Inflation from Phase Transitions in Scalar-Tensor theories and an Approach to the Hierarchy Problem

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[1] In collaboration with Fabrizio Di Marco Tirthabir Biswas And work in progress with R. Catena.

Outline

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Standard slow-roll Inflation

- Let us consider

$$S = \int d^4x \sqrt{-g} \left(\mathcal{L}_G + \mathcal{L}_M\right)$$

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  where Gravity and Matter are only (universally) coupled through $\sqrt{-g}$.

- Standard Inflation: flat potential in $\mathcal{L}_M$, and coupling to SM.

- But: naturally expect steep potentials or metastable vacua.

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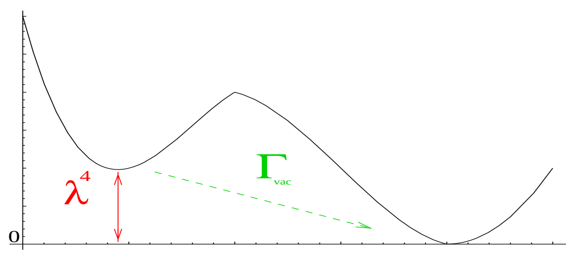

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Way-out:

- Start with $\Gamma_{vac} \ll H^4$
- And then $\Gamma_{vac} \simeq H^4$

Modifying $\mathcal{L}_G$...

- Make H variable modifying $\mathcal{L}_{\mathcal{G}}$

[2] C. Mathiazhagan and V. B. Johri, Class. Quant. Grav. **1**, L29 (1984)

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- But EI had a prediction ($n_S \lesssim 0.8$) ...and in 1992, COBE ruled it out. [4]

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Our basic idea

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$$S_G = \int d^4x \sqrt{-g}\left[\frac{1}{2}M^2 R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \beta\phi^2 R\right]$$

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- The non-minimal coupling β is generically present.

- $\mathcal{L}_M$ has a false vacuum, with $\lambda \ll M$ (classical gravity justified)

- Assume U negligible in the Early Universe.

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Early Time Evolution

$$\boxed{S = \int d^4x \sqrt{-g}\left[\frac{1}{2}M^2 R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\beta\phi^2 R - \lambda^4\right]},$$

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4. $H \propto \frac{1}{t}$ and when $H = \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit.

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We assume at $t = 0$:

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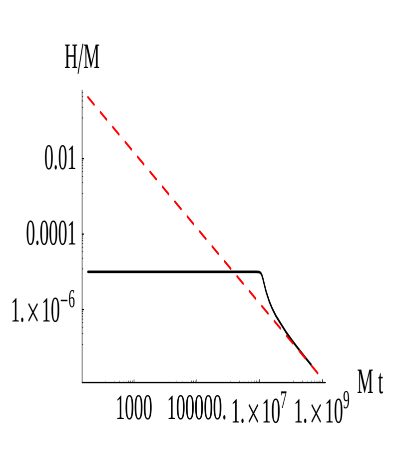

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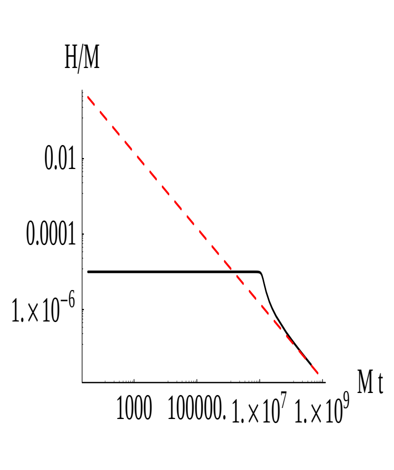

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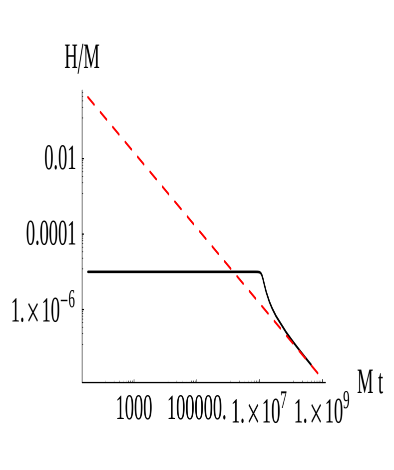

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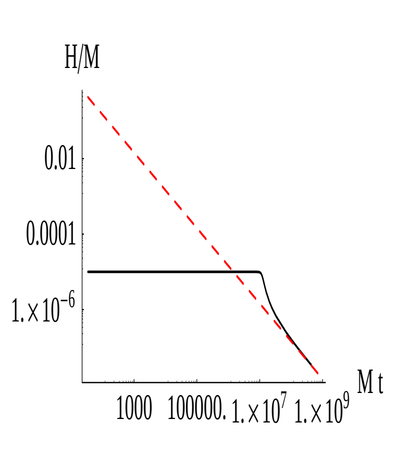

