Probing Dark Energy Perturbations: measuring the DE sound of speed with WMAP?

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c_s^2 as a potentially strong DE discriminator?

- Despite strong evidence (SN, CMB, LSS…) and despite “concordance” of those distinct observations, the nature of dark energy is still mysterious
- To address this question, a wealth of theories have been proposed, *e.g.* □, Quintessences, k-essences, Chaplygin gases, condensates, …
- So far, all those models have been characterized and tested through their w predictions, that affect both the *background* and the *perturbations* so that a wealth of various observations are available
- But most of the studies have neglected c_s that is potentially a good discriminator of those various models and that affects only perturbations
  - No perturb for □ , $c_s^{Quint}=1$, $c_s^{k\text{-}ess.}$ varies a lot, …
- We follow a mere *phenomenological* approach and address these simple questions:
  - Considering the DE to be a cosmic fluid characterized by w and c_s, what constraints can we place today ?
  - Can we rule out, on this base, any of those models ?
- Relevant refs include *Bardeen 84, Kodama & Sasaki 87, M&B95, Hu 95/01, Dedeo 02*

Brief definitions: DE perturb. described by *w* and c_s^2

- Adiabatic speed of sound, c_a^2
  - All you need for perfect fluid
  - Purely determined by background
  - Gauge/ scale /perturbation independent

$$c_a^2 = \frac{\dot{p}(t)}{\dot{\rho}(t)} = w - \frac{\dot{w}}{3H(1+w)}$$

- General speed of sound, c_s^2
  - Entropy perturbations, □
  - □ □ ≠0 □ c_s^2 perturbation / scale /gauge dependent
  - Gauge independent only in dark energy rest frame, c_s^2

$$p_i\Gamma_i = \delta p_i - c_a^2\delta\rho_i$$

$$c_{si}^2 = \frac{\delta p_i}{\delta\rho_i} = c_{ai}^2 + w_i\Gamma_i\delta_i$$

$$\hat{\delta}_i = \delta_i + 3H_c(1+w_i)\frac{\theta_i}{k^2}$$

Brief definitions II: DE perturb. described by *w* and c_s^2

- General transformation for pressure and density in any frame in terms of the rest frame sound speed

$$\hat{\delta}_i = \delta_i + 3H_c(1+w_i)\frac{\theta_i}{k^2}$$

$$\delta p_i = \hat{c}_{si}^2 \delta\rho_i + 3H_c(1+w_i)(\hat{c}_{si}^2 - c_a^2)\rho_i \frac{\theta_i}{k^2}$$

- So that in the synchronous gauge, where all quantities are here defined in the CDM rest frame (except \hat c_s^2), we have

$$\dot{\delta} = -(1+w)\left(\left[k^2 + 9H_c^2(\hat{c}_s^2 - c_a^2)\right]\frac{\theta}{k^2} + \frac{\dot{h}}{2}\right) - 3H_c\left(\hat{c}_s^2 - w\right)\delta$$

$$\frac{\dot{\theta}}{k^2} = -H_c\left(1 - 3\hat{c}_s^2\right)\frac{\theta}{k^2} + \frac{\hat{c}_s^2}{1+w}\delta$$

- To first order, the perturbations are fully characterized by *w* and c_s^2

Effect of DE perturbations: suppresses CDM growth rate

- Main effect of DE perturbations comes through the driving of cdm perturbations
- At late times when $\Omega_x > \Omega_c$, DE perturbations suppresses CDM perturbations

