A theorist's take-home message from CMB (and other observations)

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Outline

- Inflation
    - * The ABC of Inflation
    - * CMB à la WMAP9 and Planck 2015
    - * Test of inflationary predictions
    - * Status of inflationary models

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- Dark Energy
  * Dark Energy from CMB
  * Dark Energy from other observations
  * Concordance or conflict?

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  * Concordance or conflict?
- New Avenues...

Puzzles of standard Big Bang Cosmology

- Horizon
- Flatness
- Monopole
- Structure formation...

The ABC of Inflation

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Wayout

Super-fast accelerated expansion at the beginning $\Longrightarrow$ Inflation

Dynamics? $\longrightarrow$ Scalar field

EM tensor components $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$; $p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

Governing Equations

$$H^2 = \frac{1}{3M_P^2}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

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

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Employ slow roll condition

$$\dot{\phi}^2 << V(\phi) \quad ; \quad |\ddot{\phi}| << 3H|\dot{\phi}|, V'(\phi)$$

Slow roll parameters $\epsilon_V = \frac{M_P^2}{2}\left[\frac{V'}{V}\right]^2 \ll 1$

$$\eta_V = M_P^2\left[\frac{V''}{V}\right] \ll 1$$

For sufficient inflation $N = \ln\frac{a_f}{a_i} \approx -\frac{1}{M_P^2}\int_{\phi_i}^{\phi_f}\frac{d\phi}{\sqrt{2\epsilon_V}} \quad \approx 56 - 70$

Solves first 3 puzzles at a single go.

Structure formation? $\longrightarrow$ Perturbations

Quantum fluctuations of inflaton exit horizon and get frozen.
Appear as classical perturbations after horizon re-entry.

Inflation provides seeds of perturbations.

Perturbations in the metric

$\Downarrow$

$$\boxed{\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}}$$

$\swarrow$ $\downarrow$ $\searrow$

Scalar perturbation | Vector perturbation | Tensor perturbation

Scalar perturbation $\Downarrow$ Matter

Tensor perturbation $\Downarrow$ Gravitational waves

Solves Puzzle No.4

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Solves Puzzle No.4

First impression: Too good to be true!!

Inflationary predictions

Observable parameters	Scalar modes	Tensor modes
Power spectrum	$P_R(k) = \frac{k^3}{2\pi^2}\frac{\|v\|^2}{z^2}\|_*$	$P_T(k) = 2 \times \frac{k^3}{2\pi^2}\frac{2}{M_P^2}\frac{\|u\|^2}{a^2}\|_*$
Tensor to scalar ratio		$r = \frac{P_T\|_*}{P_R\|_*}$
Spectral index	$n_S = 1 + \frac{d\ln P_R(k)}{d\ln k}\|_*$	$n_T = \frac{d\ln P_R(k)}{d\ln k}\|_*$
Running of S.I.	$\alpha_S = \frac{dn_s}{d\ln k}\|_*$	$\alpha_T = \frac{dn_s}{d\ln k}\|_*$

$* \Rightarrow k = aH$

+ Consistency relation $r = -8n_T$

more or less generic for

- slow roll
- single scalar, canonical, minimally coupled
- $c_s \approx 1$

Inflationary predictions

- Universe is mostly homogeneous and isotropic

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- Perturbations generate specific peaks in CMB $\Rightarrow$ Give $\Omega's$
- Spatially flat universe $\Rightarrow \Omega_{\rm tot} \approx 1 \pm 10^{-4}$
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- Gaussian perturbations $\Rightarrow$ stochastic properties completely determined by 2PCF: Power spectrum

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- Generic spectrum $P_R(k) \simeq P_R(k_*)(\frac{k}{k_*})^{n_s-1+n_s' \ln(k/k_s)}$
  If $n_s' \neq 0 \Rightarrow$ deviation from power law

Inflationary predictions

- Tensor modes would be small but bear strong physical significance.
  A small fraction of CMB photons get polarized due to quadrupole anisotropies. $\Rightarrow$ 2 polarization modes (E & B)

  B modes $\rightarrow$ Gravitational waves
  + NG + Lensing + Magnetic field...

  Detection of tensor modes have direct reflection on energy scale of inflation (hence on fundamental physics)

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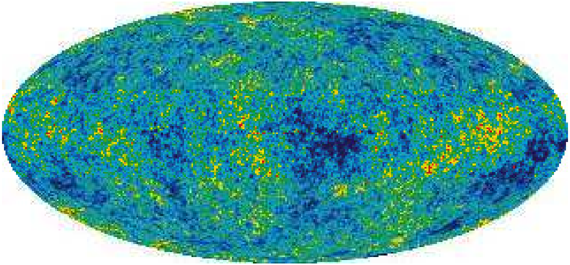
Caution :

A good fraction of the above predictions can be violated with more complicated models

The CMB sky



Background temperature $T_0 = 2.725K$ at all directions
$\Rightarrow$ The Universe is homogeneous and isotropic at largest scale

All about CMB temperature

Background : $T_0 = 2.725K \longrightarrow$ Blackbody spectrum
Fluctuations : $-200\mu K < \Delta T < 200\mu K$

$$\Delta T_{rms} \sim 70\mu K$$
$$\Delta T_{pE} \sim 5\mu K$$
$$\Delta T_{pB} \sim 10 - 100nK$$

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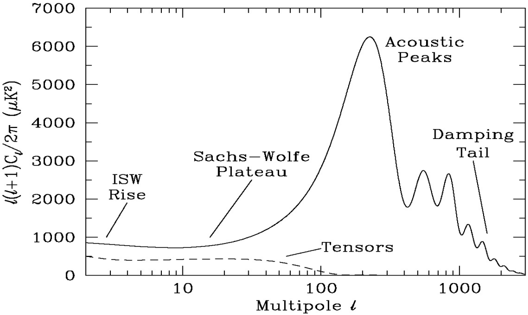
How to decode information?

