EFFECT OF DARK ENERGY PERTURBATION ON COSMIC VOIDS FORMATION (SUBMITTED TO MNRAS…)

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Dark Energy

The condition for the acceleration

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\bar{\rho} + 3\bar{P}) > 0 \quad \Rightarrow \quad w_{\rm DE} = \frac{\bar{P}}{\bar{\rho}} < -\frac{1}{3}$$

Planck 2015,

$$w = -1.019^{+0.075}_{-0.080} \quad \textit{Planck}\ \text{TT, TE, EE+lowP+lensing+ext.}$$

Dark Energy
- Cosmological Constant
- Quintessence
- k-essence
- etc...

How do we distinguish dark energy models?

The large scale structure and void

✓ The effect of dark energy should be imprinted on large scale structures.

✓ Voids are low matter density regions.

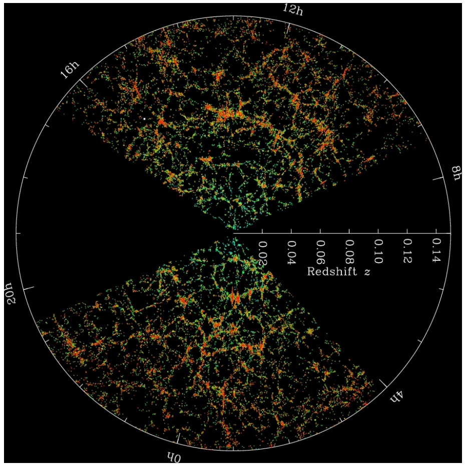
➔They are one of the "largest" structures (～10s Mpc)

➔They are regarded as "clean" objects to observe the effect of DE.

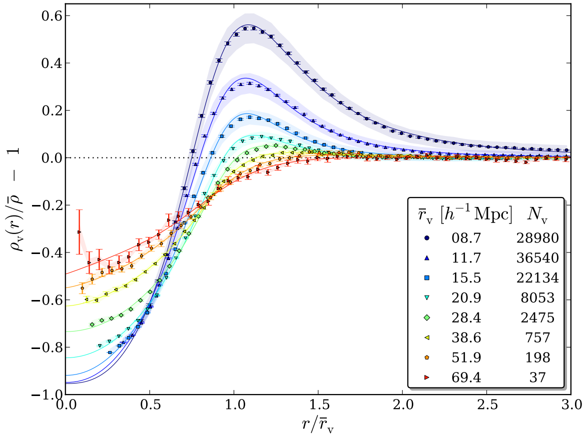
(Weygaert, 2014)

✓ Our aim

To investigate effects of DE models on void properties



credit:SDSS



Hamaus et al.(2014)

Dark Energy and Cosmic Voids

Previous works

- Shape(ellipticity)

  Park & Lee (2007), Lee & Park (2009), Lavaux & Wandelt (2010)
  Biswas et al. (2010), Bos et al. (2012)

- Density profile(Hamaus et al. (2014))

  Novosyadlyj et al. (2016, 2017) ← DE perturbation

- Size distribution (Sheth & Weygaert, (2004))

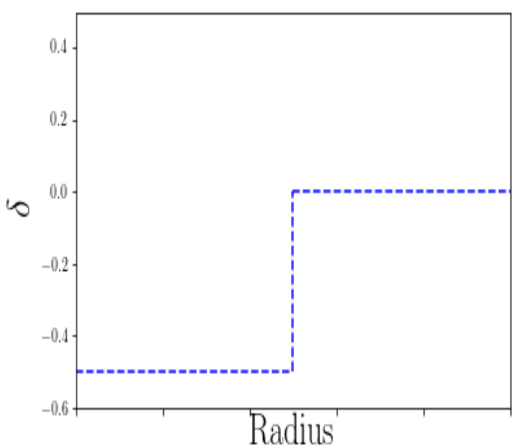
  Pisani et al. (2015)

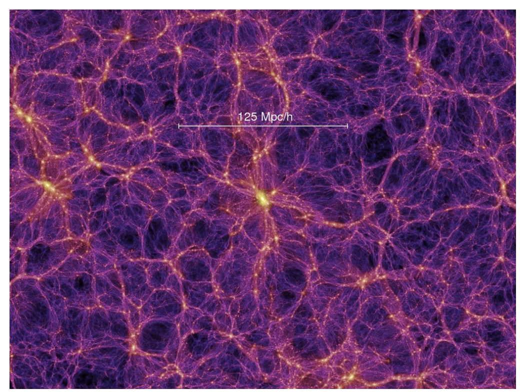
Our work

- Allow DE to be perturbed spatially ($c_s^2 < 1$)
- Focusing on size (isolated void, distribution)

