Accelerating expansion of the Universe, Dark energy and analysis of observational cosmological data

Anastasios Theodoropoulos

Supervisor: Leandros Perivolaropoulos

Department of Physics, University of Ioannina, Greece

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Dark Energy

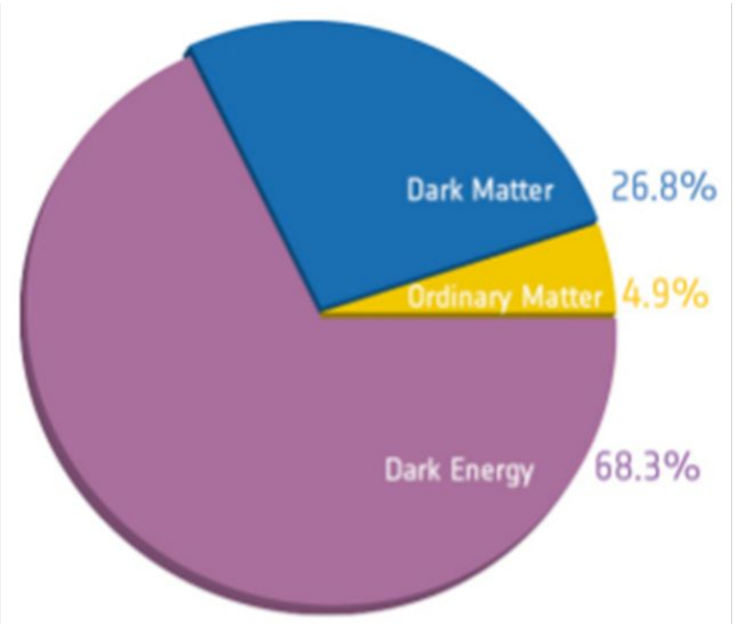
The expansion of the Universe is accelerating and in the context of GR, a new component is needed to account for that, i.e. Dark Energy.

In a flat universe Dark Energy must have:

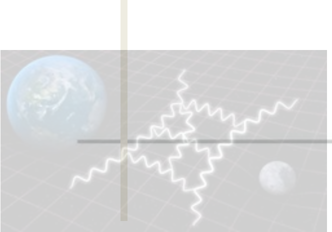
- positive energy density ($\rho_X > 0$)
- negative pressure ($p_X < 0$)

in order to cancel out gravity and potentially lead to accelerating expansion.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho_m + \rho_X\left(1+3w\right)\right]$$

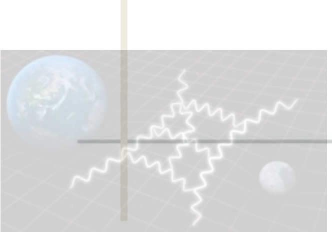


Matter, Dark Matter and Dark Energy contributions to the Mass/Energy of our Universe from the Planck Satellite.



Basic Questions

- Which is the best way to parametrize Dark Energy?
- Which are the best-fit values for the model parameters?
- What properties can we derive from the reconstruction of the fields?



Dark Energy Models: ΛCDM

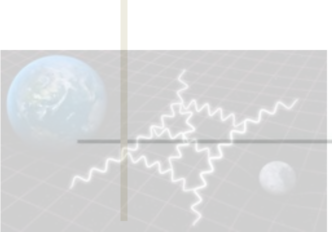
- The cosmological constant Λ is the simplest form of Dark Energy and it corresponds to the time independent energy density:

$$\rho_\Lambda = \frac{\Lambda}{8\pi G}$$

- Which we can obtain from an ideal fluid with equation of state w = -1 and Cold Dark Matter (CDM).
- The Friedmann equation in the presence of matter and a cosmological constant is:

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_\Lambda\right]$$
$$\Omega_m + \Omega_\Lambda = 1$$

- Even though it is simple and is not yet excluded by the observations, it faces some challenges both theoretical and observational.



Dark Energy Models: ΛCDM

Theoretical Challenges:

- **<u>Fine-Tuning Problem:</u> The predicted value of the energy density of the cosmological constant is 121 orders of magnitude larger than the observed one.**
- **<u>Coincidence Problem:</u> The lack of explanation for why dark energy has the same order of magnitude with non-relativistic matter density at the present epoch.**

Observational Challenges:

- H_0 tension (over 4σ):
  - BAO,CMB — $H_0 = 67.4 \pm 0.5 kms^{-1}Mpc^{-1}$
  - Local Measurements — $H_0 = 74.03 \pm 1.42 kms^{-1}Mpc^{-1}$
- Growth tension (over 2σ):
  - Weak Lensing, Redshift Space Distortion — Smaller values for: Ω_{0m} and σ_8 than the geometric probes.
  - Geometric probes — SNIa, BAO, CMB

