Large-Scale CMB Anomalies

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IPMU ACP seminar, June 30, 2009

Outline

- WMAP 5-year data plus many others

  low CMB quadrupole , running spectral index,

  nongaussianity (south-north asymmetry, axis of evil,..)

  $\rightarrow$ challenges to standard slow-roll inflation?!

- Inflaton coupled to other quantum fields

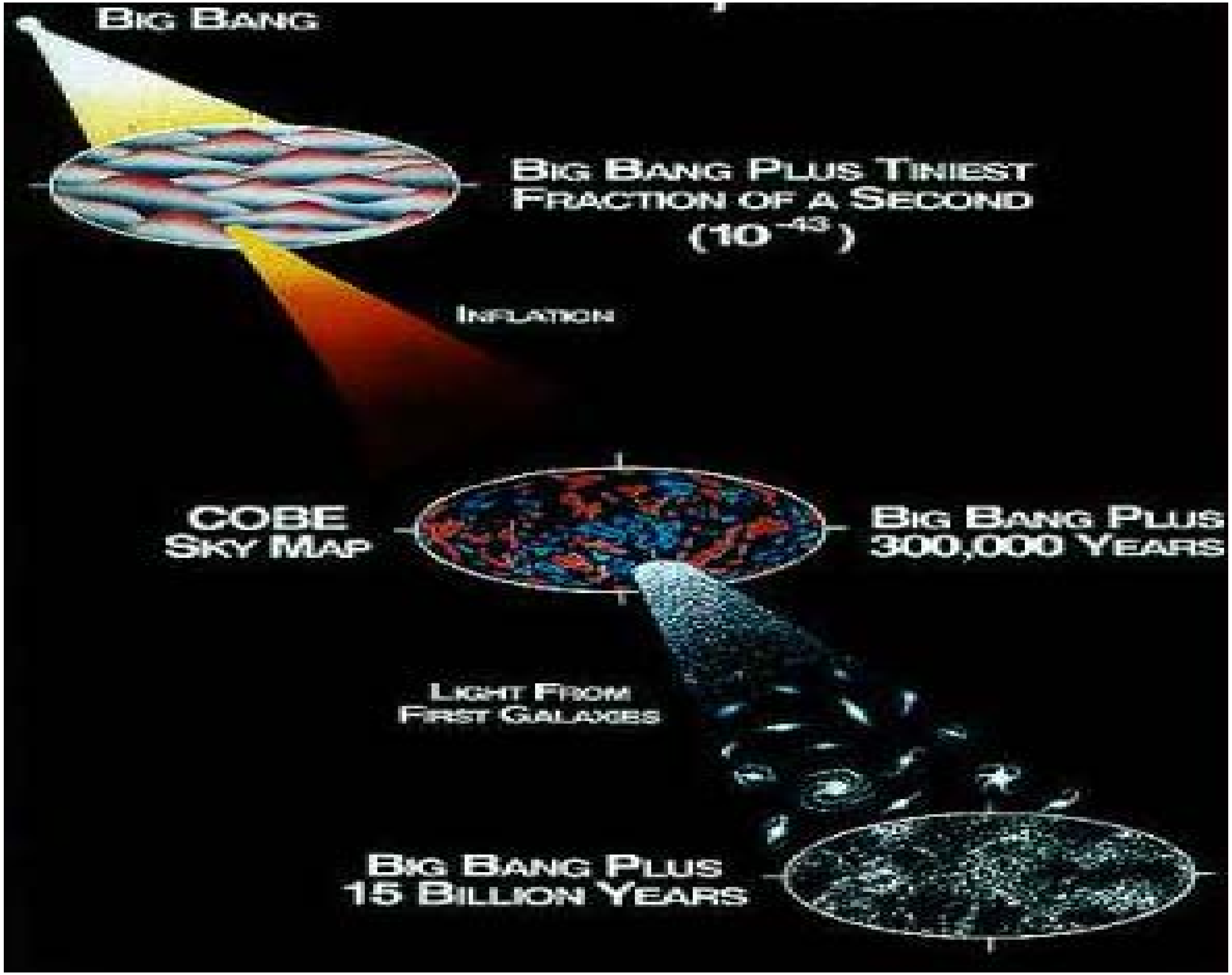
  natural, needs for reheating,..

  still single-field inflation (versus multi-field inflation)

- A phase transition to inflationary epoch

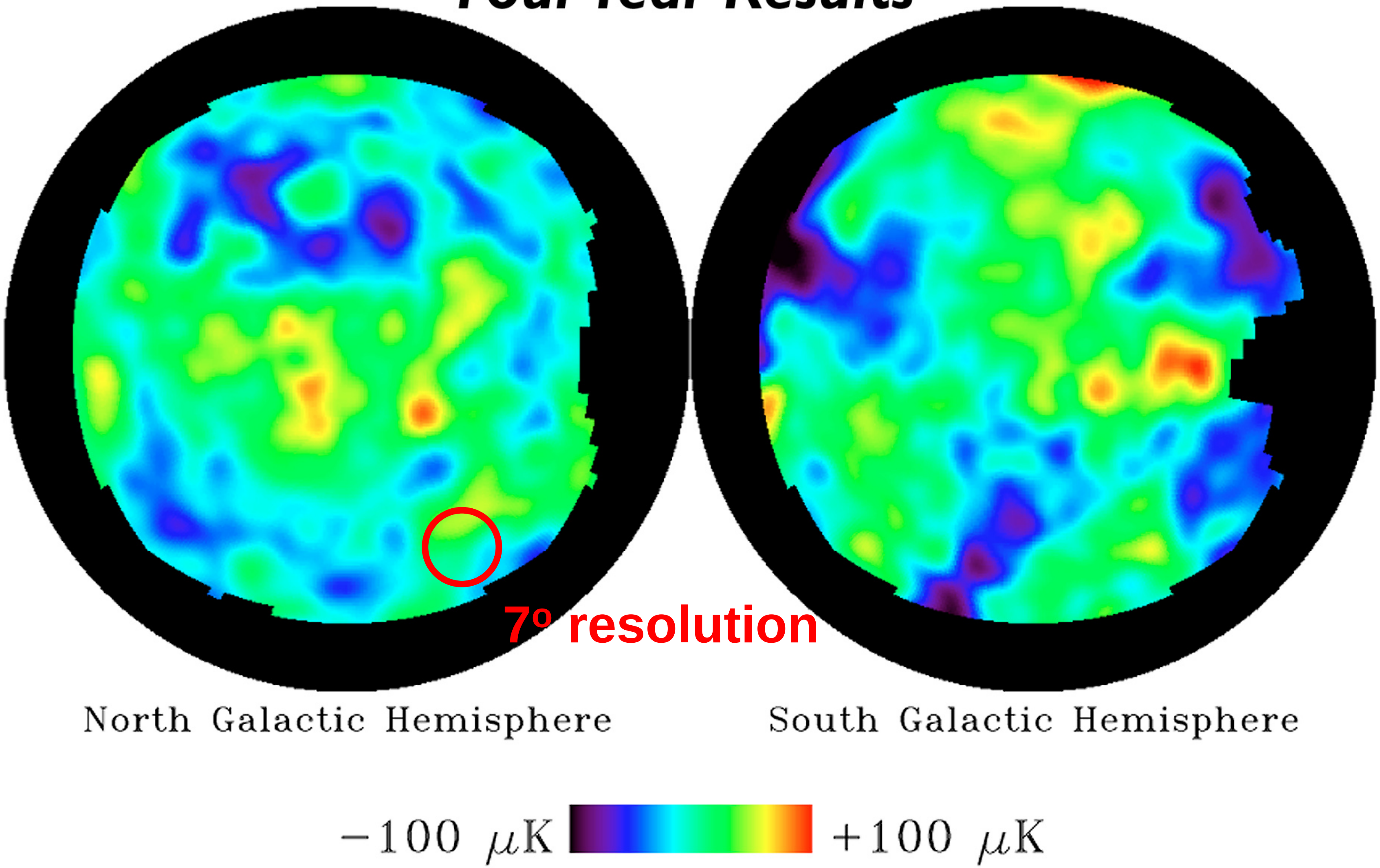
  - a pre-inflation radiation-dominated era?

  - a phase transition with formation of black holes or topological defects? (Carroll, Tseng, & Wise 08 preferred point, line, or plane)

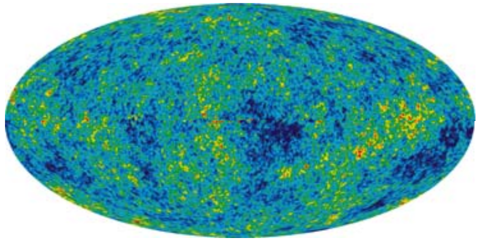


BIG BANG
BIG BANG PLUS TINIEST
FRACTION OF A SECOND
(10^{-43})
INFLATION
COBE
SKY MAP
BIG BANG PLUS
300,000 YEARS
LIGHT FROM
FIRST GALAXIES
BIG BANG PLUS
15 BILLION YEARS

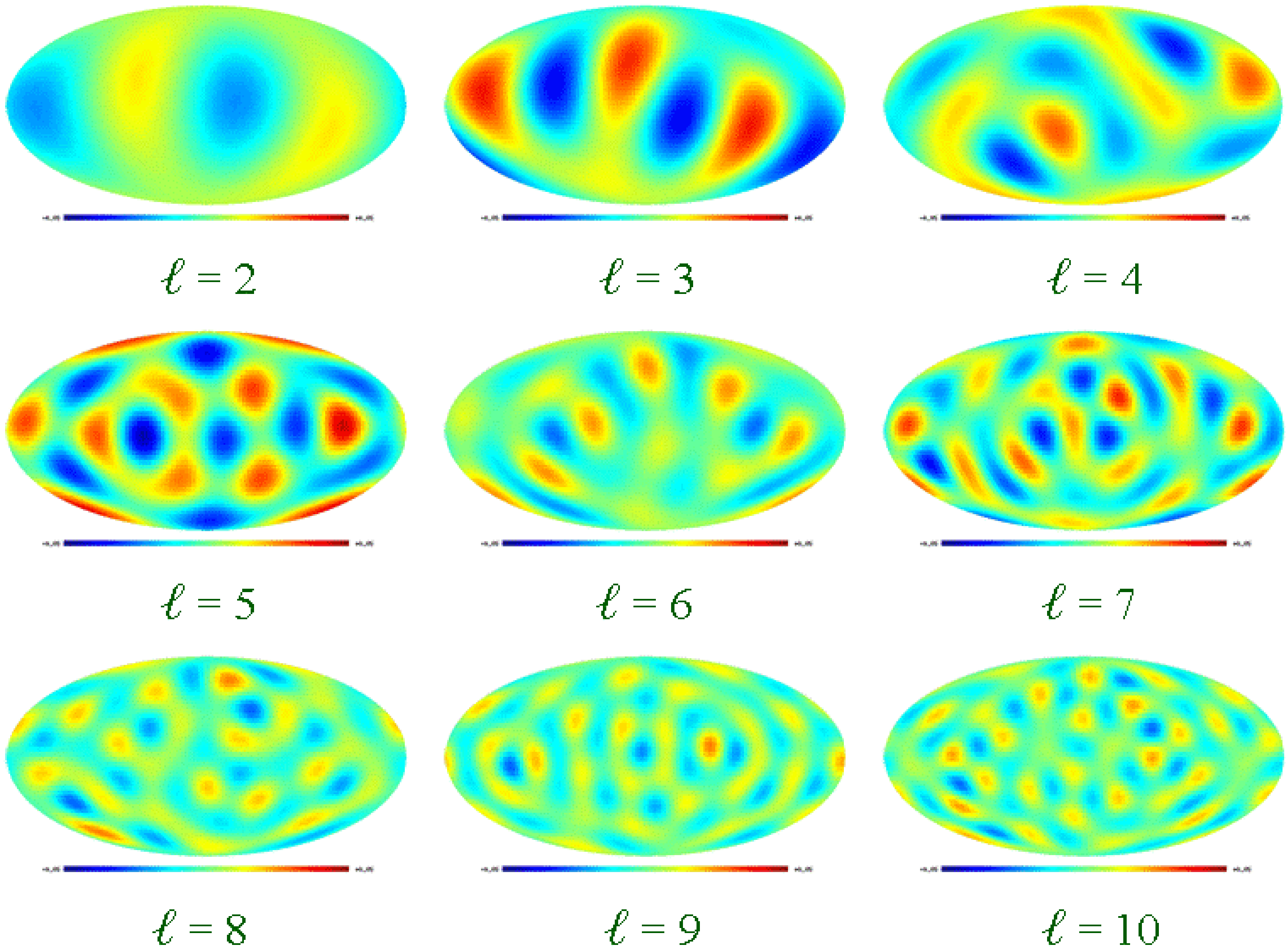
COBE - DMR Map of CMB Anisotropy
Four Year Results

