Death of the Universe

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Goal: predict death of the Universe

To reach goal need to address five issues:

1. Defining “Death”
Goal: predict death of the Universe

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Wikipedia definition of “Death”:

Death is the cessation of all biological functions that sustain a living organism

Daniel Grumiller — Death of the Universe 2/13
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To reach goal need to address five issues:
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Wikipedia definition of “Death”:
Death is the cessation of all biological functions that sustain a living organism

My definition of “Death of the Universe”:
Death of the Universe is the cessation of all complex structures, including our current laws of Nature
Predicting death

Predicting my Death using death-clock.org

input: birth date, sex, cigarette and alcohol consumption, BMI, outlook and country
Predicting death

Levine 1997: on average $10^9$ heartbeats in life of mammals

Prediction is statistical — need large ensemble for meaningful statement
Defining the Universe

Universe = “all there is, was, and will be”? 
Defining the Universe

Universe = “all there is, was, and will be”? No. “All there is, was, and will be” is what we call “Multiverse”. 
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Definition of the (observable) Universe
All that can be observed (at least in principle)

More detailed definition:
- The Universe is our causal patch of spacetime and everything in it
- Key word: “causal patch” — everything we can communicate with (at least in principle)
- Excludes regions of the Universe that are not observable as well as other patches of the Multiverse (= other Universes)
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- The Universe is our causal patch of spacetime and everything in it
- Key word: “causal patch” — everything we can communicate with (at least in principle)
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- Note: “other Universes” can have laws of Nature different from ours (for instance, other number of spacetime dimensions, other fundamental interactions, other fundamental particles, ...)

Daniel Grumiller — Death of the Universe 5/13
Our Universe

To understand our Universe we need to identify

1. the fundamental constituents of matter
2. their fundamental interactions
3. a theory of spacetime
4. how much matter and energy is there
Our Universe

1. Fundamental constituents of matter

Periodic table of particles:

- Higgs discovered 2012 at CERN using LHC by ATLAS and CMS
- Gravitational waves discovered 2016 by LIGO
- Gravitons to be discovered, but no reasonable doubt about their existence
- Three light generations
- Each of them has two leptons and two quarks
- All matter particles are fermions
- Characterized by masses and charges
- Only difference between generations: masses
- Forces mediated by bosons
- Electromagnetic force: photon $\gamma$
- Weak force: vector bosons $W^\pm$, $Z^0$
- Strong force: gluons $g$
- Additionally: Higgs, graviton
Our Universe
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1. Fundamental constituents of matter

**Periodic table of particles:**

- **Quarks:**
  - 1st generation: up, charm, top
  - 2nd generation: down, strange, beauty
  - 3rd generation

- **Leptons:**
  - 1st generation: electron, muon, tau
  - 2nd generation: neutrino electron, neutrino muon, neutrino tau
  - 3rd generation

- **Gauge Bosons:**
  - photon: γ
  - W boson: W^±
  - Z boson: Z^0
  - gluon: g

- Higgs Boson: H

- **3 light generations**

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2. Fundamental interactions between fundamental constituents: Standard Model (SM)

SM of particle physics:

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} D\Psi + h.c. + \bar{\psi} Y \psi \Phi + h.c. + |D_\mu \Phi|^2 - V(\Phi) \]

- \( F_{\mu\nu} \): bosons
- \( \Psi \): fermions
- \( \Phi \): Higgs

Gravity only fundamental force
not described by SM

▶ all experiments so far agree with SM!
Our Universe

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- ridiculously high precision
  e.g. gyromagnetic factor

Experiment (2008):

$$\frac{g_{e}^{\exp}}{2} = 1.00115965218073 \pm 0.0000000000000028$$

Theory (2012):

$$\frac{g_{e}^{\text{the}}}{2} = 1.00115965218178 \pm 0.0000000000000077$$
Our Universe

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SM of particle physics:

\[ \mathcal{L} = -\frac{i}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \gamma_\mu \Psi + \text{h.c.} + \bar{\psi} i \gamma_5 \psi \Phi + \text{h.c.} + |\partial_\mu \Phi|^2 - V(\Phi) \]

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SM currently improved at LHC

\( F_{\mu\nu} \): bosons, \( \Psi \): fermions
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gravity only fundamental force not described by SM
Our Universe

3. Theory of spacetime

Theatre metaphor:

- **spacetime = stage**
Our Universe

3. Theory of spacetime

Theatre metaphor:

- spacetime = stage
- particles/interactions = actors

Gravity (as described by Einstein's General Relativity) = theory of dynamics of spacetime sourced by matter

Einstein equations:

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = T_{\mu\nu} \]

Paradigm shift in last century: spacetime is dynamical entity

- spacetime tells matter how to move
- matter tells spacetime how to curve
Our Universe
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- essence of gravity: stage becomes an actor!
Our Universe

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Our Universe

4. How much stuff is there in our Universe right now?

- SM particles account for 5%
- Dark Matter accounts for 25% (NO CLUE WHAT IT IS!)
- Dark Energy accounts for 70% (cosmological constant $\Lambda$)

Note: despite the unknown nature of dark matter, for the dynamics of our Universe only its existence and total amount are important.