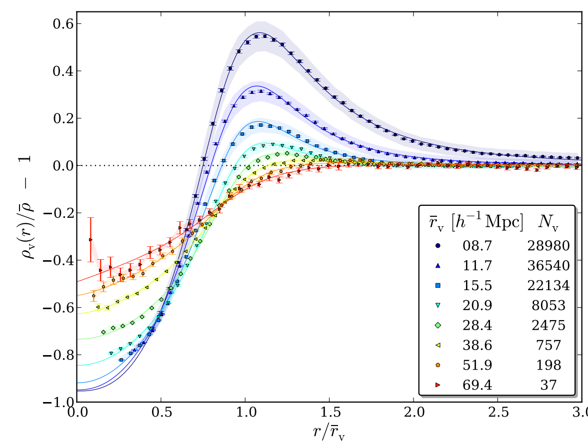
Set up

- Our set up
  - Isolated
  - Spherical
  - Top-hat(bucket) profile
- Voids in real
  - Not isolated
  - Not spherical
  - Smooth density profile





credit: millennium simulation project



Hamaus et al. (2014)

Set up

- Our set up
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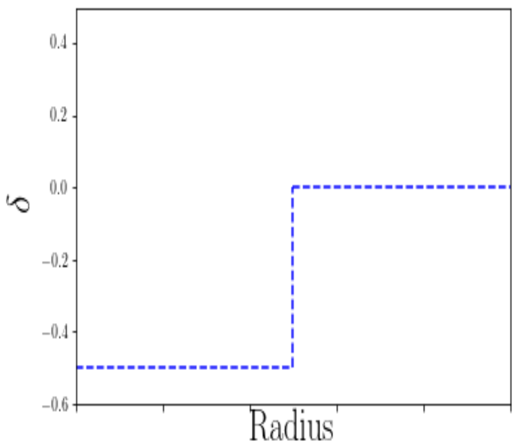
  - Spherical
  - Top-hat(bucket) profile



- calculation set up

$$\Omega_{\mathrm{m},0} = 0.3$$
$$\Omega_{\mathrm{de},0} = 0.7$$
$$H_0 = 70\ [\mathrm{km/s/Mpc}]$$
$$\delta_{\mathrm{m},i} = -5.0 \times 10^{-4}$$
$$\delta_{\mathrm{DE},i} \propto \delta_{\mathrm{m},i}$$
$$0 \leq c_s^2 < 1$$
$$w \neq -1$$

Evolution equations (comoving coordinate:Basse et al. (2011))

$$\frac{X''}{X} + \mathcal{H}\frac{X'}{X} = -\frac{4\pi G}{3}a^2\left[\bar{\rho}_{\rm m}\delta_{\rm m}^{\rm TH} + \bar{\rho}_{\rm de}\delta_{\rm de}^{\rm TH} + 3\delta P_{\rm de}^{\rm TH}\right]$$

where $X = \frac{R}{a},\ (') = \frac{d}{d\tau} = a\frac{d}{dt},\ \mathcal{H} = aH$

matter $M = \frac{4\pi}{3}\bar{\rho}_{\rm m}(1+\delta_{\rm m}^{\rm TH})R^3 = {\rm constant}$

$$\Rightarrow \delta_{\rm m}^{\rm TH} = (1+\delta_{{\rm m},i}^{\rm TH})\left[\frac{X_i}{X}\right]^3 - 1$$

