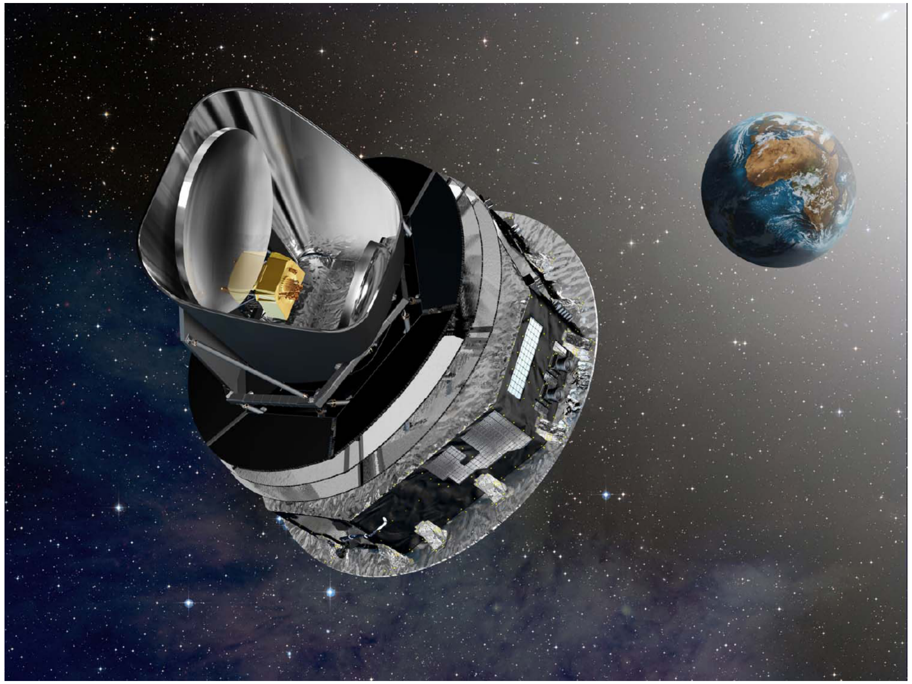
Dark Energy After Planck



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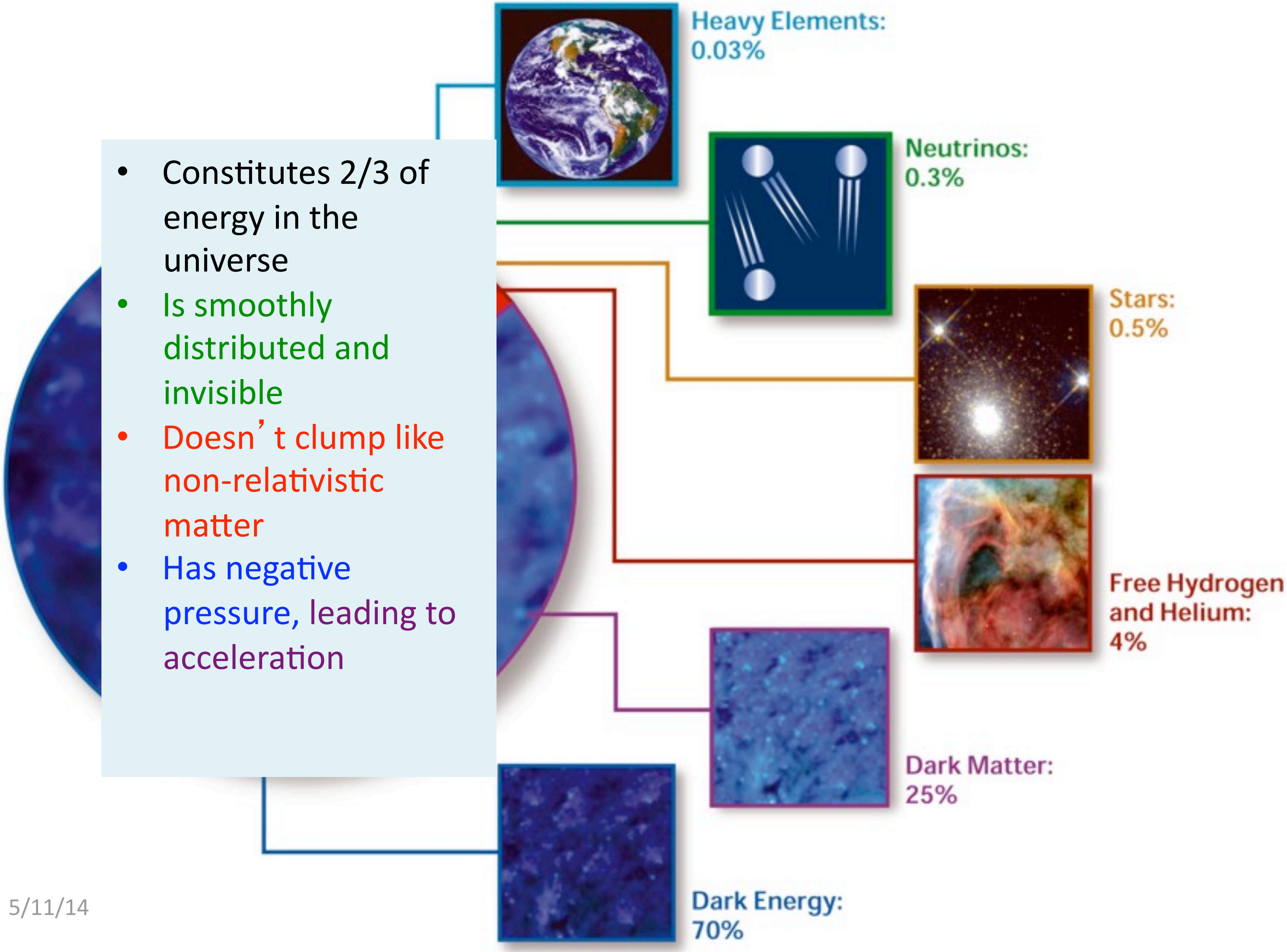
5/11/14

COMPOSITION OF THE COSMOS

- Constitutes 2/3 of energy in the universe
- Is smoothly distributed and invisible
- Doesn't clump like non-relativistic matter
- Has negative pressure, leading to acceleration



What is this Acceleration

In Newtonian Gravity the Force Equation is

$$\frac{\ddot{R}}{R} = -4\pi G\,\rho$$

Energy Density

Gravity is attractive

In General Relativity Pressure also gravitates :

$$\frac{\ddot{R}}{R} = -4\pi G(\rho + 3p)$$

$$\rho + 3p < 0$$

Gravity may be Repulsive, acceleration

Different model will have diff relation between Pressure & Density

w(time dependent) = P/ρ

Simplest model: constant w = -1

Standard Cosmology

- In terms of the density parameters $\Omega_i = \frac{\rho_i}{\rho_c}$, the Hubble parameter can be written as (assuming a FRW metric):

$$\frac{\dot{a}^2}{a^2} = H^2 = H_0^2 \left[\Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 + \Omega_k(1+z)^2 + \Omega_{x0} f(z)\right]$$

- The second Einstein equation can be written as:

$w_x < -1/3$

Acceleration

$$\frac{\ddot{a}}{a} = -\frac{H_0^2}{2}\left[\Omega_{m0}(1+z)^3 + 2\Omega_{r0}(1+z)^4 + (1+3w_x)\Omega_{x0} f(z)\right]$$

$$w_x = -1 \rightarrow f(z) = 1 \rightarrow \Lambda$$

$$w_x = constant \rightarrow f(z) = (1+z)^{3(1+w_x)}$$

$$w_x = w_x(z) \rightarrow f(z) = Exp\left[3\int \frac{1+w_x}{1+z} dz\right]$$

$\Omega_k \approx 0 \rightarrow$ CMB first acoustic Peak Location

$\Omega_{r0} \approx 10^{-5} \rightarrow$ CMB, safe to be ignored for late time evolution

Things to be measured $w_x(z),\ \Omega_{x0}\ and\ \Omega_{m0}$

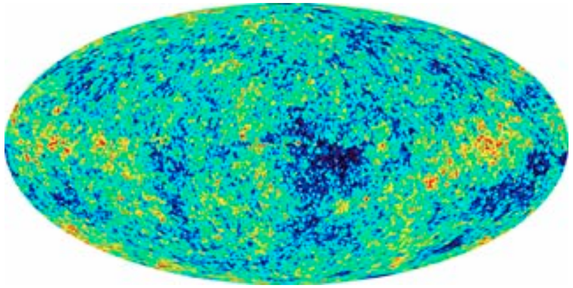
Probing The Dark Energy

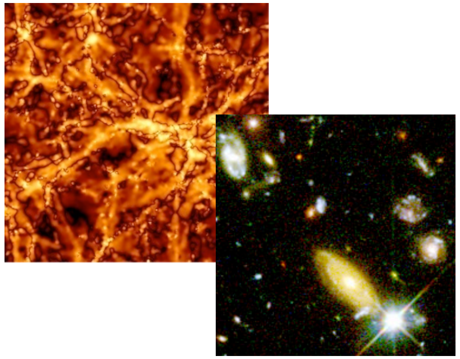
- Its effect on cosmological expansion. Includes geometric probes and involves distances and volumes, coming directly from the metric.

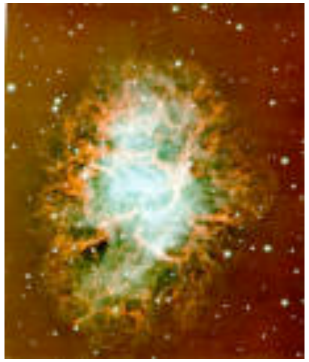
- Its indirect effects on the growth of structures from its influence on expansion. Involves growth factor and growth rate of matter density perturbations.

- Any direct contribution of it to the growth of structures. It actually modifies the growth equations itself.

Cosmic Archeology







CMB: direct probe of primordial fluctuations

Time: 0.003% of the present age of the universe.

Cosmic matter structures: less direct probes of expansion

Pattern of ripples, clumping in space, growing in time.

3D survey of galaxies and clusters - Lensing.

Supernovae: direct probe of cosmic expansion

Time: 30-100% of present age of universe

Standard Candle

If an object has luminosity L, the flux received at a distance "d" is simply $S=L/(4\pi d^2)$.

If a class of object have the same luminosity L, they are referred to as Standard Candle.

Type Ia supernovae can be considered as a standard candle.

They are like light bulb of 10^{48} Watts !!

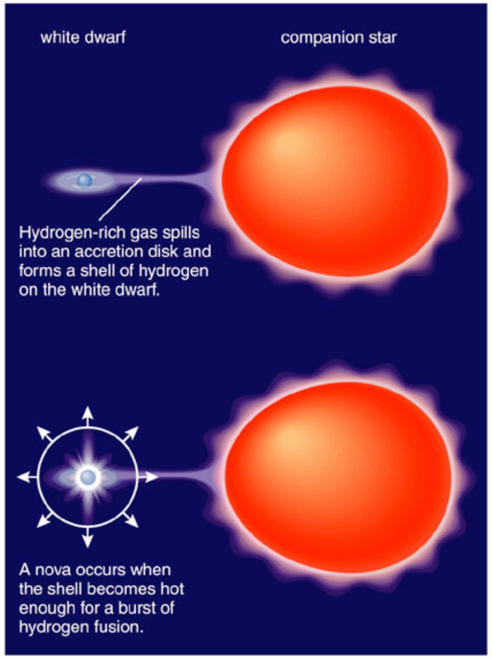
(In comparison Sun is ~ 3 x 10^{26} Watts)

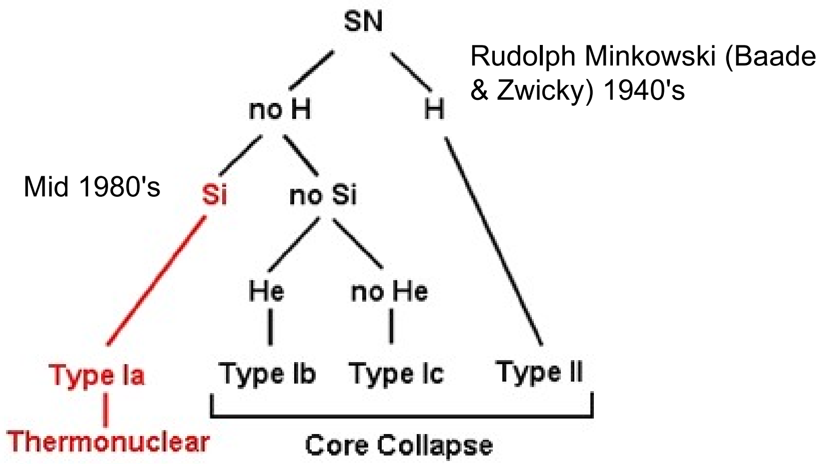
Supernova Type-Ia

- First Proposed by Baade and Zwicki in 1930s.
- Extremely Bright to be seen over cosmological distances

