September 25, 2007

First Annual School of EU Network

"Universenet" – The Origin of the Universe

Mytilene, Island of Lesvos

Voids of dark energy

Irit Maor

Case Western Reserve University

With Sourish Dutta

PRD 75, gr-qc/0612027

A very quick summary:

The universe is accelerating. [kinematics]

We do not know why. [dynamics]

Cosmological constant?

120 orders of magnitude!

wmap3: $w = -1.062^{+0.128}_{-0.079}$

"wmap does not need quintessence "

(Page)

Motivation for the cosmological constant

TABLE III Summary of the Bayes Information Criteria Results. The flat cosmological constant (flat ΛCDM model depends on only one parameter and is preferred by BIC. The ΔBIC values for all other models in the table are then measured with respect to this flat cosmological constant model. The goodness of fit (GoF) approximates the probability of finding a worse fit to the data. The models are given in order of increasing ΔBIC or complexity (derived from (Davis *et al.*, 2007).

Model	χ^2/ dof	GoF(%)	ΔBIC	Parameters Fitted
Flat cosmo const	194.5 / 192	43.7	0	$\Omega_{m0} = 0.27 \pm 0.04$
Flat Gen. Chaplygin	193.9 / 191	42.7	5	$A = 0.73 \pm 0.05,\ \alpha = 0.06 \pm 0.10$
Cosmological const	194.3 / 191	42.0	5	$\Omega_{m0}, \Omega_\Lambda$
Flat constant w_{DE}	194.5 / 191	41.7	5	$\Omega_{m0} = 0.27 \pm 0.04,\ w_{CD} = -1.01 \pm 0.15$
Flat variable $w_{DE}(z)$	193.8 / 190	41.0	10	$\Omega_{m0} = 0.27 \pm 0.04,\ w_0 = -1.0 \pm 0.4, w_a = -0.4 \pm 1.8$
Constant w_{DE}	193.9 / 190	40.8	10	$\Omega_{m0}, \Omega_\Lambda,\ w_{DE}$
Gen. Chaplygin	193.9 / 190	40.7	10	A, α, Ω_{K0}
Cardassian	194.1 / 190	40.4	10	Three parameters Ω_{m0}, q, n poorly constrained, not needed.
Flat DGP	210.1 / 192	17.6	16	Ω_{m0}
DGP	207.4 / 191	19.8	18	Ω_{m0}, β. SN+BAO strongly disagree with CMB
Chaplygin	220.4 / 191	7.1	30	$A,\ \Omega_{m0}$
Flat Chaplygin	301.0 / 192	0.0	30	A, Ω_{m0}

Bludman, 0702085

But: “CMB needs something else”

Many degeneracies for w(z).

Maor et al, 0007297

Upadhye et al, 0411803

Which parameters? — Liddle, 0401198

Which priors? — Maor et al, 0112526

Which data sets? — Bridle et al, 0303180

yesterday, Paul Hunt
today, Ed Copeland

The background:

BAO
Clusters
CMB
ISW
SN
SZ
WL
...

→ #% for w_0

maybe #% for $\frac{dw}{dz}$

Background measurements will have a very hard time differentiating between CC and DDE.

All focus on w(z).

Null experiments, how far?

Looking for the dark stuff

Perturbations

Does DDE cluster on scales less than ~100 Mpc?

(yes)

A thorough understanding of the behaviour of perturbations is needed.

If it clusters, it is not the cosmological constant!!

Implications of inhomogeneities?