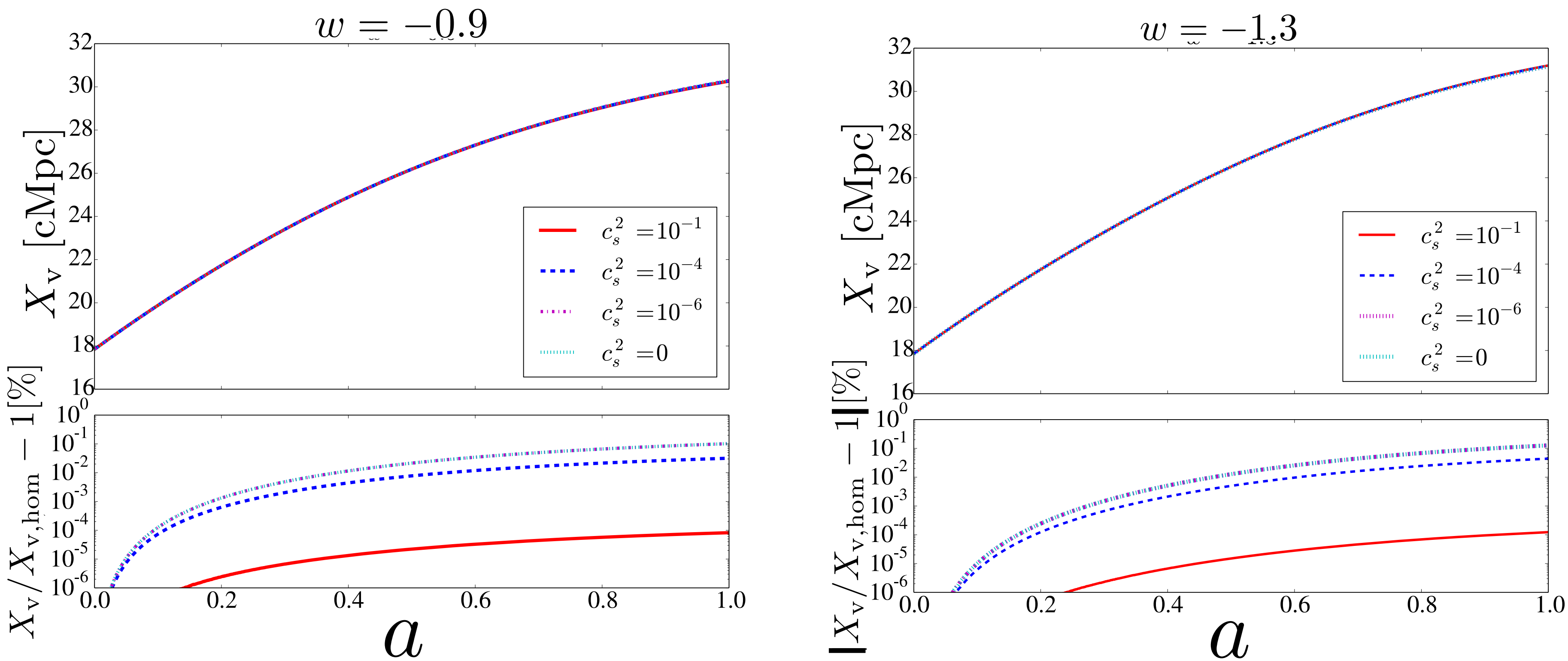
dark energy

$$\rho'_{\rm de} + 3\mathcal{H}(\rho_{\rm de} + P_{\rm de}) + \nabla\cdot[(\rho_{\rm de} + P_{\rm de})\vec{v}_{\rm de}] = 0$$

$$\vec{v}_{\rm de}{}' + \mathcal{H}\vec{v}_{\rm de} + (\vec{v}_{\rm de}\cdot\nabla)\vec{v}_{\rm de} + \frac{\nabla P_{\rm de} + \vec{v}_{\rm de}\dot{P}_{\rm de}}{\rho_{\rm de} + P_{\rm de}} + \nabla\phi = 0$$

$$\nabla^2\phi = 4\pi G a^2\left[\bar{\rho}_{\rm m}\delta_{\rm m}^{\rm TH} + \bar{\rho}_{\rm de}\delta_{\rm de}^{\rm TH} + 3\delta P_{\rm de}^{\rm TH}\right]$$

Results for an isolate void



Effects of various sound speed on the evolution of void radius.

For w = -0.9, small value of sound speed promotes the evolution, while for w=-1.3 it suppresses the evolution.

