

The baryon acoustic oscillation peak: testing the comoving rigidity hypothesis

Boud Roukema
*Toruń Centre for Astronomy
Nicolaus Copernicus University*

@1RJS 27/08/2015

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
= background expands relativistically (Einstein)

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$
 - + large-scale structure, galaxy clusters, galaxies $\delta > \Delta_{\text{vir}}$

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$
 - + large-scale structure, galaxy clusters, galaxies $\delta > \Delta_{\text{vir}} \gg 1$ (Newton)

the homogeneous model

Newt/E – $f_{\text{vir}} - \nabla A - \Omega_{\mathcal{R}}^{\text{eff}} - ds^2 - d_L^{\text{eff}} - \bullet$ | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$
 - + large-scale structure, galaxy clusters, galaxies $\delta > \Delta_{\text{vir}} \gg 1$ (Newton)
 - + voids $-1 \lesssim \delta \ll 0$ (Newton)

the homogeneous model

Newt/E – $f_{\text{vir}} - \nabla A - \Omega_{\mathcal{R}}^{\text{eff}} - ds^2 - d_L^{\text{eff}} - \bullet$ | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$
 - + large-scale structure, galaxy clusters, galaxies $\delta > \Delta_{\text{vir}} \gg 1$ (Newton)
 - + voids $-1 \lesssim \delta \ll 0$ (Newton)
- when/where should Λ CDM, EdS fail?

the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- standard model: Λ CDM ($\Omega_{m0} \approx 0.32, \Omega_{\Lambda0} \approx 0.68$) homogeneous
- simpler model: EdS ($\Omega_{m0} = 1, \Omega_{\Lambda0} = 0$) homogeneous
 - = background expands relativistically (Einstein)
 - + linear density perturbations $\delta := \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}, |\delta| \ll 1$
 - + large-scale structure, galaxy clusters, galaxies $\delta > \Delta_{\text{vir}} \gg 1$ (Newton)
 - + voids $-1 \lesssim \delta \ll 0$ (Newton)
- Newton \neq Einstein $\Rightarrow \Lambda$ CDM, EdS should fail at $\ll 3 h^{-1}$ Gpc and $z < 3$

beyond the homogeneous model

Newt/E — f_{vir} — VA — $\Omega_{\mathcal{R}}^{\text{eff}}$ — ds^2 — d_L^{eff} — • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- what parameter can measure the expected failure of the homogeneous models?

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) :=$ fraction of virialised matter (large-scale structure, clusters, galaxies)

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$

beyond the homogeneous model

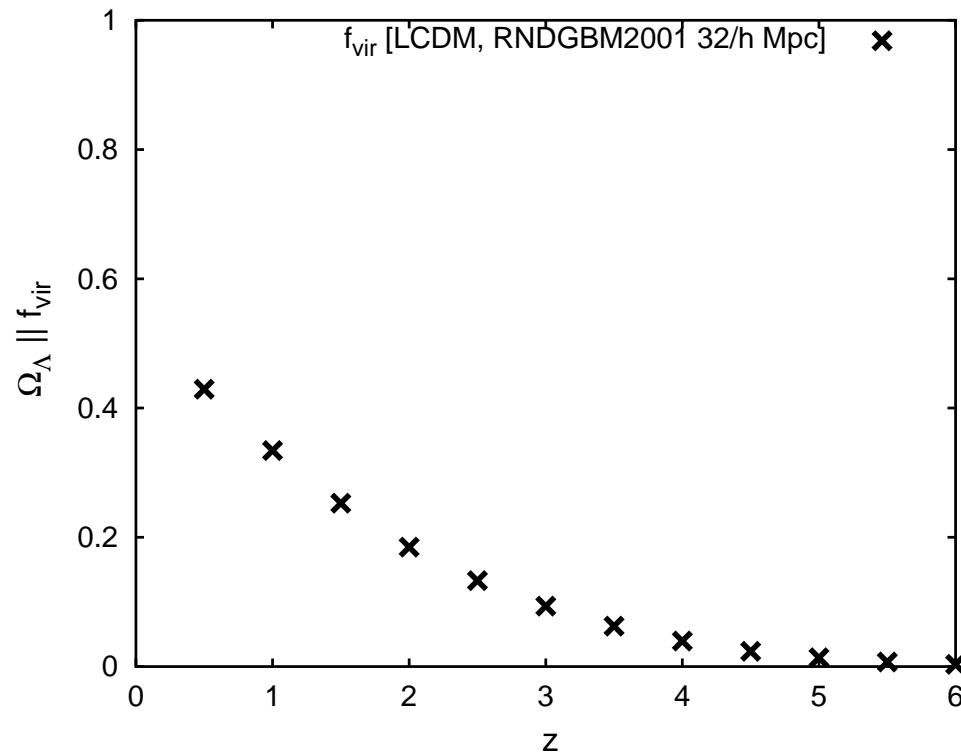
Newt/E — f_{vir} — VA — $\Omega_{\mathcal{R}}^{\text{eff}}$ — ds^2 — d_L^{eff} — • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$

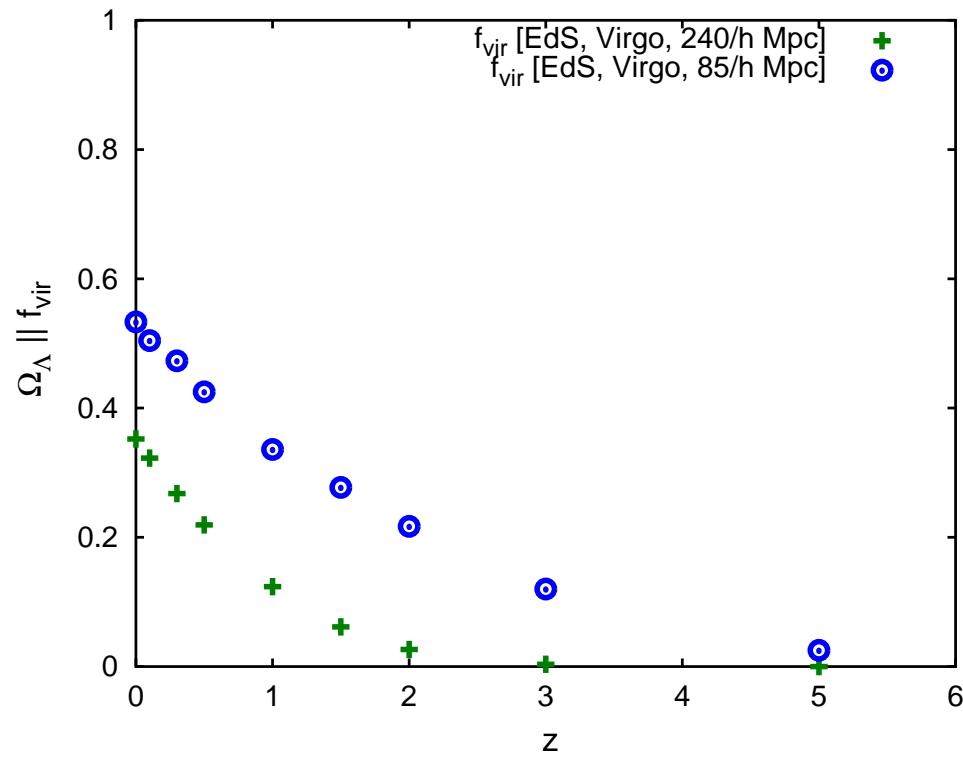


Roukema, Ninin, Devriendt, Bouchet, Guiderdoni & Mamon (2001)

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

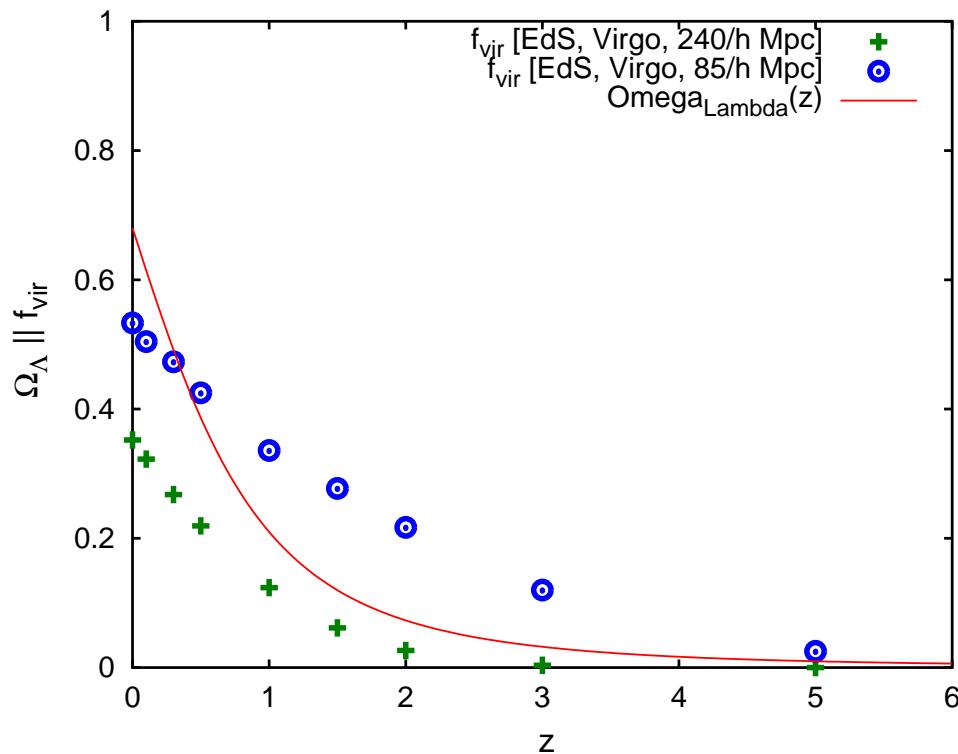
- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$



beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$



Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$
- $f_{\text{vir}}(z)$ strongly correlates with $\Omega_{\Lambda}(z)$
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043;
Roukema 2013, IJMPD, 22, 1341018;

beyond the homogeneous model

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \ll 1 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{valid}$
- $f_{\text{vir}}(z) \gg 0.01 \Rightarrow \Lambda\text{CDM}, \text{EdS} \sim \text{fail}$
- $f_{\text{vir}}(z)$ strongly correlates with $\Omega_{\Lambda}(z)$
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043;
Roukema 2013, IJMPD, 22, 1341018;
- Is $\Omega_{\Lambda}(z)$ an artefact of ignoring virialisation?

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- EdS + virialisation approximation:
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- EdS + virialisation approximation:
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043
- Newton : constant spatial curvature of structures + voids

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- EdS + virialisation approximation:
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043
- Newton : constant spatial curvature of structures + voids
Friedmann equation:

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$

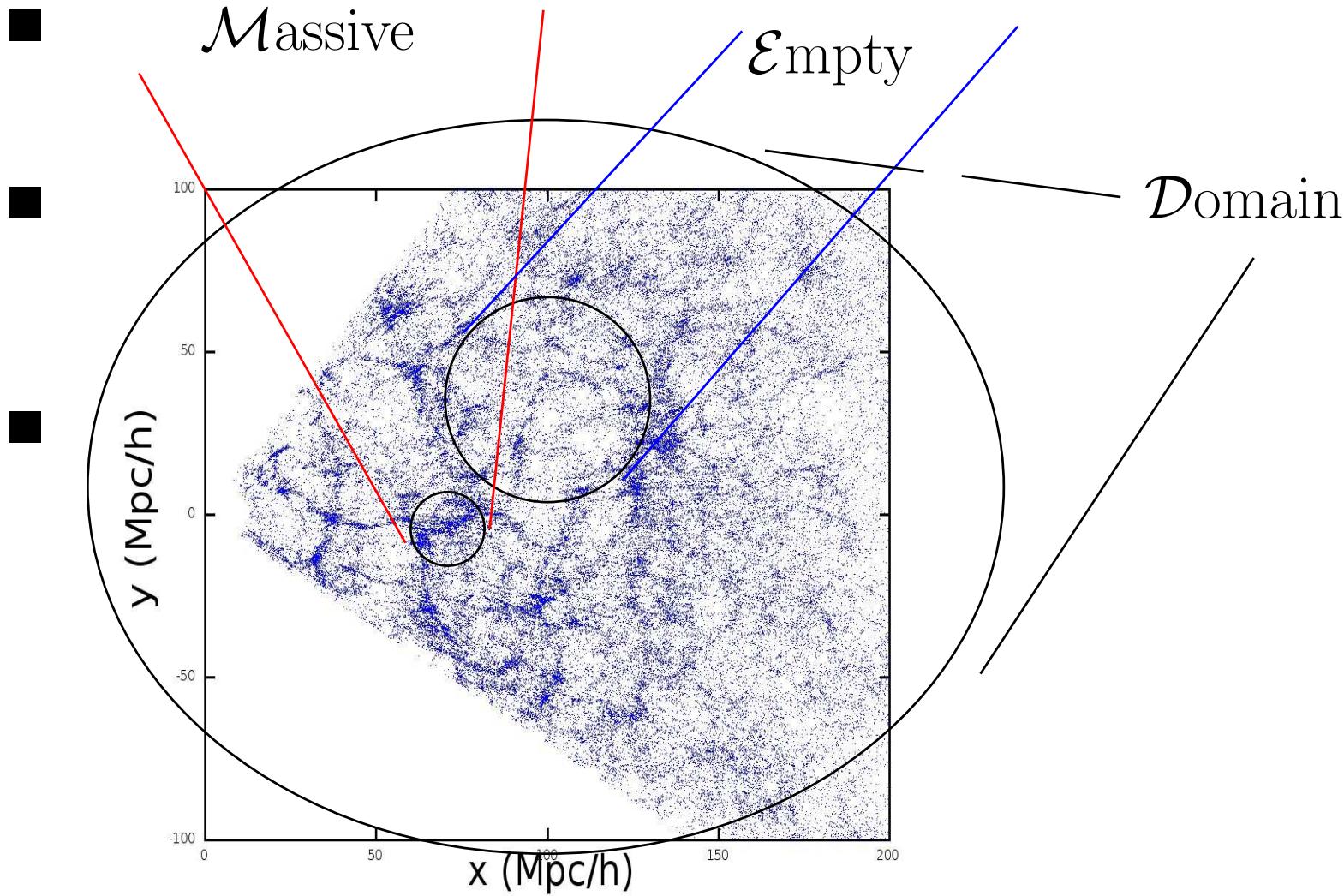
EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- EdS + virialisation approximation:
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043
- Newton : constant spatial curvature of structures + voids
Friedmann equation:
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$
- Einstein : hyperbolic voids
Buchert : volume-weighted means

