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Observational Evidence for New Physics From CMB?

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A WEIRD UNIVERSE

1) Dark Energy

$m_\Lambda \simeq H_0$
$z \simeq 0$

- Fine-Tuning ?
- Cosmic Coincidence ?
- $w < -1$?

2) CMBR Power Suppression
$\theta \simeq 60^\circ$

$\ell \leq 10$
$\lambda_\ell \simeq H_0^{-1}$
$z \simeq 0$

- Tuning (ISW + Inflation)
- Cosmic Coincidence: Why Now?
  (Melchiorri + Mersini)
- Why @ same scale as DE???

3) Entropy: $S_0 \leq S_i$. Contraversy...

- $N \leq A \operatorname{Log} \Lambda$??

(Bousso, Susskind, Banks, etc)

Entropy Arguments

No. of E-folds is Restricted Becouse

$a_i = e^{N_i}$ $H_o = 10^{-33}$ eV

$$\boxed{S_o \le S_i}$$

by 2nd Law of thermodynamics

$S_o \simeq$ Ammount of Info. $\simeq$ Volume $\simeq \underline{\Lambda}^{-3/2}$

$$\Rightarrow \quad N_i \le [\log \Lambda] \cdot \textcircled{A} \; ??$$

Hmmm....

- How Do You Define S??
- 2nd Law ??

O.K.: SPECULATIVE + PROVOCATIVE

Large Angle CMBR Power Suppression

Raises 2 New Puzzles:

1) Why is power Suppressed?
2) Why only at scales
$z \simeq 0, \; \lambda_\ell \simeq O(H_0^{-1})$??

SAME SCALE AS DE.
IS THIS A DOUBLE COINCIDENCE??

Even worse: - C_ℓ^{EE} is NOT SUPPRESSED!
- ISW SHOULD ENHANCE POWER AT DE SCALES, $H_0 = 10^{-33}$ eV.

Are DE + CMBR RELATED?
Is H_0 a Special new Scale?

Hmm... No Consistent theory yet.
DO WE NEED NEW PHYSICS??

(O.k, O.k, cosmic variance..-can be reduced)

Do We Need New Physics?

- Best way to resolve doubts is to find direct observational signatures for string theory

- **Crucial Question**: How can you discriminate from data whether 'anomalies' originate from features of inflation or are rooted in string theory?

INSIGHT

Cross-Correlations:

$$C_\ell^{TE} \quad \text{and} \quad C_\ell^{TL}$$

Reveal: 1) source of Perturbation and, 2) ISW vs. Clustering of LSS in Model Independent Way

Can Single-Field Inflation with a Feature on its Potential accomodate the observations?

- Dark Energy gives rise to ISW
- Observed TT-spectrum suppressed
- Observed TE-spectrum not suppressed

⬇

For low multipoles 'ℓ'

Put a Bump in the 'Right' place to stop slow-roll

E.g. : 1) $V(\phi) = \frac{1}{2} m^2 \phi^2 \left[1 + C \,\mathrm{Tanh}\left(\frac{\phi - \phi_*}{d}\right)\right]$

(Easther et al.)

2) A cuttoff around k_{60}

$$\delta_H^2 = \delta_H^{2(0)} \left[1 + e^{-(k/k_c)^{\alpha}}\right]$$

(Kofman et al.)

C_ℓ^{TT} is Suppressed! And all other C_ℓ

Review: Ma + Bertschinger

(CMB FAST)

$$\begin{cases} \Theta(n) = \frac{1}{3}\Phi_0 - 2\int_0^{r_0} \frac{d\Phi(r,z)}{dr}\, dr \\ C_\ell^{TT} \simeq \int \frac{dk}{k^2}\, \underline{\underline{\delta_H^2}}(k) \left[\Theta_\ell(k)\right]^2 \end{cases}$$

$$\begin{cases} L(n) = -2\int_0^{r_0} dr\, \frac{r_0 - r}{r\, r_0}\, \Phi(r,z) \\ C_\ell^{LL} \simeq \int \frac{dk}{k^2}\, \underline{\delta_H^2}(k) \left[L_\ell(k)\right]^2 \end{cases}$$

* [Same thing for C_ℓ^{EE}) *

$$\begin{cases} C_\ell^{T,L} \simeq \int \frac{dk}{k^2}\, \underline{\delta_H^2}(k) \left[\Theta_\ell(k)\, L_\ell(k)\right] \\ C_\ell^{T,E} \simeq \int \frac{dk}{k^2}\, \underline{\delta_H^2}(k) \left[\Theta_\ell(k)\, E_\ell(k)\right] \end{cases}$$

* Notice Primordial Power $\delta_H(k)$ *
Everywhere

What Can String Theory Do?

