A Low Quadrupole from Inhomogeneous Dark Energy

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References: Gordon and Hu, PRD 70, 2004; Gordon and Wands, PRD 71, 2005.

Cosmological Constant

Possible ways to falsify:

- Show $w \neq -1$.
- Show dark energy interacting, e.g. fifth force, evolution of varying fine structure constant.
- Show dark energy not homogenous.

Scalar Field Dark Energy (Quintessence)

- Satisfies the Klein-Gordon equation

$$\ddot{Q} + 3H\dot{Q} + V' = 0\,.$$

- If

$$\frac{1}{M_p^2}\left(\frac{V'}{H}\right)^2 \ll 1\,, \quad \left|\frac{V''}{H^2}\right| \ll 1$$

then

$$\dot{Q} \approx 0$$

and

$$\rho_Q \approx V \approx -p$$

giving

$$w_Q \approx -1\,.$$

Quintessence Perturbations

$$\delta\ddot{Q} + 3H\delta\dot{Q} + \left(\frac{k^2}{a^2} + m^2\right)\delta Q = 0\,.$$

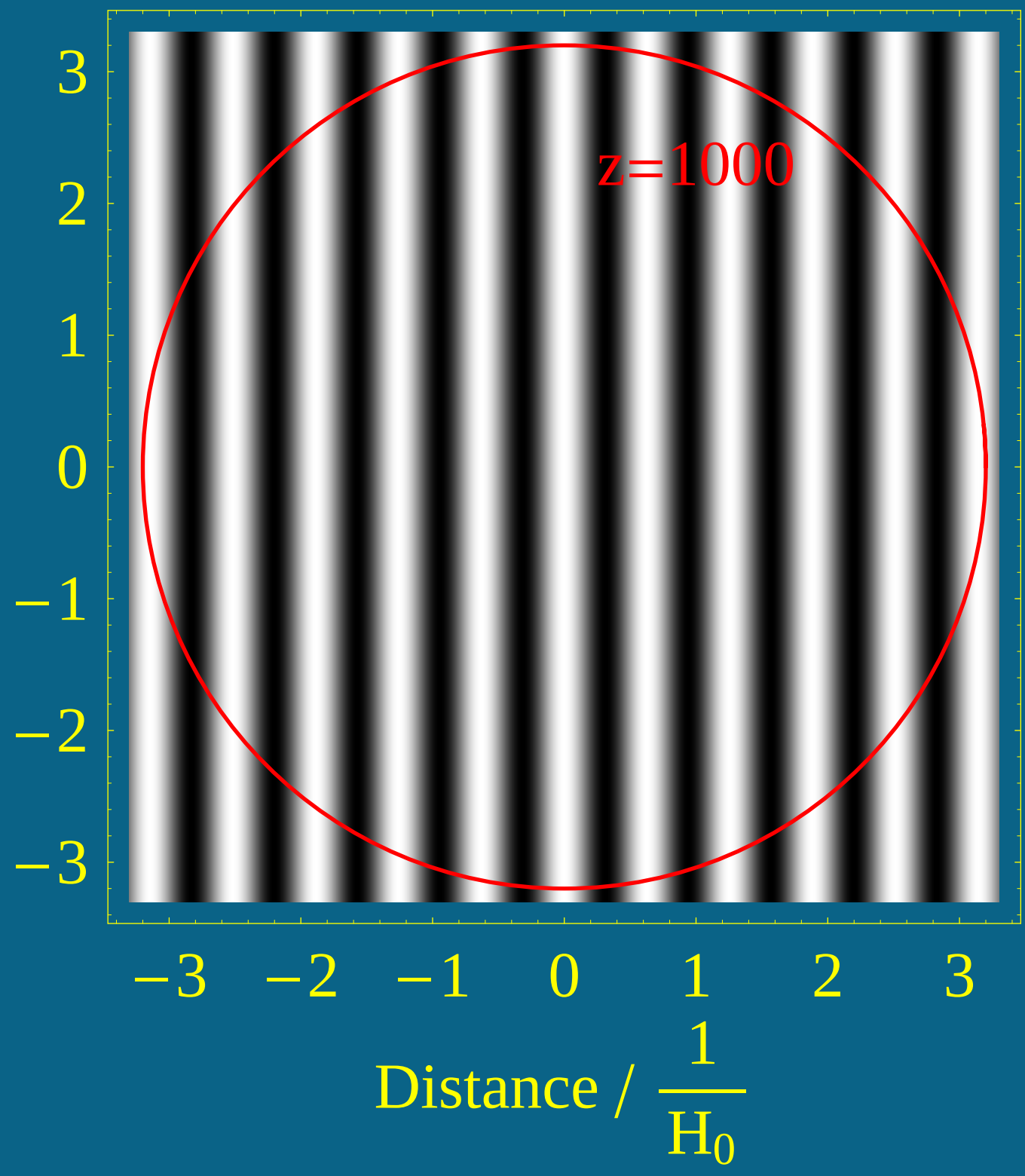
Then

$$\delta Q \approx \left.\begin{array}{ll} \text{constant}, & (k/a)^2, m^2 < H^2 \\ 1/a, & (k/a)^2, m^2 > H^2 \end{array}\right\}$$

Therefore, no appreciable perturbations on scales smaller than the Hubble length.

Projection

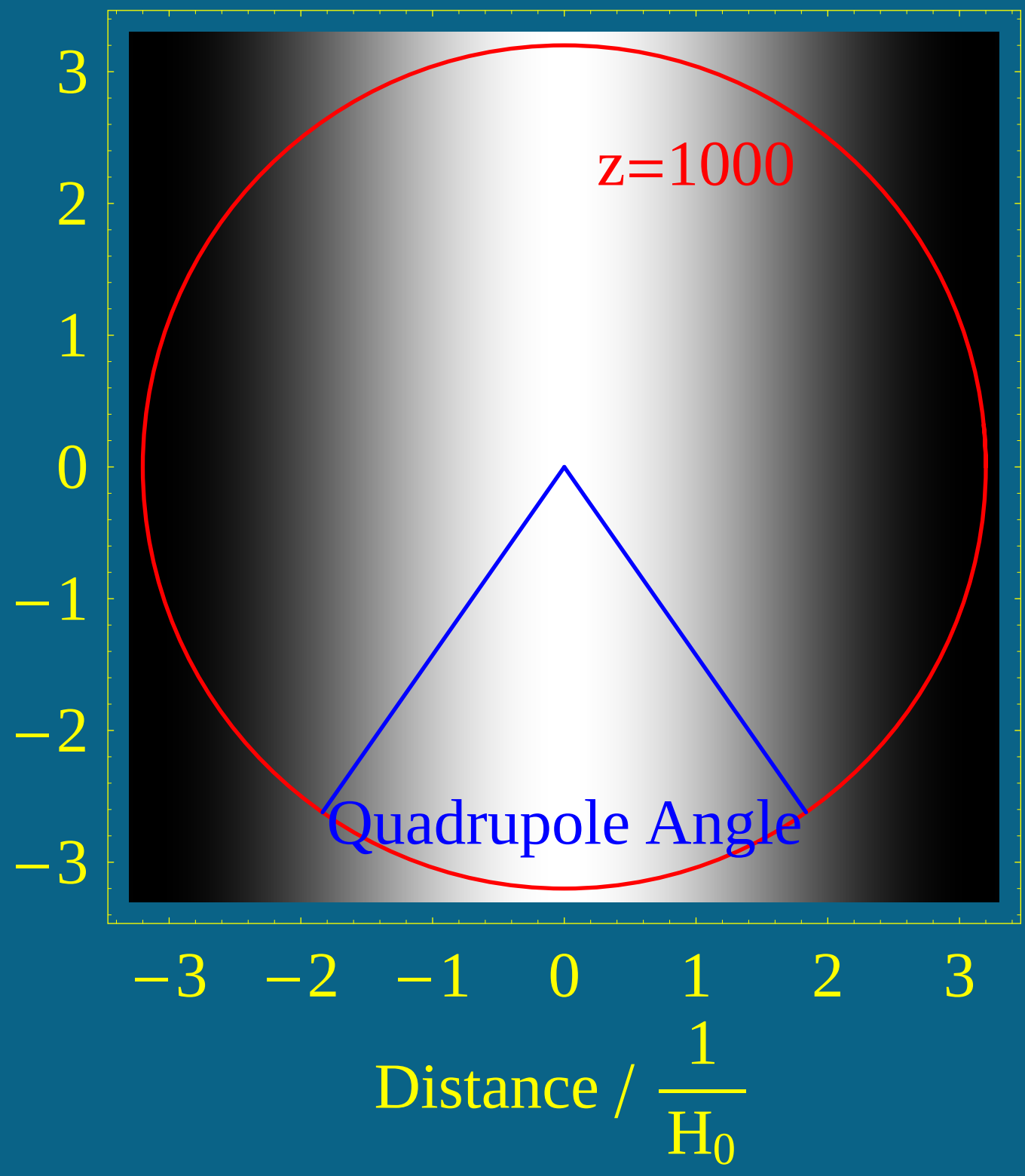
- Sachs Wolfe Effect: $\frac{\Delta T}{T} = \frac{1}{3}\Phi$.



