Cosmology at low z<0.2

Advances in Theoretical Cosmology in the light of data, Nordita
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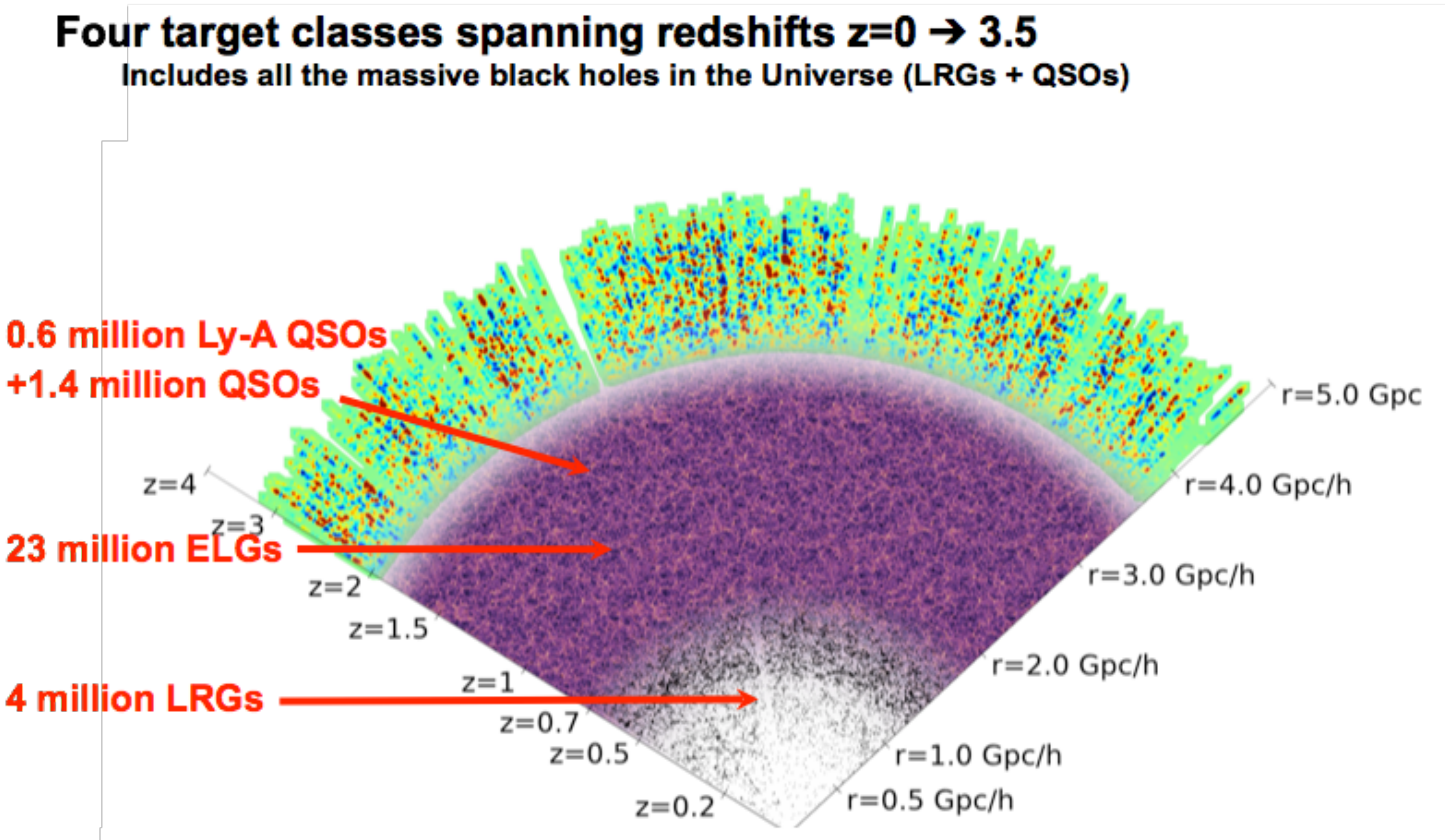
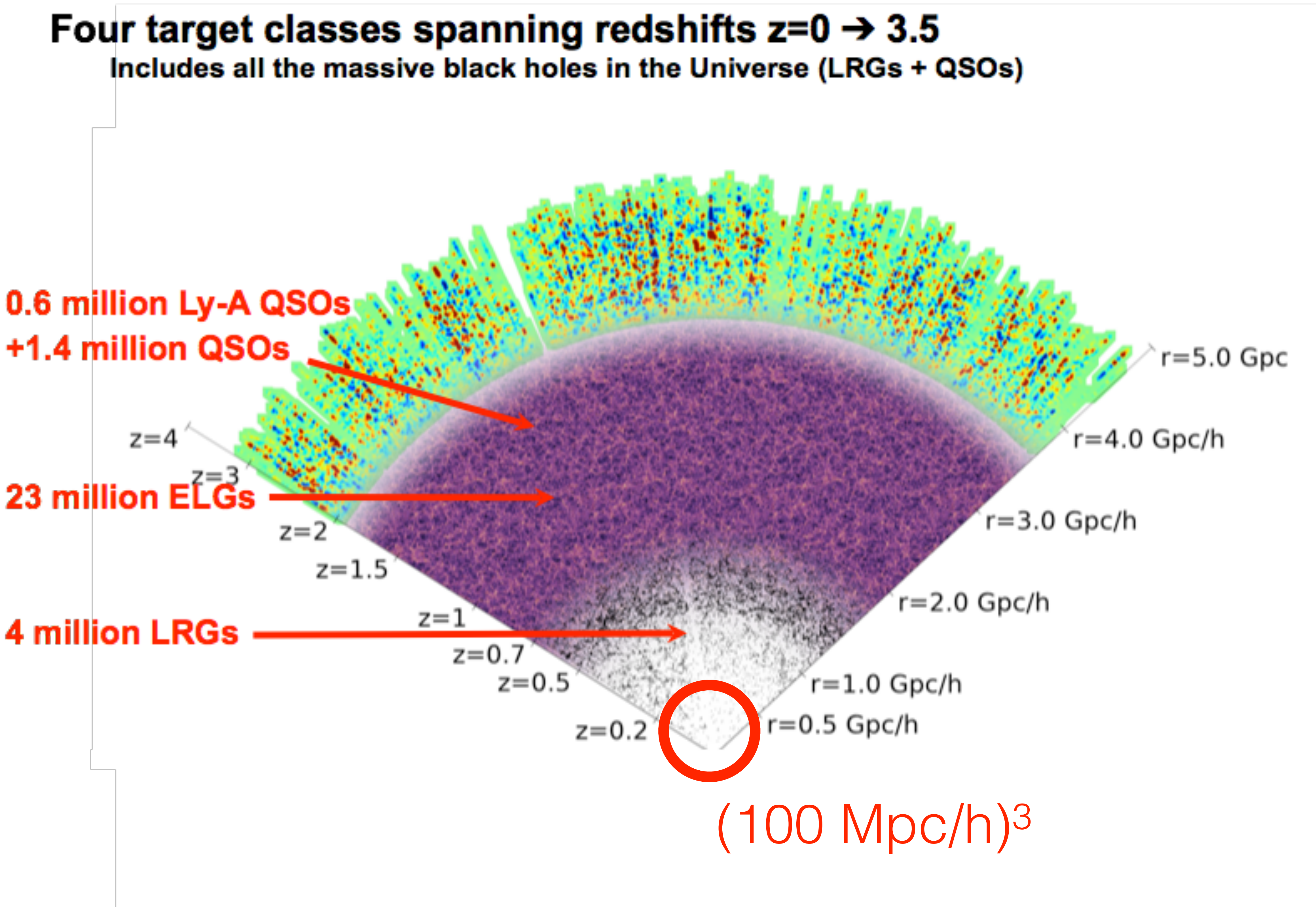
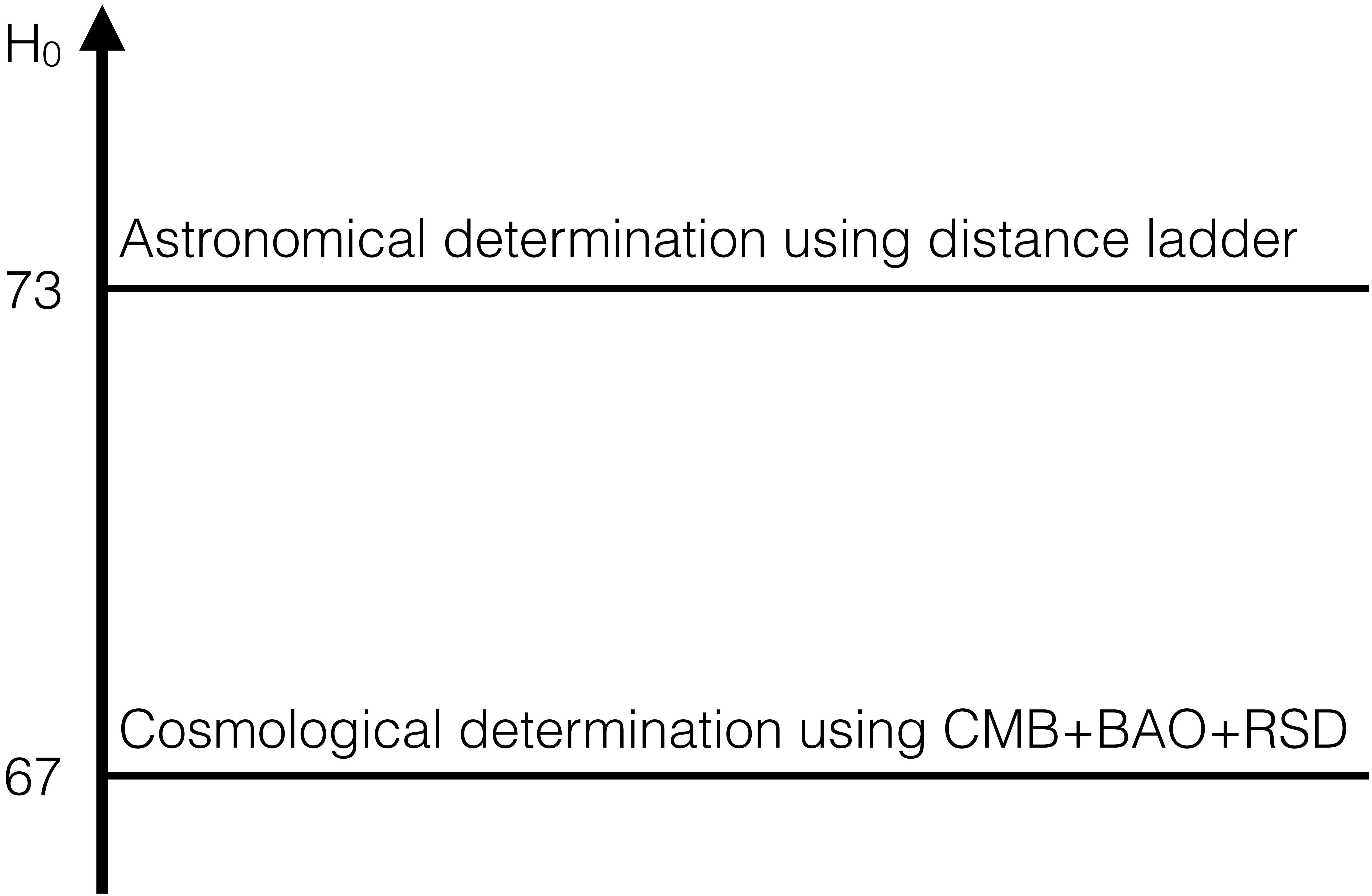
The future survey in precision