Dark Energy Models: wCDM

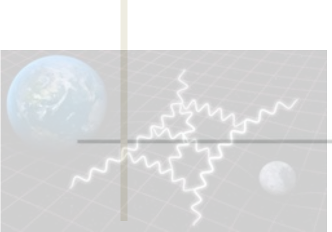
- **Another way to model Dark Energy is by introducing a spatially-homogeneous fluid with equation of state parameter w_{DE}, which we assume to be an arbitrary constant.**

$$w_{DE} = \frac{p_{DE}}{\rho_{DE}} < -\frac{1}{3}$$

- **The Friedmann equation in the presence of matter and a spatially-homogeneous fluid with equation of state parameter w_{DE} is:**

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w_{DE})}\right]$$

$$\Omega_m + \Omega_{DE} = 1$$



Dark Energy Models: Quintessence/CPL

Quintessence

- We can also model Dark Energy by introducing a self-interacting canonical scalar field φ minimally coupled to gravity.

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

- The energy density and pressure of the field is:

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi) \qquad p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)$$

- The equation of state parameter is:

$$w(\phi) = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$$

- A scalar field can play the role of Dark Energy if it satisfies the Slow-roll conditions :

$$\dot{\phi}^2 < V(\phi) \qquad \left|\ddot{\phi}\right| < |V'(\phi)|$$

- The time evolution of the scalar field is determined by the Klein-Gordon equation :

$$\ddot{\phi} + 3\left(\frac{\dot{a}}{a}\right)\dot{\phi} + \frac{dV}{d\phi} = 0$$

- Which can be obtained by the variation of the action:

$$S_\phi = \int \sqrt{-g}\mathcal{L}_\phi\left(\phi, \partial_a \phi\right) d^4x$$

Dark Energy Models: Quintessence/CPL

Quintessence

- The corresponding Friedmann equation is:

$$H^2(z) = H_0^2 \left[\Omega_{0m}(1+z)^3 + \Omega_{0\phi} \exp\left(\int_0^z \frac{3[1+w(z')]}{1+z'} \right) \right]$$

$$\Omega_{0m} + \Omega_{0\phi} = 1$$

- Thus, we need to parametrize the equation of state w(z).

CPL

- A commonly used asantz, is the Chevalier-Polarski-Linder (CPL) asantz.

$$w(a) = w_0 + w_a(1-a)$$

- Or in terms of the redshift:

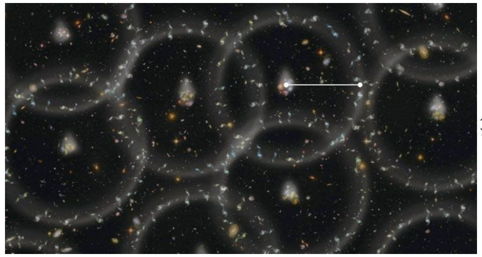
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

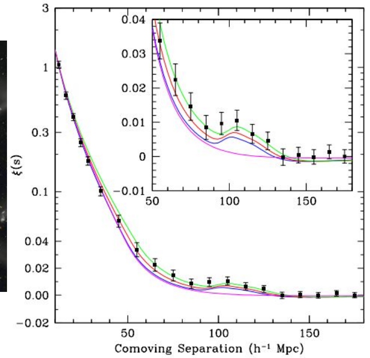
Standard rulers and Standard Candles

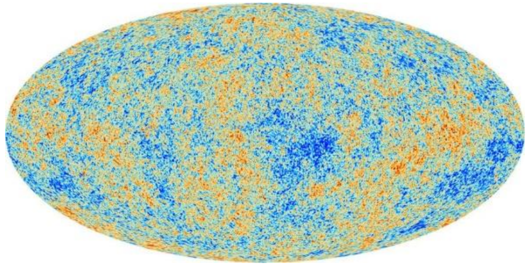
Standard rulers

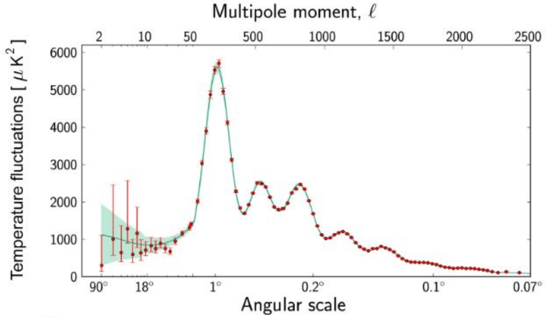
- Standard rulers are objects of know physical size such as the sound horizon which we measure from Baryonic Acoustic Oscillations (BAO) and CMB data.