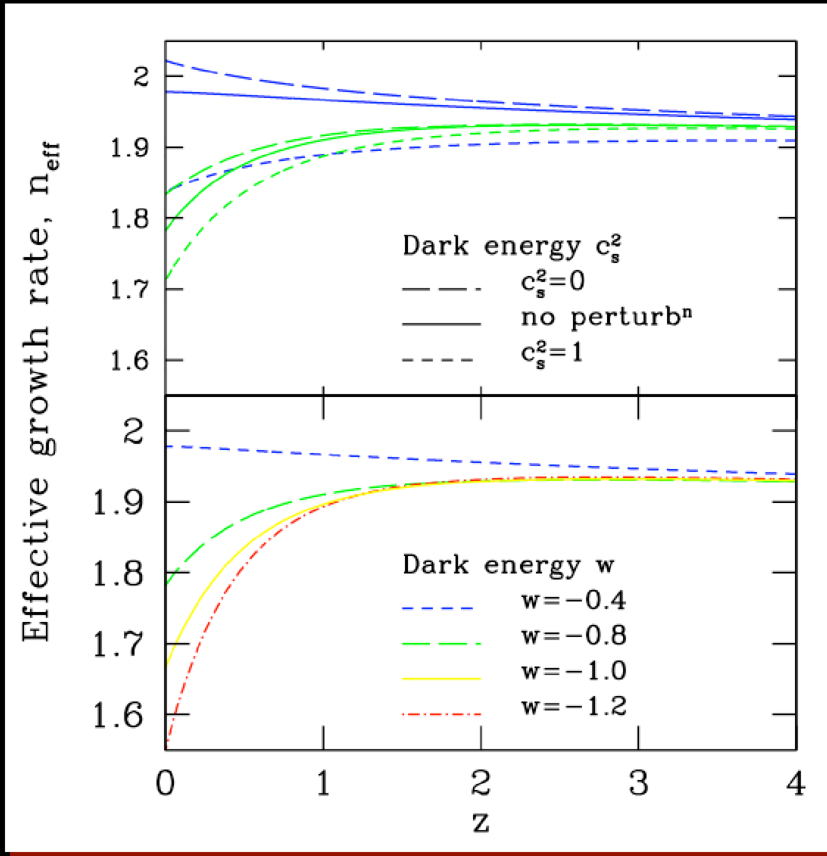
$$\ddot{\delta}_c + H_c\dot{\delta}_c - \frac{3H_c^2}{2}\Omega_c\delta_c \simeq \frac{3H_c^2}{2}(1+3c_s^2)\Omega_x\delta_x$$

