A theorist's take-home message from CMB

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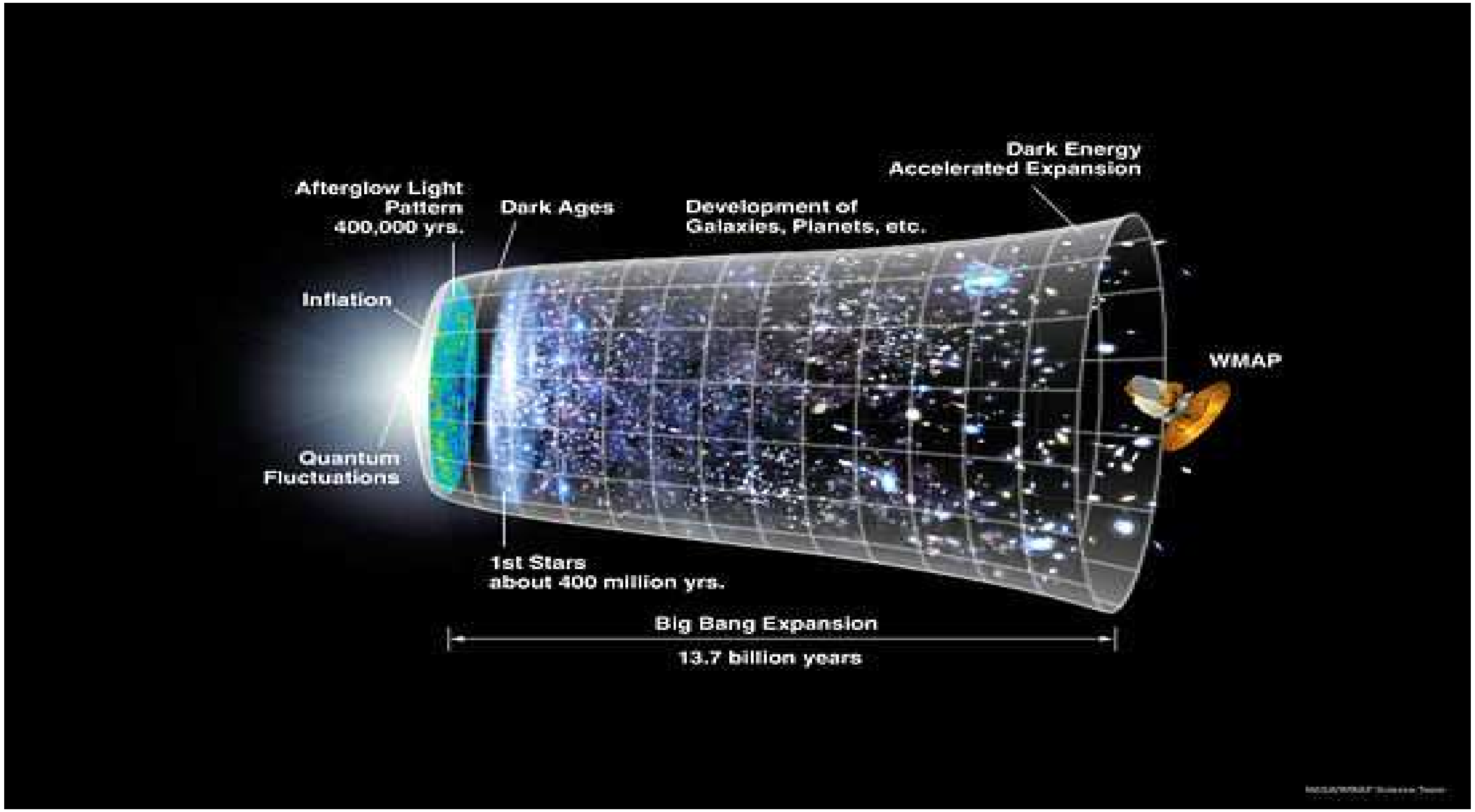
Outline

- CMB à la WMAP and Planck
- Inflation
- Dark energy
- New horizons

A cosmologist's wishlist

To explain...



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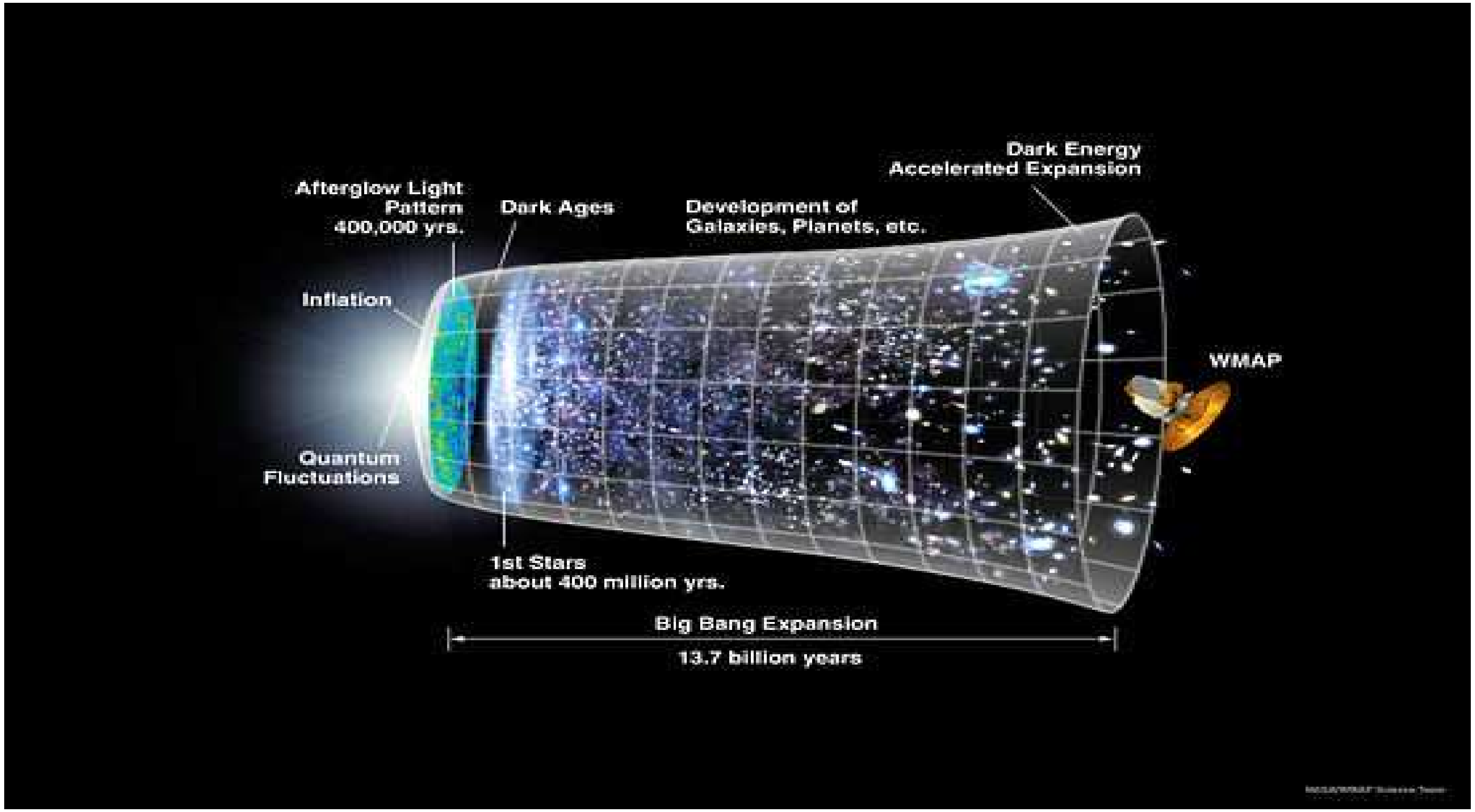
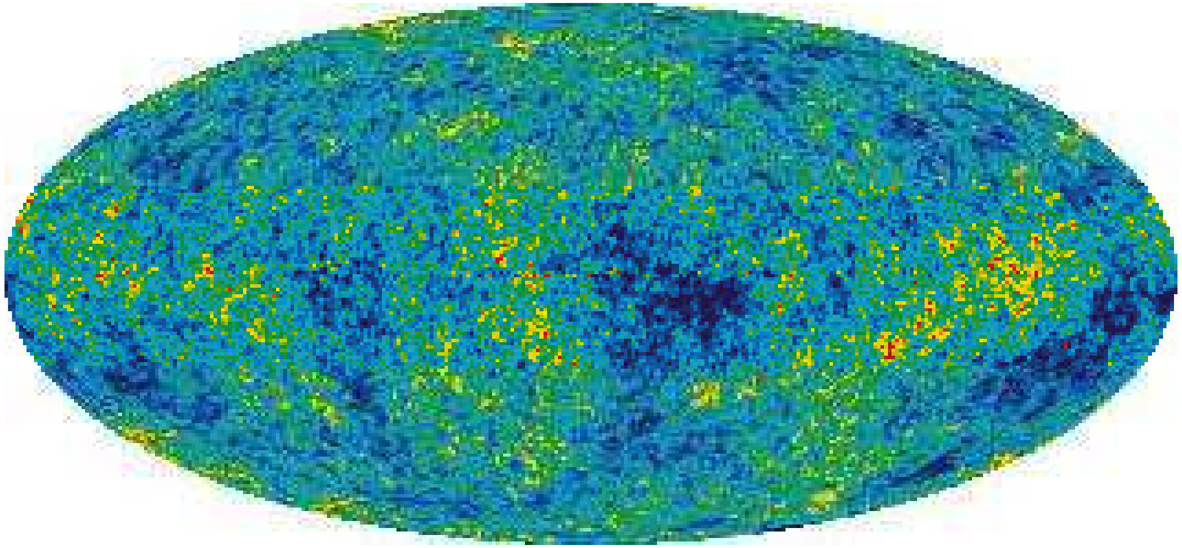


...uniquely !

