Physics Landscape Away From The High Energy Frontier

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Predictions are always a little hard, as they say, so let's look back at three of the most recent important discoveries away from the highest energy frontier

- Neutrino oscillations
- Cosmic microwave fluctuations
- Dark energy

What have we learned from these discoveries?

This question has many angles, and we really can only discuss one or two here.

One interesting point is that two of the three discoveries can be plausibly interpreted as reflecting a "GUT" scale of particle unification … even though we don't know for sure if that is the right interpretation.

(1) The CMB fluctuations fit brilliantly with the theory of "inflation" in the early Universe, and if we interpret it that way, we can "almost" measure the inflationary scale …

The amplitude for temperature fluctuations, measured to be $\frac{\delta T}{T} \sim 2 \times 10^{-5}$

is in the simplest inflationary models something like

$$\frac{H_{\mathsf{infl}}}{\epsilon M_{Pl}}$$

where the numerator is the Hubble scale during inflation and in the numerator, ϵ is a slow roll parameter and M_{Pl} is the Planck mass.

We don't really know what the slow roll parameter is, but if we assume it is only somewhat small (since inflation did end a few dozen e-foldings later), we can estimate what the mass scale of inflation should have been and we find it was near the canonical GUT scale $10^{16}\,\mathrm{GeV}$ estimated from particle physics.

(The value of the spectral index tends to support this reasoning.)

There are all kinds of ways for this picture to be wrong, but if it is right, there is a good chance that that will become clearer from the discovery of the “B-mode” in the CMB polarization.

This is proportional to H_{infl}/M_{Pl} without the $1/\epsilon$ (in the simplest inflationary models) so if it is detected, we’d get a direct measurement of the inflationary scale as well as the slow roll parameter.

It is instructive to ask how we would interpret cosmological observations if the GUT hypothesis is completely wrong – at the other extreme, if the LHC finds a low quantum gravity or string scale.

No clear answer.

At the moment we don't have a cogent framework for thinking about cosmology if that proves to be the case. To say the least, there'd be a lot to learn.

(2) Neutrino oscillations and masses may also be telling us about a GUT-like scale since the neutrino mass differences are fairly close to a see-saw scale

$$\frac{M_W^2}{M_{\mathsf{GUT}}}$$

although they are actually a little big.

Lessons from neutrinos:

Apart from being surprised that neutrino parameters are just right to be measureable, I think most physicists have been surprised that the mixing angles are so large.

Certainly the flavor violation implied by neutrino oscillations is in the spirit of the GUT idea that global symmetries are low energy accidents of the Standard Model.

Clear program for learning more

Measure the missing mixing angle θ_{13}

Search for CP violation

Neutrinoless double beta decay – is the total lepton number violated or only the differences of the $e,\ \mu,\ \tau$ numbers?

(3) Cosmic acceleration and dark energy are not obviously closely related to Grand Unification …

But they do potentially have a dramatic effect on how physicists think about the Universe as a whole – partly because, if interpreted in the most direct way as a cosmological constant, the dark energy dominates the future evolution of the Universe.

Most thinking about the dark energy is based on interpreting it at face value via a cosmological constant, and this shows what measurement could have a dramatic impact:

A discovery that the acceleration parameter w is not quite -1 would have almost as big an impact as the original discovery of dark energy.

Trying to look ahead a little bit, if the interpretation of neutrino oscillations and CMB fluctuations as pointing to something like a GUT scale is correct, where might we learn more?

Let us recall that the original – and still most compelling – clues for some form of Grand Unified Theory or a close cousin of one come from conventional particle physics.

The two most important clues are probably these:

(1) The quark and lepton quantum numbers are very messy in the Standard Model – but fit beautifully into simple representations of GUT groups such as

$$SU(5), \quad SO(10)$$

(2) The measured value of $\sin^2 \theta_W$ agrees beautifully with SUSY – GUT's.

Since this picture does depend on SUSY, what might make it most compelling would be to discover SUSY at the LHC.

But away from the energy frontier, what should we look for?

Definitely the biggest prediction is baryon number violation – proton decay.

Proton decay has been searched for without success for a long time, but the same was true for most of the other important effects that have been found away from the energy frontier – certainly including neutrino oscillations, CMB fluctuations, and cosmic ac/de/celeration.

One important point is that in addition to traditional four-dimensional GUT's, there are higher-dimensional models, based on string theory or not, that preserve the known successes of four-dimensional GUT's but can be significantly different for proton decay.

In the usual SUSY GUT's, proton decay can occur by

(a) dimension 5 operators that involve the MSSM squark and slepton fields – the amplitude is of order $1/M_{GUT}^2$ and so dangerous …

(b) dimension 6 operators

made only from quarks and leptons – the amplitude is of order $1/M_{GUT}^4$ and might be unmeasureably small.

Because of the dimension 5 contribution, pure 4d SUSY GUT's are heavily challenged by the Super-K bounds such as $\tau(p \to e^+\pi^0) > 8 \times 10^{33}$ years.

If these models at least in any of their simplest versions are right, proton decay should be seen "soon."

However, higher dimensional models give many ways that the dimension 5 contribution might be suppressed while preserving the known successes of GUT's.

And from a contemporary perspective, split supersymmetry, in which the scalar masses are moved above the TeV scale, can have this effect at the "low" energy end.