- Early Universe Modifications

e.g.: $$\boxed{H^2 = \bar{G}_N \left[\rho \pm \rho \left(\frac{\rho}{\sigma} \right)^n \right]}$$

(R-S, Arkani-Hamed et. al. etc. etc.)

- Late Universe Modifications

e.g.: $$\boxed{H^2 = \bar{G}_N \left[\rho + \frac{\left(1 - \rho/\rho_c \right) H^\alpha}{H_0^{\alpha-2}} \right]}$$

$$\tilde{G}_N \simeq G_N \left[1 + \left(r/r_c \right)^{1-\alpha} \right]$$

(Cardassian, DGP, Kogan, Durrer, etc..]

- Generic Effects of Moduli Couplings

What Can Strings Do...

1) Coupling of $\langle S \rangle$ to Gravity/Metric

$\Rightarrow$ Modifies Friedman Eqn.
(Einstein Eqns.)

2) Modulated String Perturbation

$$\frac{\delta g(s)}{g(s)} \simeq \frac{\delta T}{T} \simeq \frac{\delta \Phi(r,z)}{\Phi(r,z)}$$

3) Coupling of $\langle S \rangle$ to Matter Sector.
- 5th Forces. Long/Short Range.
- Problematic. Induces Mass
- Derivative Coupling is O.K : Symmetry

$$\mathcal{L}_I = g \frac{\langle S \rangle}{M} F_{\mu\nu} F^{\mu\nu}$$

$$\Rightarrow \boxed{\omega^2 = k^2 + k\, g \big/ \tfrac{\langle S \rangle}{M}}$$

4) Change Clustering Properties

$$\Phi(r,z) \Rightarrow \Phi(r,z) + \delta\Phi(g,z)$$

How Can We Tell What We Are Looking At?

Need a Unique Handle to Discriminate from Data, Inflation from String Theory Signatures

here it is...

- Inflation provides Only one source, $\delta_H(k)$, for all spectra and couples v. weakly to matter sector. Slow Roll, adiabacity

Thus All Spectra get Suppressed!!

- String Theory: 1) Extra Sources of Perturbation + Clustering; 2) Modified Friedman Equation; 3) 5^{th} force from Coupling to Matter; Dispersions; 4) Change LSS by variation of coupling.

Thus you can have low C_ℓ^{TT} but high C_ℓ^{EE}: ISW vs. LSS.

What have we learned?

1) We may need two sources for CMB, LSS, DE. Direct evidence even with present data.

2) Suppresion of C_ℓ^{TT} can not come from the primordial spectrum, thus:

Single-Field inflation with a feature is highly disfavored even with present data!

3) LSS clustering may be different at $r \simeq H_0^{-1}$ in order to compensate for ISW effect

4) **New Physics** corrections that become relevant at late-times are favored, (vs. early times effect).

5) Weak Lensing will provide crucial new information for Cosmology.

Data Analysis

* Word of Caution for String Models: *

- Perturbation Eqns. ???
- Poisson, Boltzman Eqn. may be different??
- What happens to G_{ii} – Eqns. when you modify G_{00}?

