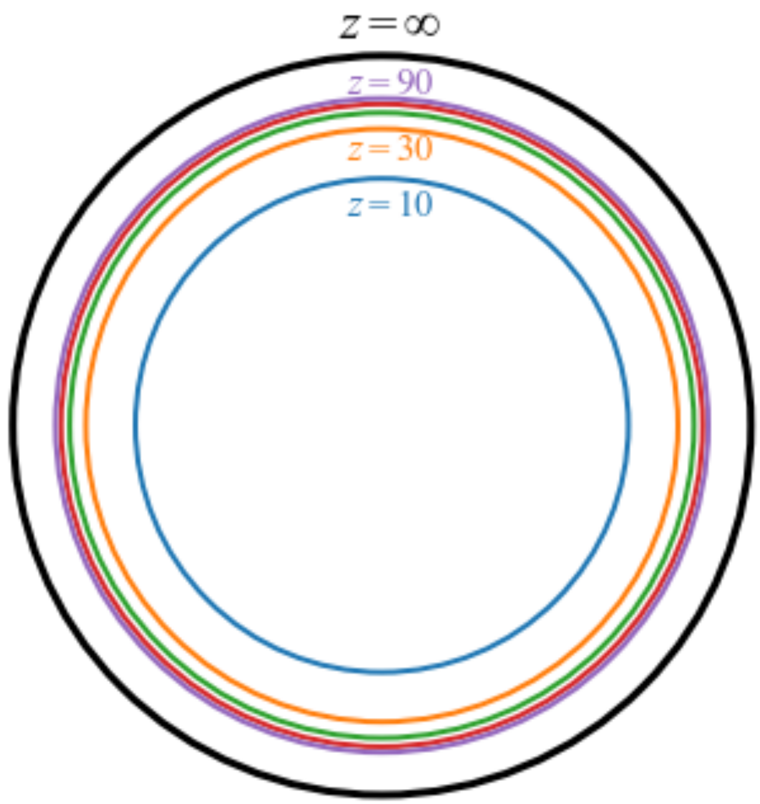
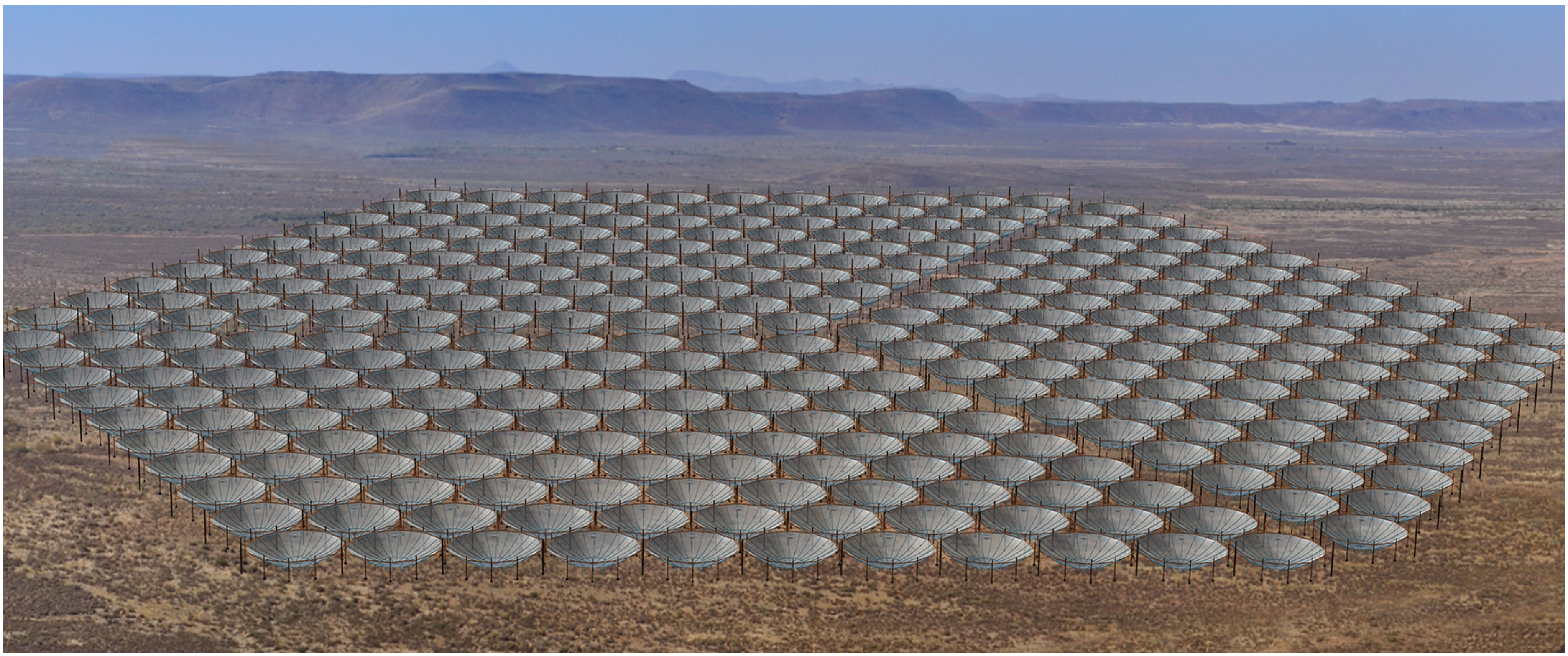
Beyond a first detection: Pushing the redshift, sensitivity, and scale frontiers of 21cm cosmology



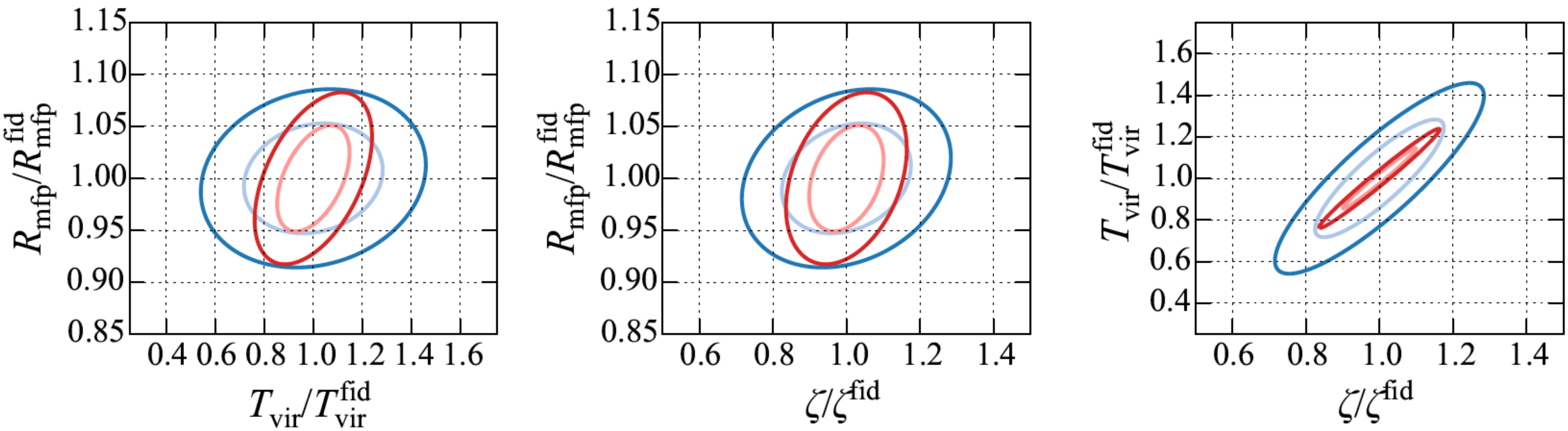
Adrian Liu, UC Berkeley

Initial conditions: HERA measures the 21cm power spectrum



~150 m

HERA will provide the first astrophysical constraints on Cosmic Dawn, and will have some sensitivity to cosmology

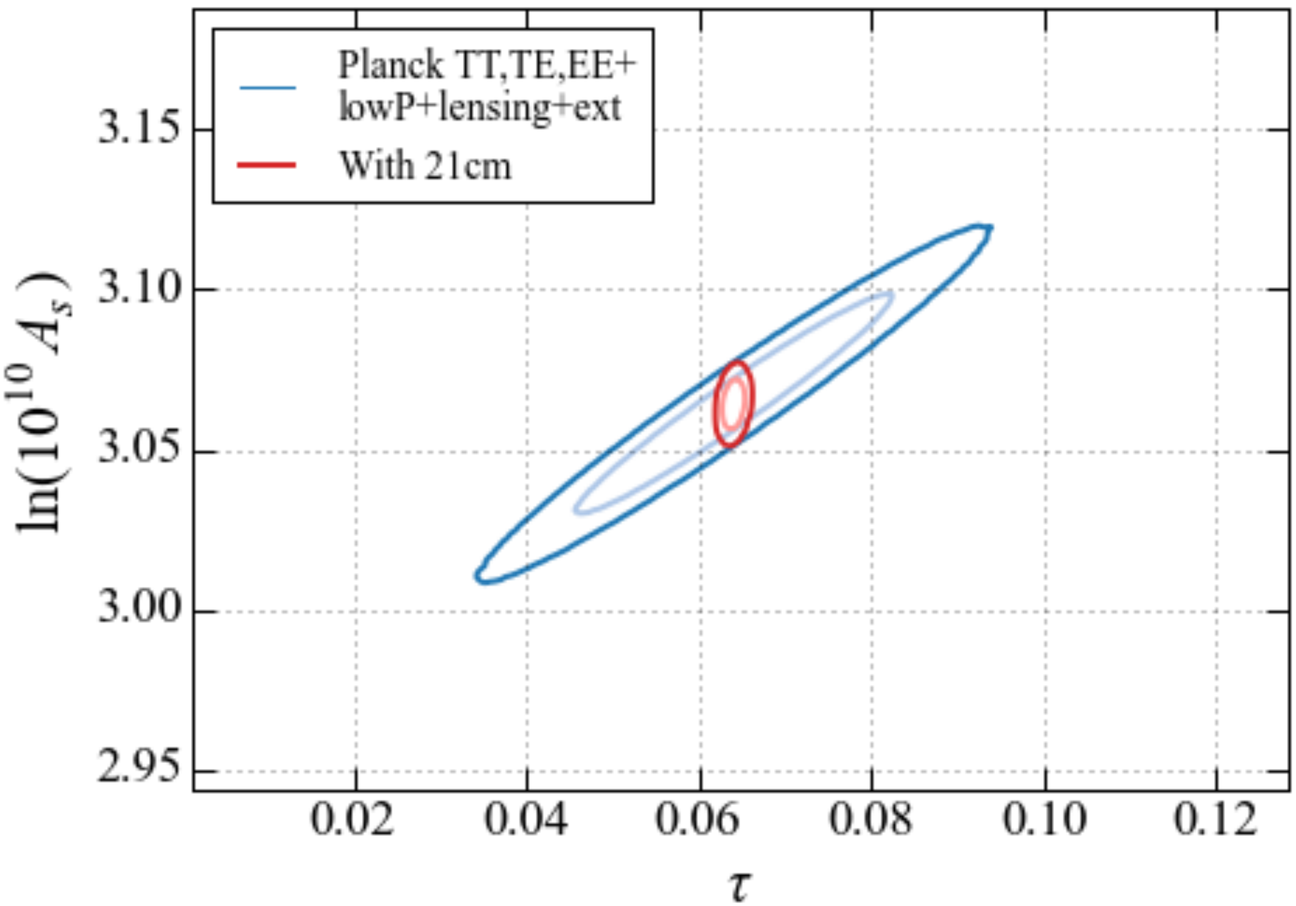


Cosmo params fixed

Cosmo params varied

AL & Parsons (2016)

HERA will provide the first astrophysical constraints on Cosmic Dawn, and will have some sensitivity to cosmology



AL et al. (2016)

