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The Lancaster, Manchester, Sheffield Consortium for Fundamental Physics

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The CMB Power Asymmetry from Scalars

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arXiv: 1309.1122

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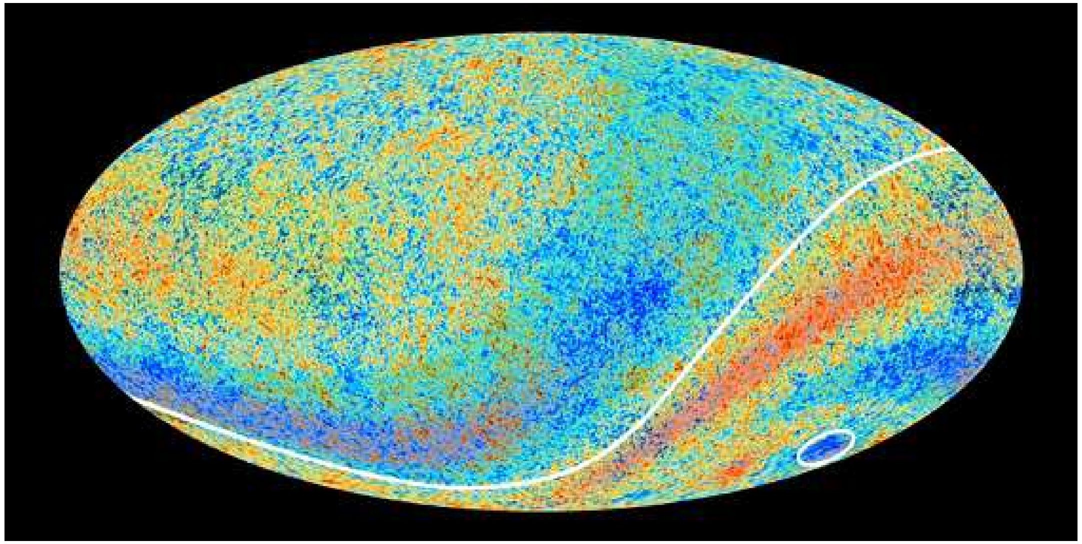
CMB Power Asymmetry



WMAP observed a hemispherical asymmetry in the magnitude of CMB temperature fluctuations on large angular scales > 5^{o} (low CMB multipoles l)

Magnitude confirmed by Planck, with much smaller errors

Suggests a superhorizon fluctuation of a scalar field

[Other large-angle anomalies: low power, Cold Spot …]

Can be modelled by a dipole

$$\frac{\delta T}{T}(\hat{n}) = s(\hat{n})\left[1 + A(\hat{n} \cdot \hat{p})\right]$$

[Gordon et al astro-ph/0509301]

WMAP5 (ILC) : A = 0.072 ± 0.022

Direction (l, b) = (224, -22) ± 24

[Hoftuft et al 0903.1229]

Planck (SMICA): A = 0.073 ± 0.010

Direction (l, b) = (217.5, -20.2) ± 15

[Planck collab 1303.5083]

Explanations?

Primordial: Scalar field-based :

Long-wavelength fluctuation of:

Inflaton: Mean CMB temp anisotropy too large

Curvaton : Probably too much non-Gaussianity

Modulated Reheating: Can fit all constraints JMcD: 1309.1122

Astrophysical, phenomenological: spatial variation of the spectral index, inhomogeneous reionization optical depth, …

[Dai et al 1303.6949]

Constraints

A successful model must satisfy:

Large angle power asymmetry: A = 0.072 (Average over $l < l_{max} = 64$)

Suppressed small-angle asymmetry (large l): Quasar number counts => $A < 0.012$ (95% cl) at $l \sim 15000$

Hirata 0907.0703

=> Need scale-dependent asymmetry

CMB temperature homogeneity No large quadrupole $a_{20} < 1.9 \times 10^{-5}$

Erickcek et al 0907.0705

Planck Non-Gaussianity bound: $f_{NL}^{local} \lesssim 80$ WMAP5

$f_{NL}^{local} = 2.7 \pm 5.8$ (1-σ) Planck

Inflaton

Erickcek, Kamionkowski, Carroll 0806.0377

Superhorizon inflaton modulation can modulate the CMB power spectrum

$$\sigma = \overline{\sigma} + \overline{\sigma}_k \sin\left(\mathbf{k}.\mathbf{x} + \omega_o\right)$$

[simply assumed]