$$r_s = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$





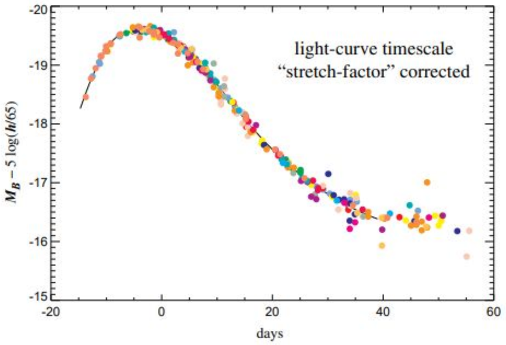




Standard candles

- Standard candles are objects of know absolute luminosity such as variable stars called cepheids and Type Ia supernovae.

$$M = -2.5 \log_{10} \left(\frac{F_{10pc}}{F_{ref}} \right)$$



Maximum Likelihood Estimation

	ΛCDM		
	BAO + CMB	SNIa	Combined
Ω_{0m}	0.3178 ± 0.0059	0.299 ± 0.022	0.3169 ± 0.0057
$\mathcal{M}$	$-$	23.809 ± 0.011	23.817 ± 0.049
h	0.6718 ± 0.0039	$-$	0.6724 ± 0.0038
χ^2	6.3927	1025.63	1032.71

$$\mathcal{M} \equiv M + 5\log_{10}\left[\frac{c/H_0}{1Mpc}\right] + 25$$

$$H_0 \equiv 100 \cdot h \cdot kms^{-1}Mpc^{-1}$$

Maximum Likelihood Estimation

	ΛCDM Combined	wCDM	CPL
Ω_{0m}	0.3169 ± 0.0057	0.315 ± 0.008	0.315 ± 0.013
w_0	-1	-1.01 ± 0.03	-1.07 ± 0.15
w_a	$-$	$-$	0.24 ± 0.47
$\mathcal{M}$	23.812 ± 0.006	$-$	$-$
M	$-$	-19.42 ± 0.02	-19.43 ± 0.02
h	0.6724 ± 0.0038	0.675 ± 0.008	0.674 ± 0.011
χ^2	1032.71	1032.6	1031.97

Reconstruction

- We can reconstruct the field for the CPL model using the best-fit parameters with these equations:

$$\rho_{DE} = \rho_{DE,0}(1+z)^{3(1+w_0+w_a)} e^{-3w_a \frac{z}{1+z}} \qquad V(z) = \frac{1}{2}\left(1 - w_0 - w_a \frac{z}{1+z}\right)\rho_{DE}$$

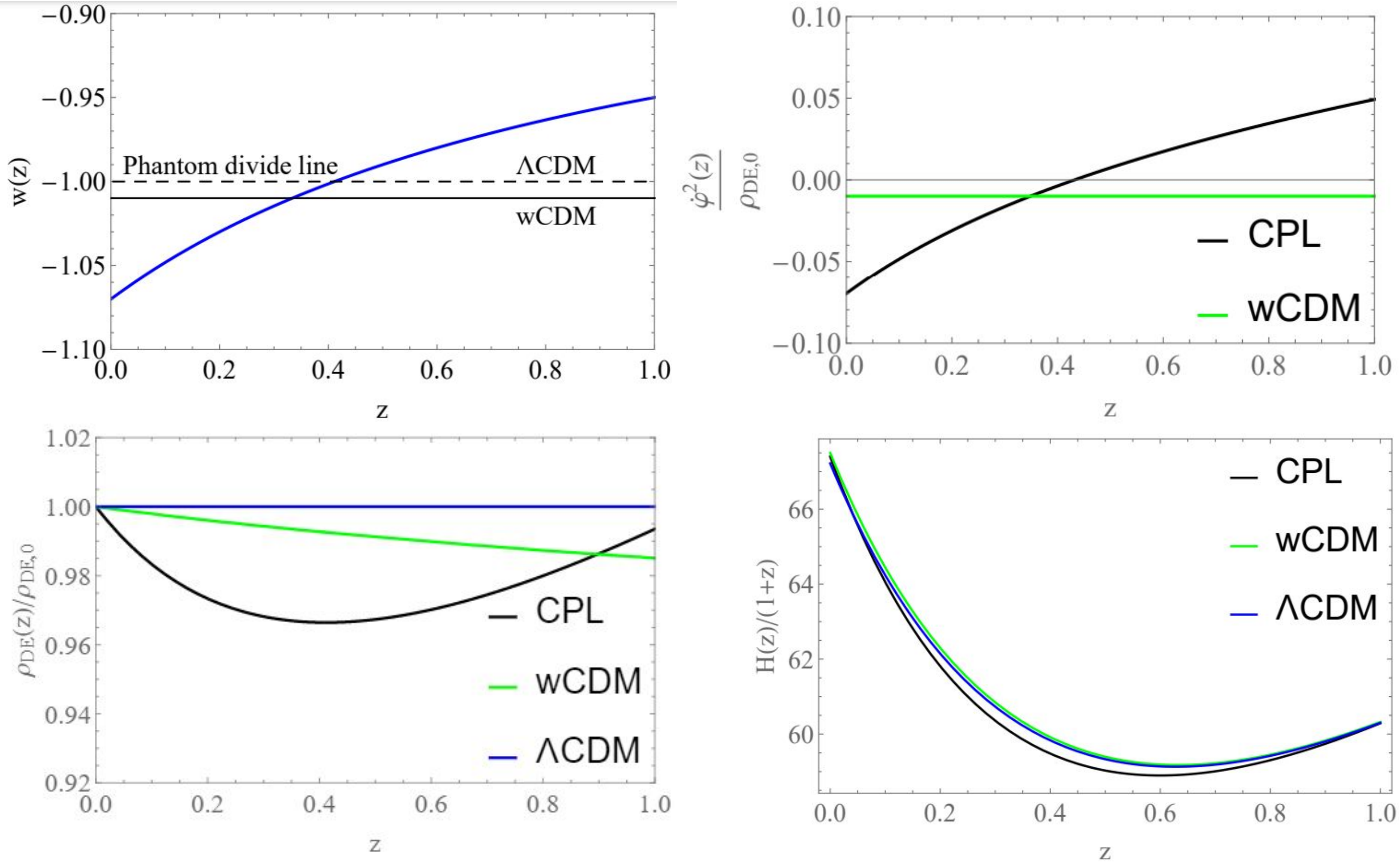
$$H^2(z) = H_0^2 \left[\Omega_{0,m}(1+z)^3 + (1-\Omega_{0,m})(1+z)^{3(1+w_0+w_a)} e^{-3w_a \frac{z}{1+z}}\right]$$

