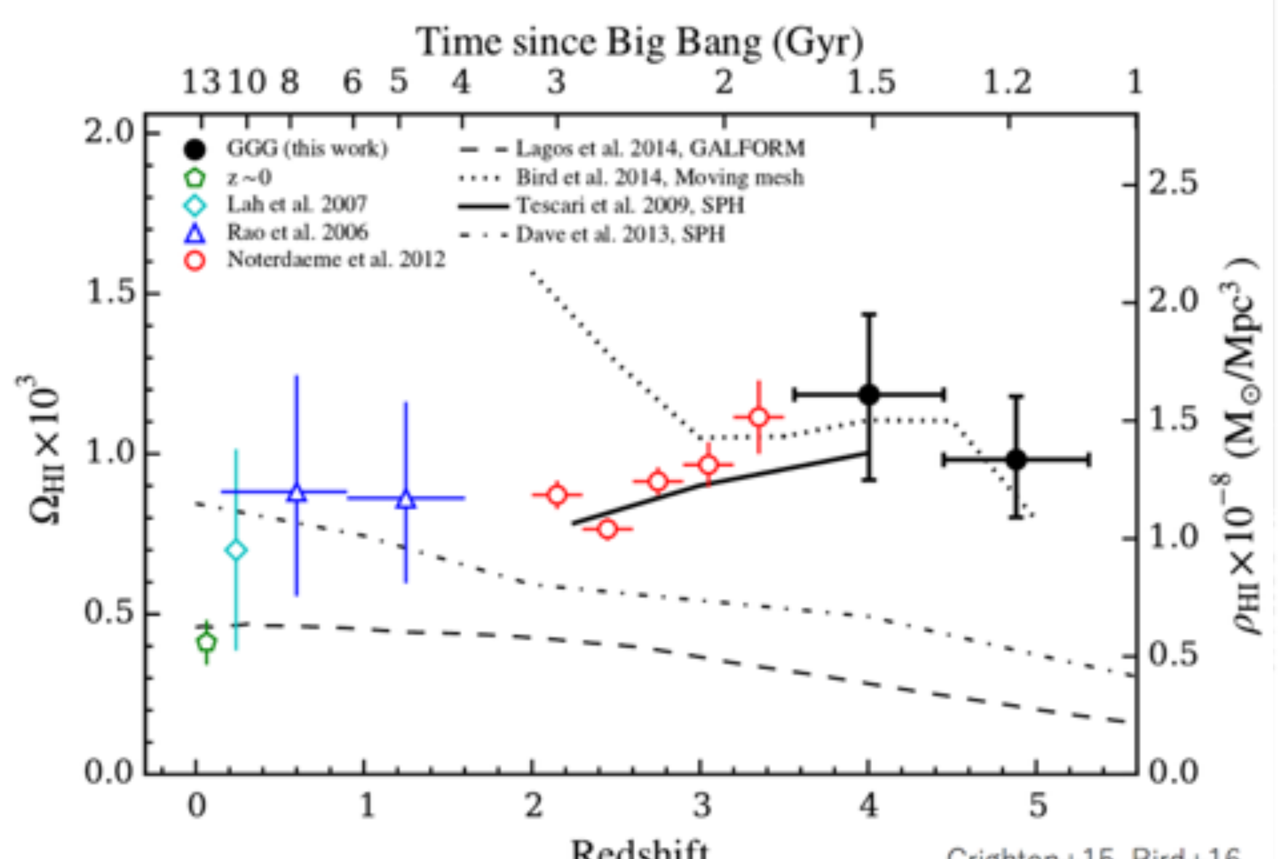
However:
1) future measurements of Damped Ly Alpha systems will constrain OmegaHI
2) cross-correlating weighted DLA and Ly forest (or 21cm) can give bHI



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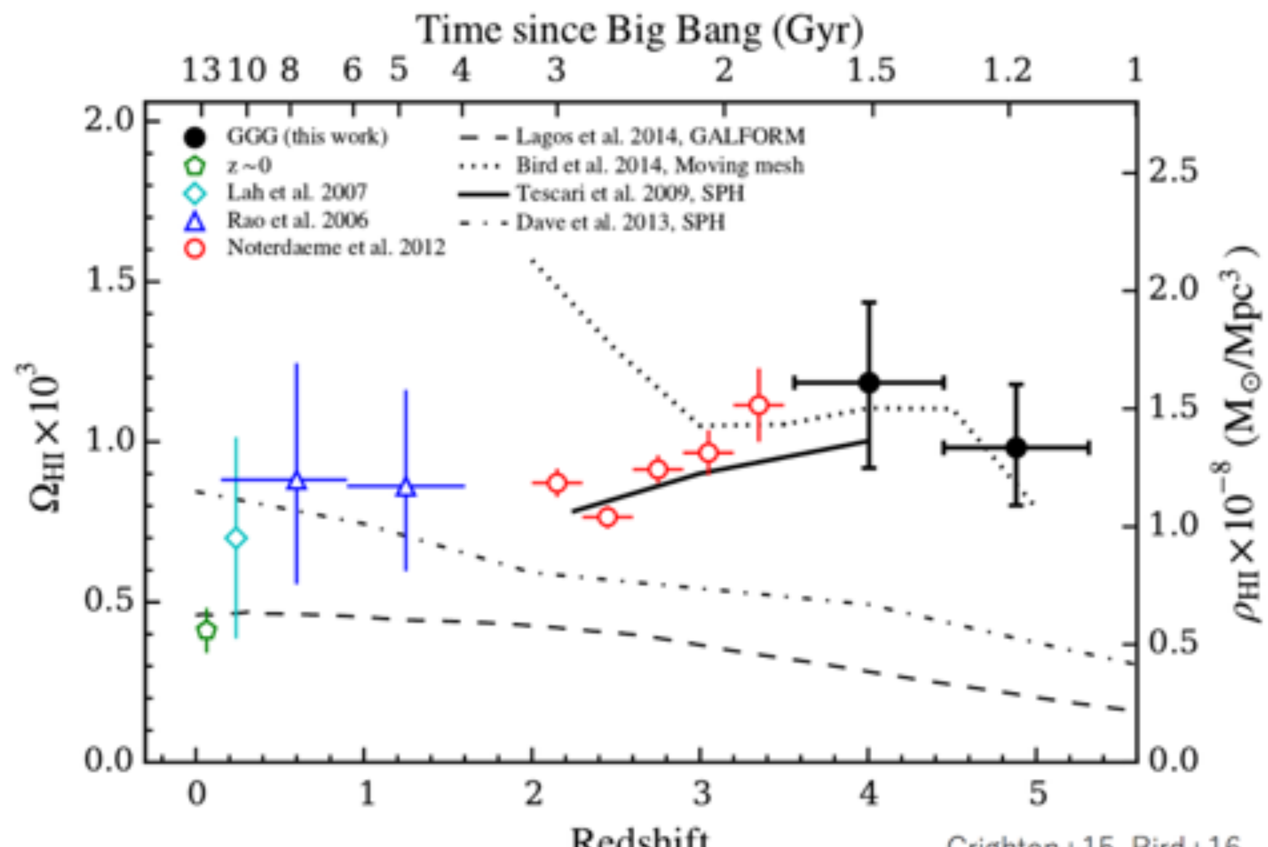
We will assume external 2%, 5% & 10% priors on both OmegaHI & bHI



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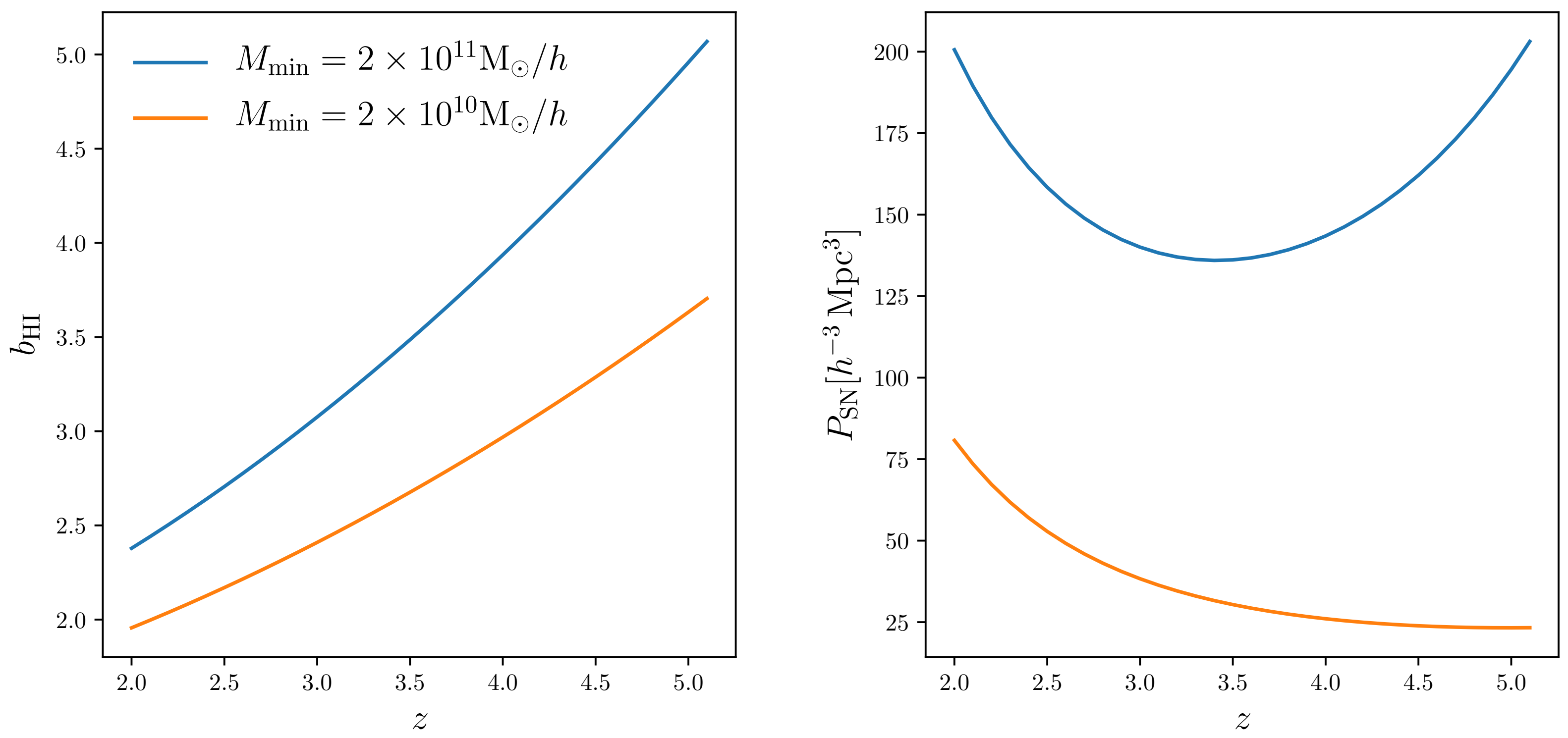
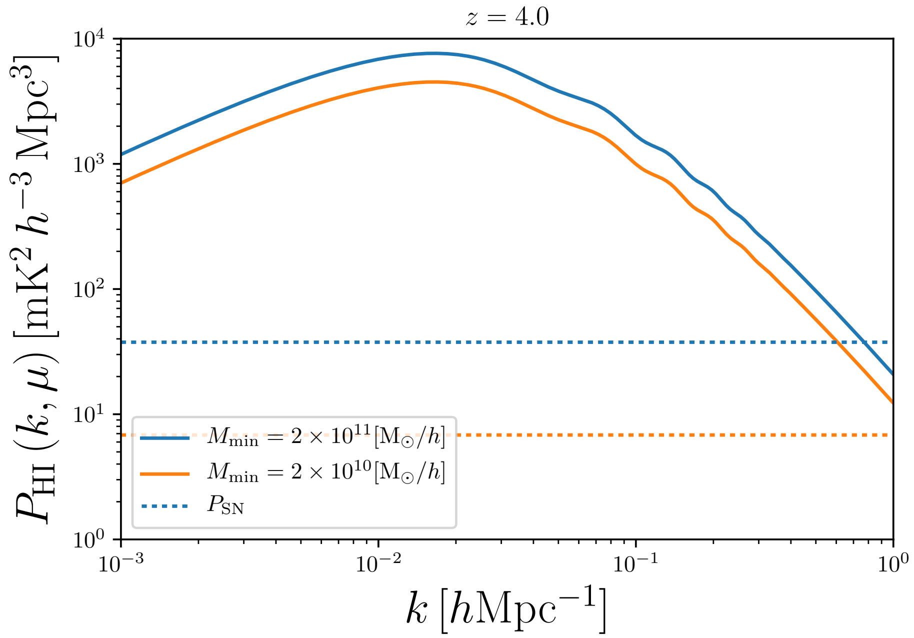
HI bias model & the shot-noise

