Cosmic evolution with silent universes

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Australian Government
Australian Research Council
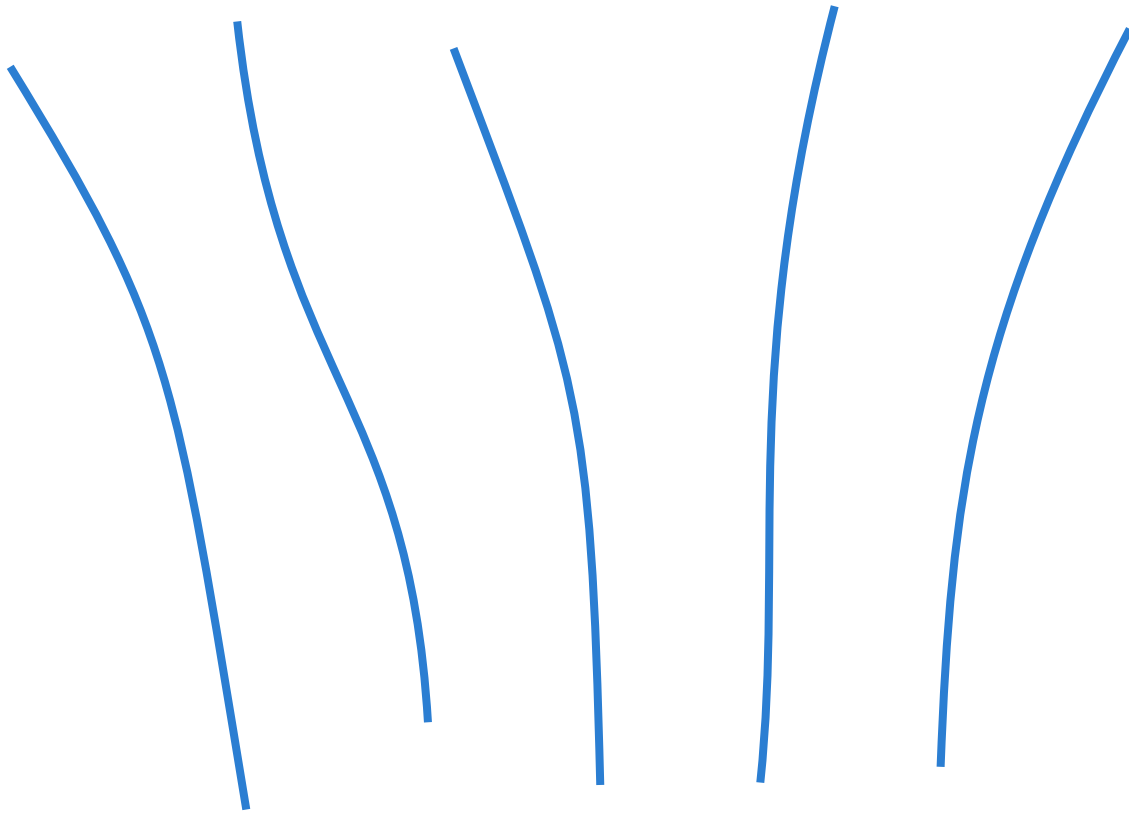
ANITA
Australian National Institute for Theoretical Astrophysics

CosmoBack: From inhomogeneous gravity to cosmological backreaction
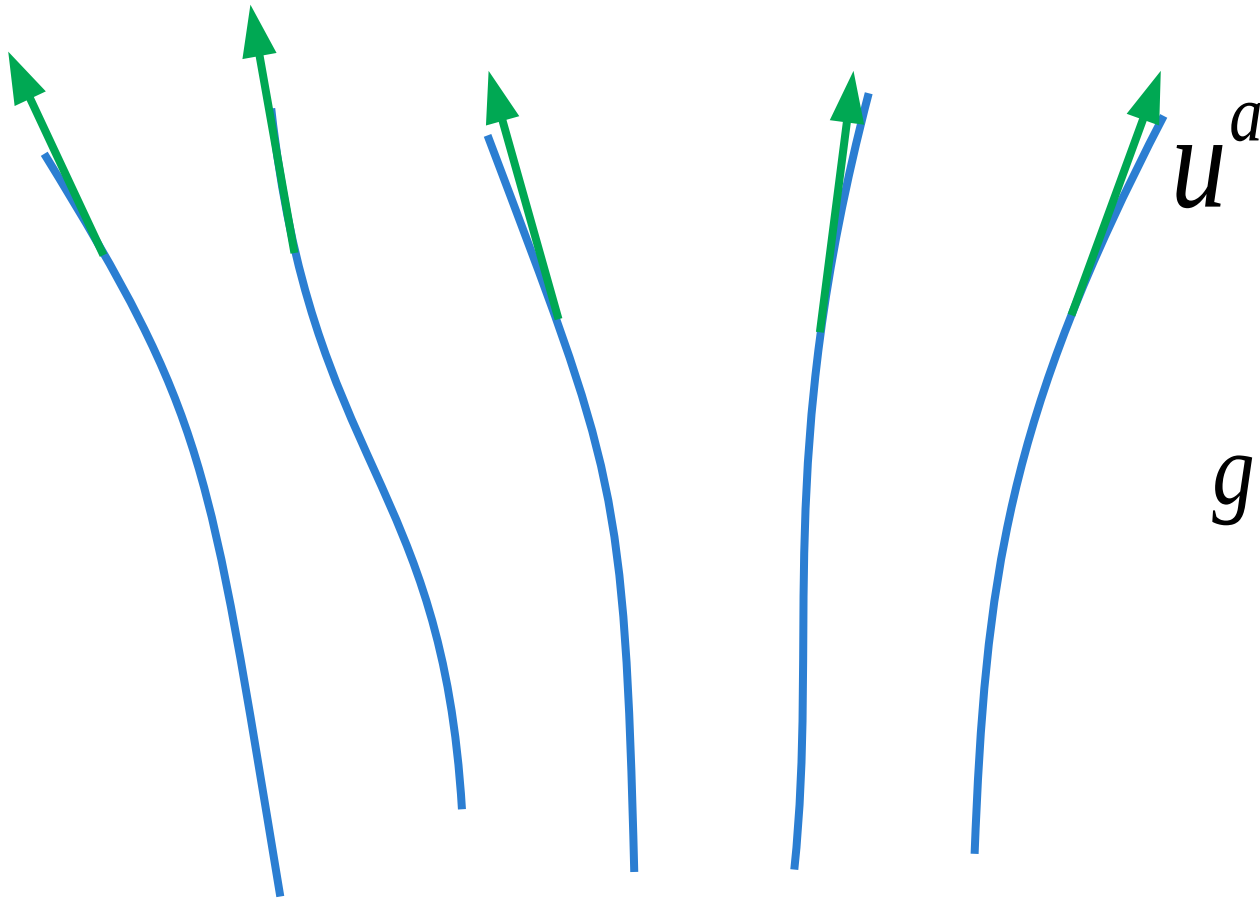**29 May 2018 Marseille, France**

Outline

- *Silent* approach to relativistic evolution

- Setting up the silent universes for cosmic evolution

- The source of backreaction

- Predictions and observational signatures
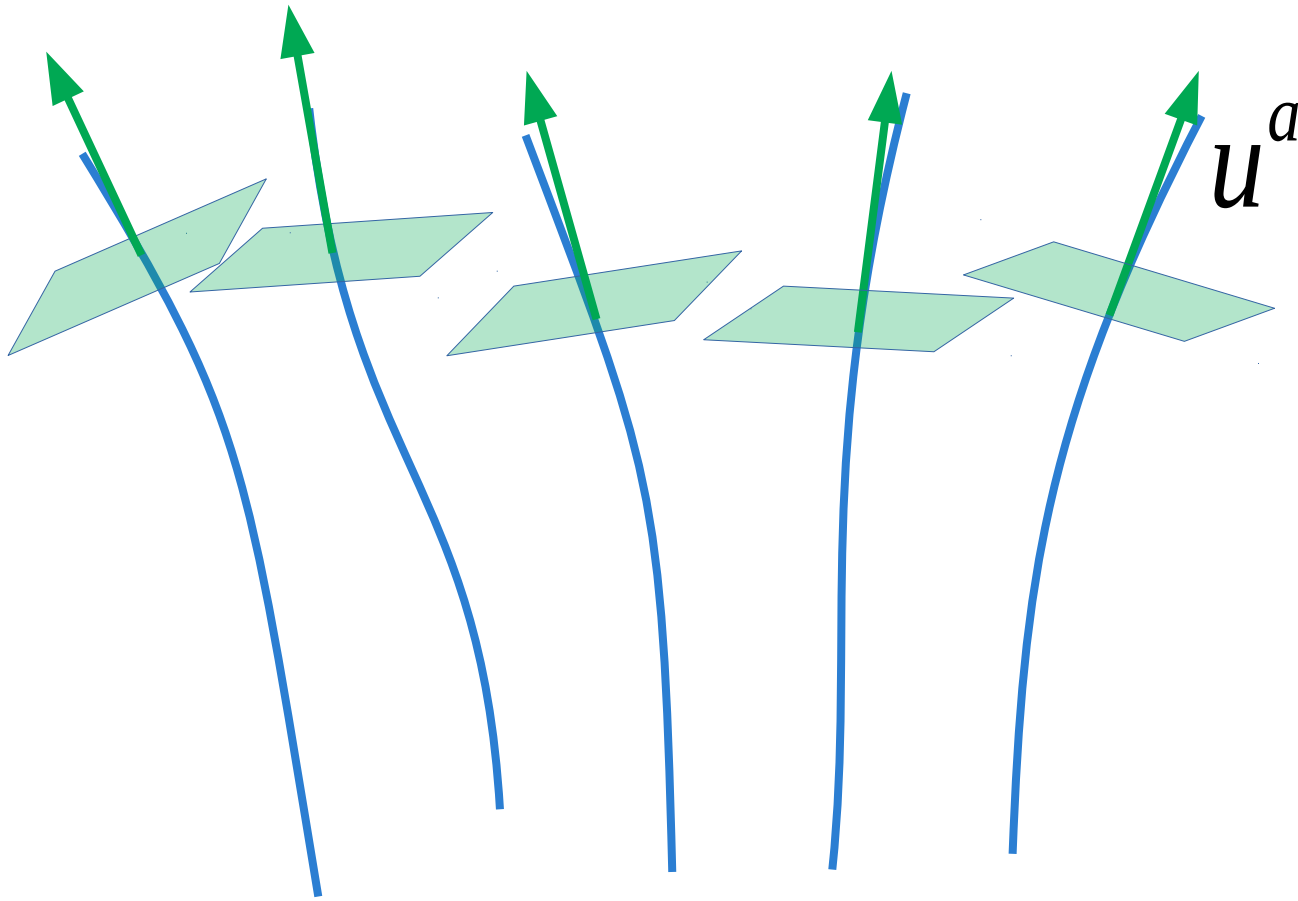
3+1 Relativistic cosmology
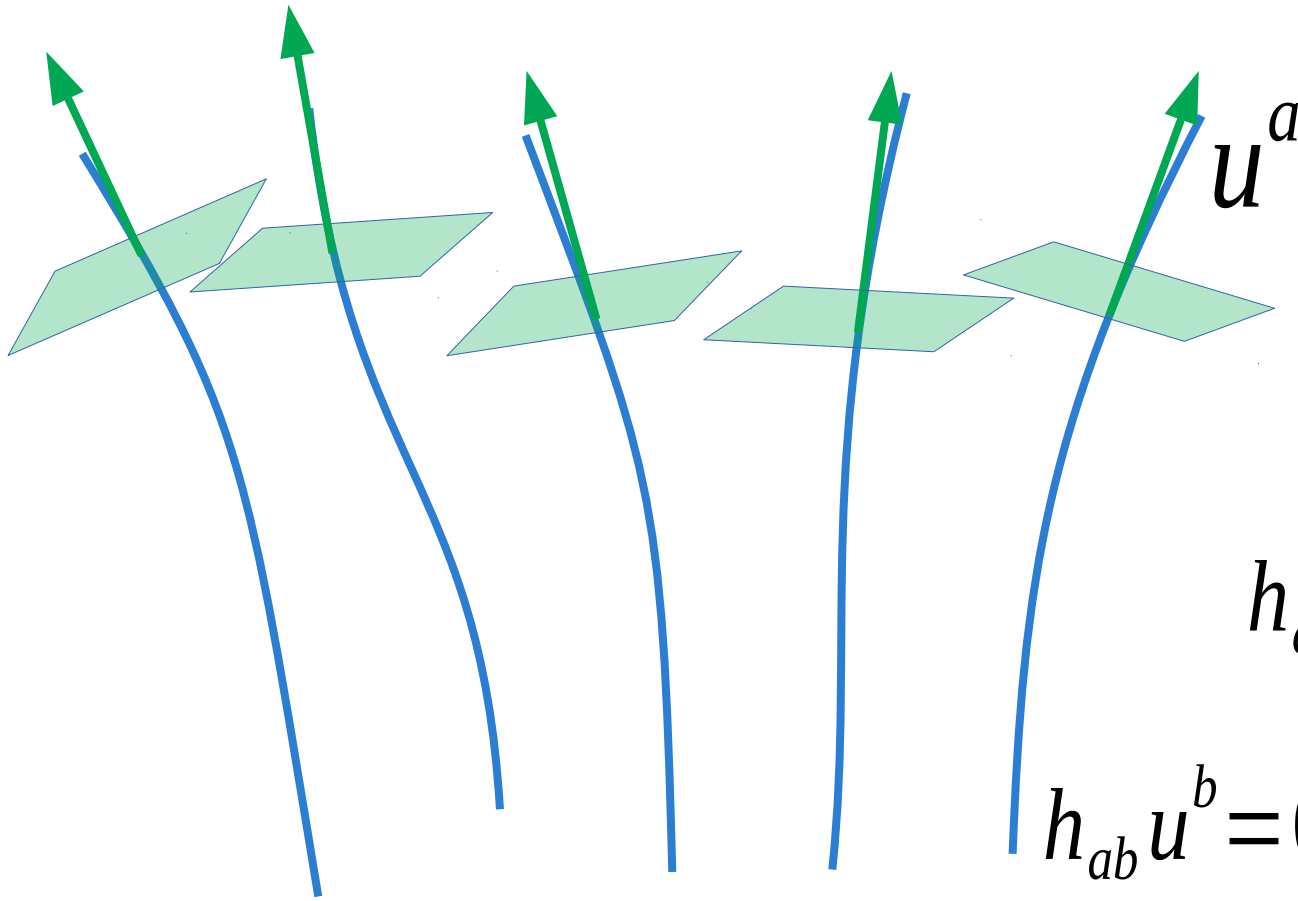
3+1 Relativistic cosmology

$$u^a$$

$$g_{ab} u^b u^a = -1$$

Ellis, *Relativistic cosmology* (1971); *Gen. Rel. Grav.* 41, 581 (2009)