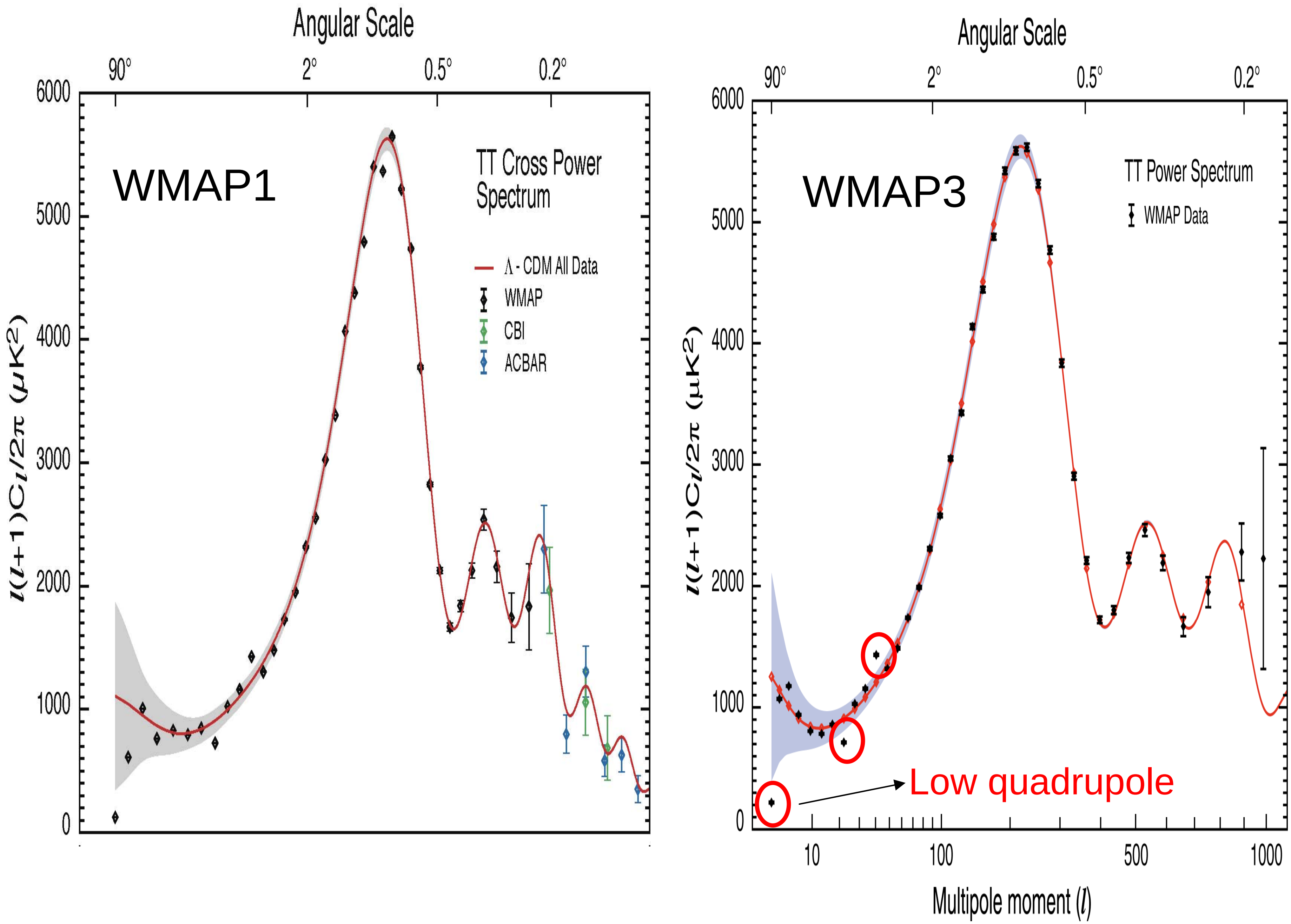


WMAP3
CMB sky map



$$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

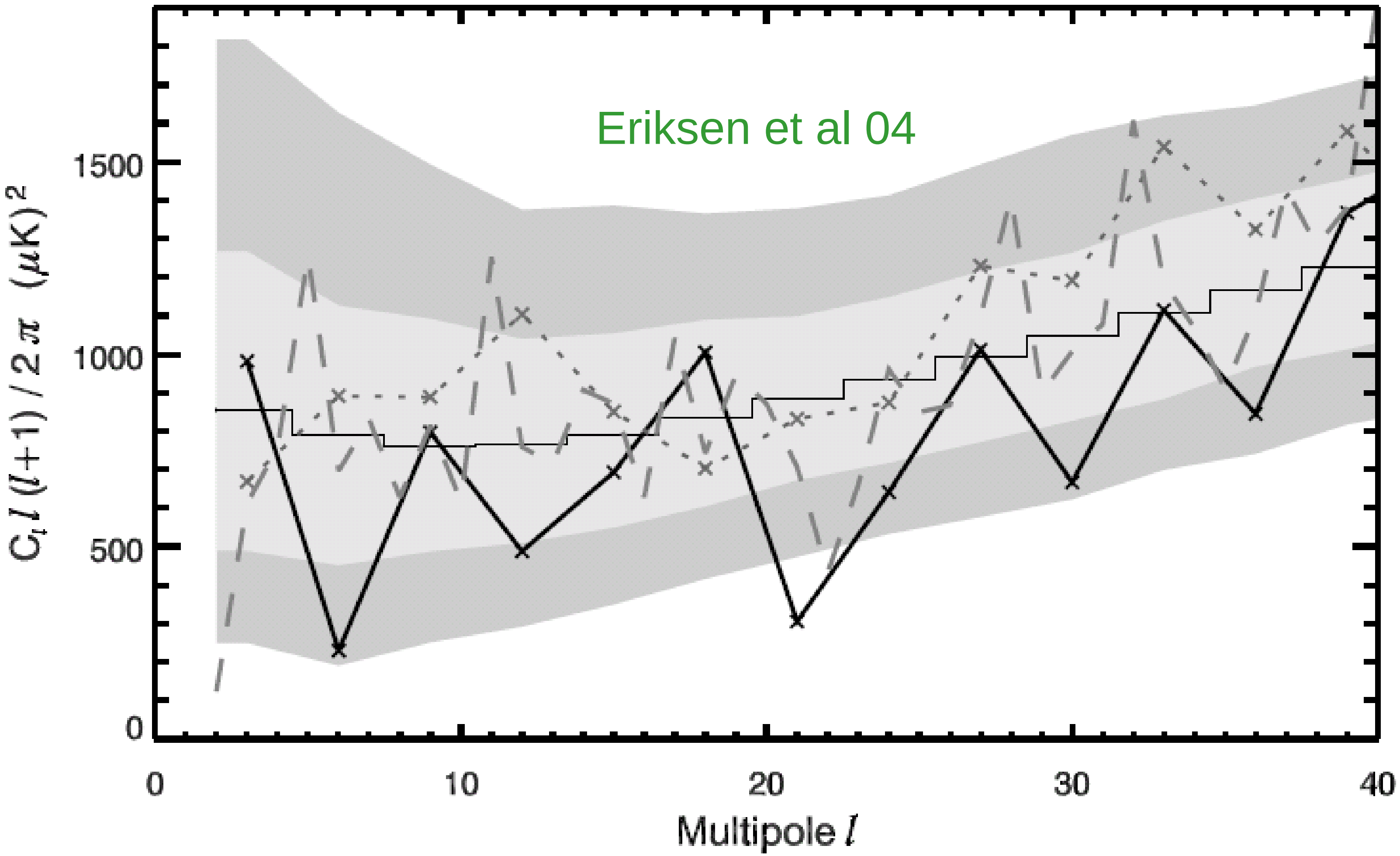




Angular Scale
90°
2°
0.5°
0.2°
WMAP1
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
Angular Scale
WMAP3
TT Power Spectrum
WMAP Data
Low quadrupole
Multipole moment (l)

South-North Power Asymmetry

Eriksen et al 04
Park 04

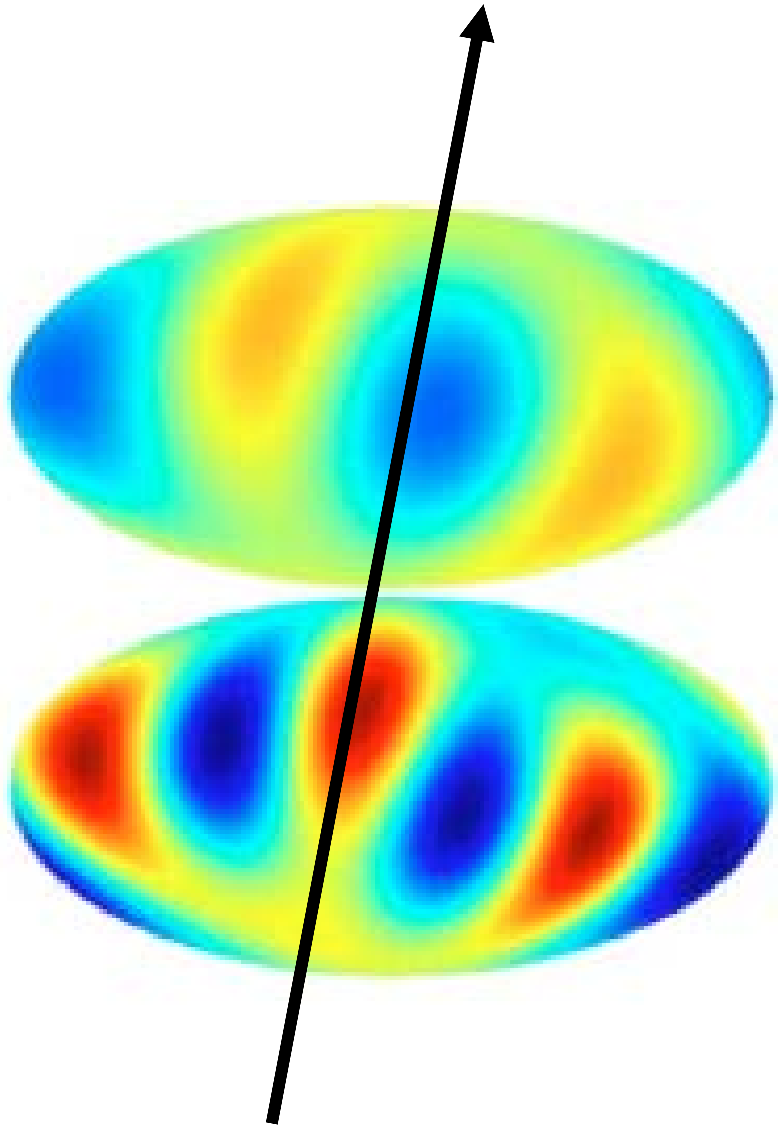


northern hemisphere
southern hemisphere
full sky

North pole (80°,57°)