We follow Castorina et al. (2016)

$$M_{\rm HI}(M) \propto e^{-M_{\rm min}/M} M^{\alpha}$$

$$\alpha = 1$$





HI shot-noise is subdominant

Thermal noise

Interferometers

$$P_{\rm N}^{\rm th}(z) = \frac{T_{\rm sys}^2(z) X^2(z) Y(z) \lambda^4(z) S_{21}}{A_{\rm eff}^2 {\rm FOV}(z) t_0 n_{\rm pol} n(\mathbf{u}, z)}$$

Single-dish

$$P_{\rm N}^{\rm th}(k,\mu) = \frac{T_{\rm sys}^2 V_{\rm pix} W^{-2}(k_\perp)}{\Delta\nu t_{\rm obs} \Omega_{\rm pix}/S_{21} N_{\rm dish} N_{\rm beam}}$$

$$T_{\rm sky}(z) = 60\,{\rm K} \times (\nu_{21}(z)/300{\rm MHz})^{-2.55}$$

Observable modes

$$k_\perp^{min}(z) = \frac{2\pi D_{min}}{D(z)\lambda(z)}$$

$$k_\perp^{max}(z) = \frac{2\pi D_{max}}{D(z)\lambda(z)}$$

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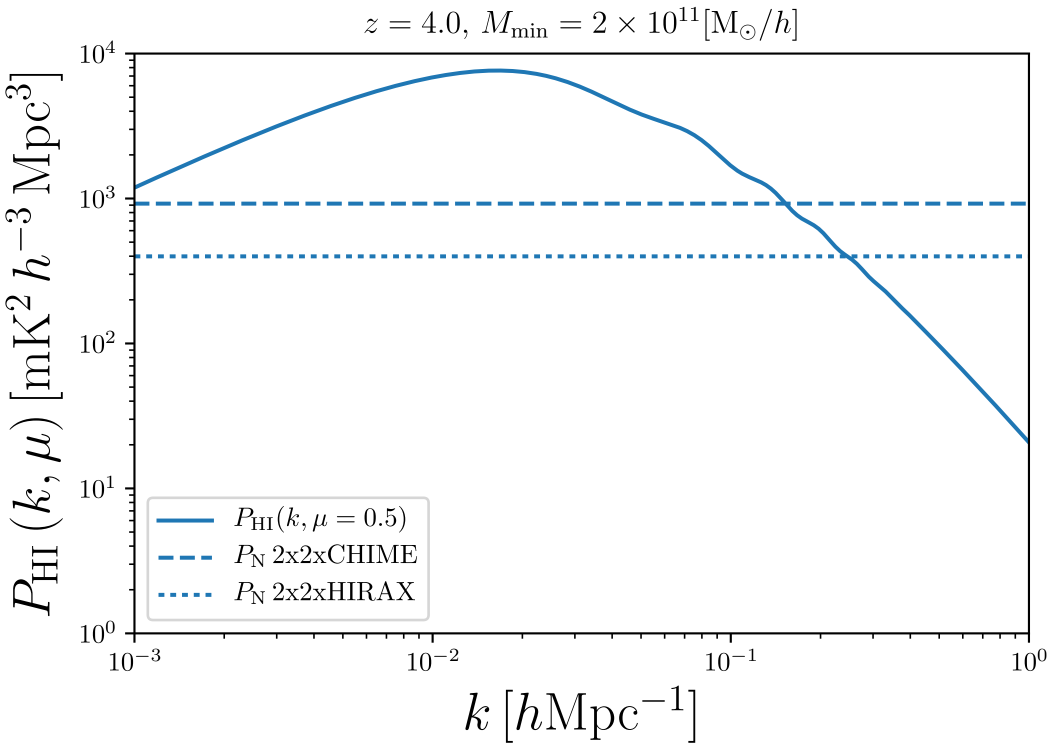

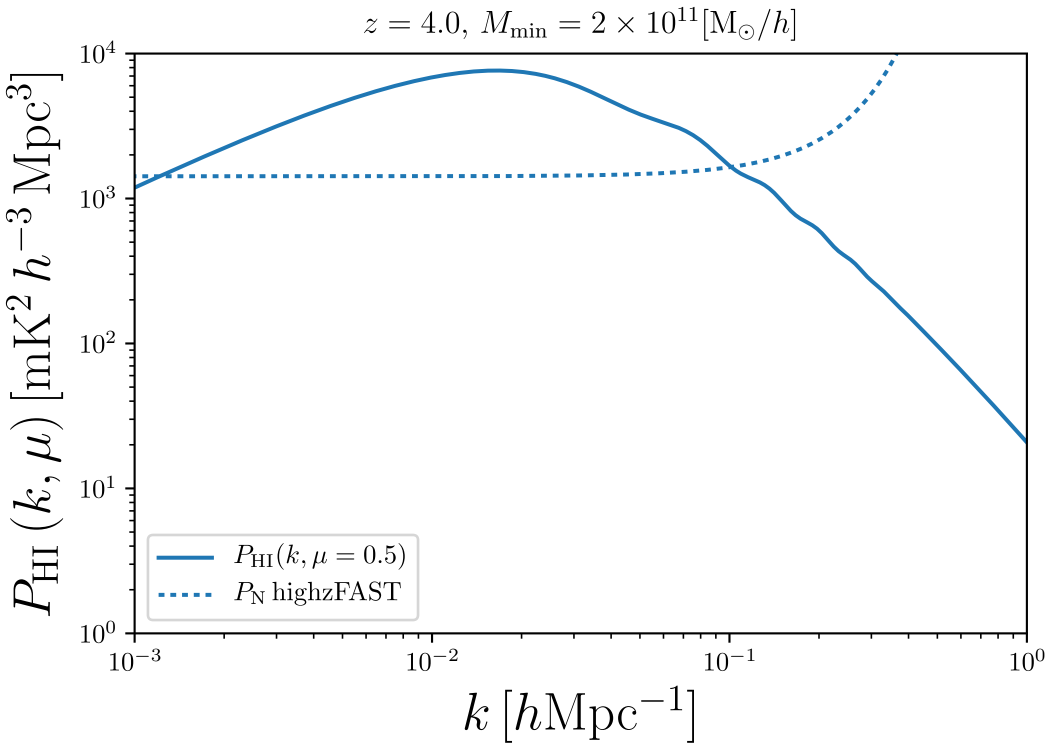

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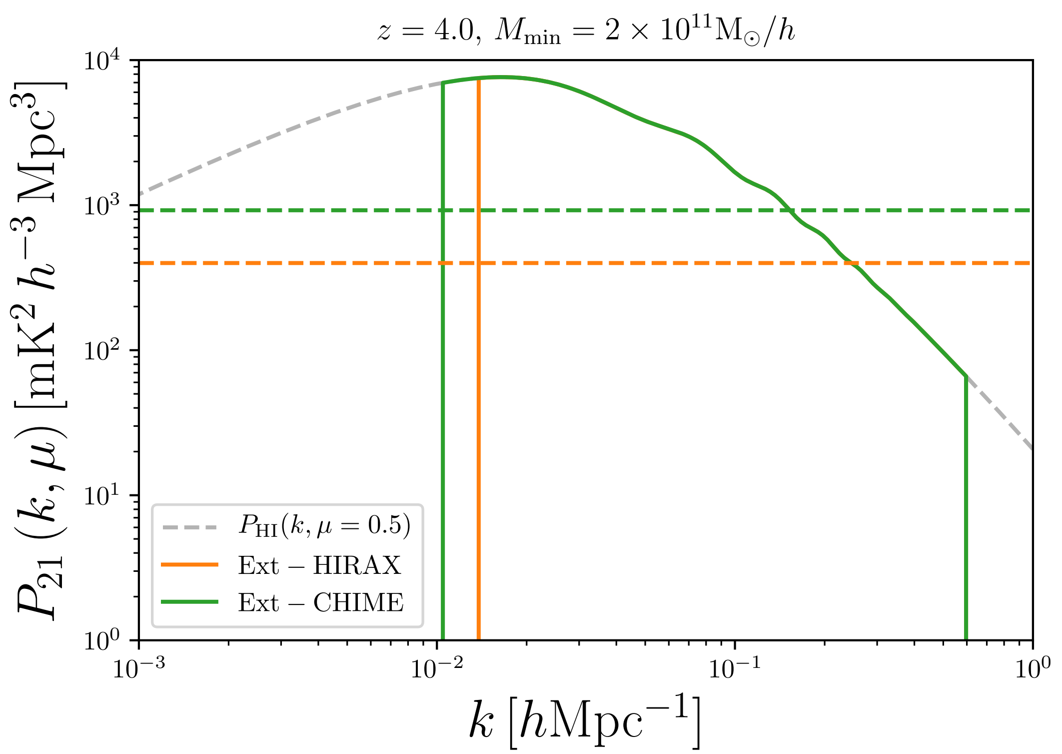