→ Therefore let's be generic rather than scrutinize specific models.

$$\left[\text{CMB} + \text{LSS}\right] + \left[\text{ISW} + 6 \text{ Parameters}\right]$$

$$\begin{array}{cccc} \downarrow & \downarrow & \downarrow & \downarrow \\ (\text{All } T, E) & (\text{SDSS}, 2\text{DF}) & (\text{DE}) & (\Omega_{m,b}, H_0, \tau, k) \end{array}$$

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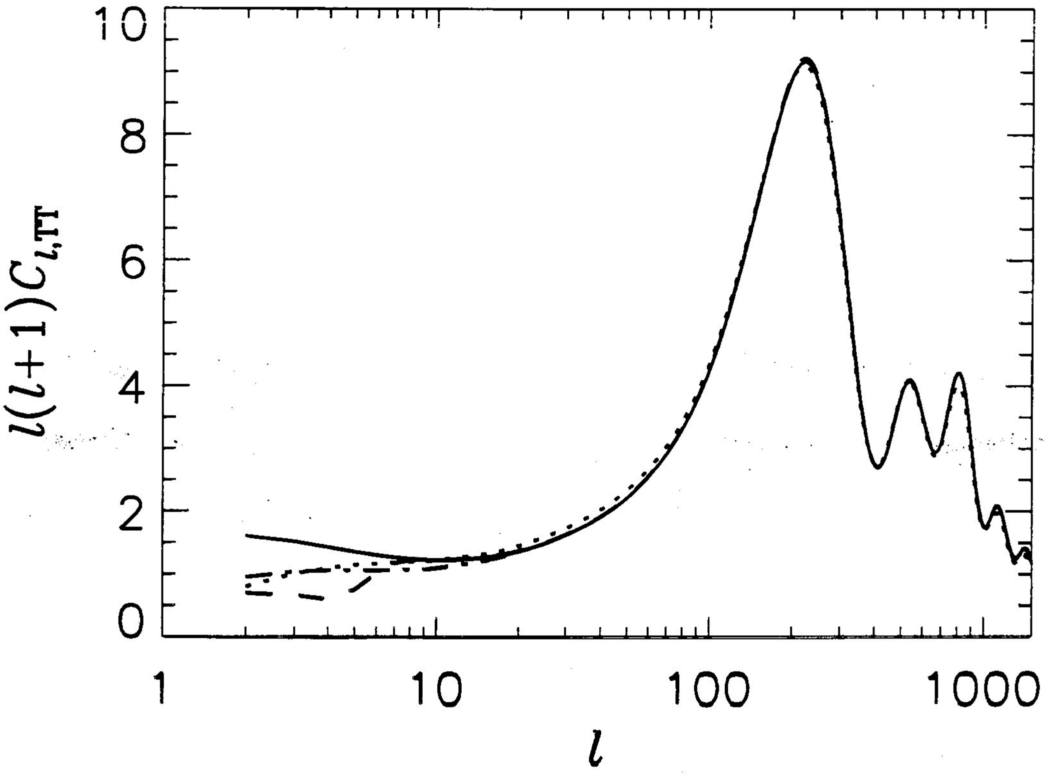
a) Fit Inflaton With a Feature

b) Early and Late Modifications of Brane-Worlds

c) Generic String Effects: Modified Perturbations or Clustering at LSS from moduli coupling and variations.

'τ' does not do the job.