But the inflaton fluctutation produces a large energy density fluctuation

=> Large fluctuation in the mean CMB temperature

=> too large CMB quadrupole

=> Modulation must come from a second scalar field

Curvaton

Erickcek, Carroll, Kamionkowski 0808.1570

Can modulate curvaton fluctuations via a superhorizon curvaton mode

$$\sigma = \overline{\sigma} + \overline{\sigma}_k \sin(\mathbf{k}.\mathbf{x} + \omega_o)$$

Curvaton: $\rho \propto \sigma^2$ => $\delta\rho \propto \sigma \times \delta\sigma$ => σ modulates $\delta\rho$

To suppress CMB temperature quadrupole, need a small contribution to the energy density from the curvaton ~ $10^{-4}\ \rho_{total}$

Then a sub-dominant curvaton contribution with large fluctuation $\delta\rho_\sigma / \rho_\sigma \sim 10^{-2}$ combined with large spatial modulation of the curvaton mean field across our horizon can account for the 10% asymmetry on large scales $\frac{\Delta\sigma}{\sigma} \gtrsim 0.5$

=> O(10) % asymmetric contribution to total adiabatic perturbation

But cannot account for suppression of asymmetry at quasar number count scales, since $\delta\sigma$ has no scale-dependence

Need to suppress the curvaton contribution to the perturbation at small scales

Curvaton + DM isocurvature model

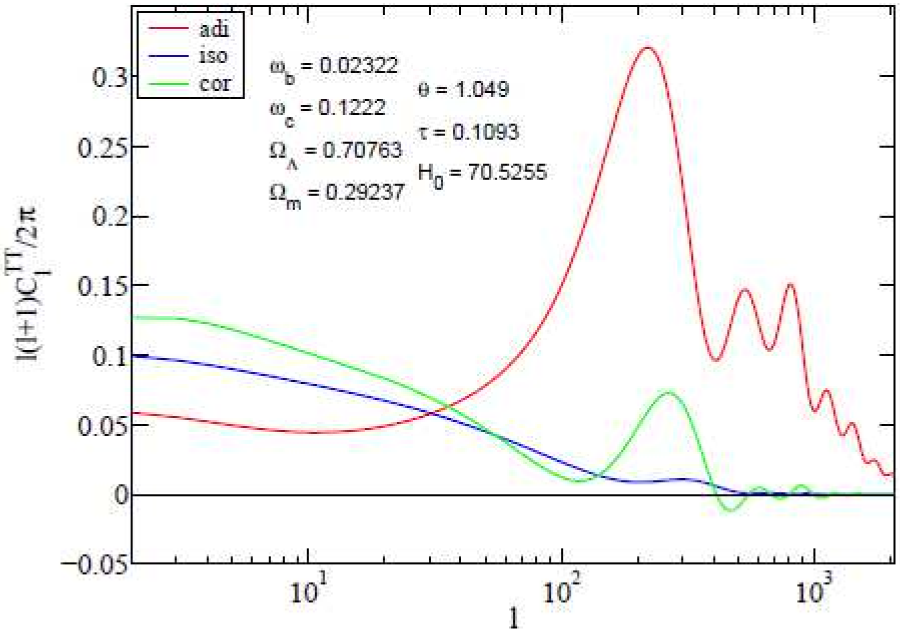
Erickcek, Hirata, Kamionkowski 0907.0705

To satisfy the quasar constraint, the asymmetry must be scale-dependent

Subdominant curvaton decays to subdominant dark matter density

=> Mixture of adiabatic and DM isocurvature from curvaton decay

Isocurvature component of CMB power decreases relative to the adiabatic perturbation at small scales => suppresses asymmetry $\Delta C_{l\ iso} / C_l$



Model can <u>just</u> produce sufficiently large asymmetry on large scales

A = 0.072 , satisfy quasar bound on small scales A < 0.012

and satisfy WMAP5 bounds on the isocurvature fraction and Non-Gaussianity + CMB quadrupole bound

Isocurvature $\alpha_{iso} < 0.072$ (2-σ)

Non-Gaussianity $f_{NL}^{local} \lesssim 80$

Planck constraints much stronger, especially non-Gaussianity

Isocurvature $\alpha_{iso} < 0.036$ (2-σ) at $k_o = 0.002\ \mathrm{Mpc}^{-1}$

Non-Gaussianity $f_{NL}^{local} = 2.7 \pm 5.8$ (1-σ)

$$f_{\rm NL} = \frac{5\xi^2}{4R} \qquad \xi \equiv \frac{P_{\zeta_{adi\,curv}}}{P_{\zeta_{adi\,total}}}$$