Large Scale, CMB

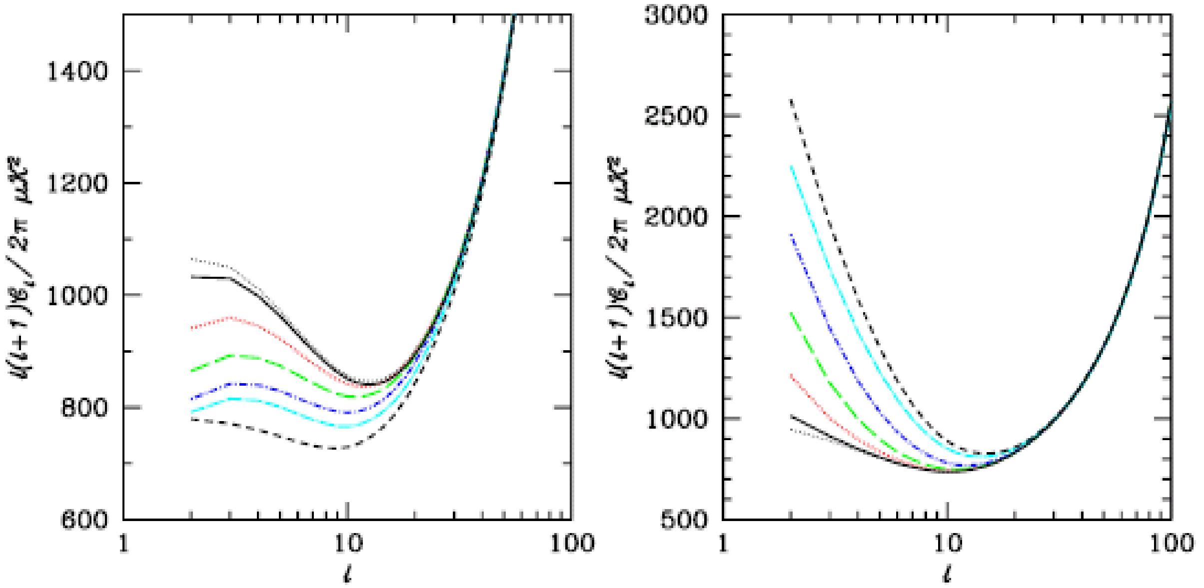


Figure 5. On the left the CMB anisotropies for the $w = -0.6$ model. The top solid line is with perturbations and the low dashed line for no perturbations. In between the speed of sound is decreasing from top to down with $c_s^2 = 0.2, 0.05, 0.01, 0.0$. On the right the CMB anisotropies for the $w = -2.0$ model. The lower solid line is with perturbations and the top dashed line for no perturbations. In between the speed of sound is increasing from top to down with $c_s^2 = 0.0, 0.01, 0.05, 0.2$. The thin dotted lines above (for $w = -0.6$) and below (for $w = -2$) correspond to sound speeds of $c_s^2 = 5.0$. Note that in both cases that $c_s^2 = 1.0$ corresponds to the solid line.

Weller and Lewis, 0307104

Smaller scale inhomogeneities

H

C

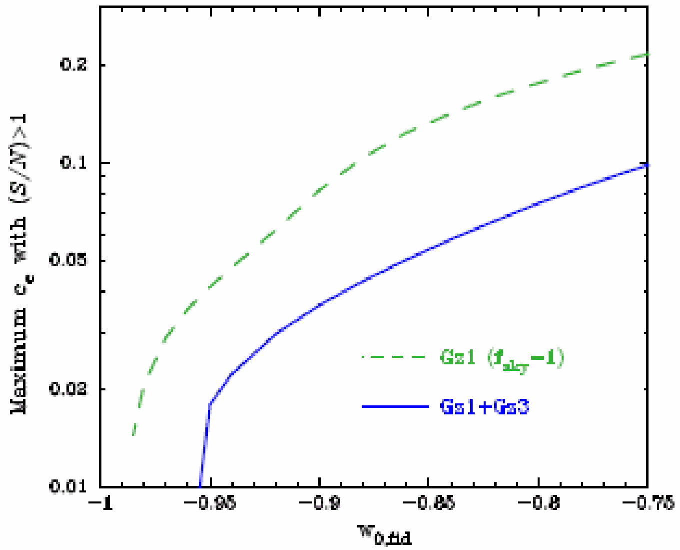


FIG. 3: A maximum dark energy sound speed with $(S/N)|_{c_e} \geq 1$ against the fiducial value of w_0. The solid and dashed curves are the results for WFMOS (Gz1 plus Gz3) and the full-sky $z \sim 1$ survey, respectively. As the underlying true cosmology approaches to the cosmological constant model, one can detect dark energy clustering from a galaxy survey only when the sound speed c_e is sufficiently small.