At a = 1, the maximum deviation is around 0.1%

Dark Energy perturbation in Fourier space

Jeans wavenumber $k_J^2 = \frac{3}{2}\frac{\mathcal{H}^2}{c_s^2}$

perturbation scale ∼/< Jeans scale

↓

The perturbation stops to evolve

↓

void scale > Jeans scale

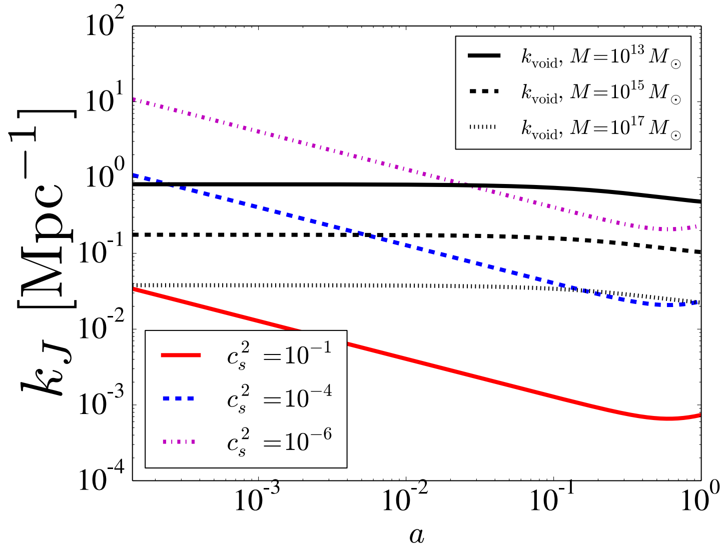
↓

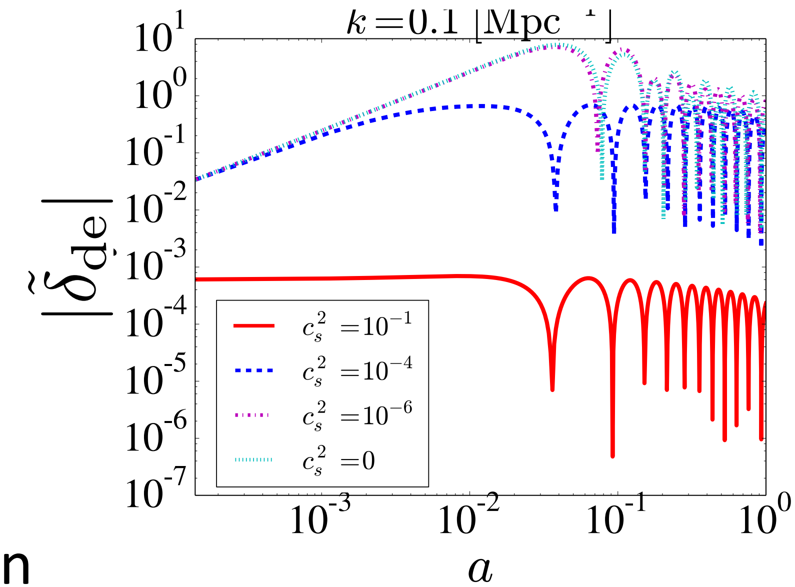
δ_{de} evolves effectively

note: even c_s^2 =0, δ_{de} decays

➔weak potential

and cosmic expansion





Void size function

Void size function: Sheth & Weygaert (2004)

$$\frac{dn}{dR} = (1+\delta_m)^{1/3}\frac{3}{4\pi R_L^3} f(\nu,\delta_v,\delta_c)\frac{d\nu}{dR_L}$$

$$f(\nu) \approx \sqrt{\frac{2}{\pi}}\exp\left(-\frac{\nu^2}{2}\right)\exp\left(-\frac{|\delta_v|}{\delta_c}\frac{\mathcal{D}^2}{4\nu^2} - 2\frac{\mathcal{D}^4}{\nu^4}\right)$$

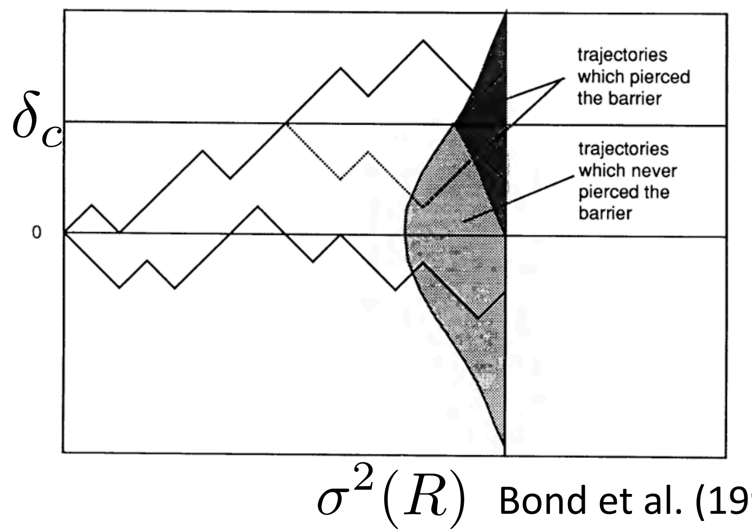
$$R = (1+\delta_m)^{-1/3} R_L$$

$$\nu = \frac{|\delta_v|}{\sigma(R_L)} \qquad \mathcal{D} = \frac{|\delta_v|}{\delta_c + \delta_v} \qquad \delta_c = 1.69$$

