Some PPPs (particle physics puzzles)

- What’s up with neutrinos?
- What is dark matter?
- What is dark energy?
- Where does inflation come from?
- Why is there more matter than antimatter?
- Are there even more fundamental entities than quarks and leptons?
- Are there unknown forces?
Neutrinos DISAPPEAR!

- Originally discovered by Ray Davis: there are too few neutrinos coming from the sun

- Original experiment in Homestead Mine (Cl): Only 1/3 of expected flux

- Confirmed by Sage, Gallex, Super-K, SNO, ...

- Confirmed with reactors: Bugey, Chooz, KamLand,... and accelerator neutrinos (T2K, NOvA,...)

- Also found disappearance of $\mu$-neutrinos in atmosphere: Super-K.
Kamiokande, Super-K

- Detect neutrinos from sun and atmospheric neutrinos
- Only 50% of solar vs
- Detection via Cherenkov Light
SNO

- Heavy Water Cherenkov detector
- Sensitive to all 3 types of $\nu$'s with different observables:
  \[ d + \nu_e \rightarrow p + p + e^\gamma; \]
  \[ d + \nu_\mu \rightarrow p + n + \nu_\mu \]
- First unambiguous confirmation that total number of $\nu$'s from sun is as expected - only flavor changes
The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"
Explanation: 2 – neutrino model

\[ P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \text{ (natural units)} \]  

\[ P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2 (2\theta) \sin^2 \left( 1.27 \frac{\Delta m^2 L}{E} \left[ \frac{\text{eV}^2}{\text{[km]}}, \frac{\text{km}}{\text{[GeV]}} \right] \right) \]  

- The mass differences, \( \Delta m^2 \), are known to be on the order of \( 1 \times 10^{-4} \) eV\(^2\)
- Oscillation distances, \( L \), in modern experiments are on the order of kilometers
- Neutrino energies, \( E \), in modern experiments are typically on order of MeV or GeV.
uncertainties. There are no best-fit values in the inverted mass hierarchy and lower $\theta_{23}$ octant because the likelihood has no local maximum in this hierarchy-octant region, as will become clear in Fig. 14. The $\chi^2$ for the overall best fit is 84.6 for 72 degrees of freedom.

The precision measurements of $\sin^2 \theta_{23}$ and $\Delta m_{23}^2$ come from the $\nu_\mu$ disappearance data. A fit to these data alone gives essentially the same values for these parameters in the normal mass hierarchy. However, the best joint $\nu_\mu - \nu_e$ fit pulls the value of $\Delta m_{23}^2$ up by $0.04 \times 10^{-3} \text{eV}^2 = 1.4$ from the $\nu_\mu$ disappearance-only fit in the inverted mass hierarchy.

2. Two-dimensional contours and significance levels of single parameters

All of the contours and significance levels that follow are constructed following the unified approach of Feldman and Cousins [56], profiling over unspecified physics parameters and systematic uncertainties.

Figure 10 shows the 1, 2, and 3σ two-dimensional contours for $\Delta m_{23}^2$ and $\sin^2 \theta_{23}$, separately for each mass hierarchy. Figure 11 shows a comparison of 90% confidence level contours for these parameters in the normal mass hierarchy for NOvA, T2K [7], MINOS [6], IceCube [57], and Super-Kamiokande [58]. All of the experiments have results consistent with maximal mixing.

Note that the range 0.4 to 0.6 in $\sin^2 \theta_{23}$ corresponds to the $23^\circ$ range for $\theta_{23}$.

2.0
2.2
2.4
2.6
2.8
3.0

σ

1σ

2σ

3σ

NH

23

θ

sin

0.3
0.4
0.5
0.6
0.7

σ

1σ

2σ

3σ

IH

FIG. 10. Regions of $\Delta m_{23}^2$ vs $\sin^2 \theta_{23}$ parameter space consistent with the $\nu_e$ appearance and the $\nu_\mu$ disappearance data at various levels of significance. The top panel corresponds to normal mass hierarchy, and the bottom panel corresponds to inverted hierarchy. The color intensity indicates the confidence level at which particular parameter combinations are allowed.

FIG. 11. Comparison of measured 90% confidence level contours for $\Delta m_{23}^2$ vs $\sin^2 \theta_{23}$ for this result (black line; best-fit value, black point), T2K [7] (green dashed), MINOS [6] (red dashed), IceCube [57] (blue dotted), and Super-Kamiokande [58] (purple dash-dotted).
Deficiencies of the Standard Model

The Standard Model is really successful, but...

• Does (fundamental particle rest) mass really come from the Higgs field?

• Why are the masses so vastly different?
  Lowest mass neutrino eigenstate $\nu_1 \rightarrow 0.01 \text{ eV}$
  Highest mass quark $t$ (top quark) $\rightarrow 170,000,000 \text{ eV}$

• Why are there so many “fundamental” particles? (6 leptons, 6 quarks, $1+3+8+1$ gauge bosons, Higgs,…). Or are there even more???

• Why are interactions so different in strength? (Gravitation is feeble compared to electroweak and strong interactions)

• How can we reconcile gravity with quantum field theory and the other 3 interactions?