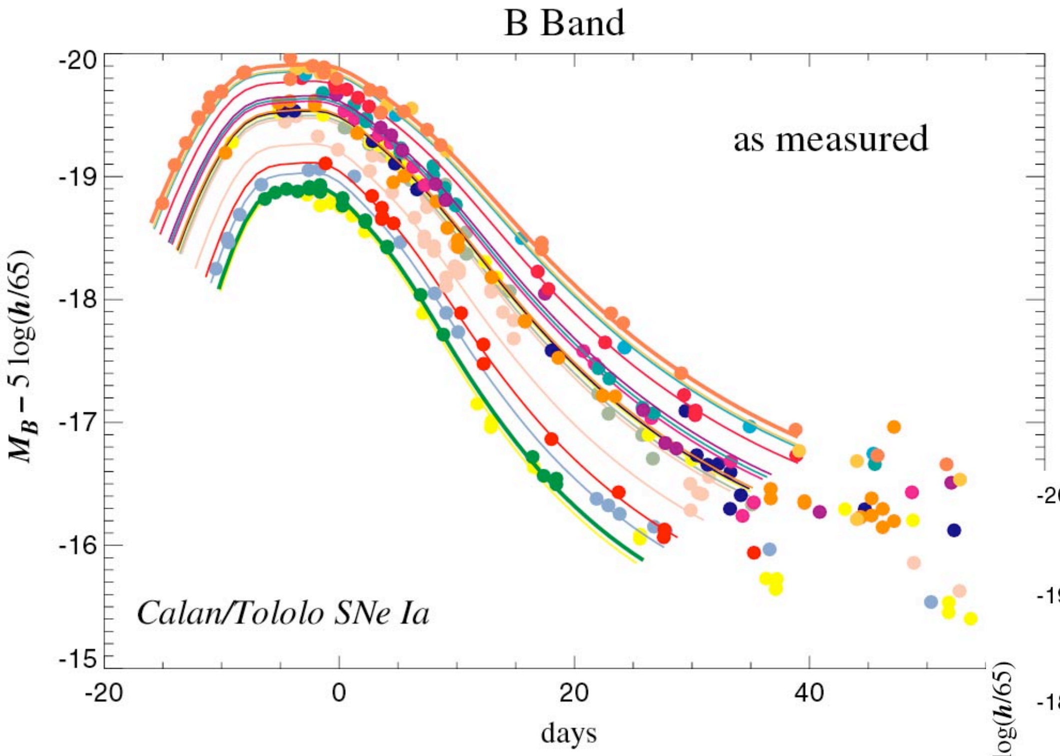
Historical Supernova Classification:

- Presence or absence of certain features in their Optical Spectra taken near maximum light.



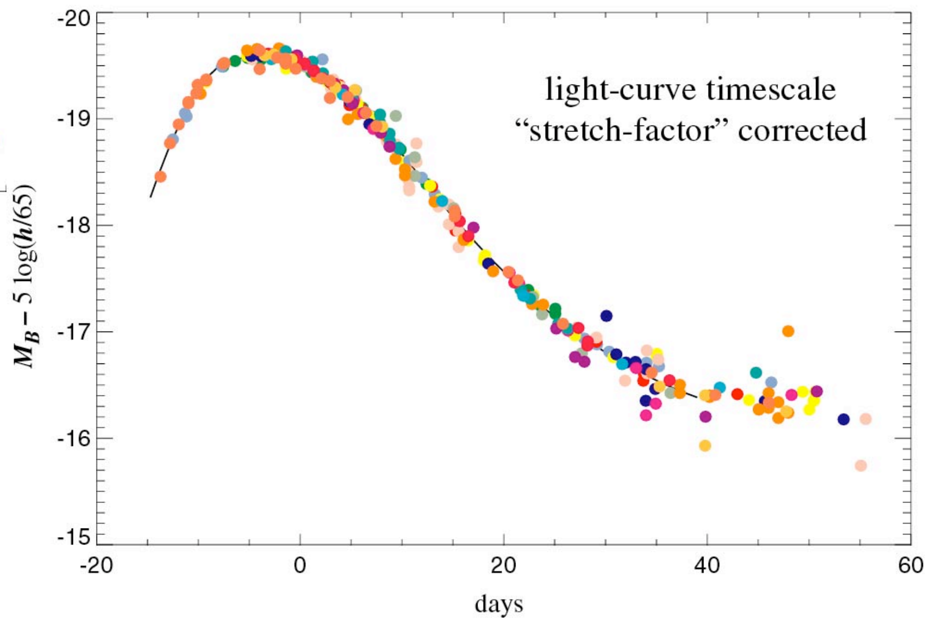


Type Ia Supernova lightcurves



Peak brightness tells us distance away (lookback time)

Redshift measured tells us expansion factor (average distance between galaxies)

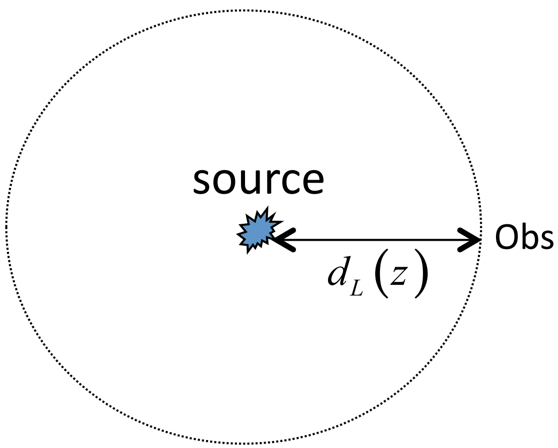


Kim, *et al.* (1997)

Apparent Luminosity Measurement

Assume a homogeneous and isotropic Universe given by a FRW metric:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + Sin^2\theta d\phi^2\right)\right]$$



$$l = \frac{L}{4\pi d_L^2}$$

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

Using only kinematical quantities and assuming a FRW metric:

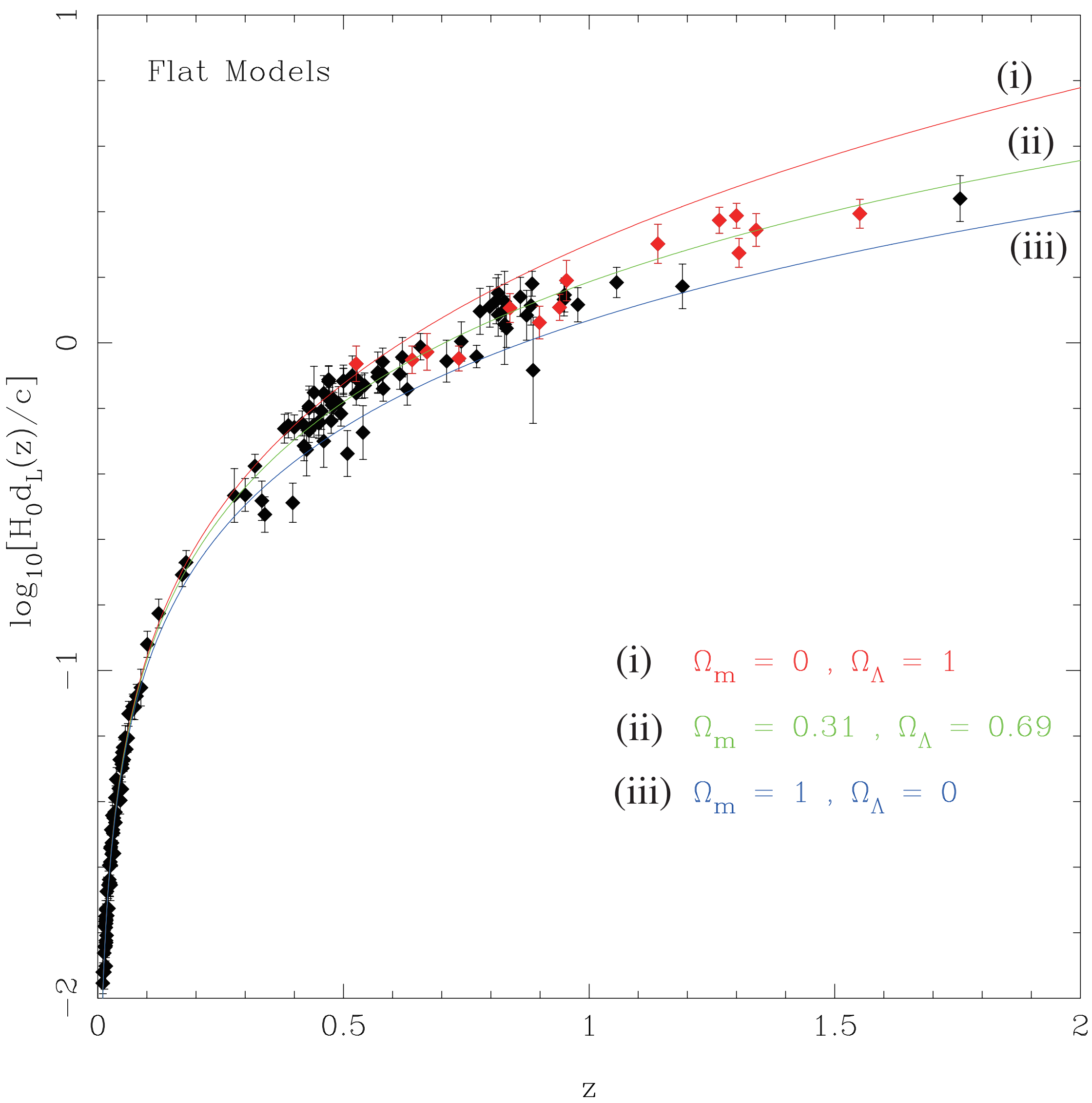
$$\boxed{H_0 d_L = z\left\{1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 \pm \frac{1}{H_0^2 R^2}\right] z^2 + o(z^3)\right\}}$$

$$H = \frac{\dot{a}}{a}, q = -\frac{\ddot{a}}{aH^2}, j = \frac{\dddot{a}}{aH^2}$$

In Practice, we measure the distance modulus:

$$\mu \approx 5\ log\frac{d_l}{Mpc}$$

Discovery!!! Acceleration!!!



Nobel Prize in Physics 2011

Saul Perlmutter

The Supernova Cosmology Project
LBNL CA, US

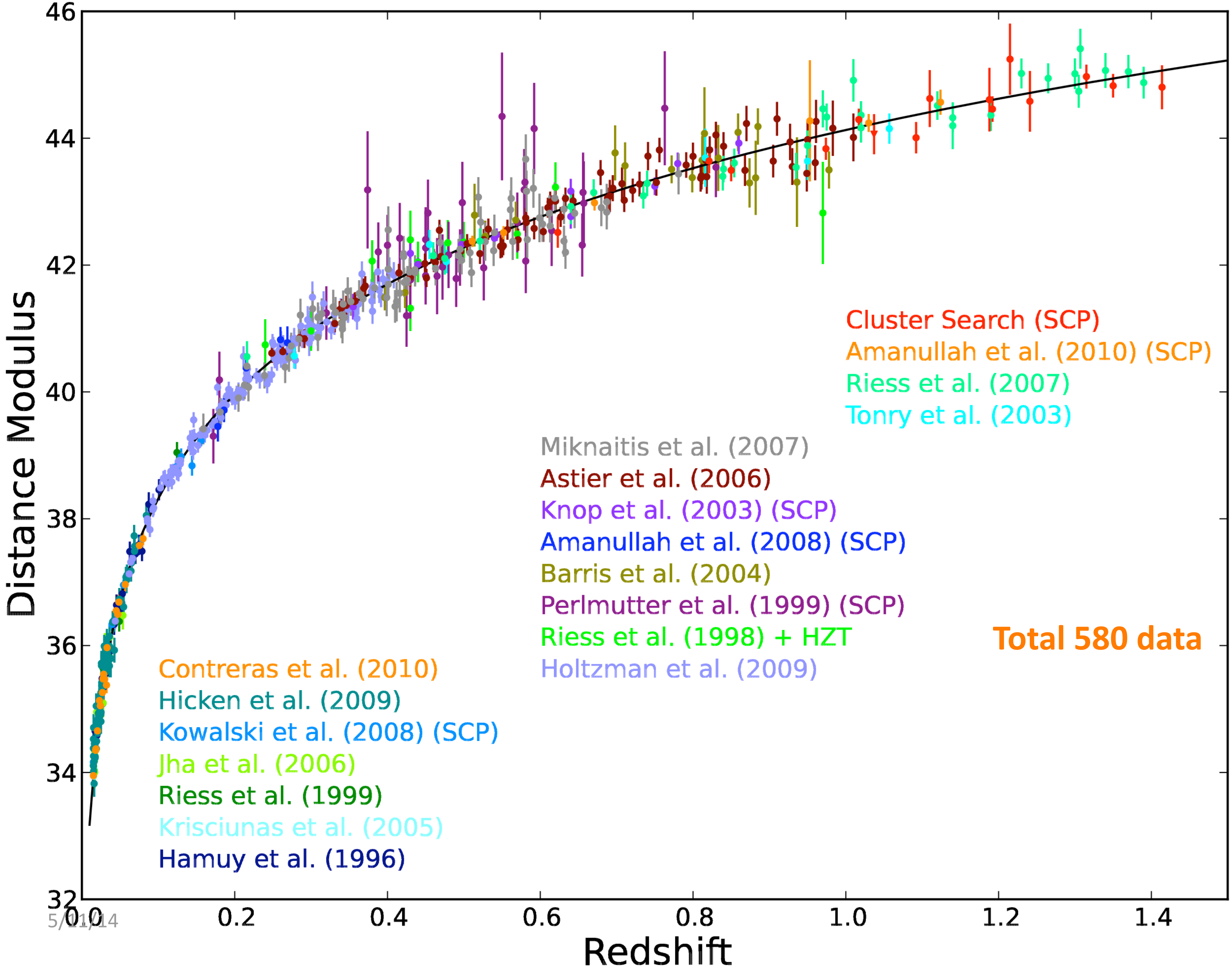
Adam Riess

The High-z Supernova Search Team
Johns Hopkins University
and Space Telescope Science Institute,
Baltimore, MD, USA

