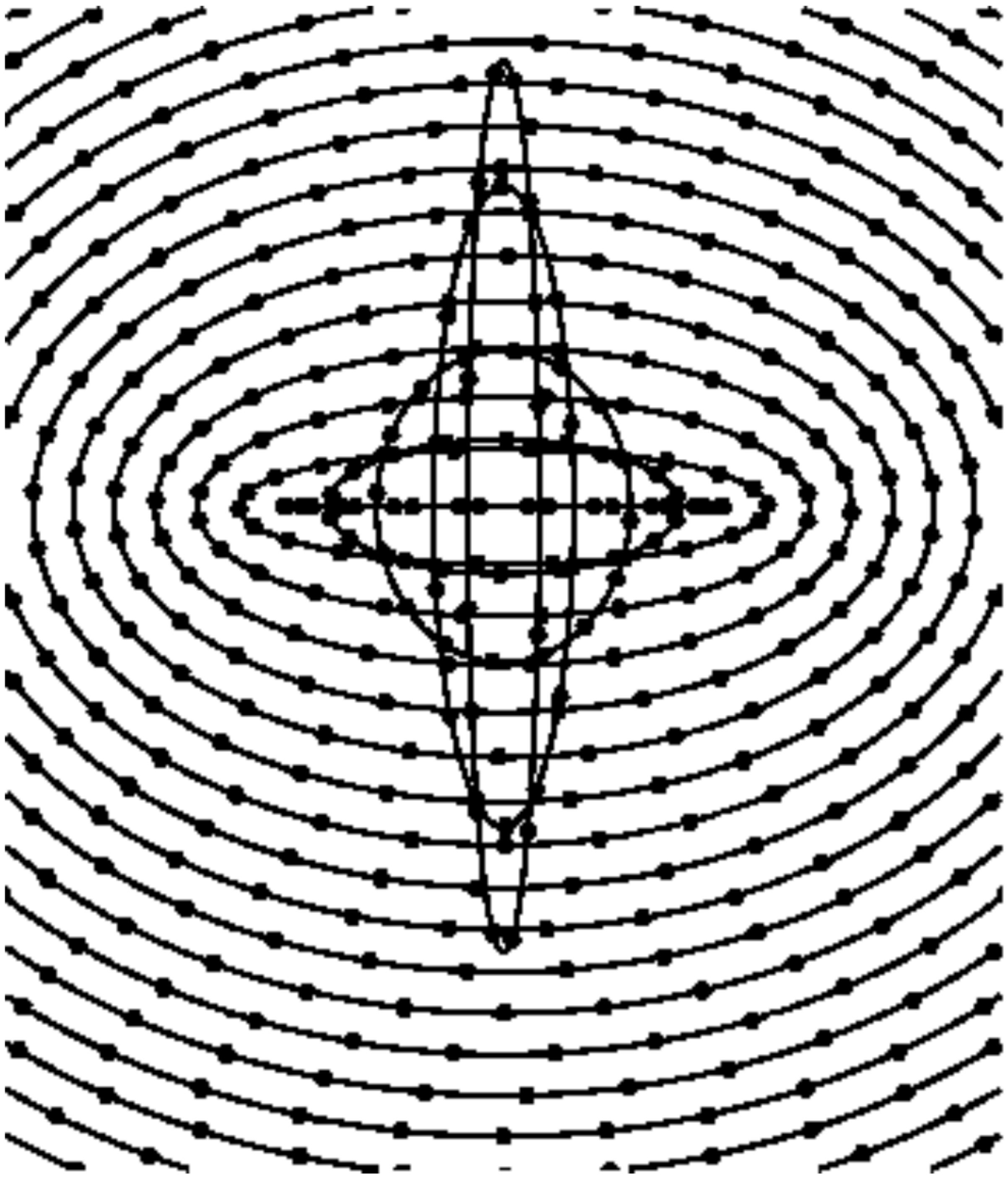
RSD beyond the distant-observer limit

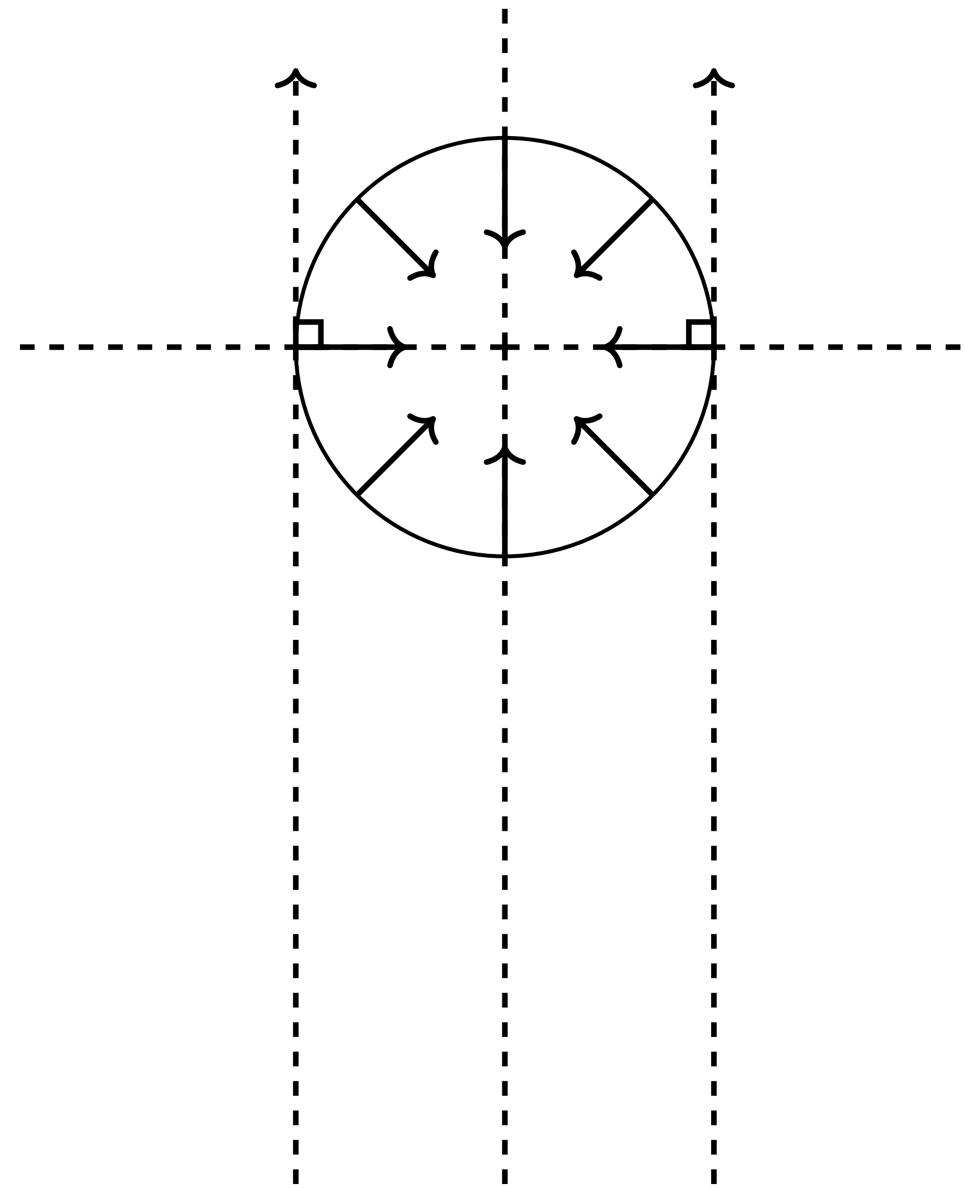
Lawrence Dam
U. Geneva

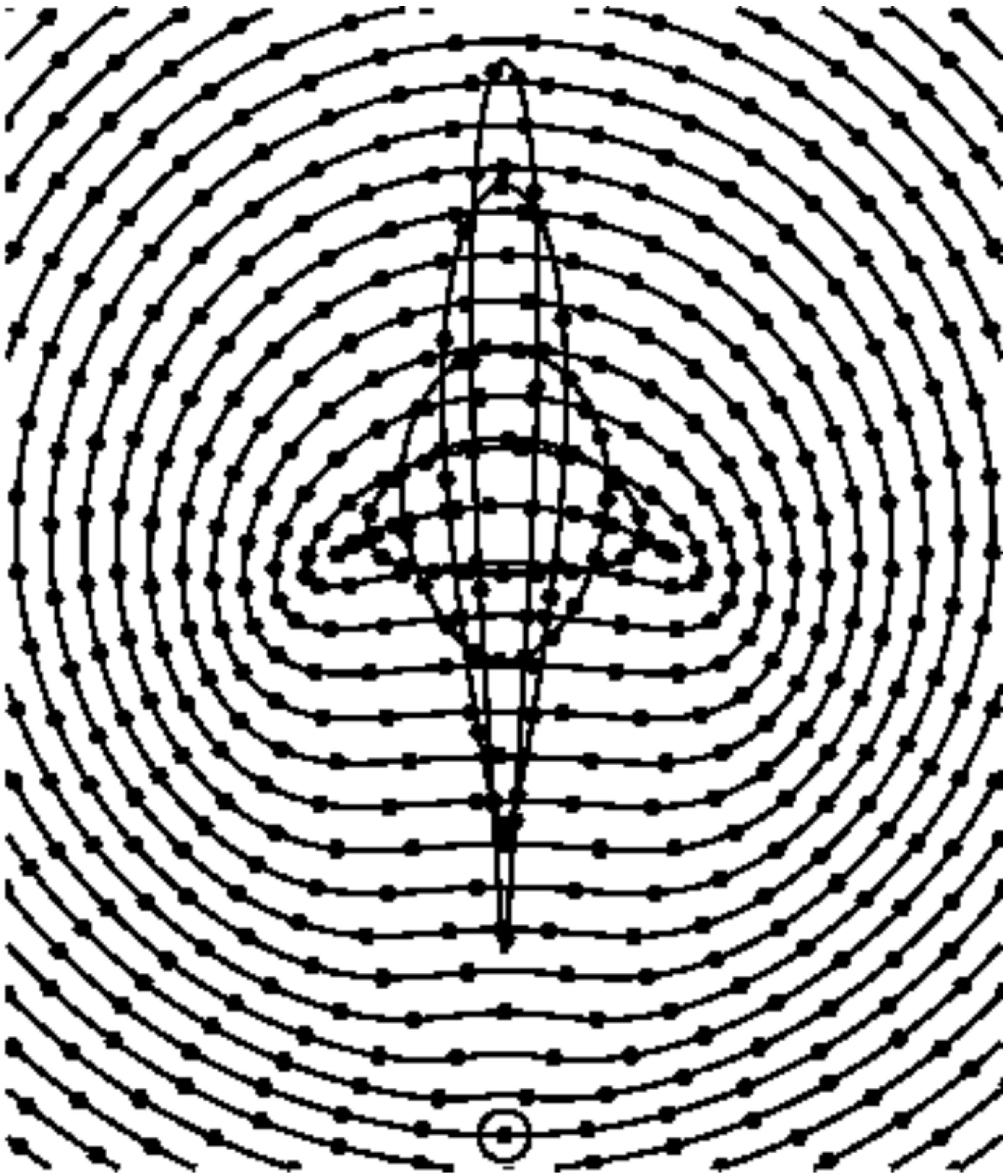
based on arXiv:2307.01294
w/ Camille Bonvin