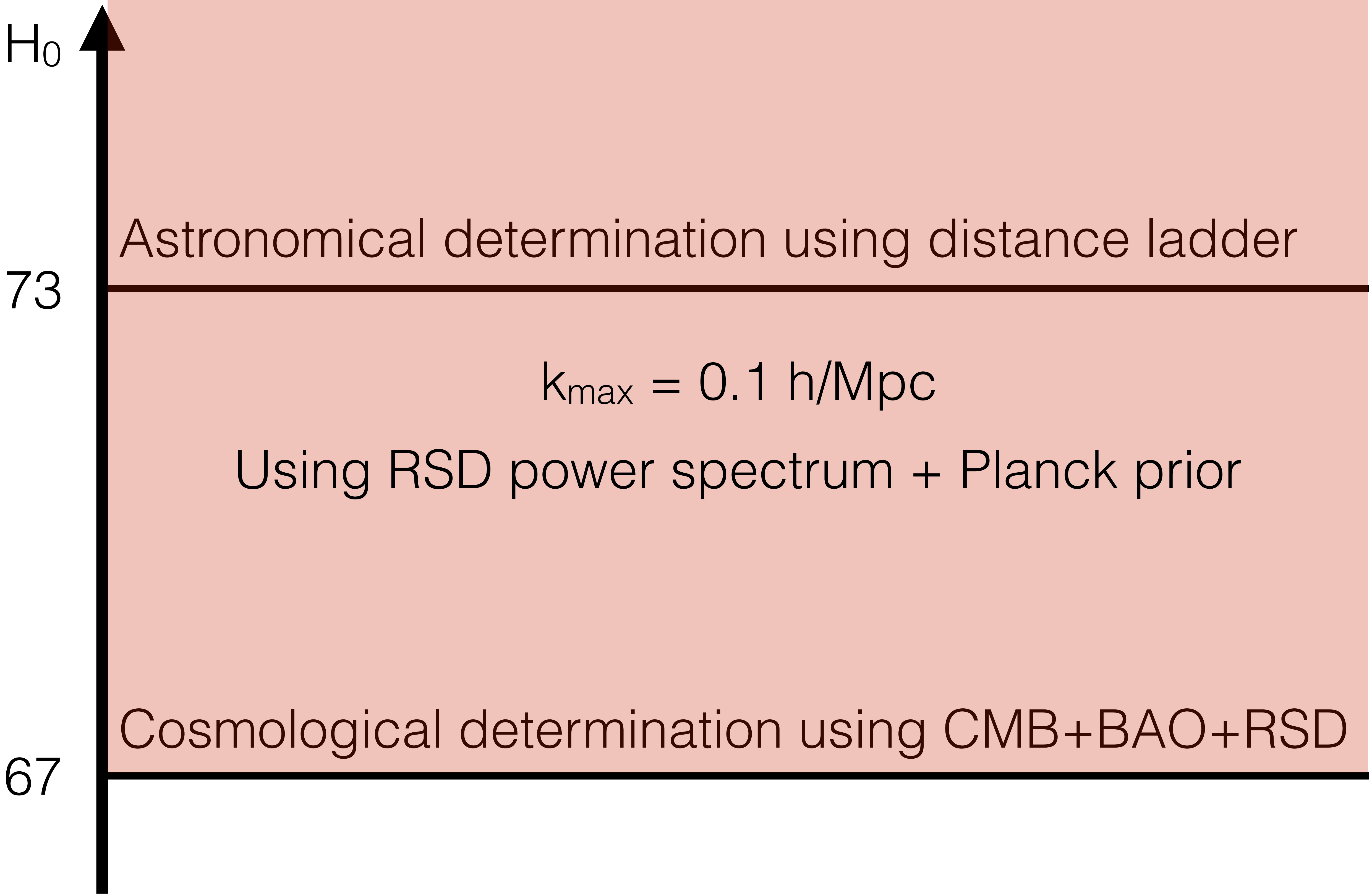
Dark time survey - the local universe



Astronomical H_0 vs Cosmological H_0



Astronomical H_0 vs Cosmological H_0



Mapping of clustering from real to redshift spaces

$$P_s(k,\boldsymbol{\mu}) = \int d^3x \, e^{ikx} \langle \boldsymbol{\delta\delta} \rangle$$