(Arkani-Hamed and Dimopoulos 2004,

Giudice and Romanino 2004)

So it is important to also consider the dimension 6 contribution. With the usual value $M_{\rm GUT} \sim 2-3\times 10^{16}\,{\rm GeV}$, one gets a proton lifetime of $10^{36}-10^{37}$ years – too long to be seen even in the next generation of experiments.

But there are many GUT-like models in which this conclusion changes – because of a slight shift in the unification scale or for other reasons.

A nice example is a higher-dimensional orbifold model of Hall and Nomura (2001) – qualitatively similar to much older string models. One "large" extra dimension (here this means $1/10^{14}\ \mathrm{GeV}$) with SU(5) broken to the Standard Model at one end

Lifetime for $p \rightarrow e^+\pi^0$ turns out to be close to 10^{34} years.

String theory realizations of related ideas by e.g. Dundee, Raby, Wingertner (2008)

Klebanov and I (2003) considered a class of Type IIA superstring models based on intersecting D6-branes

with the aim of showing another way that GUT-like string models could have observable proton decay by dimension 6 operators. It actually didn't work – the non GUT factors were large but came amazingly close to canceling.

This class of models does, however, make a non-GUT prediction that conceivably might be testable eventually if proton decay is seen – a left handed polarization of the charged lepton in e.g.

$$p \longrightarrow \mu^+ \pi^0$$

The usual picture of SUSY or SUSY-GUT's is tied to naturalness of the weak scale.

If so, the LHC should produce the superpartners.

Natural weak scale theories (with or without SUSY) tend to be highly constrained by the potential they introduce for new flavor and CP violation. If new particles such as squarks are discovered, the search for new rare processes such as $\mu - e$ conversion can give important tests of their couplings.

There is also an “unnatural” variant of split SUSY in which the scalars are heavy.

As the scalar masses are raised, rare processes vanish like $1/m^4$ but contributions to electric dipole moments only vanish quadratically. As a result, e and n electric dipole moments probably give our best chance to see the squarks up to masses of 100 TeV or more.

Of course, for natural SUSY (lighter squarks), these measurements give even sharper constraints on squark couplings.

While we are discussing EDM's, we also must remember that one aspect of the EDM problem is fundamentally unclear in the Standard Model. The Standard Model allows for much a much bigger neutron EDM than we see (up to $10^{-16}\, e\,\mathrm{cm}$) due to the QCD θ-angle.

There have been three main proposals to explain this:

(1) One involves a new particle, the axion, that couples in such a way that when one minimizes the axion potential energy V(a), the effective value of θ ends up being very small.

(2) The other involves interpreting CP as a spontaneously broken symmetry, with details set up so the breaking isn't much transmitted to θ.

(3) The problem goes away if the up quark bare mass vanishes

Lattice gauge theory seems to show that (3) is wrong.

Realizations of (2) tend to be rather detailed and technical. For what it is worth, I think option (2) is probably hard to come by in string theory. In string theory,

CP can be interpreted (usually) as a spontaneously broken symmetry, but it is hard to quarantine CP violation away from QCD.

But axions really do arise in string theory, from the way anomalies are canceled.

With standard assumptions about cosmology at very early times, a classic calculation shows that too much axionic dark matter is produced if the axion coupling parameter F_a is bigger than about $10^{12}\,\mathrm{GeV}$. Assuming that the axions really do make up a large part of the dark matter, they can be detected, in the full allowed window up to about $10^{12}\,\mathrm{GeV}$ by the Sikivie experiment – based on axion to photon conversion in a cavity.

However axions may not make up a significant part of the dark matter.

Even if not, axions will be produced in astrophysical bodies such as the Sun and can possibly be detected in searches such as CAST, whose sensitivity is in roughly the same region.

Personally, I think it would be desirable to find a way to search for axionic dark matter in the supposedly forbidden region above $F_a \sim 10^{12}\mathrm{GeV}$.

We don't have any sure knowledge about cosmology at such temperatures.

For what it is worth, string theory models that have enough GUT-like structure to give a natural explanation of $\sin^2\theta_W$ tend to put F_a near the GUT scale.

(There are many puzzles about cosmology in such a case.)

WIMP’s are another important dark matter candidate, and they have one important advantage. For WIMP’s, a standard calculation based on thermal production of WIMP’s followed by annihilation in the cooling Universe shows that WIMP’s with roughly weak scale masses and weak couplings give roughly the right dark matter abundance.

(For axions, the equivalent calculation leads to the upper bound of $F_a \sim 10^{12}\mathrm{GeV}$.)

The fact that WIMP’s give more or less the right amount of dark matter makes them a rather attractive dark matter candidate, and WIMP searches – both direct searches and indirect ones looking for WIMP annihilation products – are surely one of the leading prospects for a major discovery away from the energy frontier.

But there are plenty of other dark matter candidates.

Axions are an important particle physics possibility that we've already discussed.

There are plenty of others. What about GUT or Planck mass particles in cosmic rays?

How about black holes? Solar mass black holes are probably excluded by searches for gravitational lenses, but what about primordial black holes above or below a solar mass?

A more exotic possibility (which might be motivated by claims that cold dark matter produces more and “cuspier” minigalaxies than are observed) would be pseudoscalar particles of astronomically long wavelength, interacting more weakly than axions. It appears natural to generate such particles from string theory.

Where dark matter fits in between physics and astronomy is still very unclear.

Of course, the physics landscape away from the energy frontier contains all kinds of other possibilities … fifth forces … breakdown of quantum mechanics … new signals in cosmic rays … who knows!

Let us just hope that a good number of these things really happen!

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