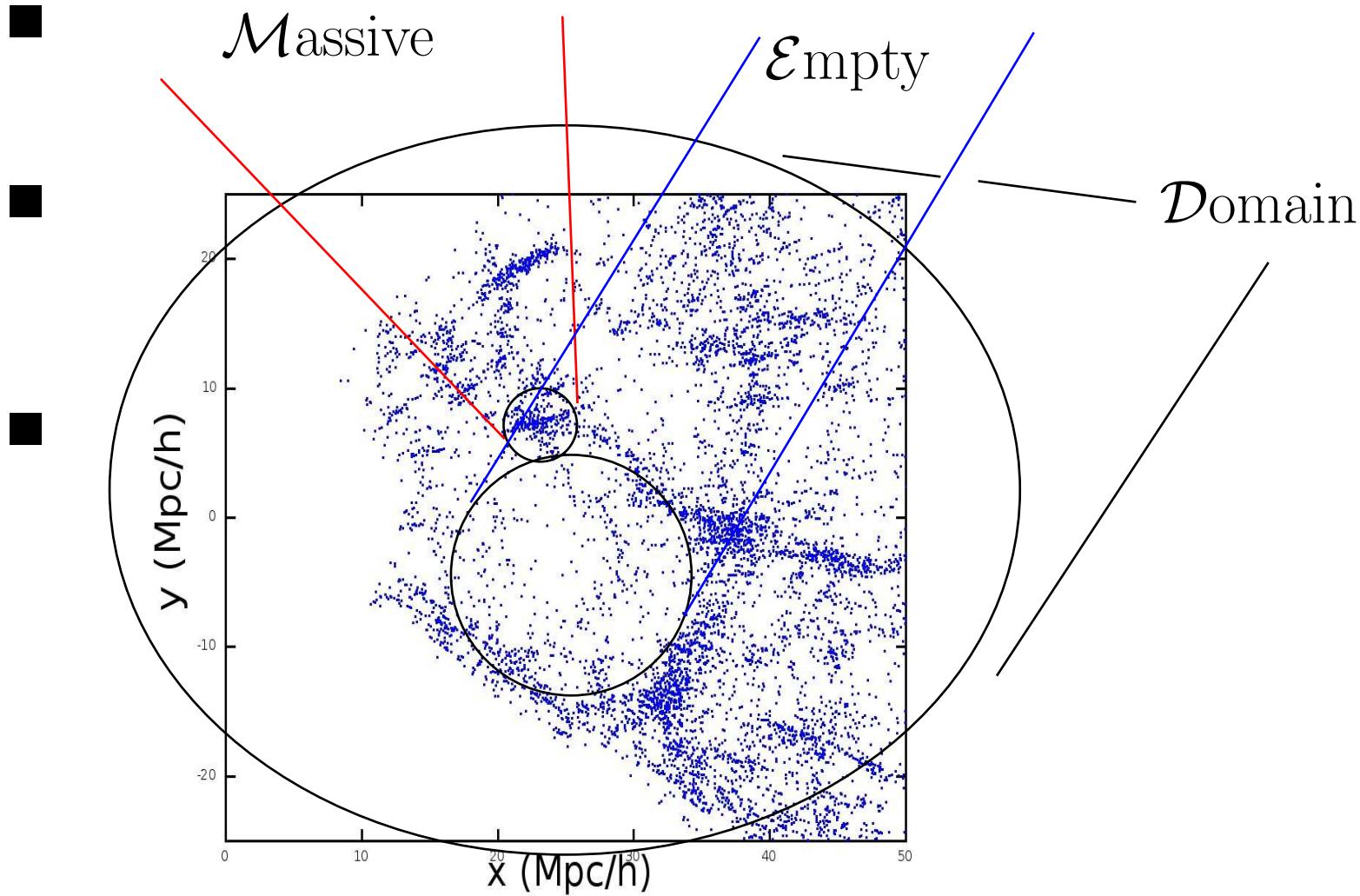
EdS + virialisation approx

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



EdS + virialisation approx

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

■ EdS + virialisation approximation:

Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

■ Newton : constant spatial curvature of structures + voids

Friedmann equation:

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$

■ Einstein : hyperbolic voids

Buchert : volume-weighted means on domains $\mathcal{D} := \mathcal{M} \cup \mathcal{E}$
generalised Friedmann equation (Hamiltonian constraint):

$$\Omega_m^{\mathcal{F}} + \Omega_\Lambda^{\mathcal{F}} + \Omega_{\mathcal{R}}^{\mathcal{F}} + \Omega_{\mathcal{Q}}^{\mathcal{F}} = \frac{H_{\mathcal{F}}^2}{H_{\mathcal{D}}^2}, \quad \text{where } \mathcal{F} \in \{\mathcal{M}, \mathcal{E}, \mathcal{D}\}$$

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

■ EdS + virialisation approximation:

Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

■ Newton : constant spatial curvature of structures + voids

Friedmann equation:

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$

■ Einstein : hyperbolic voids

Buchert : volume-weighted means on domains $\mathcal{D} := \mathcal{M} \cup \mathcal{E}$
generalised Friedmann equation (Hamiltonian constraint):

$$\Omega_m^{\mathcal{F}} + \Omega_\Lambda^{\mathcal{F}} + \Omega_{\mathcal{R}}^{\mathcal{F}} + \Omega_{\mathcal{Q}}^{\mathcal{F}} = \frac{H_{\mathcal{F}}^2}{H_{\mathcal{D}}^2}, \quad \text{where } \mathcal{F} \in \{\mathcal{M}, \mathcal{E}, \mathcal{D}\}$$

■ assume $\Omega_\Lambda^{\mathcal{F}} = 0$

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

■ EdS + virialisation approximation:

Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

■ Newton : constant spatial curvature of structures + voids

Friedmann equation:

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$

■ Einstein : hyperbolic voids

Buchert : volume-weighted means on domains $\mathcal{D} := \mathcal{M} \cup \mathcal{E}$
generalised Friedmann equation (Hamiltonian constraint):

$$\Omega_m^{\mathcal{F}} + \Omega_{\mathcal{R}}^{\mathcal{F}} + \Omega_{\mathcal{Q}}^{\mathcal{F}} = \frac{H_{\mathcal{F}}^2}{H_{\mathcal{D}}^2}, \quad \text{where } \mathcal{F} \in \{\mathcal{M}, \mathcal{E}, \mathcal{D}\}$$

■ assume $\Omega_{\Lambda}^{\mathcal{F}} = 0$

■ assume $|\Omega_{\mathcal{Q}}^{\mathcal{F}}| \ll 1$

EdS + virialisation approx

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- EdS + virialisation approximation:
Roukema, Ostrowski, Buchert, 2013, JCAP, 10, 043

- Newton : constant spatial curvature of structures + voids
Friedmann equation:

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1.$$

- Einstein : hyperbolic voids
Buchert : volume-weighted means on domains $\mathcal{D} := \mathcal{M} \cup \mathcal{E}$
generalised Friedmann equation (Hamiltonian constraint):

$$\Omega_m^{\mathcal{F}} + \Omega_{\mathcal{R}}^{\mathcal{F}} = \frac{H_{\mathcal{F}}^2}{H_{\mathcal{D}}^2}, \quad \text{where } \mathcal{F} \in \{\mathcal{M}, \mathcal{E}, \mathcal{D}\}$$

- assume $\Omega_{\Lambda}^{\mathcal{F}} = 0$
- assume $|\Omega_{\mathcal{Q}}^{\mathcal{F}}| \ll 1$

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- early: $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}} : f_{\text{vir}}$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}} / \Delta_{\text{vir}} : f_{\text{vir}} / \Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}} / \Delta_{\text{vir}}$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}} / \Delta_{\text{vir}} : f_{\text{vir}} / \Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}} / \Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\begin{aligned}\Omega_m^{\mathcal{D}} &= \lambda_{\mathcal{M}} \Omega_m^{\mathcal{M}} + (1 - \lambda_{\mathcal{M}}) \Omega_m^{\mathcal{E}} \\ H^{\mathcal{D}} &= \lambda_{\mathcal{M}} H^{\mathcal{M}} + (1 - \lambda_{\mathcal{M}}) H^{\mathcal{E}}\end{aligned}$$

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\mathcal{E}}(z) \approx \frac{(1 - f_{\text{vir}})}{(H^{\text{eff}}/H^{\text{bg}})^2} \Omega_m^{\text{bg}}$$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\mathcal{M}}(z) \approx \frac{\Delta_{\text{vir}} \Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \Omega_m^{\text{bg}}$$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}(z)$$

EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(z) a^{-1}$$

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
 \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(0) \frac{f_{\text{vir}}(z)}{f_{\text{vir}}(0)} a^{-1}$$

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

■ late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$

■ define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$

\Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(0) \frac{f_{\text{vir}}(z)}{f_{\text{vir}}(0)} a^{-1}$$

$$\begin{aligned} H_{\text{pec}}^{\text{com}}(0) := \frac{2v_{\text{infall}}}{D_{\text{void}}} &\approx \frac{4\sigma_v}{D_{\text{void}}} \\ &= 36 \pm 3 \text{ km/s/Mpc} \end{aligned}$$

\Rightarrow

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
- \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(0) \frac{f_{\text{vir}}(z)}{f_{\text{vir}}(0)} a^{-1}$$

$$\begin{aligned} H_{\text{pec}}^{\text{com}}(0) := \frac{2v_{\text{infall}}}{D_{\text{void}}} &\approx \frac{4\sigma_v}{D_{\text{void}}} \\ &= 36 \pm 3 \text{ km/s/Mpc} \end{aligned}$$

$\Rightarrow \Omega_m^{\text{eff}}(z)$ drops when $f_{\text{vir}}(z)$ grows

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$
- define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$
- \Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(0) \frac{f_{\text{vir}}(z)}{f_{\text{vir}}(0)} a^{-1}$$

$$\begin{aligned} H_{\text{pec}}^{\text{com}}(0) := \frac{2v_{\text{infall}}}{D_{\text{void}}} &\approx \frac{4\sigma_v}{D_{\text{void}}} \\ &= 36 \pm 3 \text{ km/s/Mpc} \end{aligned}$$

$\Rightarrow \Omega_m^{\text{eff}}(z)$ drops when z drops

EdS + virialisation

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

■ late : $V(\text{voids}) : V(\text{structures}) \sim 1 - f_{\text{vir}}/\Delta_{\text{vir}} : f_{\text{vir}}/\Delta_{\text{vir}}$

■ define $\lambda_{\mathcal{M}} := f_{\text{vir}}/\Delta_{\text{vir}} \ll 1$

\Rightarrow voids dominate any volume average

$$\Omega_m^{\text{eff}}(z) := \Omega_m^{\mathcal{D}}(z) \approx \frac{\Omega_m^{\text{bg}}}{(H^{\text{eff}}/H^{\text{bg}})^2}$$

$$H^{\text{eff}}(z) \approx H(z) + H_{\text{pec}}^{\text{com}}(0) \frac{f_{\text{vir}}(z)}{f_{\text{vir}}(0)} a^{-1}$$

$$\begin{aligned} H_{\text{pec}}^{\text{com}}(0) := \frac{2v_{\text{infall}}}{D_{\text{void}}} &\approx \frac{4\sigma_v}{D_{\text{void}}} \\ &= 36 \pm 3 \text{ km/s/Mpc} \end{aligned}$$

\Rightarrow curvature more negative when z drops

effective parameters

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

$$\Omega_{\mathcal{R}}^{\text{eff}}(z) = 1 - \Omega_m^{\text{eff}}(z)$$

effective parameters

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

$$\Omega_{\mathcal{R}}^{\text{eff}}(z) = 1 - \Omega_m^{\text{eff}}(z)$$

$$H^{\text{eff}}(0) = 74.0 \pm 1.6 \text{ km/s/Mpc}$$

(Riess et al. 2011; Freedman et al. 2012)

effective parameters

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

$$\Omega_{\mathcal{R}}^{\text{eff}}(z) = 1 - \Omega_m^{\text{eff}}(z)$$

$$H^{\text{eff}}(0) = 74.0 \pm 1.6 \text{ km/s/Mpc}$$

(Riess et al. 2011; Freedman et al. 2012)

$$R_C^{\text{eff}}(z) = \frac{c}{a H^{\text{eff}}(z) \sqrt{\Omega_{\mathcal{R}}^{\text{eff}}(z)}}$$

effective metric

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

$$ds^2 = -dt^2 + a^2(t) \left[d\chi^{\text{eff}2} + R_{\text{C}}^{\text{eff}2} \left(\sinh^2 \frac{\chi^{\text{eff}}}{R_{\text{C}}^{\text{eff}}} \right) (d\theta^2 + \cos^2 \theta d\phi^2) \right]$$

effective metric

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

$$ds^2 = -dt^2 + a^2(t) \left[d\chi^{\text{eff}2} + R_{\text{C}}^{\text{eff}2} \left(\sinh^2 \frac{\chi^{\text{eff}}}{R_{\text{C}}^{\text{eff}}} \right) (d\theta^2 + \cos^2 \theta d\phi^2) \right]$$

$$d\chi^{\text{eff}}(z) := \frac{c}{a^2 H^{\text{eff}}(z)} da$$

effective metric

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

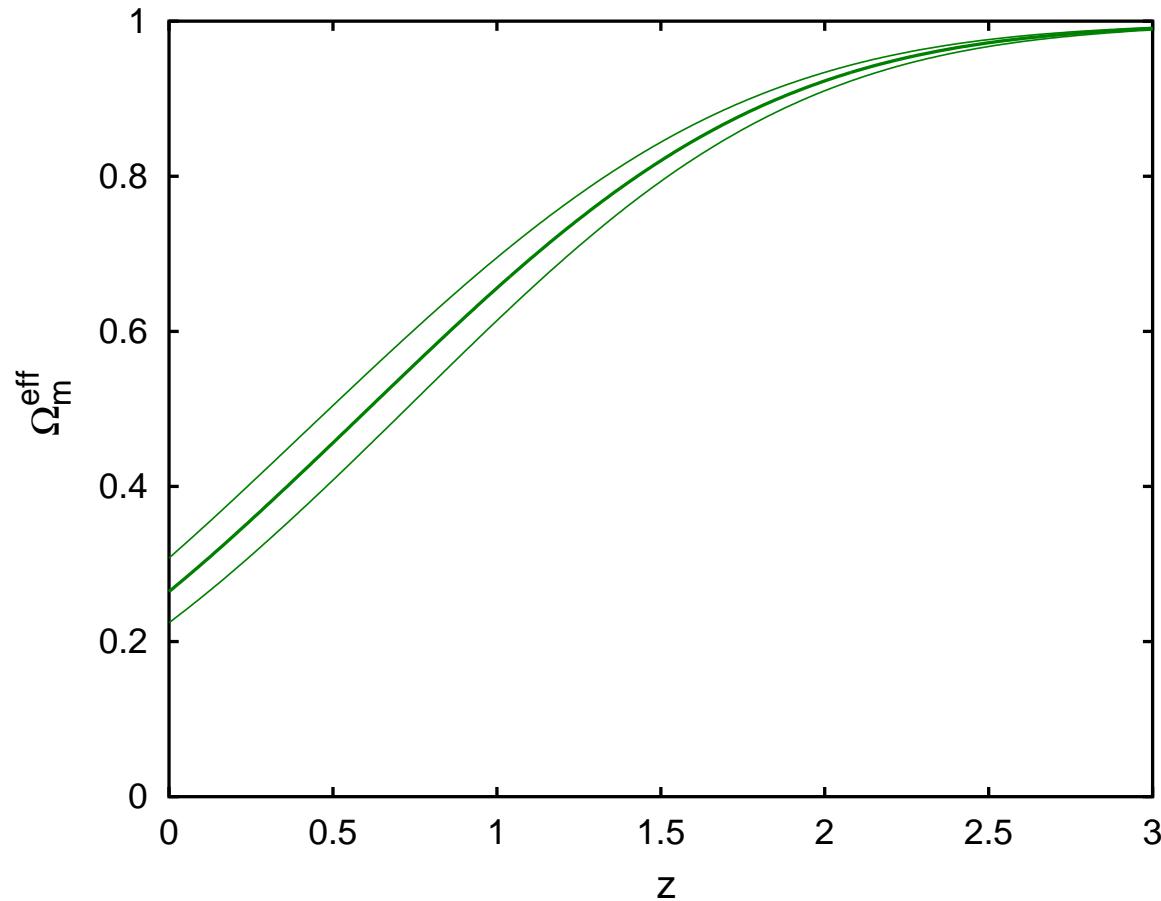
$$ds^2 = -dt^2 + a^2(t) \left[d\chi^{\text{eff}}{}^2 + R_{\text{C}}^{\text{eff}}{}^2 \left(\sinh^2 \frac{\chi^{\text{eff}}}{R_{\text{C}}^{\text{eff}}} \right) (d\theta^2 + \cos^2 \theta d\phi^2) \right]$$

$$d\chi^{\text{eff}}(z) := \frac{c}{a^2 H^{\text{eff}}(z)} da$$

$$d_L^{\text{eff}} = (1+z) R_{\text{C}}^{\text{eff}} \sinh \frac{\chi^{\text{eff}}}{R_{\text{C}}^{\text{eff}}}$$