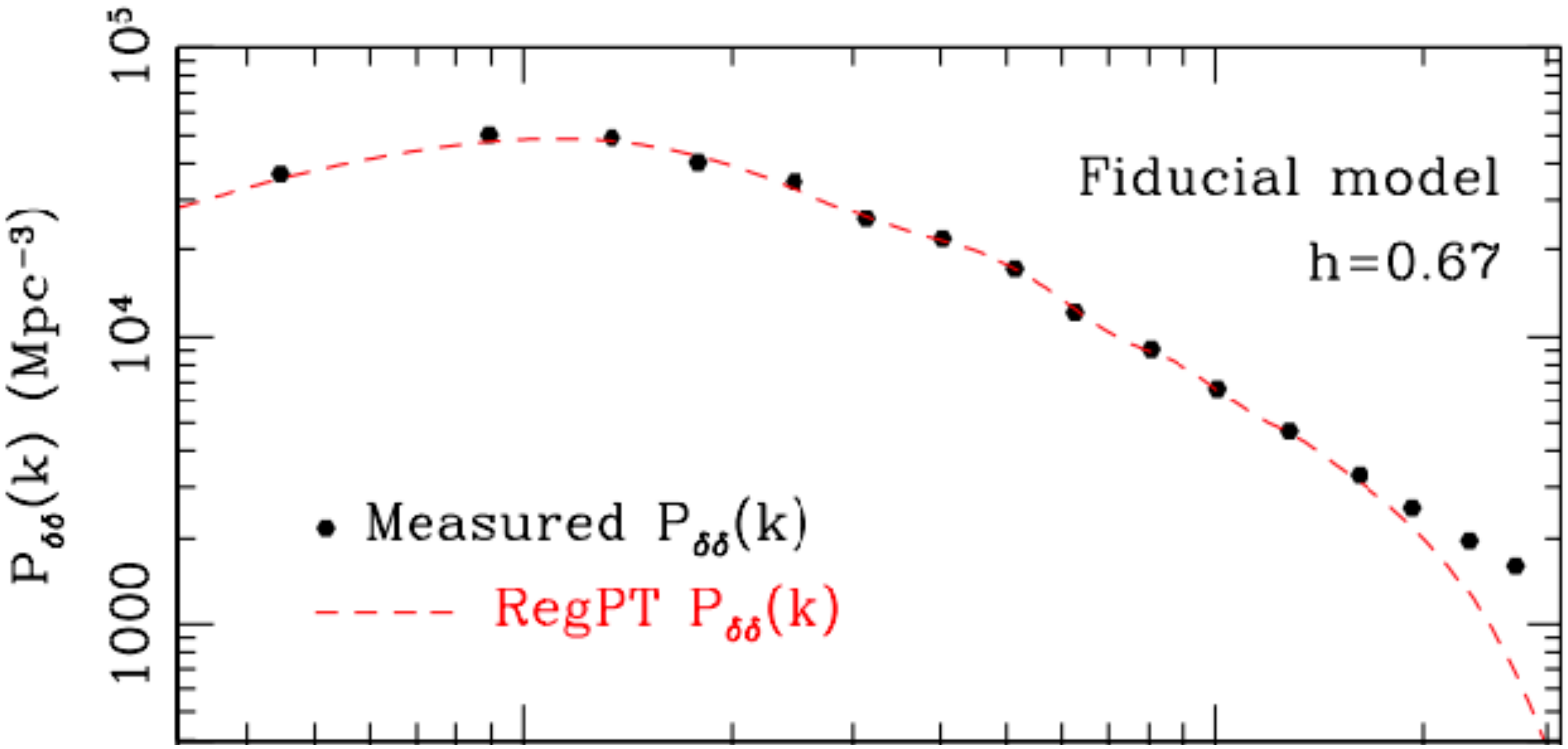
$$\Downarrow$$

$$P_s(k,\mu) = \int d^3x \, e^{ikx} \langle e^{jv} (\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta) \rangle$$

$$= \int d^3x \, e^{ikx} \exp\{\langle e^{jv} \rangle_c\} \, [\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta) \rangle_c + \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta) \rangle_c \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta) \rangle_c]$$

- We understand RSD as a mapping from real to redshift space including stochastic quantity of peculiar velocity
- The mapping contains the contribution from two point correlation functions depending on separation distance, such as the cross correlation of density and velocity and the velocity auto correlation.
- The mapping also contains the contribution from one point correlation function of peculiar velocity which can be given by a functional form in terms of velocity dispersion σ_p.

