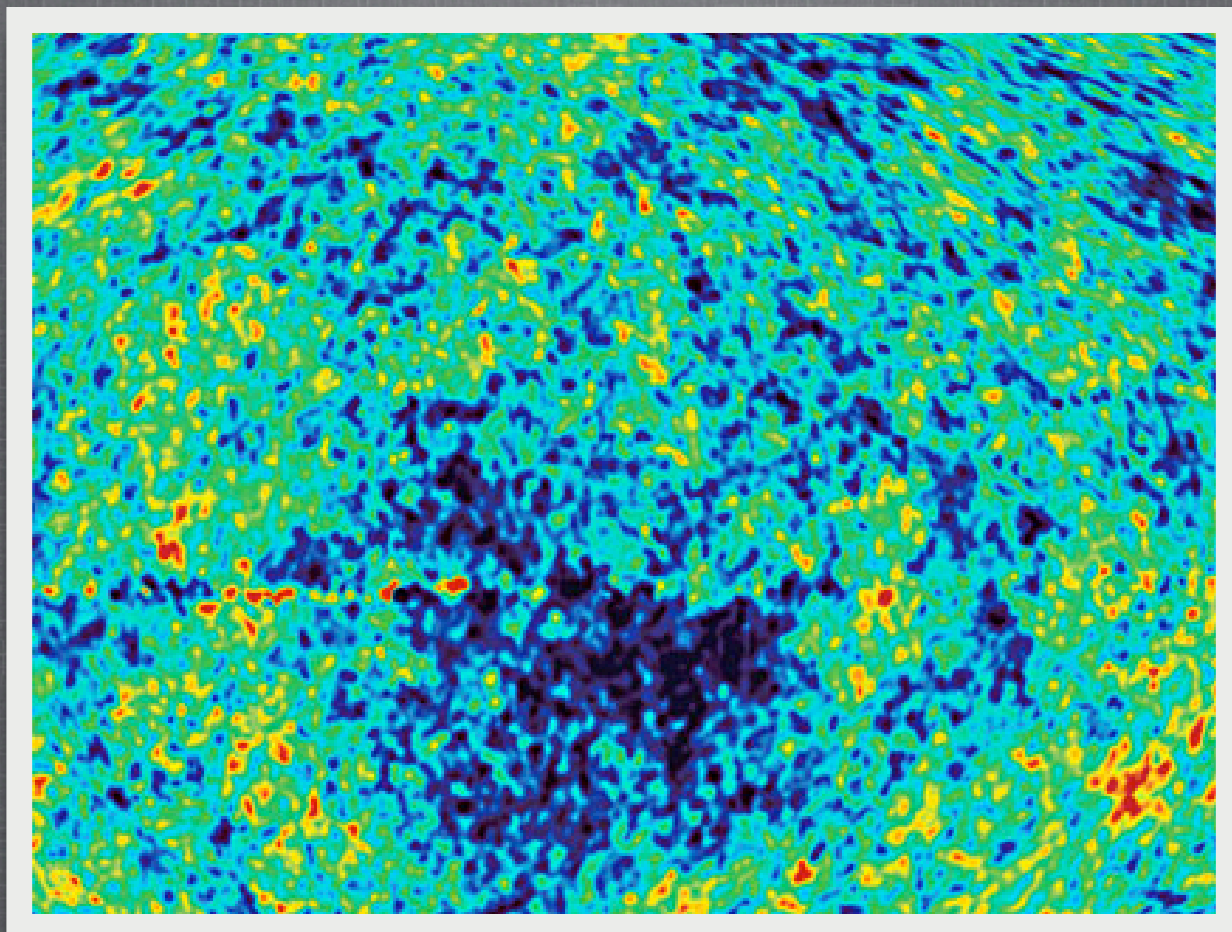
MODELS OF INFLATION



Richard Easther

EVIDENCE!

