False Vacuum Inflation

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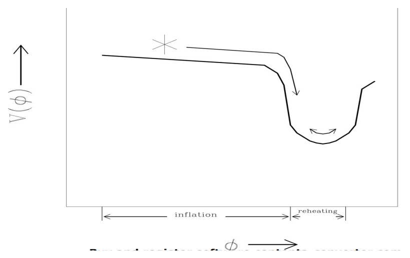
Outline

Slow-roll



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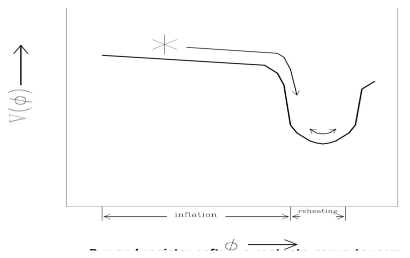

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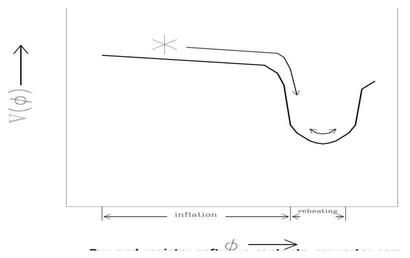

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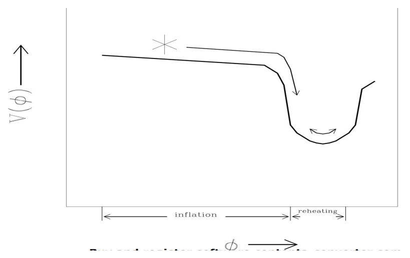

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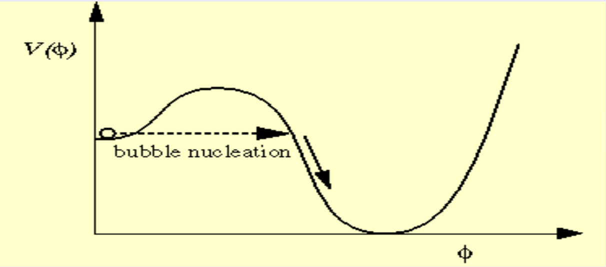
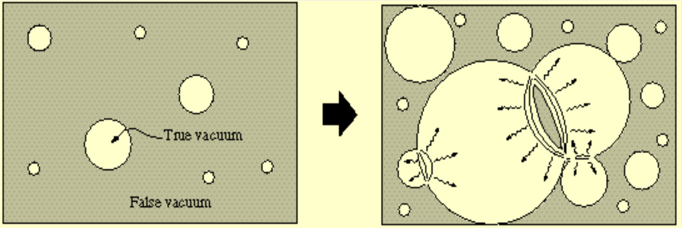
- ...It was the first way to introduce Inflation ("Old" Inflation, Guth, 1982).
- Old Inflation does not have Graceful Exit: non-successful Bubble Nucleation

Nucleation of Bubbles





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Way-out:

- Start with $\Gamma \ll H^4$
- And then $\Gamma \simeq H^4$

Get a Graceful exit

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- Need additional degree of freedom ϕ to set time dependence in Γ/H^4

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If a field χ is trapped in a false vacuum:

- Need additional degree of freedom ϕ to set time dependence in Γ/H^4
- Extra Scalar ϕ
- Two possibilities
  - Make H variable (couple ϕ to gravity)
  - Make Γ variable (couple ϕ to χ)

Variable H

- If H decreases with time
- At some point $\Gamma^{1/4} = H$

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

Adding a Non-Minimally coupled scalar field (ϕ)

$\Rightarrow$ Graceful exit

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False Vacuum Inflation, or *First order* Inflation, similar to *"Extended Inflation"*

F.Di Marco & A.N., Phys.Rev.D '05,
T. Biswas & A.N. Phys.Rev.D '06

In the context of Higgs potential:

