New Physics from neutrino mass

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Australian Government
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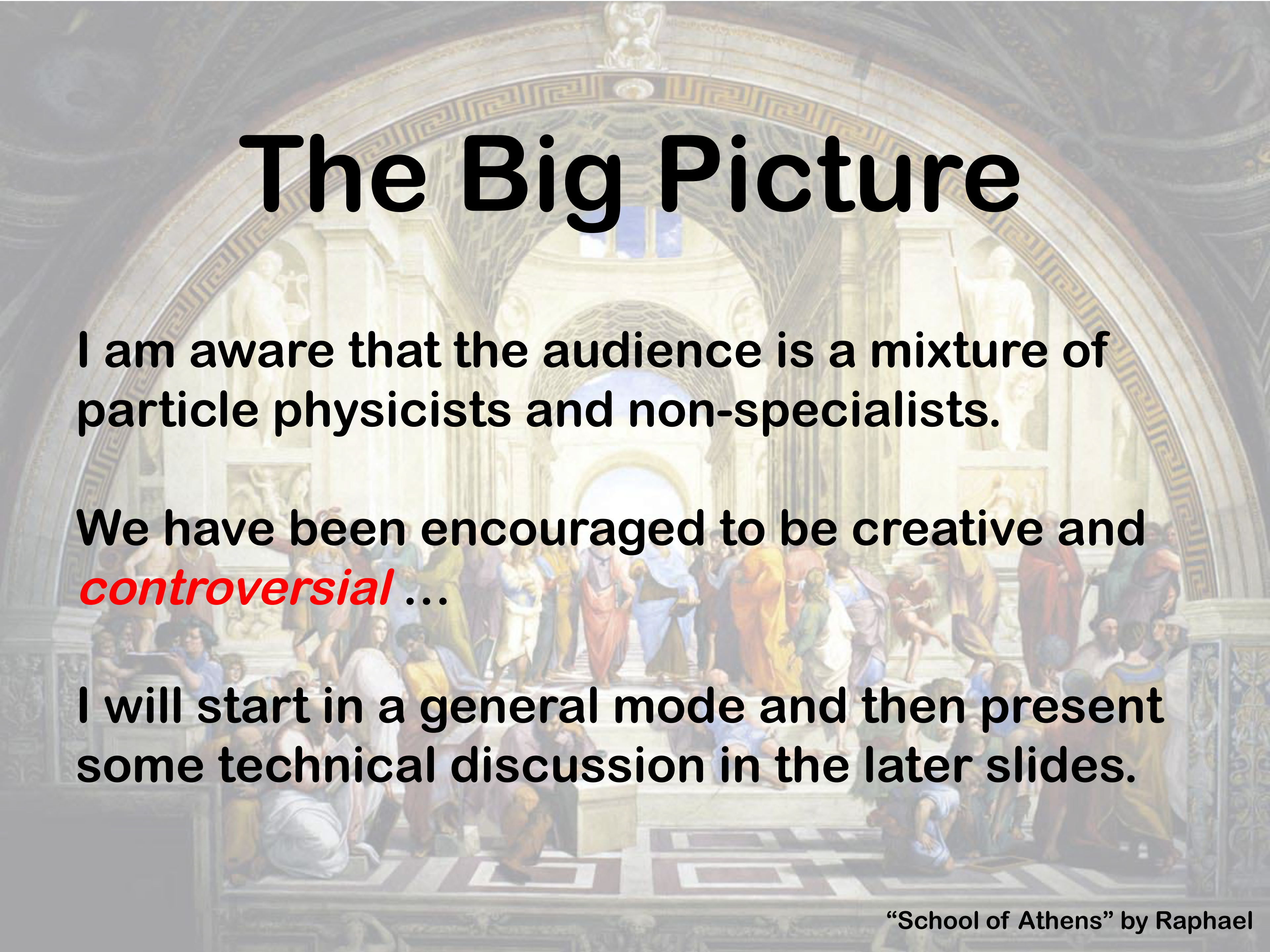


The Big Picture

I am aware that the audience is a mixture of particle physicists and non-specialists.

We have been encouraged to be creative and ***controversial*** …

I will start in a general mode and then present some technical discussion in the later slides.

“School of Athens” by Raphael

We have a wonderful theory called the "standard model" of particle physics.

It describes how the known elementary particles interact under the strong, weak and electromagnetic forces.

The famous "Higgs mechanism" (Nobel Prize 2013) explains how these particles gain mass (Wed. morning session).

But the SM is known to be incomplete.

Our goal is to discover what the bigger, better theory is.

Artist: Peter Kennedy
Title: Light rain – and everything we know about the universe (except gravity)
Image credit: National Gallery of Victoria, Australia

How do we know?

Empirical proofs: ***Nonzero neutrino masses.***
Dark matter (next session).

Empirical near-proofs:
Cosmological matter-antimatter asymmetry.
Fine-tuned cosmology.
Strong CP problem.
Dark energy (cosmology session).

Theoretical shortcomings:

Proliferation of parameters, replicated quark-lepton families, no gravity, "naturalness" concerns, …

Controversial statement #1:

The best motivations for "beyond standard model" physics are empirical, not theoretical.

Brief (and very incomplete) history of the neutrinos.

1930: Invention

Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

ges. W. Pauli

Image credit: Physics Stack Exchange

Dear Radioactive Ladies and Gentlemen,
as the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant . W. Pauli, December 1930

