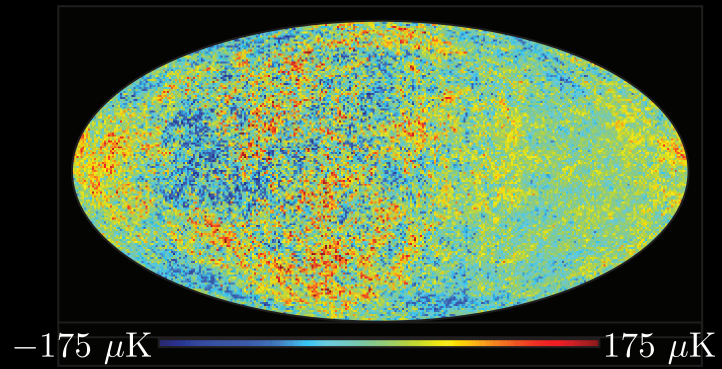
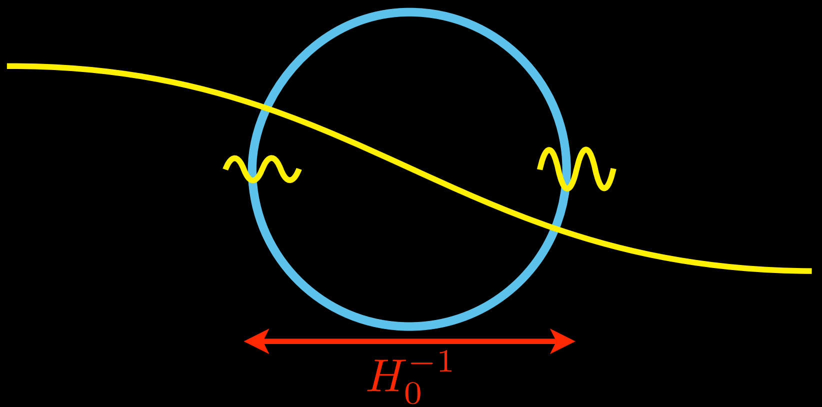
How to Generate the Cosmological Power Asymmetry during Inflation





Adrienne Erickcek

California Institute of Technology

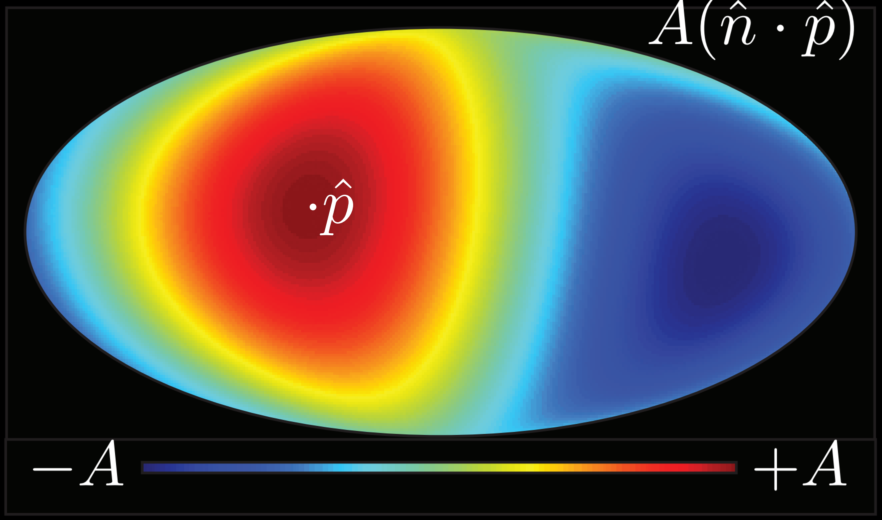
In collaboration with Sean Carroll and Marc Kamionkowski

"A Hemispherical Power Asymmetry from Inflation" arXiv:0806.0377, submitted to PRL

"Superhorizon Perturbations and the CMB" arXiv:0808.1570, submitted to PRD

Cosmo '08: August 25, 2008

A Hemispherical Power Asymmety



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

CMB Temperature

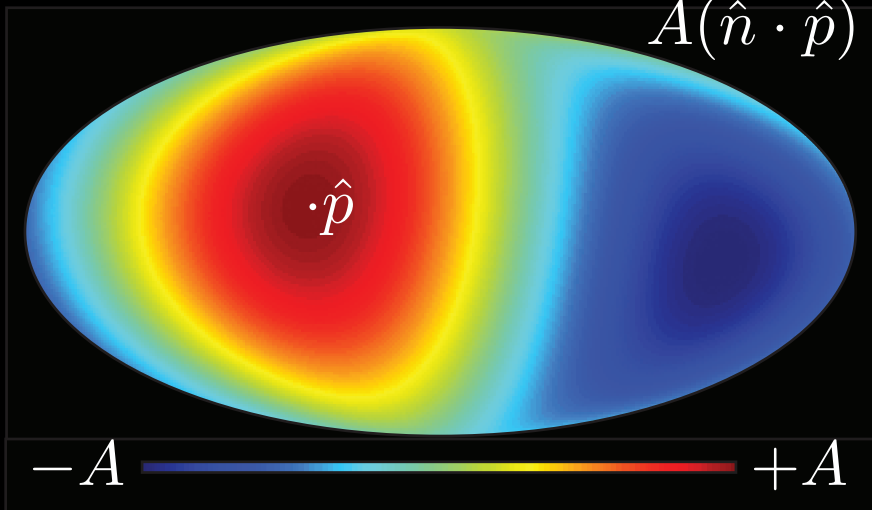
Gaussian field with isotropic power

Modulation Amplitude

"North" pole of asymmetry

Simulated maps courtesy of H. K. Eriksen

A Hemispherical Power Asymmety



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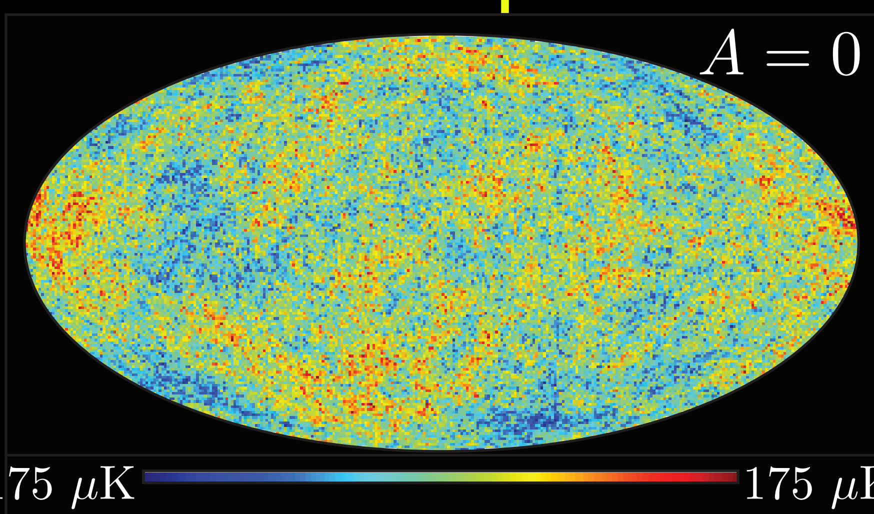
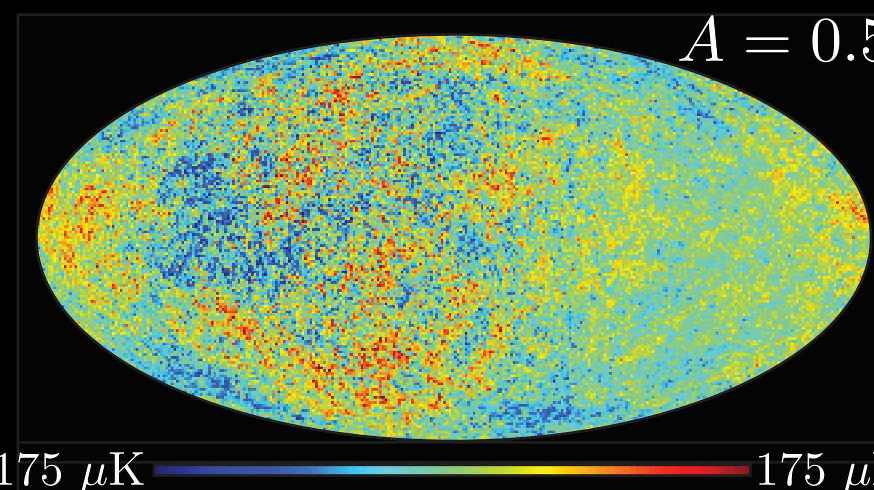


Asymmetric



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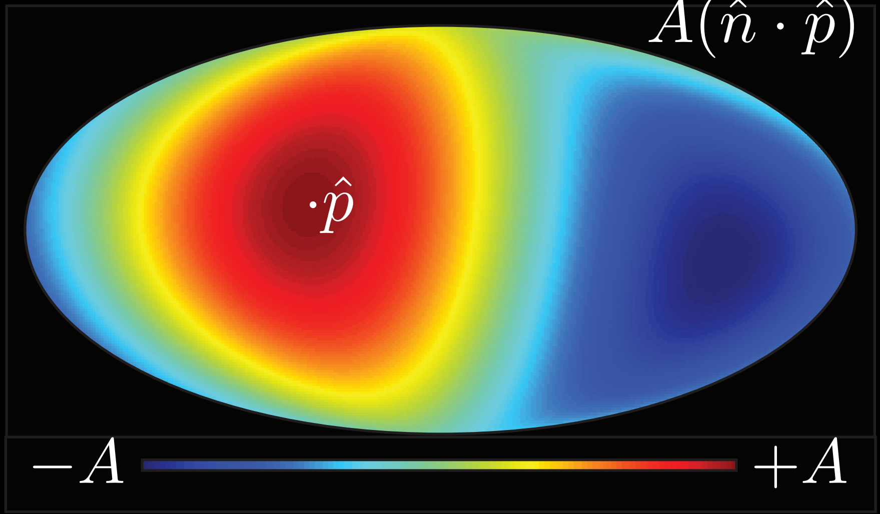

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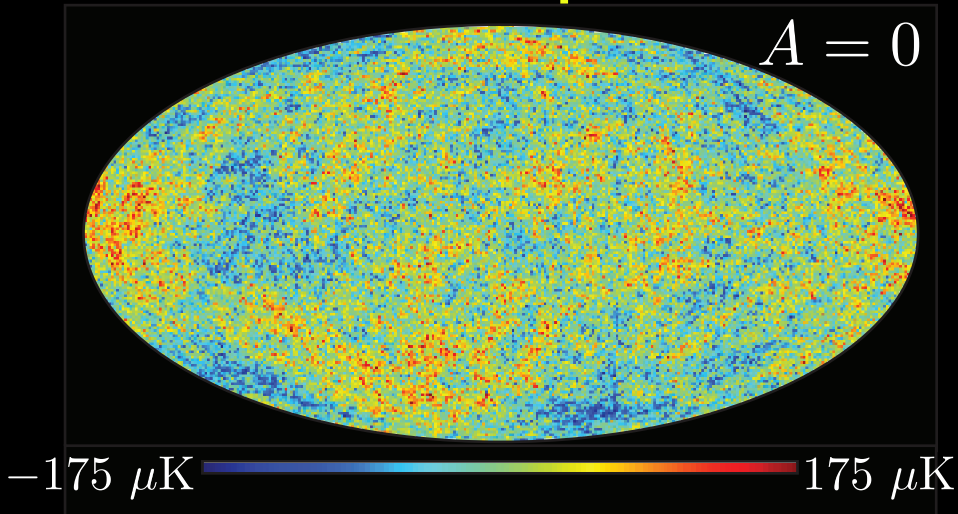

