Virialisation-induced curvature vs dark energy

based on: Roukema, Ostrowski, Buchert; arXiv:1303.4444v2 [astro-ph.CO]

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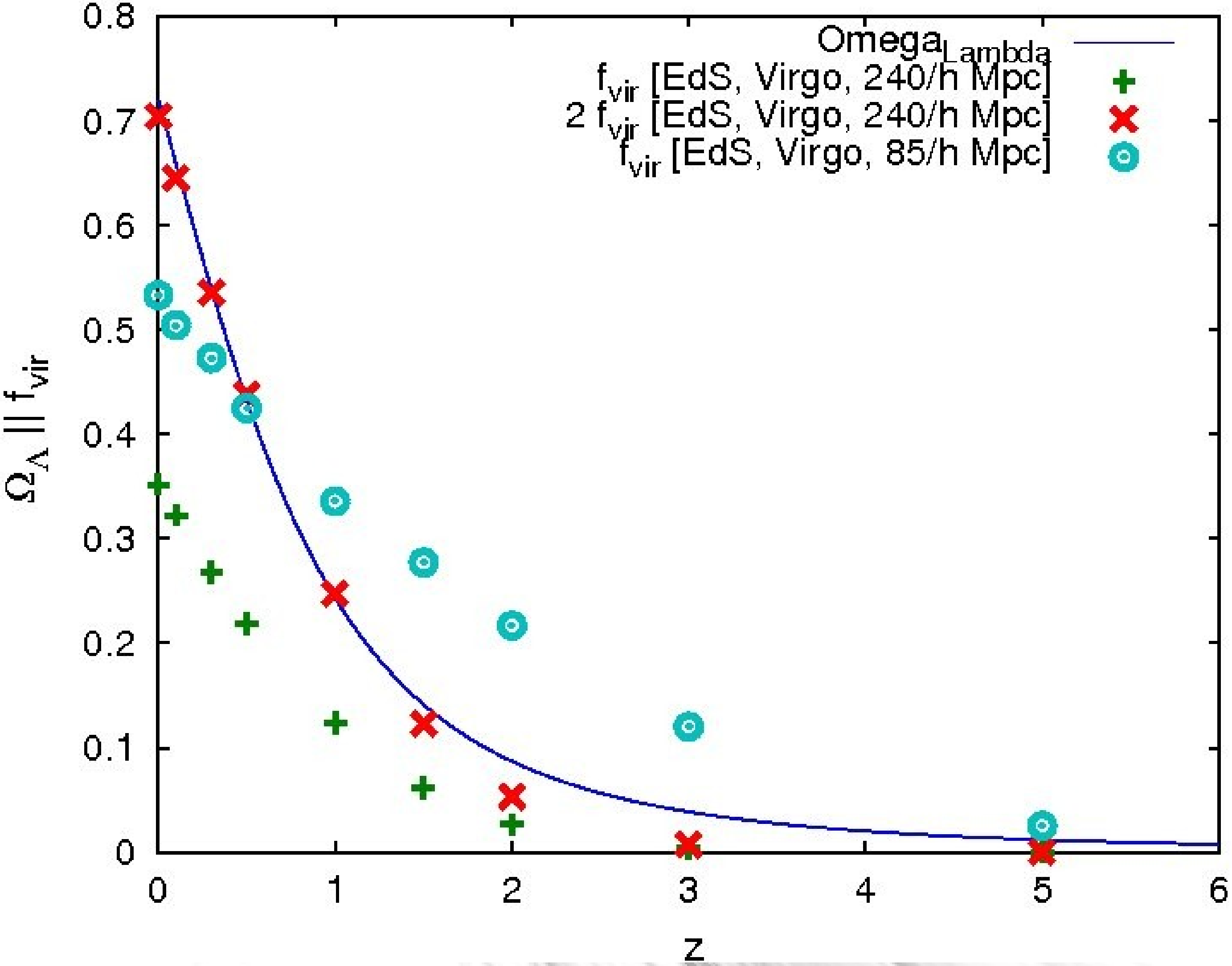
Homogeneous models

- Concordance model: FLRW metric + dark energy + dark matter
- Averaging and evolving in time are in general non-commuting operations

$$\frac{d}{dt}\langle A\rangle_{D_t}-\langle\frac{d}{dt}A\rangle=\langle A\theta\rangle_{D_t}-\langle A\theta\rangle_{D_t}\langle\theta\rangle_{D_t}$$

- FLRW metric – homogeneous expansion
- The FLRW approximation is expected to fail at small distance scales and recent epochs
- We need dark energy or cosmological constant to explain the observations

