Title: A Graceful Exit for Old Inflation and a Solution to the Hierarchy Problem

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Abstract:

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A Graceful Exit for Old Inflation and a Solution to the Hierarchy Problem

Alessio Notari 1

McGill University, Montréal

Feb. 7th 2006 / Seminar @ Perimeter Institute

¹In collaboration with

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- Motivation
 - Inflation from a False Vacuum
- Our proposal
 - Basic idea
 - After Inflation
 - The Lagrangian
 - Dynamics
- 3 Hierarchy Problem
 - A new proposal
- Cosmology Constraints
 - Sufficient Inflation
 - Cosmological Perturbations
- Experimental signatures
 - GW at LISA
 - Particle Physics

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Which vacuum?

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 In Standard Cosmology the Universe is (almost) in a zero-energy vacuum state.

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- In Standard Cosmology the Universe is (almost) in a zero-energy vacuum state.
- Why?
- Is it possible that the Universe started in another vacuum and then tunneled to the zero-energy state? (through Bubble Nucleation)

Which vacuum?

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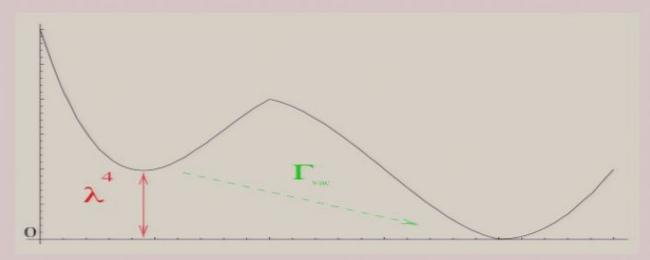
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- And, in fact, this was the first way to introduce Inflation ("Old" Inflation, Guth, 1982).
- Old Inflation does not have Graceful Exit: non-successful Bubble Nucleation
 ⇒ need for Slow-Roll inflation.

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- And, in fact, this was the first way to introduce Inflation ("Old" Inflation, Guth, 1982).
- Old Inflation does not have Graceful Exit: non-successful Bubble Nucleation
 ⇒ need for Slow-Roll inflation.
- Go back to Old Inflation, no flat potentials.

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Requirements:

• For sufficient inflation $\Gamma_{vac} \ll H^4$

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Requirements:

- For sufficient inflation $\Gamma_{vac} \ll H^4$
- For a successful transition to radiation (nucleation and collision of many bubbles) Γ_{vac} ≃ H⁴

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Requirements:

- For sufficient inflation $\Gamma_{vac} \ll H^4$
- For a successful transition to radiation (nucleation and collision of many bubbles) Γ_{vac} ≃ H⁴
- In Old Inflation either Inflation too short or Inflation never ends.

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Requirements:

- For sufficient inflation $\Gamma_{vac} \ll H^4$
- For a successful transition to radiation (nucleation and collision of many bubbles) $\Gamma_{vac} \simeq H^4$
- In Old Inflation either Inflation too short or Inflation never ends.

Way-out:

- Start with $\Gamma_{vac} \ll H^4$
- And then Γ_{vac} ~ H⁴

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One possibility: make H variable

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

³D. La and P. J. Steinhardt, Phys. Rev. Lett. **62**, 376 (1989)

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- Many other models, quite complicated, were proposed to cure the problem.

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- One possibility: make H variable
- The first models in this spirit were proposed in 1984² and in 1989: "Extended Inflation" ³.
- But EI had a prediction (n_S ≤ 0.8) ...and in 1992,
 COBE ruled it out. 4
- Many other models, quite complicated, were proposed to cure the problem.
- Our model is still as simple as original El and viable.

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In the presence of a Non-Minimally coupled scalar field (ϕ) the transition becomes viable.

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As a starting point we take the action⁵:

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

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we assume $\beta > 0$.

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 The non-minimal coupling is usually set to zero for simplicity...

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- The non-minimal coupling is usually set to zero for simplicity...
- But it is generically present.

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we assume $\beta > 0$.

- The non-minimal coupling is usually set to zero for simplicity...
- But it is generically present.
- Assume $U(\phi)$ to be negligible before tunneling $(U \leq \lambda^4)$.

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1. Start with $\sqrt{\beta}\phi \ll M \Rightarrow$ Exponential Inflation:

$$H_I^2 = \frac{\lambda^4}{3M^2}$$

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1. Start with $\sqrt{\beta}\phi \ll M \Rightarrow$ Exponential Inflation:

$$H_I^2 = \frac{\lambda^4}{3M^2}$$

2. ϕ grows due to the effective "mass" term $\beta \phi^2 R$.

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- 2. ϕ grows due to the effective "mass" term $\beta \phi^2 R$.
- 3. When $\sqrt{\beta}\phi \simeq M$ transition to power-law expansion.
- 4. $H \propto \frac{1}{t}$ and when $H = \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit.

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Friedmann equation:

$$H^2 = \frac{1}{3(M^2 + \beta\phi^2)} \left[\frac{1}{2} \dot{\phi}^2 - 6H\beta\phi\dot{\phi} + \lambda^4 \right] ,$$

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 \bullet ϕ equation:

$$\ddot{\phi} + 3H\dot{\phi} - \beta R\phi = 0.$$

 Assume that the field φ sits close to zero at the beginning:

$$H^2 \simeq H_I^2 \equiv \frac{\lambda^4}{3M^2}$$
.

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$$\Rightarrow R = 12H_1^2$$

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• The equation of motion for ϕ becomes:

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• The equation of motion for ϕ becomes:

$$\ddot{\phi} + 3H_I\dot{\phi} - 12H_I^2\beta\phi = 0\,,$$

and its growing solution is:

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

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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- We assume at t = 0:
 - ϕ_0 small
 - Minimal value given by quantum fluctuations: $\mathcal{O}(H_l)$.

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- Possible justifications:

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 - This seems the most natural choice

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- Minimal value given by quantum fluctuations: $\mathcal{O}(H_l)$.
- Possible justifications:
 - This seems the most natural choice
 - Or: starting from a random distribution,

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 - Minimal value given by quantum fluctuations: $\mathcal{O}(H_l)$.
- Possible justifications:
 - This seems the most natural choice
 - Or: starting from a random distribution, regions with small ϕ_0 inflate more
 - ⇒ they overwhelm the Universe.

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• For late time $(\sqrt{\beta}\phi \gg M)$:

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• For late time $(\sqrt{\beta}\phi \gg M)$:

$$H^2 = \frac{1}{3\beta\phi^2} \left[\frac{1}{2} \dot{\phi}^2 - 6H\beta\phi\dot{\phi} + \lambda^4 \right] ,$$

$$\ddot{\phi} + 3H\dot{\phi} - 6\beta(2H^2 + \dot{H})\phi = 0$$
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• For late time $(\sqrt{\beta}\phi \gg M)$:

$$H^2 = \frac{1}{3\beta\phi^2} \left[\frac{1}{2} \dot{\phi}^2 - 6H\beta\phi\dot{\phi} + \lambda^4 \right] \,, \label{eq:H2}$$

$$\ddot{\phi} + 3H\dot{\phi} - 6\beta(2H^2 + \dot{H})\phi = 0.$$

Solution:

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

$$\phi(t) \sim Bt$$
,

where:

$$\alpha \equiv \frac{1 + 2\beta}{4\beta} \,,$$

$$B\equiv rac{4\sqrt{eta}\lambda^2}{\sqrt{60eta^2+28eta+3}^{Page 49/196}}.$$

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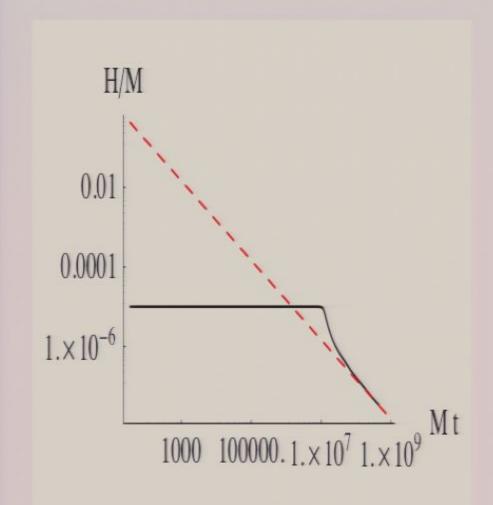
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$$(\beta = 1/56)$$

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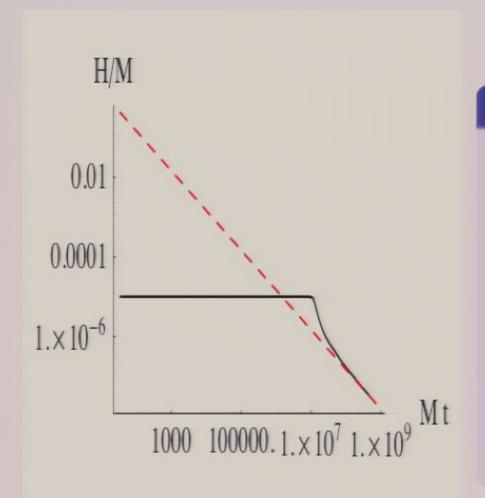
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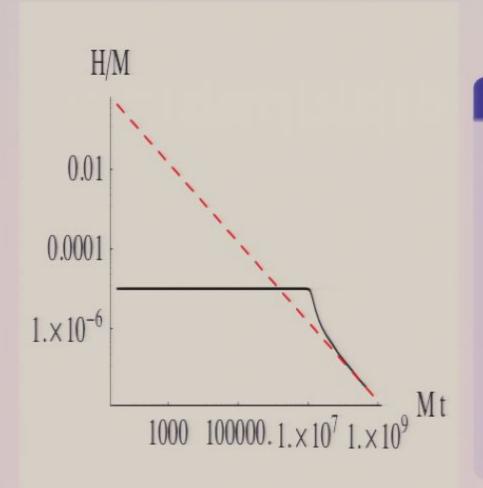
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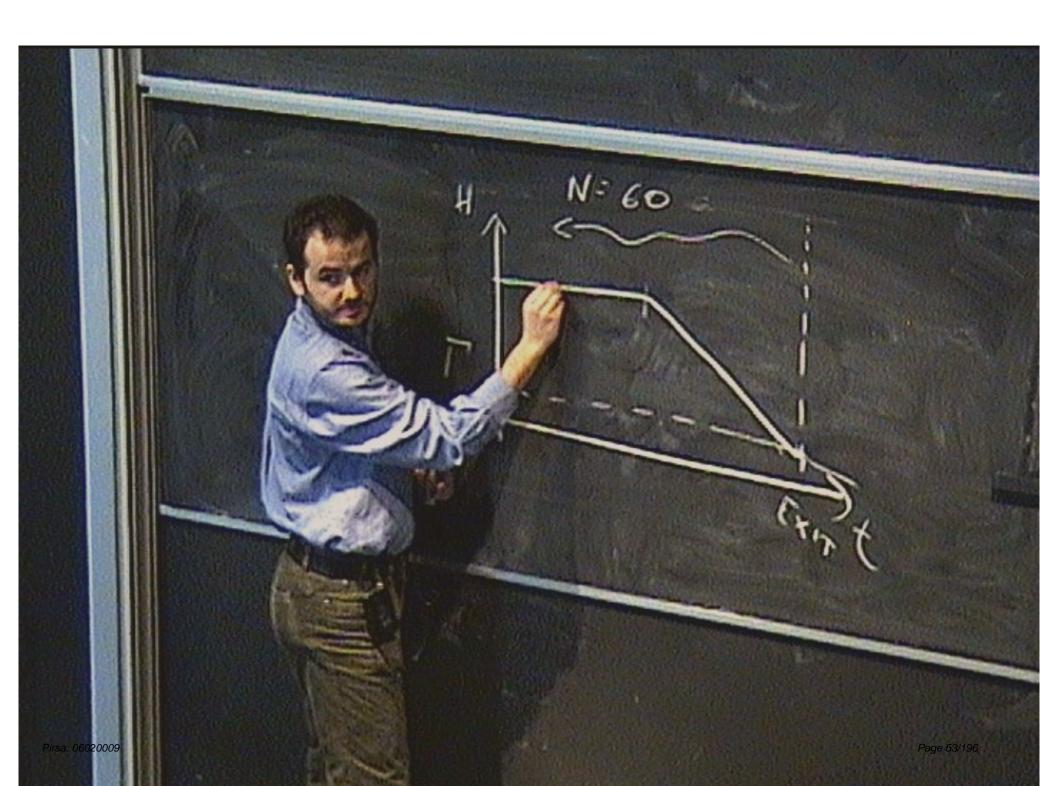
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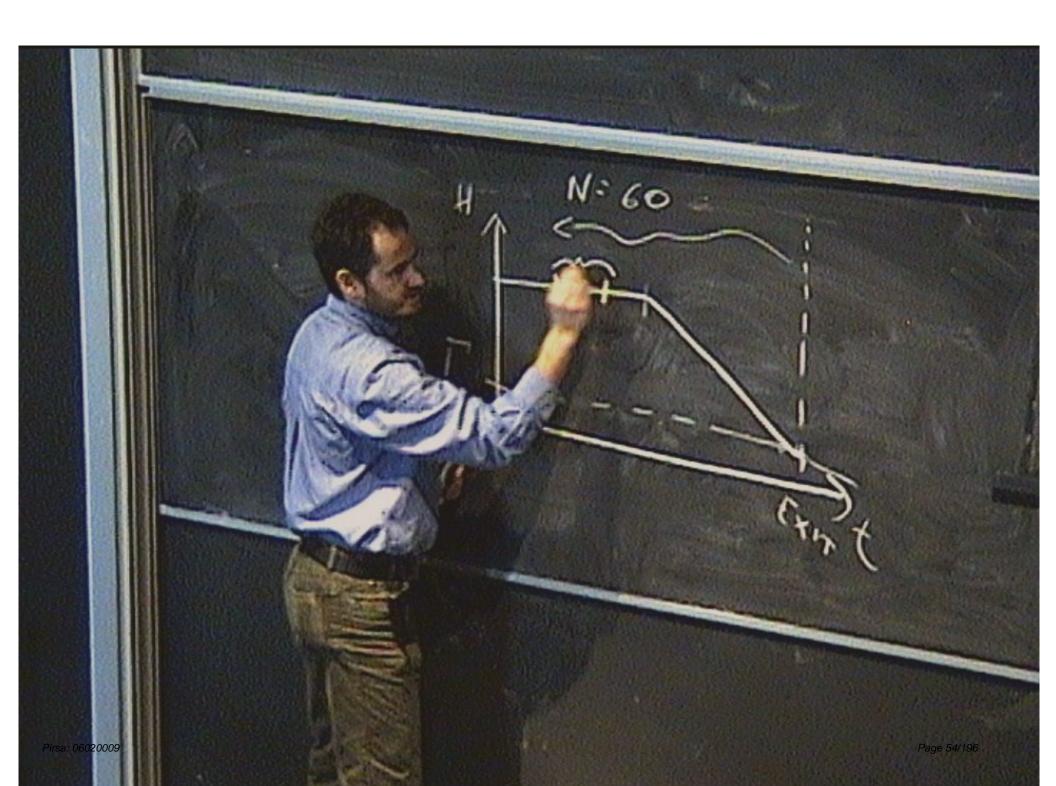