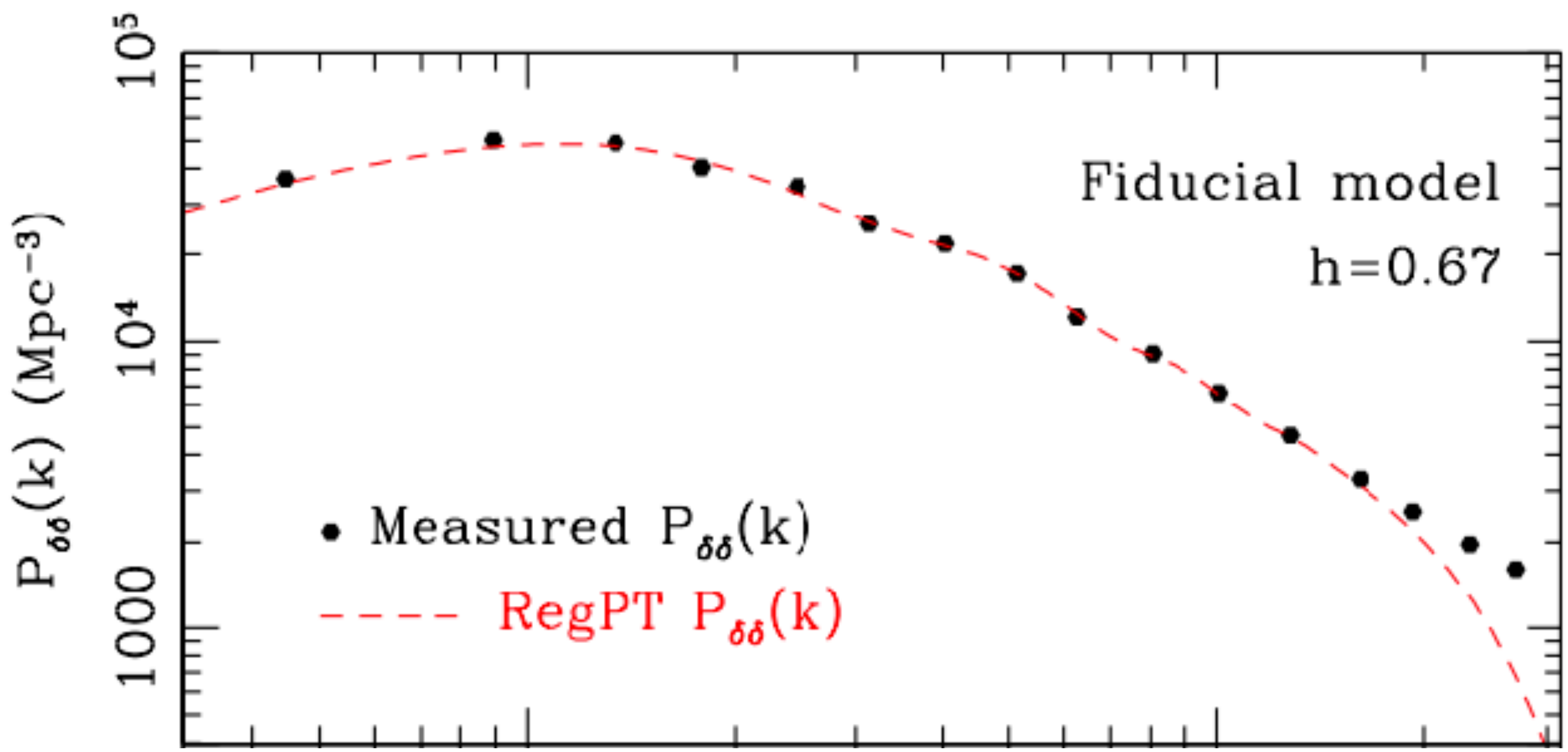
Non linear corrections



- We compare the theoretical predictions from RegPT and the measured spectrum of density fluctuations. Both are consistent up to quasi linear scale.

- As this correction is not relevant to RSD mapping, we will discuss it at later part of this talk when we need to explain the growth function projection.

Non linear corrections

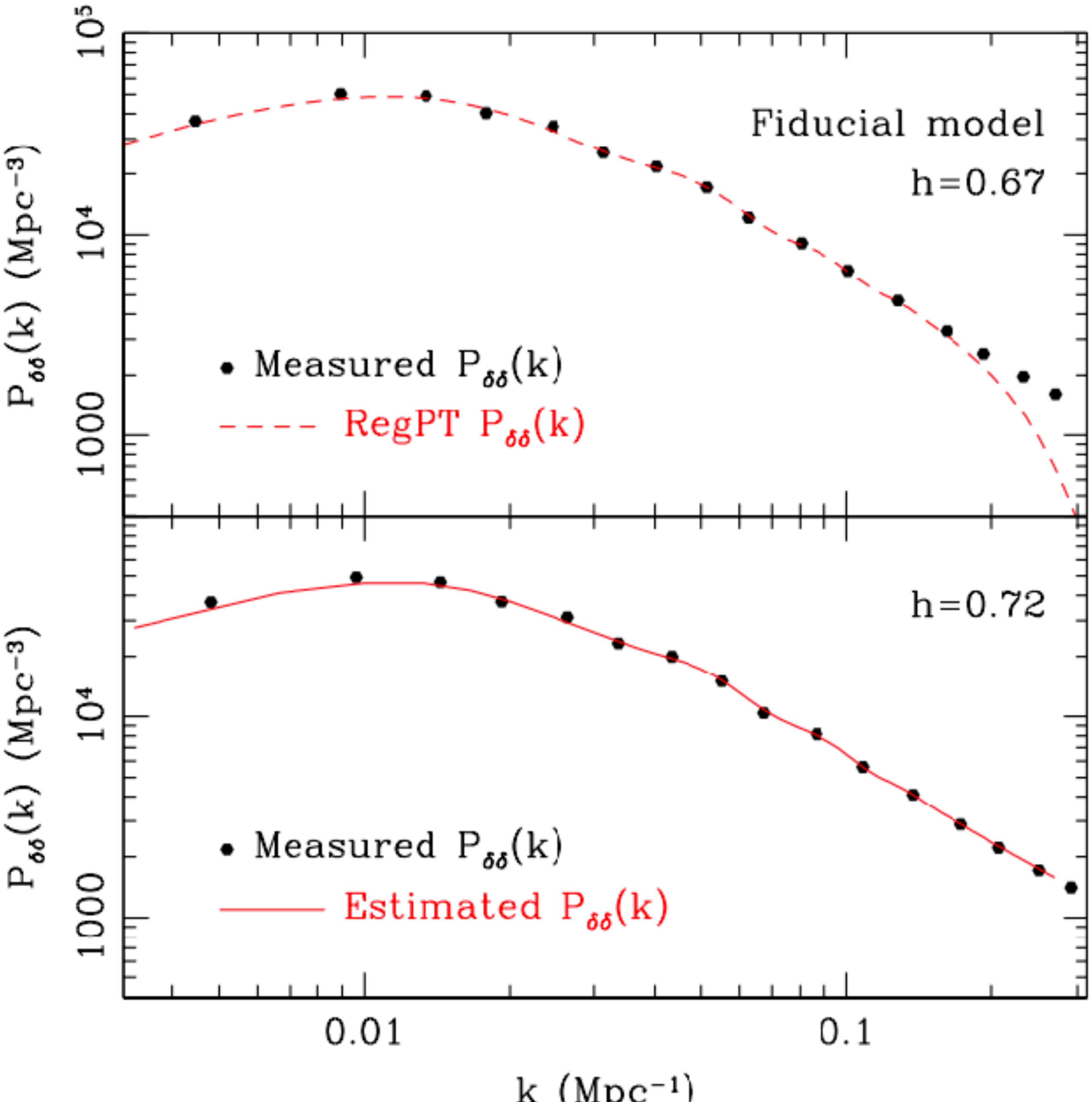


$$\bar{P}_{XY}(k,z) = \bar{P}^{\rm th}_{XY}(k,z) + \bar{P}^{\rm res}_{XY}(k,z),$$

$$\begin{aligned}\bar{P}_{XY}(k,z) &= \bar{\Gamma}^{(1)}_X(k,z)\bar{\Gamma}^{(1)}_Y(k,z)\bar{P}^i(k)\\ &+2\int\frac{d^3\vec{q}}{(2\pi)^3}\bar{\Gamma}^{(2)}_X(\vec{q},\vec{k}-\vec{q},z)\bar{\Gamma}^{(2)}_Y(\vec{q},\vec{k}-\vec{q},z)\bar{P}^i(q)\bar{P}^i(|\vec{k}-\vec{q}|)\\ &+6\int\frac{d^3\vec{p}d^3\vec{q}}{(2\pi)^6}\bar{\Gamma}^{(3)}_X(\vec{p},\vec{q},\vec{k}-\vec{p}-\vec{q},z)\bar{\Gamma}^{(3)}_Y(\vec{p},\vec{q},\vec{k}-\vec{p}-\vec{q},z)\bar{P}^i(p)\bar{P}^i(q)\bar{P}^i(|\vec{k}-\vec{p}-\vec{q}|),\end{aligned}$$

$$\begin{aligned}\bar{P}^{\rm res}_{XY} = \bar{G}_X\bar{G}_Y\bar{G}^4_\delta\Big\{&\left[\bar{\mathcal{O}}^{(1)}_{Y,5}+\text{higher}\right]\bar{P}^i + \left[\bar{\mathcal{O}}^{(1)}_{X,5}+\text{higher}\right]\bar{P}^i,\\ &+\int\left[\bar{\mathcal{O}}^{(2)}_{Y,4}\bar{F}^{(2)}_Y+\text{higher}\right]\bar{P}^i\bar{P}^i + \int\left[\bar{\mathcal{O}}^{(2)}_{X,4}\bar{F}^{(2)}_X+\text{higher}\right]\bar{P}^i\bar{P}^i,\\ &+\int\int\left[\bar{\mathcal{O}}^{(3)}_{Y,3}\bar{F}^{(3)}_Y+\text{higher}\right]\bar{P}^i\bar{P}^i\bar{P}^i + \int\int\left[\bar{\mathcal{O}}^{(3)}_{X,3}\bar{F}^{(3)}_X+\text{higher}\right]\bar{P}^i\bar{P}^i\bar{P}^i\Big\}.\end{aligned}$$