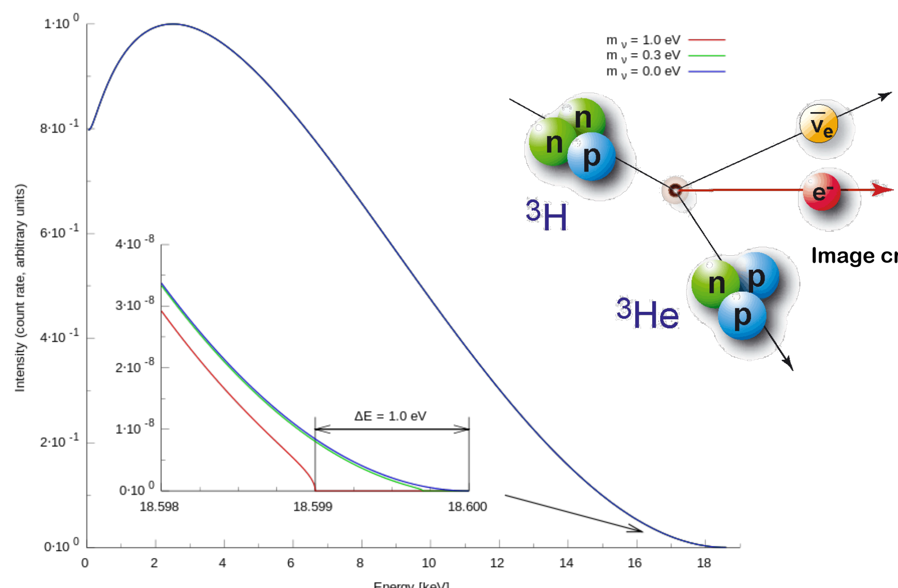
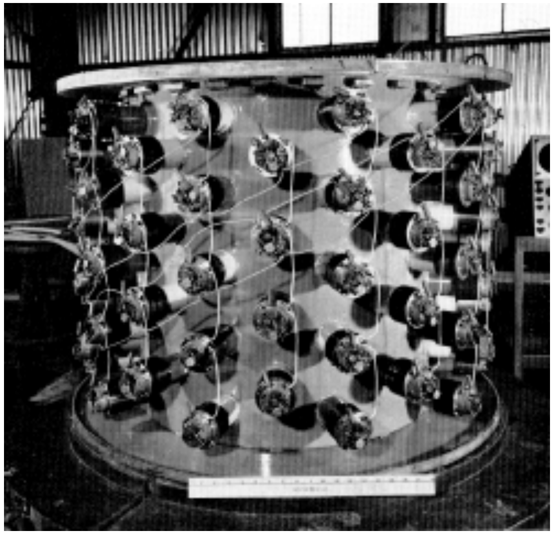
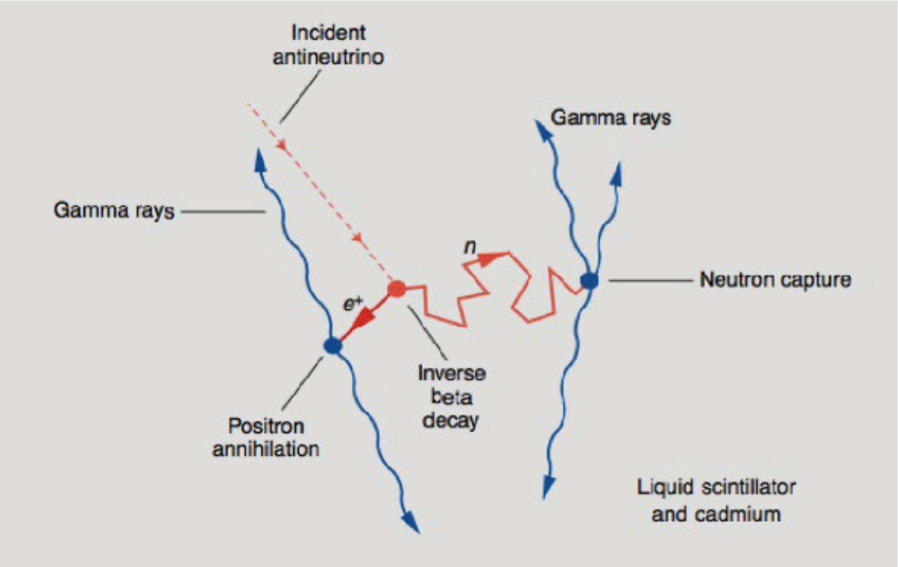


Image credit: U Utah

Image credit: Zykure

1956: Discovery





Cowan, Reines et al
Nobel Prize 1995

Image credit: Los Alamos Science

1962: There's more than one!

$$n \to p + e^- + \bar{\nu}_e$$

neutron decay

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

muon decay
pion decay

different, though similar, particle

Lederman, Schwartz, Steinberger: Nobel Prize 1988

We now know that there are 3 types or "flavours": $\nu_e, \quad \nu_\mu, \quad \nu_\tau$

They are paired with: $e, \quad \mu, \quad \tau$

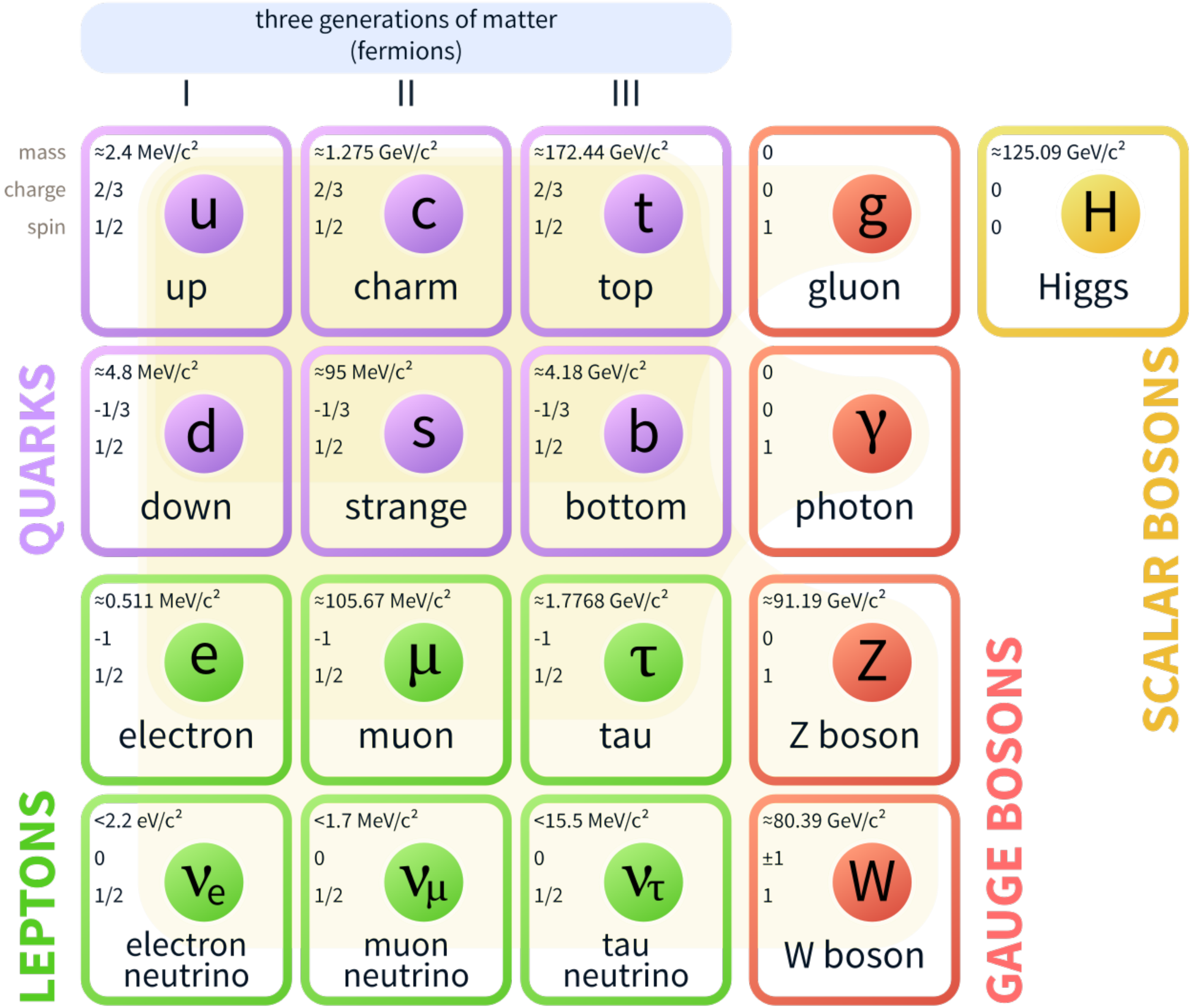
Also, we have quarks: $u, \quad c, \quad t$