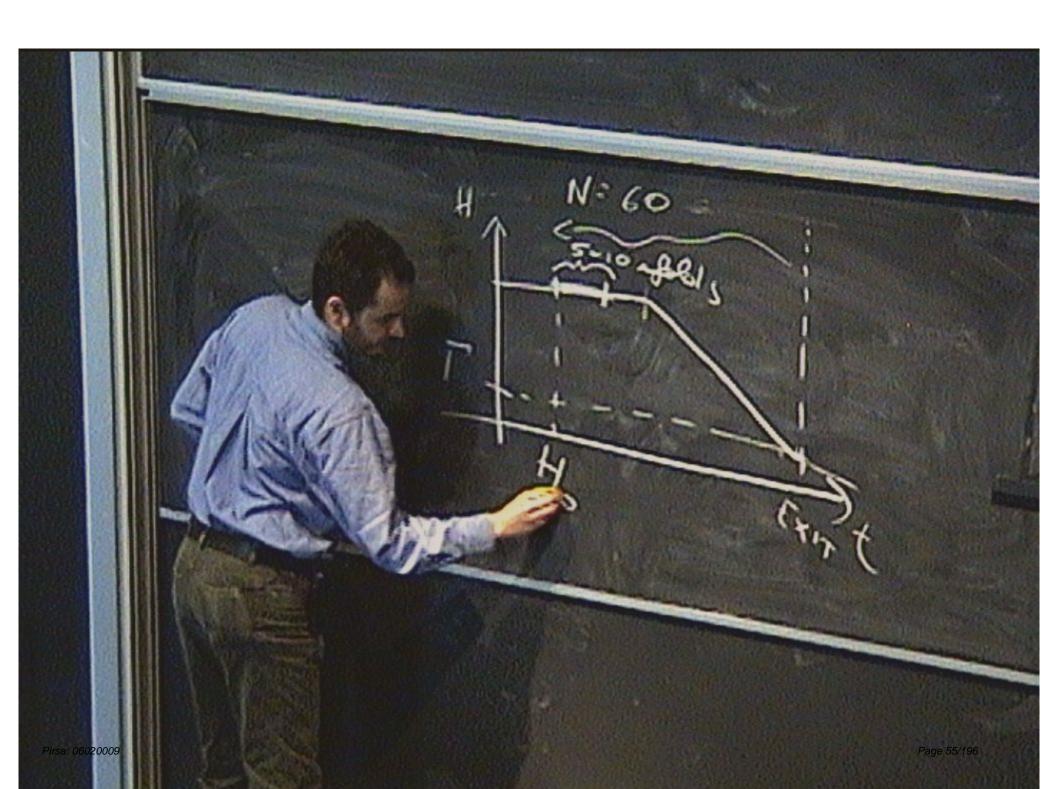
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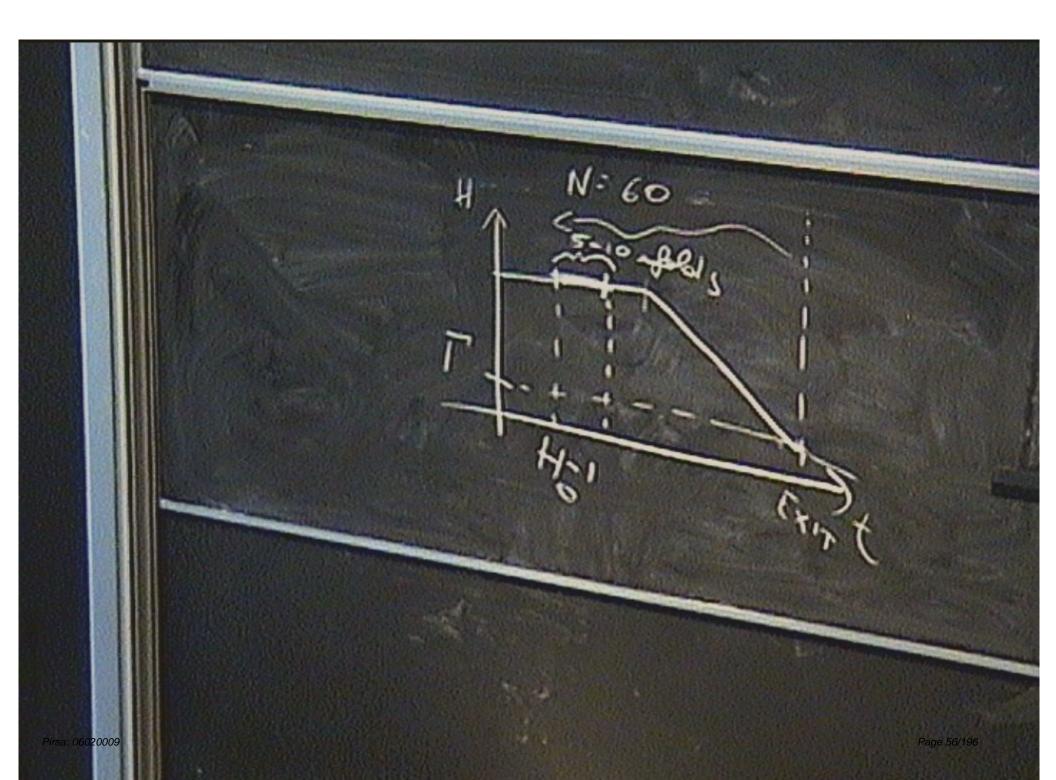
If Phase II short enough

$$(\beta = 1/56)$$









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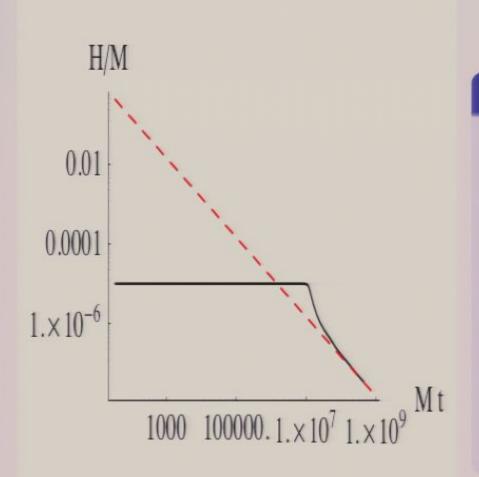
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Crucially