Takada, 0606533

C ⟷ H

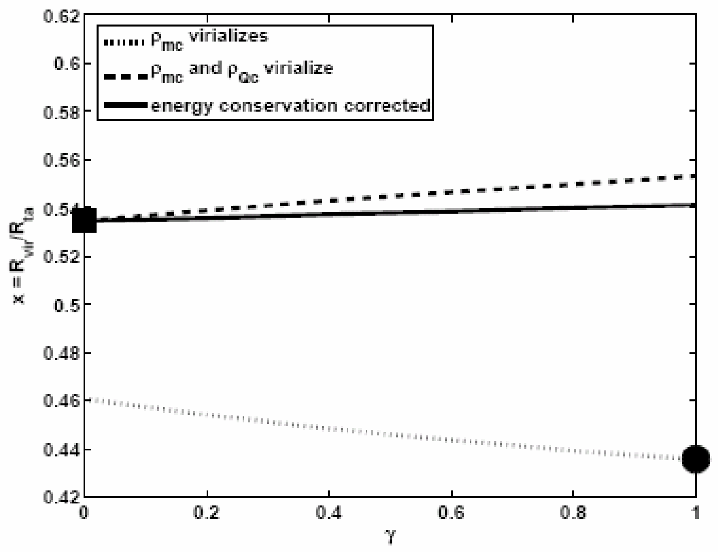


Figure 3. R_{vir}/R_{ta} as a function of γ, for $w = -0.8$ and $q = 0.2$. $\gamma = 0$ describes the case of a fully clustering Q field, and $\gamma = 1$ is the case of a homogeneous Q, allowing only the matter component to cluster. For $\gamma = 0$, taking the dark energy into the virialization is highly plausible, (see square on left). If one assumes that only the matter component virializes for $\gamma = 1$ (see circle on right), it is unclear how to extrapolate in a smooth way between the two cases. This will produce a discontinuity in the transition from the "clustering" to the "non-clustering" behaviour.