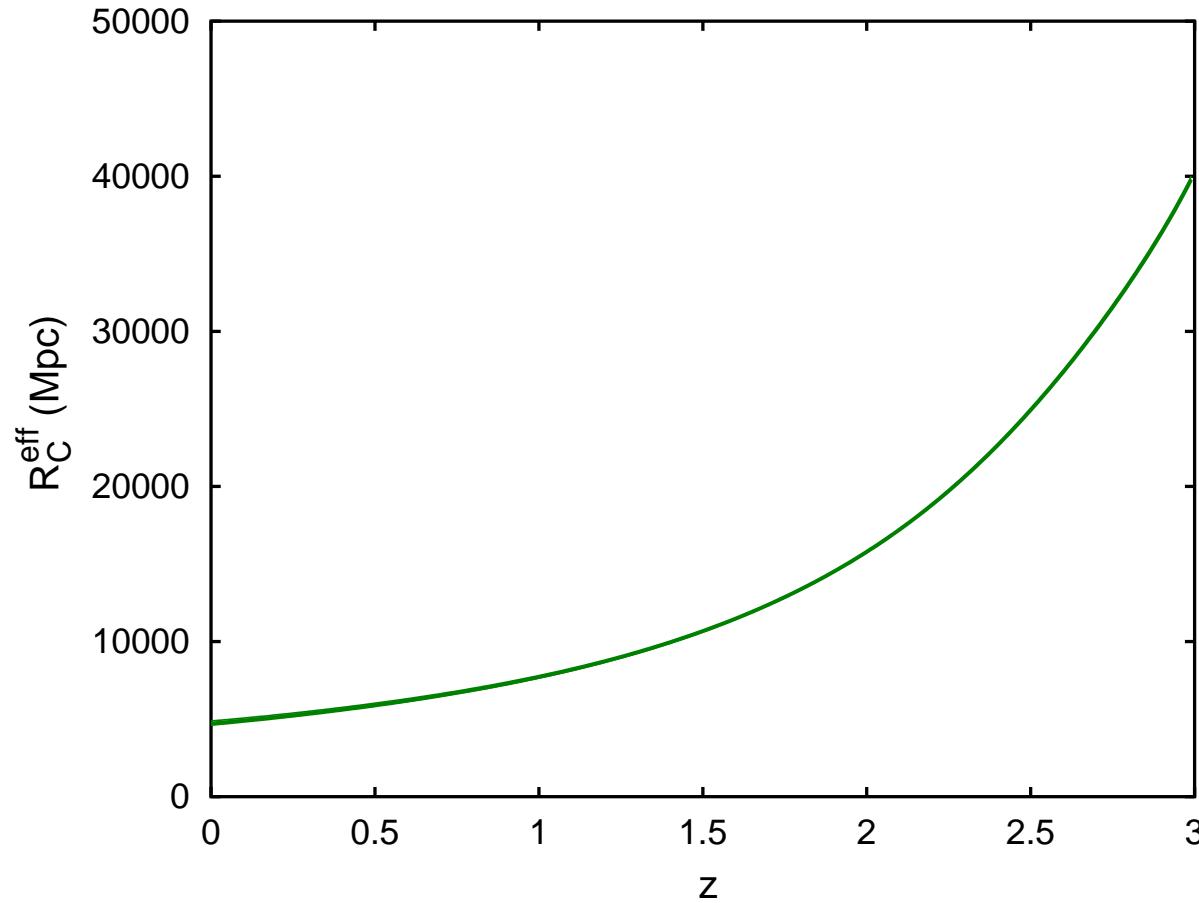
EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - ● | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



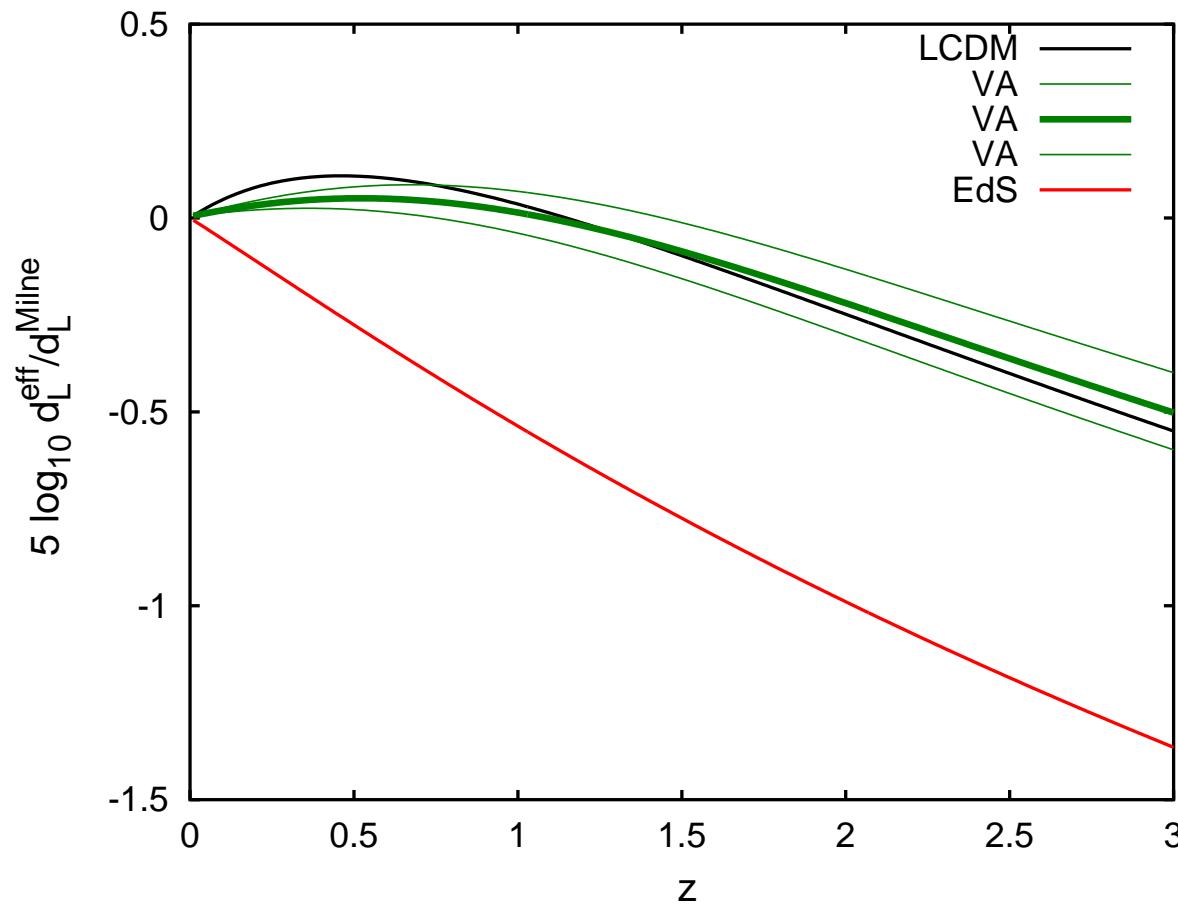
EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - ● | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



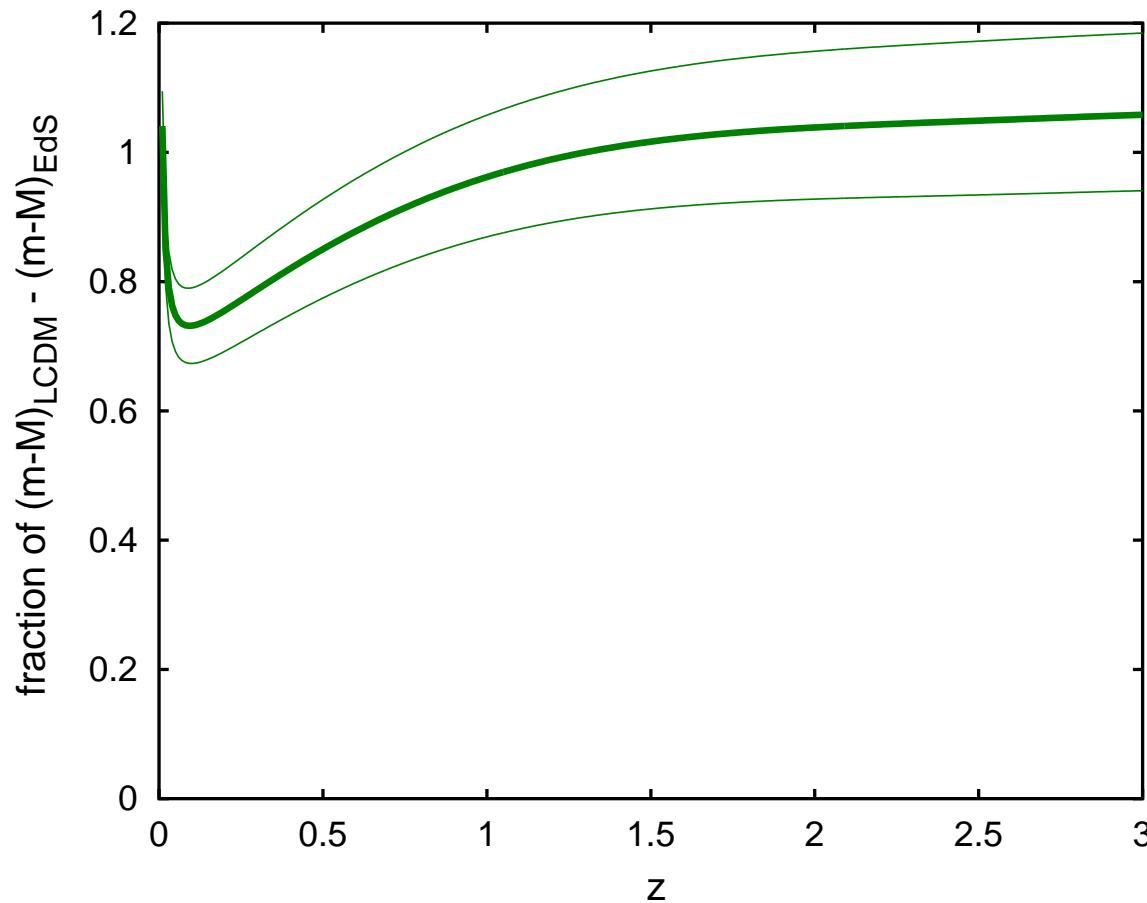
EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - ● | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



EdS + virialisation

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - ● | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- $f_{\text{vir}}(z) \sim \Omega_{\Lambda}(z)$

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;
- background model + virialisation
 \Rightarrow void-dominated neg. curvature + inhomogeneous expansion \Rightarrow
 $\Omega_m^{\text{eff}}(z = 0) \sim 0.3$

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;
- background model + virialisation
 \Rightarrow void-dominated neg. curvature + inhomogeneous expansion \Rightarrow
 $\Omega_m^{\text{eff}}(z = 0) \sim 0.3$
distance modulus $m - M$ vs z : EdS+VA $\sim \Lambda\text{CDM}$

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;
- background model + virialisation
 \Rightarrow void-dominated neg. curvature + inhomogeneous expansion \Rightarrow
 $\Omega_m^{\text{eff}}(z = 0) \sim 0.3$
distance modulus $m - M$ vs z : EdS+VA $\sim \Lambda\text{CDM}$
- dark energy \sim virialisation-epoch negative curvature

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;
- background model + virialisation
 \Rightarrow void-dominated neg. curvature + inhomogeneous expansion \Rightarrow
 $\Omega_m^{\text{eff}}(z = 0) \sim 0.3$
distance modulus $m - M$ vs z : EdS+VA $\sim \Lambda\text{CDM}$
- dark energy \sim virialisation-epoch negative curvature
Roukema, Ostrowski, Buchert 2013 JCAP, 10, 043 (arXiv:1303.4444);
Roukema 2013, IJMPD, 22, 1341018 (arXiv:1305.4415)

metric template

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

- expected homogeneous model failure $\sim \Omega_{\Lambda}(z)$
- remove free param $(\Omega_{\Lambda 0})$; assume EdS background $(\Omega_m = 1, \Omega_{\Lambda} = 0)$ at early times ($z \gg 3$)
- add GR (scalar averaging): virialisation approximation:
2 obs inputs: $H^{\text{eff}}(z = 0) = 74 \pm 1.6 \text{ km/s/Mpc}$;
 $H_{\text{pec}}^{\text{com}}(z = 0) = 36 \pm 3 \text{ km/s/Mpc}$;
- background model + virialisation
 \Rightarrow void-dominated neg. curvature + inhomogeneous expansion \Rightarrow
 $\Omega_m^{\text{eff}}(z = 0) \sim 0.3$
distance modulus $m - M$ vs z : EdS+VA $\sim \Lambda\text{CDM}$
- dark energy \sim virialisation-epoch negative curvature
Roukema, Ostrowski, Buchert 2013 JCAP, 10, 043 (arXiv:1303.4444);
Roukema 2013, IJMPD, 22, 1341018 (arXiv:1305.4415)

BAO peak—SDSS DR7

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

subset	D	R	ref
LRGs:			
dim	61899	3082871	Kazin2010 arXiv:0908.2598
bright	30272	1521736	Kazin2010
superclusters:			
dim + bright	235		NH2013 arXiv:1310.2791
$z < 0.6$	2701		Liivamägi arXiv:1012.1989
voids:			
dim + bright	83		NH2013

BAO peak—SDSS DR7

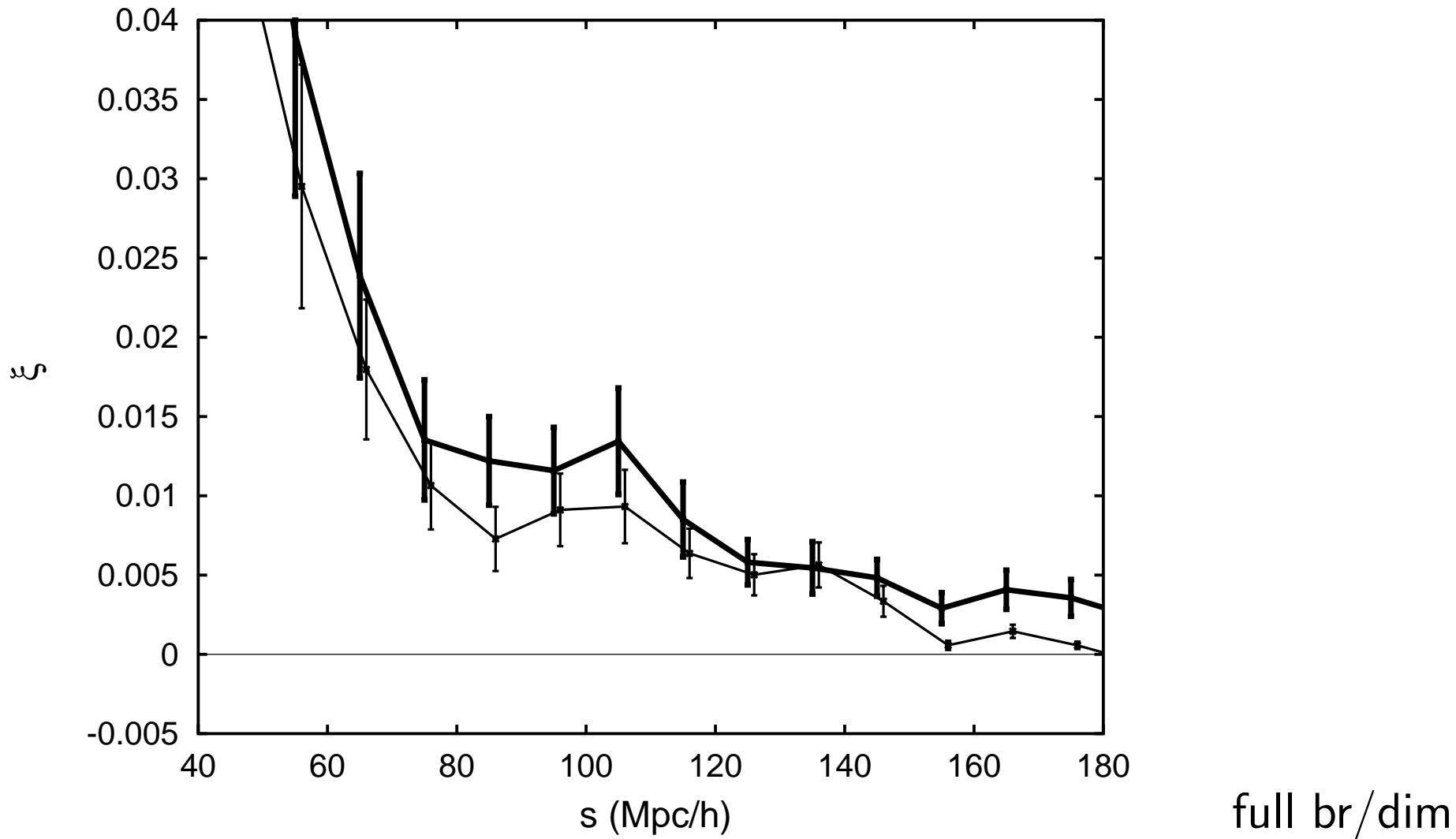
Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

subset	D	R	ref
LRGs:			
dim	61899	3082871	Kazin2010 arXiv:0908.2598
bright	30272	1521736	Kazin2010
superclusters:			
dim + bright	235		NH2013 arXiv:1310.2791
$z < 0.6$	2701		Liivamägi arXiv:1012.1989
voids:			
dim + bright	83		NH2013

$$\xi(s) = \frac{\text{DD}(s)/N_{\text{DD}} - 2\text{DR}(s)/N_{\text{DR}} + \text{RR}(s)/N_{\text{RR}}}{\text{RR}(s)/N_{\text{RR}}}$$