TT



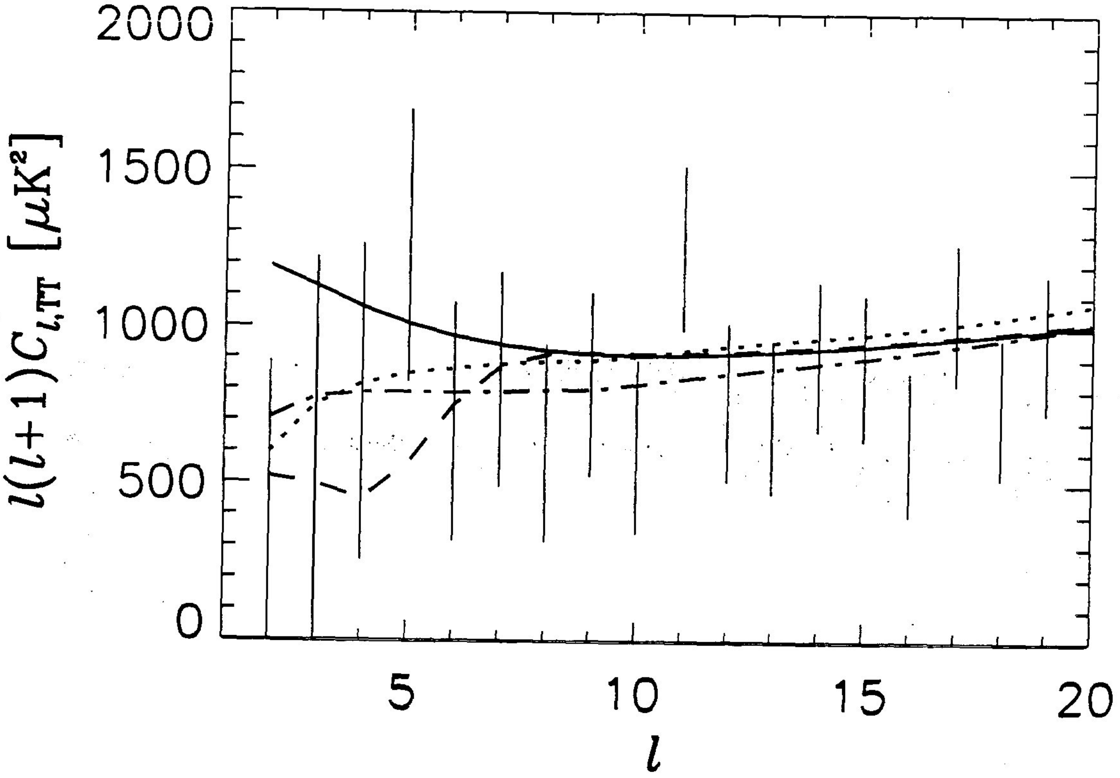
——— ΛCDM

- - - - Modified $\delta_H(k)$

-·-·-·- Modified Perturb. Source

·········· Modified Friedman Eqn.
+
Modified Source

TT



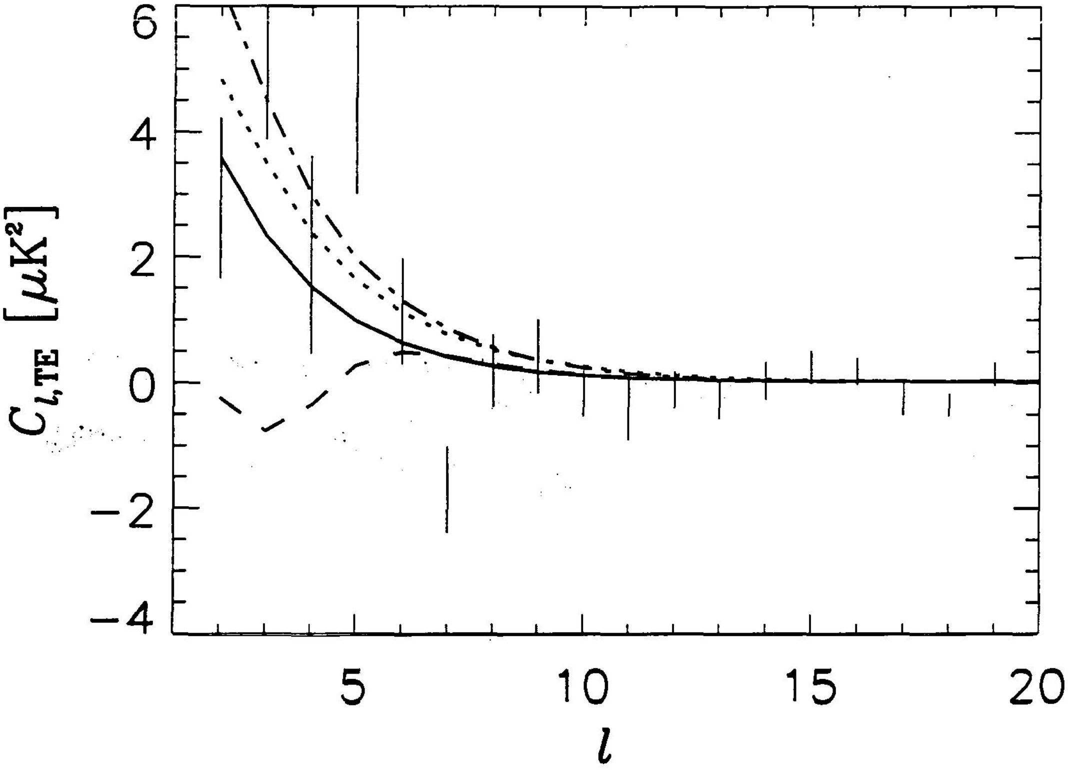
——— ΛCDM