$d, \quad s, \quad b$

Uncontroversial statement #1:

We (the theorists) have been banging our heads against the wall for decades trying to find a reason for the existence of these three families!

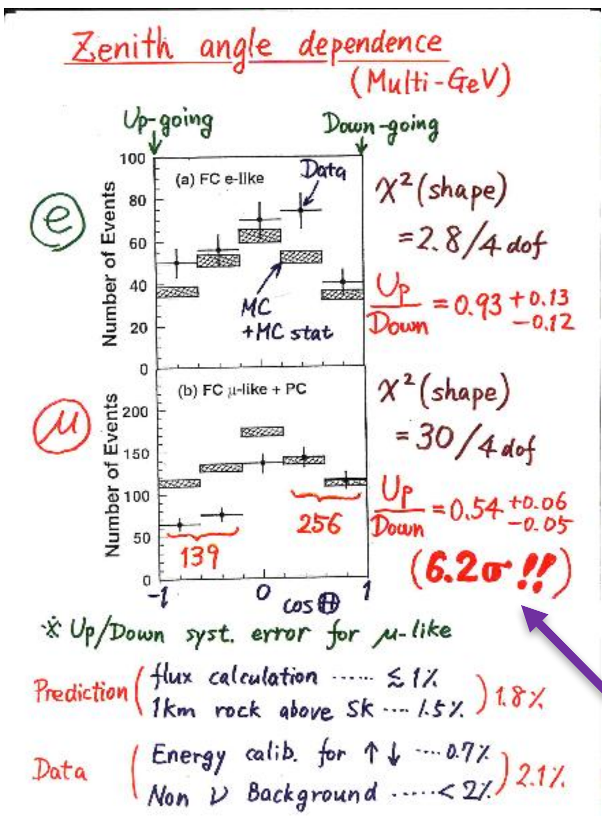
Standard Model of Elementary Particles



1970-present: Neutrinos oscillate!

A glorious experimental triumph that the next set of speakers will discuss.

Nobel Prize 2002: Ray Davis and Masatoshi Koshiba
Nobel Prize 2015: Takaaki Kajita and Art McDonald (of Canada!).



Neutrino oscillations prove three things:

- *neutrinos have mass*
- *the masses are different*
- *$\nu_{e,\mu,\tau}$ are not states of definite mass themselves – they are quantal superpositions of mass eigenstates $\nu_{1,2,3}$*

Talk by T. Kajita at Neutrino 1998, Takayama, Japan

Why are neutrinos important?

Beta decay radioactivity:

This is where the story began! Fission reactors produce copious electron antineutrinos from neutron decay (used for experiments).

Thermonuclear fusion in the sun:

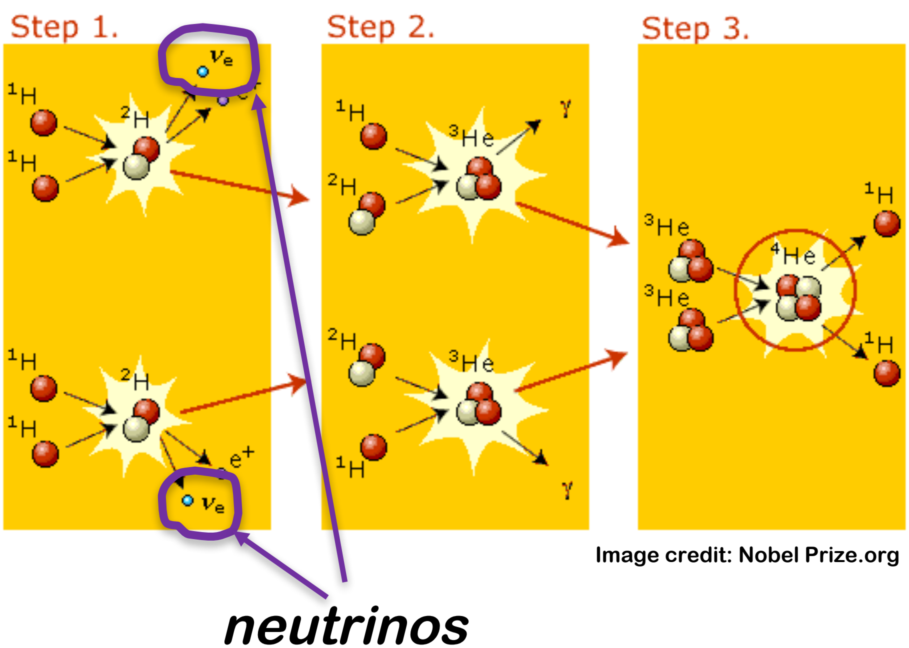


Image credit: Nobel Prize.org

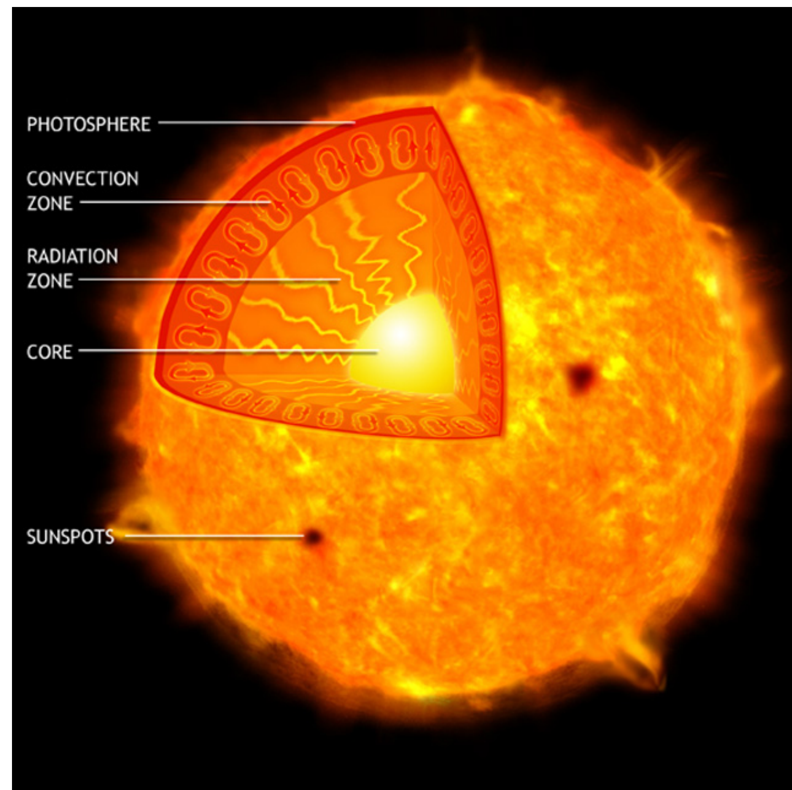
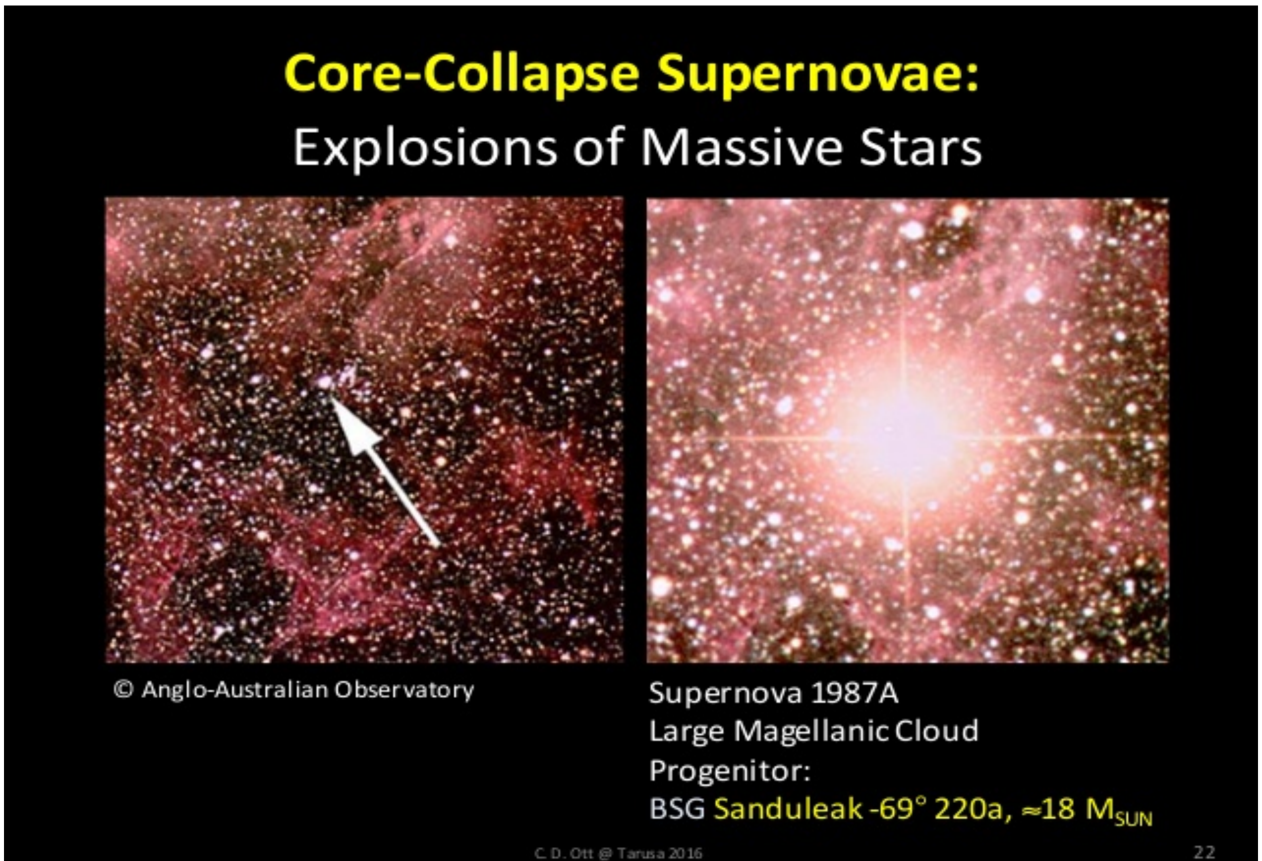


Image credit: NASA

Core-collapse supernovae:

When nuclear fuel is used up, some stars collapse to form neutron stars. They shed gravitational binding energy in light and neutrinos.

Neutrinos carry away 99% of this energy!!