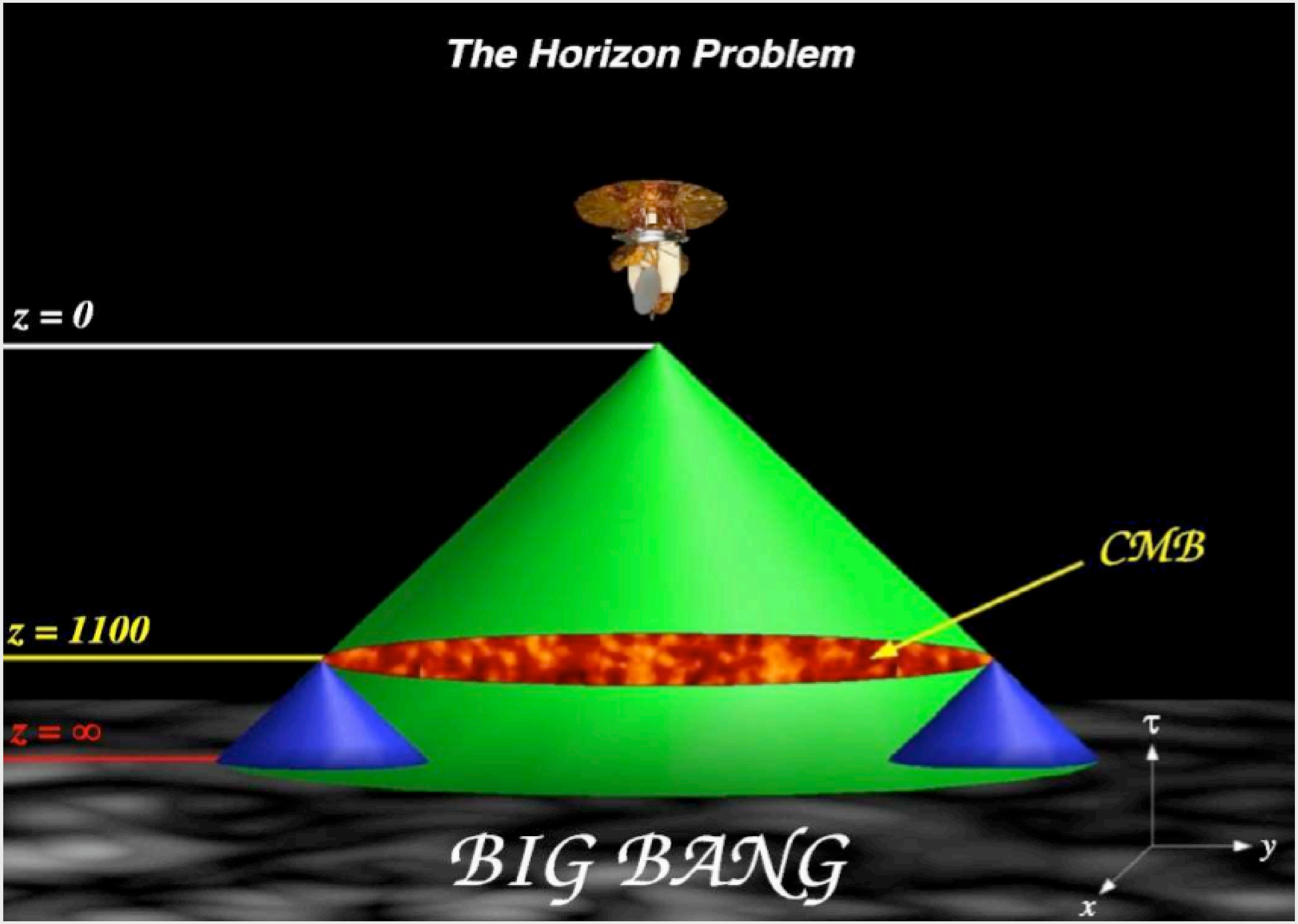
- Standard hot big bang (BBN, CMB)
  - Dominated by radiation and/or “matter”
  - Universe evolves away from $\Omega = 1$
  - Today: $\Omega = 1.00 \pm .01$
- Homogeneity & Isotropy: CMB: $\delta T/T \sim O(10^{-5})$
- Large scale correlation of CMB E-mode and $\delta T/T$

