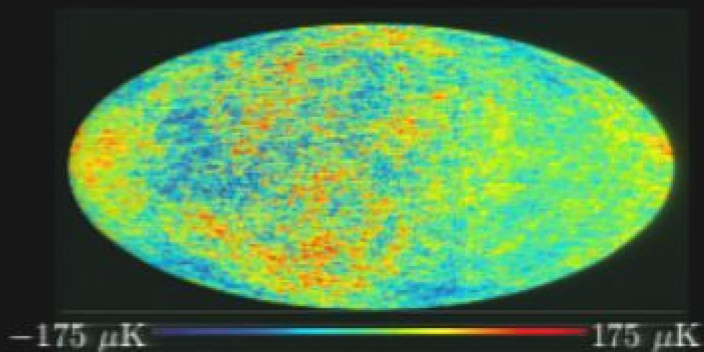
Title: Structure Beyond the Horizon: Inflationary Origins of the Cosmic Power Asymmetry

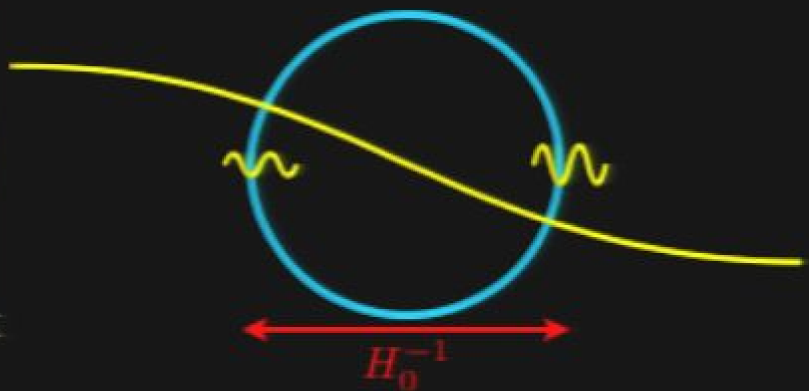
Date: Oct 14, 2008 04:00 PM

URL: http://pirsa.org/08100031

Abstract: WMAP measurements of CMB temperature anisotropies reveal a power asymmetry: the average amplitude of temperature fluctuations in one hemisphere is larger than the average amplitude in the opposite hemisphere at the 99% confidence level. This power asymmetry may be generated during inflation by a large-amplitude superhorizon perturbation that causes the mean energy density to vary across the observable Universe. Such a superhorizon perturbation would also induce large-scale temperature anisotropies in the CMB; measurements of the CMB quadrupole and octupole (but not the dipole!) therefore constrain the perturbation\'s amplitude and wavelength. I will show how a superhorizon perturbation in a multi-field inflationary theory, the curvaton model, can produce the observed power asymmetry without generating unacceptable temperature fluctuations in the CMB. I will also discuss how this mechanism for generating the power asymmetry will be tested by forthcoming CMB experiments.

Structure Beyond the Horizon:
Inflationary Origins of the Cosmic Power Asymmetry





Adrienne Erickcek
California Institute of Technology

In collaboration with Sean Carroll and Marc Kamionkowski

"A Hemispherical Power Asymmetry from Inflation" arXiv:0806.0377

"Superhorizon Perturbations and the CMB" arXiv:0808.1570

Outline

I. Power Asymmetry from Superhorizon Structure

- What power asymmety?
- How can we make one?

II. Superhorizon Perturbations and the CMB

- If there were superhorizon structures, how would we know?
- Bad news...

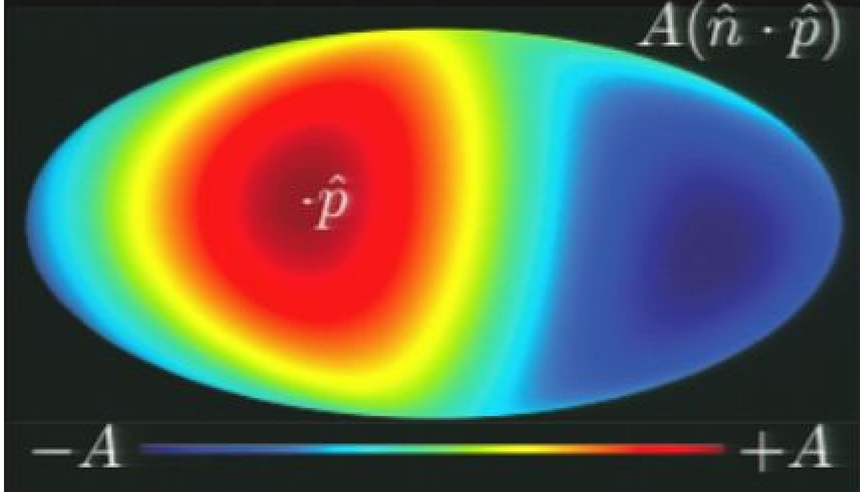
III. The Curvaton Alternative

- What went wrong, and how do we fix it?
- What's a curvaton anyway?

IV. A Power Asymmetry from the Curvaton

- How can we make a power asymmetry?
- Does it work?
- How do we test it?

A Hemispherical Power Asymmety



$$\mathbf{T}(\hat{n}) = s(\hat{n})\,[1 + A(\hat{n}\cdot\hat{p})]$$

CMB Temperature

Gaussian field with isotropic power

Modulation Amplitude

"North" pole of asymmetry

Simulated maps courtesy of H. K. Eriksen

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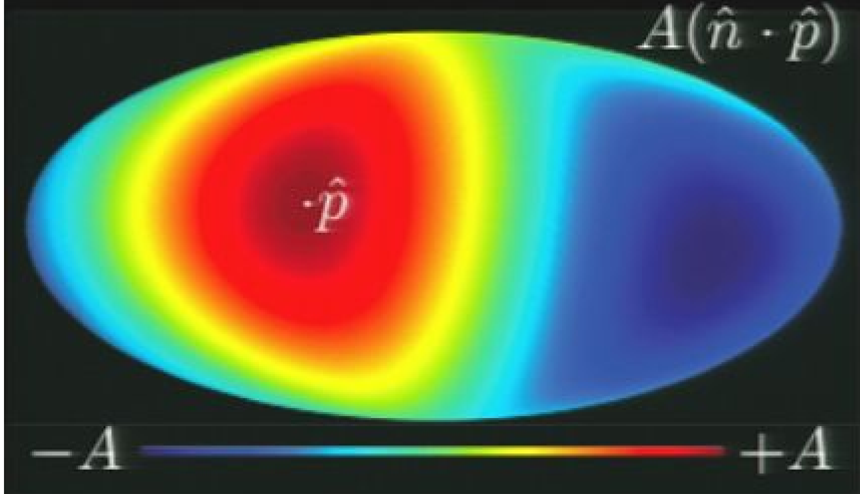

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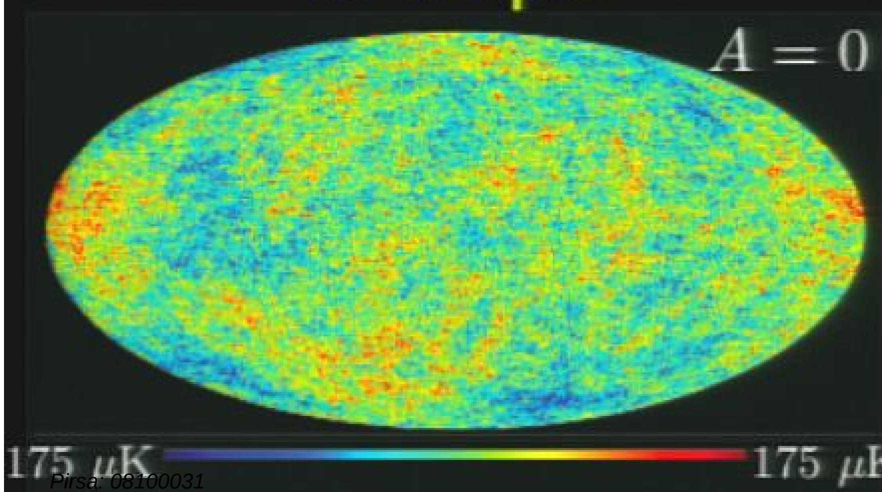
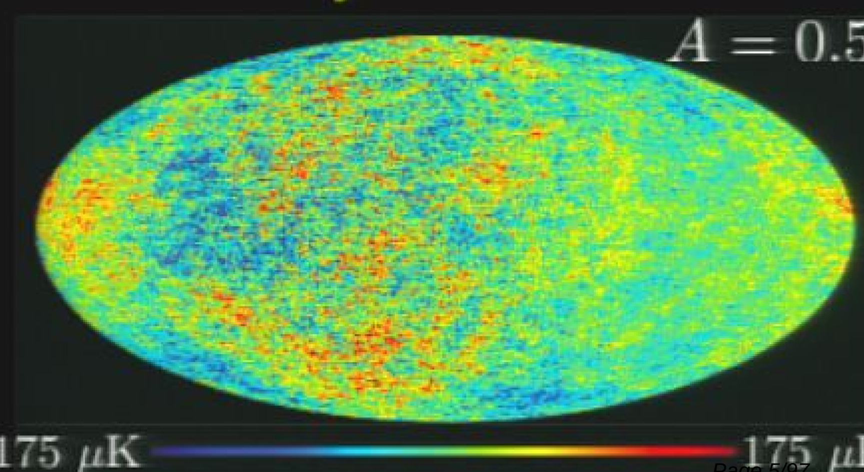


Asymmetric



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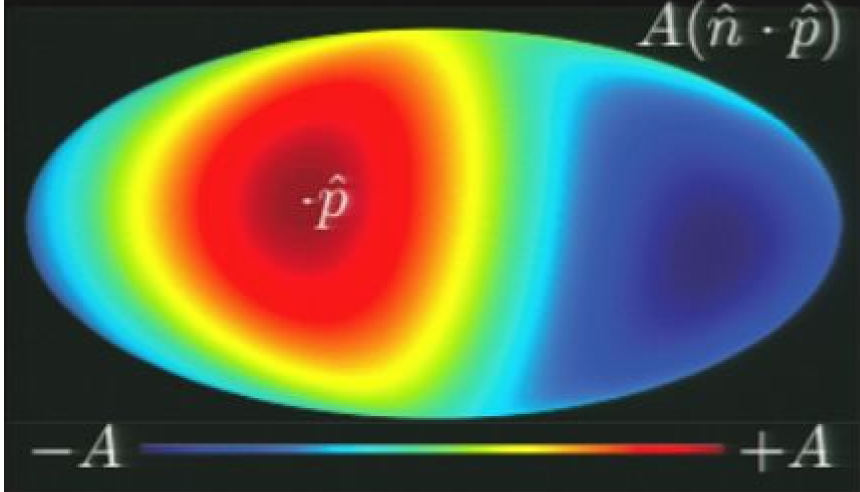

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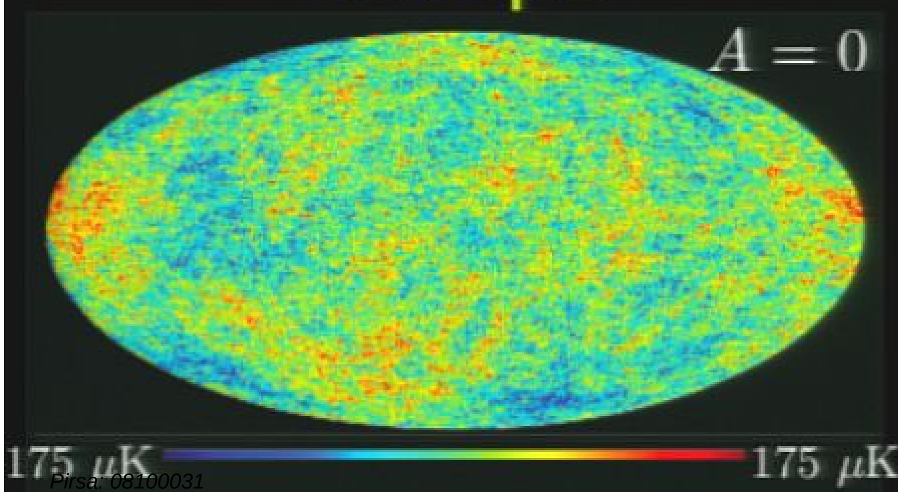

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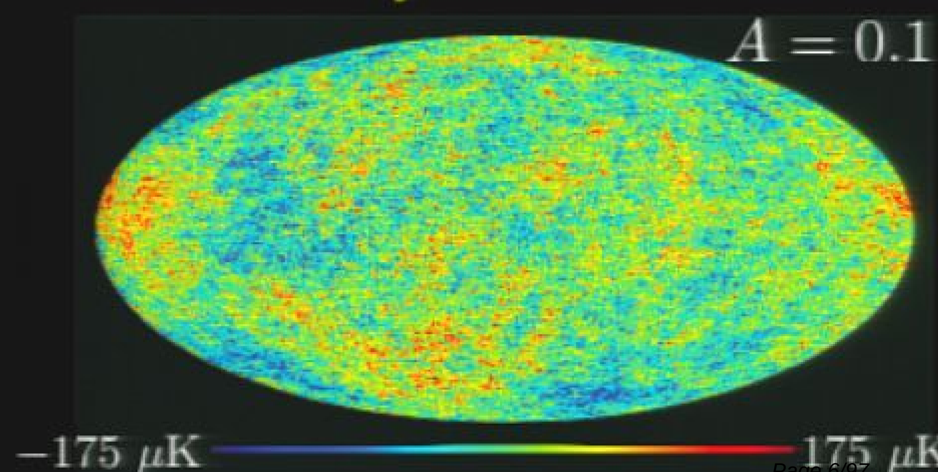

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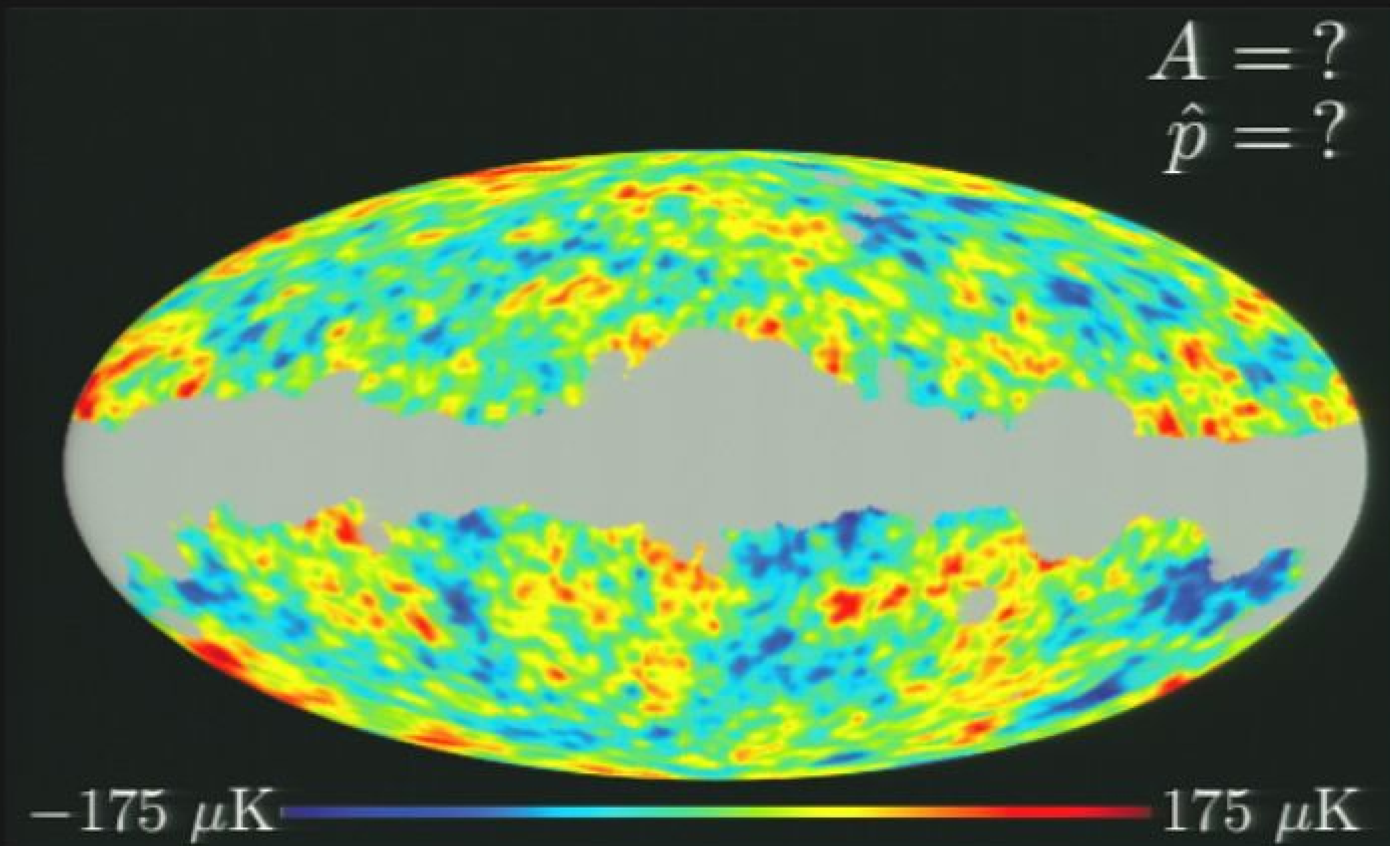
A Power Asymmety?

Isotropic or Asymmetric?



WMAP First Year Low-Resolution Map

Image from Eriksen, et al. astro-ph/0307507

An Asymmetric Universe!

There is a power asymmetry on large angular scales in the WMAP 1st year data.

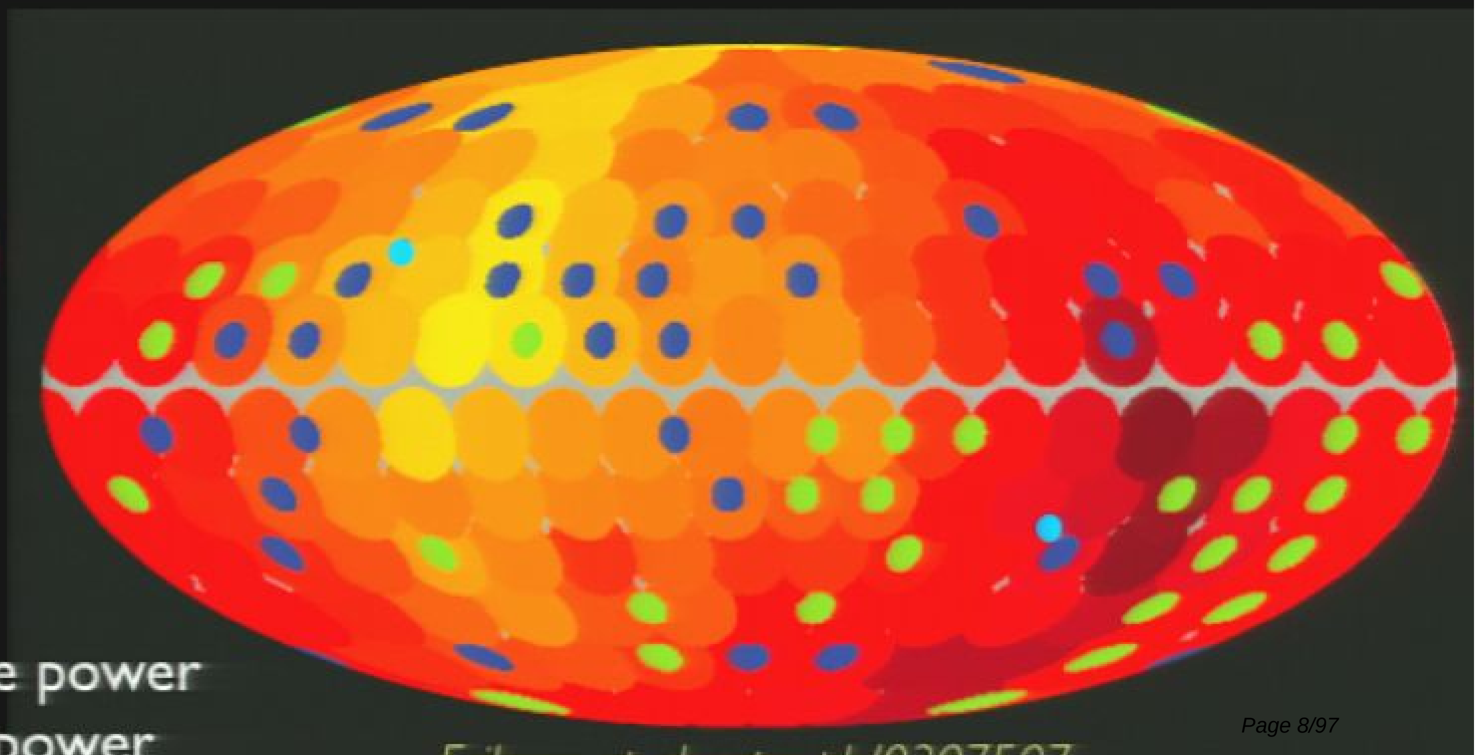
Eriksen, Hansen, Banday, Gorski, Lilje 2004