$\Delta T(n) = \sum a_{\ell m} Y_{\ell m}(n) \rightarrow$ spherical harmonics
$\Rightarrow$ 2-point correlation function $C_\ell = \frac{1}{2\ell+1} \sum |a_{\ell m}|^2$

$$\boxed{C_\ell = \int \frac{dk}{k} P_R(k) T_\ell^2(k)}$$

- Temperature anisotropy T + two polarization modes E & B
  $\Rightarrow$ Four CMB spectra: $C_\ell^{TT}, C_\ell^{EE}, C_\ell^{BB}, C_\ell^{TE}$
- Parity violation/systematics $\Rightarrow$ Two more spectra: C_ℓ^{TB}, C_ℓ^{EB}



Peak positions, heights and ratios give cosmological parameters ⇒ imprints of both early universe and late universe

Cosmological parameters from C_ℓ

Fundamental/ fit parameters

$$\begin{aligned}
\Omega_b h^2 &= \text{baryonic matter density} \\
\Omega_c h^2 &= \text{dark matter density} \\
\Omega_X &= \text{dark energy density} \\
A_s &= \text{amplitude of scalar power spectrum} \\
n_s &= \text{scalar spectral index} \\
\tau &= \text{optical depth} \\
r &= \text{tensor-to-scalar ratio}
\end{aligned}$$

Altogether 6 (or 7 if $r \neq 0$)

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Derived parameters

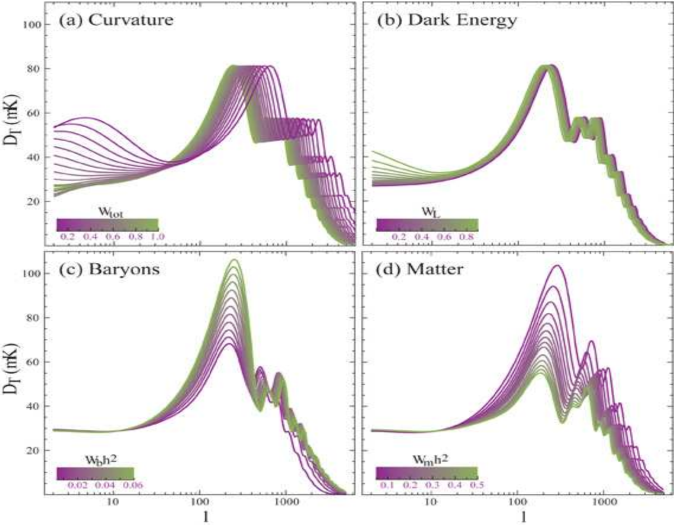
t_0, H_0, Ω_b, Ω_c, Ω_m, Ω_k, $\Omega_{\rm tot}$, σ_8, $z_{\rm eq}$, $z_{\rm reion} \ldots$

WMAP9 vis-à-vis Planck

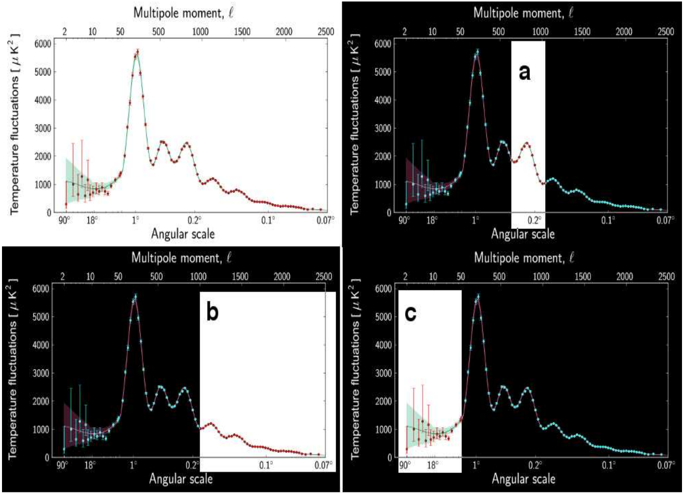
Parameters	WMAP 9	Planck 2013
A_s	$(2.464 \pm 0.072) \times 10^{-9}$	$(2.196^{+0.051}_{-0.060}) \times 10^{-9}$
n_s	0.9606 ± 0.008	0.9603 ± 0.0073
n'_s	-0.023 ± 0.001	-0.013 ± 0.009
r	< 0.13	< 0.11
$\Omega_b h^2$	0.02264 ± 0.0005	0.022007 ± 0.00033
$\Omega_c h^2$	0.1138 ± 0.0045	0.1196 ± 0.0031
Ω_X	$0.7135^{+0.0095}_{-0.0096}$	$0.685^{+0.018}_{-0.016}$
τ	0.088 ± 0.015	$0.089^{+0.012}_{-0.014}$
H_0	69.32 ± 0.80 km/s/Mpc	67.3 ± 1.2 km/s/Mpc
t_0	13.772 ± 0.059 Gyr	13.817 ± 0.048 Gyr

WMAP9 and Planck give consistent results

How sensitive to parameters the CMB TT plot is?