$$\dot{\phi}^2 = \left(1 + w_0 + w_a \frac{z}{1+z}\right)\rho_{DE} \qquad \phi(z) = \rho_{DE,0} \int_0^z \frac{\left|1 + w_0 + w_a \frac{z'}{1+z'}\right|^{1/2}}{(1+z')\left[1 - \Omega_{0,m} + \Omega_{0,m}(1+z')^{-3(w_0+w_a)} e^{3w_a \frac{z'}{1+z'}}\right]} dz'$$

- Also, we can see that the wCDM and ΛCDM models are special cases of the CPL model with w_a = 0 and w_0 = const and w_0 = -1 respectively.
- Thus, we can reconstruct their fields too.

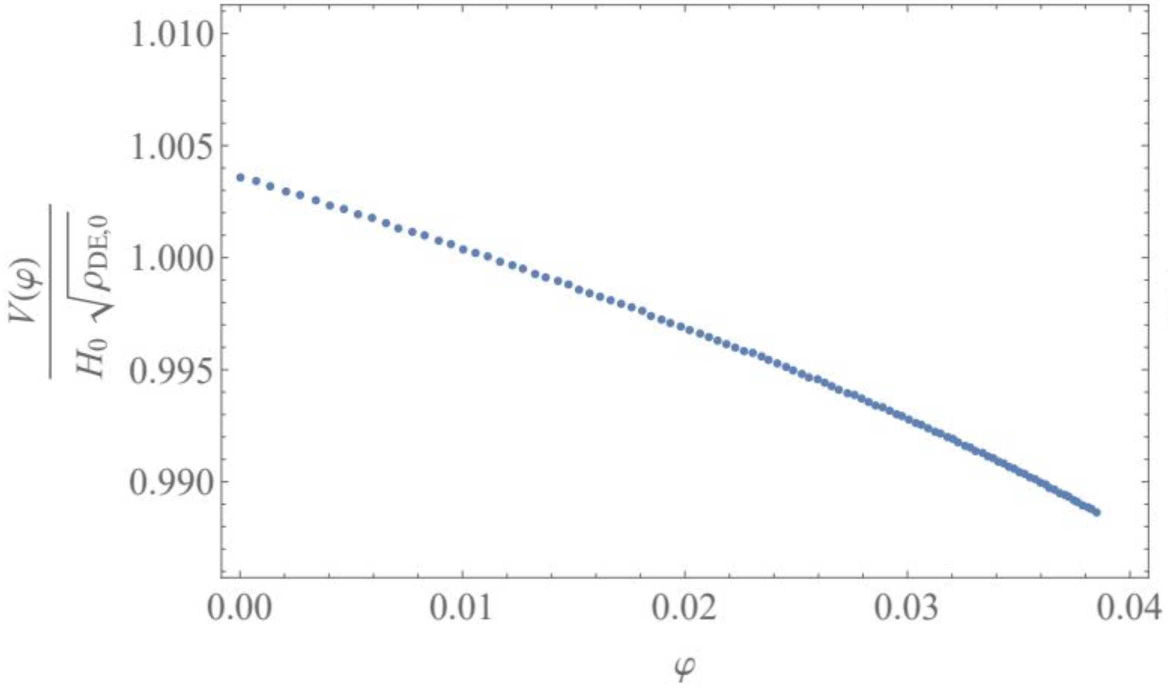
Reconstruction

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

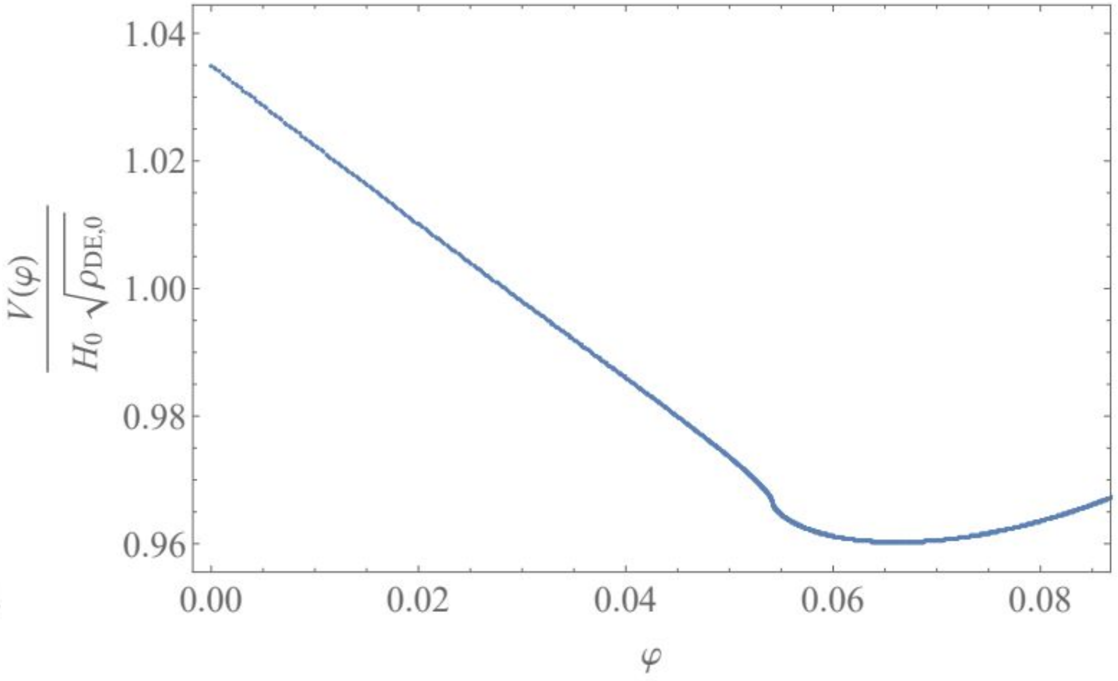


Reconstruction

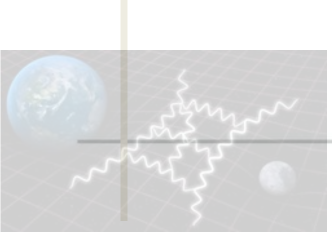
wCDM



CPL



Conclusion



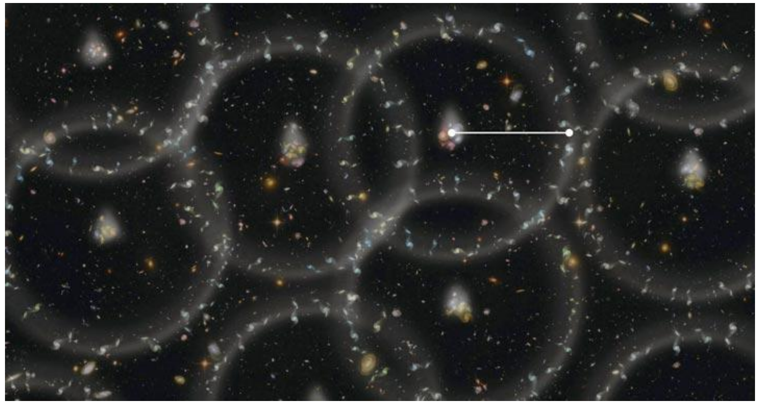
- Dark Energy is the source of the accelerating expansion of the universe and dominates in the present epoch.
- We see that recent data slightly prefer the CPL model over wCDM and ΛCDM.
- However, from the reconstruction of the field of the CPL model we can see that it crosses the Phantom Divide line ($w=-1$), which means that its kinetic term must change sign.
- This means that such models cannot play the role of dark energy and other theories are needed.
- A possible extension of this work is the use of Scalar-tensor quintessence theories.