Projection

- Sachs Wolfe Effect: $\frac{\Delta T}{T} = \frac{1}{3}\Phi$.

- Spherical Harmonic C_ℓ: $\theta \approx \frac{200}{1+\ell}$deg.

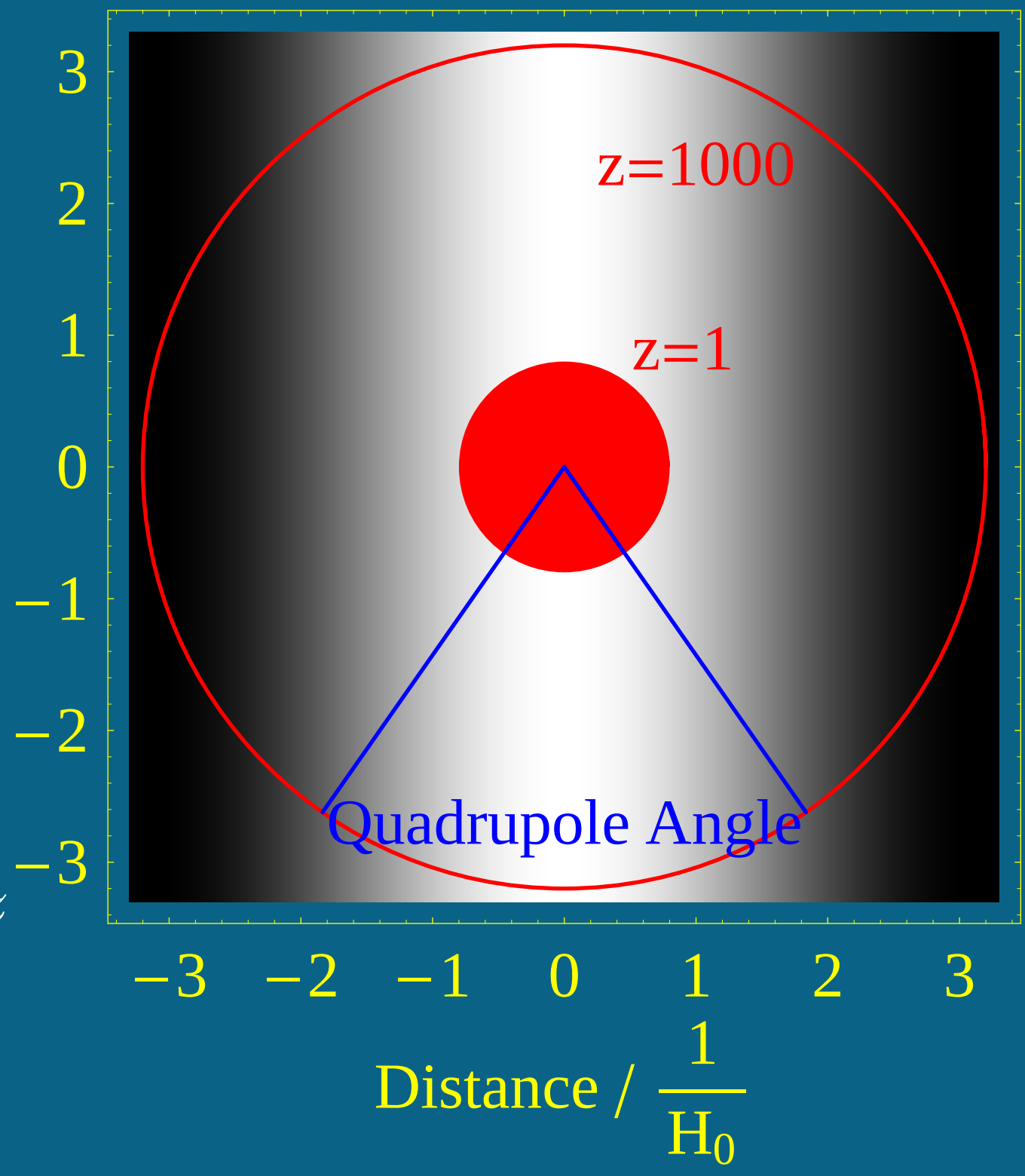


