The low quadrupole:
Theoretical issues and MCMC data analysis

Claudio Destri
claudio.destri@mib.infn.it

Dipartimento di Fisica G. Occhialini
Università Milano–Bicocca

Physics of the Standard Model of the Universe: Theory and Observations, Colloquium at the Colegio de España, Cité Internationale Universitaire de Paris, 75014 Paris

Outline

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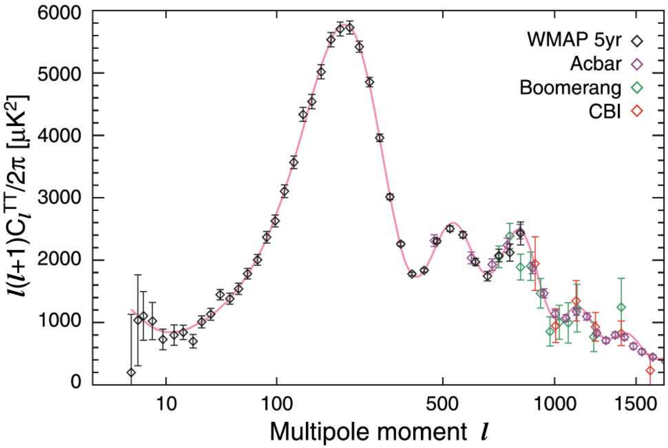
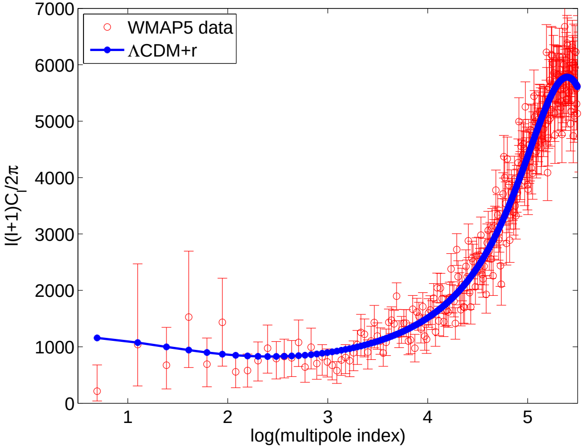
The WMAP+small scale TT multipoles (binned)

from "M. R. Nolta et al.", arXiv:0803.0593 [astro-ph] 5 Mar 2008



$$C_2 = 223\ \mu K^2 \ \text{(WMAP5 ML value)}\ , \qquad C_2 \simeq 1200\ \mu K^2\ (\Lambda\text{CDM})$$

WMAP5 unbinned C_ℓ for $\ell \leq 250$



(stat. exp. error)/(cosmic variance) = 20% at $\ell = 250$

Other analysis of WMAP5 data

- ...
- P.K. Samal, R. Saha, J. Delabrouille, S. Prunet, P. Jain, T. Souradeep, *"CMB Polarization and Temperature Power Spectra Estimation using Linear Combination of WMAP 5-year Maps"*, arXiv:0903.3634

$$C_2 = 557\ \mu K^2 \ \ (\text{WMAP5}+150\%)\ , \qquad C_3 = 306\ \mu K^2\ (\text{WMAP5}-40\%)$$

- Y. Ayaita, M. Weber, C. Wetterich, *"Too few spots in the Cosmic Microwave Background"*, arXiv:0905.3324

$$C_2, C_3, C_4 \to 0\ , \qquad C_2, C_3, C_4, C_5, C_6 \to (\text{WMAP5}-50\%)$$

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Outline

Neglecting all uncertainities but cosmic variance:

Let $X_\ell = C_\ell^{(data)}/C_\ell^{(model)}$; then

$Pr(X_\ell = x|model) \propto \frac{1}{x}\left(xe^{-x}\right)^{\ell+1/2}$ (reduced chi-square distribution) is the probability density for $C_\ell^{(data)}$ given the model, with

$$\langle X_\ell \rangle = 1 \text{ and } (X_\ell)_{ML} = \frac{2\ell-1}{2\ell+1}$$

At the same time, if $Y_\ell = 1/X_\ell = C_\ell^{(model)}/C_\ell^{(data)}$, then

$Pr(Y_\ell = y|data) \propto \left(e^{-1/y}/y\right)^{\ell+1/2}$ is the probability density for $C_\ell^{(model)}$ given the data (assuming flat priors), with

$$\langle Y_\ell \rangle = \frac{2\ell+1}{2\ell-3} \text{ and } (Y_\ell)_{ML} = 1$$

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An example: lowest 9 TT multipoles

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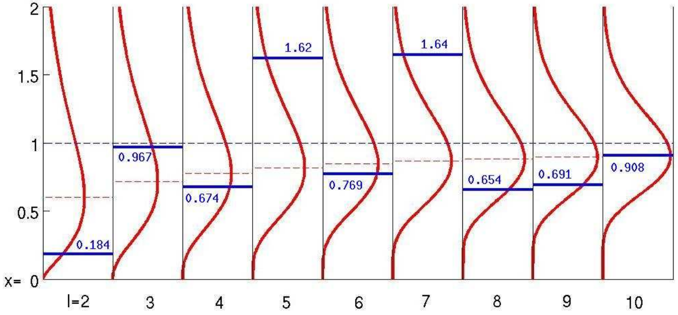
probability curves from best fit ΛCDM
WMAP5 data



$$\mathrm{Prob}[C_2^{(data)} < 0.184\, C_2^{(model)}] \simeq 0.031\ldots$$

Outline

Let $p_\ell = Pr(X_\ell \leq x | model)$ (recall $X_\ell = C_\ell^{(data)}/C_\ell^{(model)}$), then

all p_ℓ are independent random numbers flatly distributed in $(0,1)$

$$Pr[\text{there are } k \text{ of the first } n \; p_\ell \text{ in } (0,p)] = \binom{n}{k} p^k (1-p)^{n-k}$$

$$\langle k \rangle = p\,n \qquad (\Delta k)^2 = p(1-p)n$$

In the first 250 multipoles we expect (to 1σ) up to 15 $C_\ell^{(data)}$ so low w.r.t. $C_\ell^{(model)}$ to have a probability less than 0.031