3+1 Relativistic cosmology

u^a

Ellis, *Relativistic cosmology* (1971)*; Gen. Rel. Grav.* 41, 581 (2009)
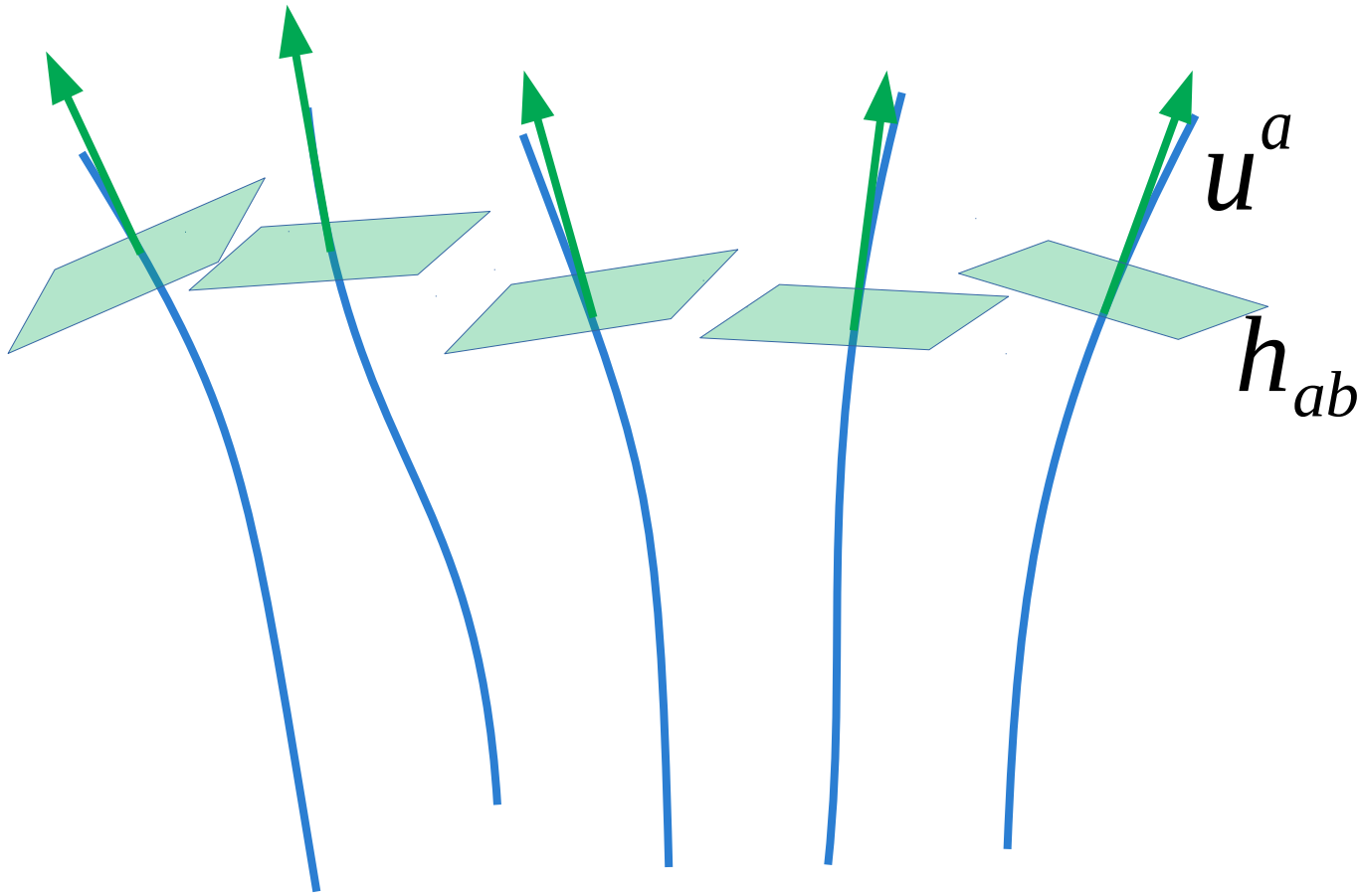
3+1 Relativistic cosmology

u^a

$$h_{ab} = g_{ab} + u_a u_b$$

$$h_{ab} u^b = 0 \qquad h_a^c h_c^b = h_a^b \qquad h_a^a = 3$$

Ellis, *Relativistic cosmology* (1971)*; Gen. Rel. Grav.* 41, 581 (2009)

3+1 Relativistic cosmology

$$ds^2 = g_{ab}\,dx^a\,dx^b = -u_a\,u_b\,dx^a\,dx^b + h_{ab}\,dx^a\,dx^b$$

$$u_{a;b} = \omega_{ab} + \sigma_{ab} + \frac{1}{3}h_{ab}\Theta - A_a u_b$$

Ellis, *Relativistic cosmology* (1971); *Gen. Rel. Grav.* 41, 581 (2009)

$$G_{ab} - \Lambda\, g_{ab} = T_{ab}$$

$$G_{ab} - \Lambda\, g_{ab} = T_{ab}$$

$$T_{ab} = \rho\, u_a u_b + p\, h_{ab} + \pi_{ab} + q_a u_b + u_a q_b$$

$$G_{ab} - \Lambda g_{ab} = T_{ab}$$

conservation equation

$$T^{ab}{}_{;b} = 0$$

$$G_{ab} - \Lambda\, g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^{a}{}_{;a} + q^{a}A_{a} = 0$$

$$G_{ab} - \Lambda g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^a{}_{;a} + q^a A_a = 0$$

Ricci identities

$$u_{a;d;c} - u_{a;c;d} = R_{abcd}u^b$$

$$G_{ab} - \Lambda g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^a{}_{;a} + q^a A_a = 0$$

Ricci identities

$$\dot{\Theta} = -\frac{1}{3}\Theta^2 - \frac{1}{2}(\rho + 3p) - 2(\sigma^2 - \omega^2) + D^a A_a + A_a A^a + \Lambda$$

$$\dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + D_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} - E_{ab} + \frac{1}{2}\pi_{ab}$$

$$\dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\Theta\omega_a - \frac{1}{2}curl\,A_a + \sigma_{ab}\omega^b$$

$$G_{ab} - \Lambda g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^a{}_{;a} + q^a A_a = 0$$

Ricci identities

$$\dot{\Theta} = -\frac{1}{3}\Theta^2 - \frac{1}{2}(\rho + 3p) - 2(\sigma^2 - \omega^2) + D^a A_a + A_a A^a + \Lambda$$

$$\dot{\sigma}_{\langle ab \rangle} = -\frac{2}{3}\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + D_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} - E_{ab} + \frac{1}{2}\pi_{ab}$$

$$\dot{\omega}_{\langle a \rangle} = -\frac{2}{3}\Theta\omega_a - \frac{1}{2}curl\,A_a + \sigma_{ab}\omega^b$$

Bianchi identities

$$R_{ab[cd;e]} = 0$$

$$G_{ab} - \Lambda\, g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^a{}_{;a} + q^a A_a = 0$$

Ricci identities

$$\dot{\Theta} = -\frac{1}{3}\Theta^2 - \frac{1}{2}(\rho + 3p) - 2(\sigma^2 - \omega^2) + D^a A_a + A_a A^a + \Lambda$$

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$$\dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\Theta\omega_a - \frac{1}{2}curl\, A_a + \sigma_{ab}\omega^b$$

Bianchi identities

$$\dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}(\rho + p)\sigma_{ab} + curl\, H_{ab} - \frac{1}{2}\dot{\pi}_{ab} - \frac{1}{6}\Theta\pi_{ab}$$
$$+ \; 3\sigma^c{}_{\langle a}\left(E_{b\rangle c} - \frac{1}{6}\pi_{b\rangle c}\right) + \epsilon_{cd\langle a}\left[2A^c H^d{}_{b\rangle} - \omega^c\left(E_{b\rangle}{}^d + \frac{1}{2}\pi^d_{b\rangle}\right)\right]$$

$$\dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - curl\, E_{ab} + \frac{1}{2}curl\,\pi_{ab} + 3\sigma^c{}_{\langle a}H_{b\rangle c} - \epsilon_{cd\langle a}\left(2A^c E^d{}_{b\rangle} + \omega^c H^d{}_{b\rangle}\right)$$

$$G_{ab} - \Lambda\, g_{ab} = T_{ab}$$

conservation equation

$$\dot{\rho} + \Theta(\rho + p) + \sigma^{ab}\pi_{ab} + q^a{}_{;a} + q^a A_a = 0$$

Ricci ident...

$$\dot{\Theta} = -\tfrac{1}{3}\Theta^2 -$$

$$\dot{\sigma}_{\langle ab\rangle} = -\tfrac{2}{3}\Theta$$

$$\dot{\omega}_{\langle a\rangle} = -\tfrac{2}{3}\Theta$$

$$\omega_{ab} = 0 \qquad A_a = 0 \qquad q_a = 0$$

$$p = 0 \qquad \pi_{ab} = 0 \qquad H_{ab} = 0$$

Bianchi identities

$$\dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \tfrac{1}{2}(\rho + p)\sigma_{ab} + \mathrm{curl}\, H_{ab} - \tfrac{1}{2}\dot{\pi}_{ab} - \tfrac{1}{6}\Theta\pi_{ab}$$

$$+\ 3\sigma^c{}_{\langle a}\left(E_{b\rangle c} - \tfrac{1}{6}\pi_{b\rangle c}\right) + \epsilon_{cd\langle a}\left[2 A^c H^d_{b\rangle} - \omega^c\left(E_{b\rangle}{}^d + \tfrac{1}{2}\pi^d_{b\rangle}\right)\right]$$

$$\dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - \mathrm{curl}\, E_{ab} + \tfrac{1}{2}\mathrm{curl}\,\pi_{ab} + 3\sigma^c{}_{\langle a}H_{b\rangle c} - \epsilon_{cd\langle a}\left(2 A^c E^d_{b\rangle} + \omega^c H^d_{b\rangle}\right)$$

Silent Cosmology

$$\dot{\rho} = -\Theta \rho$$

$$\dot{\Theta} = -\frac{1}{3}\Theta^2 - \frac{1}{2}\rho - 6\Sigma^2 + \Lambda$$

$$\dot{\Sigma} = -\frac{2}{3}\Theta\Sigma + \Sigma^2 - W$$

$$\dot{W} = -\Theta W - \frac{1}{2}\rho\Sigma - 3\Sigma W$$

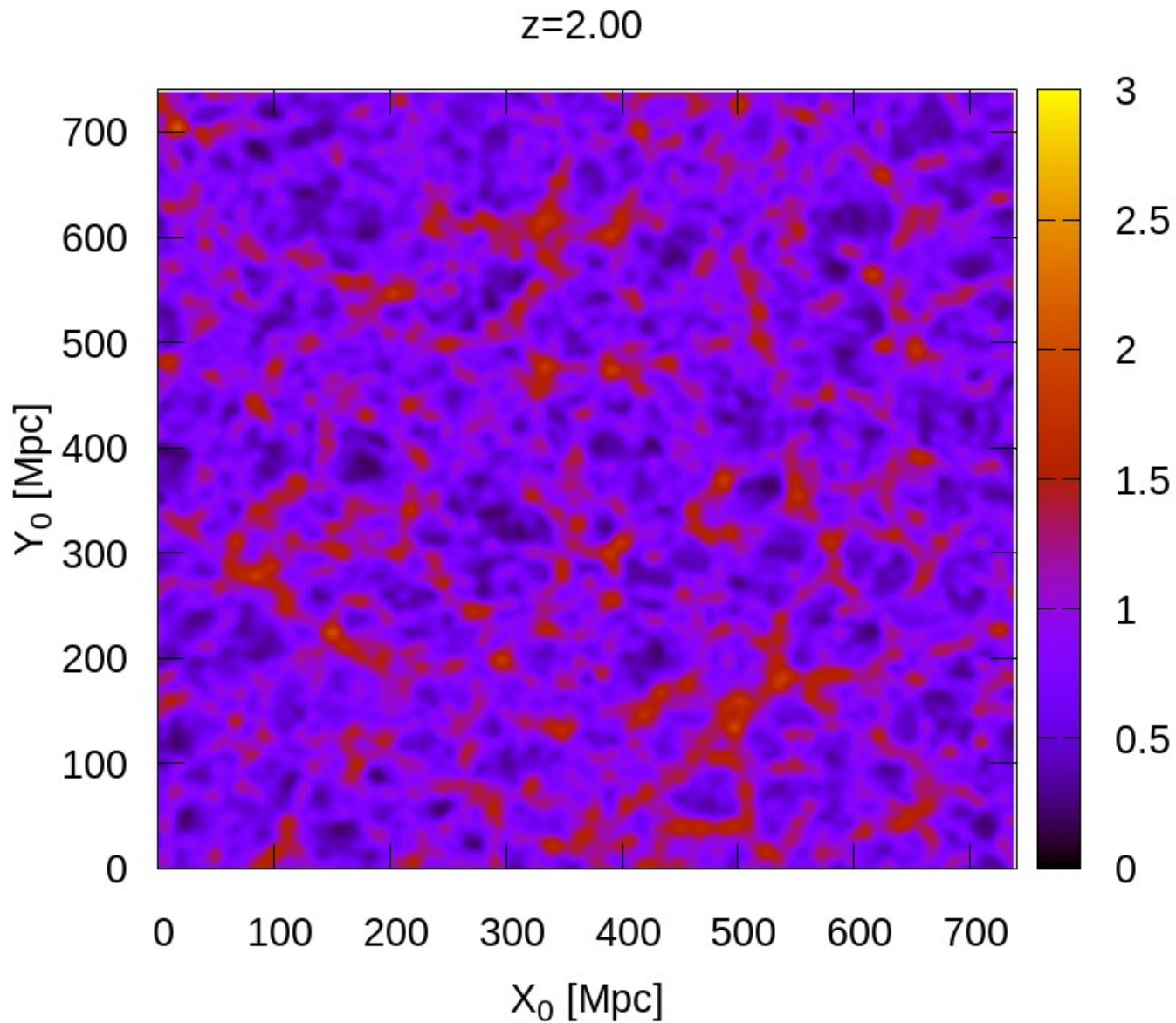Bruni, Matarrese, Pantano, *Astroph. J.* 445, 958 (1995)

van Elst, Uggla, Lesame, Ellis, Maartens, *Class. Q. Grav.* 14, 1151 (1997)

