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"

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Wkipedia definition of "Death":

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

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My definition of "Death of the Universe":

Death of the Universe is the cessation of all complex structures, including our current laws of Nature

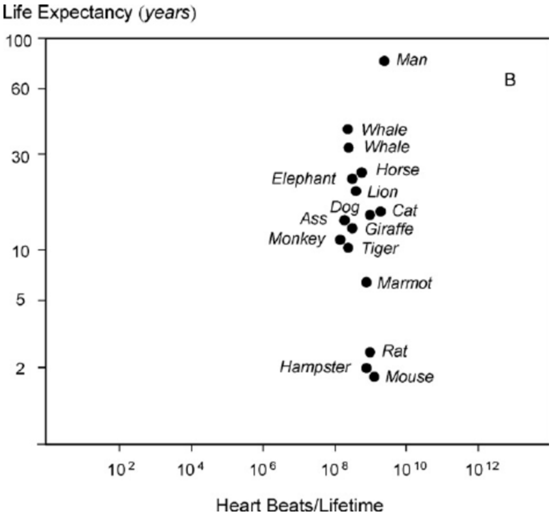
Predicting death

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

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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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- Note: "other Universes" can have laws of Nature different from ours (for instance, other number of spacetime dimensions, other fundamental interactions, other fundamental particles, ...)

Our Universe

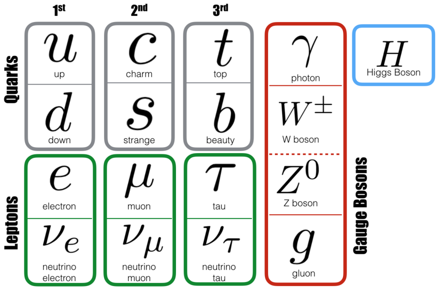
To understand our Universe we need to identify

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:



- three light generations

Our Universe

1. Fundamental constituents of matter

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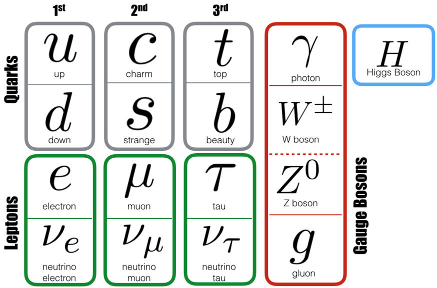

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- each of them has two leptons and two quarks

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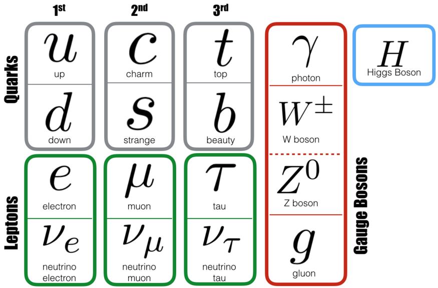

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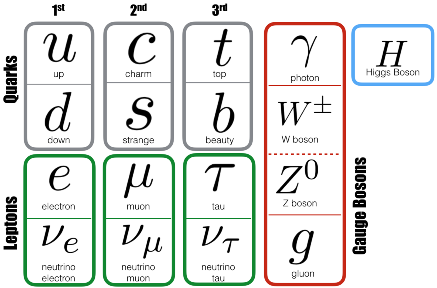

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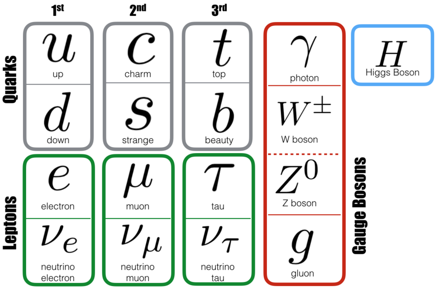

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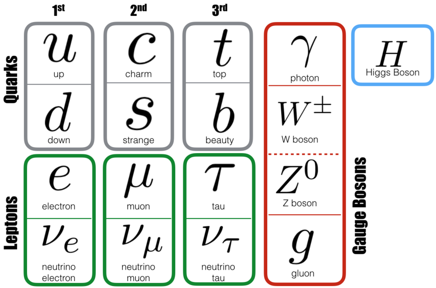