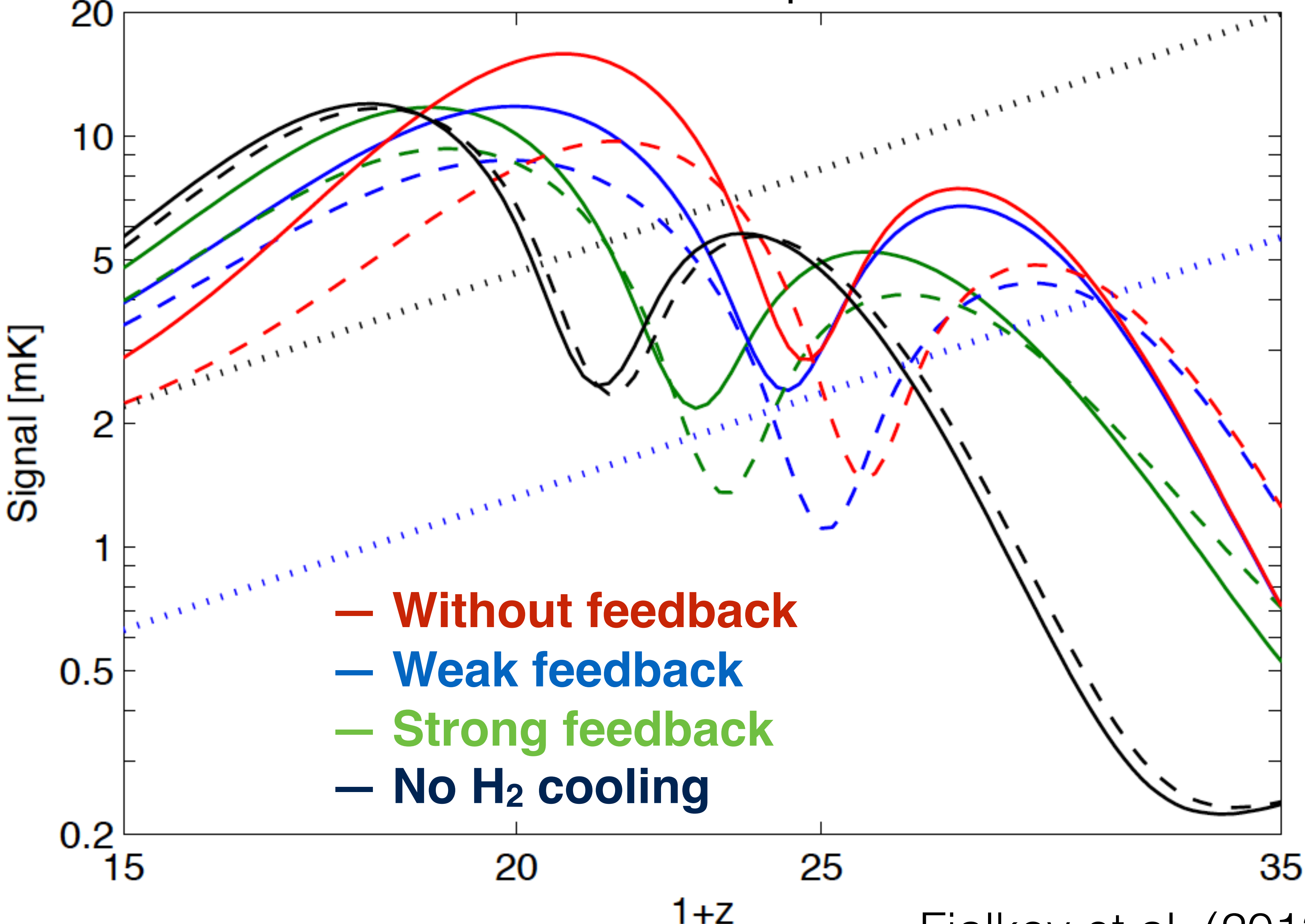
$$\Delta \ln(10^{10} A_s) = \pm 0.023 \longrightarrow \pm 0.0053$$

What’s next?

Advanced HERA and post-HERA

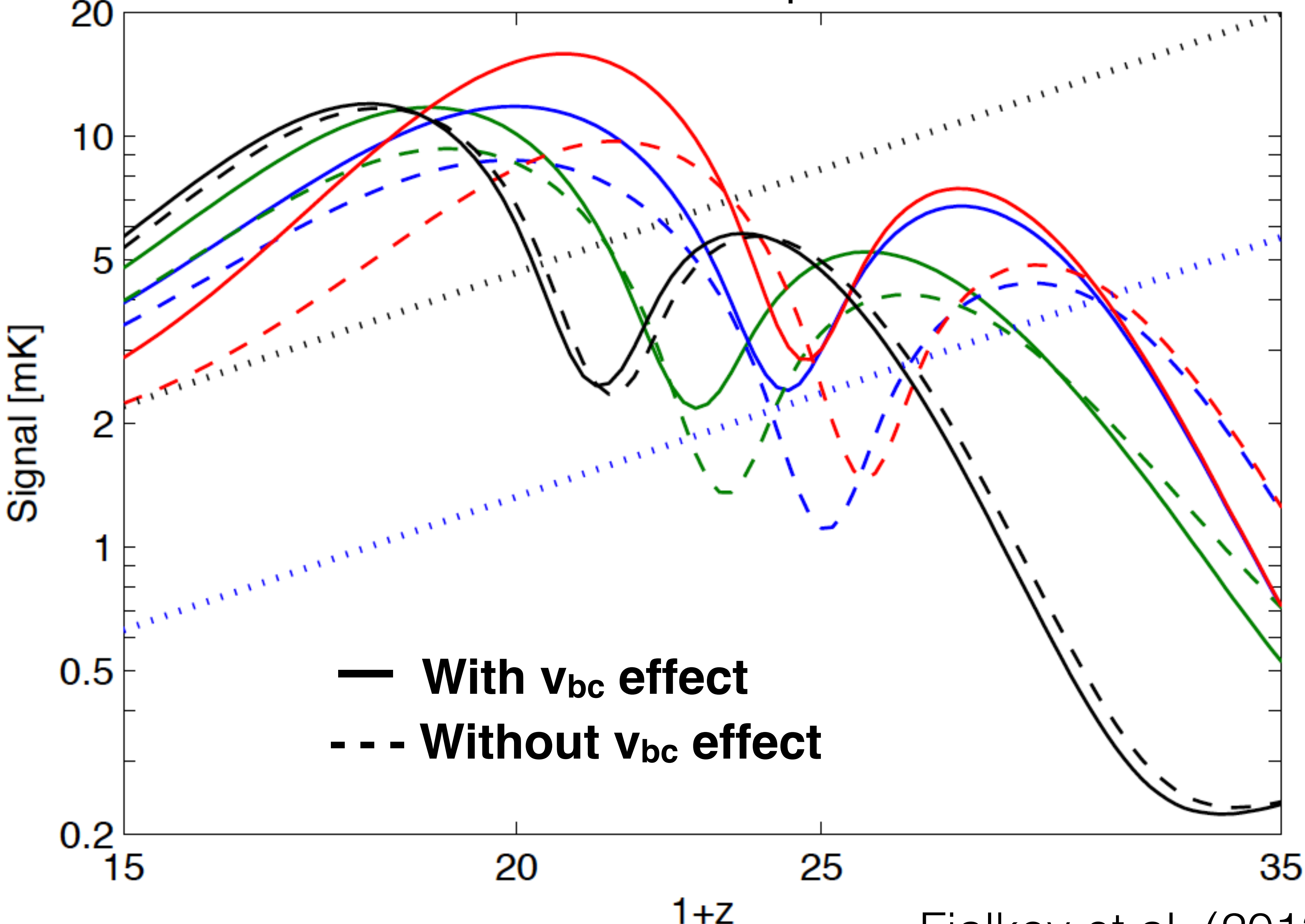
- Non-statistical information: imaging
- Precision measurements of the power spectrum

k ~ 0.1 h Mpc⁻¹



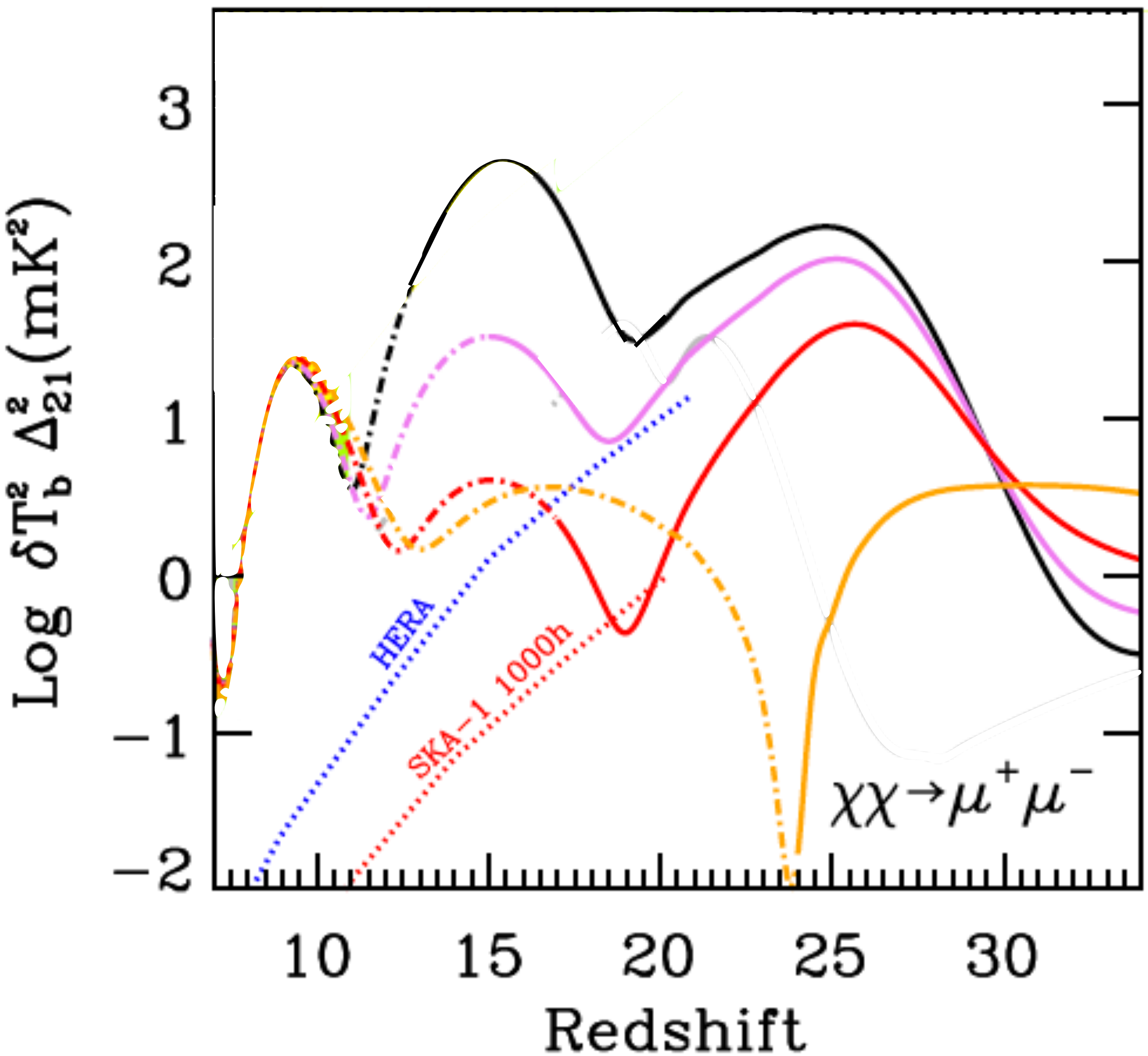
Fialkov et al. (2013)

k ~ 0.1 h Mpc^{-1}



Fialkov et al. (2013)