Theoretical modelling of large-scale structure, June 2024

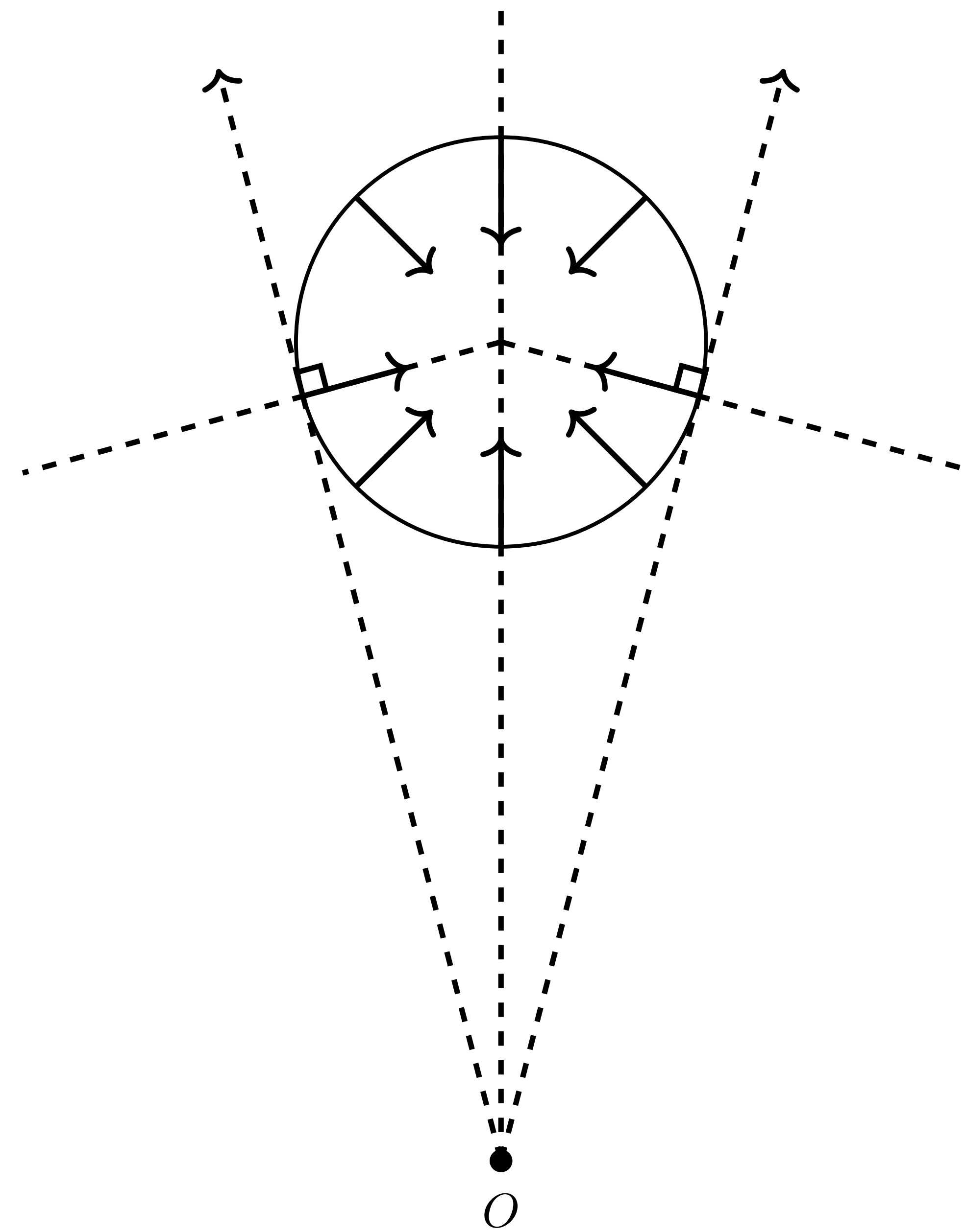


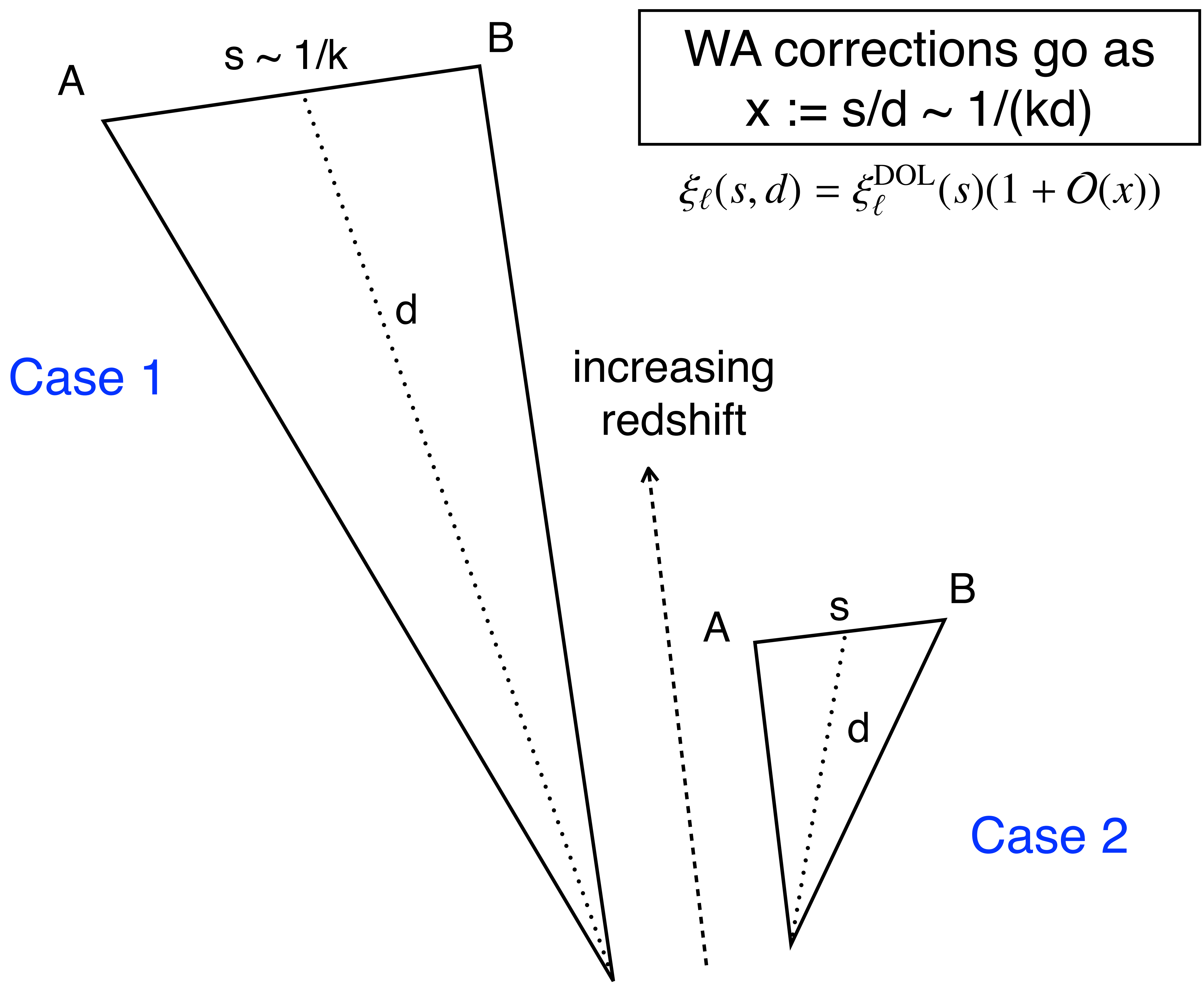
Hamilton 1998





Hamilton 1998

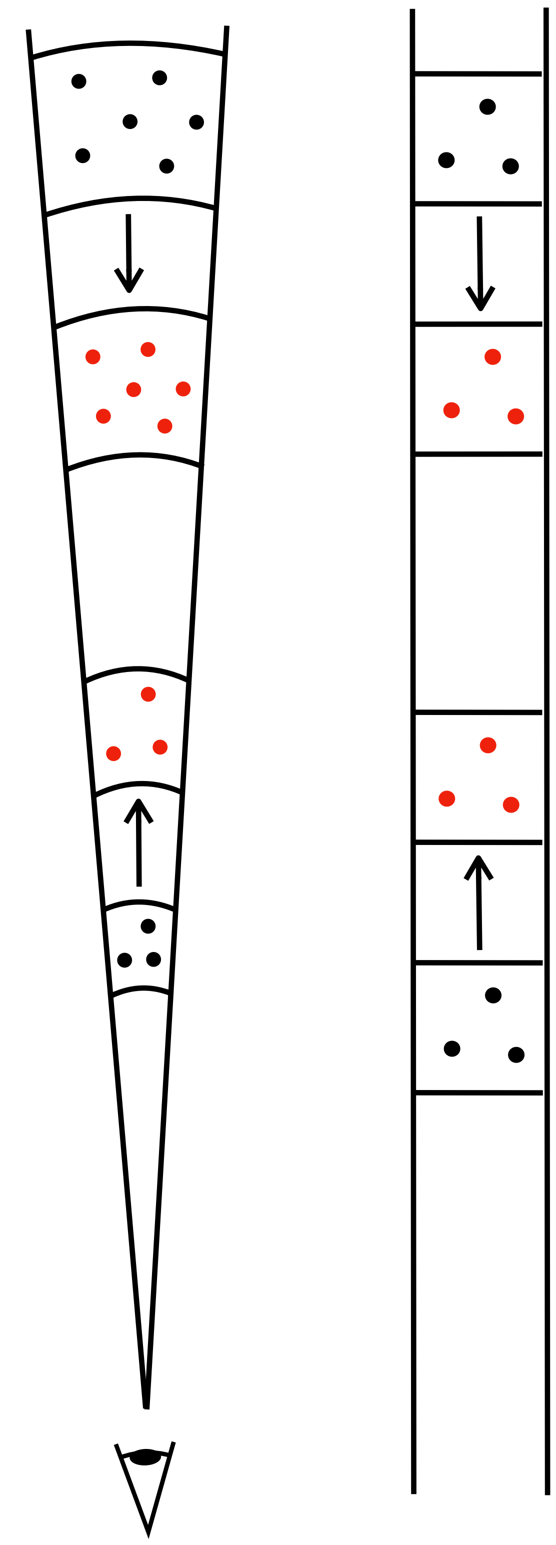



WA corrections go as
x := s/d ~ 1/(kd)
$\xi_\ell(s,d) = \xi_\ell^{\mathrm{DOL}}(s)(1+\mathcal{O}(x))$
A
B
s ~ 1/k
d
Case 1
increasing
redshift
A
B
s
d
Case 2

Linear theory

Kaiser (1987)

$$\Delta_s(\mathbf{r}) = \Delta_r(\mathbf{r}) - \left(2 + \frac{d\ln\phi}{d\ln r}\right)\left[\frac{U(\mathbf{r}) - U(\mathbf{0})}{r}\right] - \frac{dU}{dr}$$



Linear theory

Kaiser (1987)

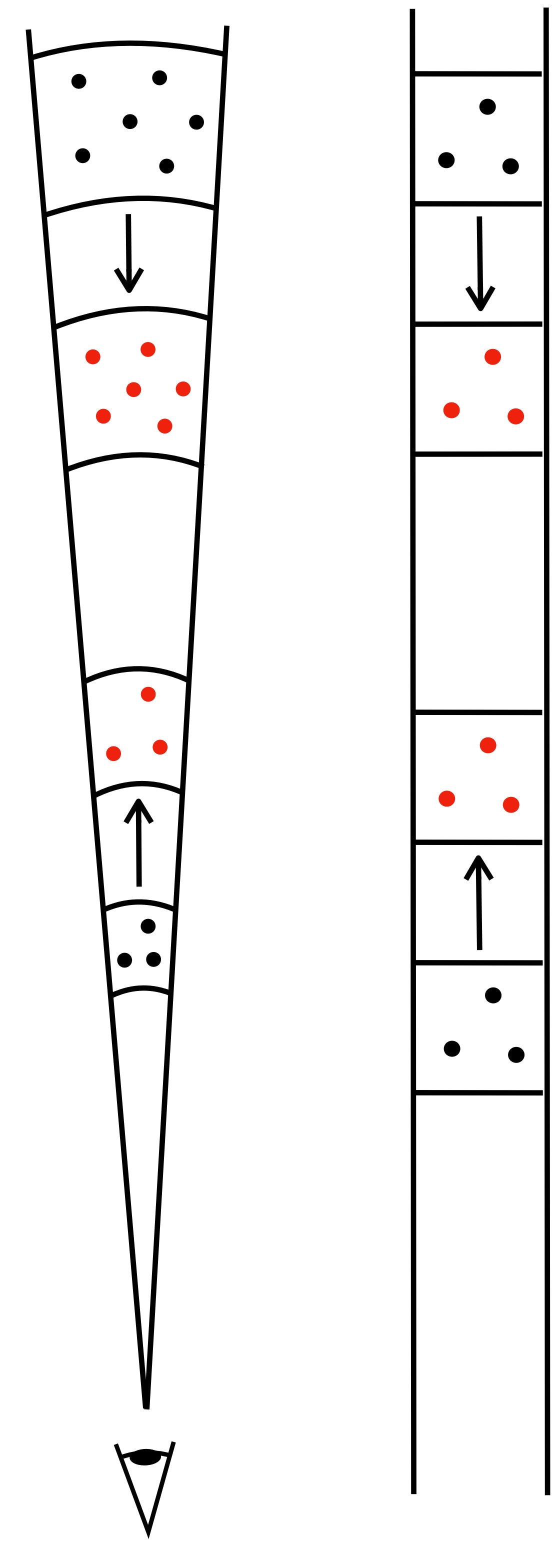
$$\Delta_s(\mathbf{r}) = \Delta_r(\mathbf{r}) - \left(2 + \frac{d\ln\phi}{d\ln r}\right)\left[\frac{U(\mathbf{r}) - U(\mathbf{0})}{r}\right] - \frac{dU}{dr}$$