The CMB sky



CMB temperature $T_0 = 2.725K$ at all directions

$\Rightarrow$ The Universe is homogeneous and isotropic at largest scale

How many parameters to describe the Universe? $\longrightarrow$ 6 (or 7?)

J von Neumann: “With four parameters I can fit an elephant and with five I can make him wiggle his trunk” :)

Are these 6 (or 7) parameters a bit too many?

All about CMB temperature

Happenings at CMB: Anisotropy, Polarization, Distortion

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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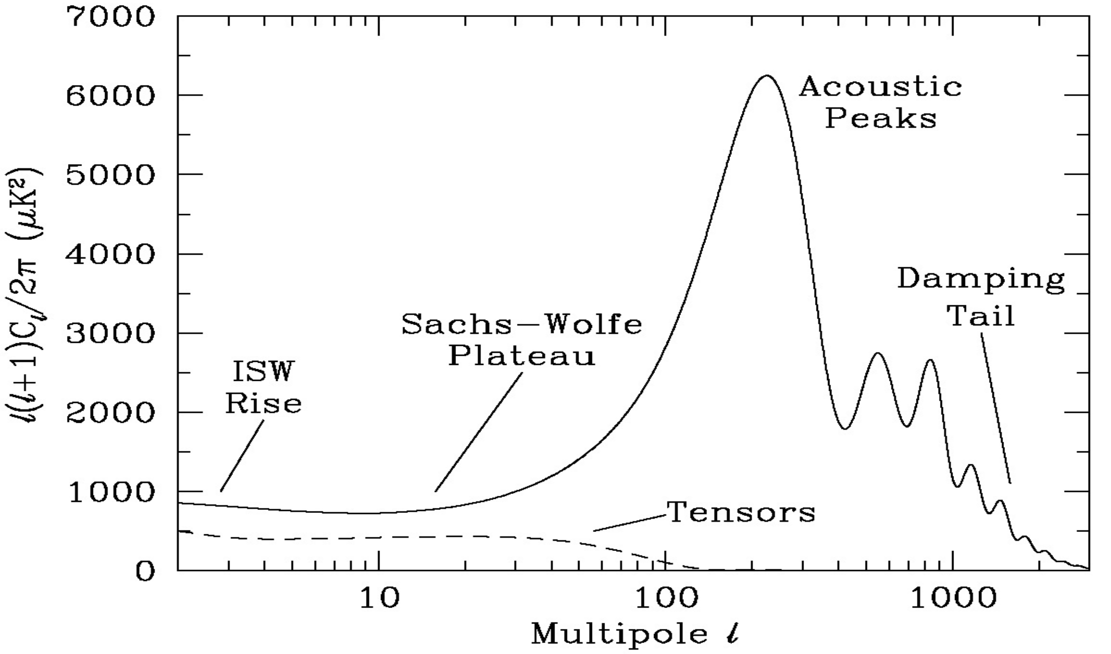
Temperature anisotropy T + two polarization modes E & B $\Rightarrow$ Four CMB spectra: $C_l^{TT}, C_l^{EE}, C_l^{BB}, C_l^{TE}$

Parity violation/systematics $\Rightarrow$ Two more spectra: C_l^{TB}, C_l^{EB}

How to decode information?

$\Delta T(n) = \sum a_{lm} Y_{lm}(n) \Rightarrow$ 2-point correlation fn. $C_l = \frac{1}{2l+1} \sum |a_{lm}|^2$

$$C_l = \int \frac{dk}{k} P_R(k) T_l^2(k)$$



Peak positions, heights and ratios give cosmological parameters $\Rightarrow$ imprints of both early universe and late universe

Cosmological parameters from C_l

Fundamental/ fit parameters

$\Omega_b h^2$ = baryonic matter density

$\Omega_c h^2$ = dark matter density

Ω_X = dark energy density

P_R = primordial scalar power spectrum

n_s = scalar spectral index

τ = optical depth

r = tensor-to-scalar ratio

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

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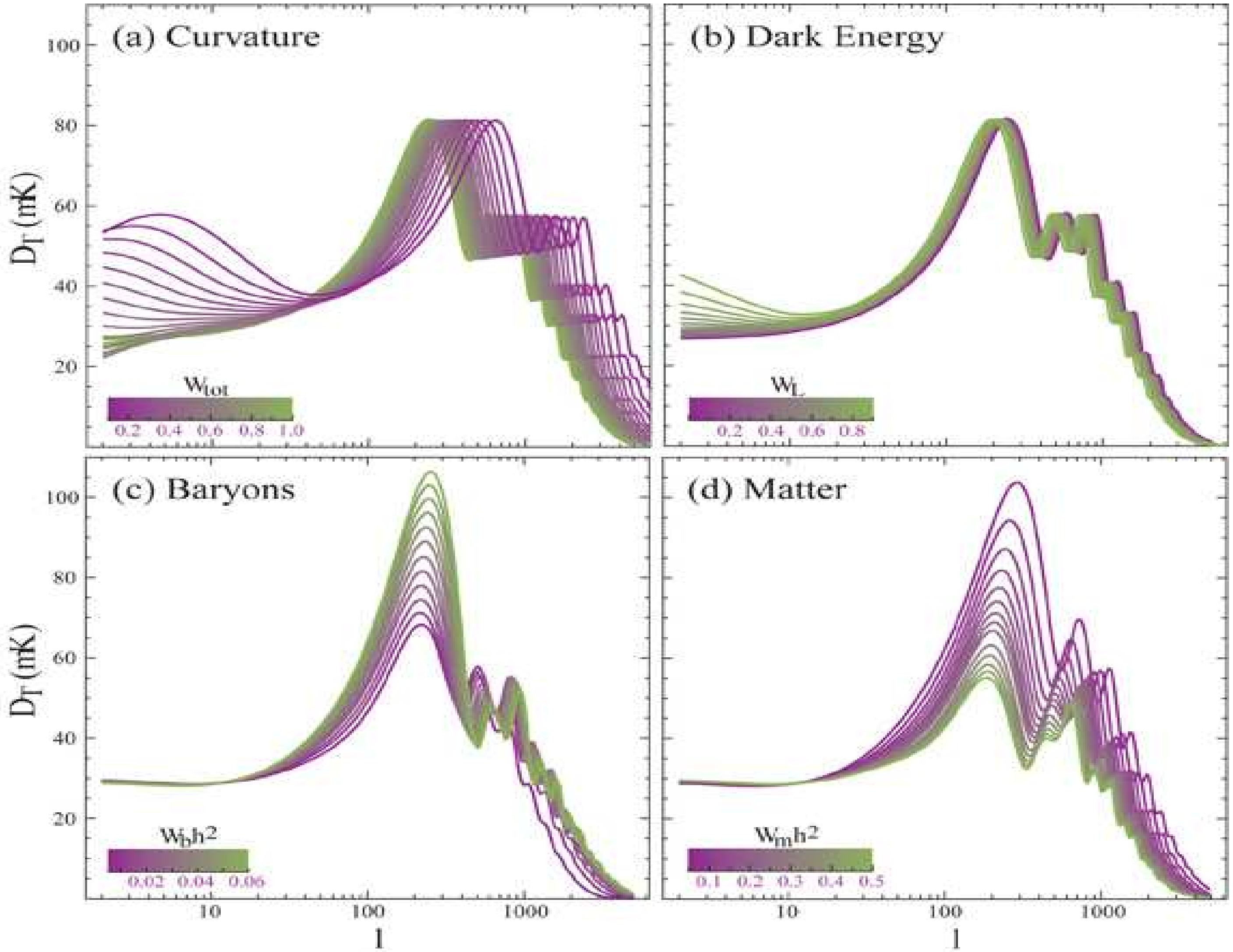
Derived parameters

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

Best fit parameters	WMAP 9	Planck
P_R	$(2.464 \pm 0.072) \times 10^{-9}$	$(2.196^{+0.051}_{-0.060}) \times 10^{-9}$
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
Ω_b	0.04628 ± 0.00093	
Ω_c	$0.2402^{+0.0088}_{-0.0087}$	$\Omega_b + \Omega_c = 0.315 \pm 0.017$
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?