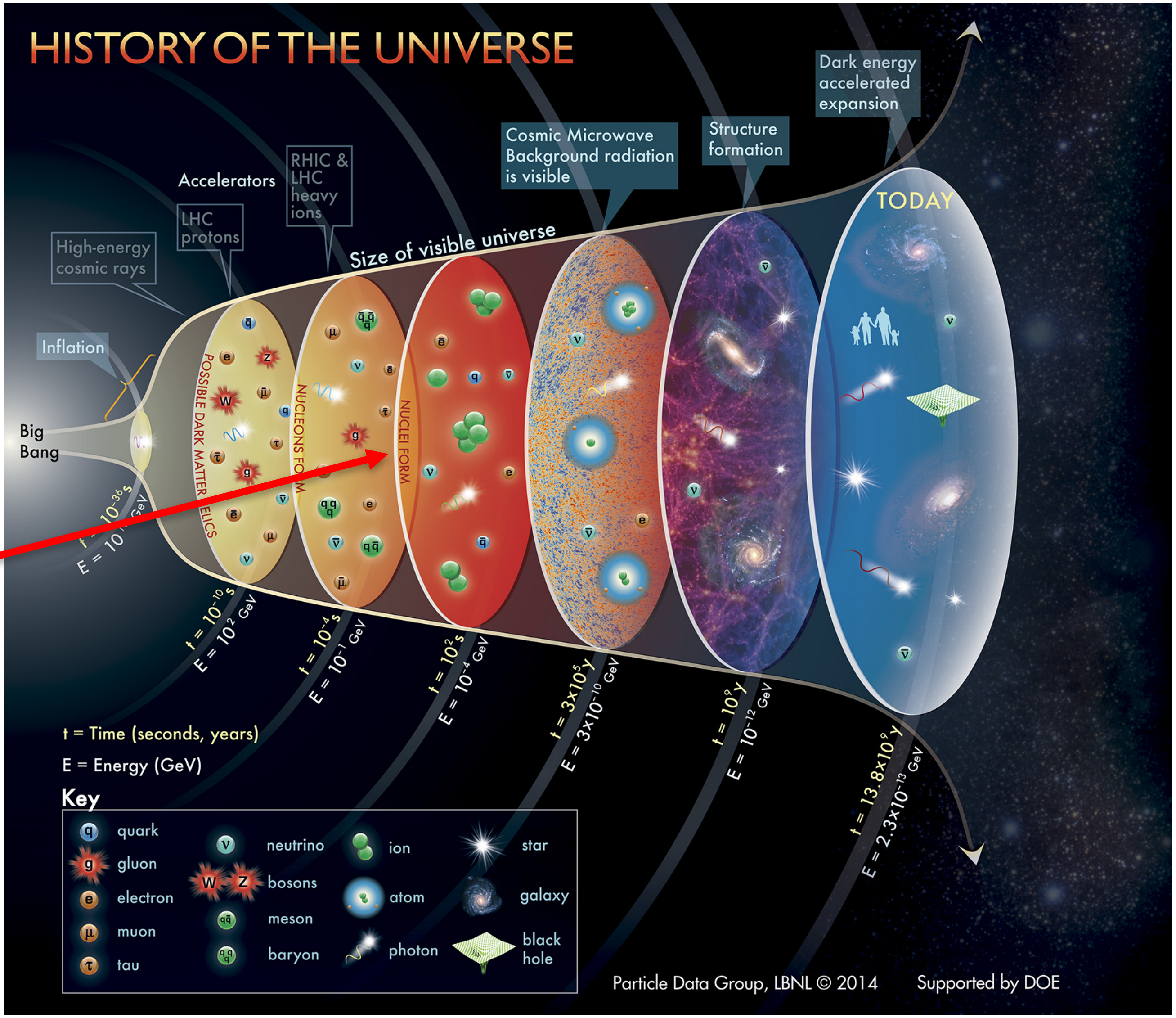
The famous optical display is just a sideshow.

Cosmology:

$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$\nu_e + n \leftrightarrow e^- + p$$

Neutrinos help determine the n/p ratio and hence the He/H ratio in the universe.



Neutrinos also help drive the expansion of the universe during big bang nucleosynthesis.

Neutrinos are special!

Neutrinos have zero electric charge – only interact via the weak force.

Neutrinos may be the only fermions (matter particles) that are their own antiparticles (Majorana fermions).

Neutrinos are very long lived. The lowest mass eigenstate is probably completely stable.

Neutrino mass is tiny: 0.05 eV < m_ν < 0.25 eV
Compare electron mass $m_e = 0.511 \times 10^6$ eV.

The neutrino mass puzzle.

Origin of elementary particle masses.

Quarks, charged leptons, W and Z bosons:

mass = coupling strength x 174 GeV

dimensionless number

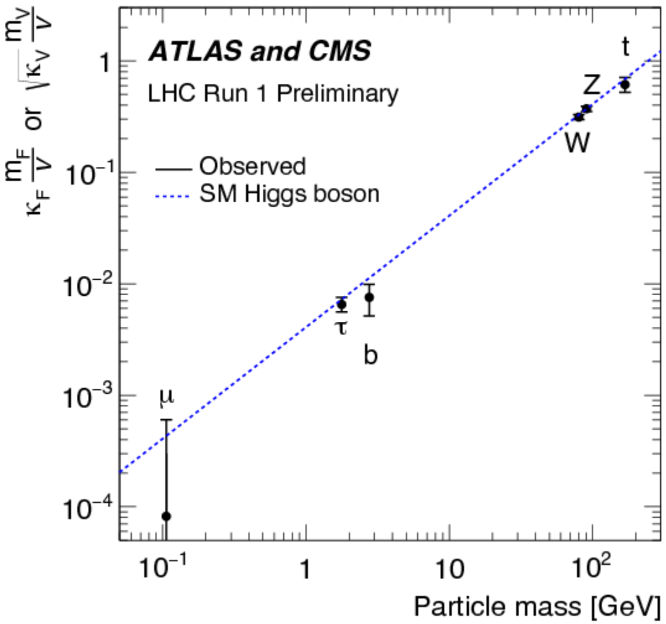
Higgs "vacuum expectation value"

top quark coupling $\simeq$ 1

electron coupling $\simeq 3\times10^{-6}$ (not proven)

$m_\nu \sim 0.1$ eV $\Rightarrow$ neutrino coupling $\simeq 6\times10^{-12}$???

Considered unsatisfactory. Finding a deep reason for the tiny neutrino masses dominates the research.