- If Phase II short enough
- Phase I: Perturbations that we see
- H decreases rapidly
- When $H \simeq \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit

$$(\beta = 1/56)$$

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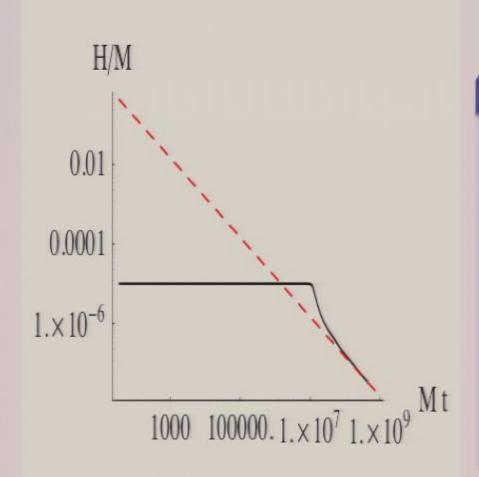
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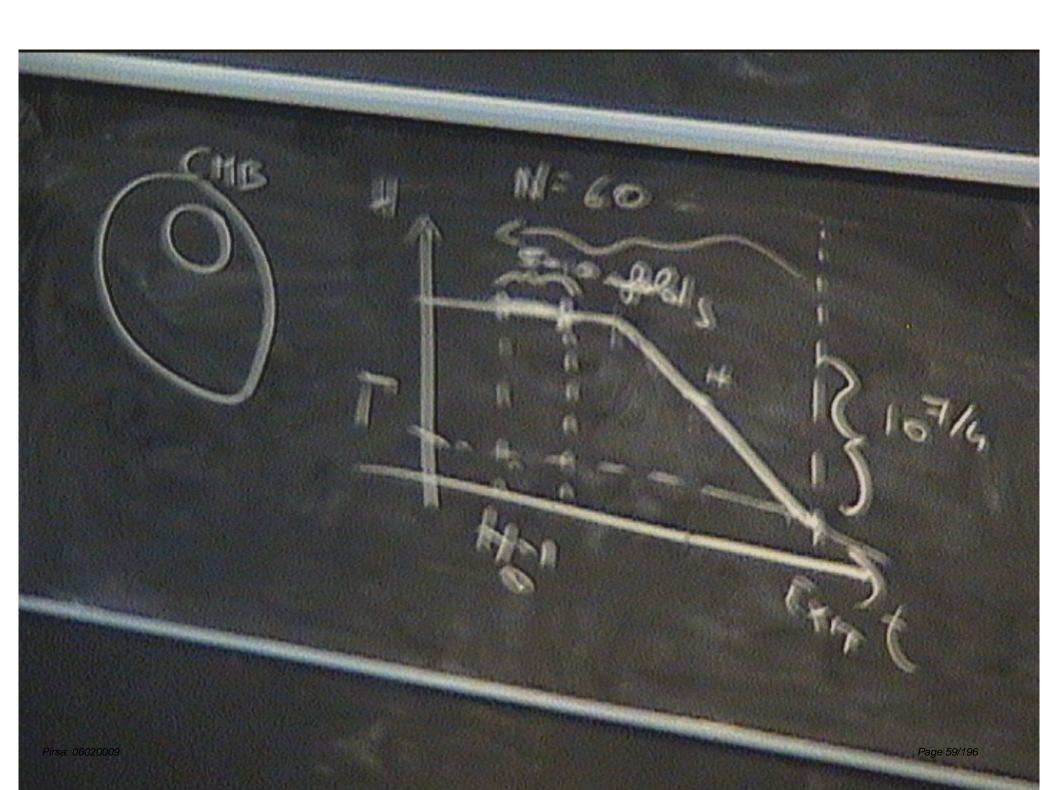
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Crucially

- If Phase II short enough
- Phase I: Perturbations that we see
- H decreases rapidly
- When $H \simeq \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit
- No Large Bubbles if

$$(\beta = 1/56)$$



Difference with Extended Inflation

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El had almost the same Lagrangian:

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

where $\beta > 0$.

Therefore only the power-law phase present

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where $\beta > 0$.

- Therefore only the power-law phase present
- H has to decrease fast to avoid early production of Large Bubbles
- COBE discovered almost flat spectrum

Transition to radiation and Stabilization

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

$$\frac{T_{RH}^4}{M_{pl}^2} \simeq \Gamma_{vac}^{1/2}$$

During radiation \(\phi \) does not evolve:

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

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• Nonetheless we need to stabilize ϕ at late times:

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- Nonetheless we need to stabilize ϕ at late times:
 - 5th force constraints

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- Nonetheless we need to stabilize ϕ at late times:
 - 5th force constraints
 - variation of G_N after equivalence.

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- Nonetheless we need to stabilize ϕ at late times:
 - 5th force constraints
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- We reintroduce the potential $U(\phi)$ in the original Lagrangian

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- Assumed to be irrelevant before $(U \lesssim \lambda^4)$.

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 - 5th force constraints
 - variation of G_N after equivalence.
- We reintroduce the potential $U(\phi)$ in the original Lagrangian
- Assumed to be irrelevant before $(U \lesssim \lambda^4)$.
- Any potential with a minimum is good...

Potential

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 For reasons clear later...we assume not to put by hand the minumum.

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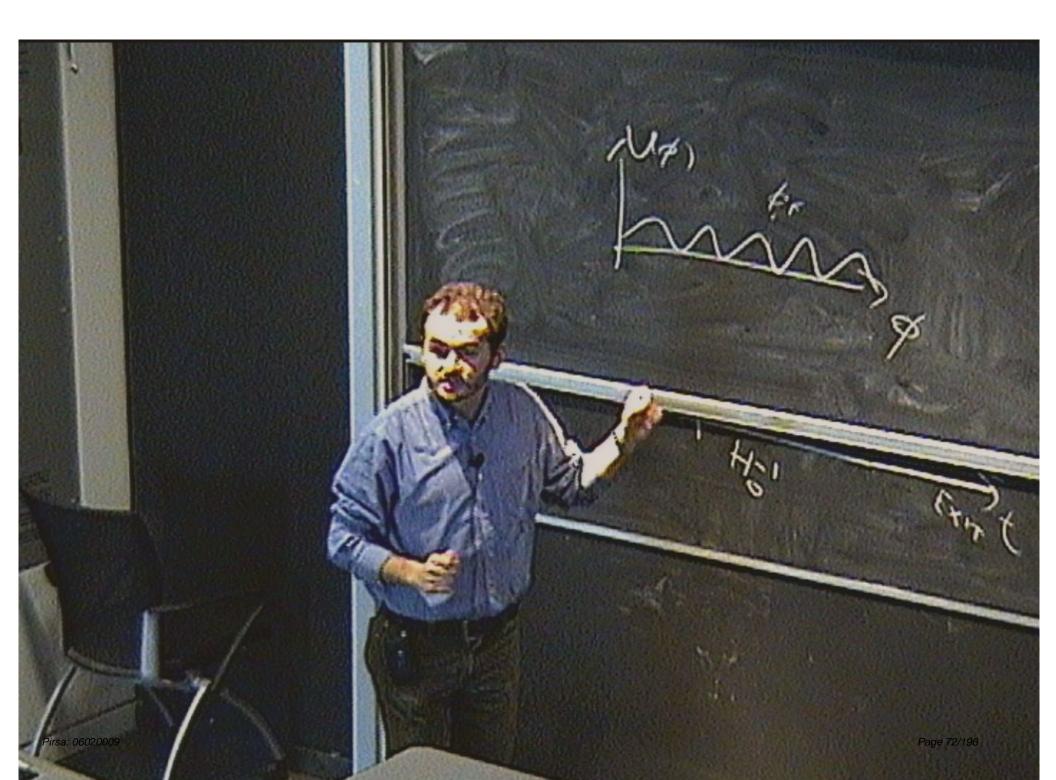
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For example: periodic potential (axion?)