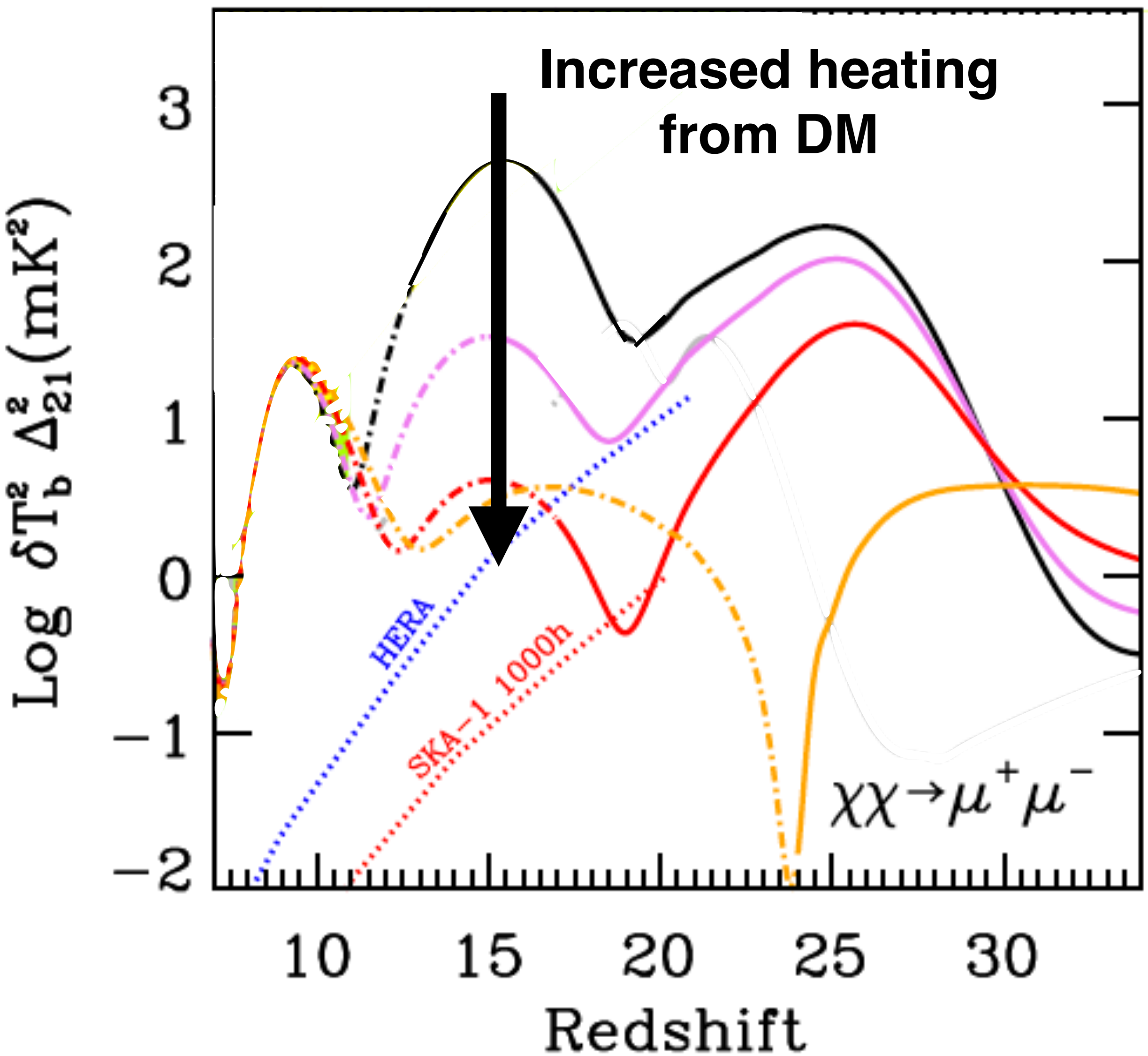
Heating from DM annihilation



$k \sim 0.15\ h\,Mpc^{-1}$

Evoli et al. 2014

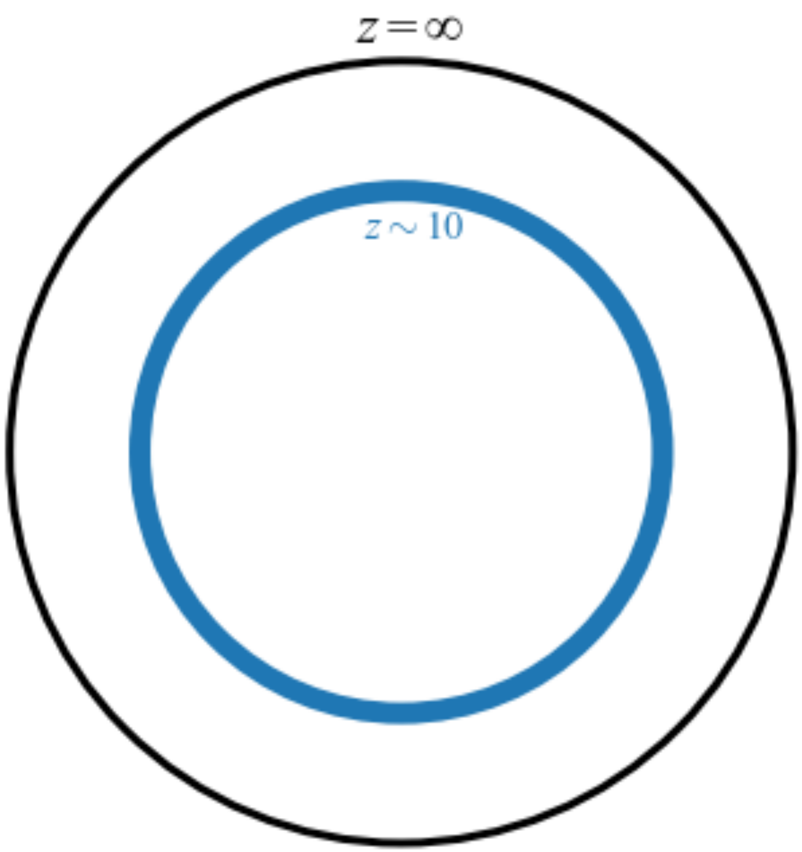
Heating from DM annihilation



$k \sim 0.15\ h\,Mpc^{-1}$

Evoli et al. 2014

Lots of modes for parameter estimation



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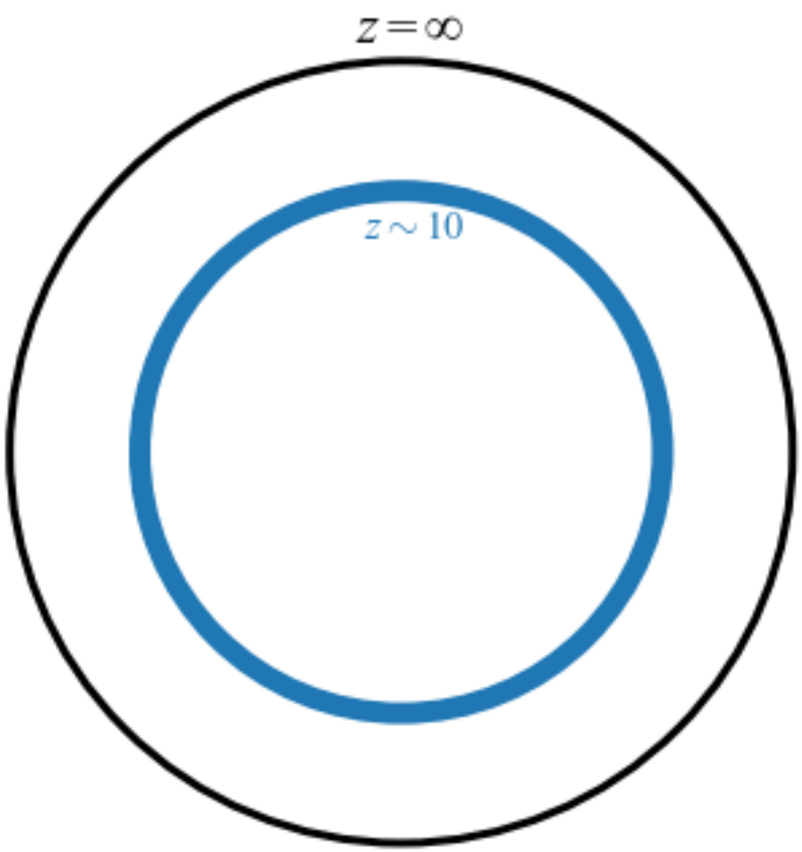


SKA:

$$\Delta\Omega_k = 0.004$$

$$\Delta\left(\sum m_\nu\right) = 0.06\text{eV}$$

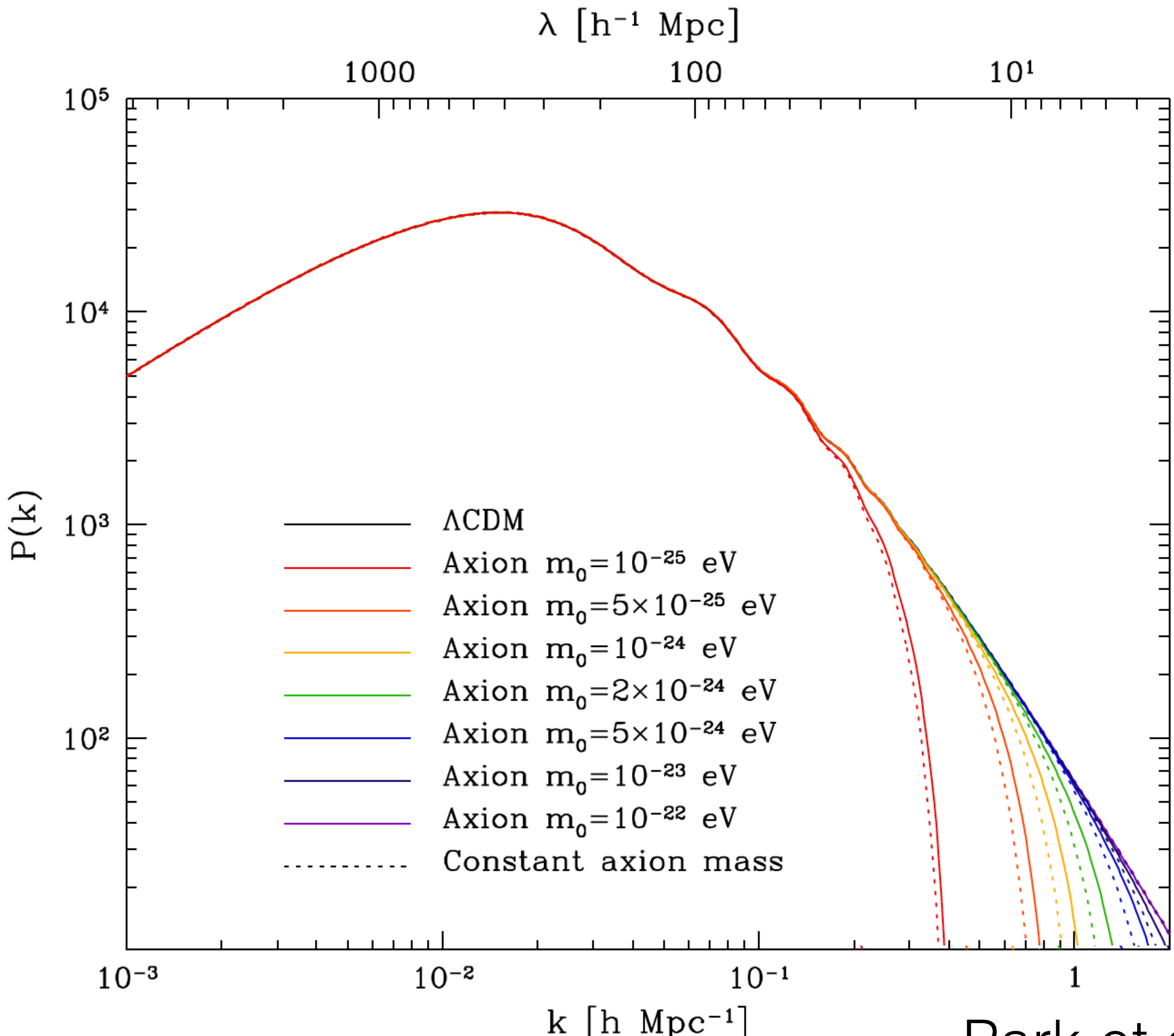
10^6 correlated dipoles:

$$\Delta\Omega_k = 0.0002$$

$$\Delta\left(\sum m_\nu\right) = 0.007\text{eV}$$

Mao et al. 2008

These modes are not Silk-damped or non-linear



Park et al. 2014

Three unifying principles for these possibilities

Tegmark & Zaldarriaga 2009

- Redshift frontier
- Sensitivity frontier
- Scale frontier

Tegmark & Zaldarriaga 2009

- Redshift frontier
    - Unique access to $15 < z < 100$
- Sensitivity frontier
- Scale frontier

Tegmark & Zaldarriaga 2009

- Redshift frontier
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    - Lots of modes for cosmic variance
- Scale frontier

Tegmark & Zaldarriaga 2009

- Redshift frontier
    - Unique access to $15 < z < 100$
- Sensitivity frontier
    - Lots of modes for cosmic variance
- Scale frontier
    - Small scale modes not affected by Silk damping + easy linear modeling

Tegmark & Zaldarriaga 2009

Pushing these frontiers in practice with 21cm cosmology

The sensitivity frontier

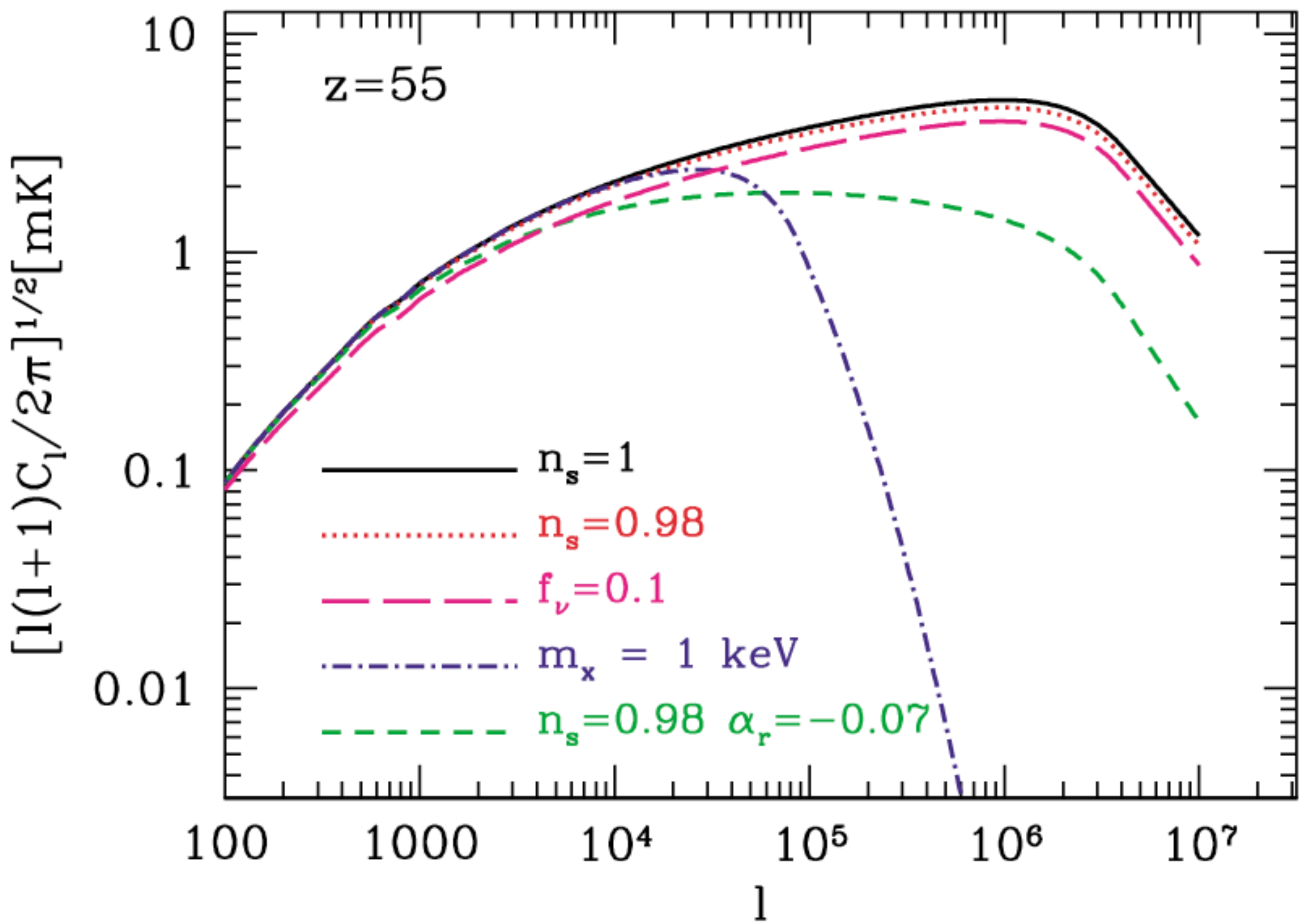
21cm interferometers are not naturally C_ℓ instruments at high z