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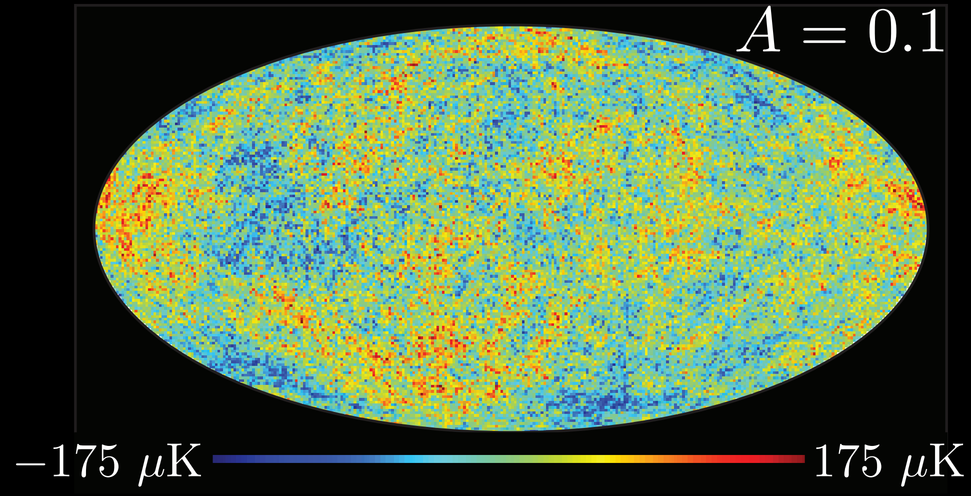

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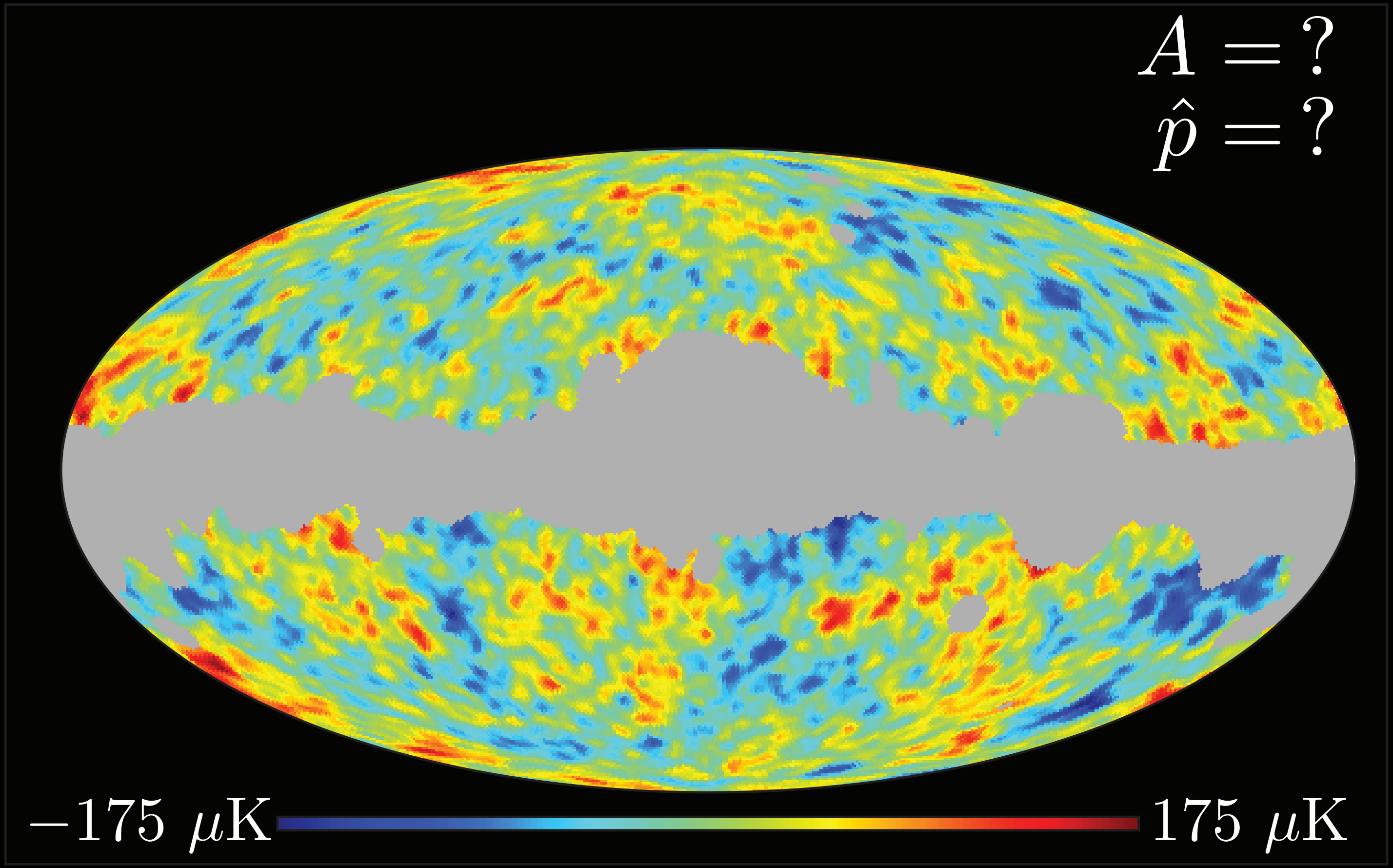
A Power Asymmety?

Isotropic or Asymmetric?



WMAP First Year Low-Resolution Map

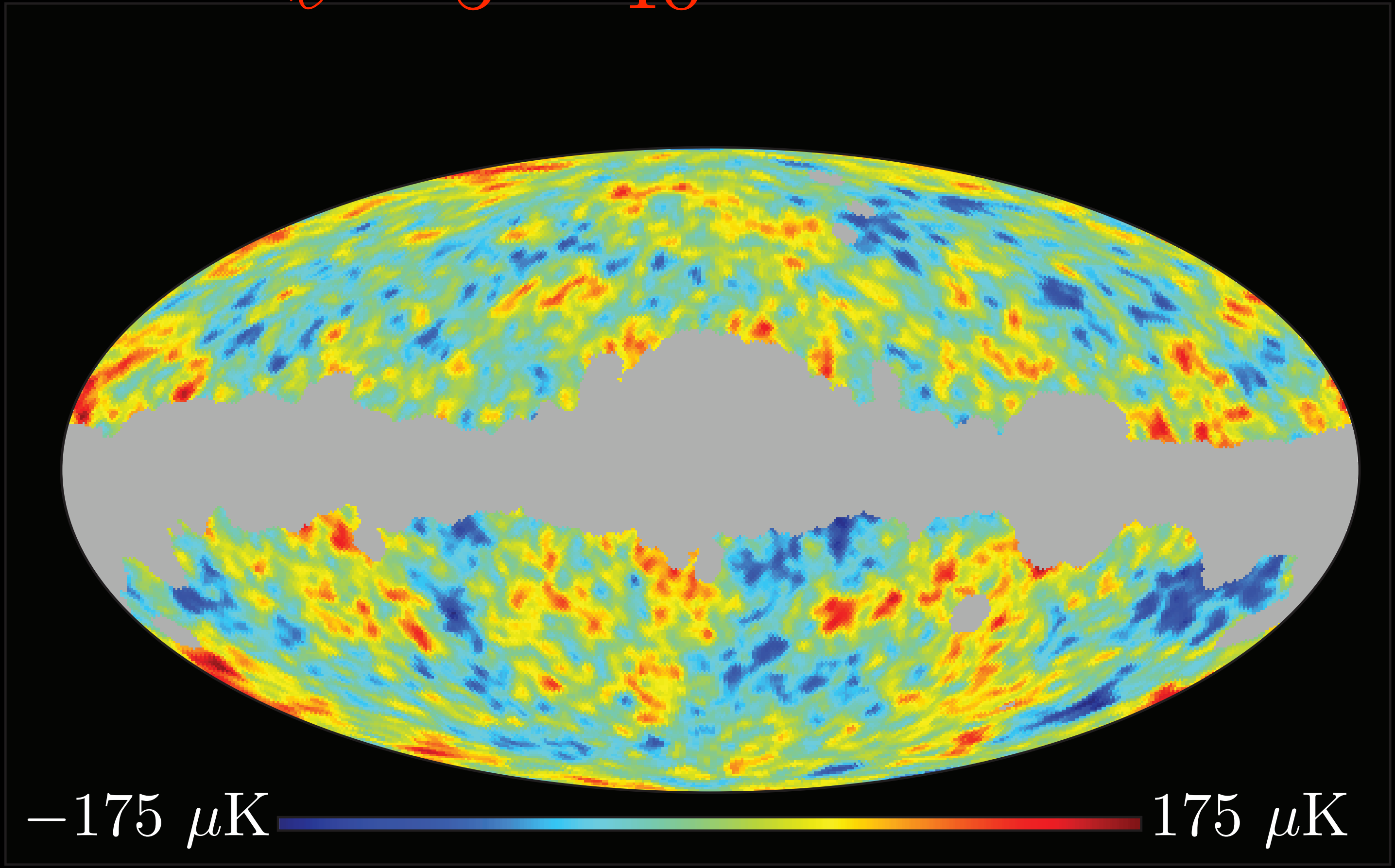
Image from Eriksen, et al. astro-ph/0307507

An Asymmetric Universe!

There is a hemispherical power asymmetry! There is more power on large scales south of the ecliptic.

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

$\ell = 5 - 40$



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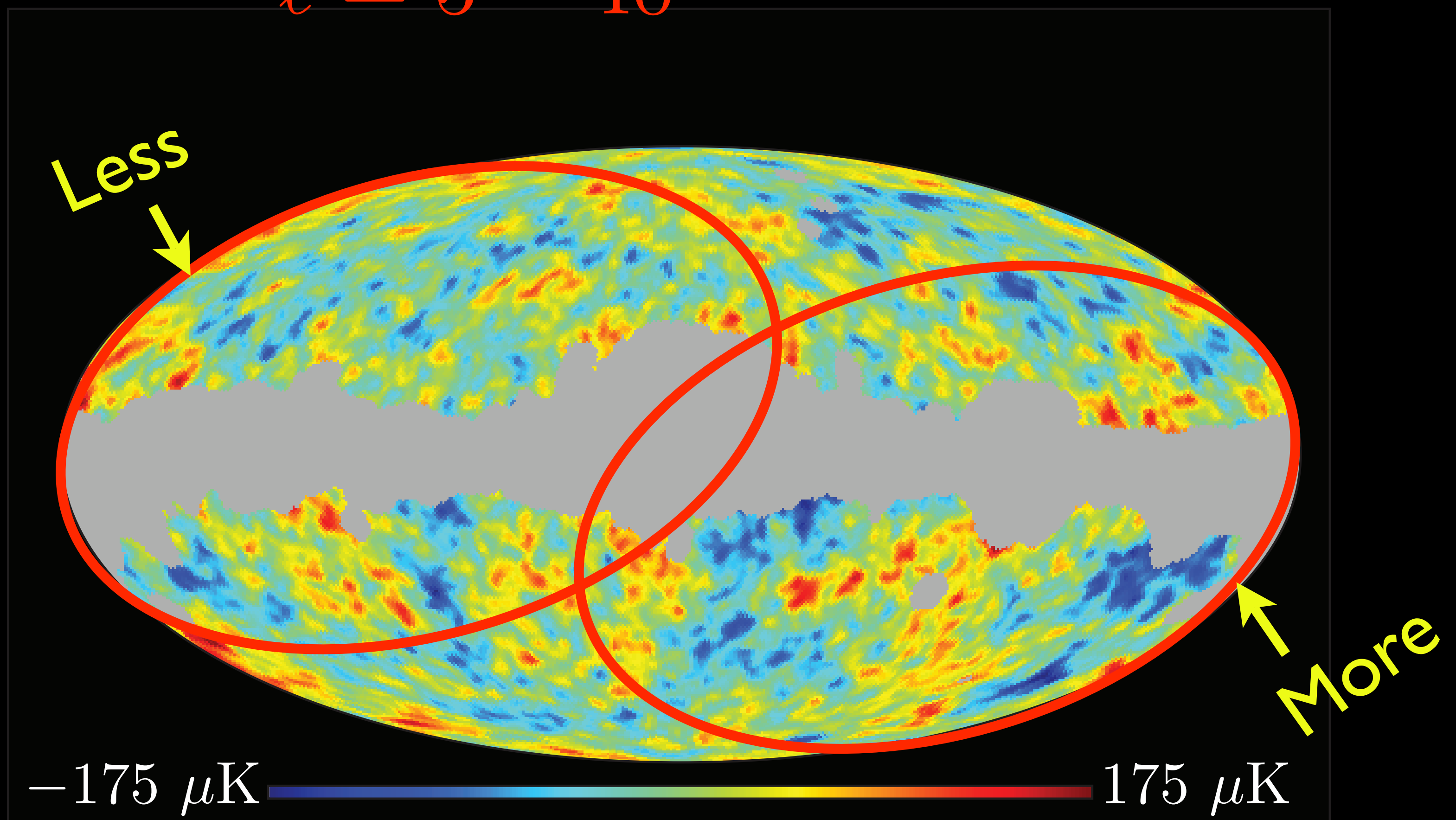

