OUTLOOK FOR THE DISCOVERY OF NEW PHYSICS

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1. New physics exists!
2. Hints, teases, disappointments
3. Experimental prospects
4. Final remarks

Note: It is not possible to cover all experimental prospects for the discovery of new physics. I will concentrate on those that can shed light on the hints and teases. The next breakthrough may or may not be connected with these.
1. New physics exists!

Empirical proofs:

- Neutrino flavour transformations
- Missing mass or missing gravity

Empirical near-proofs:

- Matter-antimatter asymmetry
- Problems with standard FRW

Plenaries by Wang, Yanagida (neutrinos), Gondolo, Lindner, Randall, Scott, McDonald, Kuo, Barberio (DM), Kusenko (baryon asymmetry), Sasaki (inflation).
Theoretical issues:

- Proliferation of SM parameters.
- Why three families?
- Strong CP problem. (Kim)
- The 16 of SO(10).
- If inflaton exists, what is it? (Yanagida, Sasaki)
- Quantum gravity.
- Hierarchy problem: why is $M_P/M_{EW} \sim 10^{17}$?
- Hierarchy problem: why is $\rho \Lambda$ so tiny? (Linder, Shafieloo, Wiltshire, Davis)

That’s 12 sometimes overlapping reasons so far, at varying levels of rigour.
Naturalness problems. Hierarchy problems.

These are two different things, but they are often confused.

A hierarchy problem is an unexplained very small or very large number.

Examples:
\[
\begin{align*}
M_P/M_{EW} &\sim 10^{17} \\
\rho &\ll (\Lambda_{QCD})^4 \ll M_{EW}^4 \\
\theta_{QCD} &< 10^{-10} \\
\frac{m_e}{m_t} &\sim 3 \times 10^{-6} \\
\frac{m_\nu}{m_t} &\sim 10^{-12} \\
V_{ub} &\sim 4 \times 10^{-3} \\
\text{Speculatively: } M_{GUT}/M_{EW} &\sim 10^{14}
\end{align*}
\]

A naturalness problem is an instability in a parameter value, an extreme sensitivity to other parameters or initial conditions, etc.

\[
\begin{align*}
\frac{m_e}{m_t}, \frac{m_\nu}{m_t}, \theta_{QCD} &\text{ are not also naturalness problems.} \\
M_{GUT}/M_{EW} &\text{ would be for non-SUSY theories.} \\
M_P/M_{EW} &\text{ is usually assumed to be, but this is unproven.}
\end{align*}
\]
Proof #1: neutrino flavour transformations.

Several experiments combine to establish that neutrino weak eigenstates are non-diagonal coherent admixtures of mass eigenstates.

2015 Nobel Prize to Takaaki Kajita and Art McDonald. Also relevant: 2002 Nobel Prize to Ray Davis.


Neutrino masses & mixings constitute new physics.

Sometimes you hear people claim that this is not true. They are incorrect.
As everyone knows, the original SM has no RH neutrinos, no $Y=2$ Higgs triplet, and nothing else that breaks $L_e, \mu, \tau$ or $L_{\text{tot}}$, 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: \textit{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: \textit{a new principle, hence new physics}.

Also: RH neutrinos are new dofs, like any new particles: \textit{new physics}.

\(^1\): Exercise for the listener: do sphalerons generate neutrino masses?
What could the new physics be?

Here are some possibilities:

- Three RH Majorana neutrinos: Type-1 seesaw, possibly with leptogenesis
- $Y=2$ Higgs triplet: Type-2 seesaw
- $Y=0$ fermion triplet: Type-3 seesaw
- Dirac masses from three RH neutrinos
- Radiatively generated (leptoquarks, vector-like fermions, etc.)
- Inverse seesaw, linear seesaw
Proof #2: missing mass or missing gravity.

- Cluster dynamics
- Rotation curves
- Velocity dispersion of elliptical galaxies
- Gravitational lensing
- Cosmic microwave background
- Baryon acoustic oscillations
- Large scale structure formation

Solution: either dark matter or modified gravity.

Both possibilities are new physics.

Dark matter fits all observations very well.
Modified gravity interesting but seems unlikely.
What about primordial black holes (PBHs)?

There are constraints on this, but it still seems possible. [Discussions during talks!]

But even if so, the mechanism for the PBH formation must be new physics, as there is nothing in FRW-SM that is violent enough to cause the required overdensities.

E.g. Inflationary scenarios have been proposed. But these, of course, are new physics!
If not modified gravity or PBHs, then DM:

- WIMPS (mainly SUSY, so-called “miracle”)
- Axions (strong CP problem)
- keV-scale sterile neutrinos (nu mass, WDM)
- Asymmetric DM \( (\rho_{\text{DM}} \sim 5 \rho_{\text{VM}}, \text{many different scenarios inc. mirror matter}) \)
- WIMPZILLAs
- Minimal real scalar
- Q-balls, solitons
- Etc.