$\ell = 5 - 40$

Low to high ratio of power in hemisphere centered on disk to power in opposite hemisphere

more power

less power



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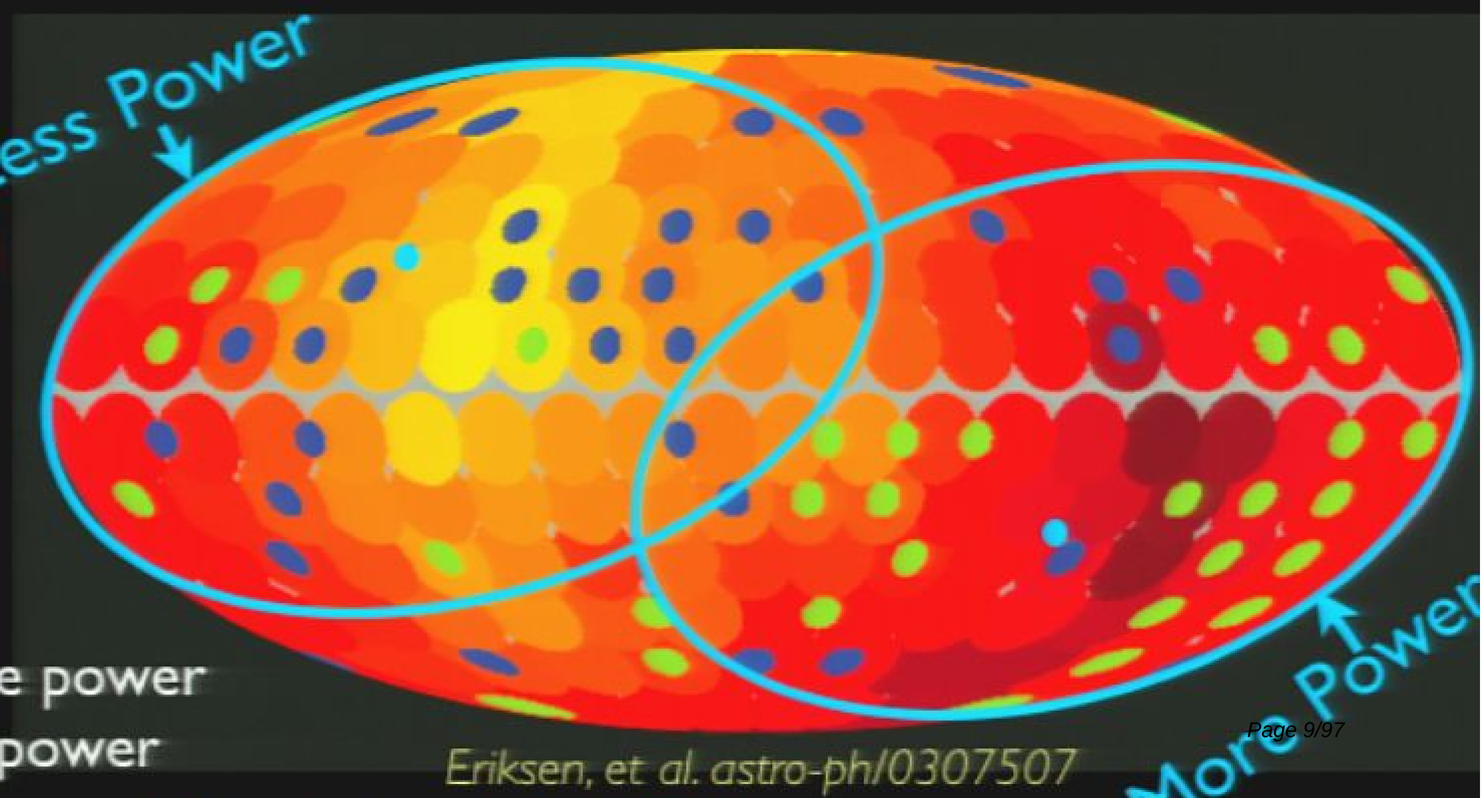

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An Asymmetric Universe!

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- Power asymmetry is maximized when the "equatorial" plane is tilted with respect to the Galactic plane: "north" pole at $(\ell, b) = (237°, -10°)$.
- Only 0.7% of simulated symmetric maps contain this much asymmetry.

Low to high ratio of power in hemisphere centered on disk to power in opposite hemisphere

more power

less power

Eriksen, et al. astro-ph/0307507

An Asymmetric Universe!

The asymmetry persists in the WMAP3 data.

Eriksen, Banday, Gorski, Hansen, Lilje 2007

$$\mathbf{T}(\hat{n}) = s(\hat{n})\,[1 + A(\hat{n}\cdot\hat{p})] + \mathbf{N}(\hat{n})$$

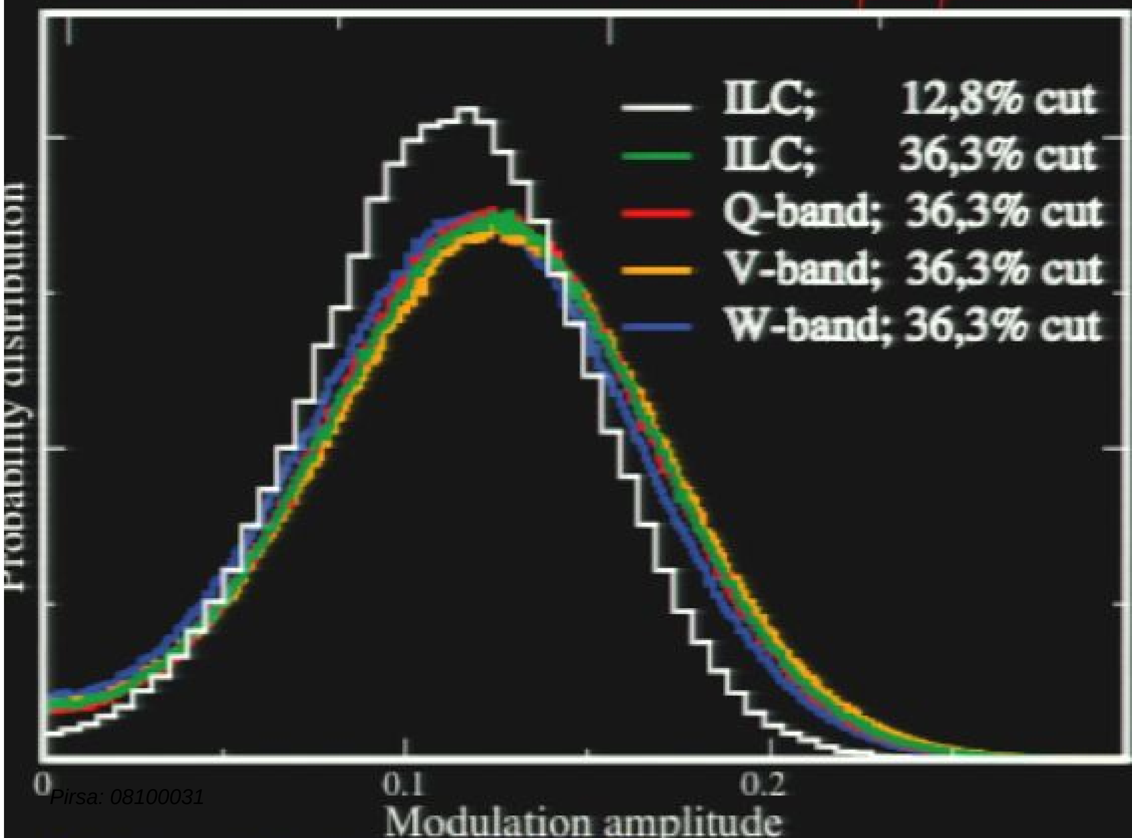
Observed CMB Temperature

Gaussian field with isotropic power

Modulation Amplitude

"North" pole of asymmetry

Noise



Eriksen et al astro-ph/070108

Bayesian analysis: $A \simeq 0.12$

"north" pole: $(\ell, b) \simeq (210°, -27°)$

The probability of measuring this amplitude or larger given an isotropic field is 0.01.

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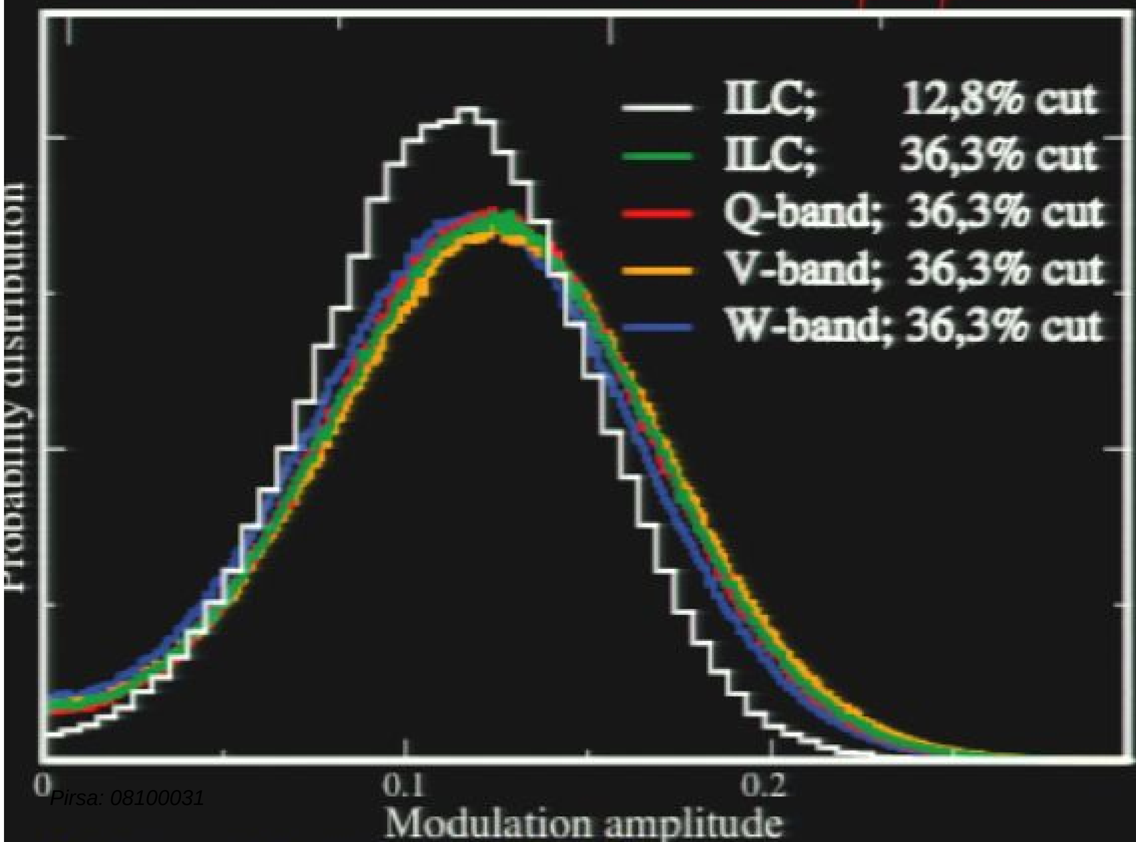


Eriksen, et al. astro-ph/070108

The asymmetry is difficult to explain with foregrounds:

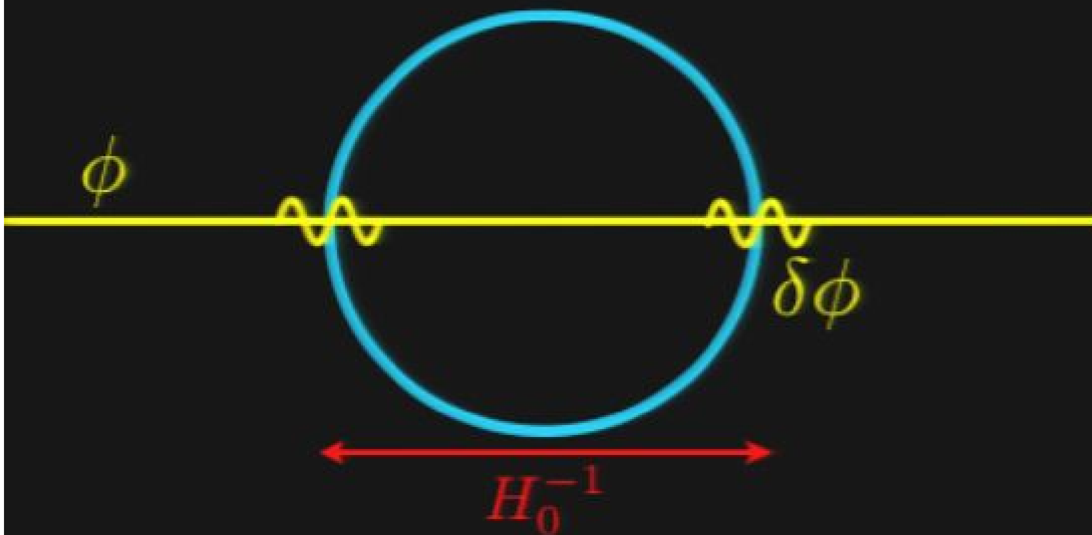
- present in all colors
- not aligned with the Galaxy

The asymmetry is difficult to explain with systematics:

- also detected by COBE

Hansen, et al. 2004, Eriksen, et al. 2004

Asymmetry from a "Supermode"



The amplitude of quantum fluctuations depends on the background value of the inflaton field.

$$P_\Psi = \frac{2}{9k^3}\left[\frac{H(\phi)^2}{\dot{\phi}}\right]^2\Bigg|_{k=aH}$$

Power Spectrum of Potential Fluctuations

$$\mathrm{d}s^2 = -(1+2\Psi)\mathrm{d}t^2 + a^2(t)\delta_{ij}(1-2\Psi)\mathrm{d}x^i\mathrm{d}x^j$$

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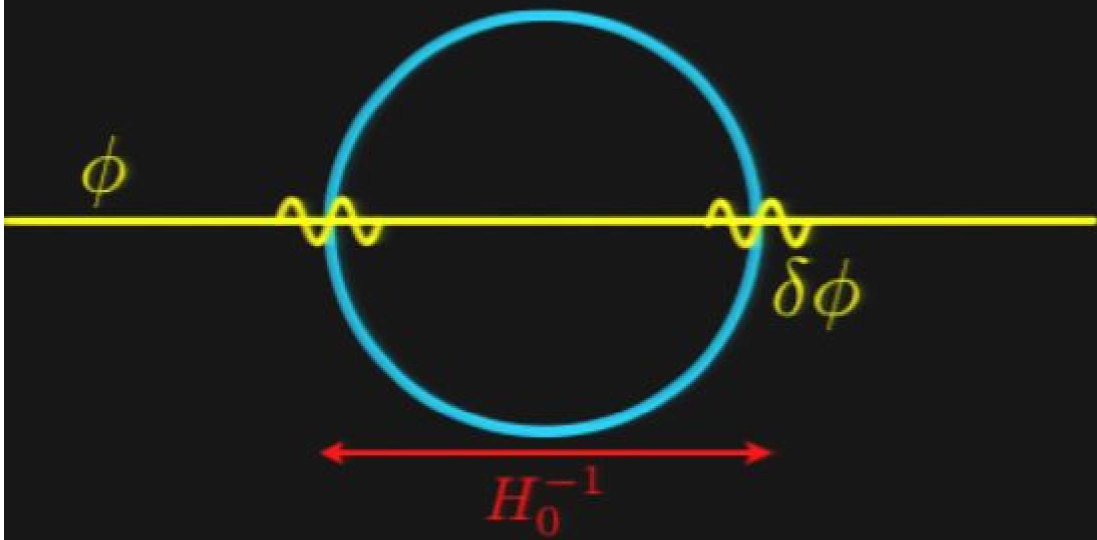

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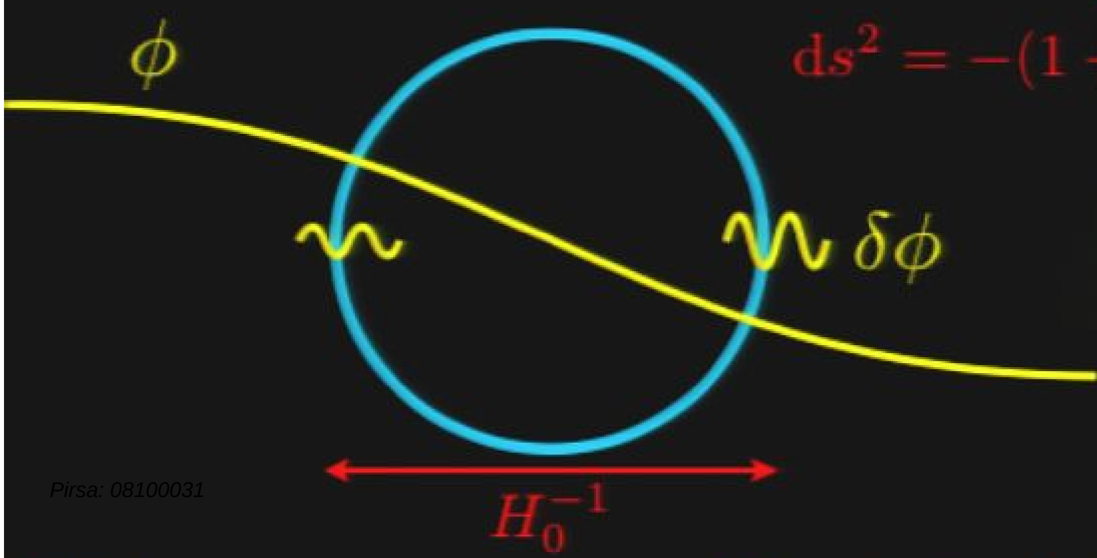


Create asymmetry by adding a large-amplitude superhorizon fluctuation: a "supermode."

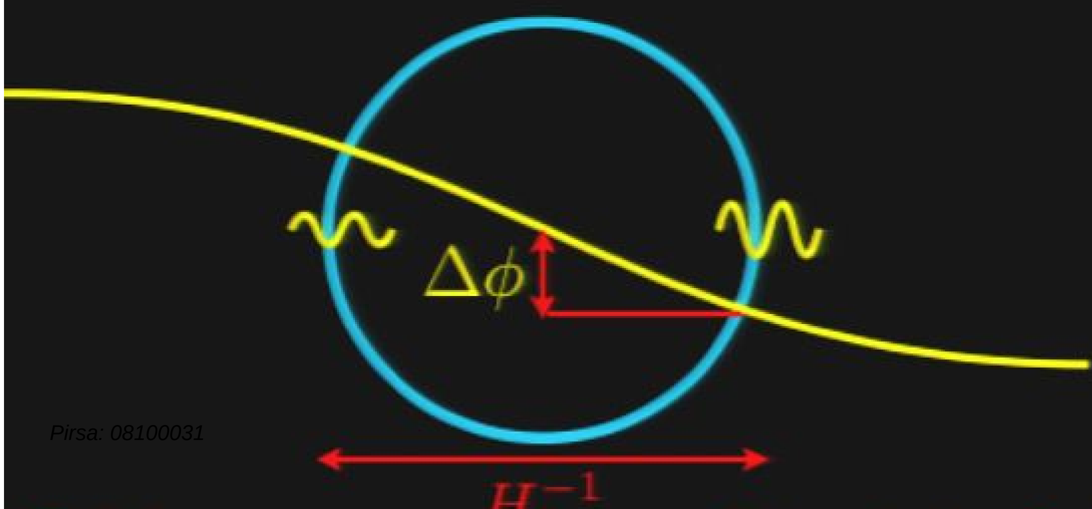
Asymmetry from a "Supermode"

A modulation amplitude $A \simeq 0.12 \Longrightarrow \dfrac{\Delta P_\Psi(k)}{P_\Psi(k)_{360^\circ}} \simeq \pm 0.20$

Generating this much asymmetry requires a **BIG** supermode.

- Perturbations with different wavelengths are very weakly coupled.
- The fluctuation power is not very sensitive to $\phi \Longleftrightarrow n_s \simeq 1$.

$$\frac{\Delta P_\Psi}{P_\Psi} = -2\sqrt{\frac{\pi}{\epsilon}}(1-n_s)\frac{\Delta\phi}{m_{\rm Pl}}$$



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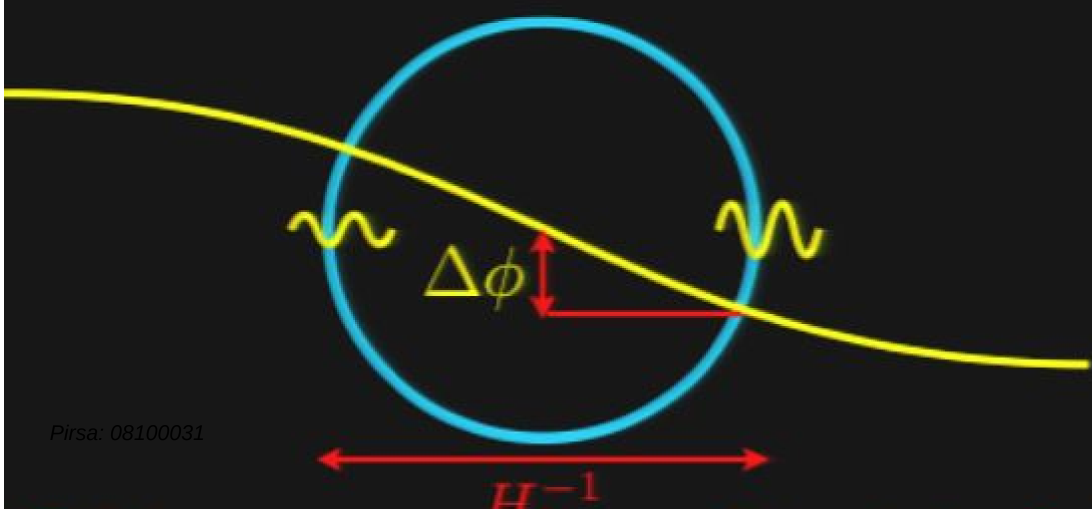


$\Delta\phi \Longrightarrow \Delta\Psi \Longrightarrow \Delta T$

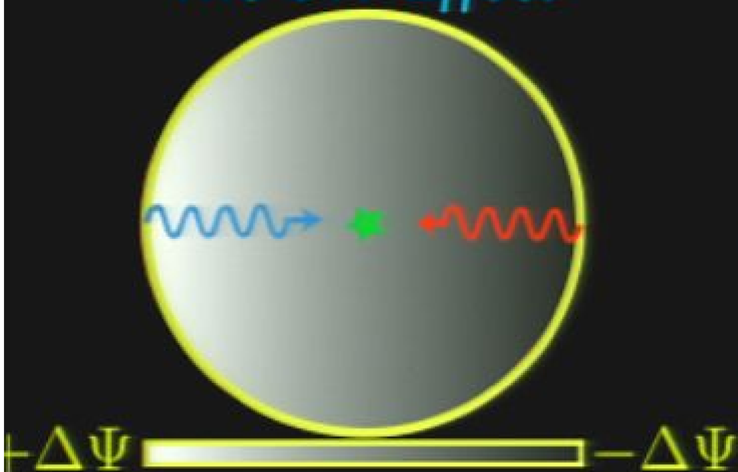
Surely the resulting temperature dipole would be far too large?