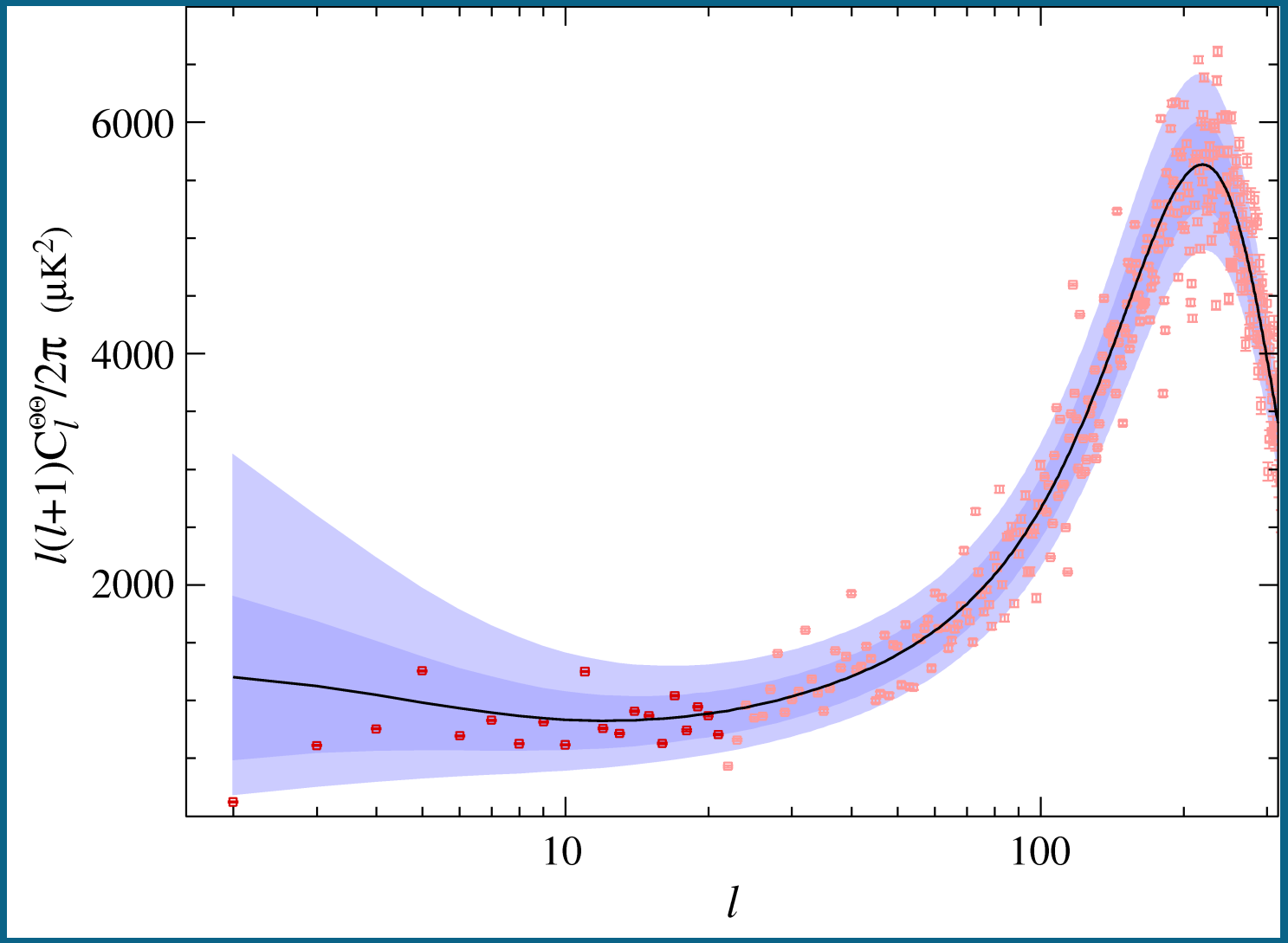
Projection

- Sachs Wolfe Effect: $\frac{\Delta T}{T} = \frac{1}{3}\Phi$.

- Spherical Harmonic C_ℓ: $\theta \approx \frac{200}{1+\ell}$deg.