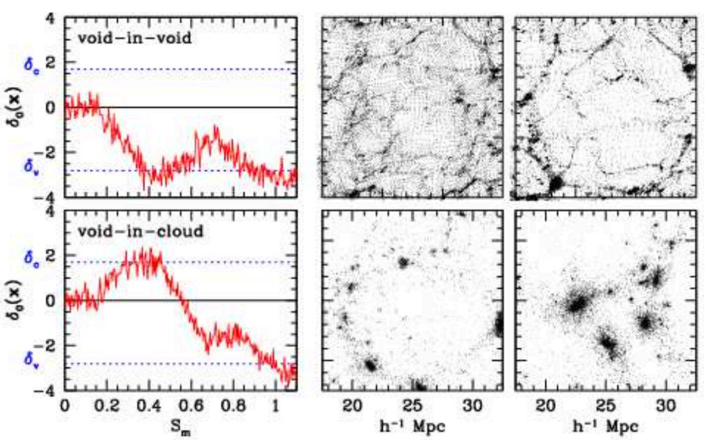
$$\sigma^2(R_L) = \int \frac{k^2 dk}{2\pi^2}\tilde{W}(kR_L)P(k)$$

DE perturbation

CAMB(Lewis et al. 2000)



Bond et al. (1991)



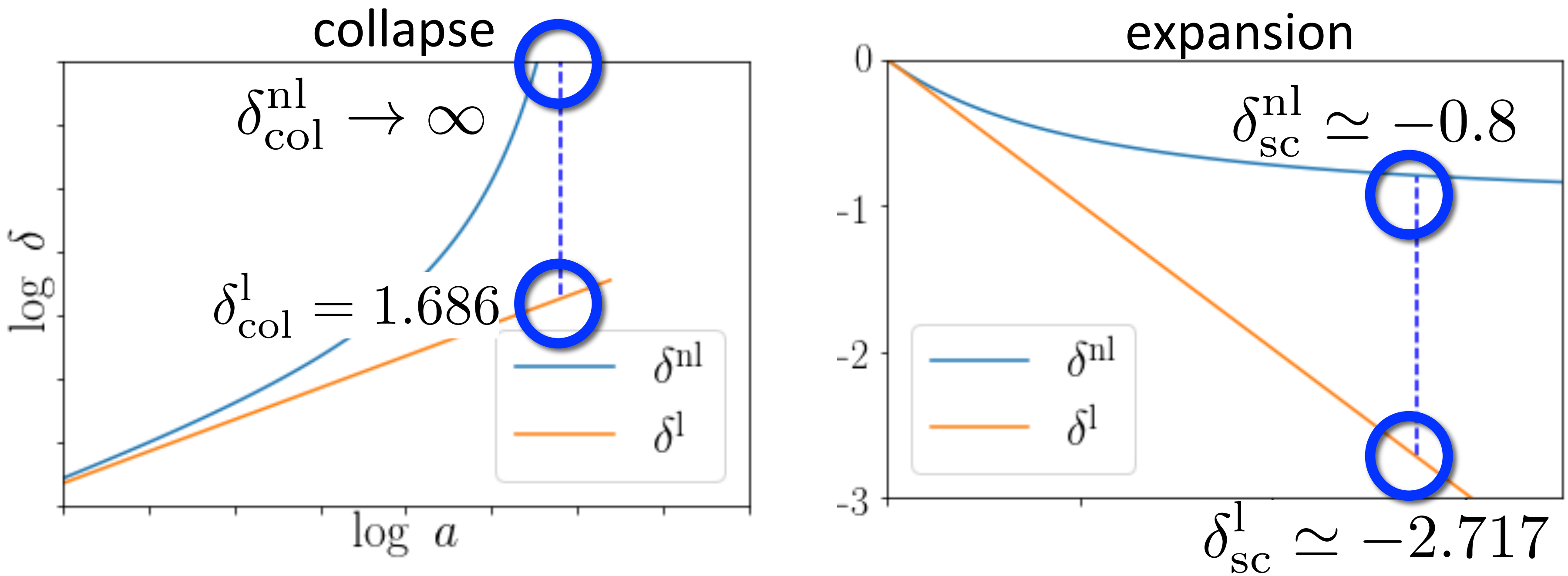
Sheth & Weygaert (2004)