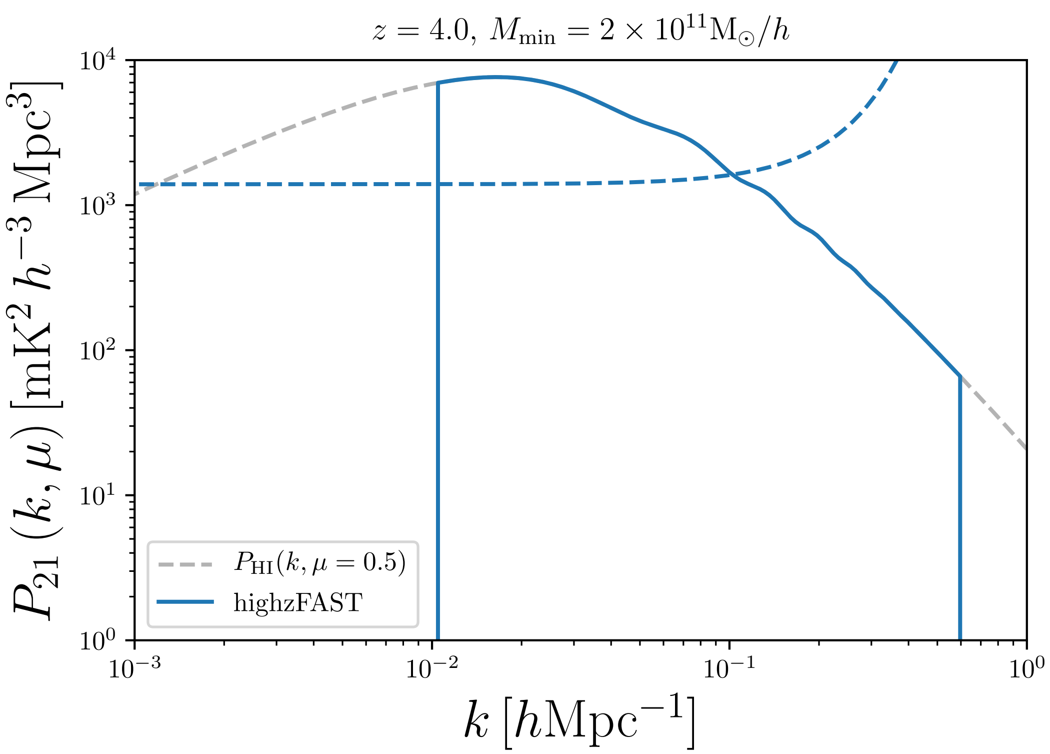

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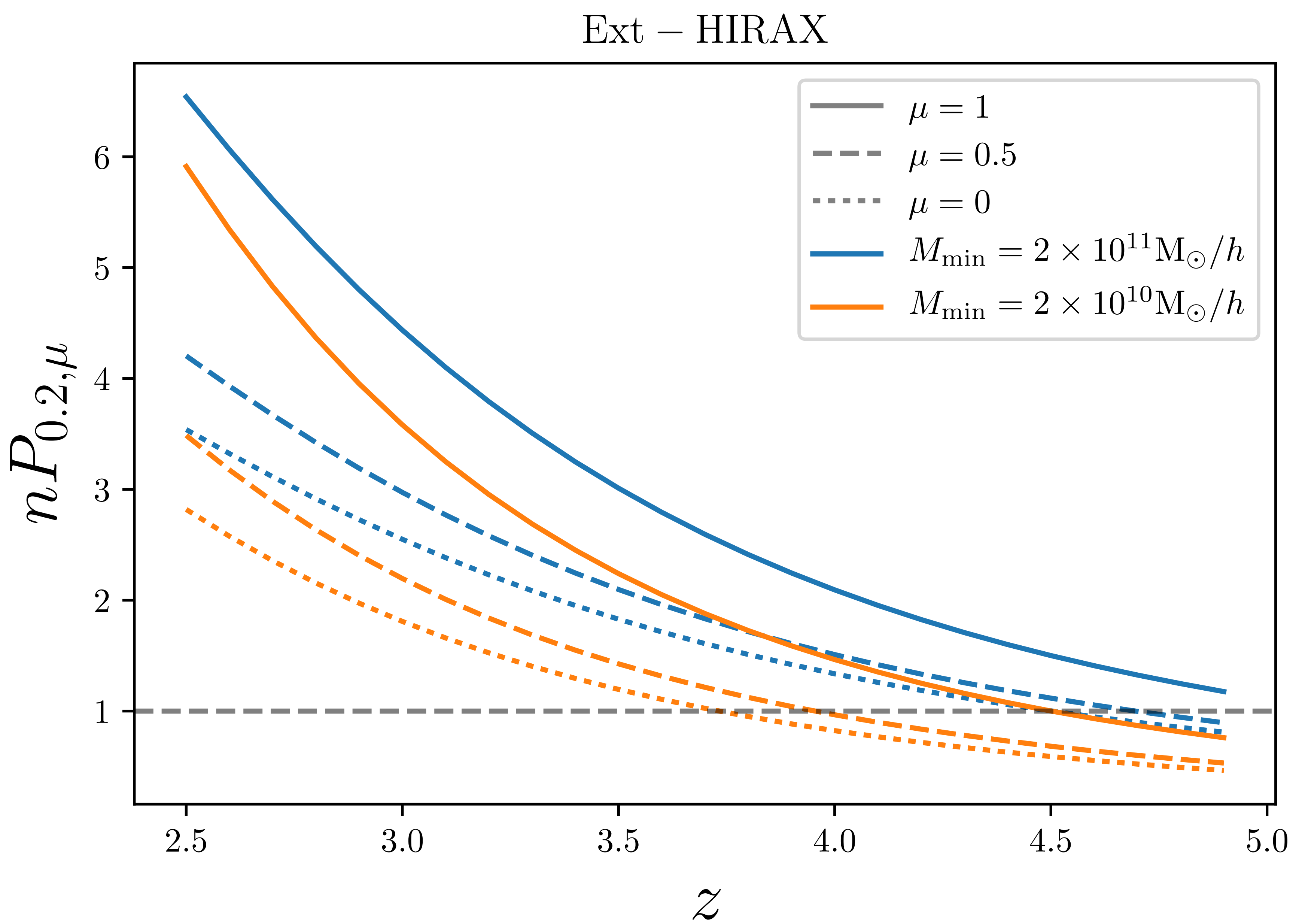
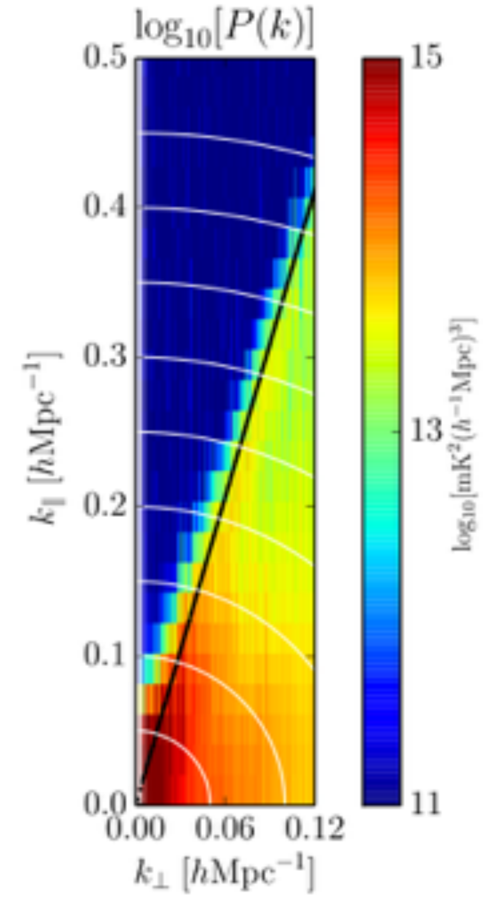


The foreground wedge

Foregrounds are expected to be smooth in frequency,
should affect only low parallel modes,
but the interferometer chromaticity makes them less smooth
as we go to larger baselines, i.e. larger transverse modes.

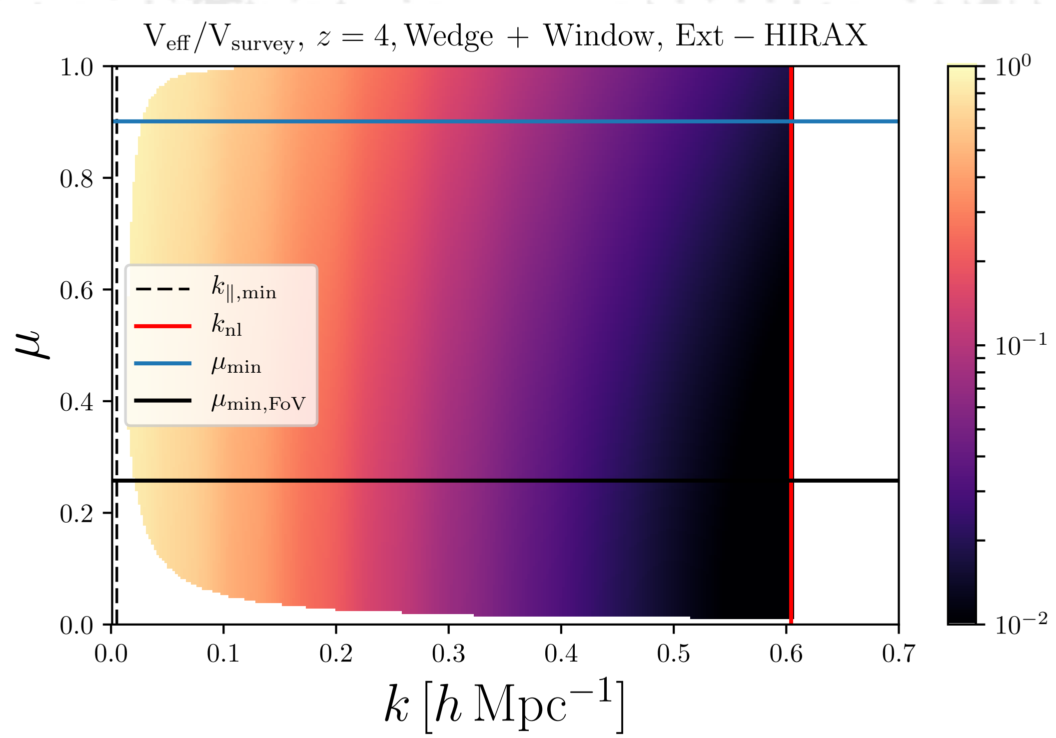


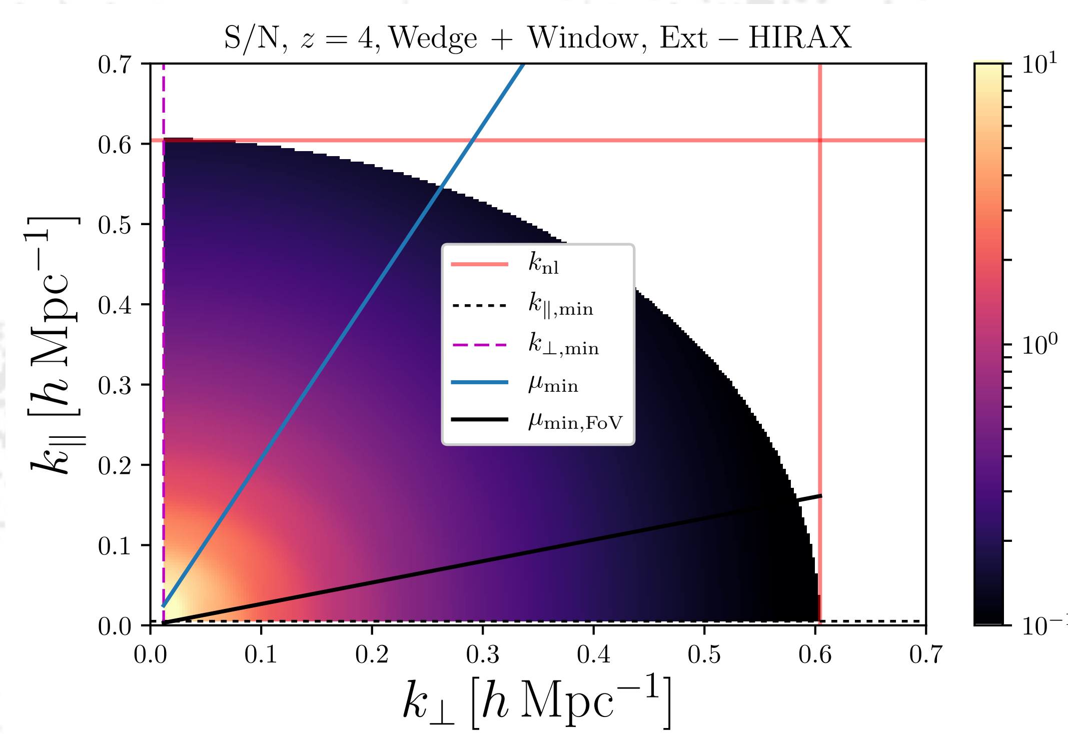
Pober et al, 2015

The wedge:

$$k_{\parallel} < \sin(\theta_{\rm FoV}) \frac{D_c(z) H(z)}{c(1+z)} k_{\perp}$$

$$\mu_{\rm min}(z) = \frac{k_{\parallel}}{\sqrt{k_{\parallel}^2 + k_{\perp}^2}}$$





Fisher forecasts

Full power spectrum:

$$P_{21}(k_f,\mu_f,z) = \overline{T}_b^2(z)\frac{D_A(z)_f^2 H(z)}{D_A(z)^2 H(z)_f}(b_{\rm HI}\sigma_8(z)+f\sigma_8(z)\mu^2)^2\frac{P(k,z)}{\sigma_{8,\rm f}^2}$$

Fisher matrix:

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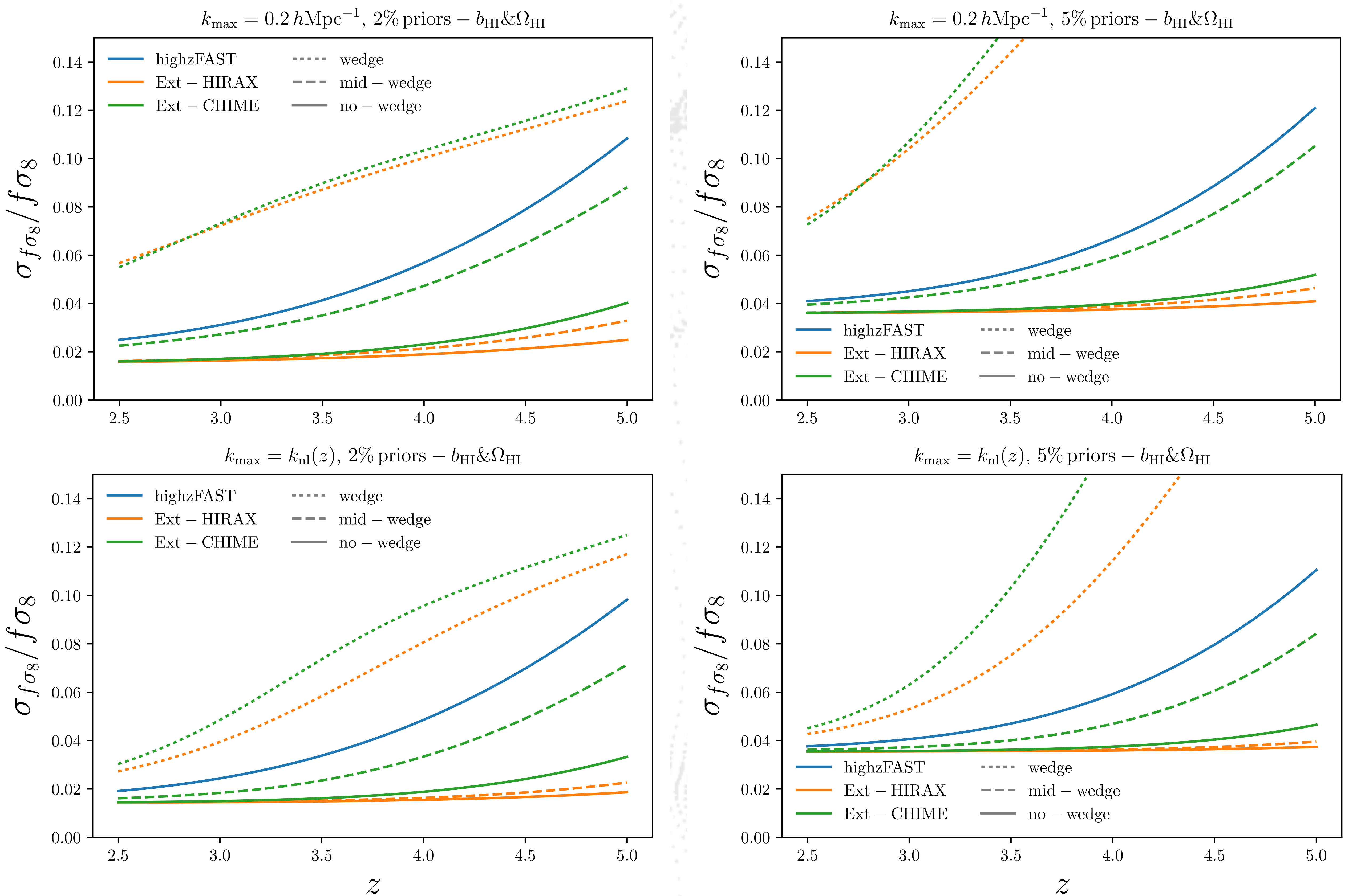
We use two different kmax scales — 0.2 & knl(z)=0.2(1+z)^2/3 h/Mpc

