Cosmology with the 21 cm line

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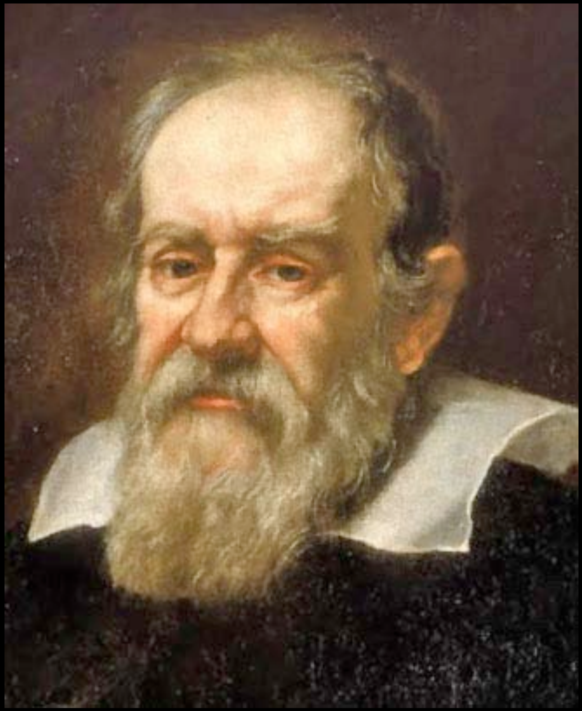
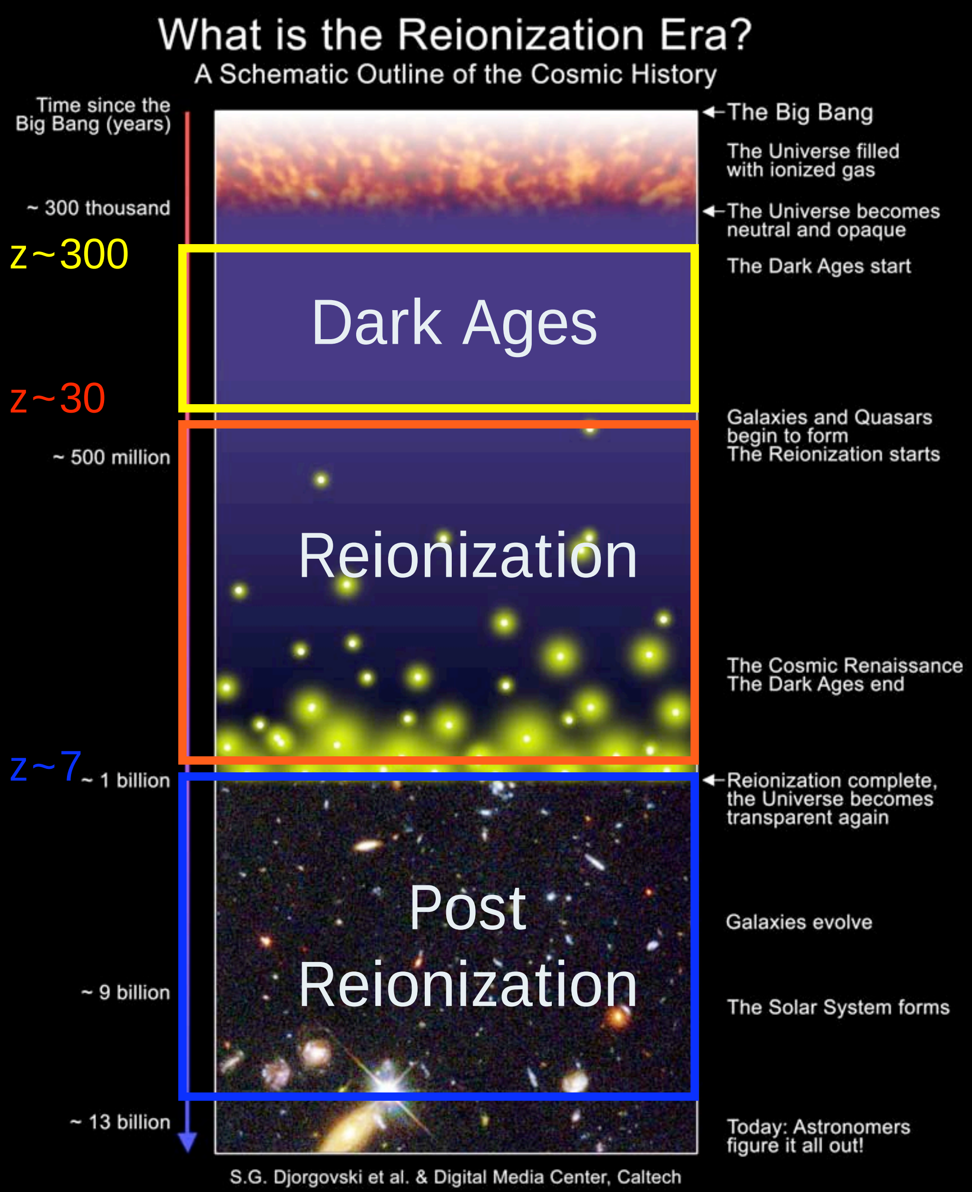
Galileo Galilei

- 400 years ago Galileo used new technology (the telescope) to open a new window onto the heavens
  - Resolved Milky Way into stars
  - Lunar features
  - New moons of Jupiter



• 21 cm interferometers very much driven by
new computing power and hope to open
new window of sensitivity in an old wavelength band
- important to know where to look

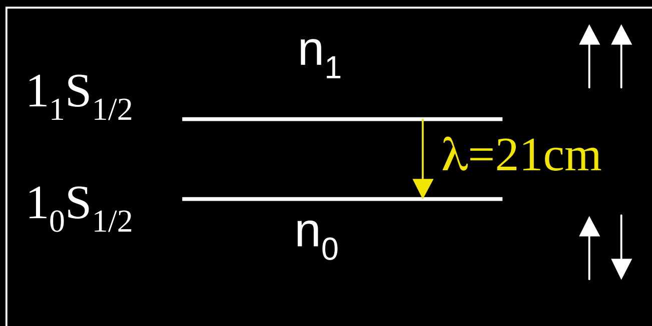
Overview



1. 21 cm overview
2. Reionization (dreams)
   - neutrino mass
   - inflation
3. Reionization (caveats)
4. Post-reionization
5. Dark ages

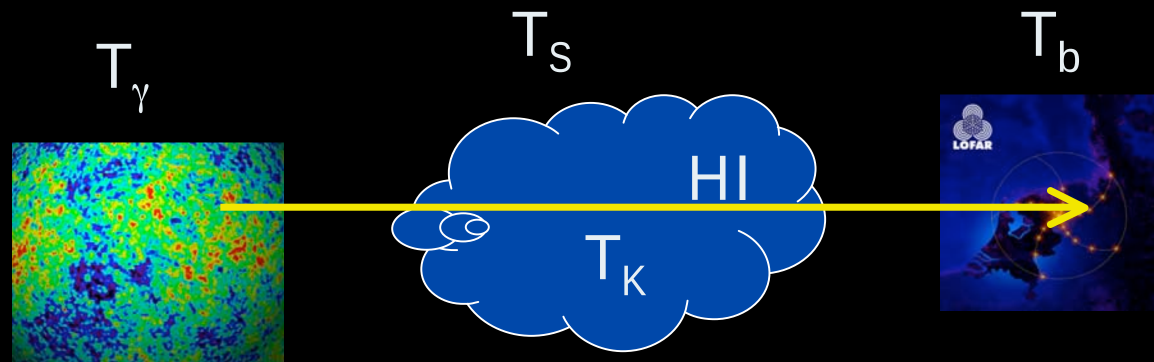
21 cm basics

- HI hyperfine structure



$n_1/n_0=3\exp(-h\nu_{21cm}/kT_s)$

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

- 3D mapping of HI possible - angles + frequency
- 21 cm brightness temperature

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ {\rm mK}$$

- 21 cm spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

Coupling mechanisms:
- Radiative transitions (CMB)
- Collisions
- Wouthuysen-Field

Wouthysen-Field effect

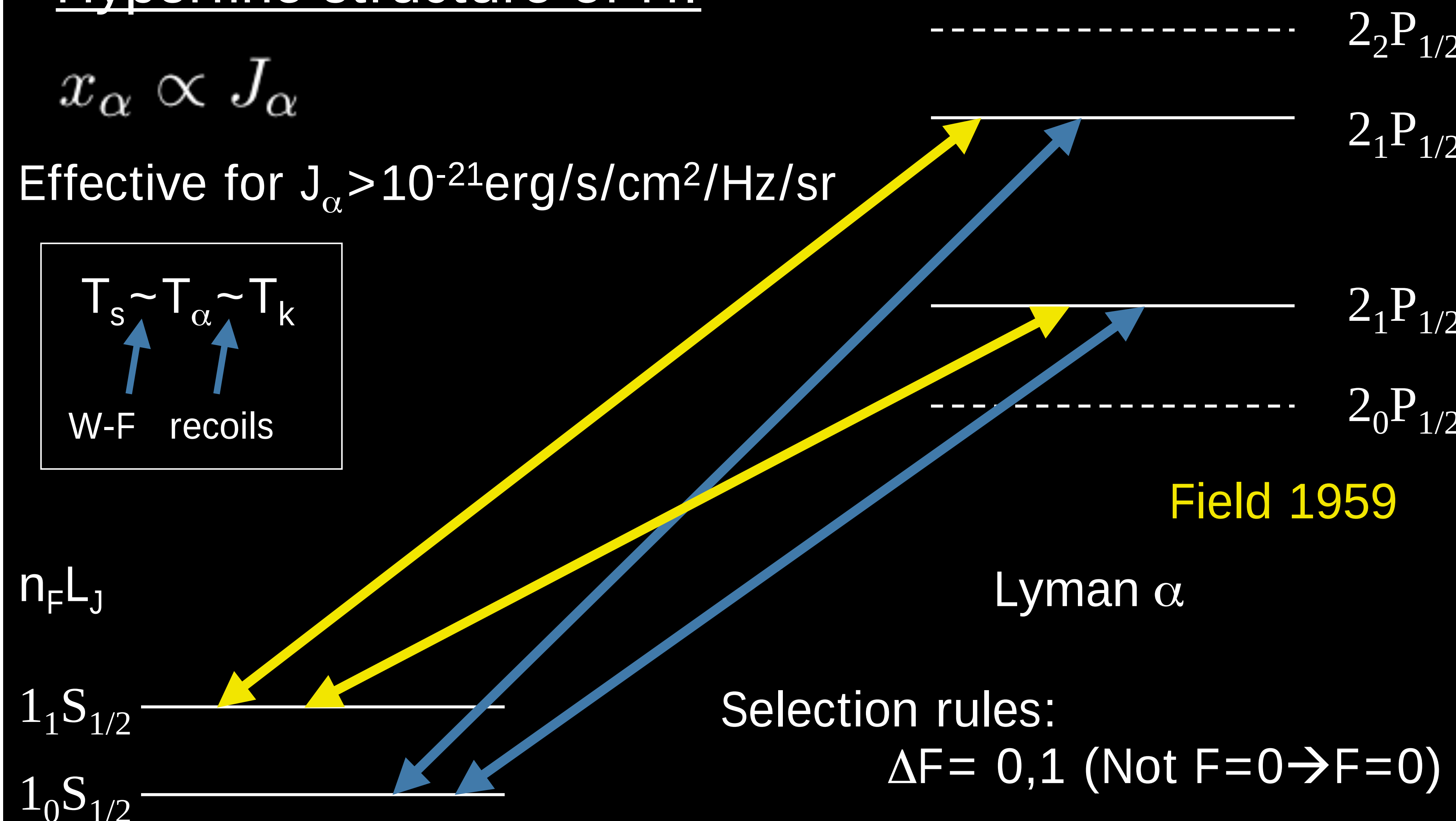
Hyperfine structure of HI

$$x_\alpha \propto J_\alpha$$

Effective for $J_\alpha > 10^{-21}$ erg/s/cm^2/Hz/sr

$T_s \sim T_\alpha \sim T_k$

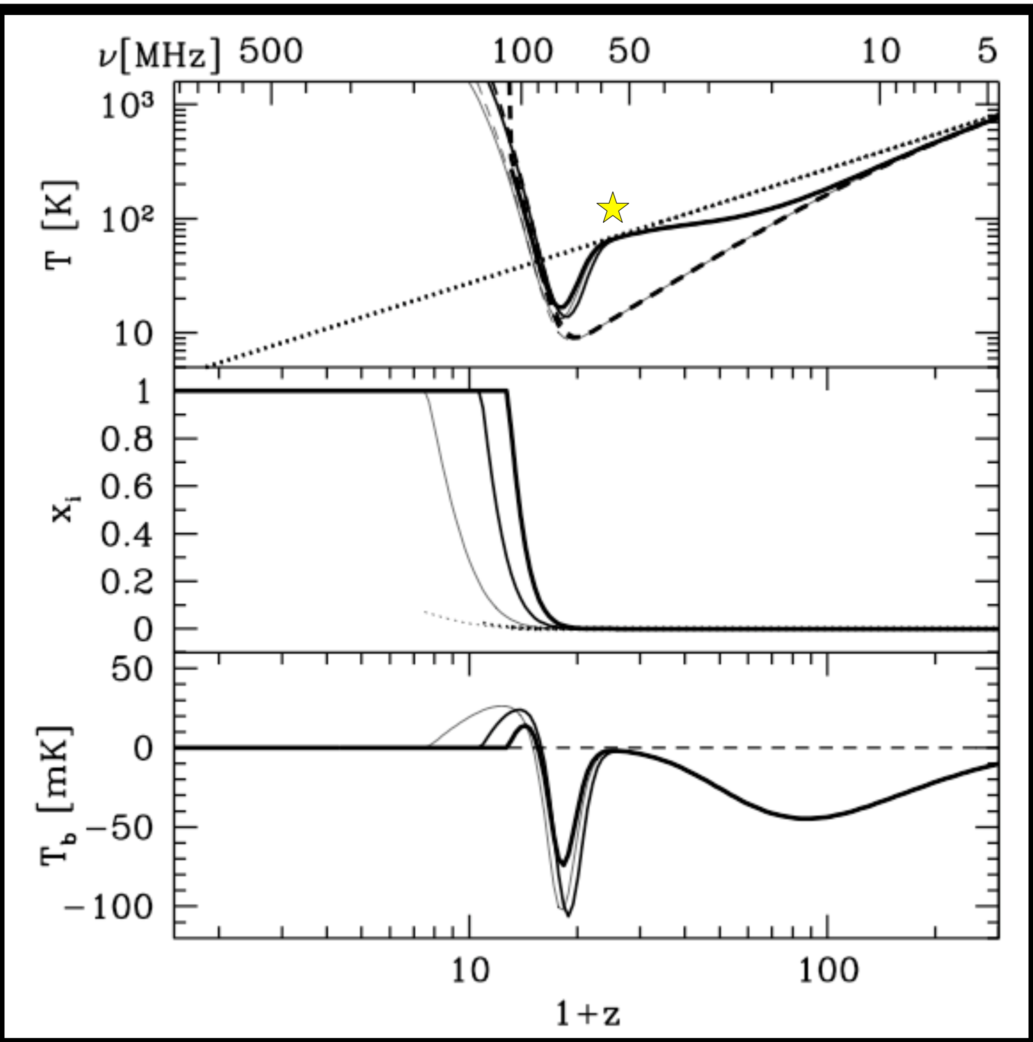
W-F recoils



Selection rules:

$\Delta F = 0,1$ (Not $F=0 \rightarrow F=0$)

Thermal history



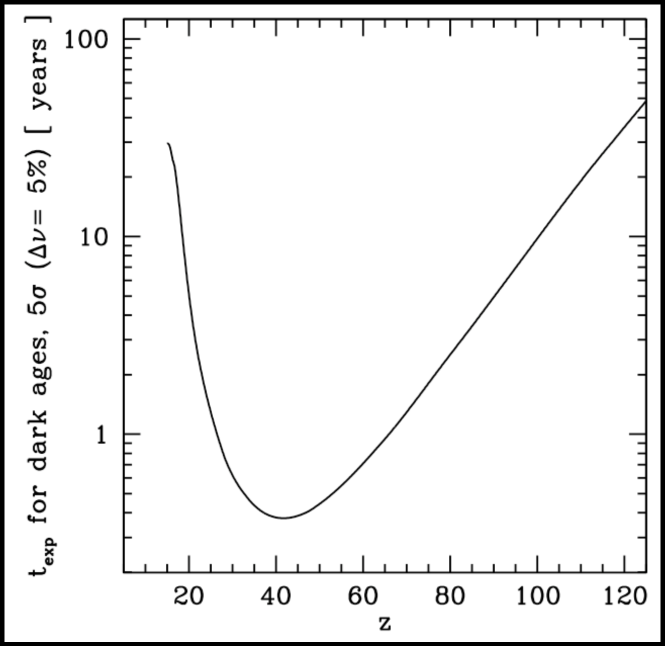
Furlanetto 2006

Pritchard & Loeb 2008

Measuring the global signal

- Isotropic signal means single dipole experiment possible
- Integration times ~100 days for z<20
- Longer for weak dark ages signal

$$T_{\mathrm{RMS}} = \frac{D_{\mathrm{max}}^2 \, T_{\mathrm{sys}}}{A_{\mathrm{eff}} \sqrt{N(N-1) \, N_{\mathrm{IF}} t_{\mathrm{exp}} \Delta\nu}}$$

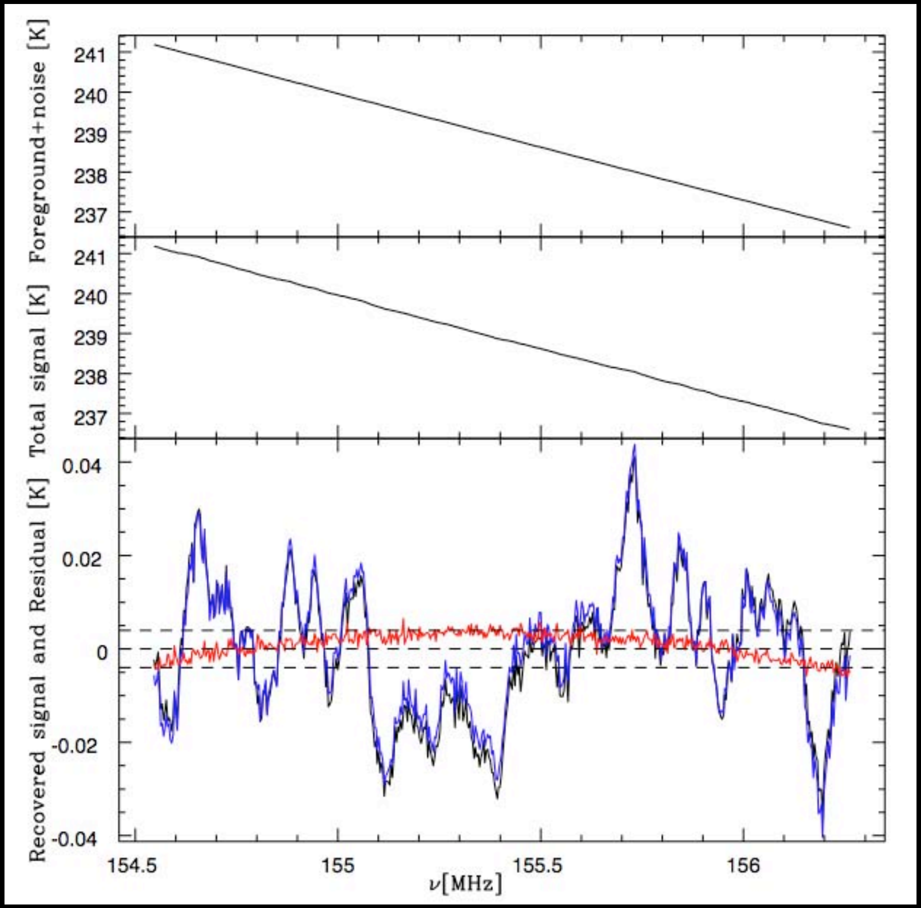


Jester & Falcke 2008

- Foregrounds and systematics are the problem...

Foregrounds

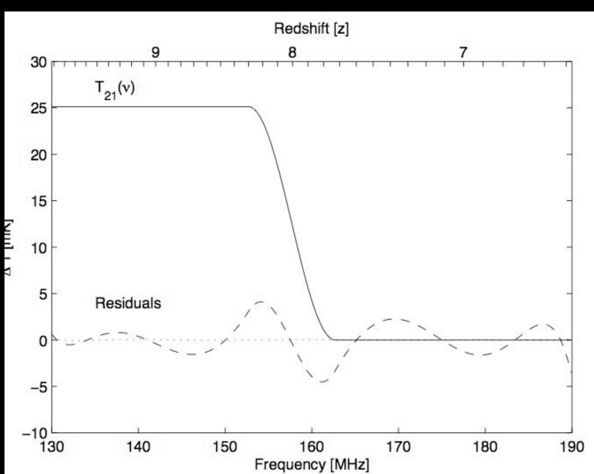
- Many foregrounds
  - Galactic synchrotron
  - Terrestrial RFI
  - Radio recombination lines
  - Radio point sources
- Foregrounds dwarf signal: foregrounds ~1000s K vs 10s mK signal
- Strong frequency dependence $T_{sky} \propto \nu^{-2.6}$
- Foreground removal exploits smoothness in nu - signal needs features

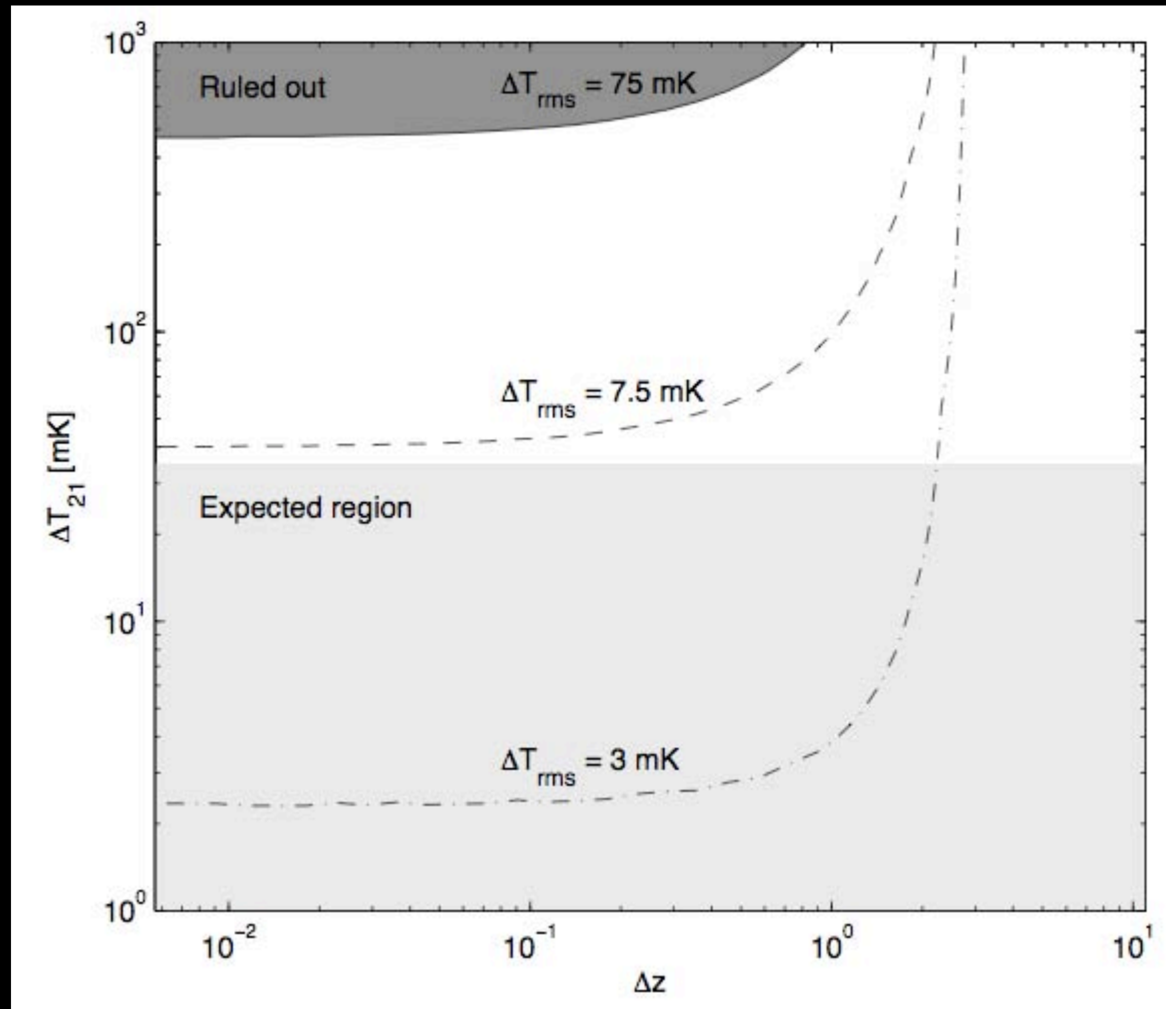


Wang, Tegmark, Santos, Knox 2005

EDGES

EDGES





- looking for reionization at z_R=8

Bowman, Rogers, & Hewitt 2008

Other sharp global features?

- End of reionization
- End of dark ages / onset of Lya pumping
- X-ray heating by stellar remnants
- Rapid heating from exotic processes during dark ages?
  - decaying dark matter
  - evaporating primordial black holes
- ???