Maor and Lahav, 0505308

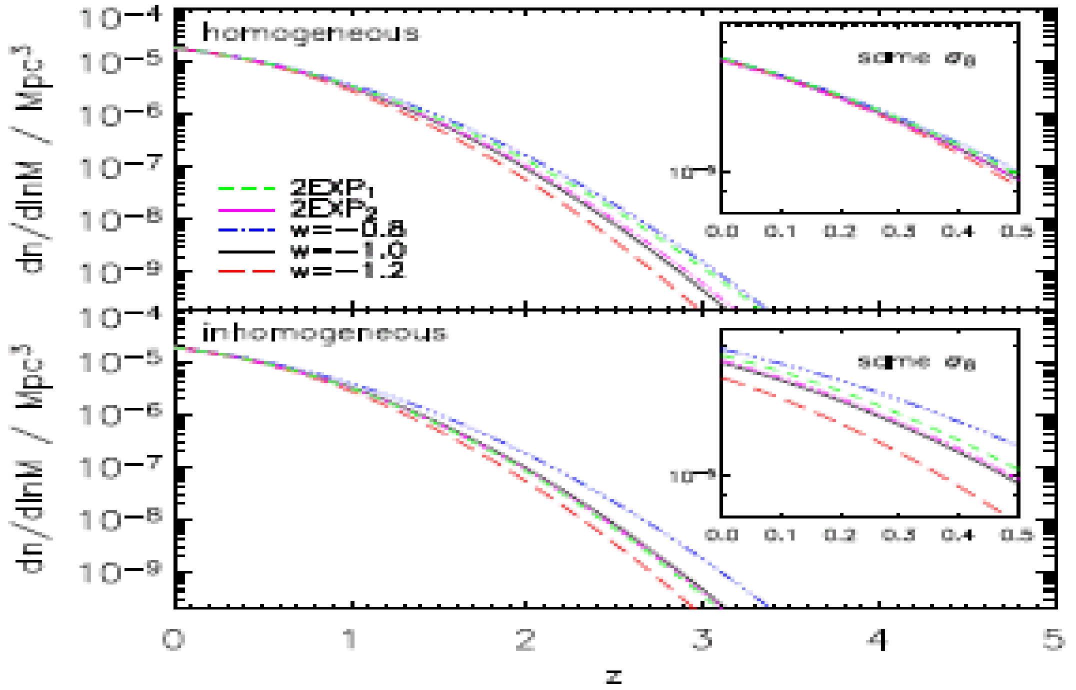


Fig. 2. Redshift evolution of the modified Press-Schechter mass function at $M = 10^{14}\,h^{-1}\,M_{\odot}$ for homogeneous (top panel) and inhomogeneous (bottom panel) dark energy models. In the main panels models were normalized to reproduce the present-day abundance of dark mater halos of the $\Lambda-$model with $\sigma_8 = 0.9$. In the embedded panels models were normalized to the same $\sigma_8 = 0.9$. Lines are the same as for Fig. 1.

H

C

Nunes et al, 0506043

Calculate, instead of parameterize, the clustering properties of DDE.

$$\mathcal{L} = \mathcal{L}_G + \mathcal{L}_m + \mathcal{L}_\phi$$

$\mathcal{L}_G$ Standard gravitational action