BAO peak—SDSS DR7

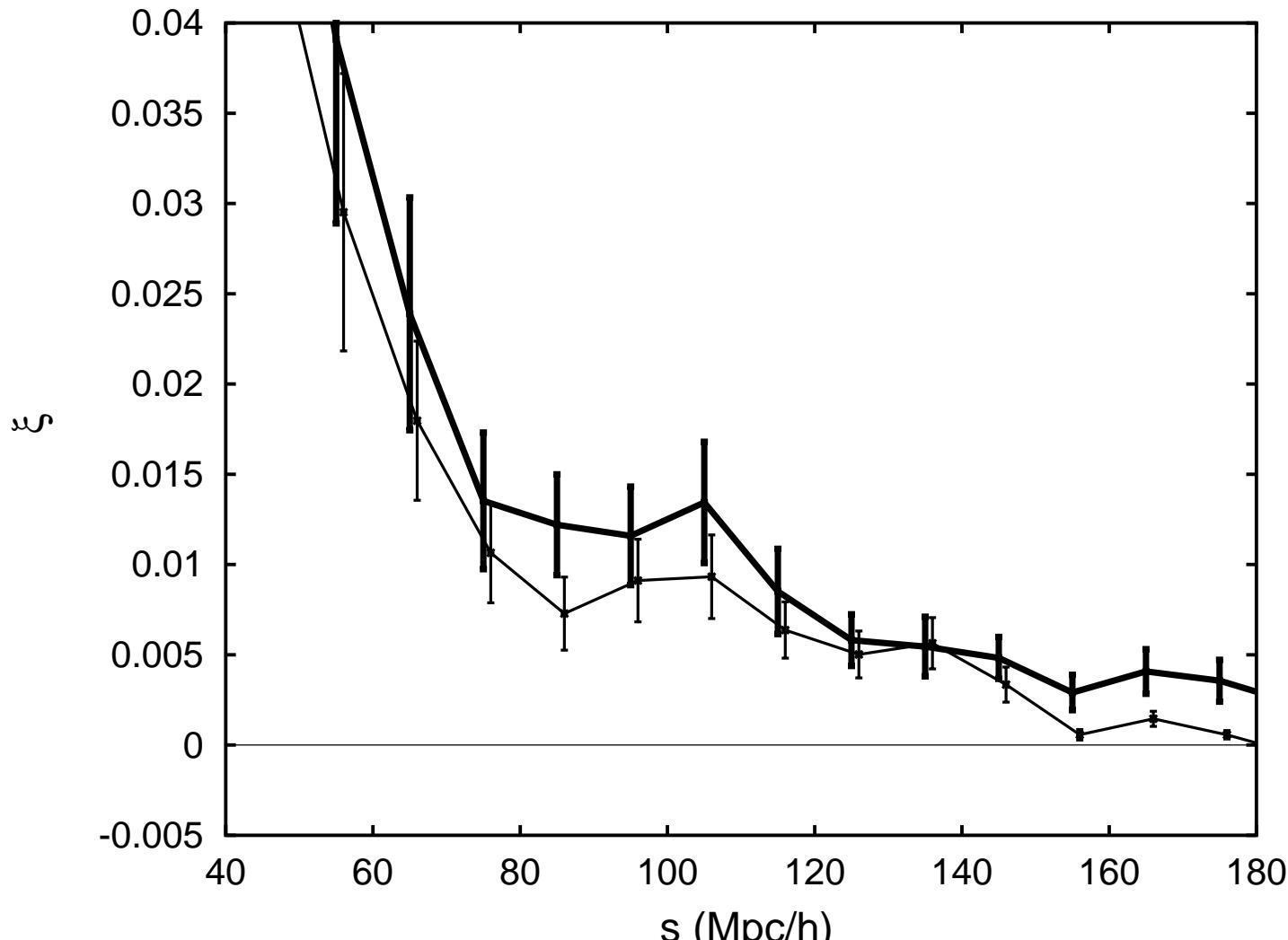
Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



full br/dim

BAO peak—SDSS DR7

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

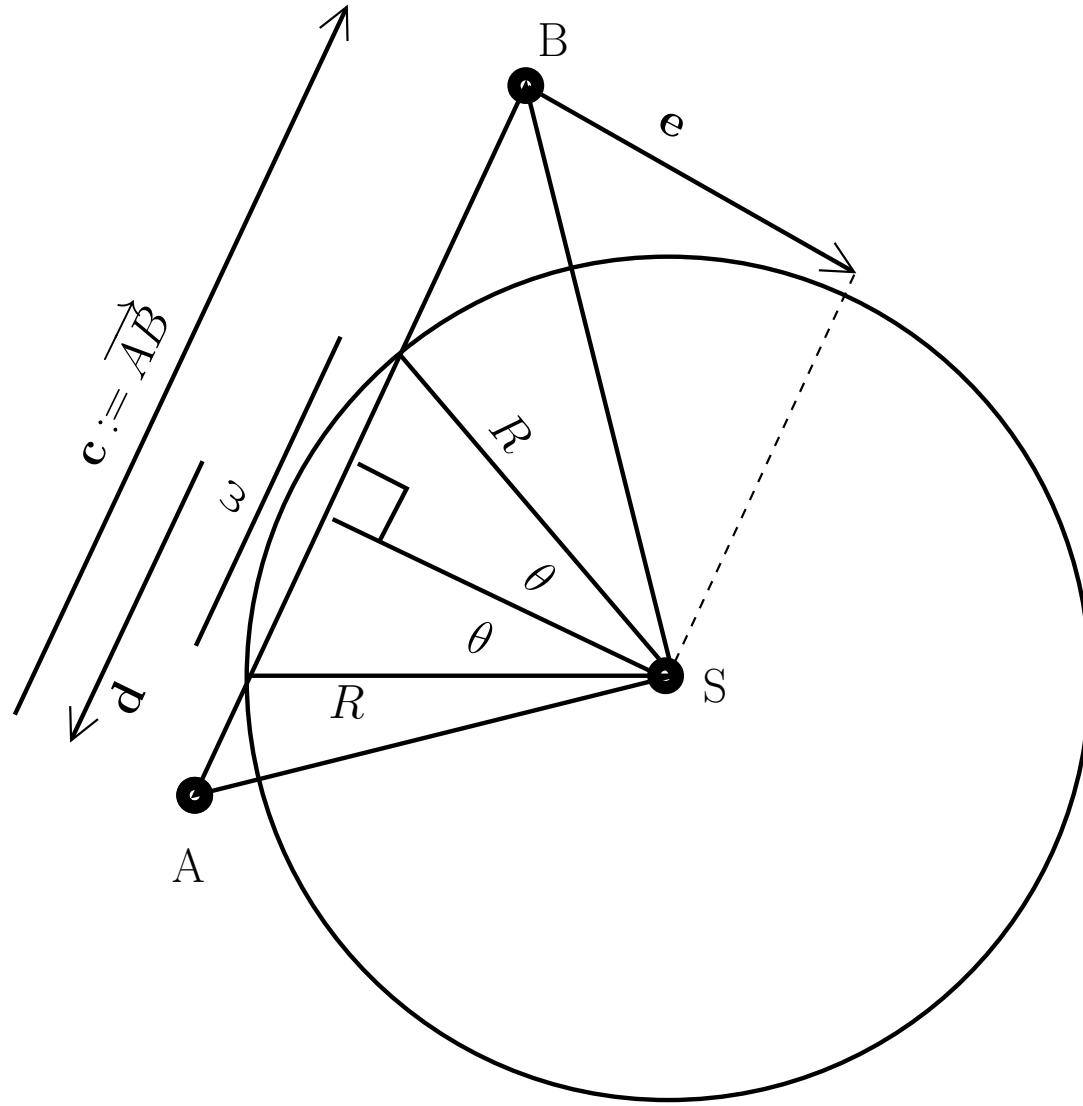


full br/dim

peak better defined in bright (bigger scale) sample

BAO peak—environment

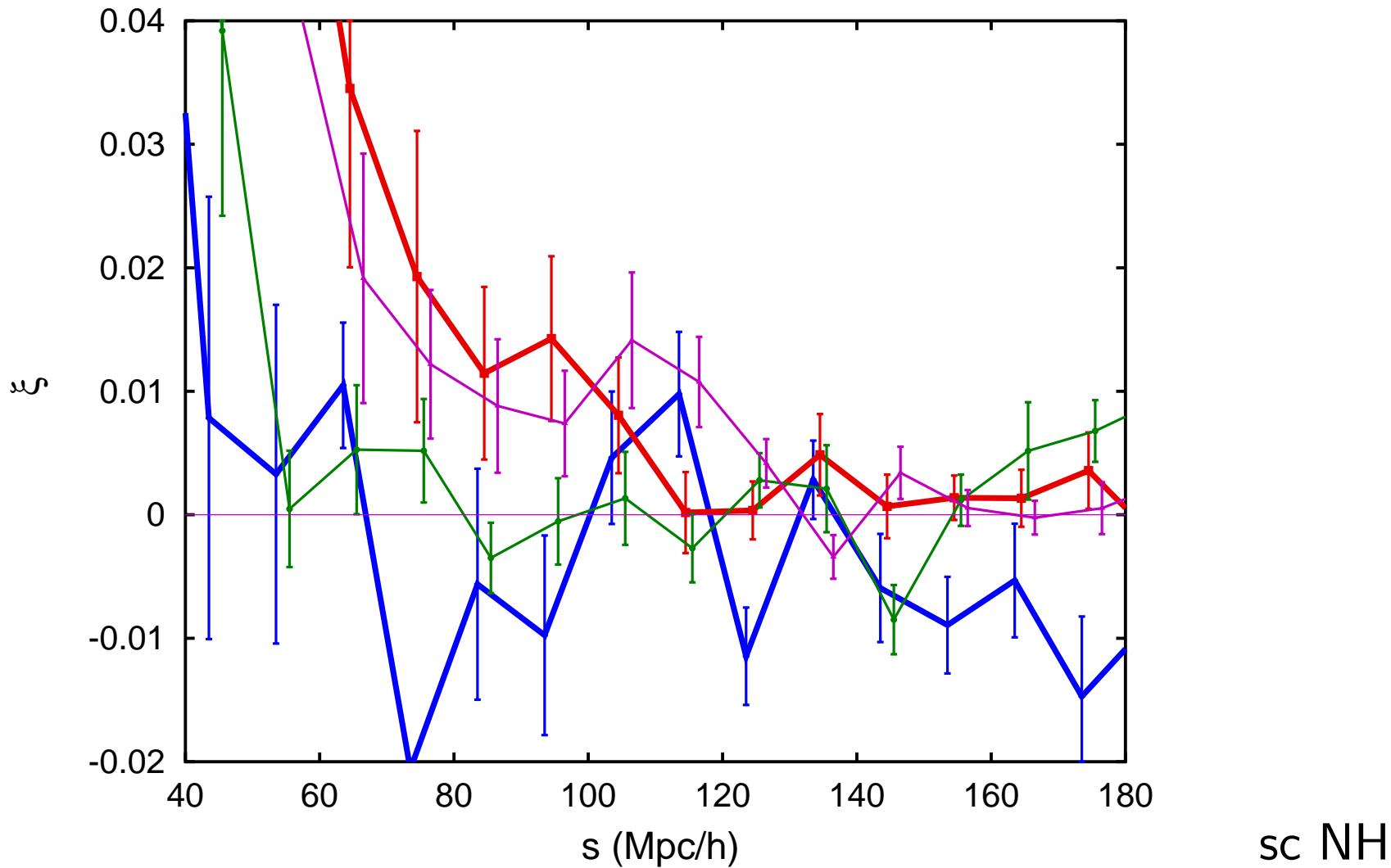
Newt/E — f_{vir} — VA — $\Omega_{\mathcal{R}}^{\text{eff}}$ — ds^2 — d_L^{eff} — • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



overlap defn

BAO peak—environment

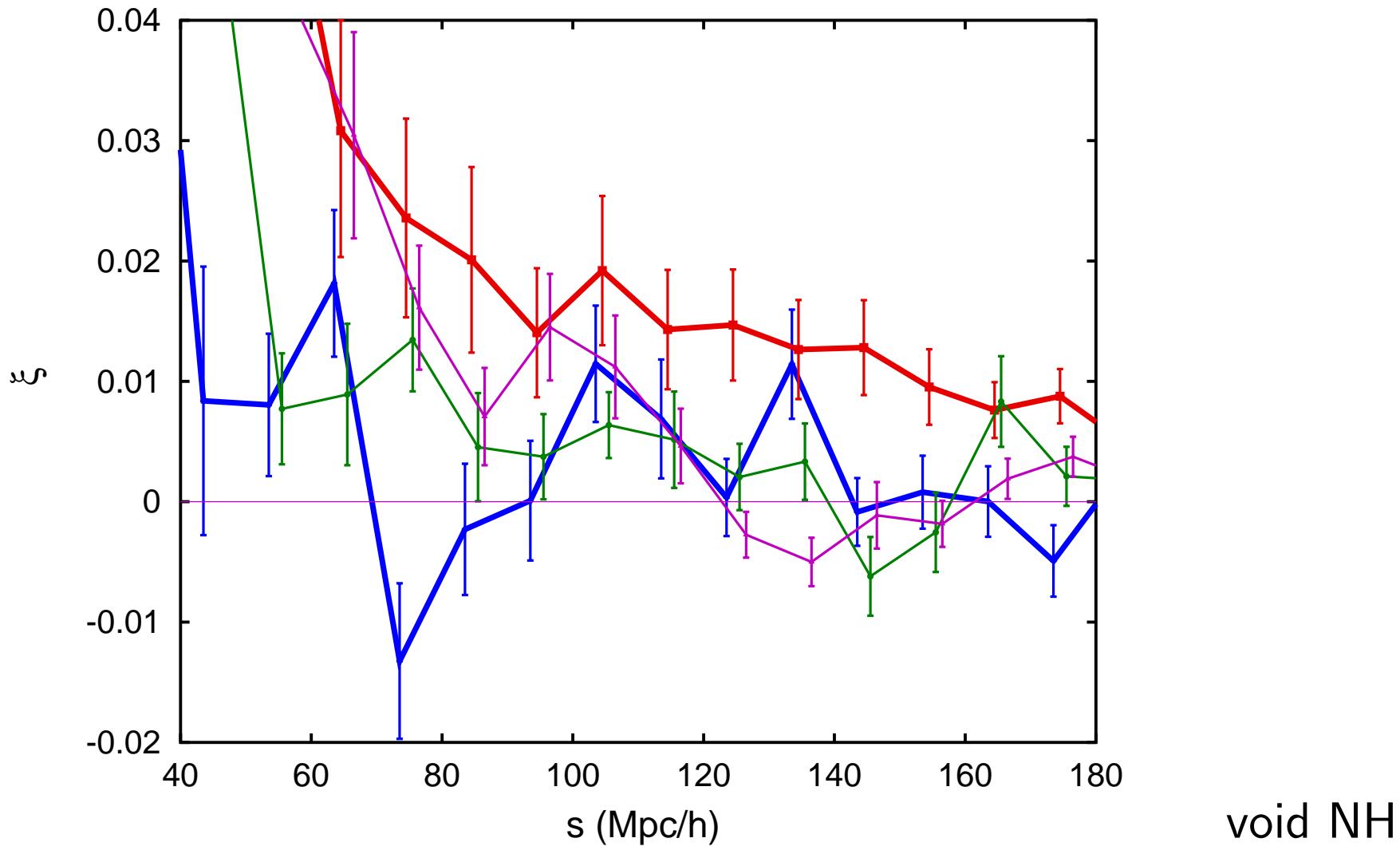
Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