$p_\ell < 0.031$

2 22 48 54 72 84 98 105 113 114
120 124 149 181 195 209 228 234 249

$p_\ell > 1 - 0.031$

69 73 83 117

Let $p_\ell = Pr(X_\ell \leq x|model)$ (recall $X_\ell = C_\ell^{(data)}/C_\ell^{(model)}$), then

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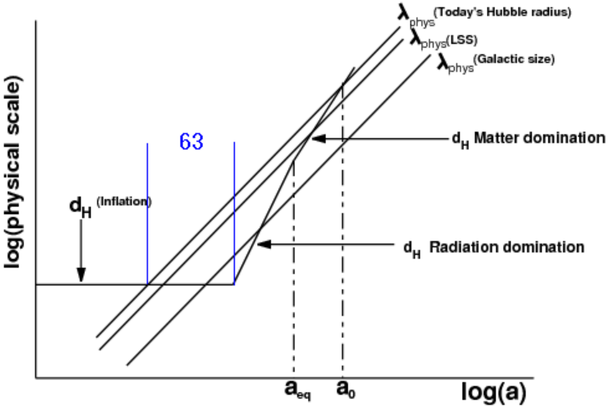
Inflation essentials

Early accelerated expansion of the Universe

$$ds^2 = dt^2 - a(t)dx^2 \quad , \qquad \ddot{a} > 0$$



EFT of (single field) inflation à la Ginsburg-Landau

D. Boyanowski, C.D., H.J. de Vega, N. Sanchez, arXiv:0901.0549, to appear on IJMP

Inflaton potential ($\hbar = 1$, $c = 1$, $M_{PL} = 2.4 \times 10^{18}$ GeV)

$$V(\varphi) = M^4 v(\phi) \,, \quad \phi = \frac{\varphi}{M_{PL}}$$

Energy scale of inflation and inflaton mass

$$M \simeq 0.57 \times 10^{16} \text{ GeV} \sim M_{\rm GUT}, \quad m = M^2/M_{PL} \sim 1.3 \times 10^{13} \text{ GeV}$$

Hubble parameter and quantum corrections

$$H \sim 7\,m \ll M_{PL} \,, \quad \text{loops} \to (H/M_{PL})^2 \sim 10^{-9}$$

Number of inflation efolds since horizon exit

$$N = \log \frac{a(t_{end})}{a(t_{exit})} \,, \quad v(\phi_{end}) = v'(\phi_{end}) = 0$$

t_{exit}: the mode with comoving k_0 becomes superhorizon ($\to N = N(k_0)$)

WMAP: $k_0 = 2 \text{ Gpc}^{-1}$, $N \simeq 61$

CosmoMC: $k_0 = 50 \text{ Gpc}^{-1}$, $N \simeq 57$

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The number of efolds N (coarse-grained: constant H, sharp ΛD$\to$ RD)

Friedmann's equation right after inflation

$$\frac{H^2}{H_0^2} = \Omega_\Lambda + \frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} \simeq \frac{\Omega_r}{a^4}\,, \qquad \frac{H}{H_0} \simeq 4.2\times 10^{55}\,, \qquad (H \simeq 2.8\times 10^{-5} M_{Pl})$$

$$\Longrightarrow \qquad \log\frac{1}{a} \simeq \frac{1}{2}\log\frac{H}{H_0\sqrt{\Omega_r}}$$

Inflation efolds for the quadrupole scale k_Q (today $k_Q = 1.014 H_0 = 0.238\ \mathrm{Gpc}^{-1} = 1.52\times 10^{-42}$ GeV)

$$N_Q \simeq \log\frac{H}{H_0} - \log\frac{1}{a} \simeq \log\frac{H\sqrt{\Omega_r}}{H_0} \simeq 62$$

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$$N = N_Q - \log\frac{k_0}{k_Q} \simeq 57\,, \qquad k_0 = 0.05\mathrm{Mpc}^{-1}\ \text{(CosmoMC)}$$

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Dimensionless setup: t in units of m^{-1}, $H = h\,m$

Equations of motion

$$h^2 = \frac{1}{3}\left[\frac{1}{2}\dot{\phi}^2 + v(\phi)\right], \quad \ddot{\phi} + 3h\,\dot{\phi} + v'(\phi) = 0, \quad \dot{h} = -\frac{1}{2}\dot{\phi}^2$$

Energy density and pressure

$$\varepsilon = M^4\left[\frac{1}{2}\dot{\phi}^2 + v(\phi)\right], \quad p = M^4\left[\frac{1}{2}\dot{\phi}^2 - v(\phi)\right]$$

Fast-roll vs. slow-roll

$$\tfrac{1}{2}\dot{\phi}^2 \sim v(\phi), \quad \tfrac{1}{2}\dot{\phi}^2 \ll v(\phi)$$

which potential $v(\phi)$?