or $\delta_s = \delta - \nabla \cdot \mathbf{U}$

Since $\mathbf{U} = U\,\hat{\mathbf{r}}$ is purely radial

$$\nabla \cdot \mathbf{U} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 U) = \frac{\partial U}{\partial r} + \frac{2}{r}U$$

Note $U \sim \delta/k$ so $U/r \sim \delta/(kr) \sim x\delta$



Linear theory

Kaiser (1987)

$$\Delta_s(\mathbf{r})=\Delta_r(\mathbf{r})-\left(2+\frac{d\ln\phi}{d\ln r}\right)\left[\frac{U(\mathbf{r})-U(\mathbf{0})}{r}\right]-\frac{dU}{dr}$$

or $\delta_s = \delta - \nabla\cdot\mathbf{U}$

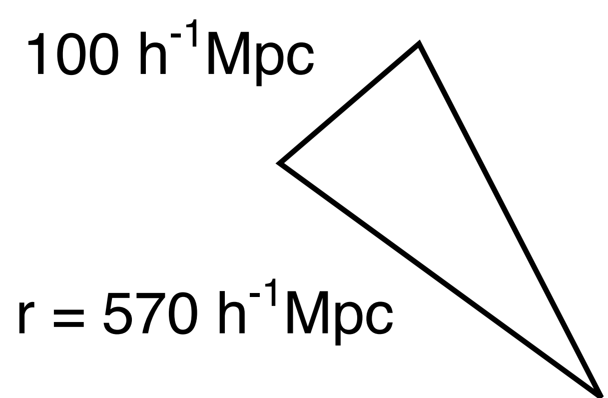
Since $\mathbf{U} = U\,\hat{\mathbf{r}}$ is purely radial

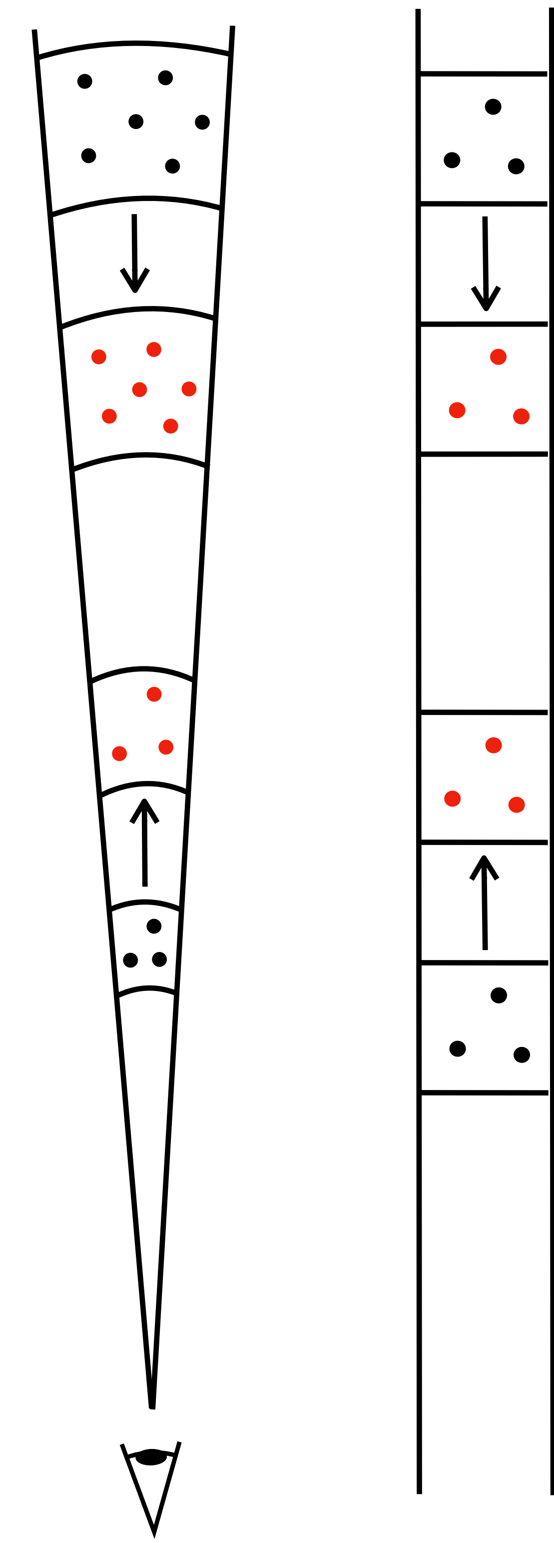
$$\nabla\cdot\mathbf{U} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 U) = \frac{\partial U}{\partial r} + \frac{2}{r}U$$