Part II

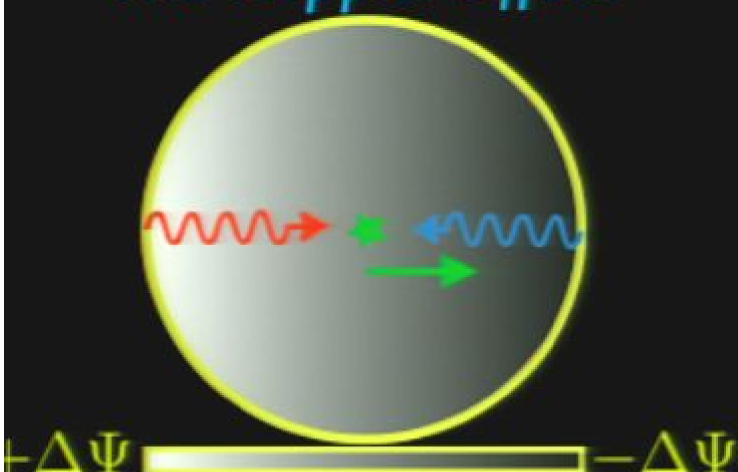
Superhorizon Perturbations and the Cosmic Microwave Background

The Dipole Sometimes Cancels...

The SW Effect



The Doppler Effect



In an **Einstein - deSitter** Universe, a superhorizon perturbation induces **no CMB dipole.** *Grishchuk, Zel'dovich 1978*

- A superhorizon mode: $\Psi(\vec{x}) \simeq \Psi_{\rm SM}\left[\vec{k}\cdot\vec{x}\right]$
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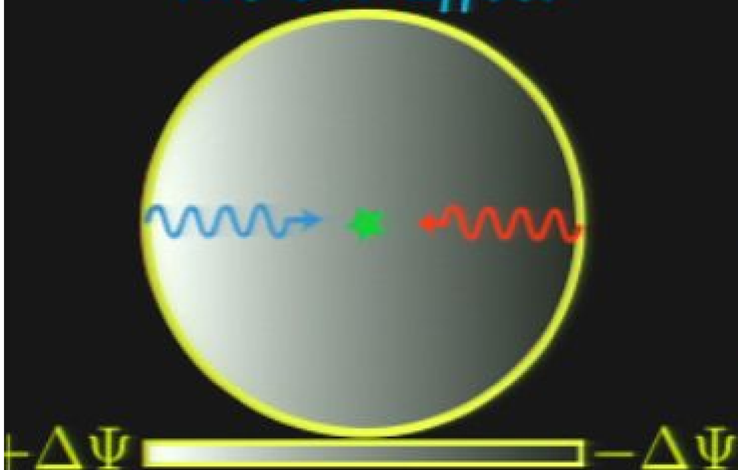

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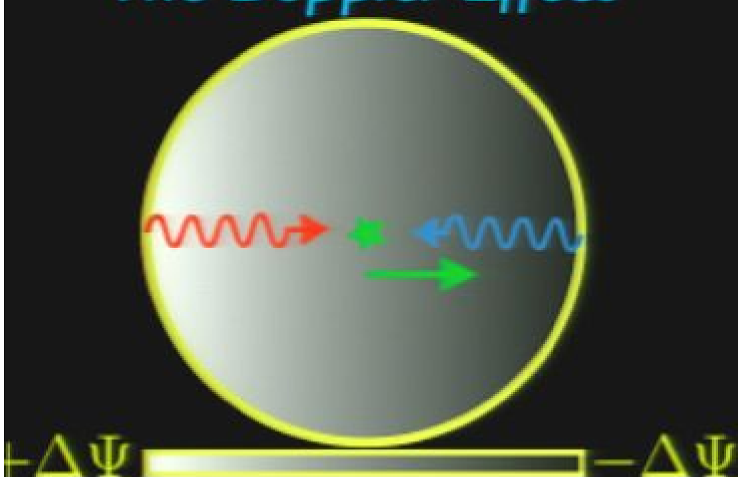

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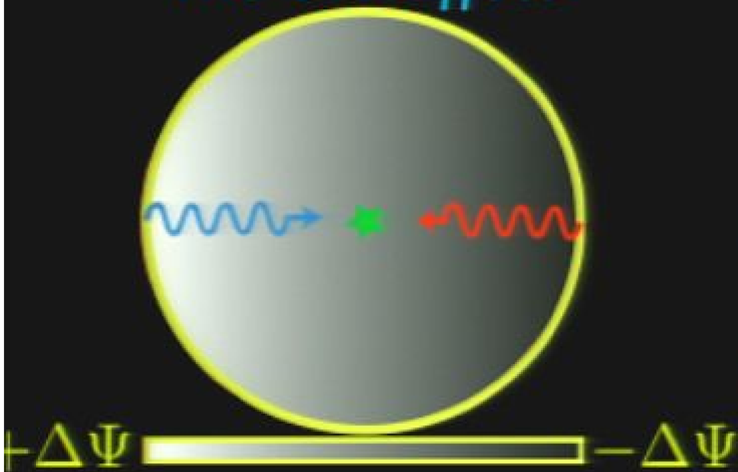

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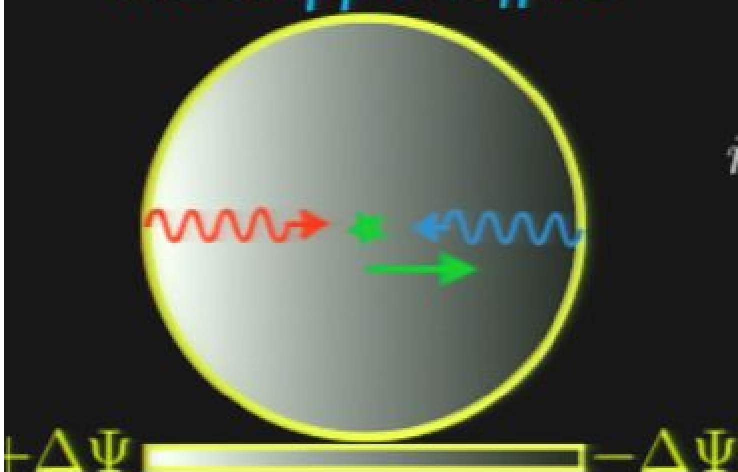

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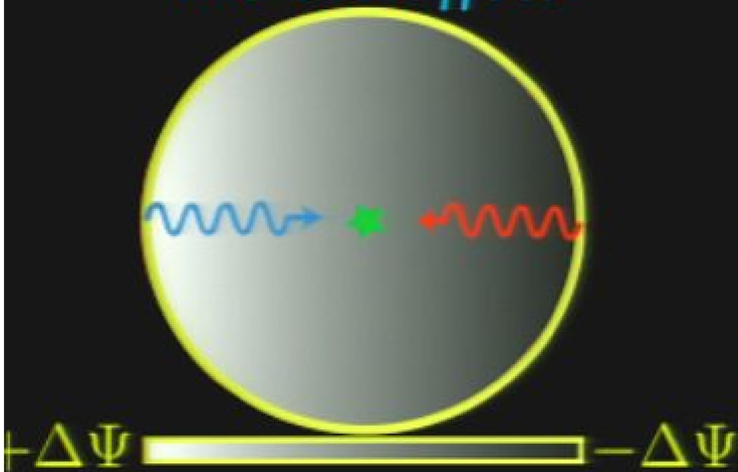

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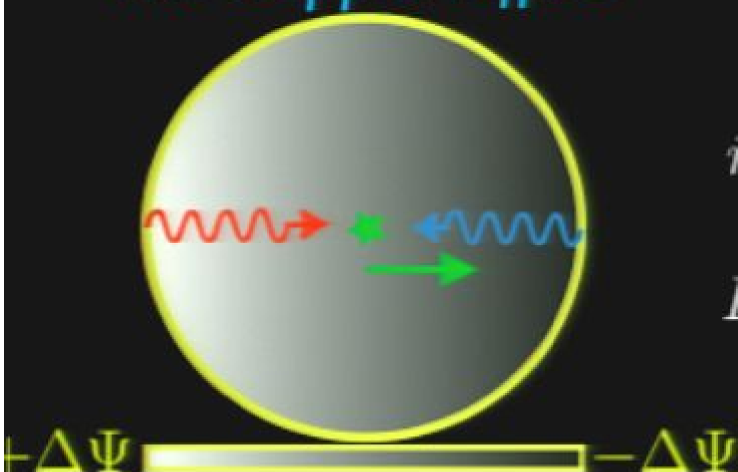

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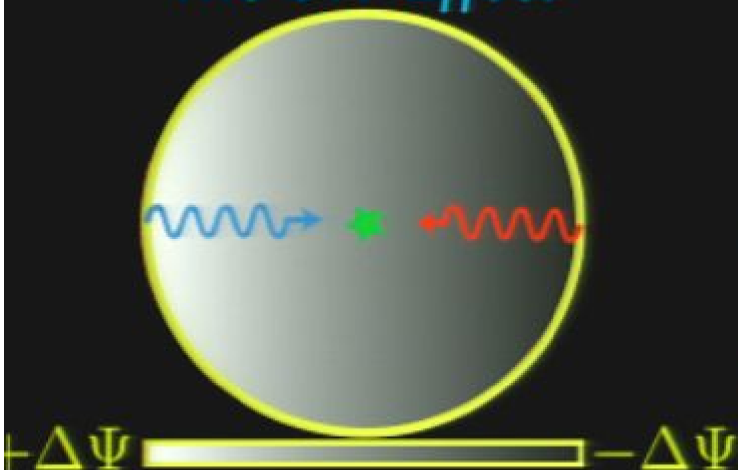

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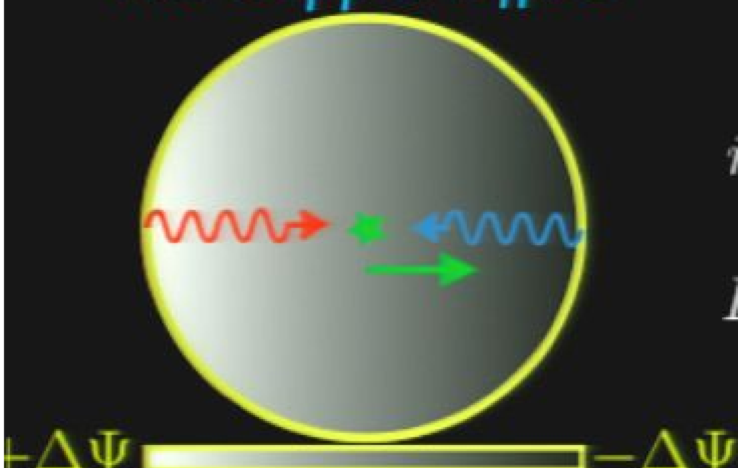

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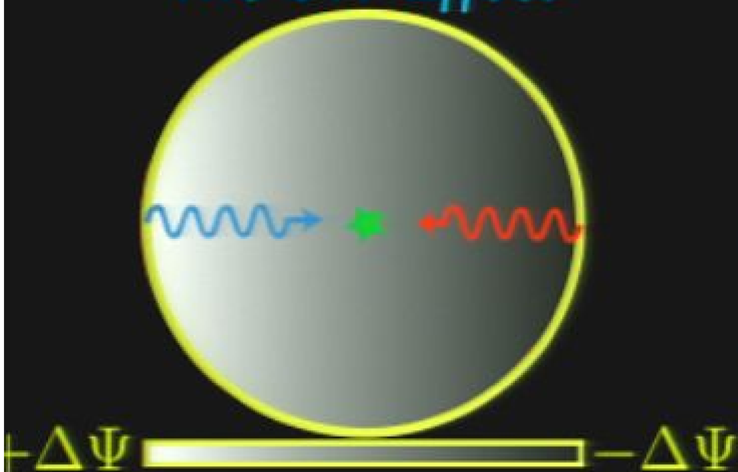

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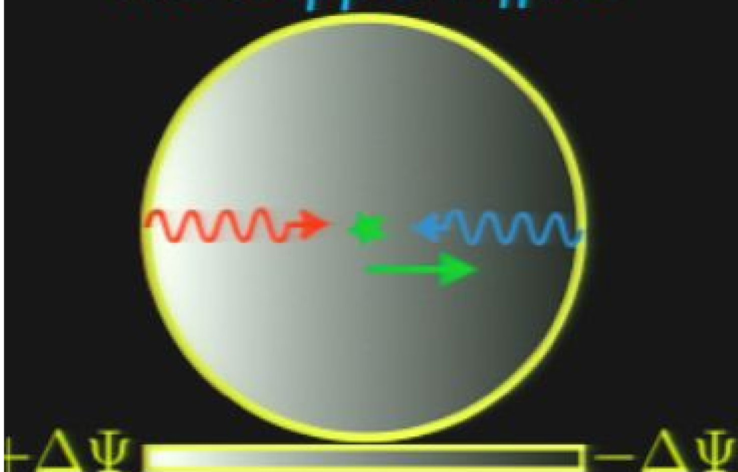

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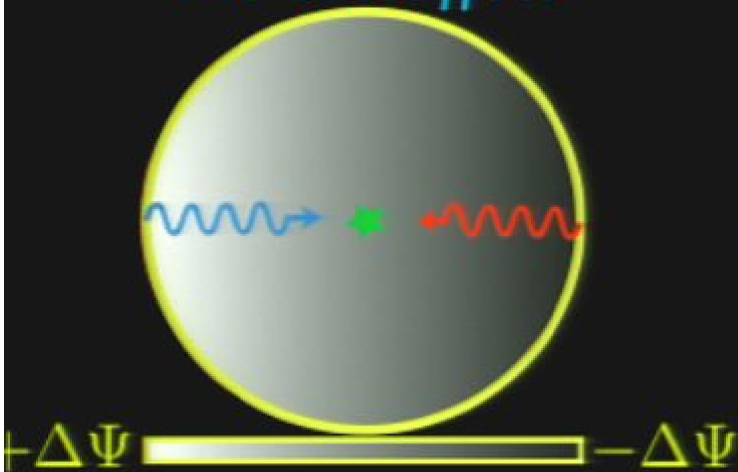

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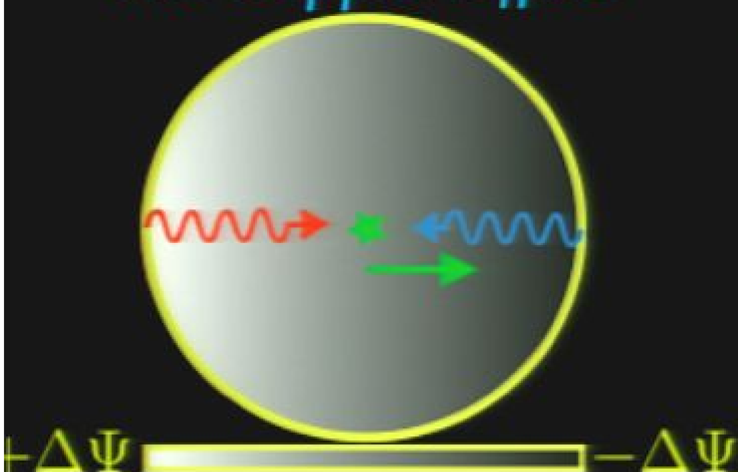

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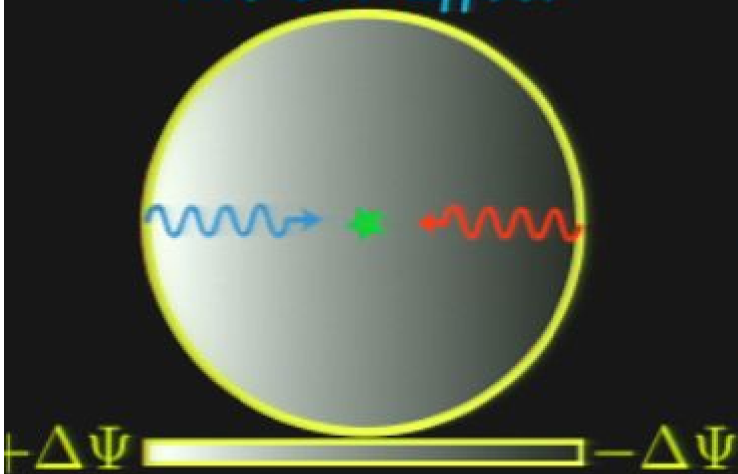

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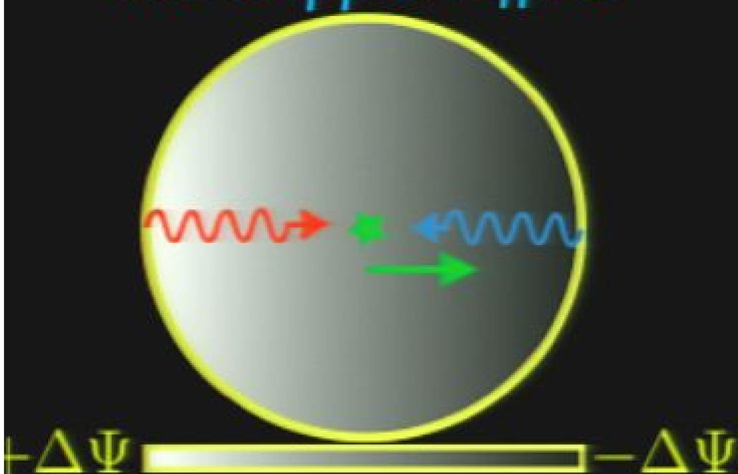

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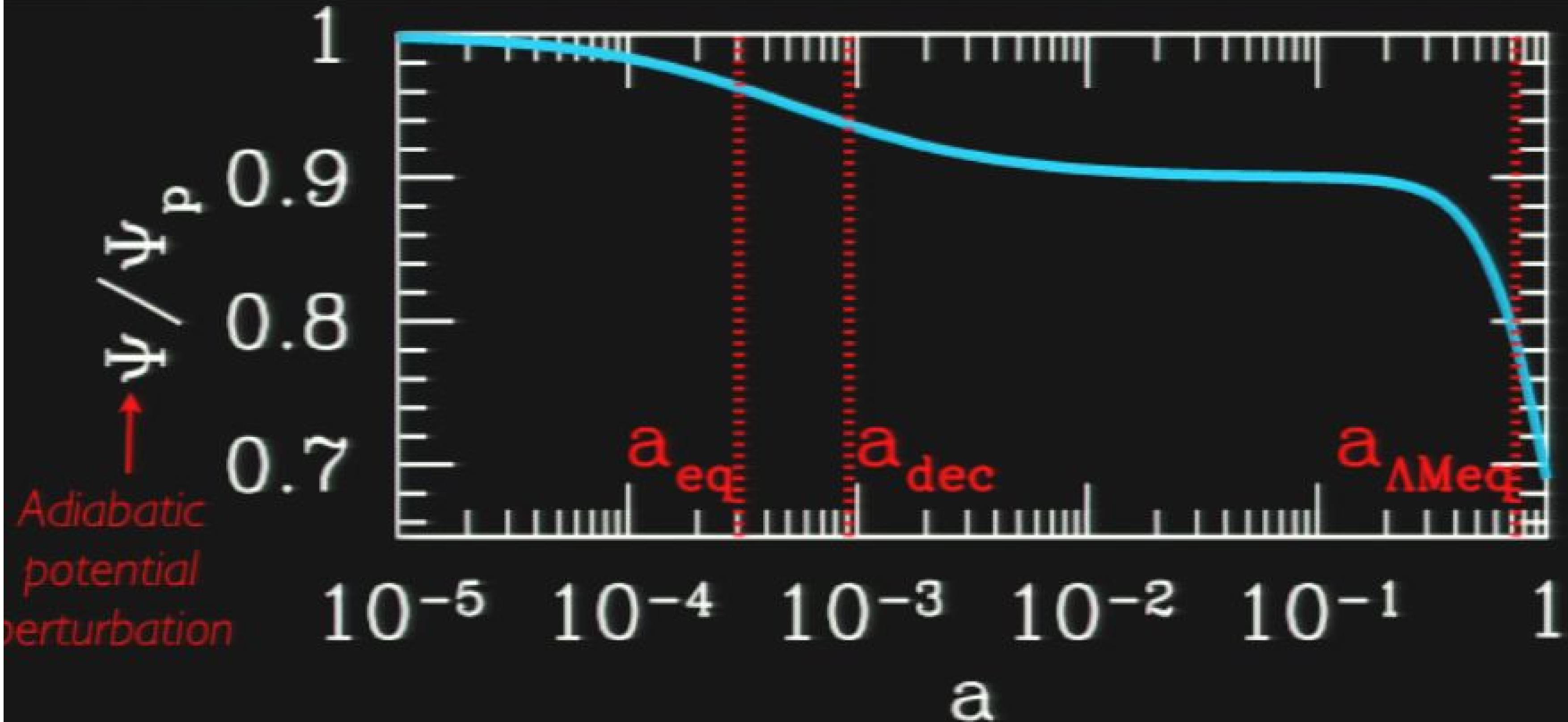
Well that's cute.