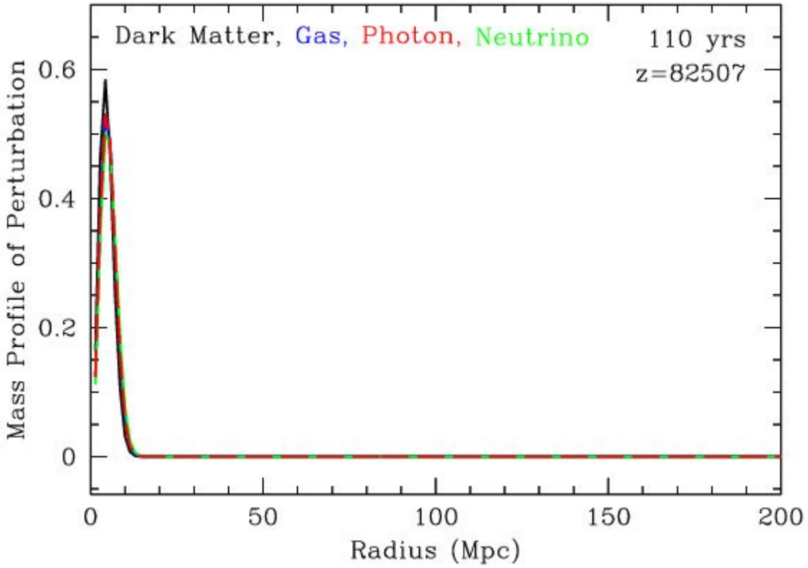
Thank you for listening!

Extra Slides: Baryonic Acoustic Oscillations (BAO)

Formation

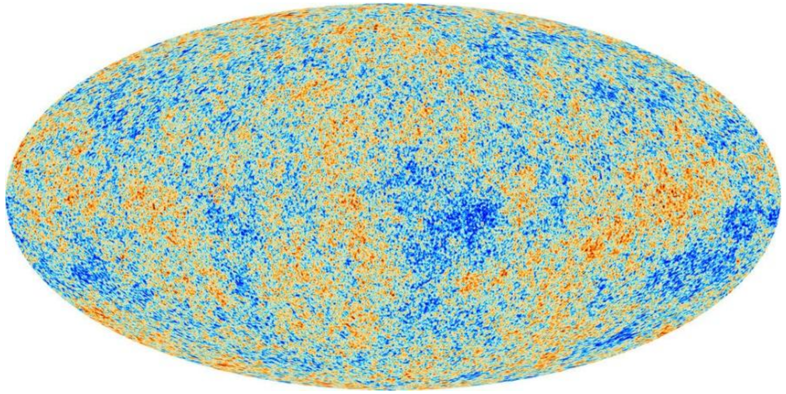
- The early universe was pretty much homogeneous except some small perturbations.
- The perturbations of the photon-Baryon fluid have both overdensity and overpressure and ,thus , an expanding sound wave is created.
- This sound wave stalls as photons decouple.
- Thus, we are left with the initial Dark Matter perturbation at the center surrounded by the Baryon perturbation in a shell.
- Then the two perturbations left attract each other through gravity and start to mix up.