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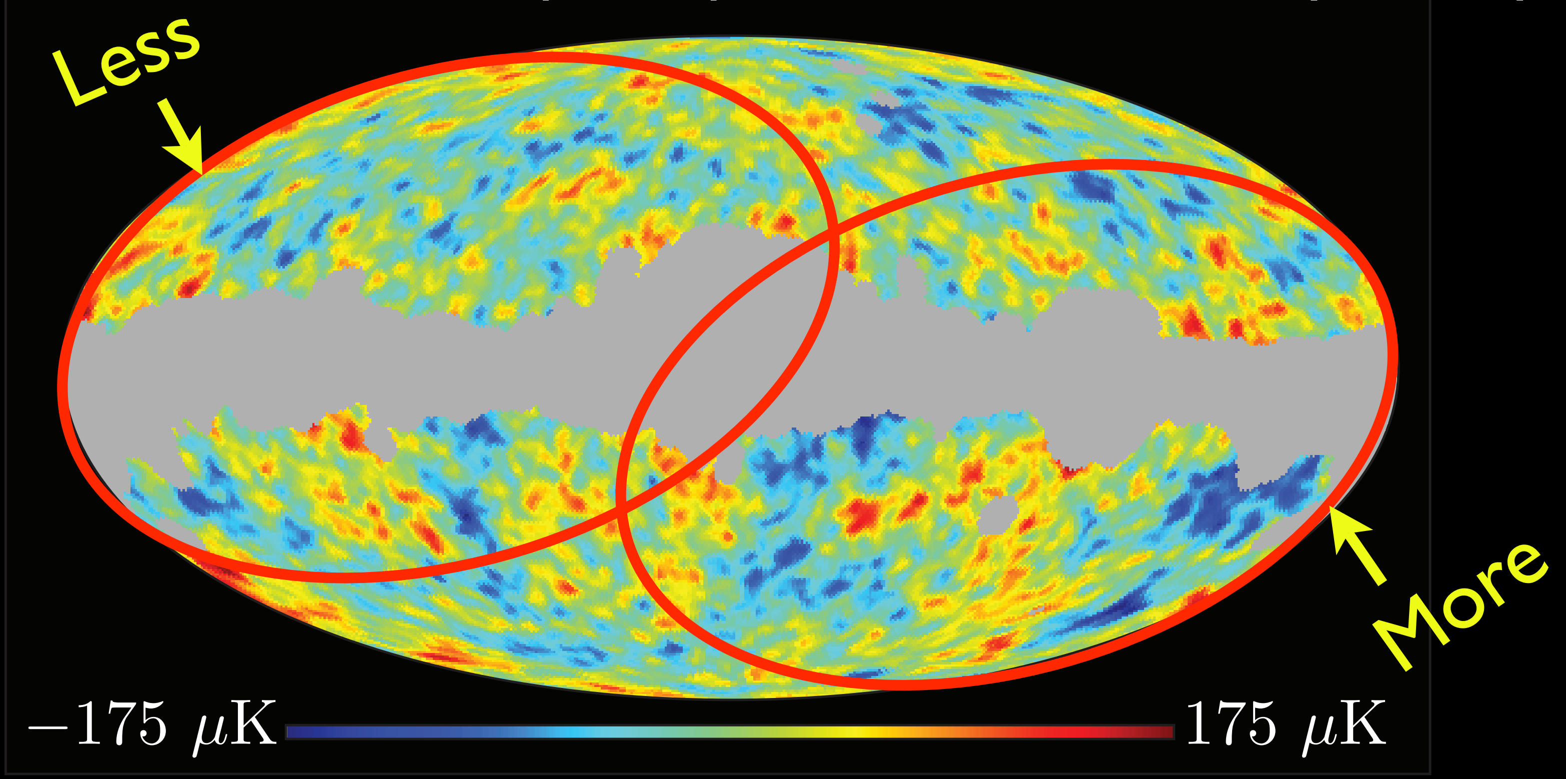
- Power asymmetry is maximized when the "equatorial" plane is tilted with respect to the Galactic plane: "north" pole at $(\ell, b) = (237^\circ, -10^\circ)$.
- Only 0.7% of simulated isotropic maps contain this much asymmetry.



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An Asymmetric Universe!

The asymmetry persists in the WMAP3 data.

Eriksen, Banday, Gorski, Hansen, Lilje 2007

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

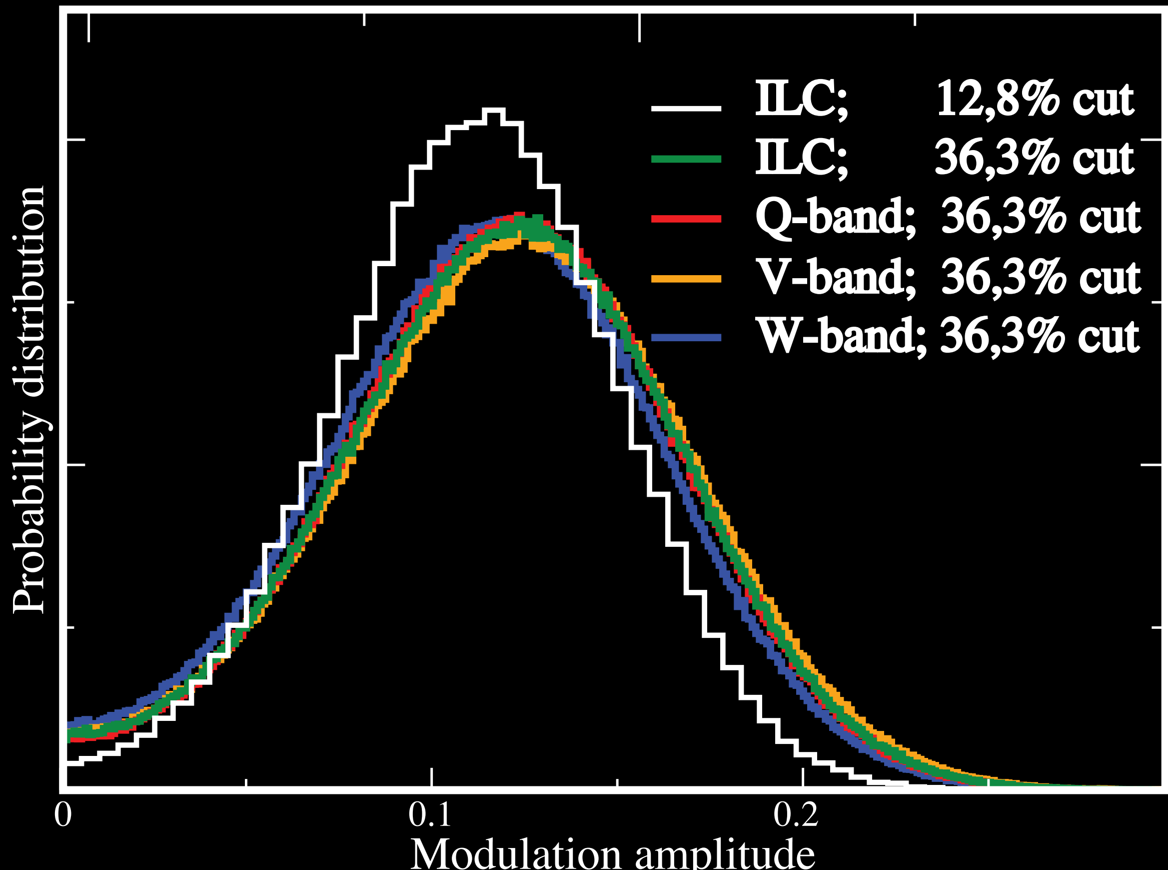
Observed CMB Temperature

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: $(\ell, b) \simeq (210^\circ, -27^\circ)$

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

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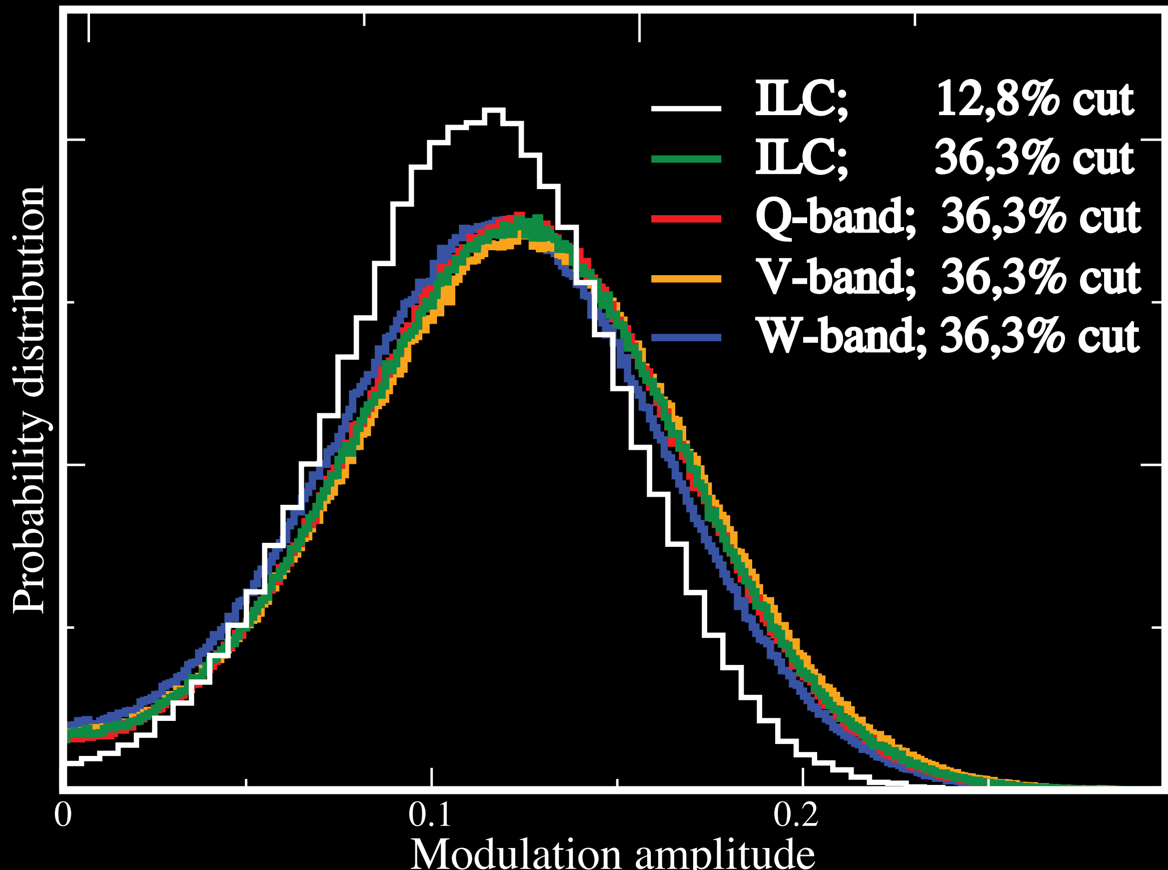


Eriksen, et al. astro-ph/070108

The asymmetry is difficult to explain with foregrounds:

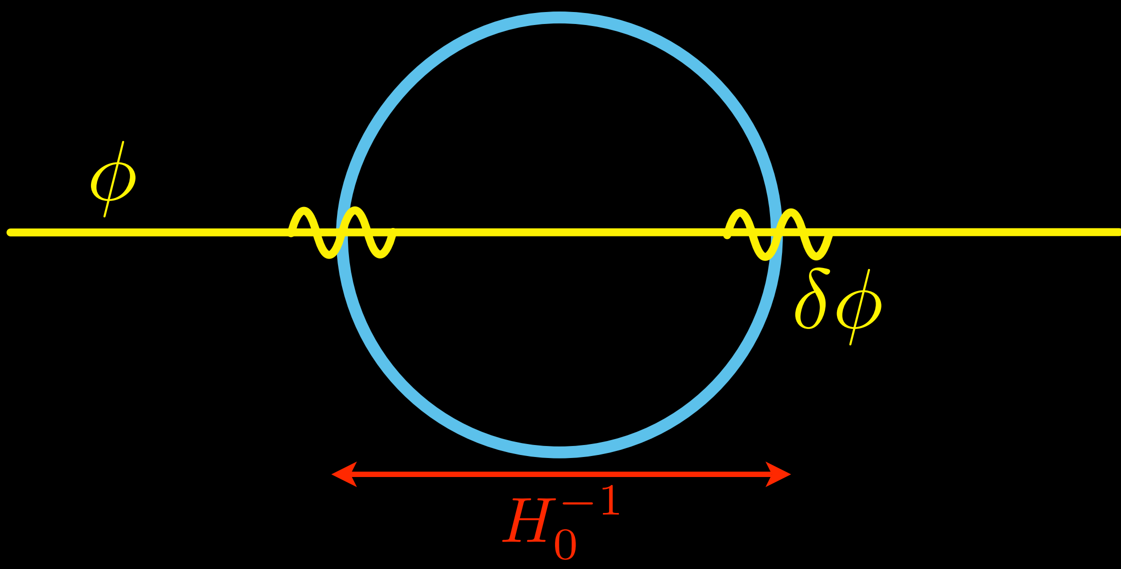
- present in all colors
- not aligned with the Galaxy

The asymmetry is difficult to explain with systematics:

- also detected by COBE

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

Asymmetry from a "Supermode"

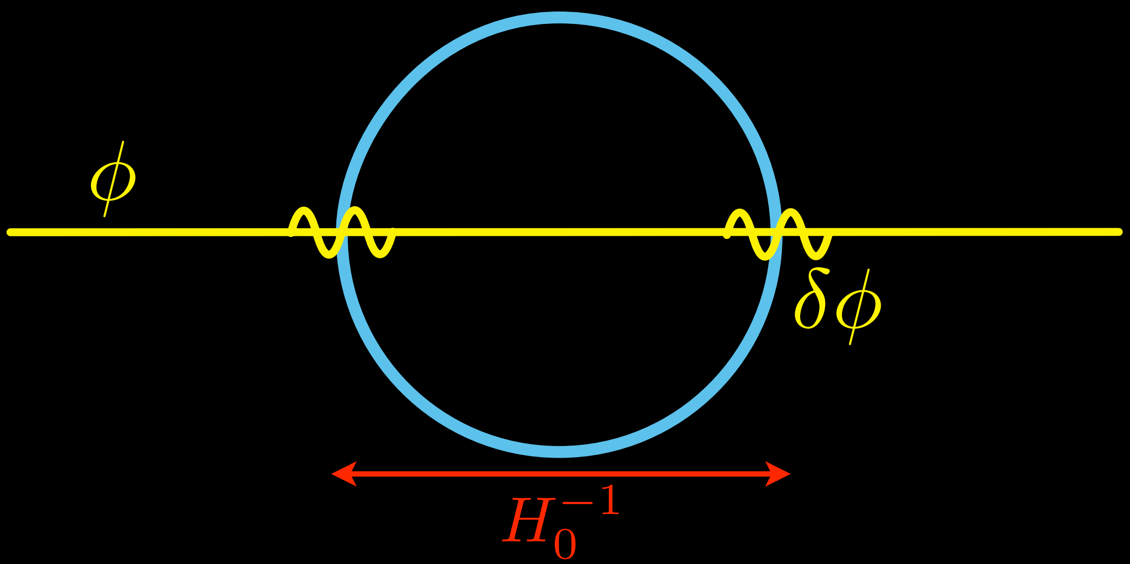


The amplitude of quantum fluctuations depends on the background value of the inflaton field.

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

Power Spectrum of Potential Fluctuations

Asymmetry from a "Supermode"



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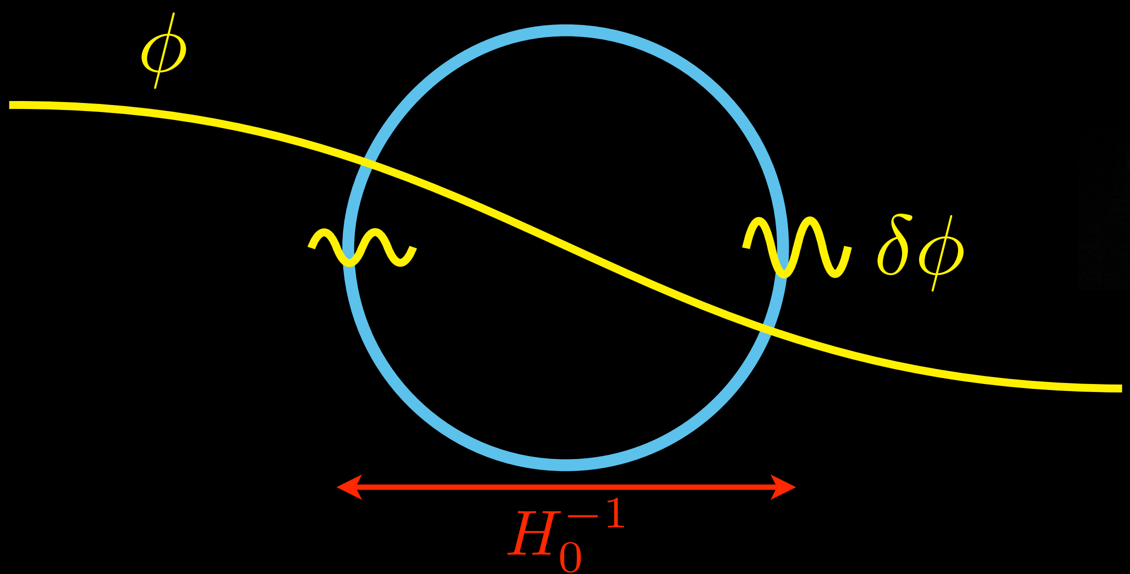
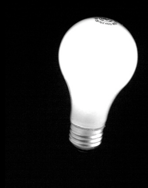




Create asymmetry by adding a large-amplitude superhorizon fluctuation: a "supermode."

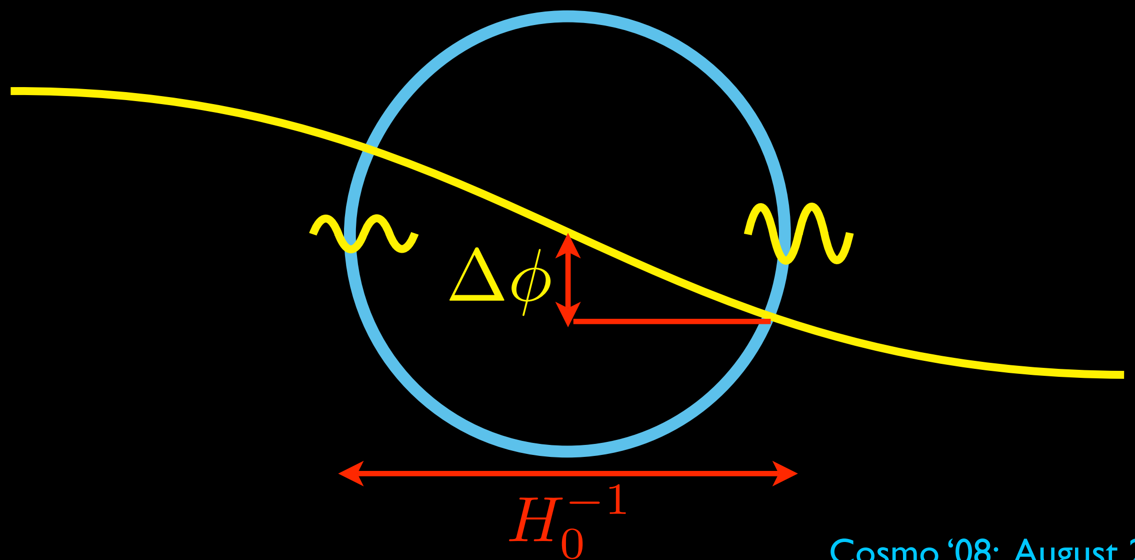
Asymmetry from a "Supermode"

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

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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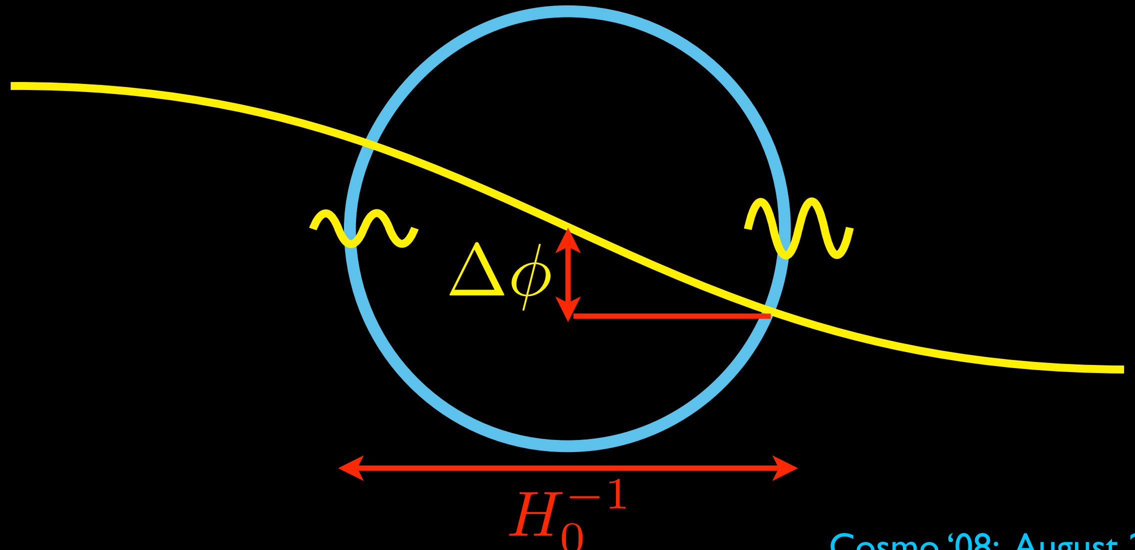
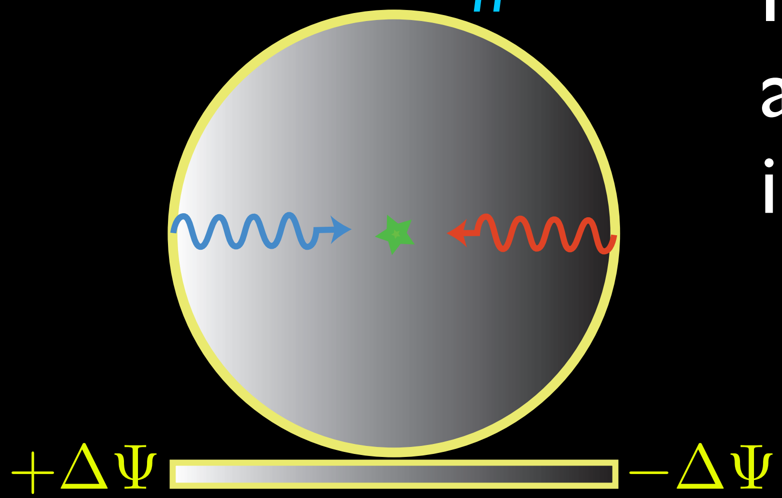


$\Delta\phi \Longrightarrow \Delta\Psi \Longrightarrow \Delta T$

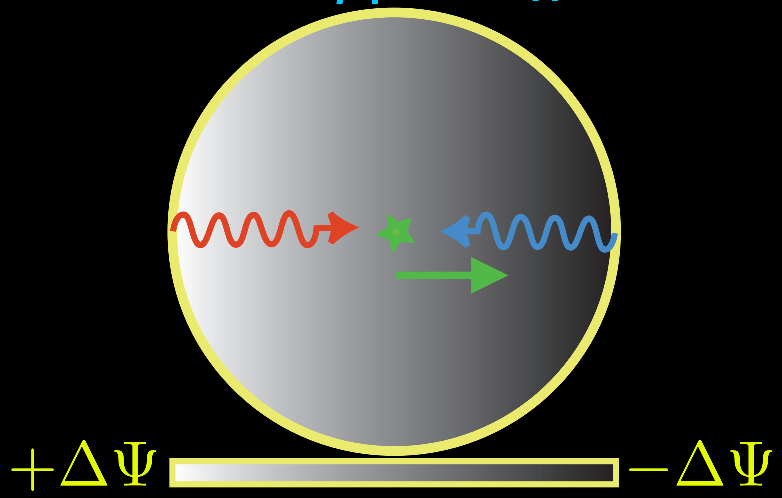
Surely the resulting temperature dipole would be far too large?