Smaller f_{NL} => smaller curvaton perturbation

⇒ Probably cannot account for the CMB asymmetry

$R = \rho_{curv}/\rho_{totoal} \sim 10^{-4}$

- Inflaton and curvaton appear ruled out as a source of the CMB power asymmetry
- Non-Gaussianity is a strong constraint

=>

Need a new source for the asymmetry which
produces small non-Gaussianity

A complete model should also explain the superhorizon
fluctuation which spatially modulates the CMB temp fluctuations

A complete model that works:

Scale-Dependent Modulated Reheating + Tachyonic Growth Model

Modulated Reheating => CMB power asymmetry from the scalar field
without large non-Gaussianity

JMcD 1309.1122

Tachyonic Growth Model => Superhorizon scalar field perturbation
with asymmetry and scale-dependence

JMcD 1305.0525 , JCAP

Tachyonic Growth Model

JMcD 1305.0525, JCAP

A way to generate large superhorizon field fluctuations

$$V(\Sigma) = -cH^2|\Sigma|^2 + V_{lift}(\Sigma)$$

$$\Sigma \equiv (\Sigma_o/\sqrt{2})e^{i\sigma/\Sigma_o} = (\sigma_1 + i\sigma_2)/\sqrt{2}$$

σ **is the field which modulates the inflaton decay rate**

Field is initially at $\Sigma = 0$. At some time a phase transition occurs and field evolves in the tachyonic part of the potential from an initial Bunch-Davies vacuum on sub-horizon scales

$\Rightarrow$ Mean field σ and change $\Delta\sigma$ in a given horizon volume after ΔN e-foldings

Superhorizon fluctuations after ΔN e-foldings =>

(a) Mean field in a horizon volume

Wigner fn. semiclassical analysis

$$\phi_{\mathbf{k}}(1) = \frac{1}{\sqrt{2k}}\left(1+\frac{H^2}{k^2}\right)^{1/2} \qquad \frac{\partial\phi_{\mathbf{k}}}{\partial a}(1) = \frac{1}{\sqrt{2k}}\left(1+\frac{H^2}{k^2}\right)^{-1/2}$$

Bunch-Davies initial conditions

$$\frac{\partial^2\phi_{\mathbf{k}}}{\partial a^2} + \frac{4}{a}\frac{\partial\phi_{\mathbf{k}}}{\partial a} + \frac{k^2}{a^4H^2}\phi_{\mathbf{k}} = \frac{c}{a^2}\phi_{\mathbf{k}}\,.$$

=>

$$\phi_{\mathbf{k}}(a) = \frac{c_1}{a^{3/2}}J_{-\frac{1}{2}\sqrt{4c+9}}\left(\frac{k}{aH}\right) + \frac{c_2}{a^{3/2}}J_{\frac{1}{2}\sqrt{4c+9}}\left(\frac{k}{aH}\right)$$

=> RMS field due to superhorizon modes:

$$\bar{\phi}^2 \equiv \langle \phi(\mathbf{x},t)^2 \rangle = \frac{1}{(2\pi)^3}\int |\phi_{\mathbf{k}}|^2 d^3k$$