Note $U \sim \delta/k$ so $U/r \sim \delta/(kr) \sim x\delta$

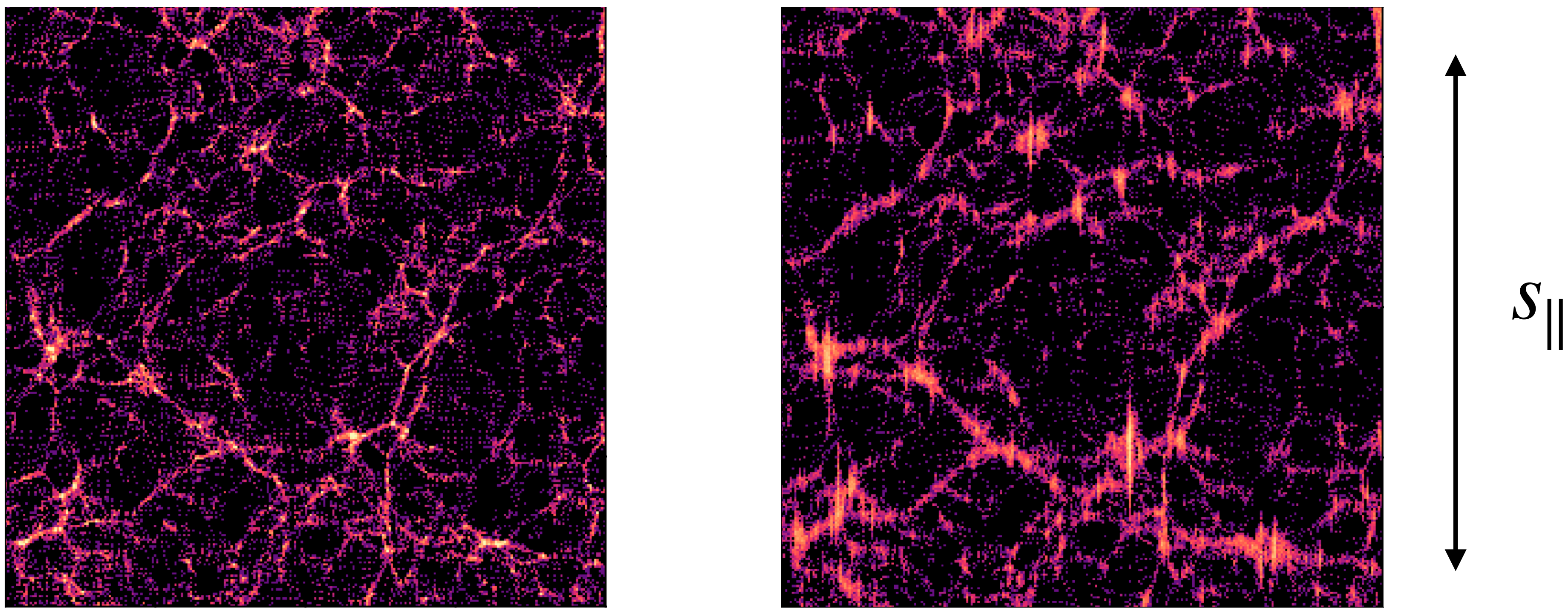
E.g. pair at z = 0.2 separated by 100 h^{-1}Mpc
has x = 100 / 570 ≈ 0.18 so

$$\delta\xi_0/\xi_0 \sim x^2 \sim 3\%$$





Streaming model - DOL



$$1 + \xi_s(s_{\parallel}, s_{\perp}) = \int_{-\infty}^{\infty} dr_{\parallel} \, [1 + \xi(r)] \, p(s_{\parallel} - r_{\parallel}; r_{\parallel})$$

Follows from

1. number conservation: $n_s(\mathbf{s}) d^3\mathbf{s} = n(\mathbf{x}) d^3\mathbf{x}$

2. redshift mapping: $s_{\parallel} = r_{\parallel} + u_{\parallel}, \quad s_{\perp} = r_{\perp}$

Peebles 1976, Fisher 1995, Scoccimarro 2004, Reid & White 2011; figure credit: Kuruvilla

Streaming model - WA regime

Number conservation $n_s(\mathbf{s})d^3\mathbf{s} = n(\mathbf{x})d^3\mathbf{x}$ implies

$$n_s(\mathbf{s}) = \int d^3\mathbf{x}\, n(\mathbf{x})\delta_D\big(\mathbf{s} - \mathbf{x} - \delta\mathbf{x}(\mathbf{x})\big)$$

Displacement is purely radial so use spherical coordinates

$$\mathbf{x} = \chi'\hat{\mathbf{x}}, \quad \mathbf{s} = \chi\hat{\mathbf{n}}$$

$$\delta_D(\mathbf{s} - \mathbf{x} - \delta\mathbf{x}) = \frac{1}{\chi^2}\delta_D(\chi - \chi' - \delta\chi)\delta_D(\hat{\mathbf{n}} - \hat{\mathbf{x}})$$

Since no angular displacement, redshift map is just $\chi = \chi' + \delta\chi$

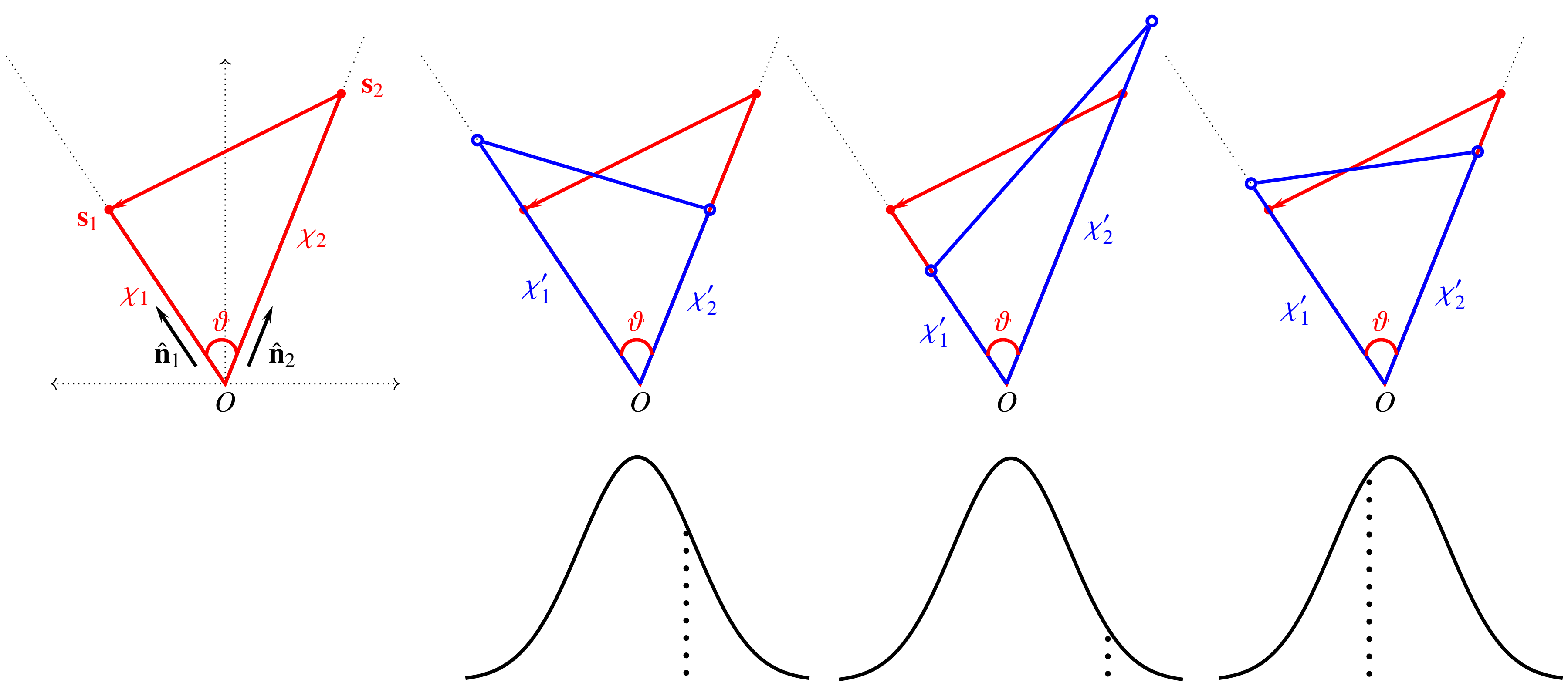
$$n_s(\chi\hat{\mathbf{n}}) = \frac{1}{\chi^2}\int \chi'^2 d\chi'\, n(\chi'\hat{\mathbf{n}})\delta_D(\chi - \chi' - \delta\chi(\chi'\hat{\mathbf{n}}))$$