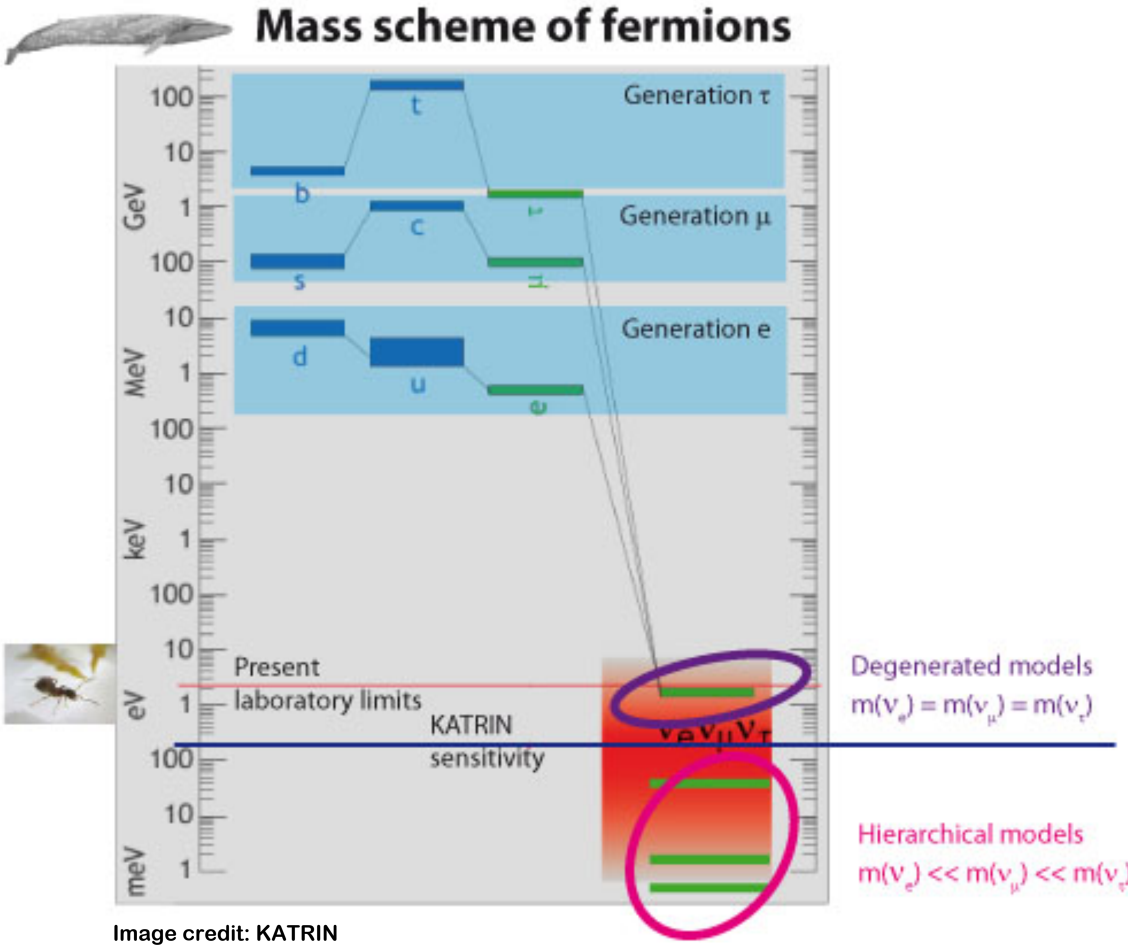


Image credit: KATRIN

The next several slides will be technical.

Recent global fits to neutrino flavour-transformation data:

Esteban+ 1611.01514, JHEP 1701 (2017) 087
Capozzi+ 1601.07777, NPB 908 (2016) 218
Forero+ 1405.7540, PRD90 (2014) 093006

Definition of PMNS matrix:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$\nu_{1,2,3}$
mass
estates
$m_{1,2,3}$

Δm^2_{12} = solar
$\Delta m^2_{32} \sim \Delta m^2_{31}$ = atmos.

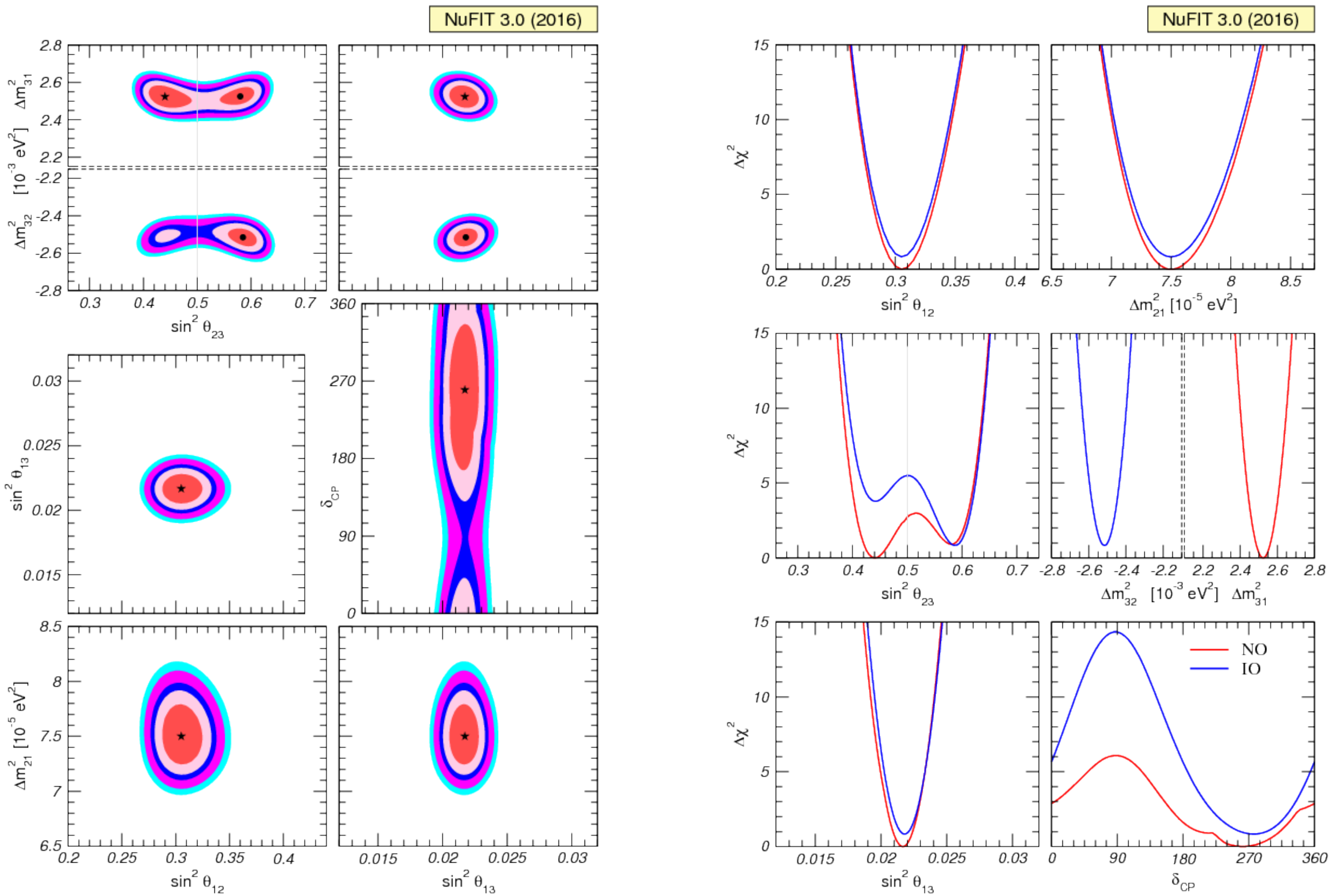
Standard parameterisation:

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

$\theta_{12} = \text{solar angle}$
$\theta_{23} = \text{atmospheric angle}$
$\theta_{13} = \text{reactor angle}$

$\delta = \text{Dirac phase}$
$\alpha_{1,2} = \text{Majorana phases}$

From the recent global fit by Esteban+:



Interesting preference for $\delta \approx 270°$.