Max. baseline length

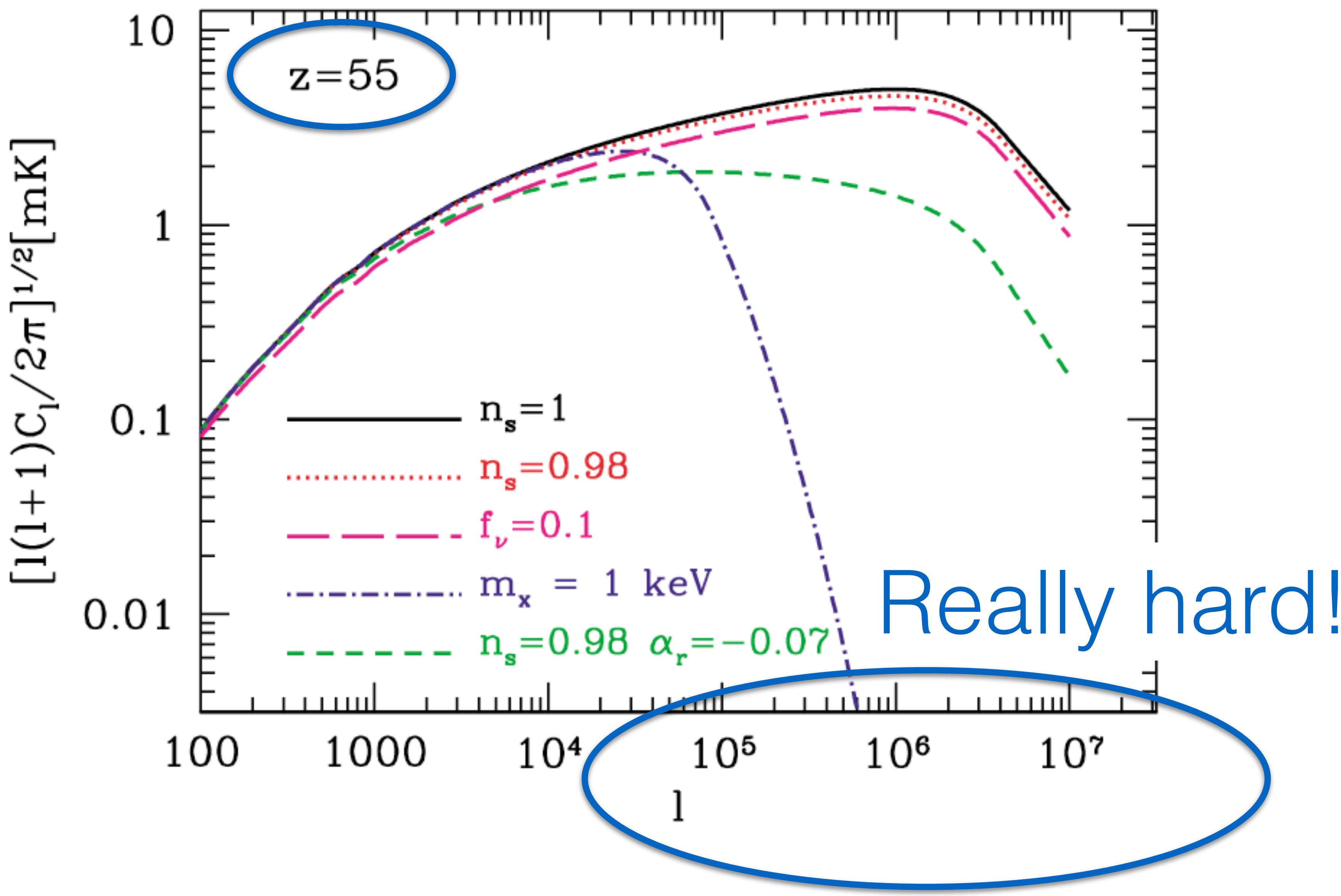
$$\ell \sim \frac{2\pi b}{\lambda} = \frac{2\pi b \nu_{21}}{c(1+z)}$$

21cm interferometers are not naturally C_ℓ instruments at high z

$$\ell \sim 960 \left(\frac{b}{1\,\mathrm{km}} \right) \left(\frac{31}{1+z} \right)$$



Loeb & Zaldarriaga 2004



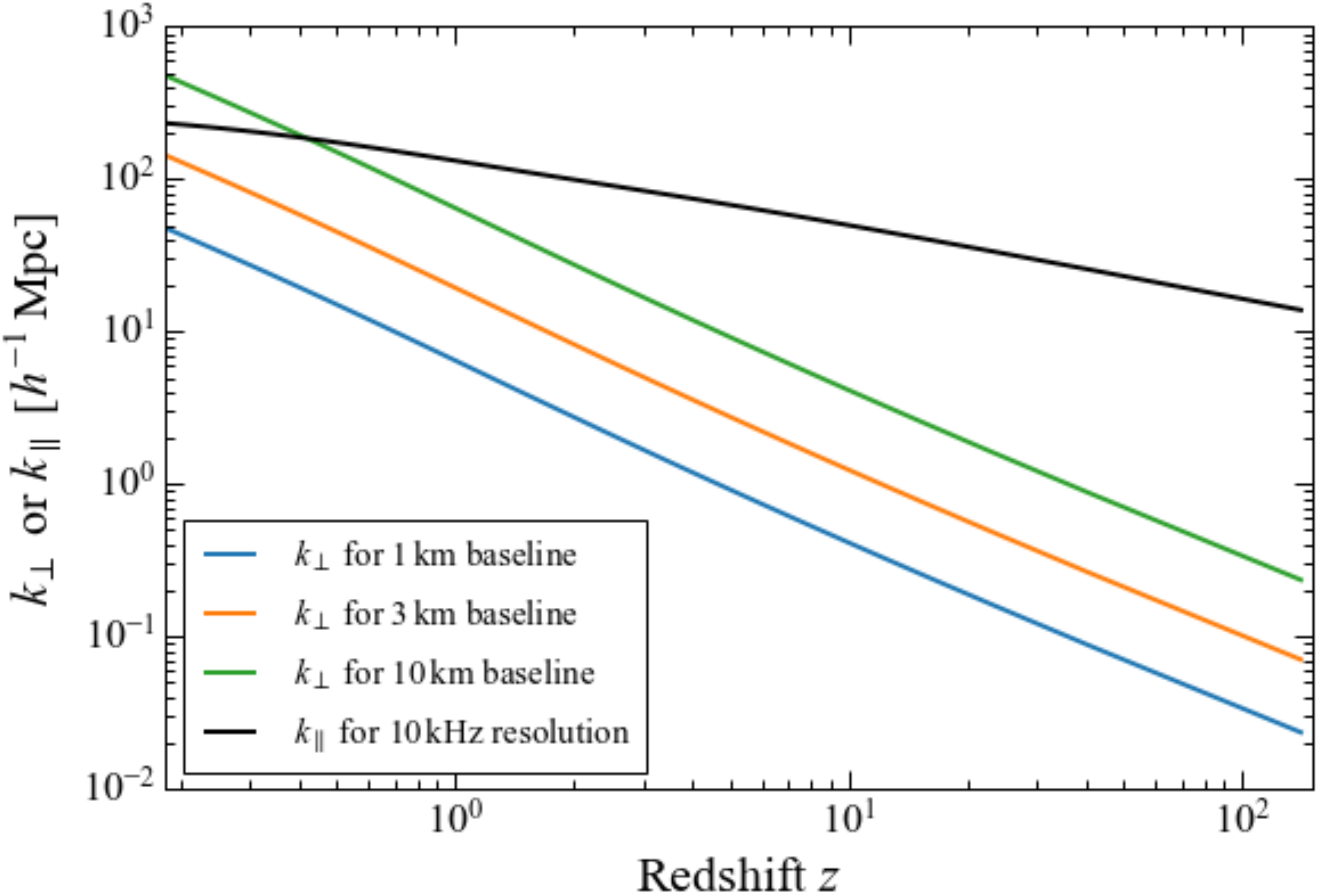
Loeb & Zaldarriaga 2004

Spatial fluctuations along the line-of-sight are “easy” to probe

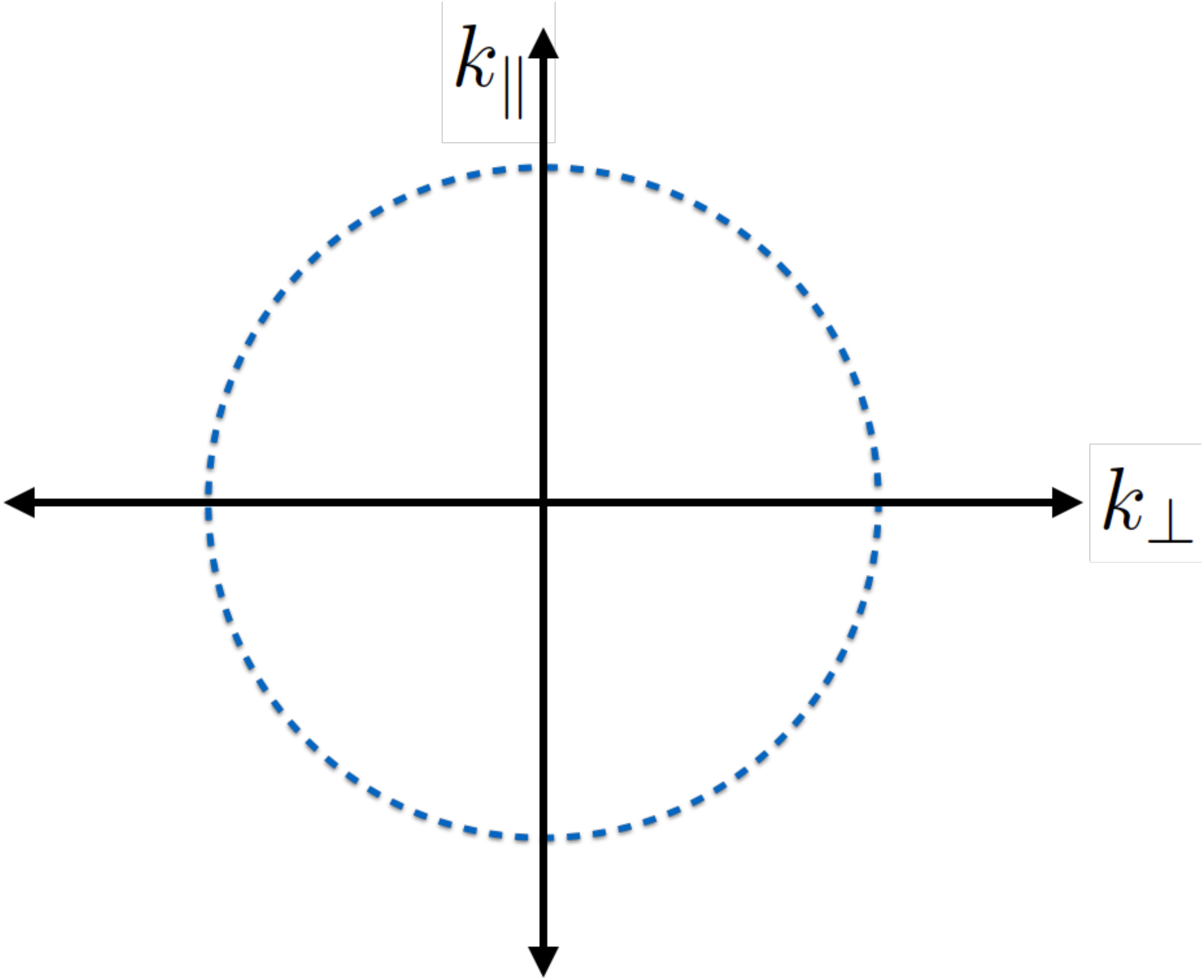
- At $z \sim 30$: a spectral resolution of 10 kHz maps to 0.21 h^{-1} Mpc (comoving) along the line-of-sight.
- At $z \sim 50$, maps to 0.27 h^{-1} Mpc
- At $z \sim 70$, maps to 0.31 h^{-1} Mpc