Non linear corrections



The contribution from two point correlations

$$P_s = \int d^3x\, e^{ikx} \exp\{\langle e^{jv}\rangle_c\}\, [\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c+\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c]$$

- The contribution from the cross correlation between density and velocity fields

$$\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c+\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

$$= j^0 \langle(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

$$+ j^1\langle v(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

$$+ j^2\langle v(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c\langle v(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

$$+ j^2\langle vv(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

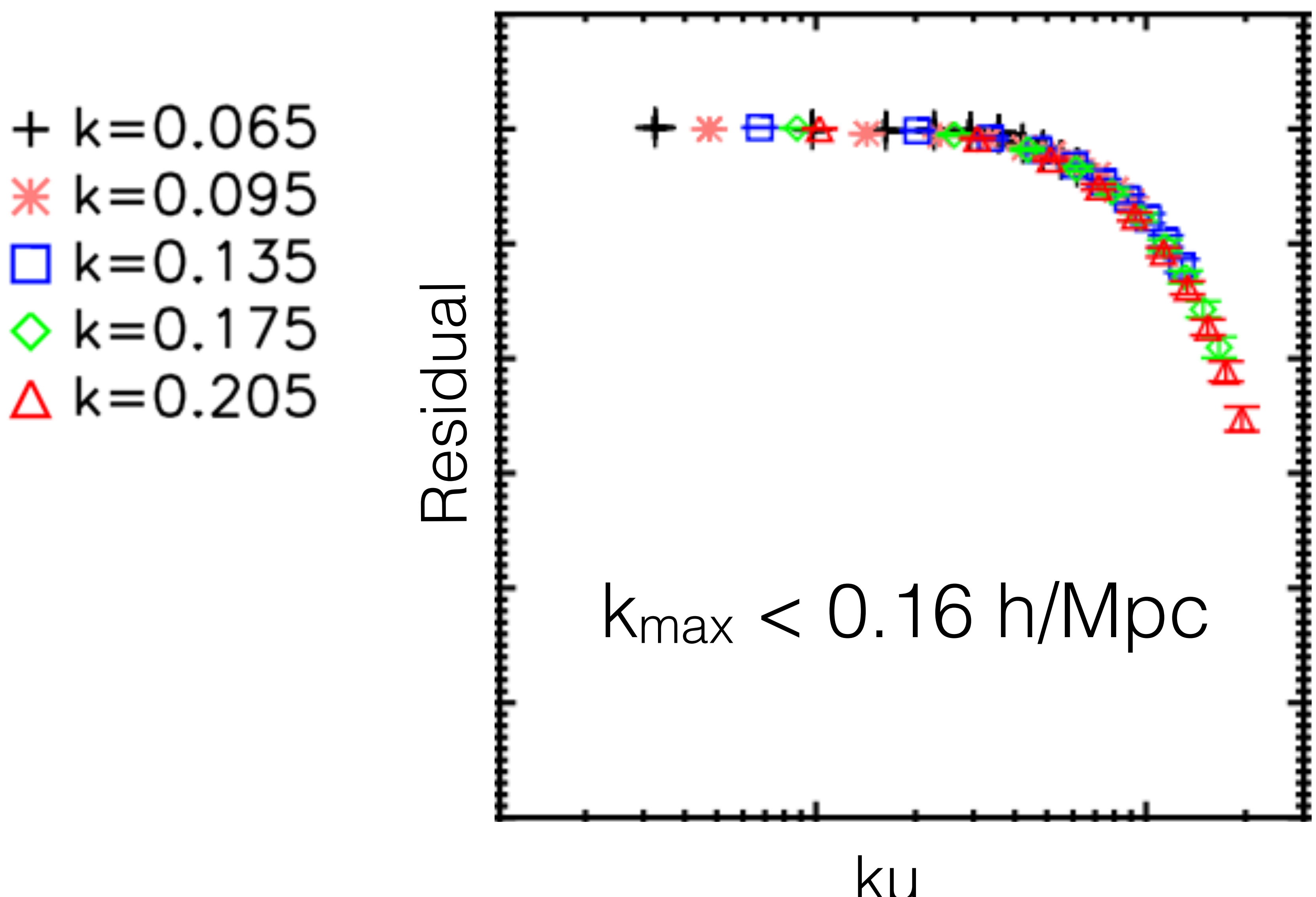
$$+ j^2\langle vv\rangle_c\langle(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c$$

$$+ O(> j^3)$$

The contribution from two point correlations

$D_{1pt} = P_s(k,\mu)/[P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$

- The residual term which is the subtraction of the measured spectrum by the perturbed terms including halo density fluctuations is well fitting to Gaussian FoG function as well



The contribution from one point correlations

$$P_s = \int d^3x\, e^{ikx} \exp\{\langle e^{jv}\rangle_c\} \left[\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c + \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c\right]$$