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Our Universe

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Josef Pradler @ HEPHY (New Frontiers Group "Dark Matter")
Our Universe

4. How much stuff is there in our Universe right now?

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- dark matter accounts for 25% (NO CLUE WHAT IT IS!)
  - lightest dark matter candidate: axions ($10^{-41}$ kg)
  - heaviest dark matter candidate: heavy black holes ($10^{32}$ kg)
  - possible range of 73 orders of magnitude!

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Predicting the Universe

Assemble all data and predict the fate of the Universe:

- Universe is expanding (Hubble’s law)
  quantitative prediction for cosmic microwave background spectrum

- Expansion is accelerating (physics Nobel prize 2011)

- Far future dominated by dark energy

- Universe (and all structure in it) dilutes, while locally all structure collapses to black holes

- Eventually also black holes evaporate (Hawking radiation)

No life in it, but Universe itself not (yet) dead!

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  reason: energy density of matter and radiation decreases as Universe increase, but cosmological constant remains constant

![Matter-energy content of the universe](image)
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Matter-energy content of the universe:
- Dark matter 63%
- Dark energy 72%
- Photons 15%
- Atoms 12%
- Neutrinos 10%

13.7 billion years ago (universe 380,000 years old)

Today

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Is our Universe stable?
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If the Universe is unstable, its decay time must be sufficiently long.
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- From particle physics: our Universe is on the edge

Caveat: no comprehensive understanding of quantum gravity
see recent articles by Timm Wrase (summarized in Der Standard)
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Is our Universe stable?

- If the Universe is unstable, its decay time must be sufficiently long
- From particle physics: our Universe is on the edge
- From **naive** application of quantum theory to cosmology:

Positive cosmological constant makes vacuum unstable against decay into a different Universe with smaller cosmological constant

\[ \Lambda t \sim 10^{10^{123}} \]

The successor of our Universe may have different fundamental interactions, different particle species, even different dimensions, but it will have the same description of gravity, albeit with smaller \( \Lambda \)

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- If the Universe is unstable, its decay time must be sufficiently long
- From particle physics: our Universe is on the edge
- From naïve application of quantum theory to cosmology:
  Positive cosmological constant makes vacuum unstable against decay into a different Universe with smaller cosmological constant

- Mean lifetime of our Universe determined by cosmological constant $\Lambda$
  
  $t \sim 10^{1/\Lambda} \sim 10^{10^{123}}$

Big puzzle: why is $\Lambda$ so small?

  Theoretical expectation: $\Lambda \sim 1$  
  Measurement: $\Lambda \sim 10^{-123}$

  “Worst prediction in theoretical physics”
Is our Universe stable?

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- The successor of our Universe may have different fundamental interactions, different particle species, even different dimensions, but it will have the same description of gravity, albeit with smaller $\Lambda$.
- **Caveat**: no comprehensive understanding of quantum gravity.
Paradigm shift to Multiverse
Multiverse idea remains somewhat controversial

Pro multiverse:
- Having many vacua is generic

Contra multiverse:
- Having a unique vacuum is great

Quoting Steven Weinberg: 'About the multiverse, it is appropriate to keep an open mind, and opinions among scientists differ widely. In the Austin airport on the way to this meeting I noticed for sale the October issue of a magazine called Astronomy, having on the cover the headline "Why You Live in Multiple Universes." Inside I found a report of a discussion at a conference at Stanford, at which Martin Rees said that he was sufficiently confident about the multiverse to bet his dog's life on it, while Andrei Linde said he would bet his own life.'

'As for me, I have just enough confidence about the multiverse to bet the lives of both Andrei Linde and Martin Rees’s dog.'

Thanks for your attention!
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**Pro multiverse:**
- Having many vacua is generic
- Anthropic explanation of cosmological constant $\Lambda$ requires Multiverse

**Contra multiverse:**
- Having a unique vacuum is great
- Multiverse may tempt us to provide anthropic explanations instead of accurate mechanisms

Here is the principle how Steven Weinberg’s anthropic explanation works:
(ant = Universe, ensemble of ants = Multiverse, number = value of $\Lambda$)
- Take a large enough ensemble (say, 100 billion ants)
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- Kill all ants that have a number bigger than 100

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- Pick one of the remaining ants and let someone else check its number

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- That person will be surprised to learn that this number (1-100) was originally part of a large ensemble of possibilities (100 billions)
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- Same person will conclude either that you committed anticide or that there is some mechanism leading to finetuned small-ant-numbers
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Weinberg’s explanation in a nutshell:
$\Lambda$ so small because Universes with large $\Lambda$ die quickly
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- Occams razor: simpler to have an ensemble of Universes rather than a finetuned Universe

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