Streaming model - WA regime

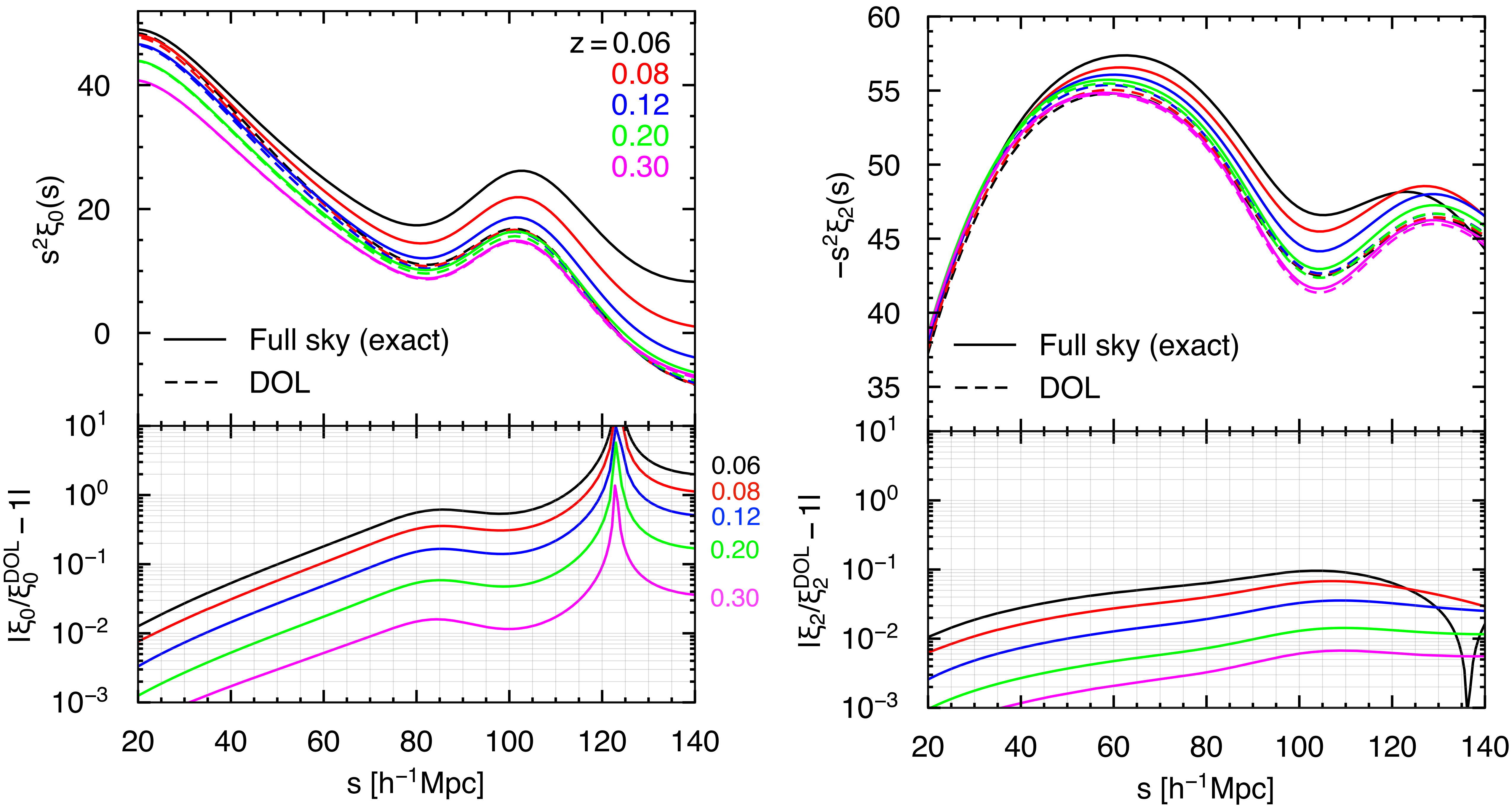
$$1+\xi_s(\chi_1,\chi_2,\vartheta) = \frac{1}{\chi_1^2}\int d\chi_1'\,\chi_1'^2 \frac{1}{\chi_2^2}\int d\chi_2'\,\chi_2'^2$$

$$\times\,[1+\xi(r)]\,p(\boldsymbol{\chi}-\boldsymbol{\chi}';\boldsymbol{\chi}',\vartheta)$$

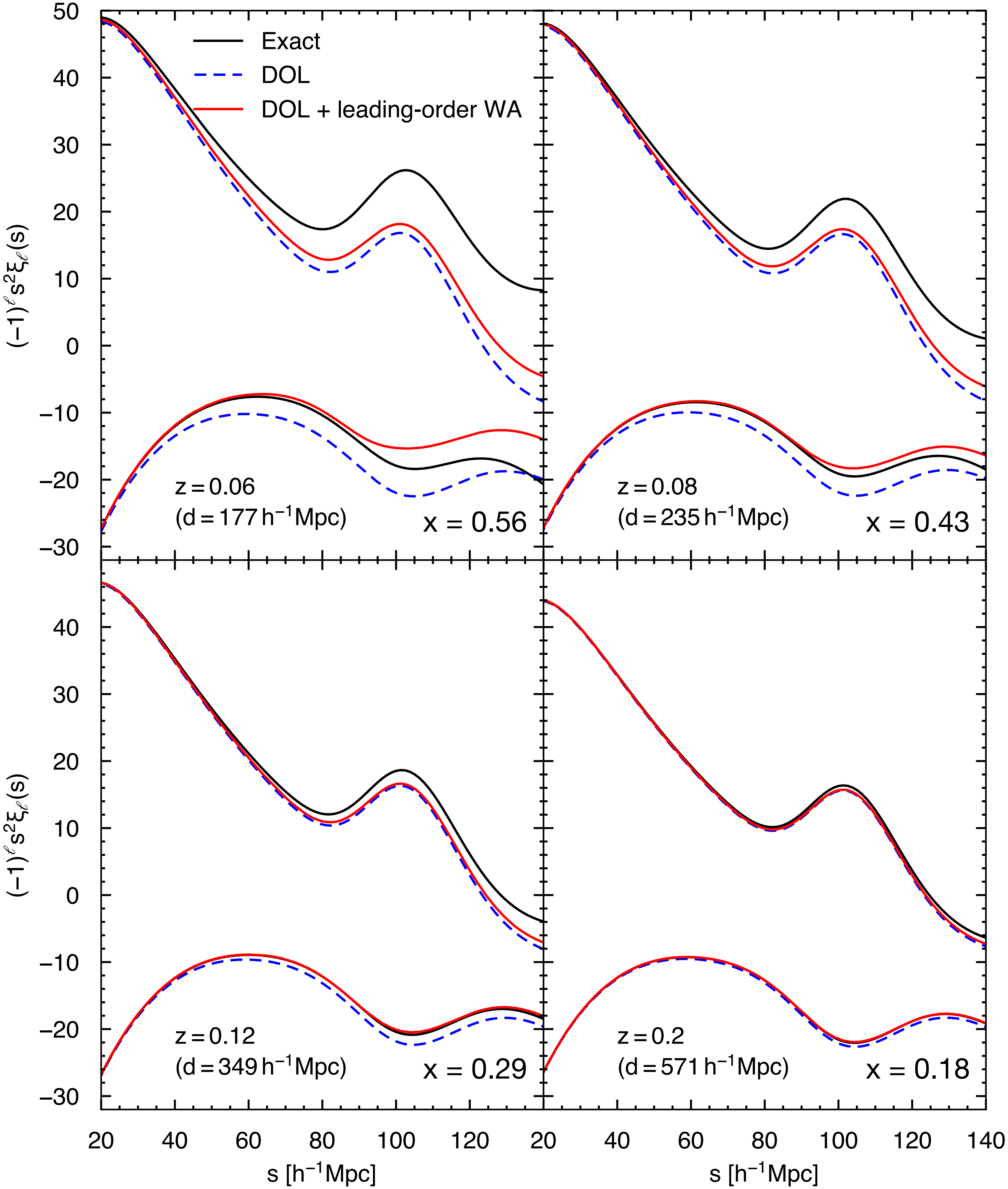
“$1+\xi_s$ is the ‘average’ of $1+\xi$ over the space of all triangles with opening angle ϑ”