21 cm fluctuations

Brightness temperature | Baryon Density | Neutral fraction | Gas Temperature | W-F Coupling | Velocity gradient

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

Cosmology | Reionization | X-ray sources | Lyα sources | Cosmology

Amount of neutral hydrogen

Spin temperature

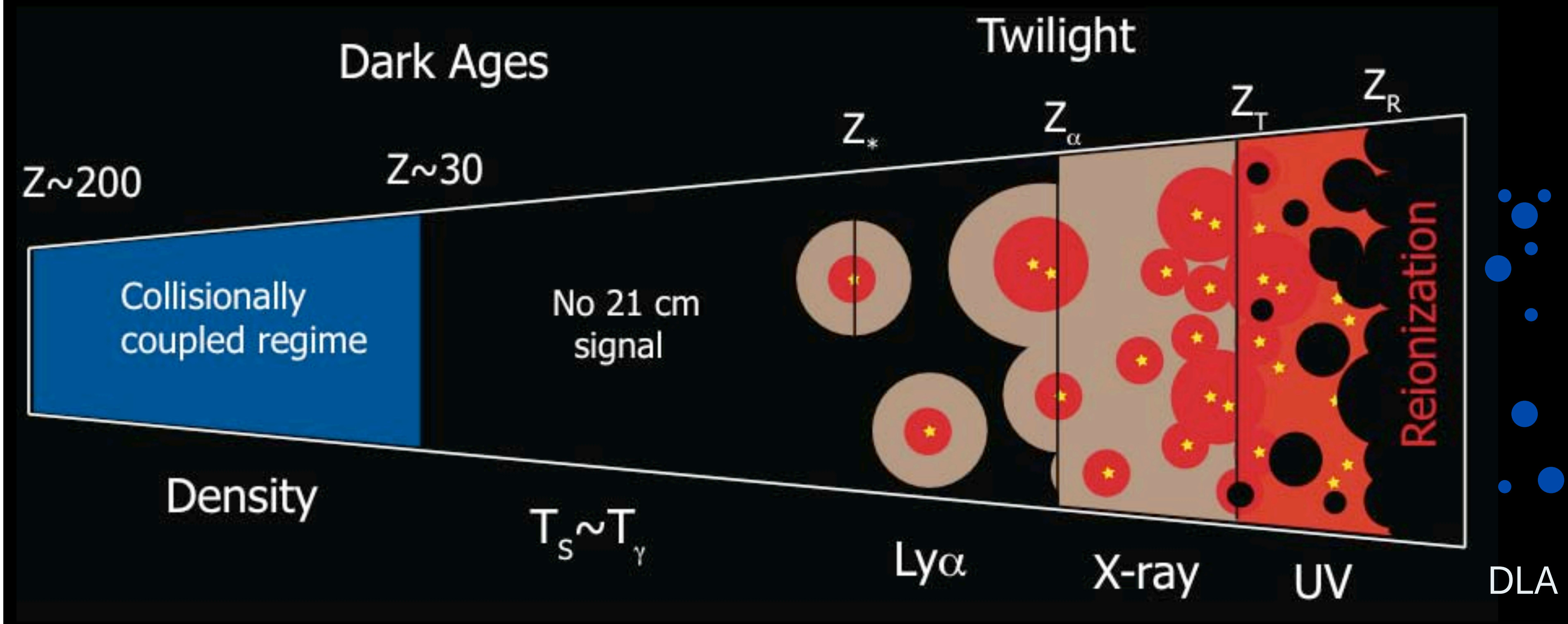
Velocity (Mass)

Temporal separation?

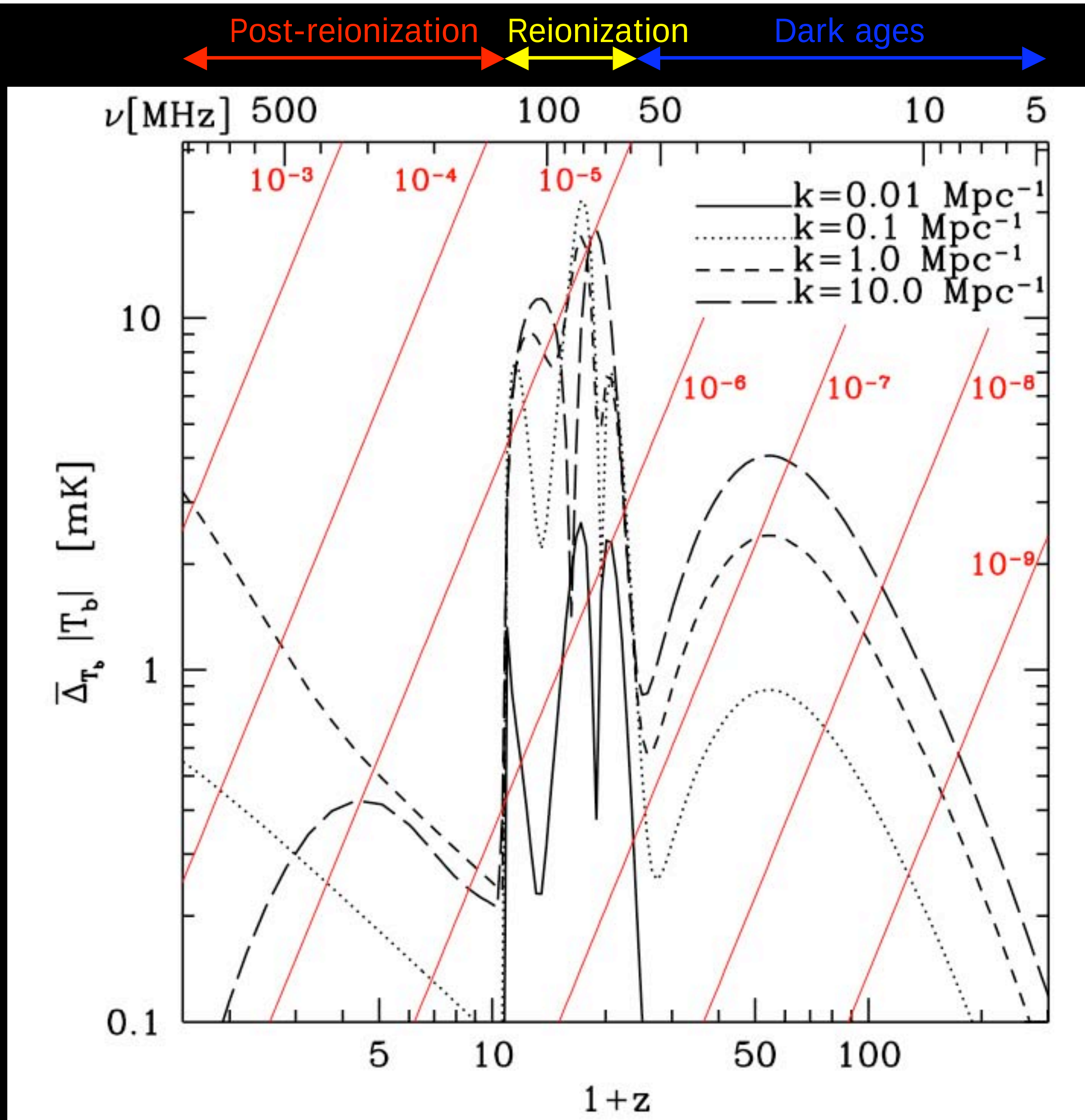
Brightness temperature		Baryon Density		Neutral fraction		Gas Temperature		W-F Coupling		Velocity gradient

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

Cosmology — Reionization — X-ray sources — Lyα sources — Cosmology



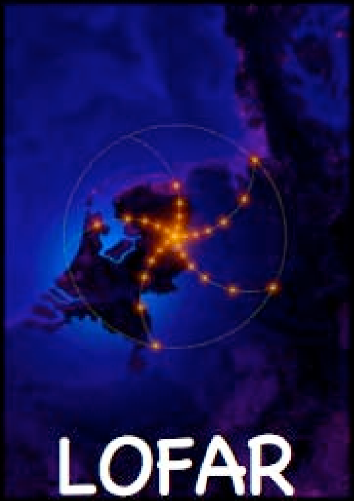
Temporal evolution



Pritchard
& Loeb 2008

21 cm experiments

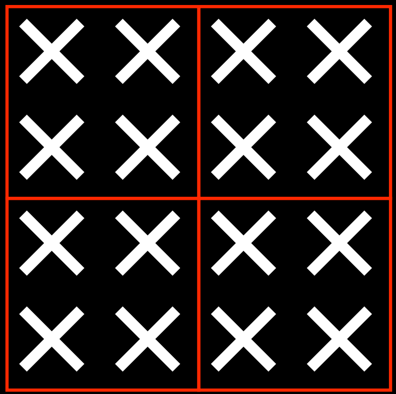
Current



Future

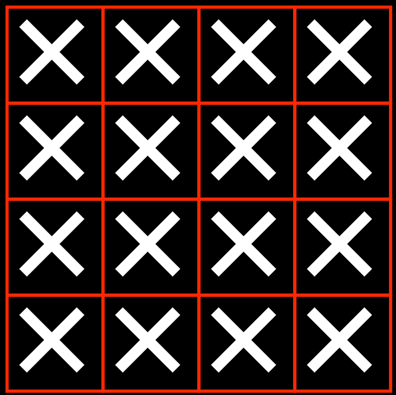
Experimental design

SKA



Group dipoles into tiles
Reduce computational cost
Lose number of UV baselines

FFTT



Regular grid of dipoles
FFTT to correlate
Greater sensitivity

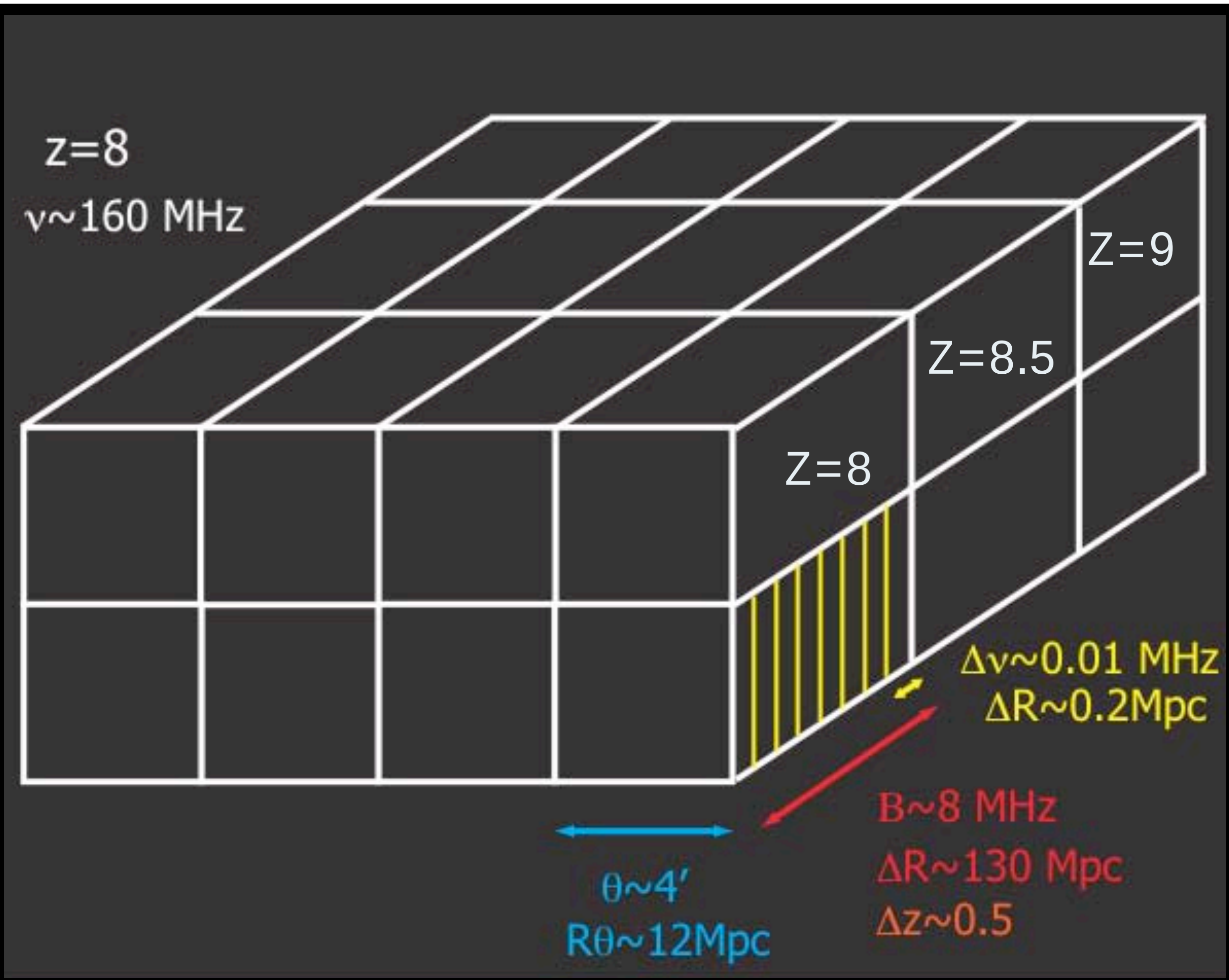
$N_{tile} << N_{dipole}$

$$T_{\mathrm{RMS}} = \frac{D_{\max}^2 \, T_{\mathrm{sys}}}{A_{\mathrm{eff}} \sqrt{N(N-1)\, N_{\mathrm{IF}} t_{\exp} \Delta\nu}}$$