Controversial statement #2:

The neutrino theory community matured when it had a dominant theoretical prejudice -- small mixing angles due to "unification" with quarks -- falsified by data.

The general BSM community is perhaps beginning a similar process with the lack of evidence for supersymmetry at the LHC.

A selection of what we don't know about neutrinos:

- Dirac or Majorana?
- The value of absolute neutrino mass scale.
- Leptonic CP violation not quite confirmed.
- Normal or inverted ordering?
- $\theta_{23} < \pi/4$ or $> \pi/4$?
- Whether or not the LSND/MiniBooNE, reactor and gallium anomalies are due to eV-scale sterile neutrinos.
- The origin of the neutrino mass scale.
- Are the mixing parameters and mass splittings free parameters, or is there a flavour symmetry or some other deep dynamics?
- Is lepton mass/mixing connected to quark mass/mixing?
- Is neutrino mass tree-level or radiative?
- What role does the 126 GeV Higgs play in neutrino mass?
- Are there other as-yet undiscovered particles that play a role in neutrino mass generation?
- Is dark matter a 10 keV-scale sterile neutrino?
- Did leptogenesis seed baryogenesis?
- *And so on.*

Sometimes you hear the view:
"We always expected neutrinos to have mass, so what's the big deal?"

As you all know, the original SM has no RH neutrinos, no Y=2 Higgs triplet, and nothing else that breaks $L_{e,\mu,\tau}$ or L_{tot}, so neutrinos are exactly massless.[1]

Massive neutrinos may be Dirac or Majorana.

If neutrinos are Majorana, they are the first such states to be discovered: *new physics*.

If neutrinos are Dirac, then the gauge-invariant RH neutrino Majorana mass terms must be omitted. This means a global symmetry – $U(1)_L$ – must be imposed: *a new principle, hence new physics*.

Also: RH neutrinos are new dofs, like any new particles: *new physics*. Majorana mass generation requires RH neutrinos or a Y=2 Higgs triplet, or any of a bunch of other new particles: *new physics*.

[1]. Sphalerons do not generate neutrino masses.

Models of light Majorana neutrinos

$\Delta L=2$ SM effective operators can be used to systematically study a large class of models of Majorana neutrino mass generation.

These operators have mass dimension d = 5, 7, 9, …

At d = 5, there is only the Weinberg operator: (1/M) LLHH
M is the scale of new physics.

It gives neutrino mass directly, via the see-saw formula $m_\nu \sim \langle H \rangle^2/M$

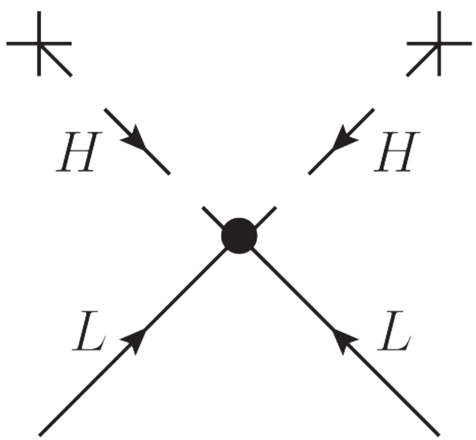
Underlying renormalisable theories yielding LLHH are constructed by "opening up" the operator. The type-1,2,3 see-saw models are the minimal, tree-level ways to open up LLHH.

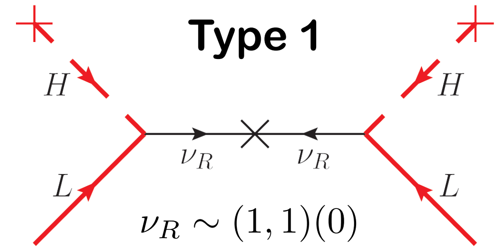
Other $\Delta L=2$ SM effective operators require external legs (quarks, additional leptons) to be closed off in loops to give neutrino mass: radiative neutrino mass generation.

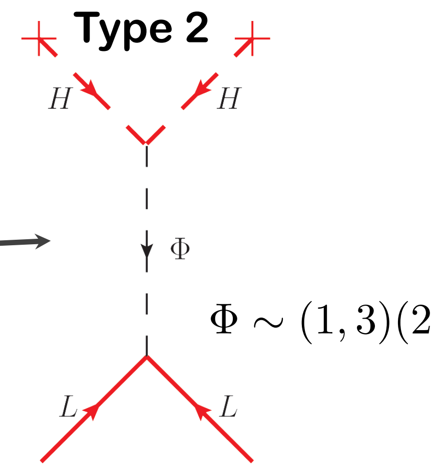
The effective operator is minimally opened up at tree-level or non-minimally at loop-level.

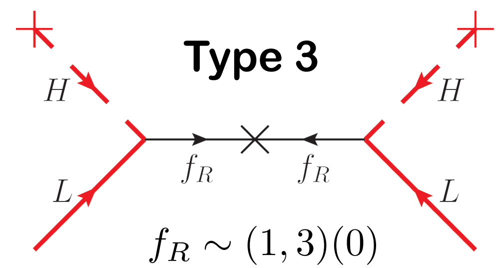
Type-1,2,3 seesaw models:

"Open up" LLHH in all minimal, tree-level ways.









An advantage of this approach to constructing models is that you don't miss any.

Radiative neutrino mass models:

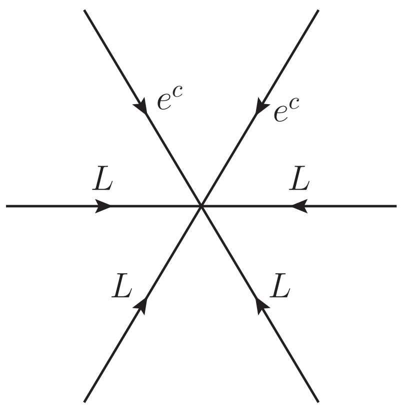
At d=7, there are 7 operators: $O'_1 = LLHH(\bar{H}H)$

$O_2 = LLLe^cH \quad O_3 = LLQd^cH(2) \quad O_4 = LL\bar{Q}\bar{u}^cH(2) \quad O_8 = L\bar{e}^c\bar{u}^cd^cH$

Opening O_2 at tree-level produces the original 1-loop ν mass Zee model.

