Matter in a multi-component Universe, Naturalness, & the quest for a fundamental theory

- Heinrich Päs -
Naturalness?

...what I usually get invited for to talk about:

"Asymmetric dark matter, baryon asymmetry and lepton number violation"
M.T. Frandsen, C. Hagedorn, W.C. Huang, E. Molinaro, H. Päss
arXiv: 1801.09314

"Falsifying high-scale baryogenesis with neutrinoless double beta decay and lepton flavor violation"
F. Deppisch, J. Harz. M. Hirsch, W.C. Huang, H. Päss

...what I’m usually not invited for… but still like to talk about:

"A fundamental Universe"
H. Päss
Contribution to the 2018 FQXi essay contest

"Can the many-worlds-interpretation be probed in psychology?"
H. Päss
...maybe this stuff has actually something to do with Naturalness or Fine Tuning...

...or at least could be sold this way...
What is Fine Tuning?

Fine-tuning describes unlikely coincidences on an effective level of description which are expected to be explained in a more fundamental theory.
Outline

‣ Matter in a multi-component Universe and the cosmological fine-tuning problem
‣ What is fundamental?
‣ Back to the “Naturalness question”
‣ Conclusions
Matter in a multi-component Universe
Let’s start with the 2015 Nobel prize for physics:

The New York Times

Takaaki Kajita of the University of Tokyo and Arthur B. McDonald of Queen’s University in Ontario were awarded the Nobel Prize in Physics on Tuesday for discovering that the enigmatic subatomic particles known as neutrinos have mass.
Neutrino mass and lepton number violation

Why is a non-zero \( v \) mass physics beyond SM?

EITHER  -  OR

\[
\begin{align*}
& m_D \nu_L \nu_R \\
& m_M \nu^c_R \nu_R
\end{align*}
\]

OR

\[
\begin{align*}
& m_M \nu^c_L \nu_L
\end{align*}
\]

Lepton Number Violation

New Symmetry, e.g. Lepton Number

\( LNV \)

e.g. Seesaw-I

[Minkowski’77]

Lepton Number (Violation) is at the core of the link between \( v \) mass & physics beyond SM!
Attractive scenario: Neutrino mass generation via LNV at the TeV scale

- Related to the gauge hierarchy problem? (combine where we know SM is broken down with where we expect the SM to be broken down)
- Testable @ LHC
- Testable in neutrinoless double beta decay
But: Such scenarios generate a serious cosmological problem!

- Neutrino Majorana masses: B-L violation
- Sphaleron processes: B+L violation within the SM:

- B-L violation and B+L violation: baryon asymmetry washout!
Leptogenesis in Reverse

Leptogenesis:

\[ B-L \] + \[ B+L \] → 

B Asymmetry

In Reverse:

\[ B-L \] + \[ B+L \] → 

B washout

e.g. LHC

Sphalerons

\( v_R \) decay
Large LNV @ TeV scale will washout ANY pre-existing Baryon Asymmetry, irrespective of the Baryogenesis mechanism (Leptogenesis, etc...)

[F. Deppisch, J. Harz, M. Hirsch, PRL 112 (2014) 221601]

\[ - \mu_q + \mu_H + \mu_{d_R} = 0 , \ -\mu_q - \mu_H + \mu_{u_R} = 0 , \ -\mu_\ell + \mu_H + \mu_{e_R} = 0 \]
\[ 3 (3 \mu_q + \mu_\ell) = 0 , \ 3 \mu_q + 6 \mu_{u_R} - 3 \mu_{d_R} - 3 \mu_\ell - 3 \mu_{e_R} + 2 \mu_H = 0 . \]
Any solution?
(apart from no LNV @ TeV scale)

Any what’s the relation with fine tuning or Naturalness?
Any solution?
(apart from no LNV @ TeV scale)

Any what’s the relation with fine tuning or Naturalness?

→ add a 3rd reservoir!
Fine-tuning Problems

- Gauge hierarchy problem
- Cosmological Constant problem
- Strong CP problem

*tough stuff...*
→ let’s go back to good old times…

COSMOLOGICAL FINE TUNING, SUPERSYMMETRY AND THE GAUGE HIERARCHY PROBLEM

Piotr H. Chankowski\textsuperscript{(a)}, John Ellis\textsuperscript{(b)}, Keith A. Olive\textsuperscript{(c)} and Stefan Pokorski\textsuperscript{(a)}