Inflation from CMB

Lagrangian density $\mathcal{L}_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

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

Choose the potential to be sufficiently steep so that $V^{''}V/V^{'2} \geq 1$

Scalar field rolls down the potential : “Tracker potential”

Governing equations

$$H^2 \simeq \frac{8\pi}{3M_P^2}V(\phi)$$

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

Guth; Linde; Starobinsky; Liddle; Lyth; Sahni...

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- Harrison-Zeldovich spectrum $P_R(k) \simeq P_R(k_0)(\frac{k}{k_0})^{n_s-1}$

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- $(n_s - 1) =$ small $\Rightarrow$ nearly scale invariant power spectrum

  $(n_s - 1) \propto \frac{dV}{d\phi}, \frac{d^2V}{d\phi^2} \neq 0 \Rightarrow V(\phi)$ slowly varying (quasi-dS)

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- Modified spectrum $P_R(k) \simeq P_R(k_0)(\frac{k}{k_0})^{n_s-1+n_s' \ln(k/k_s)}$

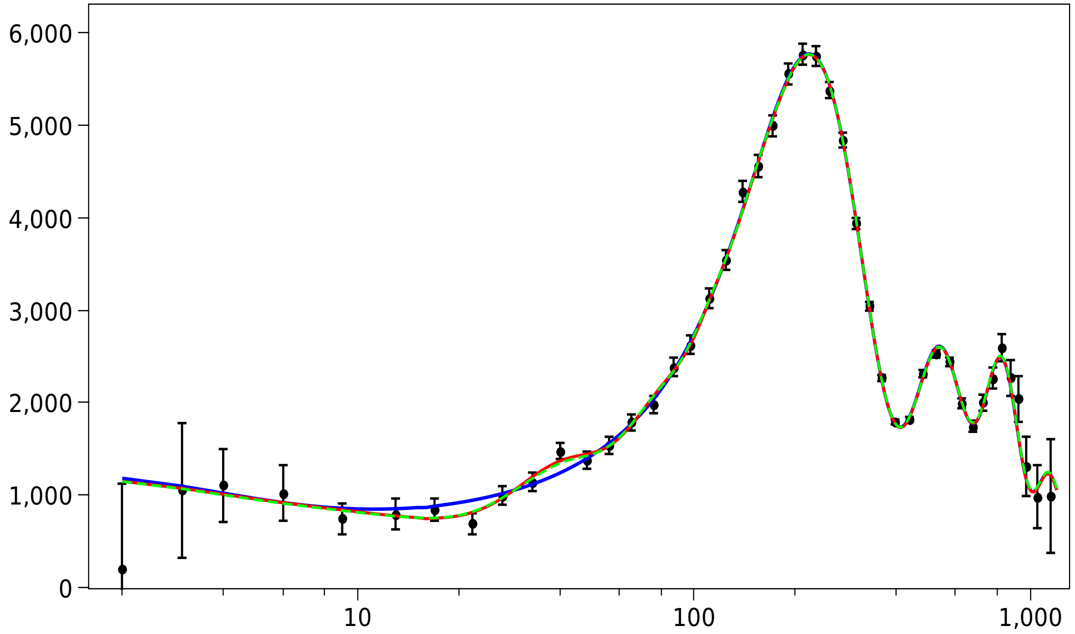
  $n_s' \neq 0 \Rightarrow$ deviation from power law / scale invariance

- Matches almost all the points for different l

  But outliners at $l = 22, 40 \Rightarrow$ step function? lensing? new physics??

  e.g.: Step function $V(\phi) \longrightarrow V(\phi)\left[1 + \alpha \tanh \frac{\phi - \phi_0}{\Delta\phi}\right]$

Souradeep, JCAP:2010



Gravitational waves

A small fraction of the CMB photons get polarized due to quadrupole anisotropies. Generates 2 polarization modes (E & B)

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

Detection of gravitational waves have direct reflection on energy scale of inflation (hence on fundamental physics)

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> Feb 2014: $r \sim 0.2 \Rightarrow$ energy scale of inflation $\sim 10^{16}$ GeV

Controversy not yet settled. If confirmed, a direct proof of inflation.

Inflationary models (confronted with WMAP7)

Choudhury, SP, PRD:2012, JCAP:2012, NPB:2013
Pal, SP, Basu, JCAP:2010, JCAP:2012

Field equations are different for different cases!

Brane

$$V(\phi) = V_0\left[1 + \left(D_4 + K_4 \ln\left(\frac{\phi}{M}\right)\right)\left(\frac{\phi}{M}\right)^4\right]$$

$$1.234 < 10^9 P_S < 3.126 \;\; ; \;\; 0.936 < n_S < 0.951$$

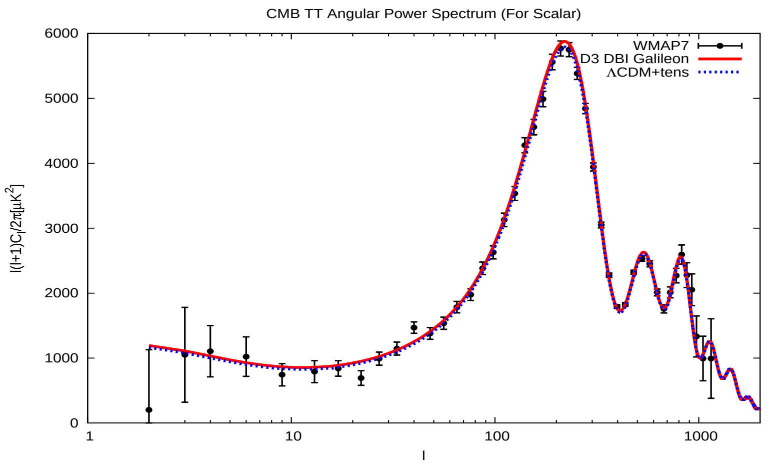
$$2.176 < 10^5 r < 4.723 \;\; ; \;\; -0.798 < 10^3 \alpha_S < -1.345$$

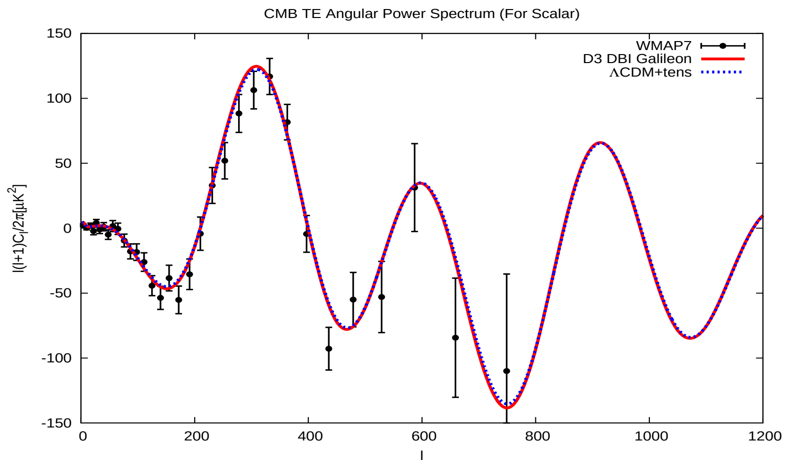
Galileon

$$V(\phi) = \sum_{m=-2(\neq -1)}^{2} C_{2m}\left[1 + D_{2m} \ln\left(\frac{\phi}{M}\right)\right]\phi^{2m}$$

