"How can the CMB constrain inflation models ?"
--particle theorist's view--

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- ❑ Can the CMB say anything about inflation?
- ❑ An example for inflation model building : Modular Cosmology

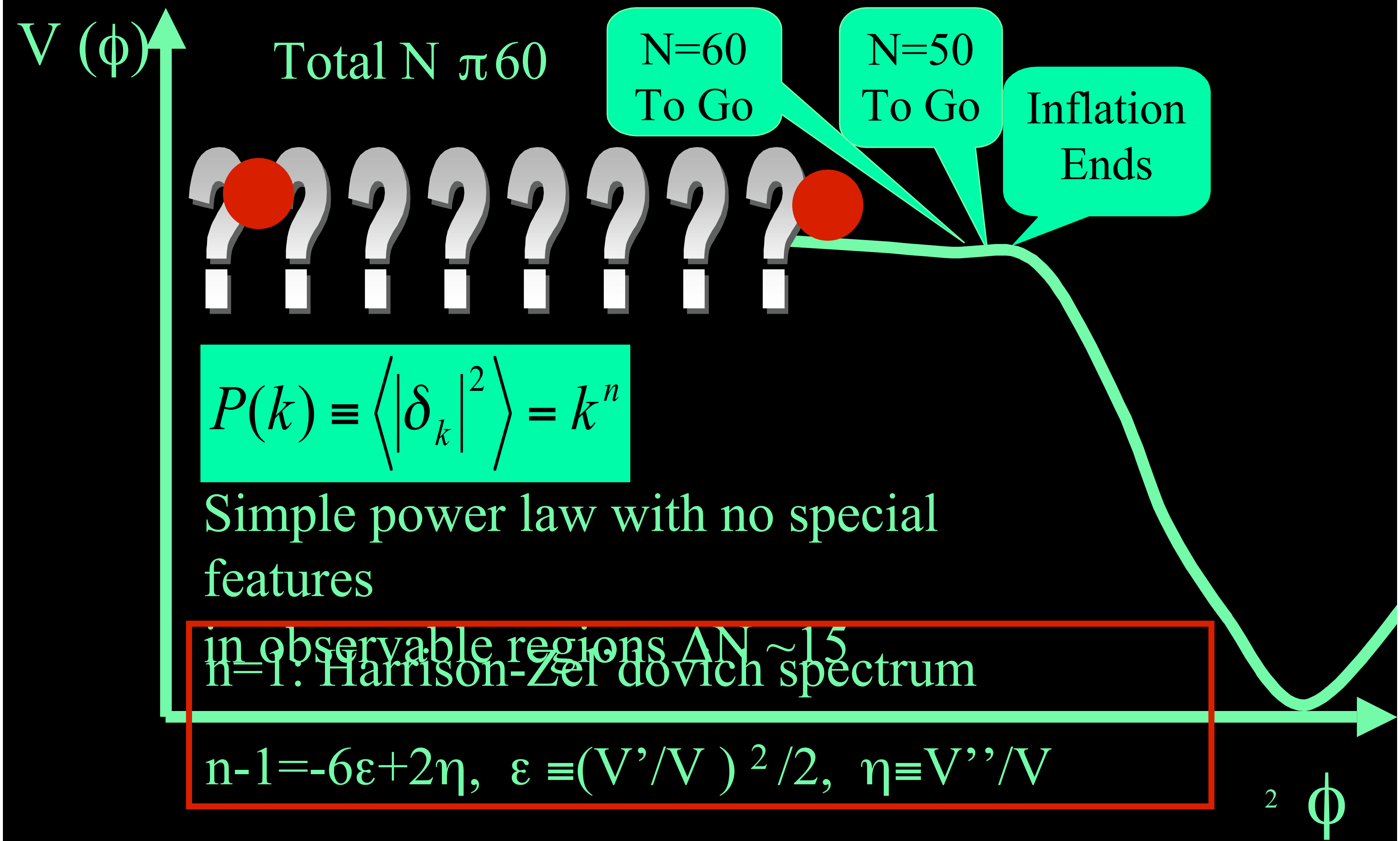
K.K. & Ewan Stewart

"Successful Modular Cosmology" (JHEP 307 (2003) 13),

"Inflation on Moduli Space and Cosmic Perturbations" (JHEP 312 (2003) 8)

- ❑ Summary and Conclusion

Can we guess the nature of inflation from the CMB ?



$$P(k) \equiv \left\langle \left| \delta_k \right|^2 \right\rangle = k^n$$

Simple power law with no special features

in observable regions ΔN ~15

n=1: Harrison-Zel'dovich spectrum

$n-1=-6\varepsilon+2\eta$, $\varepsilon \equiv (V'/V)^2/2$, $\eta \equiv V''/V$

Can we guess the nature of inflation from the CMB ?