ABSTRACT

We study the extent to which the cosmological fine-tuning problem - why the relic density of neutralino cold dark matter particles $\chi$ is similar to that of baryons - is related to the fine-tuning aspect of the gauge hierarchy problem - how one arranges that $M_W \ll M_P$ without unnatural choices of MSSM parameters. Working in the minimal supergravity framework with universal soft supersymmetry breaking parameters as inputs, we find that the hierarchical fine-tuning is
Cosmological Fine Tuning

Why???

\[ \Omega_{DM} \approx 5.3 \Omega_B, \]
Asymmetric dark matter models

Relation between the production mechanisms of the observed baryon asymmetry and the dark matter abundance


Asymmetric dark matter, baryon asymmetry and lepton number violation


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We study the effect of lepton number violation (LNV) on baryon asymmetry, generated in the early Universe, in the presence of a dark sector with a global symmetry $U(1)_X$, featuring asymmetric dark matter (ADM). We show that in general LNV, observable at the LHC or in neutrinoless double beta decay experiments, cannot wash out a baryon asymmetry generated at higher scales, unlike in scenarios without such dark sector. An observation of LNV at the TeV scale may thus support ADM scenarios. Considering several models with different types of dark matter (DM), we find that the DM mass is of the order of a few GeV or below in our scenario.

Problem

- v mass generation @ 1 TeV
- Baryon Asymmetry of the Universe
Problem

- $v$ mass generation @ 1 TeV
- Baryon Asymmetry of the Universe
- Asymmetric Dark Matter

- eight chemical potentials
- free parameter

solved !!!
Take home message so far

*Fine Tuning and other problems may disappear once one looks at the total system instead of subsystems!*
Take home message so far

Fine Tuning and other problems may disappear once one looks at the total system instead of subsystems!
What is the total system?

Finetuning describes unlikely coincidences on an effective level of description which are expected to be explained in a more fundamental theory.

What is the fundamental theory?
What is fundamental?

“There is only one world, the natural world... There are many ways of talking about the world... Our purposes in the moment determine the best way of talking” (Sean Carroll)

- Not all models (“ways of talking”) are equally fundamental
- More fundamental models constrain the space of possibilities of the higher levels
- Hierarchy of sciences
What is fundamental?

But:

"What is the characteristic feature of life? When it goes on doing something... ...for a much longer period than we would expect an inanimate piece of matter to keep going under similar circumstances”

(Erwin Schrödinger)

- Biology is about function, not about matter
- Revise traditional concept of reductionism
- No materialistic approach, rather concept in information theory
- Rather than identifying constituents, reductionism reduces complex systems by identifying the most relevant degrees of freedom on the higher layer of reality to the degrees of freedom on a more fundamental level
Even more so when turning to Quantum Mechanics

"Only the atoms and the void are real"
(Democritus, father of atoms)

versus

"There are no quantum jumps, nor are there particles"
(H. Dieter Zeh, father of decoherence)

"Quantum theory does not require the existence of discontinuities: neither in time (quantum jumps), nor in space (particles), nor in spacetime (quantum events). These apparent discontinuities are readily described objectively by the continuous process of decoherence."

Decoherence

Whenever a quantum system is measured or coupled to its environment, the system gets entangled with both observer and environment

- As the environment is not totally known to the observer
- Loss of information about the quantum system which gets delocalized into the environment
- Consequence: superpositions decay rapidly, interference terms disappear
- Quasi-classical objects such as particles with definite localizations emerge: Quantum-to-classical transition
- Metaphor: Just like a colored optical lens, decoherence seemingly creates information by actually filtering out information

DECOHERENCE

2 disturbing consequences:

- **“Many Minds”**: the observer “splits” into multiple copies observing each possible outcome
- **“Classical reality”** is a consequence of perspective! It is not fundamental but emergent!

Result looks like mixed-state density matrix!

Schrödinger cat state: pure state

Tracing out: averaging over environment

Ensemble of eigenstates: mixed state

Tegmark 1999
DECOHERENCE

“Frog perspective”
decoherence: local, classical

“Bird perspective”
no decoherence: non-local, quantum

Tegmark, Zeh

Tegmark 1999

Schlosshauer 2007
The Quantum-To-Classical transition is **perspectival!**

All open systems experience decoherence!

There exist 2 kinds of quantum systems:

- **Isolated systems**: typically microscopic
  - no interaction with environment
  - → no decoherence

- **The Universe**: global, all encompassing
  - no outside environment, non-local “bird” perspective
  - → no decoherence
  - → true fundamental quantum state
  - → possibly even time-less (Wheeler DeWitt equation)
What can we learn about a fundamental theory by taking QM serious?