But the situation is much more complicated in a Universe like ours!

The Evolving Potential in ΛCDM



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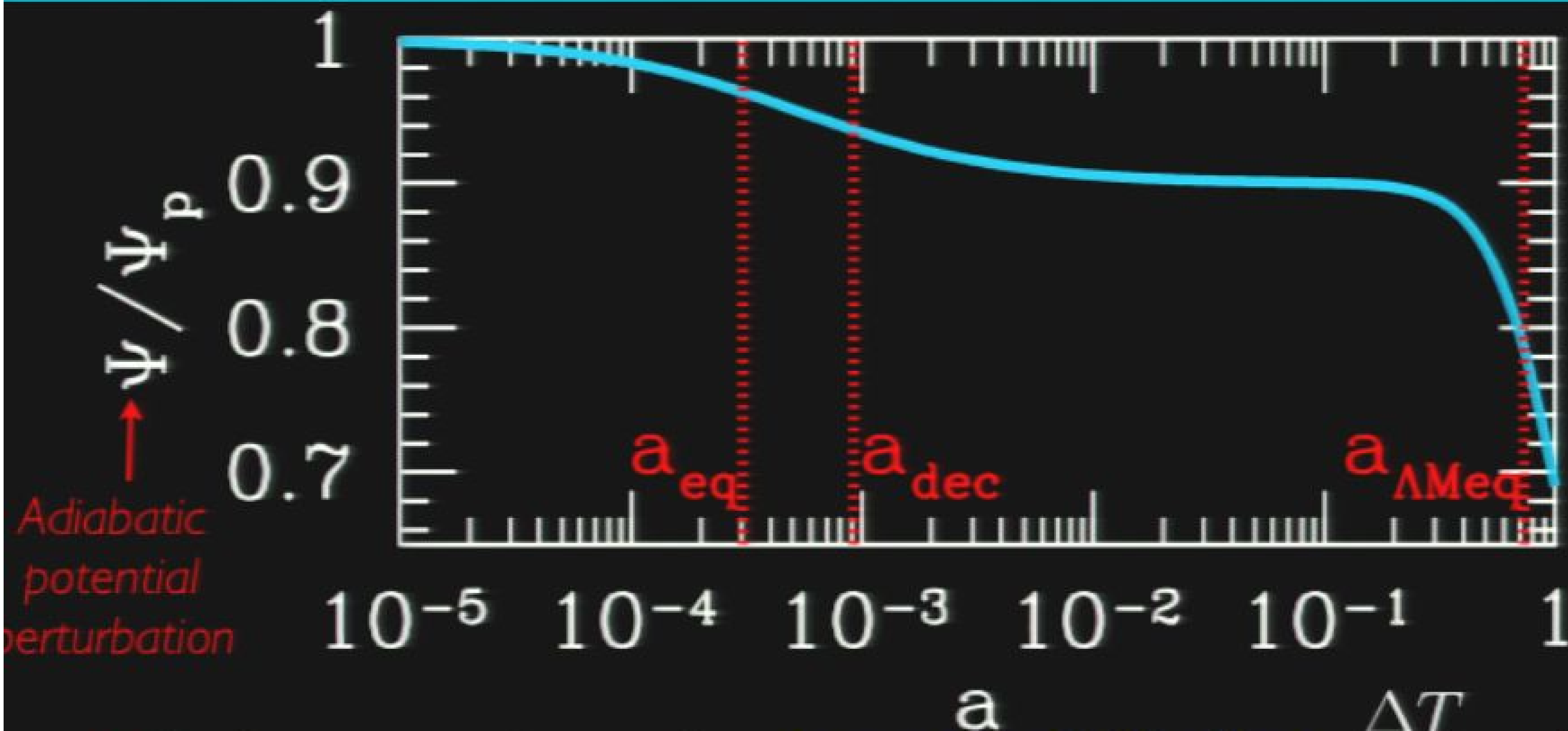

- Radiation at decoupling increases SW effect: $\frac{\Delta T}{T} = 0.4\Psi$
- Λ increases $x_{\rm dec}$ and reduces the Doppler dipole.
- Evolution of Ψ leads to ISW effect that will partially cancel the SW anisotropy: $\frac{\Delta T}{T} = 2\int_{t_{\rm dec}}^{t_0} \frac{d\Psi}{dt}[t, \vec{x}(t)]dt$

The Dipole Cancels!

Adiabatic superhorizon perturbation:

$$\Psi(\vec{x}) = \Psi_{\rm SM}\left[\vec{k}\cdot\vec{x}\right]$$

$$kH_0^{-1} \ll 1$$

Temperature anisotropy:

$$\frac{\Delta T}{T}(\hat{n}) = \delta_1 \Psi_{\rm SM}\left[\vec{k}\cdot\vec{x}_{\rm dec}\right]$$

ncludes SW, Doppler and ISW anisotropies

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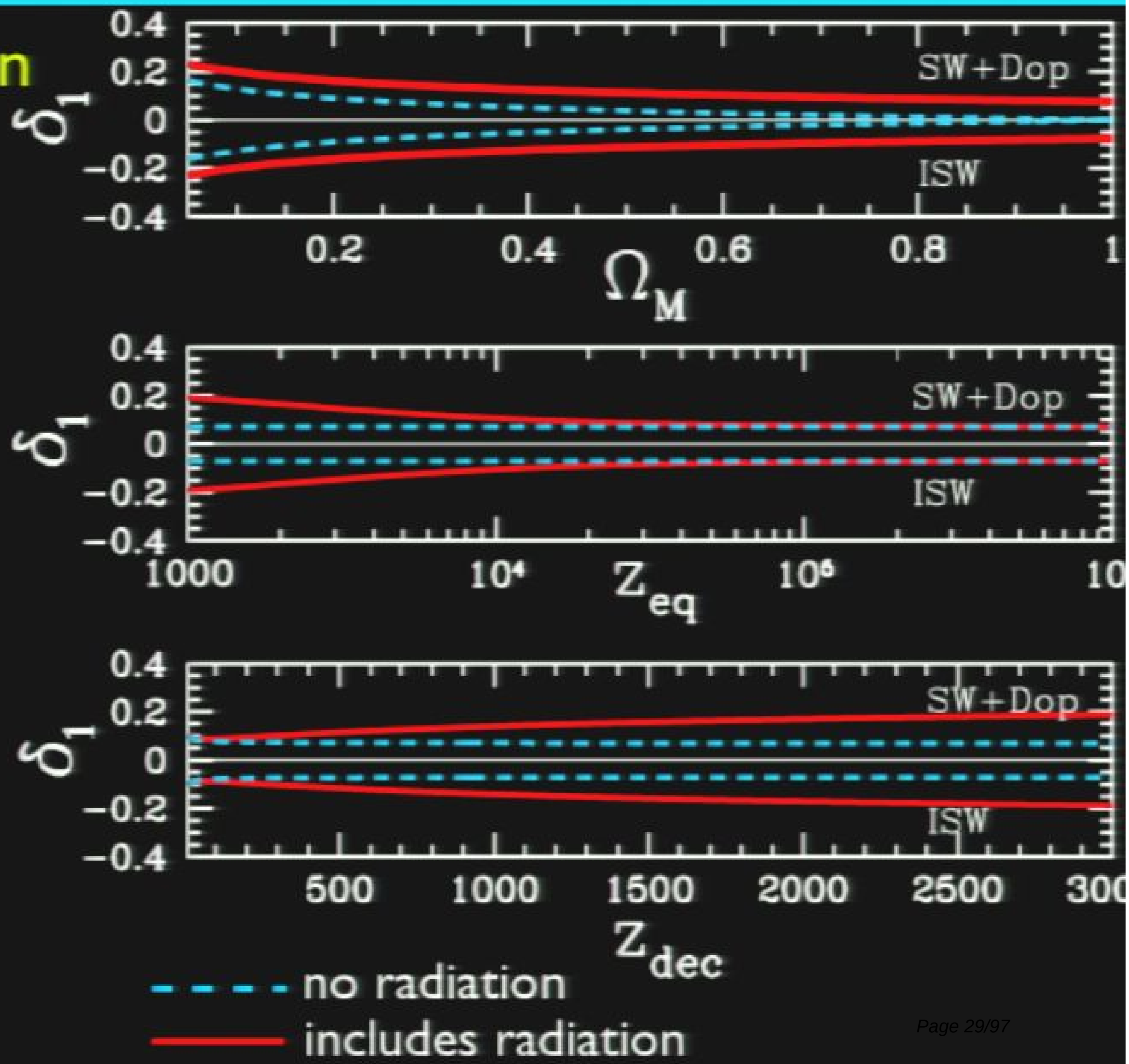
$$kH_0^{-1} \ll 1$$

Temperature anisotropy:

$$\frac{\Delta T}{T}(\hat{n}) = \delta_1 \Psi_{\rm SM}\left[\vec{k}\cdot\vec{x}_{\rm dec}\right]$$

Includes SW, Doppler and ISW anisotropies



The Dipole Cancels!

Adiabatic superhorizon perturbation:

$$\Psi(\vec{x}) = \Psi_{\mathrm{SM}}\left[\vec{k}\cdot\vec{x}\right]$$

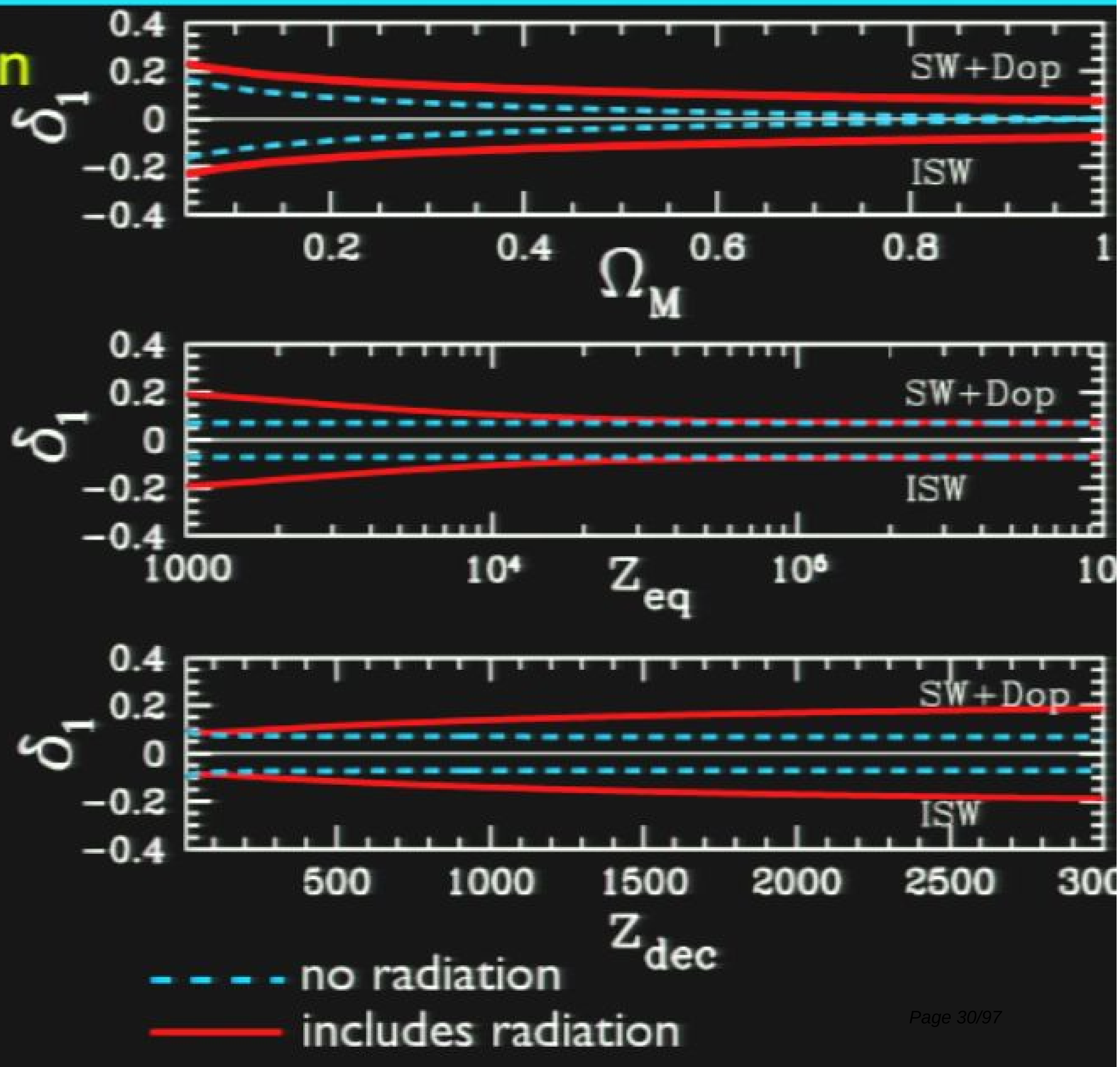
$$kH_0^{-1} \ll 1$$

Temperature anisotropy:

$$\frac{\Delta T}{T}(\hat{n}) = \delta_1 \Psi_{\mathrm{SM}}\left[\vec{k}\cdot\vec{x}_{\mathrm{dec}}\right]$$

Includes SW, Doppler and ISW anisotropies

The dipole cancels for all flat $\Lambda\mathrm{CDM}$ universes, even if radiation is included.



Matter and radiation aren't special...

The $\mathcal{O}(kx_{\rm dec})$ terms in ΔT for adiabatic perturbations cancel in flat universes that contain

- matter
- radiation
- cosmological constant

What if there's something else?

Matter and radiation aren't special...

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exotic fluid
$w \geq 1/3$
dominates early universe

What if there's something else? $H^2(a) = H_0^2\left[\frac{\Omega_X}{a^{3(1+w)}} + \Omega_\Lambda\right]$

cosmological
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What if there's something else? $H^2(a) = H_0^2 \left[\frac{\Omega_X}{a^{3(1+w)}} + \Omega_\Lambda \right]$

cosmological constant

The dipole terms still cancel for adiabatic perturbations!

s there a physical reason for dipole cancellation in flat universes with
uperhorizon adiabatic perturbations?

- special synchronous gauge: metric is FRW + $\mathcal{O}(k^2 H_0^{-2})$

  Hirata and Seljak 2005
- galaxies have no peculiar velocity in synchronous gauge
- no $\mathcal{O}(kx_{\rm dec})$ temperature anisotropies

Beyond the Dipole

A single superhorizon mode: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$

$kH_0^{-1} \ll 1$

phase of our location

Beyond the Dipole

A single superhorizon mode: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x}+\varpi]$

$kH_0^{-1} \ll 1$

distance to last scattering surface

phase of our location

Temperature anisotropy: Expansion in powers of $\vec{k}\cdot\vec{x}_{\rm d}$

$$\frac{\Delta T}{T}(\hat{n}) = \Psi_{\rm SM}\left[(\vec{k}\cdot\vec{x}_{\rm d})\delta_1\cos\varpi - (\vec{k}\cdot\vec{x}_{\rm d})^2\delta_2\frac{\sin\varpi}{2} - (\vec{k}\cdot\vec{x}_{\rm d})^3\delta_3\frac{\cos\varpi}{6}\right]$$

Observed CMB Temperature | Dipole | Quadrupole | Octupole

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Observed CMB Temperature — Dipole — Quadrupole — Octupole

Multipole moments: $$\frac{\Delta T}{T}(\hat{n}) = \sum_{\ell,m} a_{\ell m}Y_{\ell m}(\hat{n}) \longleftarrow \hat{k} = \hat{z}$$

Beyond the Dipole

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Observed CMB Temperature — Dipole — Quadrupole — Octupole

Multipole moments: $$\frac{\Delta T}{T}(\hat{n}) = \sum_{\ell,m} a_{\ell m}Y_{\ell m}(\hat{n}) \longleftarrow \hat{k}=\hat{z}$$

$$a_{10} = -\sqrt{\frac{4\pi}{3}}(kx_{\rm d})^3\delta_3\frac{\cos\varpi}{10}\Psi_{\rm SM}(t_{\rm d})$$

- residual dipole moment
- comparable to octupole moment
- less restrictive constraint due to our proper motion

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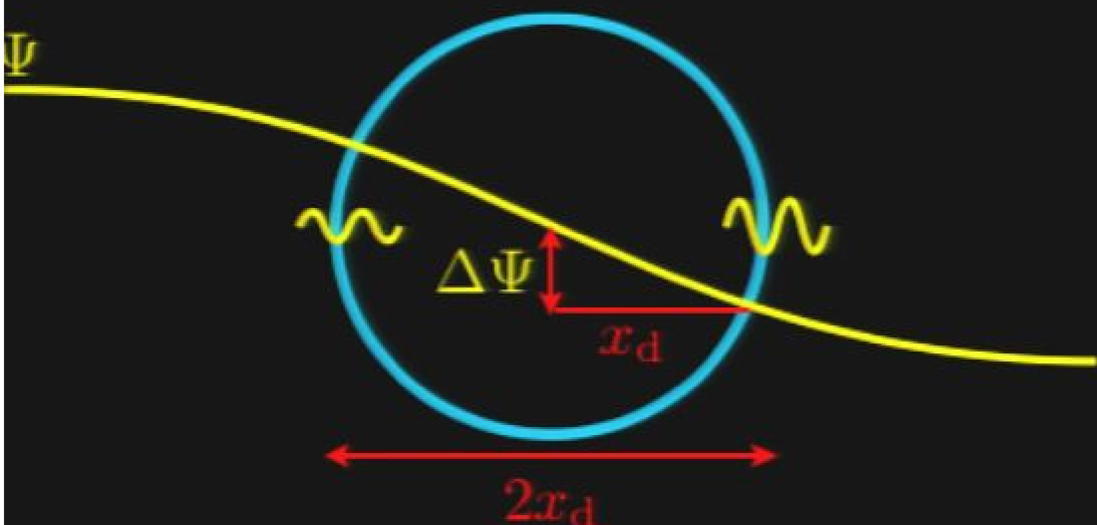
$$\boxed{\begin{aligned} a_{20} &= -\sqrt{\frac{4\pi}{5}}(kx_{\rm d})^2\delta_2\frac{\sin\varpi}{3}\Psi_{\rm SM}(t_{\rm d}) \\ a_{30} &= -\sqrt{\frac{4\pi}{7}}(kx_{\rm d})^3\delta_3\frac{\cos\varpi}{15}\Psi_{\rm SM}(t_{\rm d}) \end{aligned}}$$

The Quadrupole Constraint

Supermode: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x}+\varpi]$ ← phase of our location

Recall the motivation: $\Delta\phi \Longrightarrow$ power asymmetry

$$\Delta\phi \Longrightarrow \Delta\Psi \Longrightarrow \Delta T$$



$$\Delta\Psi \simeq (kx_{\rm d})\Psi_{\rm SM}|\cos\varpi|$$

distance to last scattering surface

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$\delta_2 = 0.33$

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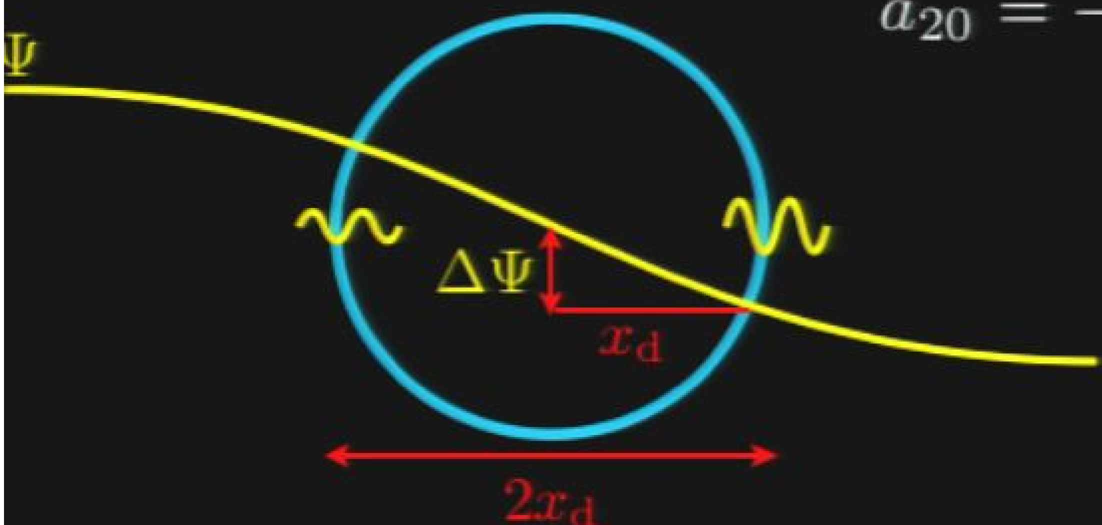