- - - - Modified $\delta_H(k)$

•—•—• Modified Perturb. Source

• • • • • Modified Friedman Equ.
+
Modified Source

TE



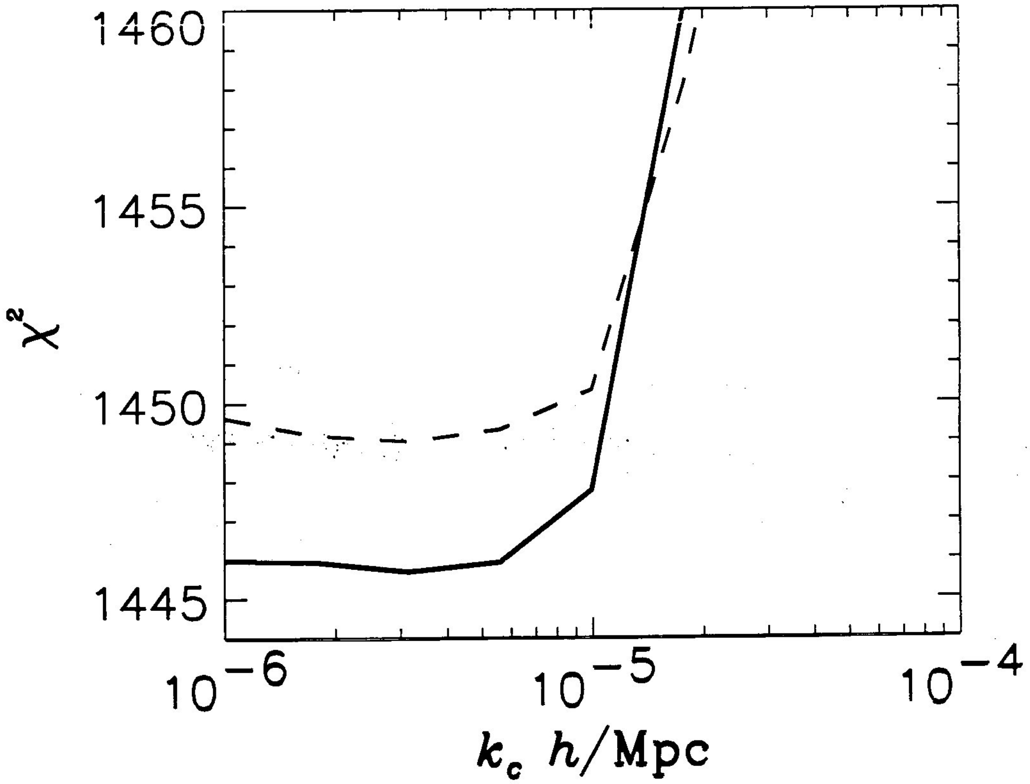
—— ΛCDM

– – – – Modified $\delta_H(k)$

●–●–●– Modified Perturb. Source