Universe is inhomogeneous



Buchert's averaging

- 3+1 foliation
- Defining the average and effective scale factor

$$\langle A \rangle_{D_t} = \frac{1}{V_{D_t}} \int_{D_t} A \, d^3x \qquad a_{D_t} = V_{D_t}^{1/3}$$

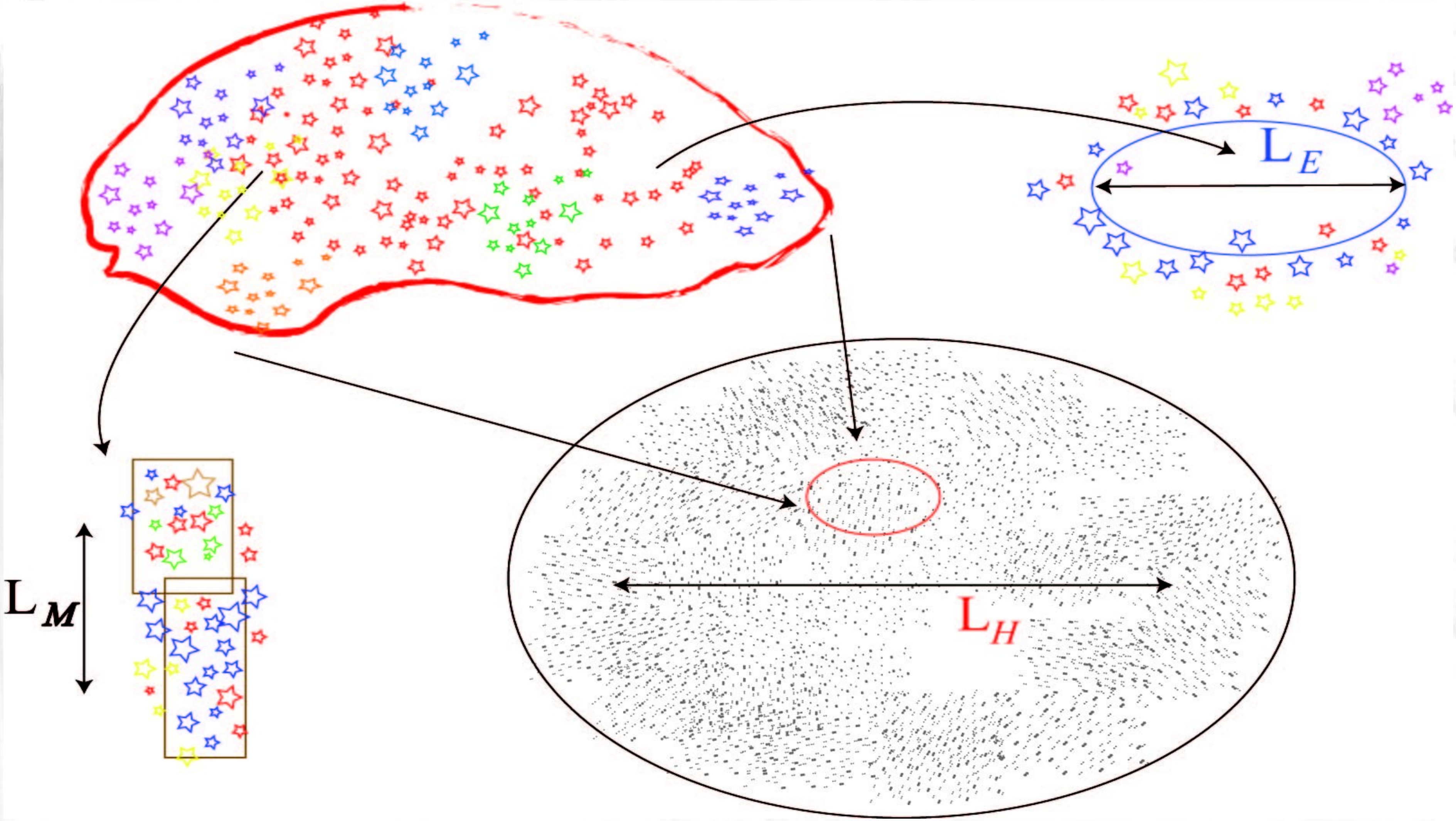
- Averaged Raychaudhuri equation + Hamiltonian constraint

$$\frac{d}{dt}\langle \theta \rangle_D = \Lambda - 4\pi G \langle \rho \rangle_D + \langle II \rangle_D - \langle \theta \rangle_D^2 \qquad 3\mathrm{H}_D^2 + \frac{3\mathrm{k}_D}{a_D^2} = 8\pi G \langle \rho \rangle_D - \frac{1}{2} W_D - \frac{1}{2} Q_D + \Lambda$$

