Transplanckian masses in inflation

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Unsolved issues in the standard model

• Horizon problem
  Why is the CMB so smooth?

• The flatness problem
  Why is the Universe flat? Why is $\Omega \sim 1$?

• The structure problem
  Where do the fluctuations in the CMB come from?

• The relic problem
  Why aren’t there magnetic monopoles?
Outstanding Problems

- **Why is the CMB so isotropic?**

  - consider matter-only universe:
    - horizon distance $d_H(t) = 3ct$
    - scale factor $a(t) = (t/t_0)^{2/3}$
    - therefore horizon expands faster than the universe
      - “new” objects constantly coming into view
  
  - CMB decouples at $1+z \sim 1000$
    - i.e. $t_{\text{CMB}} = t_0/10^{4.5}$
    - $d_H(t_{\text{CMB}}) = 3ct_0/10^{4.5}$
    - now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
    - but horizon distance now is $3ct_0$
    - so angle subtended on sky by one CMB horizon distance is only $10^{-1.5}$ rad $\sim 2^\circ$
  
  - patches of CMB sky $>2^\circ$ apart should not be causally connected
Outstanding Problems

• **Why is universe so flat?**
  - a multi-component universe satisfies

\[
1 - \Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}
\]

and, neglecting \( \Lambda \),

\[
\left( \frac{H(t)}{H_0} \right)^2 = \frac{\Omega_{r0}}{a^4} + \frac{\Omega_{m0}}{a^3}
\]

- therefore
  - during radiation dominated era \(|1 - \Omega(t)| \propto a^2\)
  - during matter dominated era \(|1 - \Omega(t)| \propto a\)
  - if \(|1 - \Omega_0| < 0.06 \) (WMAP) ... then at CMB emission \(|1 - \Omega| < 0.00006\)
  - we have a fine tuning problem!
Outstanding Problems

- Where is everything coming from?

  Models like CDM nicely explain how the fluctuations we can observe in the CMB grew to form galaxies. They can also reproduce the observed large-scale distribution of galaxies and clusters.

BUT .. why are there fluctuations in the first place?
Outstanding Problems

• Where is everything coming from?
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Outstanding Problems

• The monopole problem
  - big issue in early 1980s
    • Grand Unified Theories of particle physics → at high energies the strong, electromagnetic and weak forces are unified
    • the symmetry between strong and electroweak forces 'breaks' at an energy of \( \sim 10^{15} \text{ GeV} \) \( (T \sim 10^{28} \text{ K}, t \sim 10^{-36} \text{ s}) \)
      - this is a phase transition similar to freezing
      - expect to form 'topological defects' (like defects in crystals)
      - point defects act as magnetic monopoles and have mass \( \sim 10^{15} \text{ GeV}/c^2 \) \( (10^{-12} \text{ kg}) \)
      - expect one per horizon volume at \( t \sim 10^{-36} \text{ s} \), i.e. a number density of \( 10^{82} \text{ m}^{-3} \) at \( 10^{-36} \text{ s} \)
      - result: universe today completely dominated by monopoles (not!)
The concept of inflation

The idea (A. Guth and A. Linde, 1981): Shortly after the Big Bang, the Universe went through a phase of rapid (exponential) expansion. In this phase the energy and thus the dynamics of the Universe was determined by a term similar to the cosmological constant (vacuum energy).

Why would the Universe do that?

Why does it help?
What powers inflation?

• We need \( H_{\text{inf}}(t_{\text{end}} - t_{\text{inf}}) \geq 58 \)
  - if \( t_{\text{end}} \sim 10^{-34} \text{ s} \) and \( t_{\text{inf}} \sim 10^{-36} \text{ s} \), \( H_{\text{inf}} \sim 6 \times 10^{35} \text{ s}^{-1} \)

  - energy density \( \rho_{\Lambda} \sim 6 \times 10^{97} \text{ J m}^{-3} \sim 4 \times 10^{104} \text{ TeV m}^{-3} \)
    • cf. current value of \( \Lambda \sim 10^{-35} \text{ s}^{-2} \), \( \rho_{\Lambda} \sim 10^{-9} \text{ J m}^{-3} \sim 0.004 \text{ TeV m}^{-3} \)