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*

- The SW dipole is cancelled by the Doppler dipole.
- If there is radiation or a cosmological constant, then the Dopper dipole is reduced.
- The ISW dipole will partially cancel the SW dipole.

Will a superhorizon perturbation induce a CMB dipole in our Universe?

The Dipole Cancels!

Superhorizon perturbation: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x}+\varpi]$

Temperature anisotropy:

distance to last scattering surface

$kH_0^{-1} \ll 1$

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

Observed CMB Temperature

Dipole

Quadrupole

Octupole

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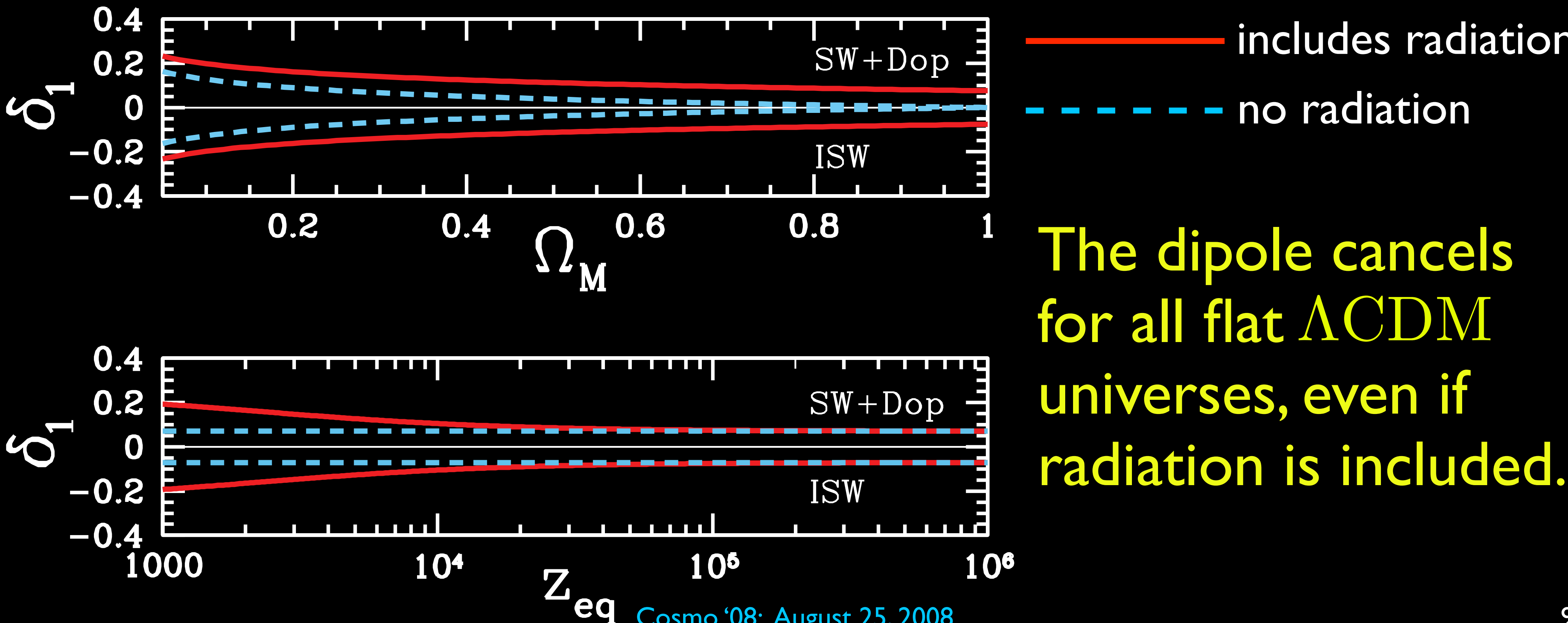
Observed CMB Temperature — *Dipole* — *Quadrupole* — *Octupole*



The dipole cancels for all flat ΛCDM universes, even if radiation is included.

The Quadrupole and Octupole

Superhorizon perturbation: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x}+\varpi]$

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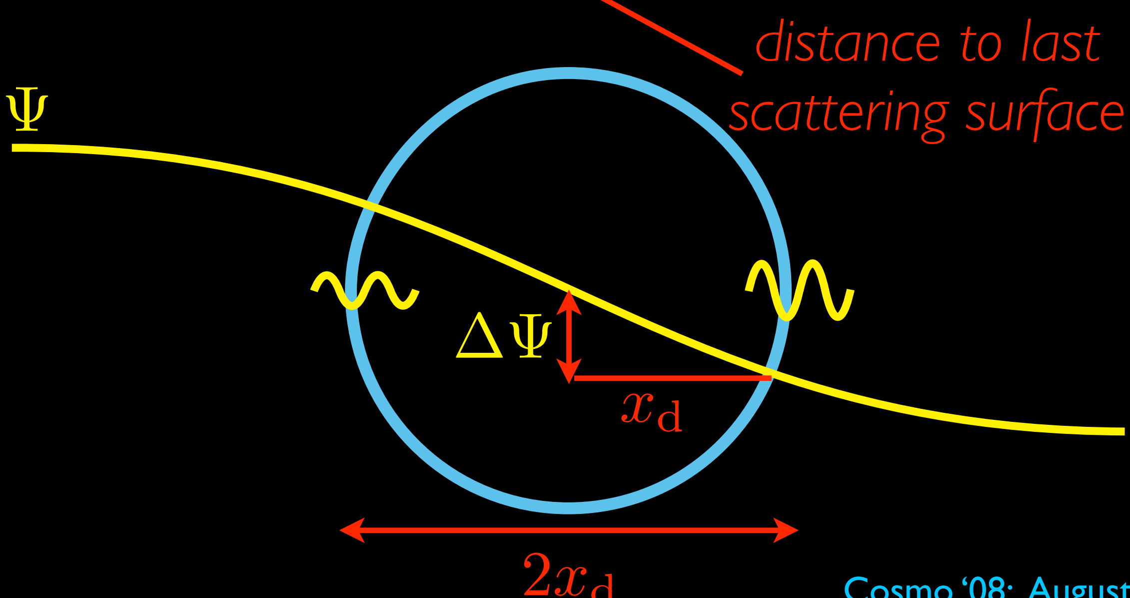
Observed CMB Temperature — *Dipole* — *Quadrupole* — *Octupole*

The supermode generates a CMB quadrupole and octupole.

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



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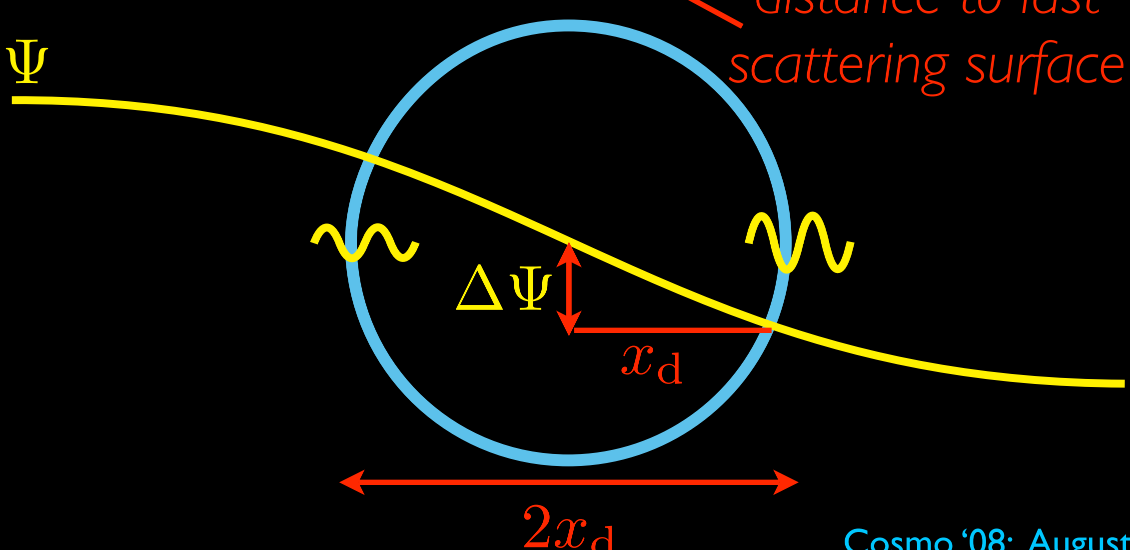

Quadrupole Constraint:

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

vanishes if $\varpi = 0$

$|a_{20}|$

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

The Quadrupole and Octupole

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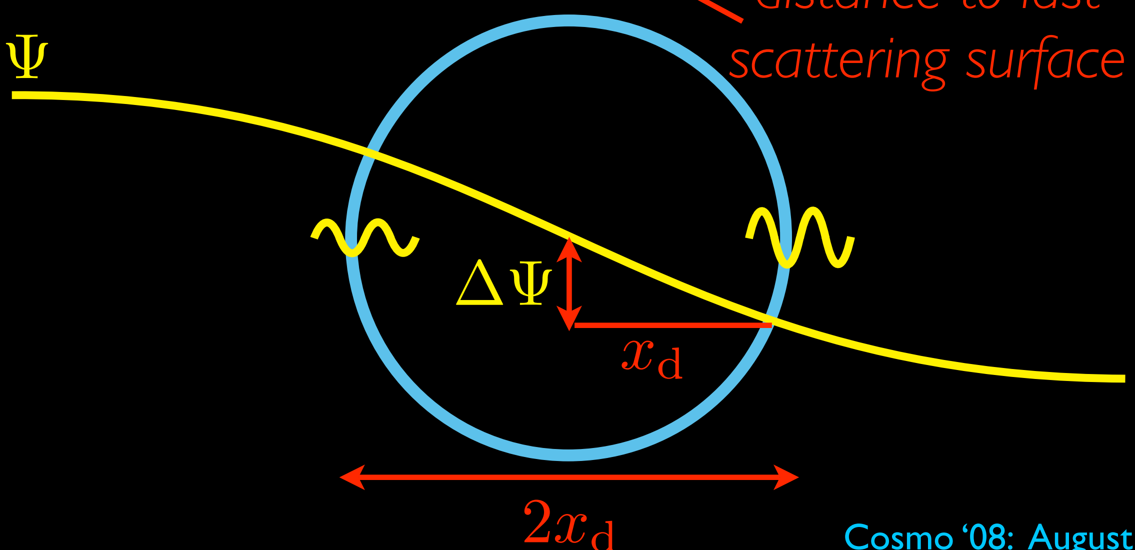
distance to last scattering surface

Octupole Constraint:

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

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



The Quadrupole and Octupole

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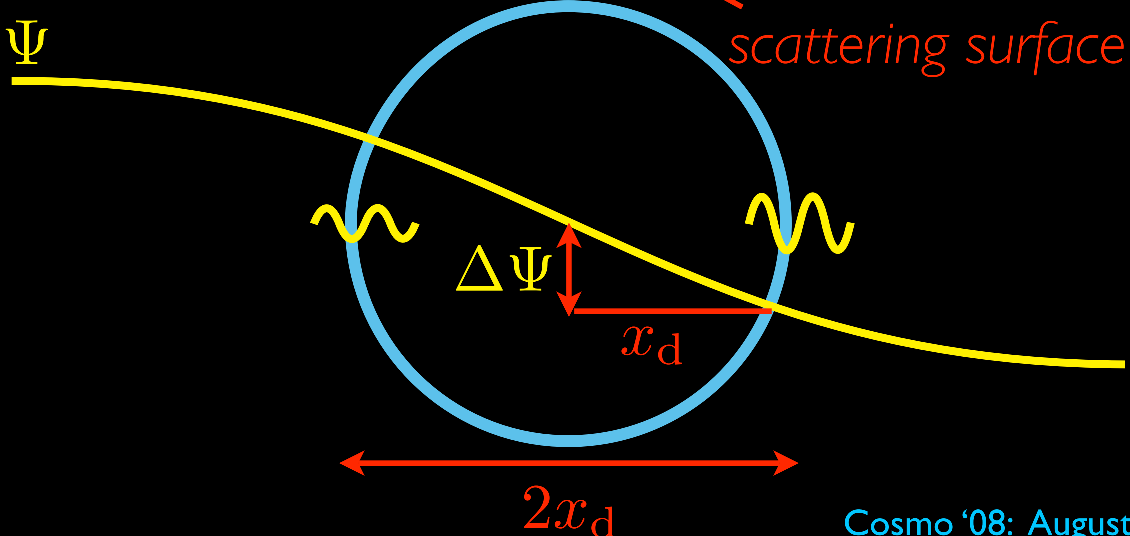