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

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We generalize as

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

• where for $\phi \ll M$ we expand $f(\phi) \simeq 1 + \beta \phi^2$

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

- where for $\phi \ll M$ we expand $f(\phi) \simeq 1 + \beta \phi^2$
- For $\phi \gg M$ assume $f(\phi) > \phi^2$

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- For $\phi \gg M$ assume $f(\phi) > \phi^2$
- The transition is strong enough (decelerated expansion), independently on the exact form of f(φ)!

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- visible scales are produced in phase I. No Large Bubbles problem.
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 One may worry about quantum gravitational corrections for a theory with φ >> M

⁶A. D. Linde, Phys. Lett. B **129** (1983) 177.

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- One may worry about quantum gravitational corrections for a theory with $\phi\gg M$
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- ...corrections due to graviton loops do not go as

$$\mathcal{O}(1)\frac{\phi^n}{M^n}$$
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- One may worry about quantum gravitational corrections for a theory with $\phi \gg M$
- As in chaotic inflation 6
- ...corrections due to graviton loops do not go as

$$\mathcal{O}(1)\frac{\phi^n}{M^n}$$
,

but as 7

$$\mathcal{O}(1)\frac{(\text{Energy})^4}{M^4}$$

(with a cutoff scale of order M).

⁶A. D. Linde, Phys. Lett. B **129** (1983) 177.

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- Motivation
 - Inflation from a False Vacuum
- Our proposal
 - Basic idea
 - After Inflation
 - The Lagrangian
 - Dynamics
- Hierarchy Problem
 - A new proposal
- Cosmology Constraints
 - Sufficient Inflation
 - Cosmological Perturbations
- Experimental signatures
 - GW at LISA
 - Particle Physics

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It is convenient to transform

$$\bar{g}_{\mu\nu}=f(\phi)g_{\mu\nu}$$
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It is convenient to transform

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,

Get:

$$S_E = \frac{1}{2} \int d^4x \, \sqrt{-\bar{g}} [M^2 \bar{R} - K(\phi)(\bar{\partial}\phi)^2] + S_{vac} \,,$$

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$$S_E = rac{1}{2} \int d^4 x \; \sqrt{-\bar{g}} [M^2 \bar{R} - K(\phi) (\bar{\partial} \phi)^2] + S_{vac} \, ,$$

where

$$K(\phi) \equiv \frac{2f(\phi) + 3M^2f'^2(\phi)}{2f^2(\phi)}$$
.

and the false vacuum energy, in this frame

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

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becomes a potential (but it disappears at decay!)

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$$M^2 f(\phi) \approx M^2 \left[1 + \beta \left(\frac{\phi}{M} \right)^n \right].$$

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$$M^2 f(\phi) \approx M^2 \left[1 + \beta \left(\frac{\phi}{M} \right)^n \right].$$

- where as we said n=2
- (But it works similarly also with any n)

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$$M^2 f(\phi) \approx M^2 \left[1 + \beta \left(\frac{\phi}{M} \right)^H \right].$$

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$$M^2 f(\phi) \approx M^2 \left[1 + \beta \left(\frac{\phi}{M} \right)^n \right].$$

- where as we said n=2
- (But it works similarly also with any n)
- (Instead the 1 is crucial).
- Therefore:

$$K(\phi) \approx 1 \,, \; \bar{V} \approx \lambda^4 \left[1 - 2 \left(\frac{\phi}{M} \right)^2 \right] \,.$$

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Expand

$$M^2 f(\phi) \approx M^2 \left[1 + \beta \left(\frac{\phi}{M} \right)^n \right].$$

- where as we said n=2
- (But it works similarly also with any n)
- (Instead the 1 is crucial).
- Therefore:

$$K(\phi) \approx 1 \; , \; \bar{V} \approx \lambda^4 \left[1 - 2 \left(\frac{\phi}{M} \right)^2 \right] \; .$$

• it looks like slow roll on top of a hill

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So in slow-roll approximation:

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So in slow-roll approximation:

$$\epsilon \equiv \frac{M^2}{2} \left| \frac{1}{V} \frac{dV}{d\phi} \right|^2 = 8\beta^2 \left(\frac{\phi}{M} \right)^2, \quad (1)$$

$$\eta \equiv M^2 \frac{1}{V} \frac{d^2 V}{d\phi^2} = -4\beta. \tag{2}$$

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And

$$ar{\mathcal{N}}_{tot} pprox rac{1}{4eta} \ln \left[rac{M}{\sqrt{eta}\phi_0}
ight] \, .$$

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small β required.

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And

$$ar{\mathcal{N}}_{tot} pprox rac{1}{4eta} \ln \left[rac{M}{\sqrt{eta}\phi_0}
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- small β required.
- When ϕ of order M: end of slow-roll

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In this phase:

$$K(\phi) \equiv rac{2f(\phi) + 3M^2f'^2(\phi)}{2f^2(\phi)} pprox rac{3M^2}{2} \left(rac{f'}{f}
ight)^2 \,, \qquad ar{V} pprox rac{\lambda^4}{f^2} \,.$$

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So we introduce a canonical variable via

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

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So we introduce a canonical variable via

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

• The kinetic term is canonical and the potential becomes:

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

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

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

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

$$\bar{a} \sim \bar{t}^p$$
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• And ϕ grows with kinetic energy proportional to \bar{V} .

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$$\bar{a} \sim \bar{t}^p$$
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- And ϕ grows with kinetic energy proportional to \bar{V} .
- The end of this phase when

$$ar{H}^2 \simeq rac{ar{V}}{M^2} = rac{\lambda^4}{f^2(\phi_F)M^2}$$

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

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

- And ϕ grows with kinetic energy proportional to \bar{V} .
- The end of this phase when

$$\bar{H}^2 \simeq rac{ar{V}}{M^2} = rac{\lambda^4}{f^2(\phi_F)M^2} = ar{\Gamma}_{vac}^{1/2}$$

• Therefore the final field value ϕ_F is given by:

$$f(\phi_F) \simeq rac{\lambda^2}{M \bar{\Gamma}_{vac}^{1/4}} \, .$$

Outline

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- Motivation
 - Inflation from a False Vacuum
- Our proposal
 - Basic idea
 - After Inflation
 - The Lagrangian
 - Dynamics
- 3 Hierarchy Problem
 - A new proposal
- Cosmology Constraints
 - Sufficient Inflation
 - Cosmological Perturbations
- Experimental signatures
 - GW at LISA
 - Particle Physics

The Hierarchy Problem

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• Two fundamental scales observed in the Universe: electroweak scale, M_{EW} , and Planck scale M_{Pl} .

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- Two fundamental scales observed in the Universe: electroweak scale, M_{EW} , and Planck scale M_{Pl} .
- $M_{EW}/M_{Pl} \approx 10^{-14} 10^{-15}$: Why?.

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Pirsa: 06020009

• Two fundamental scales observed in the Universe: electroweak scale, M_{EW} , and Planck scale M_{Pl} .

• $M_{EW}/M_{Pl} \approx 10^{-14} - 10^{-15}$: Why?.

 A deeper comprehension of physics should probably lead us to a theory with one scale

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• Two fundamental scales observed in the Universe: electroweak scale, M_{EW} , and Planck scale M_{Pl} .

• $M_{EW}/M_{Pl} \approx 10^{-14} - 10^{-15}$: Why?.

