Testing the Inflationary Picture

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Inflation provides an explanation for the origins of what we see in the universe:

– spatial structures at all scales,
– through a causal mechanism,
– nearly scale-independent perturbations,
– synchronized acoustic oscillations (CMB),
– etc. . . .

But just how far can we trust its theoretical framework ?

How does inflation make stuff?

Inflation relies on just two simple ingredients:

1) a quantum field, $\phi(t,\mathbf{x})$

2) an expanding universe

$$ds^2 = dt^2 - a^2(t)\, d\mathbf{x}\cdot d\mathbf{x}$$

Since a quantum field always fluctuates, the universe must *inevitably* have some spatial variation, or structure,

$$\langle 0(t) \,|\, \phi(t,\mathbf{x})\phi(t,\mathbf{y}) \,|\, 0(t) \rangle \neq 0$$

and the expansion makes tiny stuff big.

Testing our assumptions

~~How does inflation make stuff?~~

Inflation relies on just two simple ingredients:

Quantum Gravity?

1) a quantum field, $\phi(t,\mathbf{x})$

Who ordered this?

2) an expanding universe

$$ds^2 = dt^2 - a^2(t)\, d\mathbf{x}\cdot d\mathbf{x}$$

How did the universe find itself in this metric?

Since a quantum field always fluctuates, the universe must *inevitably* have some spatial variation, or structure,

Which quantum state?

$$\langle 0(t)\,|\,\phi(t,\mathbf{x})\phi(t,\mathbf{y})\,|\,0(t)\rangle \neq 0$$

and the expansion makes tiny stuff big.

It is possible to have <u>too</u> <u>much</u> of a good thing?

Particle physics

1) we know the background (flat space)

2) we know all the relevant ingredients (up to some energy scale)

3) we have a well defined and tested theoretical framework (QFT in flat space)

4) gravity is completely negligible

5) experimentally, we can fiddle, smash, make, and measure anything we want (again, up to some energy scale)

Particle physics versus early-universe cosmology

probably   FRW space-time

1) we know the background (~~flat space~~)

can only guess

2) we ~~know all~~ the relevant ingredients & we do not know the scale
   (up to some energy scale)

un-   QFT in curved space or quantum gravity

3) we have a ~~well~~ defined and tested
   theoretical framework (~~QFT in flat space~~)

essential

4) gravity is completely ~~negligible~~

experimentally: look, but do not touch!

5) ~~experimentally, we can fiddle, smash,~~
   ~~make, and measure anything we want~~
   ~~(again, up to some energy scale)~~

Too much of a good thing?

How much inflation is enough?

– a deliberately crude estimate:

energy now: $T_{\mathrm{CMB}} = 2.73\ \mathrm{K} = 0.24\ \mathrm{meV}$
energy during inflation: $H < 10^{14}\ \mathrm{GeV}$

$$N = \ln \frac{10^{14}\ \mathrm{GeV}}{0.24\ \mathrm{meV}} \approx 61$$

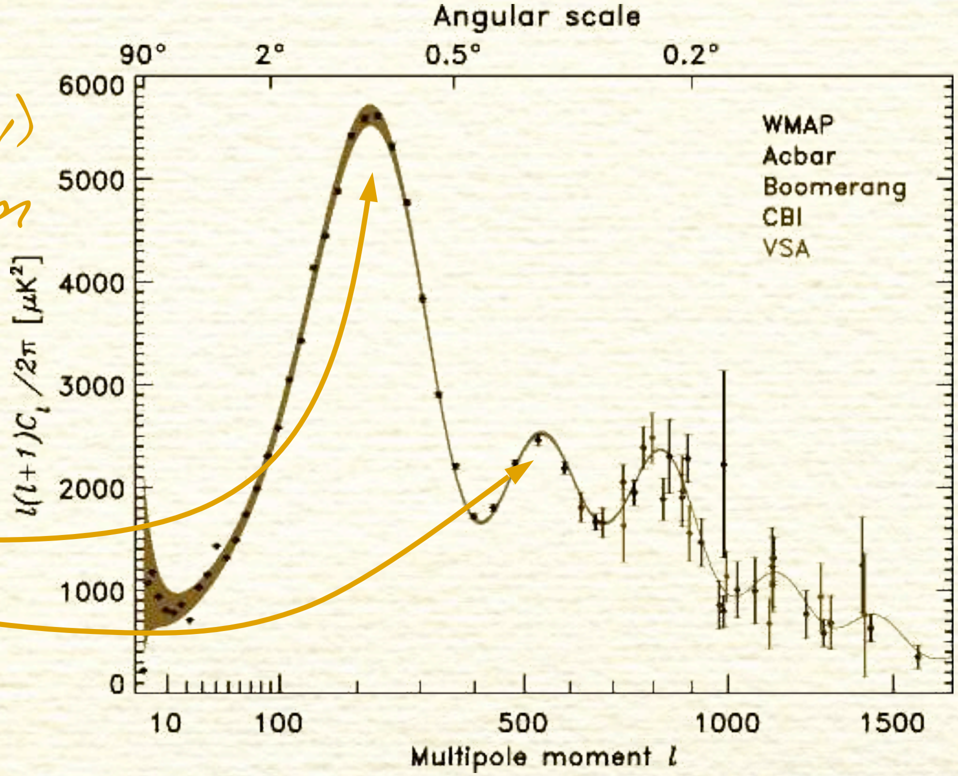
Most inflationary models produce more than this 61 "*e*-folds"

