Introduction to Quantum fields in Curved Spaces

Tommi Markkanen
Imperial College London

t.markkanen@imperial.ac.uk

April/June-2018
Solvalla

Outline

Imperial College London

The road to QFT, in a nutshell

Fundamental concepts emerge

1900 – 1927

1. Extending classical mechanics becomes unavoidable
   - Black-body radiation
   - Photoelectric effect
   - The Bohr model for hydrogen

   ...

The road to QFT, in a nutshell

Fundamental concepts emerge

1900 – 1927

1. Extending classical mechanics becomes unavoidable
    - Black-body radiation
    - Photoelectric effect
    - The Bohr model for hydrogen

   . . .

2. Special Relativity needs to be incorporated
    - Relativistic quantum mechanics has severe issues

The road to QFT, in a nutshell

Fundamental concepts emerge

1900 – 1927

1. Extending classical mechanics becomes unavoidable
   - Black-body radiation
   - Photoelectric effect
   - The Bohr model for hydrogen

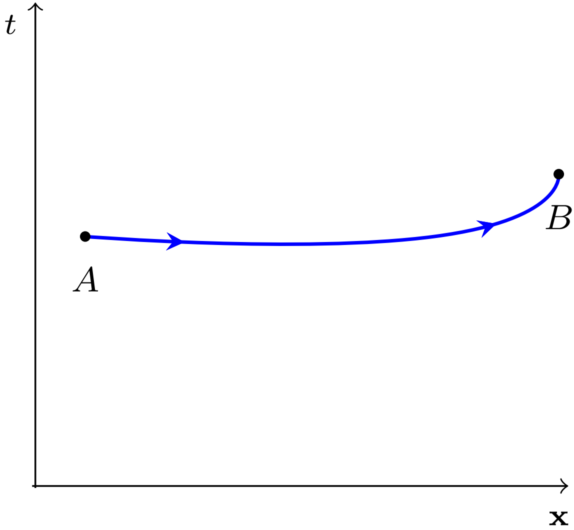
   ...

2. Special Relativity needs to be incorporated
   - Relativistic quantum mechanics has severe issues

3. 1927 $\Rightarrow$ Quantum field theory
   - Particles can be created and annihilated by the vacuum

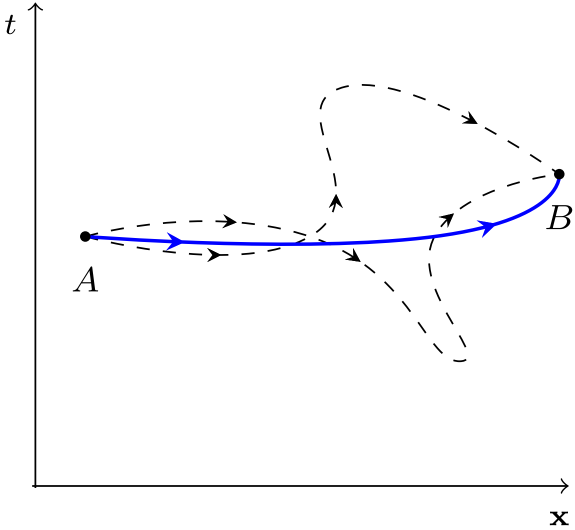
Classical Mechanics

- Deterministic



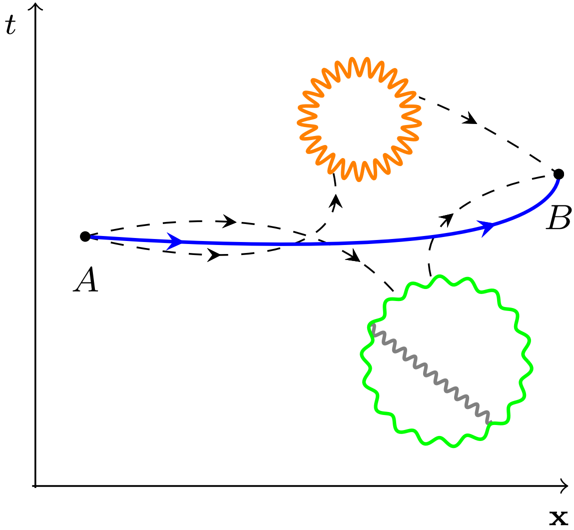
Quantum Mechanics

- Probabilistic



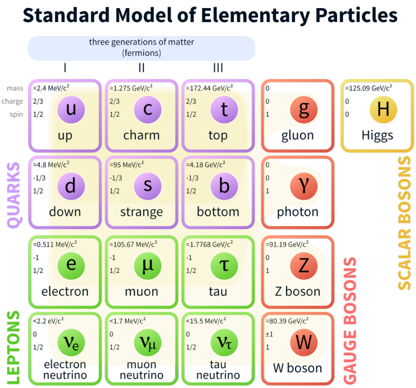
Quantum Field Theory

- Probabilistic with particle creation/annihilation



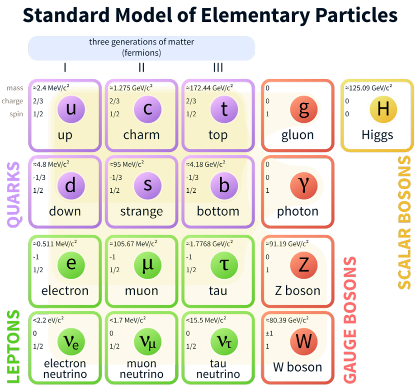
Renormalization

- The Standard model of particle physics is a very successful QFT
  - Electrodynamics
  - Strong nuclear force
  - Weak nuclear force