- So many different inflation models can lead to an identical CMB spectrum.

✓ One of reasons:

For multiple field inflation (i.e. more than one field govern the dynamics),

curvature perturbations can be time dependent even on super-horizon scales!

- Can CMB tell if inflation was single or multiple component?

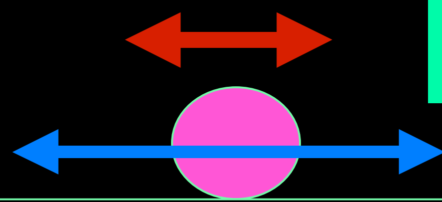
If gravitational waves can be observed.

Gravitational waves can tell if inflation is single or multiple components.

Adiabatic:

Pert. along background trajectory

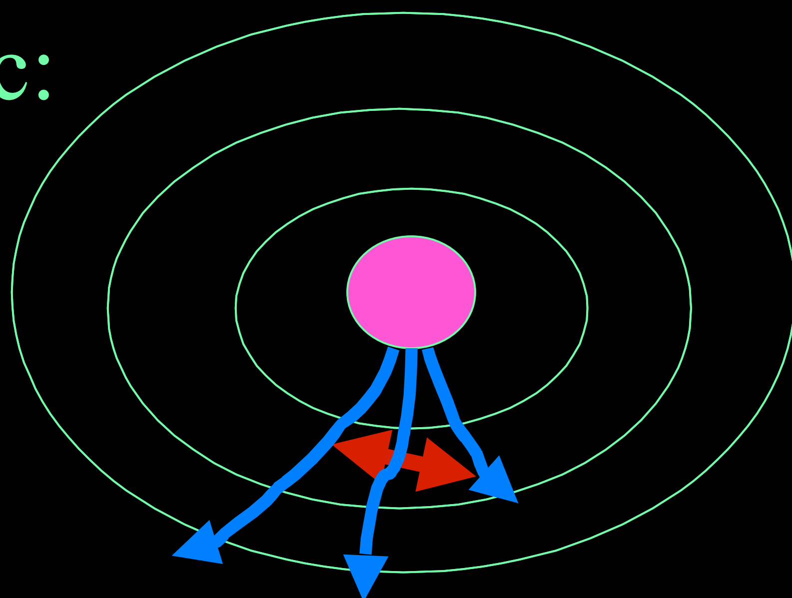
$$r \equiv \frac{\text{grav. wave}}{\text{curv. pert}} = 16\varepsilon$$



Non-adiabatic:

Pert. off traject.

Curv. Pert can be time dependent even on super-horizon scales



$$r \leq 16\varepsilon$$

Grav. waves detectable?

Need $\Delta\phi$ □ M_p, unnatural $V^{1/4}$

The bottom line

Thousands of inflation models can lead to an identical CMB spectrum.
(For instance, degeneracy due to
Non-adiabatic evolution of perturbations.)

Constraining inflation models from CMB data alone is HARD

An example of inflation model building: Modular Cosmology

(Particle theory is important)

- What is the inflaton field?

-What kind of fields were there in early Universe?

Moduli Fields

- What is the form/energy scale of the inflaton potential?

-How was supersymmetry broken in early Universe ?

Hidden Sector Supersymmetry Breaking

(CMB is important)

Particle Theory Setup: Moduli (working definition)

Flat at tree level

The form of potential

(*f* is function with O(1) coefficients)

gravitational-strength decay

$$V(\phi) = M_s^4 f\left(\frac{\phi}{M_P}\right)$$

Properties:

$$V_0 \sim M_s^4,\ m_\phi \sim M_s^2 / M_p, V'' / V \sim O(1)$$

THE energy scale of potential

$$V_0^{1/4} \sim M_s \sim 10^{10}\,\text{GeV}$$

THE mass of field

$$m_\phi \sim M_s^2 / M_p \sim TeV$$

Other choices of parameter values would be unnatural fine-tuning

Now Ask:

- Can self-consistent cosmology scenario be realized from this natural setup ?

(without any modifications or unnatural fine-tuning)

- What is the prediction for this particular scenario?

K.K. & Ewan Stewart

"Successful Modular Cosmology"

"Inflation on Moduli Space and Cosmic Perturbations"

Also related work by, for instance,

S. Thomas "Moduli Inflation from Dynamical Supersymmetry Breaking"

Banks, Berkooz, Shenker, Moore and Steinhardt "Modular Cosmology"

" …. Several speculative explanations of the discrepancy between SUSY breaking scale (10^{10} GeV) and apparent inflation scale (10^{16} GeV). …"

What kind of inflaton potential is 'natural' and/or 'simple'

- Our model is Natural in that

  -- Inflaton field is a field which already exists in Lagrangian (not ad-hoc field)

  -- The form of the potential and all the parameters naturally arise from particle theory without any fine-tuning/initial condition problems.