Land & Magueijo 05

“Axis of Evil” $(l,b)\sim(-110°,60°)$



l=2, quadrupole

l=3, octopole

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Significance of the largest scale CMB fluctuations in WMAP

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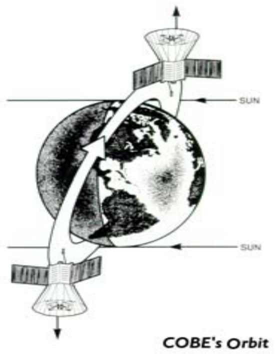
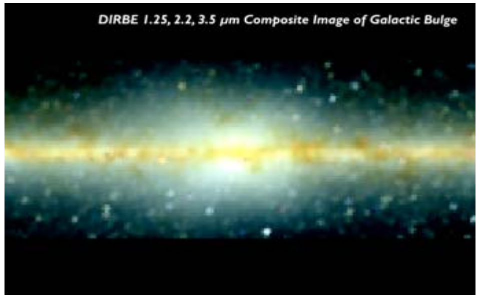
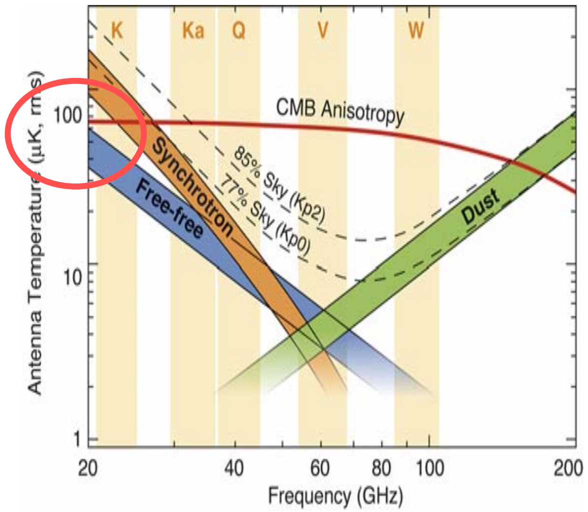
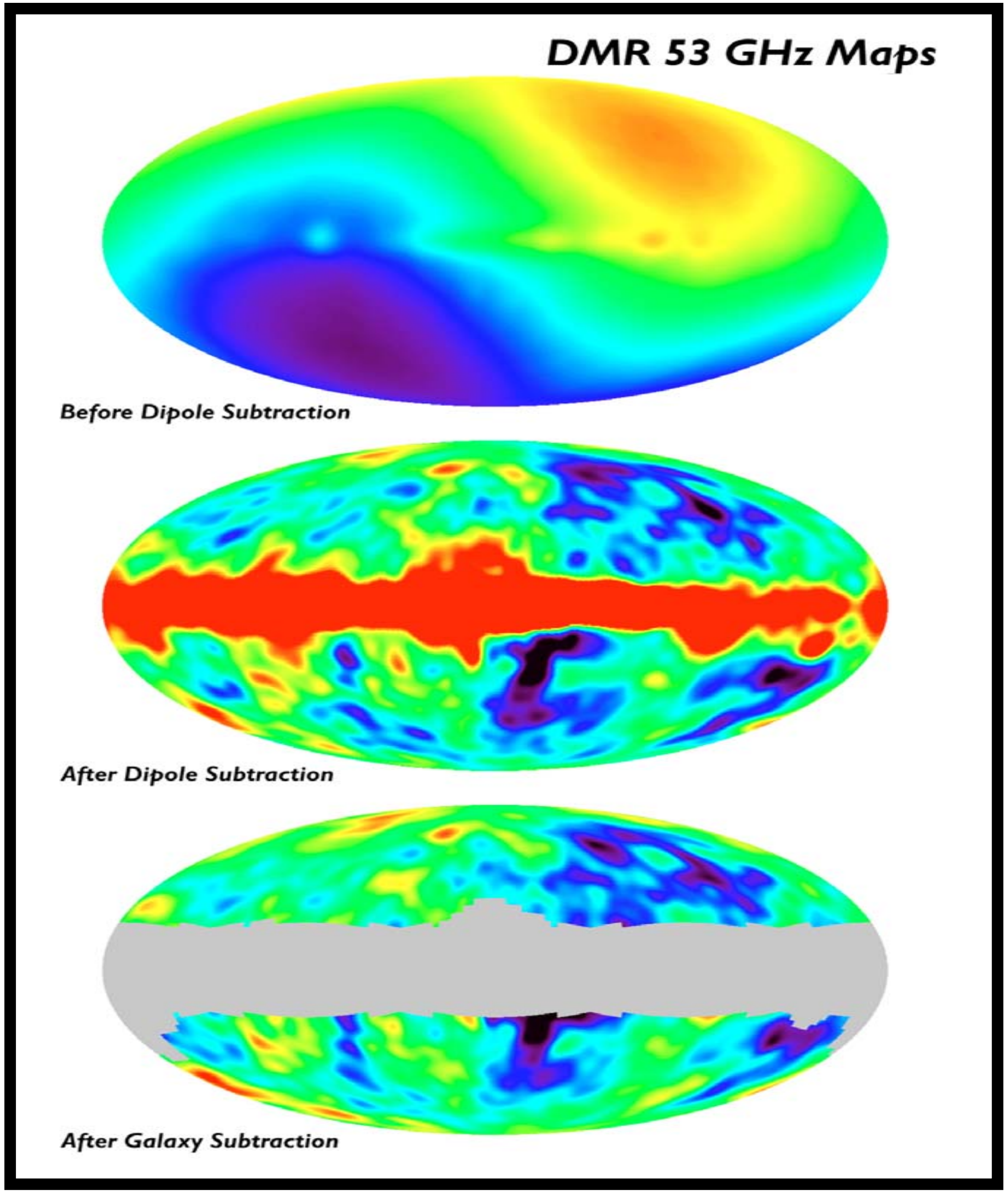
We investigate anomalies reported in the cosmic microwave background maps from the Wilkinson Microwave Anisotropy Probe (WMAP) satellite on very large angular scales and discuss possible interpretations. Three independent anomalies involve the quadrupole and octopole: (1) The cosmic quadrupole on its own is anomalous at the 1-in-20 level by being low (the cut-sky quadrupole measured by the WMAP team is more strikingly low, apparently due to a coincidence in the orientation of our Galaxy of no cosmological significance); (2) the cosmic octopole on its own is anomalous at the 1-in-20 level by being very planar; (3) the alignment between the quadrupole and octopole is anomalous at the 1-in-66 level. Although the *a priori* chance of all three occurring is 1 in 24000, the multitude of alternative anomalies one could have looked for dilutes the significance of such *a posteriori* statistics. The simplest small universe model where the universe has toroidal topology with one small dimension of order one-half the horizon scale, in the direction toward Virgo, could explain the three items above. However, we rule this model out using two topological tests: the *S* statistic and the matched circle test.

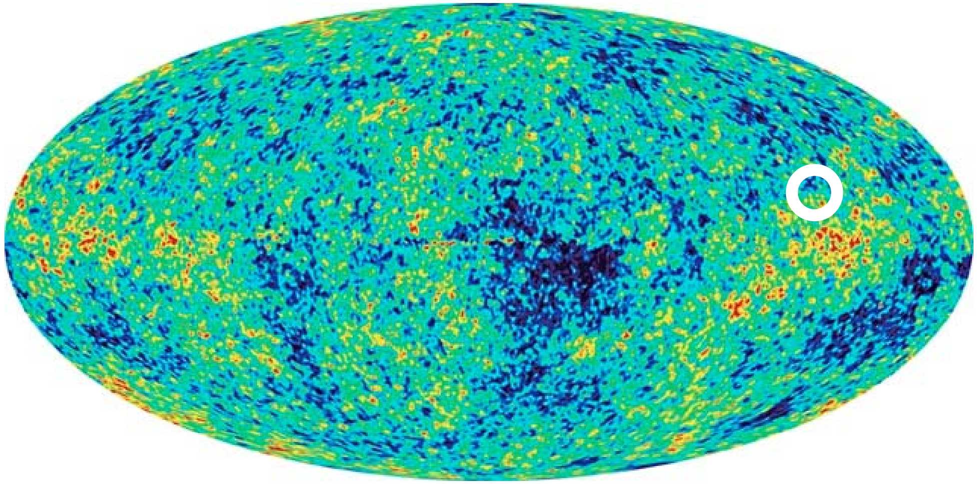
Foreground problem??





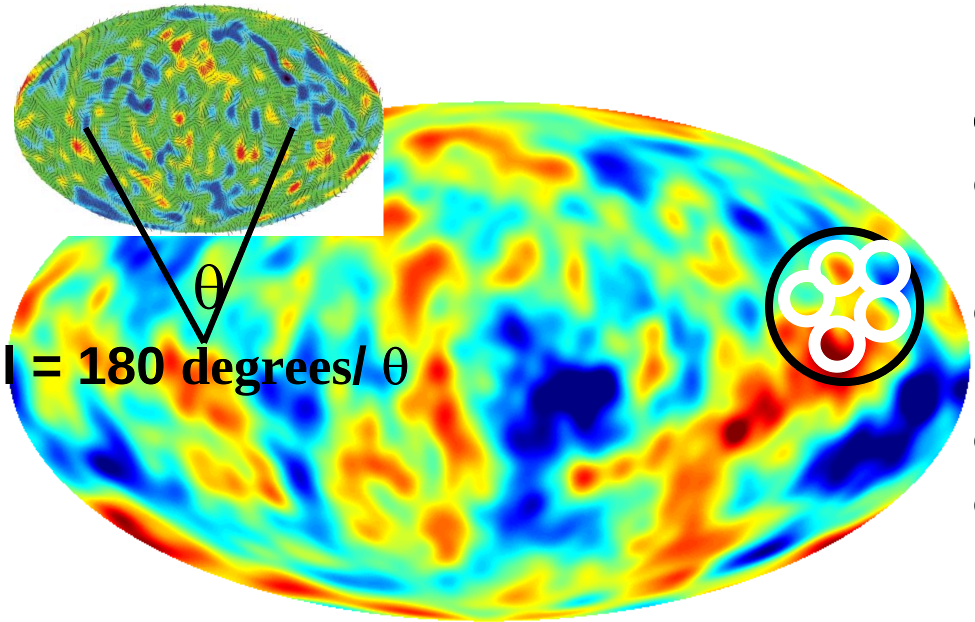






Size of a casually connected region (horizon -- distance travelled by light in 400,000 yrs) is about 1° now