Planck 2015 highlights



Planck 2015 highlights

Ade et.al., 1502.01589; 1502.01590; 1502.01592; 1502.00612

Parameters	Planck2015 TT+low P	Planck2015 TT,TE,EE+low P
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015
Ω_M	0.315 ± 0.013	0.3156 ± 0.0091
$\ln(10^{10} A_S)$	3.089 ± 0.036	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049
τ	0.078 ± 0.019	0.079 ± 0.017
H_0	67.31 ± 0.96	67.27 ± 0.66
σ_8	0.829 ± 0.014	0.831 ± 0.013
r	< 0.11	< 0.07 (+BICEP2 Keck)

NG Parameters	Planck2015 TT	Planck2015 TT+low P
$f_{\rm NL}^{\rm loc}$	2.5 ± 5.7	0.8 ± 5.0
$f_{\rm NL}^{\rm eq}$	-16 ± 70	-4 ± 43
$f_{\rm NL}^{\rm ortho}$	-34 ± 33	-26 ± 21

Test of predictions post-Planck 2015

Boring universe, 6 parameters suffice

More matter, less energy (slightly altered from Planck 2013)

Little bit older universe (13.771 Gyr WMAP9 $\longrightarrow$ 13.817 Gyr)

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Outliners are still there $\Rightarrow$ physical origin?
Large scale anomalies : hemispherical asymmetry?
Big cold spot $\Rightarrow$ superstructure?

Primordial gravity waves (PGW) revisited

- March 2013: Planck: $r < 0.11 \Rightarrow$ GW yet undetected
- Feb 2014: BICEP2: $r \approx 0.2 \Rightarrow$ Primordial GW detected??
- Feb 2015: Joint analysis of Planck + BICEP2 Keck array: $r < 0.07 \Rightarrow$ GW yet undetected but even better constrained
- Feb 2015: LIGO: GW detected from blackhole mergers!!

Hunt for primordial gravity waves is still on $\rightarrow$ PIXIE, PRISM...

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Caution: Sources of contamination in r

- Lensing in TT spectrum (due to intervening medium)
- Non-gaussianities
- Primordial magnetic field (Faraday rotation $\Rightarrow$ E-B mixing)
- Lensing in Polarized B-modes

Intrinsic, delensed, polarized B-modes will confirm proper PGW

Have we "seen" inflation in the sky?

No, not yet!!

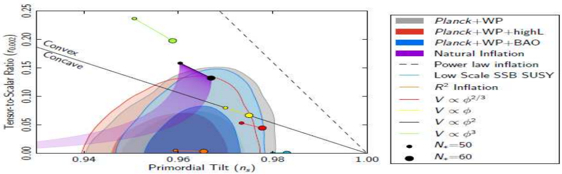
Can be claimed only when we detect

- r conclusively
- n_T independently and verify consistency relation $r = -8n_T$ for
  - * slow roll
  - * single field, canonical, minimally coupled
  - * $c_s \approx 1$
- α_T (or confirm it is zero)
- $f_{\rm NL}$ for single field vs multi field debate

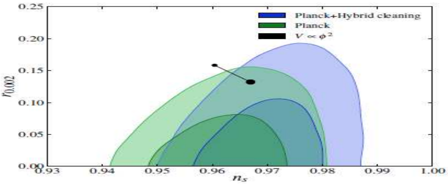
... but of course we are zeroing in!

What can we say about the inflationary models?

Chaotic + minimal copuling P.A.R.Ade et.al., 1303.5082

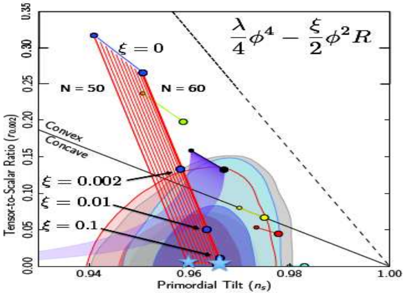


Tightly constrained. Different cleaning: Spergel et.al., PRD:2015



ϕ^2 marginally consistent.

Chaotic + non-minimal coupling   Bezrukov et.al., JHEP:2013

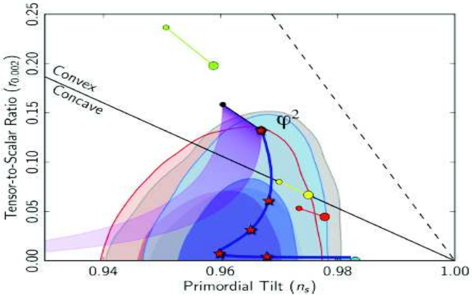


Allowed, even ϕ^4 for $\xi/2 > 10^{-3}$

but issues, e.g. candidate inflaton? Higgs?

Polynomial (SUGRA?) Kallos, Linde, JCAP: 2010

$$V(\phi) = \frac{m^2\phi^2}{2}(1 - a\phi + a^2 b\phi^2)^2$$

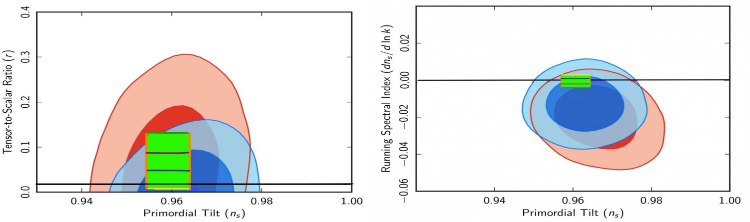


Allowed, with $b = 0.34, a = 0, 0.03, 0.05, 0.1, 0.13$

but issues, e.g. SUGRA origin is debatable

MSSM(inflection point) Choudhury, Majumdar, SP, JCAP:2013

$$V(\phi) = \alpha + \beta(\phi - \phi_0) + \gamma(\phi - \phi_0)^3 + \kappa(\phi - \phi_0)^4 + \cdots$$



Planck+WP9+BAO: Blue: ΛCDM+$r(\alpha_S)$, Red: ΛCDM+$r+\alpha_S$

Allowed, better fit for low l

Starobinsky model — Starobinsky, Sov. Astron. Lett: 1983

$$L = \sqrt{-g}\left(\frac{R}{2} + \frac{R^2}{12M^2}\right), \quad M \ll M_p$$

can be reduced to canonical gravity + scalar field by field redefinition and metric transformation

$$N \sim 60 \Rightarrow n_S \sim 0.967, r \sim 0.003$$
$$N \sim 60 \Rightarrow n_S \sim 0.964, r \sim 0.004.$$

Allowed

Many models, except a few with very high r, are still allowed.