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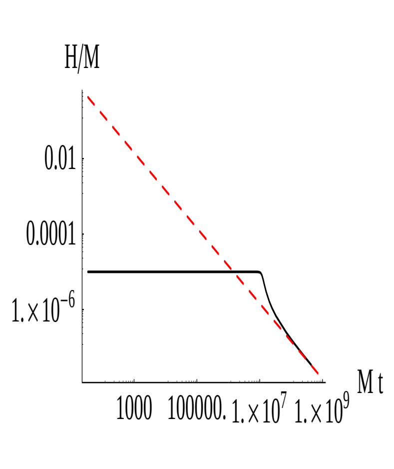

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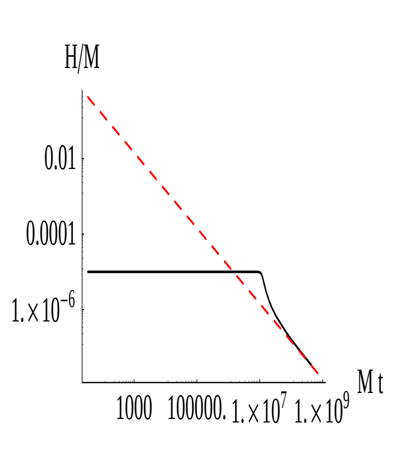

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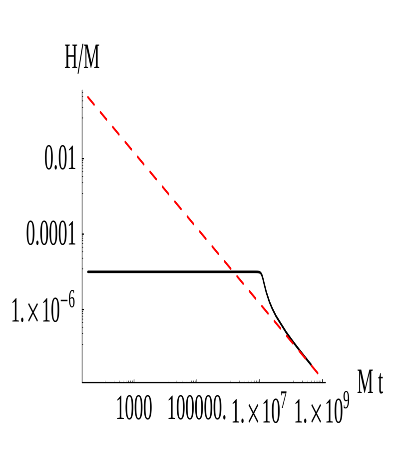

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- *Phase I*: Perturbations that we see
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- When $H \simeq \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit
- No Large Bubbles if $\Gamma_{vac} \lesssim 10^{-7} H_I^4$

Difference with Extended Inflation

- EI had almost the same Lagrangian:

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- Therefore only the power-law phase present

- H has to decrease fast to avoid early production of Large Bubbles ($n_S \lesssim 0.8$)

- COBE ruled it out

Outline

Transition to radiation and Stabilization

- When $H^4 \simeq \Gamma_{vac}$ many bubbles of true vacuum are nucleated
- They collide producing radiation, with T_{RH} given by

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- During radiation ϕ slows down:

$$R = 6(2H^2 + \dot{H}) \approx 0\,.$$

Stabilization of ϕ

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  - variation of G_N during matter domination.

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- Nonetheless we need to stabilize ϕ at late times:
  - 5^{th} force constraints
  - variation of G_N during matter domination.
- There might be different ways to avoid this problem....
- ...Reintroduce the potential $U(\phi)$ in the original Lagrangian
- Assumed to be irrelevant before ($U \lesssim \lambda^4$).

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- Or chameleon-like and higher derivatives $U(\phi, \partial\phi)$ ...(*work in progress*)

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- This means that the full theory has operators like

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- They become important at $\phi \gg M$
- Is this good or bad?

Old Inflation and Hierarchy

Generalizing the Lagrangian

- We generalize as

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M^2 f(\phi) R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \lambda^4 \right]$$

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  or $f(\phi) \simeq 1 + \beta\frac{\phi^n}{M^n}$ $(n > 2)$
- For $\phi \gg M$ assume $f(\phi) > \frac{\phi^2}{M^2}$
- The transition is strong enough (decelerated expansion), independently on the exact form of $f(\phi)$!
- Without knowing exactly $f(\phi)$ (or in other words...an infinite number of couplings)!

Outline

1. Motivation
   - Inflation from a False Vacuum
   - After Inflation
   - A closer look at the Lagrangian
   - Dynamics
2. Hierarchy Problem
   - Our approach
3. Cosmology Constraints
   - Quadratic case
   - Higher power
4. Experimental signatures
   - GW at LISA
   - Particle Physics

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- and the false vacuum energy, in this frame

$$-S_{vac} = \int d^4x \, \sqrt{-\bar{g}} \frac{\lambda^4}{f^2(\phi)} \equiv \int d^4x \sqrt{\bar{g}} \, \bar{V}(\phi) \, .$$

becomes a potential (but it disappears at decay!)

Power-law expansion

- If the kinetic term is made canonical, the potential becomes, for $\phi \gg M$

$$\bar{V}(\Phi) = \lambda^4 \exp\left(-2\sqrt{\frac{2}{3}}\frac{\Phi}{M}\right) .$$

- The exponential potential is well-known to lead to power-law expansion

$$\bar{a} \sim \bar{t}^p \quad \text{with} \quad p = \frac{3}{4} .$$

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- Our model can provide a large M_{Pl} at late time
- We can get the Hierarchy of 10^{-15} after inflation

gravity stronger at early time and very weak today
(it goes back to Dirac '38)

Explaining a large M_{Pl}

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- We have a large hierarchy if $\Gamma_{vac}^{1/4} \ll M_{EW}$: but this is not fine tuning