$$b \to \ell \to k_\perp$$

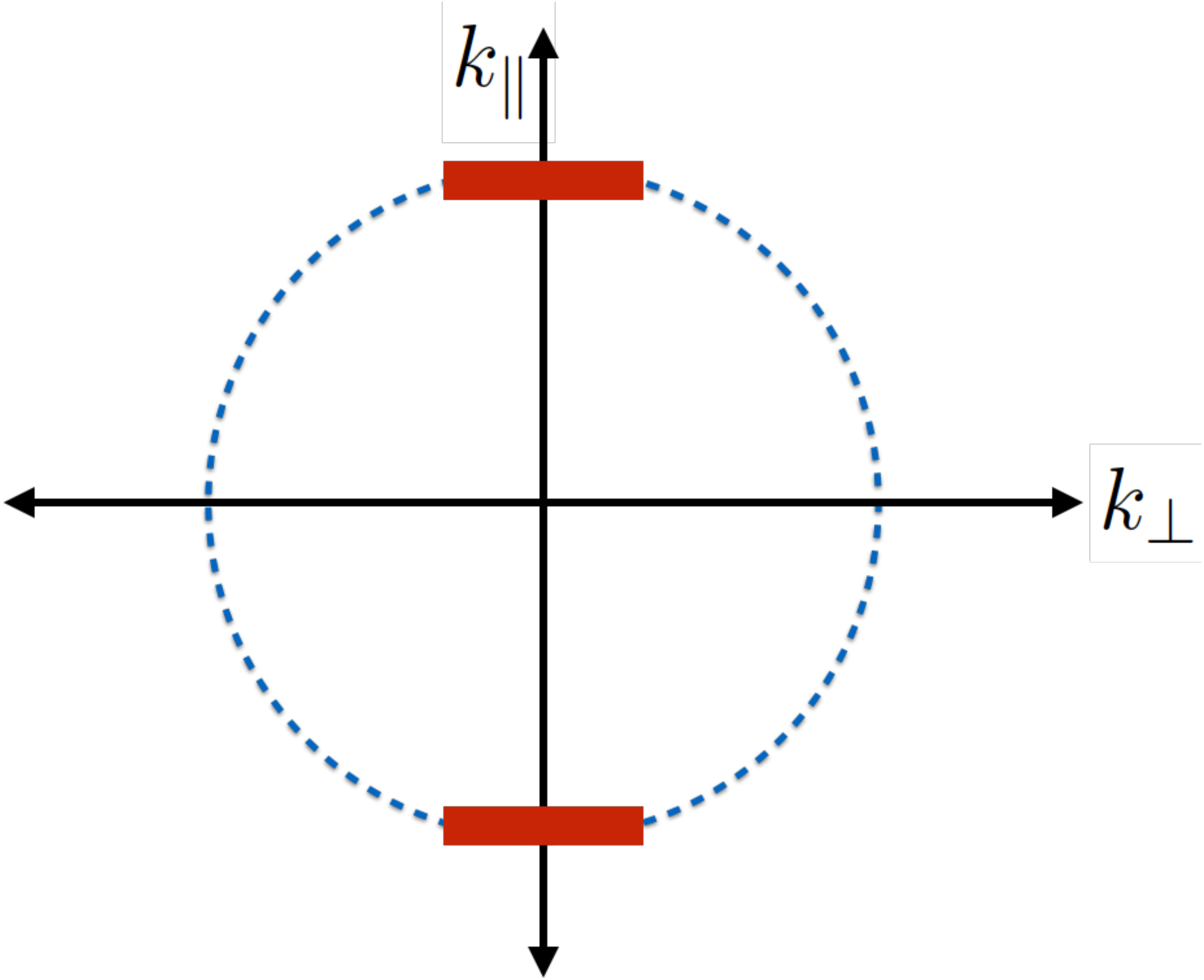
$$\Delta\nu \to k_\parallel$$

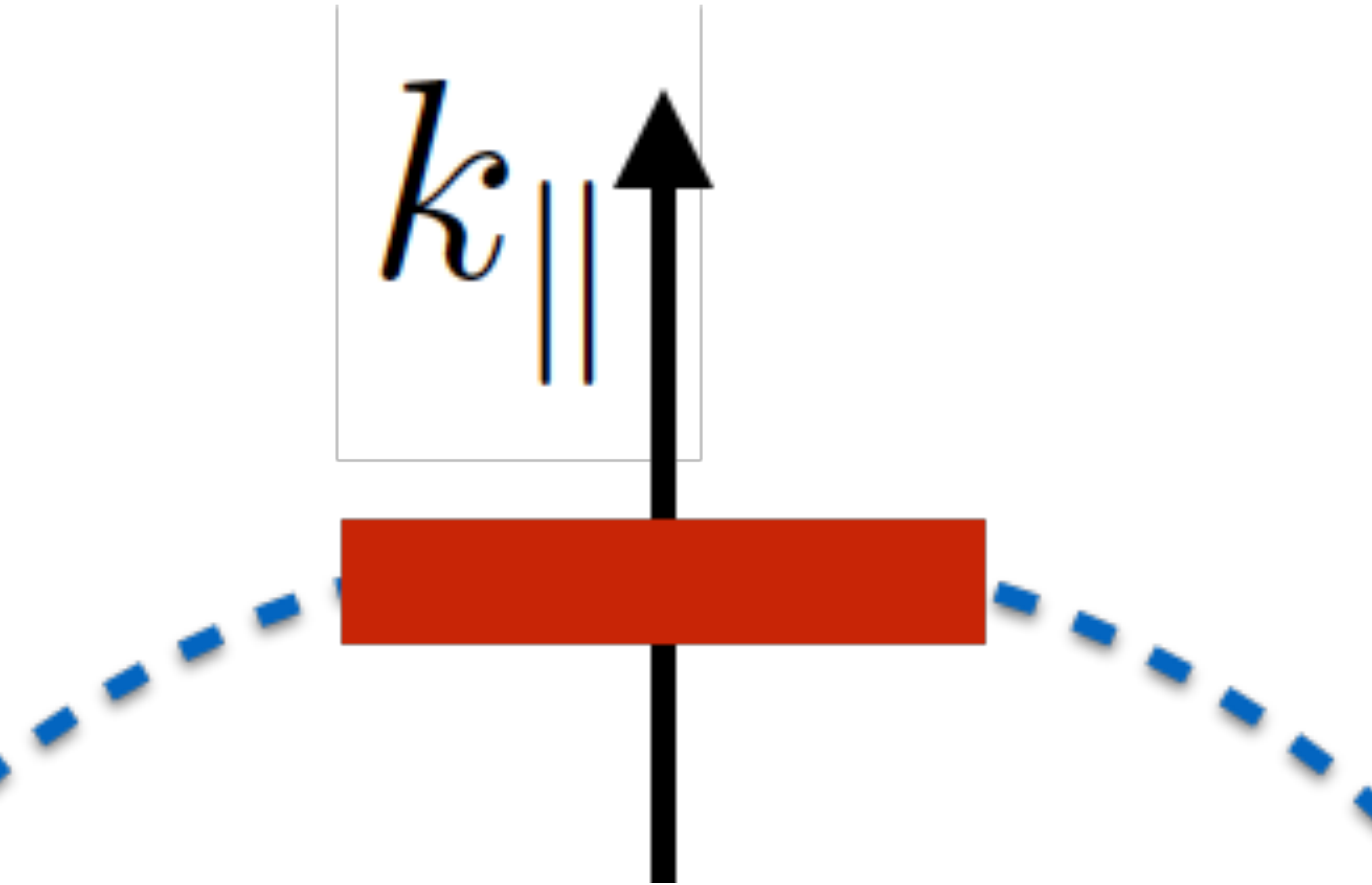


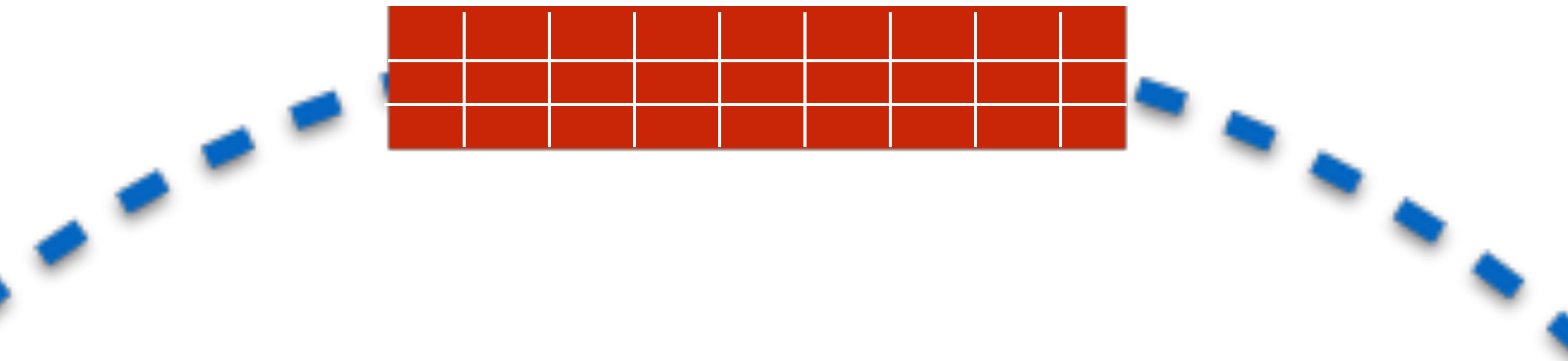
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$k_\perp$ or $k_\parallel$ $[h^{-1}\,\mathrm{Mpc}]$
$k_\perp$ for 1 km baseline
$k_\perp$ for 3 km baseline
$k_\perp$ for 10 km baseline
$k_\parallel$ for 10 kHz resolution
10^0
10^1
10^2
Redshift z