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$$\varepsilon = M^4\left[\frac{1}{2}\dot{\phi}^2 + v(\phi)\right] , \quad p = M^4\left[\frac{1}{2}\dot{\phi}^2 - v(\phi)\right]$$

Fast-roll vs. slow-roll

$$\tfrac{1}{2}\dot{\phi}^2 \sim v(\phi) , \quad \tfrac{1}{2}\dot{\phi}^2 \ll v(\phi)$$

which potential $v(\phi)$?

Dimensionless setup: t in units of m^{-1}, $H = h\,m$

Equations of motion

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Outline

MCMC analysis of current data plus Ginsburg-Landau stability point to double–well type potentials with the inflaton ϕ rolling from a region of negative curvature near $\phi = 0$ (the "false vacuum") toward the true absolute minimum ϕ_{min} of the potential where $v(\phi_{min}) = v'(\phi_{min}) = 0$.

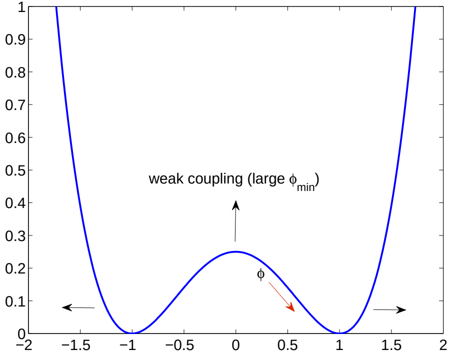
In general

$$v(\phi) = \phi_{min}^2 F(\phi/\phi_{min})$$

with $F'(x) \simeq x$ as $x \to 0$.

For instance BNI
(Binomial New Inflation)

$$F(x) = \frac{1}{4}(x^2 - 1)^2$$

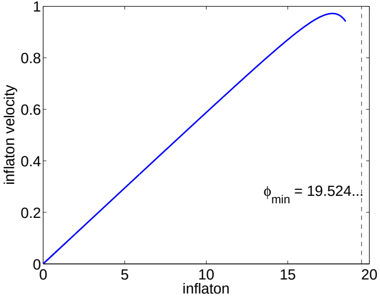


The extreme slow–roll solution (a sort of half de Sitter)

$$\ddot\phi + 3h\,\dot\phi + \phi = 0$$

$$\phi \propto \exp(\alpha t)\,, \quad t \to -\infty$$

$$\alpha = \tfrac{1}{2}\left[(\sqrt{3v(0)+4} - \sqrt{3v(0)}\right]$$



	start	$a=1$	end: $\ddot a = 0^+$
t	$-344.9514017\ldots$	0	$17.40482446\ldots$
ϕ	10^{-8}	$6.7484118\ldots$	$18.5586530\ldots$
$\dot\phi$	$\alpha\,10^{-8} = 5.89371084\ldots 10^{-10}$	$0.3973384\ldots$	$0.94150557\ldots$
$\log a$	$-1938.4867948\ldots$	0	60
h	$(12g)^{-1/2} = 5.6361006\ldots$	$4.9653973\ldots$	$0.6657449\ldots$
η	$-\infty$ (f.a.p.p)	$-0.2020610\ldots$	0

Singular solutions as $t \to t_*^+$

$$\phi \simeq \sqrt{2/3}\log\left(\frac{t-t_*}{b}\right) , \quad \dot\phi \simeq \frac{\sqrt{2/3}}{t-t_*} , \quad h \simeq \frac{1}{3(t-t_*)} , \quad a \simeq (t-t_*)^{1/3} , \quad \eta \to \eta_*$$

Pre-inflationary ($\ddot{a} < 0$!) $\longrightarrow$ fast–roll $\longrightarrow$ slow–roll

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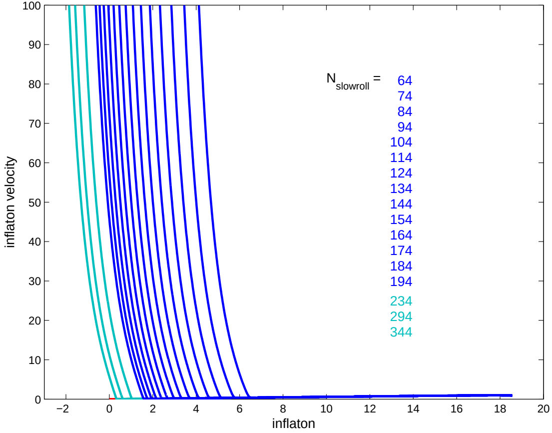

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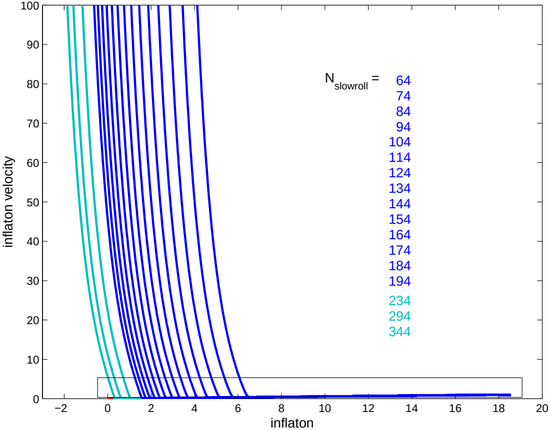

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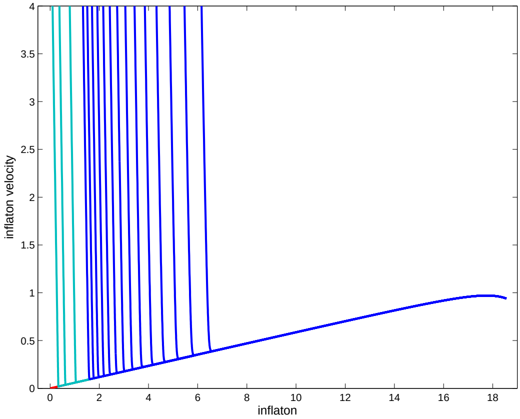