sc NH

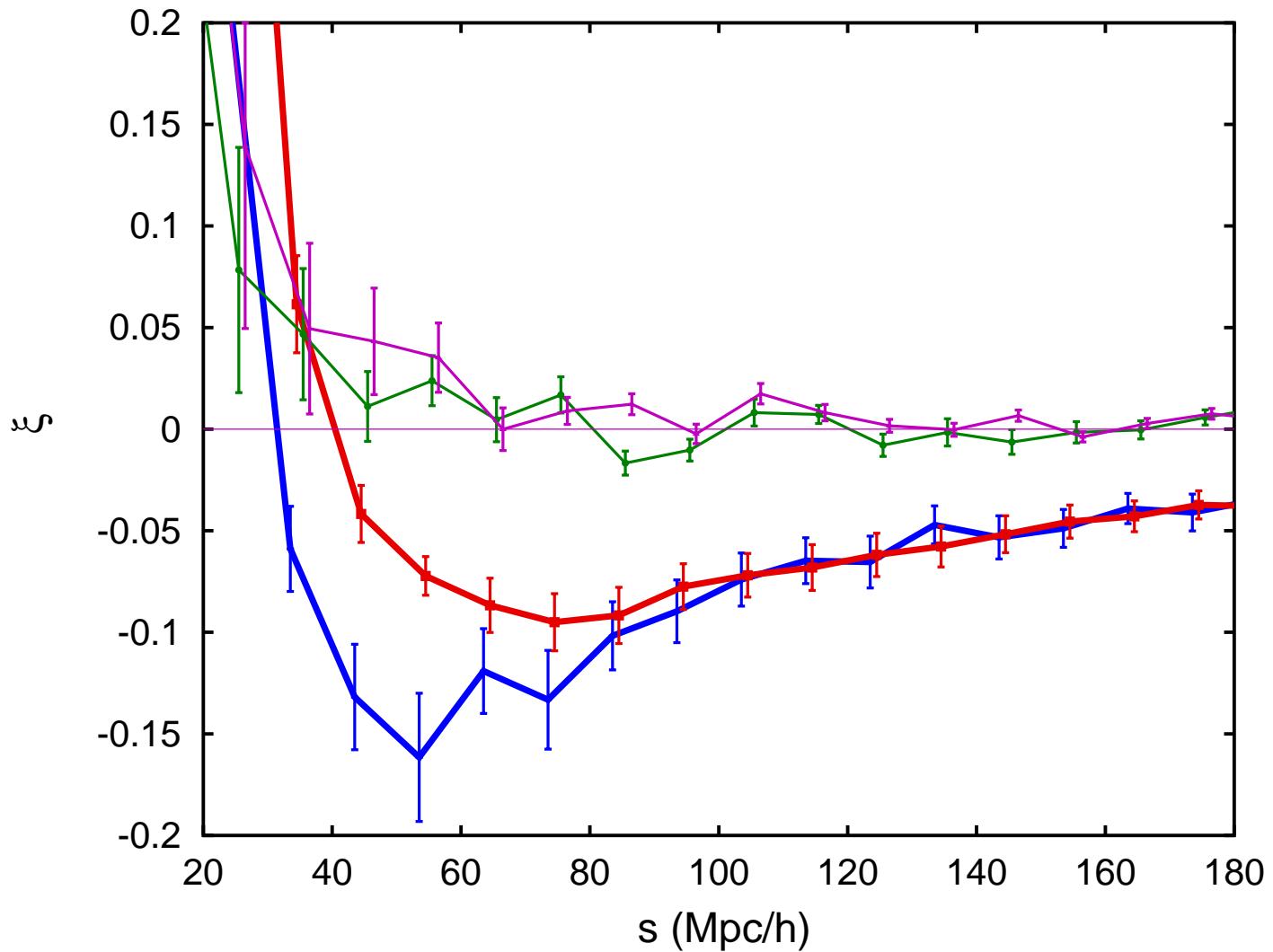
BAO peak—environment

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



BAO peak—environment

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

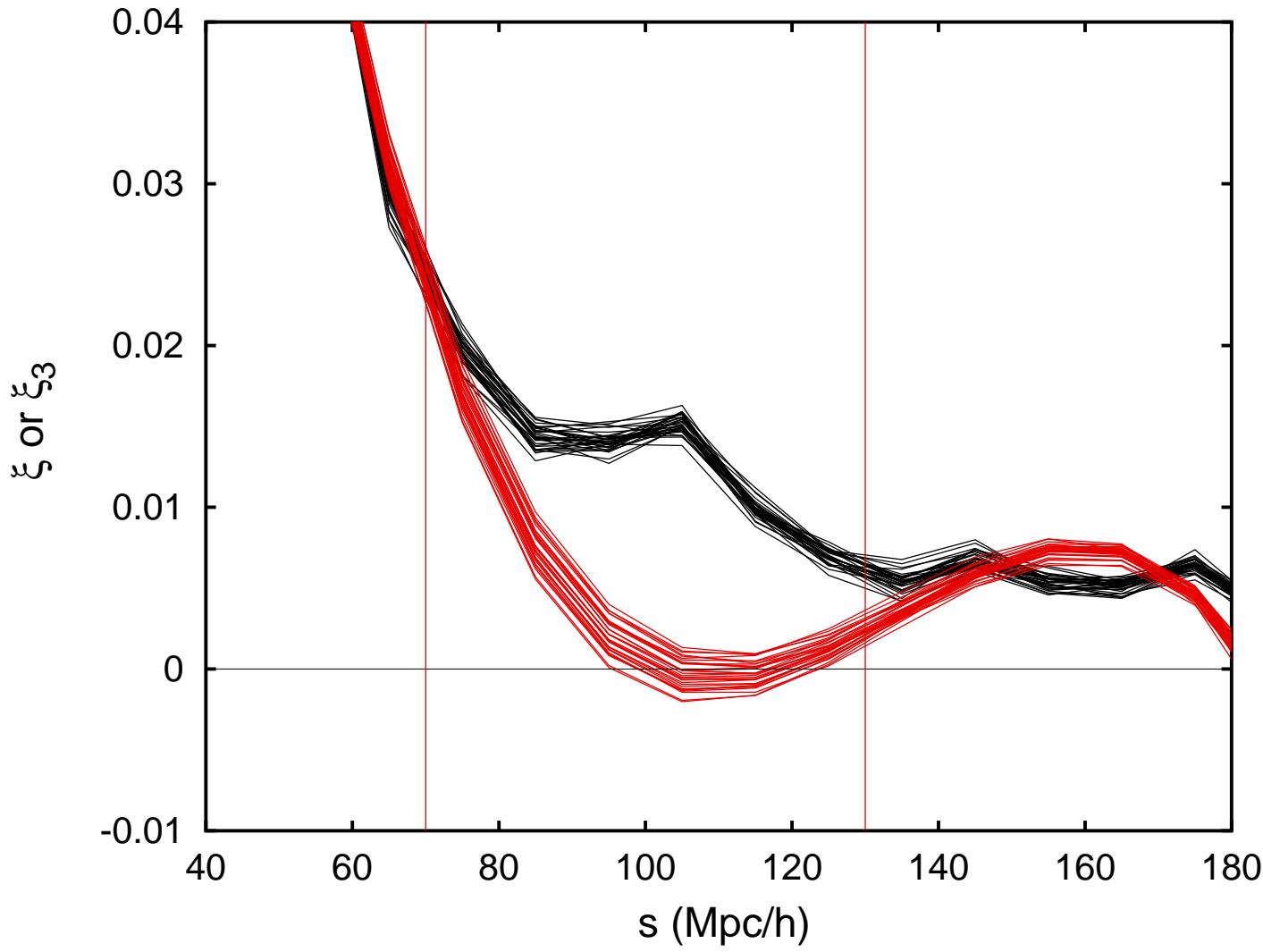


sc Liiva

BAO peak: NH superclusters



Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



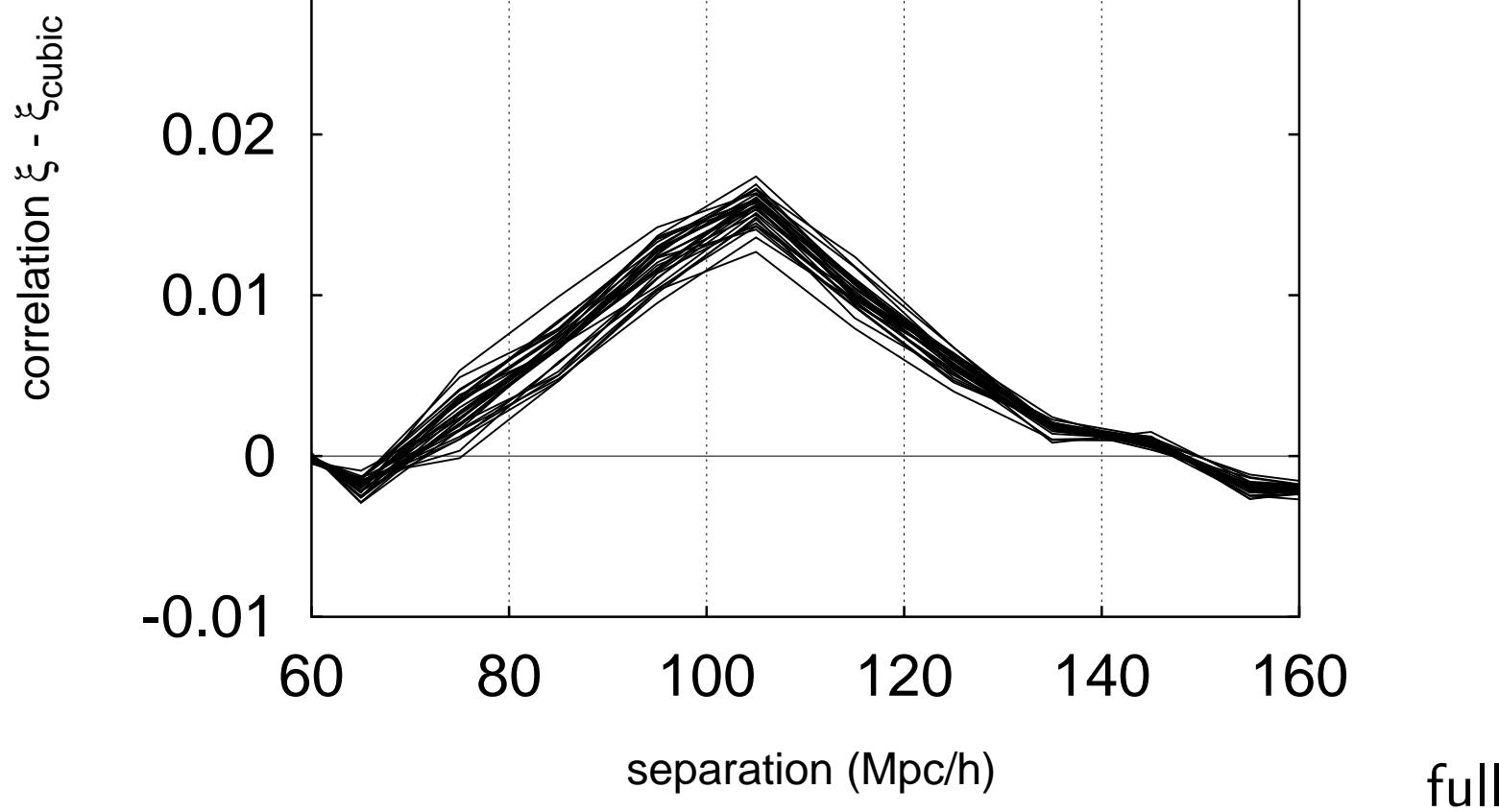
cubical fit ($< 70h^{-1}$ Mpc) \cup ($> 130h^{-1}$ Mpc)