Brian P. Schimdt

The High-z Supernova Search Team
Australian National University,
Weston Creek, Australia

" for the discovery of the accelerating expansion of the Universe through observations of distant supernovae "


Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Total 580 data
5/11/14

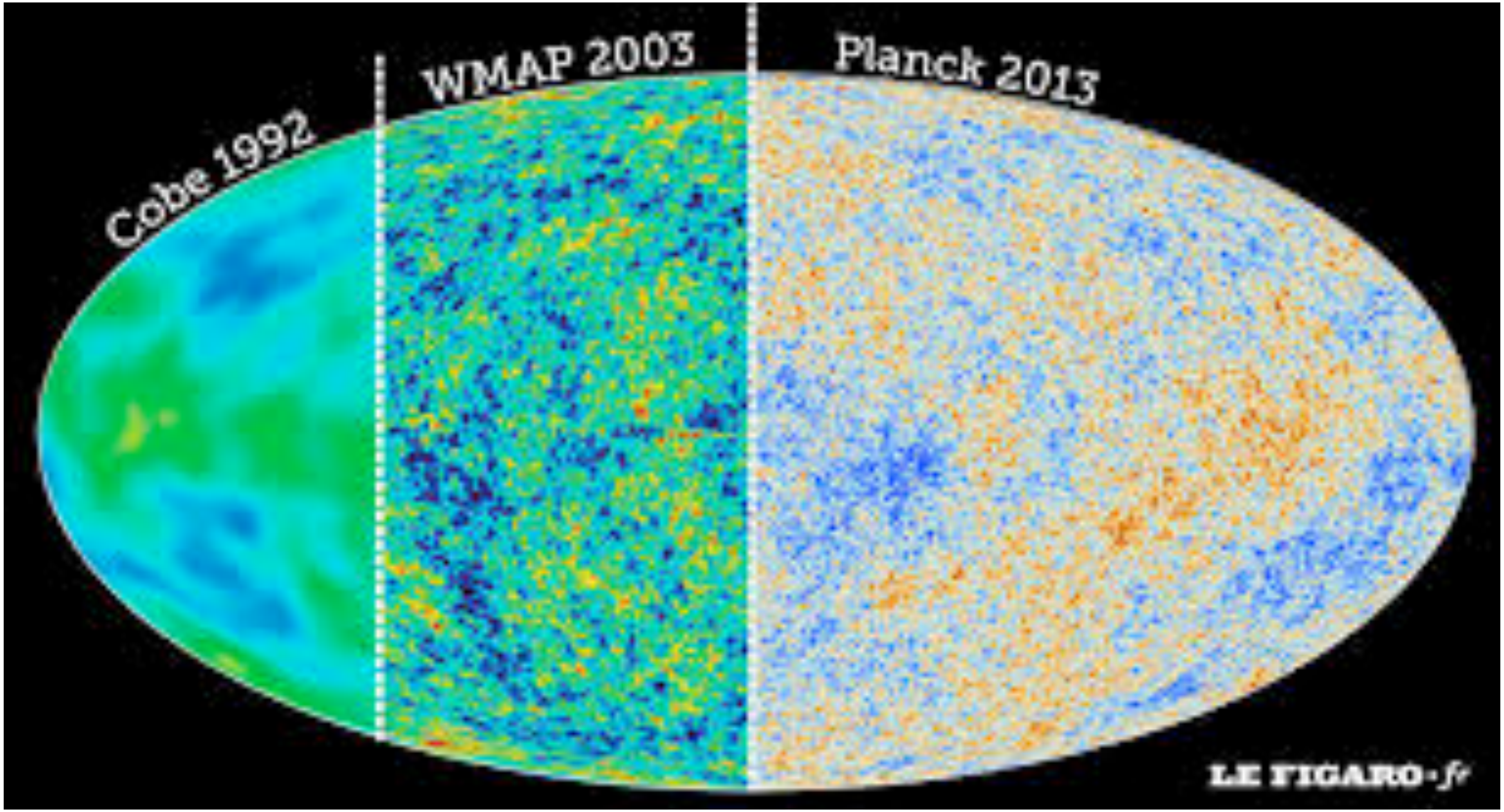
Standard Model for CMB

- We assume a homogeneous and isotropic FRW Universe which mainly contains photons, electrons, baryons, neutrinos, CDM and cosmological constant.
- Primordial fluctuations from inflation produce the temperature fluctuations in photon-baryon fluid.
- Acoustic waves due to photon pressure, amplified by intertia due to baryons and gravitational interaction.
- Photon-electron decoupling results diffusion processes inducing fluctuation damping.

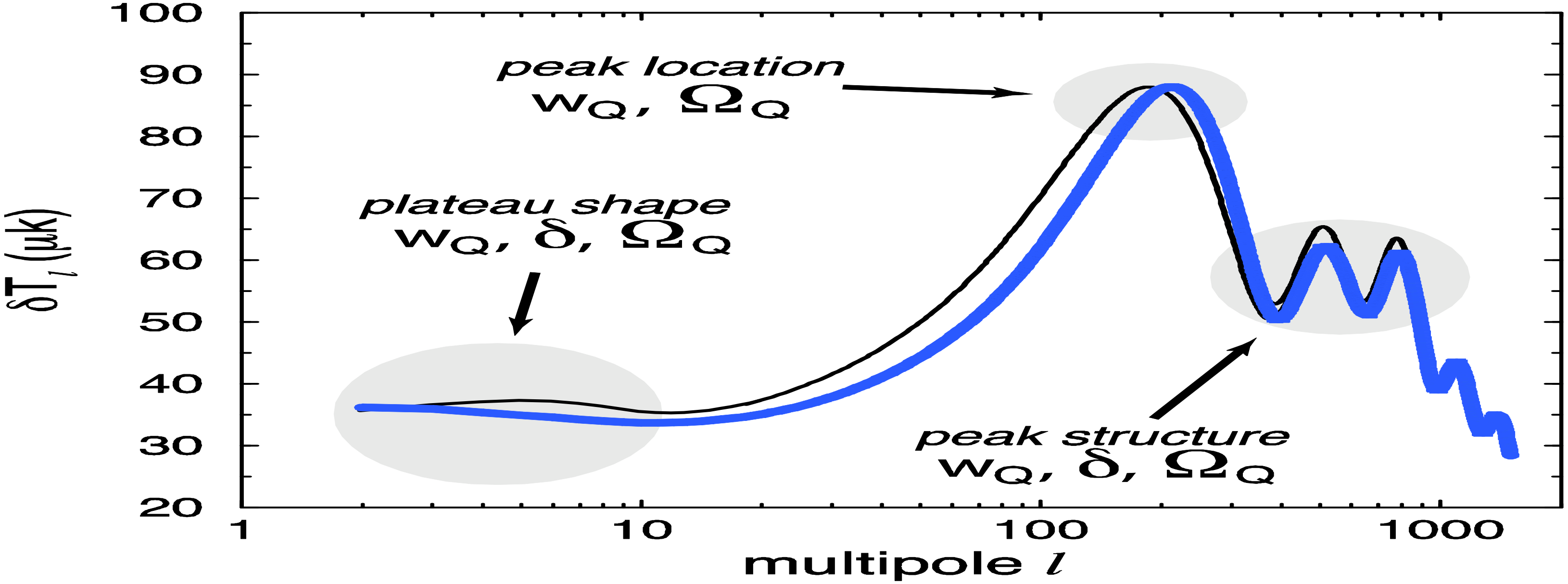
CMB Observations

- Primary Temperature Anisotropy was first discovered by COBE in 1992.
- The peak structure was first measured with good accuracy by Boomerang in 2000.
- In 2003, WMAP measured it with greater accuracy and a standard ΛCDM cosmological model was confirmed.
- In 2013, Planck Satellite by ESA measured the temperature anisotropy in CMB with best ever precision.