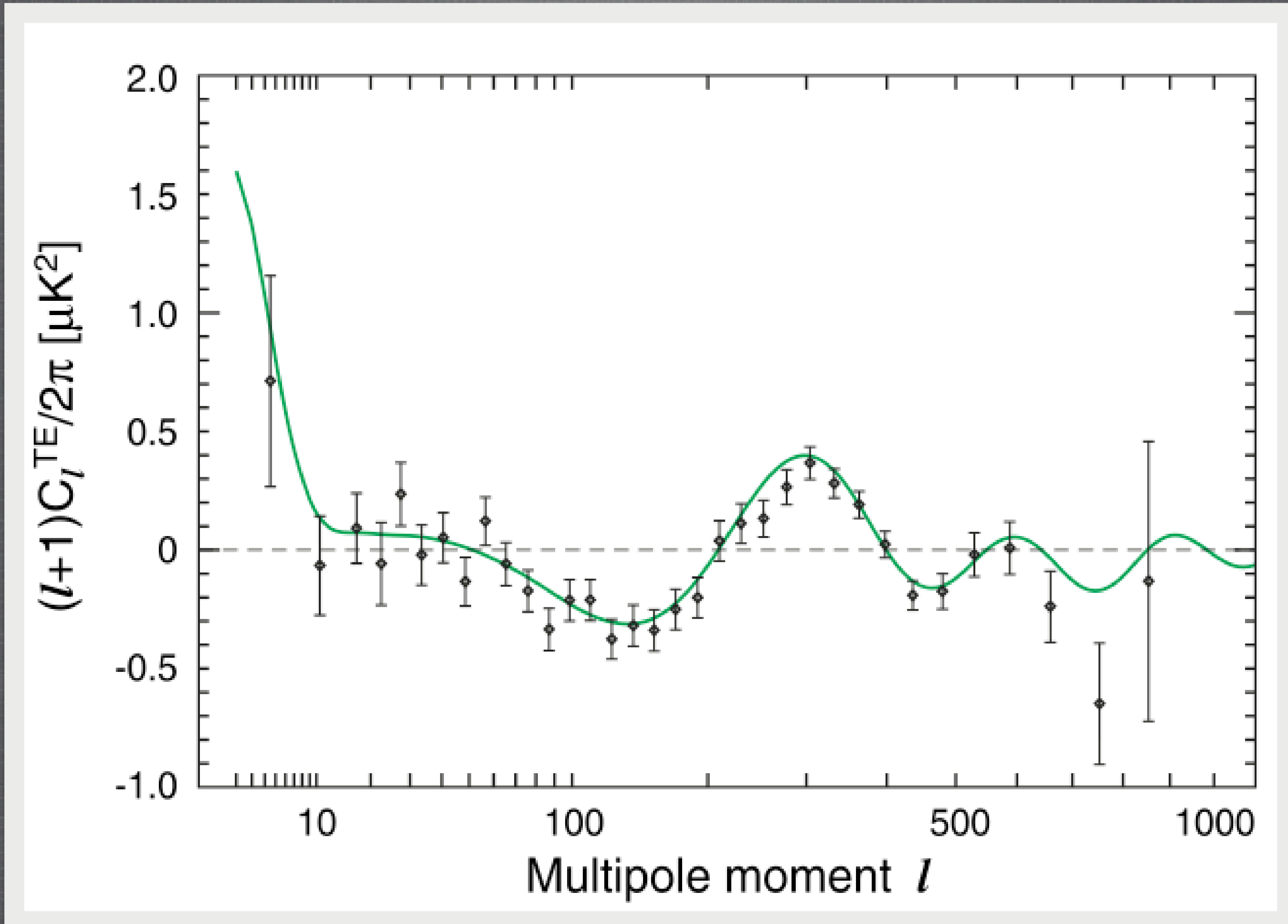
<ET> CORRELATION

- Physics of the CMB is well understood
  - General relativity and *small* inhomogeneities
  - e^-, p, He nuclei, dark matter, ν, γ, (Λ, H_o and k)
  - Boltzmann equations
  - Beautiful and largely classical physics