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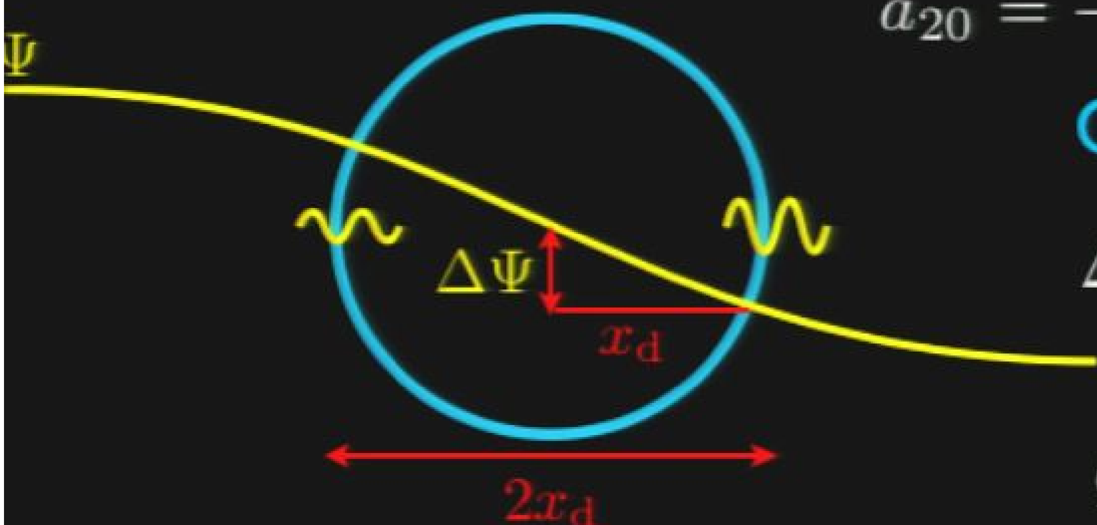

Quadrupole Constraint:

$$\Delta\Psi(kx_{\rm d})|\tan\varpi| \lesssim 5.8\mathcal{Q}$$

maximum allowed $|a_{20}|$

$$\mathcal{Q} \lesssim 3\sqrt{C_2} \simeq 1.8\times 10^{-5}$$

$$\Delta\Psi \simeq (kx_{\rm d})\Psi_{\rm SM}|\cos\varpi|$$

distance to last scattering surface

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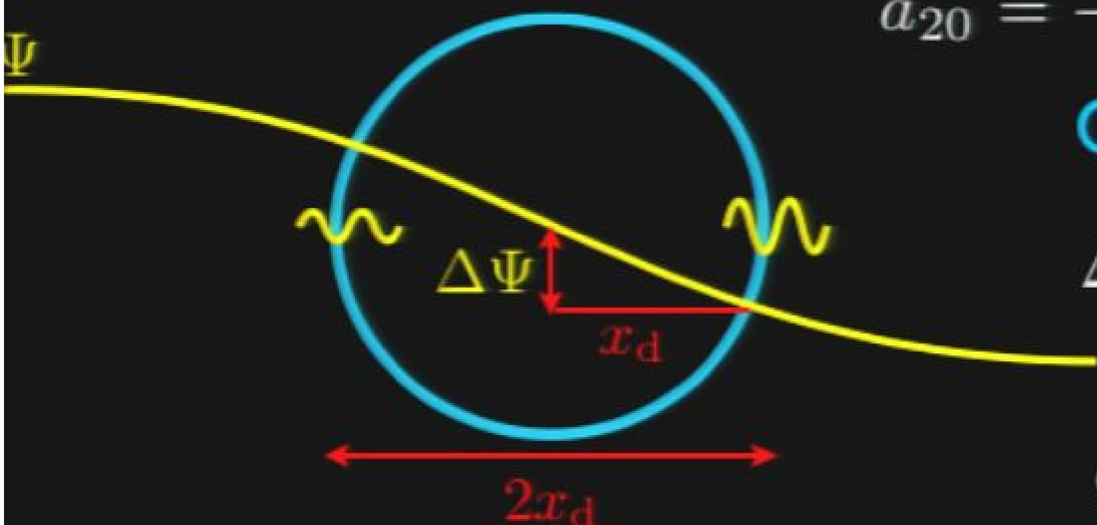

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distance to last scattering surface

Quadrupole vanishes if $\varpi = 0$.

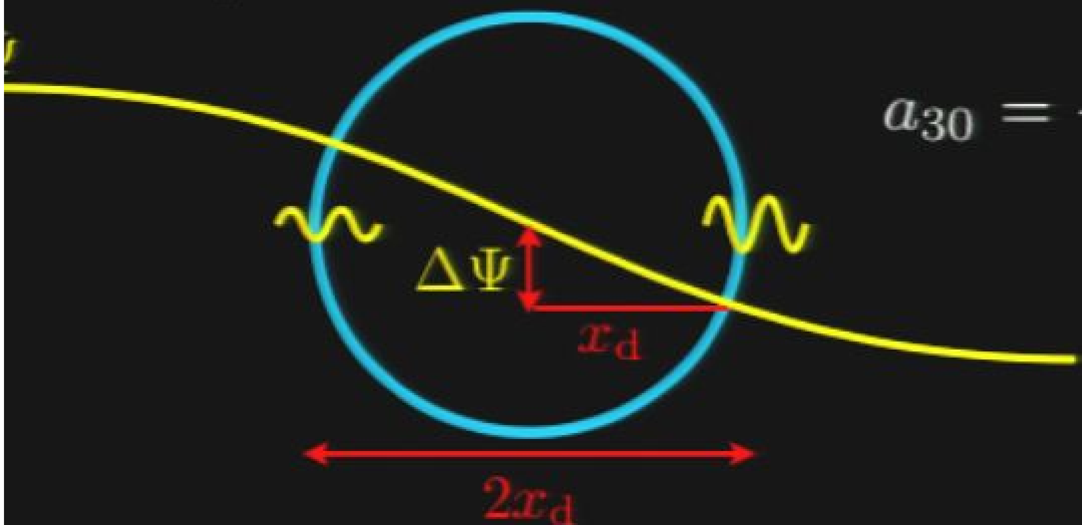
The Octupole Constraint

Supermode: $\Psi(\vec{x},t) = \Psi_{\mathrm{SM}}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$ ← *phase of our location*

The supermode induces a CMB octupole:

$\delta_3 = 0.35$

$$a_{30} = -\sqrt{\frac{4\pi}{7}}(kx_{\mathrm{d}})^3\delta_3\frac{\cos\varpi}{15}\Psi_{\mathrm{SM}}(t_{\mathrm{d}})$$



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distance to last scattering surface

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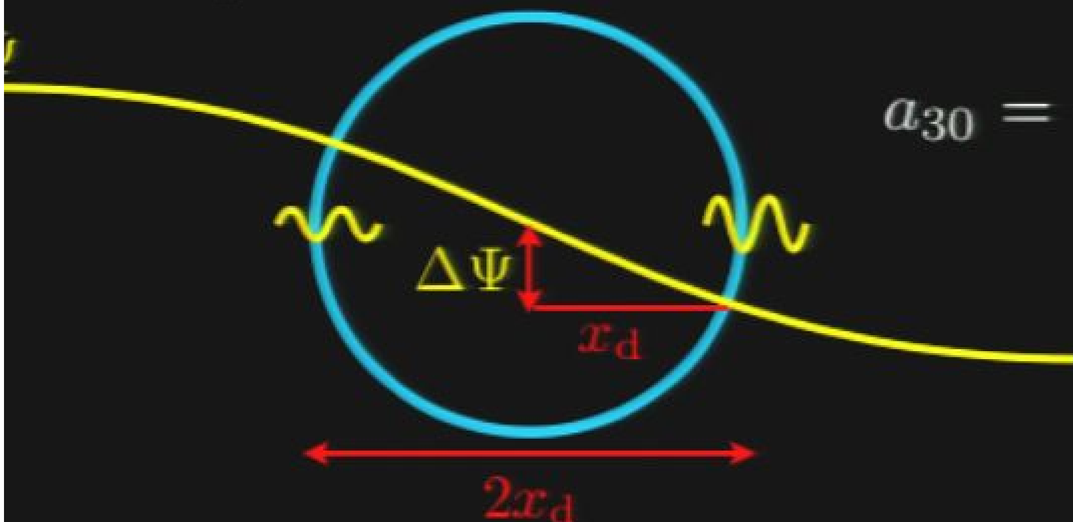

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Octupole Constraint:

$$\Delta\Psi(kx_{\rm d})^2 \lesssim 32\mathcal{O} \leftarrow |a_{30}|$$

$$\mathcal{O} \lesssim 3\sqrt{C_3} \simeq 2.7\times 10^{-5}$$

$$\Delta\Psi \simeq (kx_{\rm d})\Psi_{\rm SM}|\cos\varpi|$$

distance to last scattering surface

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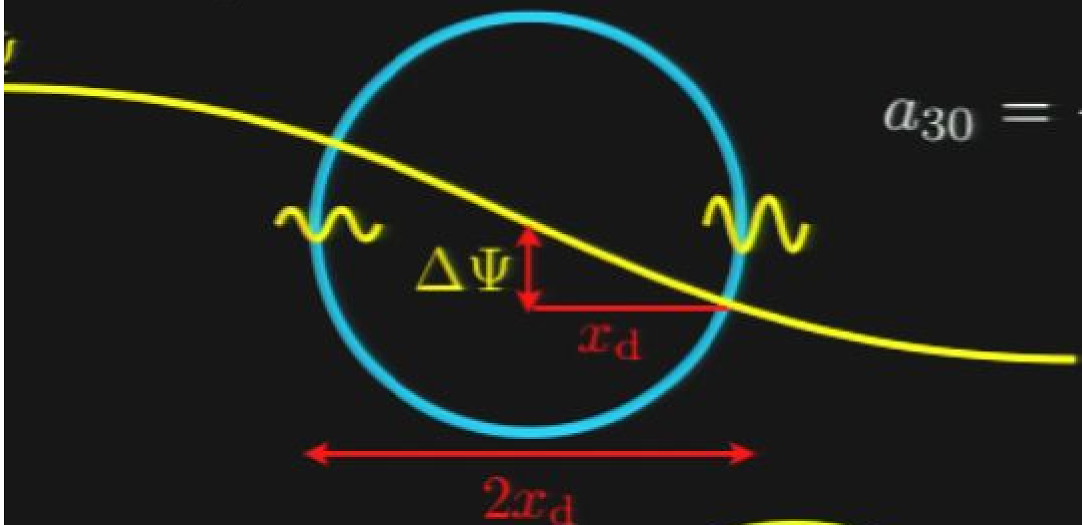

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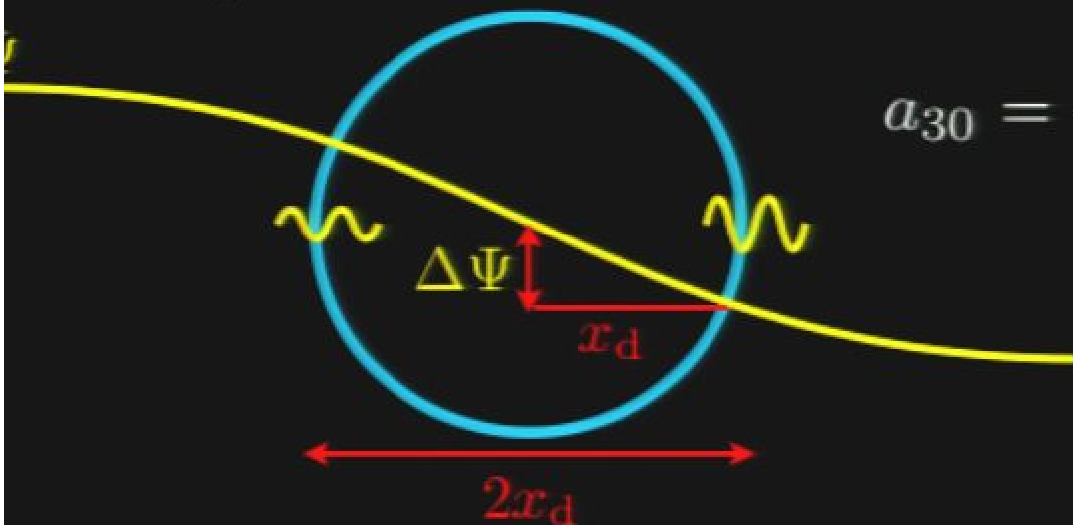

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Constraint is phase-independent.

Evade constraint by decreasing $kx_{\rm d}$?

Not if we want linearity beyond horizon!

$$|\Psi| < 1 \Longrightarrow \Delta\Psi \lesssim kx_{\rm d}$$

The Octupole Constraint

Supermode: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$ ← *phase of our location*

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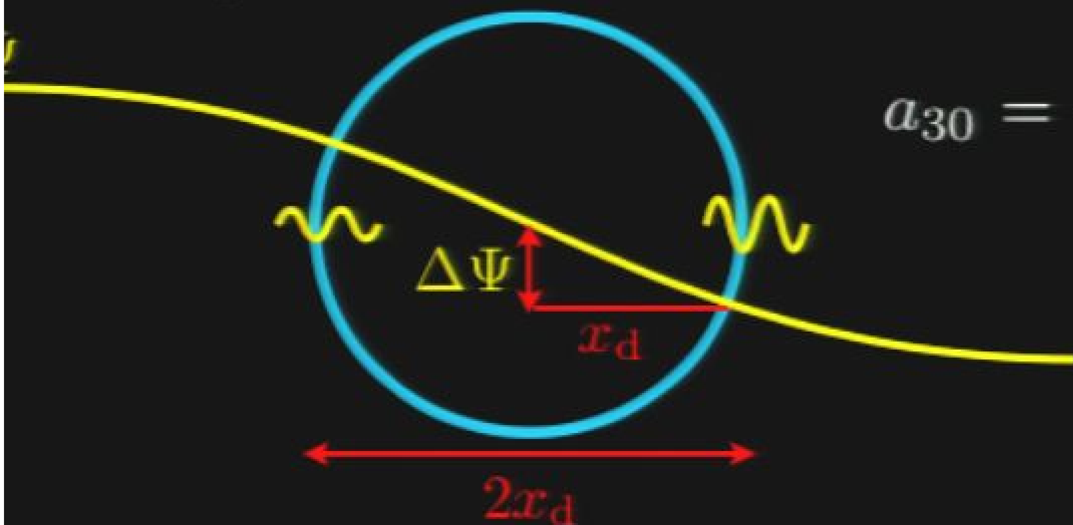

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$$\Delta\Psi(kx_{\rm d})^2 \lesssim 32\mathcal{O} \leftarrow |a_{30}|$$

$$\mathcal{O} \lesssim 3\sqrt{C_3} \simeq 2.7\times 10^{-5}$$

$$\Delta\Psi \lesssim [32\mathcal{O}]^{1/3} = 0.095$$

Recall: $\frac{\Delta P_\Psi}{P_\Psi} \propto \Delta\phi \propto \Delta\Psi$

$$\boxed{\frac{\Delta P_\Psi}{P_\Psi} \lesssim 0.01}$$

The Octupole Constraint

Supermode: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$ ← phase of our location

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$$a_{30} = -\sqrt{\frac{4\pi}{7}}(kx_{\rm d})^3\delta_3\frac{\cos\varpi}{15}\Psi_{\rm SM}(t_{\rm d})$$

Observed: $\frac{\Delta P_\Psi}{P_\Psi} \simeq 0.2$

Way too big!

Octupole Constraint:

$\Psi(kx_{\rm d})^2 \lesssim 32\mathcal{O}$ ← $|a_{30}|$

$\lesssim 3\sqrt{C_3} \simeq 2.7\times 10^{-5}$

$\Psi \lesssim [32\mathcal{O}]^{1/3} = 0.095$

all: $\frac{\Delta P_\Psi}{P_\Psi} \propto \Delta\phi \propto \Delta\Psi$

$$\boxed{\frac{\Delta P_\Psi}{P_\Psi} \lesssim 0.01}$$

Part III

The Curvaton Alternative

Mollerach 1990; Linde, Mukhanov 1997; Lyth, Wands 2002; Moroi, Takahashi 2001; and others...

The Curvaton to the Rescue!

The problem with the inflaton model is two-fold:

- The fluctuation power is only weakly dependent on the background value.
  - $\Delta P \propto (1 - n_s)\Delta\phi$
  - A small power asymmetry requires a large fluctuation in ϕ .
- The inflaton dominates the energy density of the universe, so a "supermode" in the inflaton field generates a huge potential perturbation.
  - CMB octupole places upper bound on $\Delta\Psi$.
  - $\Delta P \propto \Delta\phi \propto \Delta\Psi$ with no wiggle room.

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The solution: the primordial fluctuations could be generated by a subdominant scalar field, the curvaton.

- The fluctuation power depends strongly on the background curvaton value.
- The CMB constraints on $\Delta\Psi$ do not directly constrain ΔP. There is a new free parameter: the fraction of energy in the curvaton.

The Curvaton during Inflation

- The inflaton still dominates the energy density and drives inflation.
- The curvaton (σ) is a subdominant light scalar field during inflation.

$$\underbrace{V(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2}_{\text{potential}} \quad \text{with} \quad \underbrace{m_\sigma \ll H_{\rm inf}(\phi)}_{\text{light scalar field}} \quad \text{and} \quad \underbrace{\rho_\sigma \ll \rho_\phi}_{\text{subdominant}}$$

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potential *light scalar field* *subdominant*

- There are quantum fluctuations in both the inflaton and curvaton.

$$(\delta\phi)_{\mathrm{rms}} = (\delta\sigma)_{\mathrm{rms}} = \frac{H_{\mathrm{inf}}}{2\pi} \ll \bar{\sigma}$$

quantum fluctuations *homogeneous background value*

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potential *light scalar field* *subdominant*

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$$(\delta\phi)_{\rm rms} = (\delta\sigma)_{\rm rms} = \frac{H_{\rm inf}}{2\pi} \ll \bar{\sigma} \leftarrow$$

quantum fluctuations *homogeneous background value*

- Outside the horizon, $\delta\sigma$ and $\bar{\sigma}$ obey the same equation of motion:

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

$$\delta\ddot{\sigma} + 3H\delta\dot{\sigma} + \left[\frac{k^2}{a^2} + V''(\bar{\sigma})\right]\delta\sigma = 0$$

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potential — light scalar field — subdominant

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quantum fluctuations — homogeneous background value

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$$\ddot{\bar{\sigma}} + 3H\dot{\bar{\sigma}} + \underbrace{V'(\bar{\sigma})}_{m_\sigma^2 \bar{\sigma}} = 0$$

$$\delta\ddot{\sigma} + 3H\delta\dot{\sigma} + \left[\cancel{\frac{k^2}{a^2}} + V''(\bar{\sigma})\right]\delta\sigma = 0 \qquad \left(V''(\bar{\sigma})\,\delta\sigma = m_\sigma^2 \delta\sigma\right)$$

For superhorizon perturbations, $\frac{\delta\sigma}{\bar{\sigma}}$ is conserved both during and after inflation.

The Curvaton after Inflation

The curvaton equation of motion: $\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2\sigma^2 = 0$

- As long as $m_\sigma \ll H$, the curvaton is frozen: $\dot{\sigma} = 0$
- When $m_\sigma \simeq H$, the curvaton **oscillates**: $\langle\dot{\sigma}^2\rangle = \langle m_\sigma^2\sigma^2\rangle$

$$p = \frac{1}{2}\dot{\sigma}^2 - \frac{1}{2}m_\sigma^2\sigma^2 \implies \langle p\rangle = 0$$

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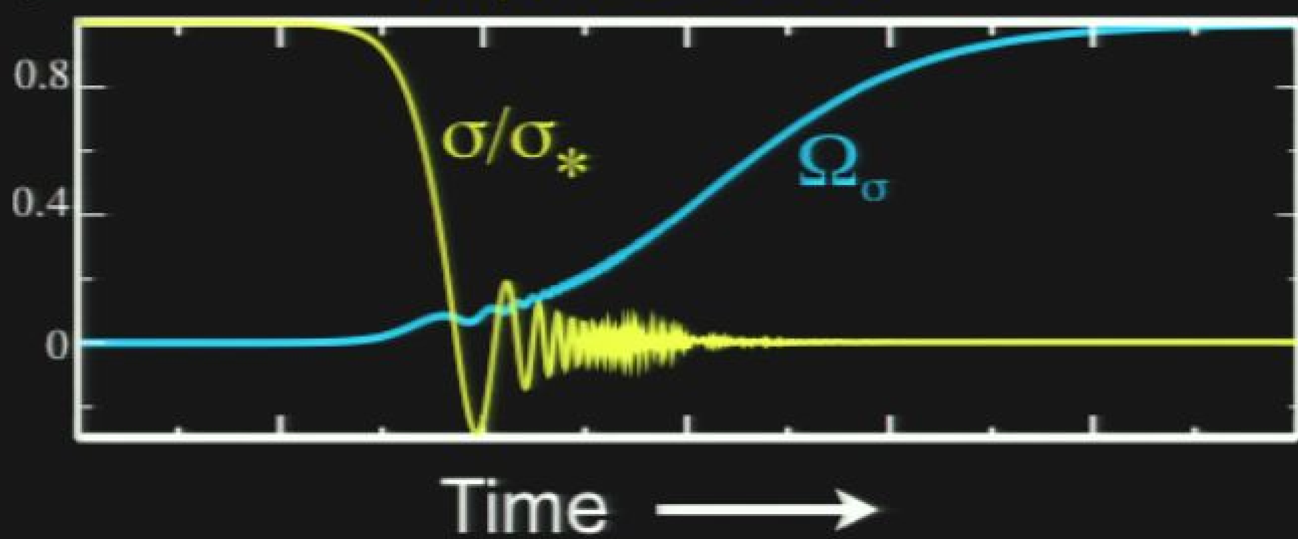
$$p = \frac{1}{2}\dot{\sigma}^2 - \frac{1}{2}m_\sigma^2\sigma^2 \implies \langle p \rangle = 0$$

While the curvaton oscillates, it **behaves as matter:** $\rho_\sigma \propto a^{-3}$

Meanwhile, $\rho_r \propto a^{-4}$, so ρ_σ / ρ_r **increases.**



Langlois and Vernizzi, PRD 70 063522 (2004).