- Backreaction and peculiar curvature

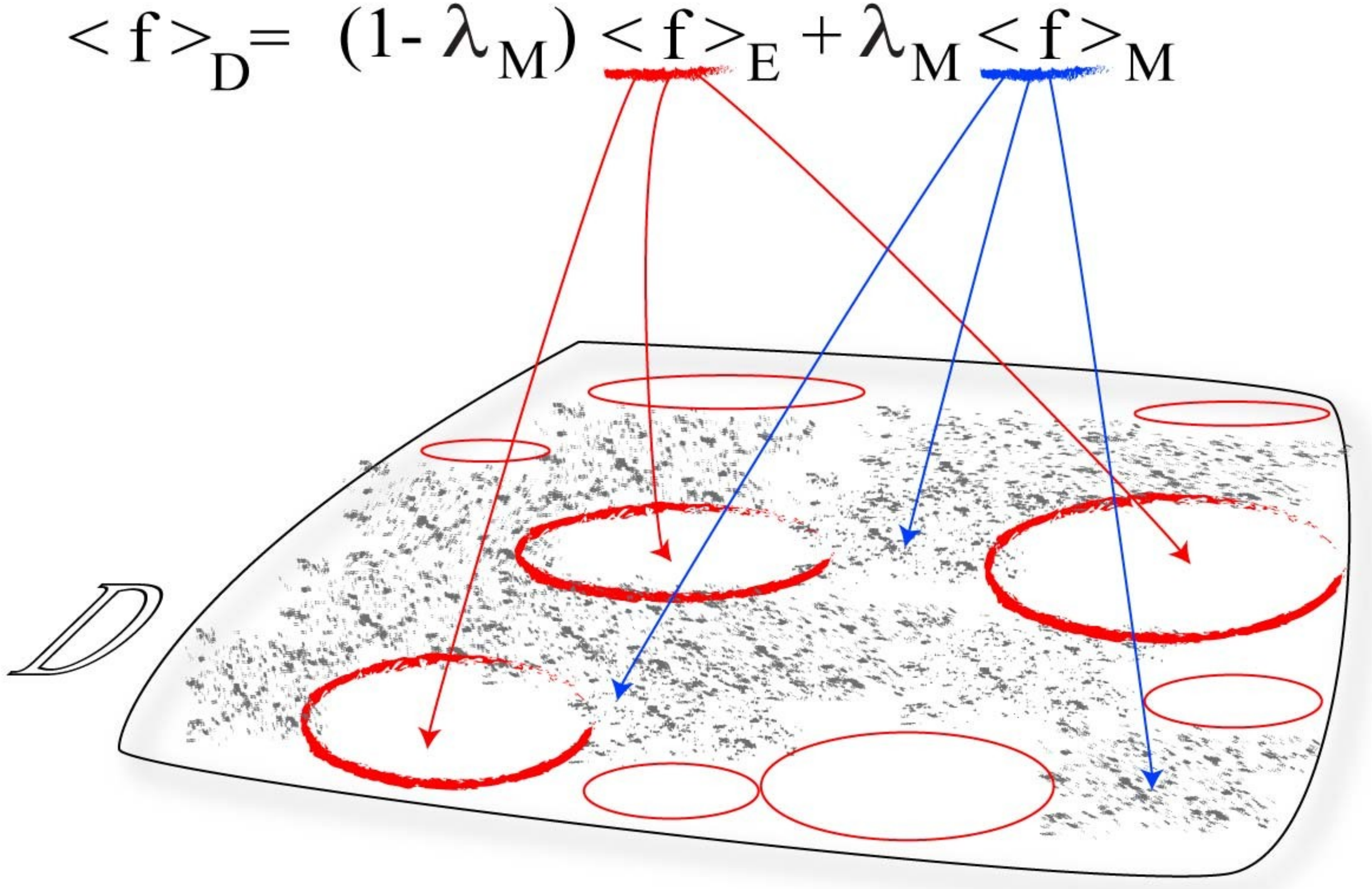
$$Q_{D_t} = \frac{2}{3}(\langle \theta^2 \rangle_{D_t} - \langle \theta \rangle_{D_t}^2) + 2\langle \omega^2 \rangle_{D_t} - 2\langle \sigma^2 \rangle_{D_t} \qquad W_D = \langle R \rangle_D - \frac{6\mathrm{k}_D}{a_D^2}$$