<ET> CORRELATION

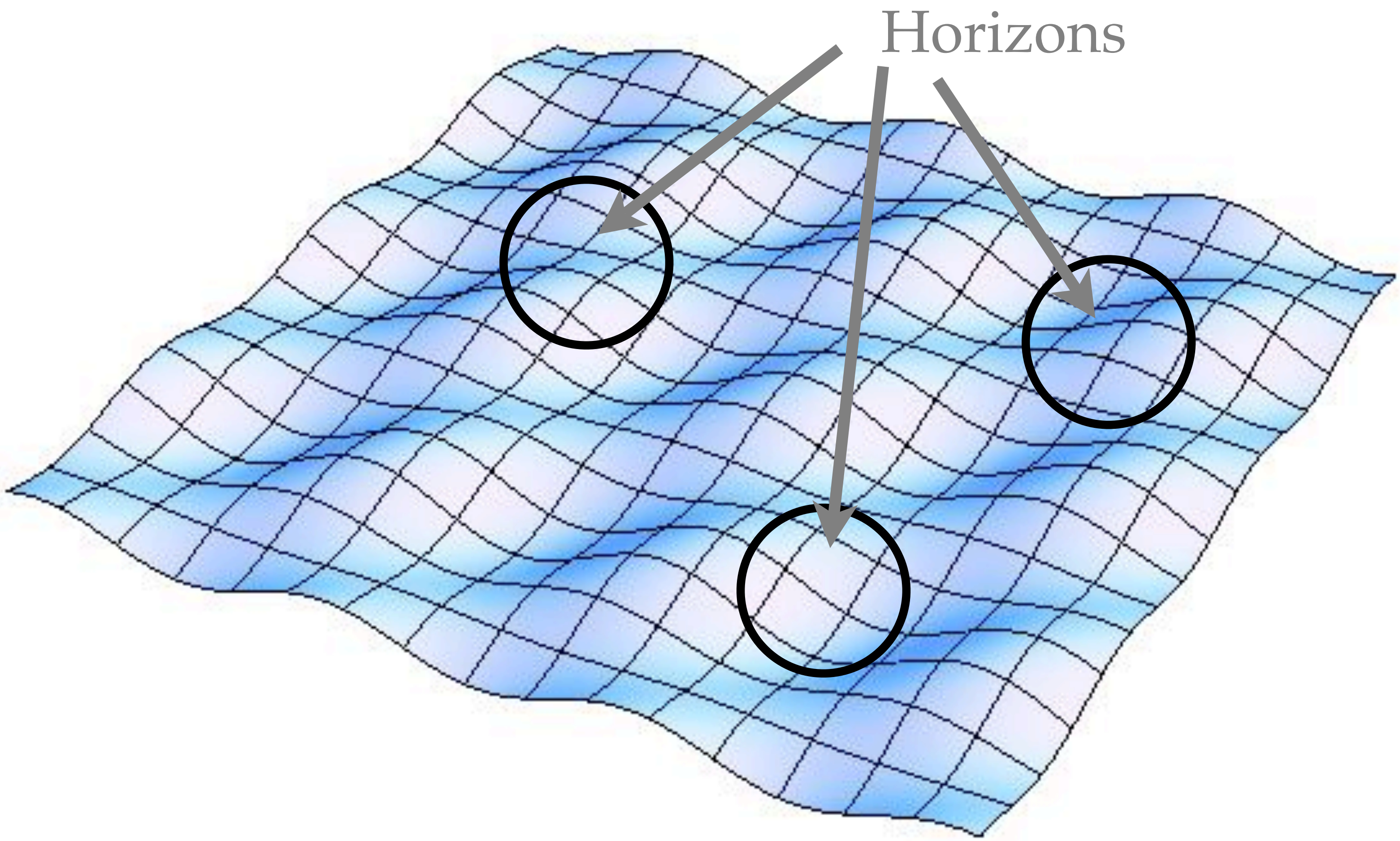
- Temperature anisotropies caused by
  - Compression / rarefaction (acoustic peaks)
  - Gravitational redshift (Sachs-Wolfe, ISW)
- *Polarization* (E or B) requires free charges
  - Ionized universe
  - Pre-recombination: $z > 1089$ (or so)
  - Post-reionization: $z < 10$ (or so)