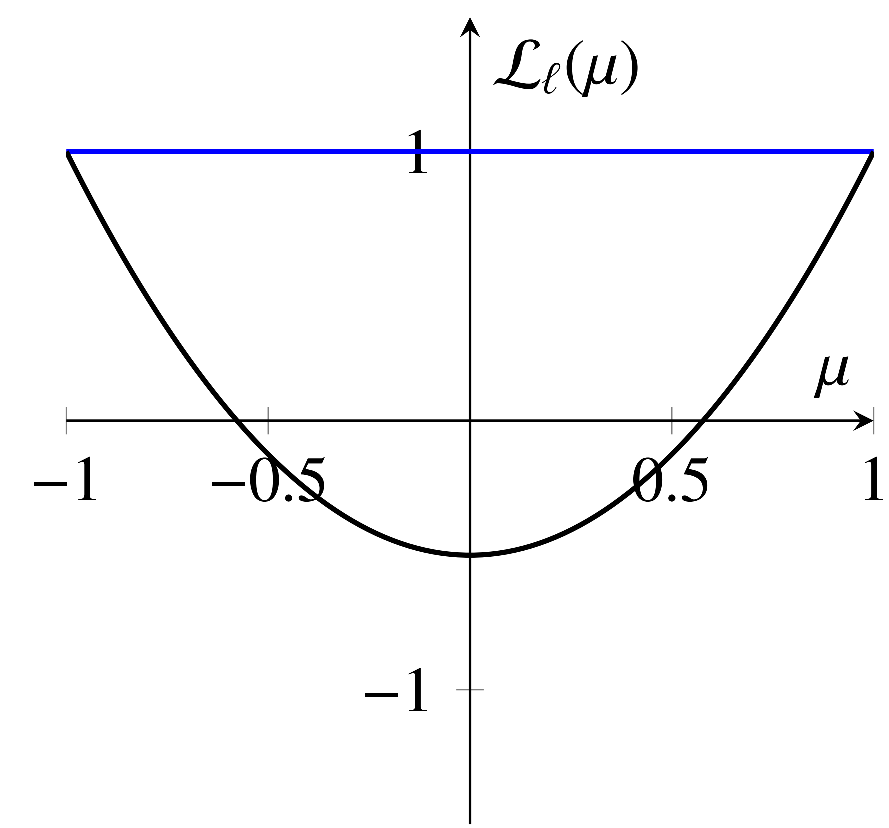
Wide-angle corrections



Here using Gaussian distribution for both full sky and DOL models

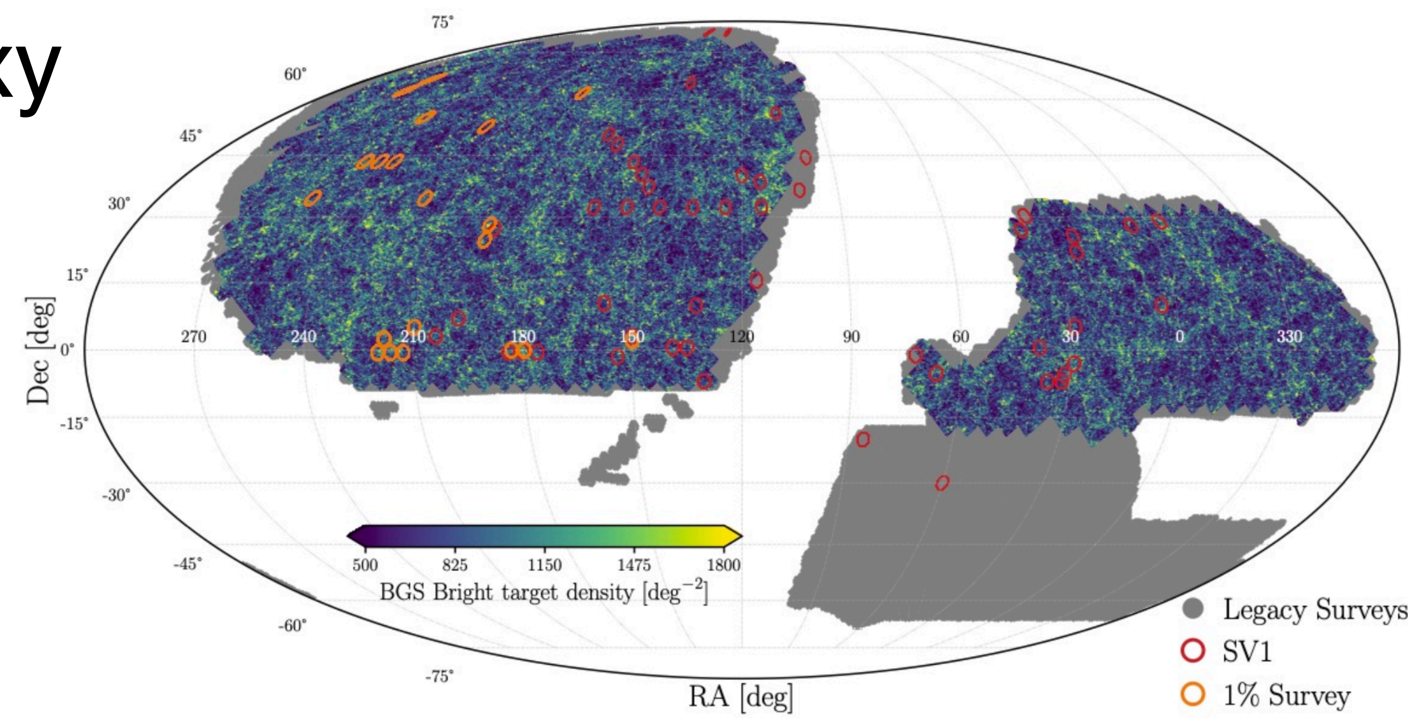


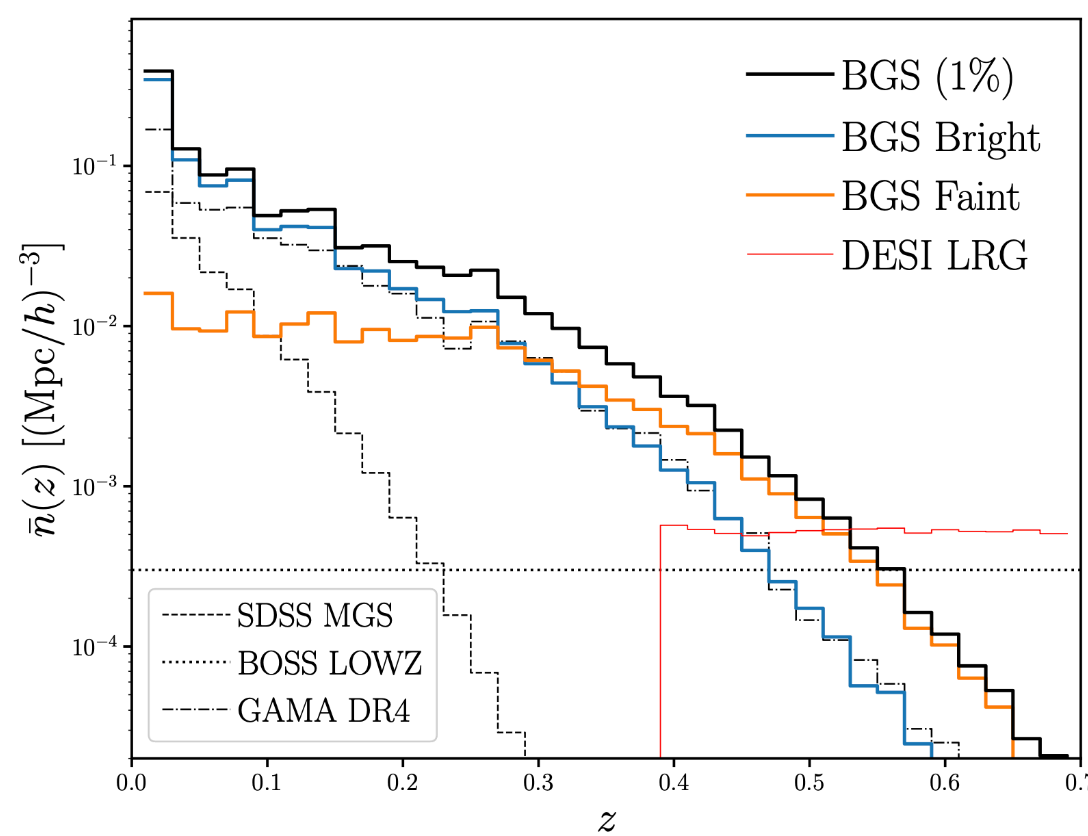
$$\xi_\ell(s) \propto \int_{-1}^{1} d\mu \, \mathcal{L}_\ell(\mu)\xi(s,\mu)$$



Application to BGS

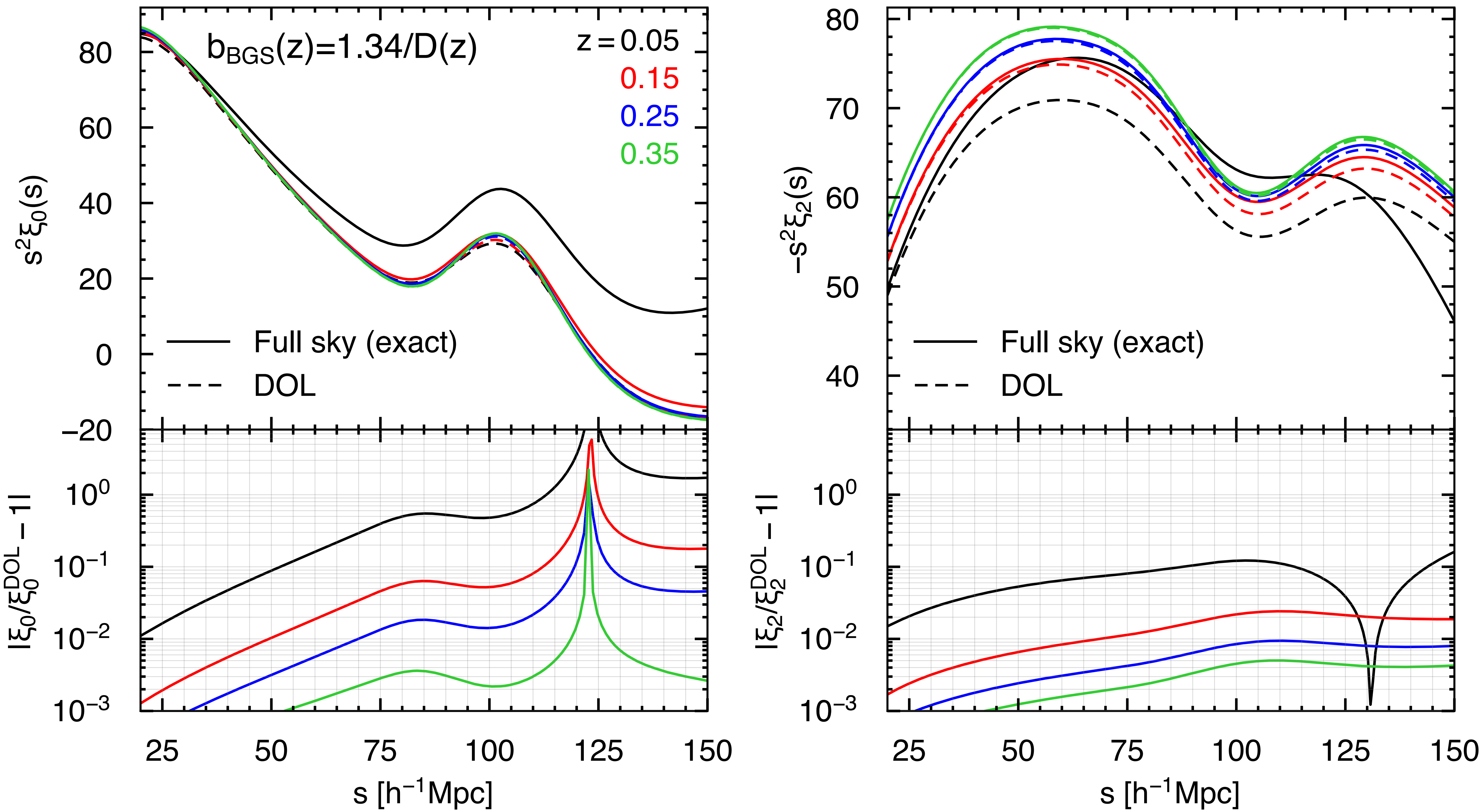
- Take DESI's Bright Galaxy Sample (BGS)
  - 10+ million galaxies
  - 14,000 deg^2
  - 140° between most separated galaxies
  - median z ~ 0.2
  - have bins z = 0.05, 0.15, 0.25, 0.35, 0.45





