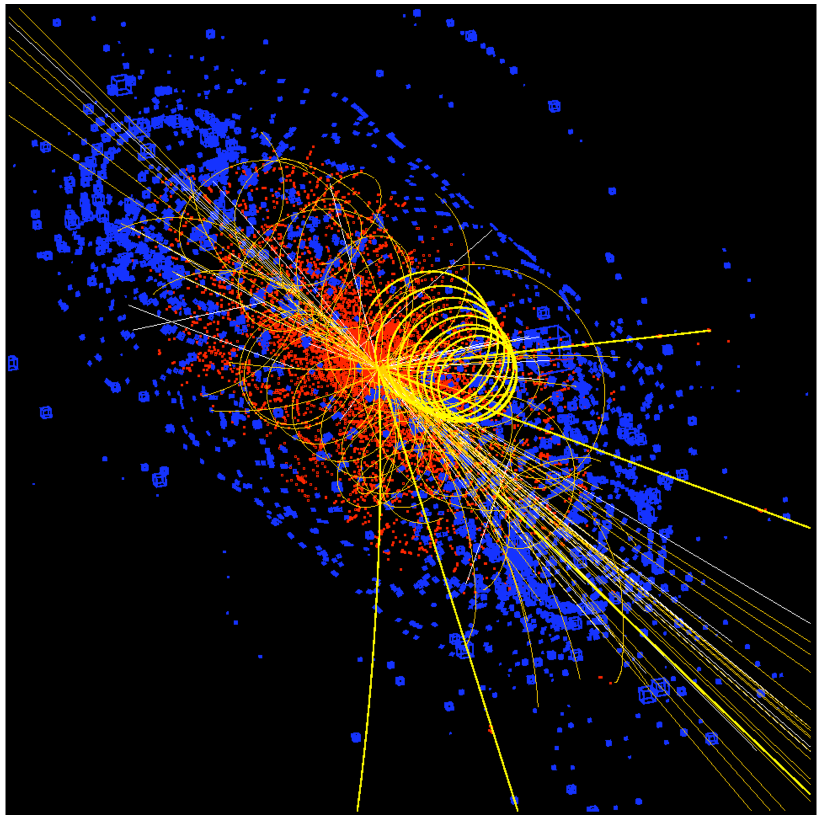
Connections of Particle Physics with other disciplines



HEPAP presentation 3/14/14

Curtis Callan (Princeton), Shamit Kachru (Stanford & SLAC)

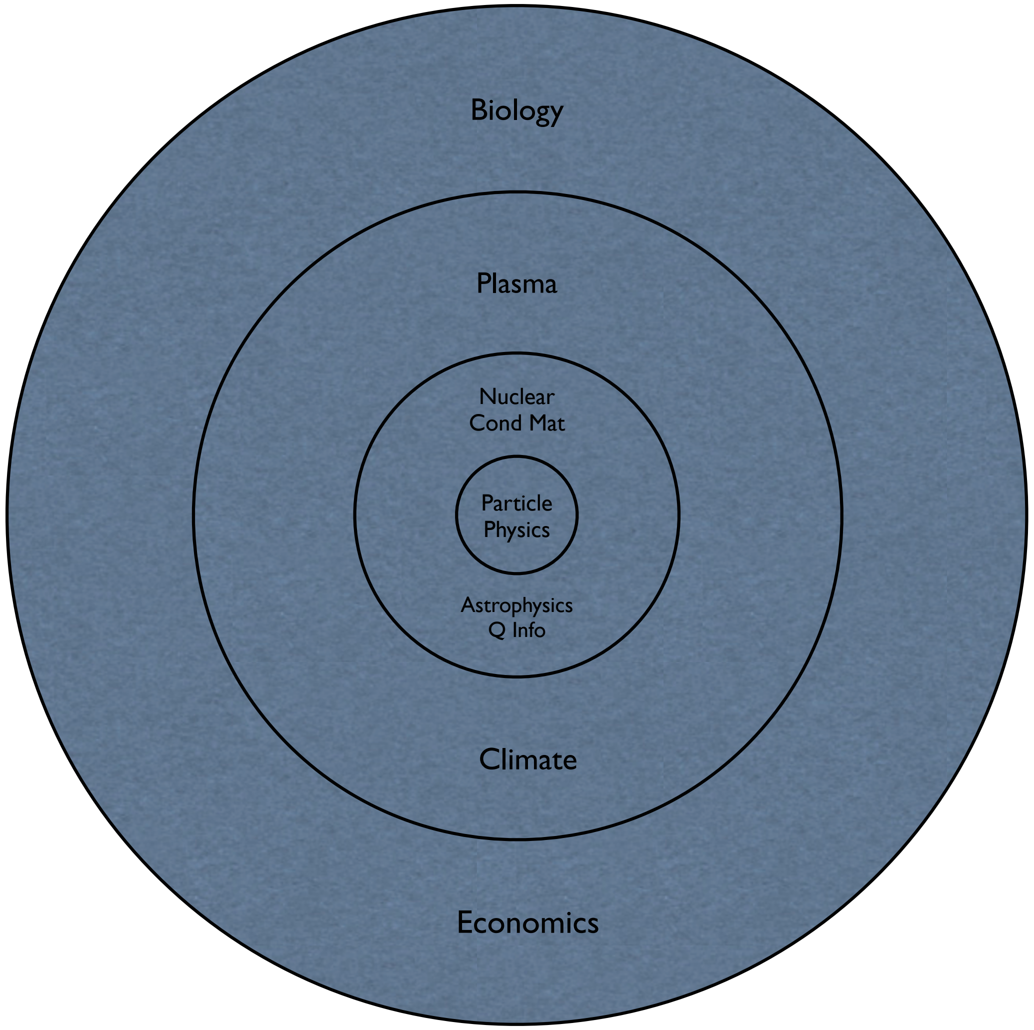
I. Introduction

Jim Siegrist's charge to us: survey connections between HEP and other sciences, with an eye towards finding exciting interdisciplinary opportunities.