Growth of structures: $f\sigma_8(z)$

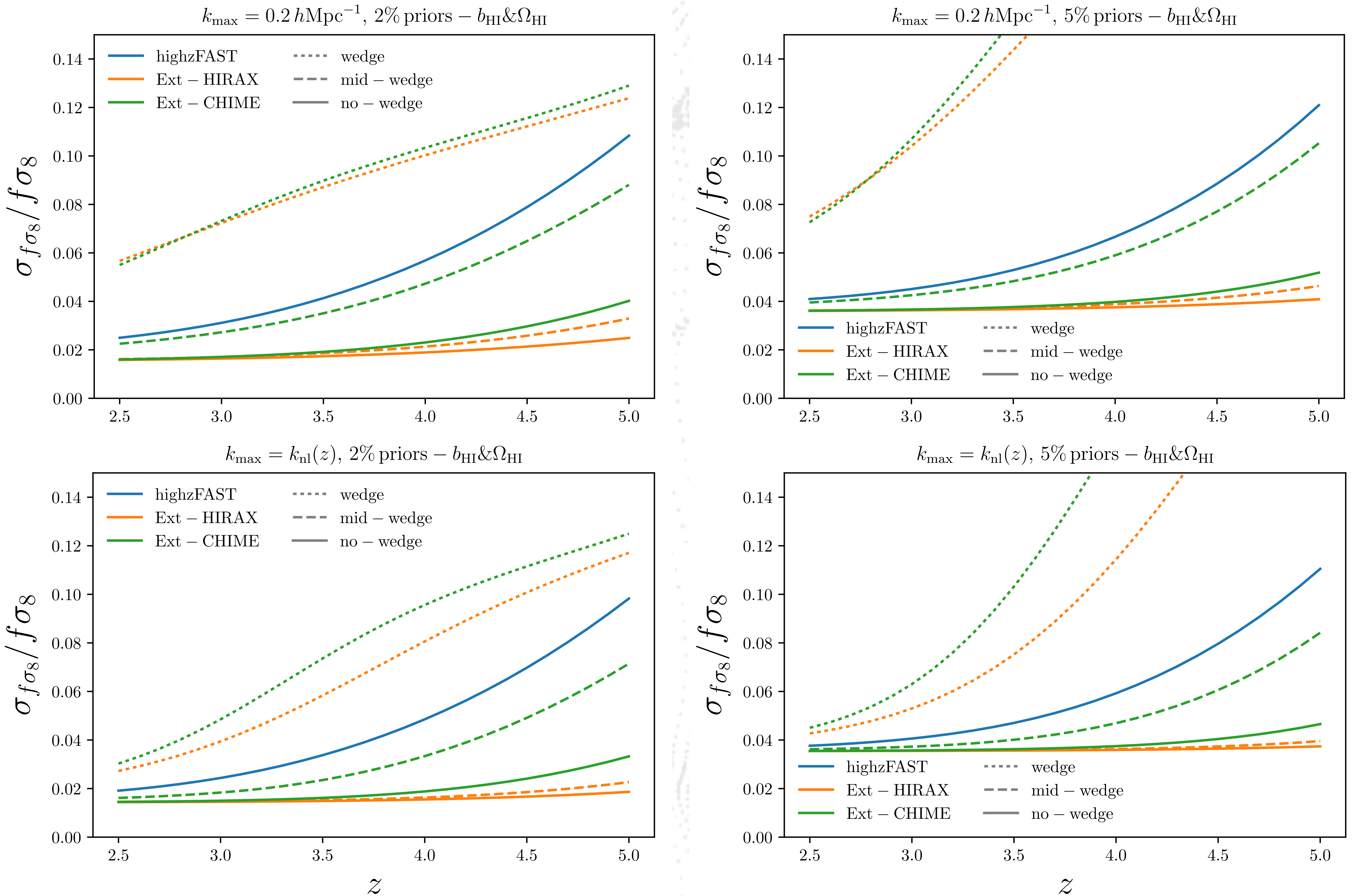
2% priors



Growth of structures: $f\sigma_8(z)$

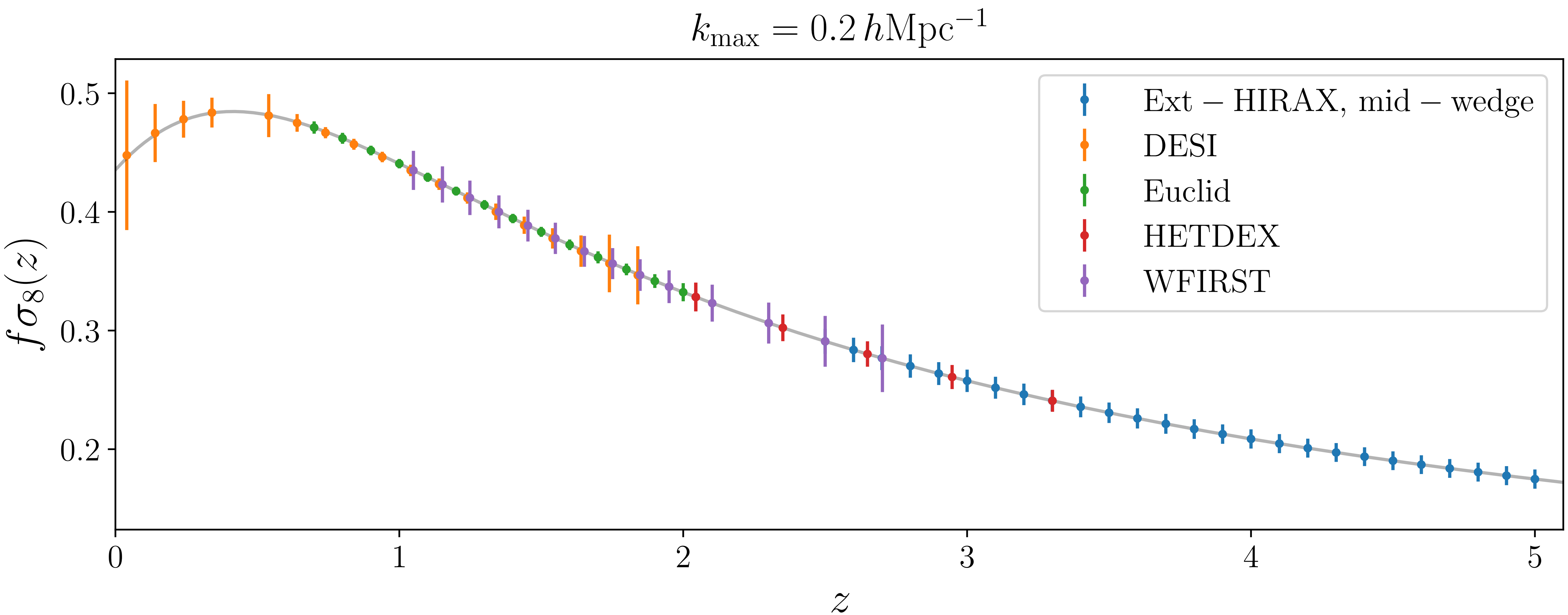
2% priors

5% priors

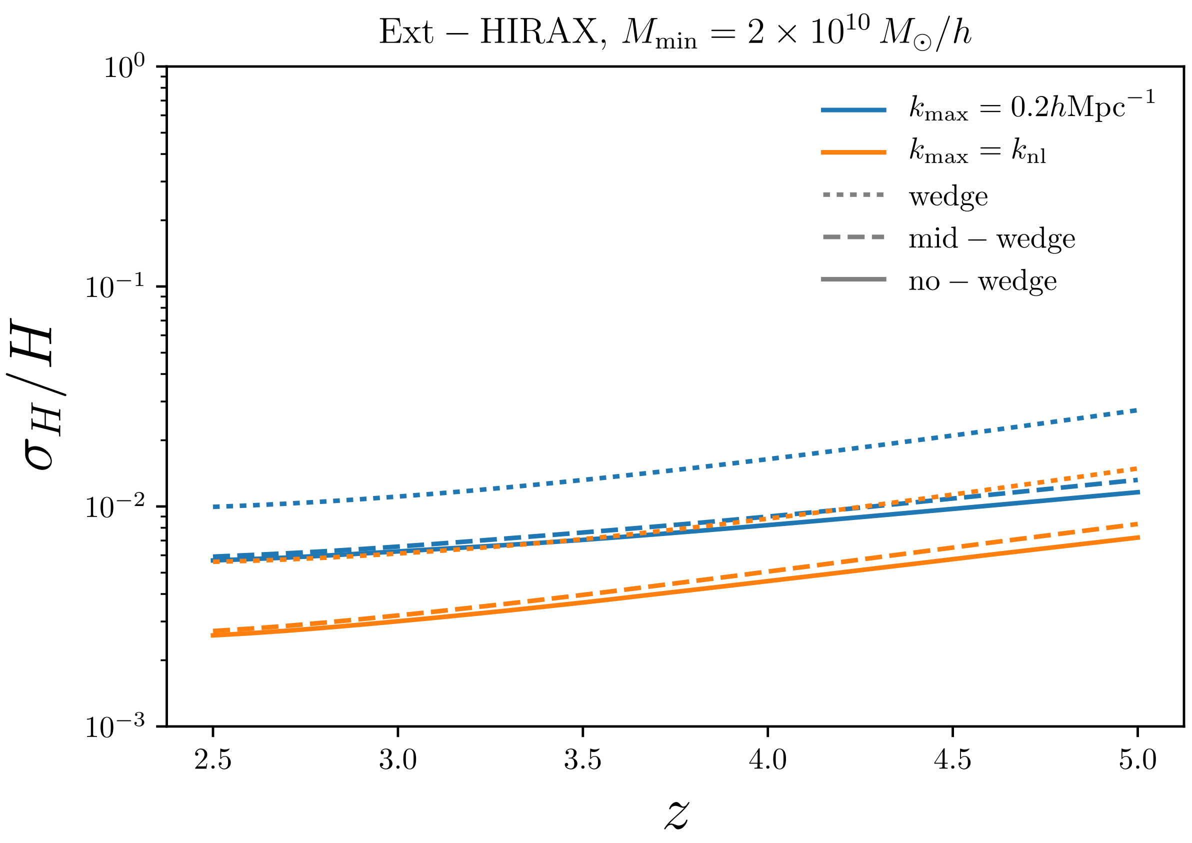


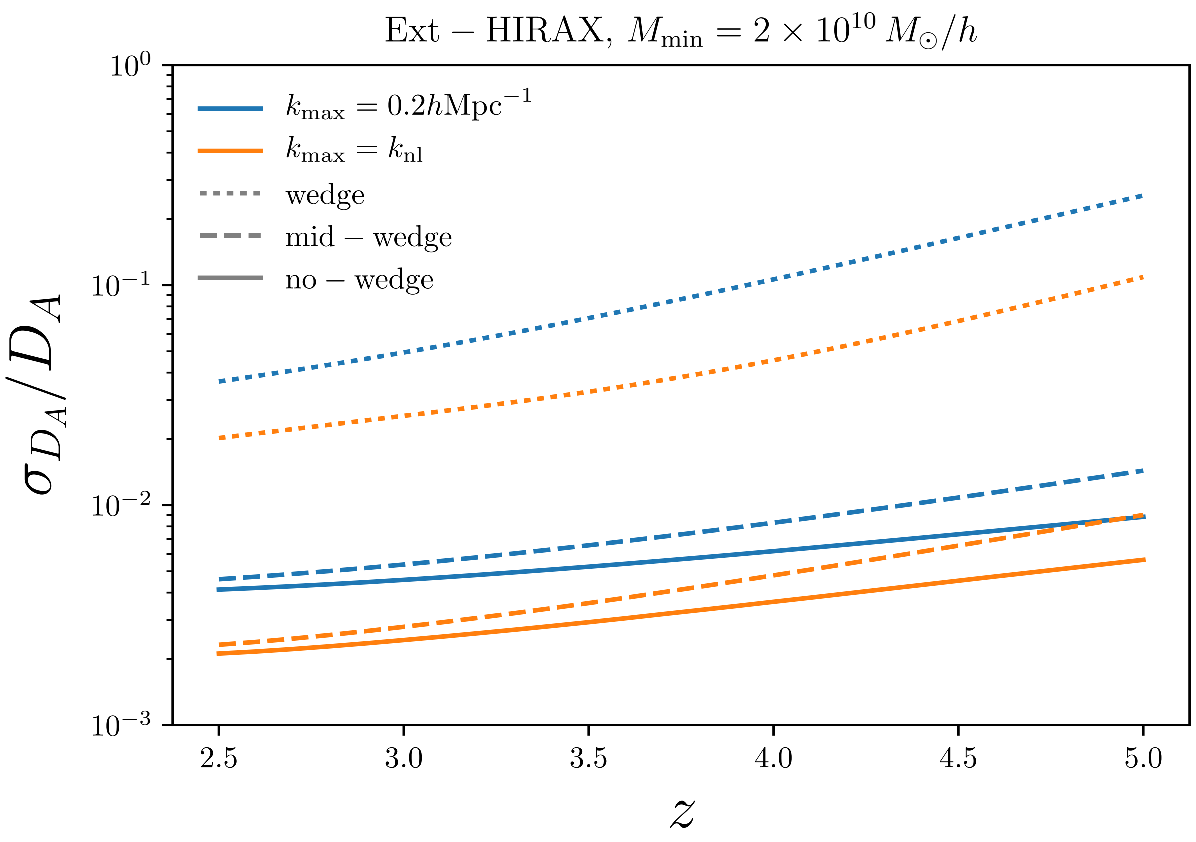
Growth of structures: $f\sigma_8(z)$

Redshift coverage comparison with other surveys

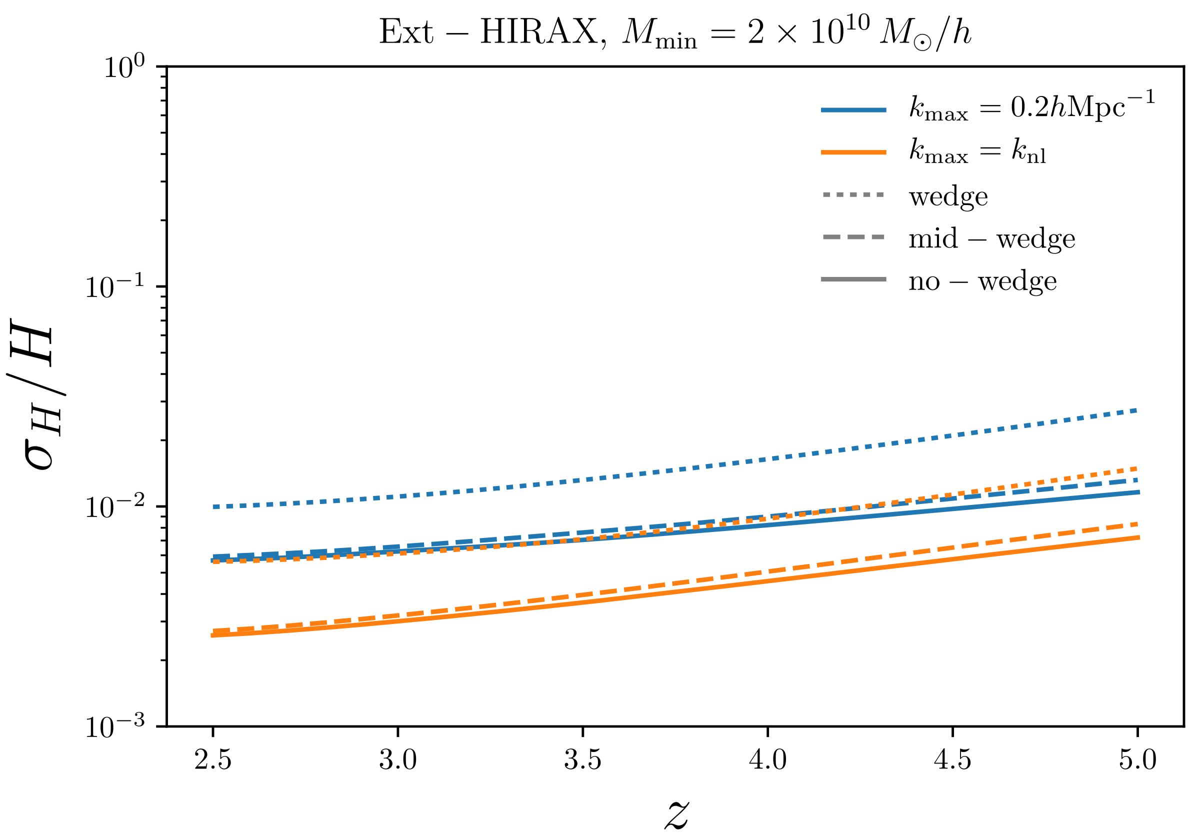