$\mathcal{L}_m$ Standard pressureless fluid

$$\mathcal{L}_\phi = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - V(\phi)$$

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

$$\frac{m}{H_0} \approx 1$$

Linear perturbation

$$\rho_m(t,r) \to \rho_m(t) + \delta\rho(t,r)$$

$$\phi(t,r) \to \phi(t) + \delta\phi(t,r)$$

$$V(\phi+\delta\phi) = V(\phi) + \delta V(\phi,\delta\phi)$$

$$ds^2 = dt^2 - a^2(t)\left[(1+2\zeta(t,r))\,dr^2 + ((1+2\psi(t,r))\,r^2 d\Omega^2\right]$$

(Synchronous gauge)

$$\xi \equiv \dot{\zeta} + 2\dot{\psi}$$

The equations

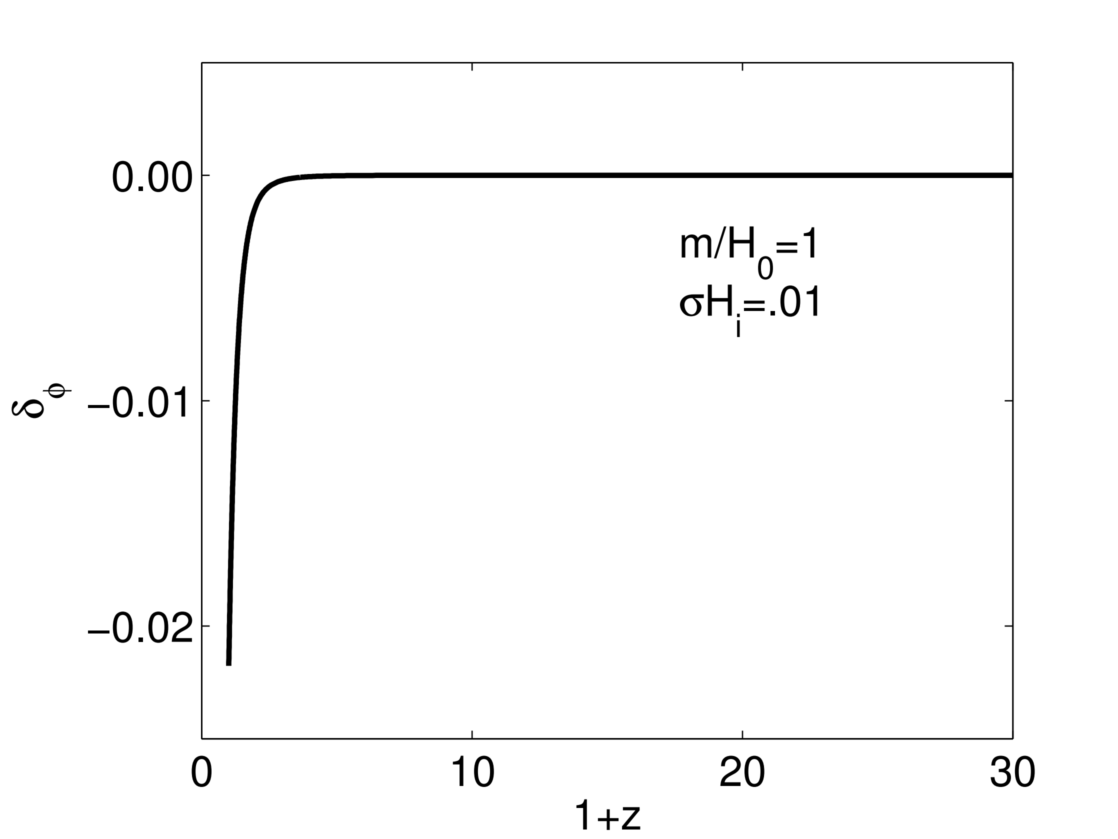
- Zeroth order: standard FRW evolution of the background.
- First order: equations for the perturbation variables, which after a Fourier transformation are ODE’s.