Tegmark &
Zaldarriaga
2008

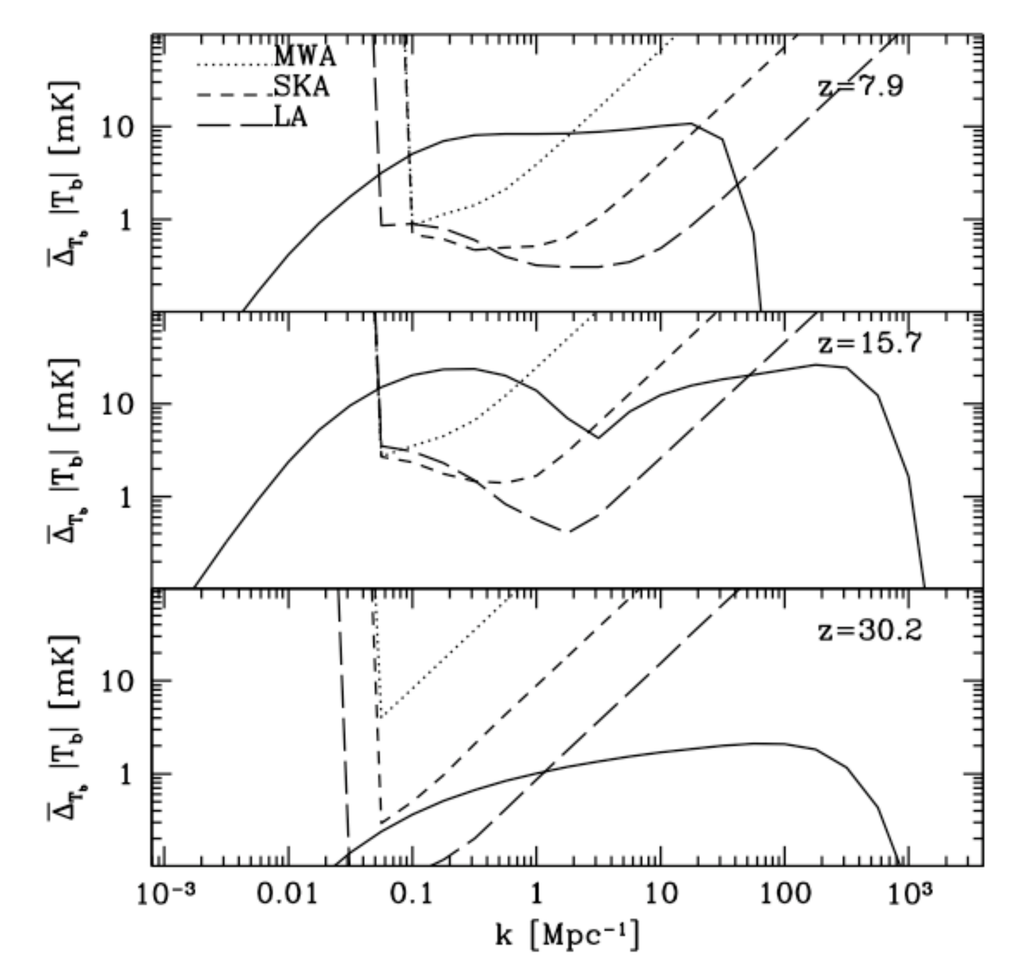
Pixel Scales

MWA



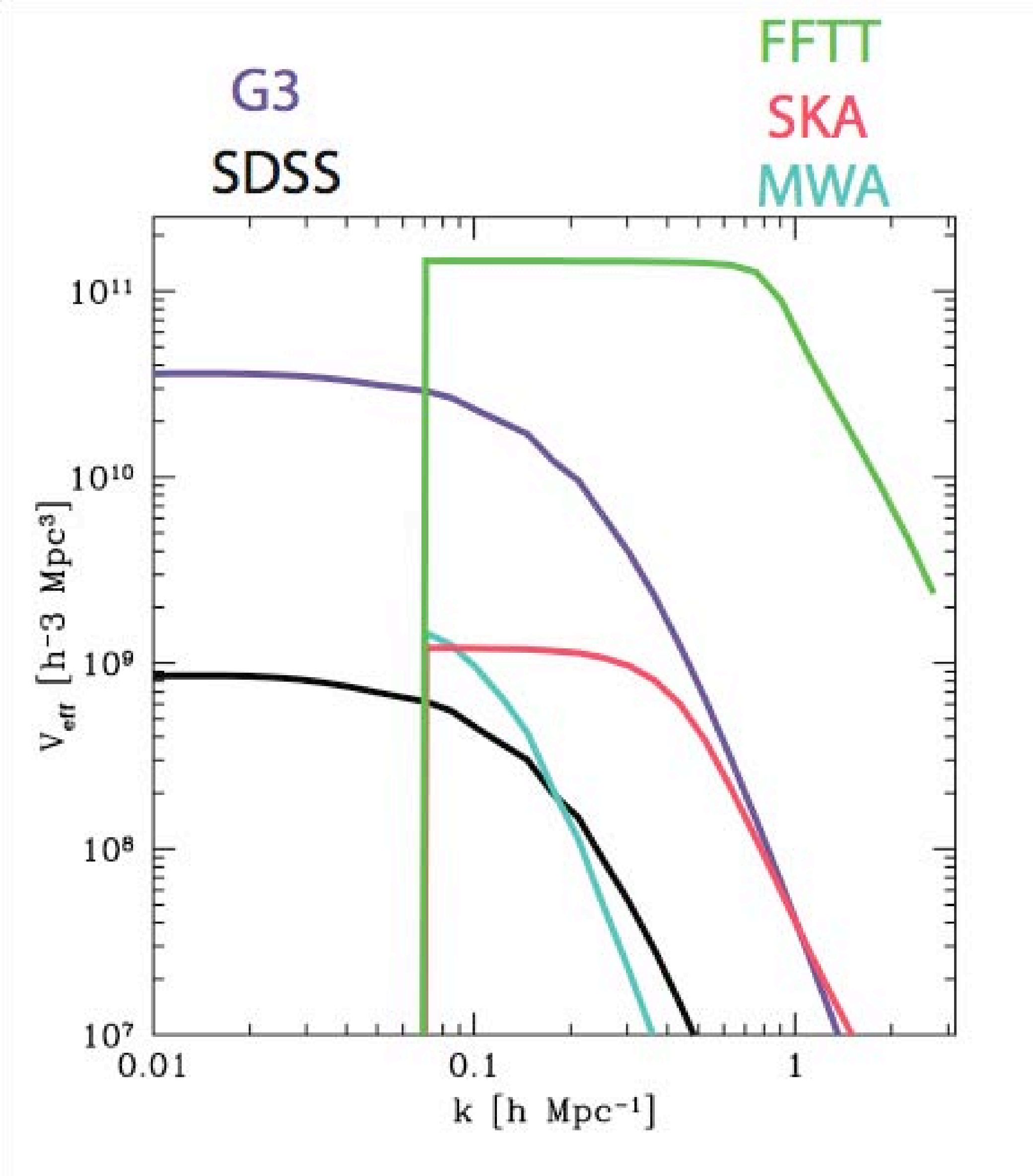
- Better frequency resolution than angular resolution
- Bandwidth limited by cosmic evolution
- FT data cube to get 3D power spectrum

Experimental sensitivity



$$\sigma_P^2(k,\mu) = \frac{1}{N_{\rm field}}\left[\bar{T}_b^2 P_{21}(k,\mu) + T_{\rm sys}^2 \frac{1}{Bt_{\rm int}} \frac{D^2 \Delta D}{n(k_\perp)} \left(\frac{\lambda^2}{A_e}\right)^2\right]^2 .$$

Comparison with galaxy surveys

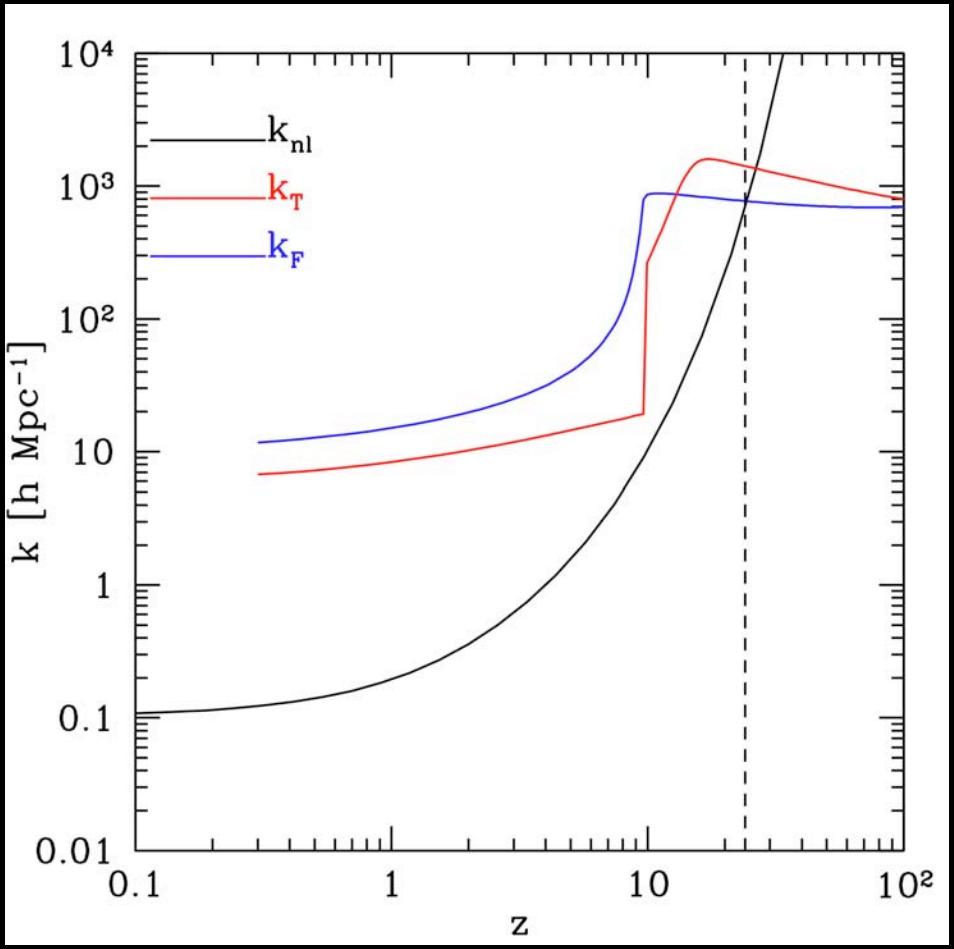


- Galaxies good on large scales
- 21 cm could extend to small scales

Array	N_a	A_{tot} (10^3 m^2)	D_{min} (m)	D_{max} (km)	B (MHz)	T_{int} (hr)	z
MWA	500	7.0	4	1.5	8	4000	7.8-8.2
SKA	5000	600	10	5	8	4000	7.8-10.3
FFTT	10^6	10^3	1	1	8	4000	7.8-10.3

Pritchard & Pierpaoli 2008

Nonlinear growth



Cosmological parameters

Density | Neutral fraction | Gas Temperature | W-F Coupling | Velocity gradient

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

IGM still mostly neutral

IGM hot $T_K >> T_\gamma$

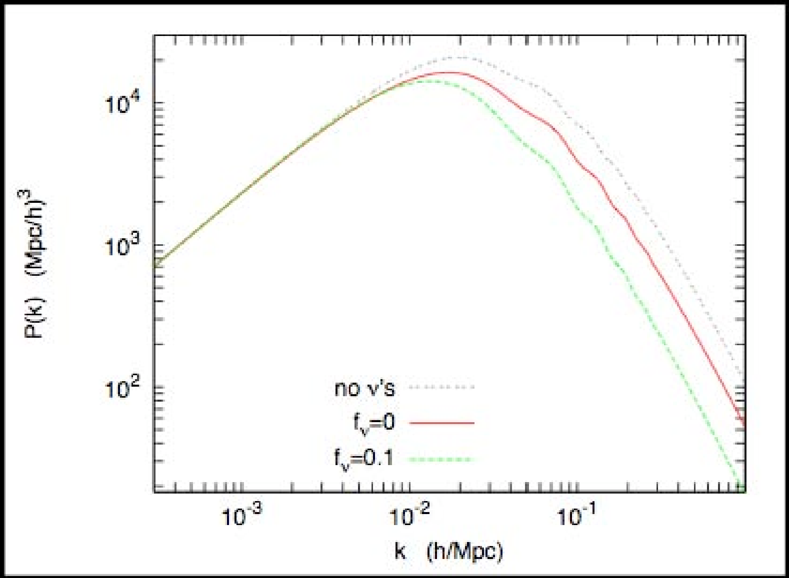
coupling saturated

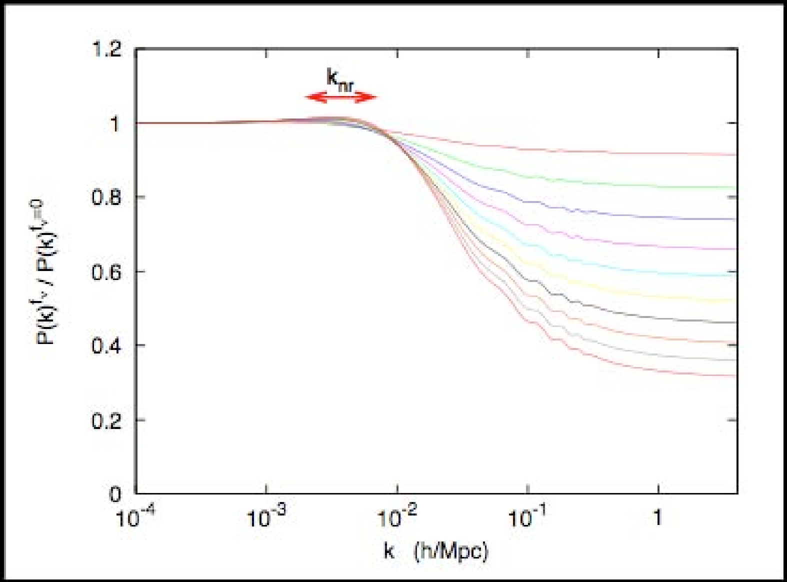
$$P_{T_b}(k,\mu) = (1+\mu^2)^2\bar{T}_b^2 P_\delta(k)$$

Massive neutrinos

Massive neutrinos reduce density fluc. on small scales
- Matter-radiation equality delayed (relative to Mnu=0)
- Free-streaming neutrinos don't clump