\(^2\) My favourite
Proof #3: matter-antimatter asymmetry

- Almost no antimatter cosmic rays
- No conspicuous annihilation lines

The only question about the need for new physics is: could it be just an initial condition?

What do you mean by initial condition?
What exactly do you mean by the big bang?

The original singularity? But then what about all the usual FRW problems?

If inflation, then primordial initial asymmetry diluted to zilch.

If equate big bang with reheating after inflation, then the B-asymmetric physics of that is new physics!
Well-known Sakharov conditions for the new physics:

- B violation
- C, CP violation
- Departure from thermal equilibrium

Several general dynamical schemes:

- Out-of-eq decays (e.g. Fukugita-Yanagida leptogen.)
- First order phase transition (EW baryogenesis)
- Affleck-Dine (flat directions in SUSY)
- Asymmetric thermal production or freeze-in
- Out-of-eq CP-violating scattering
- Spontaneous baryogenesis (effective CPT violation)
(Near-) Proof #4: problems with standard FRW

- Homogeneity problem (why CMB so isotropic?)
- Flatness problem ($\Omega_{\text{tot}} = 1$ is unstable)
- Large-scale structure (what seeded it?)

All can be elegantly solved by a brief period of de Sitter-like expansion in the early universe: inflation.

If your favourite theory predicts unseen topological defects, inflation can also explain why.
The very existence of CMB acoustic peaks provides powerful circumstantial evidence for inflation.

But, inflation is a framework, not a model.

Typically, the inflationary phase is driven by a scalar field whose dynamics induce a temporary positive vacuum energy.

The identity of this field, and how it fits in with the SM, is a complete mystery. Higgs inflation?
It is interesting that all four of these proofs or near-proofs concern Cosmology and/or Particle Astrophysics!
2. Hints, teases, disappointments

Neutrino anomalies

LSND/MiniBooNE: evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at high $\Delta m^2 \sim 1\text{eV}^2$
MB also for $\nu_\mu \rightarrow \nu_e$

Gallium: $\nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}$ $R_{\text{obs/pred}} = 0.86 \pm 0.05$

Reactor: Very short baseline effects.
Large $\Delta m^2$ not compatible with 3 flavours: sterile nu needed.

Note: there is tension between the appearance and disappearance anomalies.
Tension between the appearance and disappearance anomalies:

Kopp, Maltoni, Schwetz

Giunti et al
But, within the 3+1 sterile neutrino interpretation, there is now an exclusion by Icecube.

Note: the LSND/MB anomaly is $\nu_e$-bar appearance. The exclusion is from zenith angle dependence of $\nu_\mu$-bar survival. Some new physics other than sterile neutrinos?

The reactor and Gallium anomalies can still be due to sterile neutrinos!
DAMA/NaI and DAMA/LIBRA annual modulation


Resolution: SABRE north and south? [Barberio]
Indirect detection

Not confirmed by Fermi

“Hooperon” DM or pulsars?

3.5 keV line not confirmed by Hitomi

DM or pulsars?
Flavour anomalies

\[ R_K \equiv \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} \quad \text{b} \to \text{s transition} \]

\[ b \to s \text{ transition discrepancy} \quad 2.6 \sigma \]

SM : \(1.0003 \pm 0.0001\) \quad LHCb : \(0.745^{+0.090}_{-0.074} \pm 0.036\)

\[ R_{D(*)} \equiv \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})} \quad \text{b} \to \text{c transition} \]

SM : \(R_D \approx 0.30 \pm 0.01\), \(R_{D^*} = 0.252 \pm 0.003\)

BaBar : \(R_D = 0.440 \pm 0.058 \pm 0.042\), \(R_{D^*} = 0.332 \pm 0.024 \pm 0.018\)

Belle: between BaBar & SM; LHCb \(R_{D^*}\) similar to BaBar
g-2 of the muon

There has been a $3\sigma$ or more discrepancy between theory and the BNL E821 experiment for more than a decade:

$$\Delta a_\mu = 28.7 \pm 8.0 \times 10^{-10} \quad \text{Davier et al}$$
$$\Delta a_\mu = 26.1 \pm 8.0 \times 10^{-10} \quad \text{Hagiwara et al}$$