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$$|\Psi| < 1 \Longrightarrow \Delta\Psi \lesssim kx_{\rm d}$$

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

The Quadrupole and Octupole

Superhorizon perturbation: $\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin[\vec{k}\cdot\vec{x} + \varpi]$

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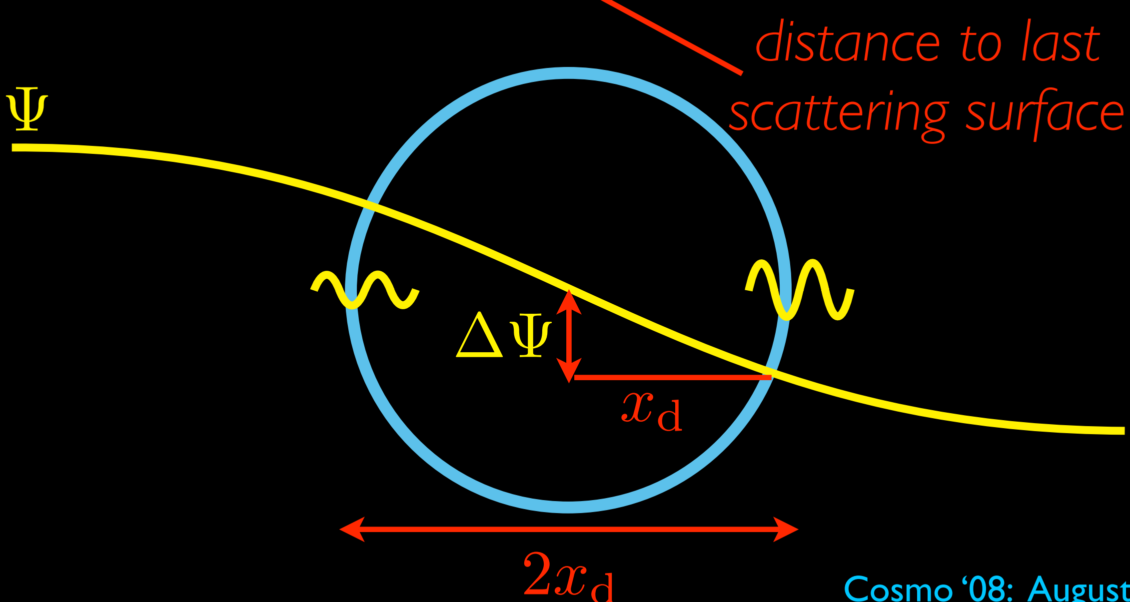

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Recall: $\dfrac{\Delta P_\Psi}{P_\Psi} \propto \Delta\phi \propto \Delta\Psi$

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

The Quadrupole and Octupole

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Observ... Quadrupole Octupole

T...

Th... adrupole and octupole.

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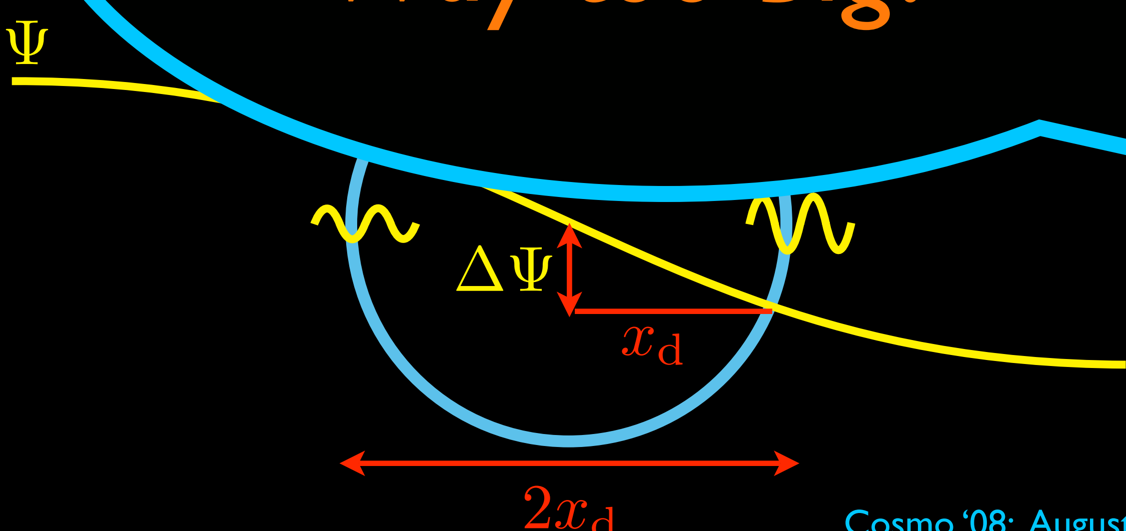
...all: $\frac{\Delta P_\Psi}{P_\Psi} \propto \Delta\phi \propto \Delta\Psi$

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

Way too big!



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

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.
- The inflaton dominates the energy density of the universe, so a "supermode" in the inflaton field generates a huge potential perturbation.

The Curvaton to the Rescue!

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

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The Curvaton Model of Inflation

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

- The inflaton still dominates the energy density and drives inflation.
- The curvaton (σ) is a light scalar field during inflation: $m_\sigma \ll H_{\rm inf}(\phi)$

potential: $V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2$ *quantum fluctuations:* $(\delta\sigma)_{\rm rms} = \frac{H_{\rm inf}}{2\pi} \ll \bar{\sigma}$

- After inflation, when $m_\sigma \simeq H$, the curvaton oscillates in its potential.
- Then the curvaton decays into radiation; its quantum fluctuations produce a spectrum of adiabatic perturbations.

$$\boxed{P_{\Psi,\sigma} \propto \left(\frac{H_{\rm Inf}}{\bar{\sigma}} \right)^2}$$

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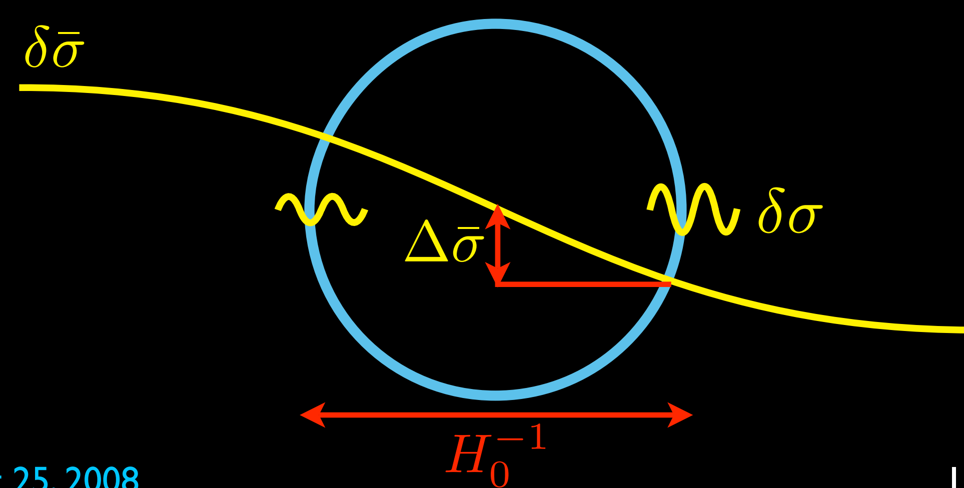

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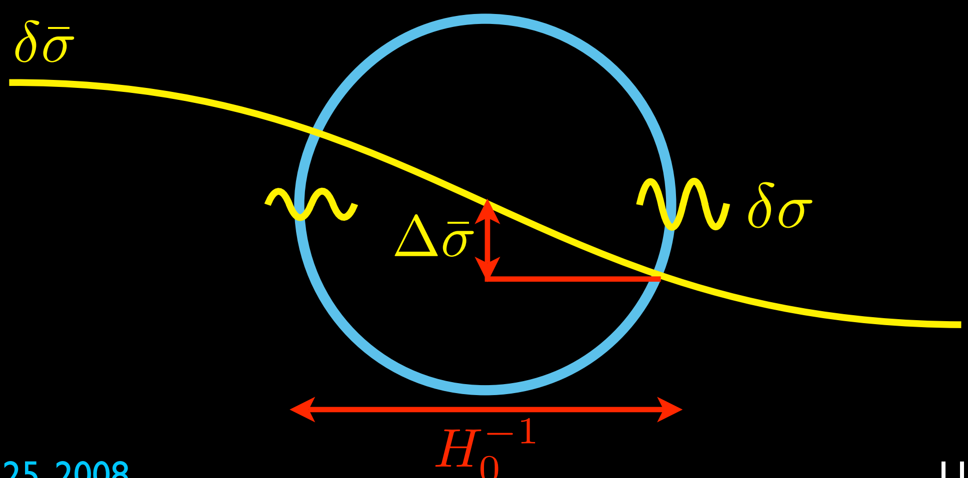
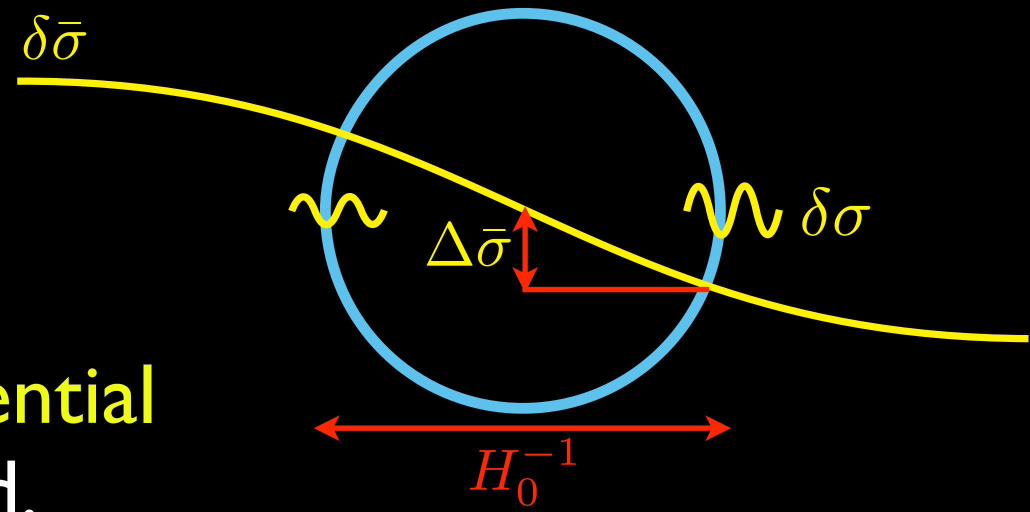
- Then the curvaton **decays into radiation**; its quantum fluctuations produce a spectrum of **adiabatic perturbations**.

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



Curvaton Supermodes in the CMB

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



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

$R = \rho_\sigma/\rho$ *just prior to decay*

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

The potential perturbation is not sinusoidal!

- The CMB quadrupole and octupole have complicated ϖ dependences.
- There is still a quadrupole if $\varpi = 0$.

Curvaton Supermodes in the CMB

The CMB quadrupole implies an upper bound:

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

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

Most other phases give similar bounds.

$R = \rho_\sigma/\rho$ *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!