Mean field in a horizon volume

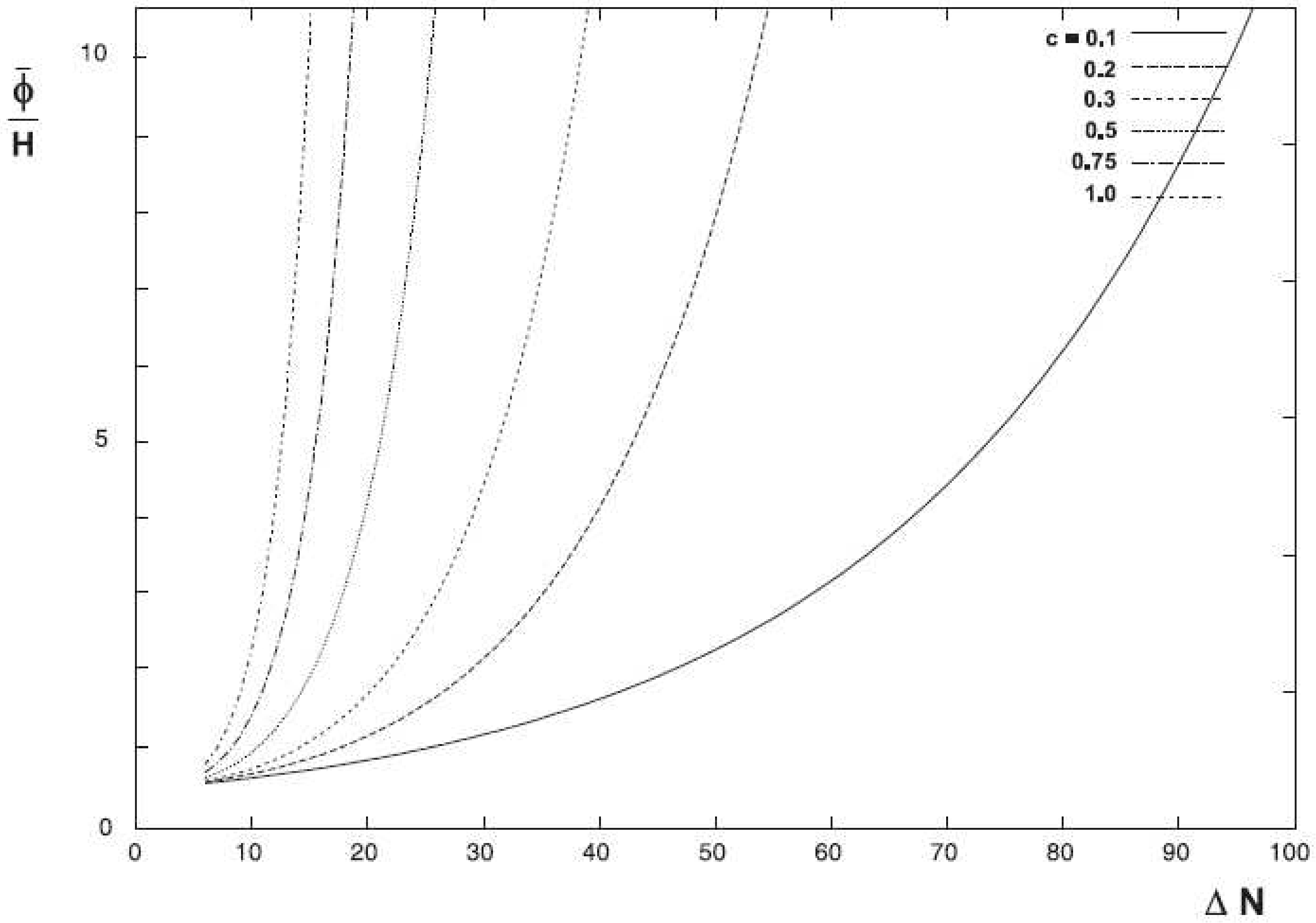


FIG. 2: Values of $\bar{\phi}/H$ versus ΔN for c in the range 0.1 to 1.0.

$\frac{\bar{\phi}}{H}$ **~ 1-10 in cases of interest**

(b) Mean change in field across the horizon

$$\overline{\Delta\phi}^2 \equiv <(\delta\phi_1(\mathbf{x}+\delta\mathbf{x})-\delta\phi_1(\mathbf{x}))^2>=\frac{2}{\pi^2}\int_{k_{min}}^{k_{max}}|\phi_{\mathbf{k}}|^2\sin^2\left(\frac{k}{2aH}\right)k^2dk$$