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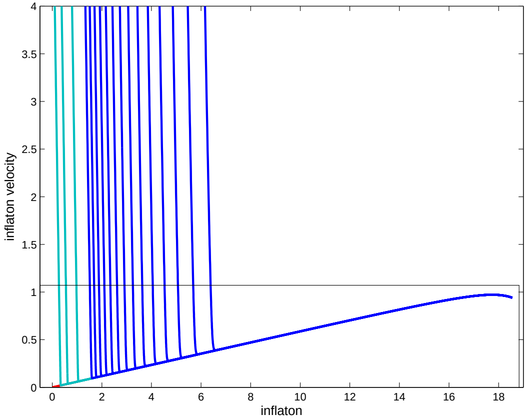

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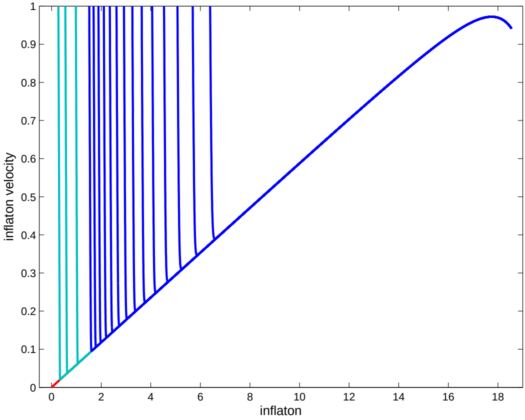

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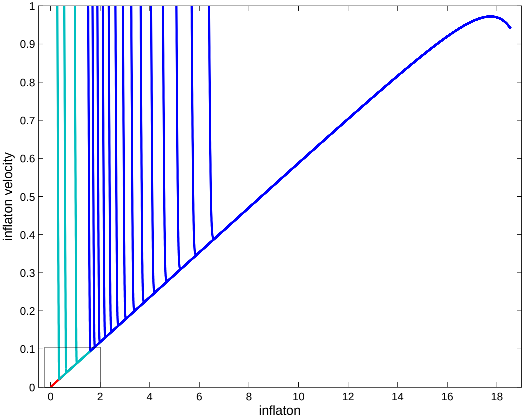

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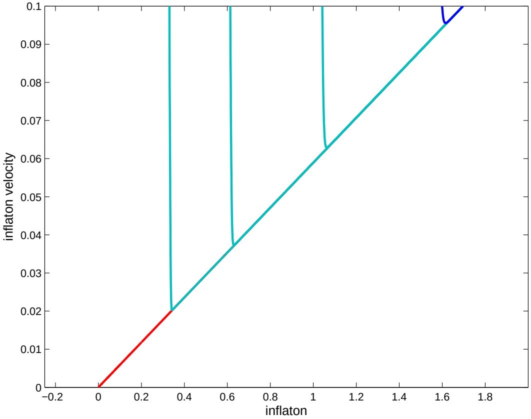

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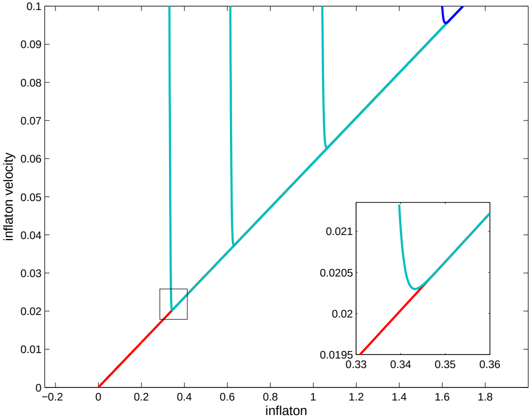

Scalar fluctuations

Gauge–invariant quantum perturbation field

$$u(x,t) = -\xi(t)R(x,t) = \int \frac{d^3k}{(2\pi)^{3/2}}\left[\alpha_k S_k(\eta)e^{ik\cdot x} + \alpha_k^\dagger S_k^*(\eta)e^{-ik\cdot x}\right]$$

$$[\alpha_k, \alpha_{k'}^\dagger] = \delta^{(3)}(k-k')\,, \quad \xi(t) = \frac{a(t)}{H(t)}\,\dot\phi(t)\,, \quad \eta = \int \frac{dt}{a(t)}$$

Schroedinger–like dynamics

$$\left[\frac{d^2}{d\eta^2} + k^2 - W(\eta)\right] S_k = 0\,, \quad W(\eta) = \frac{1}{\xi}\frac{d^2\xi}{d\eta^2}$$

$$\left[\frac{d^2}{dt^2} + h\frac{d}{dt} + \frac{k^2}{a^2} - U(t)\right] S_k = 0$$

Standard parametrization in dimensionless setup

$$U(t) = h^2(2 - 7\,\varepsilon_v + 2\,\varepsilon_v^2) - 2\,\dot\phi\,\frac{v'(\phi)}{h} - \eta_v\,v(\phi)\,, \quad \varepsilon_v = \frac{\dot\phi^2}{2\,h^2}\,, \quad \eta_v = \frac{v''(\phi)}{v(\phi)}$$