CMB Observations 1992-2013

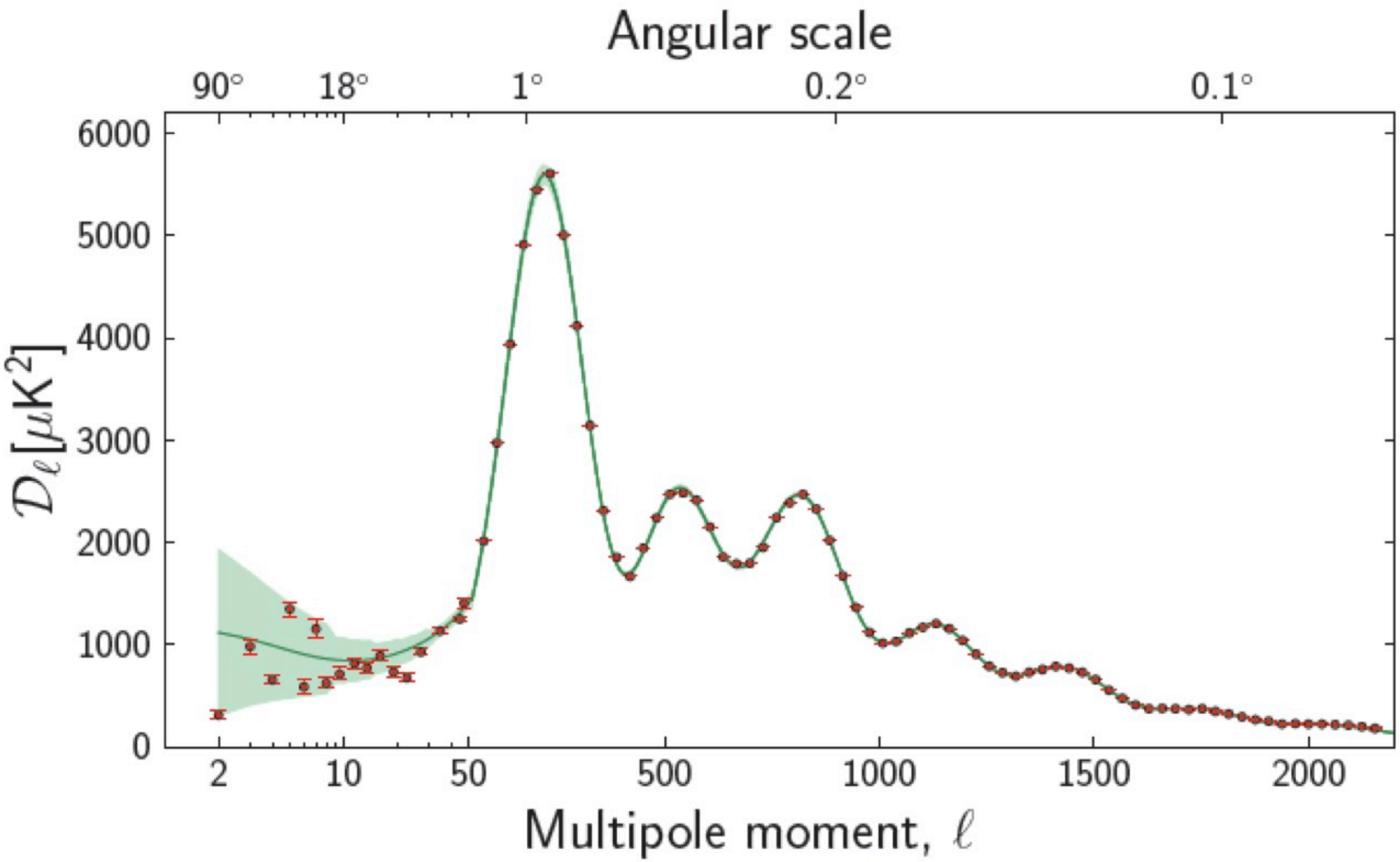


Cosmic Microwave Background Radiation

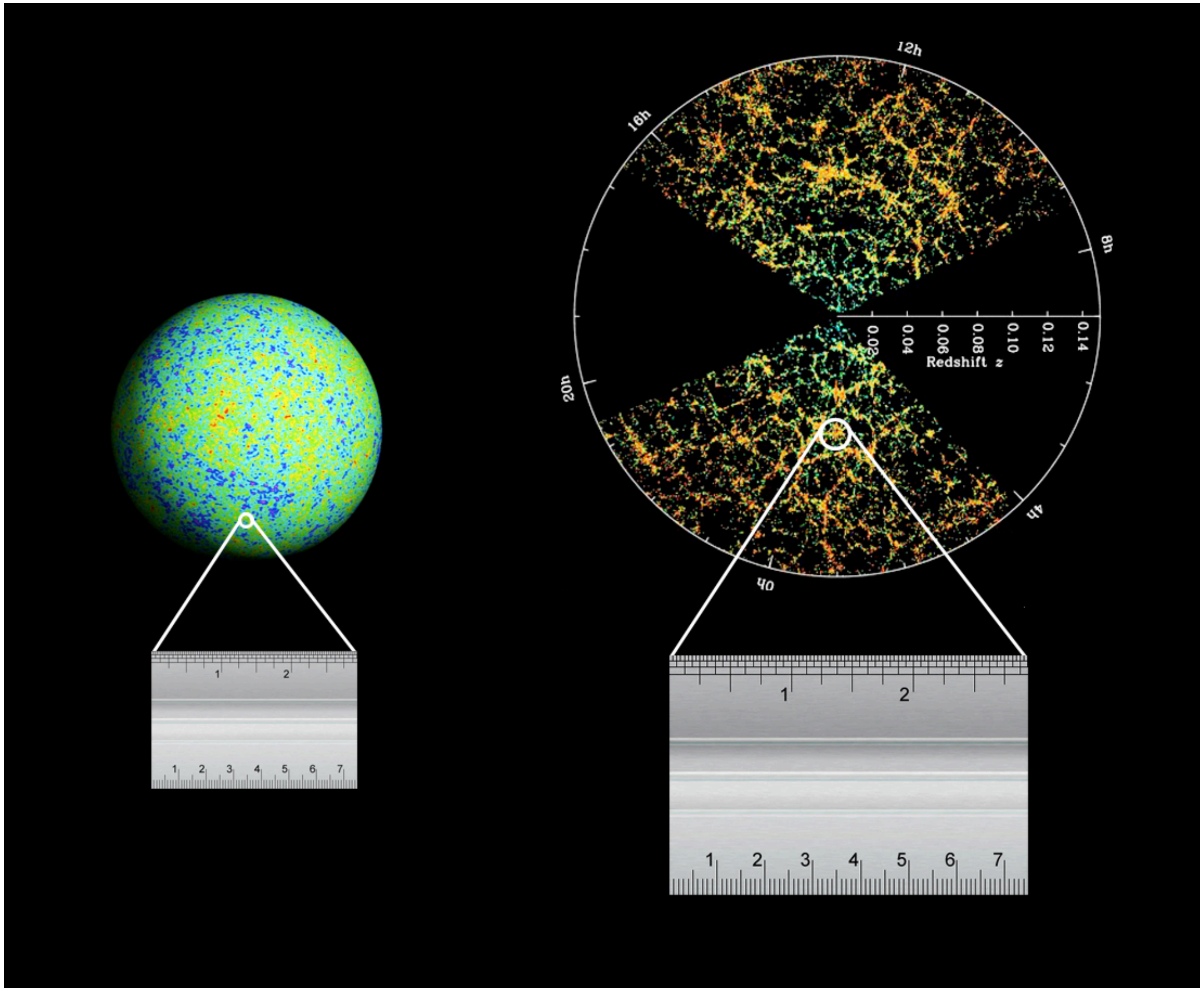


Concordance ΛCDM model

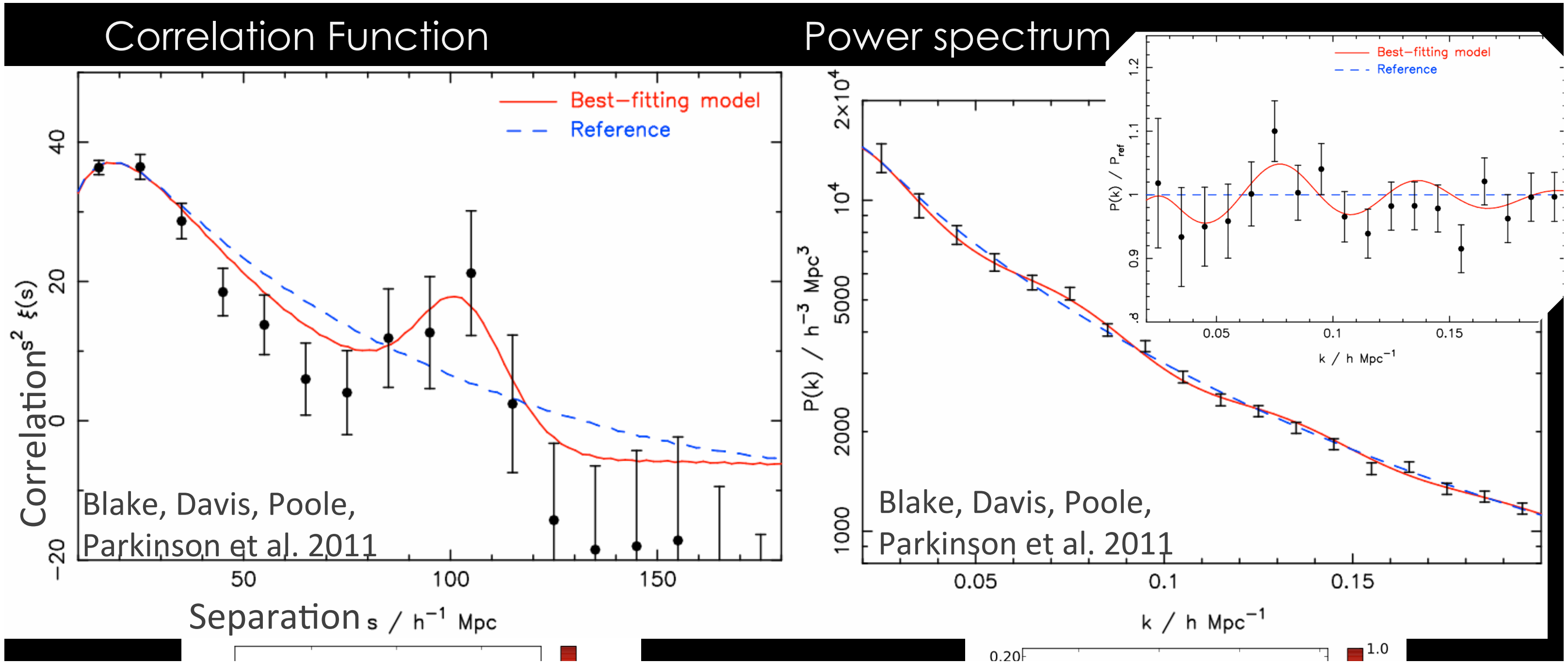
An Excellent Fit to the Data



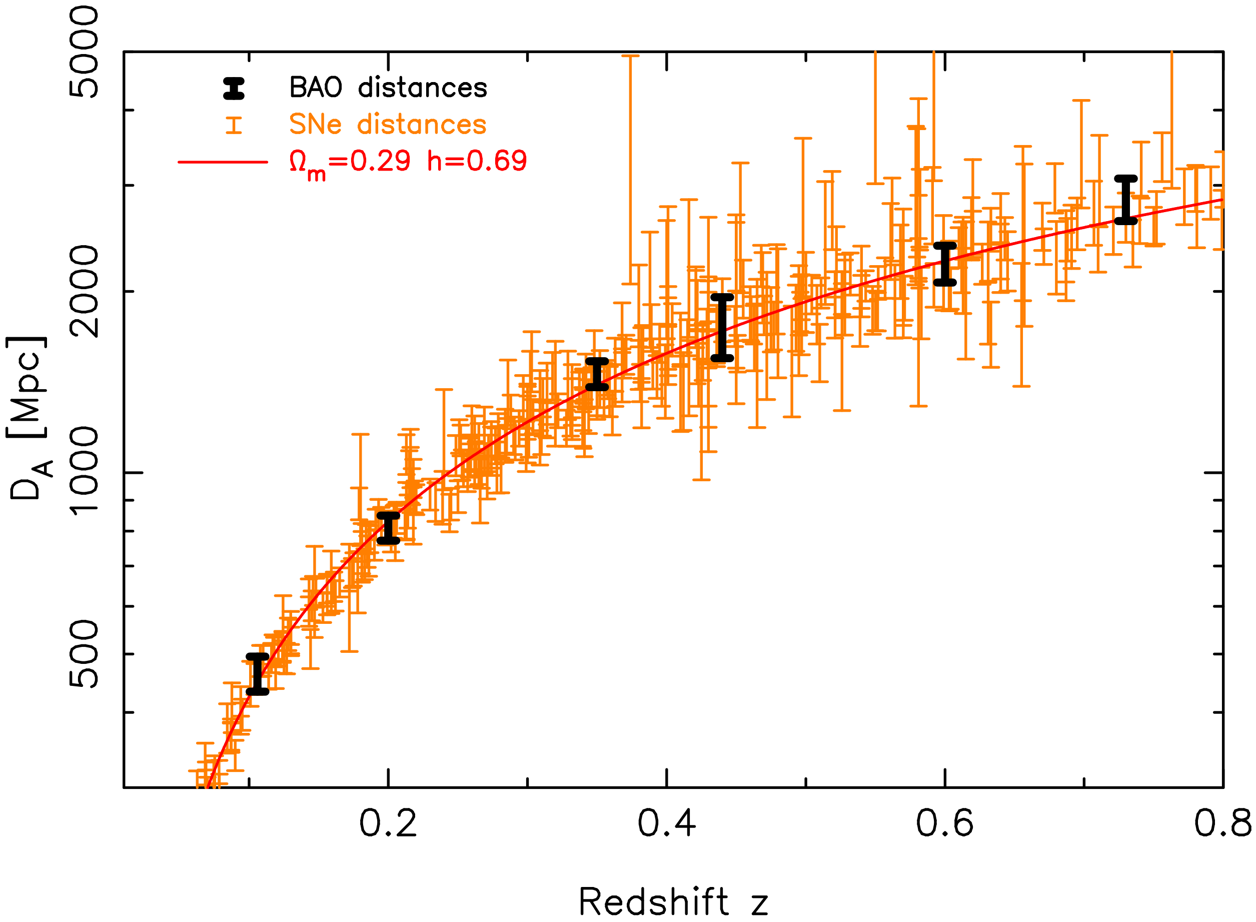
Baryon Acoustic Oscillations



Baryon Acoustic Oscillation

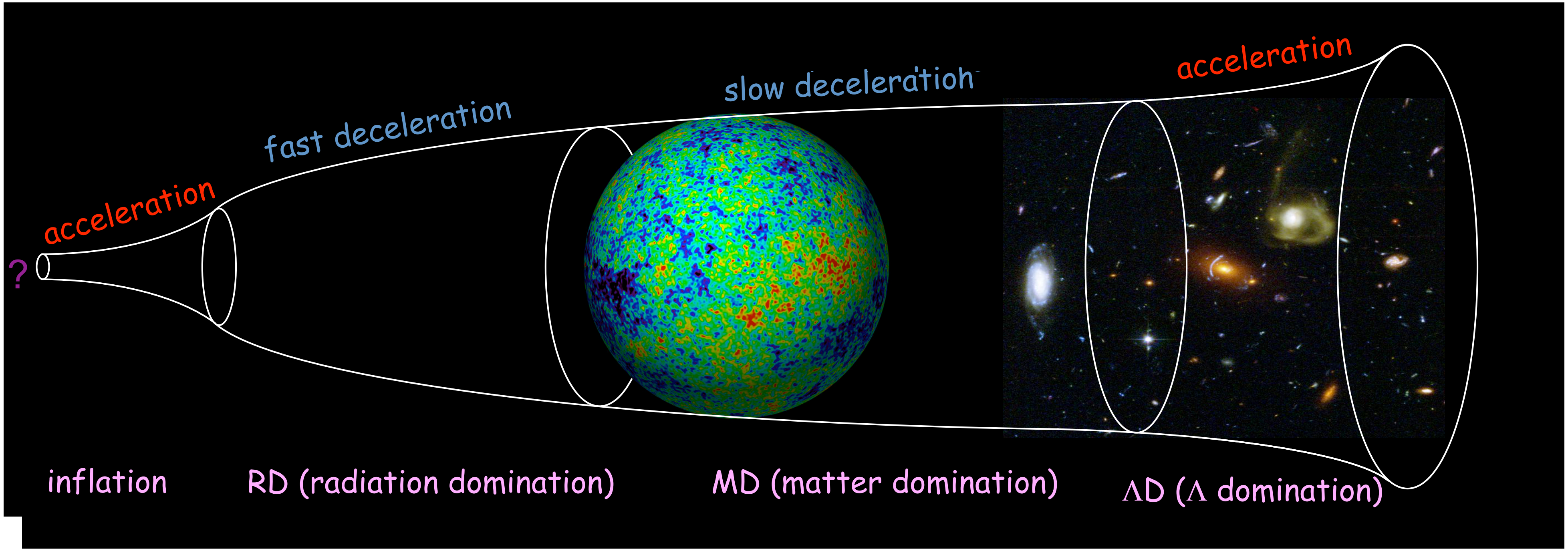


Baryon Acoustic Oscillations



Blake et al,
1108.2635

Concordance ΛCDM model



Picture taken from J. Lesgourgues

Assumes a flat homogeneous and isotropic Universe containing 5 components, e.g. Photons, neutrinos, baryons, CDM and Λ and 4 stages of cosmological evolutions.

The most popular candidate for

Dark Energy

Is

The Cosmological Constant: `Λ’.

Introduced by Einstein in 1917, the cosmological constant satisfies

$$T_i^k = \Lambda \delta_i^k$$

Which implies

$$P = -\rho \quad (\rho = \Lambda) \Longrightarrow w = \frac{p}{\rho} = -1$$

for the equation of state of the cosmological constant.

What's the Problem with Cosmological Constant?