Flat spectrum of ϕ fluctuations

- We consider fluctuations in the field ϕ that ends inflation.
- Fastest way: in the Einstein frame (we have checked both): just look at the slow-roll parameters.
- Use:

$$\begin{cases} n_S - 1 = 2\eta - 6\epsilon \\ A^2 = \left(\frac{\bar{H}_I}{M}\right)^2 \frac{1}{8\pi^2\epsilon}\Big|_{\phi=\phi(\bar{N}\approx\bar{N}_{3000h^{-1}Mpc})} \end{cases}$$

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- The amplitude (10^{-5}) requires $\lambda \simeq 3 \times 10^{-3} M$
- As in other models of Inflation (slow-roll) we have also tensor perturbations during the exponential phase.
- For $\beta \simeq 6 \times 10^{-3} \Rightarrow \frac{P_T}{P_S} \simeq 0.25$ Detectable soon

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$$n_S \simeq 1 + 2\eta \simeq 1 - \frac{2}{\mathcal{N}_{3000h^{-1}\mathrm{Mpc}}}\left(\frac{n-1}{n-2}\right) = 0.956 - \frac{0.043}{n-2}$$

- For large n: $n_S \simeq 0.95$! (central value by WMAP)

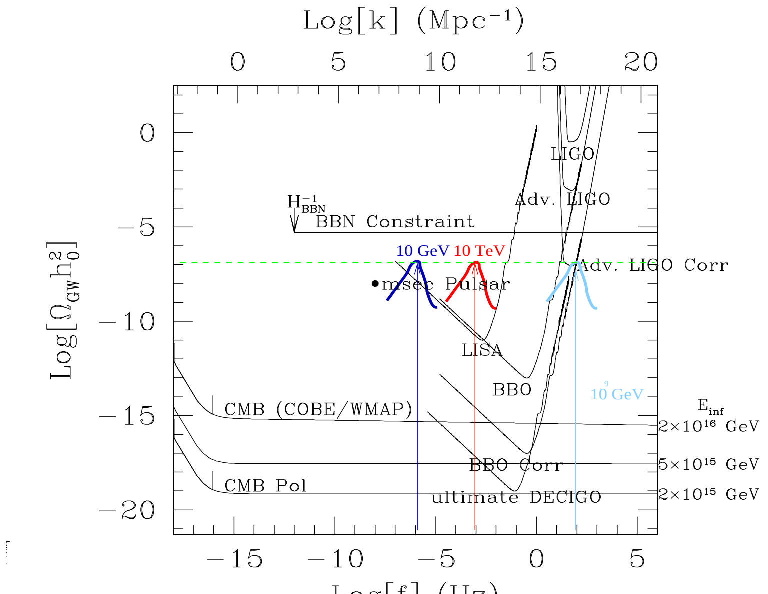
Outline

Gravity waves at LISA

- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves (GW)[6] peaked at horizon scale (set by $T_{RH} \simeq \lambda$)

[6] M. S. Turner and F. Wilczek, A. Kosowsky, R. Watkins, M. Kamionkowski (1990-1995).

GW detectors



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- And this scale can be related to a scale eventually detected by LISA (it is reheating scale).
- Combination of very different observations:

$$\left\{ \begin{array}{l} \text{Gravity waves (LISA)} \\ \text{Particle physics (LHC)} \\ \text{Spectral index and } P_T/P_S \text{ (WMAP, Planck)} \end{array} \right.$$

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- In the case with higher power we have predicted $n_S \simeq 0.95$
- We propose a new way to address the Hierarchy problem (with cutoff at the TeV scale)

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- We provide inflation from a 1^{st} order phase transition in $\mathcal{L}_M$
- In the quadratic case we provide the correct slightly red spectrum of perturbations (with $\beta \approx 6 \times 10^{-3}$ and $\lambda/M \approx 3 \times 10^{-3}$), and we predict $P_T/P_S \simeq 0.25$.
- In the case with higher power we have predicted $n_S \simeq 0.95$
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- Trying to incorporate dynamical screening of Cosmological Constant (Dolgov & Urban, '08)

...THE END!

ADDITIONAL SLIDES

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Work in progress (with S. Alexander, T. Biswas, N. Okada)

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- Specify the Particle Physics side (LHC?)

Additional phenomenology

- Baryogenesis? (TeV scale reheating with Bubble collisions...what happens to EW baryogenesis?)

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- More accurate calculation of the GW spectrum (usual assumption $\Gamma \gg H$, we have just $\Gamma \geq H$).

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- The same can be done for any tiny (or huge) quantity

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- and its growing solution is:

$$\phi(t) = \phi_0 e^{(\epsilon H_I t)/2}$$

where

$$\epsilon \equiv 3\left(-1 + \sqrt{1 + \frac{16}{3}\beta}\right) \qquad (\epsilon \simeq 8\beta \text{ for small } \beta)\,.$$

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- Solution:

$$a(t) \sim t^{\alpha}\,, \qquad \phi(t) \sim Bt\,,$$

where:

$$\alpha \equiv \frac{1+2\beta}{4\beta}\,, \qquad B \equiv \frac{4\sqrt{\beta}\lambda^2}{\sqrt{60\beta^2 + 28\beta + 3}}\,.$$