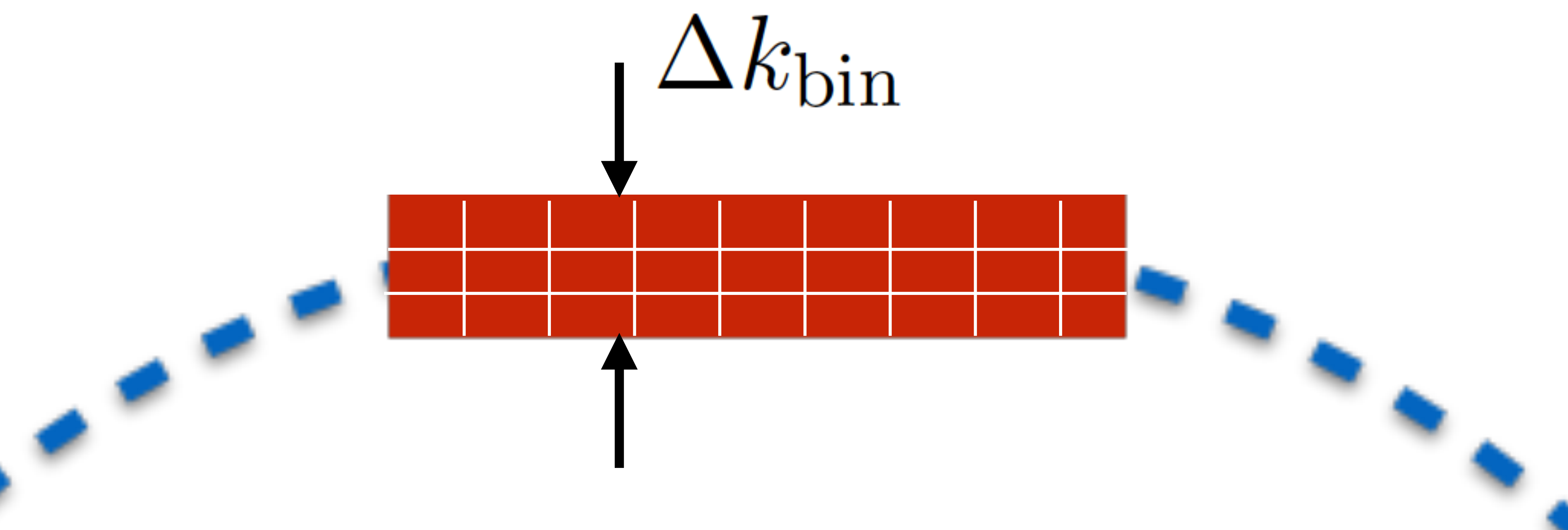


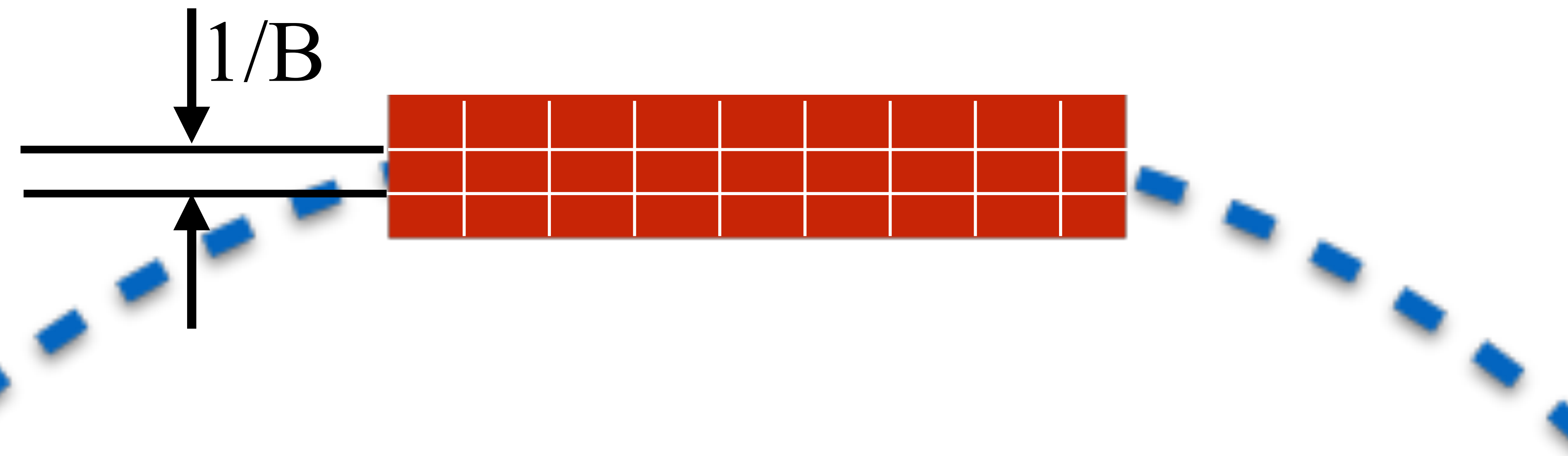
$k_{\|}$
$k_{\perp}$

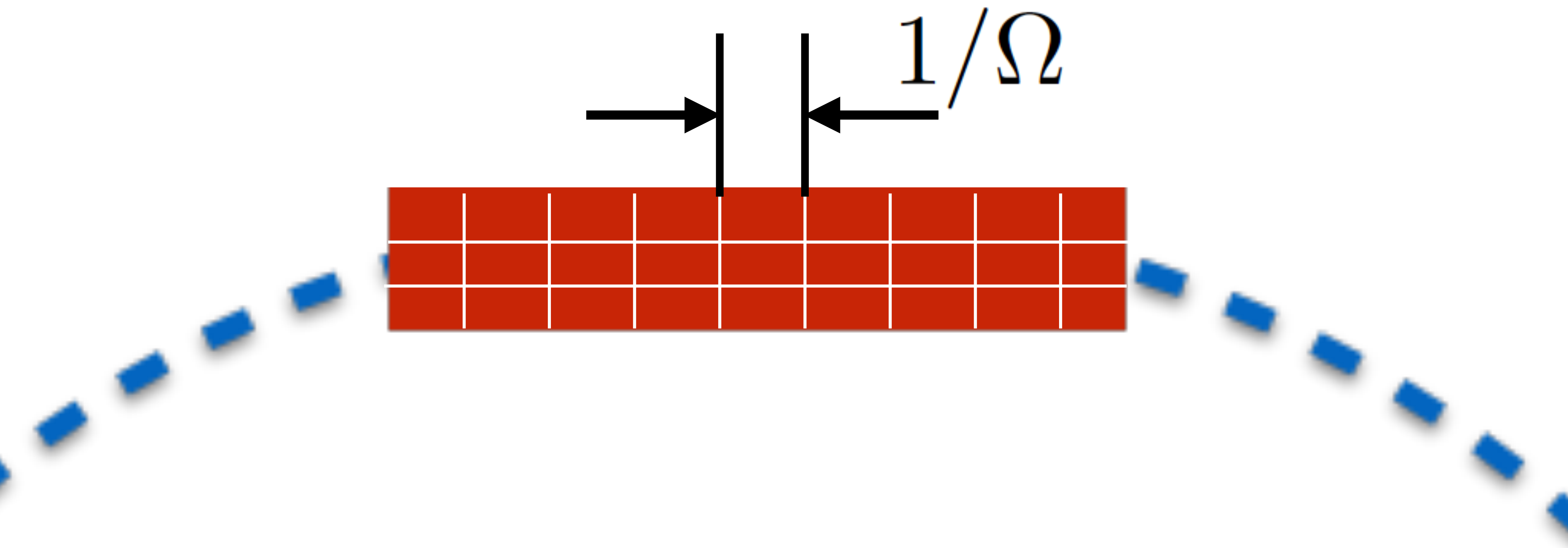

$k_{\parallel}$
$k_{\perp}$

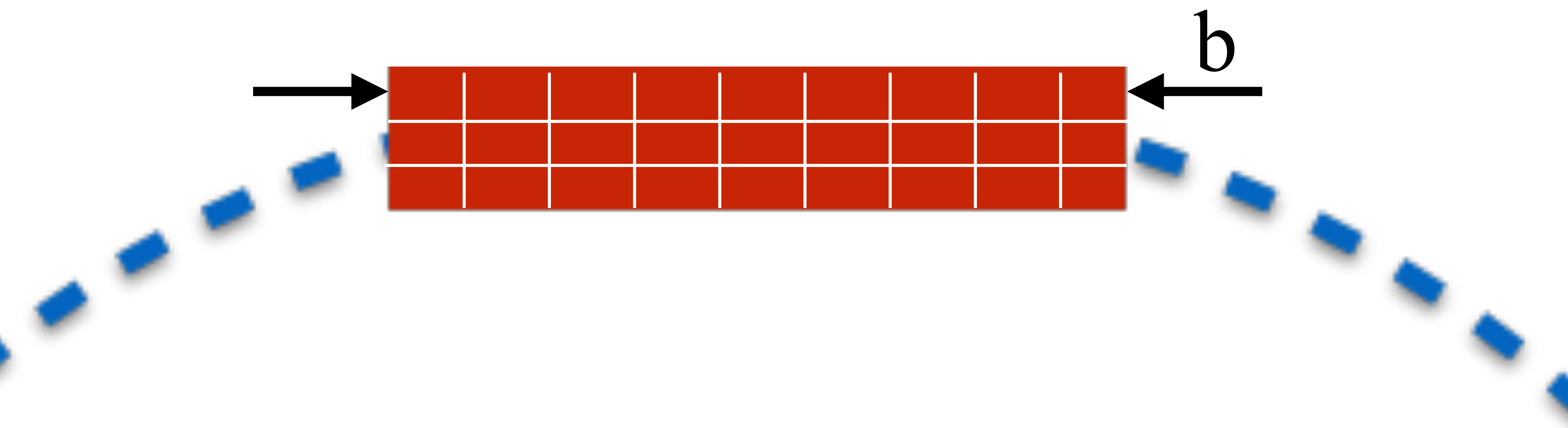

$k_{||}$




$\Delta k_{\rm bin}$


1/B

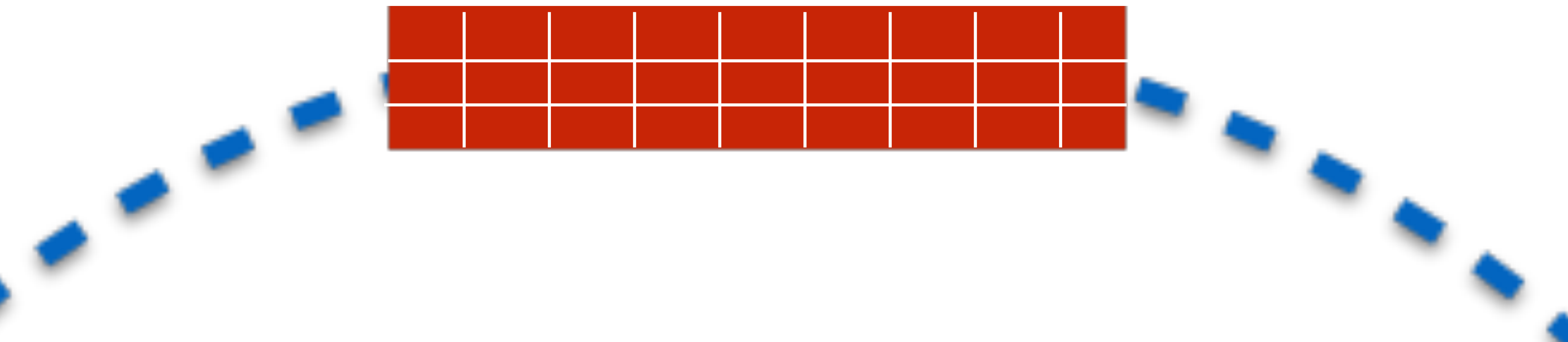

$1/\Omega$


b

z = 100:

$$N \equiv \frac{V_k}{\Delta V_k} \approx 70 \left(\frac{b}{1\,\mathrm{km}}\right)^2 \left(\frac{\Delta k_{\mathrm{bin}}}{0.05h\,\mathrm{Mpc}^{-1}}\right) \left(\frac{B}{1\,\mathrm{MHz}}\right) \left(\frac{\Omega}{0.03\,\mathrm{Str}}\right)$$

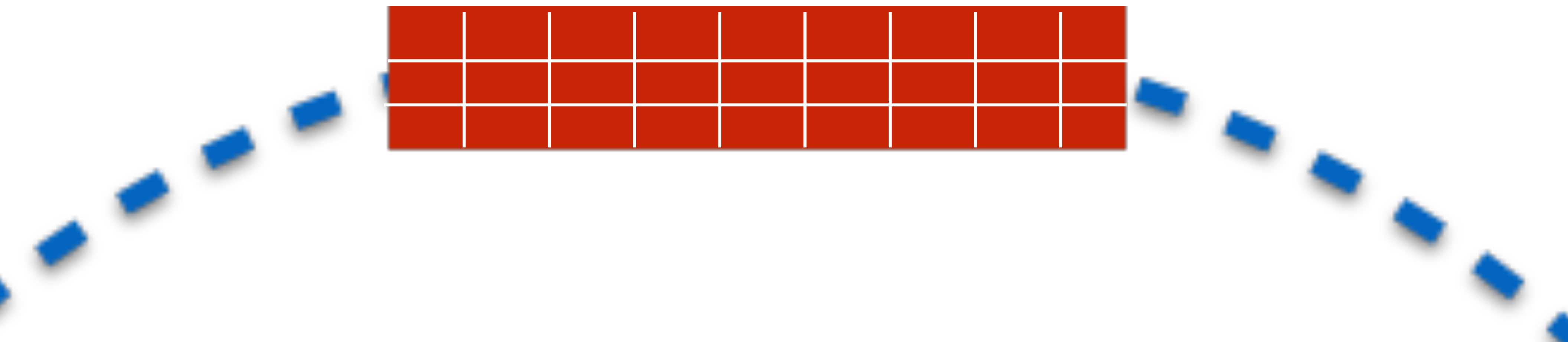
$$\frac{\Delta P}{P} \sim \sqrt{\frac{2}{N}} \sim 0.17$$



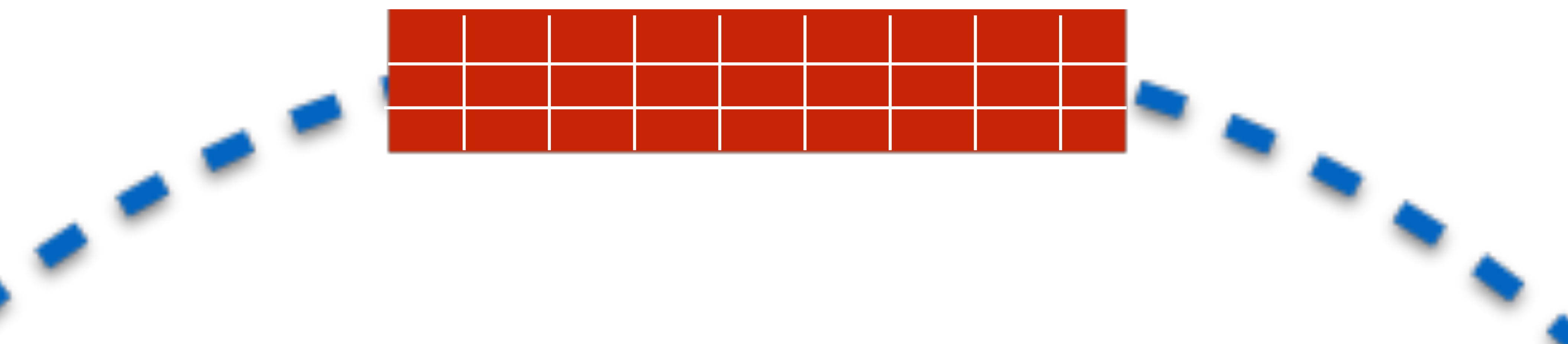
z = 20:

$$N \equiv \frac{V_k}{\Delta V_k} \approx 231 \left(\frac{b}{1\,\mathrm{km}}\right)^2 \left(\frac{\Delta k_{\mathrm{bin}}}{0.05h\,\mathrm{Mpc}^{-1}}\right) \left(\frac{B}{1\,\mathrm{MHz}}\right) \left(\frac{\Omega}{0.03\,\mathrm{Str}}\right)$$

$$\frac{\Delta P}{P} \sim \sqrt{\frac{2}{N}} \sim 0.09$$



Cosmic variance is not a huge problem, so to get greater sensitivity it makes sense to build **compact arrays**



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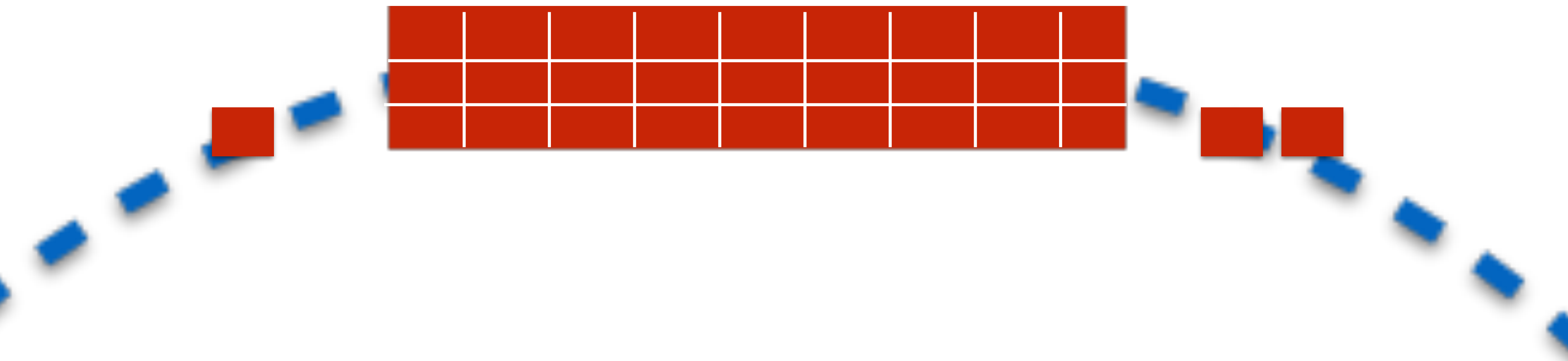


Cosmic variance is not a huge problem, so to get greater sensitivity it makes sense to build **compact arrays**

Sensitivity should not be a huge problem for z~20 and below

z = 20:

$$\Delta_N^2(k) = 3\,\mathrm{mK}^2 \left(\frac{k}{0.1h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{2000\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{1\,\mathrm{Str}}\right) \left(\frac{120\,\mathrm{days}}{t}\right) \left(\frac{4\times 10^4}{N}\right)$$

z = 20:

Sky-dominated system temp

Bin size

$$\Delta_N^2(k) = 3\,\mathrm{mK}^2 \left(\frac{k}{0.1h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{2000\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{1\,\mathrm{Str}}\right) \left(\frac{120\,\mathrm{days}}{t}\right) \left(\frac{4\times 10^4}{N}\right)$$

Num antennas on regular grid

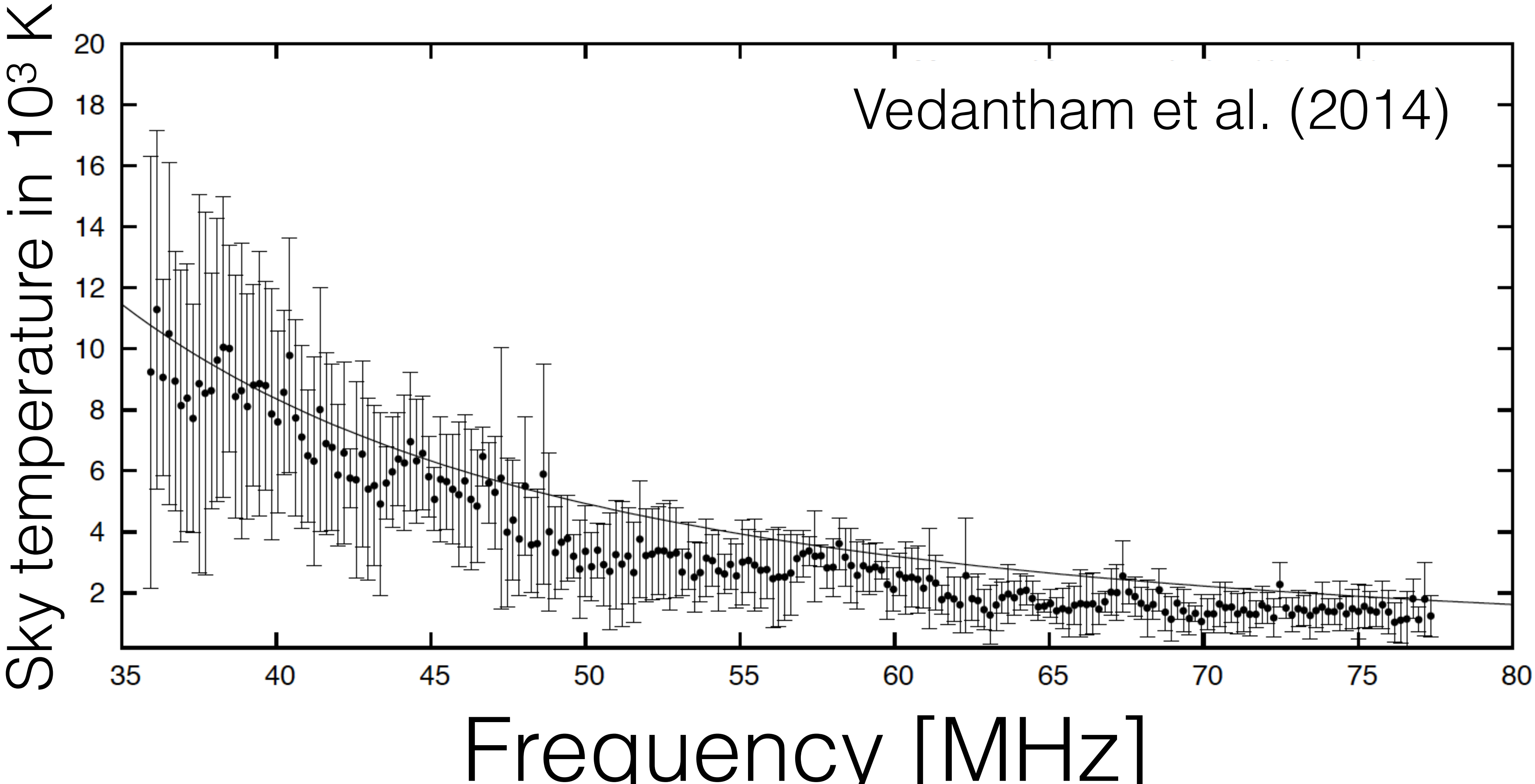
z = 20:

$$\Delta^2_N(k) = 3\,\mathrm{mK}^2 \left(\frac{k}{0.1h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{2000\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{1\,\mathrm{Str}}\right) \left(\frac{120\,\mathrm{days}}{t}\right) \left(\frac{4\times 10^4}{N}\right)$$

$$\Delta^2_S(k) \sim 10\,\mathrm{mK}^2$$

Sensitivity becomes harder to obtain when we attempt to push the sensitivity and redshift frontiers simultaneously

The sky gets brighter towards lower frequencies/higher z



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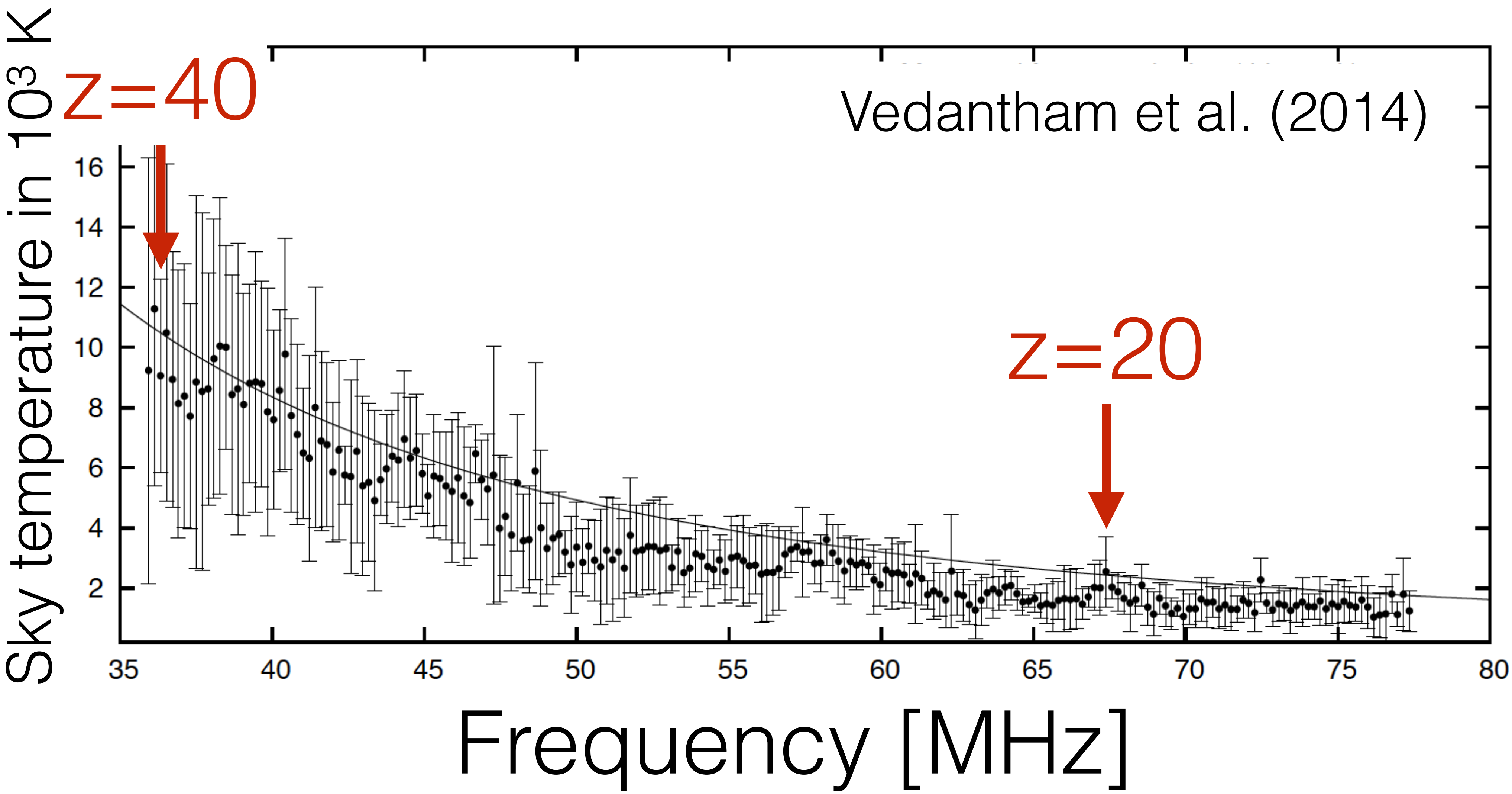

z = 40:

$$\Delta_N^2(k) = 80\,\mathrm{mK}^2 \left(\frac{k}{0.1h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{10^4\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{1\,\mathrm{Str}}\right) \left(\frac{120\,\mathrm{days}}{t}\right) \left(\frac{4\times 10^4}{N}\right)$$

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- More antennas: $N \rightarrow 4N?$
- More time: $t \rightarrow 3t?$
- Narrower FoV: $\Omega \rightarrow 0.5\Omega?$

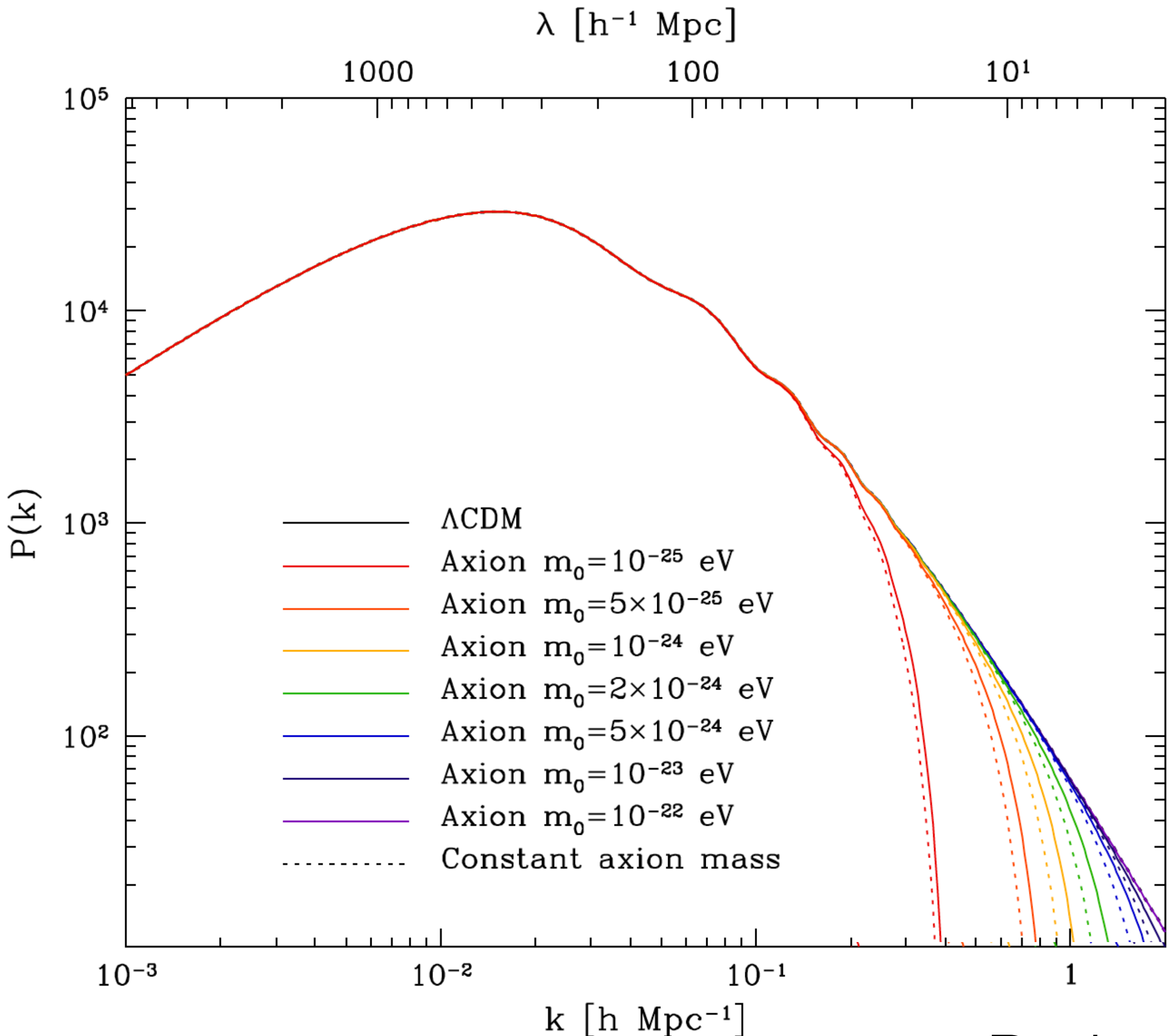
z = 40:

$$\Delta_N^2(k) = 3.3\,\mathrm{mK}^2 \left(\frac{k}{0.1h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{10^4\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{0.5\,\mathrm{Str}}\right) \left(\frac{360\,\mathrm{days}}{t}\right) \left(\frac{1.6\times 10^5}{N}\right)$$

- More antennas: $N \rightarrow 4N?$
- More time: $t \rightarrow 3t?$
- Narrower FoV: $\Omega \rightarrow 0.5\Omega?$

Simultaneously pushing the sensitivity, redshift, and scale frontiers will be challenging

Get to k > 0.2 h Mpc^{-1} to access modes that are too Silk-damped for the CMB and getting to non-linear modeling for galaxy surveys



Park et al. 2014

z = 40, k~0.3 *h* Mpc^{-1}:

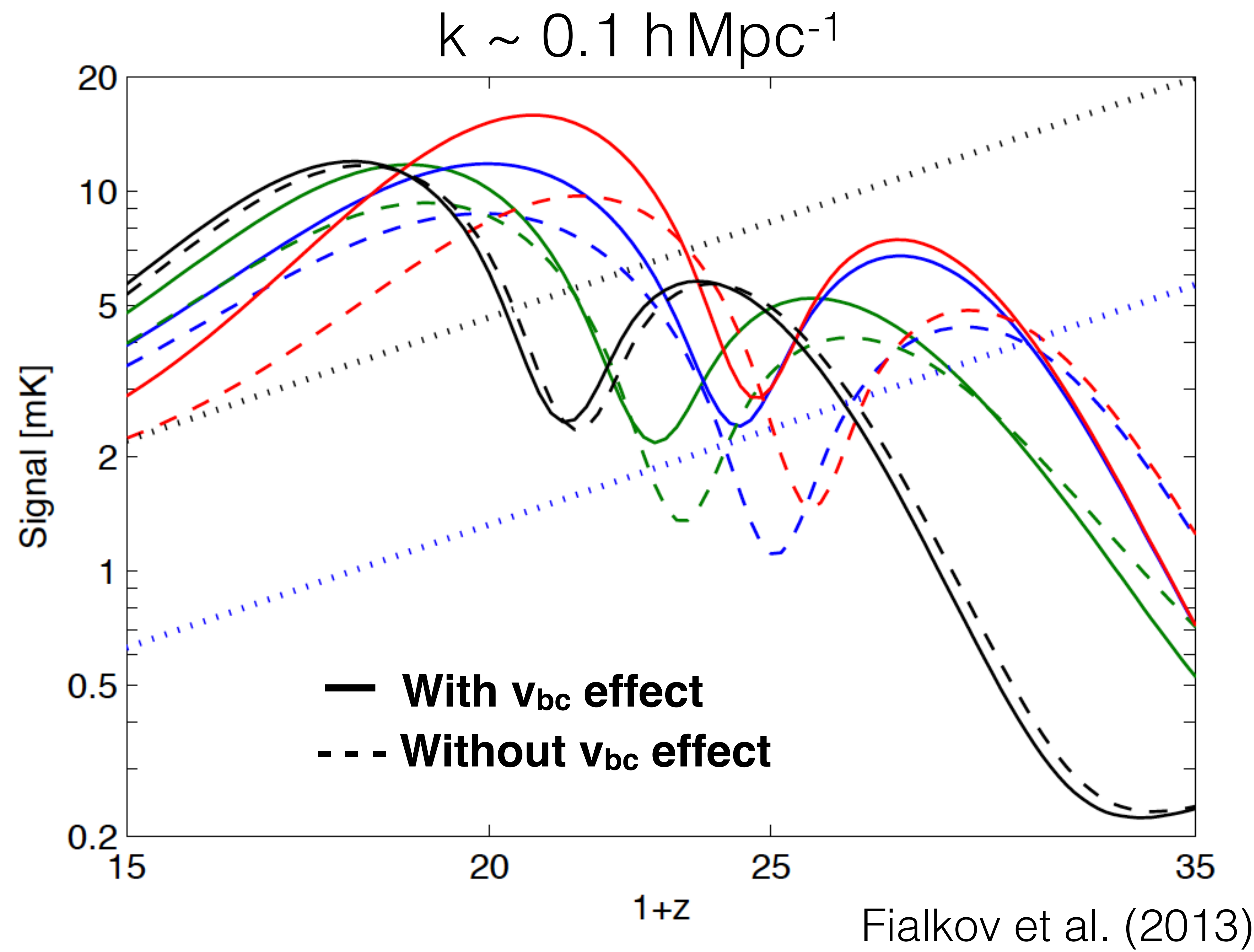
$$\Delta_N^2(k) = 90\,\mathrm{mK}^2 \left(\frac{k}{0.3h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{10^4\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right)\left(\frac{\Omega}{0.5\,\mathrm{Str}}\right)\left(\frac{360\,\mathrm{days}}{t}\right)\left(\frac{1.6\times 10^5}{N}\right)$$

z = 40, k~0.3 h Mpc^{-1}:

$$\Delta^2_N(k) = 90\,\mathrm{mK}^2 \left(\frac{k}{0.3h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.01h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{10^4\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{0.5\,\mathrm{Str}}\right) \left(\frac{360\,\mathrm{days}}{t}\right) \left(\frac{1.6\times 10^5}{N}\right)$$

Larger telescope, more integration, coarser k bins

$$\Delta^2_N(k) = 3.9\,\mathrm{mK}^2 \left(\frac{k}{0.3h\,\mathrm{Mpc}^{-1}}\right)^3 \left(\frac{0.05h\,\mathrm{Mpc}^{-1}}{\Delta k}\right)^{\frac{1}{2}} \left(\frac{T_{\mathrm{sys}}}{10^4\,\mathrm{K}}\right)^2 \times \left(\frac{6\,\mathrm{MHz}}{B}\right) \left(\frac{\Omega}{0.5\,\mathrm{Str}}\right) \left(\frac{600\,\mathrm{days}}{t}\right) \left(\frac{10^6}{N}\right)$$



k ~ 0.1 h Mpc-1
20
10
5
2
1
0.5
0.2
Signal [mK]
15
20
25
35
1+z
With vbc effect
Without vbc effect
Fialkov et al. (2013)

- Another way to reduce the noise: smaller Ω

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    - Cosmic variance not a problem anyway, and nobody to cross-correlate with!

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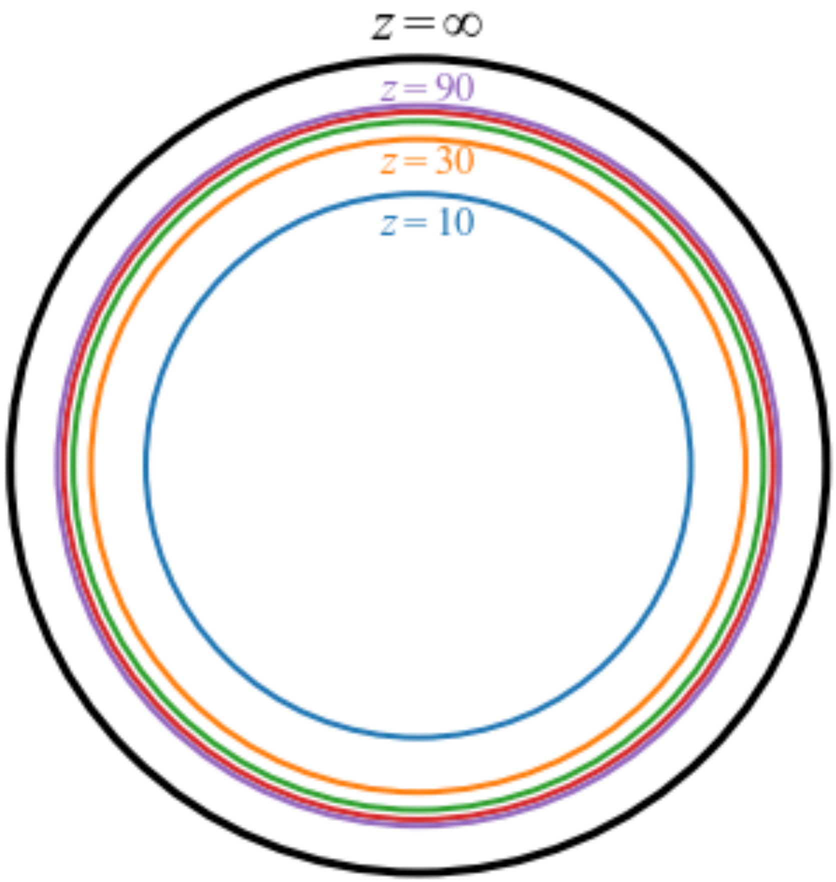
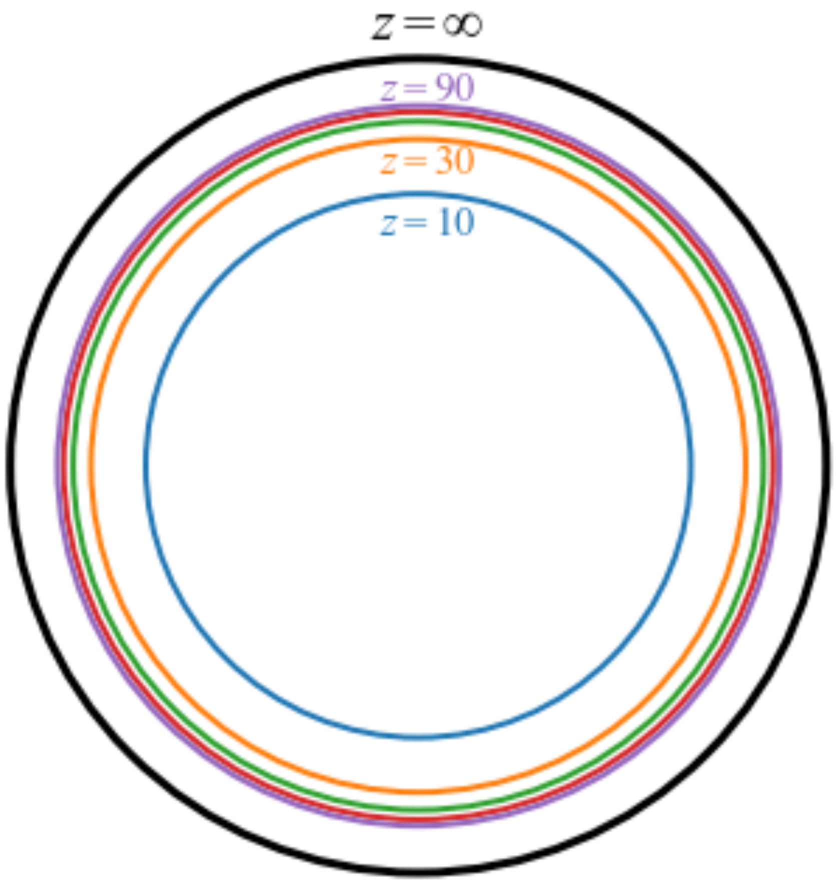
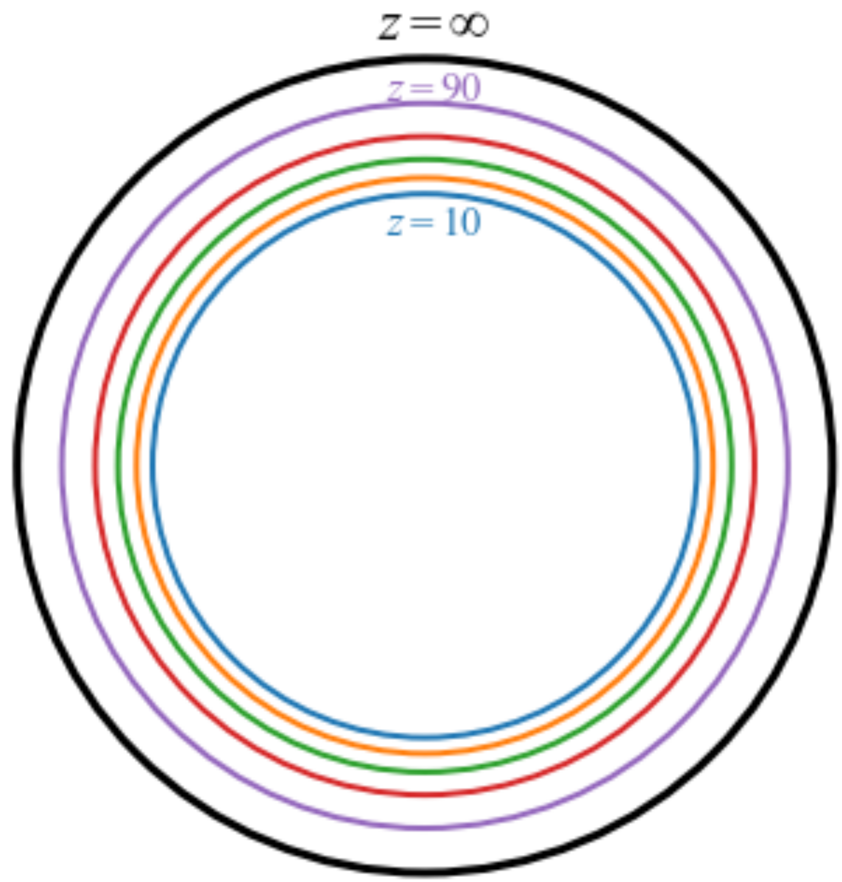
    - Cosmic variance not a problem anyway, and nobody to cross-correlate with!
    - Large elements may be unwieldy. Physical space limitations?
- Projections are conservative because of a drift-scan assumption.



Constant increments in z
in range 10 < z < 90



Constant increments in z in range $10 < z < 90$



Constant increments in frequency in range $10 < z < 90$

- At $z \sim 40$, a bandwidth of $B \sim 6\,\mathrm{MHz}$ corresponds to $\Delta z \sim 7$!

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    - Structure growth **must** be simultaneously considered when forming statistical quantities like the power spectrum

Take-home messages

- Rich astrophysical and cosmological information available beyond HERA by pushing redshift, sensitivity, and scale frontiers.
- 21cm surveys are much better suited for probing radial fluctuations than angular fluctuations.
- Sensitivity rather than cosmic variance will be the limiting factor; compact arrays are still advantageous.
- Astrophysics can act as an amplifier for cosmology.
- Simultaneously pushing the redshift, sensitivity, and scale frontiers is challenging, but with potentially great science rewards.