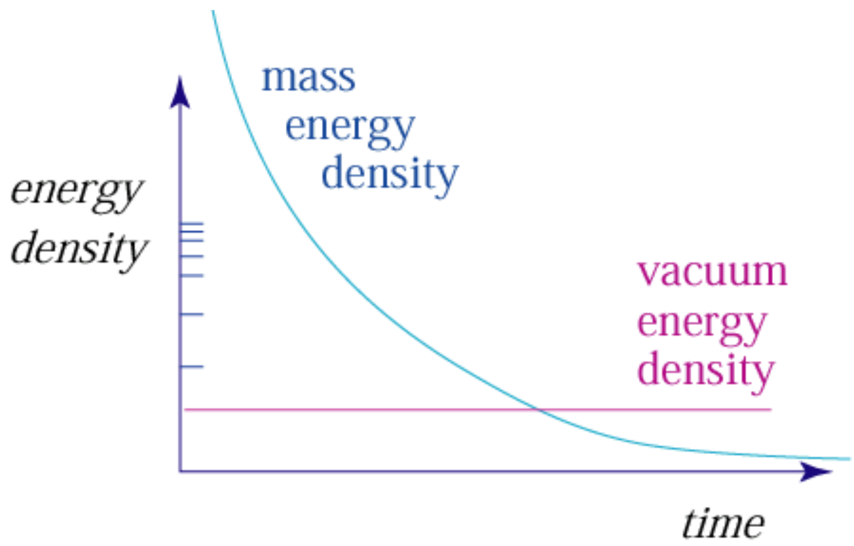
Two problems:

$$\rho_{\Lambda obs} \sim 10^{-47} Gev^4 \rightarrow$$ ***Cosmological Constant Problem !!***

- ***Why now?***

  $\rho \sim R^{-3}$

  Vacuum Energy: $\rho \sim constant$

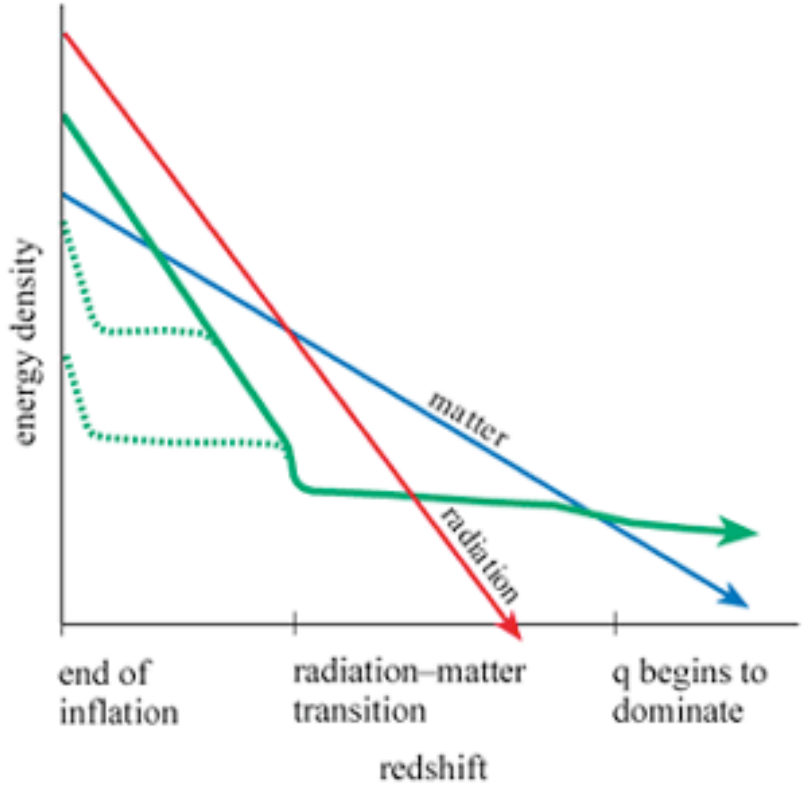


Cosmic Coincidence Problem !!

Quintessence

- Quintessence is model of Dark Energy involving standard scalar fields.

- The basic idea is same as Inflation, only the energy scale involved is much lower than that of Inflation, and also there is a large matter component present.



Quintessence Model

System of equations (Assuming FRW background):

$$3H^2 = 8\pi G(\rho_m + \rho_\phi)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_\phi + 3p_\phi)$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\frac{1}{2}\dot{\phi}^2 << V(\phi) \rightarrow w = \frac{p_\phi}{\rho_\phi} \approx -1$$

Dynamics of Quintessence

Equation of motion of scalar field

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

- driven by steepness of potential
- slowed by Hubble friction

Broad categorization -- which term dominates:

- field rolls but decelerates as dominates energy
- field starts frozen by Hubble drag and then rolls

Trackers vs. Thawers

Caldwell & Linder 2005

Thawing Vs Tracking

Thawing Models: Same as inflation. Initially frozen (w=-1)at the flat part of the potential due to large Hubble Damping. Later on as the Hubble damping decreases, the field slowly thaws away from w= -1.

Tracking Models: Field fast rolls initially mimicking the background (w= 0 or 1/3). Later on as the slope of the potential changes, it exits the tracking regime and start behaving like a dark energy (w<-2/3).

Models Close to w = -1

- We want to study models close to Λ behaviour.
- Scalar field with initial value ϕ_i in a nearly flat potential

V(ϕ) satisfying the Slow-Roll Conditions:

$$\boxed{\left(\frac{1}{V}\frac{dV}{d\phi}\right)^2 << 1, \quad \frac{1}{V}\frac{d^2V}{d\phi^2} << 1}$$

One can find the universal behaviour (irrespective of the form for potential):

$$\gamma = 1 + w = \frac{\lambda_i^2}{3}\left[\frac{1}{\sqrt{\Omega_\phi}} - \frac{1}{2}\left(\frac{1}{\Omega_\phi} - 1\right) Log\left(\frac{1+\sqrt{\Omega_\phi}}{1-\sqrt{\Omega_\phi}}\right)\right]^2$$

$$\Omega_\phi = \left[1 + (\Omega_{\phi 0}^{-1} - 1)(a/a_0)^{-3}\right]^{-1}$$

Scherrer and Sen, PRD 2008

Interesting Parametrization

Equation of State: $p = -\frac{A}{\rho^{\beta}}$ Bento, Bertolami and AAS, PRD 2002

- Plugging GCG e.o.s in the equation: $T^{\mu}_{\nu;\mu} = 0$
- $$\rho_{gcg} = \rho_{gcgo}\left[A_s + (1 - A_s)(1 + z)^{3(1+\beta)}\right]^{1/(\beta+1)}$$

$$\omega_{gcg} = -\frac{A_s}{A_s + (1 - A_s)(1 + z)^{3(1+\beta)}} \qquad A_s = \frac{A}{\rho_{gcg0}^{1+\beta}}$$

$A_s = -\,\omega_{gcg0}$ $\quad A_s = 1,\ \omega_{gcg} = -1 \rightarrow\ Cosm.Const$

$\beta = -1,\ \ constant\ \ equation\ \ of\ \ state$

$0 < A_s \leq 1,\ 1 + \beta > 0$ $\quad \rho \propto a^{-3}$ For early time; $\rho = consant$ For late time → **Trackers**

$0 < A_s \leq 1,\ 1 + \beta < 0$ $\quad \rho = consant$ For early time; $\rho \propto a^{-3}$ For late time → **Thawer**

Different Models..........

1) Cosmological Constant
2) Dark energy w =   pressure/energy density = constant
3) Dark energy w = w(z)
4) Freezing or tracker quintessence
5) Thawing quintessence
6) Phantom model w < -1
7) Scalar-Tensor models
8) Coupled Quintessence
9) K-Essence
10) Chaplygin and Generalized Chaplygin Gas
11) F (R) and f(G) models
12) DGP model
13) Cardassian model........and MANY MORE

How to constrain DE behaviour?

- Difficult to study each model with observational data.
- Look for some parametrized form for $w(z)$ that represents a broad class of dark energy behaviour.
- What kind of behaviours we are broadly interested in?

a) whether $w = -1$ (C.C) or not?

b) if it is not C.C, whether $w(z)$ is constant or evolving?

c) if evolving, what kind of evolution, e.g thawing or freezing

d) is w is phantom ($w < -1$) or non-phantom ($w > -1$)?

Where do we stand?

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$

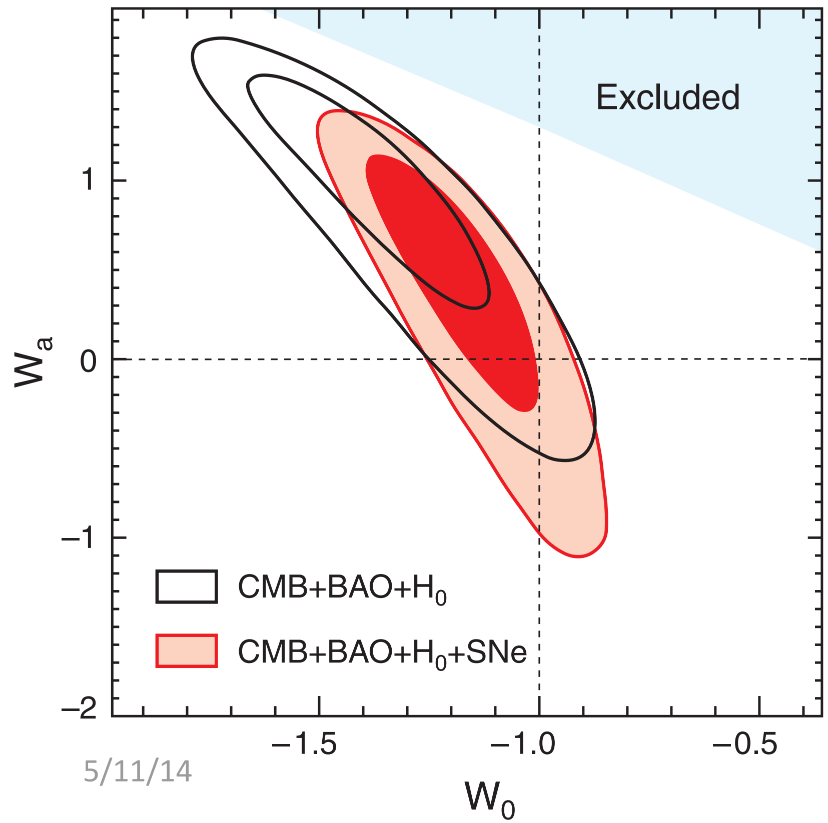
Parameter	*Planck*+WP Best fit	*Planck*+WP 95% limits	*Planck*+WP+BAO Best fit	*Planck*+WP+BAO 95% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 95% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Combining SN+BAO+CMB (WMAP9+SPT+ACT/Planck)

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

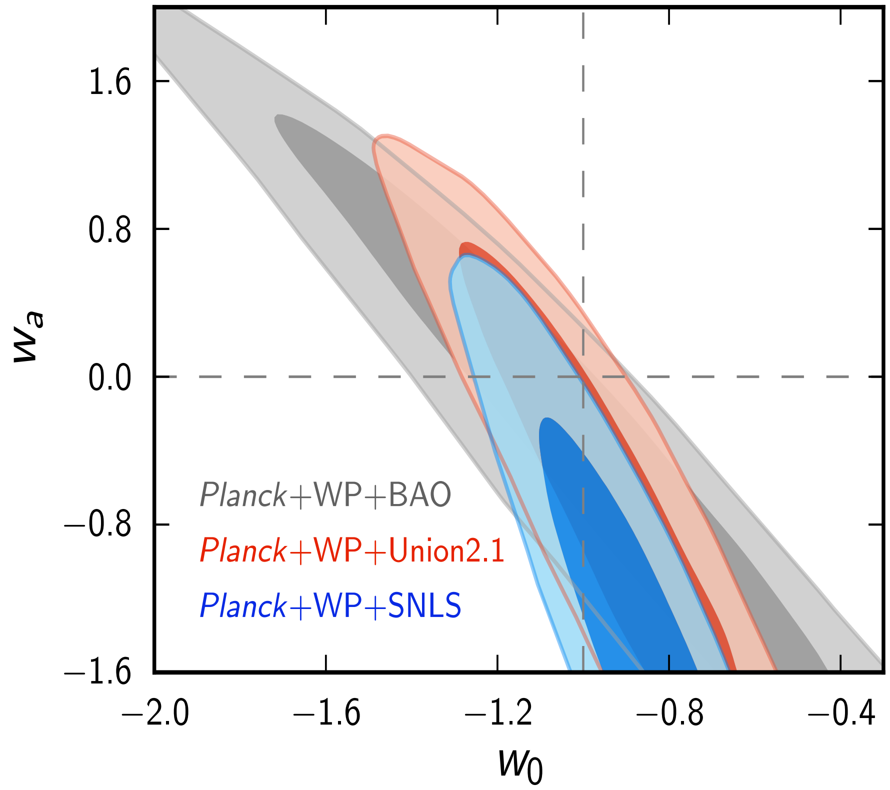
Hinshaw et al.