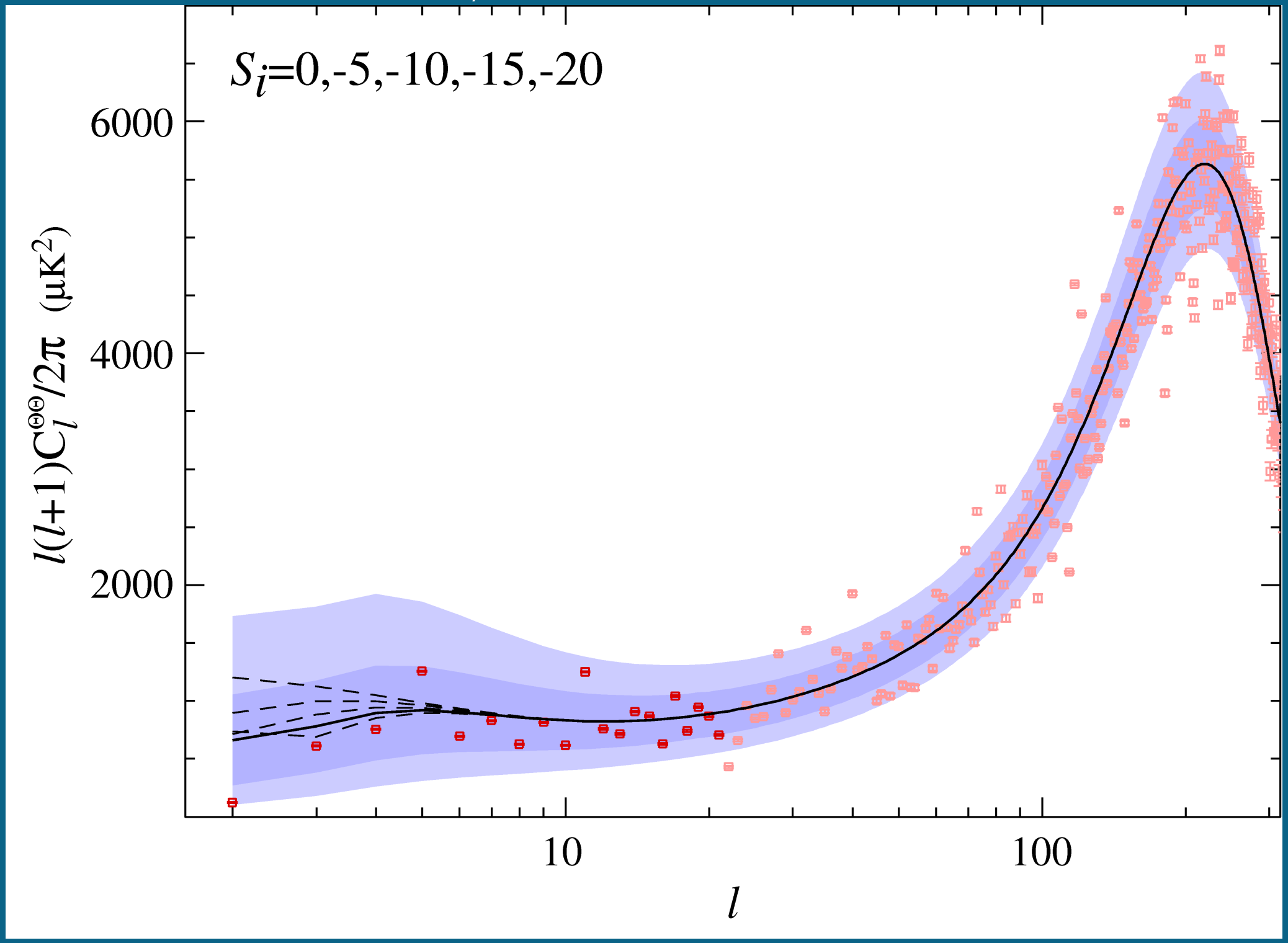
- Integrated SW Effect: $\frac{\Delta T}{T} = 2\int_{z=1000}^{0} \frac{\partial \Phi}{\partial z}\Big|_{\text{geodesic}} dz$





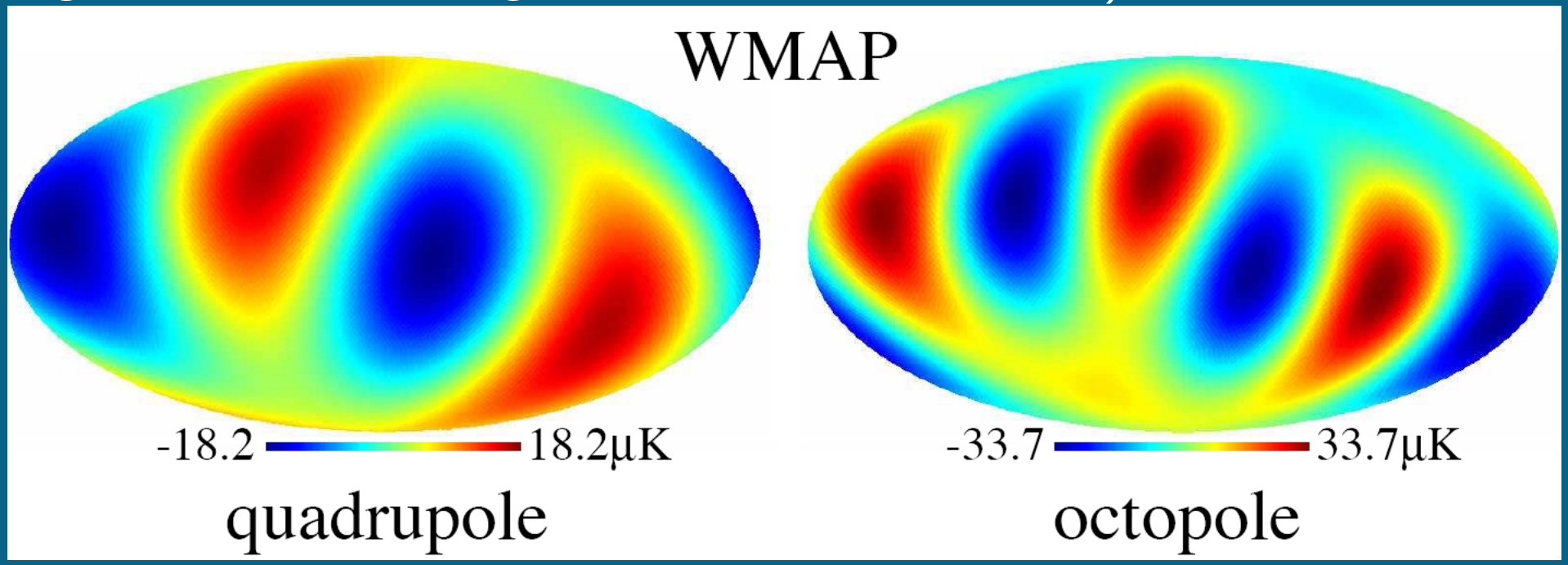
$P(C_2 \leq C_2^{\rm obs}|\Lambda{\rm CDM}) = 0.7\%$ (Spergel et al. (2003)).
However, improved treatment of low ℓ likelihood (Efstathiou 2003; Slosar and Seljak 2004):
$P(C_2 \leq C_2^{\rm obs}|\Lambda{\rm CDM}) \approx 3\%$.