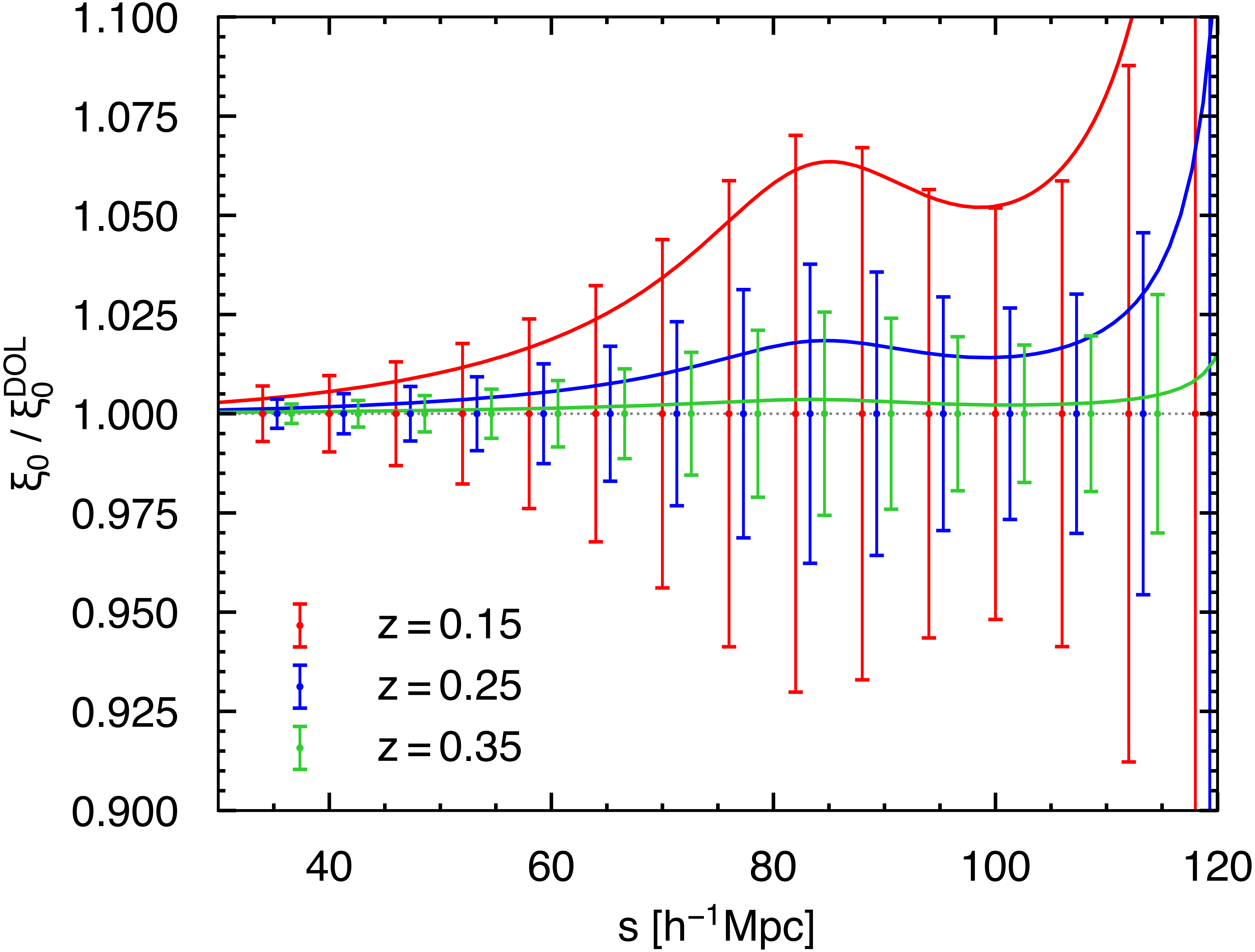
Hahn et al. 2022

Application to BGS



Corrections sizeable in lowest bins but errors largest here…

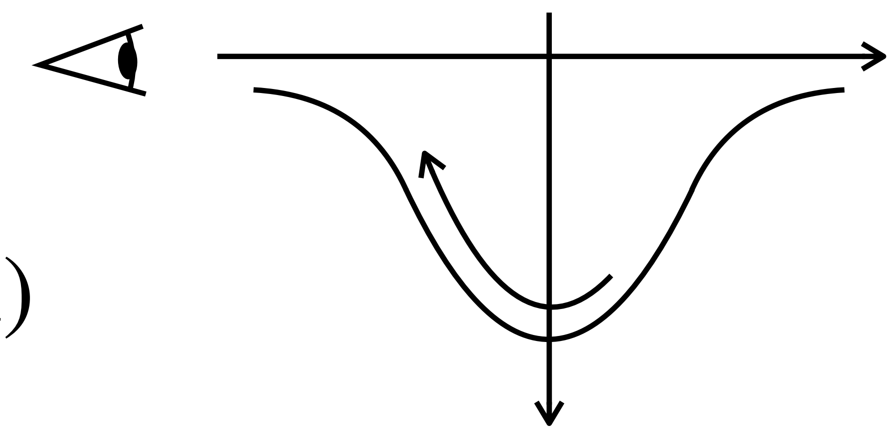
Application to BGS



Going beyond RSD

Gravitational redshift and LSS

- Photons climb out of potentials so suffer a redshift $z_g = \Delta\Phi$

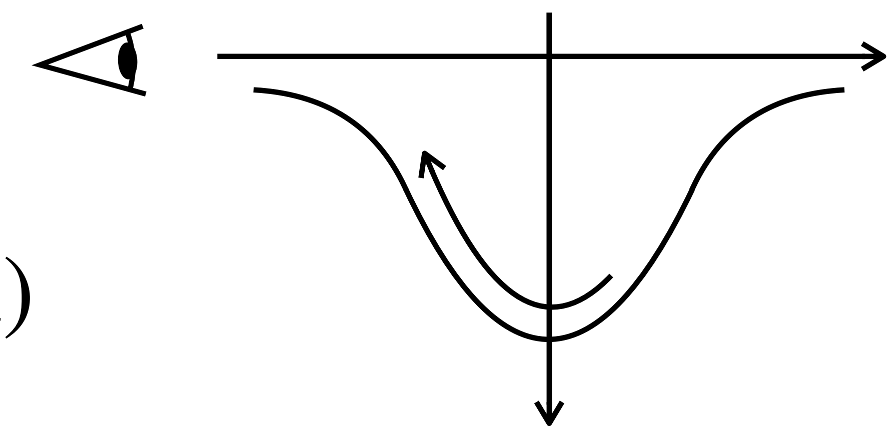


$$1 + z = (1 + \bar{z})(1 + z_{\rm pec})(1 + z_g)$$

McDonald 2009, Zhao et al 2013, Kaiser 2013, Croft 2013, Bonvin et al 2014, Cai et al 2017, Alam et al 2017

Gravitational redshift and LSS

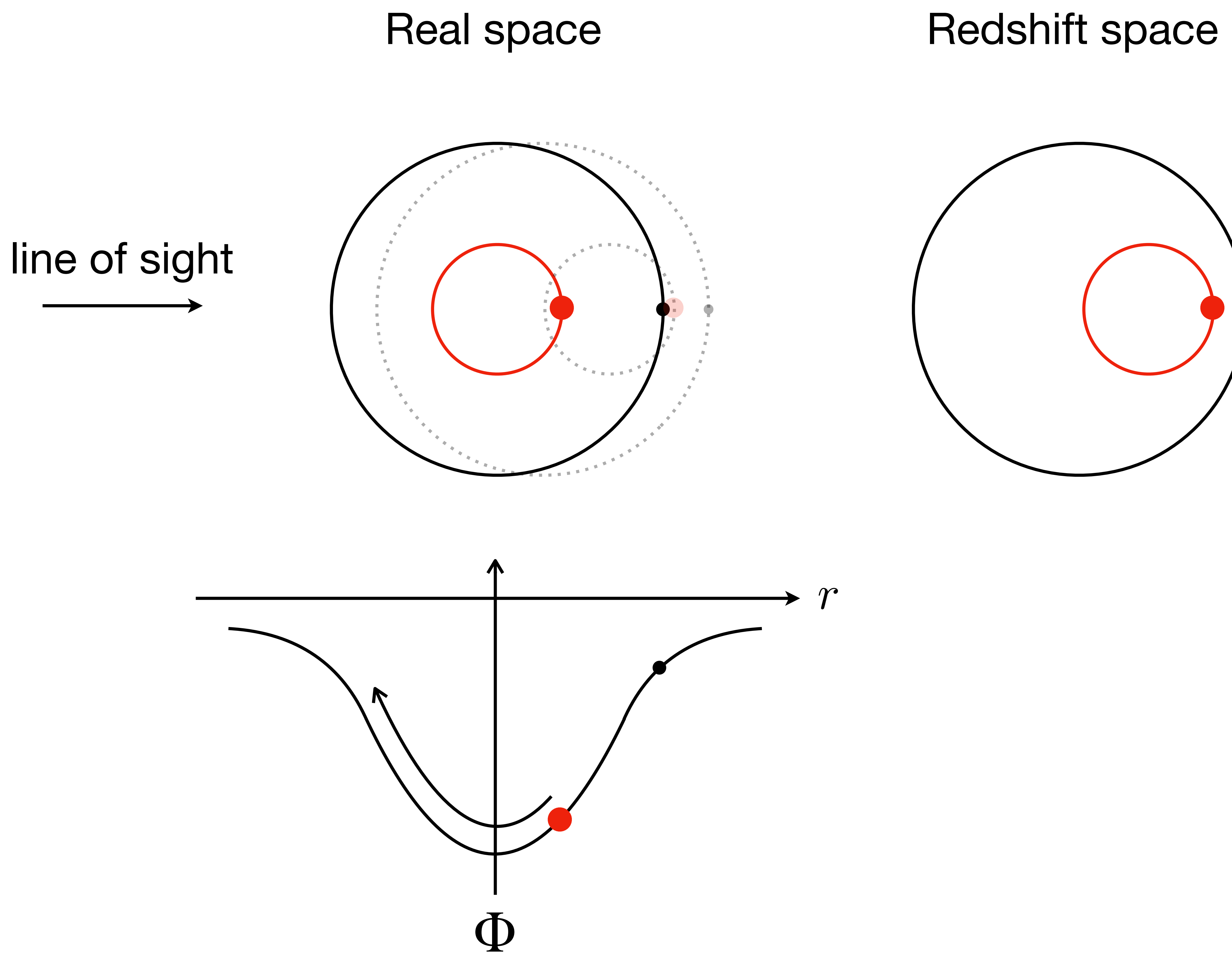
- Photons climb out of potentials so suffer a redshift $z_g = \Delta\Phi$