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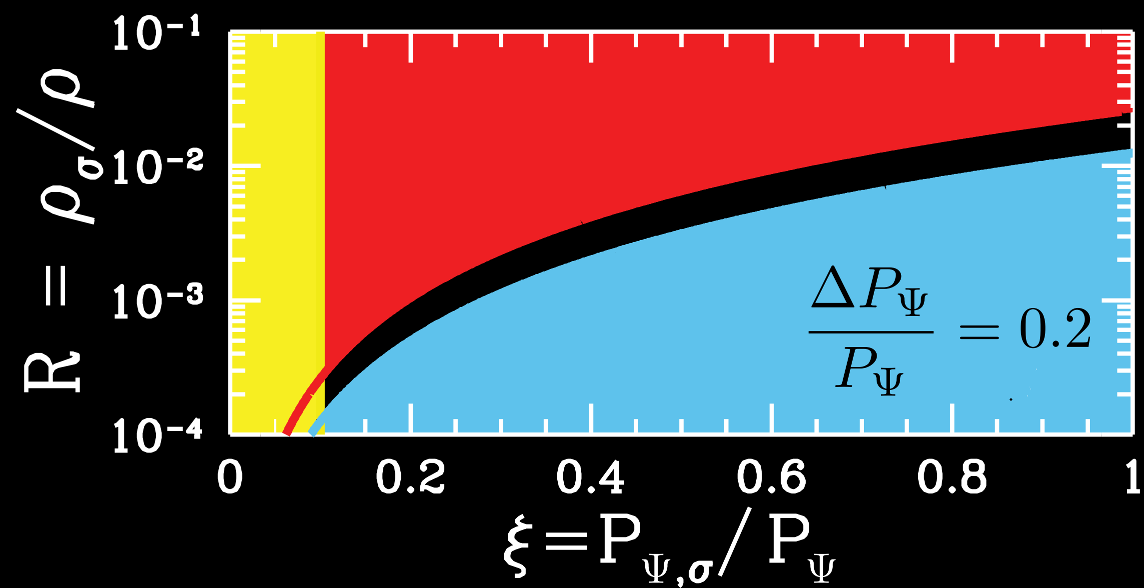
Constraining the Curvaton Model

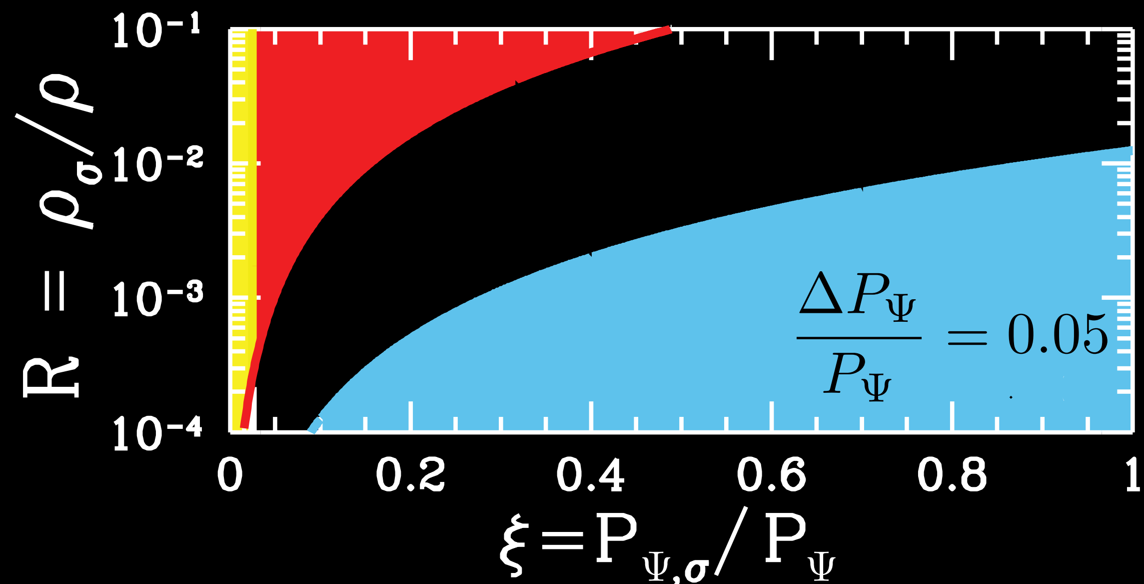
The curvaton and inflaton both contribute to $P_\Psi(k)$:

$$\xi \equiv \frac{P_{\Psi,\sigma}}{P_\Psi}$$ *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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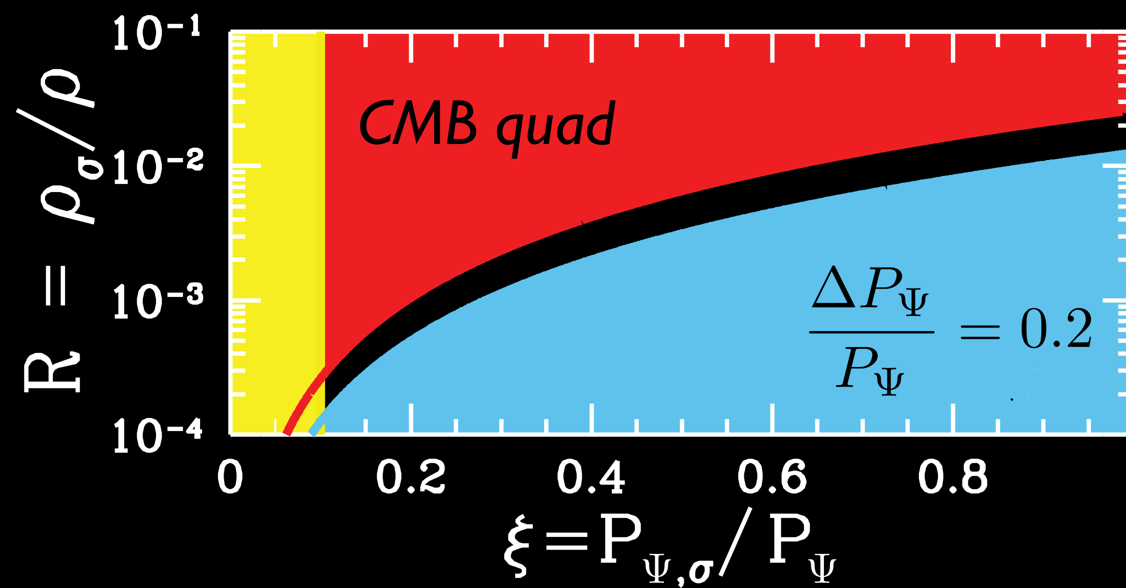
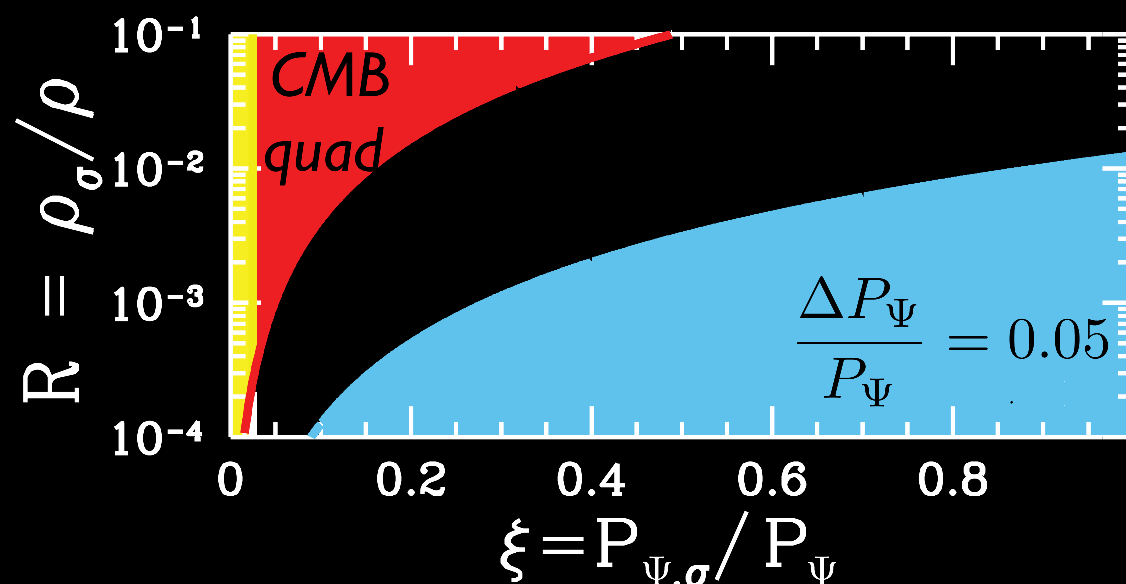
CMB Quadrupole:

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

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





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*

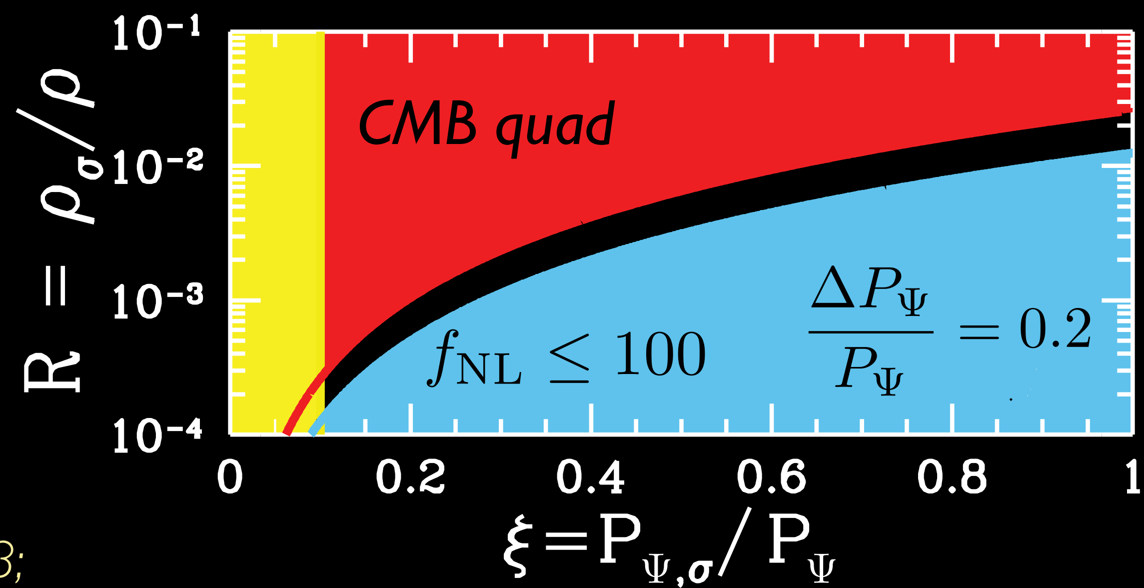
$$f_{\rm NL} \simeq \frac{5\xi^2}{4R}$$

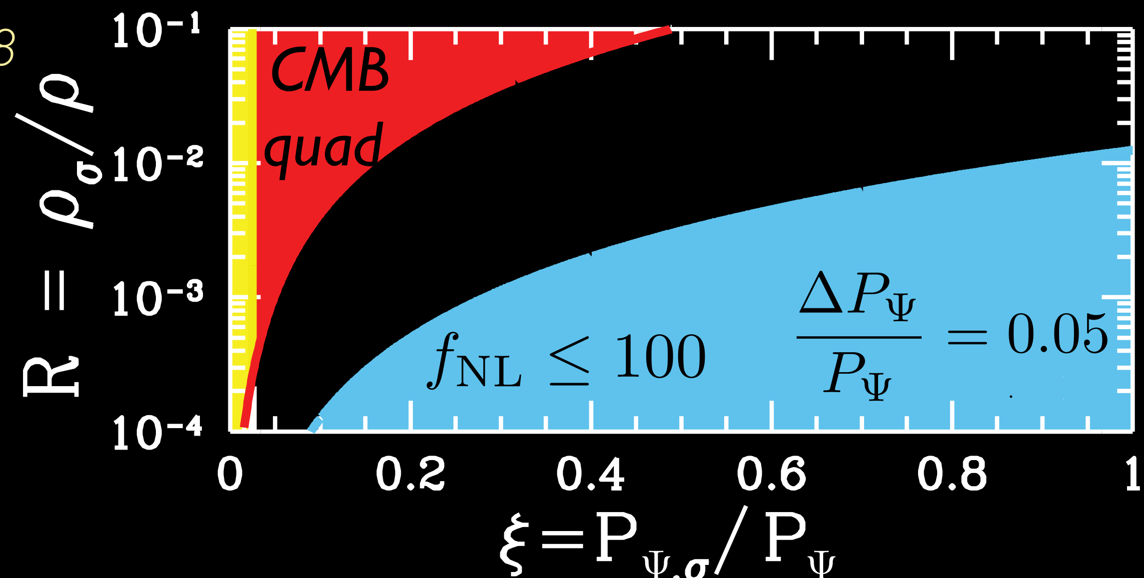
Lyth, Ungarelli, Wands 2003; Ichikawa, Suyama, Takahashi, Yamaguchi 2008