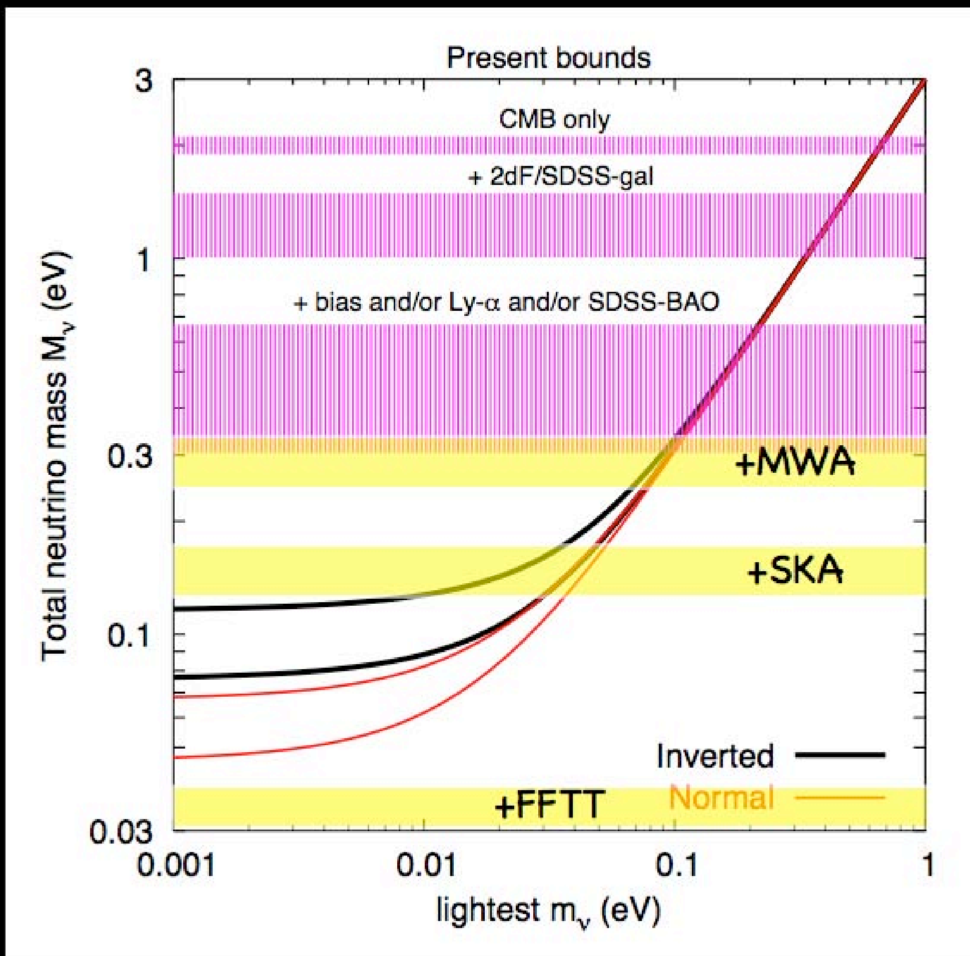
Precision measurements of P(k) at k>0.01 h Mpc^{-1} -> Mnu

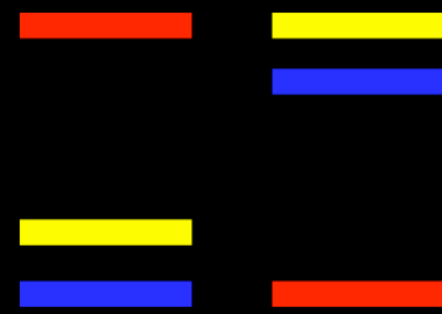




Lesgourgues
& Pastor 2006

Neutrino mass





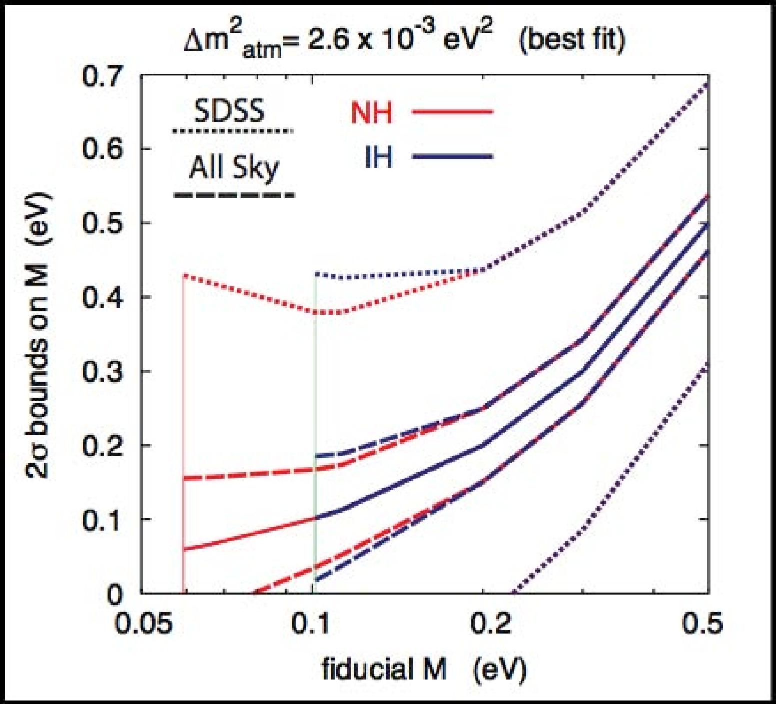
$$M_\nu^{\rm min}({\rm IH}) = 0.1\,{\rm eV}$$

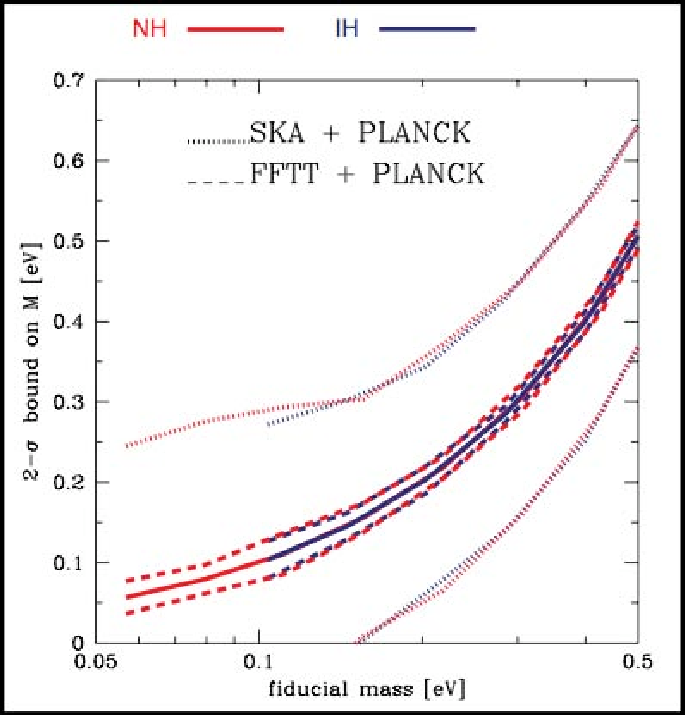
$$M_\nu^{\rm min}({\rm NH}) = 0.05\,{\rm eV}$$

	M_ν
Fiducial	0.3
Planck	0.38
+SDSS	0.217
+G3	0.046
+MWA	0.13
+SKA	0.075
+FFTT	0.0075

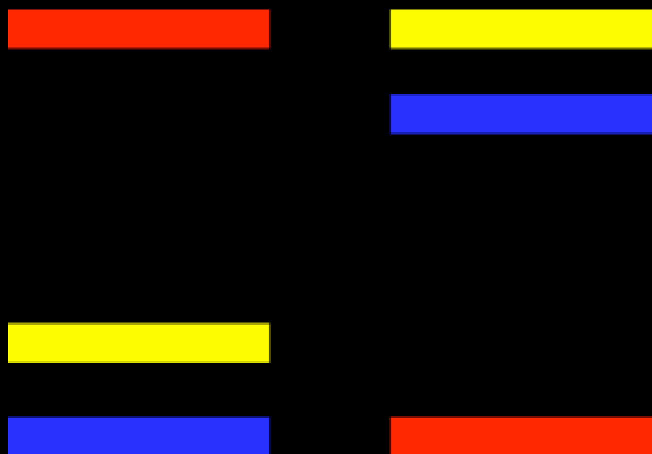
Pritchard & Pierpaoli 2008

Total mass constraints

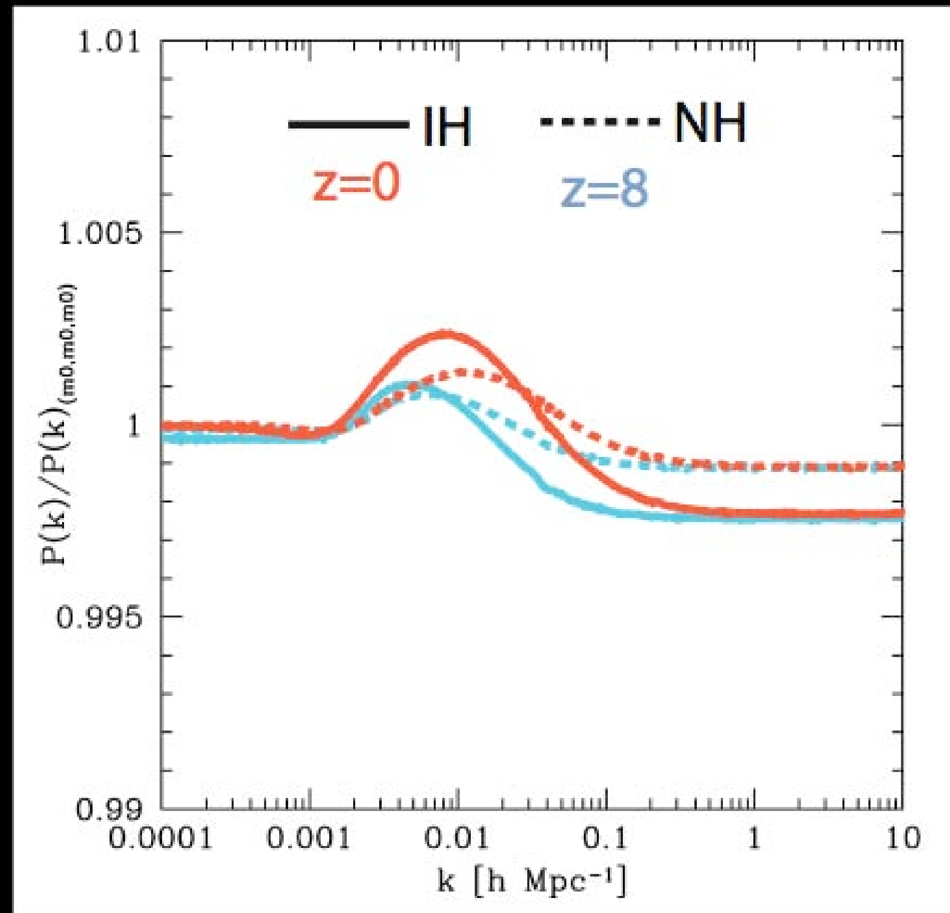




Mass hierarchy

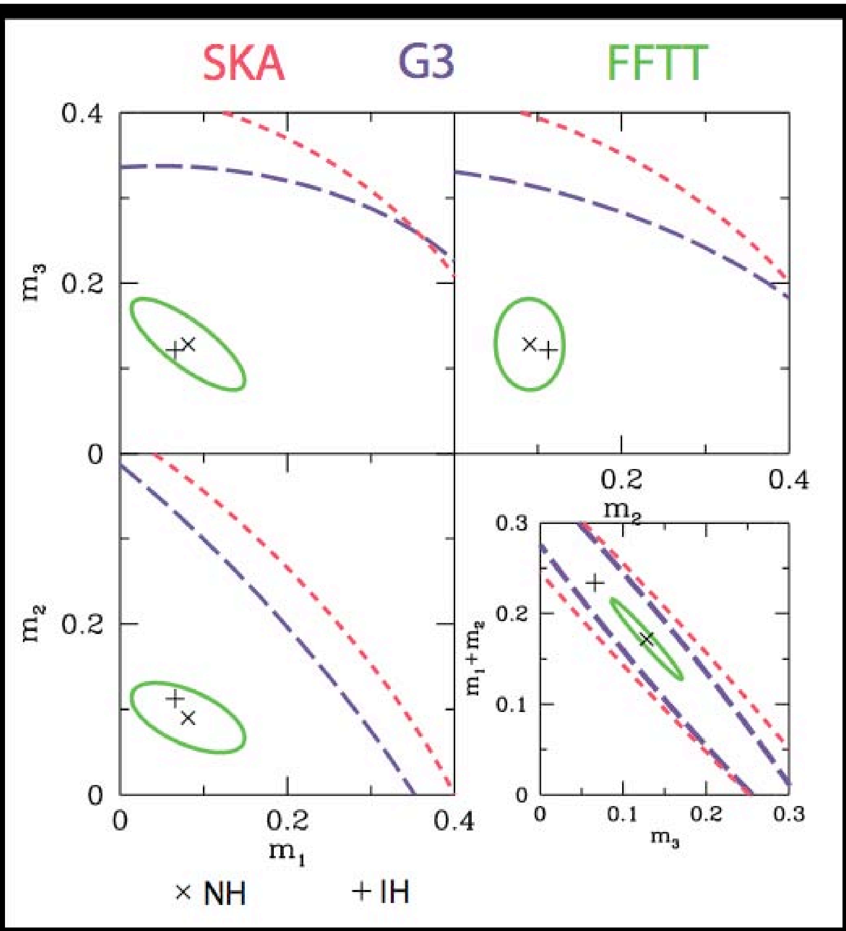


- Small signature from mass hierarchy & individual nu masses
- Requires v. high precision to detect



adapted from
Lesgourgues, Pastor & Perotto (2004)