- Dark energy perturbations suppressed in comparison to □ $_c$=1

$$\delta_x = F\left[\hat{c}_s^2, (\hat{c}_s^2 - w)\right](1+w)\delta_c$$

suppressed as c_s^2 tends to 1, as c_s^2-w increases

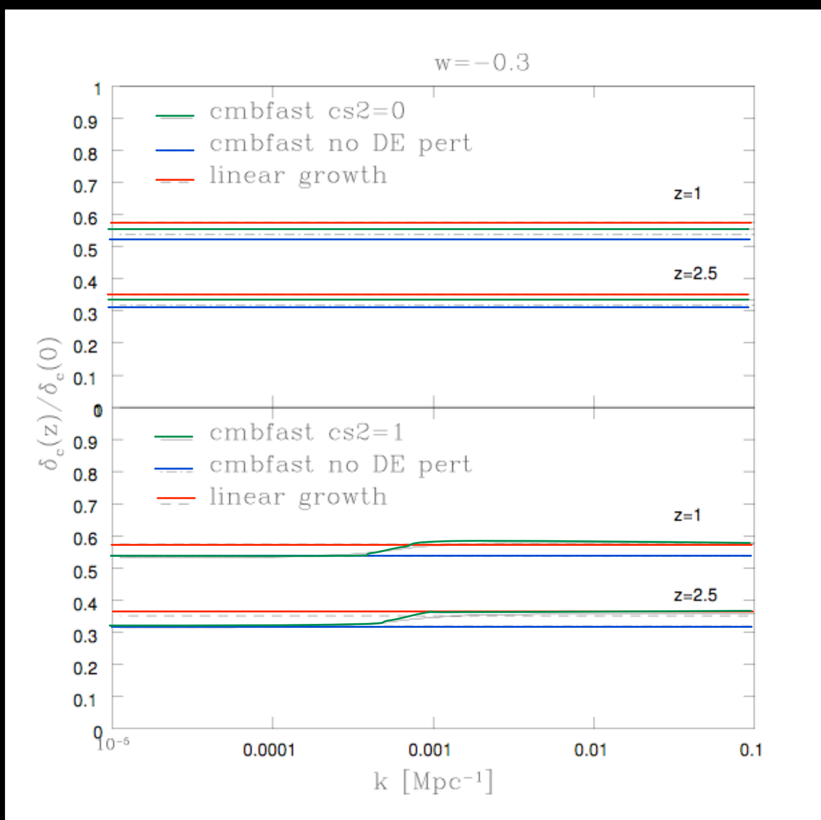
suppressed as w tends to -1



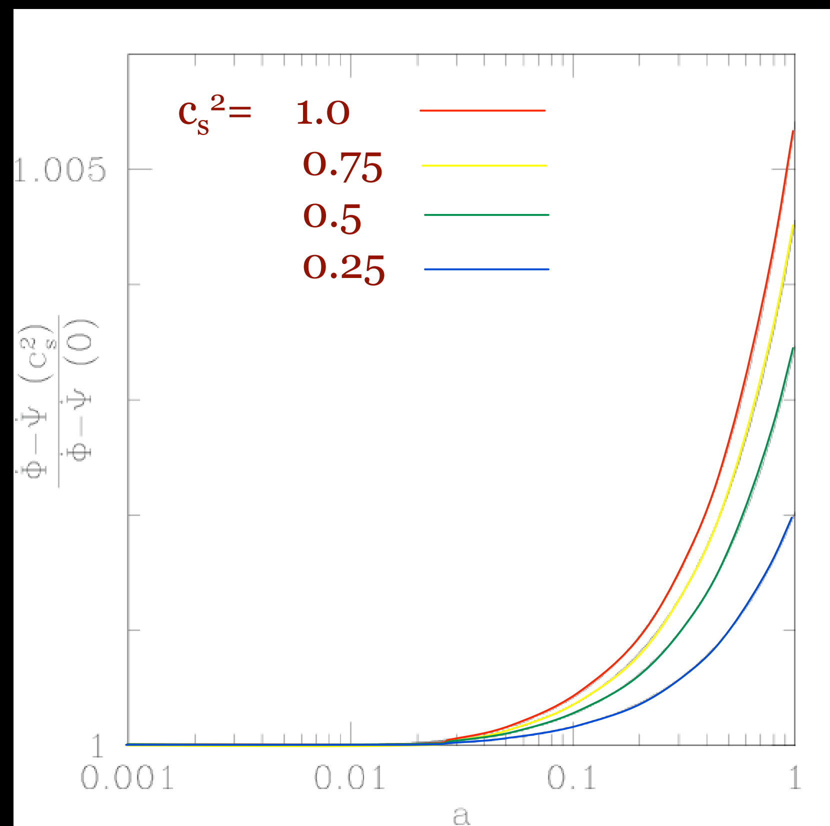
Effective growth rate □$_c$(□)µ □^{neff}

How does this affect observables scales ?

- The affected scales will be the ones that entered the DE sound horizon after the DE domination, *i.e.* $\boldsymbol{k} \leq 10^{-3}$ Mpc^{-1} (depends on c_s and w)
- For those scales, suppression has implications for linear growth factor and ISW
  - Scale and c_s^2 dependence in D(z)
  - Increase in ISW with increasing c_s^2 thus offers a way to decrease the ISW