$$2.401 < 10^9 P_S < 2.601 \;\; ; \;\; 0.964 < n_S < 0.966$$

$$0.215 < r < 0.242 \;\; ; \;\; -2.240 < 10^3 \alpha_S < -2.249$$


CMB TT Angular Power Spectrum (For Scalar)
WMAP7
D3 DBI Galileon
ΛCDM+tens
l(l+1)C_l/2π[μK^2]
l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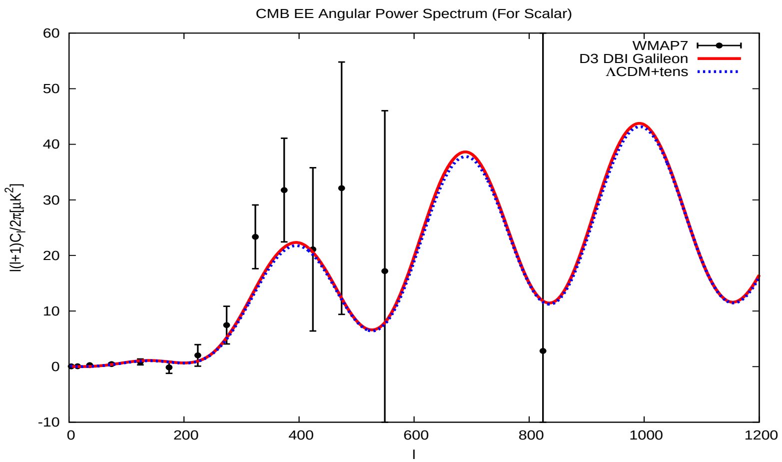
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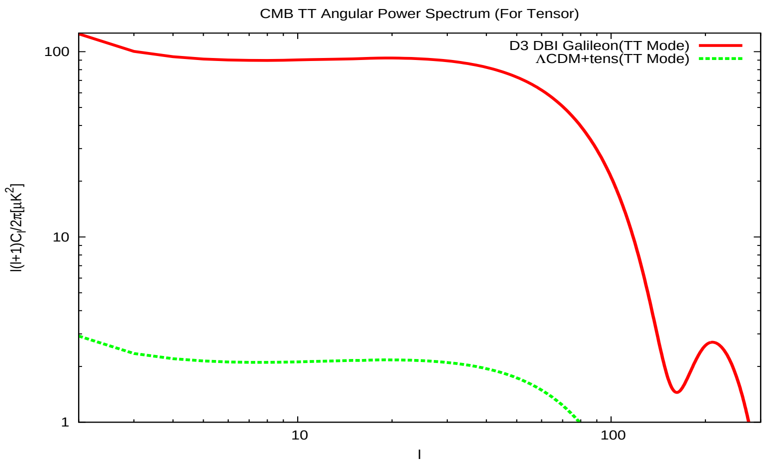
CMB TT Angular Power Spectrum (For Tensor)
D3 DBI Galileon(TT Mode)
ΛCDM+tens(TT Mode)
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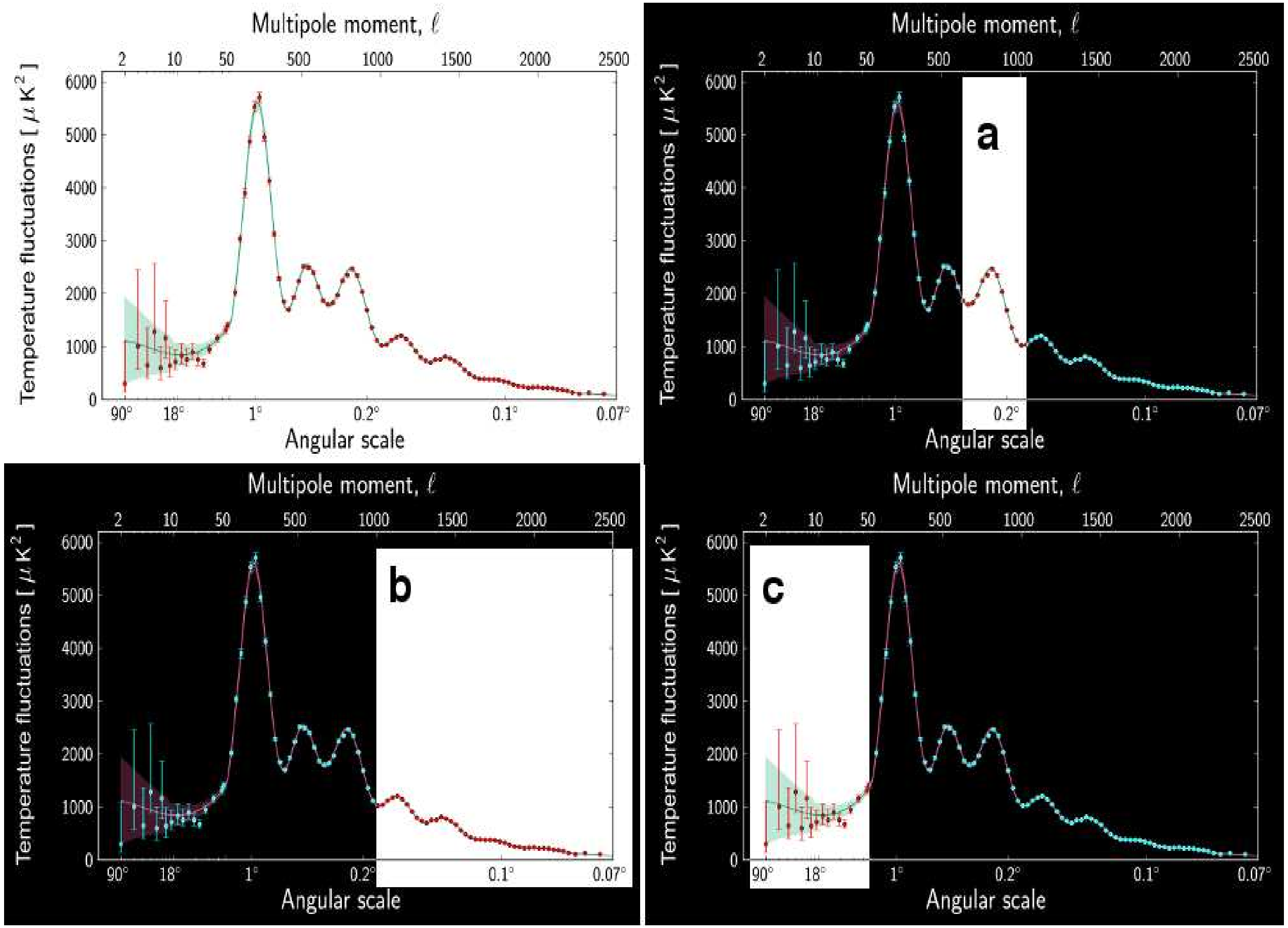
l

Planck highlights



Francis, 2013

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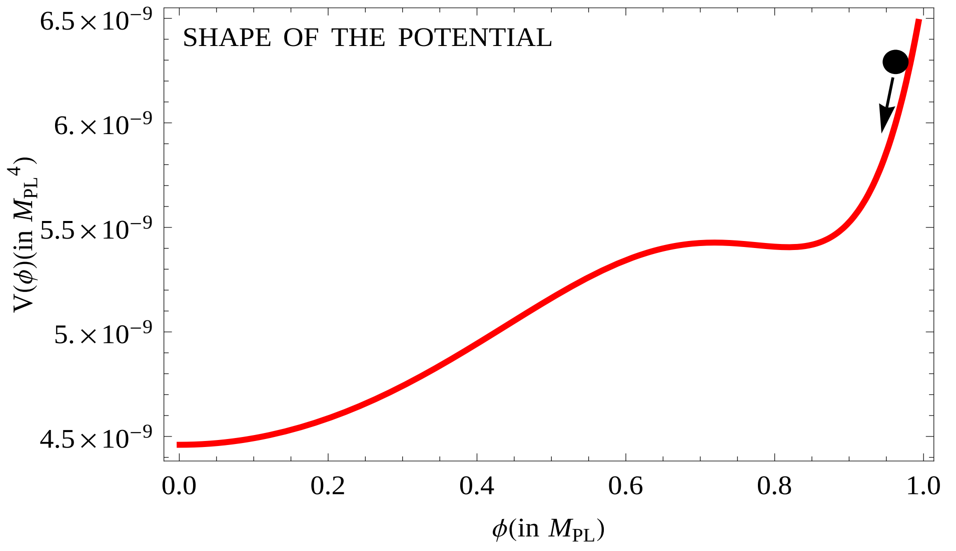
- $r < 0.11 \Rightarrow$ GW yet undetected
- Outliners are still there $\Rightarrow$ physical origin, not from systematics
- Large scale anomalies : 10% deficit of signal, hemispherical asymmetry
- Big cold spot $\Rightarrow$ superstructure?