Two open questions

- All models lead to same predictions matching with Planck.
  Can they be incorporated into a common platform?
  Superconformal theory??
  Universal attractor?? Linde, 1402.0526

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- Among all allowed models, which ones are more probable?

Most probable models

Model selection algorithm   Liddle et.al., astro-ph/0608184

Consider 2 models

- $\mathcal{M}_1$ with one model parameter θ
- $\mathcal{M}_2$ with two model parameters α and β

How do they fair against some data D? $\Rightarrow$ maximum likelihood

$\mathcal{L}_1 = \mathcal{L}_{1,\max} \exp^{-\chi^2(\theta)/2} \quad ; \quad \mathcal{L}_2 = \mathcal{L}_{2,\max} \exp^{-\chi^2(\alpha,\beta)/2}$

But this does not distinguish between "complexity" of the models.

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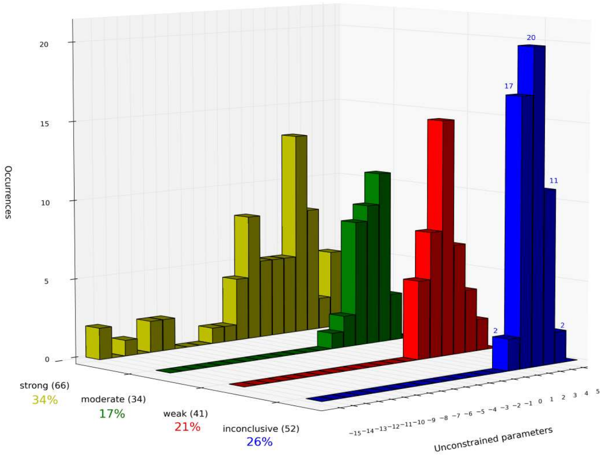
Occam's razor : penalize complex models.
Best models are those who can make best compromise between simplicity and quality of fits

Calculate Bayesian evidence
$\mathcal{E}_1 = \int \mathcal{L}_1(D/\theta)\pi(\theta)d\theta$; $\mathcal{E}_2 = \int \mathcal{L}_2(D/\alpha,\beta)\pi(\alpha,\beta)d\alpha d\beta$
Prior distributions satisfy $\int \pi(\theta)d\theta = 1$; $\int \pi(\alpha,\beta)d\alpha d\beta = 1$

Lower evidence $\Rightarrow$ More probable : Jeffrey's scale



$\sim$ 26% models are most probable. J.Martin et.al., JCAP:2014
$+$ Bayesian complexity $\Rightarrow\sim$ 9%. Preferred potential: pleatue type.
But it all depends on how reliable Bayesian evidence calculation is!

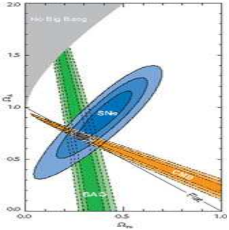
Take-home message: Inflation

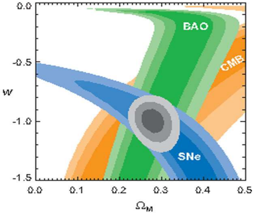
Have we "seen" inflation in the sky?

No, not yet!!

... but of course we are zeroing in!

The ABC of Dark Energy





Universe is accelerating at present $\rightarrow$ need "anti-gravity"

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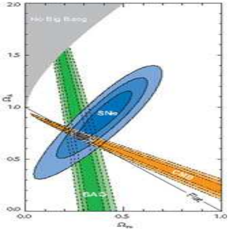

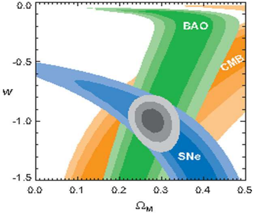

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Cosmological constant	v/s	Dynamical models
$\rho_\Lambda = \text{const.}$		$\rho_X \propto \exp\left(3\int_0^z \frac{1+\omega(z)}{1+z}dz\right)$
$p_\Lambda = -\rho_\Lambda$		$p_X = \omega(z)\rho_X$
$\delta\rho_\Lambda = 0$		$\delta\rho_X \neq 0$

- Fine-tuning problem
- Cosmic coincidence problem
-

Dynamical models: Dark Energy

- Quintessence: scalar field minimally coupled to gravity
- K-essence: Kinetic energy driven
- Tachyonic: Non-canonical
- Phantom: Opposite sign in kinetic term
- Dilatonic
- (Generalized) Chaplygin gas

Modified gravity models

- Brans-Dicke theory: G as a VEV of a geometric field
- f(R) gravity: R in the action replaced by f(R)
- DGP model: Extra dimensional effects at large scale

No unique candidate

Dark energy parametrizations

Observationally we probe two parameters of dark energy:

- Density parameter (Ω_{DE}) (by probing Ω_{M})
- Equation of State (EOS) parameter (w_{DE})

Proposal

Instead of proposing individual models, can we parametrize dark energy and constrain models from observations by constraining those parameters?