BAO peak: NH superclusters

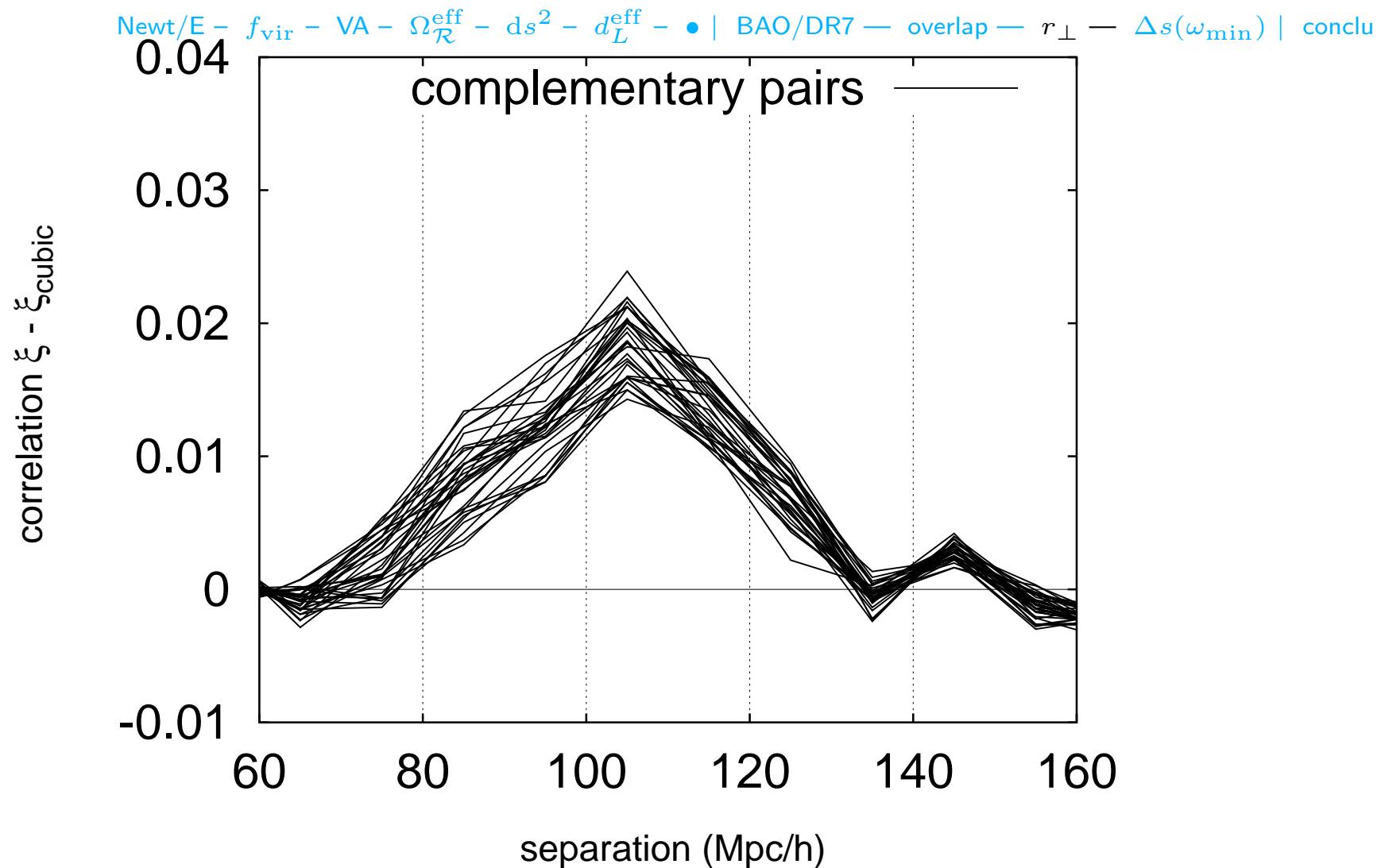


Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



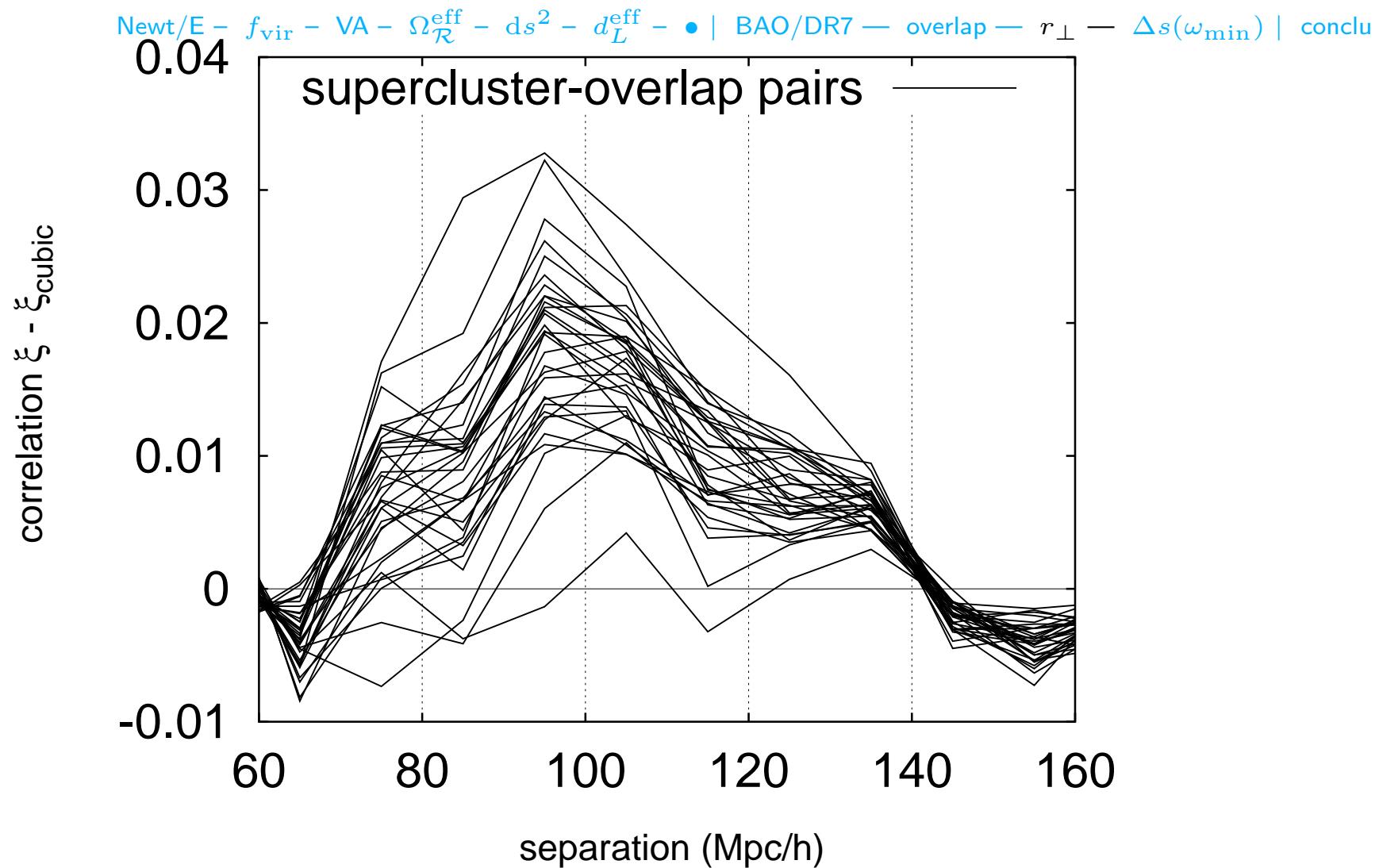
full

BAO peak: NH superclusters



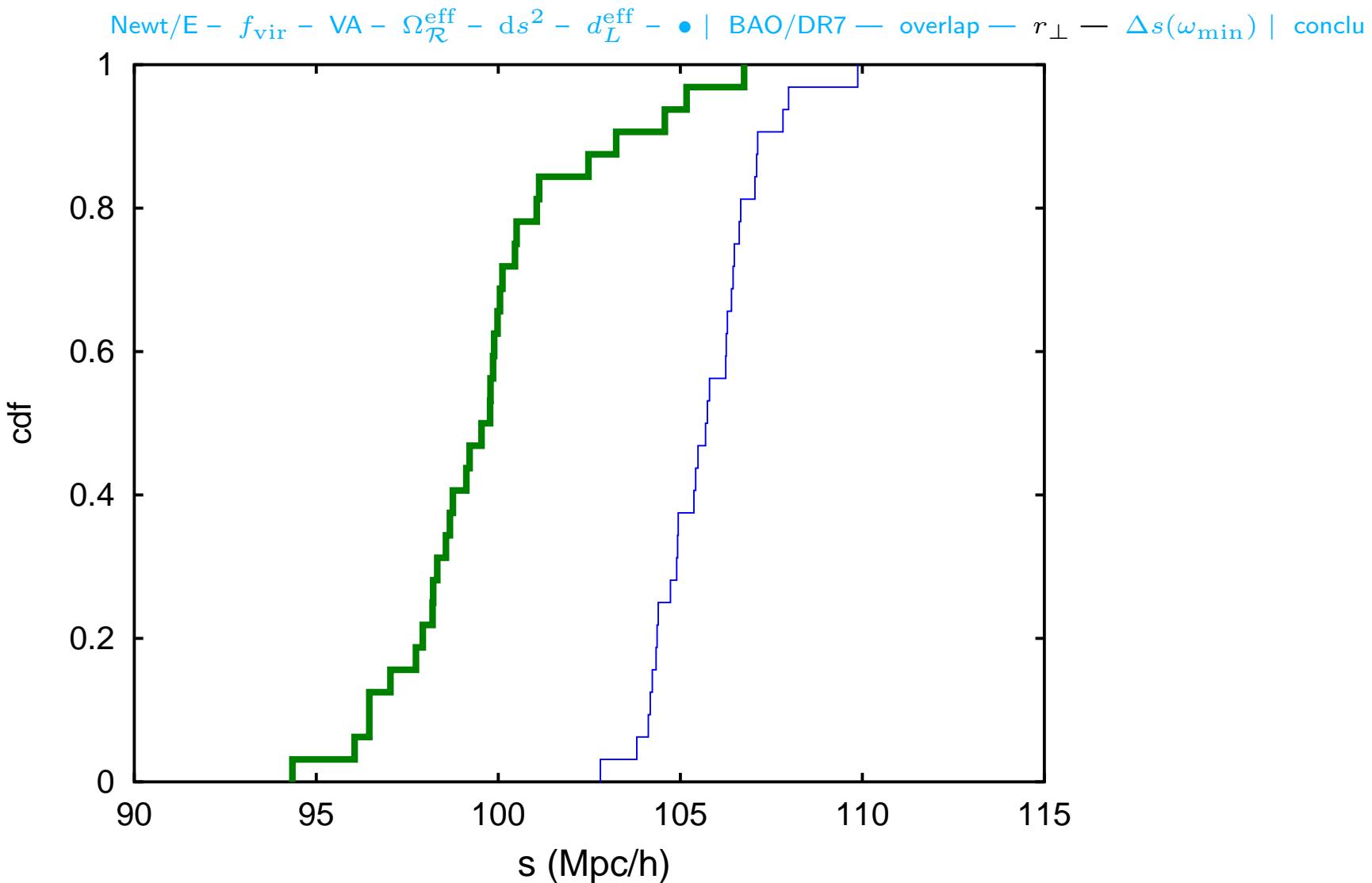
subset: LRG pairs that do **not** overlap with superclusters

BAO peak: NH superclusters

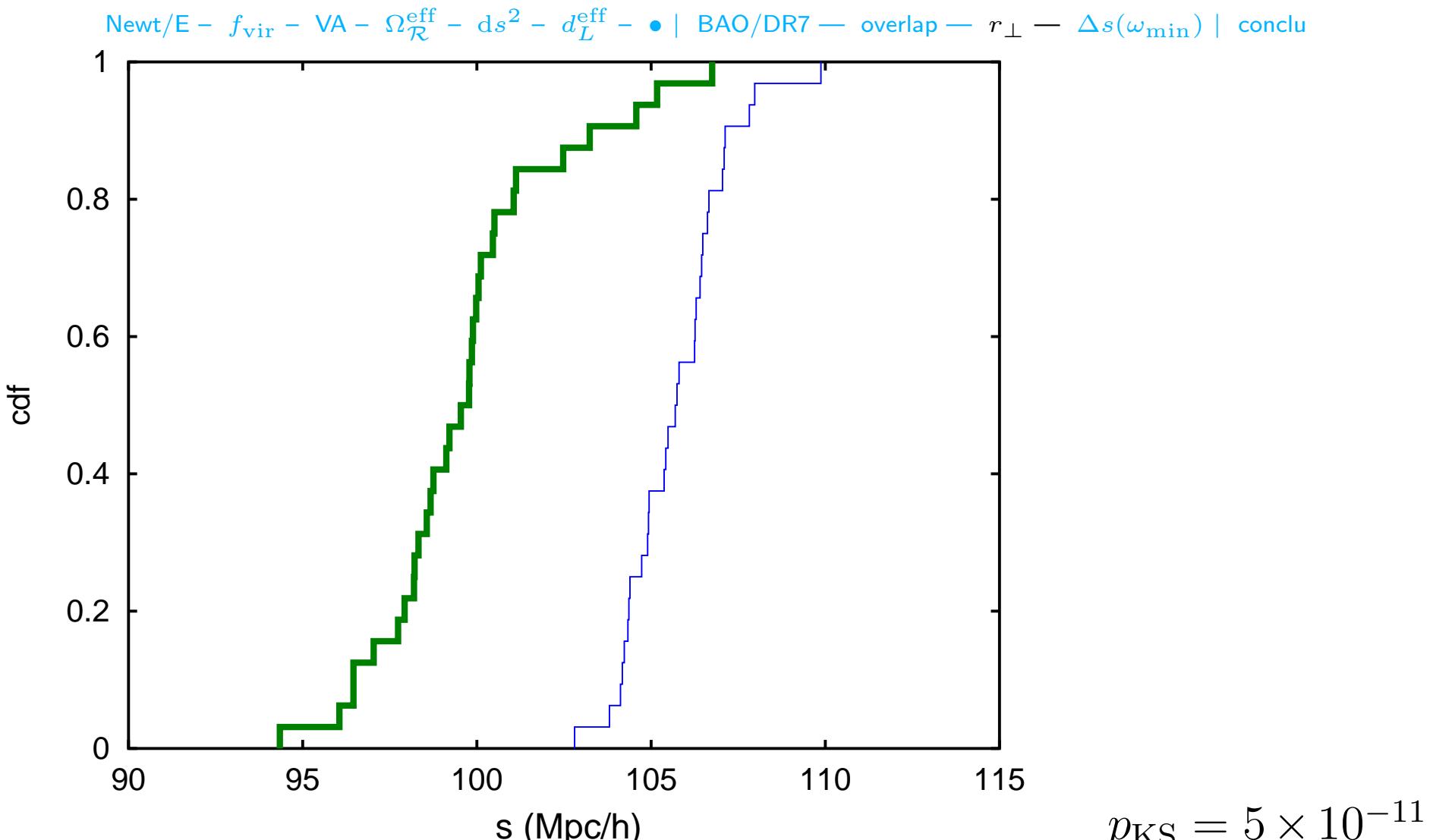


subset: LRG pairs that **overlap** with superclusters

BAO peak: NH superclusters



BAO peak: NH superclusters

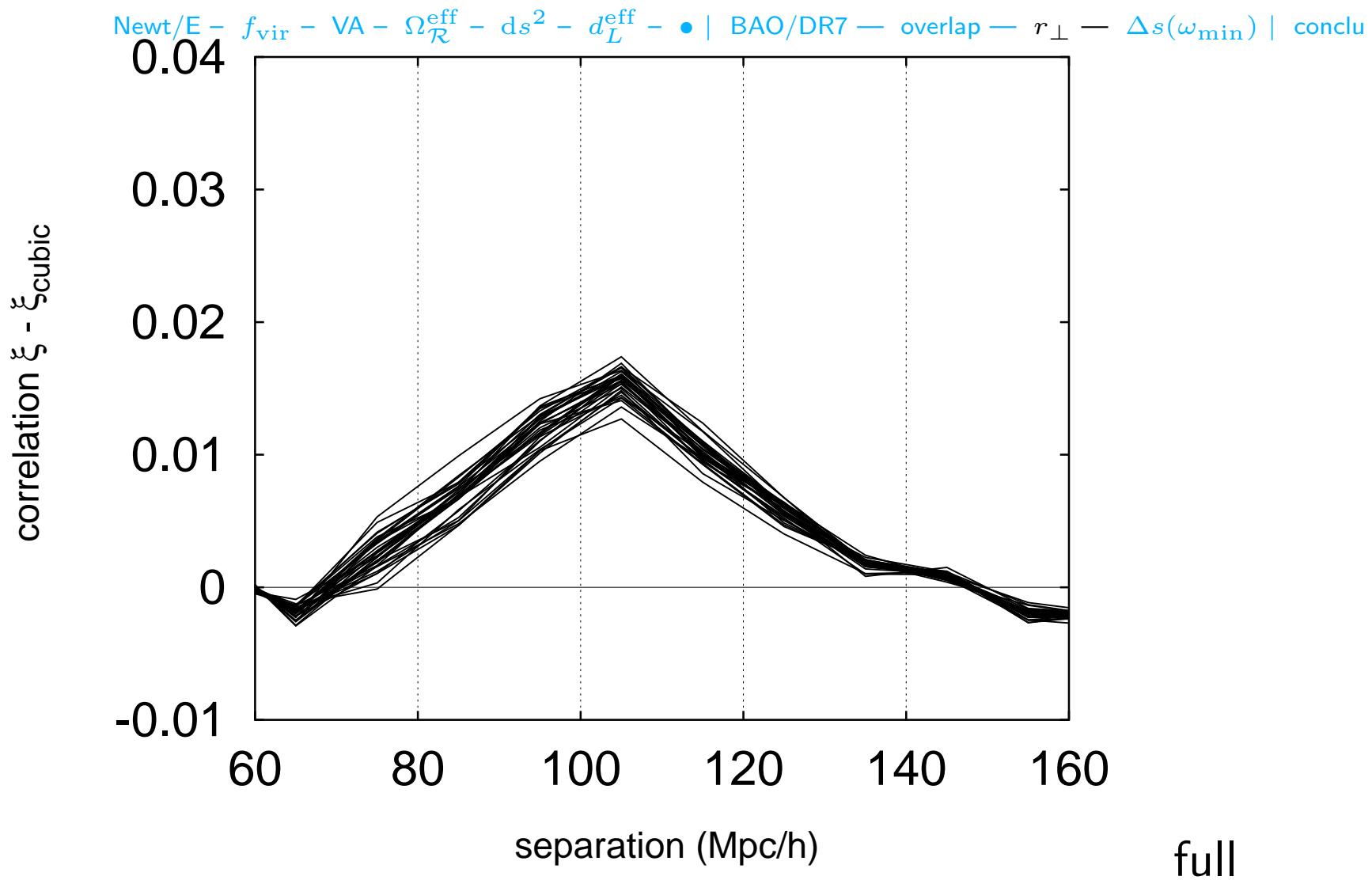


$$p_{\text{KS}} = 5 \times 10^{-11}$$

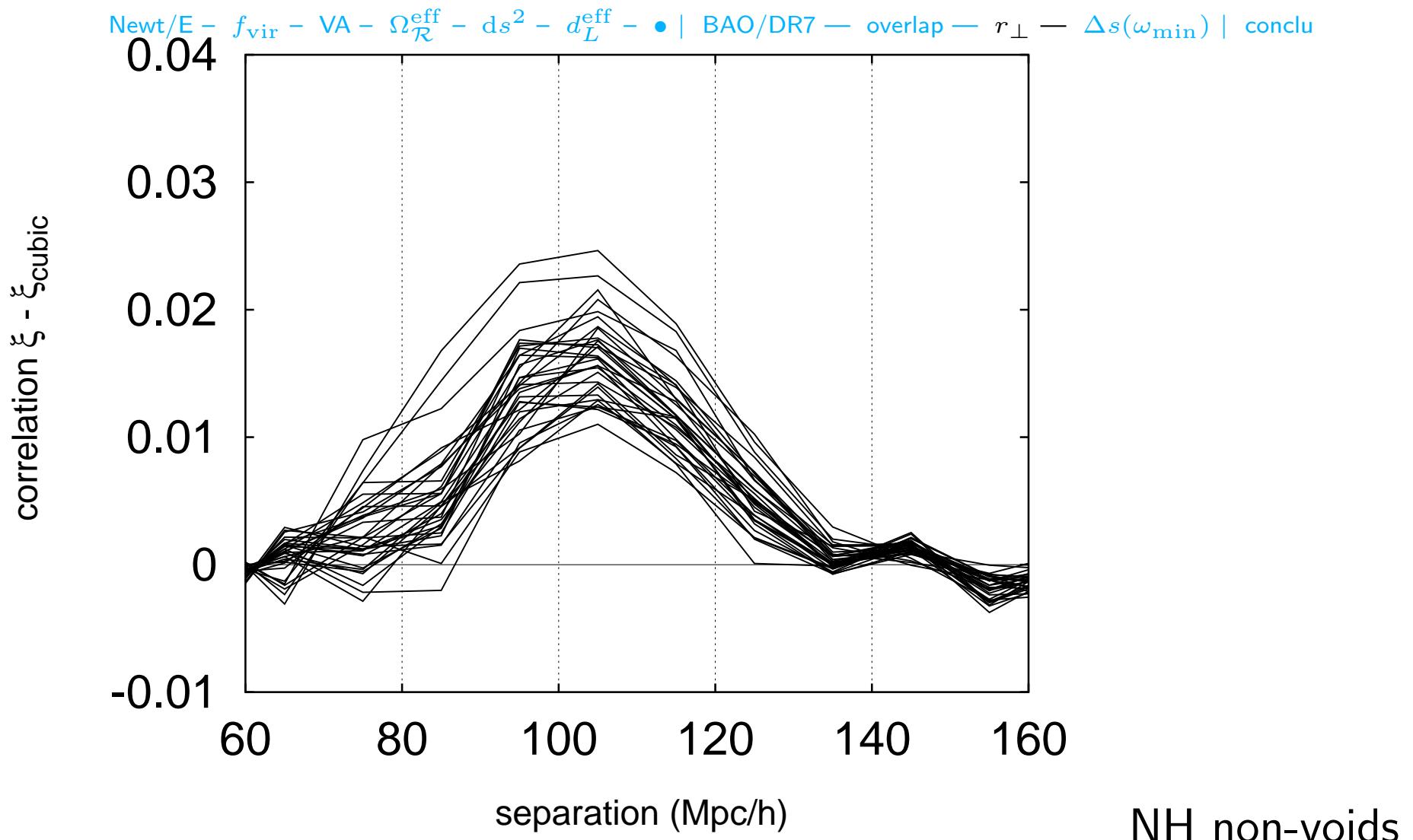
environment-dependent BAO peak shift: 6% for SDSS DR7 LRGs