●●●●●● Modified Friedman Eqn.
+
Modified Source

χ^2 vs. k_c



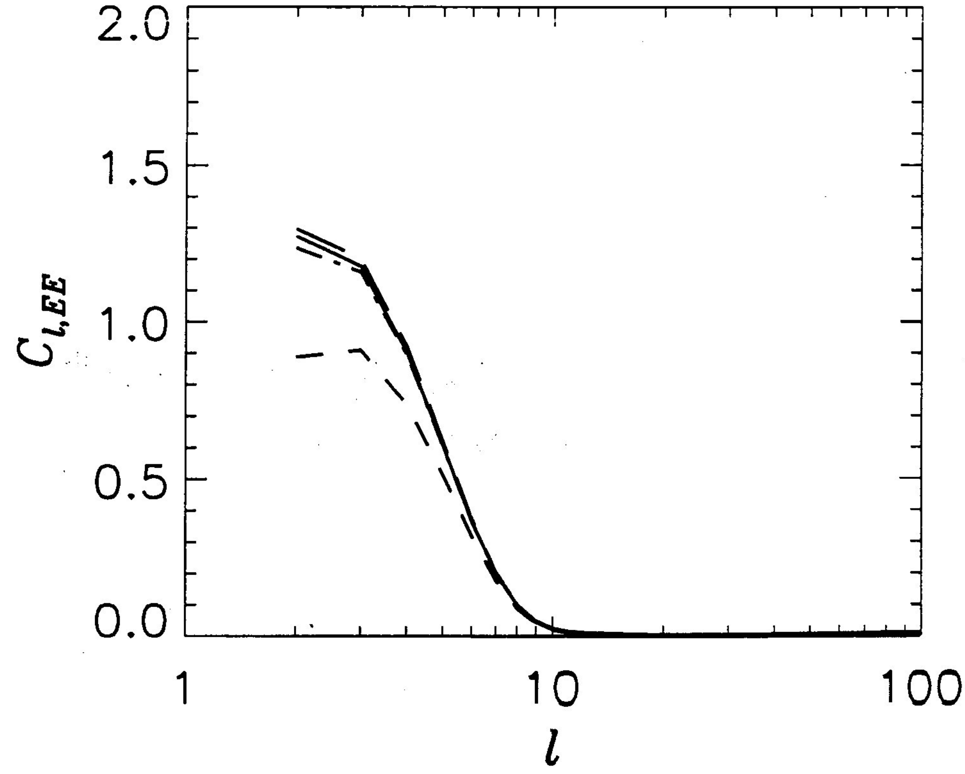
— Modified Source

- - - - Modified Friedman Eqn.

(Note: $r_c^{-1} \sim H_0^{-1} \sim 10^{-3}$ ruled out. $\chi^2 = 2 \cdot 10^{4}$)