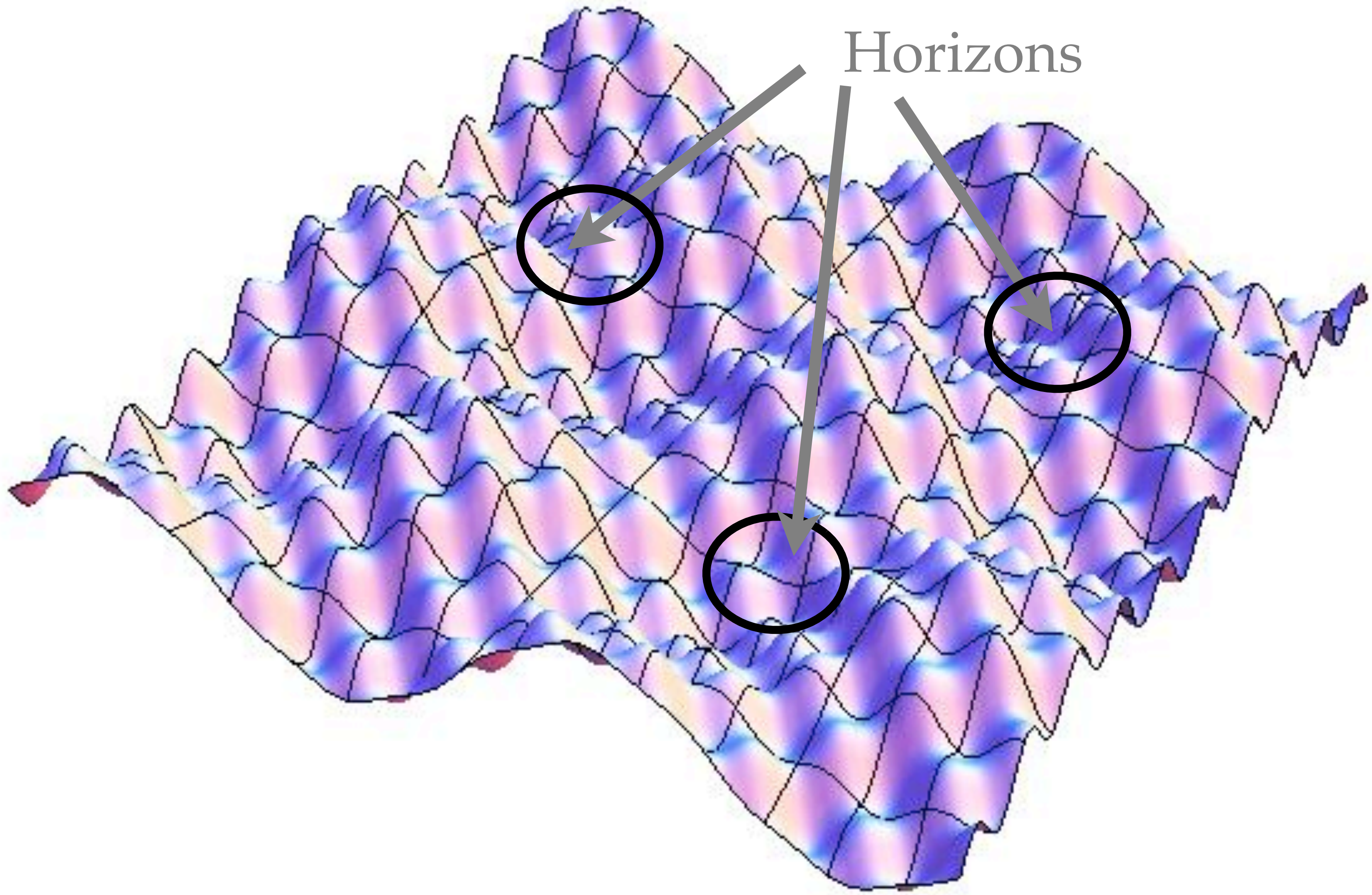

The Horizon Problem
z = 0
CMB
z = 1100
z = ∞
τ
y
x
BIG BANG



2.0
1.5
1.0
0.5
0
-0.5
-1.0
$(l+1)C_l^{TE}/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l

WMAP5


Horizons


Horizons

INFLATION: WORKING DEFINITION #1

- Comoving size of the *horizon* is *decreasing*.
  - Dynamical definition
  - Allows causal theory of initial conditions
  - Explains long range correlations in CMB.
- Standard inflation + Ekpyrosis + "pre big bang" + varying speed of light (see Khoury)

COMMENTARY...

- Amounts to: "inflation is a thing that puts long range correlations in the CMB"
    - We see long range correlations in the CMB
    - Not what we (they) would have expected in 1965!
- Do we conclude inflation happened, and go home?
- We want to know *why* it happened!

INFLATION: WORKING DEFINITION #2

- Expansion of universe is *accelerating*
  - Restricts attention to expanding universe
  - Einstein gravity (after conformal transformation?)
  - “Traditional” definition: but still dynamical
  - No mention yet of *models*

SIMPLE INFLATIONARY MODELS...

- Scalar field
  - Single field
  - Minimally coupled
  - Standard kinetic term.
- Potential $V(\phi)$ specifies model
  - $\exp(\phi)$; $\cos(\phi)$; $m^2\phi^2$; $\lambda\phi^4$ (+ many baroque forms)

WHAT *IS* THE INFLATON?

- Fundamental field in some Beyond the Standard Model theory (must be very weakly interacting)?
- Some dynamical degree of freedom related to branes / compact dimensions?
- A composite or emergent phenomenon involving many individual fields or degrees of freedom?

SCALAR FIELD EVOLUTION

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$H^2 = \frac{8\pi}{3M_p^2}\rho = \frac{8\pi}{3M_p^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

SLOW ROLL APPROXIMATION

$$H^2 \approx \frac{8\pi}{3M_p^2}V(\phi) \qquad\qquad 3H\dot{\phi} + \frac{dV}{d\phi} \approx 0$$

Slow Roll Parameters...

$$\epsilon = \frac{M_p^2}{16\pi}\left(\frac{V'}{V}\right)^2 \qquad\qquad \eta = \frac{M_p^2}{8\pi}\frac{V''}{V} \qquad\qquad \cdots$$

INFLATIONARY MODELS

- My focus is on general properties
  - Many models (~100) of inflation in literature
- Not just functional form of potential
  - e.g. k-infation / non-minimal kinetic term
  - D-brane / DBI (w. similar considerations about r)
  - Other stringy models / Curvaton / Assisted inflation

SINGLE SCALE FIELD: BASIC FEATURES…

- Need a potential which is very flat
  - Scalar field evolves slowly (“dark energy”)
  - Get slow roll parameters & plug in for predictions
- Have quantum fluctuations
  - In field and in *spacetime* (tensor)
  - Fluctuations in ϕ are fluctuations in V(ϕ) (density)

PERTURBATIONS...