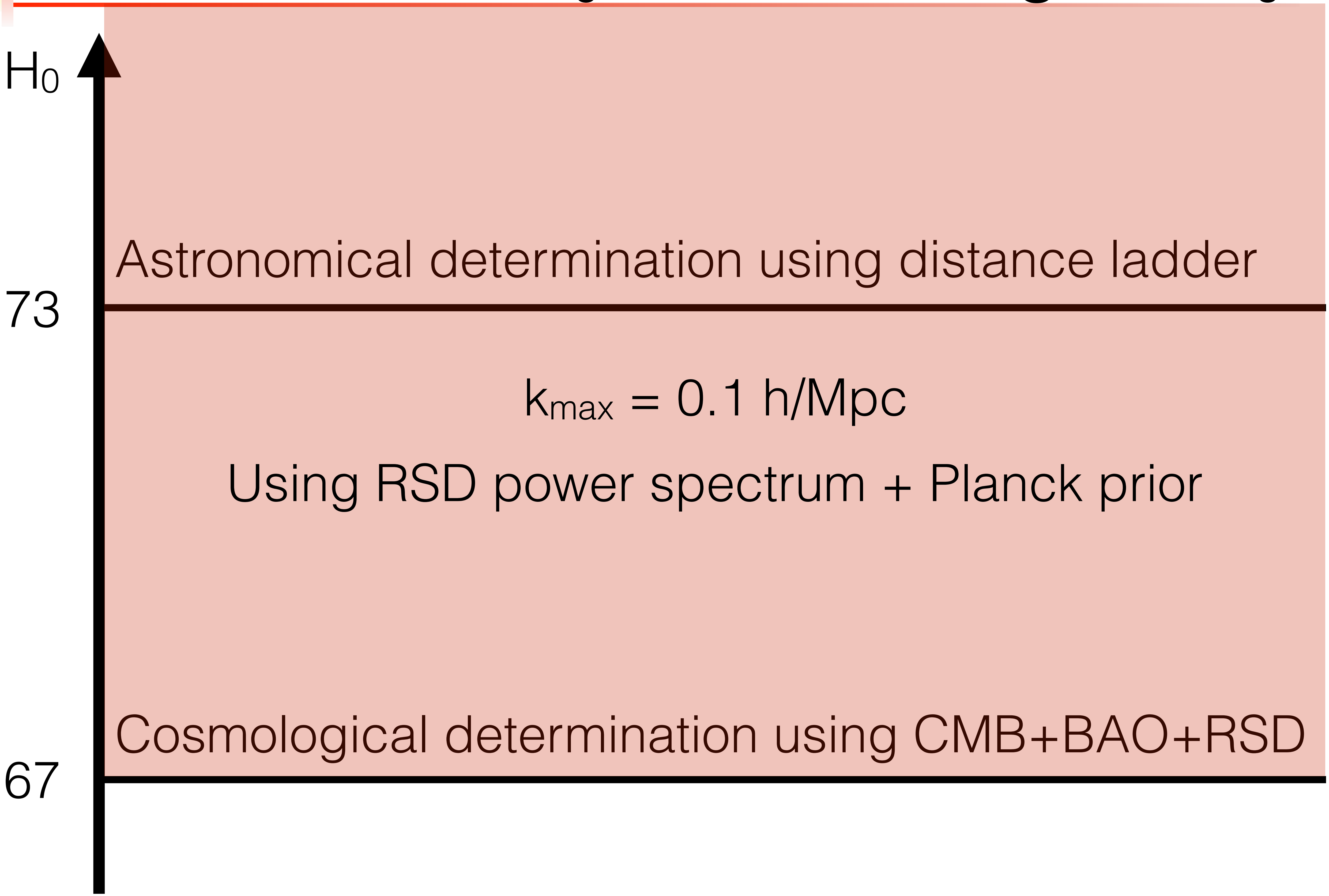
$$\Downarrow$$

$$P_s = D_{1pt}(k\boldsymbol{\mu}\sigma_p) \int d^3x\, e^{ikx}[P_{\delta\delta}(k) + 2\boldsymbol{\mu}^2 P_{\delta\Theta}(k) + \boldsymbol{\mu}^4 P_{\Theta\Theta}(k) + A(k,\boldsymbol{\mu}) + B(k,\boldsymbol{\mu}) + T(k,\boldsymbol{\mu}) + F(k,\boldsymbol{\mu})]$$

- The residual one point correlation function contribution can be identified as FoG effect, and it is also expanded into the infinite loop in terms of σ_p

$$D_{\rm 1pt}^{\rm FoG}(k\mu) = \exp\left\{ j_1^2\sigma_z^2 + 2\sum_{n=2}^{\infty} j_1^{2n}\sigma_z^{2n}\frac{K_{2n}}{(2n)!}\right\}$$

Astronomical H_0 vs Cosmological H_0



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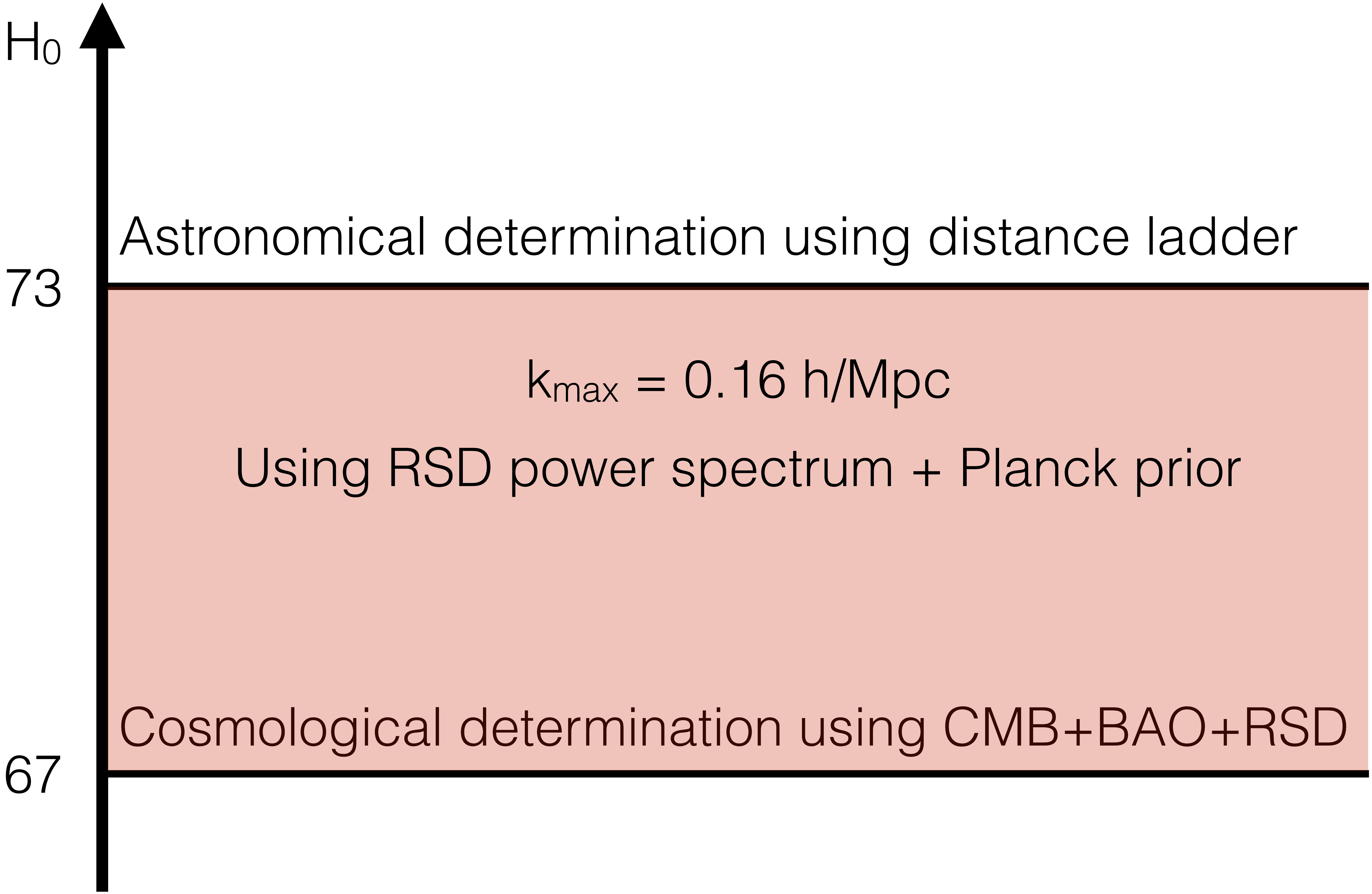