Just a few *e*-folds more, and the fluctuations are occurring in the quantum gravity regime:

$$\ln \frac{10^{19}\ \mathrm{GeV}}{10^{14}\ \mathrm{GeV}} \approx 11.5$$

Trans-Planckian questions

how big (spatially) were the quantum fluctuations originally that eventually made this? or this?



from the WMAP Science team

Do we need to understand "trans-Planckian" physics to explain the CMB?

Is there a mechanism that hides such stuff?

How big are "trans-Planckian" corrections?

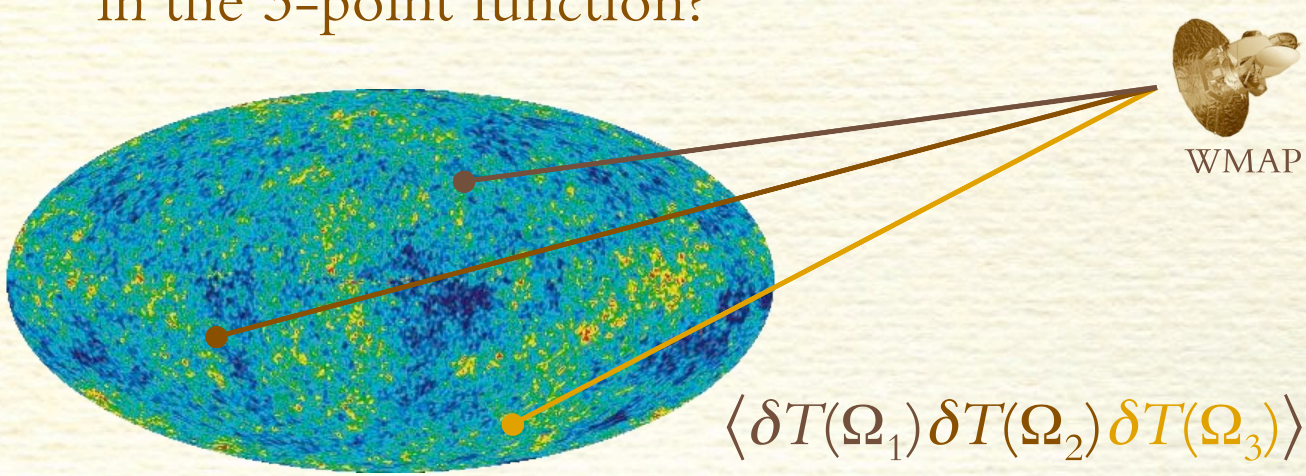
Just the results: non-Gaussianities

(Collins & Holman, appearing soon)

A little case study:

- suppose space-time *does not* look flat beyond the scale M ($< M_{\rm pl} \approx 10^{19}$ GeV)
- use an effective theory treatment (so we do not need a theory of quantum gravity)

How big are these "trans-Planckian" effects in the 3-point function?



$$\langle \delta T(\Omega_1)\,\delta T(\Omega_2)\,\delta T(\Omega_3)\rangle$$

Just the results: non-Gaussianities

(Collins & Holman, appearing soon)

The temperature fluctuations are produced by primoridal fluctuations in the background

The typical size (ignoring spatial dependence) is sometime crudely described by an $f_{\rm nl}$,

$$\langle 0(t) \,|\, \phi(t,\mathbf{x})\phi(t,\mathbf{y})\phi(t,\mathbf{z}) \,|\, 0(t) \rangle \approx \frac{f_{\rm nl}}{\varepsilon^2} \frac{H^4}{M_{\rm pl}{}^4}$$

Under the usual assumptions, $f_{\rm nl} \sim \varepsilon$

But less symmetry beyond the scale M, can lead to a much larger "effective" $f_{\rm nl}$,

$$\frac{M_{\rm pl}}{M} < f_{\rm nl}{}^{\it eff} < \frac{M_{\rm pl}}{H}$$

These signals are *easier* to see than analogous corrections to the power spectrum (2-point)

Collins & Holman, Phys. Rev. D 77, 105016 (2008)

<u>Additionally. . .</u>

For further results on the trans-Planckian problem of inflation,

– power spectrum, scalar-to-tensor ratio, effective-state approach, etc.

www.nbi.dk/~hael/pubs.html

For student-level introductions to

– Inflation and the Primordial Perturbations → ready
– Primordial non-Gaussianities from Inflation → soon
– The trans-Planckian Problem → soon

see

www.nbi.dk/~hael/general.html