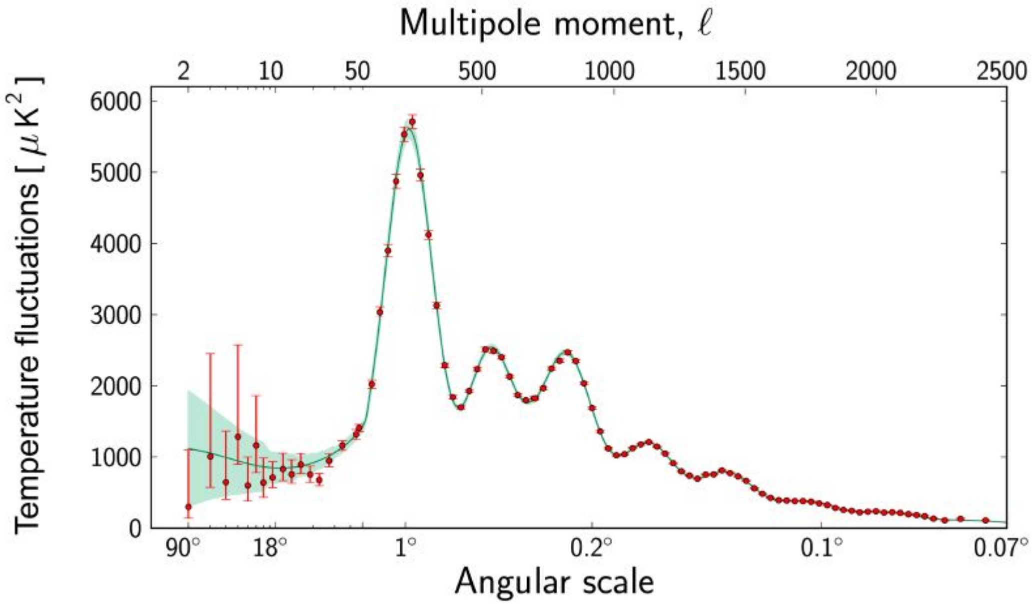


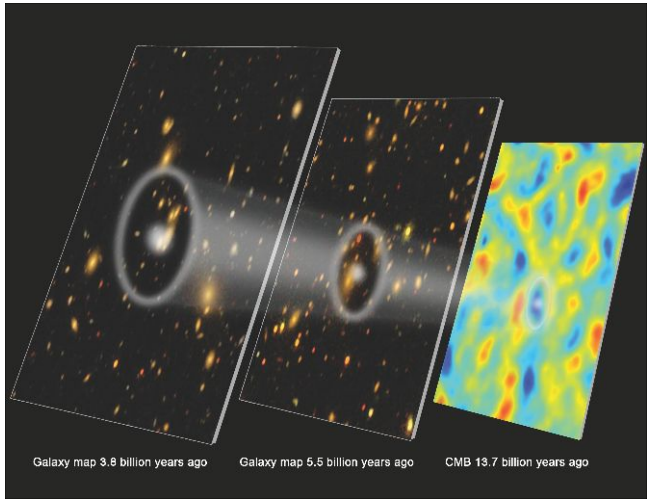


Extra Slides: Cosmic Microwave Background (CMB)

- The CMB can be treated as a BAO measurement at z = z_* = 1090 measuring the angular scale of the sound horizon at high redshift.