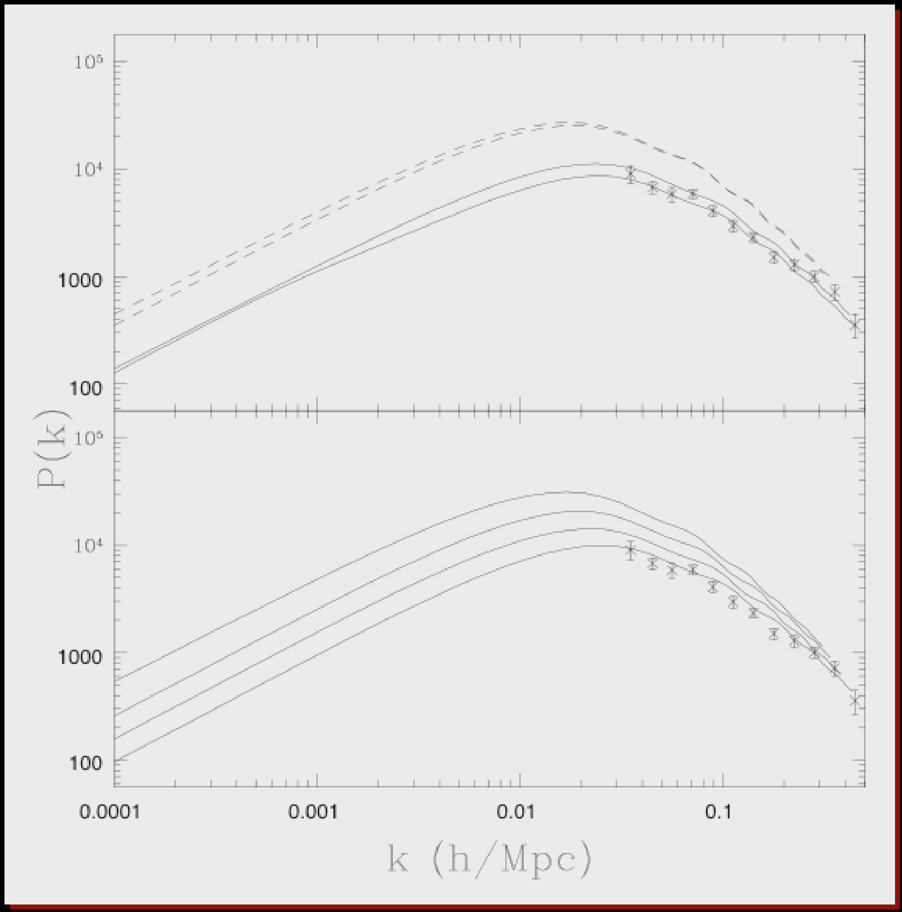


Linear growth factor for various scales , k for c_s^2=0 and 1



ISW source evolution in comparison to c_s^2=0

Can we directly probe those scales ? net effect on *P(k)*



- Cobe normalized

w = -0.9 (dashed)

(c_s^2 = 0., 1. (top., bot.))

w = -0.3 (solid)