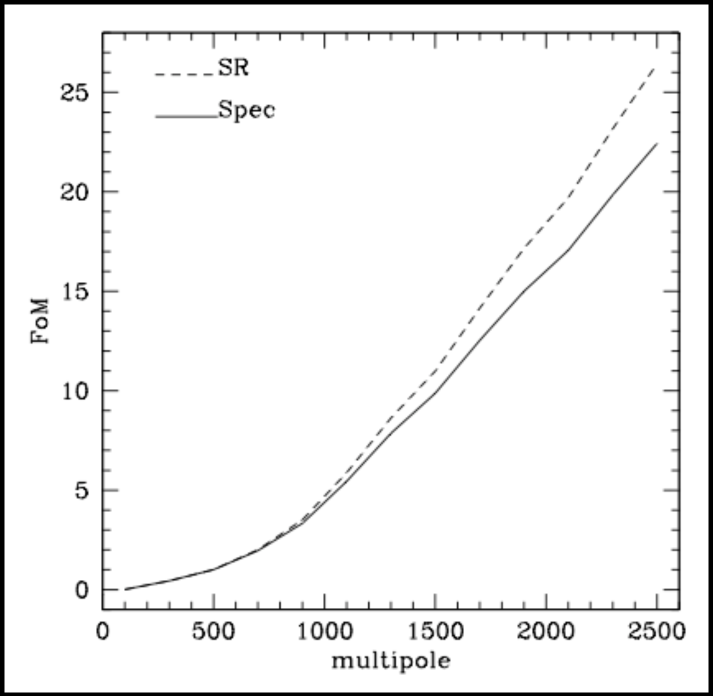
Individual masses

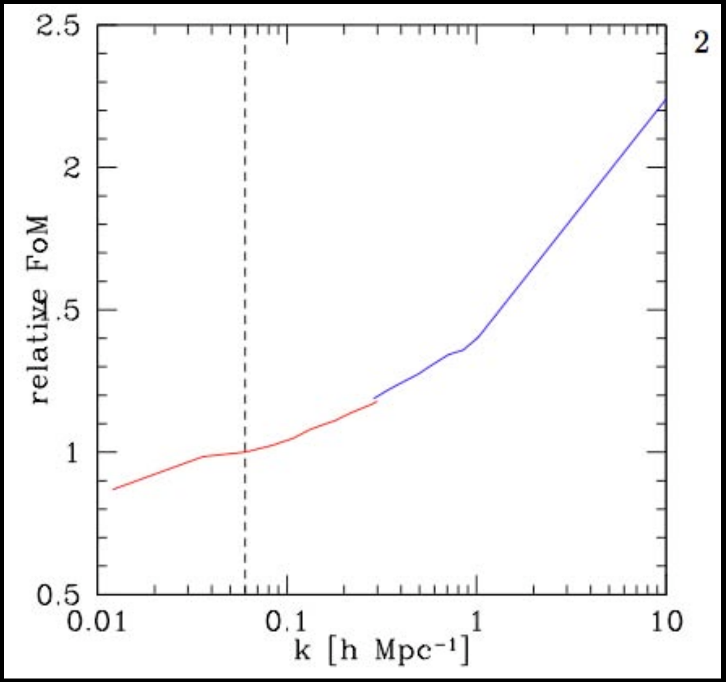


	m_1	m_2	m_3	m_1+m_2	m_3	M_ν
Fiducial	0.081	0.09	0.13	0.17	0.13	0.3
Planck	0.922	0.950	0.552	0.633	0.550	0.44
+G3	0.654	0.78	0.295	0.296	0.265	0.046
+SKA	0.645	0.631	0.405	0.41	0.405	0.077
+FFTT	0.037	0.03	0.03	0.03	0.029	0.0076

Inflation - lever arm

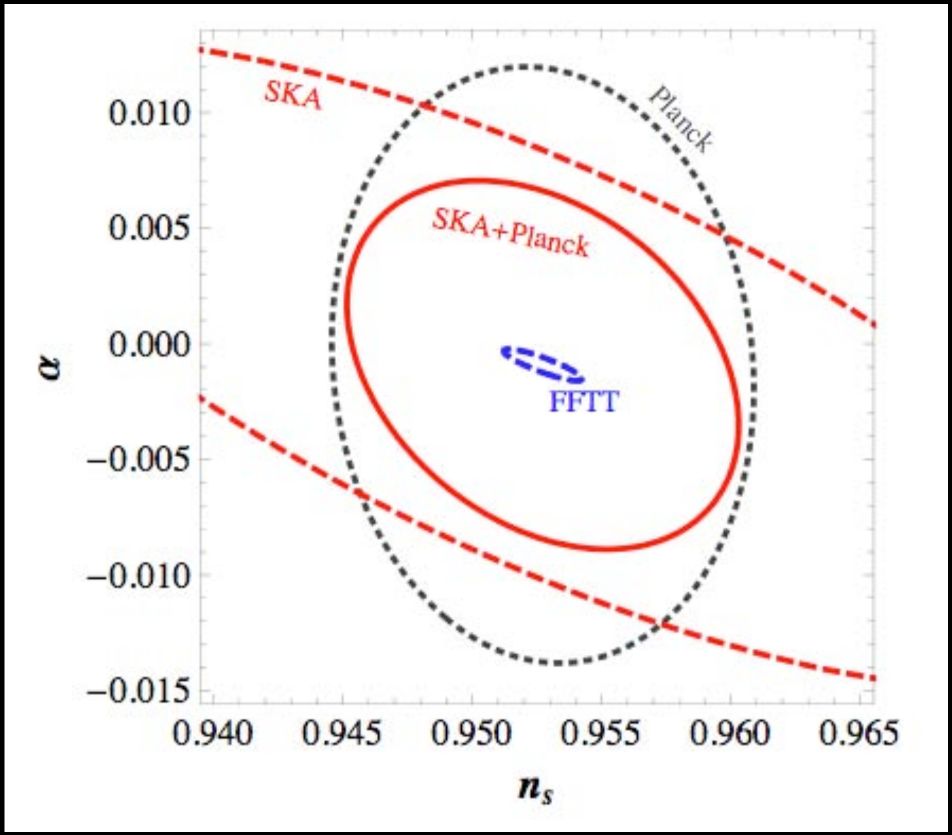
- CMB probes k~0.002-0.2 h Mpc^{-1}
- Adding in galaxies, Lya forest, 21 cm extends lever arm
- With long lever arm assumption of slow roll tightens constraints over spectral parametrization





Adshead & Easther 2008

Tilt and running



SKA+Planck $\delta n_s = 0.0031,\ \delta\alpha = 0.0032$

FFTT+Planck $(\delta n_s = 6 \times 10^{-4},\ \delta\alpha = 2.7 \times 10^{-4})$

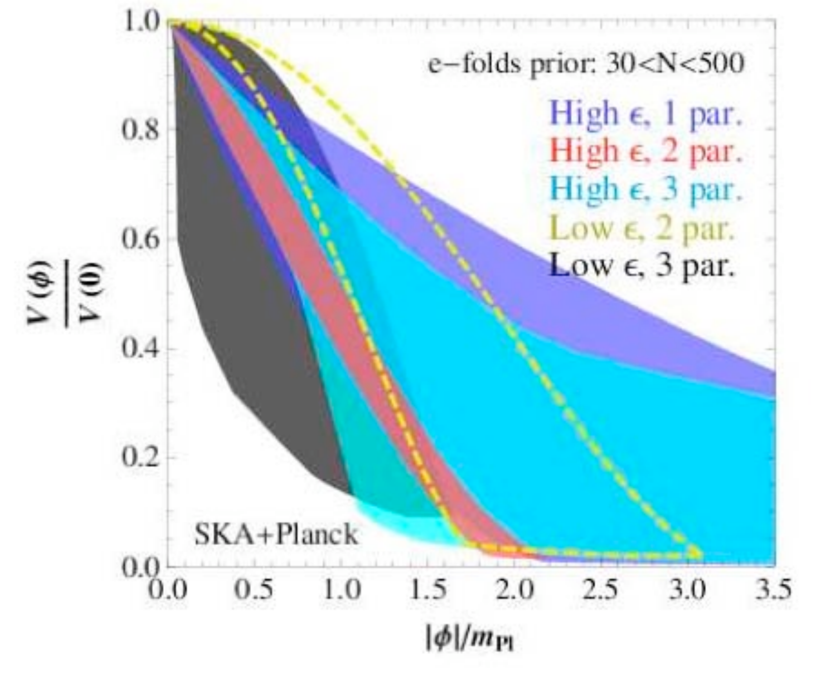
Mao+ 2008
Barger, Gao, Mao & Marfatia 2008

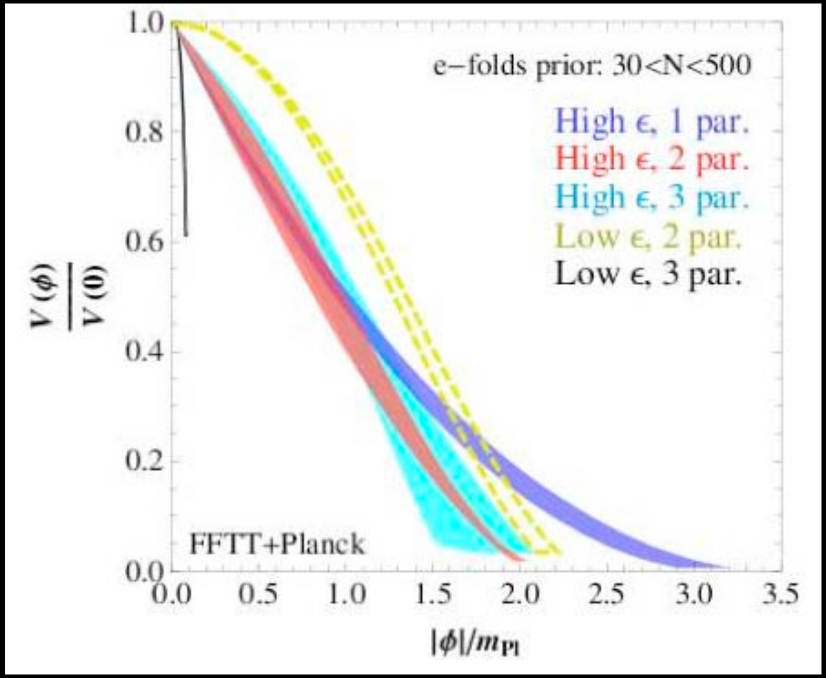
Start to get down to $(n-1)^2$ level=constrain 3rd slow roll param

Potential reconstruction

- Tight constraints on running aid slow roll potential reconstruction

$$\frac{d\epsilon}{dN} = 2\epsilon(\lambda_1 - \epsilon)\,,$$
$$\frac{d\lambda_n}{dN} = \left[(n-1)\lambda_1 - n\epsilon\right]\lambda_n + \lambda_{n+1}$$