Growth of a Curvature Perturbation

Curvature perturbation: $\zeta = -\Psi - H\frac{\delta\rho}{\dot\rho}$

Superhorizon ζ is not conserved due to curvaton isocurvature fluctuation, but $\zeta_i = -\Psi - H\frac{\delta\rho_i}{\dot\rho_i}$ is constant.

$$\zeta = \frac{4\rho_r\zeta_r + 3\rho_\sigma\zeta_\sigma}{4\rho_r + 3\rho_\sigma}$$

As ρ_σ/ρ_r increases, ζ evolves.

In the very early universe, the curvaton decays into radiation.

- decay at $\Gamma \simeq H$
- residual curvature perturbation:

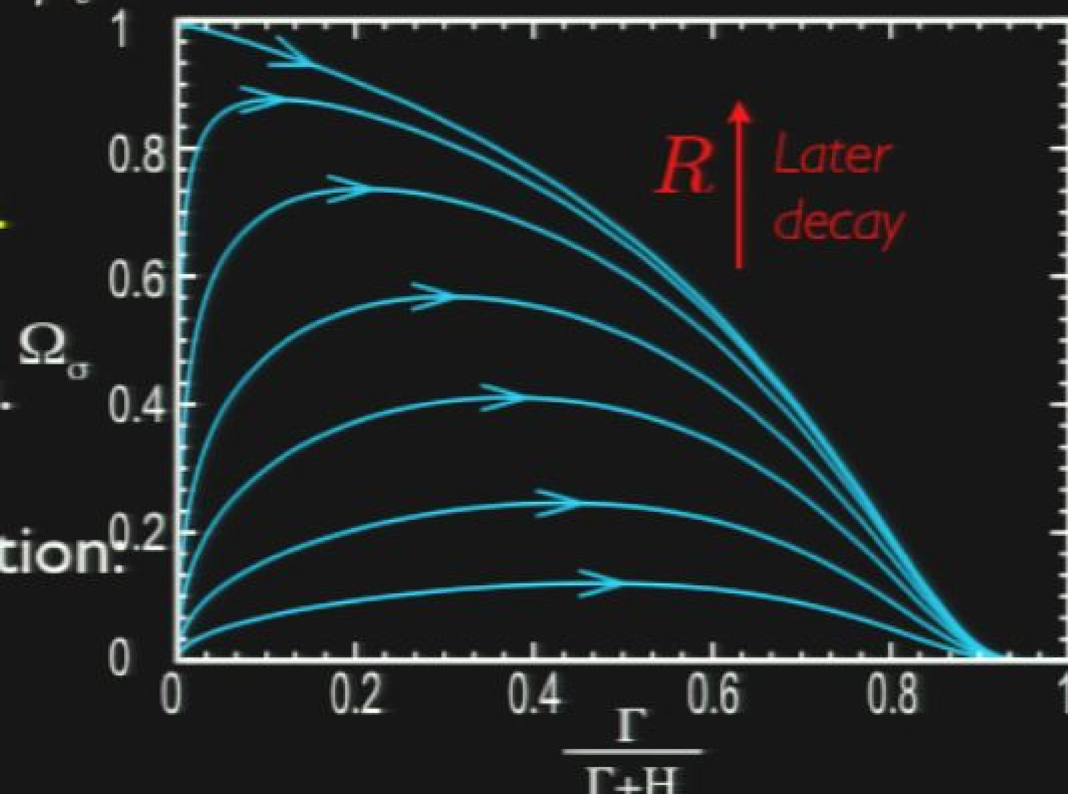
$\zeta = R\zeta_\sigma$

curvature perturbation from curvaton

new parameter

$$R \simeq \frac{3}{4}\left.\frac{\rho_\sigma}{\rho_r}\right|_{\Gamma=H}$$

$R \ll 1$



Malik, Wands and Ungarelli. PRD 67 063516 (2003)

Power Spectrum from the Curvaton

Fluctuations in the curvaton field become curvature perturbations.

$$\zeta = R\zeta_\sigma = \frac{R}{3}\frac{\delta\rho_\sigma}{\rho_\sigma} \quad \text{where} \quad R \simeq \frac{3}{4}\left.\frac{\rho_\sigma}{\rho_r}\right|_{\Gamma=H} \quad \text{and} \quad R \ll 1$$

curvature perturbation from curvaton

evaluated just prior to curvaton decay

keep the curvaton subdominant

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curvature perturbation from curvaton

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keep the curvaton subdominant

Curvaton energy: $\rho_\sigma = \frac{1}{2}m_\sigma^2\sigma^2 \Longrightarrow \frac{\delta\rho_\sigma}{\rho_\sigma} = 2\left(\frac{\delta\sigma}{\bar{\sigma}}\right) + \left(\frac{\delta\sigma}{\bar{\sigma}}\right)^2$

conserved outside horizon

Power Spectrum from the Curvaton

Fluctuations in the curvaton field become curvature perturbations.

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curvature perturbation from curvaton

evaluated just prior to curvaton decay

keep the curvaton subdominant

Curvaton energy: $\rho_\sigma = \frac{1}{2}m_\sigma^2\sigma^2 \Longrightarrow \frac{\delta\rho_\sigma}{\rho_\sigma} = 2\left(\frac{\delta\sigma}{\bar\sigma}\right) + \left(\frac{\delta\sigma}{\bar\sigma}\right)^2$

conserved outside horizon

Quantum fluctuations: $(\delta\sigma)_{\rm rms} = \frac{H_{\rm inf}}{2\pi} \ll \bar\sigma$

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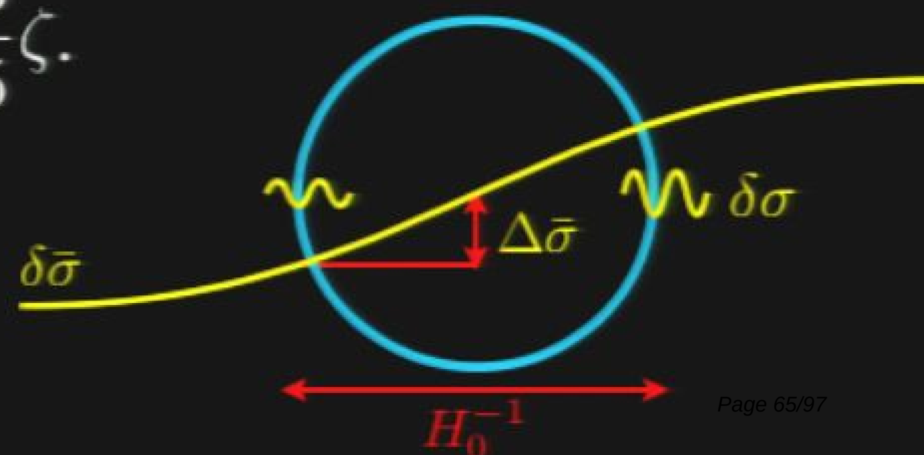

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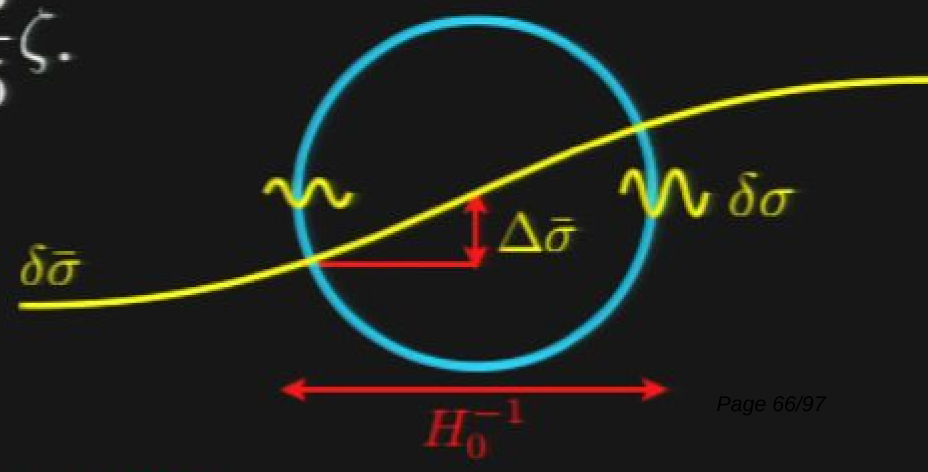
$$\boxed{\frac{\Delta P_{\Psi,\sigma}}{P_{\Psi,\sigma}} = 2\frac{\Delta\bar{\sigma}}{\bar{\sigma}}}$$



Part IV

A Power Asymmetry from the Curvaton

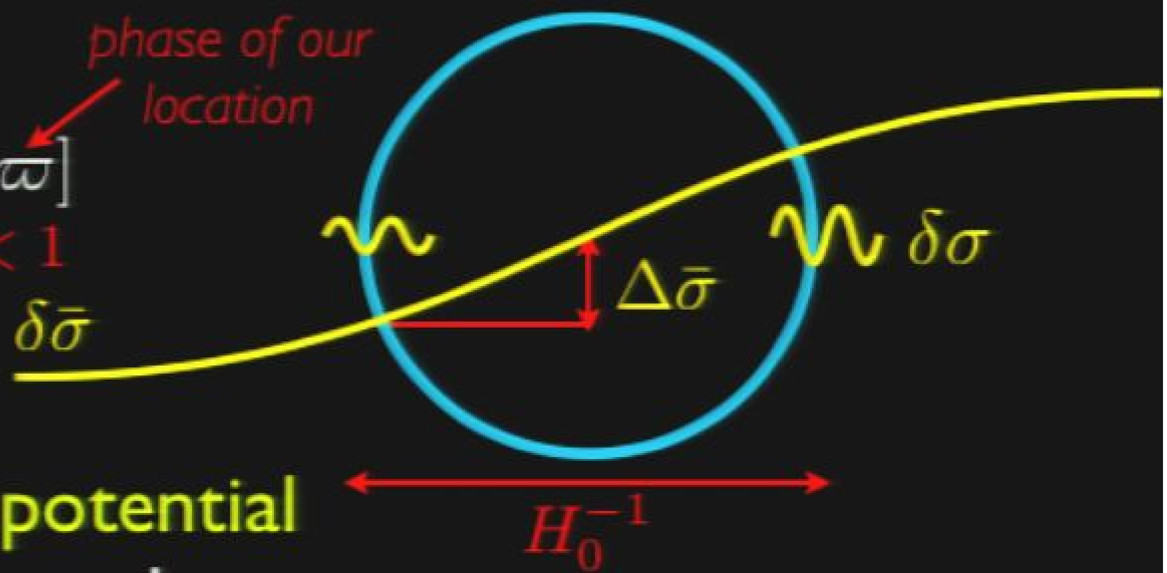
Curvaton Supermodes in the CMB

Curvaton supermode:

$$\delta\bar{\sigma}(\vec{x},t) = \bar{\sigma}_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$$

phase of our location

$kH_0^{-1} \ll 1$



The curvaton supermode generates a superhorizon potential fluctuation, but it is suppressed.

$R \simeq \dfrac{3\rho_\sigma}{4\rho}$ *just prior to decay*

$$\Psi = -\frac{R}{5}\left[2\left(\frac{\delta\bar{\sigma}}{\bar{\sigma}}\right) + \left(\frac{\delta\bar{\sigma}}{\bar{\sigma}}\right)^2\right] \longleftarrow \frac{\delta\rho_\sigma}{\rho_\sigma}$$

The potential perturbation is not sinusoidal!

Part IV

A Power Asymmetry from the Curvaton

$$P_{\Psi,\phi} \propto \frac{H^2}{\varepsilon}$$

$$P_{\Psi,\sigma} \propto \frac{H^2}{\sigma^2}$$

Part IV

A Power Asymmetry from the Curvaton

Curvaton Supermodes in the CMB

The CMB quadrupole implies an upper bound:

$$R\left(\frac{\Delta\bar{\sigma}}{\bar{\sigma}}\right)^2 \lesssim \frac{5}{2}(5.8\mathcal{Q}) \quad \text{for} \quad \varpi = 0$$

$$\left(\frac{\Delta P_\Psi}{P_\Psi}\right)$$

Most other phases give similar bounds.

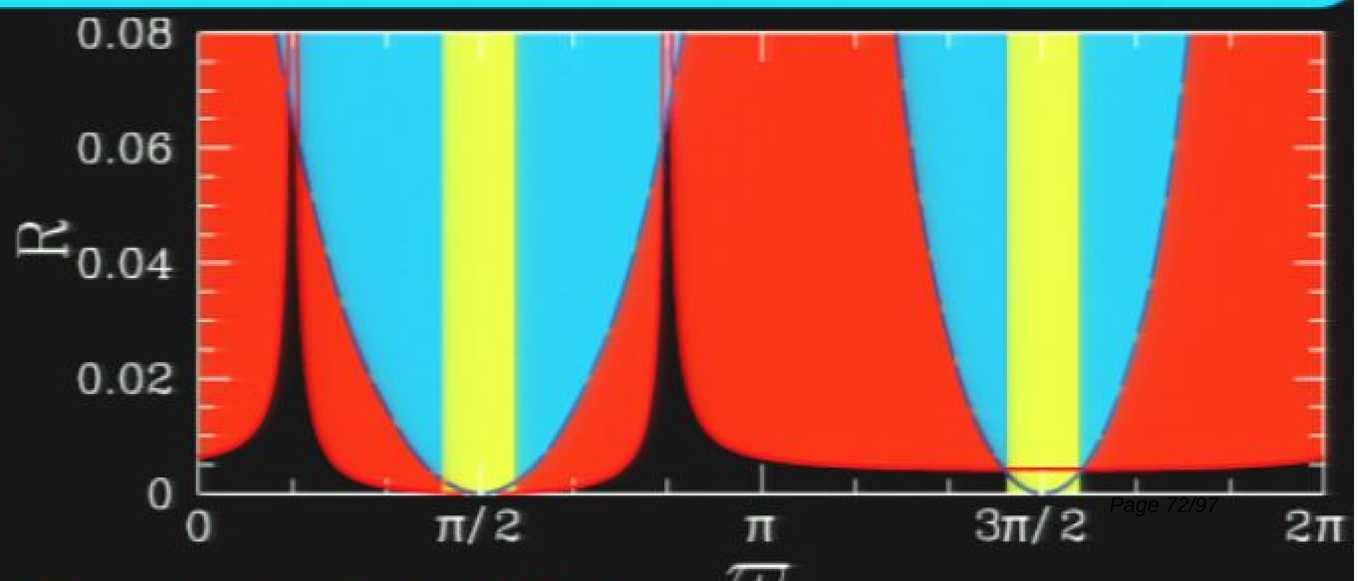
Excluded by Quadrupole

Excluded by Octupole

Not superhorizon

$\bar{\sigma}_{\rm SM} = \bar{\sigma}$

$\Delta\bar{\sigma}/\bar{\sigma} = 0.2$



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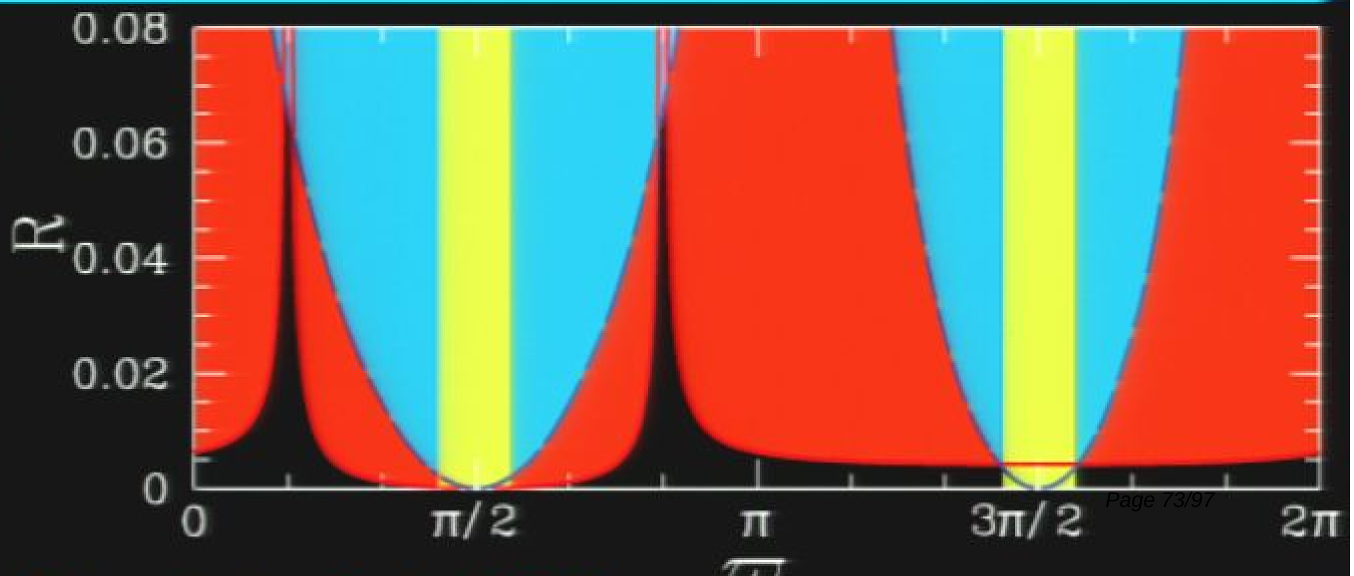

Perturbation Mixture

Both the curvaton and the inflaton may contribute to P_Ψ.

$$(\delta\phi)_{\mathrm{rms}} = (\delta\sigma)_{\mathrm{rms}} = \frac{H_{\mathrm{inf}}}{2\pi}$$

quantum fluctuations

$$\epsilon \equiv \frac{m_{\mathrm{Pl}}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2$$

$$R \simeq \frac{3}{4}\left.\frac{\rho_\sigma}{\rho_r}\right|_{\Gamma=H}$$

$$P_{\Psi,\phi} = \left(\frac{9}{10}\right)^2 \frac{8\pi}{9\epsilon}\left(\frac{H_{\mathrm{inf}}^2}{k^3 m_{\mathrm{Pl}}^2}\right)$$

$$P_{\Psi,\sigma} = \left(\frac{2R}{5}\right)^2 \frac{H_{\mathrm{inf}}^2}{2k^3\bar{\sigma}^2}$$

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Define a new parameter: $\xi \equiv \dfrac{P_{\Psi,\sigma}}{P_{\Psi,\sigma}+P_{\Psi,\phi}}$

$$\xi = \frac{\tilde{\epsilon}}{\tilde{\epsilon}+1} \qquad \tilde{\epsilon} \equiv \frac{1}{9\pi}\left(\frac{m_{\rm Pl}}{\bar{\sigma}}\right)^2 R^2\epsilon$$

$\bar{\sigma} \ll m_{\rm Pl} \Longrightarrow \xi \simeq 1$

$\bar{\sigma} \lesssim m_{\rm Pl} \Longrightarrow \xi \ll 1$

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$$\bar{\sigma} \ll m_{\rm Pl} \Longrightarrow \xi \simeq 1$$

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Tensor-Scalar Ratio:

$$r = 16\epsilon(1-\xi)$$

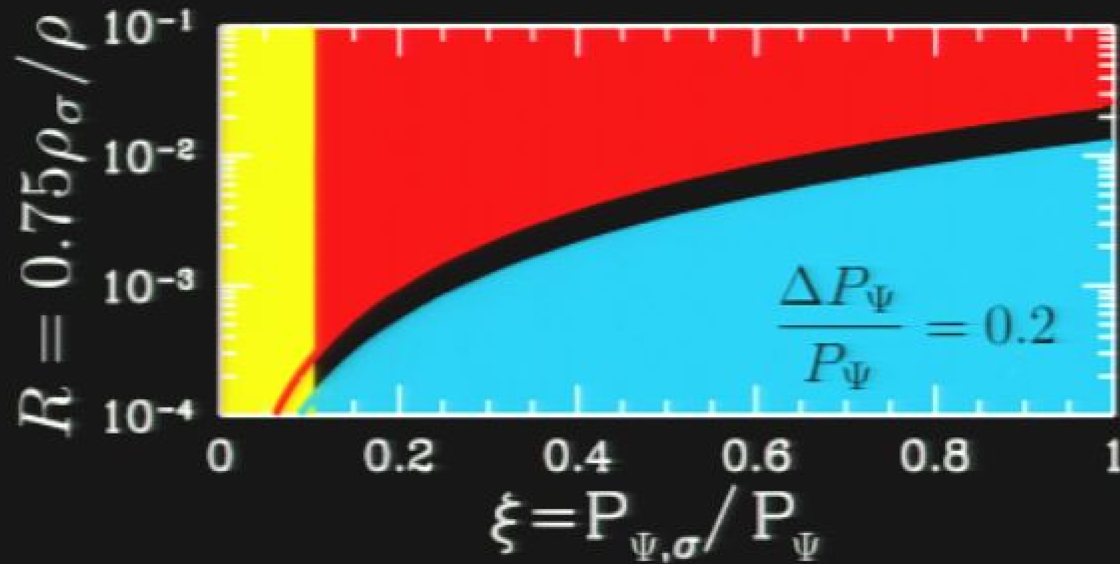
Constraining the Curvaton Model

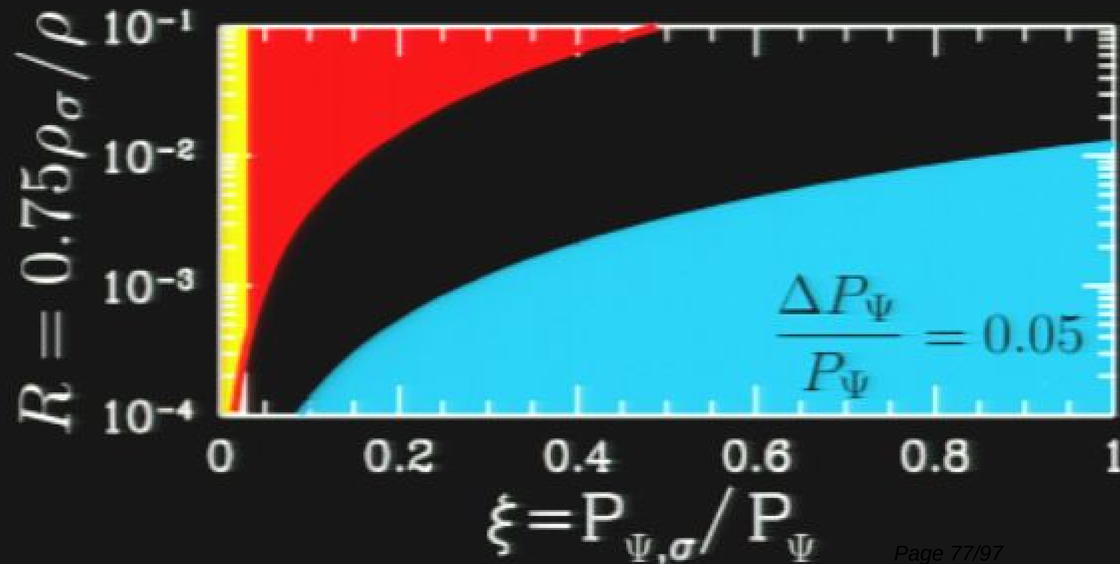
The curvaton and inflaton both contribute to $P_\Psi(k)$:

$$\xi \equiv \frac{P_{\Psi,\sigma}}{P_\Psi}$$ fractional power from curvaton

$$\frac{\Delta P_\Psi}{P_\Psi} = 2\xi \frac{\Delta\bar{\sigma}}{\bar{\sigma}}$$ power asymmetry

$$\frac{\Delta\bar{\sigma}}{\bar{\sigma}} \lesssim 1 \Longrightarrow \xi \gtrsim \frac{1}{2}\frac{\Delta P_\Psi}{P_\Psi}$$