sum over superhorizon modes

c = 0.5 =>
ΔΦ/Φ = 0.5 after 20 e-foldings

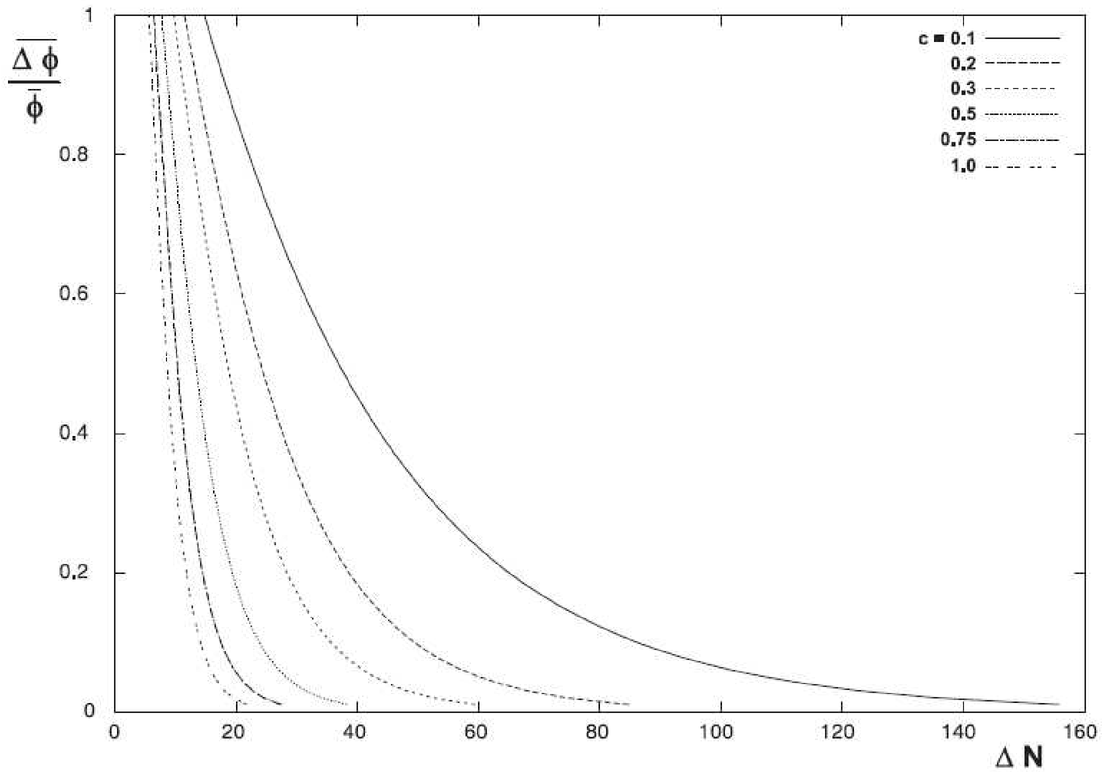


FIG. 1: Values of $\overline{\Delta\phi}/\bar{\phi}$ versus ΔN for c is the range 0.1 to 1.0.

Dominated by modes close to horizon size

The perturbation spectrum of the modulating field σ

$\phi \leftrightarrow \sigma_1, \sigma_2$ $$\Sigma \equiv (\Sigma_o/\sqrt{2})e^{i\sigma/\Sigma_o} = (\sigma_1 + i\sigma_2)/\sqrt{2}$$

σ_1 = radial direction $\delta\sigma_2$ = phase fluctuation

$$P_{\delta\sigma} = \left(\frac{P_{\delta\sigma_2}}{\overline{\sigma}_1^2}\right)_N \frac{\Sigma_o^2}{\left(1+\frac{\Delta\overline{\sigma}_1}{\overline{\sigma}_1}\right)_*^2} \qquad P_{\delta\sigma_2} = H^2/4\pi^2$$

Red spectrum for c > 0

Due to time evolution of mean radial field

=> Scale-dependence

$$n_\sigma = 4 - \sqrt{4c+9}$$

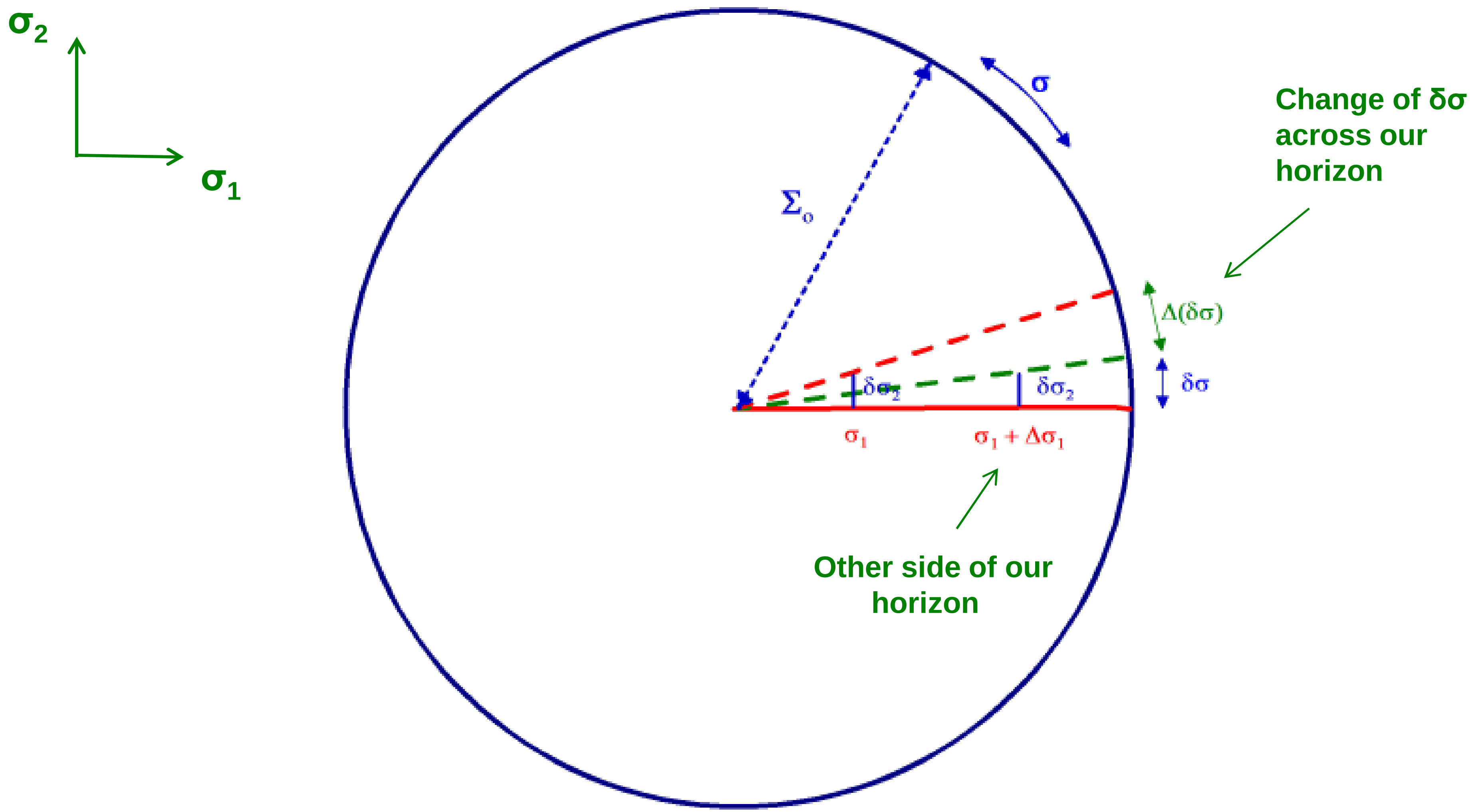
Intrinsic spatial variation of σ power spectrum