- Massless free field has fluctuations of amplitude H
- Inflaton field more complicated
  - Fluctuations gives density perturbations
  - Regions which fluctuate ''uphill'' need time to roll back to central value
  - $\delta\phi \sim \delta N \sim \delta\rho$
  - N = # of e-folds = log(scale factor)

MOTIVATING δN

- $\delta\phi \sim \delta H$
  - Velocity of field from slow roll approximation
- Hubble time $1/H$, $\delta N \sim 1$

$$\begin{aligned} \dot{\phi} &\sim \frac{\delta\phi}{\delta t} \approx \frac{V'(\phi)}{3H} \\ \delta t &\approx \frac{3H\delta\phi}{V'} = \frac{3H^2}{V'} \\ \delta N &\approx \frac{\delta t}{\frac{1}{H}} \sim \frac{H}{M_p}\frac{1}{\sqrt{\epsilon}} \end{aligned}$$

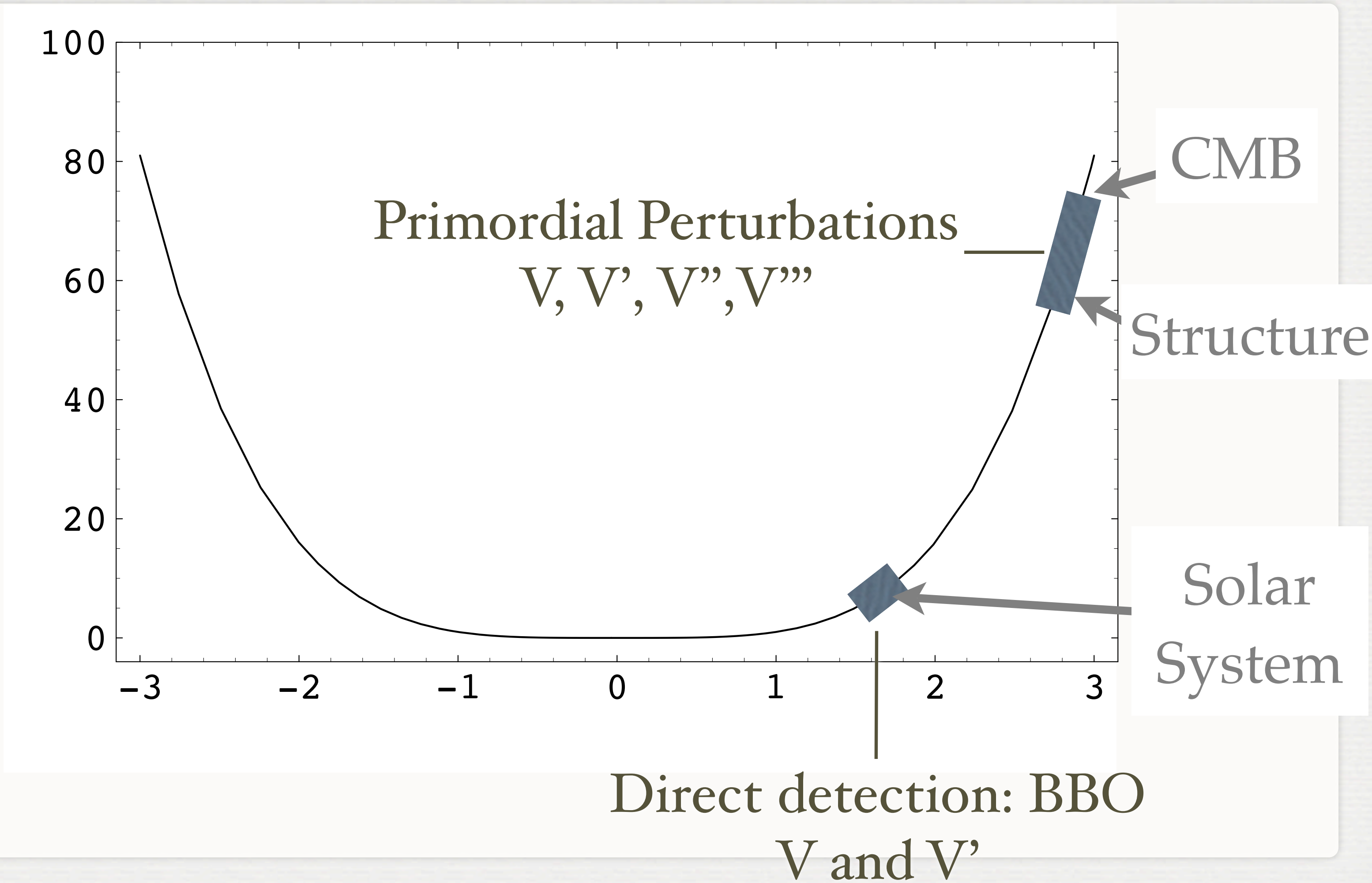
PERTURBATION SPECTRA

$$
\begin{aligned}
P_T &= 16\frac{H^2}{M_p^2} = A_T k^{n_t}, \qquad n_t = -2\epsilon \\
P_S &= \frac{H^2}{M_p^2\epsilon} = A_S k^{n_s - 1}, \qquad n_s = 1 - 6\epsilon + 2\eta \\
\frac{P_T}{P_S} &= r = 16\epsilon
\end{aligned}
$$