• We also need an equation of state with negative pressure
  \[
  \frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3P)
  \]

  accelerating expansion needs \( P < 0 \)
Inflation with scalar field

- Need potential $U$ with broad nearly flat plateau near $\varphi = 0$
  - metastable false vacuum
  - inflation as $\varphi$ moves very slowly away from 0
  - stops at drop to minimum (true vacuum)
    - decay of inflaton field at this point *reheats* universe, producing photons, quarks etc.
      (but not monopoles - too heavy)
    - equivalent to latent heat of a phase transition
Inflation and particle physics

At very high energies particle physicists expect that all forces will become unified
- this introduces new particles
- some take the form of scalar fields $\phi$ with equation of state

$$
\rho_\phi = \frac{1}{2\hbar c^3} \dot{\phi}^2 + U(\phi)
$$

$$
P_\phi = \frac{1}{2\hbar c^3} \dot{\phi}^2 - U(\phi)
$$

if $\dot{\phi}^2 << 2\hbar c^3 U(\phi)$ this looks like $\Lambda$
... the scalar field turns out to be transplanckian
... the scalar field turns out to be transplanckian

\[
\frac{\Delta \phi}{M_{Pl}} \geq 5.8 \left( \frac{N_e}{50} \right) \left( \frac{r}{0.2} \right)^{1/2}
\]
... the scalar field turns out to be transplanckian

\[ \frac{\Delta \phi}{M_{Pl}} \geq 5.8 \left( \frac{N_e}{50} \right) \left( \frac{r}{0.2} \right)^{1/2} \]

but the field is a "dummy" variable... it is just a field redefinition away from being subplanckian.
A field redefinition to turn the field subplanckian may end up shedding light on the shape of gravity close to the Planck scale
\[ S = - \int d^4x \sqrt{-g} \left[ \frac{k^2}{4} D(\theta) R - \frac{1}{2} g^{\mu\nu} \partial_\mu \theta \partial_\nu \theta + V(\theta) \right] \]
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\[ D(\theta) \ H^2 = \frac{\dot{\theta}^2}{3k^2} + \frac{2V(\theta)}{3k^2} - \dot{D}(\theta) \ H \]

\[ \ddot{\theta} + 3H \dot{\theta} + \frac{k^2}{4} \ D'(\theta) \ R + V'(\theta) = 0 \]
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\[ \tilde{H} = \frac{H + \dot{D}(\theta)/(2D(\theta))}{\sqrt{D(\theta)}} \]
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\[ \phi(\theta) = \pm \int \sqrt{\frac{3}{2} \left( \frac{D'(\theta)}{D(\theta)} \right)^2 + \frac{2}{k^2 D(\theta)}} \ d\theta \]
Non-minimal coupling to gravity

\[ D(\theta) = \left( 1 - \frac{\theta^2}{3k^2} \right) \]
Non-minimal coupling to gravity

\[ D(\theta) = (1 - \theta^2/(3k^2)) \]

\[ \phi(\theta) = 2\sqrt{6\pi} \, k \circ \text{arctanh} \left[ \frac{\theta}{\sqrt{3} \, k} \right] \]

\[ \theta(\phi) = \sqrt{3} \, k \circ \text{tanh} \left[ \frac{\phi}{2\sqrt{6\pi} \, k} \right] \]
Generic scalar-tensor theories

\[ a = \exp (-\theta / b) \]
Generic scalar-tensor theories

\[ a = \exp \left( -\frac{\theta}{b} \right) \quad H = \frac{\dot{a}}{a} = -\frac{\dot{\theta}}{b} \]

\[ N_e = \int H \, dt = - \int \frac{\dot{\theta}}{b} \, dt = -\frac{1}{b} \int d\theta = \frac{1}{b} (\theta_i - \theta_f) \sim \frac{\theta_i}{b} \]

\[ \frac{H'}{H} = \frac{2b/k^2 + bD'' + D'}{2D - bD'} \]
f(R) gravity
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\[ f(R) = R \left(1 + \left(\frac{R}{M^2}\right)^{5/4}\right) \]
\[ f(R) = R \left( 1 + \left( \frac{R}{M^2} \right)^{5/4} \right) \]

\[ F(R) = \exp \left( \sqrt{\frac{2}{3}} \phi \right) \]
f(R) gravity
Conclusions

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Maybe transplanckian values are telling us that it is gravity and not the inflation self-couplings the true driver of inflation.