Multi-scale partitioning approach



Buchert&Carfora 2009

Multi-scale partitioning approach



Buchert&Carfora 2009

Multi-scale partitioning approach

- Averaged scalars

$$\lambda_M = M/D = f_{vir}/\delta_{vir}$$

$$\langle \rho \rangle = \lambda_M \langle \rho \rangle_M + (1-\lambda_M) \langle \rho \rangle_\epsilon$$

$$\langle R \rangle_D = \lambda_M \langle R \rangle_M + (1-\lambda_M) \langle R \rangle_\epsilon$$

$$H_D = \lambda_M H_M + (1-\lambda_M) H_\epsilon$$

- Backreaction term:

$$Q_D = \lambda_M Q_M + (1-\lambda_M) + (1-\lambda_M) Q_\epsilon + 6\lambda_M (1-\lambda_M)(H_M - H_\epsilon)^2$$

Multi-scale partitioning approach: cosmolgical parameters

- Cosmic quartet

$$\Omega_Q^F := -\frac{Q_F}{6\mathrm{H}_D^2} \qquad \Omega_\Lambda^F := \frac{\Lambda}{3\mathrm{H}_D^2} \qquad \Omega_m^F := \frac{8\pi G}{3\mathrm{H}_D^2}\langle\rho\rangle_F \qquad \Omega_R^F := -\frac{\langle R\rangle_F}{6\mathrm{H}_D^2}$$

- Averaged Hamiltonian constraint

$$\Omega_m^F + \Omega_\Lambda^F + \Omega_R^F + \Omega_Q^F = \frac{H_F^2}{H_D^2}$$

Virialisation fraction

- Assumptions:

  - overdensity from virial theorem $\delta_{vir} \approx 178$

  - no dark energy $\Lambda = 0$

  - stable clustering hypothesis $H_M \approx 0$

- Set of equilibria

$$\Omega_X^D = \lambda_M \Omega_X^M + (1-\lambda_M)\Omega_X^E - \frac{\lambda_M}{1-\lambda_M} \qquad \Omega_m^D = (1-\lambda_M)\Omega_m^E + \lambda_M \Omega_m^M$$

$$\Omega_m^M + \Omega_X^M = 0 \qquad \Omega_m^D + \Omega_X^D = 1 \qquad \Omega_R^F + \Omega_Q^F = \Omega_X^F$$

Background model

- We use the FLRW metric as a background model to approximate the void region and virialised region density parameters

$$\Omega_m^{\epsilon} = \frac{8\pi G}{3 H_D^2} \langle \rho \rangle_E \approx \frac{8\pi G}{3 H_D^2} (1 - f_{vir}) \langle \rho \rangle^{bg} = (1 - f_{vir}) \left(\frac{H^{bg}}{H_D} \right)^2 \Omega_m^{bg}$$

$$\Omega_m^{eff}(z) := \Omega_m^D \approx \left(1 - \frac{f_{vir}}{\delta_{vir}} (1 - f_{vir}) \right) \left(\frac{H^{bg}}{H^{eff}} \right)^2 \Omega_m^{bg} \approx \left(\frac{H^{bg}}{H^{eff}} \right)^2 \Omega_m^{bg}$$

- We introduce an effective expansion rate

$$H^{eff}(z) := H_D = (1 - \lambda_M) (H^{bg}(z) + H_{pec}^{com} a^{-1})$$

Background model

- Effective expansion rate has to match the background expansion rate at higher redshifts and observational estimates at zero redshift
- We choose the simplest solution

$$H_{pec}^{com}(z) = H_{pec}^{com}(0)\frac{f_{vir}(z)}{f_{vir}(0)}$$

- Checking the detailed shape of this function should be considered as both theoretical and observational test

Virialisation fraction approach

- Combining zero dark energy and small backreaction assumptions we define an effective parrameters:

$$\Omega_R^{eff}(z) = 1 - \Omega_m^{eff}(z)$$

$$\Omega_m^{eff}(z) \approx \left(1 - \frac{f_{vir}}{\delta_{vir}}(1 - f_{vir})\right)\left(\frac{H_0^{bg}}{H^{eff}}\right)^2 a^{-3}$$

$$R_C^{eff}(z) = \frac{c}{a\,H^{eff}(z)} \frac{1}{\sqrt{\Omega_R^{eff}(z)}}$$

Observational inputs

- Low-redshift limit of expansion rate

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

- Comoving void radius

$$D_{void}/2 \approx 25 \pm 2\mathrm{h}^{-1}\, Mpc$$

- Infall velocity around rich cluster

$$v_{infall} \approx 1202 \pm 26\, km/s$$

- Zero-redshift value of peculiar expansion rate

$$H_{pec}^{com}(0) = \frac{2\mathrm{v}_{infall}}{D_{void}} = 36 \pm 3\, km/s/Mpc$$