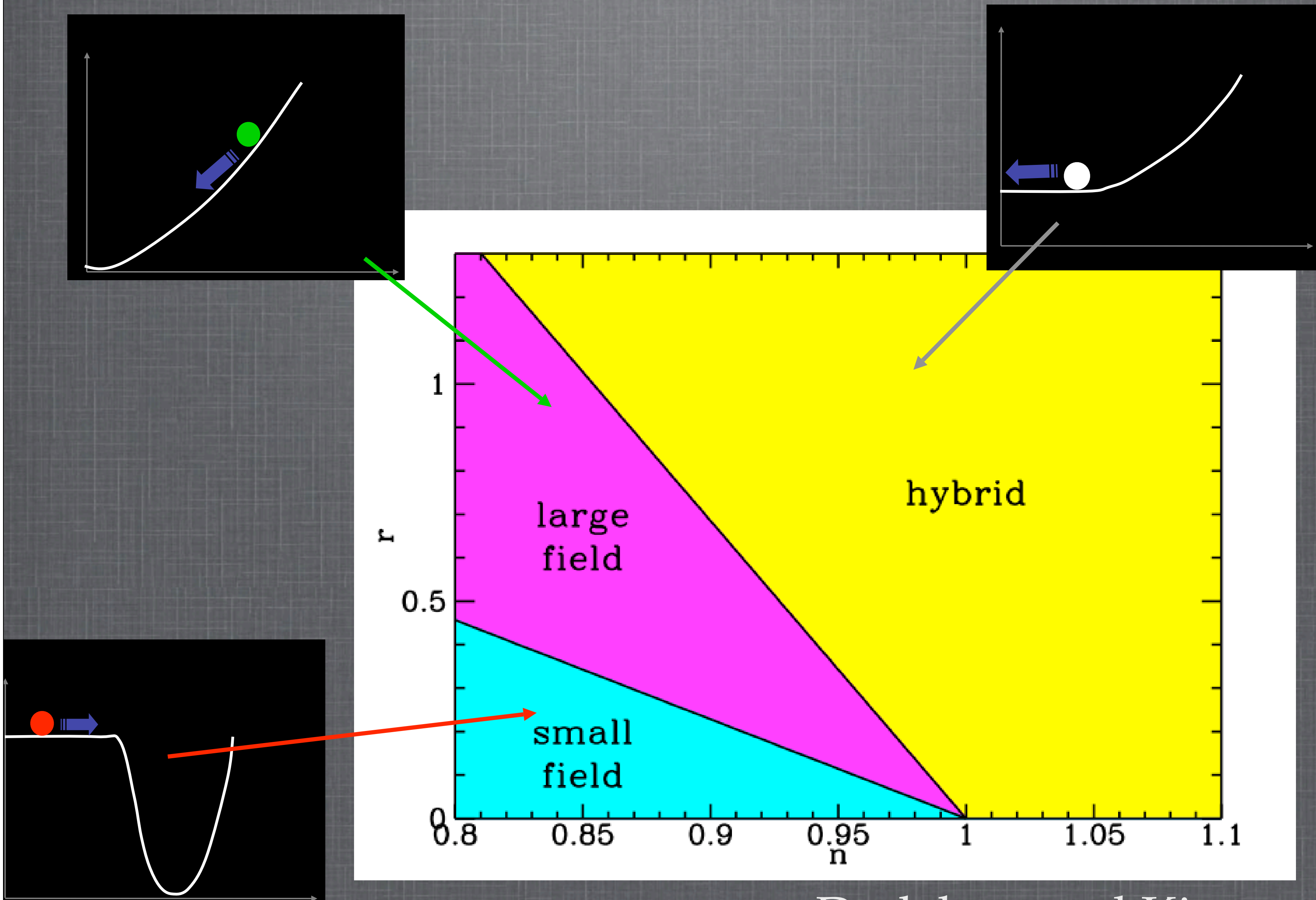
Consistency Condition

- Indices *change* as field evolves
- Tensors suppressed relative to scalars

CARTOON VERSION...