Dark energy parametrizations

Observationally we probe two parameters of dark energy:

- Density parameter ($\Omega_{\rm DE}$) (by probing $\Omega_{\rm M}$)
- Equation of State (EOS) parameter ($w_{\rm DE}$)

Proposal

Instead of proposing individual models, can we parametrize dark energy and constrain models from observations by constraining those parameters?

- CPL Parametrization

$$
\begin{aligned}
w(a) &= w_0 + w_{\rm a}(1-a) \\
&= w_0 + w_{\rm a}\frac{z}{1+z}
\end{aligned}
$$

$$\rho_{\rm DE} \propto a^{-3(1+w_0+w_{\rm a})} e^{-3w_{\rm a}(1-a)}$$

- SS Parametrization

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

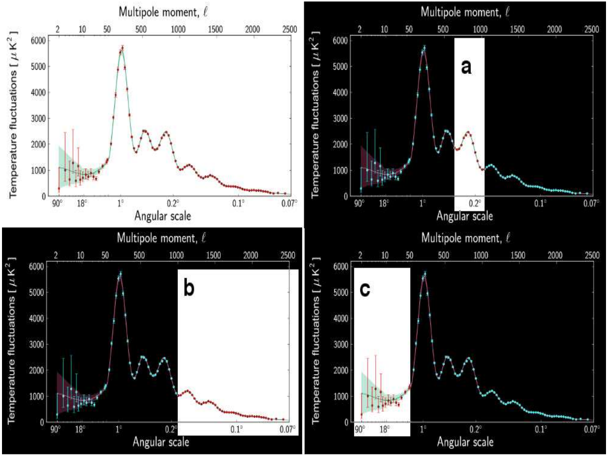
- GCG Parametrization

$$p = -\frac{c}{\rho^\alpha}$$

$$w(a) = -\frac{A}{A+(1-A)a^{-3(1+\alpha)}} \; ; \; A = \frac{c}{\rho_{\rm GCG}^{1+\alpha}}$$

Dark Energy from CMB

- Shift parameter (position of peaks)
- Integrated Sachs-Wolfe effect (low-ℓ)



Shift Parameter

DE $\Leftrightarrow$ Shift in position of peaks by $\sqrt{\Omega_m}D$
D= Angular diameter distance (to LSS) $\Rightarrow$ Shift Parameter

$$R = \sqrt{\frac{\Omega_m h^2}{|\Omega_k| h^2}}\chi(y)$$

$$\chi(y) = \sin y (k < 0) \quad ; \quad = y (k = 0) \quad ; \quad = \sinh y (k > 0)$$

$$y = \sqrt{|\Omega_k|} \int_o^{z_{\rm dec}} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_X (1+z)^{3(1+\omega_X)}}}$$

$$\chi^2_{\rm CMB}(\omega_X, \Omega_m, H_0) = \left[\frac{R(z_{\rm dec}, \omega_X, \Omega_m, H_0) - R}{\sigma_R}\right]^2$$

Integrated Sachs-Wolfe Effect

Some CMB anisotropies may be induced by passing through a time varying gravitational potential

- linear regime: integrated Sachs-Wolfe effect
- non-linear regime: Rees-Sciama effect

Poisson equation : $\nabla^2 \Phi = 4\pi G a^2 \bar{\rho} \delta$

$\Phi \rightarrow$ constant during matter domination
$\rightarrow$ time-varying when dark energy comes to dominate
(at large scales $\ell \leq 20$)

$$C_\ell = \int \frac{dk}{k} P_R(k) T_\ell^2(k)$$
$$T_\ell^{\mathrm{ISW}}(k) = 2 \int d\eta \exp^{-\tau} \frac{d\Phi}{d\eta} j_\ell(k(\eta - \eta_0))$$

But cosmic variance!

Supernova Type Ia Data

Probe Luminosity distance: $D_L(z) = H_0 d_L(z)$ via distance modulus

$$\mu(z) = 5\log_{10}(D_L(z)) + \mu_0$$

$$\chi^2_{\mathrm{SN}}(w_X^0, \Omega_m^0, H_0) = \sum_i \left[\frac{\mu_{\mathrm{obs}}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, H_0)}{\sigma_i}\right]^2$$

Marginalizing over the nuisance parameter μ_0,

$$\chi^2_{\mathrm{SN}}(w_X^0, \Omega_m^0) = A - B^2/C$$

$$A = \sum_i \left[\frac{\mu_{\mathrm{obs}}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, \mu_0 = 0)}{\sigma_i}\right]^2$$

$$B = \sum_i \left[\frac{\mu_{\mathrm{obs}}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, \mu_0 = 0)}{\sigma_i}\right]; \; C = \sum_i \frac{1}{\sigma_i^2}$$

Union 2.1 compilation of 580 Supernovae at $z = 0.015 - 1.4$, considered as standard candles

Baryon Acoustic Oscillation (BAO) data

Used to measure $H(z)$ and angular diameter distance $D_A(z)$ via a combination

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

Confront models via a distance ratio

$$d_z = \frac{r_s(z_{\rm drag})}{D_V(z)}$$

$r_s(z_{\rm drag})$ = comoving sound horizon at a redshift where baryon-drag optical depth is unity

Give 6 data points:

- WiggleZ : $z = 0.44, 0.6, 0.73$
- SDSS DR7 : $z = 0.35$
- SDSS DR9 : $z = 0.57$
- 6DF : $z = 0.106$