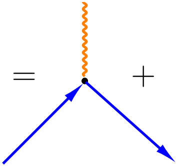
Renormalization

- The Standard model of particle physics is a very successful QFT
  - Electrodynamics
  - Strong nuclear force
  - Weak nuclear force



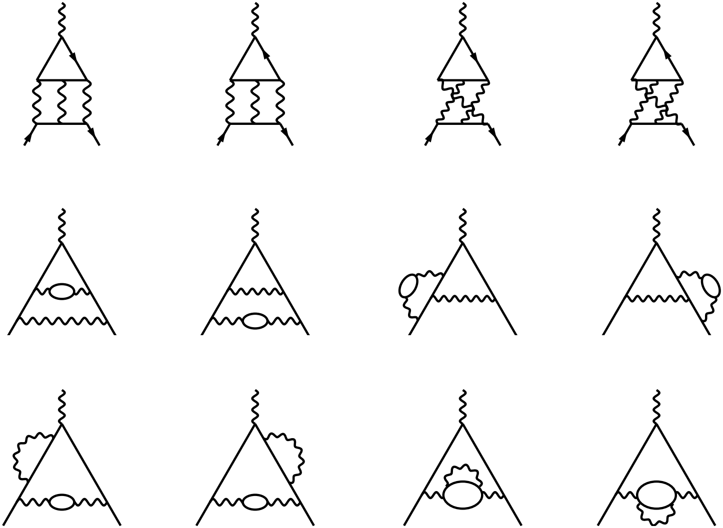
- Renormalizability is a crucial requirement
  - QFTs are plagued by infinities that need to be consistently dealt with

electron photon scatter =



\+ "loops"

Loops



Issues with Quantum Gravity

- A major problem in General Relativity as a QFT: Non-Renormalizability

$\Rightarrow$ The ”usual” approach of QFT fails!

- Non-perturbative theories are not well-behaved as loop expansions
  - Questionable predictability

Issues with Quantum Gravity

- A major problem in General Relativity as a QFT: Non-Renormalizability

$\Rightarrow$ The ”usual” approach of QFT fails!

- Non-perturbative theories are not well-behaved as loop expansions
  - Questionable predictability

- Currently many ideas are explored
  - String Theory
  - Loop Quantum Gravity
  - Supergravity
  - Non-commutative spacetime

  ...

Quantum field theory in curved space

- A middle ground: Quantize everything except gravity
  - No issues with renormalization
  - The ”usual” QFT techniques are applicable

Quantum field theory in curved space

- A middle ground: Quantize everything except gravity
  - No issues with renormalization
  - The "usual" QFT techniques are applicable

- Example: a (quantized) scalar field with background gravity

$$S = -\int d^4x \sqrt{|g|}\left[\frac{1}{2}\nabla^\mu\hat{\phi}\nabla_\mu\hat{\phi} + \frac{1}{2}m^2\hat{\phi}^2 + \frac{\xi}{2}R\hat{\phi}^2 + \frac{\lambda}{4}\hat{\phi}^4\right]$$

(in flat space: $g \to 1$, $\nabla_\mu \to \partial_\mu$ and $R \to 0$)

Quantum field theory in curved space

- A middle ground: Quantize everything except gravity
  - No issues with renormalization
  - The ”usual” QFT techniques are applicable

- Example: a (quantized) scalar field with background gravity

$$S = -\int d^4x \sqrt{|g|}\left[\frac{1}{2}\nabla^\mu\hat{\phi}\nabla_\mu\hat{\phi} + \frac{1}{2}m^2\hat{\phi}^2 + \frac{\xi}{2}R\hat{\phi}^2 + \frac{\lambda}{4}\hat{\phi}^4\right]$$

(in flat space: $g \to 1$, $\nabla_\mu \to \partial_\mu$ and $R \to 0$)

1. Allows the study of how curvature effects quantum observables
2. Allows the study of *backreaction*
   - Semi-Classical Einstein equation ($M_{\mathrm{P}}^2 \equiv 1$):

$$\underbrace{G_{\mu\nu}}_{\text{classical}} = \underbrace{\langle\hat{T}_{\mu\nu}\rangle}_{\text{quantum}}$$