- Fundamental descriptions in modern physics sacrifice the requirement of direct observability for the sake of an observer-independent description: spacetime versus space and time, quantum mechanical wave function versus eigenstates, isospin doublets versus neutrinos and electrons.

- Thermodynamics: The emergent theory is characterized by macrostates with finite entropy.

- Entropy: Normalized logarithm of the number of microstates corresponding to a macrostate.

- A microstate is fundamental, a macrostate is not.

- Zero-entropy defines a concept of fundamentality that is more general than the spoiled constituent concept of traditional reductionism.
Identifying the fundamental concept

- Turning back to QM: During the quantum-to-classical transition the von-Neumann entropy increases as a consequence of information loss into the environment.
- The fundamental state of the Universe cannot be a constituent.
- It has to be the entangled system of observer, measured system and environment, i.e.:

**The fundamental system is the quantum Universe itself!**
Lessons for the quest for the Theory of Everything

A heretic (and very vague) idea:

‣ Will the hierarchy of sciences starting from Sociology and Economy, over Psychology, Biology, Chemistry to Atomic physics, Nuclear Physics and Particle Physics will continue towards String Theory, where particles are described as excitations of localized, one-dimensional objects?

‣ Or will it be more promising to try to derive the Standard Model of particle physics directly from a non-local concept such as the wave function of the Universe in Quantum Cosmology?

‣ Could this be obtained by identifying our perspective onto the Universe, by realizing that:

   \[
   \text{Reality} = \text{Universe} + \text{Perspective}
   \]
Coming back to naturalness

Adopting universal applicability of quantum mechanics, in this framework the behavior of subsystems can be understood as the perspectival experience of an entangled quantum Universe perceived through the "lens of decoherence". In this picture the fundamental reality is non-local!

- “Unexpected correlations” reminiscent of Bell states (maximally entangled 2-Q-bit states):
  \[ |\Phi^+\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B) \]
  \[ |\Phi^-\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |0\rangle_B - |1\rangle_A \otimes |1\rangle_B) \]
  \[ |\Psi^+\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B) \]
  \[ |\Psi^-\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B) \]

- “Conspiracy”: Related to fine tuning?

- Dramatic change of probability distribution in theory space (talks by Wells and Hossenfelder)
Typical strategies to deal with fine tuning:

- symmetries: when looking at a macrostate permutations among microstates look like symmetries → emergent?
- or multiverse + anthropic reasoning: only 1 example of discussing the role of our perspective onto the Universe (and not a very interesting one as information about the fundamental state/the multiverse itself is very limited)
- Compare: Bain (relation of naturalness and emergence), Hossenfelder (still looking for better explanations but not with unjustified probability distributions), Jegerlehner (giving up scale autonomy)
- Aristotle quote by Williams: “Look for precision in each class of things”, “scale autonomy”: separation of classes may not be appropriate for a fundamental theory!
More Plato, less Aristotle!

“Plato’s thinking pursues only ‘the One’”  (Karl Albert)
What seems problematic and/or finetuned when looking at the subsystem may be resolved when one takes into account the total system.

Trivial example: Lepton Number Violation can lead to Baryon Number washout, LNV + Asymmetric Dark Matter + Baryons works.

Finetuning: unlikely coincidence in EFT to be explained in fundamental theory.

Quantum cosmology: Fundamental theory = Quantum Universe.

Reality = Universe + Perspective.

Vague idea: Fine-tuning: Artefacts of our perspective?

Prominent example of apparent conspiracy: EPR correlations.
Reduced density matrix: $\rho^r$

- **consider** $\rho = |\psi><\psi| \text{ in basis } |a>$:
  $$\rho_{a'a} = <a'|\psi><\psi|a> \equiv \psi(a')\psi^*(a)$$

- **total system combined from 2 entangled subsystems:**
  $$\rho_{a'b'ab} = \psi(a,b)\psi^*(a',b')$$

- **observable $L$ acting only on $a$-subsystem:**
  $$L_{a'b'ab} \equiv L_{a'a}\delta_{b'b}$$

- **⇒ expectation value:**
  $$<L> = \text{Tr}(\rho L) = \sum_{a,b,a',b'} \psi^*(a',b')L_{a'a}\delta_{b'b}\psi(a,b)$$
  $$= \sum_{a',a} \sum_{b'} \psi^*(a',b')\psi(a,b')L_{a'a} \equiv \sum_{a',a} \rho^r_{a'a} L_{a'a}$$

*By looking only at the $a$-subsystem we “trace out”/”average over” the degrees of freedom of the remainder of the system!*