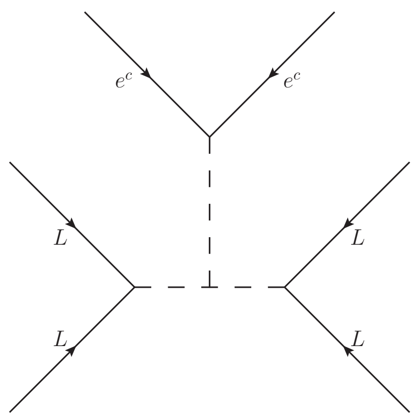
There are many d=9 and d=11 operators. Here is a well-known d=9 case:

Zee-Babu model:

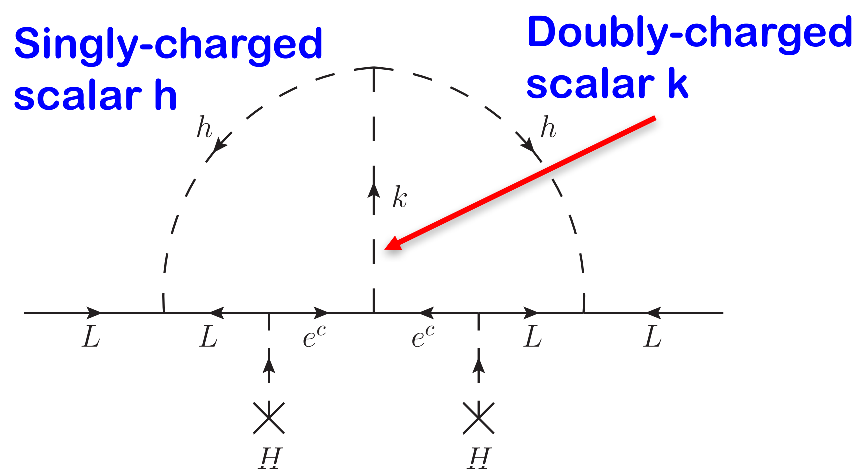


$O_9 = LLLe^cLe^c$

Effective op



Opening it up



2-loop nu mass diagram

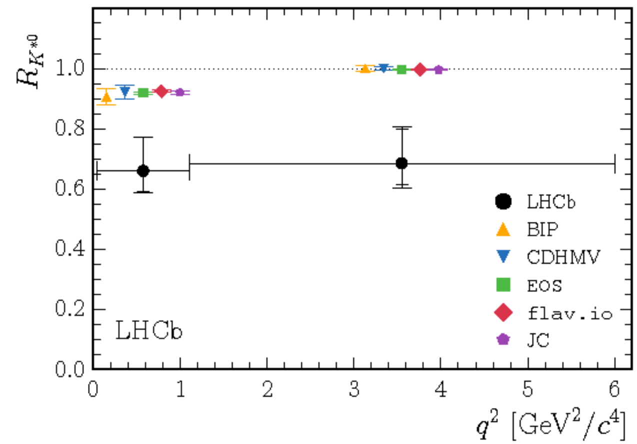
The exotics (k, h in this case) can be searched for at the LHC.

Effective operators containing quarks can feature leptoquarks as members of their "completons".

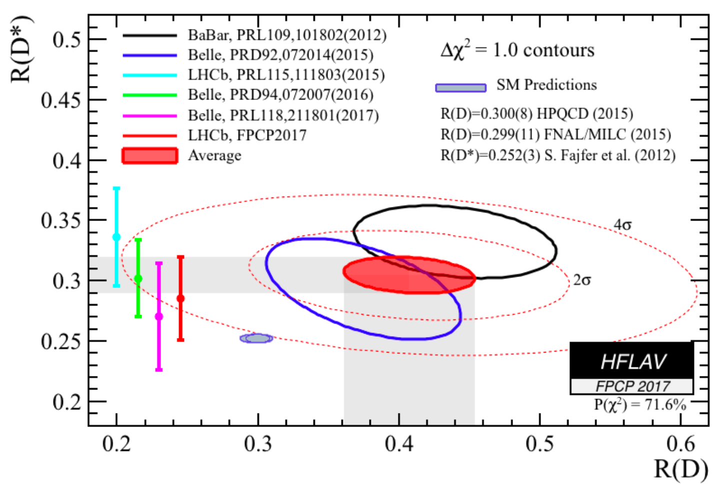
Leptoquarks are being studied intensively as possible ways to resolve some very intriguing flavour anomalies:

(flavour session tomorrow)

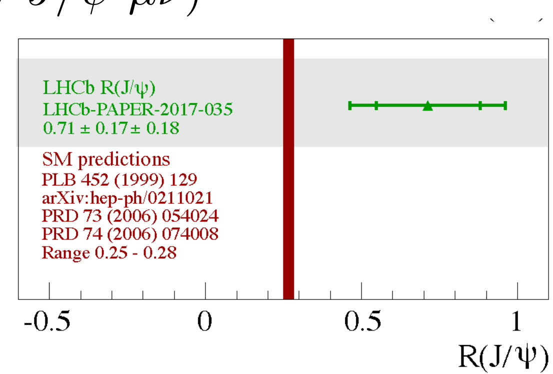
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$



$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$



$$R_{J/\psi} = \frac{\Gamma(B_c \to J/\psi\ \tau\bar{\nu})}{\Gamma(B_c \to J/\psi\ \mu\bar{\nu})}$$



Among the completions of d=7 operators, appear these two LQs:

(3,1)(-1/3) and (3,3)(-1/3) where $Q = I_3 + Y$.

(3,1)(-1/3) does b → c transitions at tree-level.
(3,3)(-1/3) does b → s and b → c transitions at tree-level.

There is potentially a strong connection between radiative neutrino mass models and the flavour anomalies.

Controversial statement #3:

Flavour experiments provide the most hope for the discovery of New Physics in the relatively near future.

Final remarks

The discovery of neutrino masses is the discovery of new physics.

The smallness of neutrino masses remains a principle concern.

The tree-level seesaw mechanisms are viable and interesting.

Radiative models are more testable and have intriguing links to the flavour physics anomalies.

The theoretical and experimental study of neutrinos will remain important for a long time. On the experimental side, both precision and energy-frontier experiments are relevant.