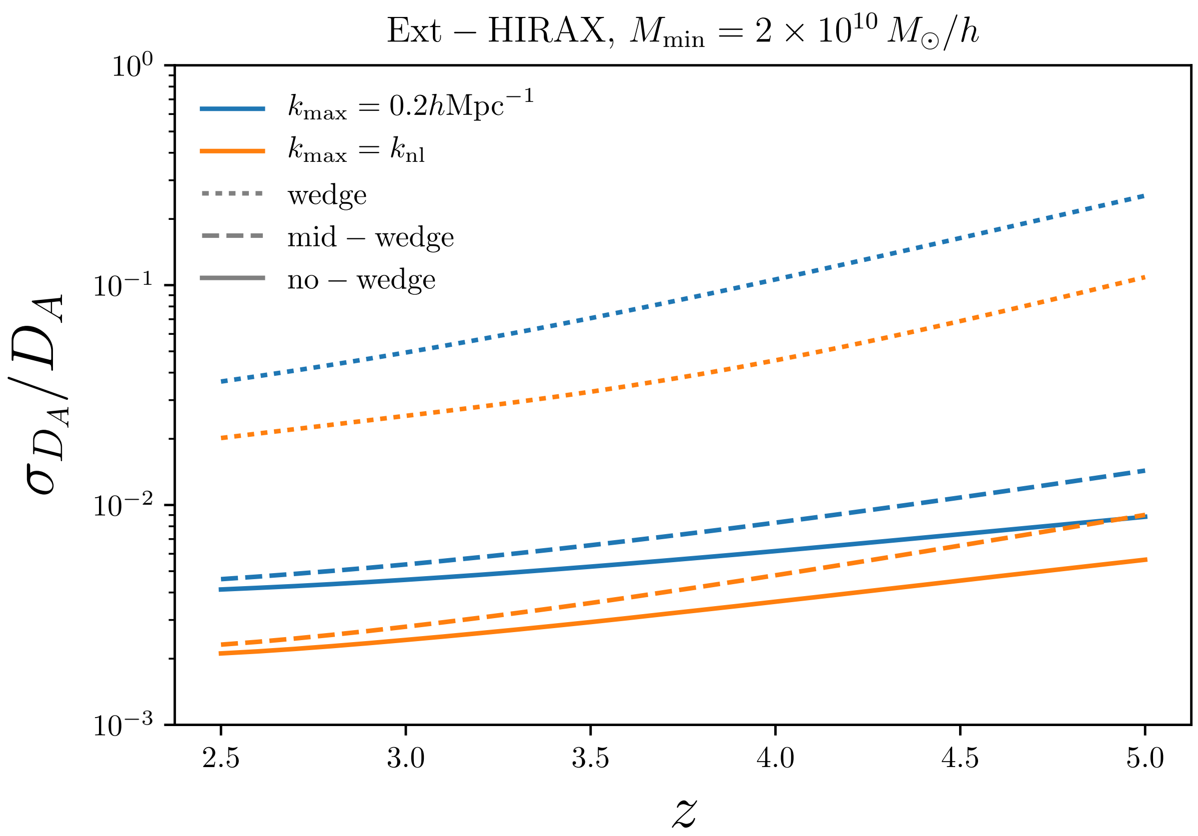
BAO: AP parameters $H(z)\,\&D_A(z)$

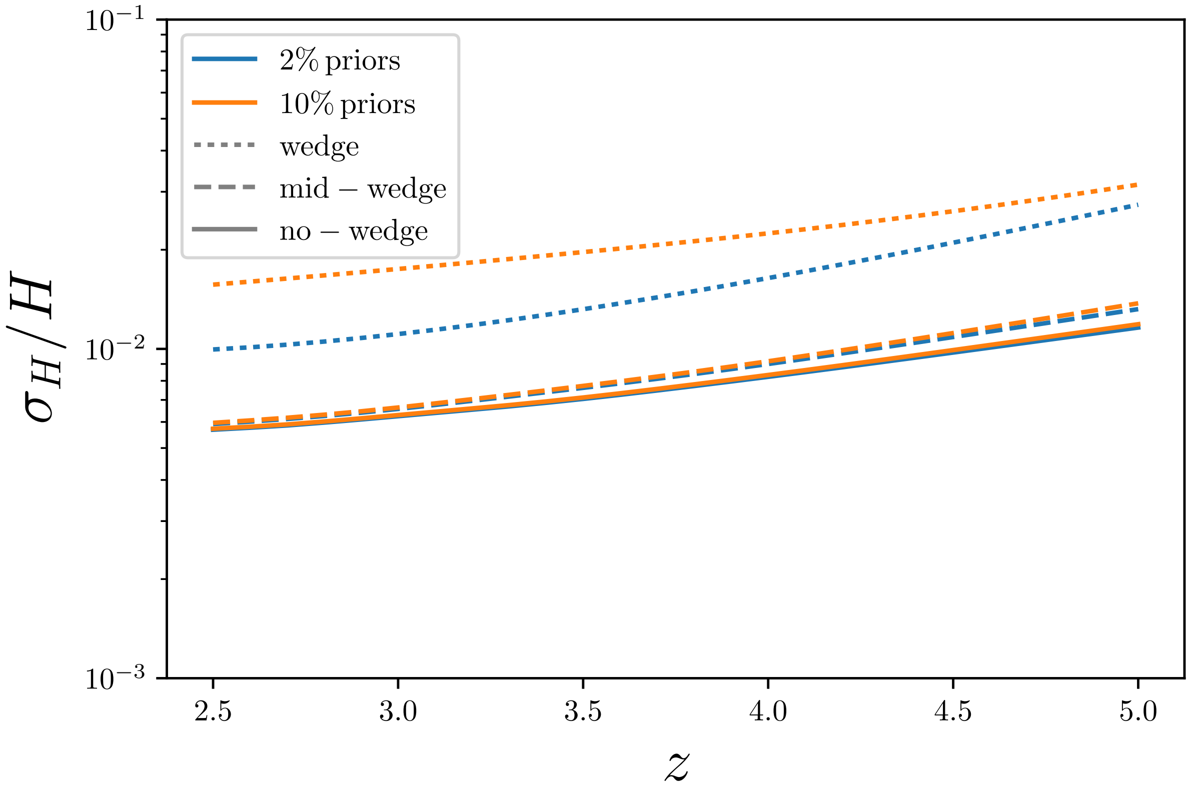




BAO: AP parameters $H(z)$ & $D_A(z)$







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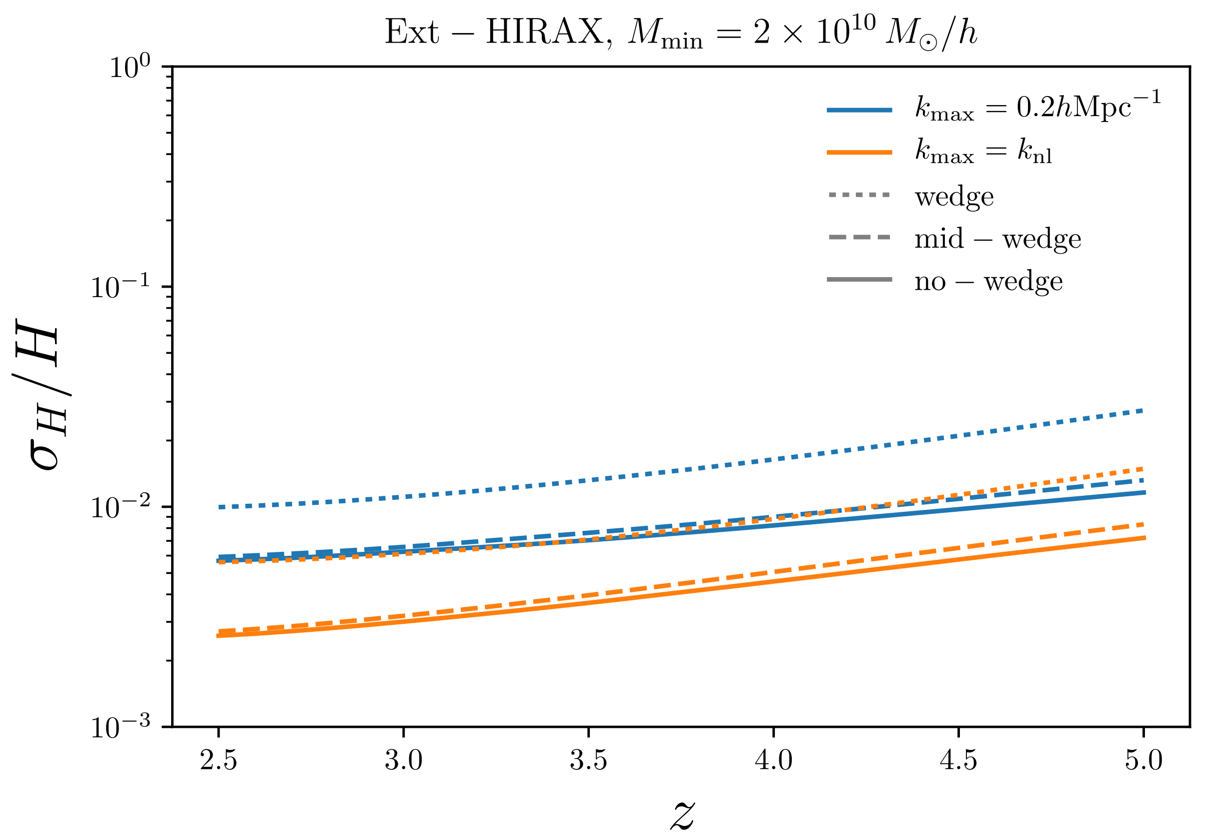
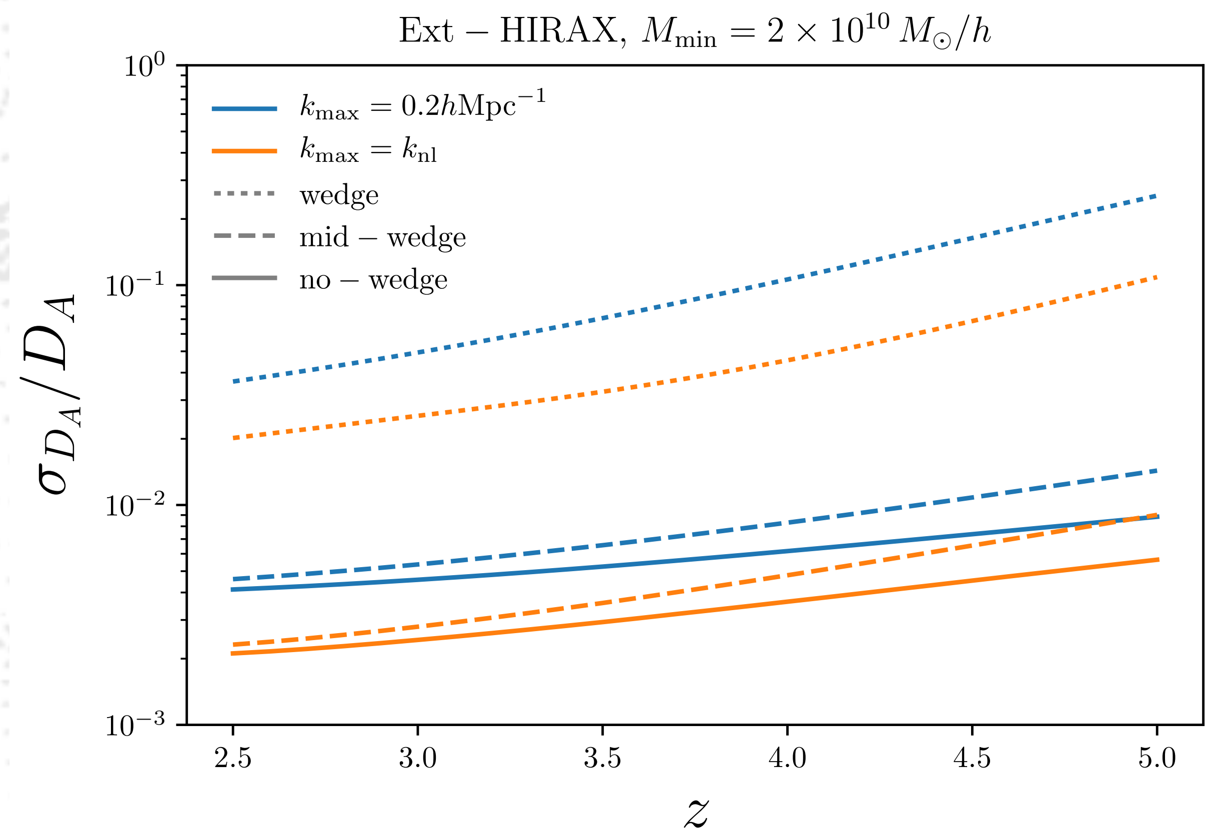
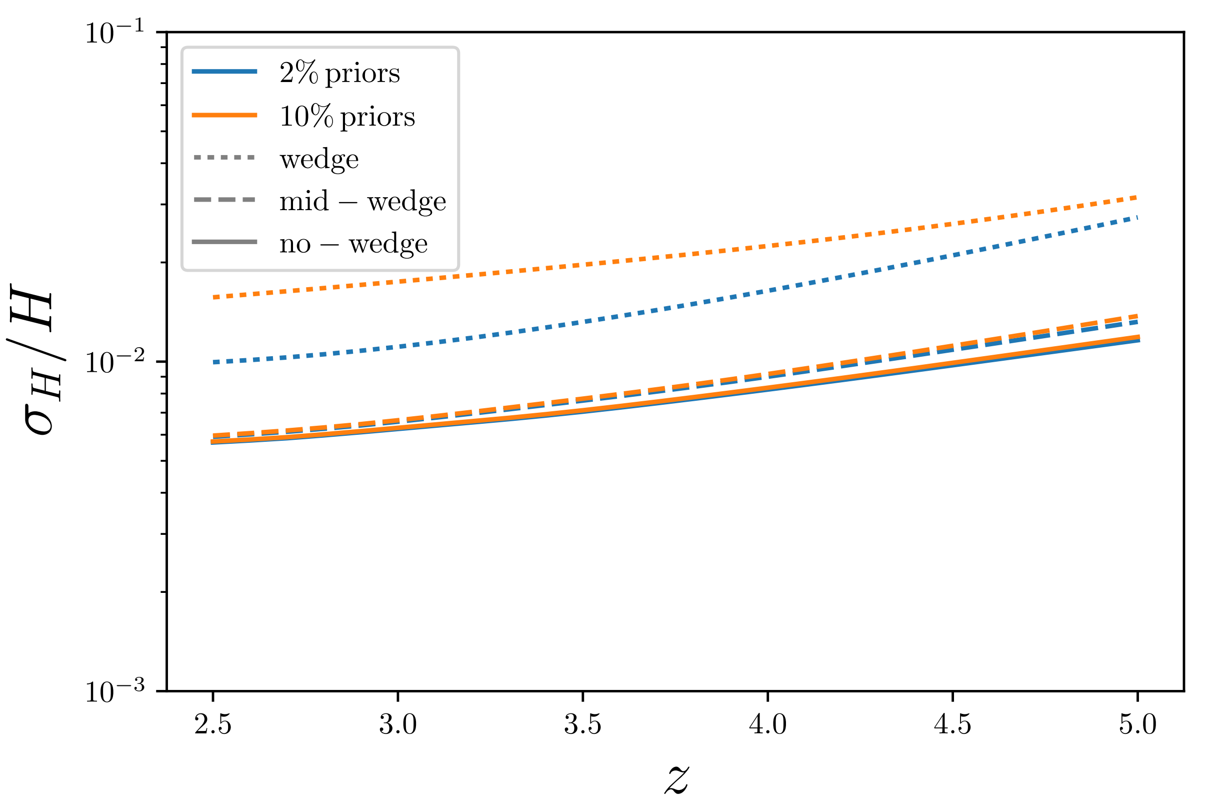
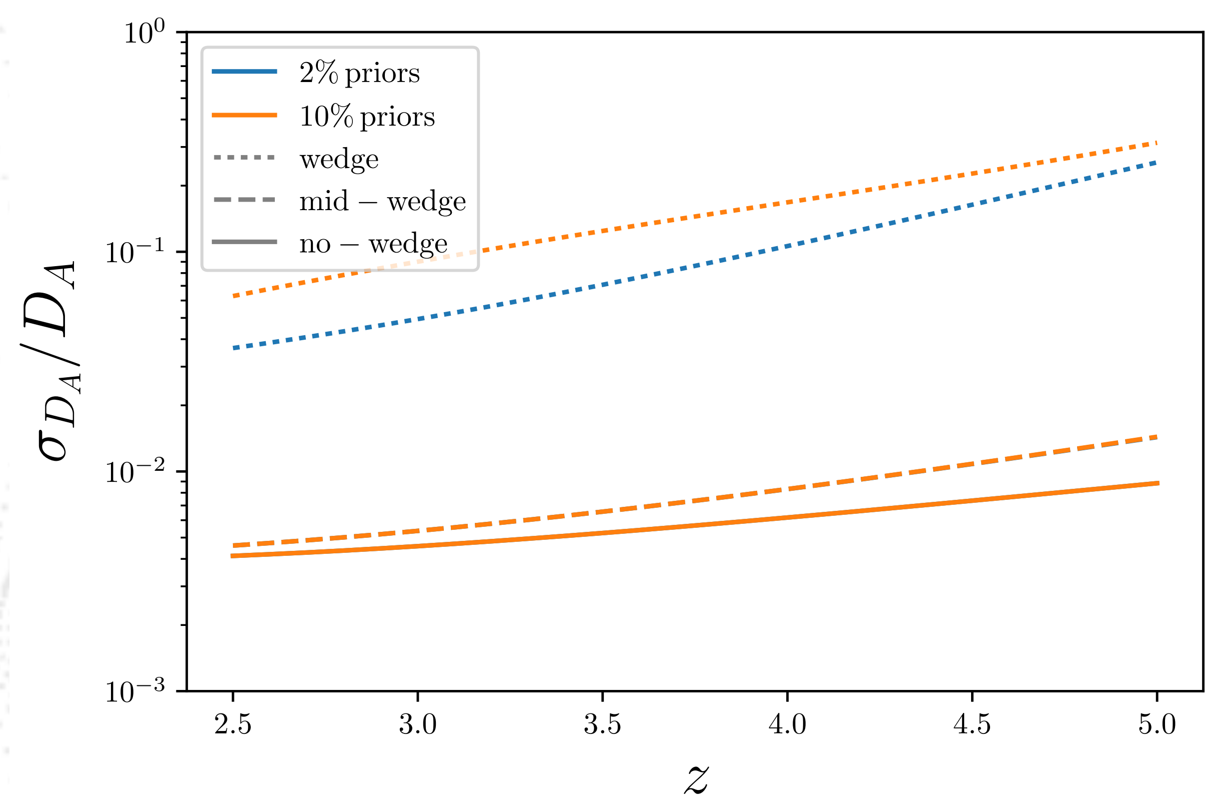