General remarks

- A lot of theoretical works in the 60's, and 70's and 80's
  - Nowadays not so much...
  - Interactions were rarely discussed

General remarks

- A lot of theoretical works in the 60's, and 70's and 80's
  - Nowadays not so much...
  - Interactions were rarely discussed

Important applications

- Black hole evaporation (70's)
- Early Universe physics
  - Inflation (quite recent)
  - Vacuum stability of the SM (very recent)

General remarks

- A lot of theoretical works in the 60's, and 70's and 80's
  - Nowadays not so much...
  - Interactions were rarely discussed

Important applications

- Black hole evaporation (70's)
- Early Universe physics
  - Inflation (quite recent)
  - Vacuum stability of the SM (very recent)

Textbooks:

1. Birrell & Davies:
   Quantum Fields in Curved Space
2. Parker & Toms:
   Quantum Field Theory in Curved Spacetime
3. Mukhanov & Winitzki:
   Introduction to Quantum Effects in Gravity

Cosmological particle creation

General remarks

- Assume a homogeneous and isotropic spacetime, but which may expand or contract (FLRW)
- The *metric*: $g_{\mu\nu}dx^\mu dx^\nu = -dt^2 + a(t)d\mathbf{x}^2$

The *scale factor* $a(t)$

- Characterizes cosmic expansion
- $\dfrac{l(t_2)}{l(t_1)} = \dfrac{a(t_2)}{a(t_1)}$

General remarks

- Assume a homogeneous and isotropic spacetime, but which may expand or contract (FLRW)
- The *metric*: $g_{\mu\nu}dx^{\mu}dx^{\nu} = -dt^2 + a(t)d\mathbf{x}^2$

The *scale factor* $a(t)$

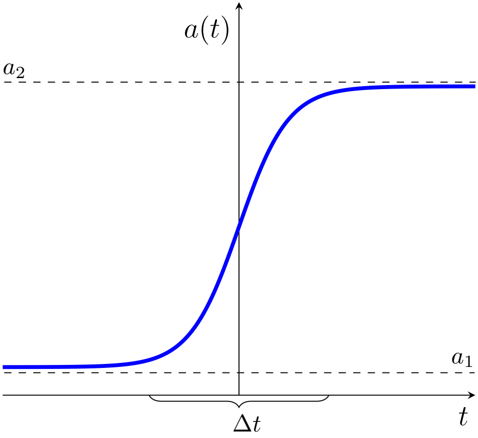
- Characterizes cosmic expansion
- $\dfrac{l(t_2)}{l(t_1)} = \dfrac{a(t_2)}{a(t_1)}$

- The concepts of particle and vacuum are not global
  i.e. they are observer dependent
- First proper treatment in Parker (69)

Cosmological particle creation (Example)

Example:

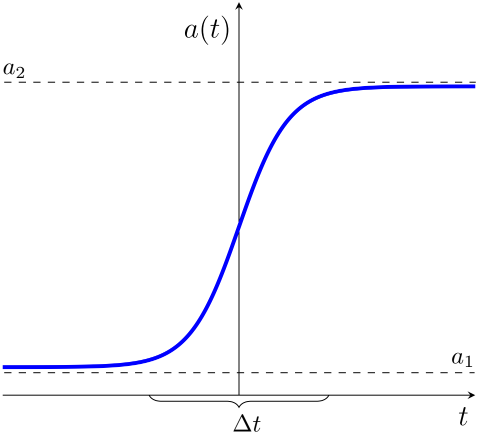
$$a(t) = \frac{a_1 + a_2}{2} + \frac{a_2 - a_1}{2} \tanh\left(\frac{t}{\Delta t}\right); \quad \begin{cases} a(-\infty) & = a_1 \\ a(+\infty) & = a_2 \end{cases}$$



Cosmological particle creation (Example)

Example:

$$a(t) = \frac{a_1 + a_2}{2} + \frac{a_2 - a_1}{2} \tanh\left(\frac{t}{\Delta t}\right); \quad \begin{cases} a(-\infty) & = a_1 \\ a(+\infty) & = a_2 \end{cases}$$



The "in" *quantum mode*

$$f^{\mathrm{in}}_{\mathbf{k}}(t) = \frac{\exp\left\{-i\omega_+ t - i\Delta t\omega_- \ln\left[2\cosh(t/\Delta t)\right]\right\}}{\sqrt{2\omega_{\mathrm{in}}}} \times {}_2F_1\left[1 + i\Delta t\omega_-, i\Delta t\omega_-; 1 - i\Delta t\omega_{\mathrm{in}}; \frac{1+\tanh(t/\Delta t)}{2}\right] \xrightarrow[t \to -\infty]{} e^{-i\omega_{\mathrm{in}} t}$$

$$\omega^2_{\mathrm{in/out}} = \mathbf{k}^2 + a^2_{1/2} m^2; \quad \omega_{\pm} = \frac{\omega_{\mathrm{out}} \pm \omega_{\mathrm{in}}}{2}$$