Silent Cosmology

$$D^b \sigma_{ab} = \frac{2}{3} D_a \Theta$$

$$curl\ \sigma_{ab} = 0$$

$$D^b E_{ab} = \frac{1}{3} D_a \rho$$

$$\sigma^b{}_d E^{cd} = 0$$

Bruni, Matarrese, Pantano, *Astroph. J.* 445, 958 (1995)

van Elst, Uggla, Lesame, Ellis, Maartens, *Class. Q. Grav.* 14, 1151 (1997)

Silent Cosmology

$$\dot{\rho} = -\Theta \rho$$

$$\dot{\Theta} = -\frac{1}{3} \Theta^2 - \frac{1}{2} \rho - 6 \Sigma^2 + \Lambda$$

$$\dot{\Sigma} = -\frac{2}{3} \Theta \Sigma + \Sigma^2 - W$$

$$\dot{W} = -\Theta W - \frac{1}{2} \rho \Sigma - 3 \Sigma W$$

Bruni, Matarrese, Pantano, *Astroph. J.* 445, 958 (1995)

van Elst, Uggla, Lesame, Ellis, Maartens, *Class. Q. Grav.* 14, 1151 (1997)

Millennium universe

125 Mpc/h
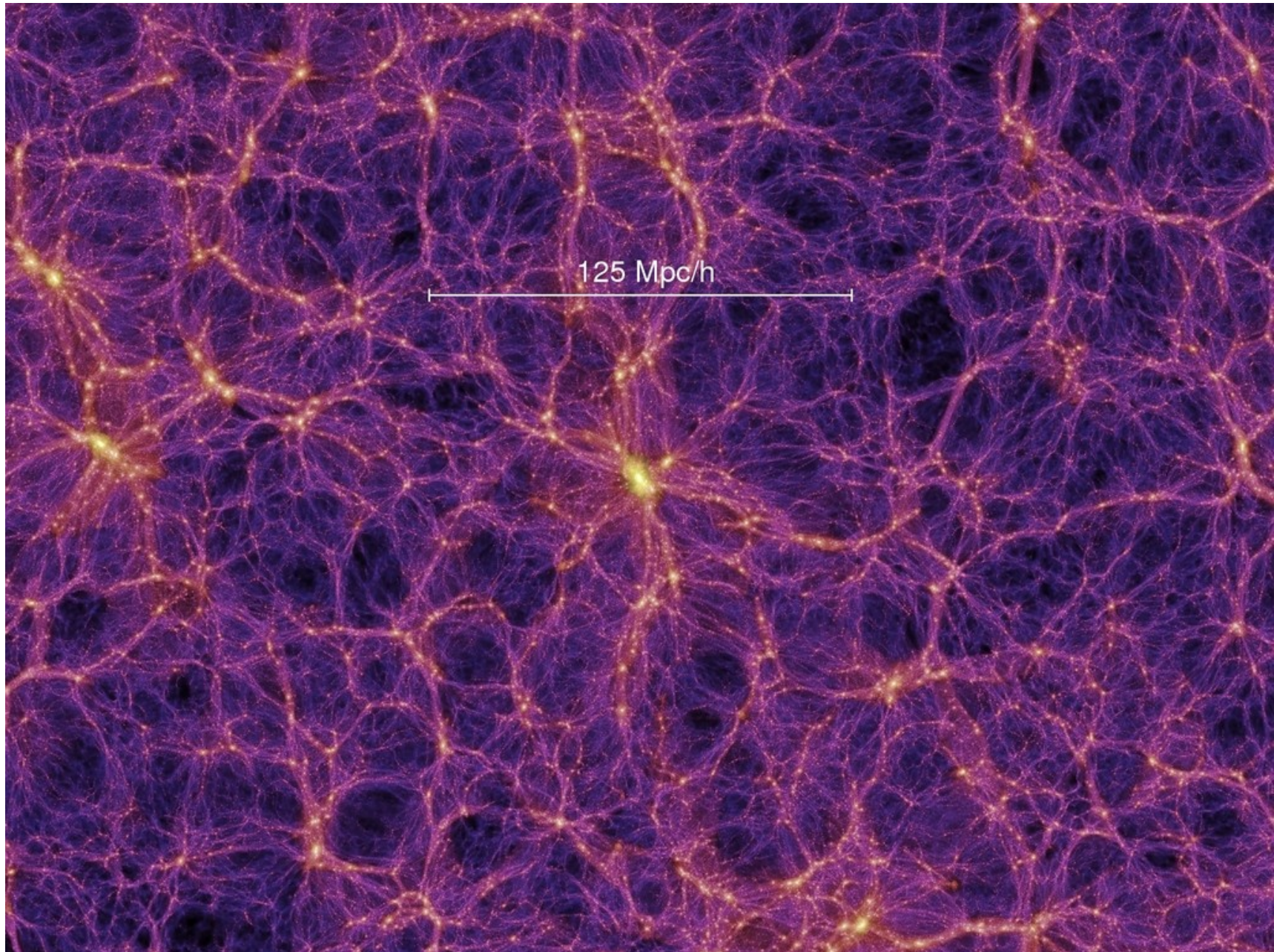
Approximation of silent universes

$$\rho_i = \bar{\rho} + \Delta \rho = \bar{\rho} \left(1 + \delta_i \right)$$

$$\Theta_i = \bar{\Theta} + \Delta \Theta = \bar{\Theta} \left(1 - \frac{1}{3} \delta_i \right)$$

$$\Sigma_i = -\frac{1}{3} \Delta \Theta = \frac{1}{9} \bar{\Theta} \delta_i$$

$$W_i = -\frac{1}{6} \bar{\rho} \delta_i$$

Approximation of silent universes

$$\dot{\rho} = -\Theta \, \rho$$

$$\dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,\rho - 6\,\Sigma^2 + \Lambda$$

$$\dot{\Sigma} = -\frac{2}{3}\,\Theta\,\Sigma + \Sigma^2 - W$$

$$\dot{W} = -\Theta\,W - \frac{1}{2}\,\rho\,\Sigma - 3\,\Sigma\,W$$

Silent Universe Simulation
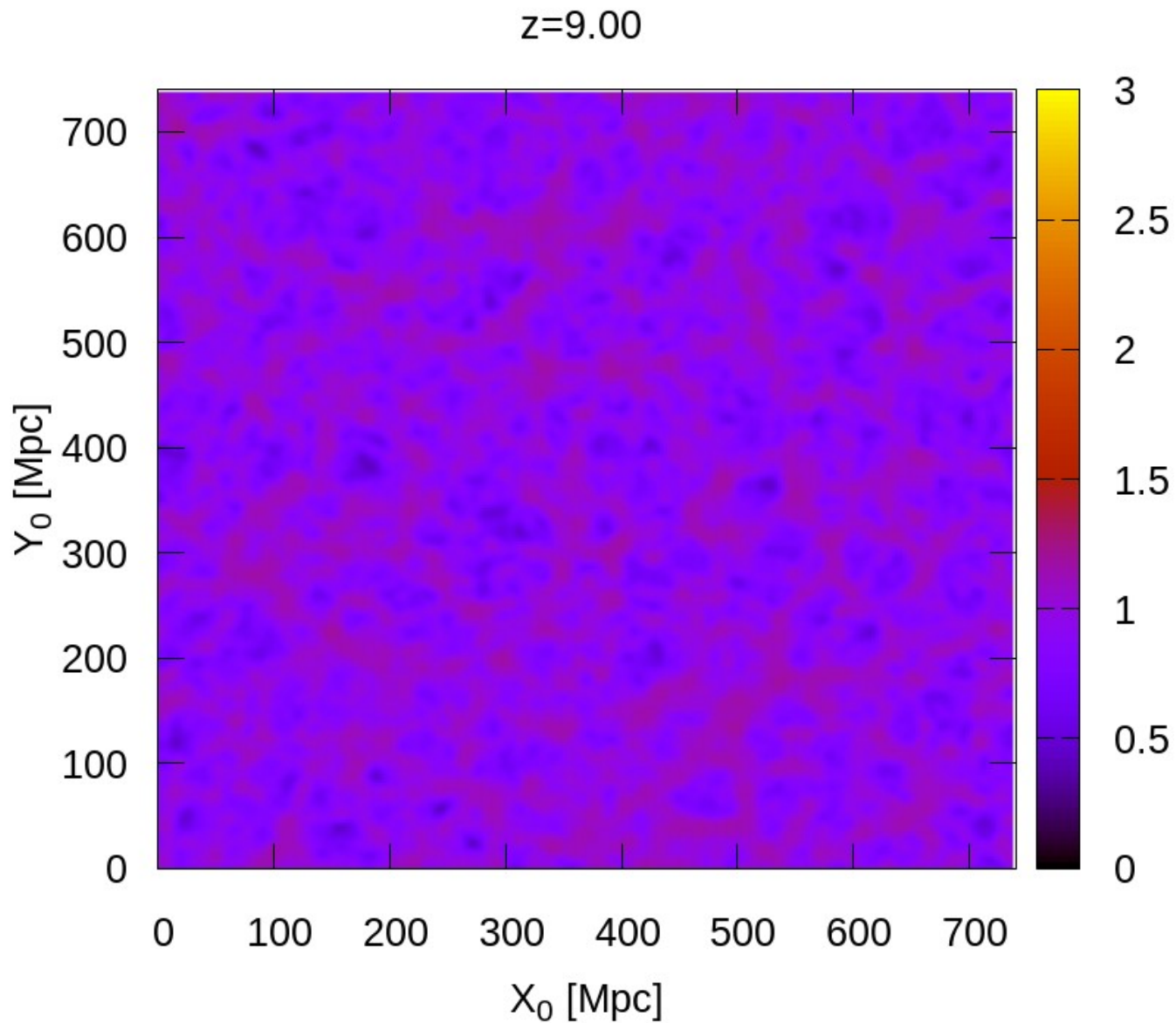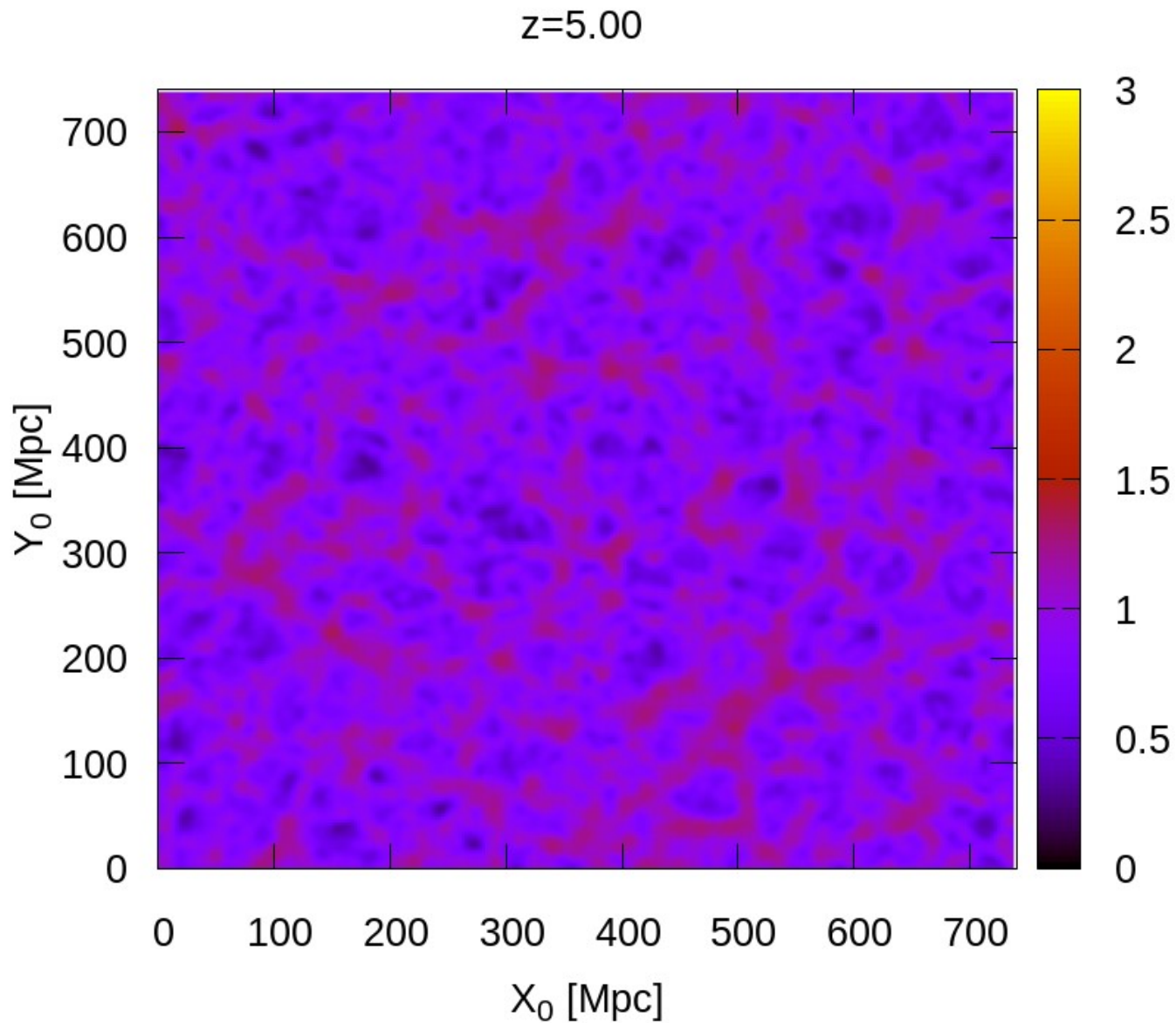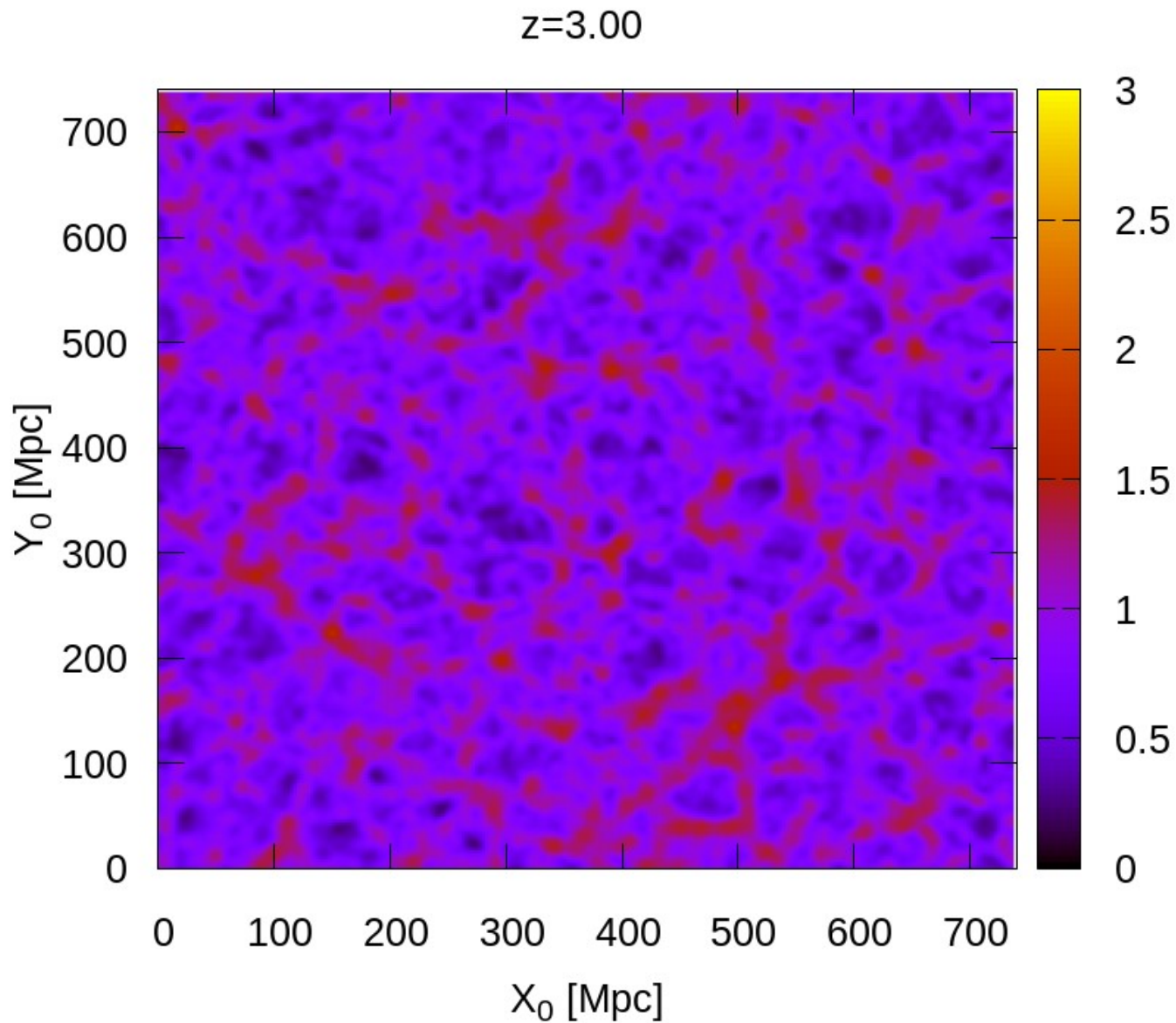
z=9.00