I. Masina & A.N., Phys.Rev. D85 (2012); I. Masina & A.N., Phys.Rev.Lett. 108 (2012); A.N., Phys.Rev. D91 (2015)

An initial Lagrangian

- As a starting point we take the action
$$S_1 = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - f(\phi)R + V(\chi_0)\right]$$

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$$f(\phi) = M^2 + \beta\phi^2 + \gamma_4\frac{\phi^4}{M^2} + \gamma_6\frac{\phi^6}{M^4} + \ldots$$

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- Two cases: β dominant or γ_n dominant
- Assume $U(\phi)$ to be negligible ($U \lesssim \Lambda^4$) during Inflation (..but important later)

Early Time Evolution

$$S_1 = \int d^4x \sqrt{-g} \left[\frac{1}{2} M^2 R + \frac{1}{2} \gamma \frac{\phi^n}{M^{n-2}} R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \Lambda^4 \right] ,$$

where $\gamma > 0$, $n > 2$.

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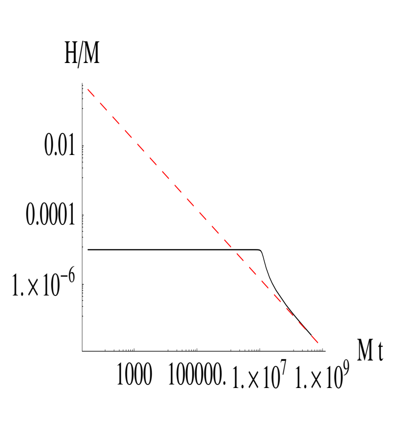
4. $H \propto \frac{1}{t}$ and when $H = \Gamma^{1/4} \Rightarrow$ Graceful Exit.

Evolution of H



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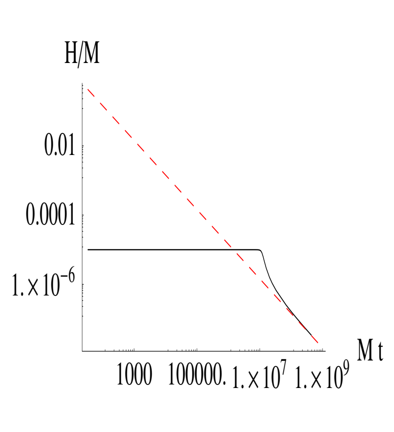

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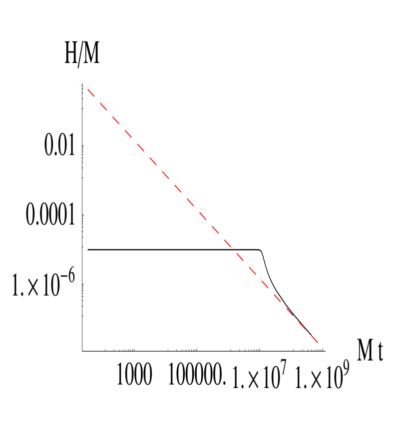

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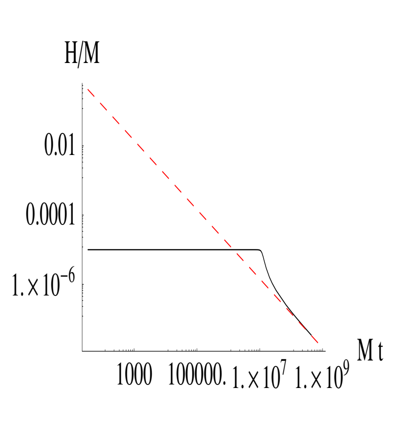

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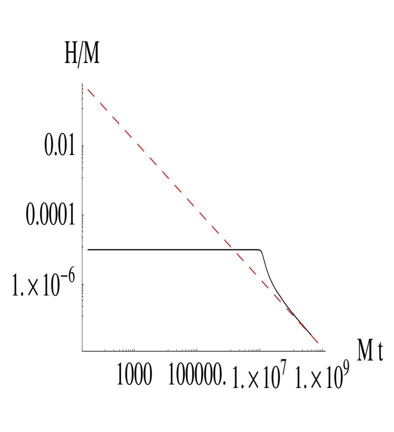