Moroi and Takahashi, PRL 2003.



Statistical Significance

Assuming scale invariant primordial power spectrum (Gordon, Hu 2004) $P[\text{correlated}|\text{WMAP}] = 3.5\%$. However using improved likelihood for low ℓ: $P[\text{correlated}|\text{WMAP}] = 7.2\%$. But (de Oliveira-Costa, Tegmark, Zaldarriaga and Hamilton 2003)



and (Gordon, Hu, Huterer, Crawford 2005):
$\langle (T + \text{foreground})^2 \rangle = \langle T^2 \rangle + \langle (\text{foreground})^2 \rangle$.

Polarization

(Gordon and Hu 2004)

- Anticorrelated quintessence perturbations imply temperature/polarization correlation is suppressed at quadrupole scales while polarization is not.

- Current error bars on polarization/temperature correlation about twice cosmic variance. Polarization power spectrum no yet measured at quadrupole scales.

Inflationary Context

- Moroi and Takahashi (2003): 3 field curvaton model
- Variable decay, Dvali, et. al. (2004) and Kofman (2003): $\Phi_i = -\frac{1}{10}\frac{\delta\Gamma}{\Gamma}$.
- For coupling $\mathcal{L} = \cdots + \frac{Q}{M_p}\phi q\bar{q} + \cdots$ we have $\Gamma \sim \left(\frac{Q}{M_p}\right)^2 m_\phi$ which gives $\Phi_i = -\frac{1}{5}\frac{\delta Q}{Q}$.

Gravitational Waves

$$\frac{\delta\rho_Q}{\rho_Q} \approx 6 \times 10^{-4}$$
$$= \frac{V_Q'}{V_Q}\delta Q$$