Silent Universe Simulation

z=5.00

Silent Universe Simulation

z=3.00

Silent Universe Simulation

z=2.00

Silent Universe Simulation

z=1.00

Silent Universe Simulation

z=0.50

Silent Universe Simulation

z=0.10

Bolejko, Class. Q. Grav 35, 024003 (2018)

Silent Universe Simulation

z=0.01
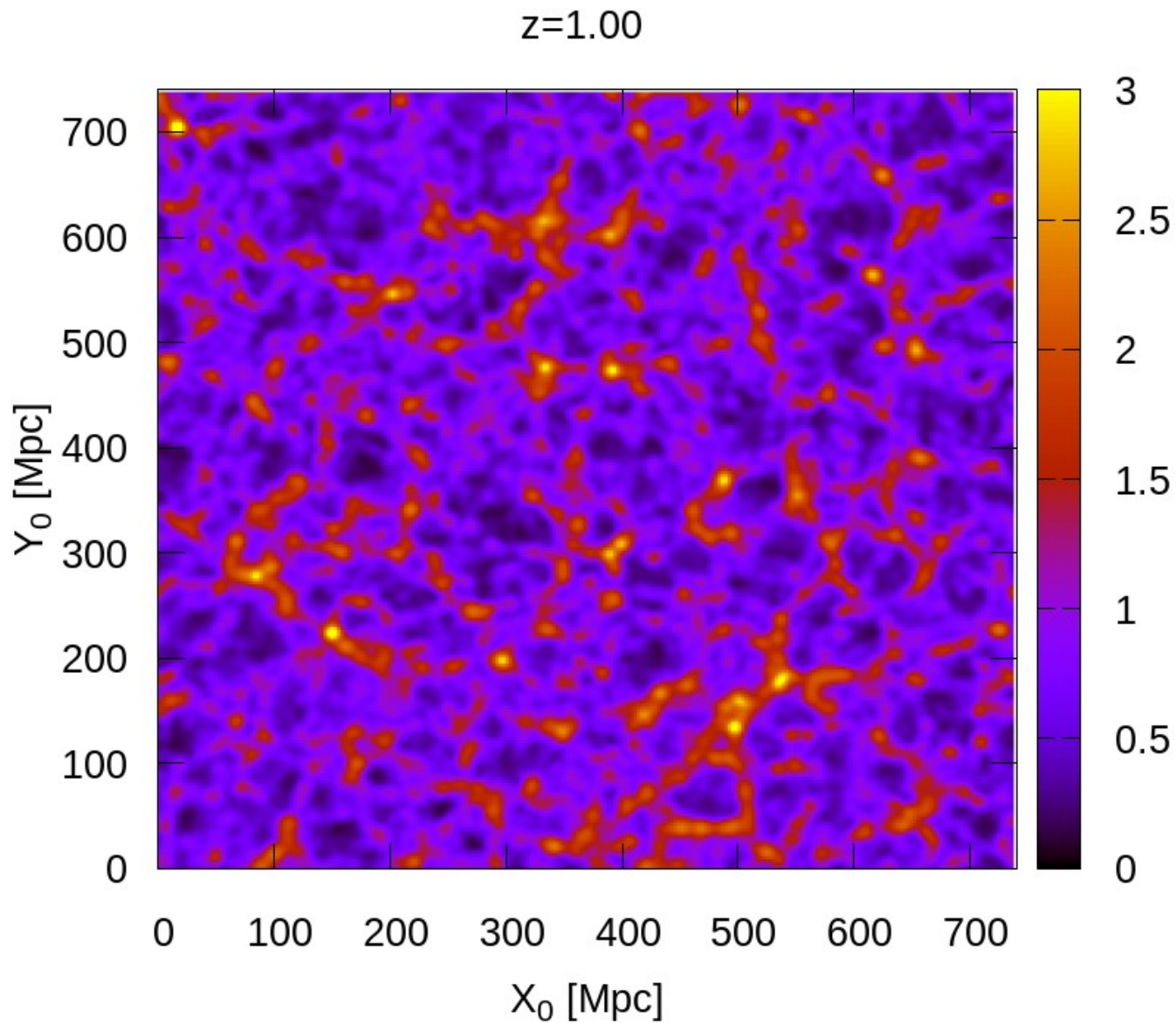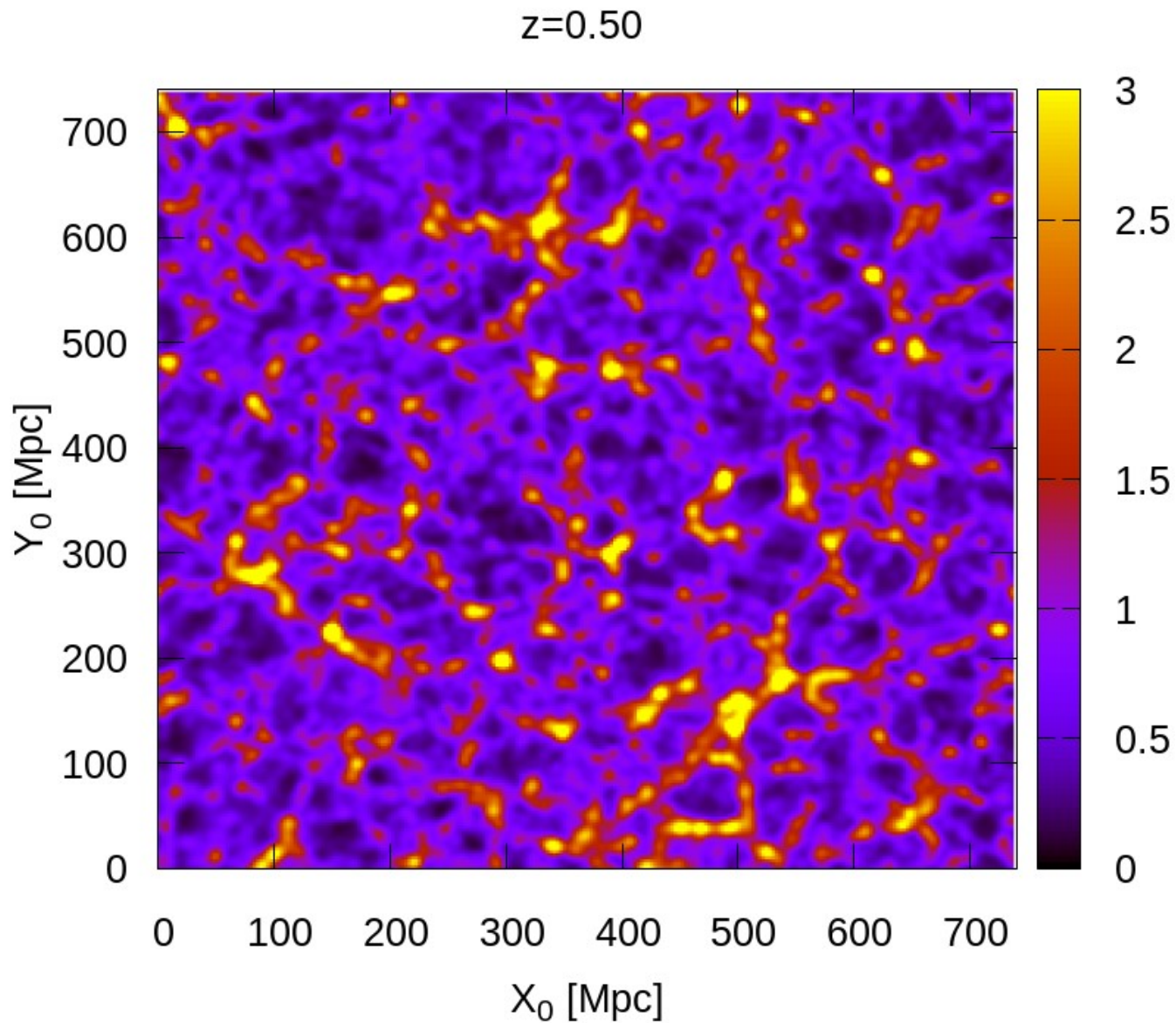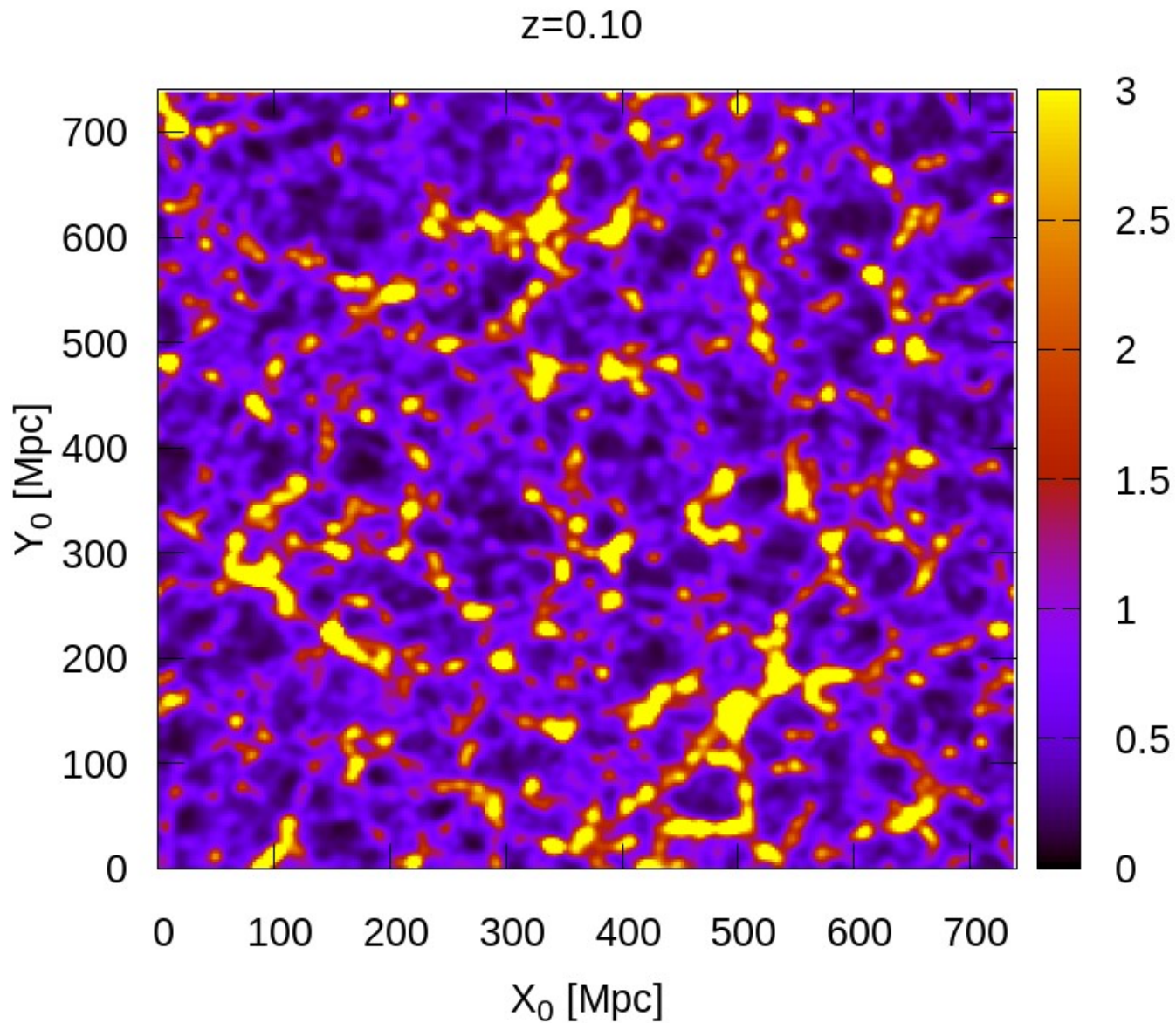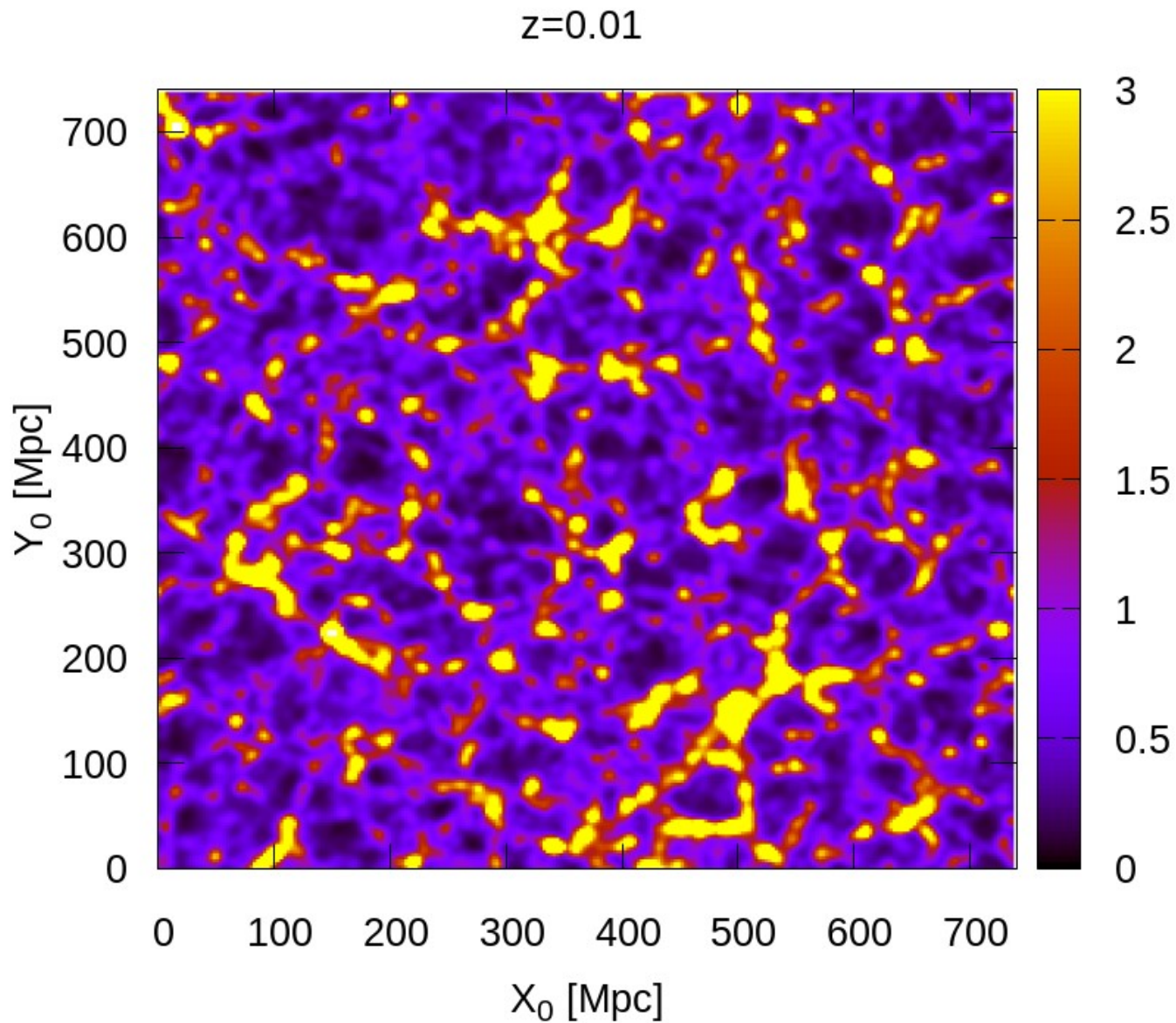
Evolution of the cosmic parameters
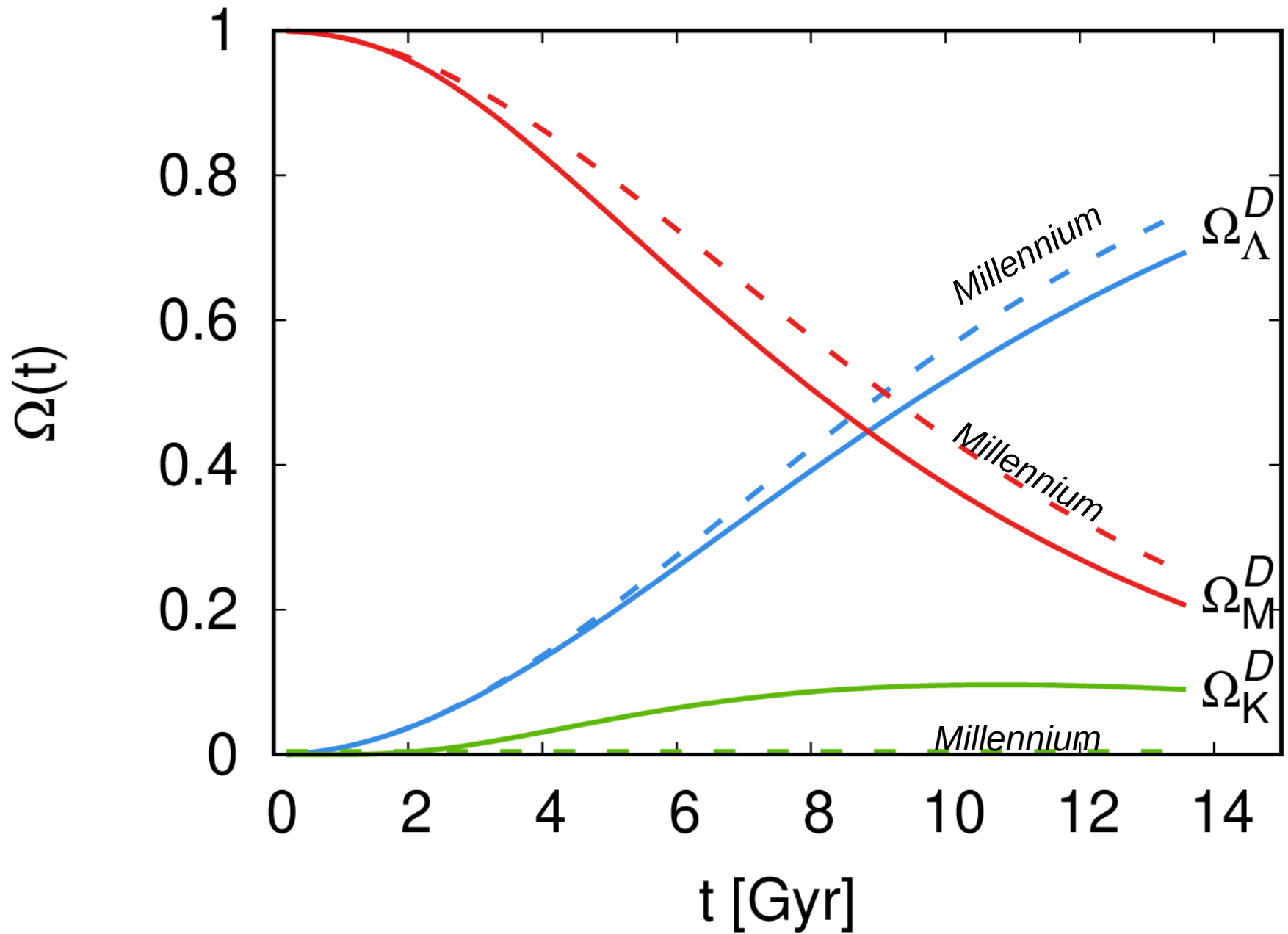
Evolution of volume