Roukema, Buchert, Ostrowski & France 2015 MNRAS, 448, 1660

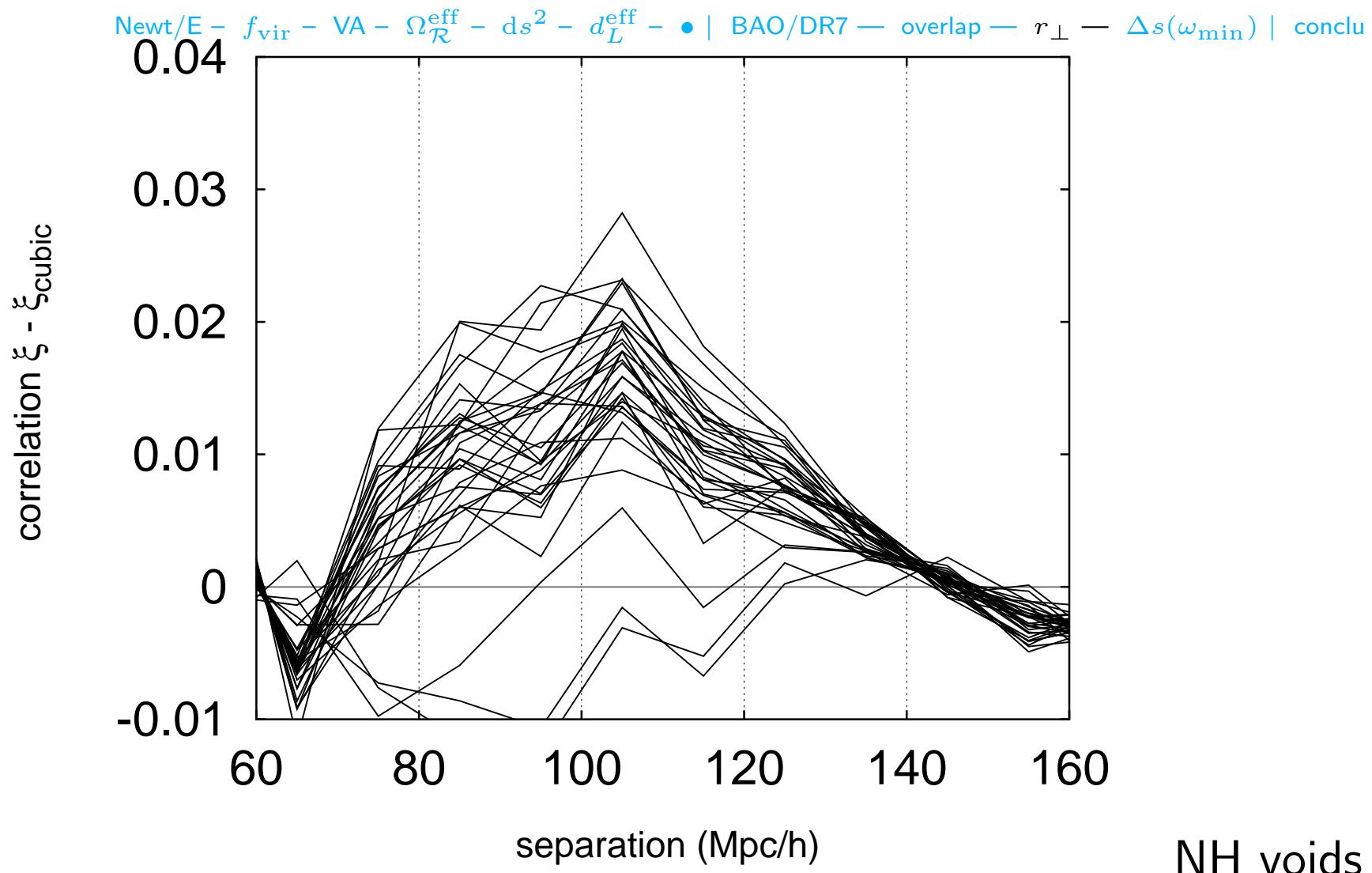
BAO peak: NH voids



BAO peak: NH voids

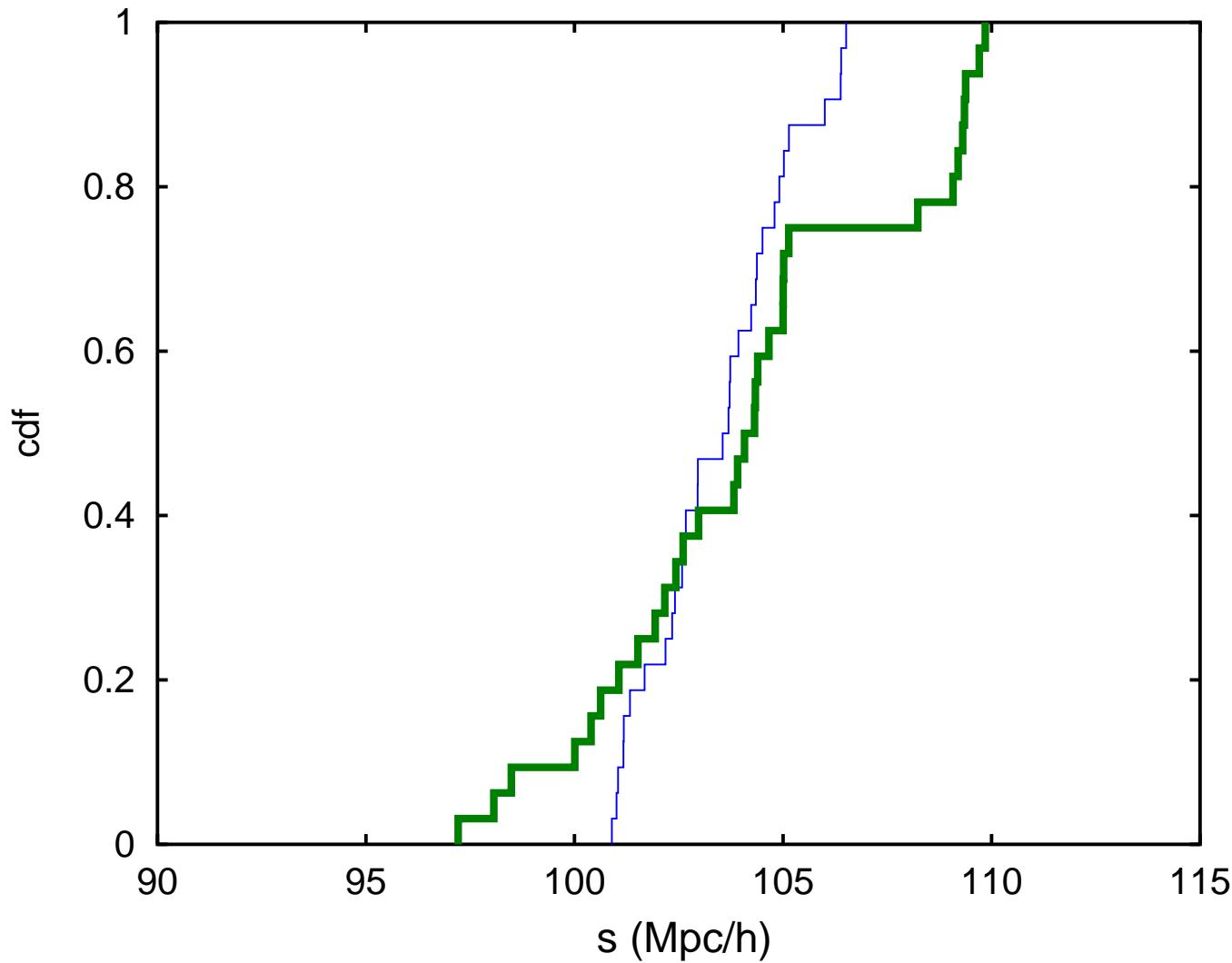


BAO peak: NH voids



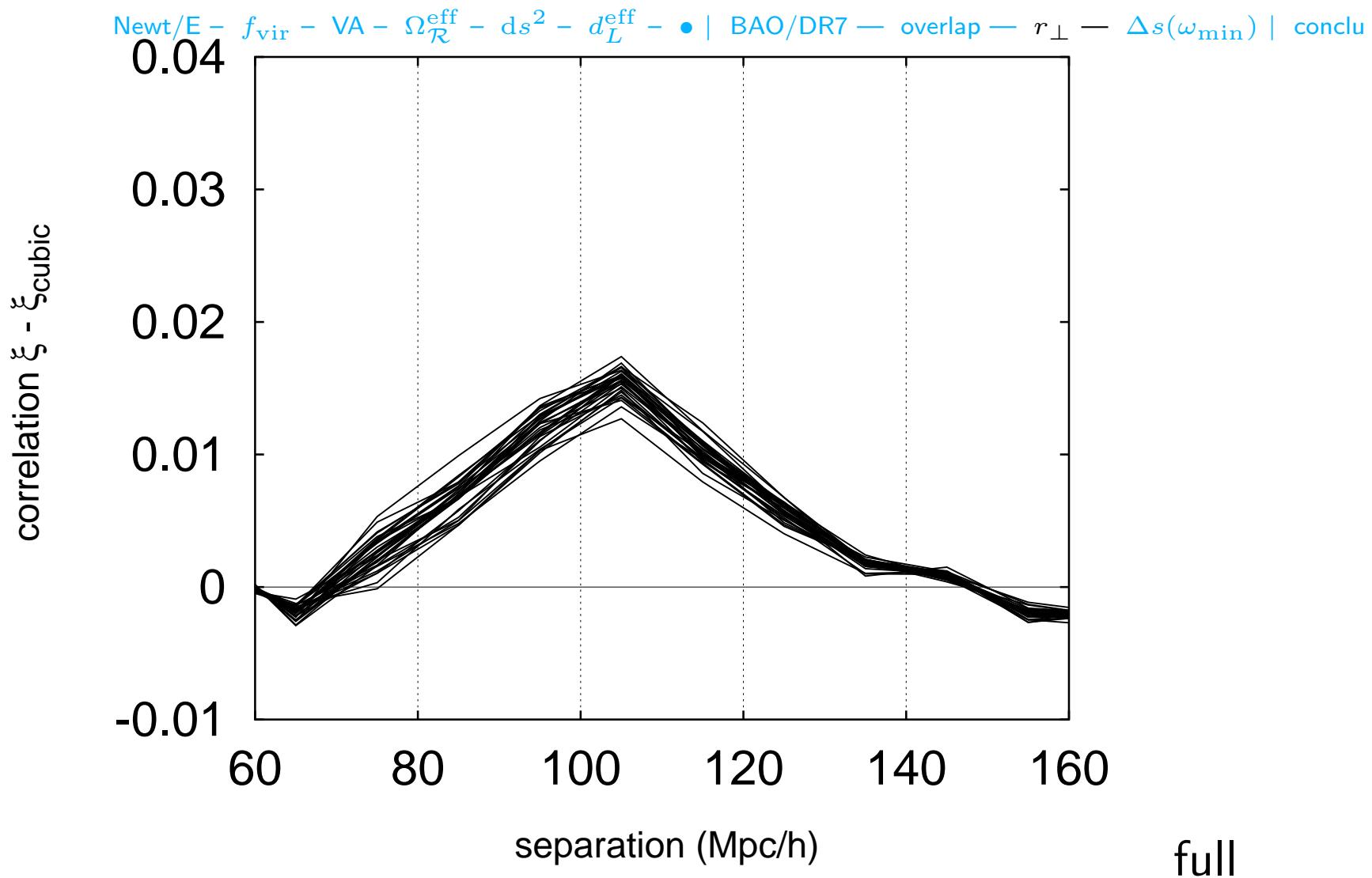
BAO peak: NH voids

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

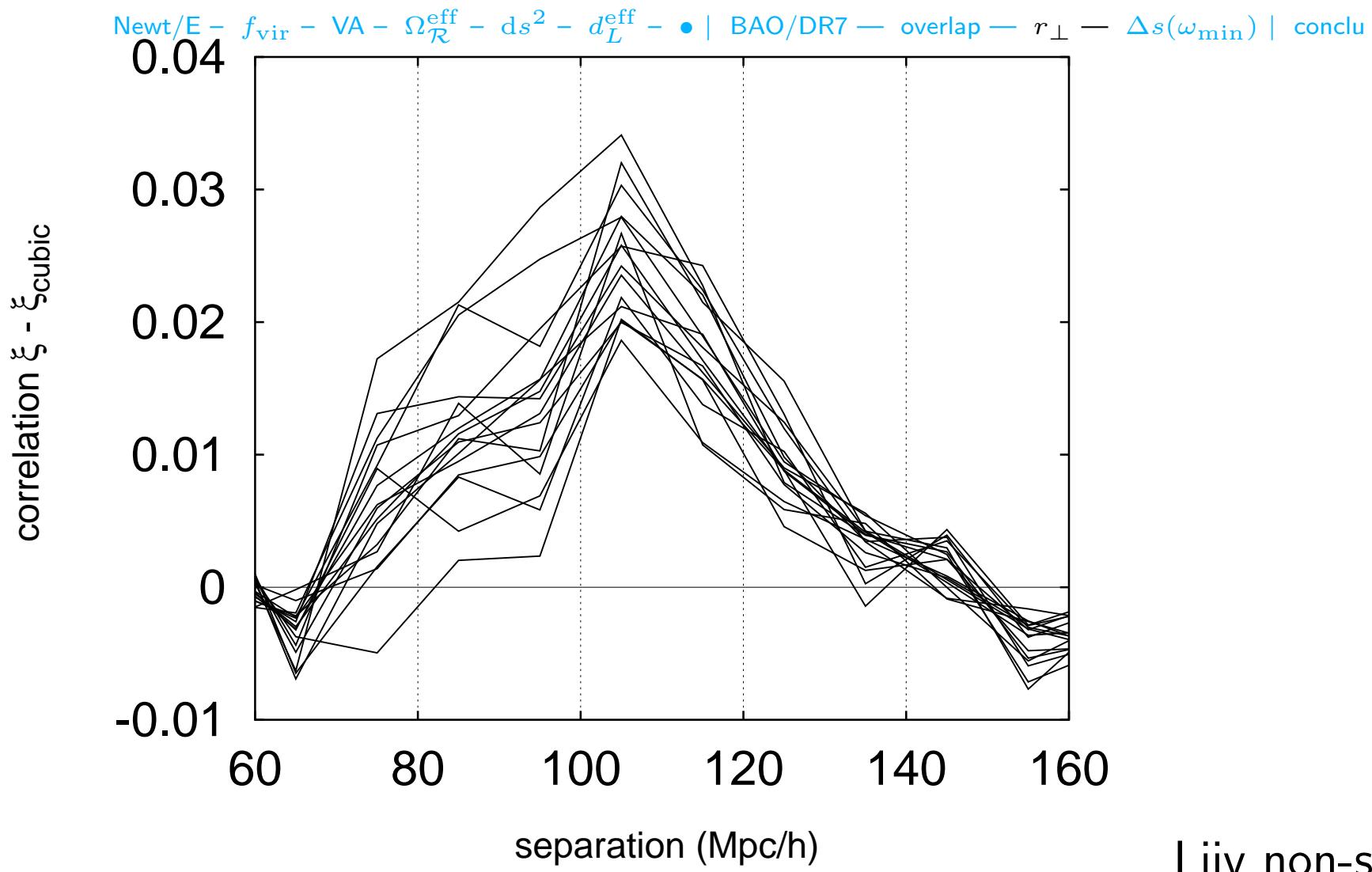


$$p_{\text{KS}} = 0.3$$

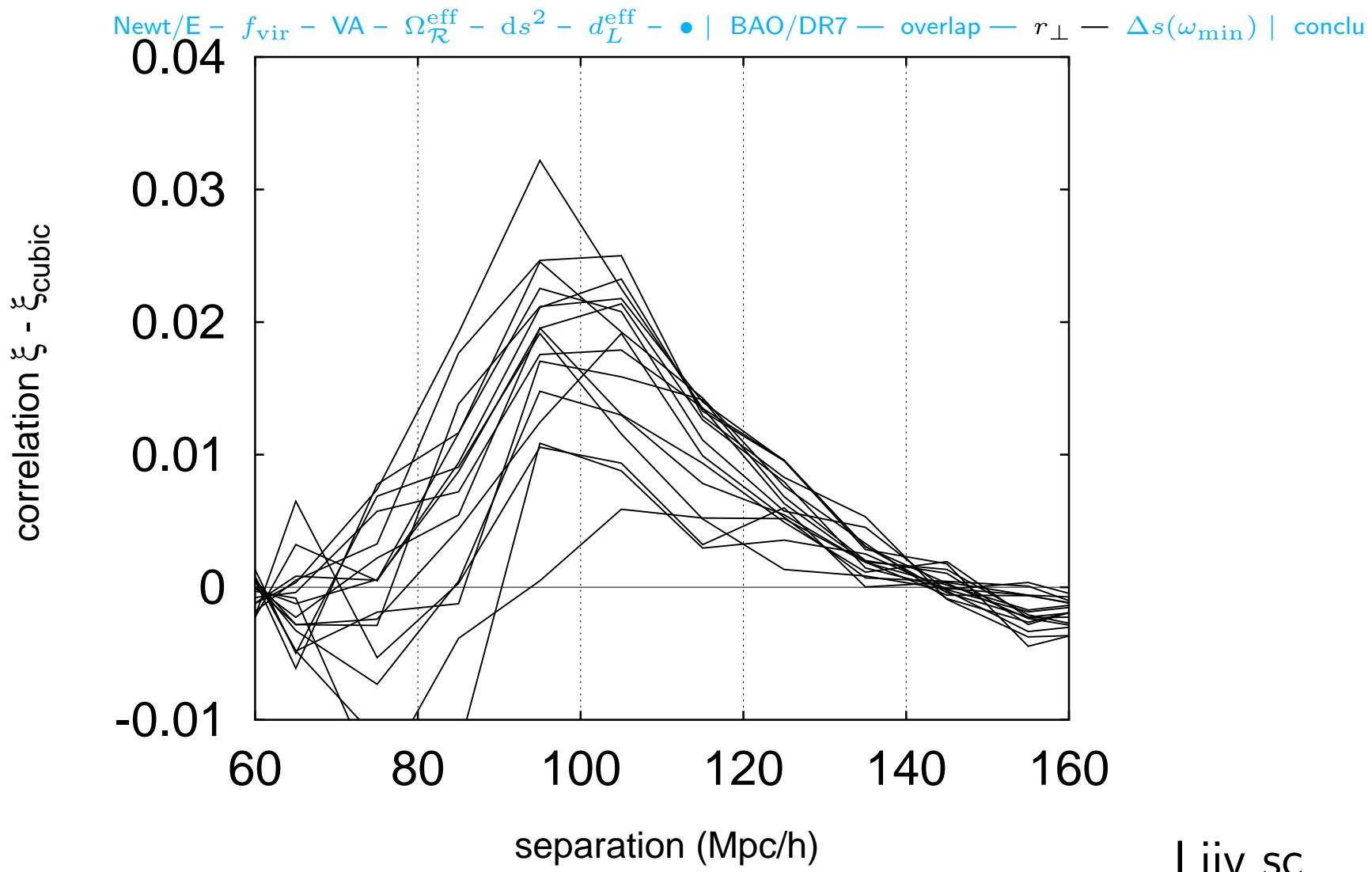
BAO peak: Liivamägi sc's



BAO peak: Liivamägi sc's

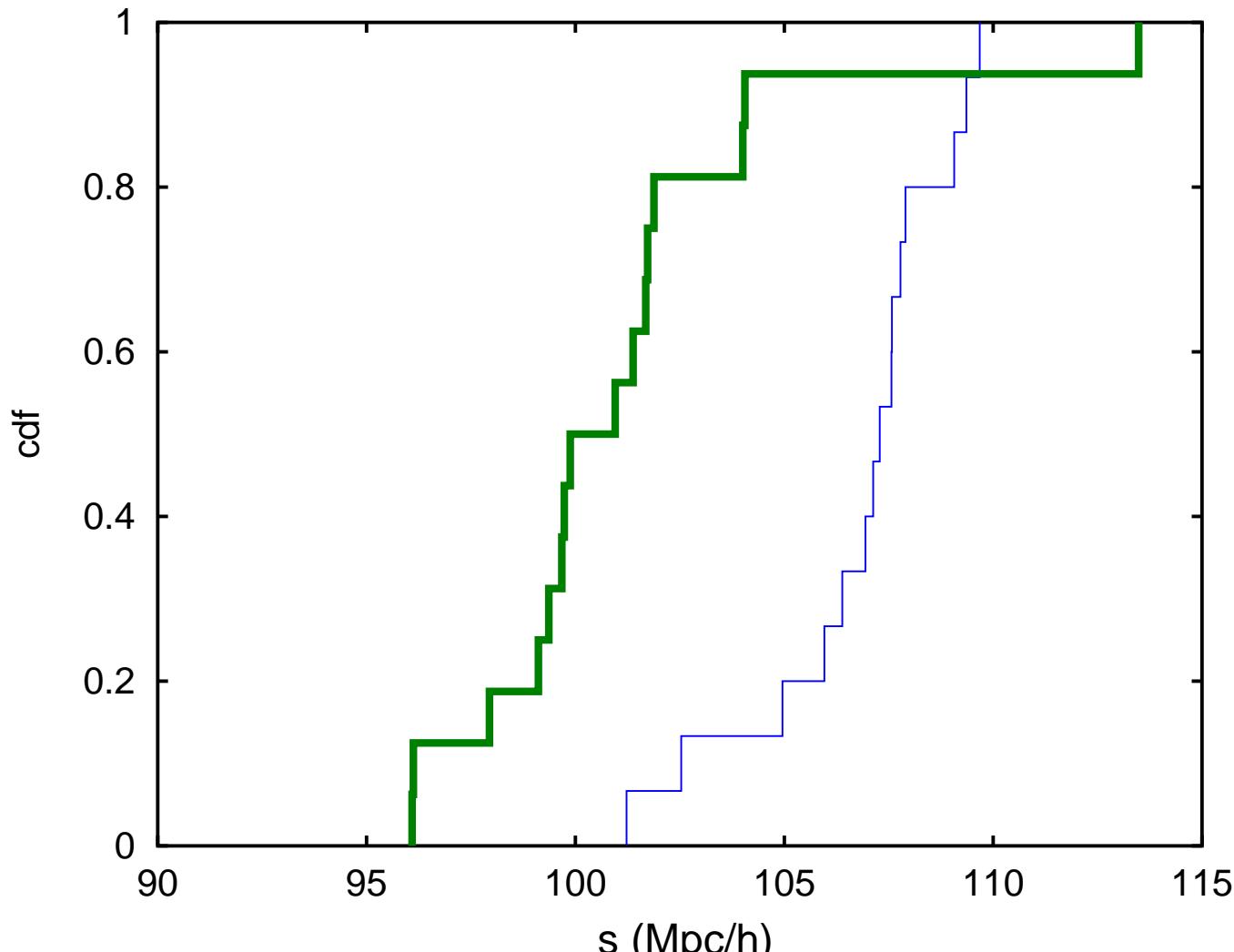


BAO peak: Liivamägi sc's



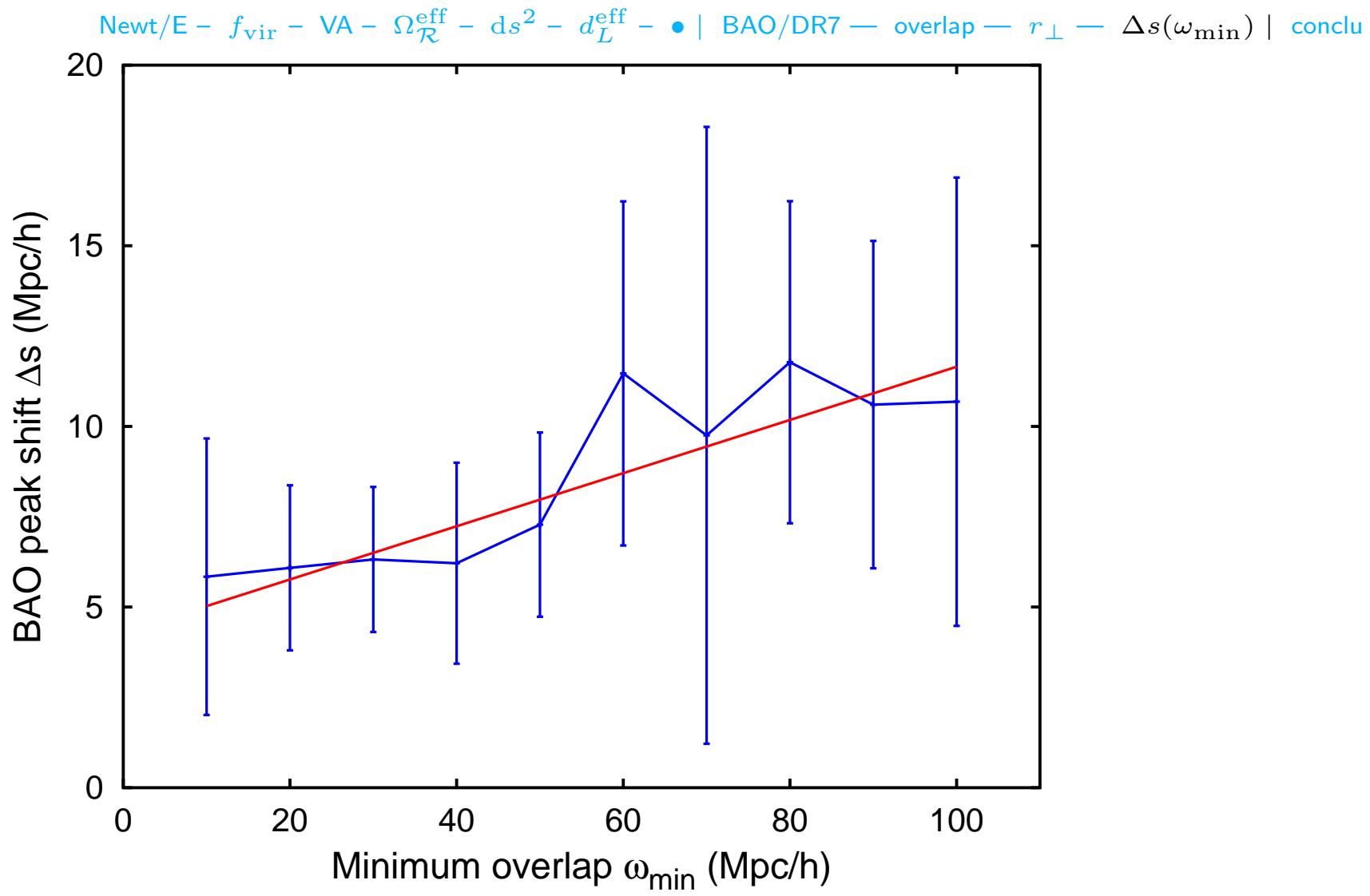
BAO peak: Liivamägi sc's

Newt/E - f_{vir} - VA - $\Omega_{\mathcal{R}}^{\text{eff}}$ - ds^2 - d_L^{eff} - ● | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl



$$p_{\text{KS}} = 3 \times 10^{-5}$$

$\Delta s(\omega_{\min})$ relation



Roukema, Buchert, Fujii & Ostrowski 2015

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$
- effect too noisy for void-overlapping pairs

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | concl

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$
- effect too noisy for void-overlapping pairs
- unpredicted in FLRW; expected from scalar averaging

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$
- effect too noisy for void-overlapping pairs
- unpredicted in FLRW; expected from scalar averaging
- **Roukema, Buchert, Ostrowski & France 2015 MNRAS, 448, 1660**

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$
- effect too noisy for void-overlapping pairs
- unpredicted in FLRW; expected from scalar averaging
- **Roukema, Buchert, Ostrowski & France 2015 MNRAS, 448, 1660;**
Roukema, Buchert, Fujii & Ostrowski 2015 arXiv:1506.05478

Summary

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

catalogue	$r_{\perp}^0 - r_{\perp}^{\text{sc}}$	$r_{\perp}^{\text{non-sc}} - r_{\perp}^{\text{sc}}$	$r_{\perp}^0 - r_{\perp}^{\text{void}}$	$r_{\perp}^{\text{non-void}} - r_{\perp}^{\text{void}}$
N&H	4.3 ± 1.6	6.6 ± 2.8	-0.2 ± 4.0	-1.1 ± 5.5
LTS	3.7 ± 2.9	6.3 ± 2.6		all in h^{-1} Mpc