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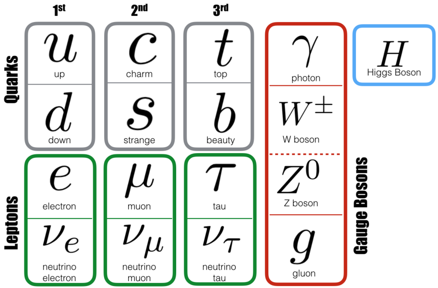

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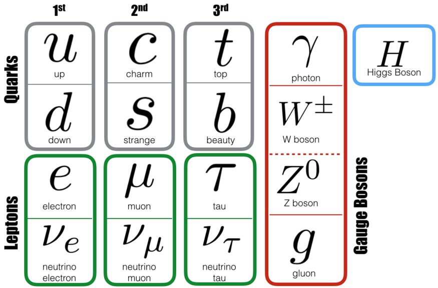

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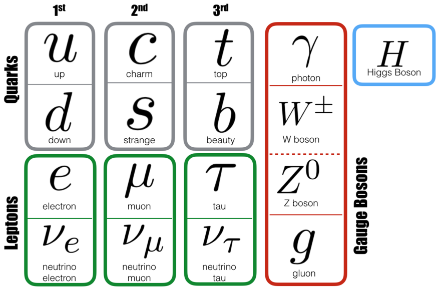

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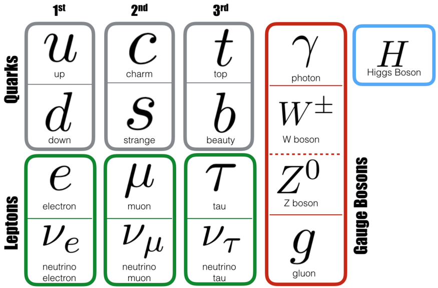

- Higgs discovered 2012 at CERN using LHC by ATLAS and CMS
- gravitational waves discovered 2016 by LIGO
- gravitons to be discovered, but no reasonable doubt about their existence

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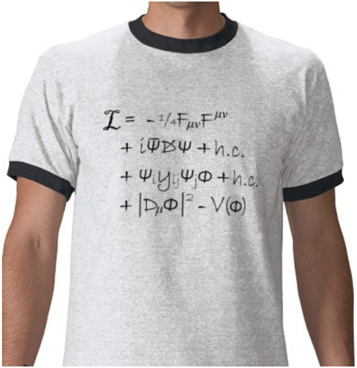
- additionally: Higgs, graviton

SM of particle physics:



$F_{\mu\nu}$: bosons, Ψ: fermions
Φ: Higgs
gravity only fundamental force not described by SM

- all experiments so far agree with SM!

Our Universe

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

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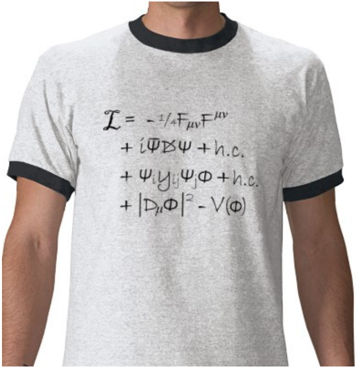

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  e.g. gyromagnetic factor
  Experiment (2008):

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Theory (2012):

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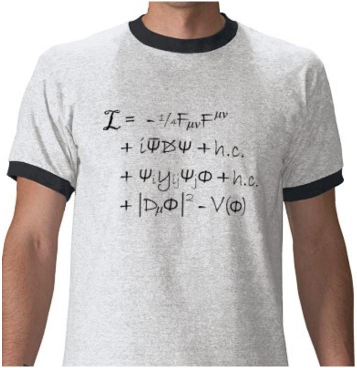

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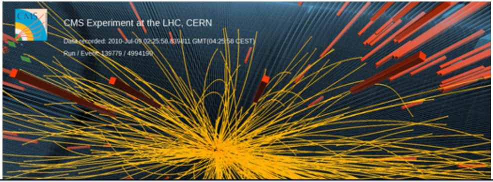
- SM currently improved at LHC



Theatre metaphor:

- spacetime = stage

Our Universe

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

Einstein equations:

$$\text{spacetime} = \text{matter} \qquad \leftrightarrow \qquad R_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu} R + \Lambda\, g_{\mu\nu} = T_{\mu\nu}$$

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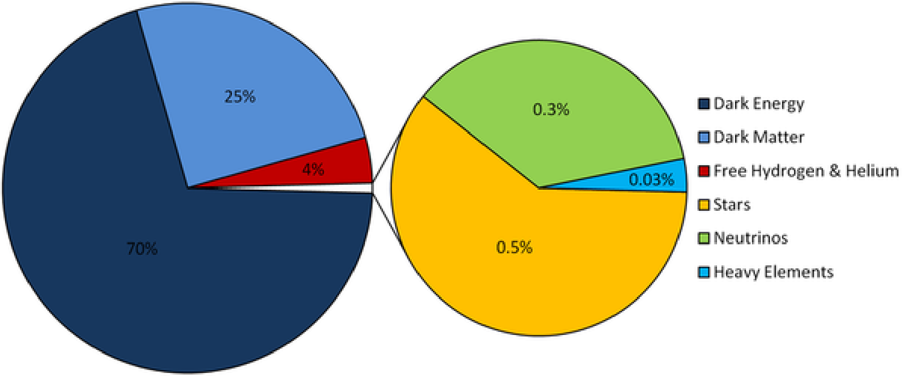
- matter tells spacetime how to curve

Our Universe

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



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Our Universe

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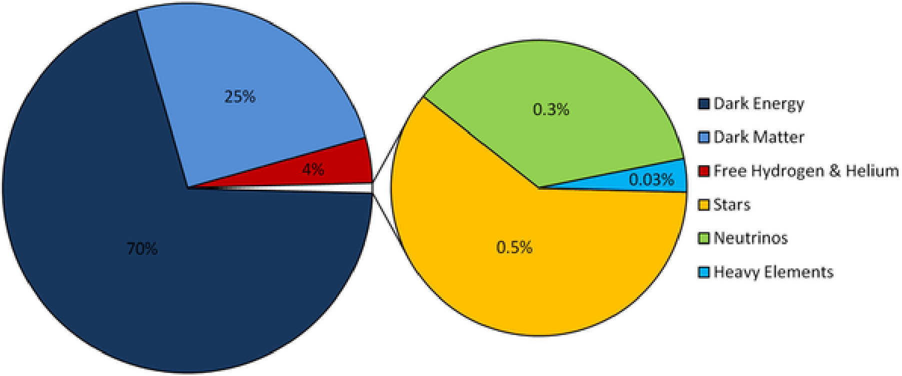

- SM particles account for 5%
- dark matter accounts for 25% (NO CLUE WHAT IT IS!)
  Josef Pradler @ HEPHY (New Frontiers Group "Dark Matter")

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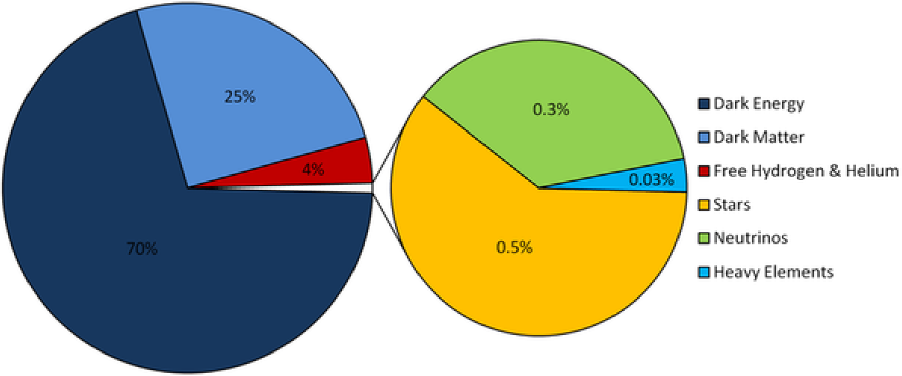

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- dark matter accounts for 25% (NO CLUE WHAT IT IS!)
  lightest dark matter candidate: axions (10^{-41} kg)
  heaviest dark matter candidate: heavy black holes (10^{32} kg)
  possible range of 73 orders of magnitude!