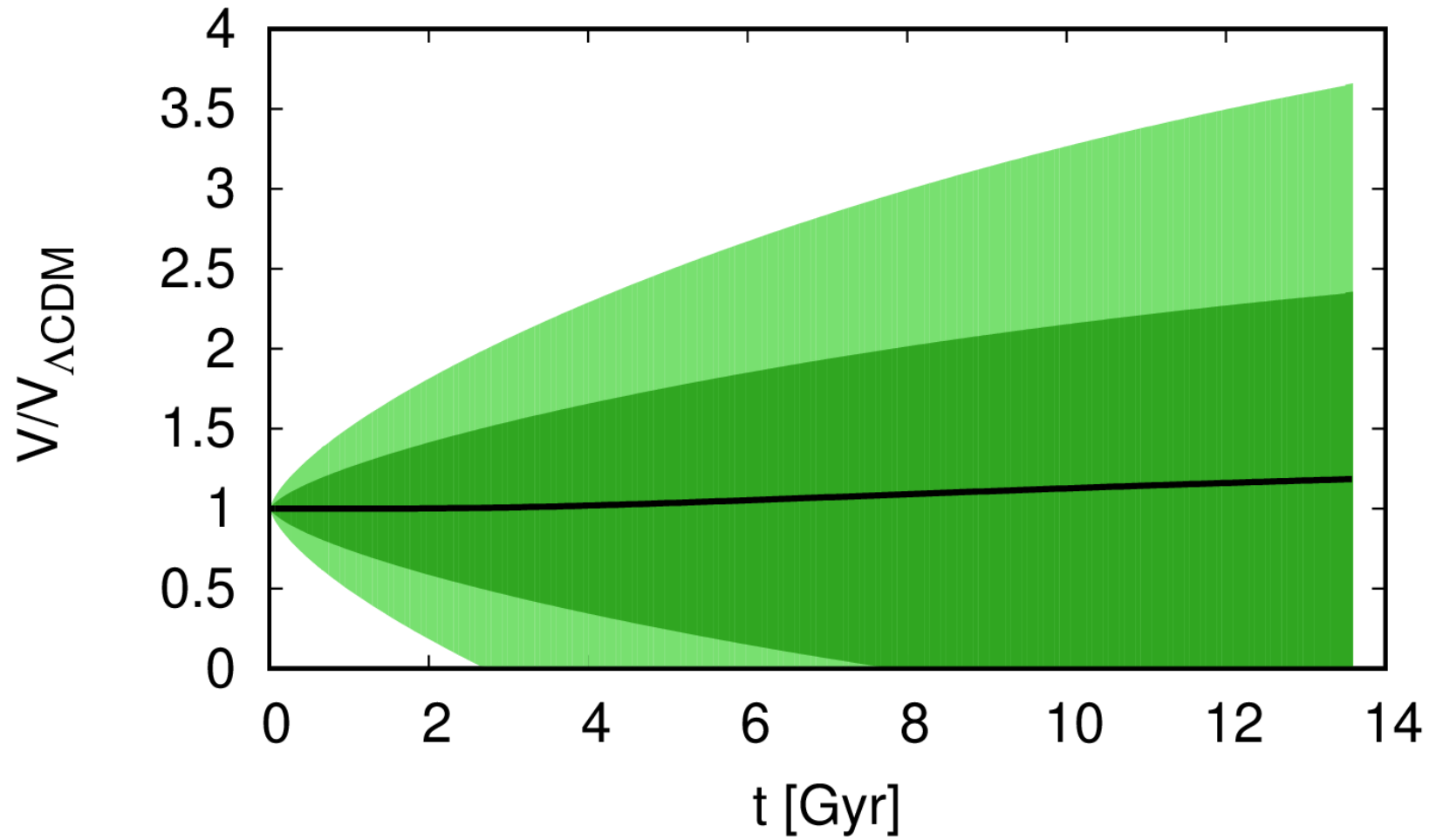
Evolution of volume
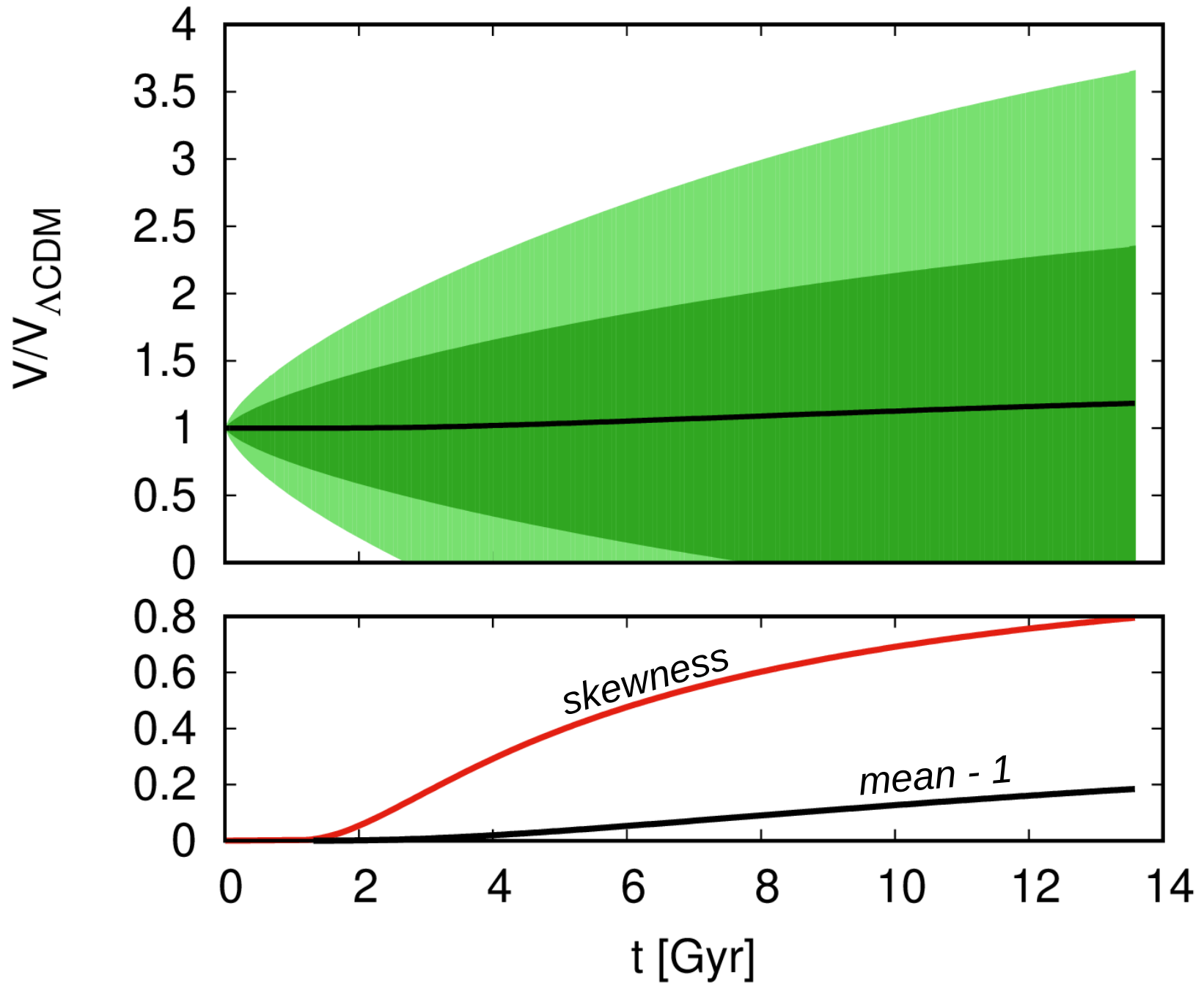
1. Larger volume
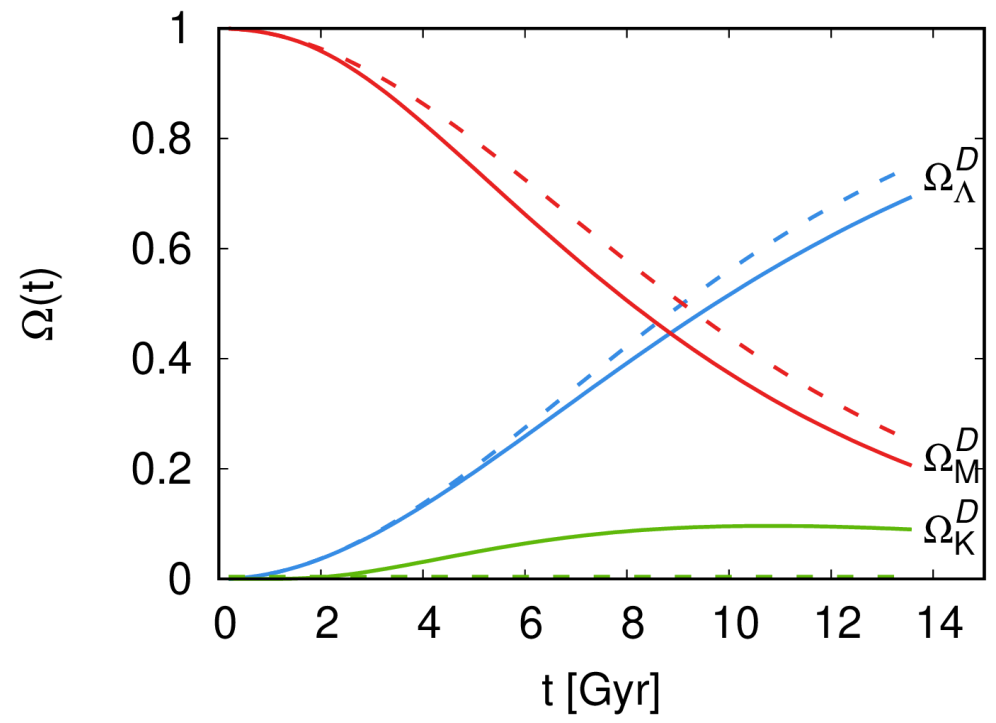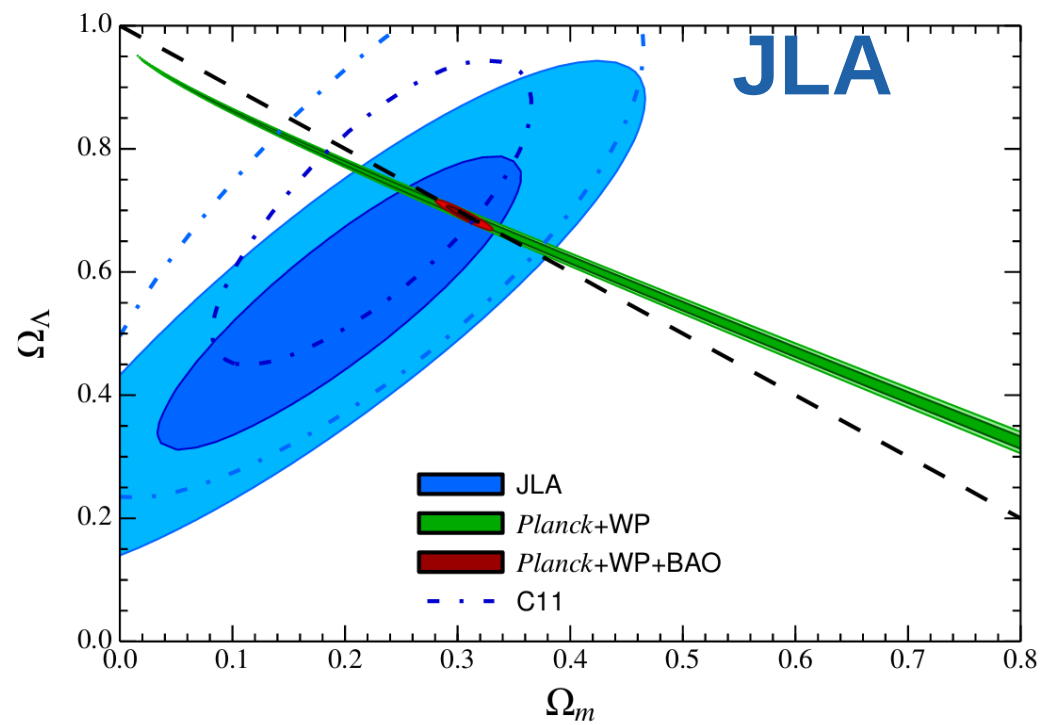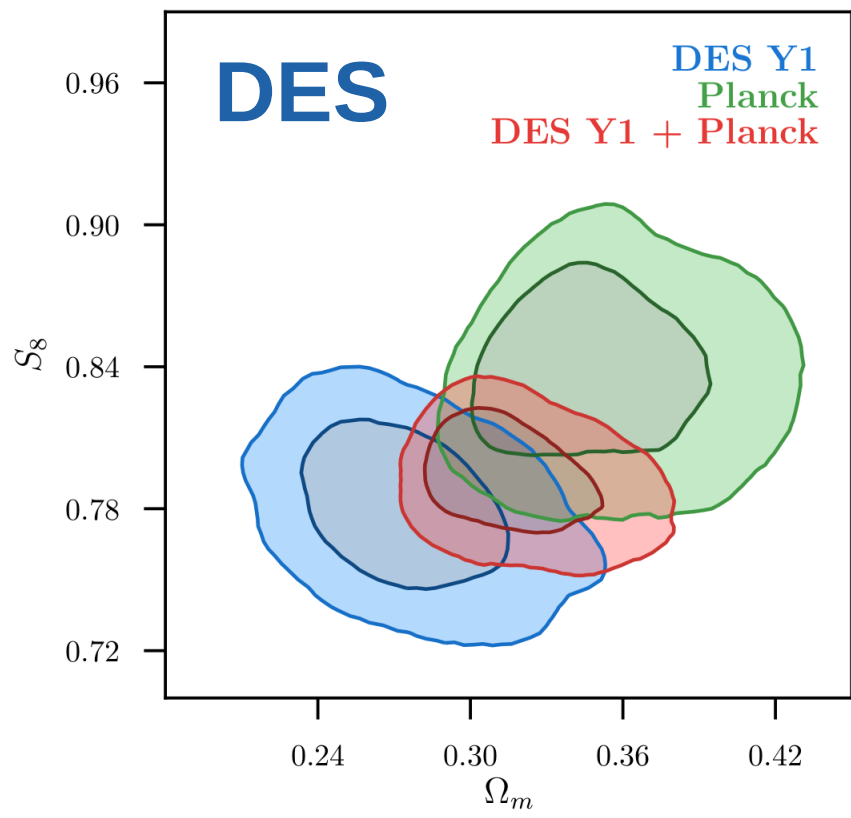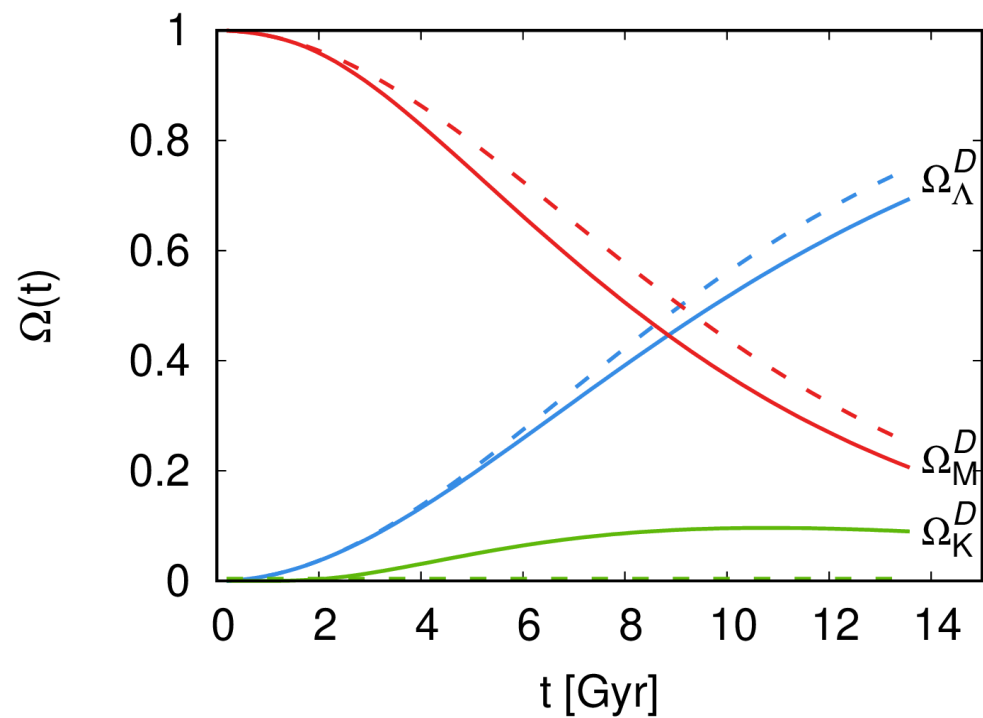
1. Larger volume