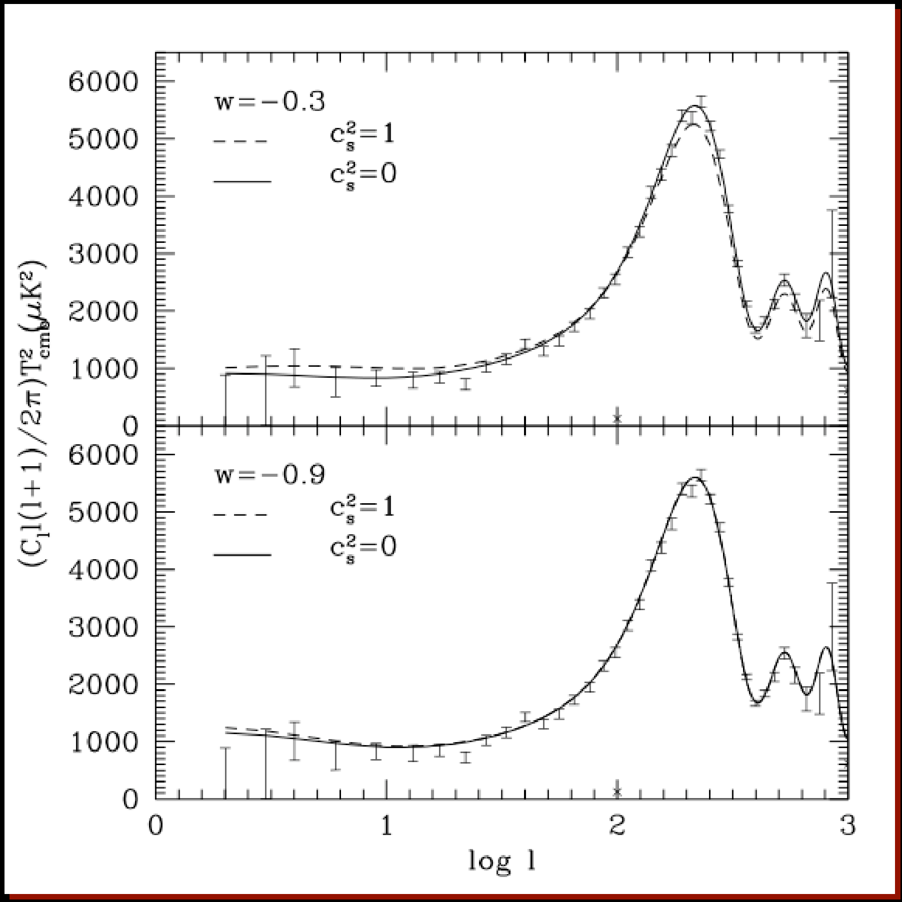
- c_s^2 =1,

w = -1, -0.75,-0.5,-0.25

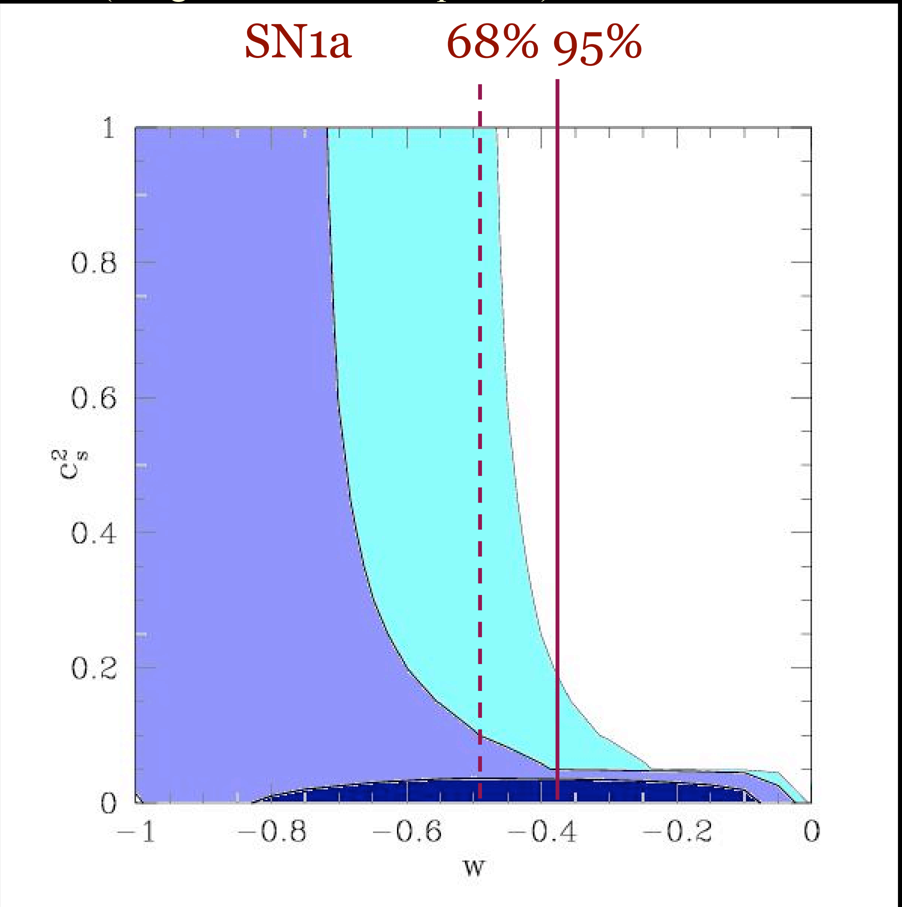
- The normalisation is affected in 3 ways :
  - Reduction of the growth rate
  - Change of absolute amplitude for large scales
  - Modify CMB power at large scales

- No observations of the relevant very large scales at low z except for the ISW… and thanks to WMAP, we can do it now…

CMB angular power spectrum as a probe of the late ISW



Moving along the D_A degeneracy
(marginalized over amplitude)



- 1 □ effect due to the low *l* WMAP points
- Cosmic variance limited - can we hope better from other probe of the ISW ?