Full covariance approach

Fisher matrix is given by

$$F_{\alpha\beta} = \Sigma_k \Sigma_{k1k2k3} (\partial S/\partial p_\alpha)\, C^{-1}\, (\partial S/\partial p_\beta)$$

where the vector field S is given by

$$S = \begin{pmatrix} P(k,\mu) \\ B(k_1,k_2,k_3,\mu_1,\mu_2) \end{pmatrix}$$

The full covariance matrix is given by,

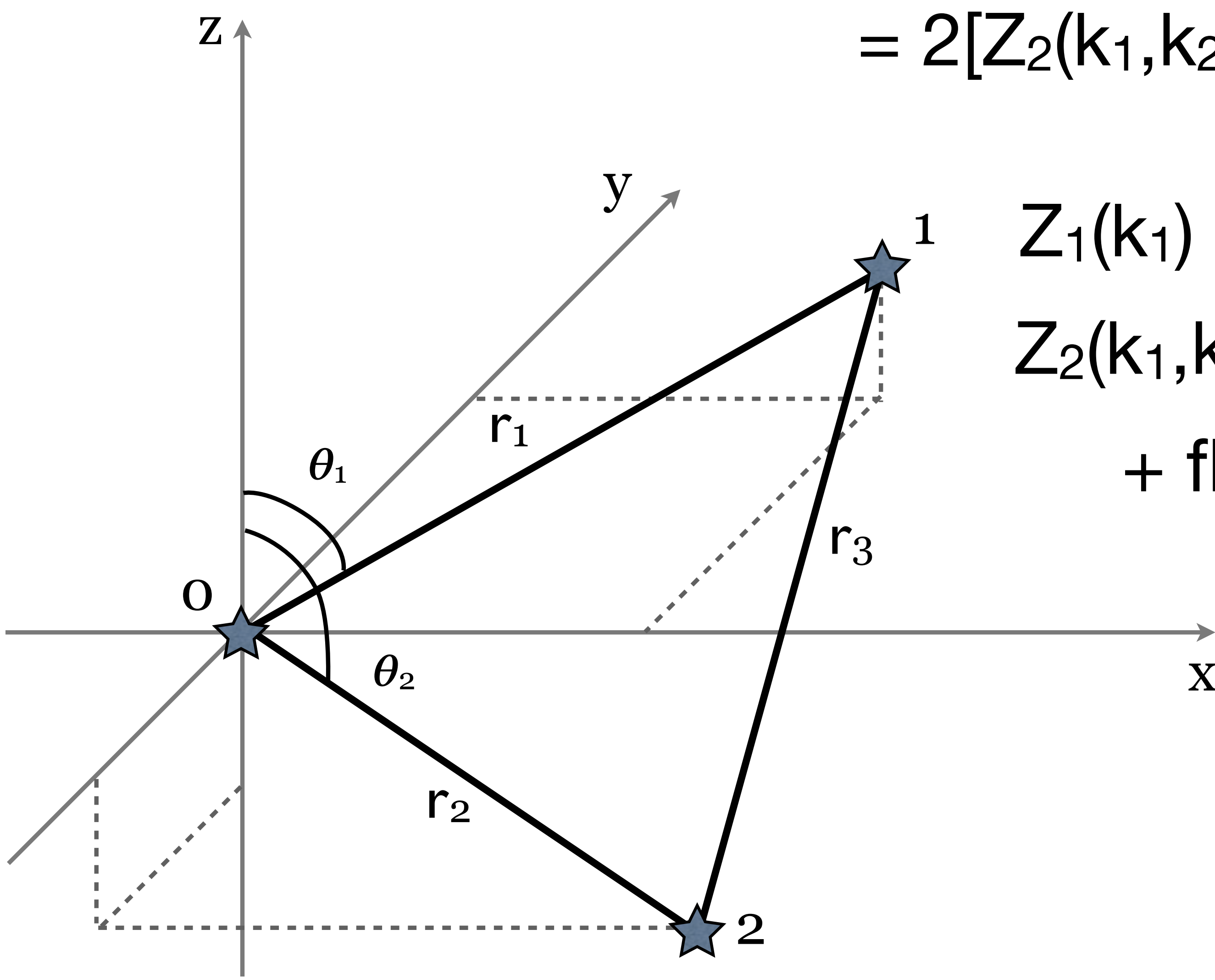
$$C^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BB}^{-1}M & C_{BB}^{-1}+C_{BB}^{-1}C_{Bp}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

This full covariance calculation is performed for DESI forecast.

Bispectrum in redshift space

$$B(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2) = D^{B}{}_{FoG}\, B^{PT}(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2)$$

$$B^{PT}(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2)$$
$$= 2[Z_2(k_1,k_2)Z_1(k_1)Z_2(k_2)P(k_1)P(k_2) + \text{cyclic}]$$



$$Z_1(k_1) = b+f\boldsymbol{\mu}_1{}^2$$

$$Z_2(k_1,k_2) = b_2/2 + bF_2 + f\boldsymbol{\mu}_{12}G_2$$
$$+ fk_{12}\boldsymbol{\mu}_{12}/2[\boldsymbol{\mu}_1/k_1Z_2(k_2)+\boldsymbol{\mu}_1/k_1Z_2(k_2)]$$