- But not so Simple in that

  -- We spent ~10 pages explaining the dynamics for this scenario

------e.g. Comparison with $V= m^2 \phi^2$ --------

- $m^2 \phi^2$ is Simple in that

  -- We don't need to spend ~10 pages to explain the dynamics for this model

- But $m^2 \phi^2$ is not Natural in that

  -- How can we get such a form of potential in Supergravity ?

  (Kawasaki, Yamaguchi and Yanagida (2000))

  -- Who is ϕ ? (would not be natural if it is ad-hoc field put by hand)

Warning: Don't judge inflaton potential just by its superficial appearance!

Predicted Cosmic Perturbations

$$n-1 \equiv \frac{d \ln P}{d \ln k}$$

$$n-1 = -Ak^{2\alpha}$$

$$n' \equiv \frac{dn}{d \ln k} = -2\alpha A k^{2\alpha}$$

$$|n-1| \sim |n'| \sim |n''| \text{ for } \alpha \sim 1$$

Watch Out ! Running of running

(Can’t use slow-roll approximations .
Low-energy scale inflation?)

$$\alpha = 0.4 \cdots 2.2$$

(Slow - Roll for $\alpha < 1$)

1

k/k_0

Summary and Conclusion

- ❑ Gravitational Waves? (If detected, big challenge to particle theory.)
  (What's the 'natural' energy scale of inflation?
  Particle theory is important to answer this kind of question!)
- ❑ Thousands of inflation models can lead to identical observations
- ❑ An example for inflation model building :
  particle theory should be able to tell us
  - ➢ what THE inflaton is
  - ➢ what THE values of the parameters such as inflation energy scale are
  - ➢ what THE inflaton potential should look like, etc

  Based on those setups, particle theory can make "testable" predictions.
- ❑ Cosmological observations can falsify/justify particle theory's predictions

More and more collaboration between particle theorists and astrophysicists, please!!

Can we guess nature of inflation from CMB ?

- So many different inflation models can lead to the identical CMB spectrum.
- Multiple component inflation ?

$$\dot{\mathrm{R}} \approx -\dot{\zeta} = -3H\frac{\dot{P}}{\dot{\rho}}\mathrm{S}$$

$$\mathrm{S} = H\left(\frac{\delta P}{\dot{P}} - \frac{\delta\rho}{\dot{\rho}}\right) = \frac{H}{\dot{P}}\left(\delta P - \frac{\dot{P}}{\dot{\rho}}\delta\rho\right) = \frac{H}{\dot{P}}\delta P_{nad}$$

- Can CMB tell if inflation was single or multiple component?

If gravitational wave can be observed.

Can CMB tell anything about type of inflation?