Initial conditions

- Matter: gaussian, with width well within the horizon.
- Scalar field: homogeneous IC, with no kinetic energy ($w = -1$).
- Metric: by the constraints equations.

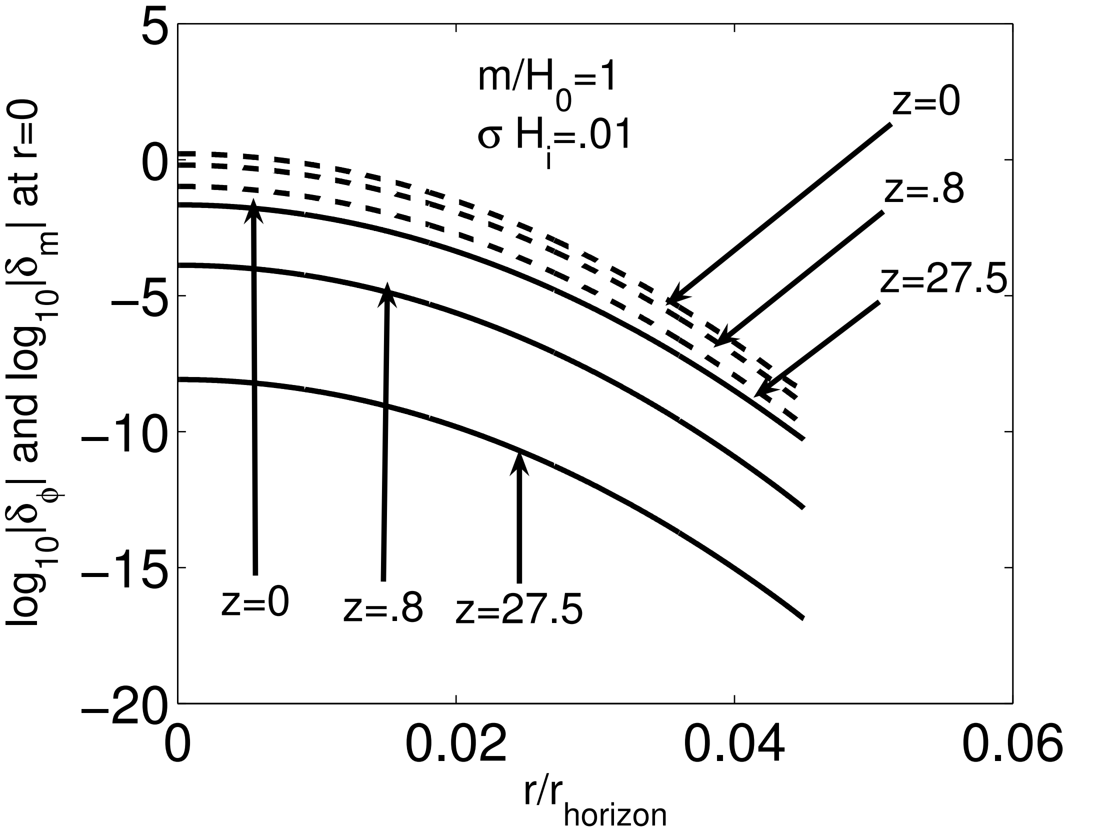
Results are insensitive to IC

Results



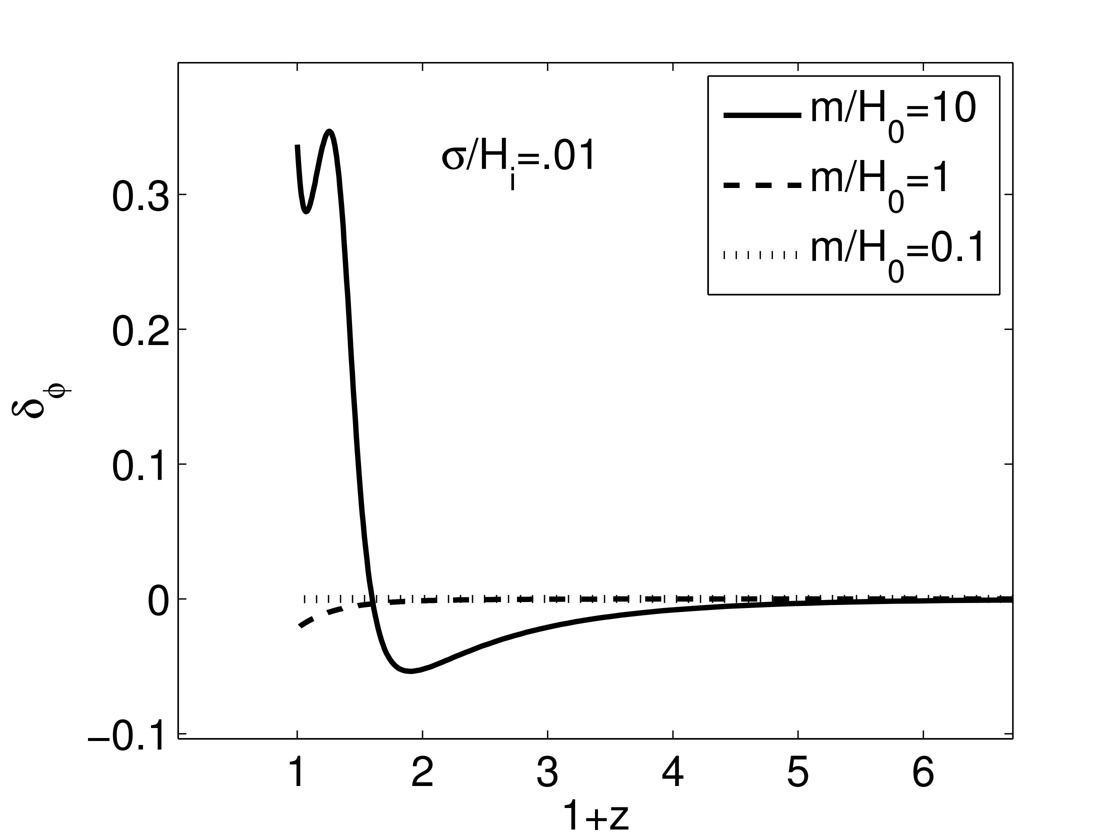
Anti-correlation between matter and DE perturbations

Results



Amplitude grows fast!

Results



"cross-over"

Equation of State

$$w_0 = \frac{p_0}{\rho_0} = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$$