••••••

EE



Modified Source $\Phi(r,z)$

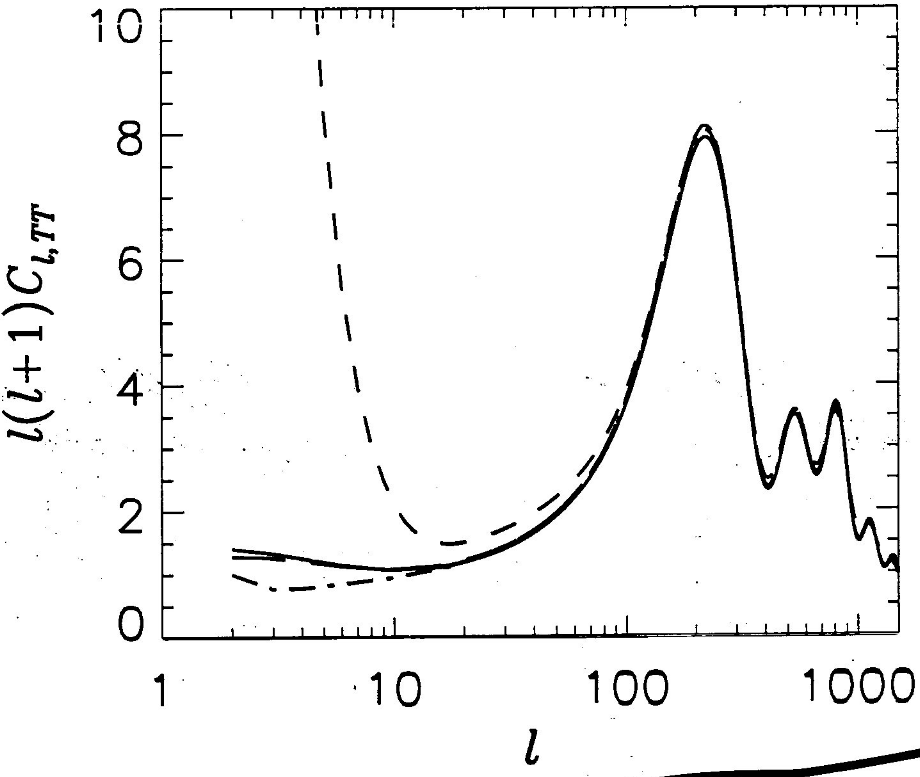
—— $k_c = 0$

— — $k_c = 10^{-6}\ h M_{pc}^{-1}$

—●—●— $k_c = 10^{-5}\ h\ M_{pc}^{-1}$

- - - $k_c = 10^{-4}\ h\ M_{pc}^{-1}$

TT



Modified Source $\Phi(r,z)$

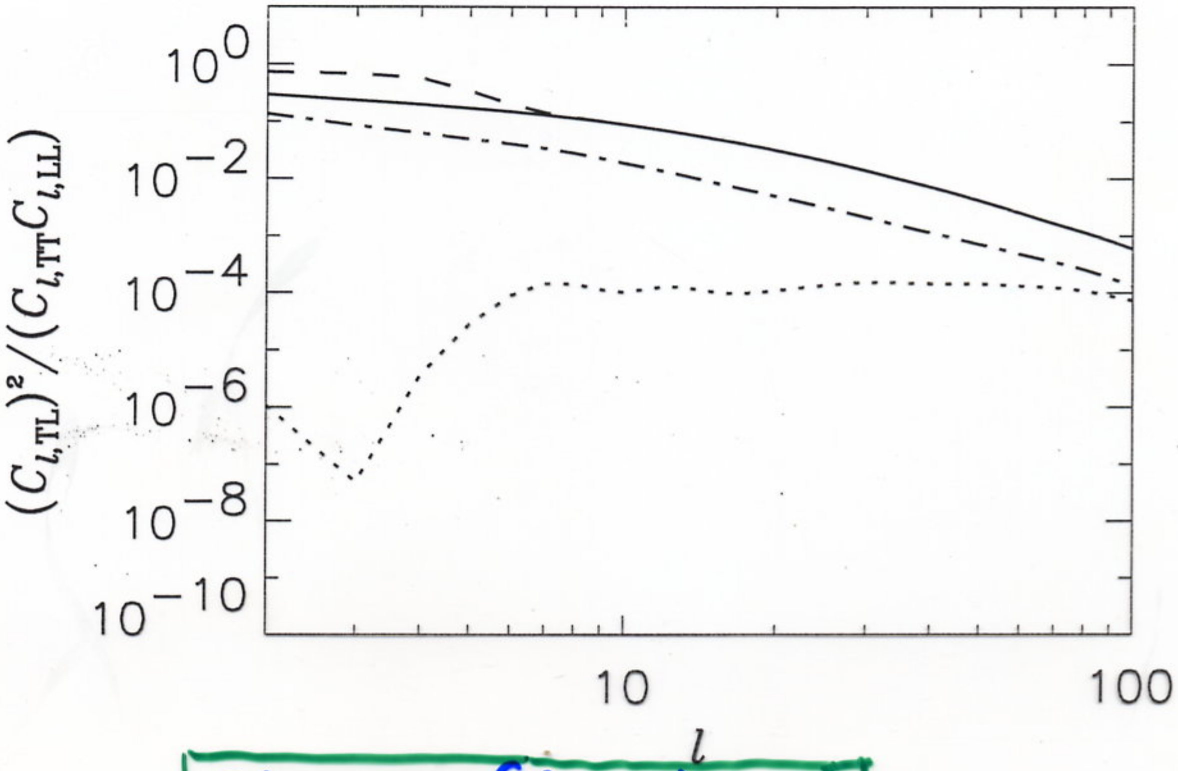
——— $k_c = 0$

— — $k_c = 10^{-6}\ h\mathrm{Mpc}^{-1}$

—•—•— $k_c = 10^{-5}\ h\mathrm{Mpc}^{-1}$

- - - - - $k_c = 10^{-4}\ h\mathrm{Mpc}^{-1}$

TL



Clear Signature

—— ΛCDM