Sabiu, YSS 2016 prepared

YSS, Taruya, Akira 2015

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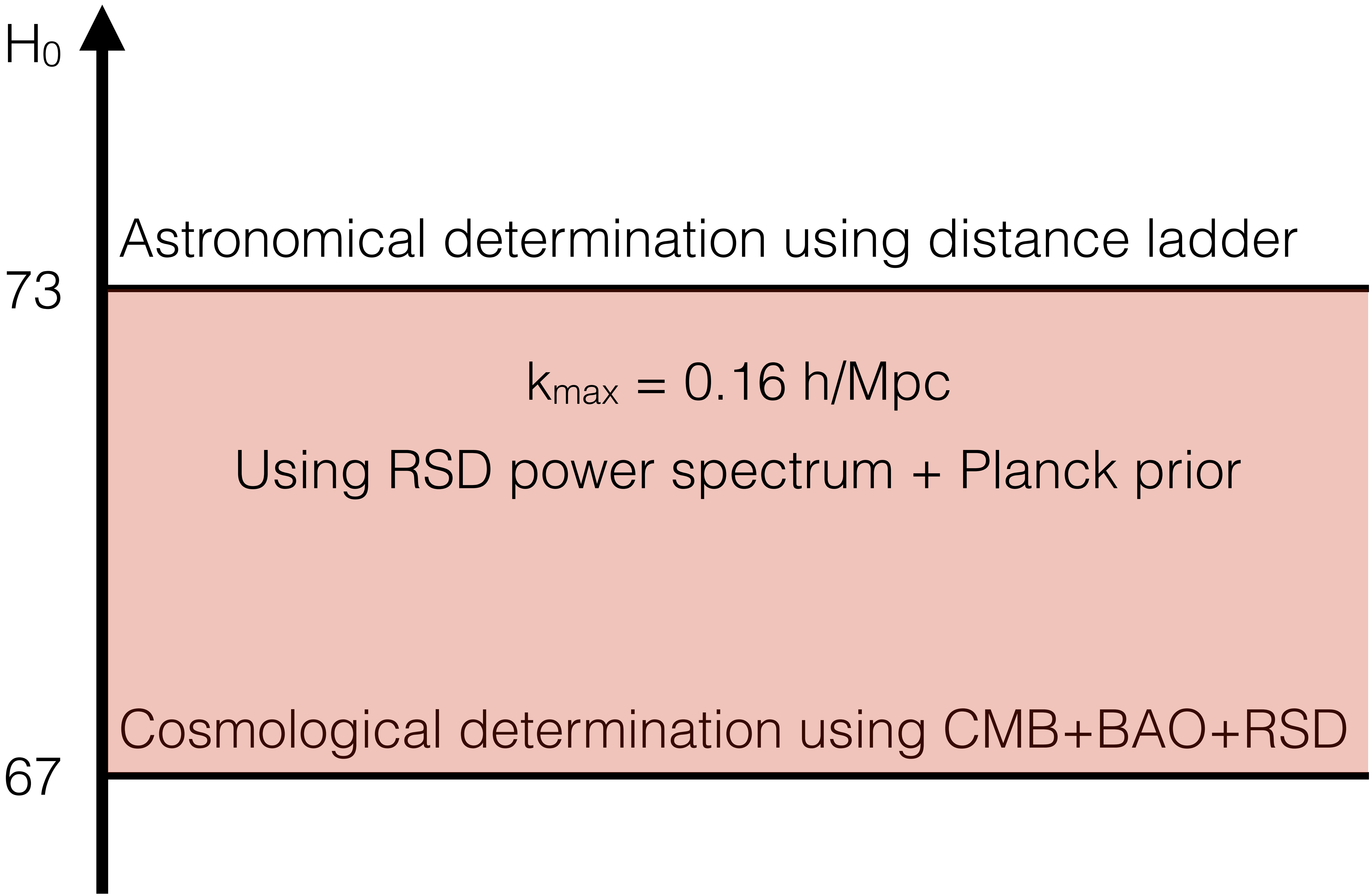
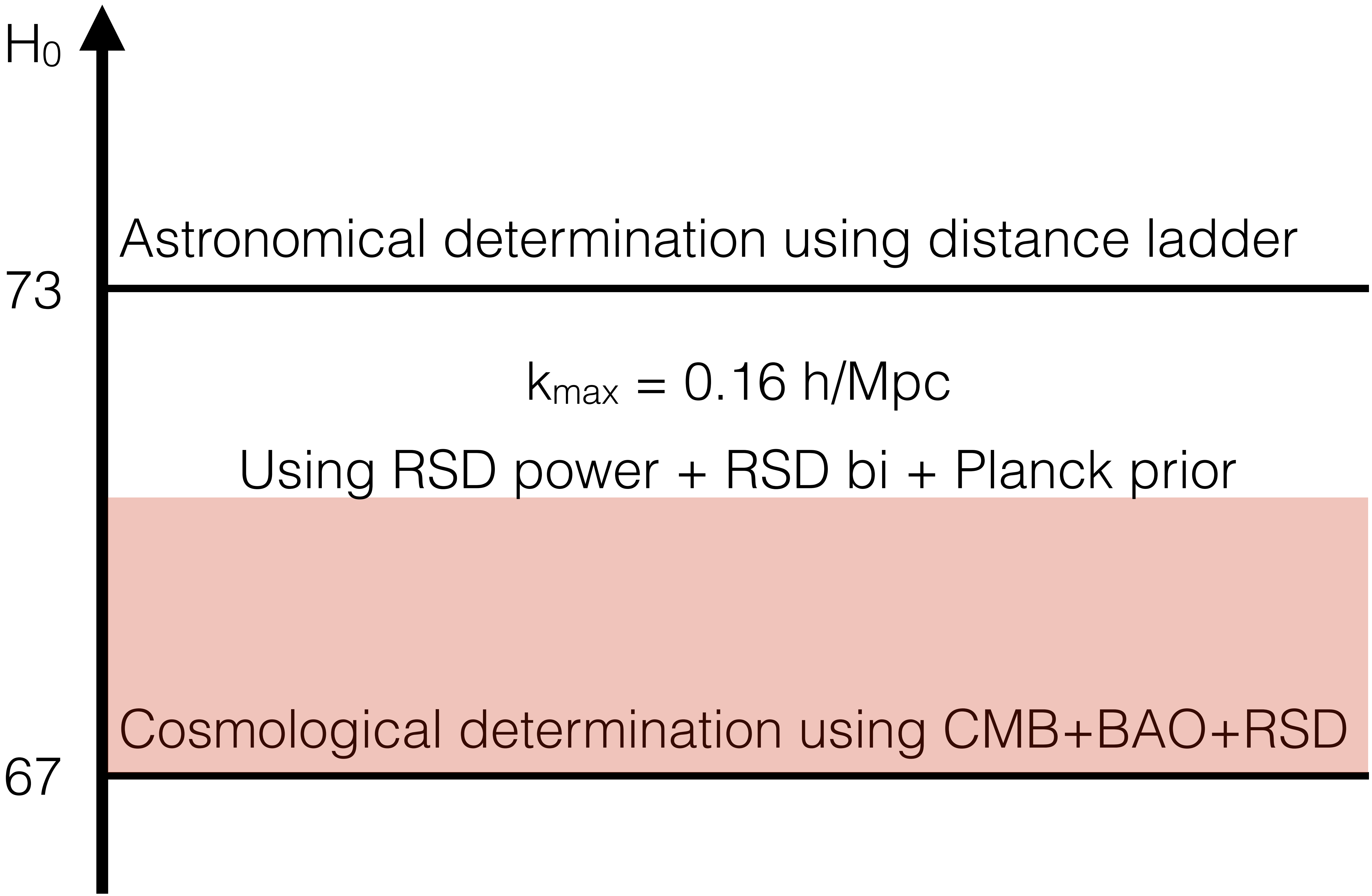
Astronomical H_0 vs Cosmological H_0



Astronomical H_0 vs Cosmological H_0



Challenges in RSD bispectrum

First order (equivalent to Kaiser term)

$$
\begin{aligned}
&\Big[\langle\Delta\Delta'\Delta''\rangle_c\\
&+j_1\left(\langle V\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c\right)\\
&+j_2\left(\langle V'\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c\right)
\end{aligned}
$$

Second order

$$
\begin{aligned}
&+j_1j_2(\langle VV'\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle VV'\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle VV'\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle VV'\Delta\rangle_c\\
&\quad+\langle V\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle V'\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle V\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle V'\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c\\
&\quad+\langle V\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c+\langle V'\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c)\\
&+j_1^2(\frac{1}{2}\langle V^2\Delta\Delta'\Delta''\rangle_c+\frac{1}{2}\langle\Delta\Delta'\rangle_c\langle V^2\Delta''\rangle_c+\frac{1}{2}\langle\Delta''\Delta\rangle_c\langle V^2\Delta'\rangle_c+\frac{1}{2}\langle\Delta'\Delta''\rangle_c\langle V^2\Delta\rangle_c\\
&\quad+\langle V\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle V\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c+\langle V\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c)\\
&+j_2^2(\frac{1}{2}\langle V'^2\Delta\Delta'\Delta''\rangle_c+\frac{1}{2}\langle\Delta\Delta'\rangle_c\langle V'^2\Delta''\rangle_c+\frac{1}{2}\langle\Delta''\Delta\rangle_c\langle V'^2\Delta'\rangle_c+\frac{1}{2}\langle\Delta'\Delta''\rangle_c\langle V'^2\Delta\rangle_c\\
&\quad+\langle V'\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle V'\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle V'\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c)\Big]
\end{aligned}
$$

FoG term

$$
\begin{aligned}
&\exp\Big\{\frac{1}{2}(j_1^2+j_2^2+j_3^2)\sigma_z^2-j_1^2\langle u_z(\vec{r})u_z(\vec{r}')\rangle_c-j_2^2\langle u_z(\vec{r})u_z(\vec{r}'')\rangle_c\\
&+j_1j_2\left[\langle u_z(\vec{r}')u_z(\vec{r}'')\rangle_c-\langle u_z(\vec{r})u_z(\vec{r}')\rangle_c-\langle u_z(\vec{r})u_z(\vec{r}'')\rangle_c\right]\Big\}
\end{aligned}
$$

Conclusion

- The cosmology at the local Universe will be an interesting target to pursue, as the conflict with astronomical determination is outstanding
- Although the total volume is small, we might be able to extend the determination toward non-linear regime
- The upper bound of scale will be mainly constrained by RSD mapping, in which higher order correlation functions should be computed in accuracy
- The combination of power spectrum and bispectrum will enhance the detectability significantly, but the precise RSD mapping formulation will be difficult to be computed
- We are able to make cosmological test at our local universe through highly non-linear regime, but it will be challenging. We have to know whether it is indeed valuable or not