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$$\epsilon_v \simeq \frac{1}{2}\left[\frac{v'(\phi_{exit})}{v(\phi_{exit})}\right]^2 , \quad \eta_v \simeq \frac{v''(\phi_{exit})}{v(\phi_{exit})} , \quad W(\eta) = \frac{\nu^2 - 1/4}{\eta^2} , \quad \nu = \frac{3}{2} + 3\epsilon_v - \eta_v$$

Power spectrum

$$P(k) = \lim_{\eta \to 0} \left(\frac{m}{M_{PL}}\right)^2 \frac{k^3}{2\pi^2} \left|\frac{S_k \eta)}{\xi(\eta)}\right|^2$$

Bunch–Davies vacuum at $t \to -\infty$ in extreme slow–roll

$$S_k(\eta \to -\infty) = \frac{e^{ik\eta}}{\sqrt{2k}} , \quad P_\infty = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} , \quad A_s = \left(\frac{m}{M_{PL}}\right)^2 \frac{N^2}{12\pi^2} \mathscr{O}(1)$$

Bunch–Davies vacuum at finite times?

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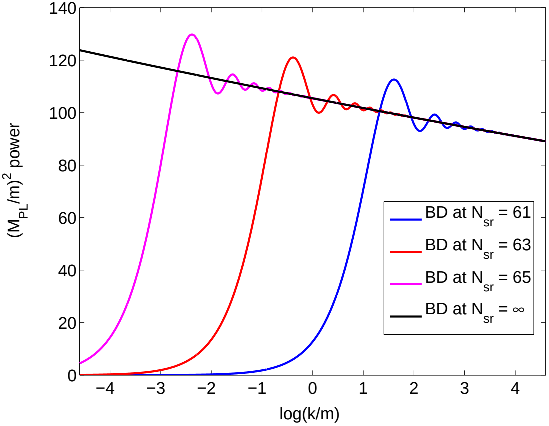

Compare the small $k-$ behavior of BD and quasi-De Sitter modes

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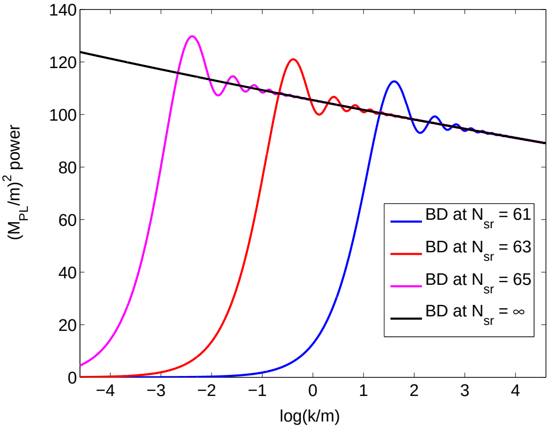

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The transfer function of initial conditions

$$P(k) = P_\infty(k)\Big[1 + D(k)\Big]$$

more formally ...

Effect on quadratic observables of linear combinations of the solutions of linear differential equations of second order, or Bogoliubov transformations on creation–annihilation operators.

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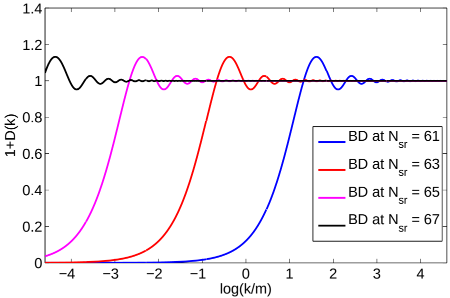
Effect on quadratic observables of linear combinations of the solutions of linear differential equations of second order, or Bogoliubov transformations on creation–annihilation operators.

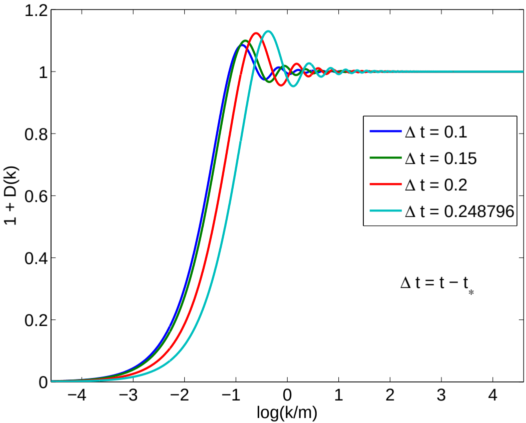
$$D(k) \simeq D(k\eta_0)$$

$$D(k) \sim k^{-2}\ , \quad k \to \infty$$

to have a negligible back–reaction on the metric



Transfer function for fast–roll trajectories
C.D., H.J. de Vega and N. Sanchez, in preparation



$\Longrightarrow$ depression of lowest multipoles

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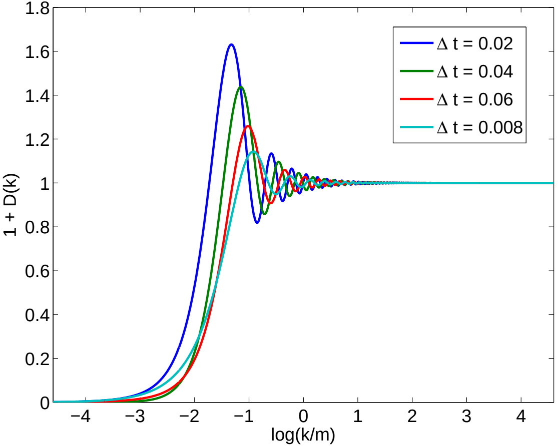