Background EOS

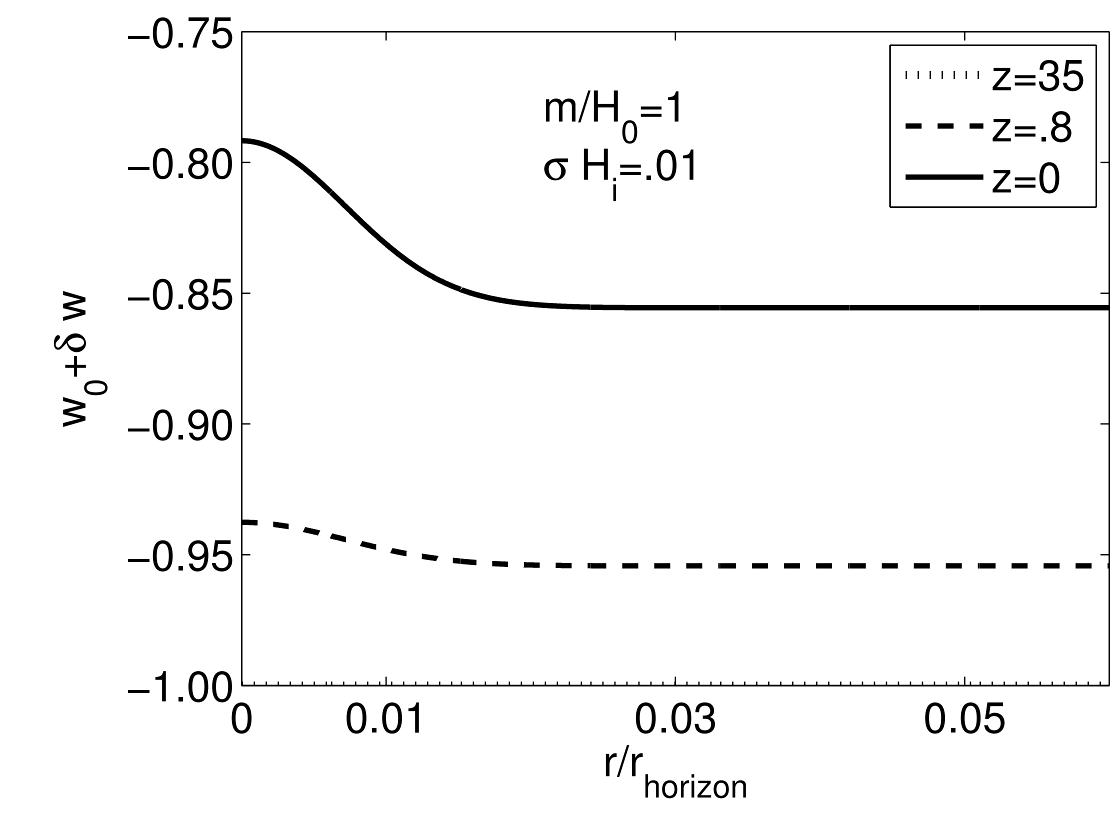
$$\delta w = \frac{1}{\rho_0}\left(\delta p - w_0 \delta\rho\right)$$