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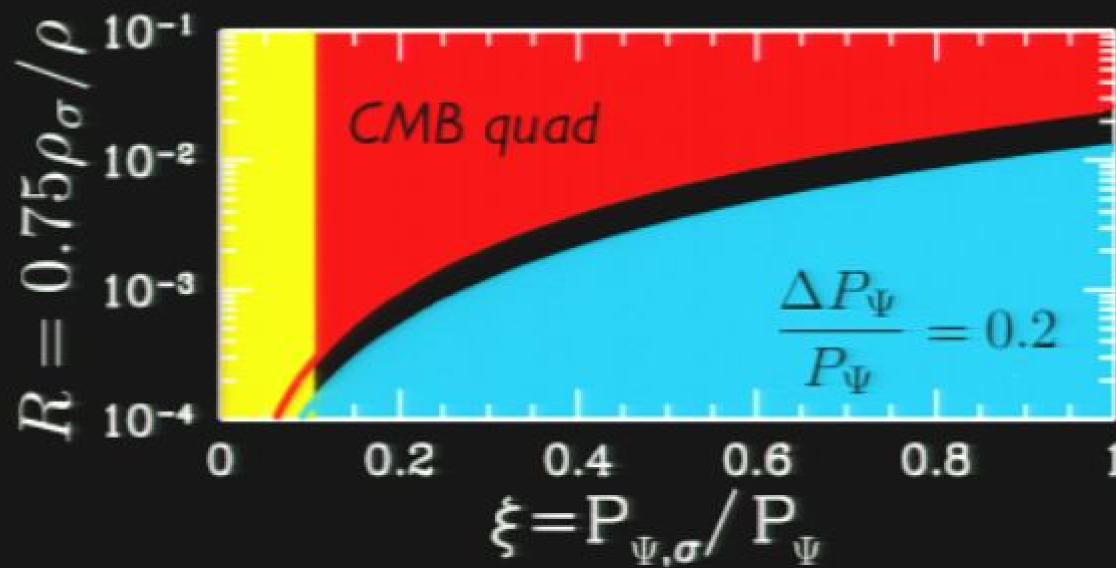
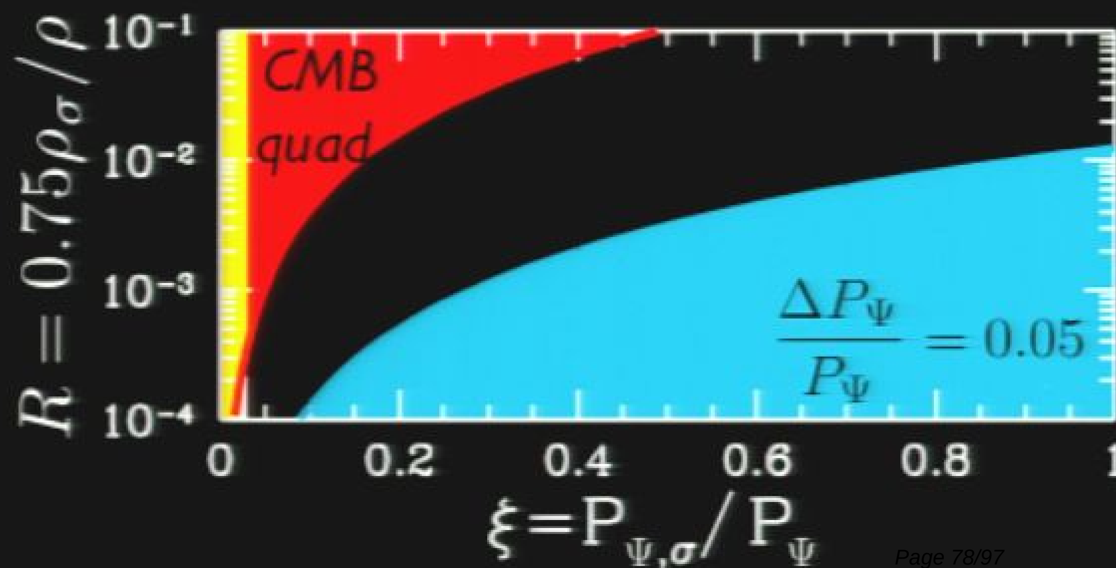
CMB Quadrupole:

$$R\left(\frac{\Delta\bar{\sigma}}{\bar{\sigma}}\right)^2 \lesssim \frac{5}{2}(5.8\mathcal{Q})$$

$$R \lesssim 58\mathcal{Q}\,\xi^2\left(\frac{\Delta P_\Psi}{P_\Psi}\right)^{-2}$$





Constraining the Curvaton Model

Non-Gaussianity Constraints

$$\Psi = -\frac{R}{5}\left[2\left(\frac{\delta\sigma}{\bar{\sigma}}\right) + \left(\frac{\delta\sigma}{\bar{\sigma}}\right)^2\right]$$

potential fluctuation — Gaussian fluctuation — Gaussian fluctuation squared

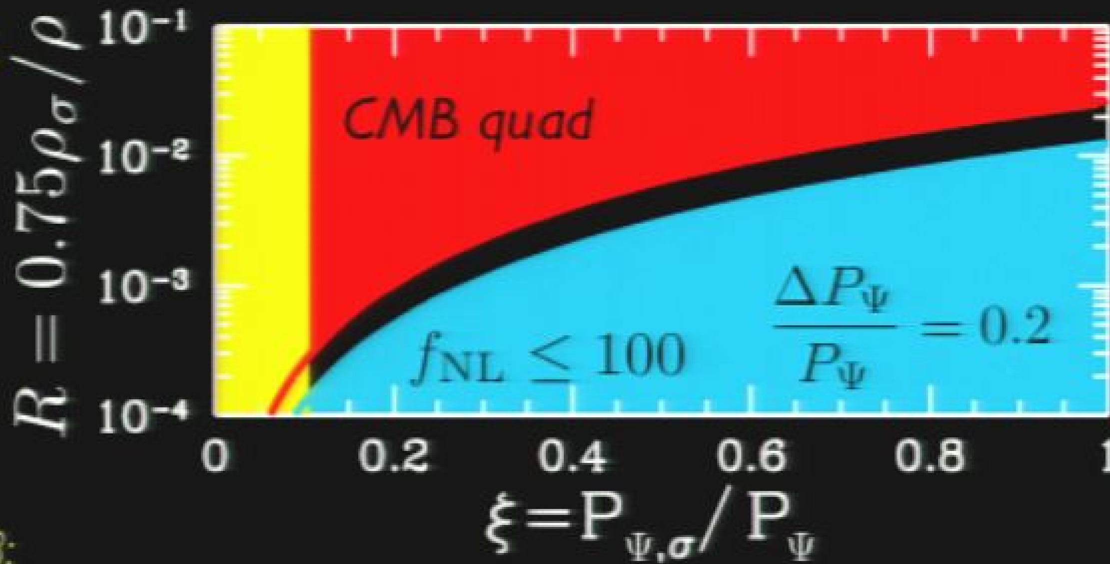
$$f_{\rm NL} \simeq \frac{5\xi^2}{4R}$$

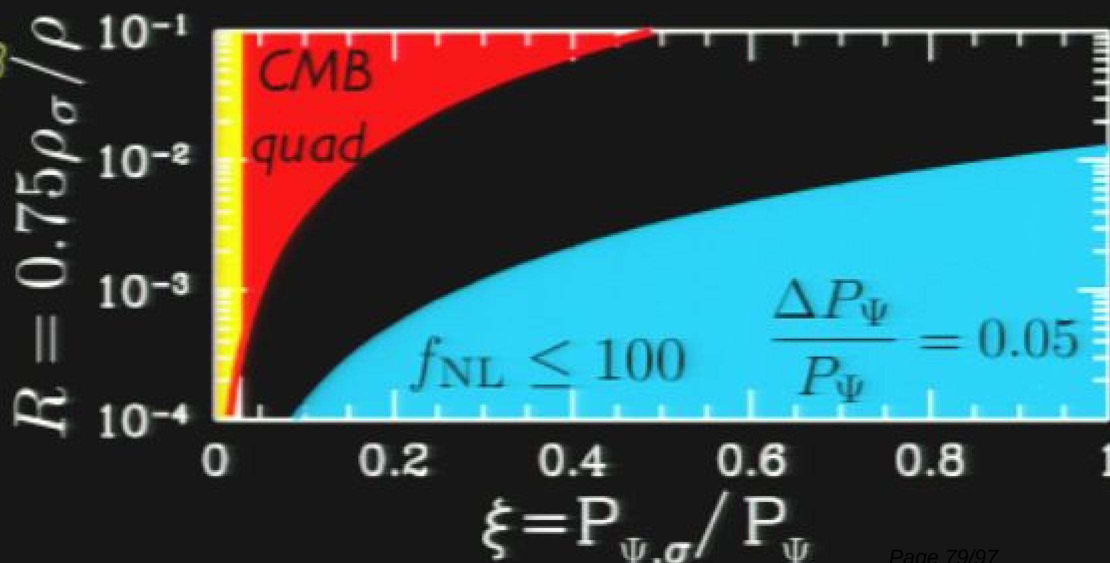
Lyth, Ungarelli, Wands 2003; Ichikawa, Suyama, Takahashi, Yamaguchi 2008

Upperbound from WMAP:

$$f_{\rm NL} \lesssim 100$$

Komatsu et al. 2008
Yadav, Wandelt 2008





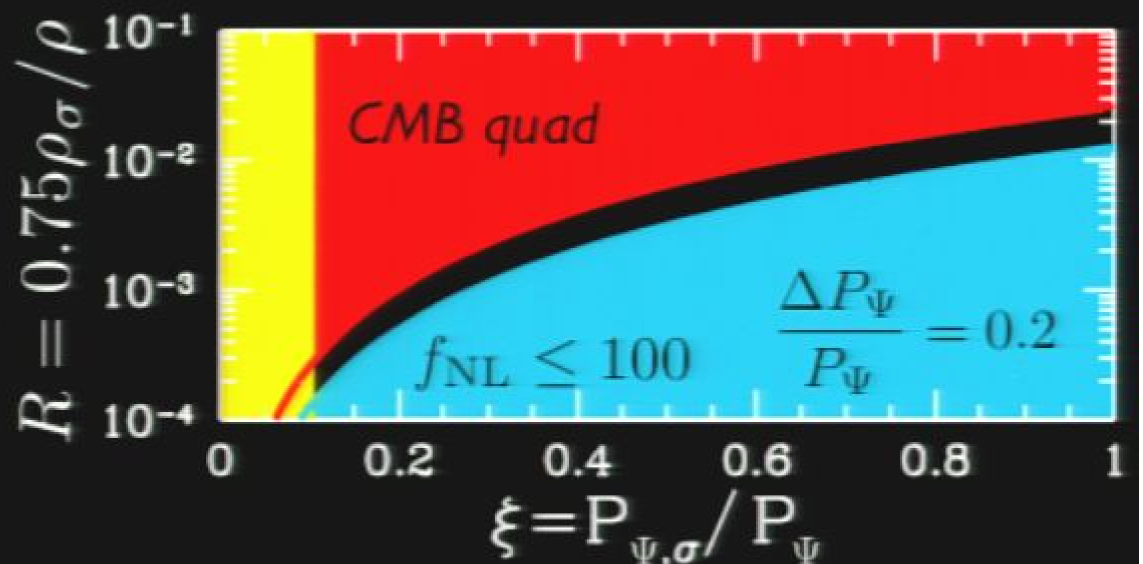
Constraining the Curvaton Model

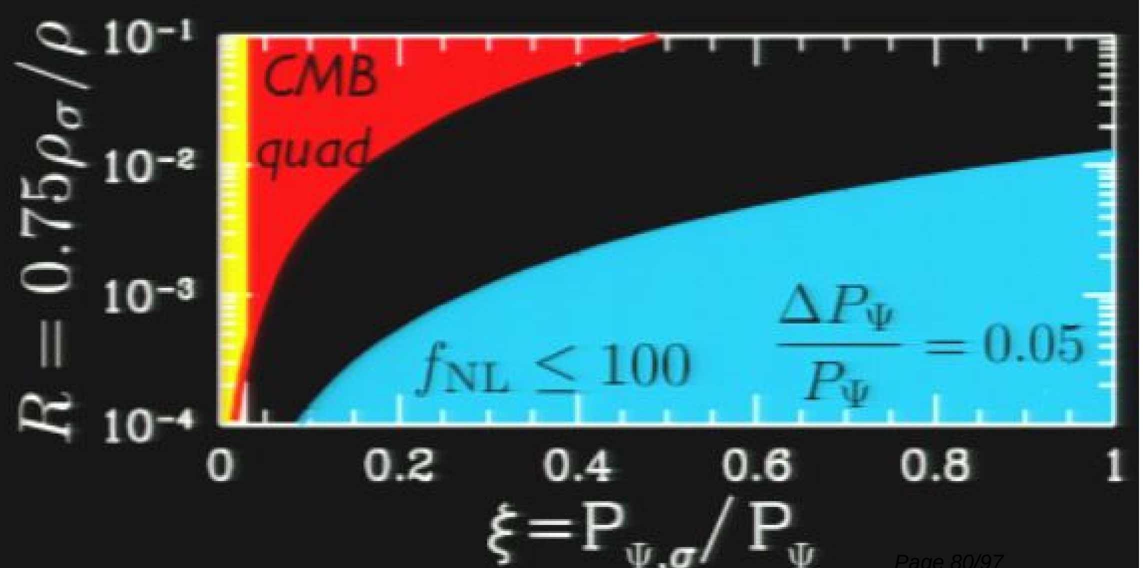
The Allowed Region

$$\frac{5}{4\, f_{\rm NL,max}} \lesssim \frac{R}{\xi^2} \lesssim \frac{58\, Q}{(\Delta P_\Psi / P_\Psi)^2}$$

Non-Gaussianity — CMB Quadrupole

Allowed window





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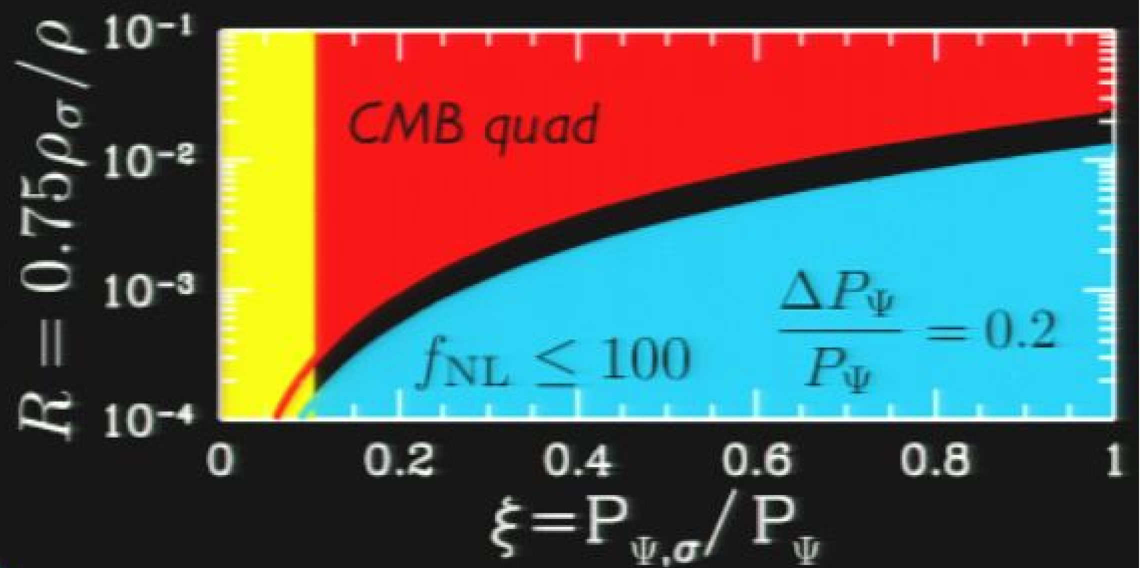
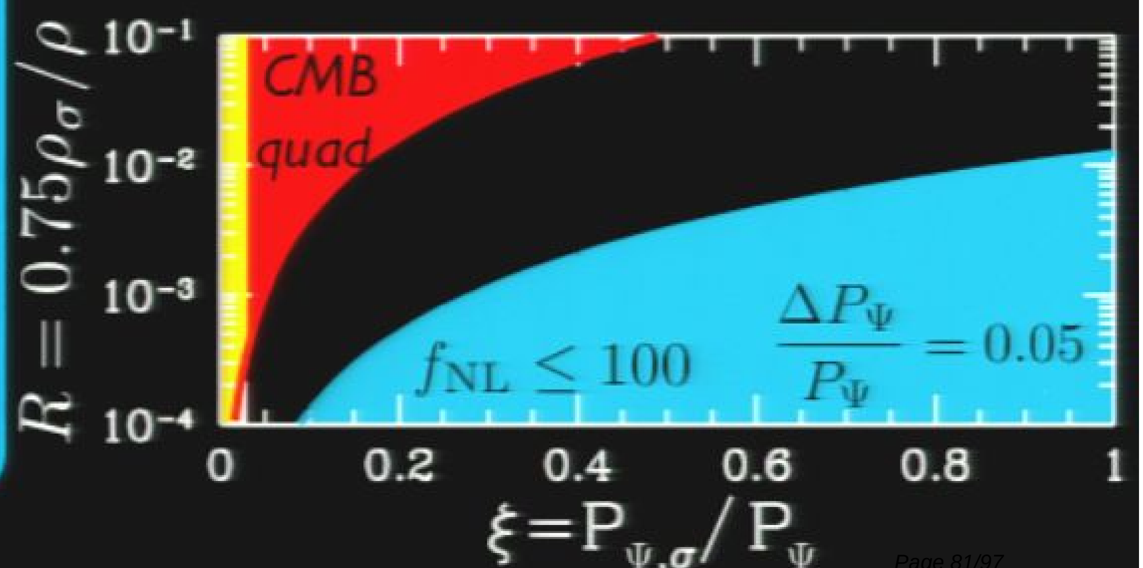


The Dealbreaker

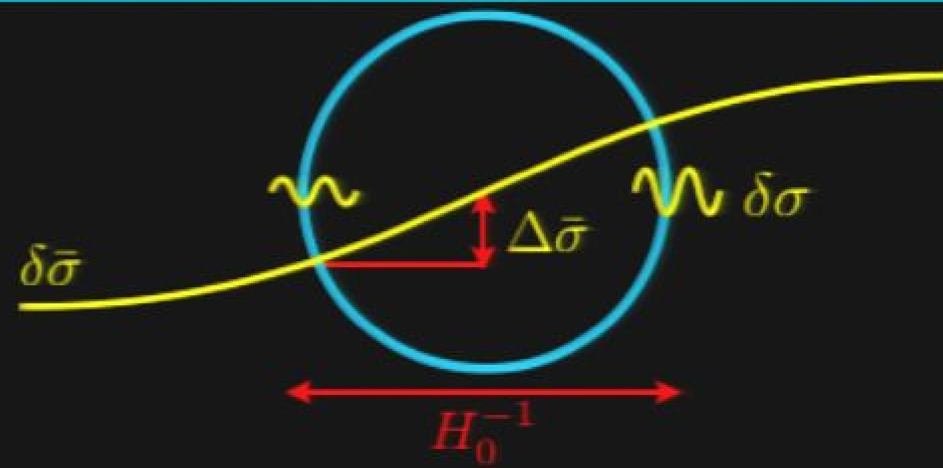
The window for $\frac{\Delta P_\Psi}{P_\Psi} = 0.2$

disappears if $f_{\mathrm{NL,max}} \lesssim 50$



Origins of the Supermode

Could the supermode be a **quantum fluctuation**?