$\Longrightarrow$ up and down with little change on average

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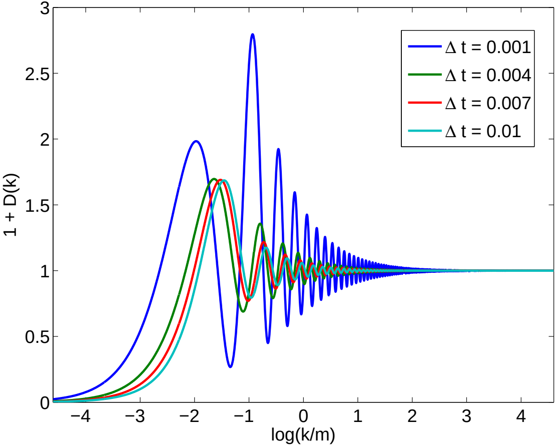

$\Longrightarrow$ up and down with net overall enhancement

Outline

Extreme slow–roll scenario

- Pro:
  - It's unique
  - Allows adiabatic Bunch–Davies vacuum of de Sitter spacetime
  - Gravity always semiclassical ($H \ll M_{PL}$ at any time)
- Con:
  - It's unique
  - All quantum modes were once trans–planckian

Fast–roll scenario

- Pro:
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in the matter dominated era there was a very low quadrupole that would later (now) become a very low $\ell = 22$ multipole.

The argument based on fastroll to explain such a low quadrupole would have given $N_{slowroll} = 54$ but would have been proven wrong when more superhorizon modes reentered. Except that ...

The entropy lower bound

$$N_{slowroll} \geq 62.4 - \frac{1}{2}\log\left(\frac{10^{-4}M_{PL}}{H}\right) - \frac{1}{12}\log\frac{g_{rh}}{1000} \simeq 62$$

Yet another cosmic coincidence

We live when the homogeneity and entropy lower bounds almost coincide!

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Binomial New Inflation with sharpcut or (simplified) fastroll
C.D., H.J. de Vega, N. Sanchez, Phys. Rev. D78

Simplification

- Born's approximation for k not too small.
- $k_{tran} = -1/\eta_0$ is the comoving wavenumber that exits the horizon when fast-roll ends and slow-roll starts.

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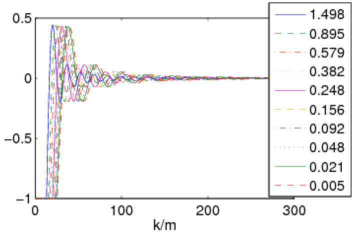
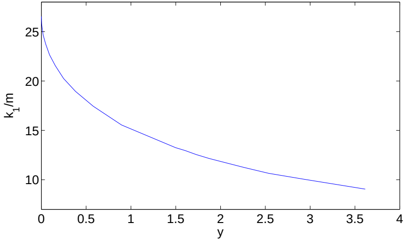
For BNI, $v(\phi) = \frac{1}{4}g(\phi^2 - 1/g)^2$, $g = y/(8N)$, $y = z - 1 - log(z)$





Outline

BNI+sharpcut vs. BNI+fastroll

MCMC parameters:	ω_b, ω_c, θ, τ, (slow), A_s, z, k_{tran} (fast)
Context:	$N = 60$, $\Omega_\nu = 0$, ... ; standard priors, no SZ, lensed CMB, linear mpk, ...
Datasets:	WMAP5, SDSS, ACBAR08

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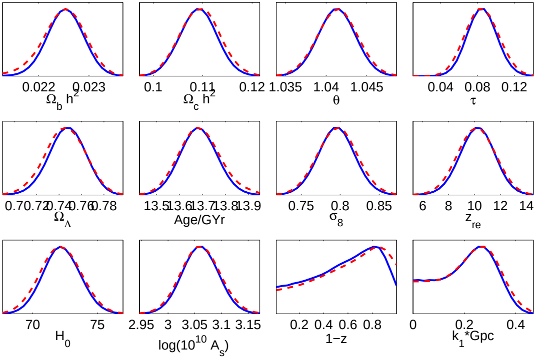
param	best fit
$100\Omega_b h^2$	2.256
$\Omega_c h^2$	0.110
θ	1.041
100τ	8.83
H_0	71.82
σ_8	0.803
$\log[10^{10} A_s]$	0.307
z	0.162
k_1	0.260
$-\log(L)$	1253.96

sharp-cut

flat $0 < z < 1$ prior



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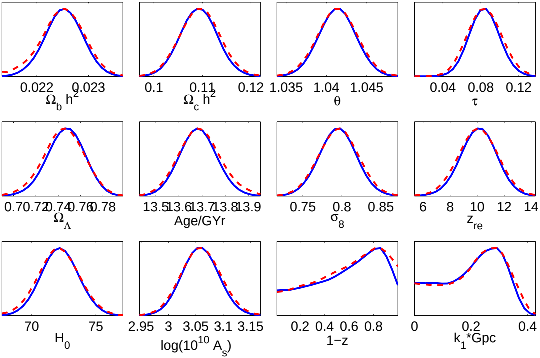
Datasets: WMAP5, SDSS, ACBAR08

param	best fit
$100\Omega_b h^2$	2.253
$\Omega_c h^2$	0.109
θ	1.041
100τ	8.42
H_0	72.00
σ_8	0.794
$\log[10^{10} A_s]$	0.306
z	0.102
k_1	0.284
$-\log(L)$	1253.82

fast-roll

flat $0 < z < 1$ prior



Outline

$\Delta\chi^2$ w.r.t. ΛCDM+r

	WMAP5	+SDSS+ACBAR08	+SDSS+SN
BNI+sharpcut	-1.07	-0.71	-1.02
BNI+fastroll	-1.15	-0.99	-1.45