Modeling inflation in the light of Planck

Choudhury, Majumdar, SP, JCAP(2013)

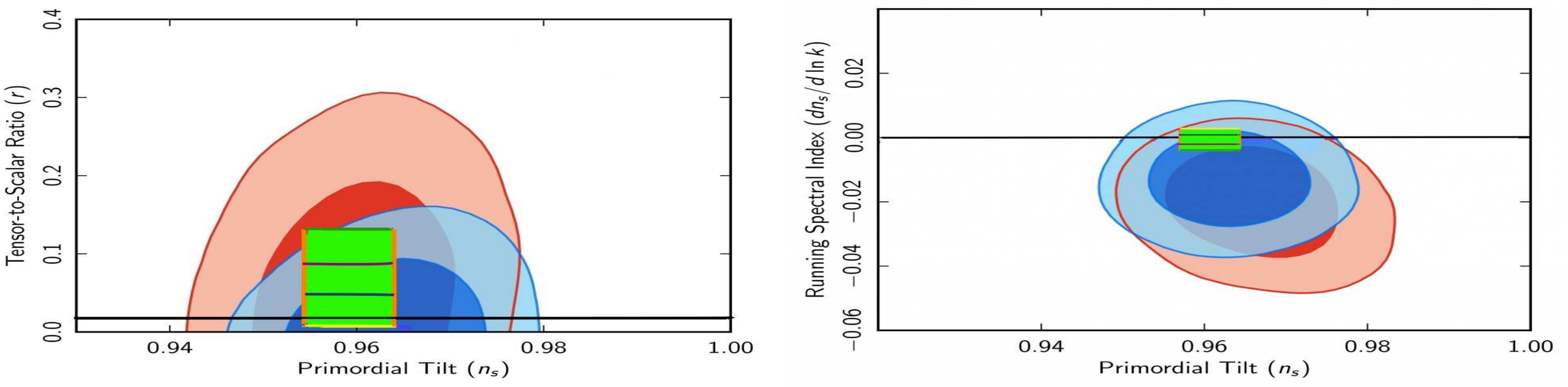
Inflection point inflation from MSSM

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

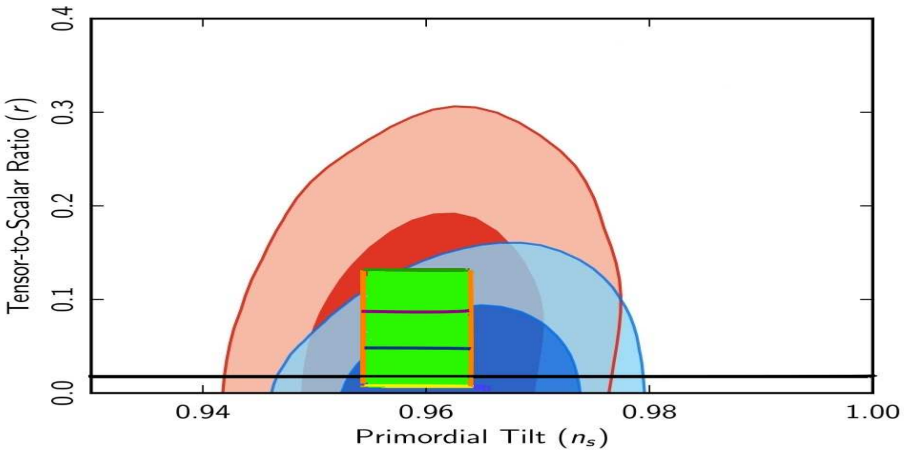


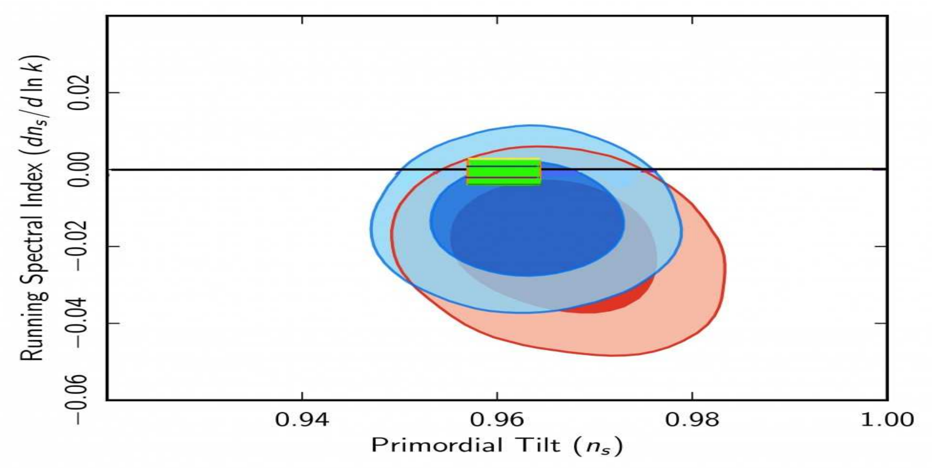
$$2.092 < 10^9 P_S < 2.297 \;\; ; \;\; 0.958 < n_S < 0.963$$

$$r < 0.12 \;\; ; \;\; -0.0098 < \alpha_S < 0.0003$$



Planck+WMAP9+BAO: Blue: ΛCDM+$r(\alpha_S)$, Red: ΛCDM+$r + \alpha_S$





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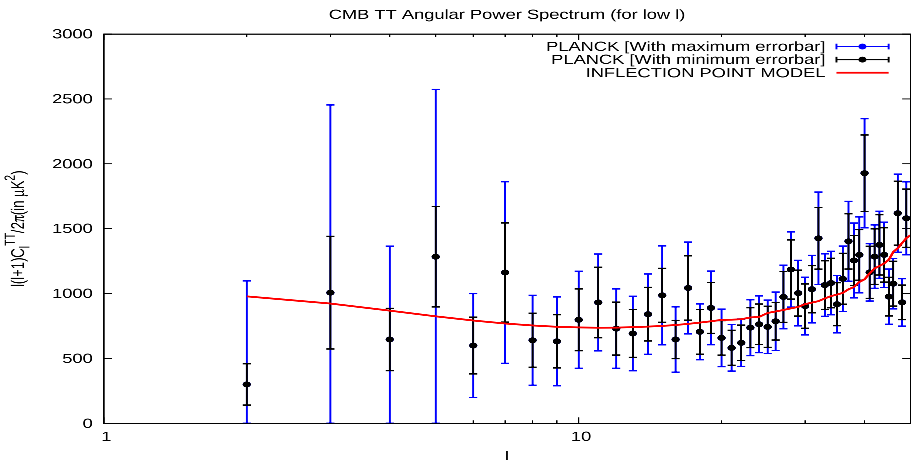

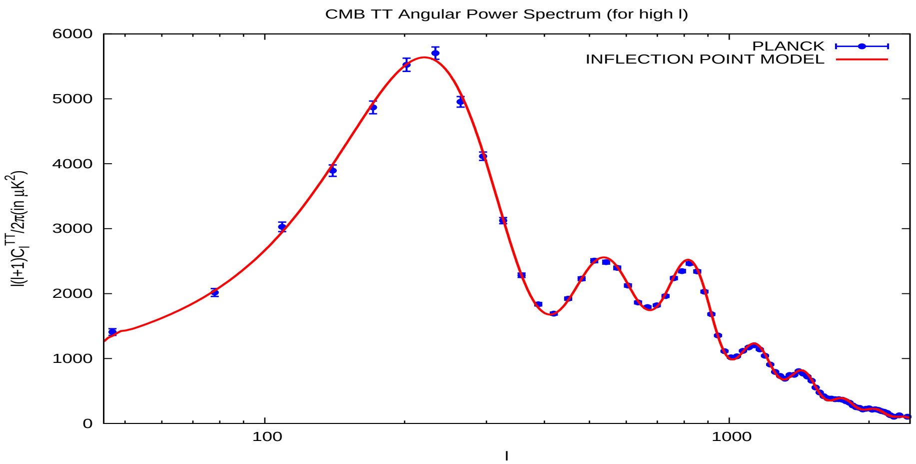

Good fit with Planck for both low and high l

Dark energy from CMB

Cosmological constant

$\rho_\Lambda =$ const.