Hence calculate $\chi^2_{\rm BAO}$

Hubble Space Telescope Data (HST)

Use nearby Type-Ia Supernova data with Cepheid calibrations to constrain the value of H_0 directly.
Combine and calculate χ^2 for the analysis of HST data

$$\chi^2_{\rm HST}(w_X^0, \Omega_m^0, H_0) = \sum_i \left[\frac{H_{\rm obs}(z_i) - H(z_i; w_X^0, \Omega_m^0, H_0)}{\sigma_i}\right]^2$$

Two methods of analysis

- Riess et. al. (2011)
- Efstathiou (2014)

Dark Energy from different datasets

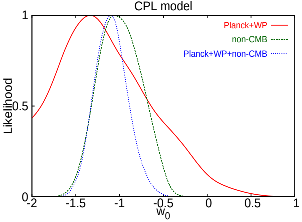
Hazra, Mazumdar, SP, Panda, Sen, PRD:2015

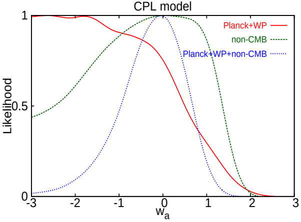
Used all three parametrizations $\Longrightarrow$ Analysis is robust

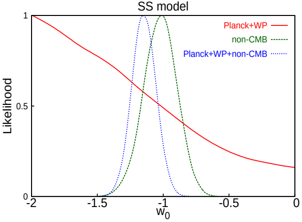
Data	ΛCDM	CPL	SS	GCG
Planck (low-ℓ + high-ℓ)	7789.0	7787.4	7788.1	7789.0
WMAP-9 low-ℓ polarization	2014.4	2014.436	2014.455	2014.383
BAO : SDSS DR7	0.410	0.073	0.265	0.451
BAO : SDSS DR9	0.826	0.793	0.677	0.777
BAO : 6DF	0.058	0.382	0.210	0.052
BAO : WiggleZ	0.020	0.069	0.033	0.019
SN : Union 2.1	545.127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

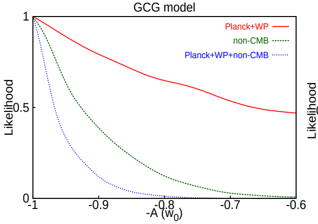
Best fit $\chi^2_{\rm eff}$ obtained in different model upon comparing against CMB + non-CMB datasets using the Powell's BOBYQA method of iterative minimization.

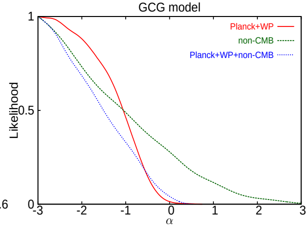
Likelihood functions for different parameters of EOS