At last scattering surface, 400,000 yrs after big-bang

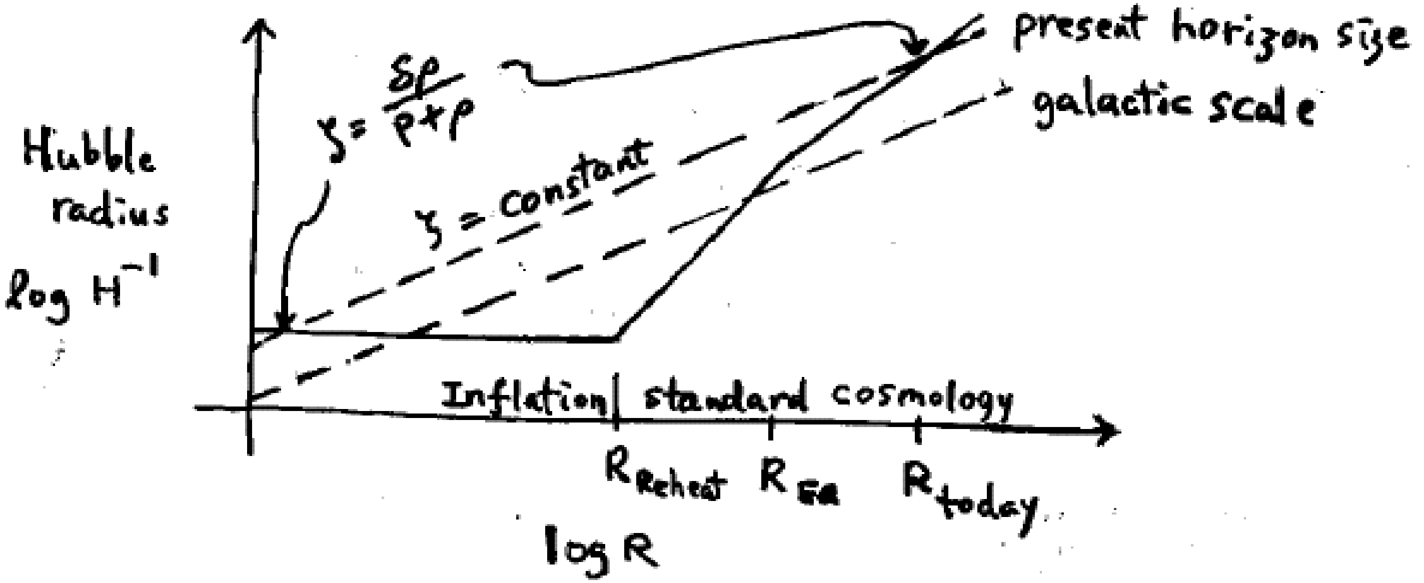


- 7° angular scale
- Each 7° pixel contains many 1° regions
- Measuring super-horizon temperature fluctuations
- So smooth (1 in 10^5)!! Why??
- Primordial density fluctuations that seed large scale structures

COBE DMR MAP

Inflation and Primordial Density Fluctuations

Evolution of cosmological density perturbation

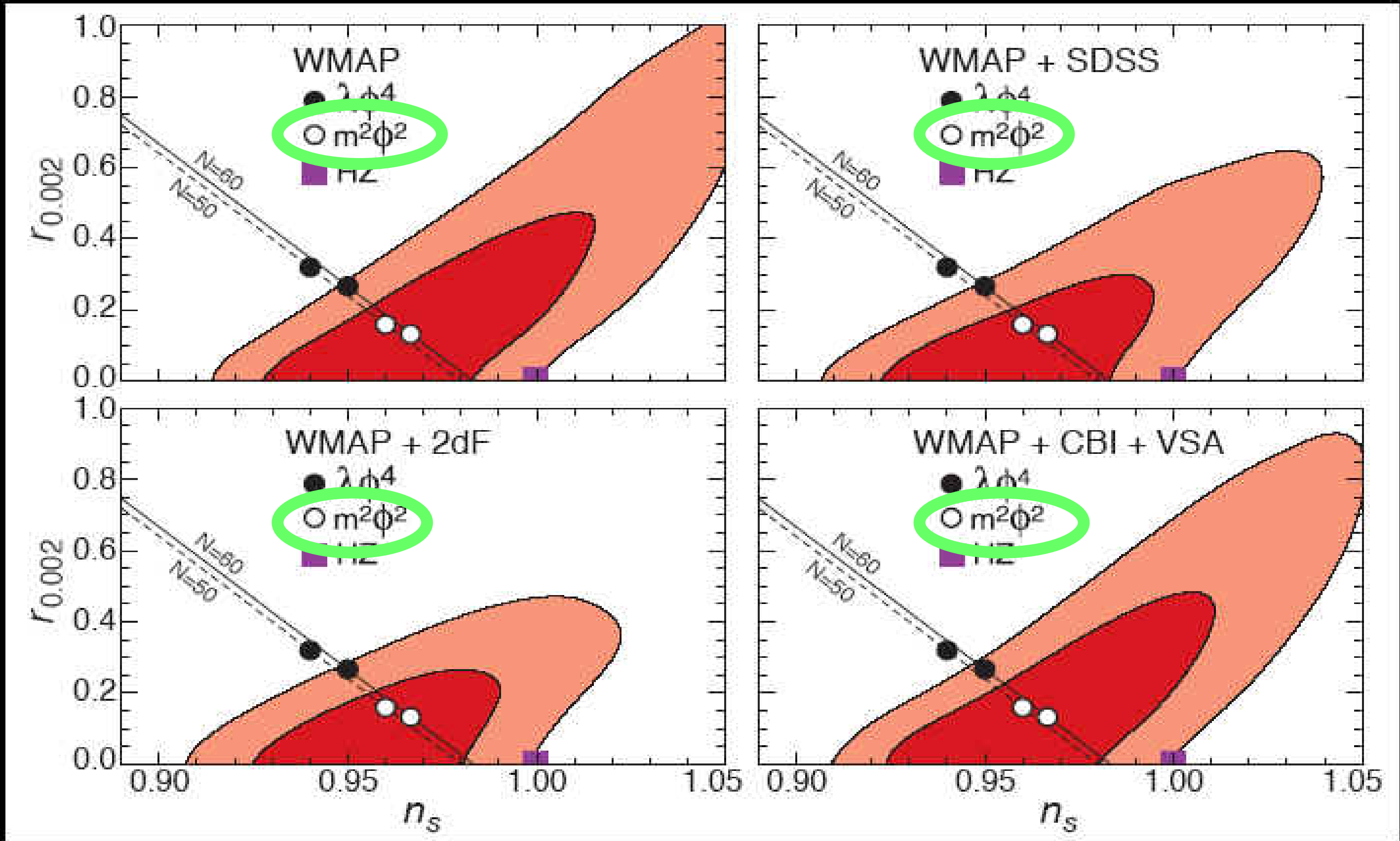


Evolution of gauge-invariant ζ Bardeen, Steinhardt & Turner 1983

- For super-horizon modes ζ = constant
- At horizon crossing $(\sim H^{-1})$ $\zeta = \dfrac{\delta\rho}{p+\rho}$

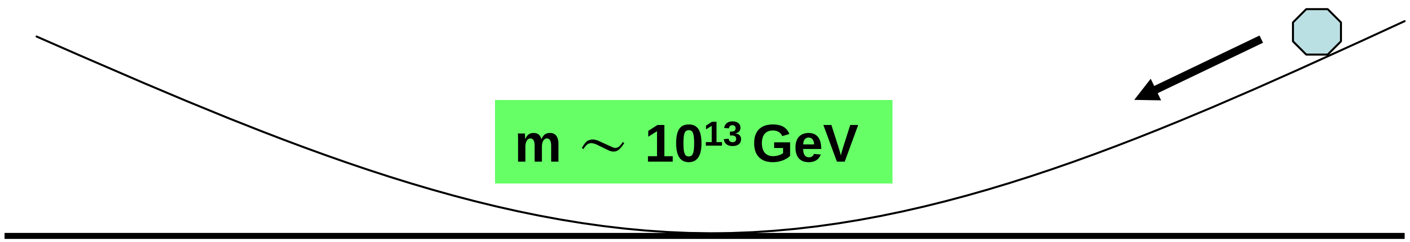
WMAP3 and chaotic inflation

r : tenor/scalar



Spectral index $n(k) - 1 \equiv \frac{d \ln \mathcal{P}_{\mathcal{R}}}{d \ln k}$

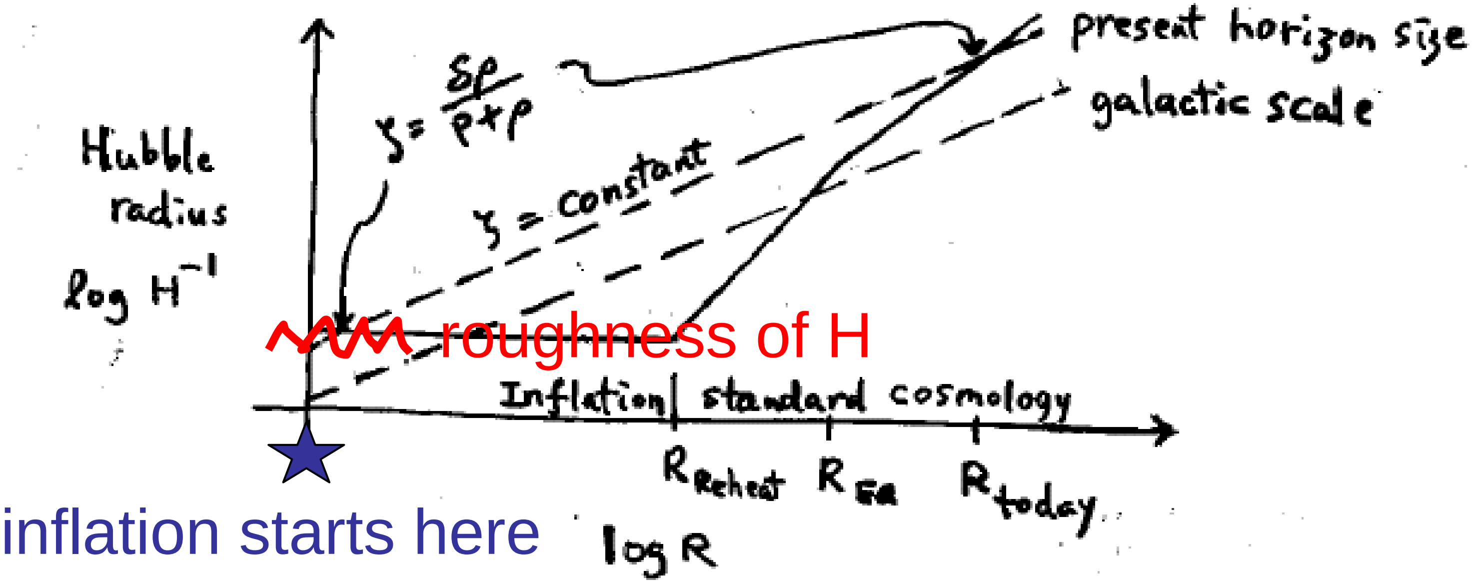
Spergel et al (2006)



m $\sim 10^{13}$ GeV

Inflation and Primordial Density Fluctuations

Evolution of cosmological density perturbation



Evolution of gauge-invariant ζ Bardeen, Steinhardt & Turner 1983

- For super-horizon modes ζ = constant
- At horizon crossing $(\sim H^{-1})$ $\zeta = \frac{\delta\rho}{p+\rho}$

periodic universe, more…..

During inflation

$$\delta\rho = \delta\rho_\phi = \frac{\partial V}{\partial \phi}\delta\phi$$

$$P+\rho = P_\phi + \rho_\phi = \left(\frac{1}{2}\dot{\phi}^2 - V\right) + \left(\frac{1}{2}\dot{\phi}^2 + V\right) = \dot{\phi}^2$$

$$\therefore \quad \left.\frac{\delta\rho}{\rho}\right|_{\substack{\text{horizon}\\ \text{cross-in}}} \simeq \left.\frac{\delta\rho_\phi}{P_\phi+\rho_\phi}\right|_{\substack{\text{horizon}\\ \text{cross-out}}} = \left.\frac{\frac{\partial V}{\partial \phi}\delta\phi}{\dot{\phi}^2}\right|_{\substack{\text{horizon}\\ \text{cross-out}}}$$

$(P+\rho \simeq \rho)$

$\delta\phi \sim \frac{H}{2\pi}$ de Sitter quantum fluctuations

Hawking
Starobinsky 1982
Guth & Pi

A Challenge to Standard Slow-roll inflation!?