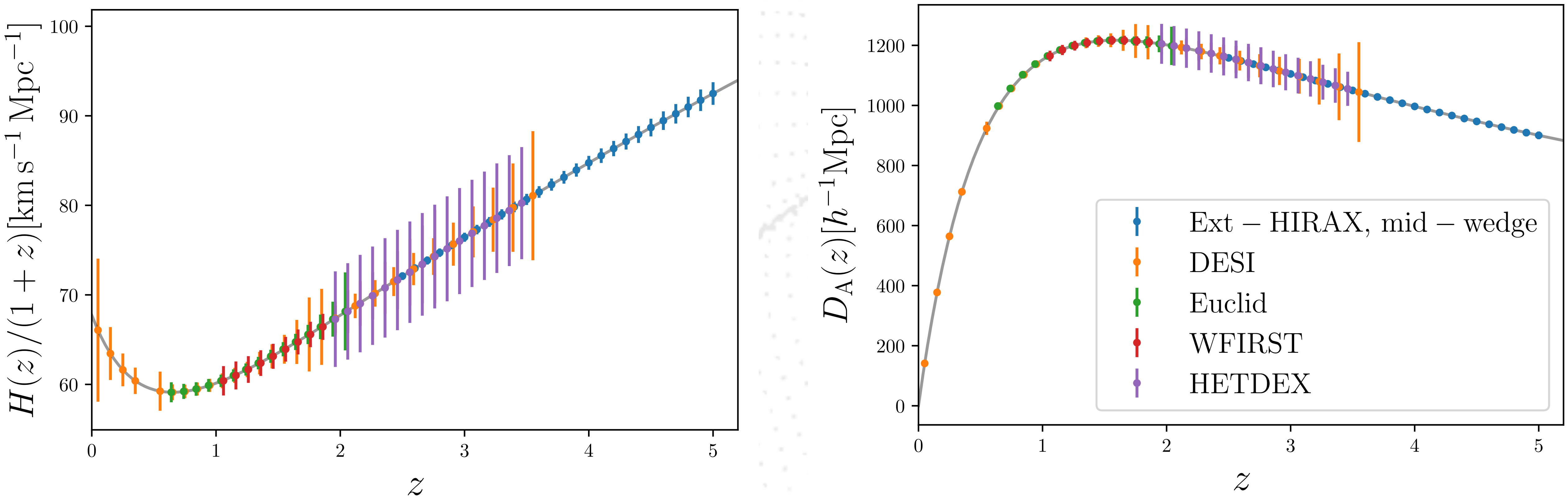






BAO: AP parameters

Redshift coverage comparison with other surveys



LambdaCDM extensions using the broadband shape

- The sum of neutrino masses
- The effective number of relativistic degrees of freedom

LambdaCDM extensions using the broadband shape

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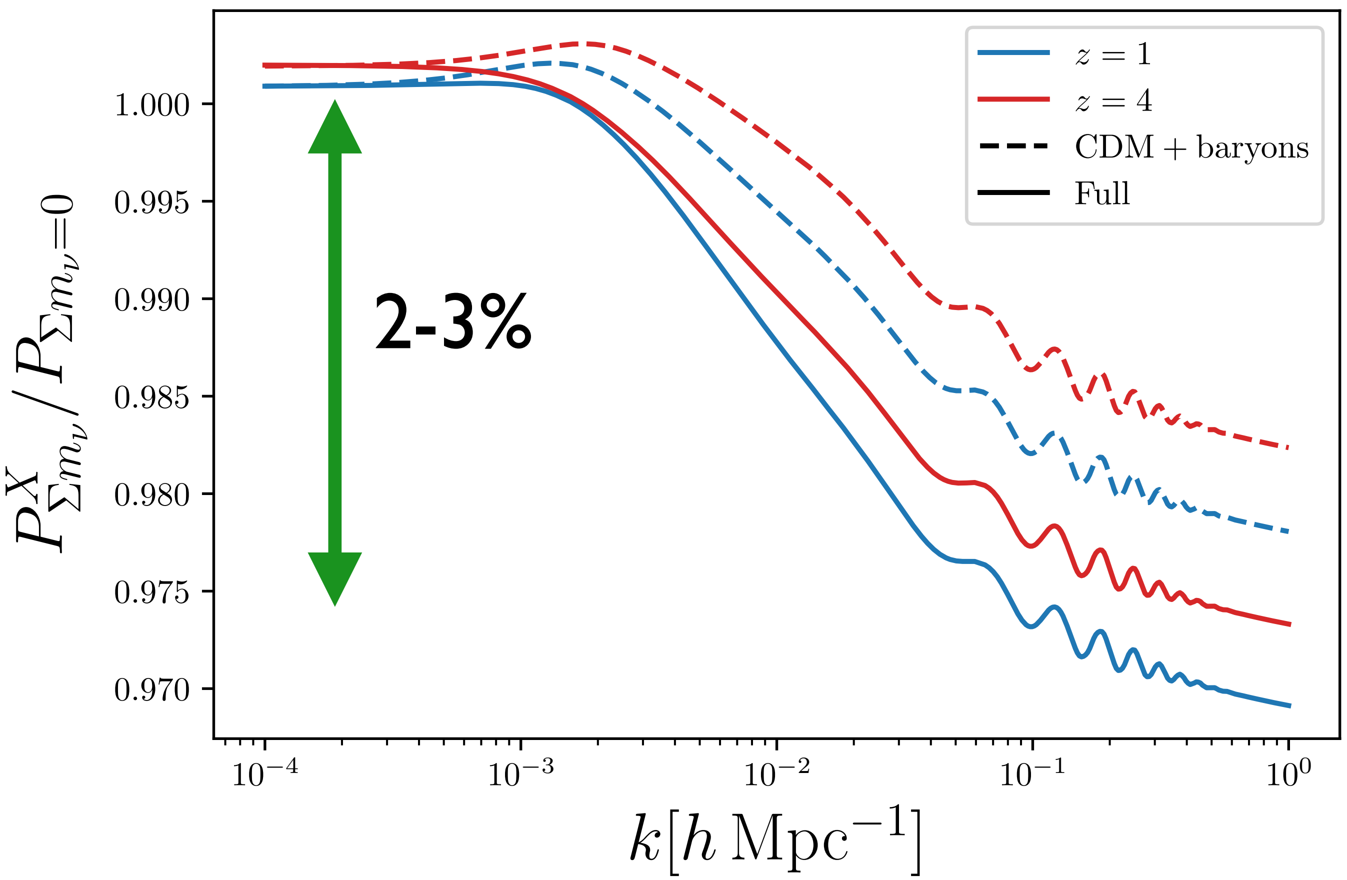
We make use of the synergy with current and future datasets and forecasts:

- Planck 2015 + BOSS BAO
- Future galaxy redshift survey — Euclid
- Future CMB Stage 4

Broadband shape + massive neutrinos

The effect of massive neutrinos on the power spectrum

CDM+baryons power spectrum



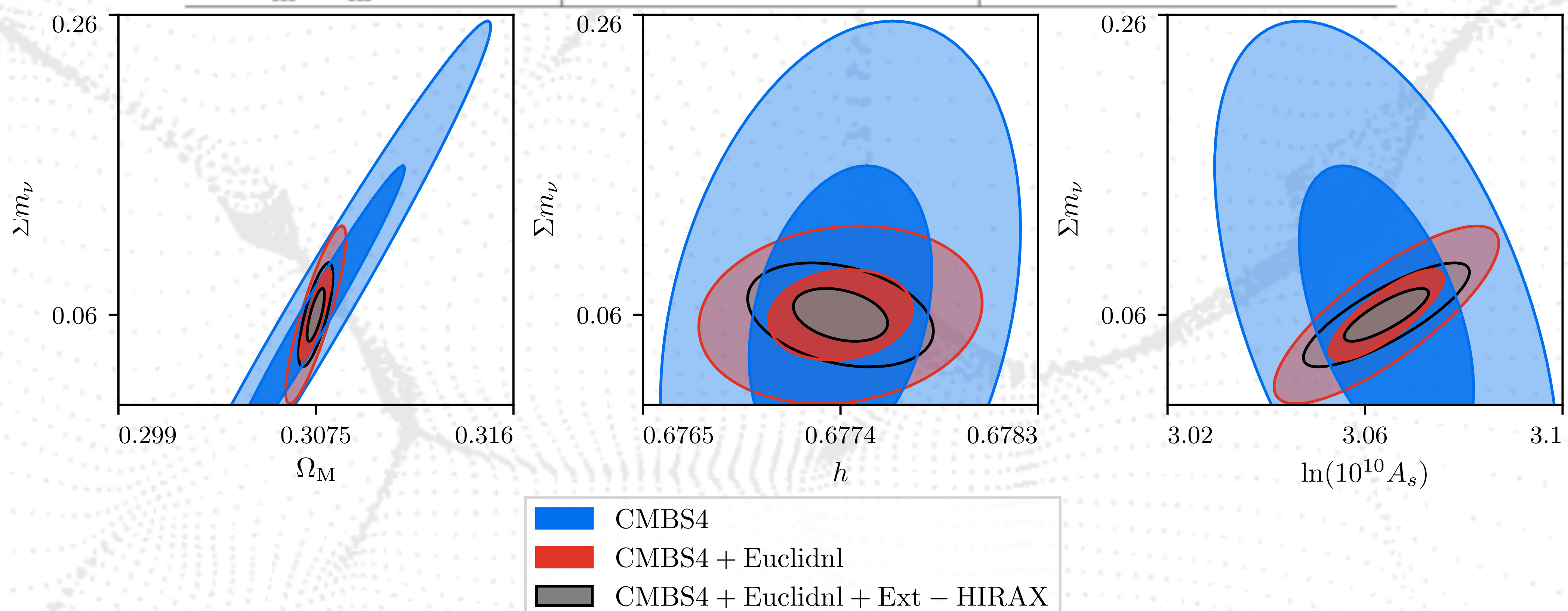
Ext-HIRAX alone

Ext-HIRAX Σm_ν					
	Ω_M	h	Σm_ν[eV]	$\ln(10^{10} A_s)$	n_s
Fiducial values	0.3075	0.6774	0.060	3.064	0.9667
No wedge $k_{\max} = 0.2h\mathrm{Mpc}^{-1}$					
2% b_{HI} & Ω_{HI}	0.0016	0.0010	0.059	0.026	0.0036
2% b_{HI} & Ω_{HI}, diff $M_{\min}$	0.0015	0.0009	0.056	0.025	0.0033
2% b_{HI} & Ω_{HI}, 1-loop	0.0020	0.0010	0.081	0.038	0.014
5% b_{HI} & Ω_{HI}	0.0024	0.0015	0.093	0.047	0.0038
10% b_{HI} & Ω_{HI}	0.0029	0.0018	0.11	0.065	0.0040