1. Larger volume

2. Spatial curvature
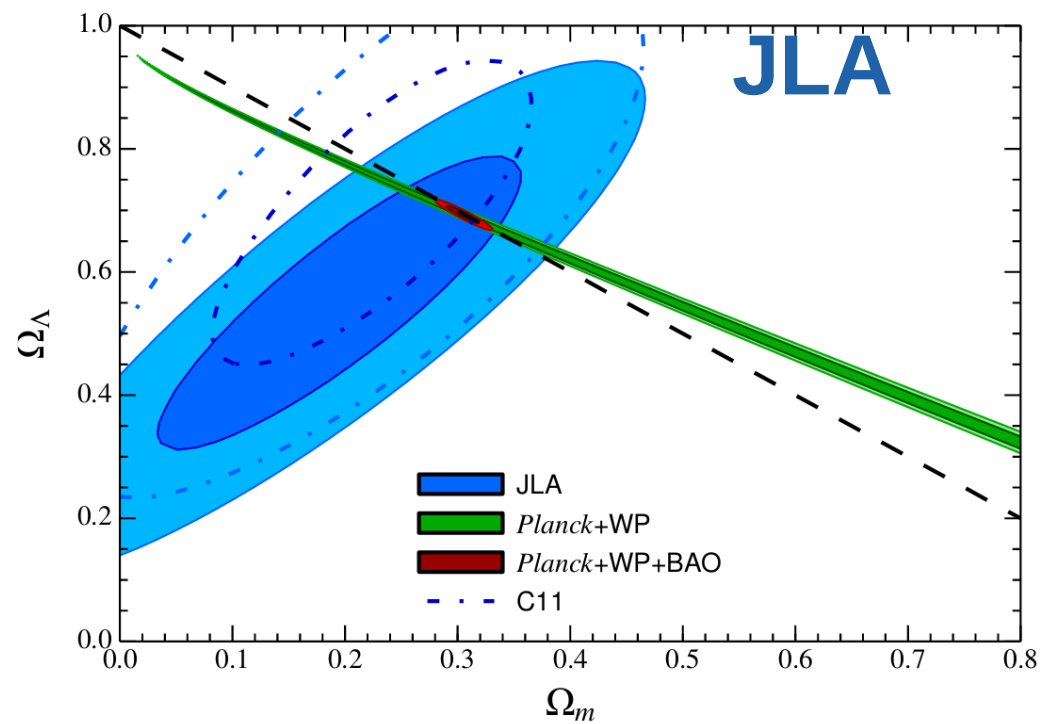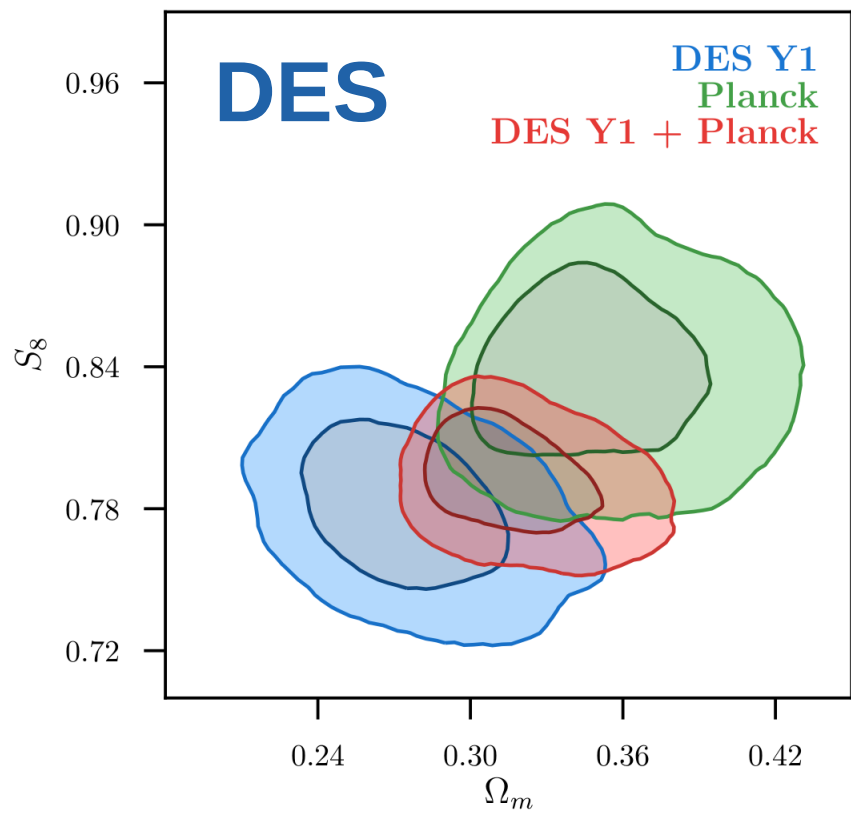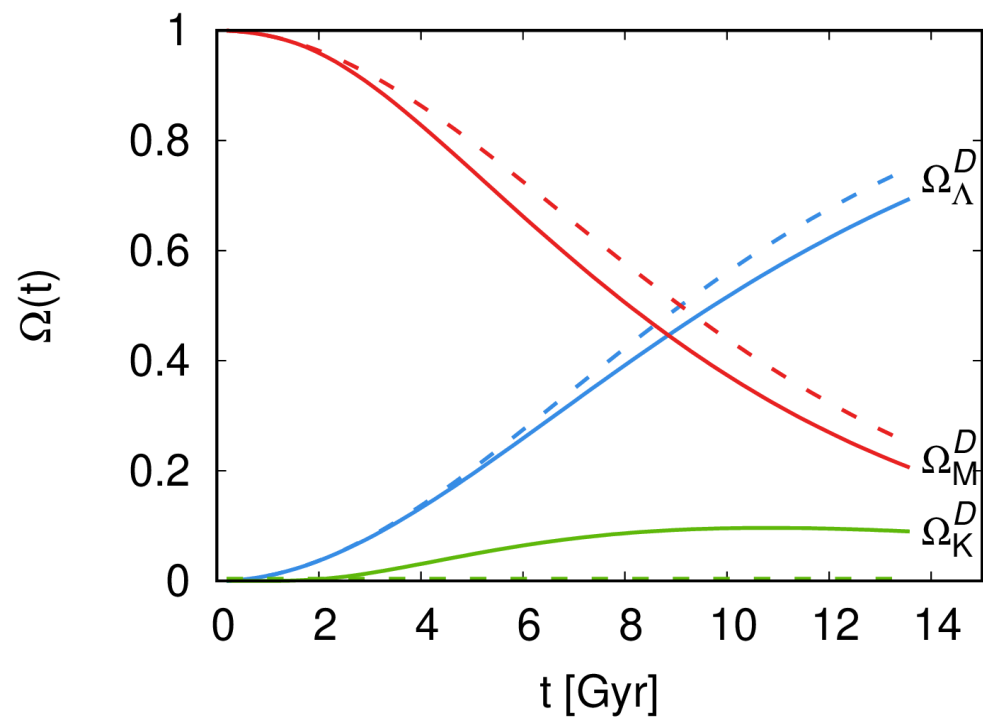
1. Larger volume
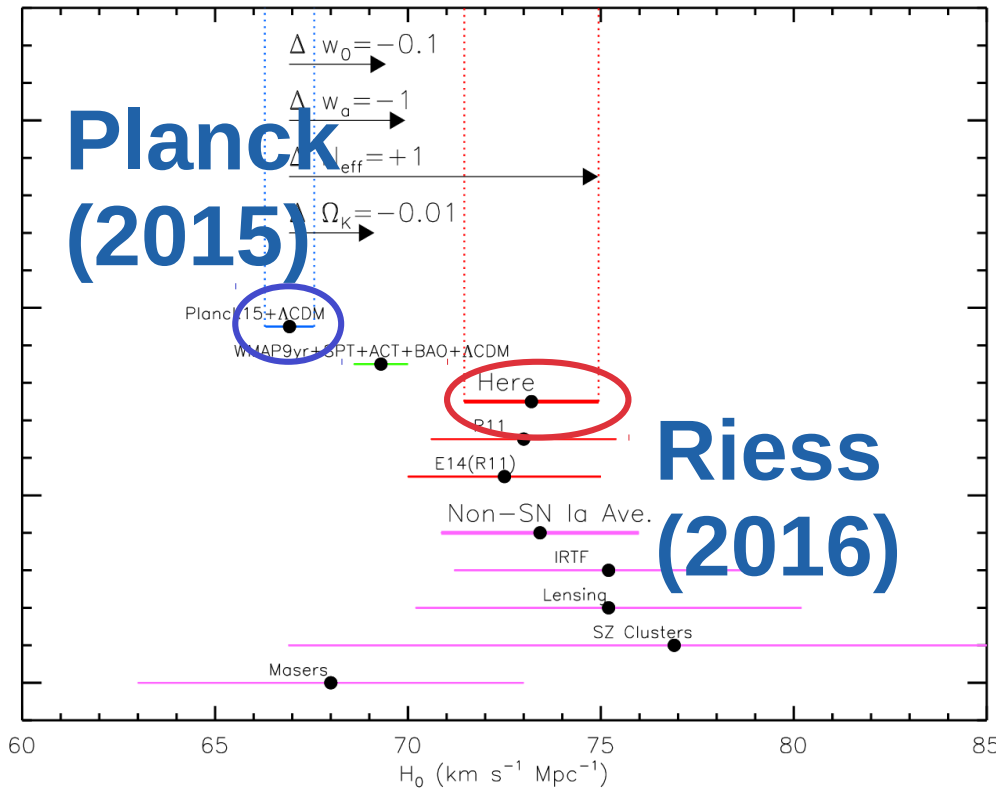
2. Spatial curvature

Current data:
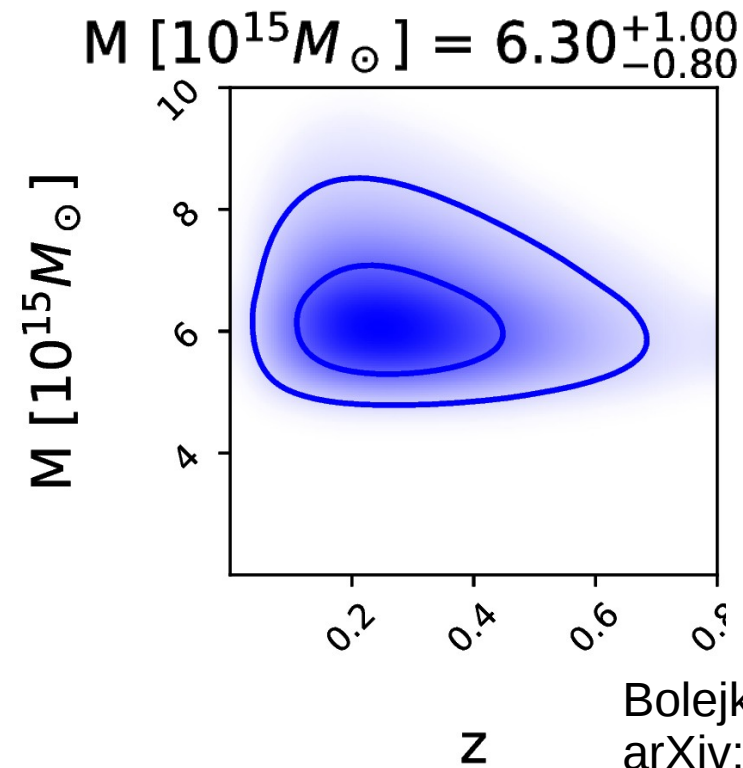*580 supernovea and
30 lensed galaxies*
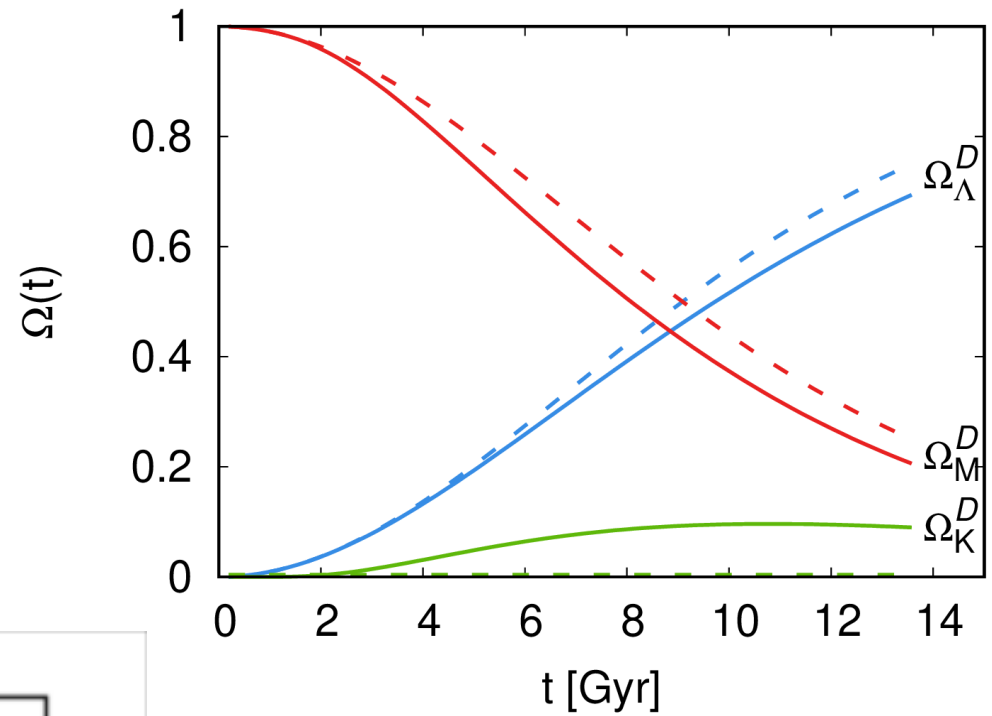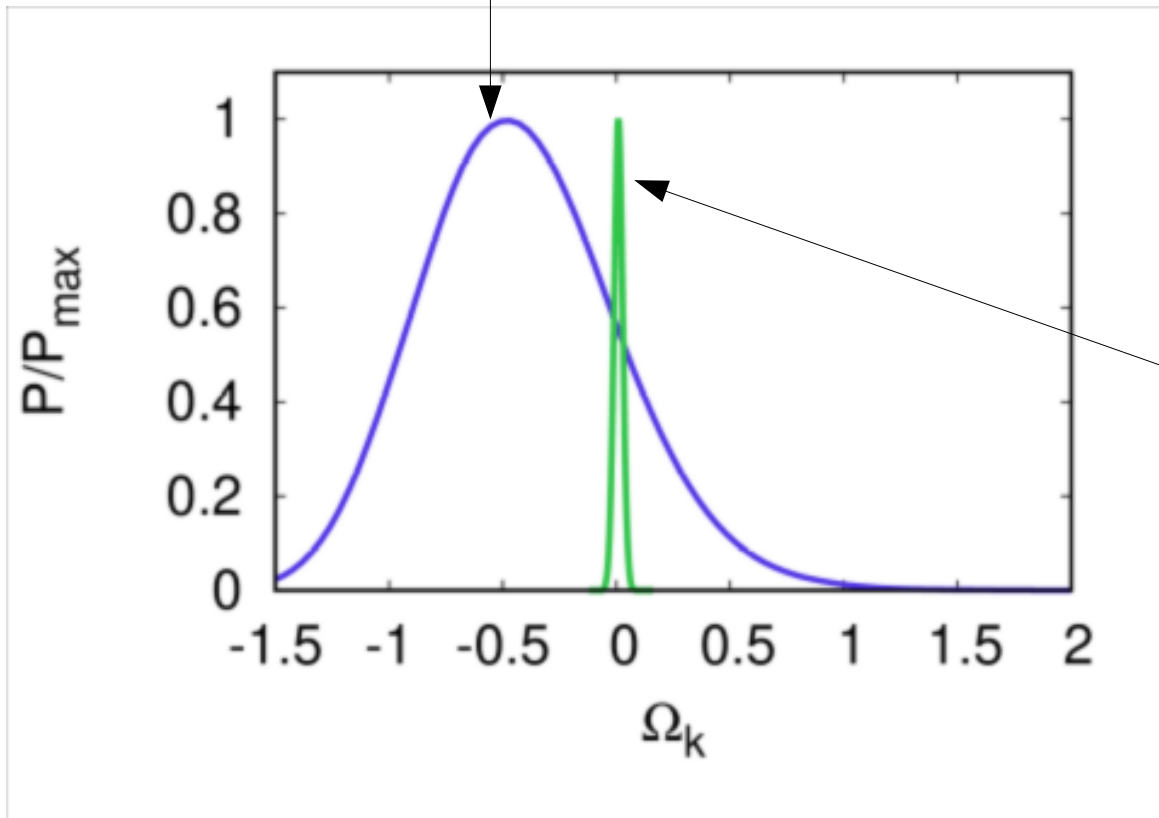
Future data:
*10,000 supernovea and
10,000 lensed galaxies*