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 \left(\frac{H}{2\pi}\right)^2$$

Slow-roll kinematics

Quantum fluctuations

● Slow-roll conditions violated after horizon crossing (Leach et al)

●General slow-roll condition (Steward)

|n-1|~|dn/dlnk|

●Multi-field (Vernizzi, Tent, Rigopoulos, Yokoyama et al)

●etc

● Chaotic inflation – classical fluctuations driven by a white noise (Starobinsky) or by a colored noise (Liguori, Matarrese et al.) coming from high-k inflaton

●Driven by a colored noise from interacting quantum environment (Wu et al)

●Others

Our Inflaton-Scalar Interacting Model

(Wu et al 07)

To mimic the quantum environment, we consider a slow-rolling inflaton ϕ coupled to a quantum massive scalar field σ, with a Lagrangian given by

$$\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\,\partial_\nu\sigma - V(\phi) - \frac{m_\sigma^2}{2}\sigma^2 - \frac{g^2}{2}\phi^2\sigma^2, \tag{1}$$

where $V(\phi)$ is the inflaton potential that complies with the slow-roll conditions and g is a coupling constant.

Single-field inflation $\langle\, \sigma \,\rangle$ **= 0**

Trace out sigma field to obtain :

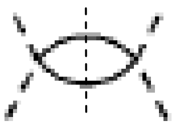
Langevin equation for ϕ

Feynman & Vernon 1963
Influence Functional Method

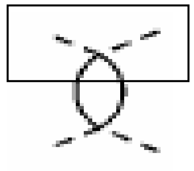
$$\ddot{\phi} + 2aH\dot{\phi} - \nabla^2\phi + a^2\left(V'(\phi) + g^2\langle\sigma^2\rangle\phi\right) - g^4a^2\phi \times$$
$$\int d^4x' a^4(\eta')\theta(\eta-\eta')\, i\, G_-(x,x')\phi^2(x') = \frac{\phi}{a^2}\xi, \qquad (3)$$

Dissipation

Noise



imaginary part



real part

Colored, dependent on history

$$\langle\xi(x)\xi(x')\rangle = g^4a^4(\eta)a^4(\eta')G_+(x,x')$$

$$G_\pm(x,x') = \langle\sigma(x)\sigma(x')\rangle^2 \pm \langle\sigma(x')\sigma(x)\rangle^2$$

To solve Eq. (3), let us first drop the dissipative term which we will discuss later. Then, after decomposing ϕ into a mean field and a classical perturbation: $\phi(\eta, \vec{x}) = \bar{\phi}(\eta) + \varphi(\eta, \vec{x})$, we obtain the linearized Langevin equation,

$$\boxed{\ddot{\varphi} + 2aH\dot{\varphi} - \nabla^2\varphi + a^2 m_{\varphi\mathrm{eff}}^2\varphi = \bar{\phi}\xi/a^2, \qquad (6)}$$

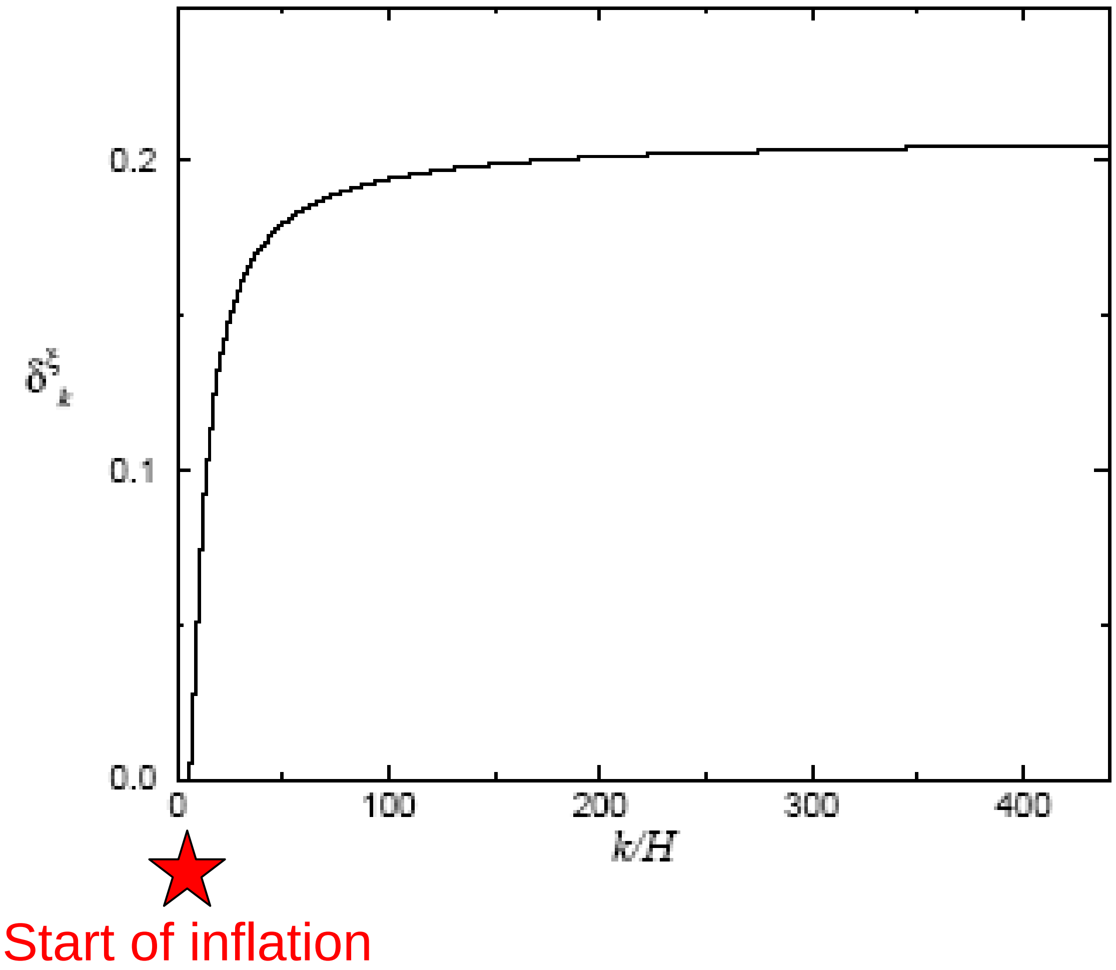
where the effective mass is $m_{\varphi\mathrm{eff}}^2 = V''(\bar{\phi}) + g^2\langle\sigma^2\rangle$ and the time evolution of $\bar{\phi}$ is governed by $V(\bar{\phi})$. The equation of motion for σ from which we construct its Green's function can be read off from its quadratic terms in the Lagrangian (1) as

$$\boxed{\ddot{\sigma} + 2aH\dot{\sigma} - \nabla^2\sigma + a^2 m_{\sigma\mathrm{eff}}^2\sigma = 0,} \qquad (7)$$

where $m_{\sigma\mathrm{eff}}^2 = m_\sigma^2 + g^2\bar{\phi}^2$.

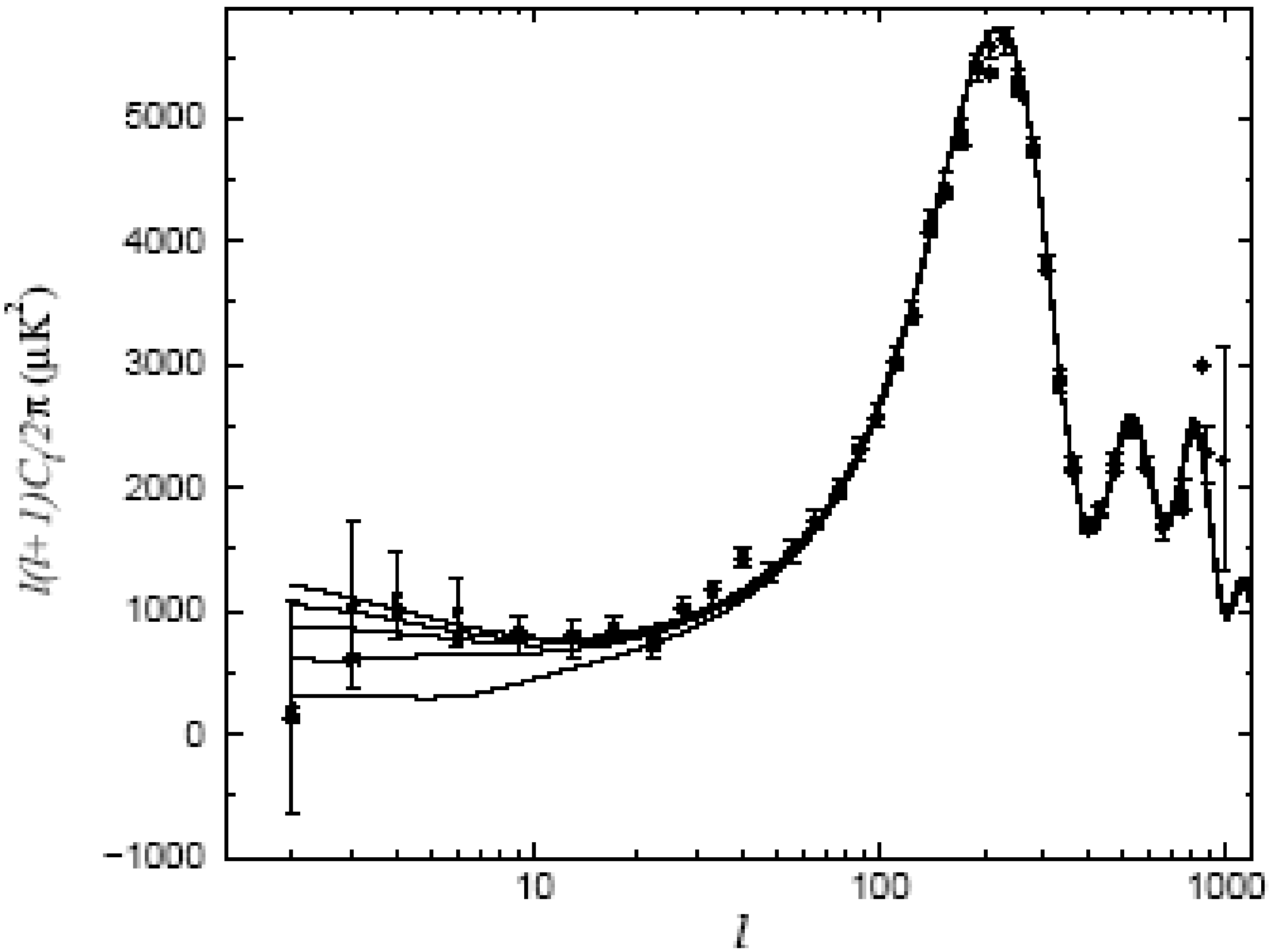
noise-driven power spectrum

$$\langle \varphi_{\vec{k}}(\eta)\varphi^*_{\vec{k}'}(\eta)\rangle = \frac{2\pi^2}{k^3}\Delta^{\xi}_{k}(\eta)\delta(\vec{k}-\vec{k}') \qquad \delta^{\xi}_{k} \equiv 4\pi^2\Delta^{\xi}_{k}/g^4\bar{\phi}_0^2$$



$$m^2_{\varphi\mathrm{eff}} \ll H^2$$
$$m^2_{\sigma\mathrm{eff}} = 2H^2$$
$$g^2\bar{\phi}^2 \le 2H^2$$

Dominant passive fluctuations and low CMB quadrupole



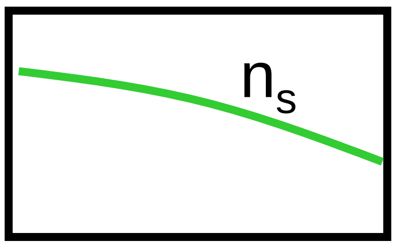
assuming no active de Sitter quantum fluctuations

Conclusion (I)

- We propose a new dynamical source for density perturbation: Colored Quantum Noise

  - give a low CMB quadrupole

- Can be applied to trapped inflation (Green et al. 09)
- Working on running spectral index and non-Gaussianity, both are natural with colored noise



Dissipation?