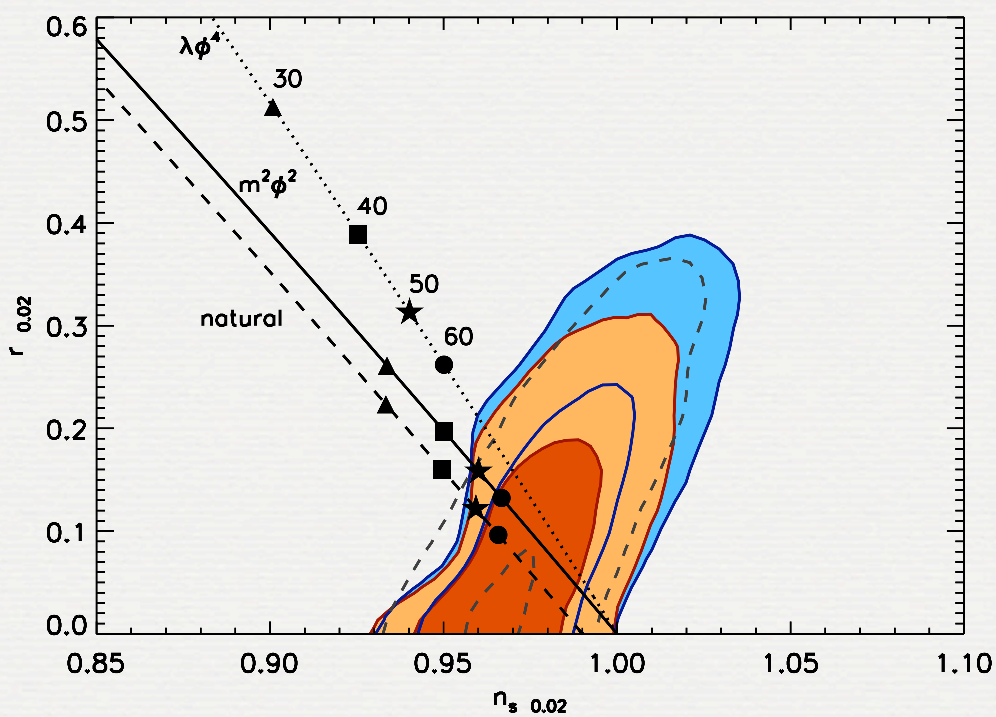
THE INFLATIONARY ZOO



Dodelson and Kinney '97

RECONSTRUCTION...

- Constrain ε and η directly
  - w. Peiris, & Adshead
  - Better ways of doing slow roll expansion
- Ambiguity in N



PHYSICAL MOTIVATION FOR POTENTIALS

- Very few inflationary models are *derived*
  - e.g. potential *and* parameters extracted from some larger theory (string theory / branes)
- Some are *motivated*
  - e.g. natural inflation - cosine potential from axions
- Many just written down out of thin air...
  - What is normal?

TENSOR AMPLITUDE & "LYTH BOUND"

- Q: How far does field move in an e-fold?

$$\frac{dN}{d\phi} = \frac{dN}{dt}\frac{dt}{d\phi} = H\frac{1}{\frac{d\phi}{dt}}$$

IMPLICATIONS...

- If field moves by more than M_p (for $\Delta N \sim 50$):
  - Do not have perturbative control of potential
  - "Explicit" single field models all have $\delta\phi < M_p$
  - Can write down potentials with $\delta\phi > M_p$
  - But unsure about physical motivation

$$\Delta\phi \sim \Delta N \frac{M_p}{8\sqrt{\pi}} \sqrt{r}$$

EXPECTATIONS FOR TENSORS…

- "Natural" for single field models to have $r \ll 1$??
  - e.g. $r \sim 10^{-6}$ or less
- Experiment: can get to $r \sim 10^{-2}$ from ground?
  - And maybe 10^{-3} or 10^{-4} from space??
- So tensors may be effectively undetectable

IS IT THIS BAD?

- If we look at *algebraically* simple potentials
  - Typically: ε and $\eta \sim 10^{-2}$; $r \sim 0.1$ is "natural"
- $r \sim 10^{-5}$ implies $\varepsilon \sim 10^{-6}$
  - Now *this* looks tuned
- Examples of stringy models; including those with large r: Kachru and Silverstein

DESIGN DECISIONS...

- Expectations for tensors are bimodal...
- Either r~ 0.01 - 0.2
  - 2σ detection from ground/balloon/Planck?
- Or r ~ 10^{-5} or less
  - Even a dedicated satellite may not see them!
- Food for thought: How do we respond to each case?

POSSIBLE LEVERS...

- What is the status of the consistency condition?
  - If r is very large can we observe it?
  - How robust is this prediction?
- Can we observe *running* of the spectral index?
  - Not in the CMB alone for "natural" values
- What about the 3-point function?

THOUGHTS

- An experiment that could measure r ~ 0.001 would rule out / confirm a *class* of inflationary models
  - A null result would not rule out inflation itself
- Inflation takes us to territory we do not understand
  - GUT scale physics; a probe of string theory?

THANKS TO...

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