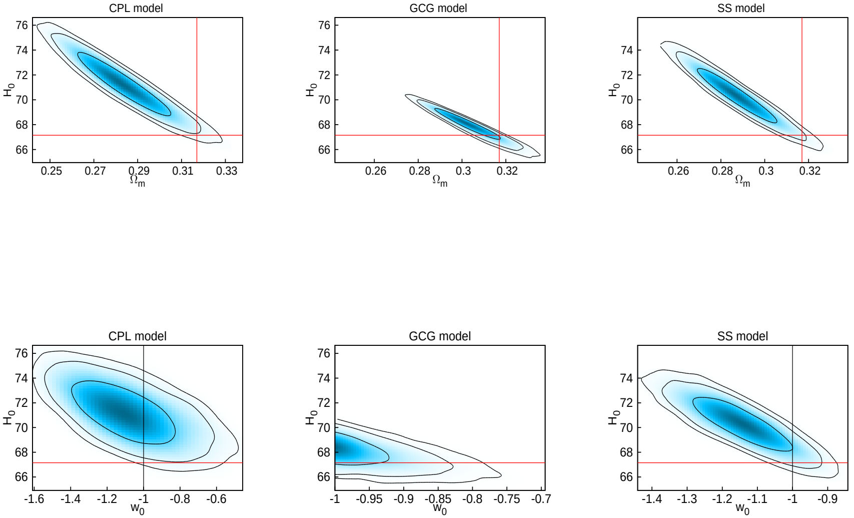




Mean value and 1σ range for CMB+non-CMB

		CPL	SS	GCG
$\Omega_b h^2$	CMB	0.0221 ± 0.00028	0.0221 ± 0.00026	0.022 ± 0.00028
	CMB + non-CMB	0.022 ± 0.00026	$0.0221^{+0.00026}_{-0.00024}$	0.0223 ± 0.00024
	Non-CMB	$0.027^{+0.004}_{-0.005}$	$0.028^{+0.004}_{-0.006}$	0.029 ± 0.005
$\Omega_{CDM} h^2$	CMB	0.1196 ± 0.0027	0.1198 ± 0.0026	$0.1199^{+0.0026}_{-0.0028}$
	CMB + non-CMB	0.1209 ± 0.0023	0.1192 ± 0.0018	0.117 ± 0.0015
	Non-CMB	$0.126^{+0.014}_{-0.017}$	$0.128^{+0.014}_{-0.018}$	$0.127^{+0.015}_{-0.018}$
100θ	CMB	1.041 ± 0.0006	1.041 ± 0.0006	1.041 ± 0.0006
	CMB + non-CMB	1.041 ± 0.0006	1.041 ± 0.00056	1.042 ± 0.00056
	Non-CMB	1.042 ± 0.023	1.048 ± 0.022	$1.05^{+0.019}_{-0.027}$
τ	CMB	$0.09^{+0.012}_{-0.014}$	$0.09^{+0.012}_{-0.015}$	$0.09^{+0.013}_{-0.014}$
	CMB + non-CMB	$0.087^{+0.012}_{-0.014}$	0.091 ± 0.013	0.094 ± 0.014
	Non-CMB	...	...	...
$w_0[-A]$	CMB	$-1.13^{+0.37}_{-0.66}$	$-1.31^{+0.19}_{\text{unbounded}}$	$-0.827^{+0.06}_{\text{non-phantom prior cut}}$
	CMB + non-CMB	$-1.005^{+0.15}_{-0.17}$	$-1.14^{+0.08}_{-0.09}$	$-0.957^{+0.007}_{\text{non-phantom prior cut}}$
	Non-CMB	$-0.995^{+0.23}_{-0.27}$	-1.02 ± 0.12	$-0.92^{+0.018}_{\text{non-phantom prior cut}}$
$w_a[\alpha]$	CMB	$-1.15^{+0.6}_{\text{unbounded}}$	...	$-1.97^{+0.32}_{\text{unbounded}}$
	CMB + non-CMB	$-0.48^{+0.77}_{-0.54}$	...	$-2.0^{+0.29}_{\text{unbounded}}$
	Non-CMB	$-0.5^{+1.64}_{-0.94}$	...	$-1.49^{+0.4}_{\text{unbounded}}$
n_S	CMB	0.9607 ± 0.007	0.9603 ± 0.007	$0.9603 \pm +0.00073$
	CMB + non-CMB	$0.9579^{+0.0063}_{-0.0066}$	$0.9619^{+0.0059}_{-0.0057}$	$0.9669^{+0.00056}_{-0.00059}$
	Non-CMB	...	...	...
$\ln[10^{10} A_S]$	CMB	$3.089^{+0.023}_{-0.027}$	$3.089^{+0.023}_{-0.028}$	3.09 ± 0.025
	CMB + non-CMB	$3.087^{+0.024}_{-0.026}$	3.091 ± 0.025	3.092 ± 0.026
	Non-CMB	...	...	...
Ω_m	CMB	$0.239^{+0.028}_{-0.099}$	$0.27^{+0.04}_{-0.1}$	$0.344^{+0.022}_{-0.032}$
	CMB + non-CMB	$0.291^{+0.011}_{-0.013}$	$0.288^{+0.012}_{-0.013}$	$0.304^{+0.009}_{-0.011}$
	Non-CMB	0.29 ± 0.024	$0.298^{+0.02}_{-0.026}$	$0.3^{+0.021}_{-0.024}$
H_0	CMB	$80^{+17.8}_{-7.8}$	$74.8^{+13.3}_{-9.8}$	$64.6^{+2.61}_{-1.91}$
	CMB + non-CMB	70.26 ± 1.4	70.3 ± 1.4	$67.9^{+0.9}_{-0.7}$
	Non-CMB	72.68 ± 2.2	72.67 ± 2.15	72.4 ± 2.16

Analysis: value of H_0



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  - The parameters stay close to the values obtained in ΛCDM model analysis.
  - H_0 is not that degenerate with dark energy equation of state for CMB.

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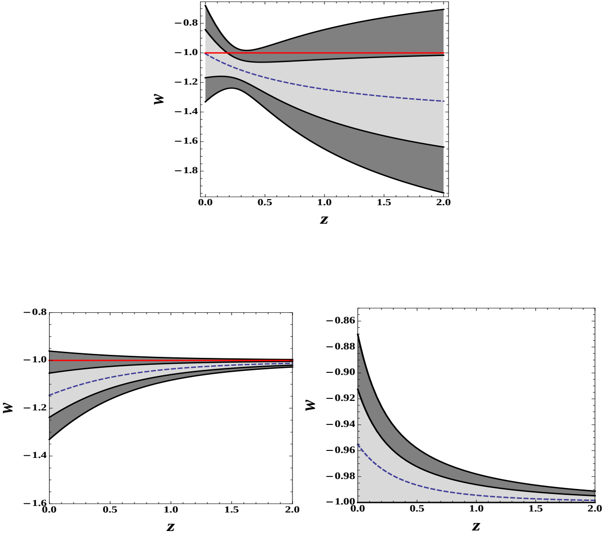
  - The parameters stay close to the values obtained in ΛCDM model analysis.
  - H_0 is not that degenerate with dark energy equation of state for CMB.
- If phantom is **NOT** forbidden by theoretical prior (CPL+SS):
  - Better fit to the CMB data comes with a large value of H_0 $\Rightarrow$ agrees better with the HST data (better total χ^2)
  - But background cosmological parameter space (e.g., $\Omega_{\rm m} - H_0$) is dragged s.t. best-fit base model and that from Planck becomes 2σ away.
  - H_0 becomes highly degenerate with dark energy EOS for CMB only measurements.

Analysis: Equation of State



Top: CPL, Bottom left: SS, Bottom right: GCG

- If phantom is forbidden by theoretical prior (GCG):
  - Show consistency between CMB and non-CMB data
  - But they have marginally worse likelihood than other parametrizations.
  - CMB and non-CMB observations are separately sensitive to the two model parameters but the joint constraint is consistent with $w = -1$.

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    - CMB and non-CMB observations are separately sensitive to the two model parameters but the joint constraint is consistent with $w = -1$.
- If phantom is **NOT** forbidden by theoretical prior (CPL+SS):
    - CMB data: the non-phantom equation of states stays at the edge of 2σ region.
    - Non-CMB data: non-phantom behavior favored for every parametrization considered.

What can we say from CMB and non-CMB observations?