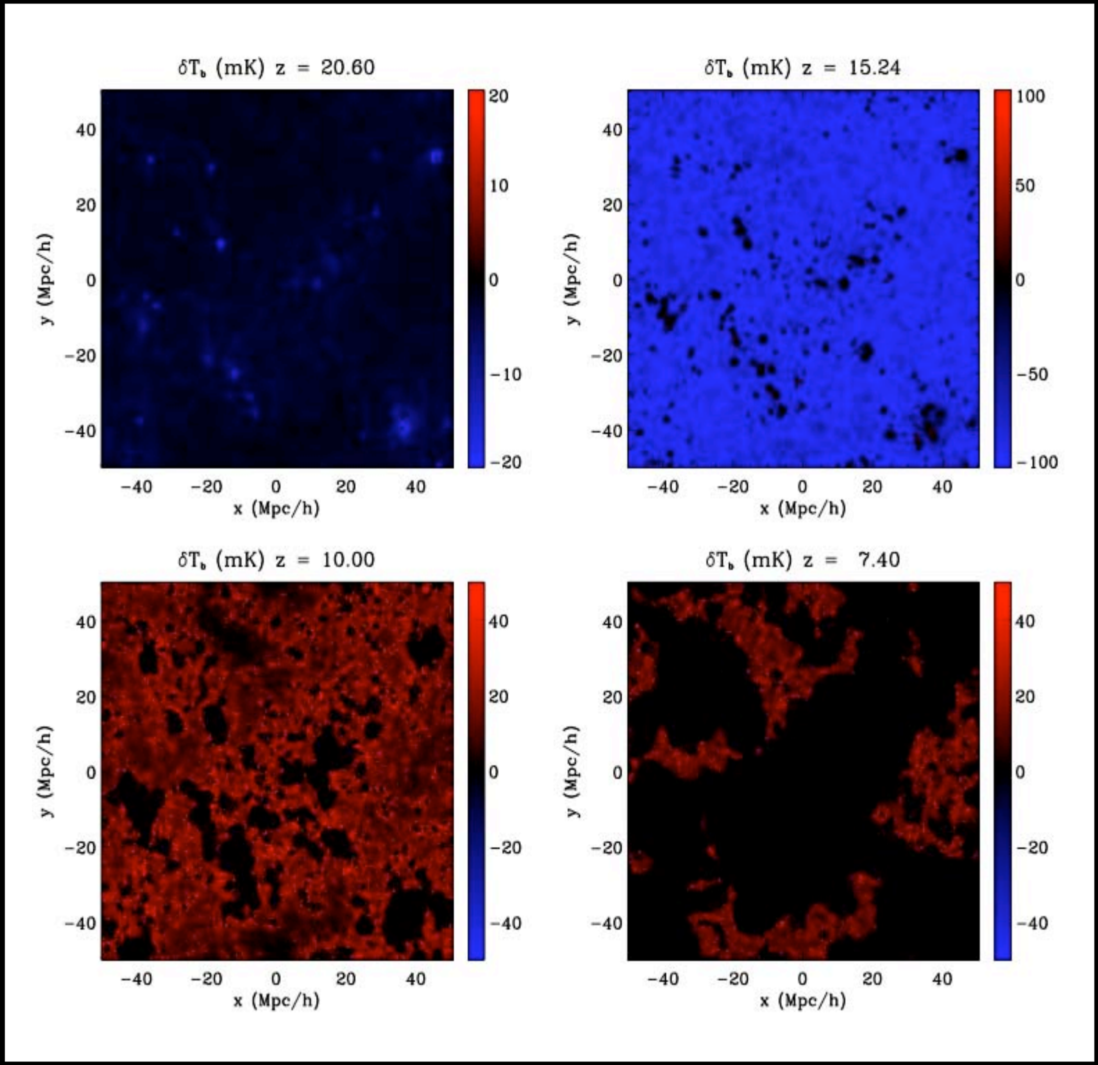




Barger, Gao, Mao & Marfatia 2008

Challenges

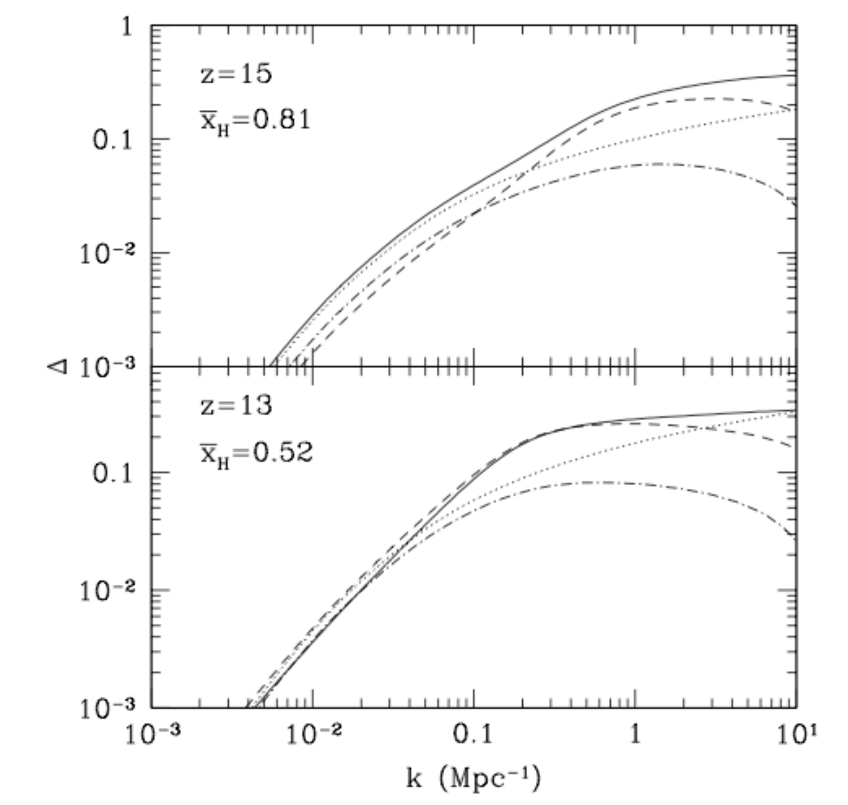
$$\delta_{T_b} = \beta\delta + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$



Santos, Amblard, JRP, Trac, Cen, Cooray 2008

Reionization

- Ionized bubbles modify P21 on large scales



Furlanetto, Zaldarriaga, Hernquist 2004

- Can reasonably model ionization contribution

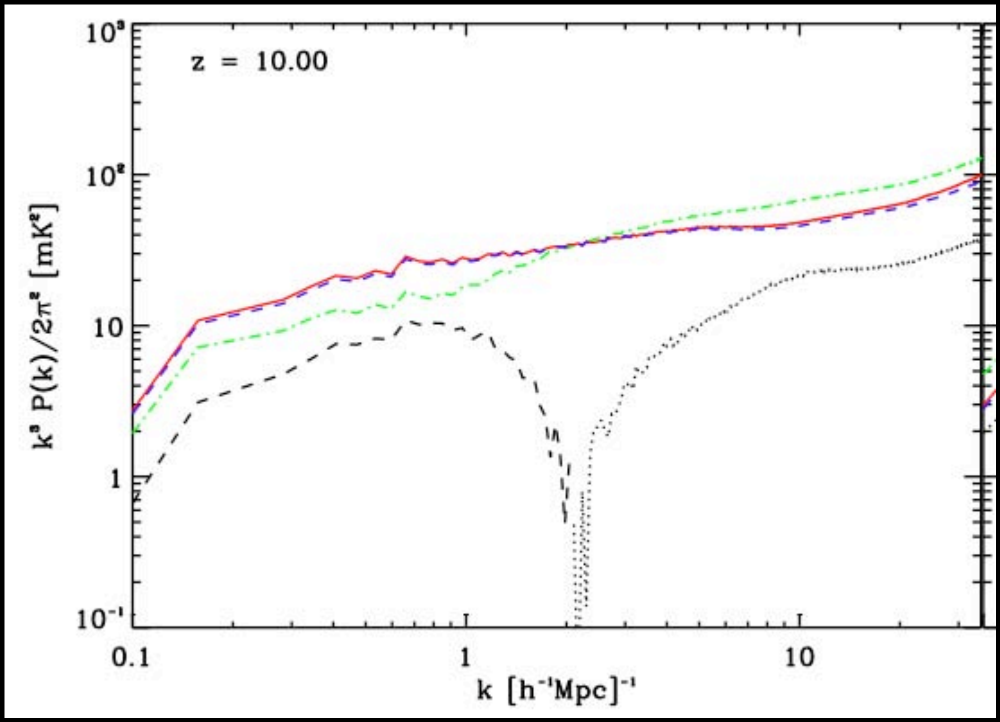
$$\mathcal{P}_{xx}(k) = b_{xx}^2 \left[1 + \alpha_{xx}(k\,R_{xx}) + (k\,R_{xx})^2\right]^{-\frac{\gamma_{xx}}{2}} \mathcal{P}_{\delta\delta}\,,$$

$$\mathcal{P}_{x\delta}(k) = b_{x\delta}^2 \exp\left[-\alpha_{x\delta}(k\,R_{x\delta}) - (k\,R_{x\delta})^2\right]\mathcal{P}_{\delta\delta}\,,$$

non-Gaussianity

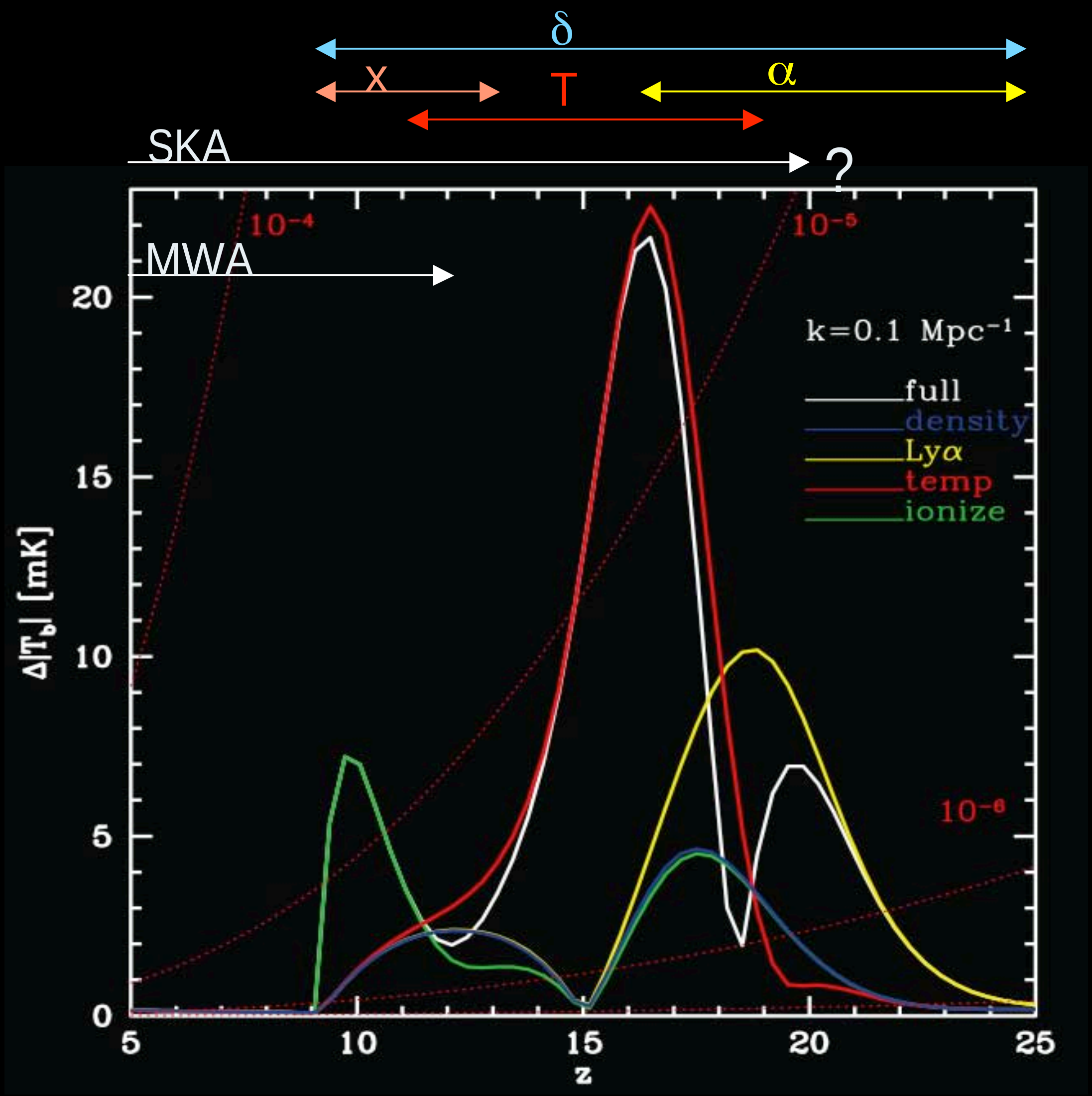
- Ionization fluctuations are not small $\delta X_H \sim 1$
- Higher order (in X) terms modify P21 on small scales
- non-G from bubbles poorly understood - may be useful

$$P_{21}(k) = T_c^2 \left[\bar{f}_{\rm HI}^2 P_{\delta,\delta}(k) + P_{x_i,x_i}(k) - 2\bar{f}_{\rm HI} P_{x_i,\delta}(k) + 2P_{x_i\delta,x_i}(k) - 2\bar{f}_{\rm HI} P_{x_i\delta,\delta}(k) + P_{x_i\delta,x_i\delta}(k) \right],$$



Lidz+ 2007
Santos+ 2008

You can’t always get what you want…



- Ideally would run to higher z where ionization small, but gas already heated and coupled
- Can minimise, but not evade astrophysics. Overlap between ionization/temp/Lya fluctuations

Pritchard & Loeb 2008

Angular separation

Baryon Density | Neutral fraction | Gas Temperature | W-F Coupling | Velocity gradient

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

- In linear theory, peculiar velocities correlate with overdensities

$$\delta_{d_r v_r}(k) = -\mu^2\delta$$

Bharadwaj & Ali 2004

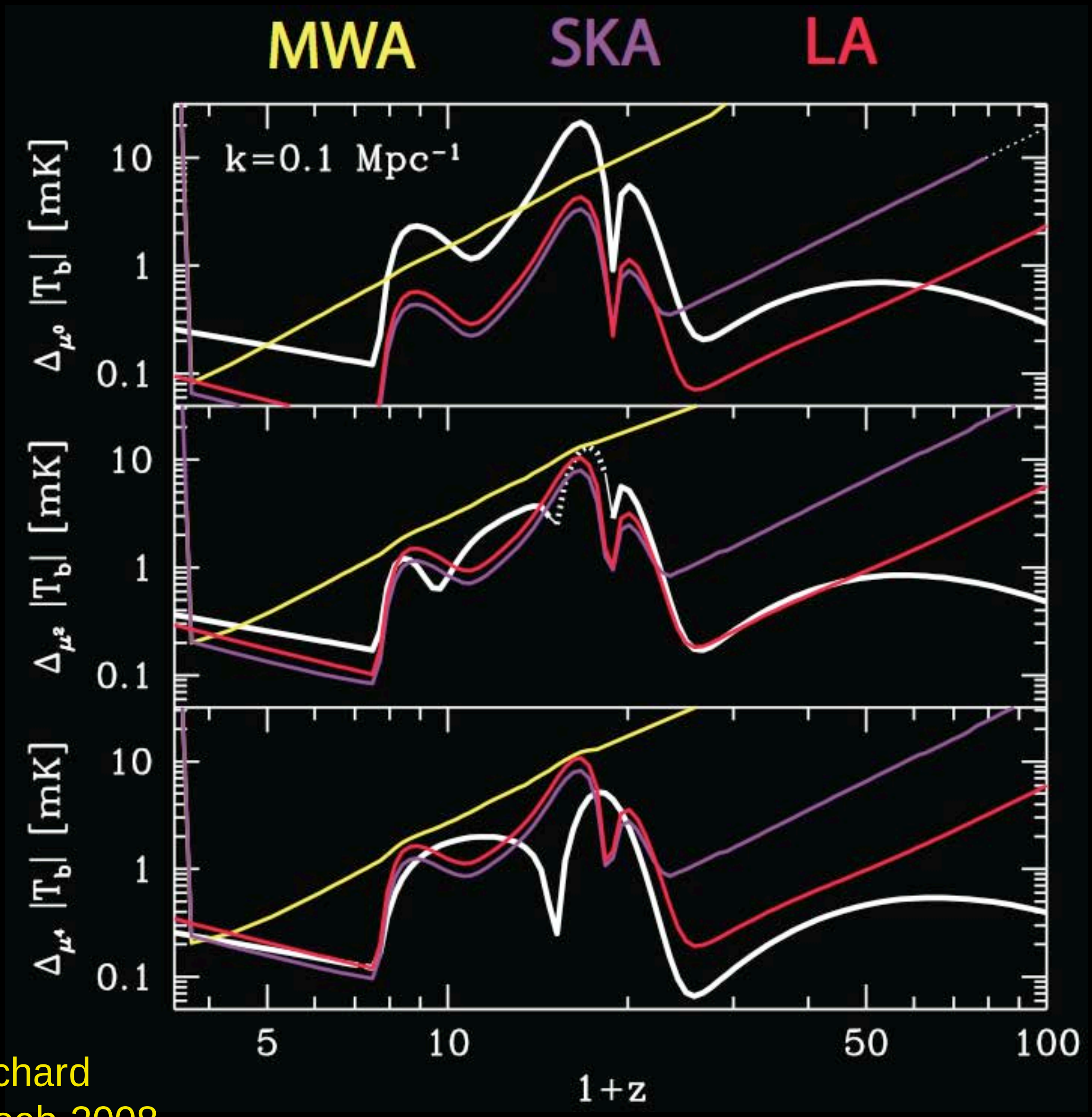
- Anisotropy of velocity gradient term allows angular separation

$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

Barkana & Loeb 2005

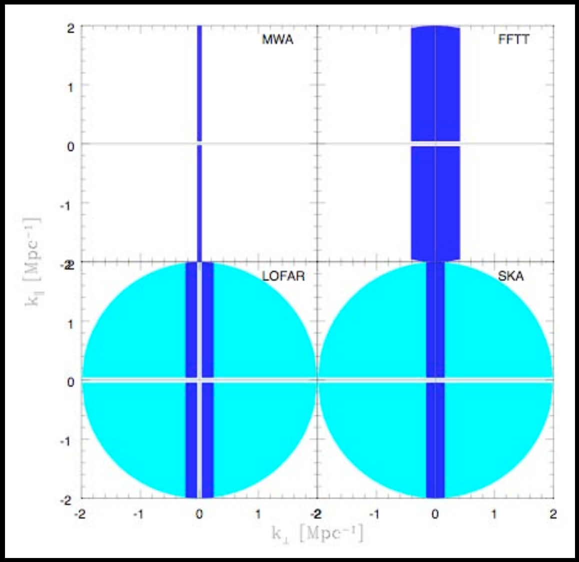
- μ^4 term just depends on density

Angular separation



Pritchard & Loeb 2008

- Works best when isotropic component small - tends to be when density already significant
- Some regions where might be useful



... you get what you need?