$$a_\mu = (g-2)_\mu / 2$$
**ATLAS SUSY Searches - 95% CL Lower Limits**

**Status:** August 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\mu$, $\tau$, Jets</th>
<th>$\sigma_{\text{cross}}^\text{NNLO}$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>USUGRA/CMSSM</strong></td>
<td>$0$-jet</td>
<td>$0$</td>
<td>$1.85$ TeV</td>
</tr>
<tr>
<td>$\tilde{e}^-$, $\tilde{\mu}^-$, $\tilde{\tau}^-$</td>
<td>$0$-jet</td>
<td>$0$</td>
<td>$1.38$ TeV</td>
</tr>
<tr>
<td><strong>Inclusive Searches</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{e}^-$, $\tilde{\mu}^-$, $\tilde{\tau}^-$</td>
<td>$0$-jet</td>
<td>$0$</td>
<td>$1.17-1.76$ GeV</td>
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</tr>
<tr>
<td><strong>Gravitino LSP</strong></td>
<td></td>
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</tbody>
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**No supersymmetry**
| Model | $\ell$, $\gamma$ | Jets | $E_{T}^{miss}$ | $\int \mathcal{L} dt/|b^{-1}|$ | Limit | Reference |
|-------|-----------------|-------|----------------|---------------------|-------|-----------|
| ADD GGEK + $g/q$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| ADD non-res X $\ell$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| ADD GQB | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| ADD GQ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| ADD BH high $p_T$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| ADD BH multijet | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| RS1 GGEK $\ell$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| RS1 GGEK $\gamma$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Bulk RS GGEK $WW$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Bulk RS GGEK $HZ$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Bulk RS $g_{KK}$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| 2UED/RPP | 1, $e$, $\mu$ | 2, $b$, $j$ | 20.3 | | | |
| SSM $Z' \rightarrow \ell\ell$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| SSM $Z' \rightarrow \tau\tau$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| OS/LS $Z'/bb$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| SSM $W' \rightarrow \ell\nu$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| HVT $W' \rightarrow WZ + qq\nu\nu$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| HVT $W' \rightarrow WZ + qqq$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| HVT $V' \rightarrow WH/ZH$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| LRSM $W_{L} \rightarrow tb$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| LRSM $W_{R} \rightarrow tb$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Cl $q_{q}q_{q}$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Cl $\ell\ell q_{q}$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Cl $\ell\ell\ell$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| DM A | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| DM A | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Scalar LQ 1st gen | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Scalar LQ 2nd gen | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Scalar LQ 3rd gen | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| VLQ TTT | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| VLQ TQQQ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| VLQ $g_{V} \rightarrow W_{L}W_{L}$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| VLQ $g_{V} \rightarrow W_{R}W_{R}$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| VLQ $g_{V} \rightarrow W_{L}W_{R}$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited quark $q' \rightarrow q''$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited quark $q' \rightarrow q''$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited quark $b' \rightarrow W_{L}$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited quark $b' \rightarrow W_{R}$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited lepton $\tau'$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Excited lepton $\tau''$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| LSTC $g_{V} \rightarrow W_{L}$ | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| LRSM Majorana | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Higgs triplet $H^{\pm} \rightarrow ee$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Higgs triplet $H^{\pm} \rightarrow \tau\tau$ | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Monotop (non-res prod) | 1, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Multi-colored particles | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |
| Magnetic monopoles | 2, $e$, $\mu$ | 1, $j$ | 20.3 | | | |

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

± Small-radius (large-radius) jets are denoted by the letter $j$ (J).
For example: 750 GeV R.I.P.
3. Experimental prospects

Neutrinos:

Many, many experiments underway or planned!

See http://www.nu.to.infn.it/exp/ for a list and links.

But let me specifically mention:

Fermilab Short-Baseline Neutrino Program will test LSND/MB $\nu_e$-bar appearance.

Several very short-baseline expts. for reactor/Gallium anomalies.

Several neutrinoless double-beta decay expts. to find Majorana mass.
Dark matter:

Annual modulation:
KIMS experiment in Korea

Radio-pure DAMA-like detector with active veto.
Northern site at Gran Sasso.
Southern site at Stawell, Australia.

Stawell Underground Physics Laboratory (SUPL) under development

Many other direct and indirect detection experiments, and also axion searches underway.
Flavour anomalies:

Of course, LHCb is on-going.

Belle 2 at KEK in Japan under construction:

U. Melbourne-built Belle 2 SVDs
g-2 of the muon:

Fermilab E989 and J-PARC E34 experiments.

Factor of 4 improvement. If the discrepancy persists, the significance could be well above $5\sigma$. 
ATLAS and CMS:

No new physics yet at 13 TeV. Mass reach will only go up slightly with 14 TeV run. Focus is now on rarer events.

Most importantly, this includes measuring Higgs branching ratios as precisely as possible.

Higgs Factory:

Very strong motivation for precision measurement of Higgs properties, including self-coupling, at an electron-positron collider: ILC, CEPC or FCC.
4. Final remarks

There is absolutely no doubt that new physics exists.

Cosmology and astroparticle physics important in providing the strongest evidence.

A multi-pronged experimental and observational program is absolutely vital. There is no reliable way to predict where the next breakthrough will happen. It may or may not be connected with the hints and teases I chose to focus on.

It may even be something apparently random. Think muon.