1212.5226

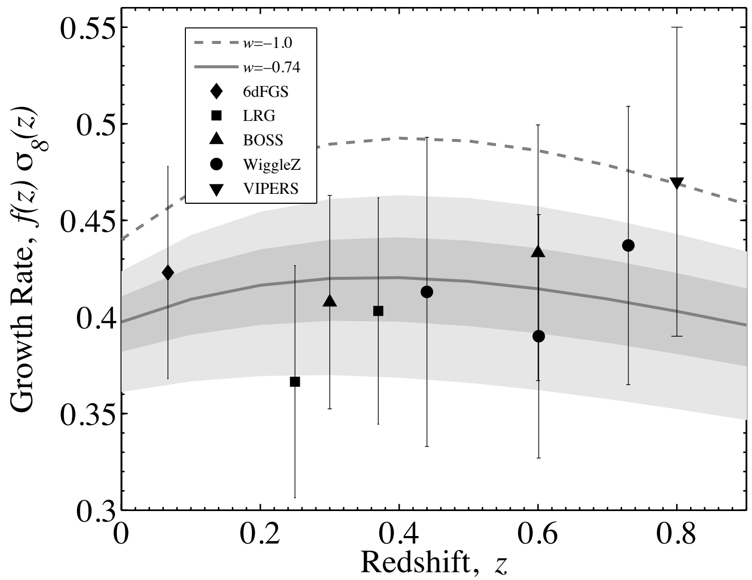


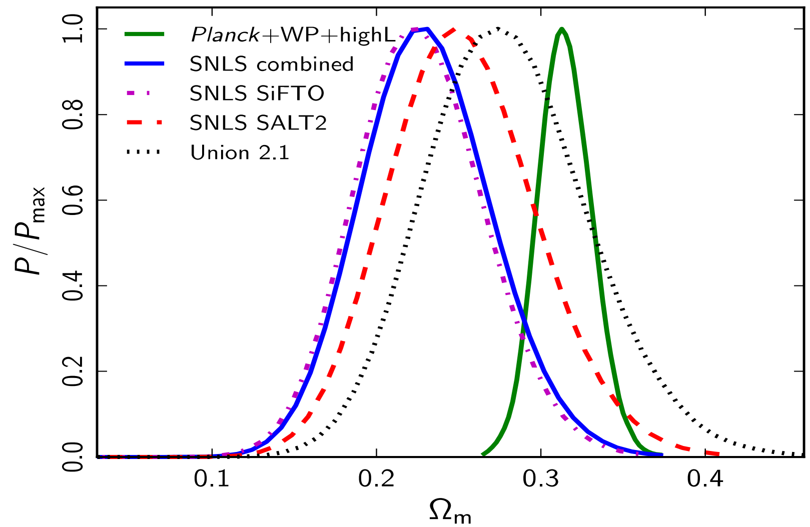
Planck Collab:

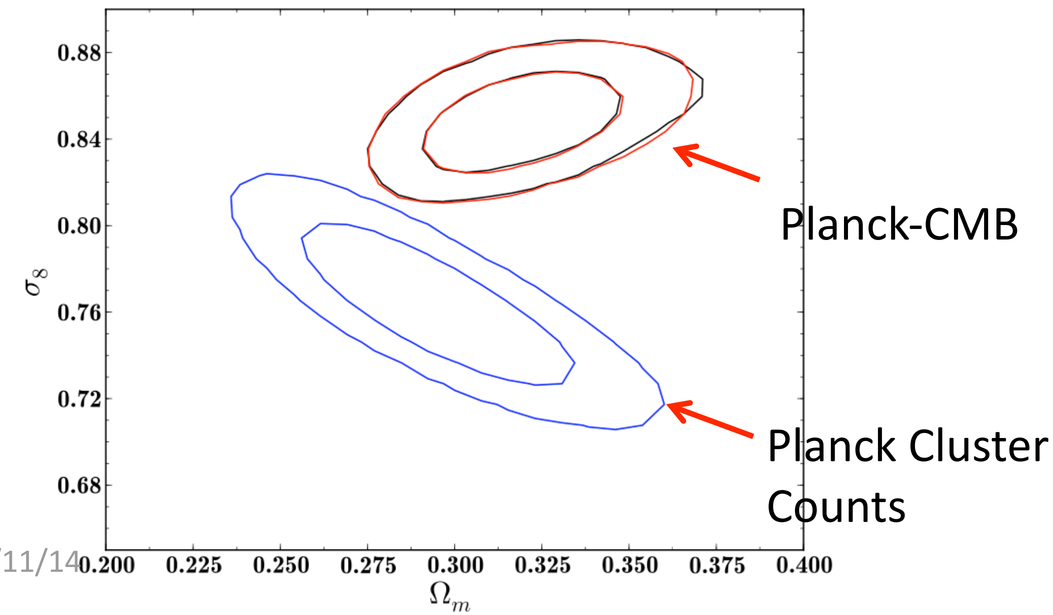
1303.5076

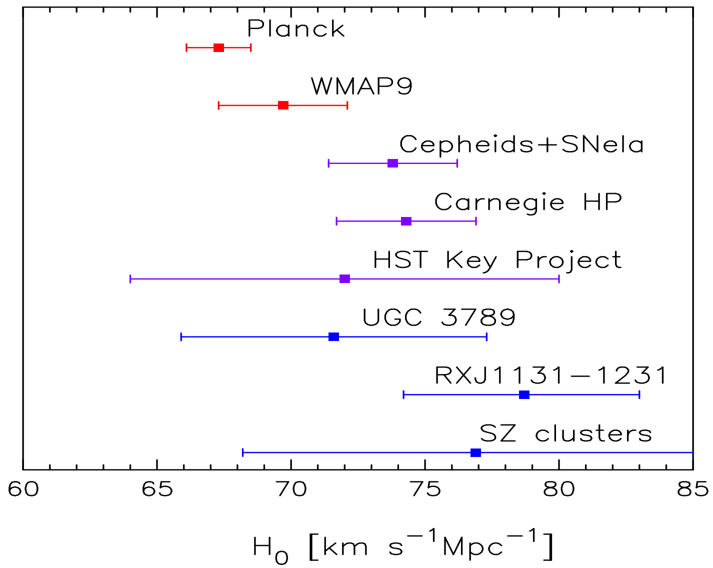


Some Inconsistencies









Issues to be discussed

- Possible tensions between CMB and Non-CMB data
- How different data prefer cosmological behaviour
- Consistency for the LCDM model
- Any preference for phantom/non phantoms
- Any possibility for transition from phantom to non-phantom or vice versa
- Any possibility that acceleration to be a transient phenomena

- Data Used:

Planck + WMAP polarization, SN (Union3), BAO, HST.

D. Hazra, S. Majumdar, S.Pal, S. Panda, AAS, **arXiv: 1310.6161**

W(z) Parameterizations

- Motivation is to explore the dark energy constraints more elaborately.
- To see how robust are the constraints: whether depend on the dark energy parameterization.
- We use three parameterization:

(i) $w(a) = w_0 + w_a(1-a)$ CPL Parameterization

(ii) $$w(a) = (1+w_0)\left[\sqrt{1+(\Omega_{\rm DE}^{-1}-1)a^{-3}} - (\Omega_{\rm DE}^{-1}-1)a^{-3}\tanh^{-1}\frac{1}{\sqrt{1+(\Omega_{\rm DE}^{-1}-1)a^{-3}}}\right]^2 \times$$
$$\times\left[\frac{1}{\sqrt{\Omega_{\rm DE}}} - \left(\frac{1}{\Omega_{\rm DE}}-1\right)\tanh^{-1}\sqrt{\Omega_{\rm DE}}\right]^{-2} - 1.$$ SS Parameterization

(iii) $w(a) = -\frac{A}{A+(1-A)a^{-3(1+\alpha)}}$, GCG Parameterization (non-phant)

Likelihood Comparison

Data	ΛCDM	CPL	GCG	SS
Planck (low-ℓ + high-ℓ)	7789.0	7787.4	7789.0	7788.1
WMAP-9 low-ℓ polarization	2014.4	2014.436	2014.383	2014.455
BAO : SDSS DR7	0.410	0.073	0.451	0.265
BAO : SDSS DR9	0.826	0.793	0.777	0.677
BAO : 6DF	0.058	0.382	0.052	0.210
BAO : WiggleZ	0.020	0.069	0.019	0.033
SN : Union 2.1	545.127	546.1	545.131	545.675
HST	5.090	2.088	5.189	2.997
Total	10355.0	10351.4	10355.0	10352.4

Table 1. Best fit χ^2_{eff} obtained in different model upon comparing against CMB + non-CMB datasets. The breakdown of the χ^2_{eff} for individual data is provided as well. To obtain the best fit we have used the Powell's BOBYQA method of iterative minimization.

Likelihood Plots

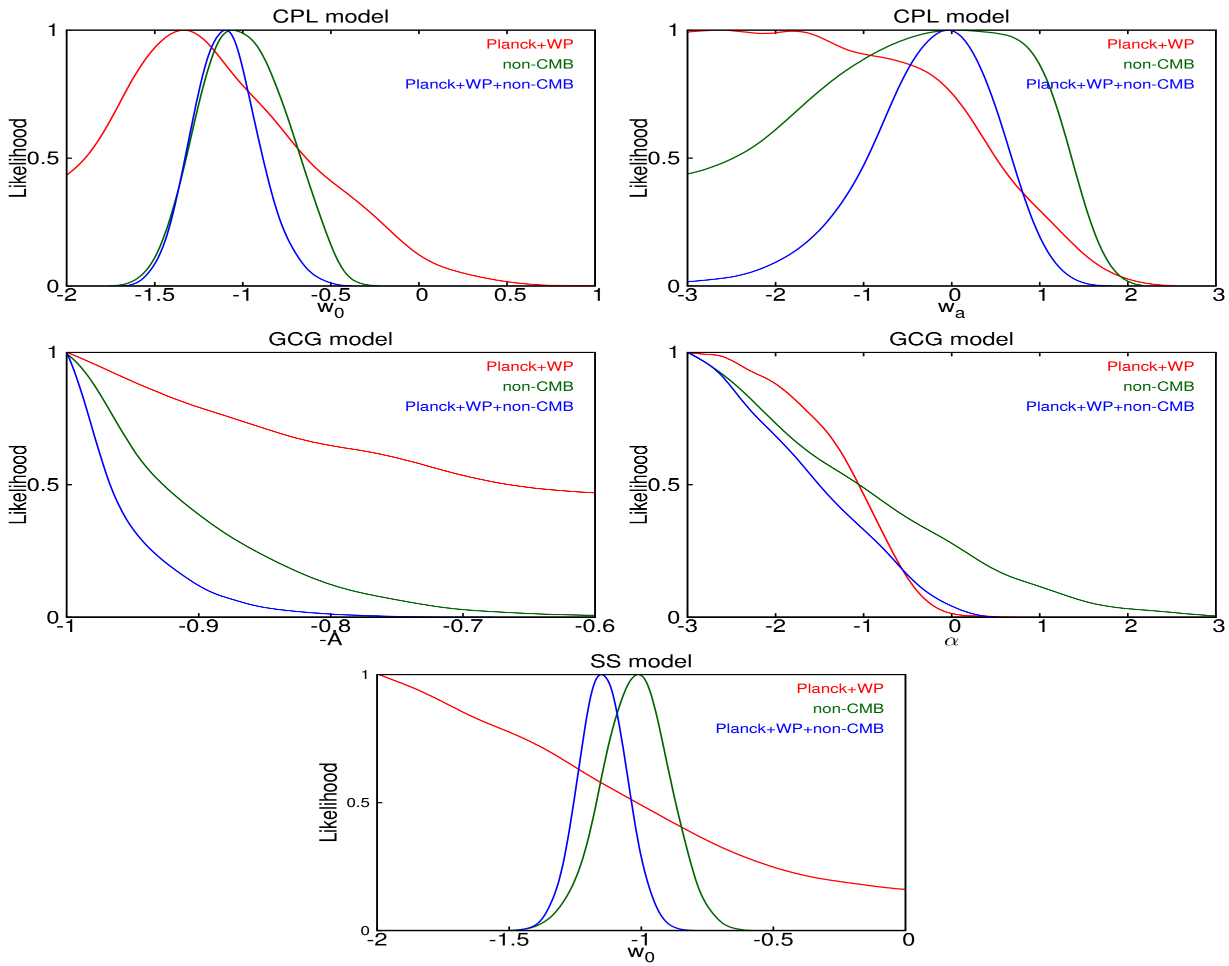


Figure 1. The likelihood functions for different parameters of equation of state. The upper ones are for the CPL parametrization, the middle ones for the GCG parametrization and the bottom one for the SS parametrization. The color codes are for different analysis with different observations and are described in the plot.