Broadband shape + massive neutrinos

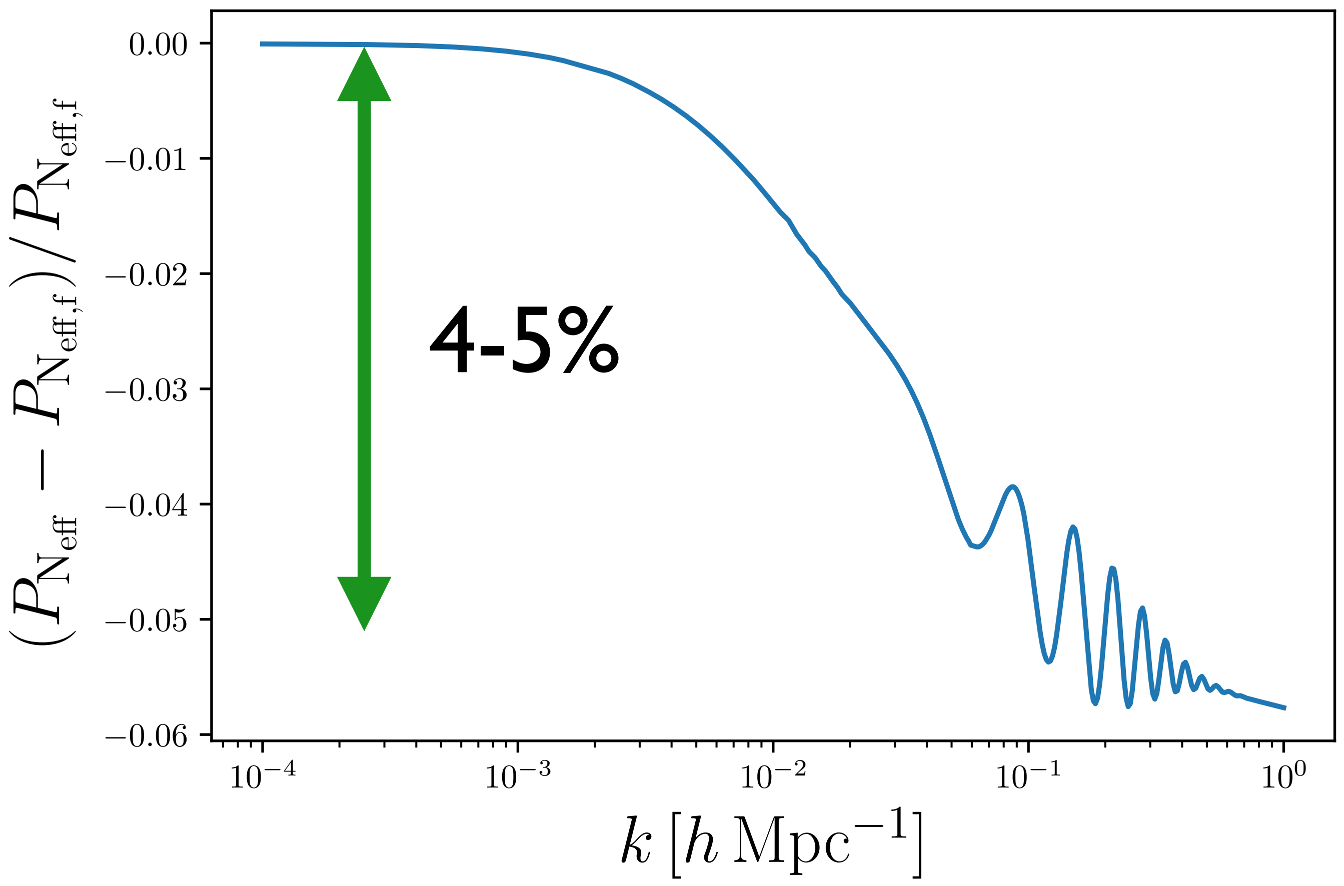
CMB S4 + Euclid + Ext-HIRAX

Ext-HIRAX Σm_ν[eV]						
	$k_{\rm max} = 0.2h{\rm Mpc}^{-1}$			$k_{\rm max} = k_{\rm nl}(z)$		
Euclid No Rec.+PlanckBAO	0.050			0.049		
+21cm	No wedge	Mid wedge	Wedge	No wedge	Mid wedge	Wedge
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.037	0.038	0.045	0.030	0.031	0.040
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$, diff $M_{\rm min}$	0.037	0.038	0.044	0.028	0.029	0.039
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$, 1-loop	0.038	0.039	0.046	0.035	0.035	0.042
5% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.042	0.043	0.048	0.034	0.035	0.043
10% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.044	0.045	0.049	0.035	0.036	0.044
Euclid No Rec.+CMB-S4	0.031			0.030		
+21cm	No wedge	Mid wedge	Wedge	No wedge	Mid wedge	Wedge
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.022	0.022	0.028	0.018	0.018	0.025
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$, diff $M_{\rm min}$	0.021	0.021	0.028	0.017	0.017	0.024
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$, 1-loop	0.023	0.023	0.028	0.020	0.020	0.025
5% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.023	0.023	0.028	0.018	0.019	0.025
10% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.023	0.023	0.028	0.019	0.019	0.025



Broadband shape + Neff

The effect of Neff on the power spectrum



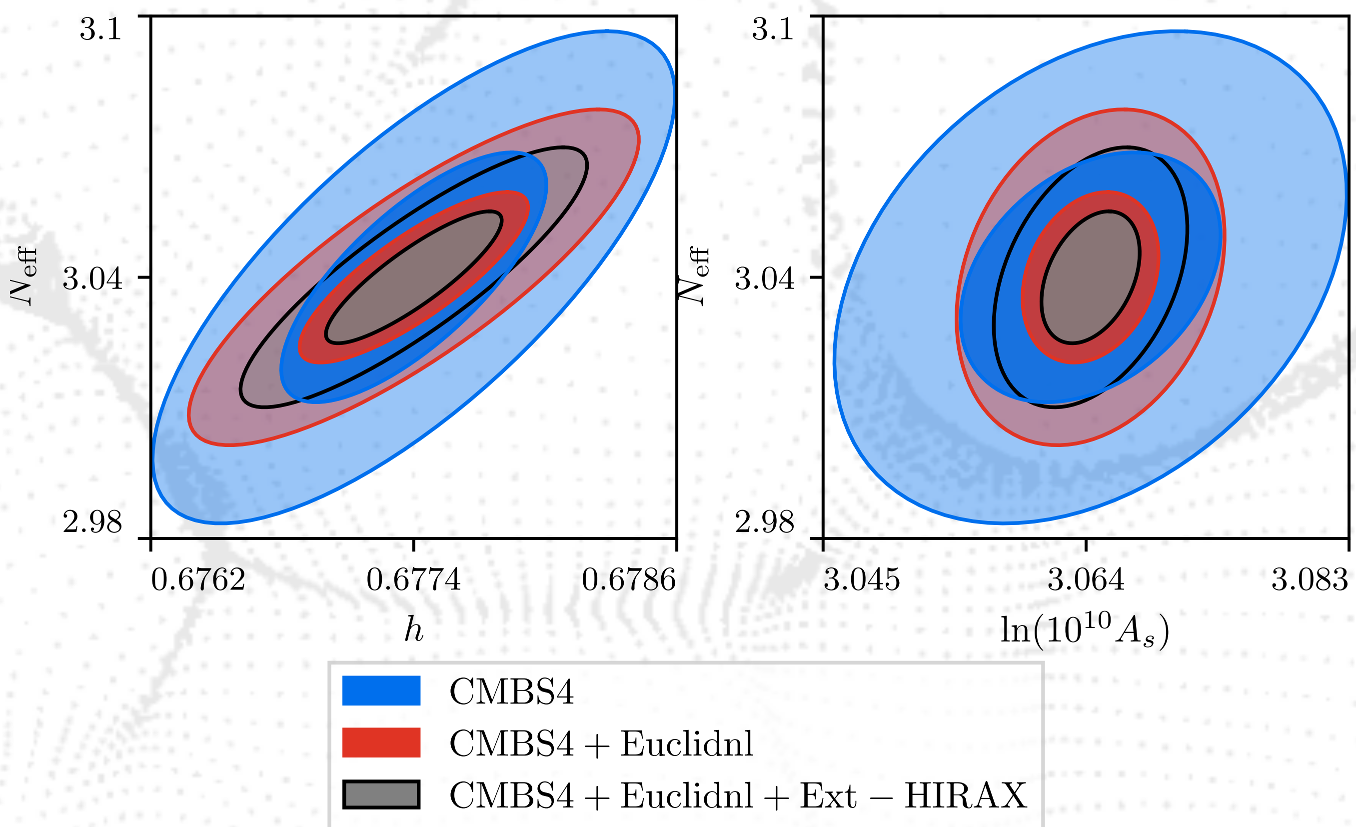
Ext-HIRAX alone

Ext-HIRAX $N_{\rm eff}$					
	Ω_M	h	$\ln(10^{10}A_s)$	n_s	$N_{\rm eff}$
Fiducial values	0.3075	0.6774	3.064	0.9667	3.04
No wedge $k_{\rm max} = 0.2h\mathrm{Mpc}^{-1}$					
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.0017	0.0036	0.013	0.0061	0.22
5% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.0019	0.0037	0.023	0.0061	0.23
10% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.0020	0.0037	0.041	0.0061	0.23

Broadband shape + Neff

CMB S4 + Euclid + Ext-HIRAX

Ext-HIRAX $N_{\rm eff}$						
	$k_{\rm max} = 0.2h{\rm Mpc}^{-1}$			$k_{\rm max} = k_{\rm nl}(z)$		
Euclid Rec.+PlanckBAO	0.067			0.064		
+21cm	No wedge	Mid wedge	Wedge	No wedge	Mid wedge	Wedge
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.046	0.047	0.057	0.038	0.039	0.049
5% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.047	0.048	0.057	0.039	0.040	0.049
10% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.047	0.048	0.057	0.039	0.041	0.050
Euclid Rec.+CMB-S4	0.022			0.020		
+21cm	No wedge	Mid wedge	Wedge	No wedge	Mid wedge	Wedge
2% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.019	0.019	0.021	0.015	0.015	0.017
5% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.020	0.020	0.022	0.015	0.016	0.018
10% $b_{\rm HI}$ & $\Omega_{\rm HI}$	0.020	0.020	0.022	0.015	0.016	0.018



Main conclusions

- We investigate the possibility of performing cosmological studies in the redshift range $2.5 < z < 5$ through suitable extensions of existing and upcoming radio-telescopes like CHIME, HIRAX and FAST.
- We use Fisher formalism to forecast tight constraints on growth parameter fs8 (4%) and AP parameters (1%) as a function of redshift in narrow redshift bins dz=0.1.
- In combination with data from Euclid-like galaxy surveys and CMB S4, the sum of the neutrino masses can be constrained with an error equal to 23 meV (1σ), while Neff can be constrained within 0.02 (1σ).
- We study in detail the dependence of our results on the instrument, amplitude of the HI bias, the foreground wedge coverage, the non-linear scale used in the analysis, uncertainties in the theoretical modeling and the priors on bHI and ΩHI.

Thank you