Relative large three-point functions

$$\langle \xi(x_1)\xi(x_2)\xi(x_3)\rangle$$

A Phase Transition

A ~ radiation component

B ~ vacuum energy

$$\rho = 3M_G^4\left(\frac{A}{a^4} + B\right)$$

Our simple model

Wang & Ng 08

$$a(t) = \left(\frac{A}{B}\right)^{\frac{1}{4}}\left[\sinh\left(2\sqrt{B}\Lambda t\right)\right]^{\frac{1}{2}}$$

$$a(t) \begin{cases} \Lambda t \ll \frac{1}{2}B^{-\frac{1}{2}} \;, \quad a(t) \sim \sqrt{2}A^{\frac{1}{4}}(\Lambda t)^{\frac{1}{2}} & \text{radiation} \\ \Lambda t \gg \frac{1}{2}B^{-\frac{1}{2}} \;, \quad a(t) \sim 2^{-\frac{1}{2}}\left(\frac{A}{B}\right)^{\frac{1}{4}} e^{\sqrt{B}\Lambda t} & \text{inflation} \end{cases}$$

Equation for inflation fluctuation

$$\varphi(t,\vec{y}) = \overline{\varphi} + \phi(t,\vec{y}) \qquad \Box\phi(t,\vec{y}) = 0$$

$$ds^2 = g_{\mu\nu}dy^\mu dy^\nu = dt^2 - a^2(t)d\vec{y}^2$$

$$\boxed{\ddot{\phi}_k(t) + 3\frac{\dot{a}}{a}\dot{\phi}_k(t) + \left(\frac{k^2}{a^2}\right)\phi_k(t) = 0 \qquad \dot{\phi}_k(t) \equiv \frac{d\phi_k(t)}{dt}}$$

$$\frac{d}{dt} = \frac{da}{dt}\frac{d}{da} \quad , \quad A/a_c^4 = B \quad , \quad x \equiv a - a_c \quad , \quad \rho = 3M_G^4\left(\frac{A}{a^4} + B\right)$$

$$\left[B(x+a_c)^4 + A\right]\phi_k''(x) + \left[4B(x+a_c)^3 + \frac{2A}{x+a_c}\right]\phi_k'(x) + k^2\phi_k(x) = 0 \ , \quad \phi_k'(x) \equiv \frac{d\phi_k(x)}{dx}$$

Initial condition

radiation-dominated when a is small

$$\begin{cases} \phi_k(x) = \dfrac{1}{a}\dfrac{1}{\sqrt{2k}}e^{ika/\sqrt{A}} \\[2ex] \phi_k'(x) = \left[-\dfrac{1}{\sqrt{2k}a^2} + \dfrac{i\sqrt{k}}{\sqrt{2A}a}\right]e^{ika/\sqrt{A}} \end{cases}$$

The power spectrum is a smooth curve…

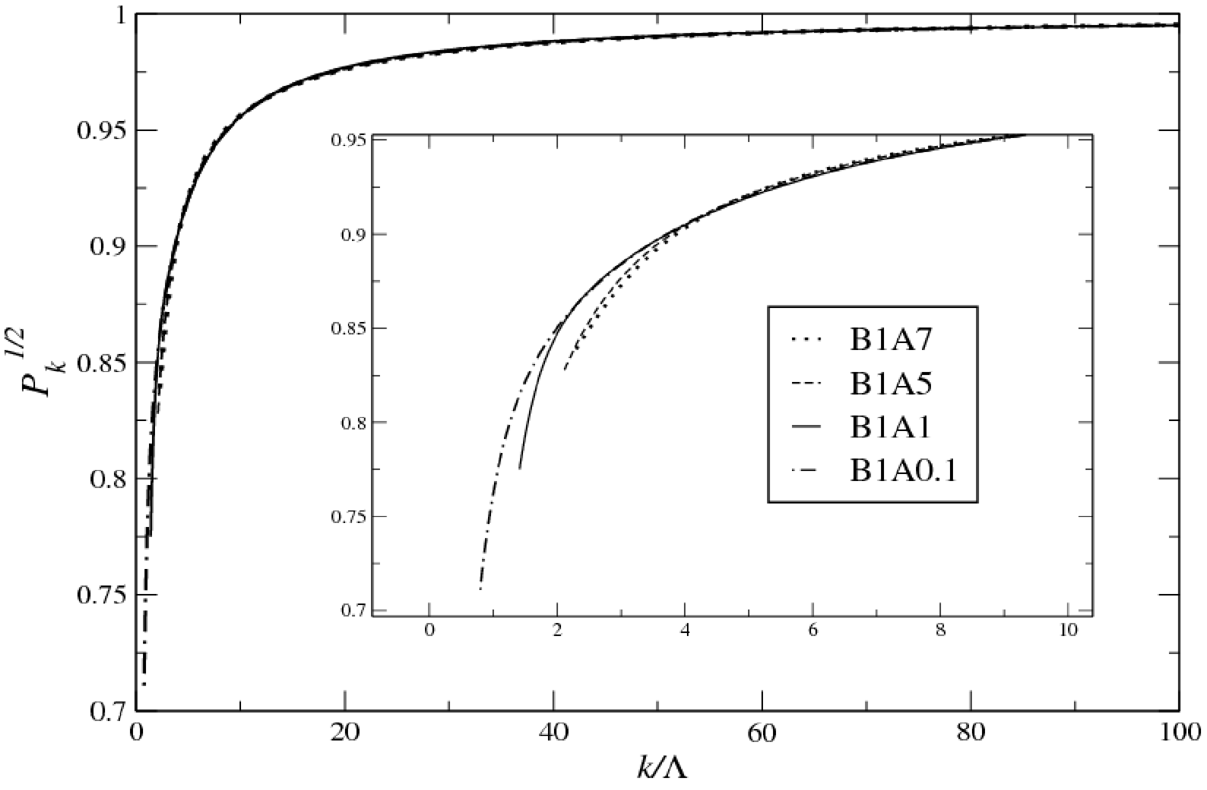
$$P_k^{1/2} \propto k^{3/2}\phi_k$$

$$k = aH$$

horizon crossing k mode

A ~ radiation component

B ~ vacuum energy



But…

A smooth power spectrum is obtained under two conditions

(1) a(t) is a smooth transition function

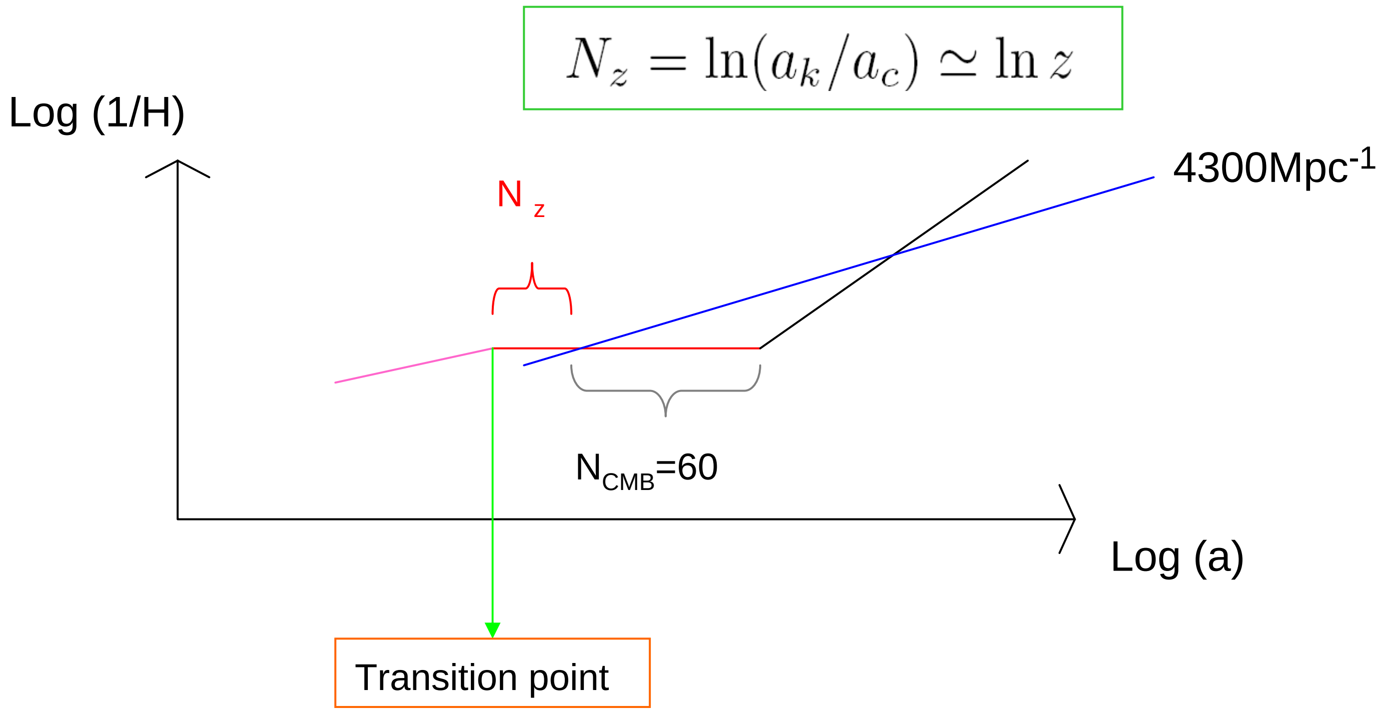
(2) initial a(t) can't be too close to the phase transition point

or

it will lead to oscillations on power spectrum

e.g. Contaldi et al. 03, Powell & Kinney 07

The meaning of z :



Pink line : radiation-dominated

Red line : inflation (vacuum energy dominated)