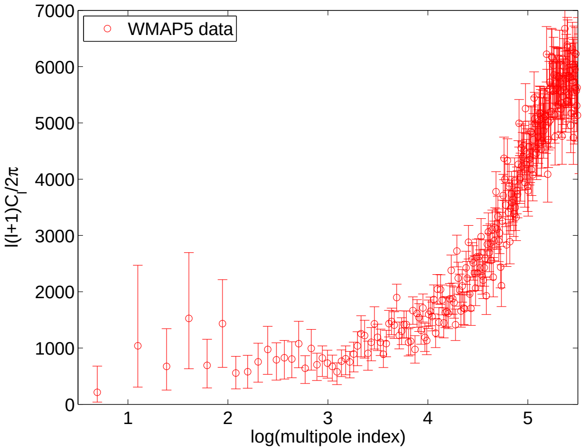
95% lower bound on r

	WMAP5	+SDSS+ACBAR08	+SDSS+SN
BNI+sharpcut	0.025	0.033	0.022
BNI+fastroll	0.024	0.032	0.023

most likely value of k_{tran} (in Gpc^{-1})

	WMAP5	+SDSS+ACBAR08	+SDSS+SN
BNI+sharpcut	0.258	0.260	0.244
BNI+fastroll	0.298	0.284	0.291

Comparing TT multipoles



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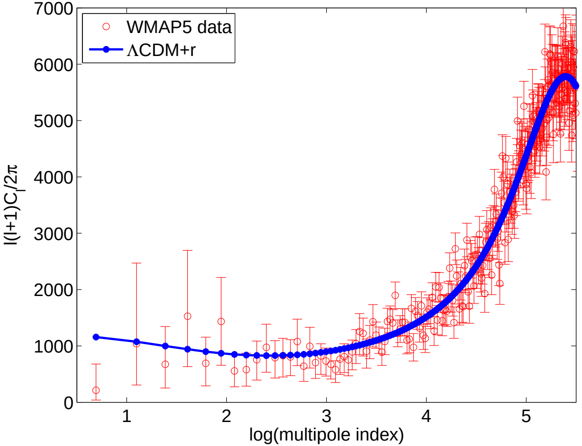

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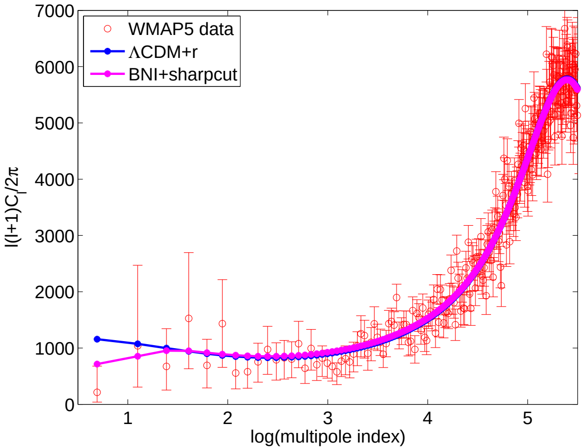

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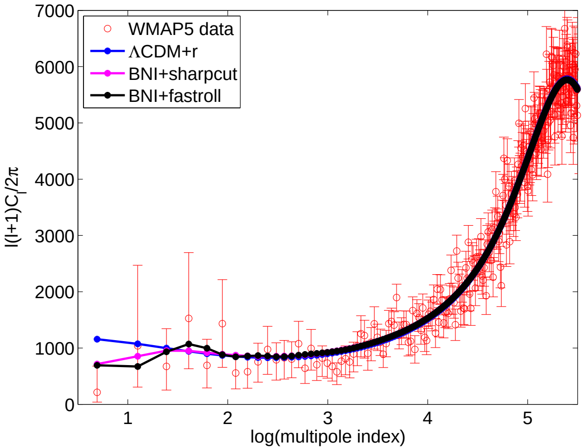

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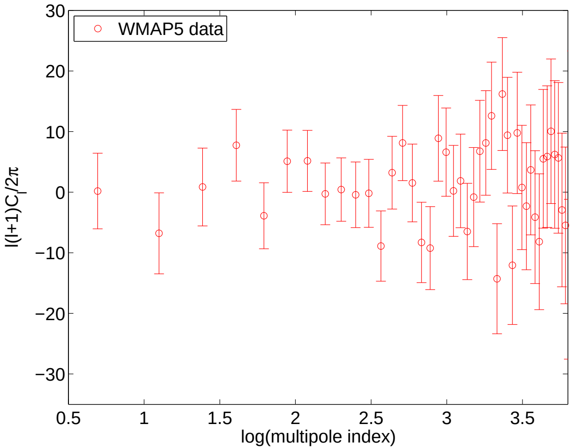

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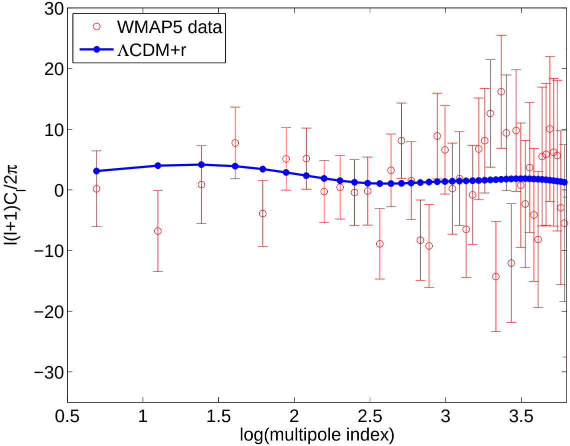