- A deeper comprehension of physics should probably lead us to a theory with one scale
- At which scale new physics will appear? (important for LHC)

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- Two fundamental scales observed in the Universe: electroweak scale, M_{EW} , and Planck scale M_{Pl} .
- $M_{EW}/M_{Pl} \approx 10^{-14} 10^{-15}$: Why?.
- A deeper comprehension of physics should probably lead us to a theory with one scale
- At which scale new physics will appear? (important for LHC)
- Why the Higgs is so light? (if the mass is quadratically sensitive to the cutoff $\gg M_{EW}$)

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⁸ N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998)

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Popular solutions are:

Supersymmetry or Technicolor at weak scale.

⁸ N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998)

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Popular solutions are:

 Supersymmetry or Technicolor at weak scale. Higgs mass insensitive to M_{Pl}.

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- Supersymmetry or Technicolor at weak scale. Higgs mass insensitive to M_{Pl}.
- Large Extra Dimensions 8

⁸ N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998)

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- Supersymmetry or Technicolor at weak scale. Higgs mass insensitive to M_{Pl}.
- Large Extra Dimensions ⁸ M_{EW} as a fundamental scale and gravity diluted by a Large Extra Dim

⁸N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998)

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N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429, 263 (1998)

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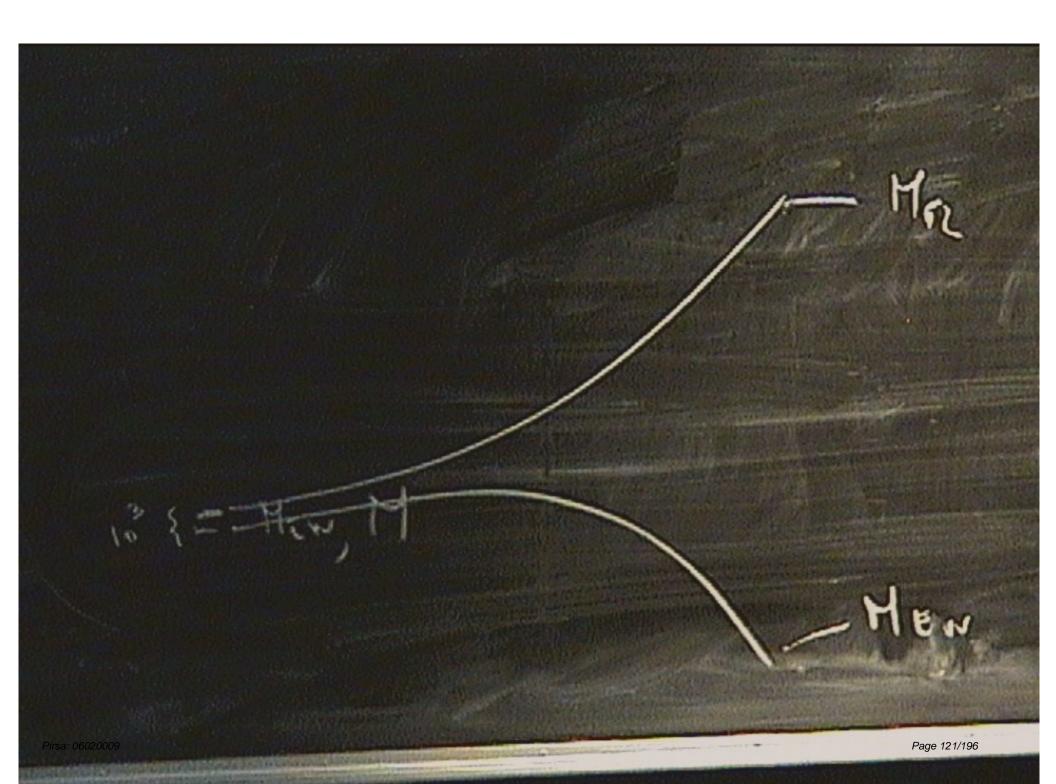
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- Supersymmetry or Technicolor at weak scale. Higgs mass insensitive to M_{Pl}.
- Large Extra Dimensions ⁸ M_{EW} as a fundamental scale and gravity diluted by a Large Extra Dim
- Warped Extra Dimensions⁹: M_{Pl} exponentially enhanced w.r.t. M_{EW}
- Our proposal provides a large M_{Pl}/M_{EW} at late time
- Starting with a smaller hierarchy at early time

N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429, 263 (1998)



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

- Scales in the problem:
 - Scale λ
 - Amplitude of potential |U|1/4

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- Scales in the problem:
 - Scale λ
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 - Scale of \mathcal{L}_m : M_{EW}
 - Scale of gravity during inflation M

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- Scales in the problem:
 - Scale λ
 - Amplitude of potential $|U|^{1/4}$
 - Scale of \mathcal{L}_m : M_{EW}
 - Scale of gravity during inflation M
- Assume all scales to be close (up to 10³).

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- Quantum corrections are cutoff at this scale (close to M_{EW})

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

- Scales in the problem:
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- Assume all scales to be close (up to 10³).
- Quantum corrections are cutoff at this scale (close to M_{EW})
- We'll get dynamically $M_{Pl} \simeq 10^{15} M_{EW}$

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• However we still need M somewhat larger than λ and $U^{1/4}$

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• However we still need M somewhat larger than λ and $U^{1/4} \Rightarrow$ so classical GR is still ok

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• However we still need M somewhat larger than λ and $U^{1/4} \Rightarrow$ so classical GR is still ok :

 $M \simeq 10^3 \lambda \Leftarrow \text{from } \delta T/T \approx 10^{-5}.$

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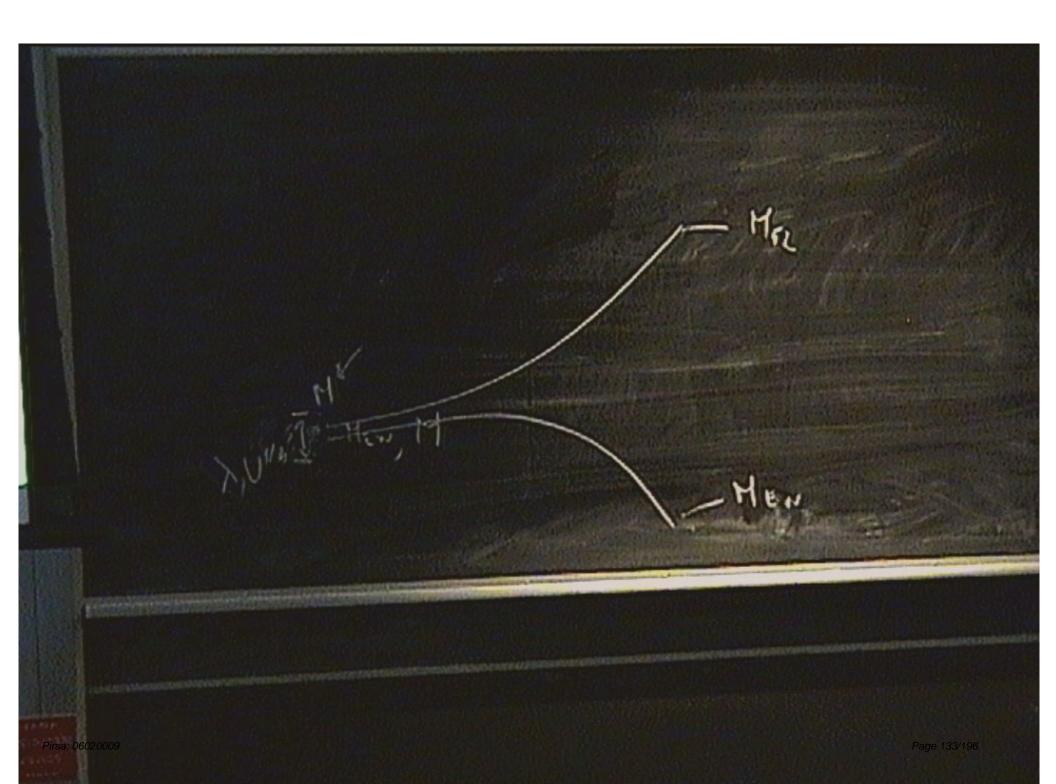
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 - 1. Assume M to be the fundamental scale (M_{EW}) :
 - Take λ and $|U|^{1/4}$ somewhat smaller $(\mathcal{O}(10^{-3}))$