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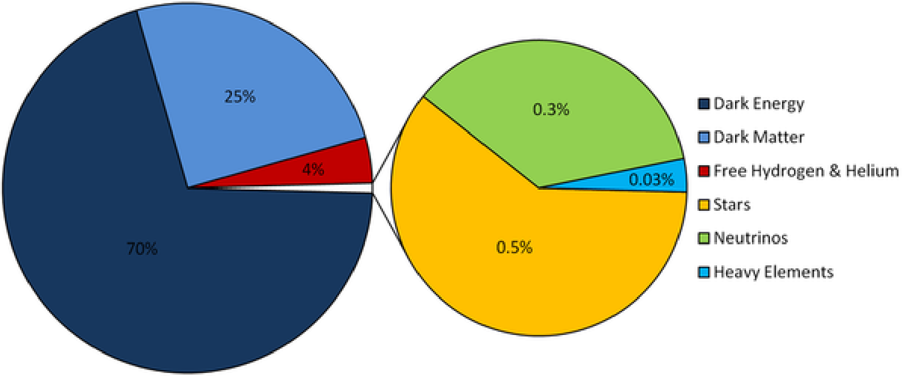

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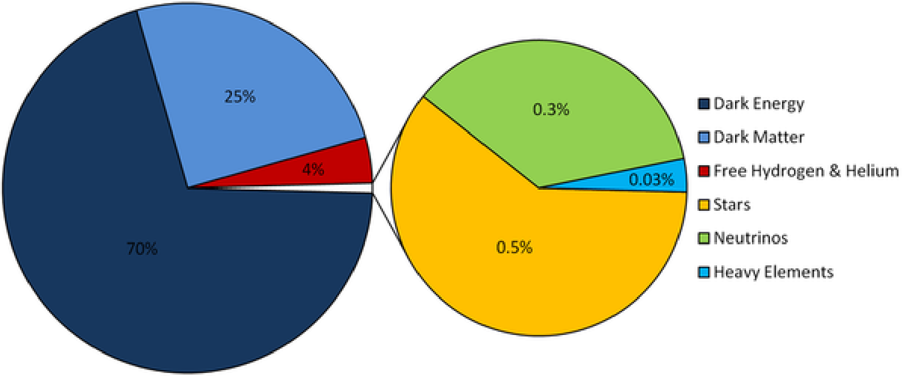

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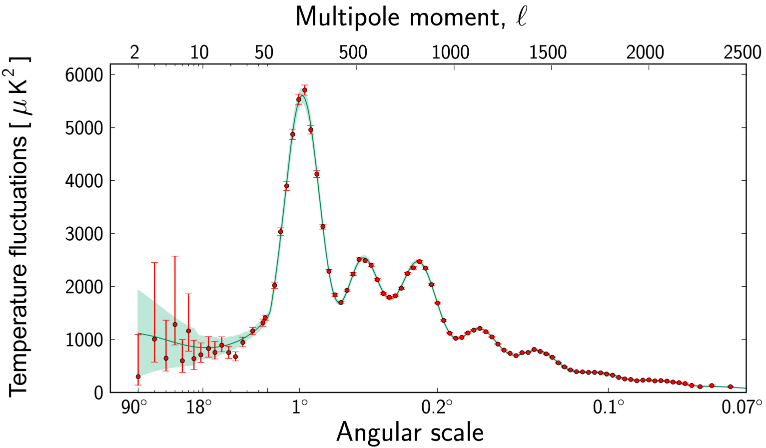
Note: despite of unknown nature of dark matter, for dynamics of our Universe only its existence and total amount are important

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



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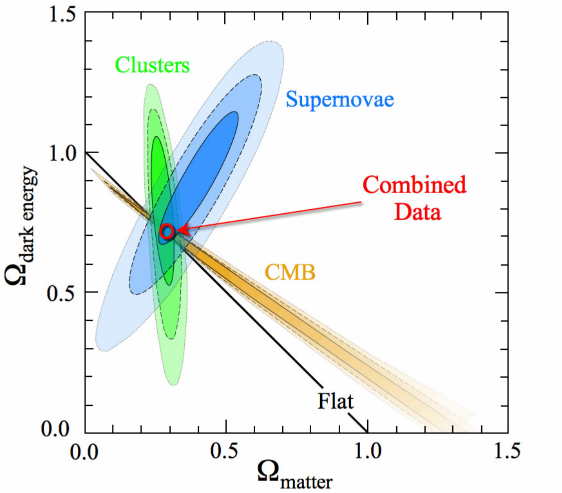