$p_\Lambda = -\rho_\Lambda$

$\delta\rho_\Lambda = 0$

Dark energy

$\rho_X \propto \exp\left(3\int_0^z \frac{1+\omega(z)}{1+z}dz\right)$

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Reflections in CMB

- CMB shift parameter (position of peaks)
- Integrated Sachs-Wolfe effect

Shift Parameter

DE $\Leftrightarrow$ Shift in position of peaks by $\sqrt{\Omega_m}D$

D= Angular diameter distance (to LSS) $\Rightarrow$ Shift Parameter

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

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

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

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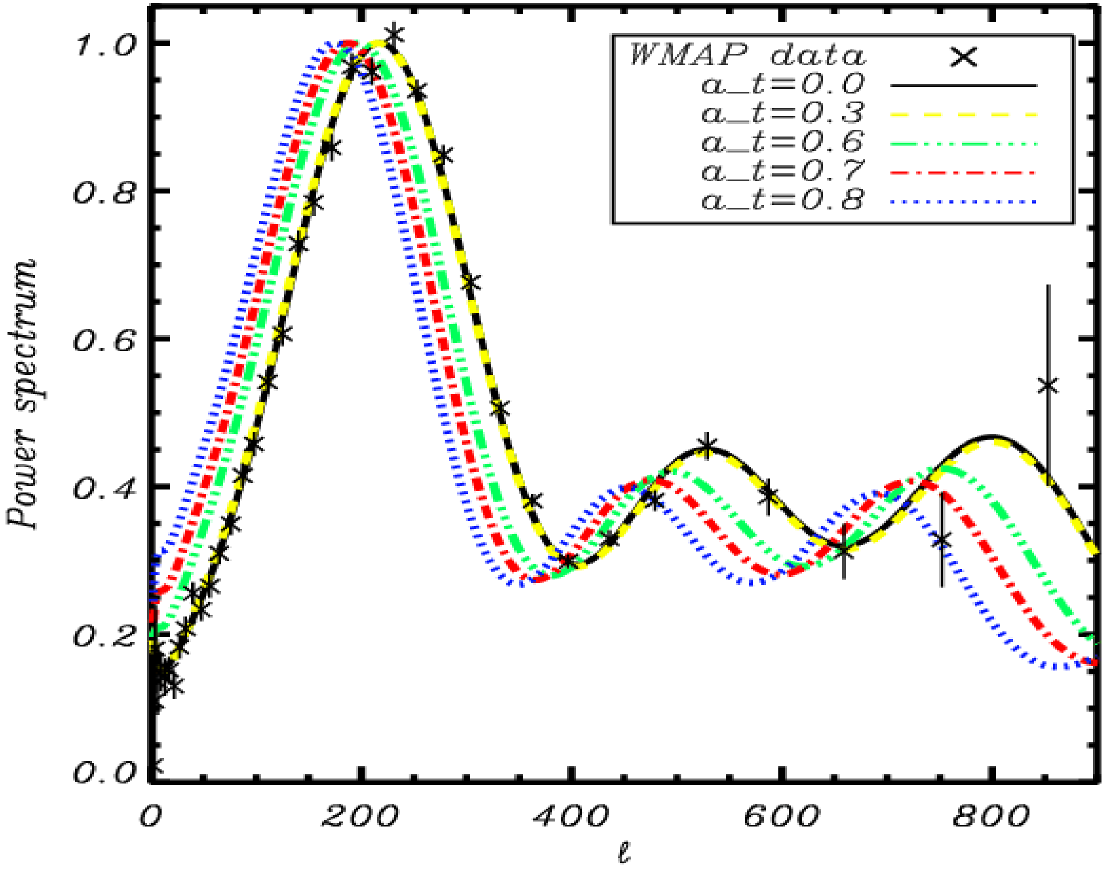
Hence, for $k = 0$

$$\boxed{R = \sqrt{\Omega_m H_0^2} \int_o^{z_{\rm dec}} \frac{dz}{H(z)}}$$

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

+ low z results (SNIa, BAO, OHD...) and find combined $\chi^2 = \sum \chi_i^2$

DE ⇒ change in angular diameter distance and shift parameter



Is CMB constraint on shift parameter model independent?

Model	R	l_a
ΛCDM	1.707 ± 0.025	302.3 ± 1.1
wCDM ($c^2_{DE} = 1$)	1.710 ± 0.029	302.3 ± 1.1
wCDM ($c^2_{DE} = 0$)	1.711 ± 0.025	302.4 ± 1.1
ΛCDM $m_\nu > 0$	1.769 ± 0.040	306.7 ± 2.1
ΛCDM $N_{eff} \neq 3$	1.714 ± 0.025	304.4 ± 2.5
ΛCDM $\Omega_k \neq 0$	1.714 ± 0.024	302.5 ± 1.1
$w(z)$CDM CPL ($c^2_{DE} = 1$)	1.710 ± 0.026	302.5 ± 1.1
ΛCDM $+$ tensor	1.670 ± 0.036	302.0 ± 1.2
ΛCDM $+$ running	1.742 ± 0.032	302.8 ± 1.1
ΛCDM $+$ running $+$ tensor	1.708 ± 0.039	302.8 ± 1.2
ΛCDM $+$ features	1.708 ± 0.028	302.2 ± 1.1

Melchiorri, PRD:2008

Integrated Sachs-Wolfe Effect

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

- linear regime: integrated Sachs-Wolfe effect
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Poisson equation $\nabla^2\Phi = 4\pi G a^2 \bar{\rho}\delta$

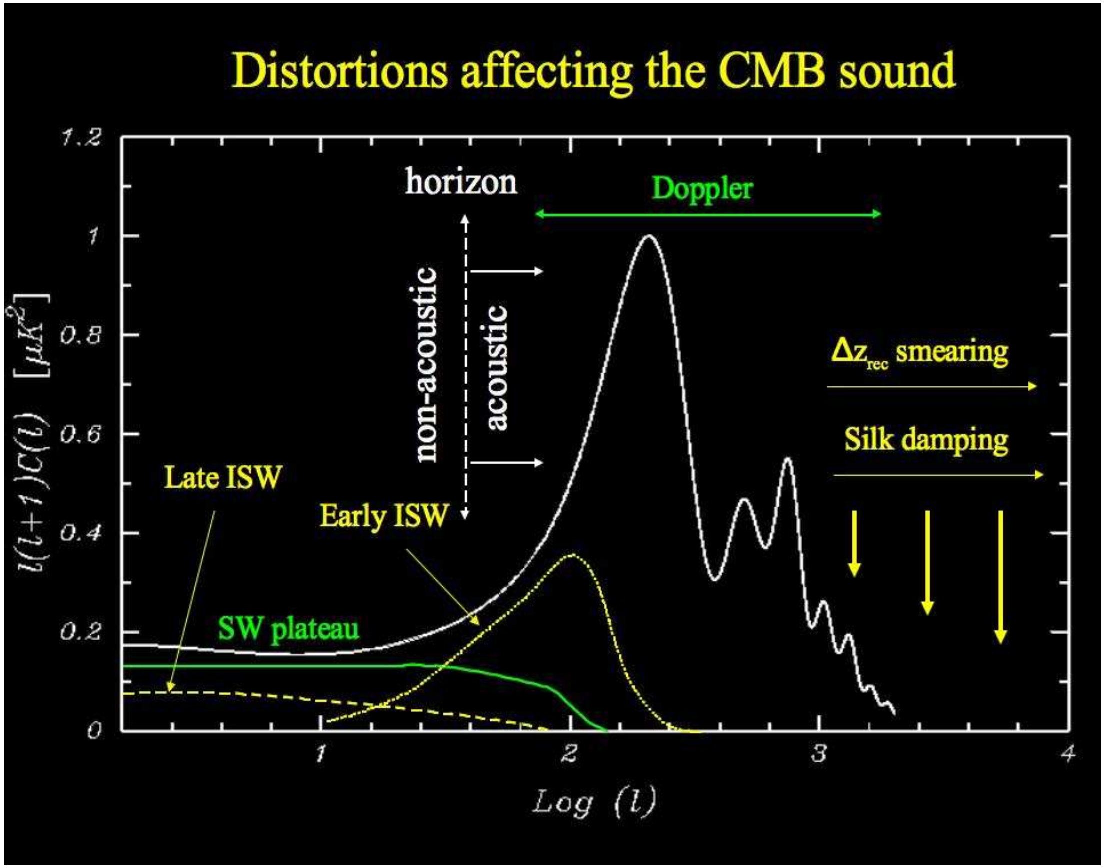
$\Phi \rightarrow$ constant during matter domination

$\rightarrow$ time-varying when dark energy comes to dominate

(at large scales $l \leq 20$)

$$C_l = \int \frac{dk}{k} P_R(k) T_l^2(k)$$

$$\boxed{T_l^{\rm ISW}(k) = 2\int d\eta \exp^{-\tau} \frac{d\Phi}{d\eta} j_l(k(\eta-\eta_0))}$$