Cosmological particle creation (continued)

- Energy density changes from vacuum to thermal:

$$\frac{E(t\to\infty)}{V}-\frac{E(t\to-\infty)}{V}=\int\frac{d^3k}{(2\pi)^2}\,\omega e^{-\omega/T}\,;\quad T\sim\Delta t$$

Cosmological particle creation (continued)

- Energy density changes from vacuum to thermal:

$$\frac{E(t\to\infty)}{V}-\frac{E(t\to-\infty)}{V}=\int\frac{d^3k}{(2\pi)^2}\,\omega e^{-\omega/T}\,;\quad T\sim\Delta t$$

- ”Quantum friction”

> Lenz’s Law:
> *The outcome is always such as to oppose the change producing it.*

Cosmological particle creation (continued)

- Energy density changes from vacuum to thermal:

$$\frac{E(t \to \infty)}{V} - \frac{E(t \to -\infty)}{V} = \int \frac{d^3k}{(2\pi)^2}\,\omega e^{-\omega/T}\,; \quad T \sim \Delta t$$

- "Quantum friction"

> Lenz's Law:
> *The outcome is always such as to oppose the change producing it.*

- Early work on cosmological particle creation laid the foundation for Hawking's calculation

Black Hole evaporation

Commun. math. Phys. 43, 199—220 (1975)

Particle Creation by Black Holes

S. W. Hawking

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Received April 12, 1975

Abstract. In the classical theory black holes can only absorb and not emit particles. However it is shown that quantum mechanical effects cause black holes to create and emit particles as if they were hot bodies with temperature $\frac{\hbar\kappa}{2\pi k} \approx 10^{-6}\left(\frac{M_\odot}{M}\right)$ °K where κ is the surface gravity of the black hole. This thermal emission leads to a slow decrease in the mass of the black hole and to its eventual disappearance: any primordial black hole of mass less than about 10^{15} g would have evaporated by now. Although these quantum effects violate the classical law that the area of the event horizon of a black hole cannot decrease, there remains a Generalized Second Law: $S+\frac{1}{4}A$ never decreases where S is the entropy of matter outside black holes and A is the sum of the surface areas of the event horizons. This shows that gravitational collapse converts the baryons and leptons in the collapsing body into entropy. It is tempting to speculate that this might be the reason why the Universe contains so much entropy per baryon.

8. **Gauge theory correlators from noncritical string theory**
(7650) S.S. Gubser, Igor R. Klebanov, Alexander M. Polyakov (Princeton U.). Feb 1998. 14 pp.
Published in **Phys.Lett. B428 (1998) 105-114**
PUPT-1767
DOI: 10.1016/S0370-2693(98)00377-3
e-Print: **hep-th/9802109 | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; AMS MathSciNet
Detailed record - Cited by 7650 records 1000+

9. **Partial Symmetries of Weak Interactions**
(7169) S.L. Glashow (Copenhagen U.). 1961. 10 pp.
Published in **Nucl.Phys. 22 (1961) 579-588**
DOI: 10.1016/0029-5582(61)90469-2
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
OSTI.gov Server
Detailed record - Cited by 7169 records 1000+

10. **Particle Creation by Black Holes**
(7059) S.W. Hawking (Cambridge U., DAMTP & Caltech). Aug 1975. 22 pp.
Published in **Commun.Math.Phys. 43 (1975) 199-220,** Erratum: **Commun.Math.Phys. 46 (1976) 206**
DOI: 10.1007/BF01608497, 10.1007/BF02345020
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
AMS MathSciNet; Project Euclid
Detailed record - Cited by 7059 records 1000+

11. **The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problem**
(6789) Alan H. Guth (SLAC). Jul 1980. 32 pp.
Published in **Phys.Rev. D23 (1981) 347-356**
SLAC-PUB-2576
DOI: 10.1103/PhysRevD.23.347
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document; ADS Abstract Service; OSTI.gov Server; SLAC Document Server; Link to Full
Detailed record - Cited by 6789 records 1000+

12. **Asymptotic Freedom in Parton Language**
(6342) Guido Altarelli (Ecole Normale Superieure), G. Parisi (IHES, Bures-sur-Yvette). Mar 1977. 21 pp.
Published in **Nucl.Phys. B126 (1977) 298-318**
LPTENS-77-6
DOI: 10.1016/0550-3213(77)90384-4
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 6342 records 1000+

Black holes, classically

- Bardeen et al. (73) & Bekenstein (73):
  Black holes have entropy?
  - Dynamics similar to first law of thermodynamics
  - Area cannot decrease i.e second law of thermodynamics

    $$A_1 + A_2 \leq A_{12}$$

  - Degradation of energy (cannot be transformed into work)
  - Information loss

    $$S = -\sum_n p_n \log p_n$$

Black holes, classically

- Bardeen et al. (73) & Bekenstein (73):
  Black holes have entropy?
  - Dynamics similar to first law of thermodynamics
  - Area cannot decrease i.e second law of thermodynamics

    $$A_1 + A_2 \leq A_{12}$$

  - Degradation of energy (cannot be transformed into work)
  - Information loss

$$S = -\sum_n p_n \log p_n$$

- Bekenstein (73): Black hole entropy

$$S \propto A$$

A crucial question:

How can a black hole have temperature!?

$$\delta Q = T\, dS$$

Hawking radiation

- Hawking (74,75): Black holes radiate thermally
  - Calculationally similar to cosmological particle creation

$$T = \frac{c^3 \hbar}{8\pi G M k_B}$$

- Assuming thermodynamics this fixes the entropy

$$dU = TdS - pdV \quad \Rightarrow \quad S = \frac{c^3 k_B A}{4\hbar G}$$

Hawking radiation

- Hawking (74,75): Black holes radiate thermally
  - Calculationally similar to cosmological particle creation

$$T = \frac{c^3 \hbar}{8\pi G M k_B}$$

- Assuming thermodynamics this fixes the entropy

$$dU = TdS - pdV \quad \Rightarrow \quad S = \frac{c^3 k_B A}{4\hbar G}$$

- One of the few glimpses we have into quantum nature of gravity

- A complete microscopic description does not yet exist

Important features

Common misconceptions

- ✗ ”Particles that have once fell in can tunnel out.”
- ✗ ”Antiparticles fall into the hole making it shrink.”

Important features

Common misconceptions

✗ ”Particles that have once fell in can tunnel out.”

✗ ”Antiparticles fall into the hole making it shrink.”

- Energy conservation $\Rightarrow$ negative energy flux
  - Not trivial in General Relativity

Important features

Common misconceptions

✗ ”Particles that have once fell in can tunnel out.”

✗ ”Antiparticles fall into the hole making it shrink.”

- Energy conservation $\Rightarrow$ negative energy flux
  - Not trivial in General Relativity

> Hawking (75):
>
> *Thus it will give positive energy flux out across the event horizon or, equivalently, a negative energy flux in across the event horizon.*

Important features

Common misconceptions

✗ "Particles that have once fell in can tunnel out."

✗ "Antiparticles fall into the hole making it shrink."

- Energy conservation $\Rightarrow$ negative energy flux
  - Not trivial in General Relativity

> Hawking (75):
> *Thus it will give positive energy flux out across the event horizon or, equivalently, a negative energy flux in across the event horizon.*

- The produced spectrum does not depend on the infallen matter

The information loss paradox

- Introduced in Hawking (76)

Another misconception

✗ "Since the system contains a thermally distributed particle number it *is* thermal."

The information loss paradox

- Introduced in Hawking (76)

Another misconception

✗ "Since the system contains a thermally distributed particle number it *is* thermal."

- No(!) information paradox in cosmological particle creation
- The key ingredient is the emergence of an *event horizon*

The information loss paradox

- Introduced in Hawking (76)

Another misconception

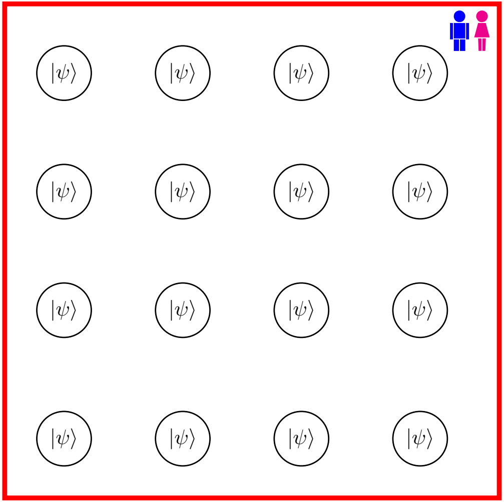
✗ ”Since the system contains a thermally distributed particle number it *is* thermal.”

- No(!) information paradox in cosmological particle creation
- The key ingredient is the emergence of an *event horizon*
- Implies non-Unitary evolution
  - Probability is not conserved
  - A pure states evolves into a mixed one
  - Should not occur in QFT

$$|\psi\rangle \longrightarrow \hat{\rho}\,; \qquad \hat{\rho}^2 \neq \hat{\rho}$$