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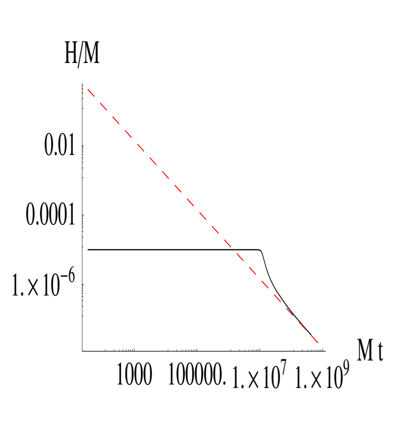

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Difference with “Extended Inflation" (Mathiazhagan, C. and Johri, V. B. , CQG, 1984, "La, D. and Steinhardt, P., PRL,1989": only $\beta\phi^2$. Steinhardt, P. and Accetta F., PRL,1990": used $M = 0$.

General Lagrangian

- If we regard M as the fundamental scale of the theory
- The full theory has operators like

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- Without knowing exactly $f(\phi)$ (...an infinite number of couplings)!

Outline

1. Model
   - Einstein frame

2. Post-Inflation
   - Gravitational Waves

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and the false vacuum energy, in this frame

$$-S_0 = \int d^4x \, \sqrt{-\bar{g}} \frac{\Lambda^4}{f^2(\phi)} \equiv \int d^4x \sqrt{\bar{g}} \, \bar{V}(\chi_0, \phi) \,.$$

becomes a potential (but it disappears after tunneling)

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- Therefore:

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- it looks like slow roll on top of a hill

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- When ϕ of order M: end of slow-roll

Phase II: $\phi \gg M$

- In this phase:

$$K(\phi) \equiv \frac{2f(\phi) + 3M^2 f'^2(\phi)}{2f^2(\phi)} \approx \frac{3M^2}{2}\left(\frac{f'}{f}\right)^2 , \qquad \bar{V}(\phi) \approx \frac{\Lambda^4}{f(\phi)^2} .$$

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$$\Phi \equiv \sqrt{\frac{3}{2}} M \ln f(\phi) ,$$

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- The kinetic term is canonical and the potential becomes:

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

Phase II: $\phi \gg M$

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- $\Longrightarrow$ the final field value ϕ_F is given by:

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- M_{Pl} at the end of Inflation can be huge if $\bar{\Gamma}_{vac}$ tiny: $M_{Pl}^2/M^2 = f(\phi) \gg 1$.
- Can address the Hierarchy problem! *(if ϕ stabilized at ϕ_F)*

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- They collide producing a nearly homogeneous field χ_{out} + radiation
- χ rolls down, produces more radiation and relaxes to true minimum
- During radiation ϕ slows down:

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

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- ...We can reintroduce the potential $U(\phi)$ in the original Lagrangian
- Assumed to be irrelevant before ($U \lesssim \Lambda^4$).
- A potential which drives ϕ to a minimum is good
  - Maybe $\phi \to 0$? ($U(\phi) \propto \phi^n$, with large n)

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Stabilization of ϕ

- Nonetheless we need to stabilize ϕ at late times:
  - variation of G_N during matter domination.
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- Screening mechanisms?

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- In Einstein frame there is a potential $\Rightarrow$ almost flat spectrum

$$\bar{V} \approx \Lambda^4 \left[1 - 2\gamma \left(\frac{\phi}{M} \right)^n \right] .$$

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

Parameter values (quadratic term absent)

- Predicted spectral index:

$$n_S \simeq 1 + 2\eta \simeq 1 - \frac{2}{\bar{\mathcal{N}}_{3000h^{-1}\mathrm{Mpc}}} \left(\frac{n-1}{n-2}\right) = 0.95 - \frac{0.04}{n-2}$$

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- For large n: $n_S \simeq 0.94 - 0.95$ (close to measured central value)

T.Biswas & A.N., PRD '05.