Linear correction to EOS

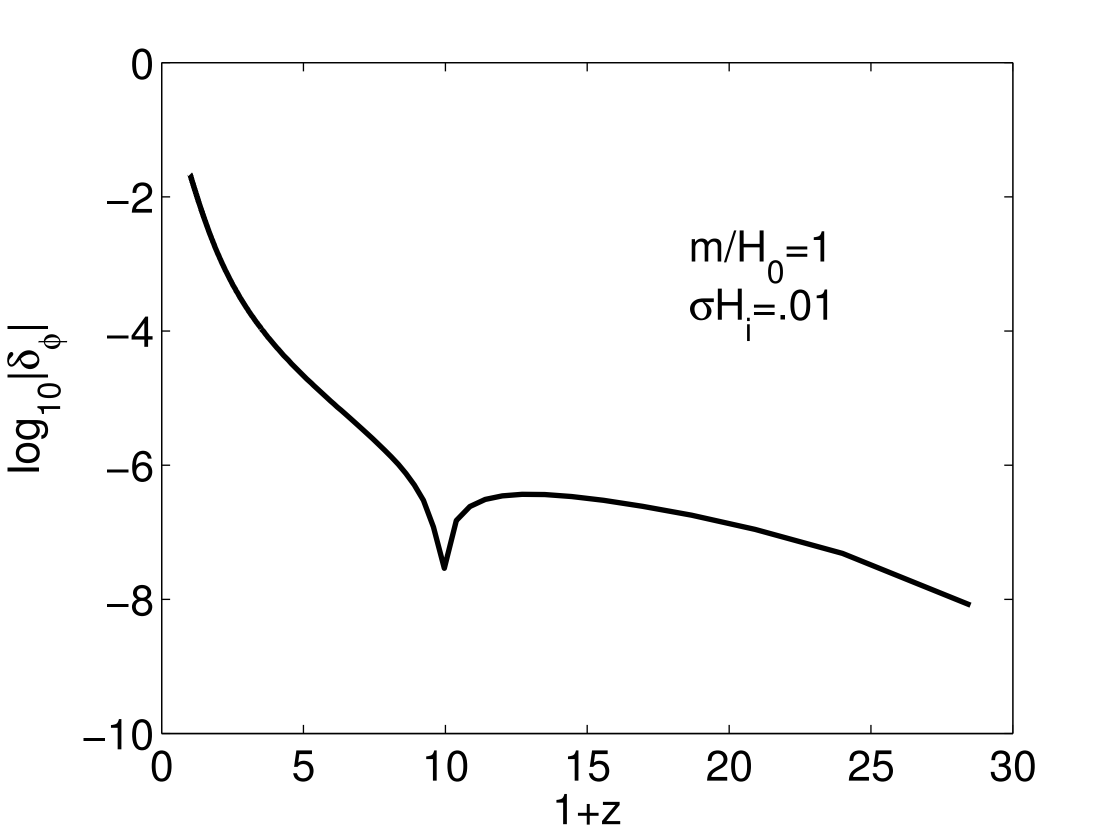
$$w_1 = w_0 + \delta w$$

First order corrected EOS

Equation of state



Spatial profile of the equation of state



Why a void?

Void formation

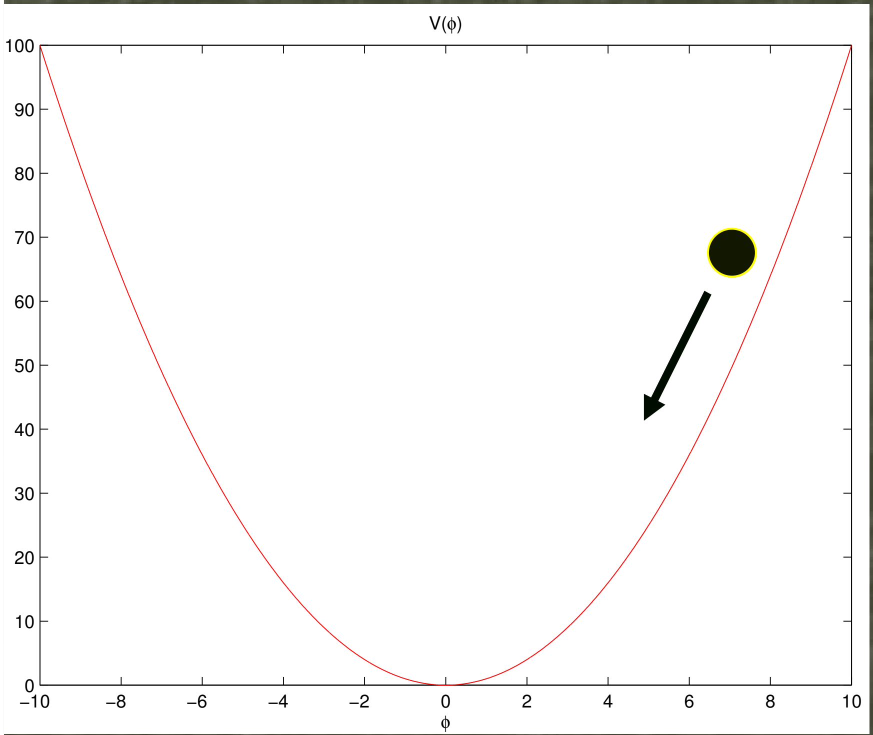
Energy density correction:

$$\delta\rho_\phi = m^2\phi\delta\phi + \dot{\phi}\delta\dot{\phi}$$

PE correction < 0

KE correction > 0

PE correction quickly dominates → void



$$\phi > 0 \qquad \dot{\phi} < 0$$

$$\delta\phi < 0 \qquad \delta\dot{\phi} < 0$$

$$\downarrow \qquad \downarrow$$

$$\delta PE < 0 \qquad \delta KE > 0$$

Acceleration slows, but doesn't change sign: $\ddot{\phi} < 0$

Conclusions

At the linear level, DDE develops voids [ripples].

Our results are generic for slow-roll DDE.

Possible interesting dynamics in the non-linear regime?

Model sensitivity vs. generality?

Observables?