$$1 + z = (1 + \bar{z})(1 + z_{\rm pec})(1 + z_g)$$

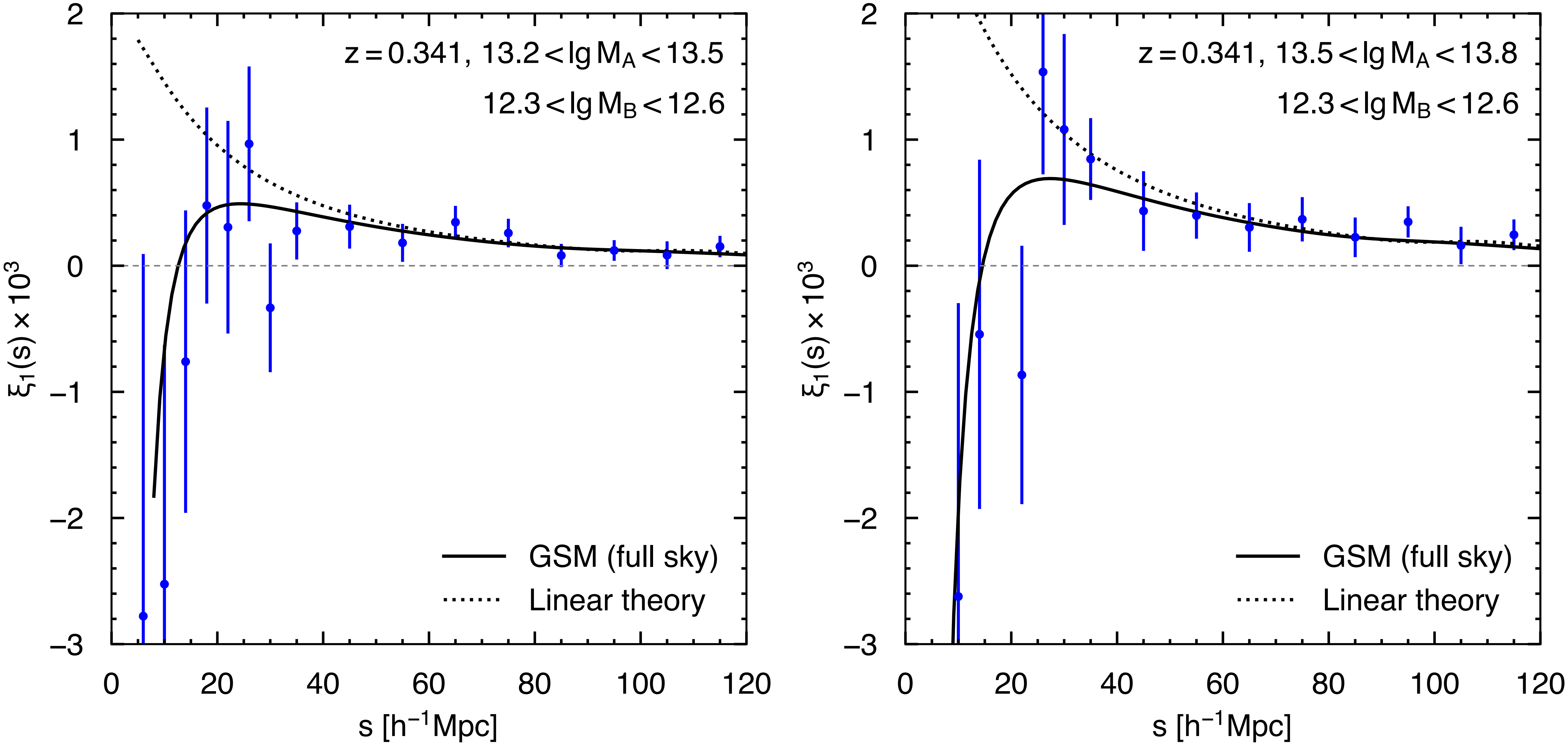
- Small: $z_g \sim 10^{-5}$ (cf. $z_{\rm pec} \sim 10^{-3}$)
  - subdominant to RSD: $\Phi \sim (H/k)v$
  - suppressed in auto-correlations
  - look in cross-correlations due to asymmetry

McDonald 2009, Zhao et al 2013, Kaiser 2013, Croft 2013, Bonvin et al 2014, Cai et al 2017, Alam et al 2017

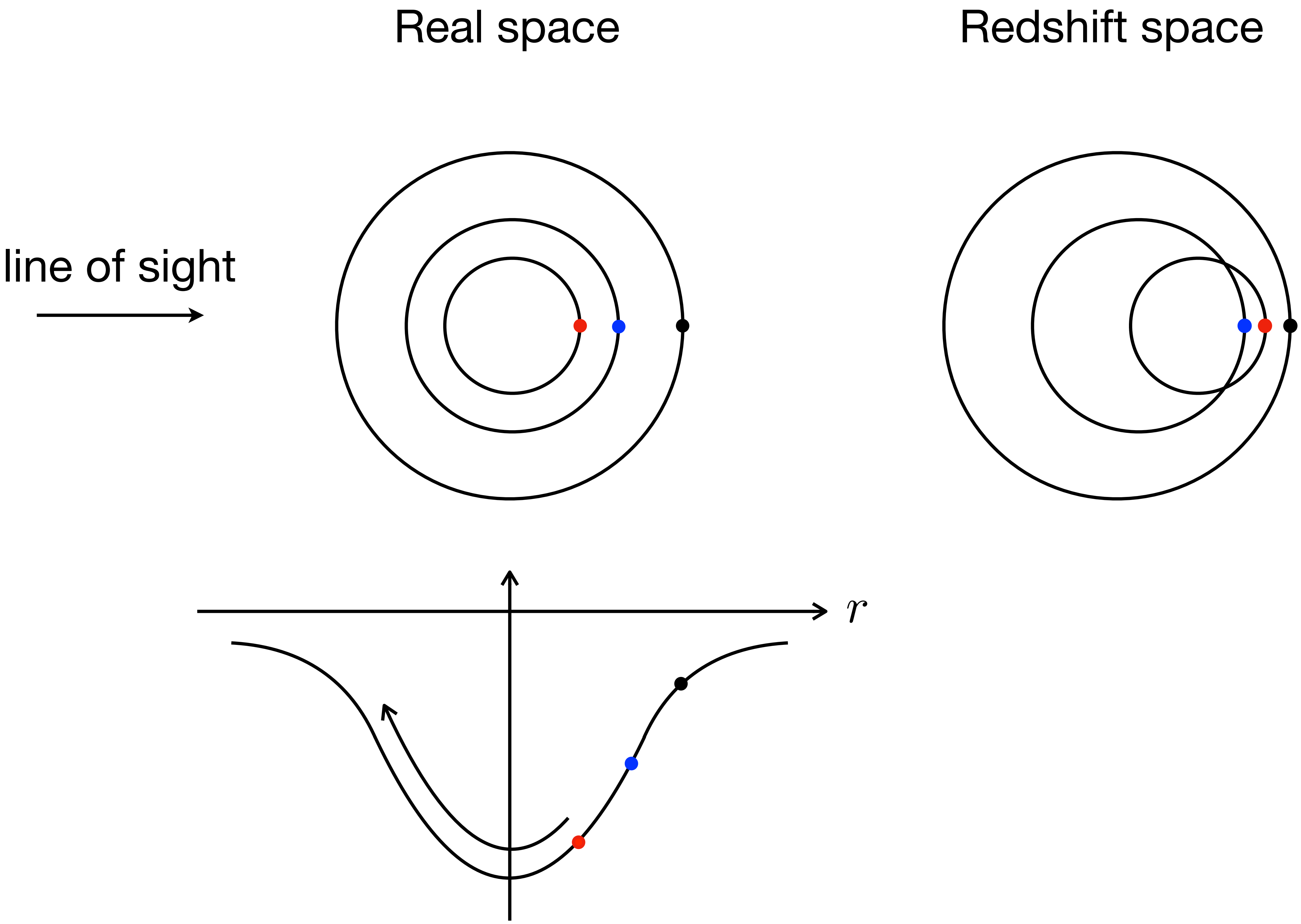


Real space
Redshift space
line of sight
r
Φ

Dipole in cross-correlation

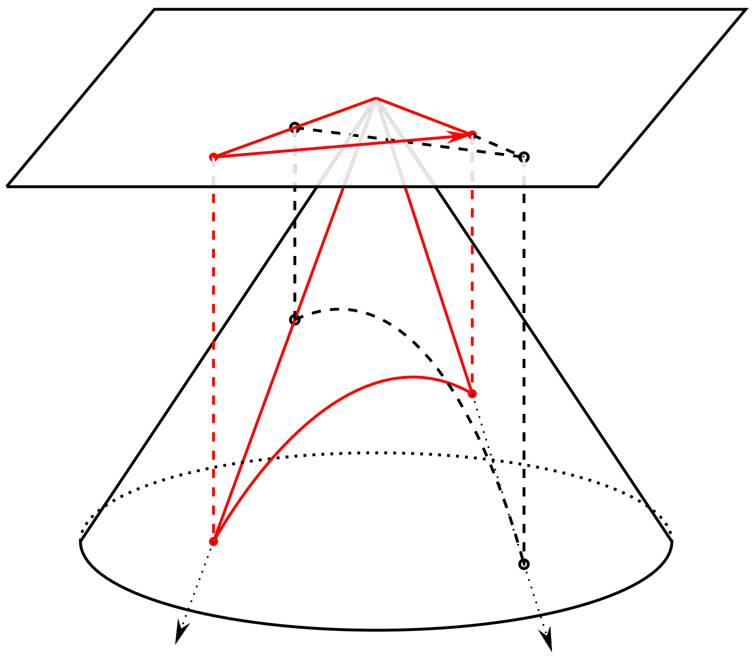


- Ray-traced N-body sims (RayGalGroup)
- Ongoing work: linear bias, no lightcone effects, etc
- Turn-around and sign change due to shell crossing


Real space
Redshift space
line of sight
r

Going further

- Gravitational redshift
- Lensing - allow angular displacements $\delta \mathbf{x}_\perp$ in mapping $\delta \mathbf{x} = \delta\chi\,\hat{\mathbf{x}} + \delta \mathbf{x}_\perp$
- Lookback-time effects
  - distance degenerate with time; leads to evolution effects
- Selection effects
  - pdf is reweighted by the selection function
- Lightcone effect
  - photons 'intercept' galaxies not in their rest-frame



Yoo et al 2009, Bonvin & Durrer 2011, Challinor & Lewis 2011, Jeong et al 2012, Kaiser 2013

Conclusions

- The streaming model can be generalised to the wide-angle regime without approximation
- WA effects appear to be a sizeable fraction of BGS errors
- The streaming model is a compact and conceptually simple way to capture a lot of physics - not just RSD