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- Two possibilities to explore:
 - 1. Assume M to be the fundamental scale (M_{EW}) :
 - Take λ and $|U|^{1/4}$ somewhat smaller $(\mathcal{O}(10^{-3}))$
 - One has to explain this tuning: maybe $U(\phi)$ is an axion potential with an amplitude Λ_{QCD} ?
 - 2. Assume λ and $|U|^{1/4}$ as fundamental scale (M_{EW}) :

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- Two possibilities to explore:
 - 1. Assume M to be the fundamental scale (M_{EW}) :
 - Take λ and $|U|^{1/4}$ somewhat smaller $(\mathcal{O}(10^{-3}))$
 - One has to explain this tuning: maybe $U(\phi)$ is an axion potential with an amplitude Λ_{QCD} ?
 - 2. Assume λ and $|U|^{1/4}$ as fundamental scale (M_{EW}) :
 - Then quantum corrections are all of this order

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• However we still need M somewhat larger than λ and $U^{1/4} \Rightarrow$ so classical GR is still ok : $M \simeq 10^3 \lambda \Leftarrow \text{from } \delta T/T \approx 10^{-5}$.

- Two possibilities to explore:
 - 1. Assume M to be the fundamental scale (M_{EW}) :
 - Take λ and $|U|^{1/4}$ somewhat smaller $(\mathcal{O}(10^{-3}))$
 - One has to explain this tuning: maybe $U(\phi)$ is an axion potential with an amplitude Λ_{QCD} ?
 - 2. Assume λ and $|U|^{1/4}$ as fundamental scale (M_{EW}) :
 - Then quantum corrections are all of this order
 - But one has to explain why M is larger...

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- In any case we explain how MPI becomes so big to 180/196

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• The field ϕ which ends Inflation also sets the value M_{Pl} :

$$M_{Pl}^2 = M^2 f(\phi)$$

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• The field ϕ which ends Inflation also sets the value M_{Pl} :

$$M_{Pl}^2 = M^2 f(\phi)$$

• Even starting close to M_{EW} , today M_{Pl} is set by $f(\phi_F)$:

$$rac{M_{Pl}}{M_{EW}} \propto rac{1}{\sqrt{f(\phi_F)}}$$

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- New kind of solution:

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- We have a large hierarchy if $\Gamma_{vac}^{1/4} \ll M_{EW}$: but this is not fine tuning!
- New kind of solution: starting with a Hierarchy of order 10⁻³ (fixed by COBE) we get the Hierarchy of 10⁻¹⁵
- gravity stronger at early time and very weak today

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• A scale L (today) left the horizon at number of efolds \bar{N}_L if:

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A scale L (today) left the horizon at number of efolds \(\bar{N}_L\)
if:

$$L\left(\frac{T_0}{T_{\rm RH}}\right)\left(\frac{\bar{a}_E}{\bar{a}_{RH}}\right)e^{-\bar{\mathcal{N}}_L}=\bar{H}_I^{-1}\,,$$

- After bubble nucleation (assumed almost istantaneous): $T_{RH}^4 \simeq \Gamma_{vac}^{1/2} M_{Pl}^2 \simeq \lambda^4$.
- The redshift during the power-law phase is given by $\bar{a}_E/\bar{a}_{RH}=(\bar{t}_E/\bar{t}_{RH})^{3/4}\simeq(\bar{\Gamma}_{vac}^{1/4}/\bar{H}_I)^{3/4}.$

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- The horizon scale (3000h⁻¹Mpc) corresponds to:

$$ar{\mathcal{N}}_{3000h^{-1}Mpc} pprox {49} + \ln\left[rac{\lambda}{M}
ight] \ .$$

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- The horizon scale (3000h⁻¹Mpc) corresponds to:

$$ar{\mathcal{N}}_{3000h^{-1}Mpc} pprox {f 49} + {\sf In} \left[rac{\lambda}{M}
ight] \,.$$

• Horizon problem solved if $\bar{\mathcal{N}}_{tot} \ge 49$.

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• We consider fluctuations in the field ϕ that ends inflation.

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- We consider fluctuations in the field ϕ that ends inflation.
- In the original (Jordan) frame H = constant but the field is not minimally coupled ⇒ not exactly flat spectrum

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- We consider fluctuations in the field ϕ that ends inflation.
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- We consider fluctuations in the field φ that ends inflation.
- In the original (Jordan) frame H = constant but the field is not minimally coupled ⇒ not exactly flat spectrum
- In the Einstein frame there is a potential ⇒ not exactly flat spectrum
- Fastest way: in the Einstein frame (we have checked both): just look at the slow-roll parameters.

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- In the Einstein frame there is a potential ⇒ not exactly flat spectrum
- Fastest way: in the Einstein frame (we have checked both): just look at the slow-roll parameters.
- Use:

$$\left\{egin{array}{l} n_S-1=2\eta-6\epsilon \ & \ A^2=\left(rac{ar{H}_I}{M}
ight)^2rac{1}{8\pi^2\epsilon} \,
ight|_{\phi=\phi(ar{\mathcal{N}}pproxar{\mathcal{N}}_{3000h-1Mp}$$
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• So, the spectral index is $n_S \simeq 1 - 8\beta$

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- So, the spectral index is $n_S \simeq 1 8\beta$
- The total duration of inflation is $\bar{\mathcal{N}}_{tot} \approx \frac{1}{4\beta} \ln \left[\frac{M}{\sqrt{\beta}\phi_0} \right]$.

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- If $8\beta \lesssim 0.1 \Rightarrow$ flat spectrum and enough inflation.

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- So, the spectral index is $n_S \simeq 1 8\beta$
- The total duration of inflation is $\bar{\mathcal{N}}_{tot} \approx \frac{1}{4\beta} \ln \left| \frac{M}{\sqrt{\beta}\phi_0} \right|$.
- If $8\beta \lesssim 0.1 \Rightarrow$ flat spectrum and enough inflation.

• The amplitude requires
$$\frac{H_L}{M} \frac{e^{100\beta}}{8\pi\sqrt{\beta}} = 2 \times 10^{-5}$$
 (COBE)

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- The amplitude requires $\frac{H_I}{M} \frac{e^{100\beta}}{8\pi\sqrt{\beta}} = 2 \times 10^{-5}$ (COBE)
- A reasonable choice of parameters is

$$eta \simeq 10^{-2}$$
 and $rac{\lambda}{M} \simeq 10^{-3}$

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We expect to see some red tilt

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Reheating proceeds through bubble collisions.