Rasanen, Bolejko, Finoguenov, *Phys. Rev. Lett.* 115, 101301 (2015)

1. Larger volume

2. Spatial curvature

3. Faster expansion rate

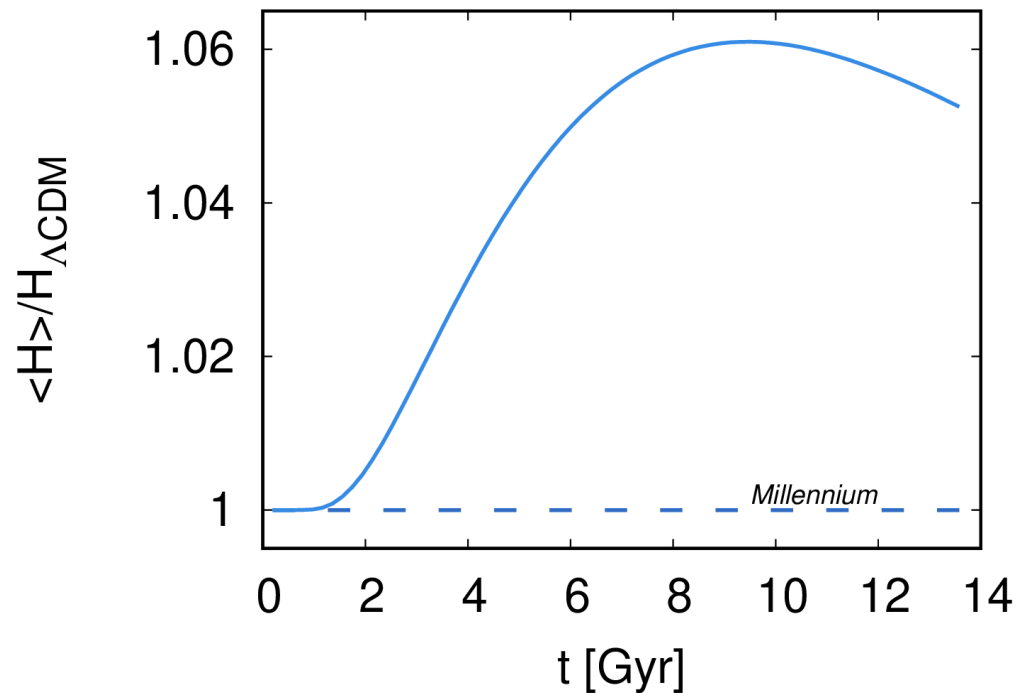Planck (2015)

Riess (2016)
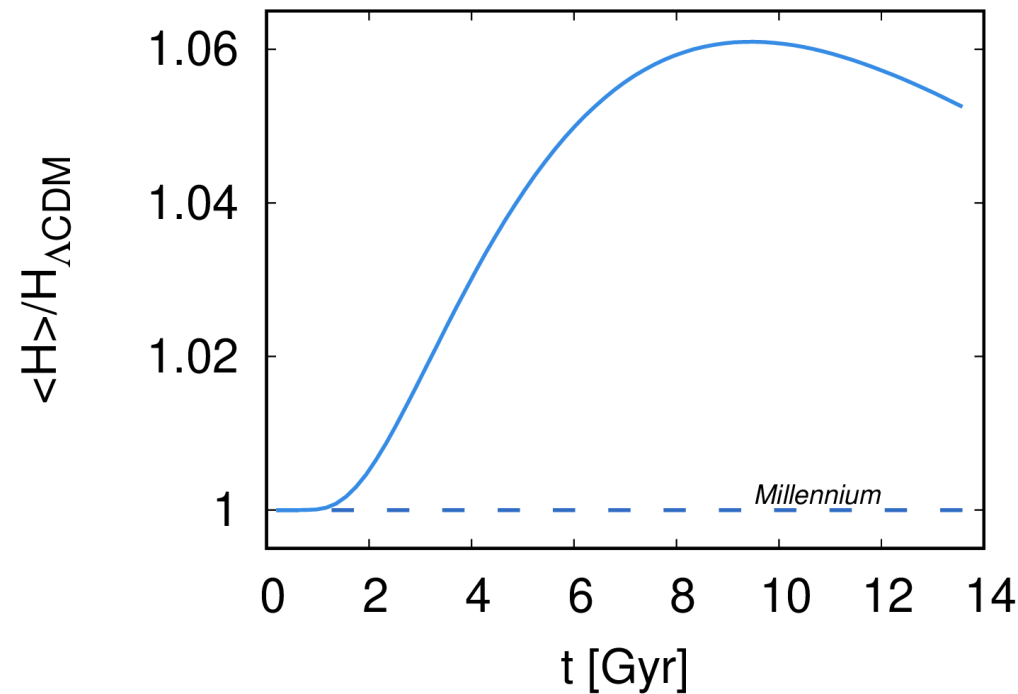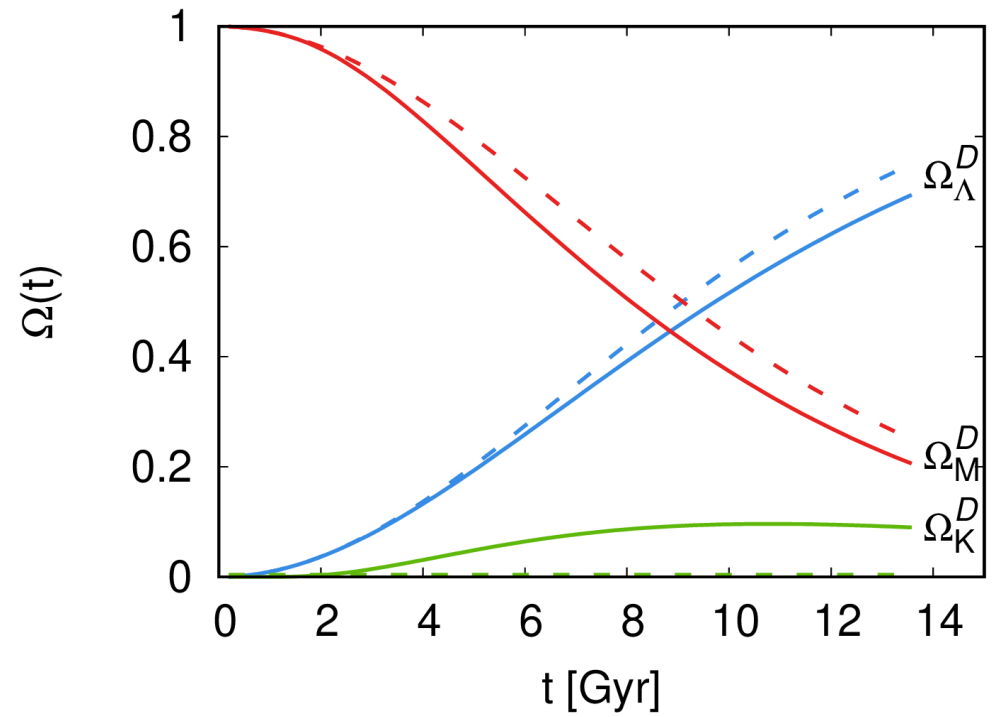
cf. Bolejko, arXiv:1712.02967

1. Larger volume

2. Spatial curvature

3. Faster expansion rate

4. Most massive clusters

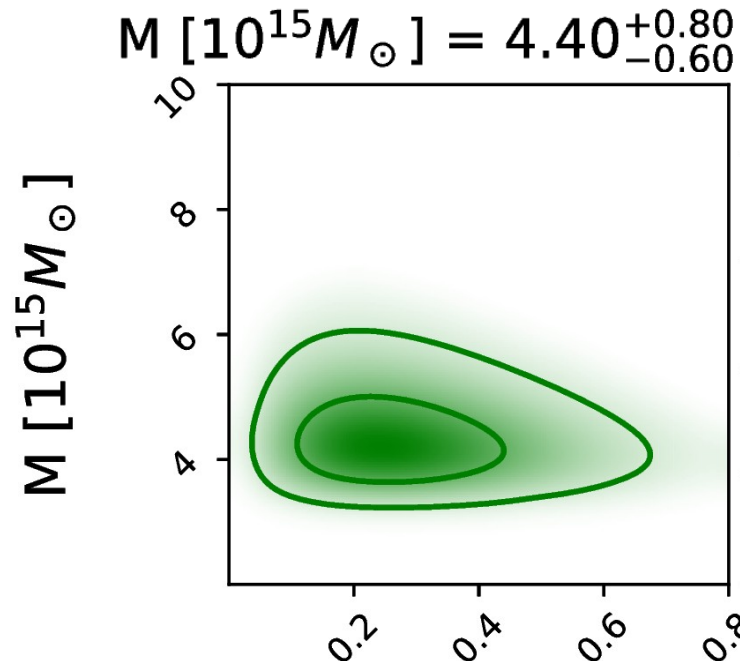$M [10^{15} M_\odot] = 6.30^{+1.00}_{-0.80}$

Bolejko & Ostrowski
arXiv:1805.11047

1. **Larger volume**

2. **Spatial curvature**

3. **Faster expansion rate**

4. **Most massive clusters**

$M [10^{15} M_\odot] = 6.30^{+1.00}_{-0.80}$

$M [10^{15} M_\odot] = 4.40^{+0.80}_{-0.60}$

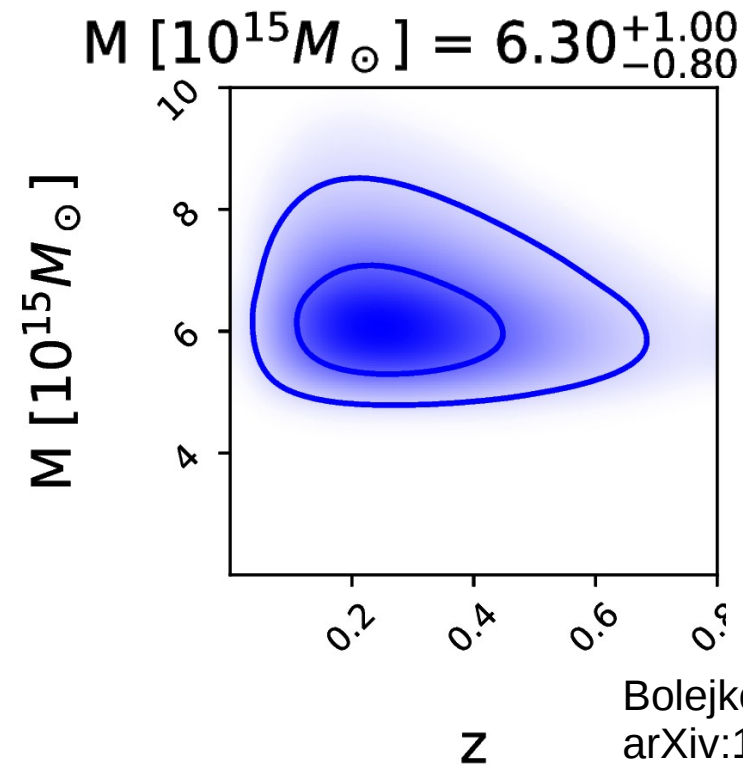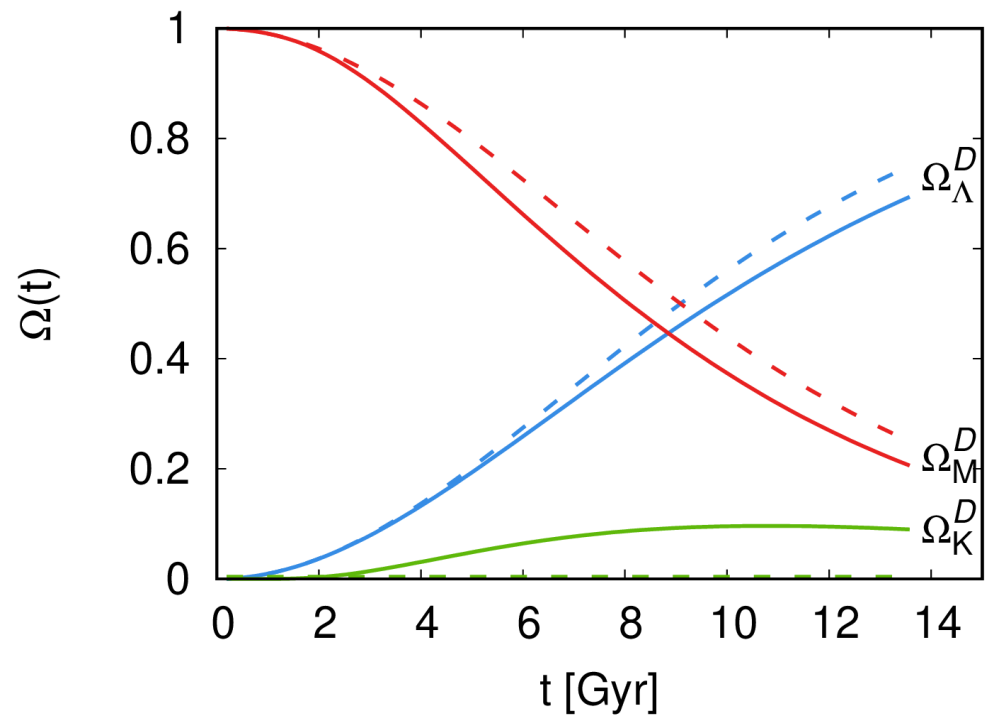Bolejko & Ostrowski
arXiv:1805.11047

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Bolejko & Ostrowski
arXiv:1805.11047