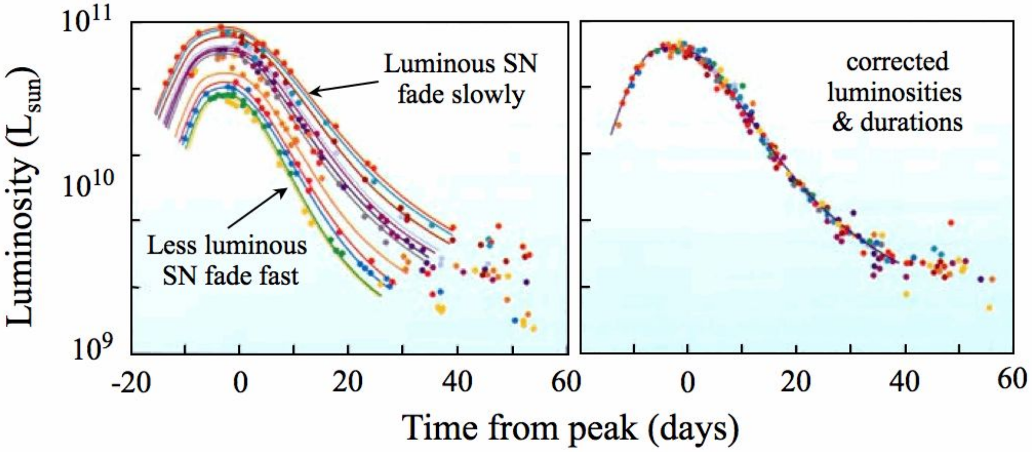




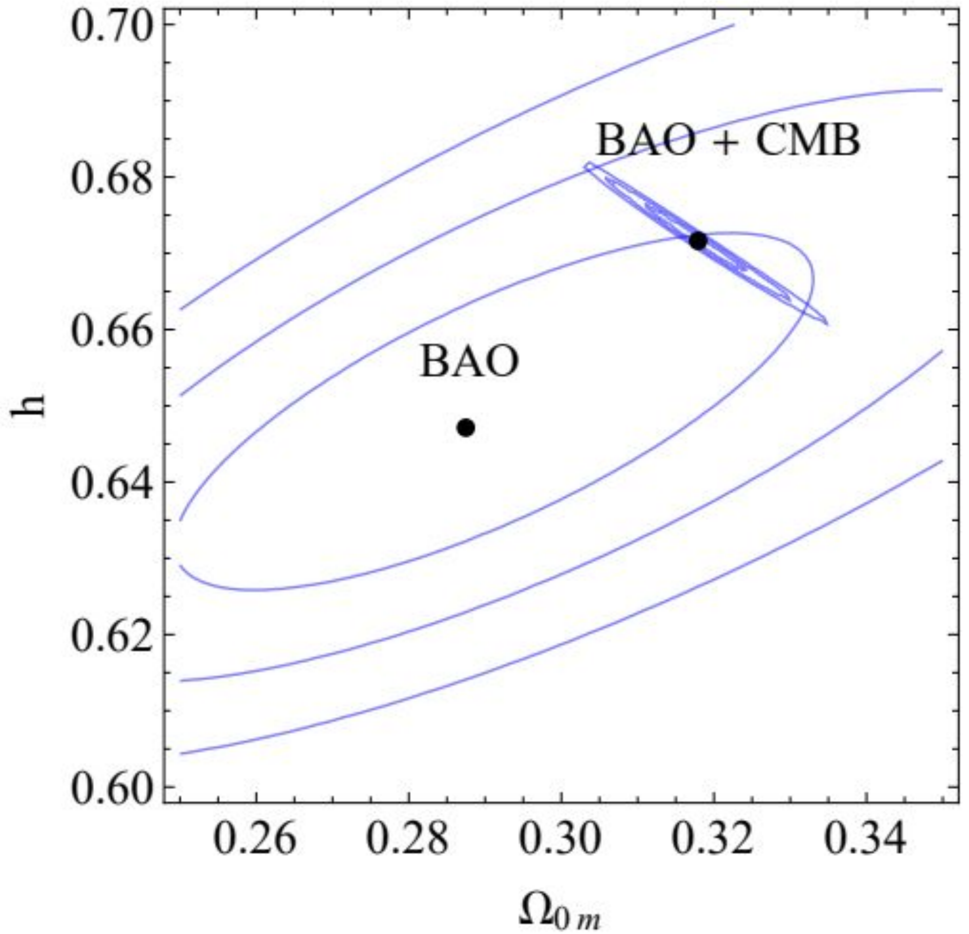


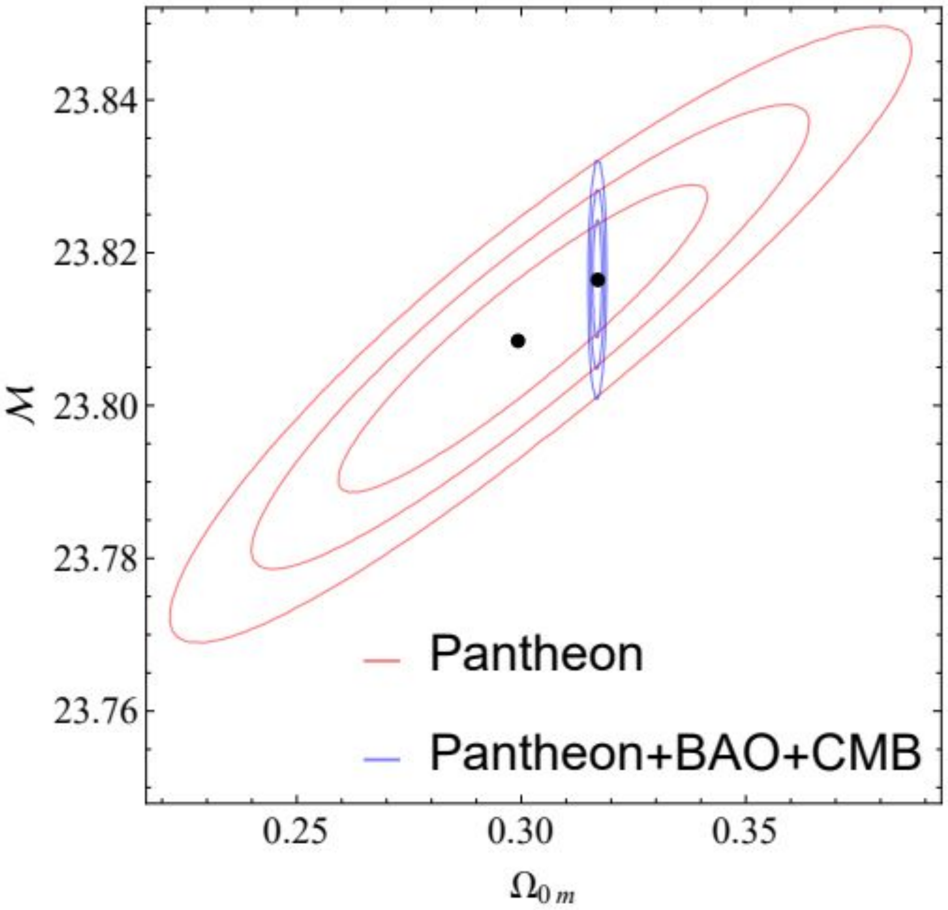
Extra Slides: Type Ia Supernovae (SNIa)

- Type Ia supernovae are called standardizable candles.
- If someone measures the apparent magnitude of a Type Ia Supernova and the width of its light curve he can predict its absolute magnitude which is almost constant at the peak of brightness.
- In this way, we can determine the distance to a distant supernova by measuring its apparent magnitude.



Extra Slides: Maximum Likelihood Estimation: ΛCDM





Extra Slides: Maximum Likelihood Estimation: wCDM