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- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves (GW)¹⁰

*

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- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves $(GW)^{10}$ peaked at horizon scale (set by $T_{RH} \simeq \lambda$)

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- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves (GW)¹⁰ peaked at horizon scale (set by $T_{RH} \simeq \lambda$)
- If λ is some TeV



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- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves (GW)¹⁰ peaked at horizon scale (set by $T_{RH} \simeq \lambda$)
- If λ is some TeV $\Rightarrow \nu_{\rm peak} \approx$ 0.1 mHz (in the sensitivity range of LISA)



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- Reheating proceeds through bubble collisions.
- This produces a lot of relic gravity waves (GW)¹⁰ peaked at horizon scale (set by $T_{RH} \simeq \lambda$)
- If λ is some TeV $\Rightarrow \nu_{\rm peak} \approx$ 0.1 mHz (in the sensitivity range of LISA)
- Amplitude at the peak is big enough to be detectable:



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Expected value at peak
$$\Omega_{GW}h^2 \approx 10^{-7}$$
 LISA sensitivity $\Omega_{GW}h^2 \approx 10^{-11}$



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Expected value at peak
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 LISA sensitivity $\Omega_{GW}h^2 \approx 10^{-11}$

• If, $M \simeq \text{few } TeV$, so $\lambda \simeq \text{few } GeV$:



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Expected value at peak
$$\Omega_{GW}h^2 \approx 10^{-7}$$
 LISA sensitivity $\Omega_{GW}h^2 \approx 10^{-11}$

• If, $M \simeq \text{few } \text{TeV}$, so $\lambda \simeq \text{few } \text{GeV}$: $\nu_{\text{peak}} \approx 10^{-4} \text{ mHz}...$ much harder to see.



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- If λ is some TeV $\Rightarrow \nu_{\rm peak} \approx$ 0.1 mHz (in the sensitivity range of LISA)
- Amplitude at the peak is big enough to be detectable:

Expected value at peak
$$\Omega_{GW}h^2 \approx 10^{-7}$$
 LISA sensitivity $\Omega_{GW}h^2 \approx 10^{-11}$

- If, $M \simeq \text{few } TeV$, so $\lambda \simeq \text{few } GeV$: $\nu_{\text{peak}} \approx 10^{-4} \text{ mHz...}$ much harder to see.
- If $\lambda \gg TeV$ (only Inflation, no solution to Hierarchy) \Rightarrow higher frequency (LIGO, Virgo, TAMA?)



Outline

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- Motivation
 - Inflation from a False Vacuum
- Our proposal
 - Basic idea
 - After Inflation
 - The Lagrangian
 - Dynamics
- Hierarchy Problem
 - A new proposal
- Cosmology Constraints
 - Sufficient Inflation
 - Cosmological Perturbations
- Experimental signatures
 - GW at LISA
 - Particle Physics



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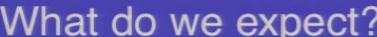
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Pirsa: 06020009

From the LHC we expect only generic predictions



What do we expect?

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Pirsa: 06020009

From the LHC we expect only generic predictions

 A new scale should be seen, by appearance of higher order operators.

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What do we expect?

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- From the LHC we expect only generic predictions
- A new scale should be seen, by appearance of higher order operators.
- And this can be related to a scale eventually detected by LISA.



What do we expect?

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- From the LHC we expect only generic predictions
- A new scale should be seen, by appearance of higher order operators.
- And this can be related to a scale eventually detected by LISA.
- Combination of three very different observations:

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Gravity waves (LISA)
Particle physics (LHC)
Spectral index (WMAP? Planck?)
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Pirsa: 06020009

Other tunings are present in late-time physics.



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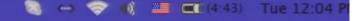
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- Other tunings are present in late-time physics.
- Once we have a large hierarchy $f(\phi_F) \simeq 10^{30} \gg 1$, we can in principle explain any other tuning,



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- Other tunings are present in late-time physics.
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- Example: A potential term

$$W(\phi) = \frac{M^4}{f^2(\phi)},$$

generates
$$\frac{\Lambda}{M_{Pl}^4} = 10^{-120}$$
 without any tuning.

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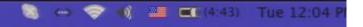
- Other tunings are present in late-time physics.
- Once we have a large hierarchy $f(\phi_F) \simeq 10^{30} \gg 1$, we can in principle explain any other tuning, just by coupling to ϕ !
- Example: A potential term

$$W(\phi) = \frac{M^4}{f^2(\phi)},$$

generates $\frac{\Lambda}{M_{Pl}^4} = 10^{-120}$ without any tuning.

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

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Therefore with one field ϕ :

 We provide inflation from a false vacuum and without flat potentials



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- We provide inflation from a false vacuum and without flat potentials
- We provide the correct nearly flat spectrum of perturbations (with $\beta \approx 10^{-2}$ and $\lambda/M \approx 10^{-3}$).



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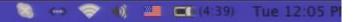
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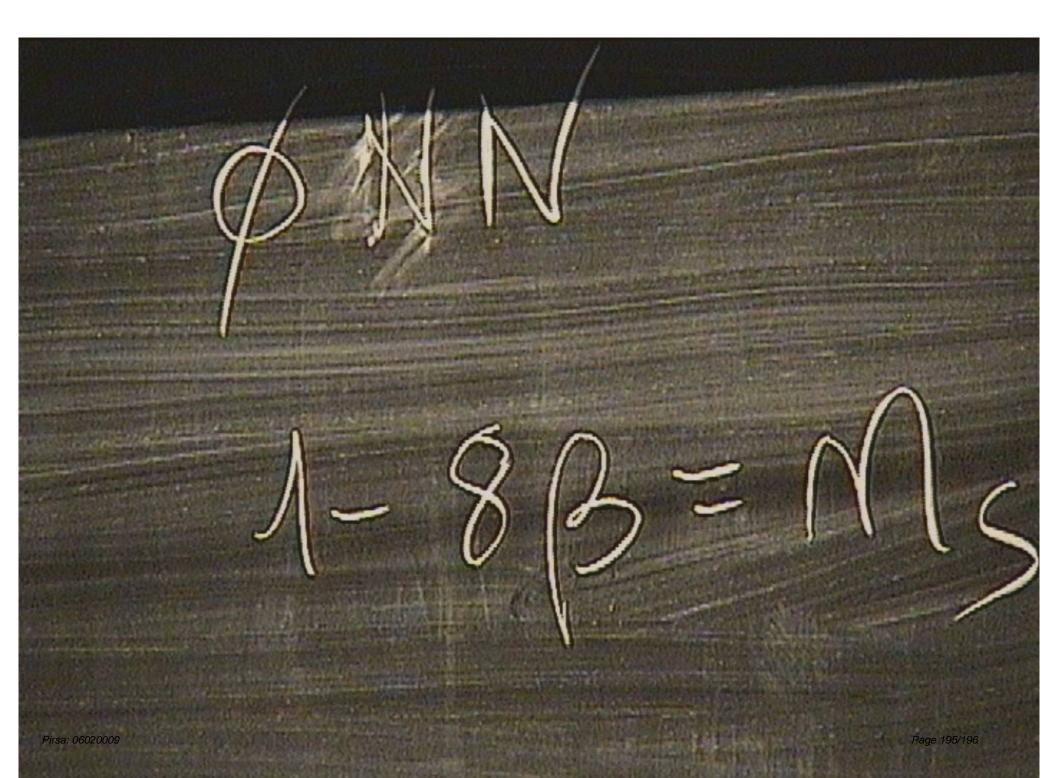
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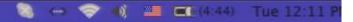
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