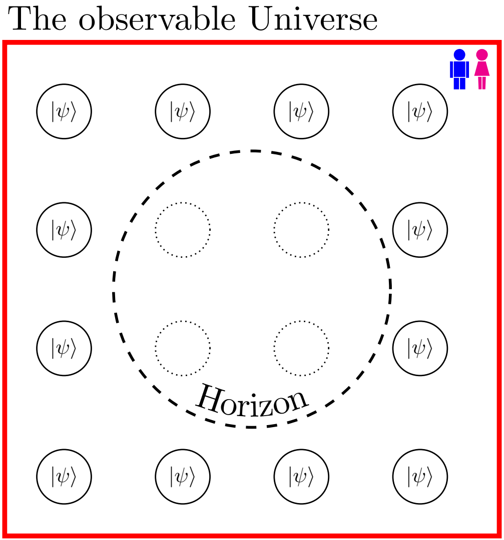
Initially, complete information

The observable Universe



State of the system:

$$\left|\Psi\right\rangle$$



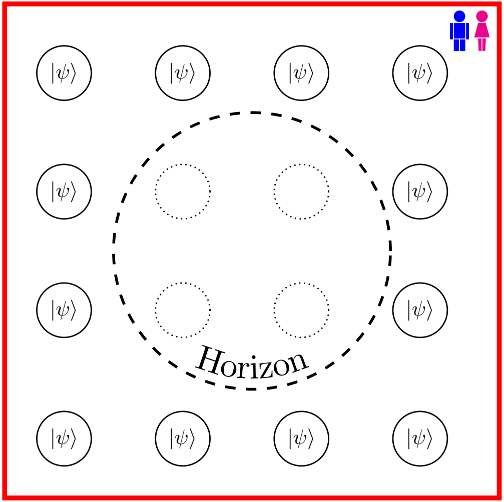
State of the system:

$$|\Psi\rangle$$

$$\hat{\rho} = \mathrm{Tr}_{\mathrm{IN}}\left\{|\Psi\rangle\langle\Psi|\right\}$$

Information loss from the cosmological Horizon

The observable Universe



State of the system:

$$|\Psi\rangle$$

$$\hat{\rho} = \mathrm{Tr}_{\mathrm{IN}}\left\{|\Psi\rangle\langle\Psi|\right\}$$

Suggested resolutions

- Remnants
- Firewalls
- Fuzzballs
- Supertranslations
- Quantum Gravity

Cosmological implications: PBHs

- *Primordial* black holes could be **dark matter**

Cosmological implications: PBHs

- *Primordial* black holes could be **dark matter**
- The smaller a black hole the higher its temperature
  - ⇒ Small black holes evaporate quickly
  - ⇒ Minimum size bounded by the age of the Universe

Important relations to remember

$$T \propto \frac{1}{M} \qquad \Rightarrow \qquad \text{lifetime} \propto M^3$$

- *PBHs smaller than $\sim 10^{15} g$ will evaporate too early!*

Cosmological implications: PBHs

- *Primordial* black holes could be **dark matter**
- The smaller a black hole the higher its temperature
  - $\Rightarrow$ Small black holes evaporate quickly
  - $\Rightarrow$ Minimum size bounded by the age of the Universe

Important relations to remember

$$T \propto \frac{1}{M} \qquad \Rightarrow \qquad \text{lifetime} \propto M^3$$

- *PBHs smaller than* $\sim 10^{15} g$ *will evaporate too early!*

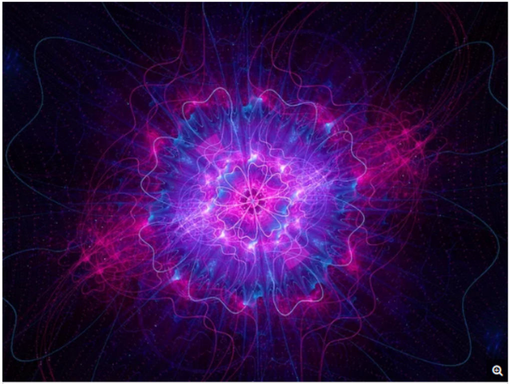
- The recent LIGO discovery sparked renewed interest
  - 30 $M_\odot$ BHs are astrophysically non-trivial

PBHs do not seem a robust candidate for all **DM**

; see for example Carr et. al. (17)

Meet the Higgs Bubble That Will Destroy the Universe. Maybe.

By Erik Vance, Live Science Contributor | April 6, 2018 07:43am ET



An artist's conception of the Higgs boson.

Credit: Shutterstock

Scientists say they know how the universe will end. It won't be a cosmic collapse but rather a giant cosmic bubble that devours everything in its path.

Science Space

Was it Gravity that Saved the Universe After the Big Bang?

By **Matteo Bonetti** - April 5, 2017

One thing that's always puzzled physicists is how the universe didn't collapse immediately after the Big Bang. According to the studies carried out involving the Higgs particle, the production of these during

Motivation

- One of the most profound implications of QFT is the *Renormalization Group*
  - Parameters of the theory run

Motivation

- One of the most profound implications of QFT is the *Renormalization Group*
  - Parameters of the theory run
- Example: The Yukawa theory

$$S = \int d^4x \left[\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{\lambda}{4}\varphi^4 + \bar{\psi}\partial\!\!\!/\psi - g\varphi\bar{\psi}\psi \right].$$