Numerical results

B=1, A=7, 5, 1 and 0.1

A ~ radiation component

B ~ vacuum energy

FIG. 2 (a) B1A7

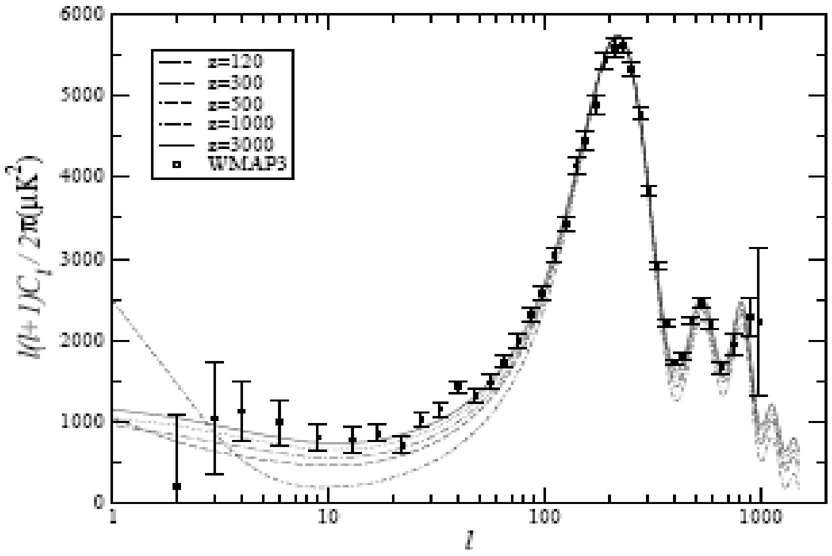


FIG. 2 (b) B1A5

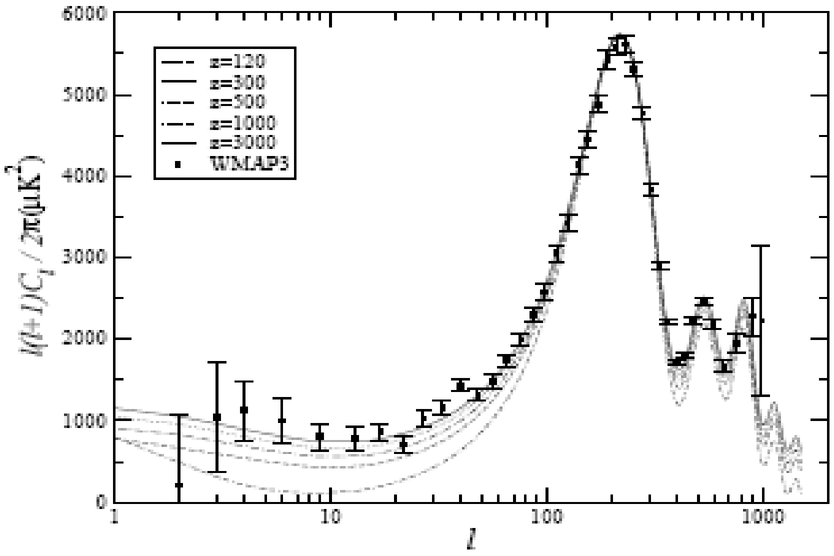


FIG. 2 (c) B1A1

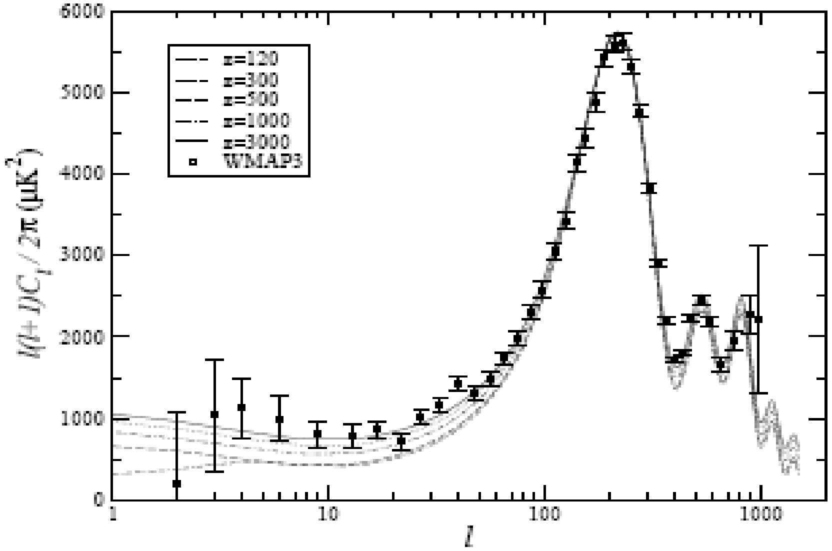
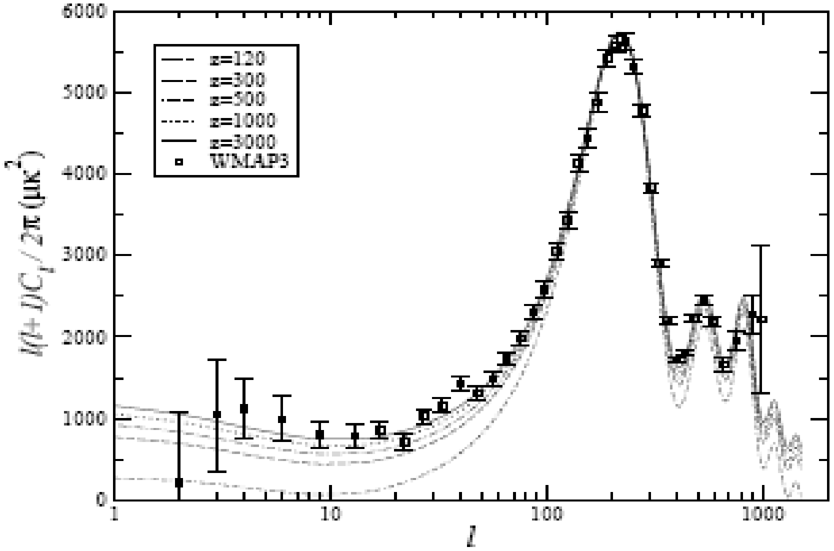


FIG. 2 (d) B1A0.1



B=0.1, A=7, 5, 1 and 0.1

FIG. 3 (a) B0.1A7

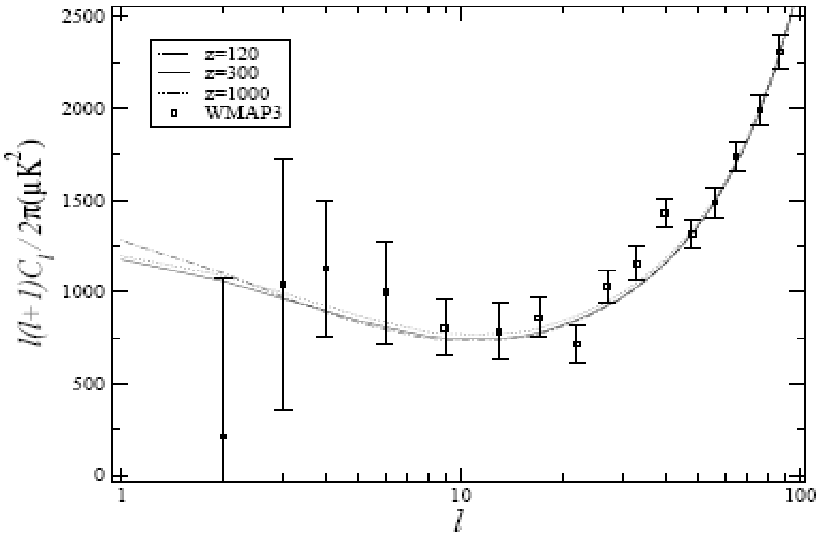


FIG. 3 (b) B0.1A5

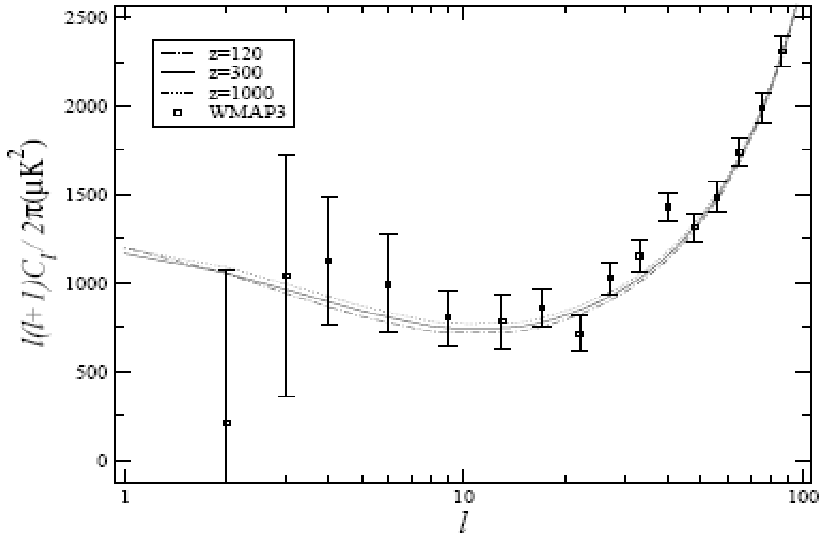


FIG. 3 (c) B0.1A1

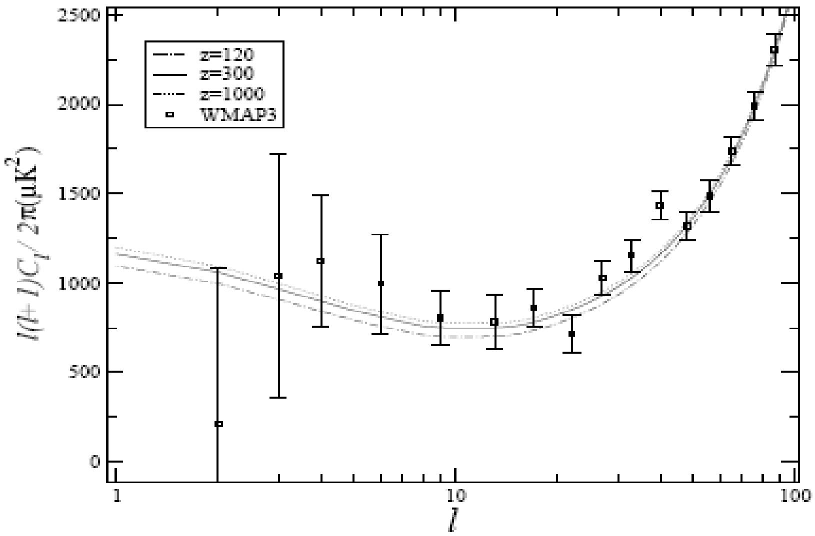
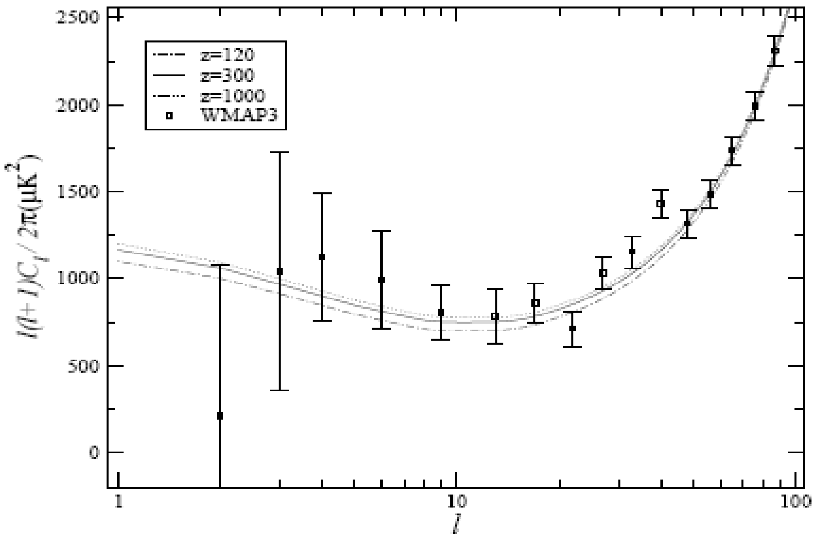


FIG. 3 (d) B0.1A0.1



Using WMAP3 data to the chi-square fitting of the CMB anisotropy spectrum

	$z=120$	$z=1000$	$z=3000$	$z=10^4$	$z=10^5$
$\chi^2(B0.1A7)$	59	49.83	47.97	47.43	47.11
$\chi^2(B0.1A5)$	67.3	49.66	47.89	47.32	47.11
$\chi^2(B0.1A1)$	80.08	49.08	47.67	47.23	47.09
$\chi^2(B0.1A0.1)$	77.98	48.63	47.49	47.2	47.08

$\rightarrow N_z \simeq 11.5$

Note the chi-square fitting for ΛCDM model is 47.09 in WMAP3 data

$$N = N_z + N_{cmb} \simeq 71.5 \text{ e-folds}$$

Using WMAP1 data to the chi-square fitting of the CMB anisotropy spectrum

	$z=120$	$z=1000$	$z=3000$	$z=10^4$	$z=10^5$
$\chi^2(B0.1A7)$	67.13	64.49	64.66	64.87	64.99
$\chi^2(B0.1A5)$	69.68	64.49	64.68	64.87	64.98
$\chi^2(B0.1A1)$	74.51	64.50	64.75	64.91	64.99
$\chi^2(B0.1A0.1)$	73.54	64.51	64.80	64.95	64.99