Upperbound from WMAP:

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

Komatsu et al. 2008
Yadav, Wandelt 2008





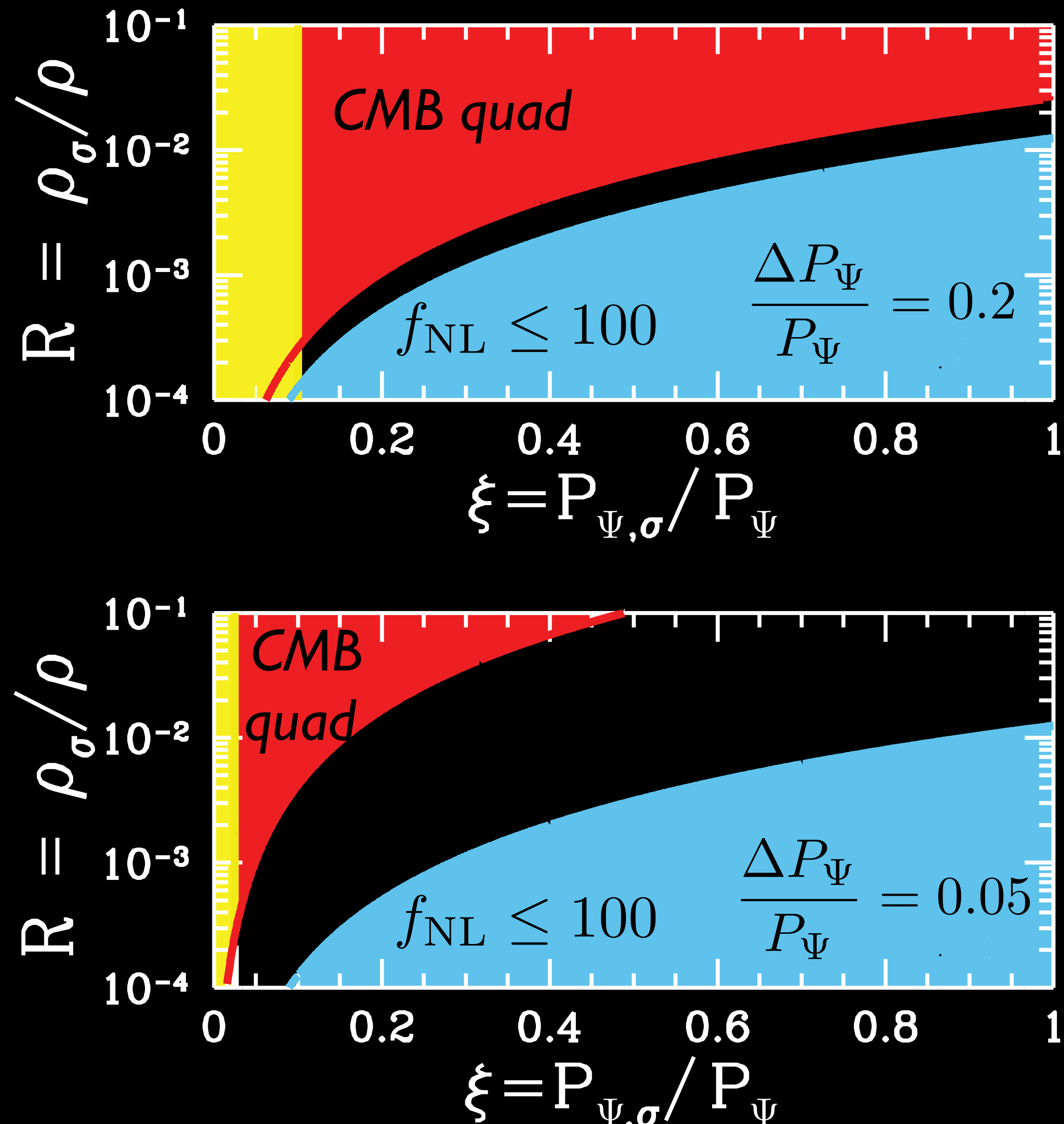
Constraining the Curvaton Model

The Allowed Region

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

Non-Gaussianity *CMB Quadrupole*

Allowed window



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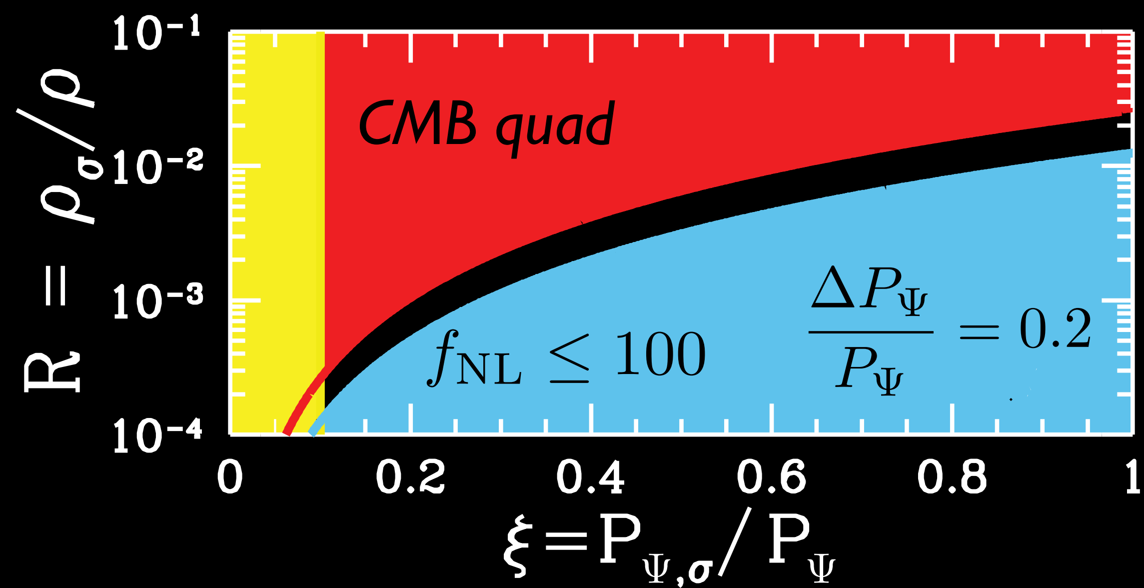
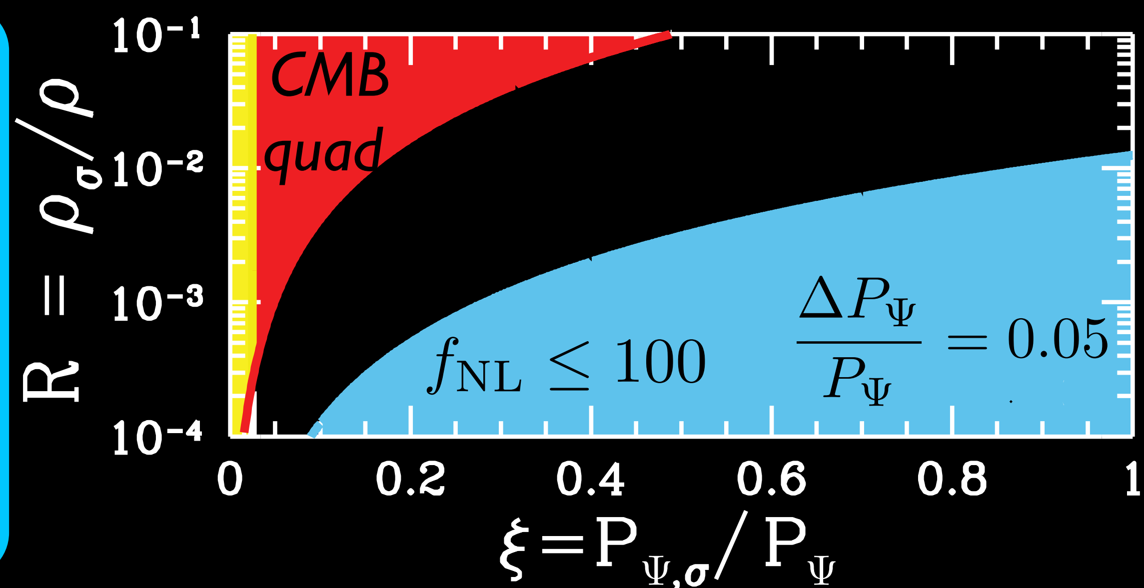


The Dealbreaker

The window for $\frac{\Delta P_\Psi}{P_\Psi} = 0.2$ disappears if $f_{\rm NL,max} \lesssim 50$



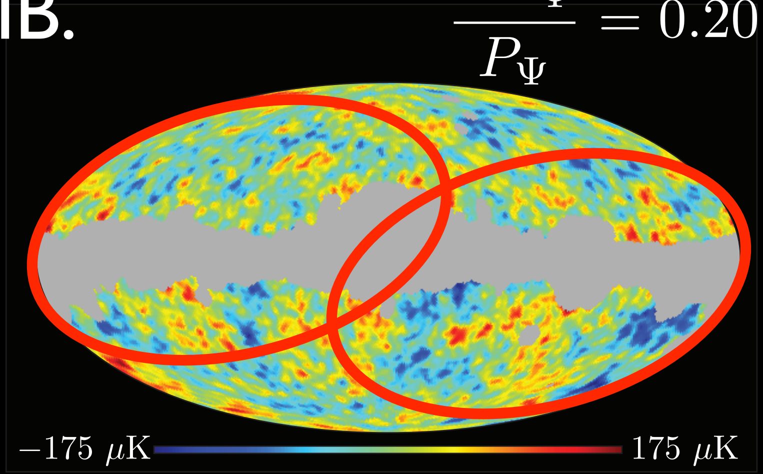
Summary: How to Generate the Power Asymmetry

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

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



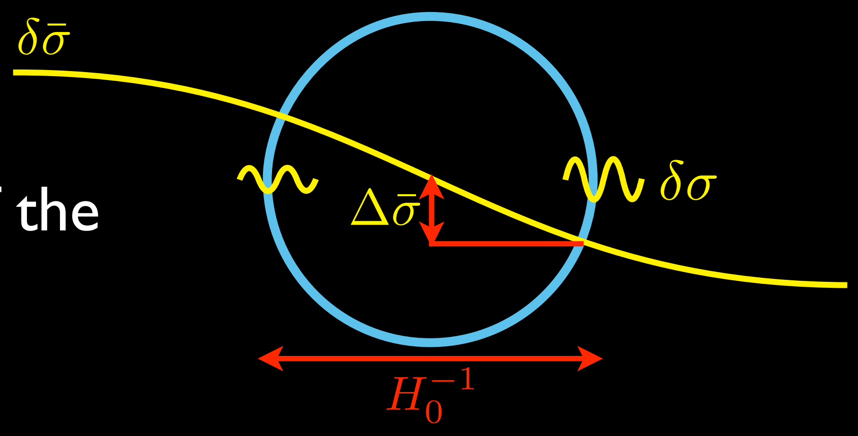
A superhorizon perturbation during inflation generates a power asymmetry.

- 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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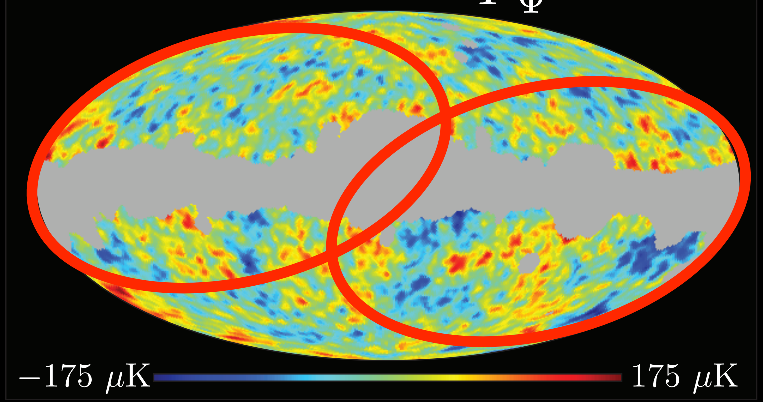

Features of the Curvaton-Generated Power Asymmetry

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