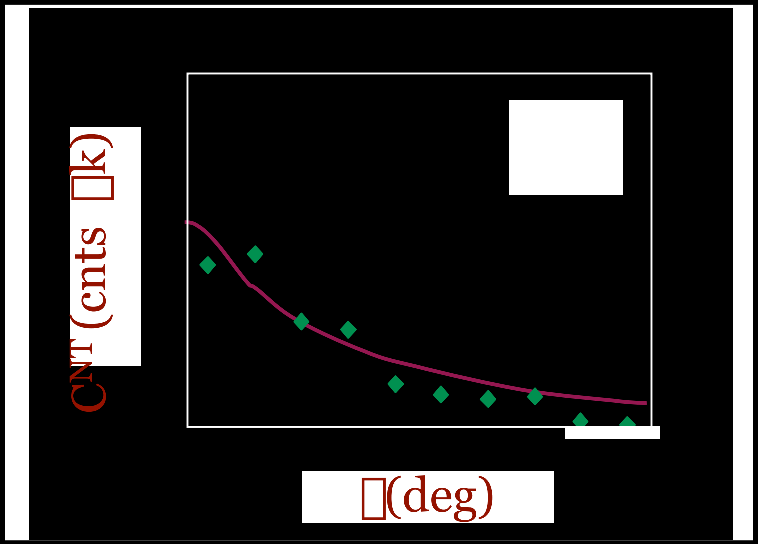
Probing the ISW through CMB x LSS

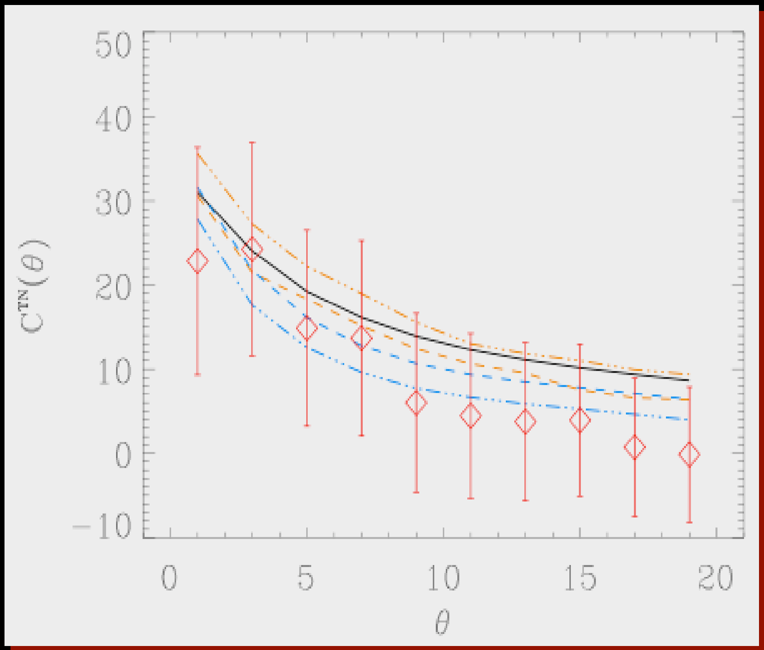
- ISW signature should be intimately correlated with any large scale tracer (linear regime) of the matter distribution (Crittenden & Turok 96)

$$\frac{\delta T}{T} = 2\int_{\eta}^{\eta_0} d\eta \dot{\Phi} \propto \frac{\delta_c^0}{k^2}\int_{\eta}^{\eta_0} d\eta \frac{d(D/a)}{d\eta}$$

$$\frac{\delta N}{\bar{N}} = b_r \delta_c^0 \int d\eta \frac{dN}{d\eta}$$

- Now marginally detected using WMAP by several groups (*Boughn & Crittenden, Nolta et al., Fosalba & Gatzanaga*)
- We attempted to measure it using WMAP and NVSS
- Currently limited by uncertainty in bias and error bars in cross correlation
- Variation in *w* gives 1 effect at best so that c_s^2 is currently undetectable





Conclusions and prospects

- The sound of speed is potentially a powerful discriminator of various DE theories so should not be neglected

- The effect through the damping of CDM perturbations affect large scales today only ($k<10^{-2}$ Mpc^{-1}) and thus is difficult to assess directly

- Best probe looks to be through the ISW

- Current data do not allow constraining measurements
  - Definite answer for CMB (TT & Pol.) power spectra
  - Room for improvement for the direct probe of the ISW (better bias determination, better surveys (LSST/PanSTARRS), better probe of the ISW (e.g. CMB lensing), using polarization)

- Time evolution neglected here but should not

- One simple question to be answered is : What would it take to detect it ?

(in progress with Joe Hennawy (Princeton))