Formation of voids

- Void shell crossing condition (EdS model): Blumenthal et al. (1992)

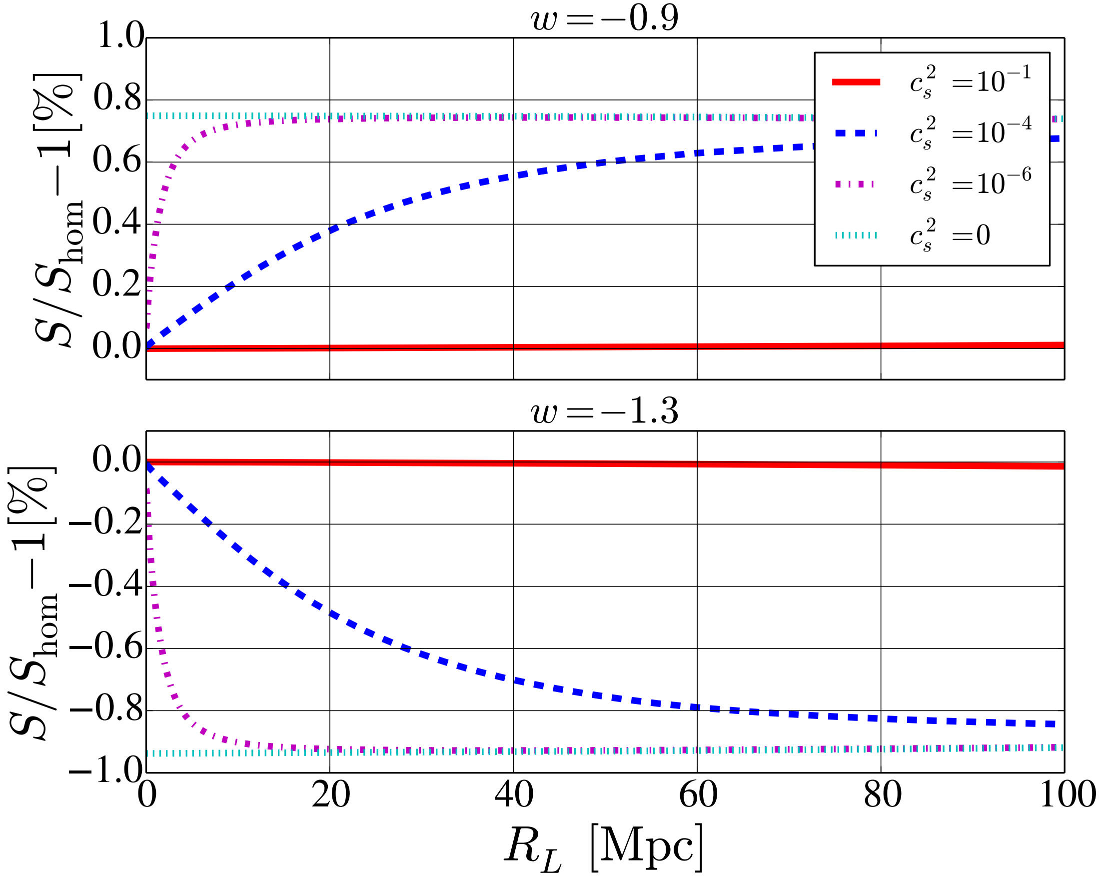
$$\delta R = \frac{\delta R_i}{2|\delta_{\mathrm{m},i}|}(\cosh\theta - 1)\left(1 - \frac{\partial \ln|\delta_{\mathrm{m},i}|}{\partial \ln R_i}\left[1 + \frac{3}{2}\frac{\sinh\theta\cdot(\sinh\theta-\theta)}{(\cosh\theta-1)^2}\right]\right)$$