Due to mean change in radial field across the horizon

=> Asymmetry

=> σ has the right form of perturbation to generate the CMB power asymmetry

Spatial variation of δσ perturbation



$$\Sigma \equiv (\Sigma_o/\sqrt{2})e^{i\sigma/\Sigma_o} = (\sigma_1 + i\sigma_2)/\sqrt{2}$$

The perturbation spectrum of the modulating field σ.

$\phi \leftrightarrow \sigma_1,\ \sigma_2$

$$\Sigma \equiv (\Sigma_o/\sqrt{2})e^{i\sigma/\Sigma_o} = (\sigma_1 + i\sigma_2)/\sqrt{2}$$

σ_1 = radial direction $\delta\sigma_2$ = phase fluctuation

$$P_{\delta\sigma} = \left(\frac{P_{\delta\sigma_2}}{\bar{\sigma}_1^2}\right)_N \frac{\Sigma_o^2}{\left(1+\frac{\Delta\bar{\sigma}_1}{\bar{\sigma}_1}\right)_*^2}$$

$$P_{\delta\sigma_2} = H^2/4\pi^2$$

Red spectrum for c > 0

Due to time evolution of mean radial field

=> Scale-dependence

$$n_\sigma = 4 - \sqrt{4c+9}$$

Intrinsic spatial variation of $\delta\sigma$ power spectrum

Due to mean change in radial field across the horizon

=> Asymmetry

=> σ has the right form of perturbation to generate the CMB power asymmetry

CMB power asymmetry from Modulated Reheating

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Modulated reheating can produce a large CMB power asymmetry without large non-Gaussianity if the inflaton decay rate is linear in the modulating field.

=> Modulating field perturbation must have an intrinsic asymmetry

$\delta\rho \propto \delta\sigma$ [unlike curvaton $\delta\rho \propto \sigma\delta\sigma$]

- Modulated reheating contribution should have a red scale-dependence to suppress the asymmetry at small quasar scales

Both properties consistent with the Tachyonic Growth Model

Modulated Reheating model

Couple the complex Σ from tachyonic growth to the inflaton decay process

$$L_{int} \supset -y(\Sigma)\phi\psi_a\psi_a \ + \ h.c.$$

ϕ = **inflaton**

$$y(\Sigma) = y_o\left(1+\alpha\frac{\Sigma}{\Lambda}+\beta\frac{\Sigma^2}{\Lambda^2}+\dots\right)$$

$$\Sigma = (\Sigma_o/\sqrt{2})e^{i\sigma/\Sigma_o}$$ **=>** $$\frac{\sigma}{\Sigma_o} \lesssim 0.1$$

$$\Gamma = \Gamma_o\left(1+\frac{\tilde{\alpha}\sigma}{\Sigma_o}+\frac{\tilde{\beta}\sigma^2}{\Sigma_o^2}+\dots\right)$$