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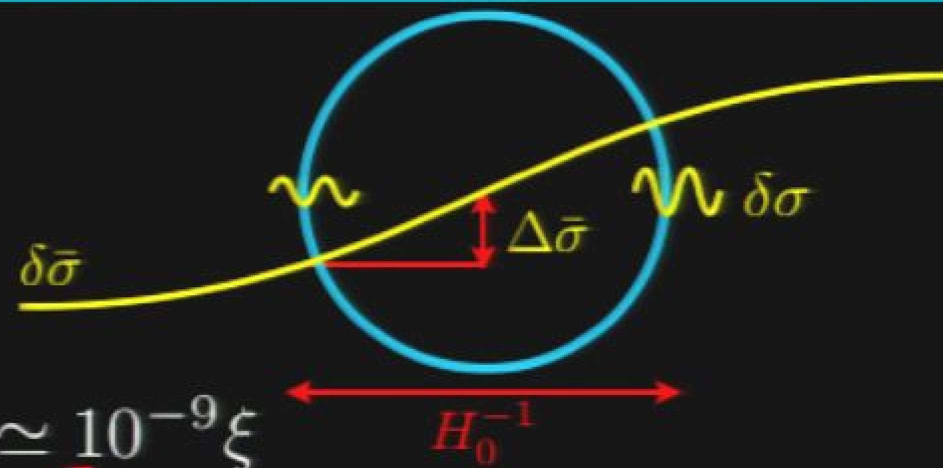

Power spectrum from curvaton

$$P_{\Psi,\sigma} = \left(\frac{2R}{5}\right)^2 \left\langle \left(\frac{\delta\sigma}{\bar{\sigma}}\right)^2 \right\rangle = \xi P_\Psi \simeq 10^{-9}\xi$$

Observed power spectrum

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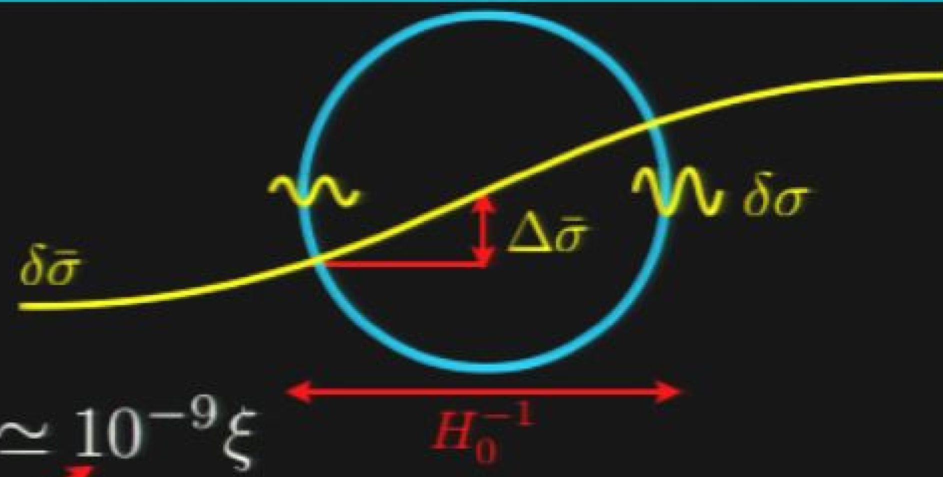

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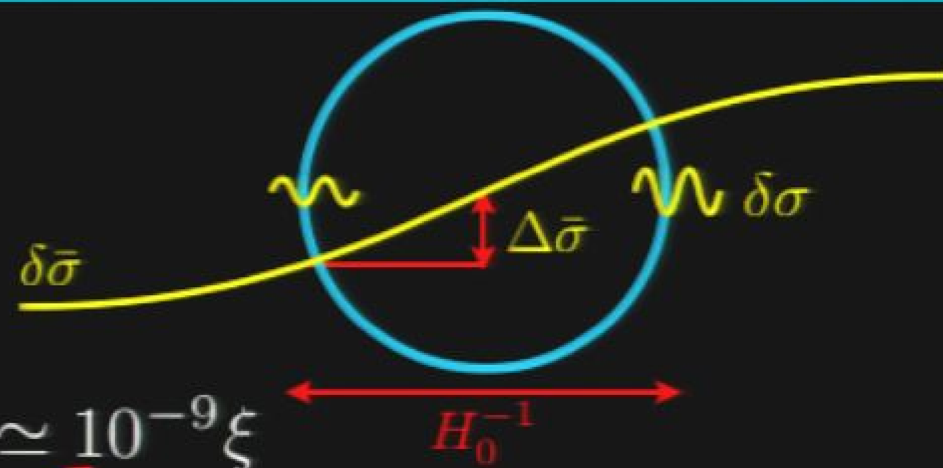

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$$\bar{\sigma}_{\mathrm{SM}} > \Delta\bar{\sigma} > 5(\delta\sigma)_{\mathrm{rms}}$$

The supermode would be at least a 5-sigma fluctuation: that's highly improbable!

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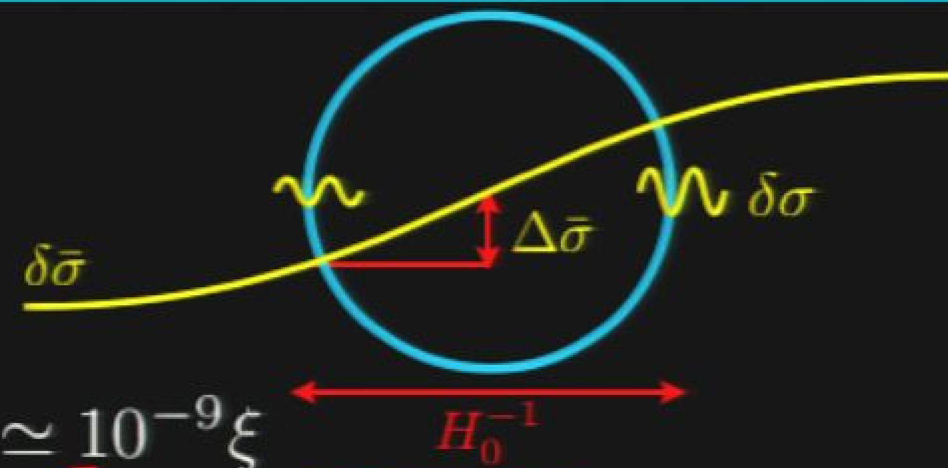

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0.2 … 00 … $\frac{\Delta P_\Psi}{2\ P_\Psi}$

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Signature of
"**curvaton web?**"
Linde and Mukhanov, 2006

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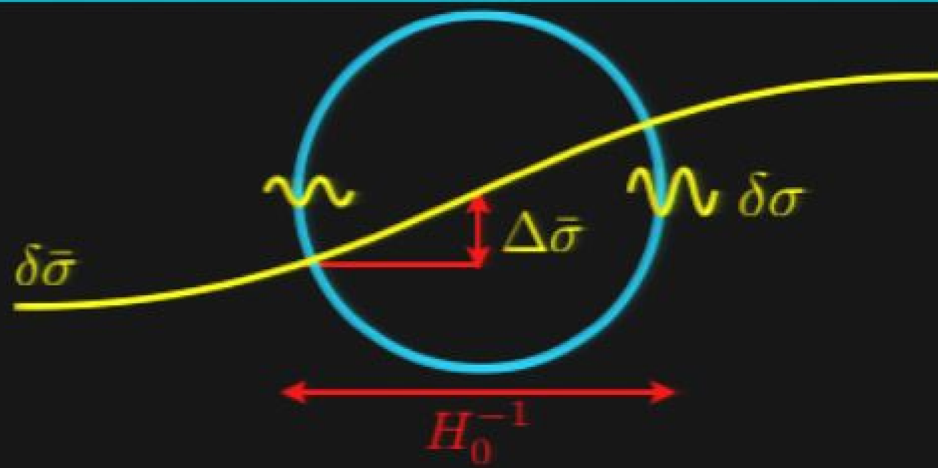

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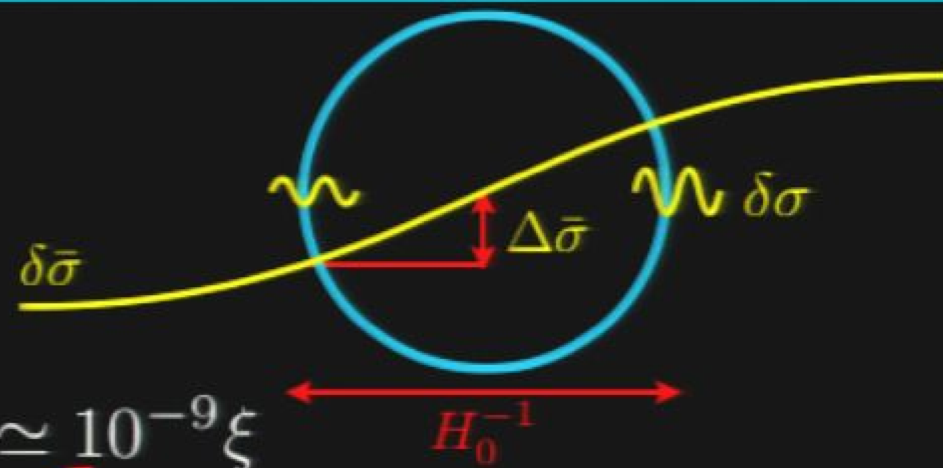

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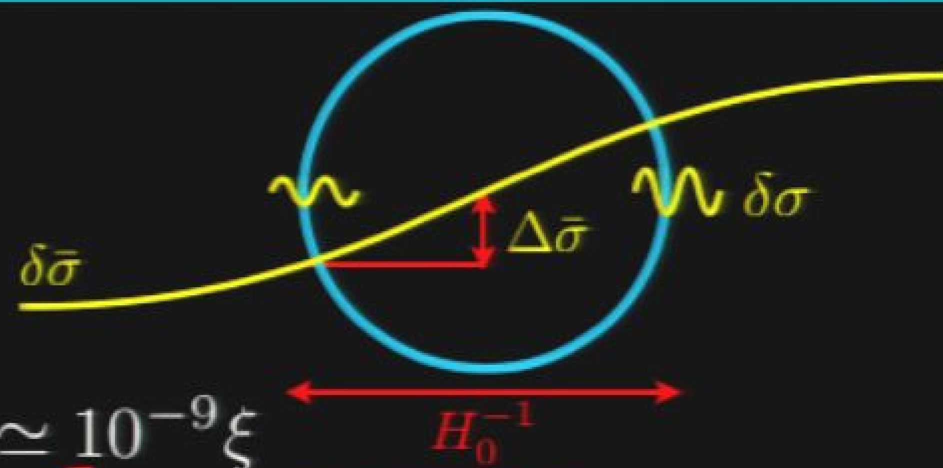

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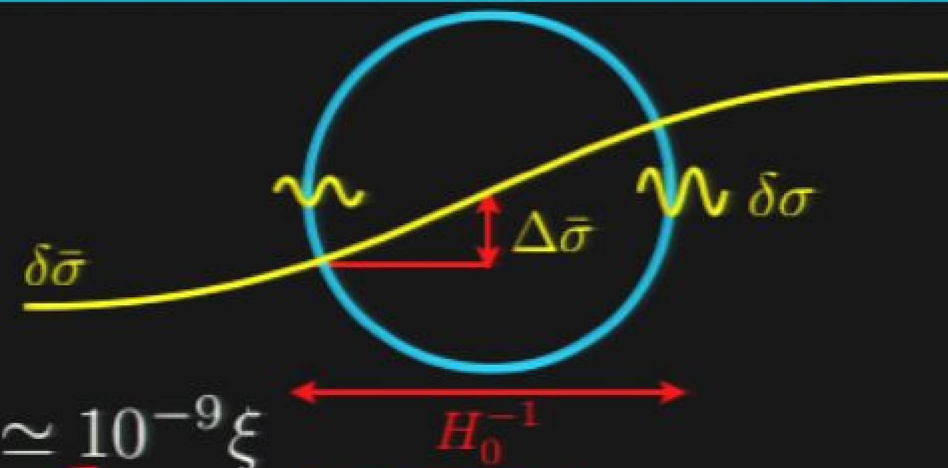
Could the supermode be a

A *pre-inflationary* remnant?



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...bserved power s...

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Signature of "*curvaton web?*"

Linde and Mukhanov, 2006

$$\bar{\sigma}_{\rm SM} > \Delta\bar{\sigma} > 5\,(\delta\sigma)_{\rm rms}$$

The supermode would be at least a 5-sigma fluctuation: that's highly improbable!

A Scale-Dependent Asymmetry?

There are indications that only large scales are asymmetric.

- Asymmetry detected for $\ell = 5 - 40$.
- Some analyses see reduced asymmetry for $\ell \gtrsim 100$.

Donoghue and Donoghue 2005; Lew 2008.

How could the asymmetry disappear at small scales?

Only the perturbations from the curvaton are asymmetric; the inflaton perturbations are still statistically isotropic.

Introduce scale dependence through $\xi \equiv \dfrac{P_{\Psi,\sigma}}{P_{\Psi,\sigma} + P_{\Psi,\phi}}$.

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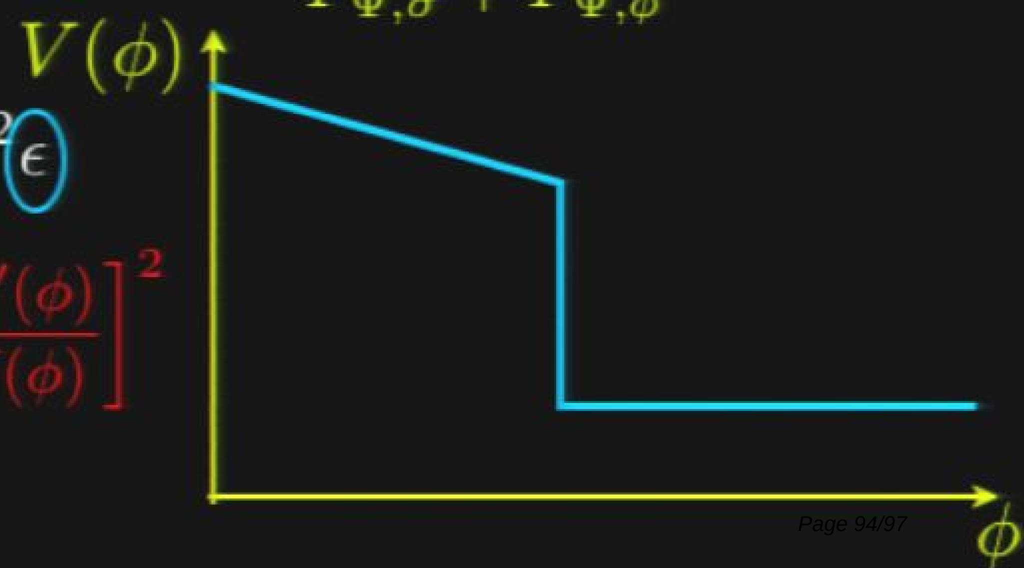
$$\epsilon \downarrow \rightarrow P_{\Psi,\phi} \uparrow \rightarrow \xi \downarrow \qquad \epsilon \equiv \frac{m_{\rm Pl}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2$$

$$V(\phi) \downarrow \rightarrow P_{\Psi} \leftrightarrow$$



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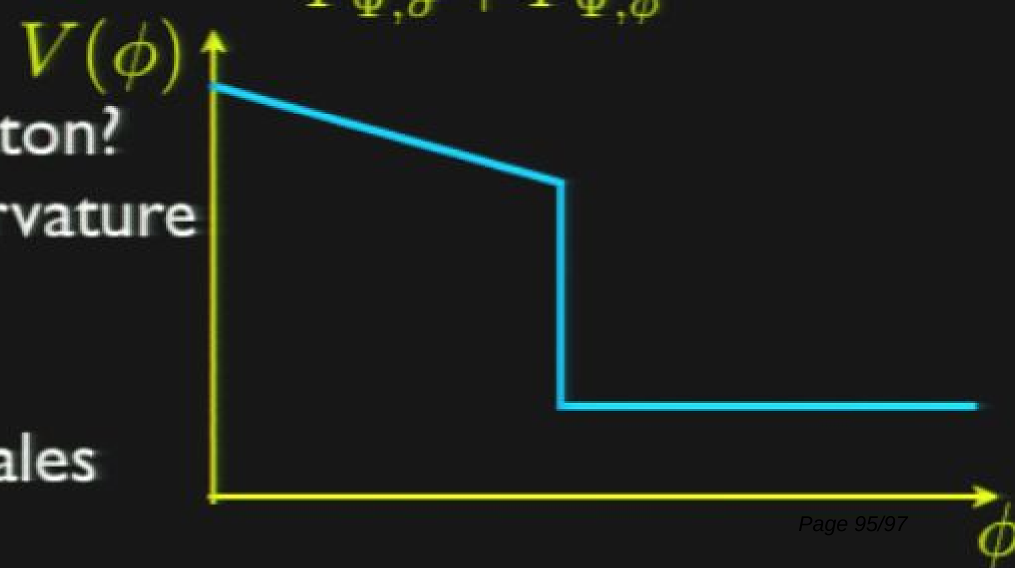
- A feature in $V(\phi)$ *Gordon 2007*
- **Isocurvature** modes from curvaton?
  - curvaton can produce isocurvature perturbations
  - isocurvature perturbations contribute more on large scales



Work in progress....

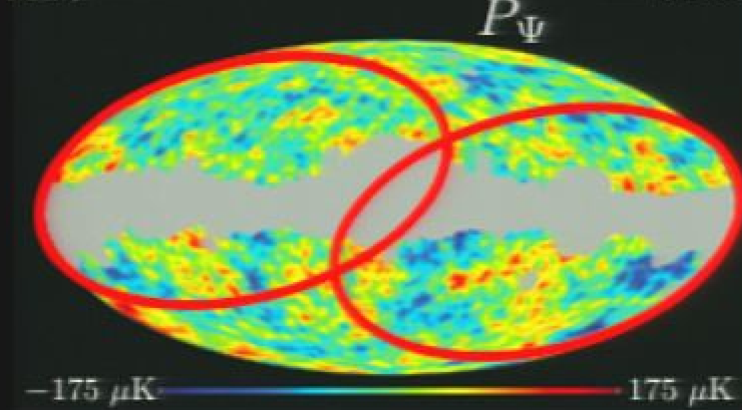
Summary: How to Generate the Power Asymmetry

There is a power asymmetry in the CMB.

- present at the 99% confidence level
- detected on large scales

Hansen, Banday, Gorski, 2004
Eriksen, Hansen, Banday, Gorski, Lilje 2004
Eriksen, Banday, Gorski, Hansen, Lilje 2007

$$\frac{\Delta P_\Psi}{P_\Psi} = 0.20$$



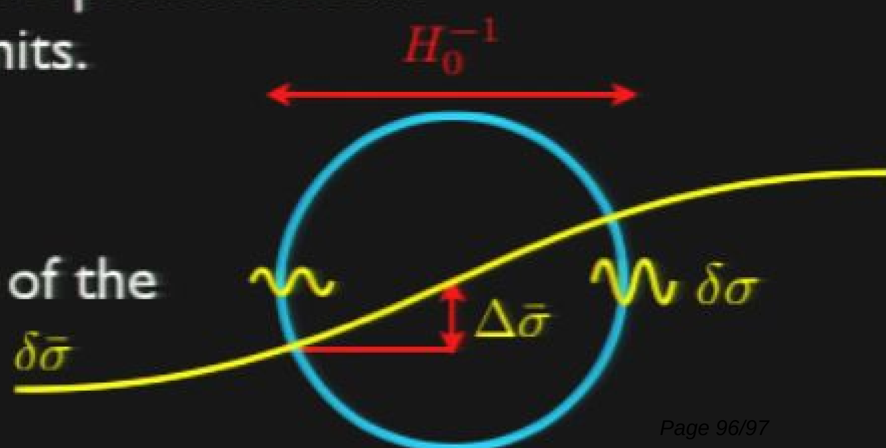
A superhorizon perturbation during inflation generates a power asymmetry.

- also generates large-scale CMB temperature perturbations
- no dipole; quadrupole and octupole set limits.

Erickcek, Carroll, Kamionkowski arXiv:0808.1570

- an inflaton perturbation is ruled out
- a curvaton perturbation is a viable source of the observed asymmetry

Erickcek, Kamionkowski, Carroll arXiv:0806.0377



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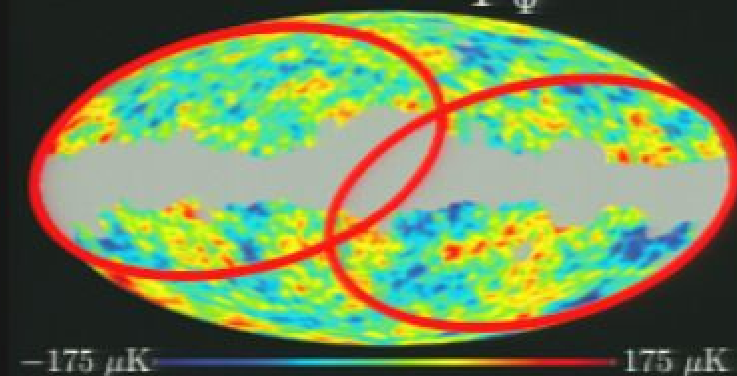

Features of the Curvaton-Generated Power Asymmetry

- the superhorizon curvaton perturbation is not a quantum fluctuation
- the produced asymmetry is scale-invariant, but it is possible to modify that
- suppressed tensor-scalar ratio: $r \propto (1-\xi)$
- high non-Gaussianity: $f_{\rm NL} \gtrsim 50$