$$\delta R = 0 \Rightarrow \delta_{\mathrm{m,sc}} \simeq -0.8$$



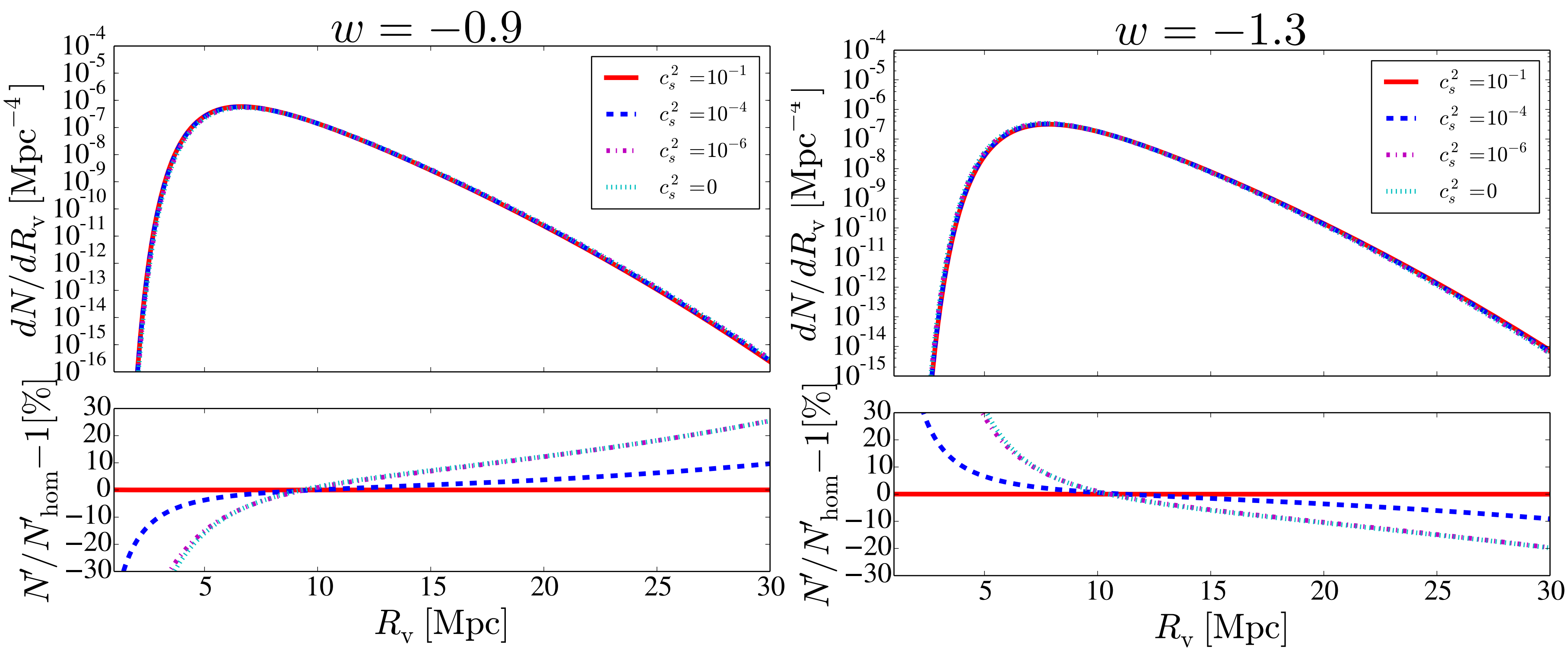
variance (a=1)

For w = -0.9 dark energy perturbation enhances the variance while it suppresses for w = -1.3



$$S = \sigma^2(R_L)$$

Results for void abundance (a=1)



Effects of various sound speed on the evolution of void radius.

For w = -0.9, small value of sound speed increases the number of large voids, while for w=-1.3 it decreases.

At R = 30 Mpc, the maximum deviation is around 20%

Summary

- we characterize dark energy in terms of its constant equation of state and sound speed.
- For calculation, we adopt spherical model for an isolate void and excursion set theory for void abundance.

- The maximum deviation from homogeneous dark energy model is about 0.1 % at present time for the isolate void
- When w=-0.9 dark energy perturbation works to promote the evolution of void radius while for w= -1.3 it works opposite direction.

- For void abundance, the maximum deviation is more than 20% at the void radius of 30 Mpc.
- At large scale, in case of w=-0.9 dark energy perturbation increases the number of voids, while w =-1.3, it decreases.