		Vanilla Alone								
		$\Delta\Omega_\Lambda$	$\Delta\ln(\Omega_m h^2)$	$\Delta\ln(\Omega_b h^2)$	Δn_s	$\Delta\ln A_s$	$\Delta\tau$	$\Delta\Omega_k$	Δm_ν [eV]	$\Delta\alpha$
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+LOFAR	All OPT	0.0044	0.0052	0.0051	0.0018	0.0087	0.0042	0.0022	0.023	0.00073
	All MID	0.0070	0.0081	0.0059	0.0032	0.0088	0.0043	0.018	0.22	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+MWA	All OPT	0.0063	0.0074	0.0055	0.0024	0.0087	0.0043	0.0056	0.017	0.00054
	All MID	0.0061	0.0070	0.0056	0.0030	0.0087	0.0043	0.021	0.19	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+SKA	All OPT	0.00052	0.0018	0.0040	0.00039	0.0087	0.0042	0.0011	0.010	0.00027
	All MID	0.0036	0.0040	0.0044	0.0025	0.0087	0.0043	0.0039	0.056	0.0022
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+FFTT[b]	All OPT	0.00010	0.0010	0.0029	0.000088	0.0086	0.0042	0.00020	0.0018	0.000054
	All MID	0.00038	0.00034	0.00059	0.00033	0.0086	0.0042	0.00023	0.0066	0.00017
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.14	0.0025

Mao+ 2008

- OPT - density only, MID - model ion, PESS - velocity only
- MID constraints still interesting
- FFTT MID constraints very interesting
- So key is ability to model ionization well
- (velocities and non-Gaussianity may help constrain models)

Intensity mapping

Residual HI left in dense clumps (e.g. DLA)

1) Use radio telescope to do galaxy survey
   - fully spectroscopic
   - SKA could find 10^9 galaxies out to z=1.5
   - measure distances to from BAO

Abdulla & Rawlings 2004

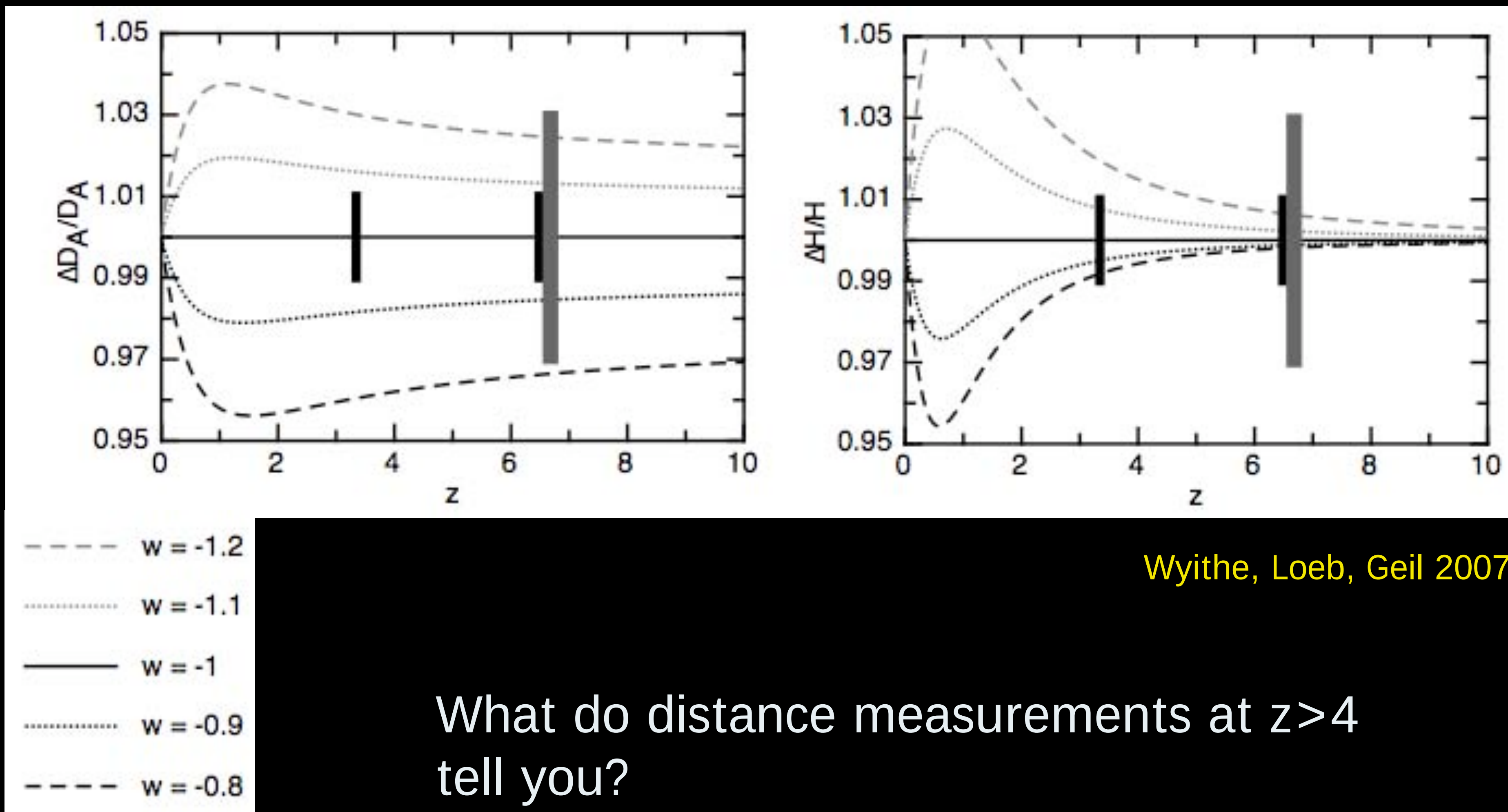
2) Instead of resolving galaxies just integrate 21 cm intensity to get a map of the density
   - at z=1.5 BAO 3rd peak at 20'
   resolvable by ~200 m telescope
   - smoothing over smaller scale information
   - comparable to DETF stage IV mission

Chang et al. 2007
Wyithe & Loeb 2007

21 cm intensity fluctuations found in cross-correlation between HIPASS and 6dF

Pen, Wu, Peterson, Chang 2008

BAO at high z?



Wyithe, Loeb, Geil 2007

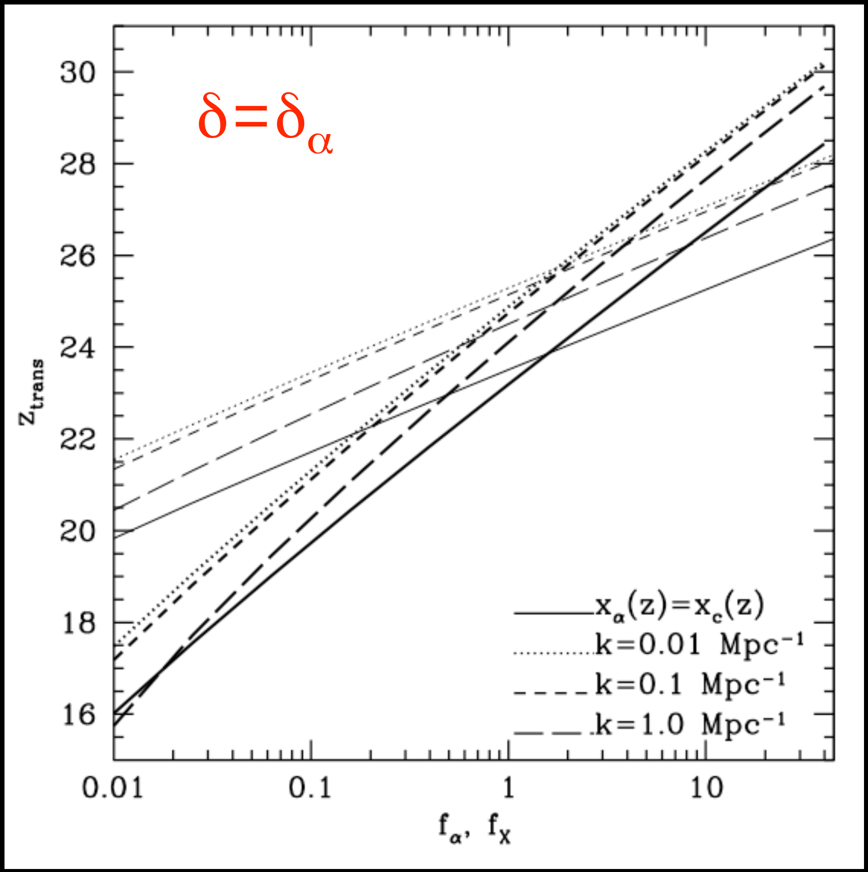
What do distance measurements at z>4 tell you?

Dark Ages

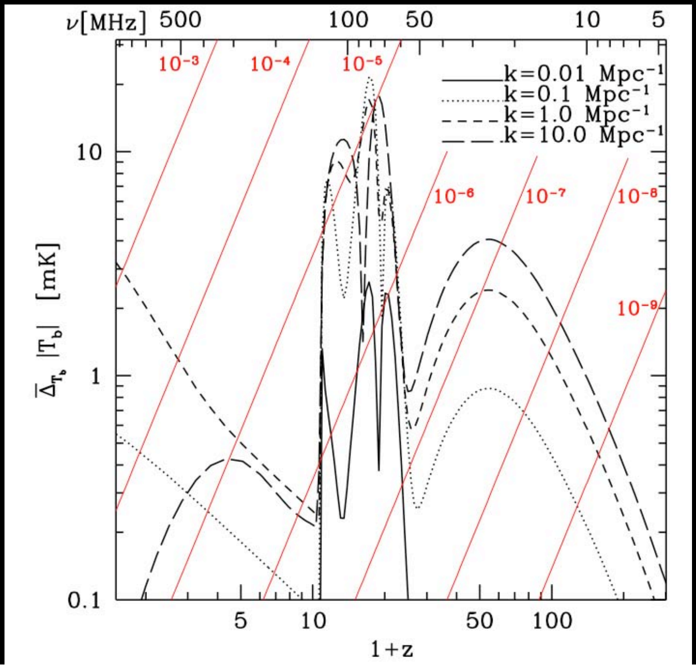
- Avoid astrophysics by going to highest redshifts
- Pristine power spectrum
- Primordial bispectrum
- Heating of exotic decays after CMB and before star formation
- Much weaker signal than during reionization
  ->requires large collecting area (many km^2)
  - going to small scales for running requires high angular resolution ->need long baselines + better antennae

When do dark ages end?

- when Lya flux builds up



- Onset of Lya fluctuations log parameter dependent
- Hard to make robust predictions
- Somewhere in range z~22-28
- Earth ionosphere important at nu<50 MHz (z>26) so hard to get at dark ages from earth



Pritchard
& Loeb 2008

Why go to the moon?

- Earth Ionosphere reflective below 10 MHz
  in 10-50 MHz region scattering smears objects
  - limited angular resolution
- Radio interference (RFI)
- LARC - Lunar Array for Radio Cosmology (PI Hewitt)
- DALI - Dark Ages Lunar Interferometer (PI Lazio)
- Mass requirements challenging
  - many km of wire = tonnes of mass
  - energy requirement of correlator
  - data transmission back to Earth
- Active area of NASA interest
  - for the moment...
- Plan is for mission ~2020

Conclusions

- Possibility of making very sensitive measurements of P(k) over wide range of scales and redshifts
  - neutrino mass at 0.008 eV level
  - running at 0.0003 level
  - Can you do anything qualitatively new with this precision?
- Largest signal during reionization. Need to...
  - find windows where astrophysics least important
  - use velocities and non-Gaussianity to understand
  - model astro to get cosmology
- Intensity mapping good for BAO in $1<z<6$ window
- Dark Ages requires going to moon...
  ...and 10s km^2 collecting area
  ...and funding... >2020
- Large uncertainties in modeling due to ignorance of high redshift sources