Modulated inflaton decay rate

Adiabatic perturbation

$$\zeta_{MR} = Q_\sigma\delta\sigma + \frac{1}{2}Q_{\sigma\sigma}\delta\sigma^2 + \dots,$$

[Ichikawa et al 0807.3988]

$$Q_\sigma = A\Gamma_\sigma/\Gamma \ ; \ Q_{\sigma\sigma} = A\Gamma_{\sigma\sigma}/\Gamma + B(\Gamma_\sigma/\Gamma)^2$$

$$A = -1/6$$
$$B = 1/6$$

=> $$\zeta_{MR} \approx -\frac{1}{6}\frac{\Gamma_\sigma}{\Gamma}\delta\sigma \approx -\frac{1}{6}\frac{\tilde{\alpha}}{\Sigma_o}\delta\sigma$$

CMB Asymmetry on large angles

CMB adiabatic perturbation is sum of inflation + modulated reheating

$$\zeta = \zeta_{inf} + \zeta_{MR} \quad \Rightarrow \quad P_\zeta = P_{inf} + P_{\zeta_{MR}}$$

$$\Rightarrow \quad \frac{\Delta C_l}{C_l} = \frac{\Delta P_{\zeta_{MR}}}{P_\zeta} = \xi \frac{\Delta P_{\zeta_{MR}}}{P_{\zeta_{MR}}}$$

Change of C_l across horizon

$$\frac{\Delta P_{\zeta_{MR}}}{P_{\zeta_{MR}}} = \frac{\Delta P_{\delta\sigma}}{P_{\delta\sigma}} \quad , \quad P_{\delta\sigma} = \left(\frac{P_{\delta\sigma_2}}{\overline{\sigma}_1^2}\right)_N \frac{f_d^2 \Sigma_o^2}{\left(1 + \frac{\Delta\overline{\sigma}_1}{\overline{\sigma}_1}\right)_*^2}$$

(tachyonic growth)

$$\Rightarrow \quad \left|\frac{\Delta C_l}{C_l}\right| \approx 2 \left|\frac{\Delta\overline{\sigma}_{1\,*}}{\overline{\sigma}_{1\,*}}\right| \xi$$

$$\xi \equiv \frac{P_{\zeta_{MR}}}{P_{\zeta_{inf}}}$$

Ratio of adiabatic power from MR to that from inflaton

Radial field when our universe exits the horizon during inflation

Need to convert $\Delta C_l / C_l$ to A

$$\frac{\delta T}{T}(\hat{n}) = s(\hat{n})\left[1 + A(\hat{n}\cdot\hat{p})\right]$$

$$\frac{\Delta\left(\frac{\delta T}{T}\right)^2}{\left(\frac{\delta T}{T}\right)^2} = \frac{\Delta C_l}{C_l} \quad \Rightarrow \quad A = \frac{1}{2}\frac{\Delta C_l}{C_l}$$

$$\Rightarrow \quad A = \left|\frac{\Delta\overline{\sigma}_{1\,*}}{\overline{\sigma}_{1\,*}}\right|\xi$$

<u>if</u> no ξ scale-dependence

If ξ is scale-dependent, average over $\frac{\Delta C_l}{C_l}$ up to $l_{max} = 64$

$$\Rightarrow \quad A \equiv \left|\frac{\Delta\overline{\sigma}_{1\,*}}{\overline{\sigma}_{1\,*}}\right|\tilde{A}$$

Erickcek, Hirata, Kamionkowski 0907.0705

where $$\tilde{A} = \sum_{l=2}^{l_{max}} \frac{2l+1}{(l_{max}-1)(l_{max}+3)}\xi(l) \qquad \xi = \left(\frac{l}{l_o}\right)^{n_\sigma - 1}\xi_o$$

Small-scale asymmetry: Quasar bound

Quasar number counts probe scales   k = (1.3-1.8) h Mpc^{-1}

=>   l ≈ 12400-17200

$\xi(l)$ does not change much over this range => set l = 15000

$$A_{small} \approx \frac{\Delta\sigma_*}{\overline{\sigma_*}}\xi(l = 15000)$$

A_{small} < 0.012

Power asymmetry from modulated reheating + tachyonic growth

c	ξ_o	A_{small}
0.0	0.049	0.072
0.2	0.052	0.034
0.4	0.055	0.016
0.49	0.0558	0.012
0.6	0.057	0.0081
0.8	0.060	0.0040
1.0	0.062	0.0021

$$P_{\zeta_{MR}} \propto \left(\frac{k}{k_o}\right)^{n_\sigma - 1}$$

$$n_\sigma = 4 - \sqrt{4c+9}.$$

$$V(\Sigma) = -cH^2|\Sigma|^2$$

TABLE I: ξ_o and A_{small} as a function of c when $A_{large} = 0.072$ and $\Delta\bar{\sigma}_{1*}/\bar{\sigma}_{1*} = 0.5$.