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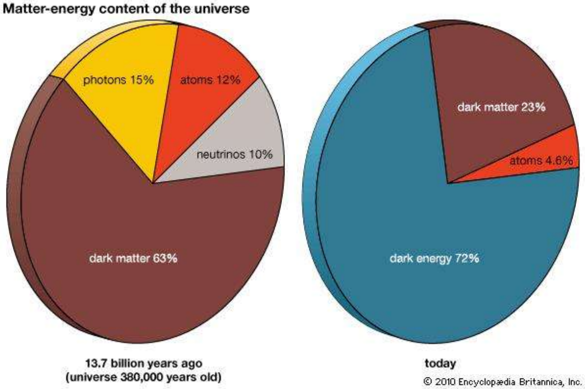
- Far future dominated by dark energy

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



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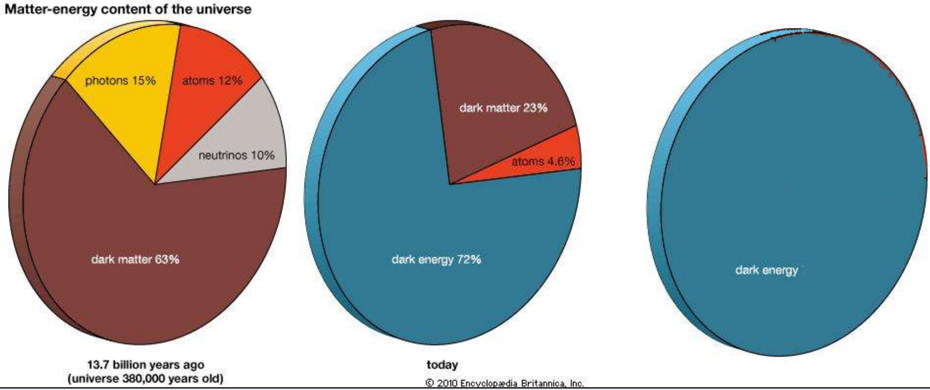

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No life in it, but Universe itself not (yet) dead!

Warning: entering zone of speculations

Is our Universe stable?

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- If the Universe is unstable, its decay time must be sufficiently long

Death of the Universe

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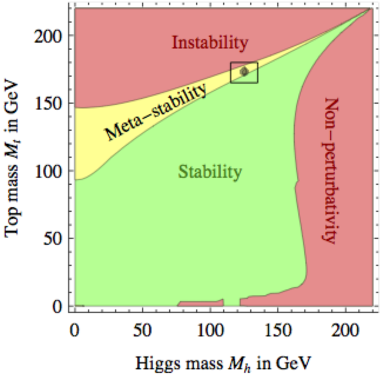
- From particle physics: our Universe is on the edge



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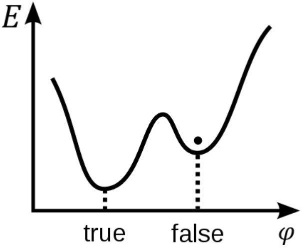
Positive cosmological constant makes vacuum unstable against decay into a different Universe with smaller cosmological constant



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- Mean lifetime of our Universe determined by cosmological constant Λ

$$t \sim 10^{1/\Lambda} \sim 10^{10^{123}}$$

Big puzzle: why is Λ so small?

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

"Worst prediction in theoretical physics"

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- **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

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- Anthropic explanation of cosmological constant Λ requires Multiverse

Contra multiverse:

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- 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 Λ)

- Take a large enough ensemble (say, 100 billion ants)

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

Weinberg's explanation in a nutshell:

Λ so small because Universes with large Λ die quickly

Paradigm shift to Multiverse

Multiverse idea remains somewhat controversial

Pro multiverse:

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- Occams razor: simpler to have an ensemble of Universes rather than a finetuned Universe

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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.’

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Thanks for your attention!