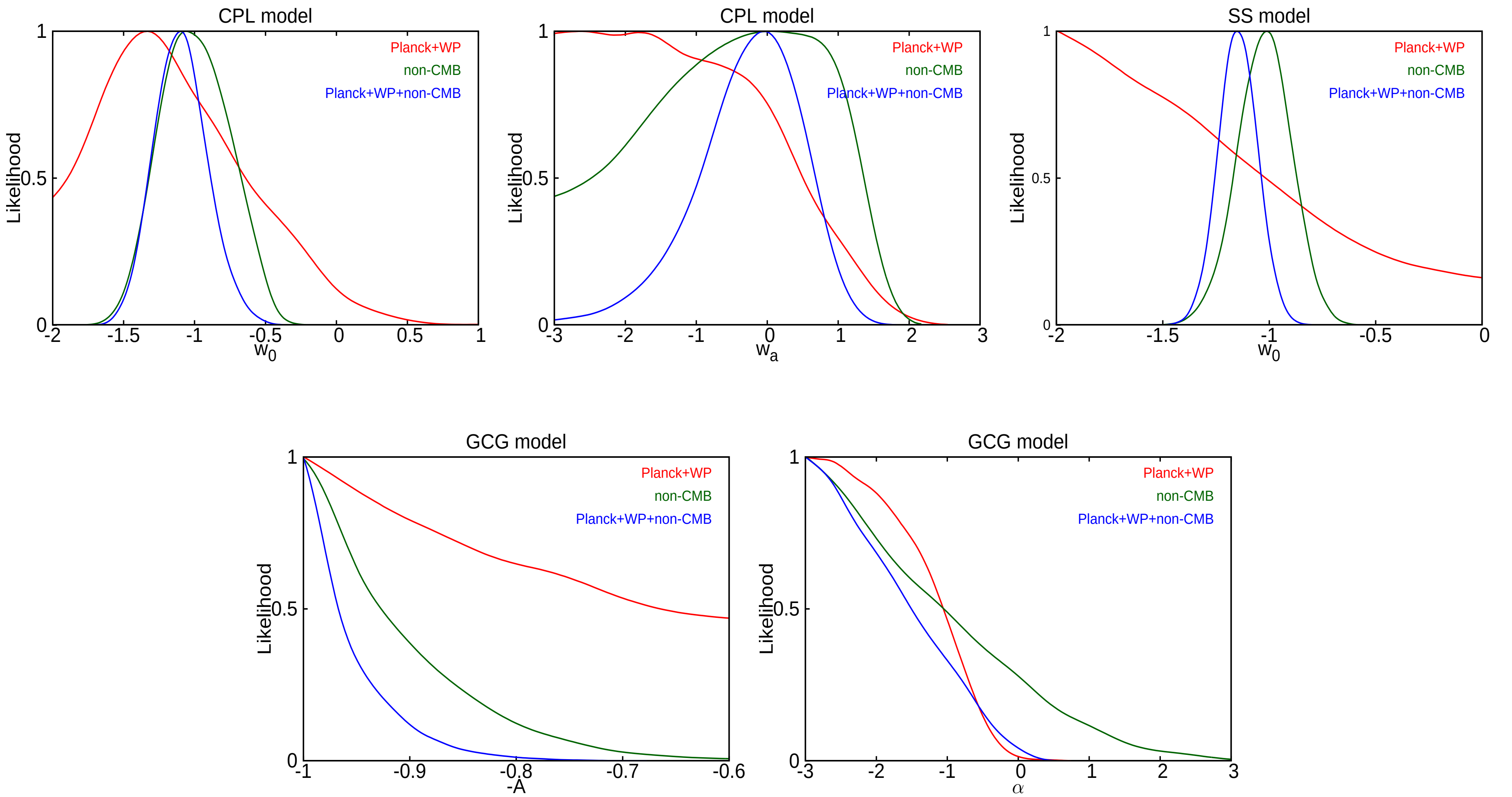
But... Huge error bars! Perturbations in dark energy can remove degeneracy.

Dark energy in the light of Planck

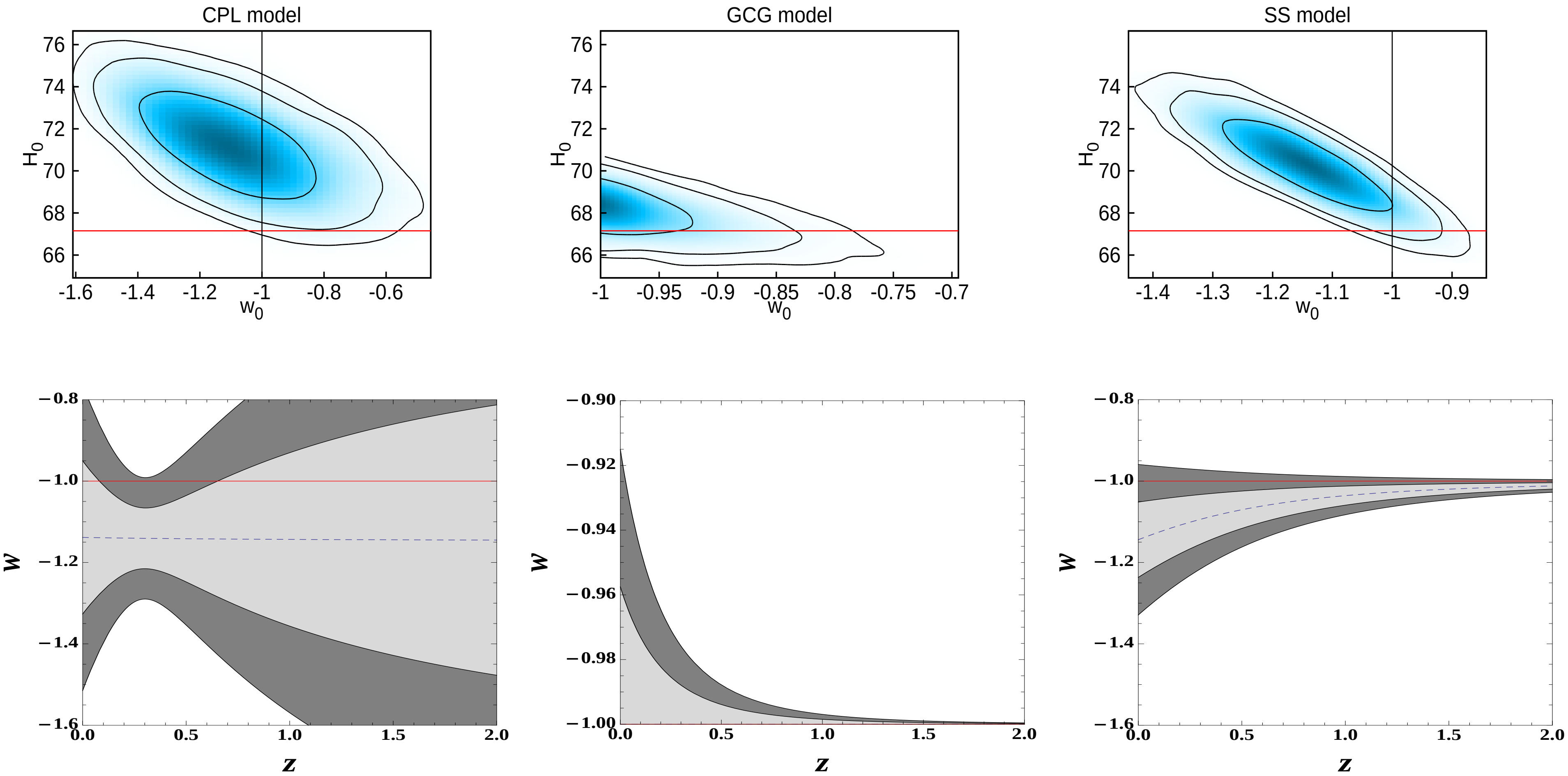
Hazra,... SP,..., 1310.6161

Used 3 different parametrizations: CPL, SS, GCG $\Rightarrow$ Analysis is robust

	CPL	SS	GCG
$w_0/(-A)$	$-1.09^{+0.168}_{-0.206}$	$-1.14^{+0.08}_{-0.09}$	$-0.957^{+0.007}_{-0.043}$
w_a/α	$-0.27^{+0.86}_{-0.56}$	-	$-2.0^{+0.29}_{\text{unbounded}}$
Ω_m	$0.284^{+0.013}_{-0.015}$	$0.288^{+0.012}_{-0.013}$	$0.304^{+0.009}_{-0.011}$
H_0	$71.2^{+1.6}_{-1.7}$	$70.3^{+1.4}_{-1.4}$	$67.9^{+0.9}_{-0.7}$