Outline

Gravity waves

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

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Amplitude of Gravity waves

- $$\boxed{\Omega_{GW} \approx \Omega_{CMB} \left(\frac{H_*}{\beta}\right)^2 f^2}$$

[2] A. Kosowsky, M. S. Turner , R. Watkins 1992, A. Kosowsky, M. S. Turner 1993.

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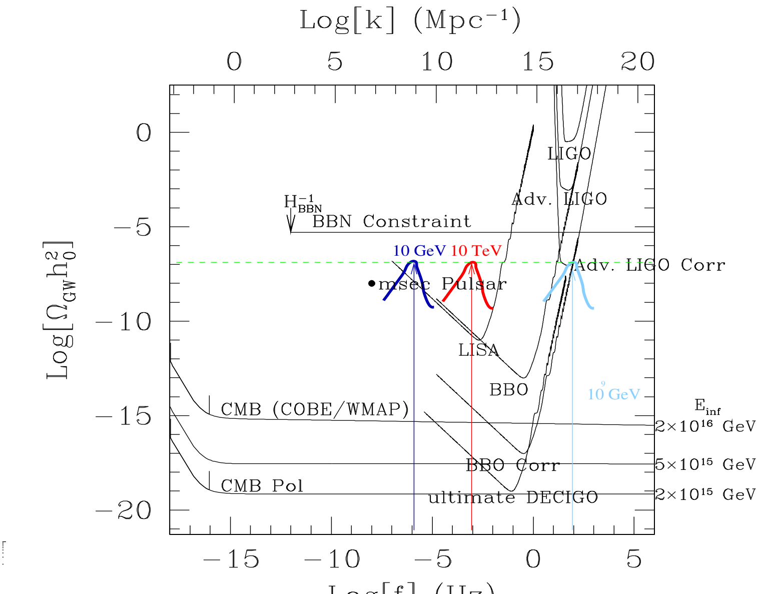
$$\begin{cases} \text{Expected value at peak} & \Omega_{GW} h^2 \approx 10^{-7} \\ \text{LIGO bound} & \Omega_{GW} h^2 \lesssim \mathcal{O}(10^{-6}) \\ \text{aLIGO sensitivity} & \Omega_{GW} h^2 \approx 10^{-9} \\ \text{LISA sensitivity} & \Omega_{GW} h^2 \approx 10^{-11} - 10^{-12} \end{cases}$$

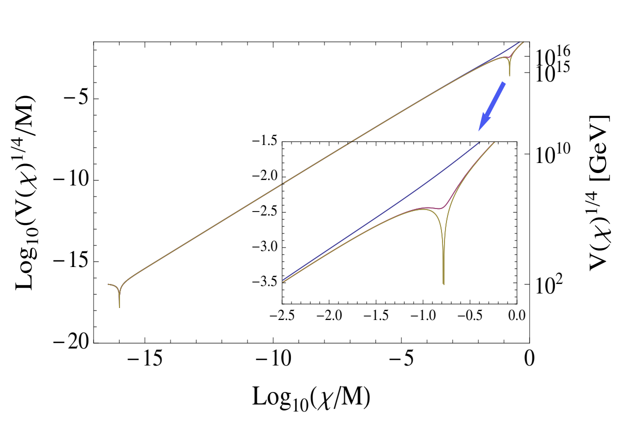
- * Assuming all energy converted into bubbles

[2] A. Kosowsky, M. S. Turner , R. Watkins 1992, A. Kosowsky, M. S. Turner 1993.

GW detectors



Higgs False Vacuum Inflation



- $m_H = 125.2, 125.158, 125.157663$ GeV, $m_t = 171.8$ GeV

I. Masina & A.N., Phys.Rev. D85 (2012); I. Masina & A.N., Phys.Rev.Lett. 108 (2012); A.N., Phys.Rev. D91 (2015)

Primordial Black Holes?

- Bubbles produce $\mathcal{O}(1)$ density fluctuations on scales close to H^{-1}
- Convert into black holes [3]
- If Energy scale $> 10^8 GeV$ such Back Holes evaporate

[3] S.Hsu, Phys.Lett.B, 1990