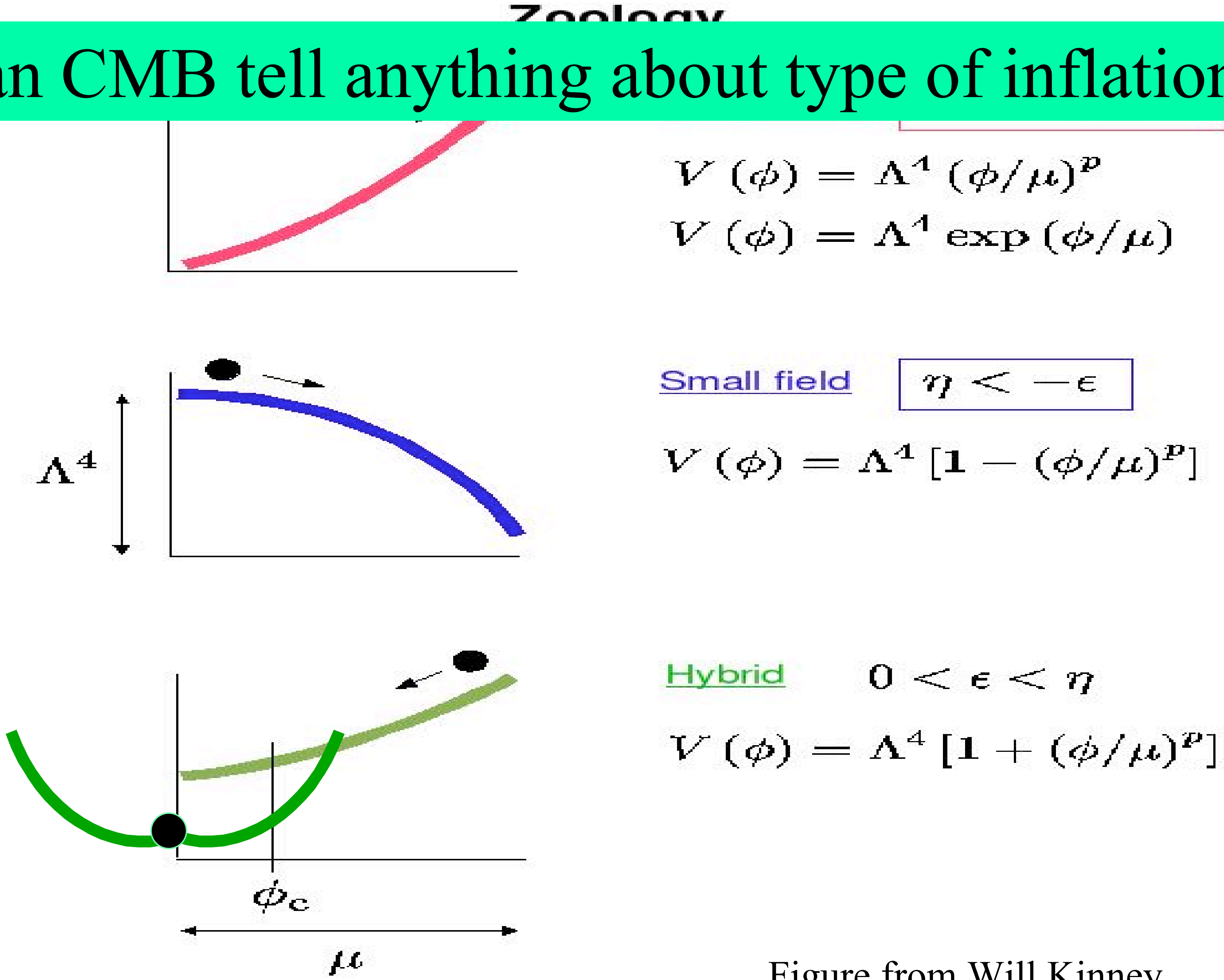
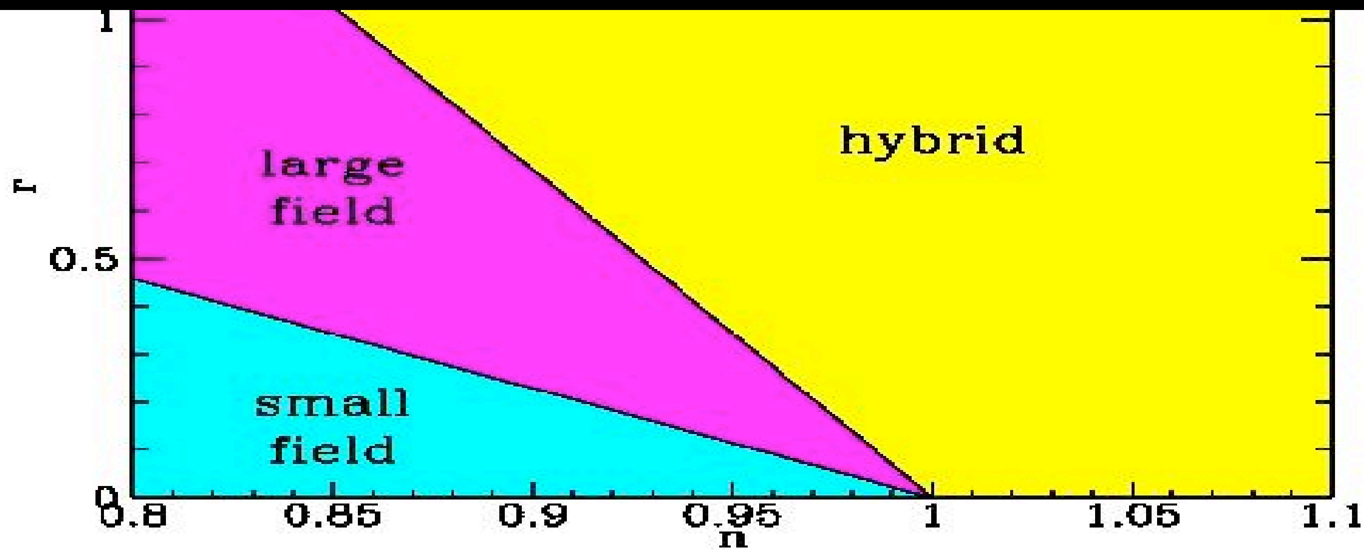


Figure from Will Kinney

Can CMB tell anything about inflation?



- Classes completely cover (r, n) plane

Figure from Scott, Will & Rocky