- Classically

$$V(\varphi) = \frac{\lambda}{4}\varphi^4$$

- But in QFT

$$V(\varphi) \approx \frac{\lambda(\varphi)}{4}\varphi^4$$

Motivation

- One of the most profound implications of QFT is the *Renormalization Group*
  - Parameters of the theory run
- Example: The Yukawa theory

$$S = \int d^4x \left[\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{\lambda}{4}\varphi^4 + \bar{\psi}\not{\partial}\psi - g\varphi\bar{\psi}\psi\right].$$

- Classically

$$V(\varphi) = \frac{\lambda}{4}\varphi^4$$

- But in QFT

$$V(\varphi) \approx \frac{\lambda(\varphi)}{4}\varphi^4$$

- Precise behaviour depends on the initial parameter values

$$\lambda_0 \lessgtr \frac{2g_0^2}{3} \qquad \Rightarrow \qquad \lambda(\varphi \to \infty) \to \pm\infty\,.$$

Motivation

- One of the most profound implications of QFT is the *Renormalization Group*
  - Parameters of the theory run
- Example: The Yukawa theory

$$S = \int d^4x \left[\frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - \frac{\lambda}{4} \varphi^4 + \bar{\psi} \partial\!\!\!/ \psi - g \varphi \bar{\psi} \psi \right] .$$

- Classically

$$V(\varphi) = \frac{\lambda}{4} \varphi^4$$

- But in QFT

$$V(\varphi) \approx \frac{\lambda(\varphi)}{4} \varphi^4$$

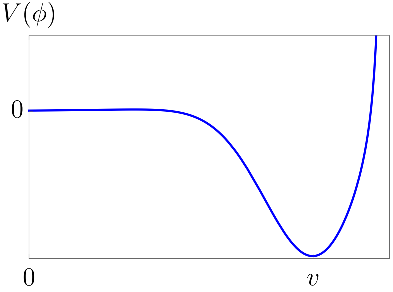
In curved space this gets modified!

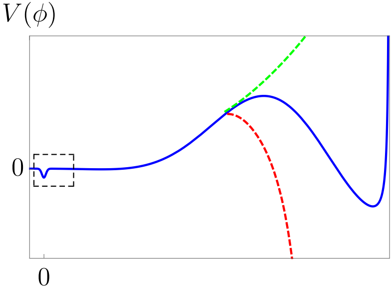
- Precise behaviour depends on the initial parameter values

$$\lambda_0 \lessgtr \frac{2g_0^2}{3} \qquad \Rightarrow \qquad \lambda(\varphi \to \infty) \to \pm\infty .$$

Standard Model Higgs potential

$$V(\phi) \approx -\frac{m^2}{2}\phi^2 + \frac{\lambda(\phi)}{4}\phi^4$$

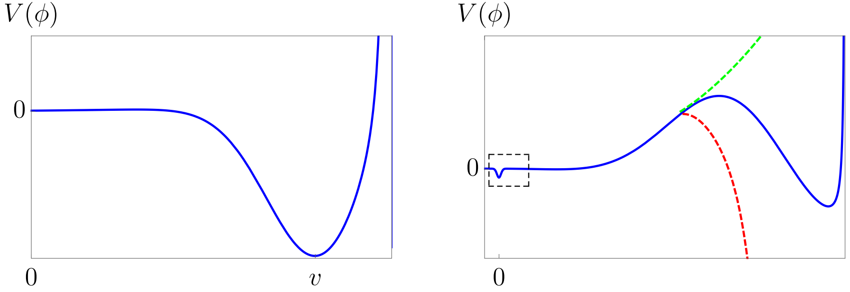




- Minimum at $\phi = v$
  - New minimum $\Leftrightarrow$ $\lambda(\phi) < 0$
  - A vacuum at $\phi \neq v$ incompatible with observations
- Sensitive to M_h and M_t

Standard Model Higgs potential

$$V(\phi) \approx -\frac{m^2}{2}\phi^2 + \frac{\lambda(\phi)}{4}\phi^4$$

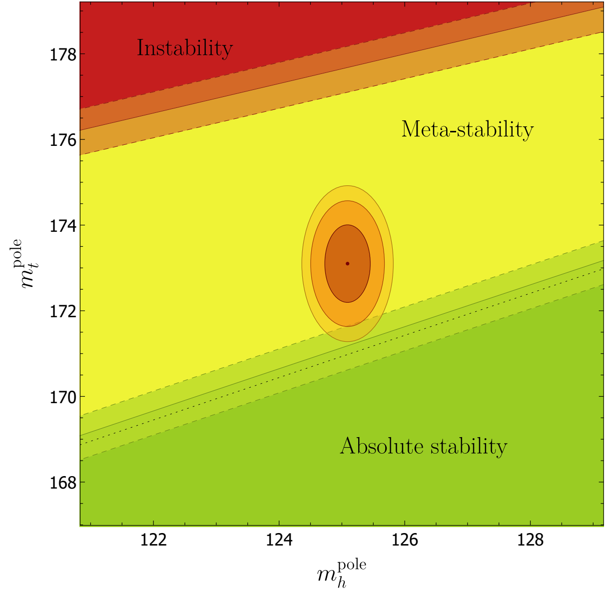


- Minimum at $\phi = v$
  - New minimum $\Leftrightarrow$ $\lambda(\phi) < 0$
  - A vacuum at $\phi \neq v$ incompatible with observations
- Sensitive to M_h and M_t

- What about the early Universe (inflation, reheating)?
- New physics needed to stabilize the vacuum?