- BAO comoving ruler compressed by $\approx 6\%$ for supercluster-overlapping pairs for $\omega_{\min} = 1 h^{-1}$ Mpc
- similar result for both NH2013 and Liivamägi2012 supercluster catalogues
- Δs increases with ω_{\min} to $\sim 10\%$; $P(\text{no increase}) = 0.0008$
- effect too noisy for void-overlapping pairs
- unpredicted in FLRW; expected from scalar averaging
- **Roukema, Buchert, Ostrowski & France 2015 MNRAS, 448, 1660;**
Roukema, Buchert, Fujii & Ostrowski 2015 arXiv:1506.05478

Green & Wald

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- see Buchert, Carfora, G.F.R. Ellis, Kolb, MacCallum, Ostrowski, Räsänen, Roukema, Andersson, Coley & Wiltshire
[arXiv:1505.07800](https://arxiv.org/abs/1505.07800)

Planck vs homogeneity

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

■ Planck (1303.5076v1) cosmo parameters:

Planck vs homogeneity

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- Planck (1303.5076v1) cosmo parameters:
- high- z : $H_0 = 67.3 \pm 1.2$ (68%; Planck + WMAP polar.)

Planck vs homogeneity

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- Planck (1303.5076v1) cosmo parameters:
- high- z : $H_0 = 67.3 \pm 1.2$ (68%; Planck + WMAP polar.)
low- z : $H_0 = 74.05 \pm 1.6$ (Riess et al. 2011, Freedman et al 2012)
homogeneous model rejected at 3.38σ

Planck vs homogeneity

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- Planck (1303.5076v1) cosmo parameters:
- high- z : $H_0 = 67.3 \pm 1.2$ (68%; Planck + WMAP polar.)
low- z : $H_0 = 74.05 \pm 1.6$ (Riess et al. 2011, Freedman et al 2012)
homogeneous model rejected at 3.38σ (euphemism: “tension”)

Planck vs homogeneity

Newt/E – f_{vir} – VA – $\Omega_{\mathcal{R}}^{\text{eff}}$ – ds^2 – d_L^{eff} – • | BAO/DR7 — overlap — r_{\perp} — $\Delta s(\omega_{\min})$ | conclu

- Planck (1303.5076v1) cosmo parameters:
- high- z : $H_0 = 67.3 \pm 1.2$ (68%; Planck + WMAP polar.)
low- z : $H_0 = 74.05 \pm 1.6$ (Riess et al. 2011, Freedman et al 2012)
homogeneous model rejected at 3.38σ (euphemism: “tension”)