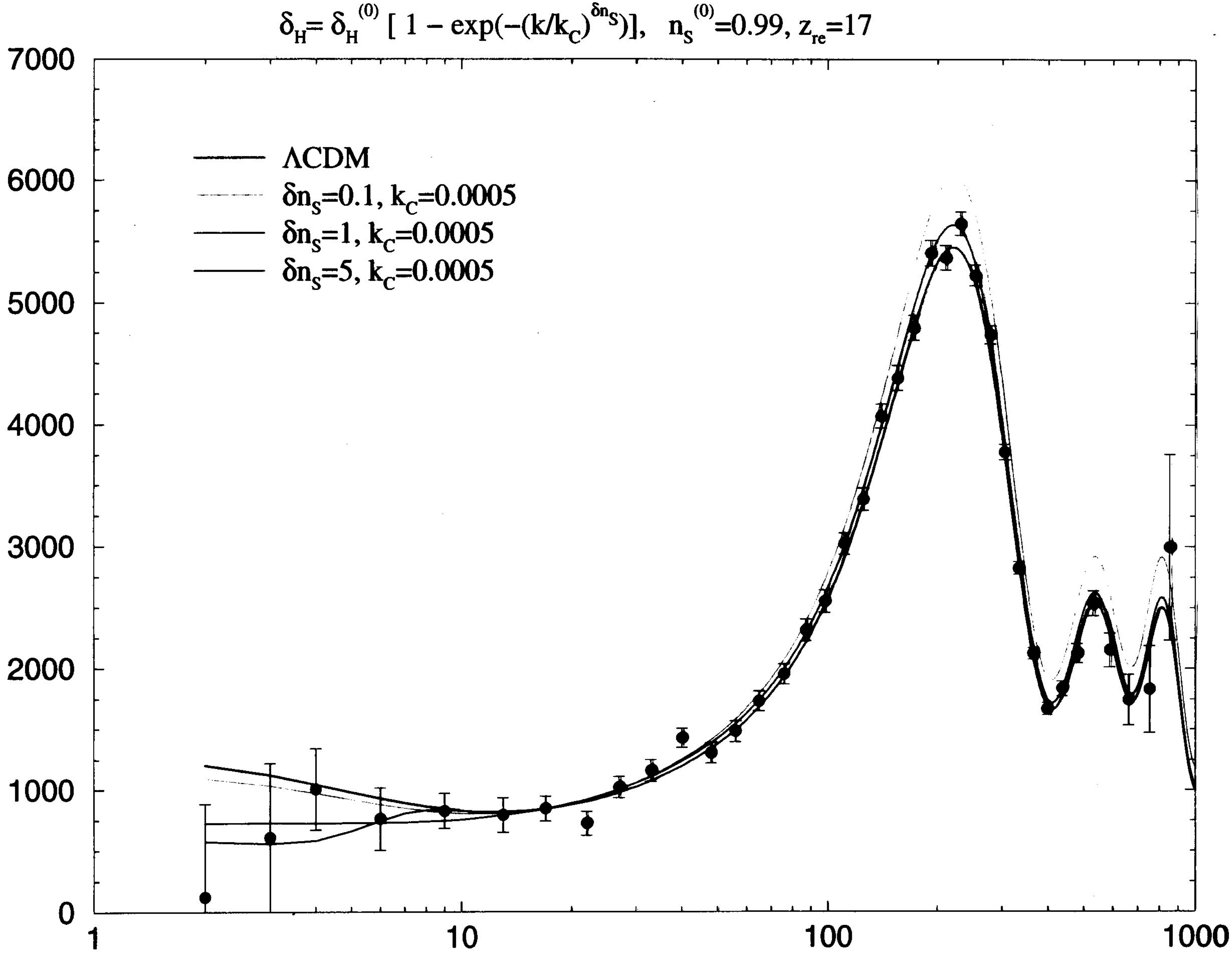
– – – Modified $\delta_H(k)$

–•–• Modified Source

••••• Modified Friedman Equ. + Modified Source

Notice $C^{TL} \Rightarrow 0$ for ••••• 2 Sources.

Should see it from Weak lensing.


$\delta_H = \delta_H^{(0)} [\, 1 - \exp(-(k/k_C)^{\delta n_S})]$, $n_S^{(0)} = 0.99$, $z_{re} = 17$
ΛCDM
$\delta n_S = 0.1$, $k_C = 0.0005$
$\delta n_S = 1$, $k_C = 0.0005$
$\delta n_S = 5$, $k_C = 0.0005$
7000
6000
5000
4000
3000
2000
1000
0
1
10
100
1000