Likelihood functions for different parameters of EOS



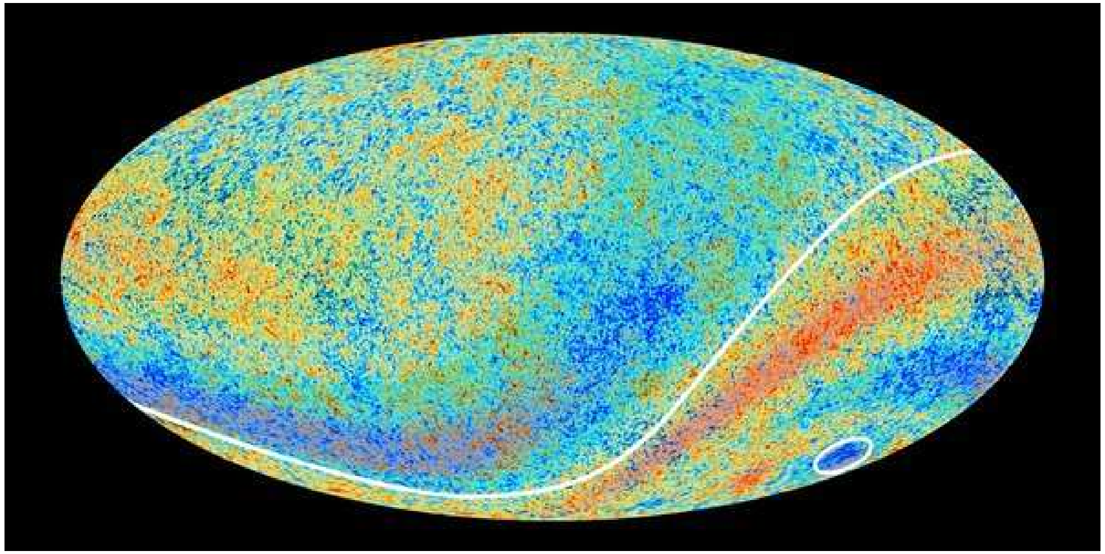
Planck shows tension with Λ at 1-σ

PanSTARRS rules out Λ at $2.4\sigma \leftrightarrow$ low z result (Rest, 1310.3828)

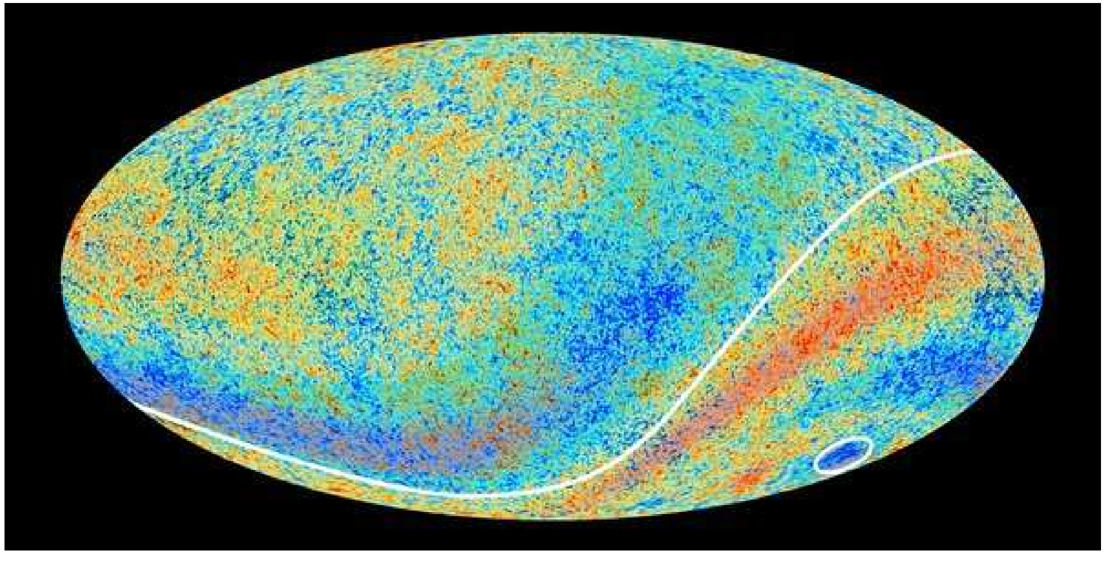
New horizons

- Large scale anomalies
- Lensing
- Non-Gaussianity
- Magnetic field

Large scale anomalies



Large scale anomalies



- Modifications to inflation? (Carroll, PRD:2008)
- Earlier universe preceding Big Bang? (Efstathiou,)
- Undiscovered source in solar system? (Yoho, PRD:2011)

A nice review by Huterer, 1004.5602

Lensing

Effects of lensing

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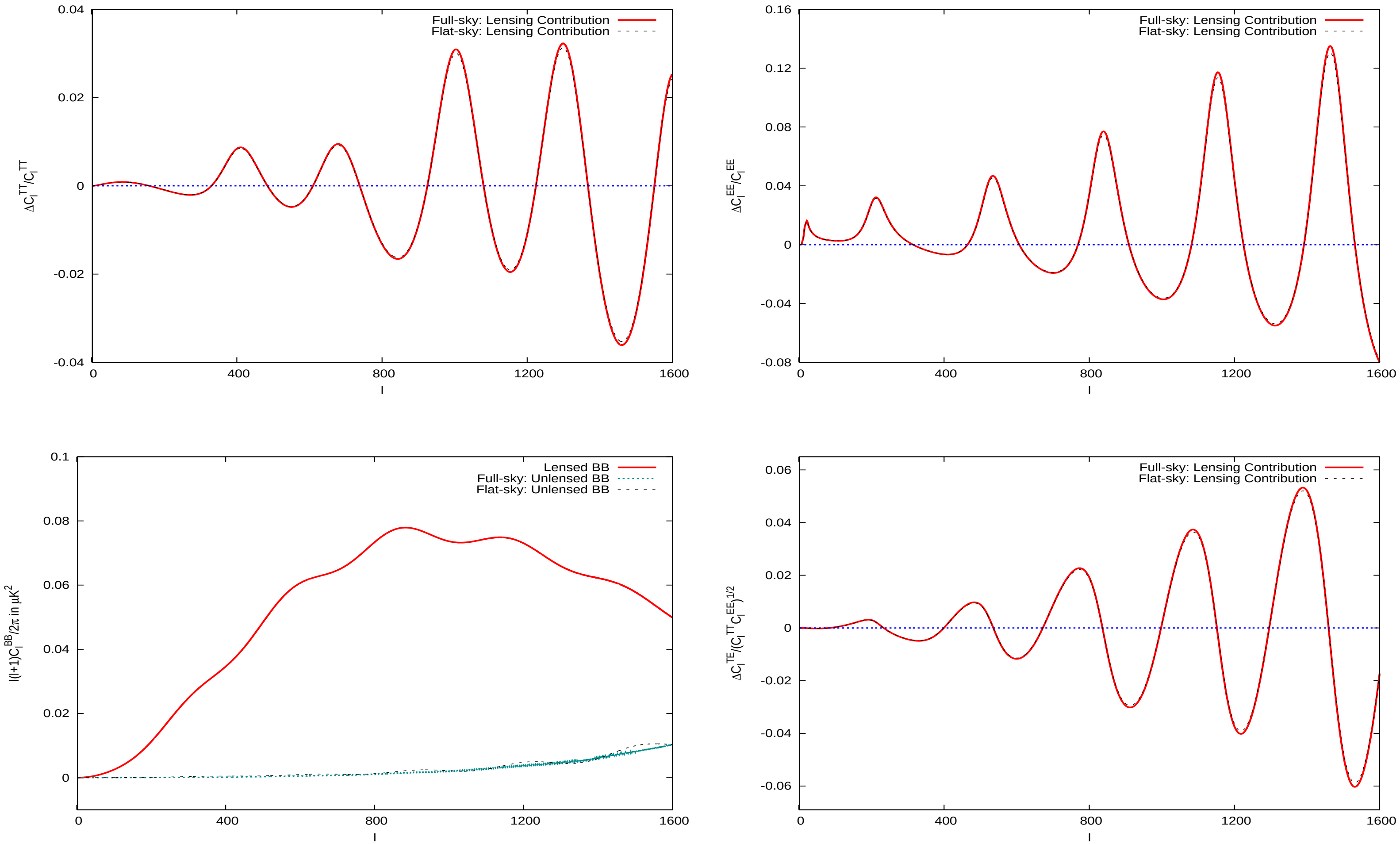
To do

- Propose delensing techniques
- Wait for Planck polorization & CMBPol data

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-point correlation fn.

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

3- and 4-point correlation fn. $\Rightarrow$ bispectrum f_{NL} & trispectrum g_{NL}, τ_{NL}

WMAP7 $\Rightarrow -10 < f_{NL} < 74 \ ; \quad -7.4 \times 10^5 < g_{NL} < 8.2 \times 10^5$

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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
- Suyama-Yamaguchi consistency relation between f_{NL} & τ_{NL}

Take-home message

- 6 parameter description of the universe
- Adiabatic, Gaussian initial perturbations
- Inflation confirmed, with a pinch of salt (anomalies!)
- Gravitational waves detected?
- Outliners yet unexplained
- Dynamical DE ? Probe ISW
- Large scale anomalies need to be explained
- Need delensing for B modes
- Non-Gaussian features to be explored