$\rightarrow N_z \simeq 7$

Note the chi-square fitting for ΛCDM model is 64.99 in WMAP1 data

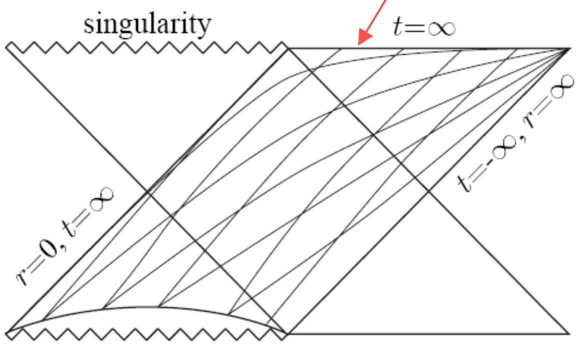
$$N = N_z + N_{cmb} \simeq 67$$

A black hole in inflation Cho, Ng, Wang 09

Schwarzschild-de Sitter

M - black hole mass
H - Hubble parameter

cosmological horizon



$$ds^2 = -\left(1 - \frac{2GM}{r} - H^2 r^2\right) dt^2 + \left(1 - \frac{2GM}{r} - H^2 r^2\right)^{-1} dr^2 + r^2 d\Omega^2,$$

change to the planar coordinates, see e.g. Shiromizu et al. 01

$$ds^2 = -f(r,\tau)d\tau^2 + h(r,\tau)(dr^2 + r^2 d\Omega^2),$$

$d\tau = a^{-1}(\tau)dt$ is the conformal time

$$f(r,\tau) = a^2(\tau)\left[1 - \frac{GM}{2a(\tau)r}\right]^2 \left[1 + \frac{GM}{2a(\tau)r}\right]^{-2}$$

$$a(t) = e^{Ht}$$

$$h(r,\tau) = a^2(\tau)\left[1 + \frac{GM}{2a(\tau)r}\right]^4$$

$$a(\tau) = -1/(H\tau)$$

Inflaton fluctuations

$$\phi(x) = \sum_{lm} \varphi_l(r,\tau) Y_{lm}(\theta,\phi) \qquad \varphi_l(r,\tau) = \int_0^\infty dk\, k^2 j_l(kr) \varphi_{kl}(\tau),$$

$d\tau = a^{-1}(\tau)dt$ is the conformal time

$$\varphi_l = \varphi_l^{(0)} + \varphi_l^{(1)} + \varphi_l^{(2)} + \cdots$$

$\epsilon \equiv GMH$

Expansion parameter

$$\partial_\tau^2 \varphi_l^{(0)} - \frac{2}{\tau}\partial_\tau \varphi_l^{(0)} - \partial_r^2 \varphi_l^{(0)} - \frac{2}{r}\partial_r \varphi_l^{(0)} + \frac{l(l+1)}{r^2}\varphi_l^{(0)} = 0.$$

$$\partial_\tau^2 \varphi_l^{(1)} - \frac{2}{\tau}\partial_\tau \varphi_l^{(1)} - \partial_r^2 \varphi_l^{(1)} - \frac{2}{r}\partial_r \varphi_l^{(1)} + \frac{l(l+1)}{r^2}\varphi_l^{(1)} = J_1\,,$$

where the source term is given by

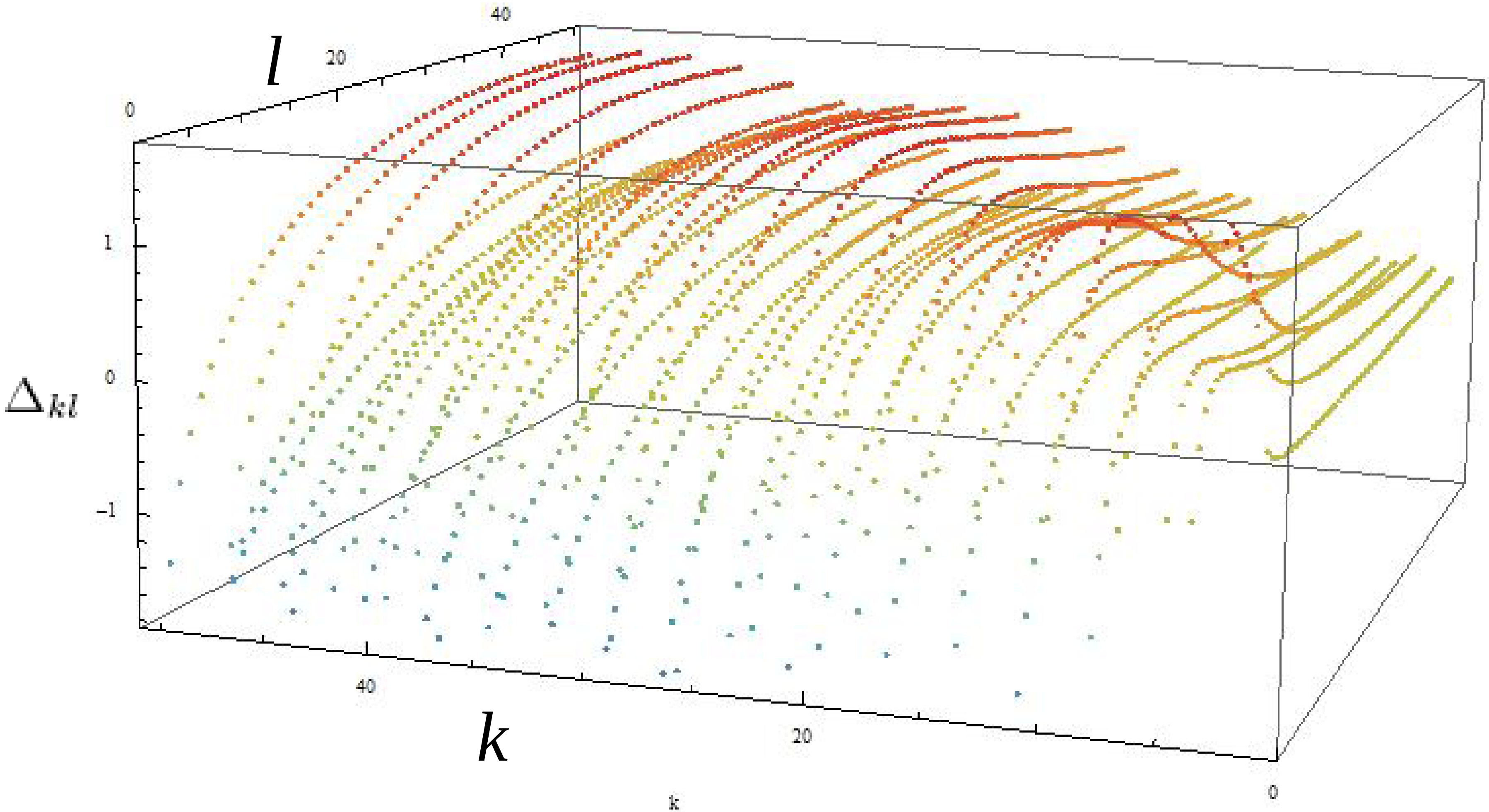
$$J_1(r,\tau) \ = \ \frac{4\epsilon\tau}{r}\left(\partial_\tau^2 \varphi_l^{(0)} - \frac{1}{\tau}\partial_\tau \varphi_l^{(0)}\right)$$

Power spectrum

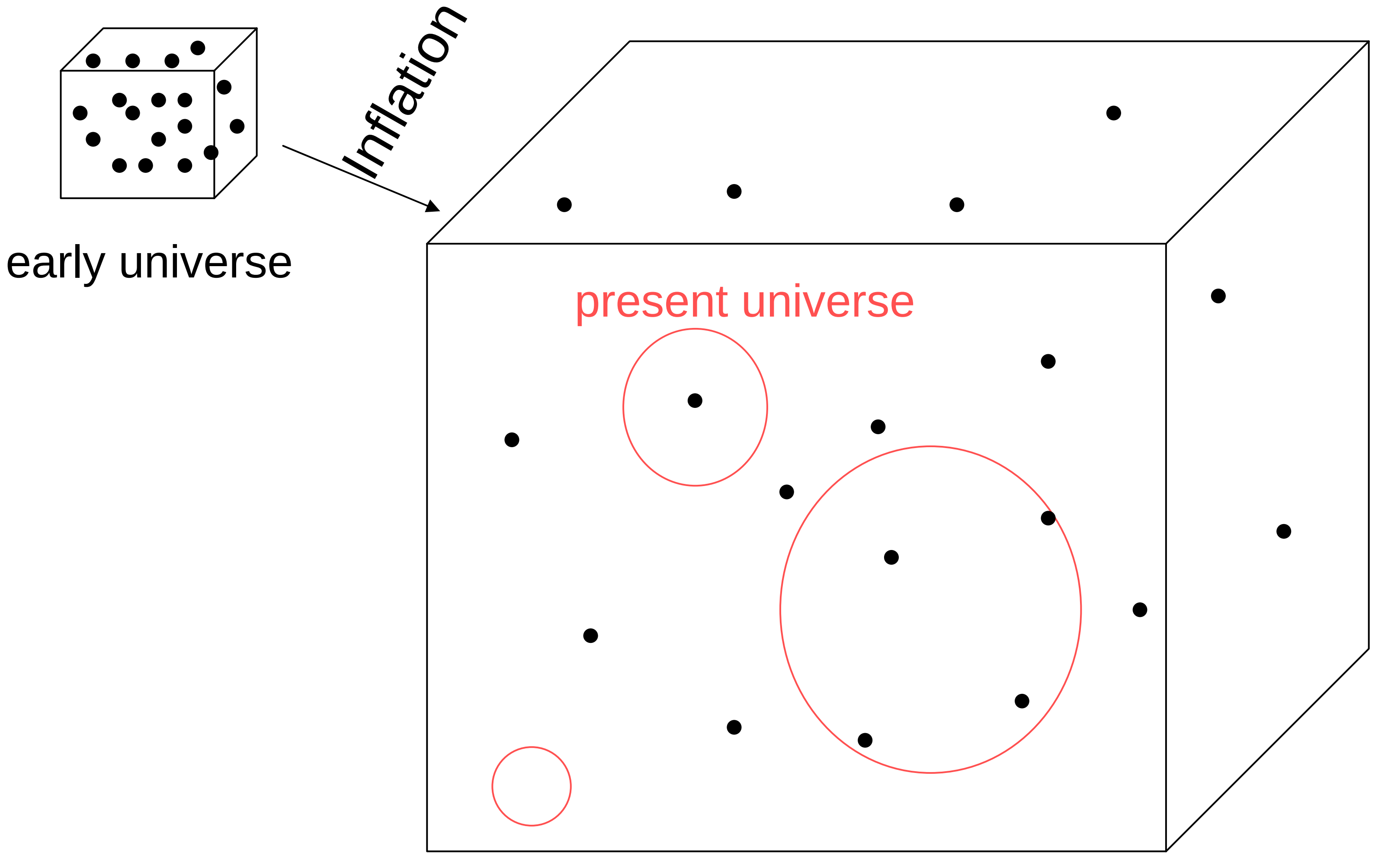
$$P_{kl}^{(0)}(\tau) = \frac{k^5}{4\pi}\left|\varphi_{kl}^{(0)}(\tau)\right|^2 = \frac{H^2}{4\pi^2}(1 + k^2\tau^2).$$

de Sitter
quantum fluctuations

End of inflation $\tau \to 0$ $\quad P_{kl}^{(1)} \longrightarrow \frac{H^2}{4\pi^2}\epsilon\Delta_{kl}, \quad \epsilon \equiv GMH$



Possible effects to CMB anisotropy



Carroll, Tseng, & Wise 08 preferred point, line, or plane

Final Conclusions

- Hints from WMAP data on beyond standard slow-roll inflation !?
- A fine tuning – physics just at 60 e-foldings
- Maybe there is a window to see the first few e-foldings of inflation !?
- Or we are all fooled by probability – it is indeed a Gaussian quantum process
- Nongaussianity is an important check