Current status

Figure: Andreassen, Frost & Schwartz (18):



Fate of the Standard Model

- At the moment metastability is not an issue

> Andreassen, Frost & Schwartz (18):
> *With 95% confidence, we expect our Universe to last more than* 10^{58} *years.*

Fate of the Standard Model

- At the moment metastability is not an issue

> Andreassen, Frost & Schwartz (18):
> *With 95% confidence, we expect our Universe to last more than* 10^{58} *years.*

- In the Early Universe vacuum decay *can* occur
  - Provides a connection between the SM an inflation

Fate of the Standard Model

- At the moment metastability is not an issue

> Andreassen, Frost & Schwartz (18):
> *With 95% confidence, we expect our Universe to last more than* 10^{58} *years.*

- In the Early Universe vacuum decay *can* occur
  - Provides a connection between the SM an inflation
- During inflation the fluctuations of the Higgs can be calculated from (Fokker-Planck)

$$\dot{P}(t,\phi) = \frac{1}{3H}\frac{\partial}{\partial\phi}\left[P(t,\phi)V'(\phi)\right] + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(t,\phi)$$

Fate of the Standard Model

- At the moment metastability is not an issue

> Andreassen, Frost & Schwartz (18):
> *With 95% confidence, we expect our Universe to last more than* 10^{58} *years.*

- In the Early Universe vacuum decay *can* occur
  - Provides a connection between the SM an inflation
- During inflation the fluctuations of the Higgs can be calculated from (Fokker-Planck)

$$\dot{P}(t,\phi) = \frac{1}{3H}\frac{\partial}{\partial\phi}\left[P(t,\phi)V'(\phi)\right] + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(t,\phi)$$

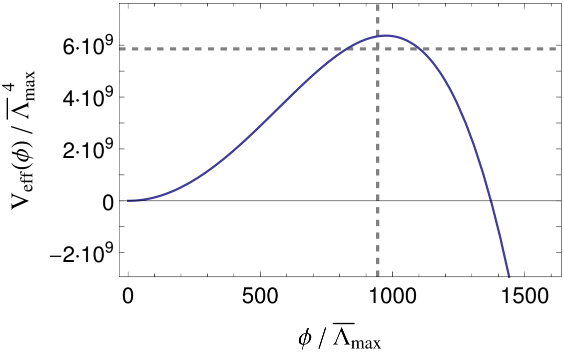
Currently actively studied!

Needs QFT in curved space!

Stabilization from curvature corrections

- The quantum corrected potential

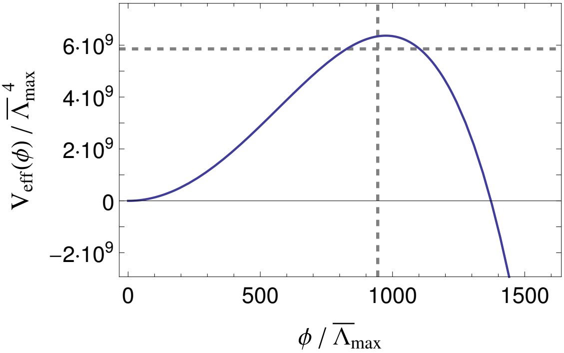
$$V_{\text{eff}}(\phi) \approx \frac{\lambda(\mu)}{4}\phi^4 + \frac{\xi(\mu)}{2}R\phi^2$$



Stabilization from curvature corrections

- The quantum corrected potential

$$V_{\rm eff}(\phi) \approx \frac{\lambda(\mu)}{4}\phi^4 + \frac{\xi(\mu)}{2}R\phi^2$$



- Even if $\lambda(\mu) < 0$, the potential can be stable due to ξ
- ξ is *generated* by quantum effects on a curved background Herranen et al. (14)

Summary

Summary

QFT in curved spacetime

- A window into quantum gravity
  - However only an approximate approach

Summary

QFT in curved spacetime

- A window into quantum gravity
  - However only an approximate approach
- Can be used to show that black holes evaporate
  - From a theoretical point very important
  - Also relevant for cosmological applications

Summary

QFT in curved spacetime

- A window into quantum gravity
  - However only an approximate approach
- Can be used to show that black holes evaporate
  - From a theoretical point very important
  - Also relevant for cosmological applications
- Crucial for studying the Standard Model in the early universe
  - The electroweak vacuum may be destabilized