2D Confidence Contours

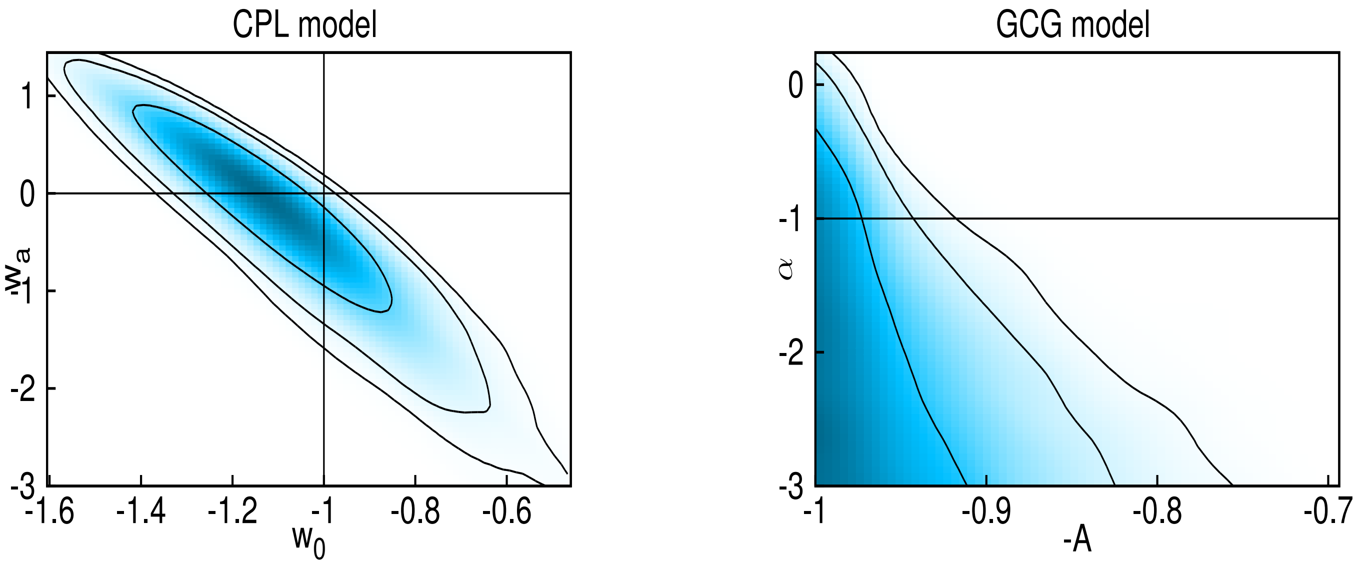


Figure 2. Contour plots in the $w_0 - w_a$ plane for CPL and $A - \alpha$ plane for the GCG parametrization.

2D Confidence Contours

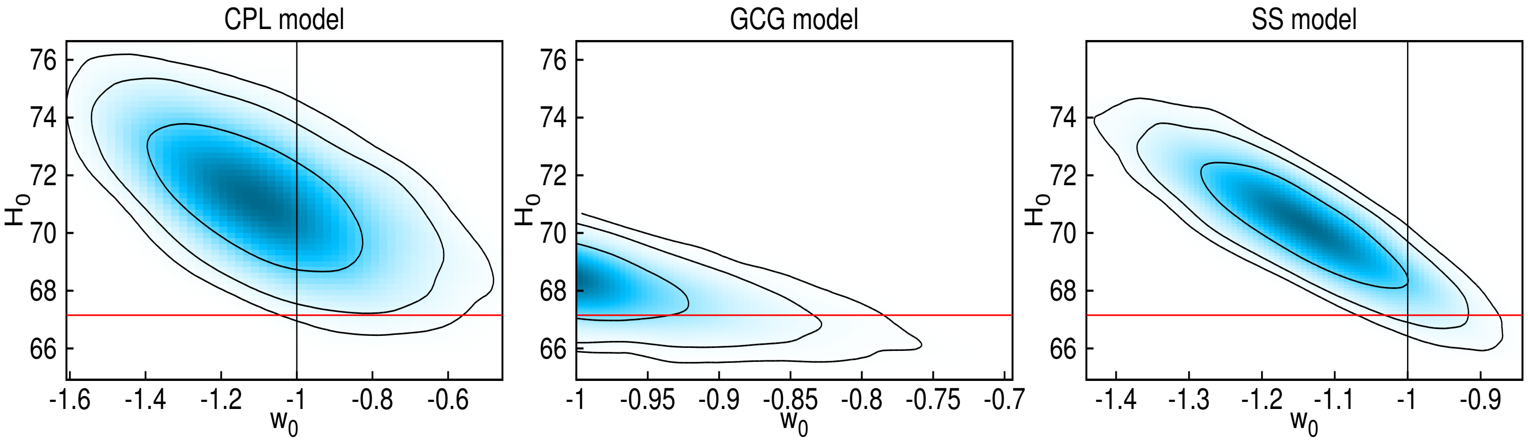


Figure 3. Contour plots in $w_0 - H_0$ parameter plane for CPL (left), GCG (middle) and SS (right) parametrization. The red line represents the best fit value for H_0 obtained Planck for ΛCDM case.

2D Confidence Contours

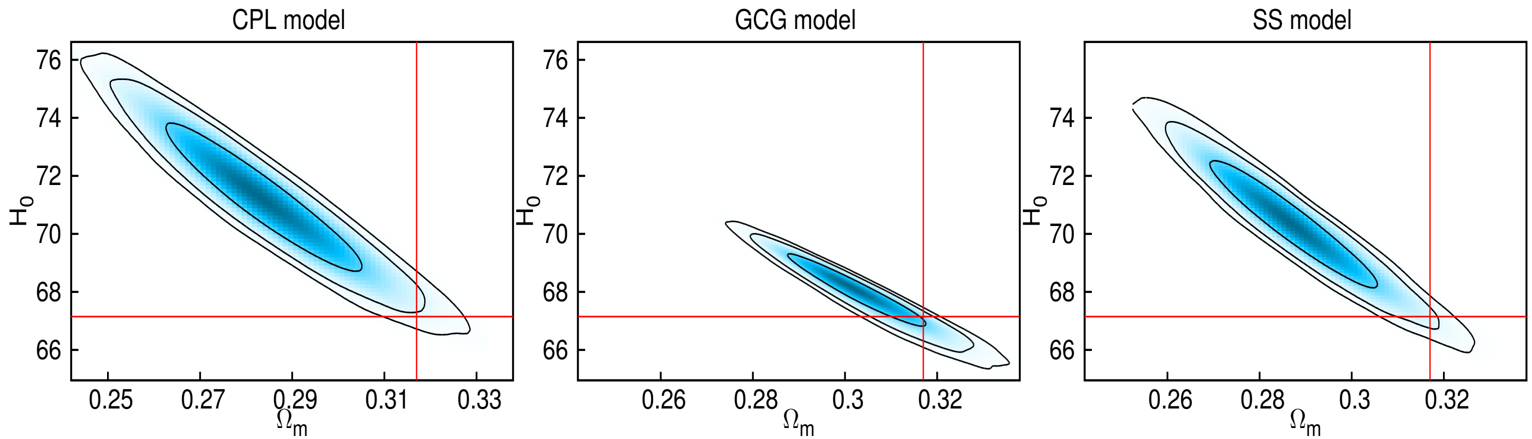


Figure 4. Contour plots in $\Omega_{\rm m} - H_0$ parameter plane for CPL (left), GCG (middle) and SS (right) parametrization. The red lines represents the best fit values for H_0 and $\Omega_{\rm m}$ obtained Planck *only* for ΛCDM model.

Reconstructed Equation of State

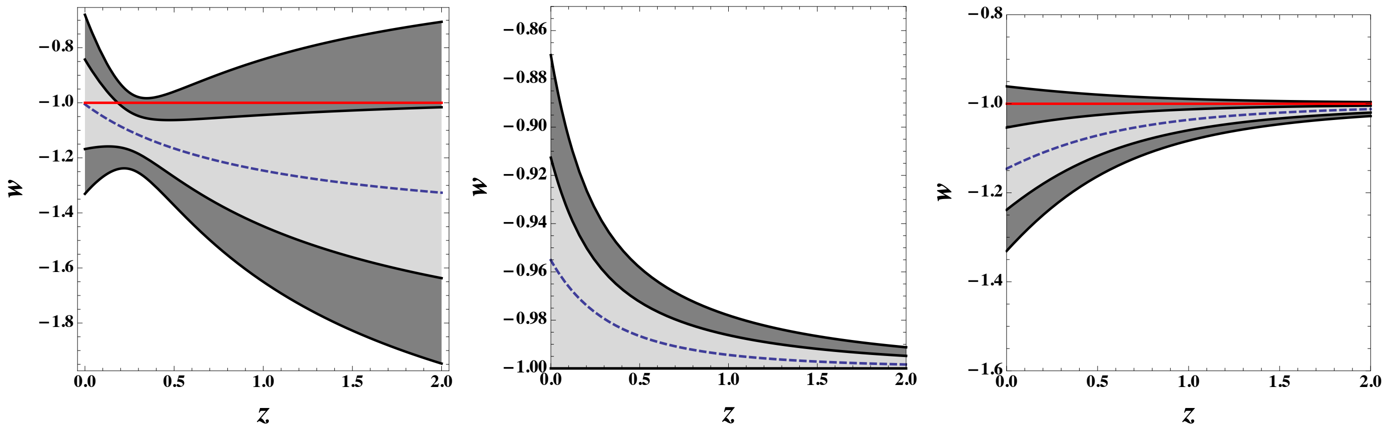


Figure 5. Behavior of equation of state w as a function of redshift z for CPL (left), GCG (middle) and SS (right) parametrization for $1-\sigma$ and $2-\sigma$ confidence level. The red and blue lines correspond to $w=-1$ and the mean w respectively.

Discussions

- If we allow phantom behavior, CMB data favor it compared to non-phantom behavior. On the other hand, non-CMB data consistently prefer non-phantom model. This tension between the two data sets may be attributed to unknown systematics or the lack of better theory/parameterization of the dark energy equation of state.

- The GCG parameterization which is a non-phantom one, shows consistency between CMB and non-CMB data, although with worse likelihood values. The cosmological parameters are also consistent with base Planck best-fit measurements.

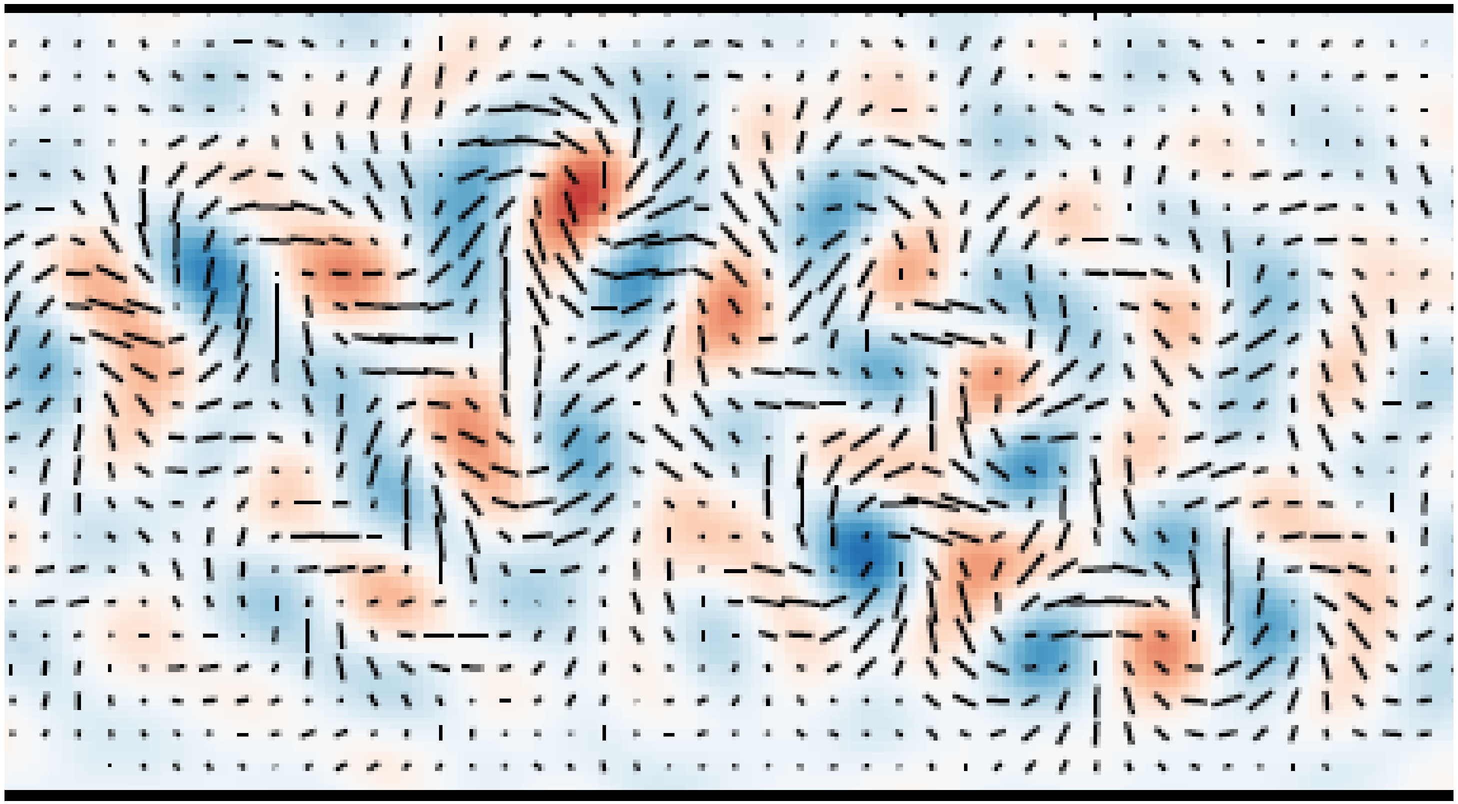
Discussions

- With the reconstruction of the equation of state for DE, find that for models allowing phantom, the w=-1 line stays outside the 1σ allowed band.
- For the CPL case, we find that within 2σ band, there does not exist a equation of state that has not passed through a phantom region, unless one does extreme fine tuning at redshift around z = 0.3.
- Regarding the thawing and freezing behavior, thawing behavior (where acceleration is transient) is more favorable.