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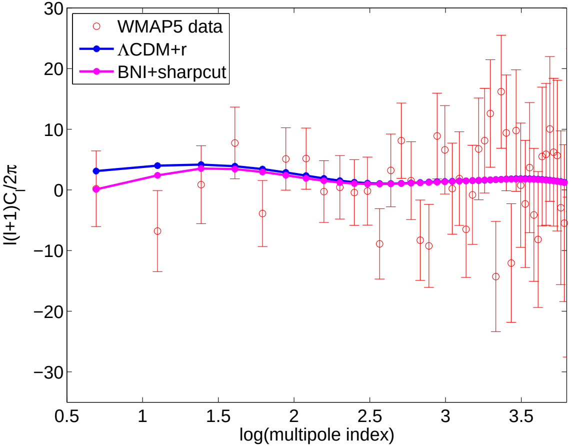

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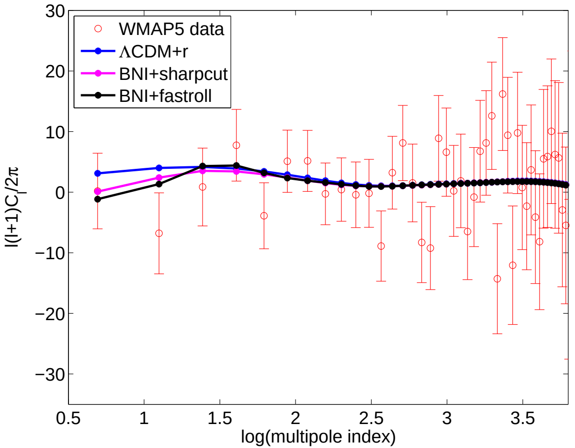
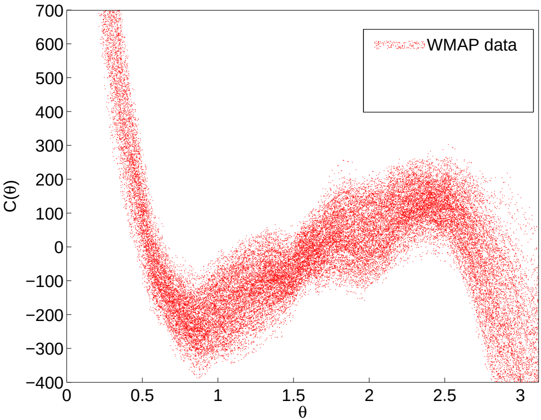


Comparing real-space TT correlations



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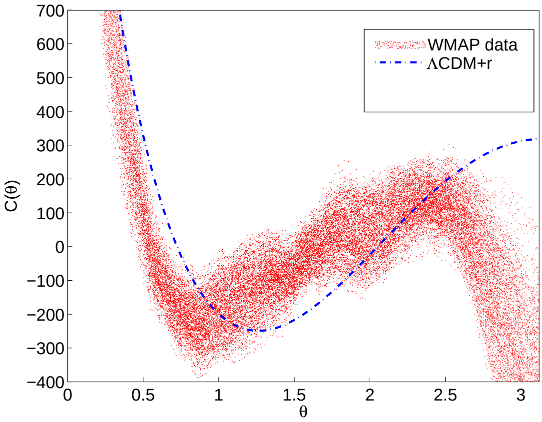

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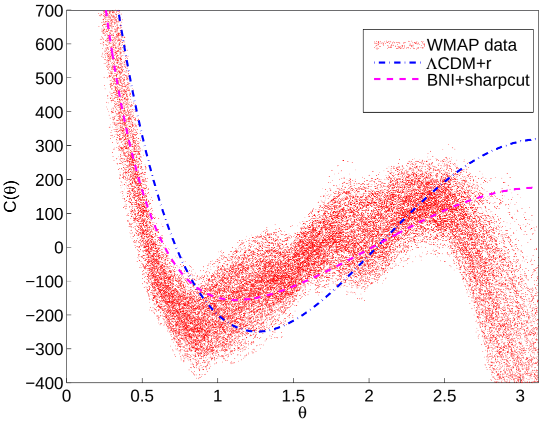

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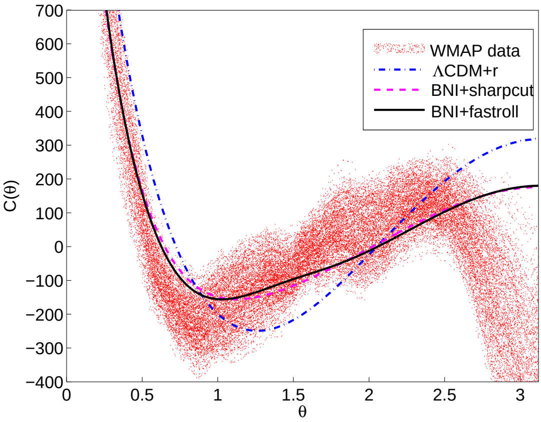

Highlight

The quadrupole wavenumber

$k_Q \simeq 0.83\, k_{tran}$ and exits roughly 1/10 of an efold before k_{tran}

$$N_{slowroll} \simeq 63$$

Summary

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- Early fast-roll inflation is generic and provides a mechanism for lowest multipoles depression.
- BNI+fastroll significantly improves the fit w.r.t. ΛCDM$+r$.
- BNI+fastroll improves the fits also w.r.t. BNI+sharpcut.
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  - Wait for better data (Plank, Atacama, ...)
  - Refine, refine, refine