Effective metric

- Effective, spherically symmetric, observer-centered metric

$$ds^2 = -c^2 dt^2 + a^2(t)\left((d\chi^{eff})^2 + (R_C^{eff})^2 \sinh^2 \frac{\chi^{eff}}{R_C^{eff}}(d\theta^2 + \cos^2\theta\, d\phi^2)\right)$$

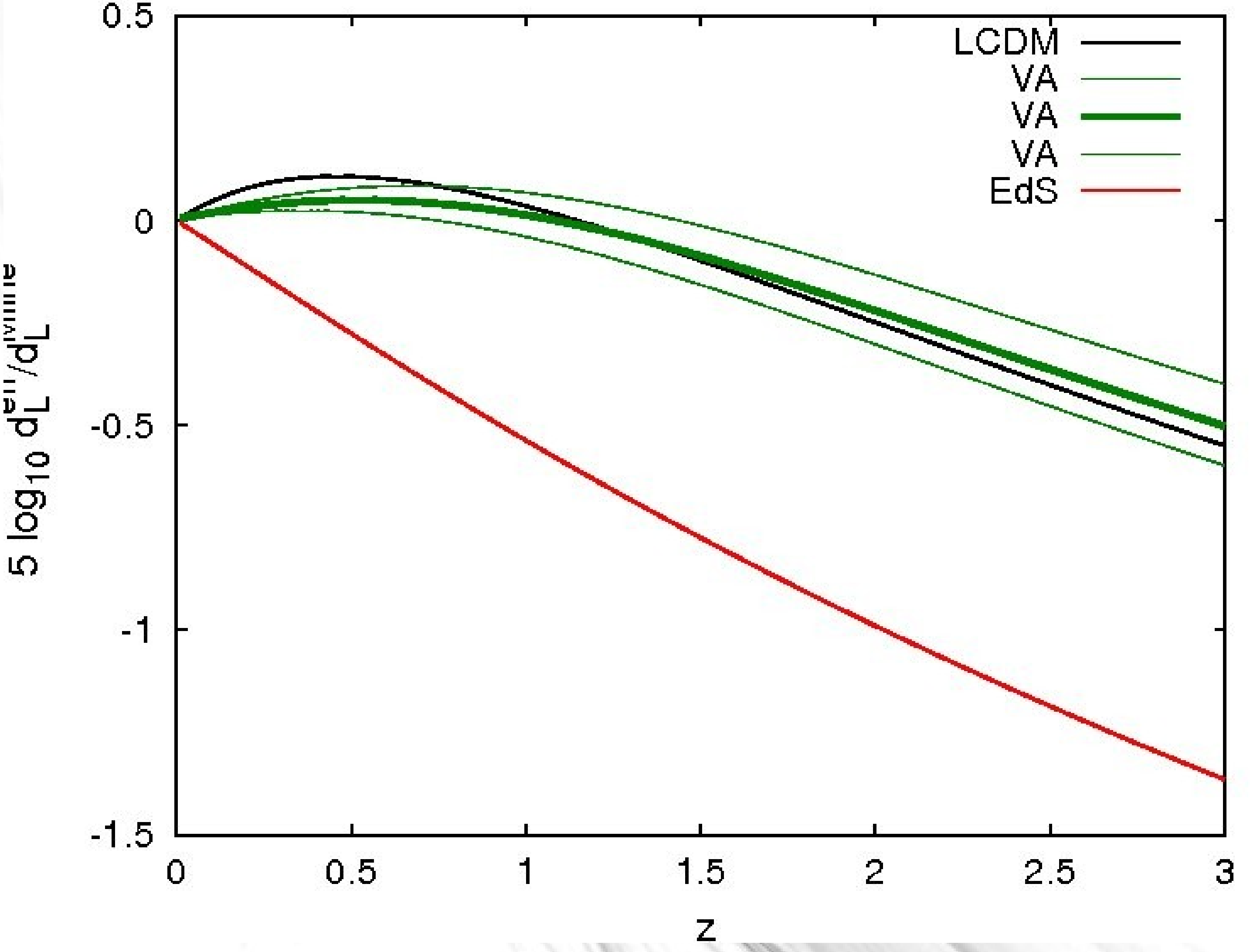
- Differential radial cmoving distance

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

- Luminosity distance

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

Redshift-distance relations



EdS-to-LCDM fraction