  This is interesting due to recent construction of thawing class of dark energy models in string Theory.

  Panda, Sumimoto and Trivedi, PRD, 2011.

BICEP2 Results



Status of Inflation After Planck-2013

- Key Predictions for a simple inflationary models:

1. Flat Universe $\Omega_k = -0.0096 \pm 0.01$

2. Initial curvature fluctuations is almost scale invariant and power-law:

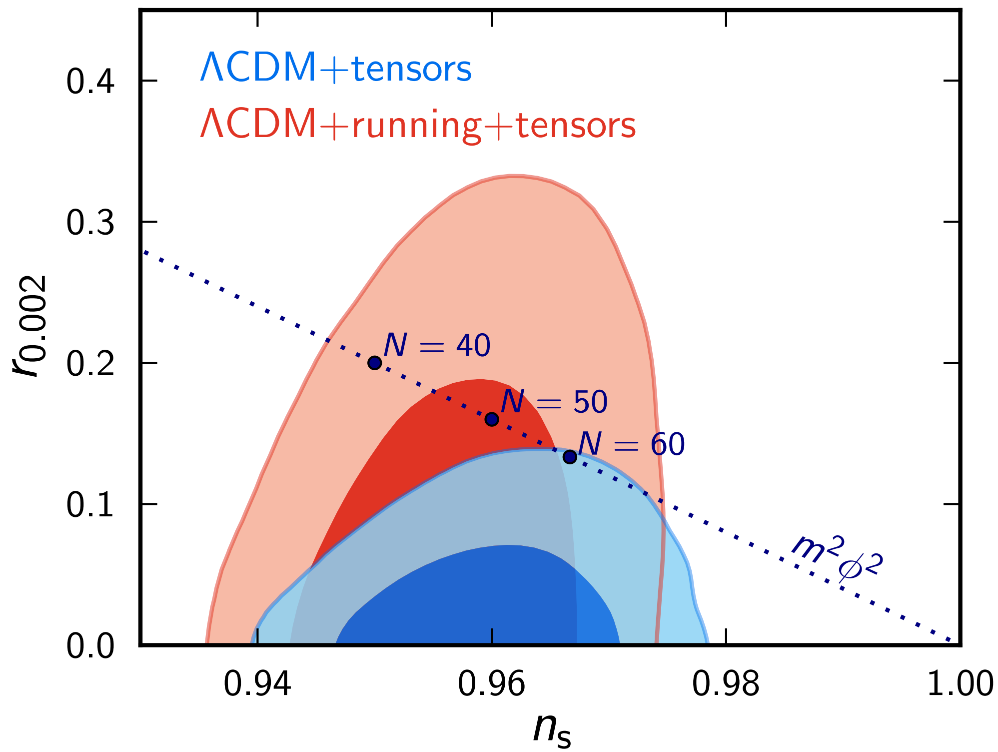
$$\mathcal{P}_{\mathcal{R}}(\frac{k}{k_0}) \approx A_s(\frac{k}{k_0})^{n_s-1}, A_s = \frac{H^2}{8\pi^2\epsilon_V M_p^2}, n_s - 1 = -6\epsilon_V + 2\eta_V$$

3. Primordial Fluctuations are Gaussian.

4. Primordial gravity waves:

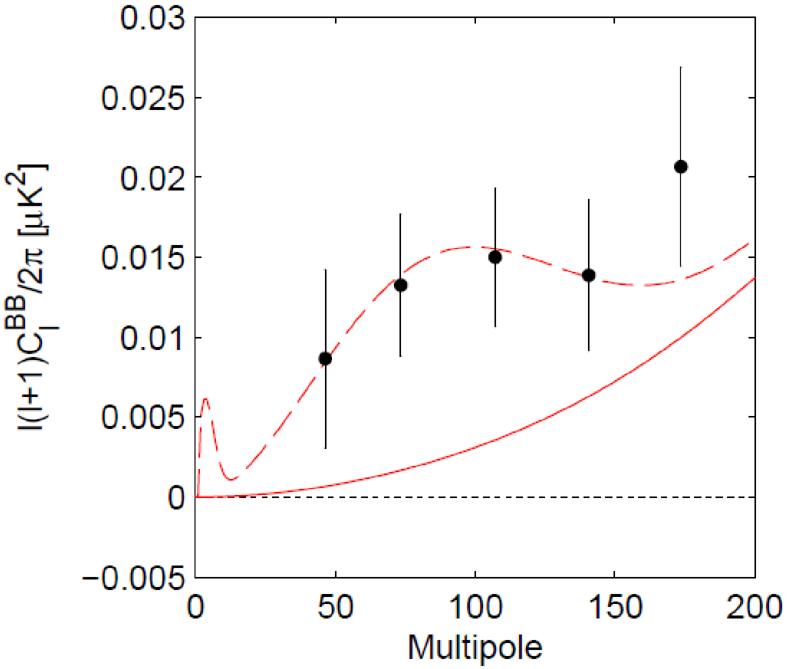
$$\mathcal{P}_h(k) \approx A_t(\frac{k}{k_0})^{n_t}, A_t = rA_s = \frac{2H^2}{\pi^2 M_p^2}, n_t = -2\epsilon_V$$

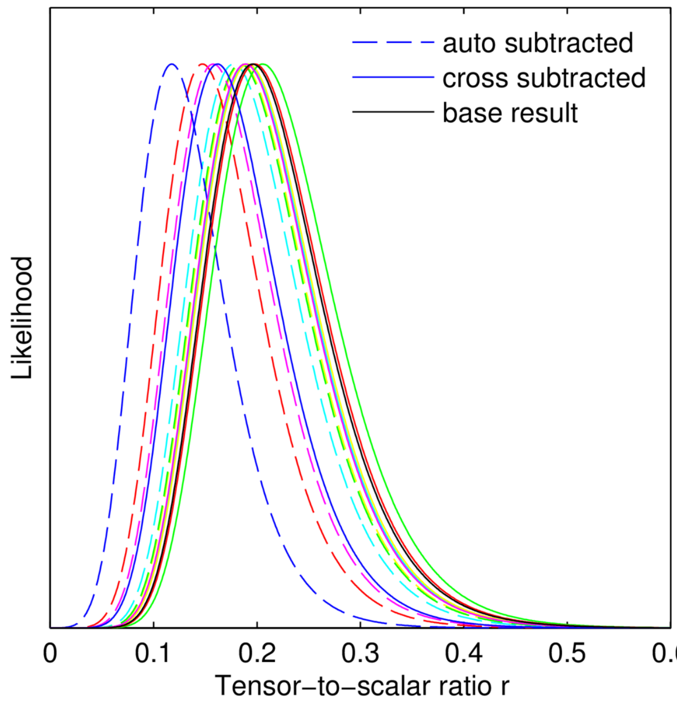
Planck Constraint 2013



- r < 0.11 (95% CL with Planck + WP + Low-L ; No running)
- r < 0.26 (95% CL with Planck + WP + Low-L; with running)

BICEP2 measurement of r

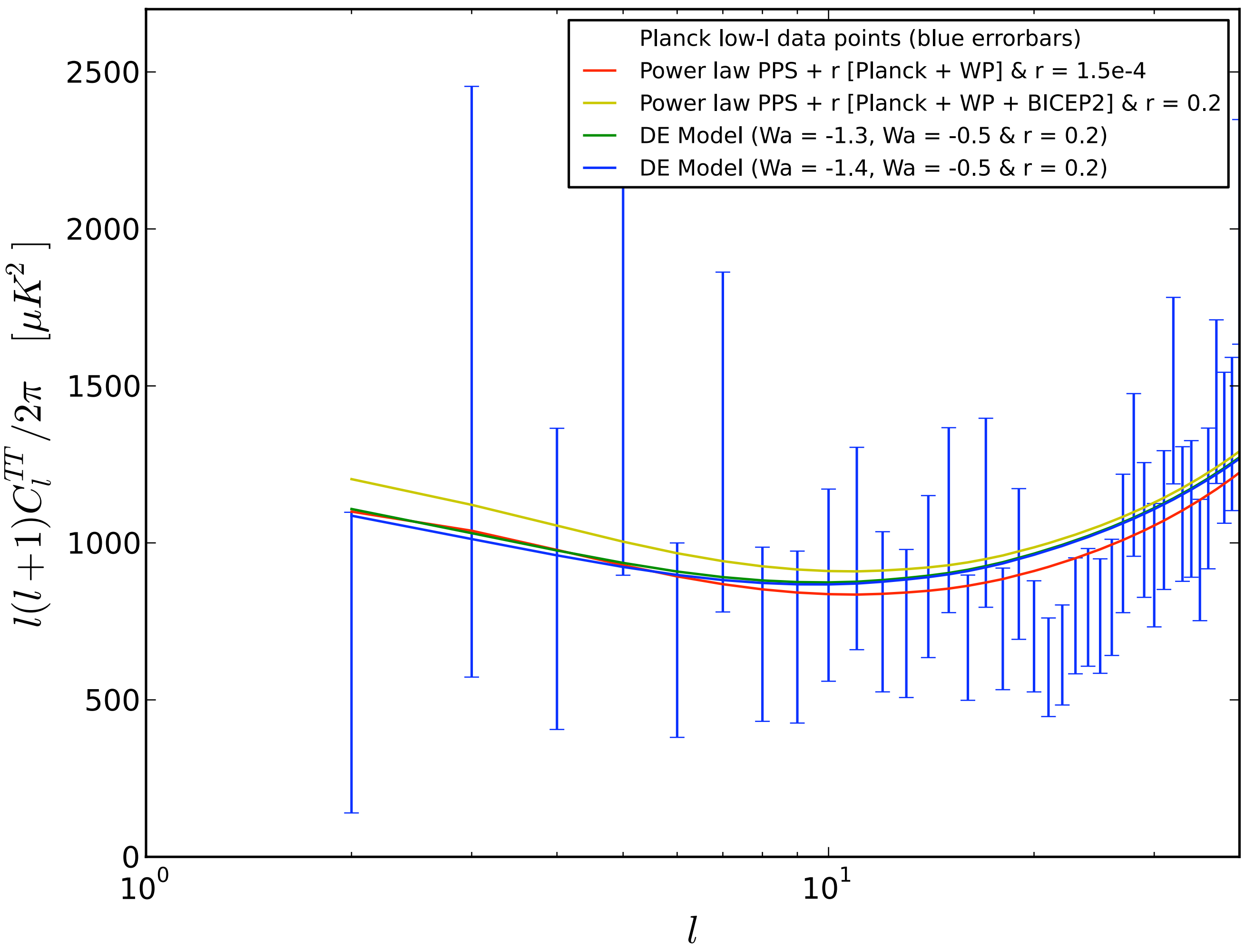




$$r = 0.2^{+0.07}_{-0.05}$$

This assumes LCDM + power-Law spectrum for primordial fluctutaions

Problem with large r



Whether Phantom DE can play a role?

Comparison of the ΛCDM with Phantom DE				
	Planck + WP		**Planck + WP + BICEP2**	
$n_{\mathrm{T}} = -r/8$	ΛCDM	Phantom	ΛCDM	Phantom
$\Omega_{\mathrm{b}} h^2$	0.02217	0.0223	0.0221	0.0223
$\Omega_{\mathrm{CDM}} h^2$	0.1183	0.1171	0.1177	0.116
100θ	1.041	1.042	1.041	1.041
τ	0.088	0.088	0.089	0.089
n_s	0.9658	0.9676	0.9686	0.9732
w_0	-1	-1.408	-1	-1.599
w_a	0	-0.894	0	-1.17
r	0.009	0.01	0.16	0.17
$\ln(10^{10} A_{\mathrm{S}})$	3.085	3.081	3.085	3.081
$-2\ln\mathcal{L}$ [Best fit]				
`commander`	-7.454	-8.61	-1.695	-4.802
`CAMspec`	7796.235	7795.474	7797.54	7796.988
`WP`	2014.141	2014.55	2013.321	2013.572
`BICEP2`	-	-	39.141	38.281
Total	9802.92	9801.41	9848.31	9844.04
$-2\Delta\ln\mathcal{L}$	-	-1.51	-	-4.3

To Summarize

- Provided CMB and Non-CMB joint analysis does not impose systematic errors as discussed, allowing phantom provides a better fit to the joint data. Adding BICEP2 fits improve further.
- This is an invitation to build model for dark energy that allow phantom behavior.
- It may be blow to standard scalar field models for dark energy as one can not violate weak energy condition in this case.
- But higher derivative corrections, as well as coupled model for dark matter and dark energy can results effective equation of state that may be phantom.
- On the other hand, non-phantom behavior although provides worse fit than phantom, it shows consistencies with both CMB+non-CMB data sets as well as with LCDM results.

Current and Future Projects in Observational Cosmology

CMB:

WMAP, SPT, ACT, Planck

Large Scale Surveys:

SDSS, Chandra, Wiggle-Z, BOSS, Big-BOSS, e-Rosita, Euclid, DES, SKA…….

Supernova-Ia Observations:

SCP, SNLS, High-z Sn Search, Essence, LSST, JWST, TMT…..

Common Goal:

Studying the Nature of Dark Energy

Thank You