• ALL IN ALL, why are there so many parameters? (12 fermion masses, 8 mixing angles, $4+1+1$ interaction parameters,…). And why are they so finely tuned to allow ordinary matter to exist in our Universe?

• What is the dark matter and dark energy observed in the Universe?
Deficiencies of the Standard Model

We observe much more gravitation in the Universe than can be explained by visible mass (and even by all hadronic and leptonic mass left over from the big bang) → WIMPs.

Frank Wilczek
Deficiencies of the Standard Model

Gravitation - what happens at the Planck Scale?

- The Planck Scale - a universal size, time and energy scale
  - Einstein: \( E^2 = m^2 c^4 + p^2 c^2 \Rightarrow E \geq pc \)
  - Heisenberg: \( \Delta p \cdot \Delta x \geq \hbar/2 \Rightarrow E \geq pc \geq \hbar c/2\Delta x \)
  - Newton: \( U_{\text{grav}} = m GM/r \Rightarrow \) Escape velocity \( v_{\text{esc}} = (2GM/r)^{1/2} \leq c \Rightarrow \)
    Black hole: Schwartzschild radius \( R = 2GM/c^2 \)
  - Einstein: \( M \leftarrow E/c^2 \Rightarrow R = 2GE/c^4 \geq 2G\hbar/(2c^3 R) \)
  - \( \Rightarrow \) Planck length: \( R = (G\hbar/c^3)^{1/2} = 1.6 \cdot 10^{-35} \text{ m} \);
    Planck Mass 22\( \mu \)g (10^{19} \text{ GeV})
    Planck Energy 2\cdot10^9 \text{ J}
- What happens at the Planck Scale?
  - Space-Time becomes “frothy”
  - Pointlike interactions make no sense
  - Pointlike particles make no sense
Supersymmetry

• Fundamental Space-Time-Spin symmetry
• Every Particle has a Super-Partner of different spin (different statistics!):
  – Fermions (S = 1/2) ↔ sFermions (S = 0)
    • sneutrinos, selectrons, smus, staus, squarks
  – Bosons (S = 0,1,2) ↔ Bosinos (S = 1/2)
    • winos, zino, photino, gluino, gravitino, higgsino
• May explain dark matter (WIMPs = lightest Super-partner)
• Supersymmetry is broken at high energy scale (1 TeV?) - should be accessible at LHC
Supersymmetry - some (minor?) problems

• Now we are supposed to **double** the number of particles (not a single one has been detected yet)? First LHC run came up empty!

• Add to that a whole bunch of other parameters and possibly new interactions (sfermion decays, quark decays -> proton should be unstable, but so far only upper limits have been found)

• Why is supersymmetry broken, and why is it broken at yet another mass scale?
Super-Strings

- All particles are vibrations of incredibly tiny strings (of size of the Planck scale, $10^{17}$ times smaller than resolution of present accelerators). Tension = $10^9\text{J}/10^{-35}\text{m} = 10^{40}$ tons
- They are “wrapped” around extra dimensions
- Their vibrational energies determine their masses.
- Vibration patterns determine charges and spin (determined by geometry of extra dimensions).
- Original idea: Kaluza-Klein.
Super-Strings

- Require 9+1 dimensions to avoid negative probabilities
- Extra dimensions “curled up”
- “Calabi Yau Spaces”
- Compare to ants on a hose
Super-String Theory

- Unified picture of all four interactions
- Avoids singularities in particle interactions - you can’t make them smaller than the Planck Length
- Includes Supersymmetry “automatically”
- Could be compatible with all 4 forces uniting in strength at the Planck scale
- Might explain beginning of Universe
Super-Strings - some (minor?) Problems

- Nobody can write down the exact theory (equations aren’t fully known)
- Only approximate solutions known
- Many competing versions (Brane theory...) -> too many solutions
- Presently hard to see how we can test them experimentally

But the same calculations confirmed that string theory could have a vast number of solutions, each representing a different universe with slightly different laws of physics. The detailed characteristics of any particular one of these universes — the laws that describe the basic forces and particles — might be decided by chance.

As a result, string theorists and cosmologists are confronted with what Dr. Leonard Susskind of Stanford has called “the cosmic landscape,” a sort of metarealm of space–times. Contrary to Einstein’s hopes, it may be that neither God nor physics chooses among these possibilities, Dr. Susskind contends. Rather it could be life.

Only a fraction of the universes in this metarealm would have the lucky blend of properties suitable for life, Dr. Susskind explained. It should be no surprise that we find ourselves in one of these. “We live where we can live,” he said.

Dr. Susskind conceded that many colleagues who harbor the Einsteinian dream of predicting everything are appalled by that notion that God plays dice with the laws of physics.

Among them is Dr. David Gross, director of the Kavli Institute of Theoretical Physics in Santa Barbara, Calif., who said, “I’m a total Einsteinian with respect to the ultimate goal of science.” Physicists should be able to predict all the parameters of nature, Dr. Gross said, adding, "They're not adjustable."