- Constraints on w and hence the nature of dark energy that we infer from CMB and non-CMB observation depends on the choice of parametrization of the EOS.

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- Can it be due to lack of better understanding of dark energy EOS, i.e., non-availability of data at high redshift?

  Yes, in all probability

Some more analyses

- Parallel analysis : For dataset Planck13(WMAP9)+ HST+BAO+SNLS3 ΛCDM is outside 2σ (1σ) confidence regime, give similar results.

  Durrer et.al., JCAP:2013

- Alternative analysis : Discripancy attributed to the mismatch of value of H_0 due to degeneracy with other parameters ($\Delta N_{\rm eff}, r_s, Y_{\rm BBN} \ldots$)

  Riess et.al., JCAP:2016

- Even low-redshift PAN-STARRS1 data show tension with ΛCDM at 2.4σ with a constant EOS

  Rest et.al., ApJ:2013

Need more probes and more data at high redshifts

Possible probes

- Weak lensing
- Galaxy clusters
- Gamma ray bursts
- X-ray observations
- Growth factor
- Dark Energy perturbations
- Interacting dark sectors
- 21 cm observations (SKA)
- Cosmic shear and sound speed (TMT)
- ....

Take-home message: Dark Energy

What do we know about dark energy till now?

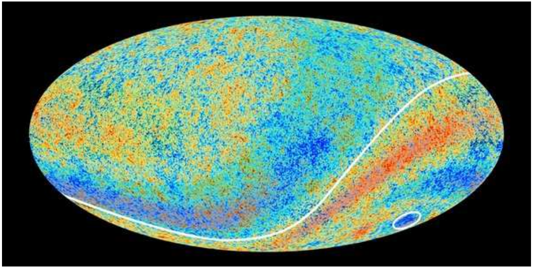
Constraints on w are different for different observations and parametrizations

We need more probes and more data at high redshifts

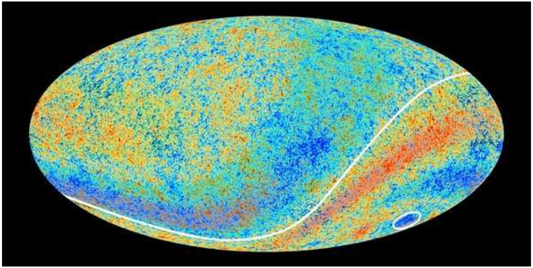
New avenues

- Hemispherical asymmetry
- Delensing techniques
- Primordial non-Gaussianity
- CMB spectral distortions
- Primordial magnetic fields
- Dark Energy perturbations and ISW
- .....

Hemispherical asymmetry



Hemispherical asymmetry



- Modifications to inflation? (Carroll, PRD:2008; Qureshi, 1610.05776)
- Earlier universe preceding Big Bang? (Efstathiou,)
- Undiscovered source in solar system? (Yoho, PRD:2011)
- Intrinsic anisotropy? (Souradeep et. al., JCAP:2016)

A nice review by Huterer, 1004.5602

Lensing

Effects of lensing

- Broadening of peaks
- Non-Gaussianity

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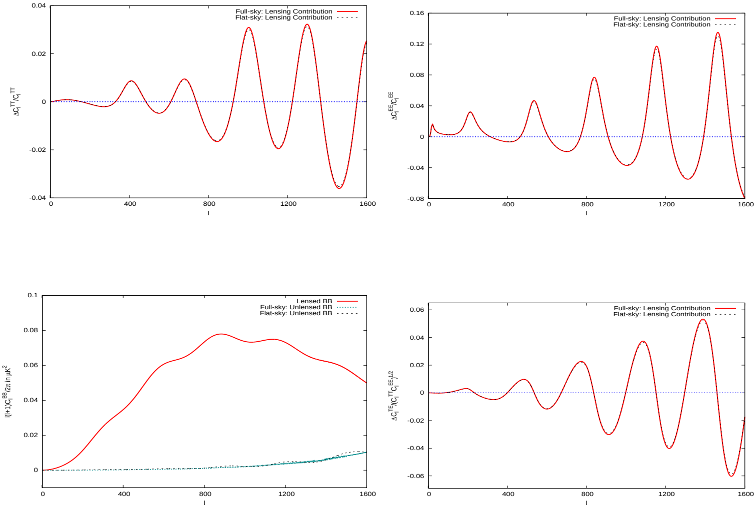
To do

- Propose delensing techniques
- Check if better result than CAMB
- Estimate unlensed parameters afresh

Delensing using matrix inversion technique

Pal, Padmanabhan, SP, MNRAS:2014



Fractional difference between lensed and unlensed power spectra

Non-Gaussianity

Perturbations mostly Gaussian, described by 2-PCF

If (small) non-Gaussianities are present $\longrightarrow$ reflected via B modes

3- and 4-PCF $\Rightarrow$ bispectrum f_{NL} & trispectrum g_{NL}, τ_{NL}

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Why important?

- Maldacena limit $\Rightarrow$ single field ($|f_{NL}| < 1$) vs multifield ($|f_{NL}| > 5$)
- B modes = GW + NG + lensing $\Rightarrow$ Need to separate out NG for correct estimate of GW
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Planck 2015 bounds

NG Parameters	Planck2015 TT	Planck2015 TT+low P
$f_{\rm NL}^{\rm loc}$	2.5 ± 5.7	0.8 ± 5.0
$f_{\rm NL}^{\rm eq}$	-16 ± 70	-4 ± 43
$f_{\rm NL}^{\rm ortho}$	-34 ± 33	-26 ± 21

Final take-home message

The point is not to pocket the truth but to chase it. – Elio Vittorini