Modulated Reheating can account for the large scale asymmetry and satisfy quasar bound if $\xi_o \approx 0.05$, $c > 0.5$ (=> $n_\sigma < 0.689$)

5% of the adiabatic perturbation power is from modulated reheating
Strongly scale dependent and with a large asymmetry

JMcD 1309.1122

Other Constraints

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$$\Gamma = \Gamma_o \left(1 + \frac{\tilde{\alpha}\sigma}{\Sigma_o} + \frac{\tilde{\beta}\sigma^2}{\Sigma_o^2} + \ldots \right) \qquad f_d = \frac{\sigma}{\Sigma_o}$$

CMB quadrupole:

$$\tilde{\alpha} \lesssim \frac{1.0 \times 10^{-2}}{\left(\frac{\Delta\bar{\sigma}_1}{\bar{\sigma}_1}\right)_* \left(\frac{kx_{dec}}{0.1}\right) \sin\omega_o f_d}$$

Non-Gaussianity:

$$\tilde{\alpha} \gtrsim 3.6 \times 10^{-3} \frac{1}{|\tan(\delta)|} \left(\frac{14}{|f_{NL\ lim}|} \right) \left(\frac{\xi_o}{0.1} \right)^2$$

Generation of adiabatic power:

$$\tilde{\alpha} \approx \frac{5.7 \times 10^{-4}}{f_d} \left(\frac{\xi_o}{0.1} \right)^{1/2} \left(\frac{\bar{\sigma}_1}{H} \right)_{N_o}$$

All constraints can be satisfied with reasonable values $\xi_o \sim 0.1$, $\tilde{\alpha} \sim 0.01 - 0.1$, $f_d \approx 0.01 - 0.1$

[f_d => damping of σ after tachyonic growth ends]

Testable Predictions?

The model introduces a strongly scale-dependent O(10)% contribution to the adiabatic perturbation

=> Shift of spectral index and running spectral index

$$P_\zeta = P_{\zeta_{inf}} + P_{\zeta_{MR}} = P_{\zeta_{inf}} \left(1 + \xi_o \left(\frac{k}{k_o} \right)^{n_\sigma - 1} \right)$$

$$n_s - 1 = \frac{1}{P_\zeta} \frac{dP_\zeta}{d\ln k}$$

$$\Delta n_s \approx \xi_o (n_\sigma - 1) \left(\frac{k}{k_o} \right)^{n_\sigma - 1}$$

$$n' \equiv \frac{dn_s}{d\ln k} = \xi_o (n_\sigma - 1)^2 \left(\frac{k}{k_o} \right)^{n_\sigma - 1}$$

Example: $\Delta\overline{\sigma}_{1*}/\overline{\sigma}_{1*} = 0.5$ $\quad c = 0.49$ **=>** $\xi_o = 0.0558$ $\quad n_\sigma = 0.689$

=> $\Delta n_s = -0.0174$ **,** $n' = 0.002$ at $k = 0.05\mathrm{Mpc}^{-1}$

Planck: $n_s = 0.9603 \pm 0.0073$ $\quad n' = -0.013 \pm 0.009$

Modifies common inflation models eg log potential hybrid inflation:

$$n_{s\,inf} = 1 - 1/N = 0.983$$
$$n' = -1/N^2 \sim -3 \times 10^{-4}$$

→

$$n_{s\,inf} + \Delta n_s = 0.966$$
$$n' = 0.002$$

Summary

Modulated Reheating can account for the CMB power asymmetry via a subdominant and scale-dependent adiabatic perturbation

Non-Gaussianity is reduced if inflaton decay rate is linear in the modulating field

Tachyonic growth of a complex field can generate modulating field perturbations of the necessary form and magnitude

- **Existence proof for scalar field model explanation**

Predicts significant shifts of spectral index and running spectral index relative to common inflation models

- **Observation of a small positive running spectral index would support a scalar field explanation of the CMB power asymmetry**

End