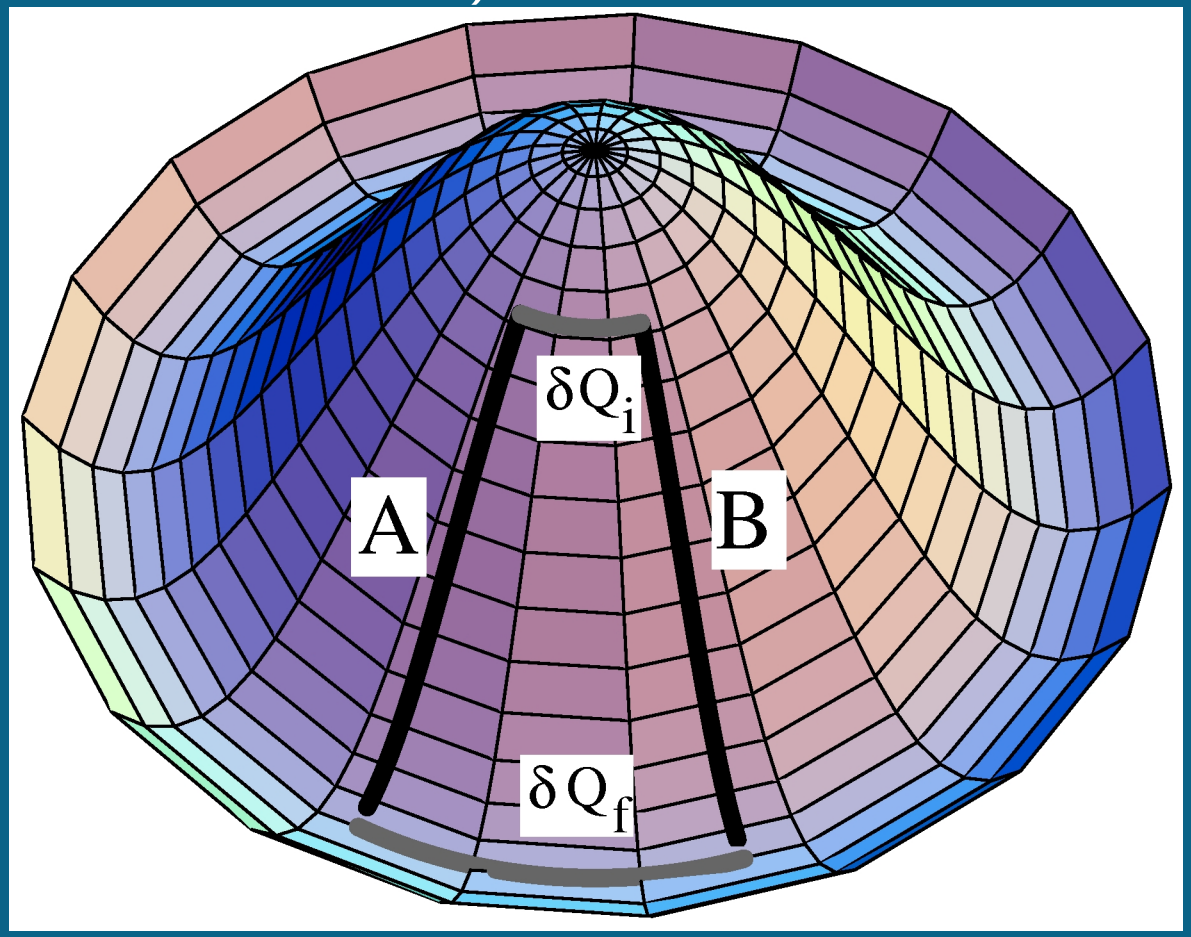
which gives

$$\delta Q \approx \frac{4 \times 10^{-4} M_p}{\sqrt{\epsilon_Q}} = \frac{H_{\rm inf}}{2\pi}$$

Therefore, Gravity waves 30 times too large.

Tachyonic Amplification

(Gordon and Wands 2005)



$$\delta Q_f = \frac{r_f}{r_i} \delta Q_i \, .$$

After reheating, quintessence is a Pseudo-Nambu-Goldstone Boson (Frieman, et al. 1995).

Conclusions

- Perturbations in quintessence only on scales larger than Hubble length.
- Thus, would only effect low ℓ harmonics.
- Quadrupole observed to be low.
- Lower prediction for quadrupole if quintessence has perturbations anti-correlated with matter perturbations.
- Fit not statistically significant but could be improved with more polarization data.
- To get large enough quintessence perturbations from inflation a tachyonic amplification mechanism is needed.