This is a good time to take stock of the current HEP portfolio to see where to go next:

Recent discovery of Higgs boson completes the Standard Model, but leaves many fundamental questions open.

At the same time, particle physics enjoys fruitful connections with many close-by but distinct scientific disciplines:



Are there exciting new opportunities at the interfaces here that might merit special attention?

We took on this project because we think this is a good time to consider the broader connections of particle physics to science and society as a whole.

Our method: to discuss the fruitful connections between fields with experts in a variety of connected disciplines, chosen for their broad view and/or expertise with questions of science management.

Important disclaimer: This study was undertaken from a theoretical physics viewpoint, and is really a "study for a study" -- idiosyncratic and unsystematic in its pursuit of disciplines and opportunities.

The experts we consulted included:

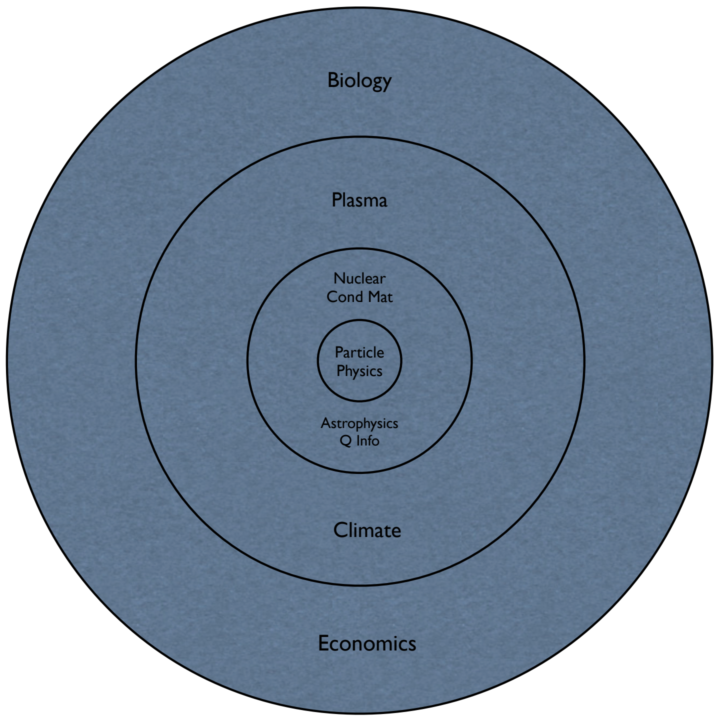
- Astrophysics (Roger Blandford, Jeremy Goodman)
- Nuclear Physics (K. Rajagopal, H. Robertson, M Ramsey-Musolf)
- Fusion Plasma (Stewart Prager, Ronald Davidson)
- Atomic and Molecular Physics (David deMille, Savas Dimopoulos)
- Condensed Matter (Subir Sachdev, Paul Steinhardt, Ashvin Vishwanath)
- Quantum Information Science (Chetan Nayak, John Preskill)
- Mathematics (Miriam Cvetic, Mike Douglas, S-T Yau)
- Climate Science (Bill Collins, Andy Majda, Inez Fung)
- Biology (Herbert Levine, Larry Abbott, Terry Sejnowski)
- Econophysics (George Papanicolao, David Shaw)

Of course, any errors of perspective or emphasis are our own.

I will first discuss rapidly developing areas at borders between high energy physics and other disciplines. I will then recount a few of the most spectacular recent successes of interdisciplinary developments involving particle physics. I close with a few general statements about exciting present opportunities.

II. Interfaces of HEP with other fields

We will organize in accord with the concentric circles:



A. The inner circle

These include fields that enjoy a common language with HEP -- e.g., a framework of quantum mechanics and field theory, or a history of focusing on measurement of "fundamental" parameters.

Included here would be disciplines like atomic physics (AMO), nuclear physics, condensed matter physics, mathematics, and quantum information.

Are there substantial new frontiers between HEP and these areas, that one might wish to pursue? Here are a few of the ideas we encountered...

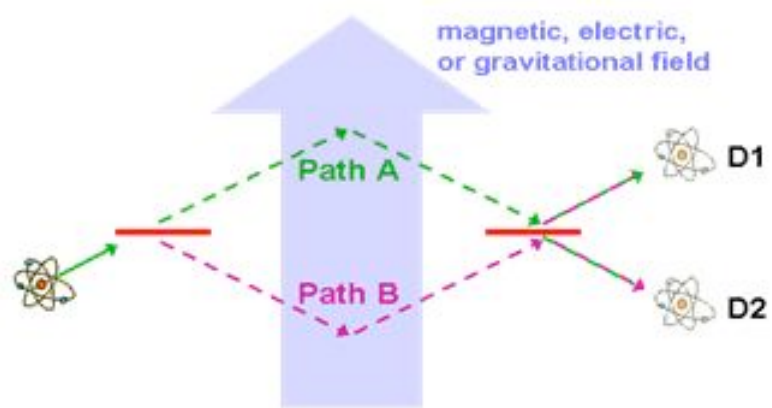
With AMO:

There is a long history of measuring EDMs, a key precision indicator of physics beyond the Standard Model. Notable as a window onto very high energy physics (via CP violation) independent of high energy accelerators.

According to Dave DeMille (Yale):

"I strongly suspect some type of multi-university or university - national lab collaborative efforts, involving a handful of PIs ... could advance this field much more quickly."

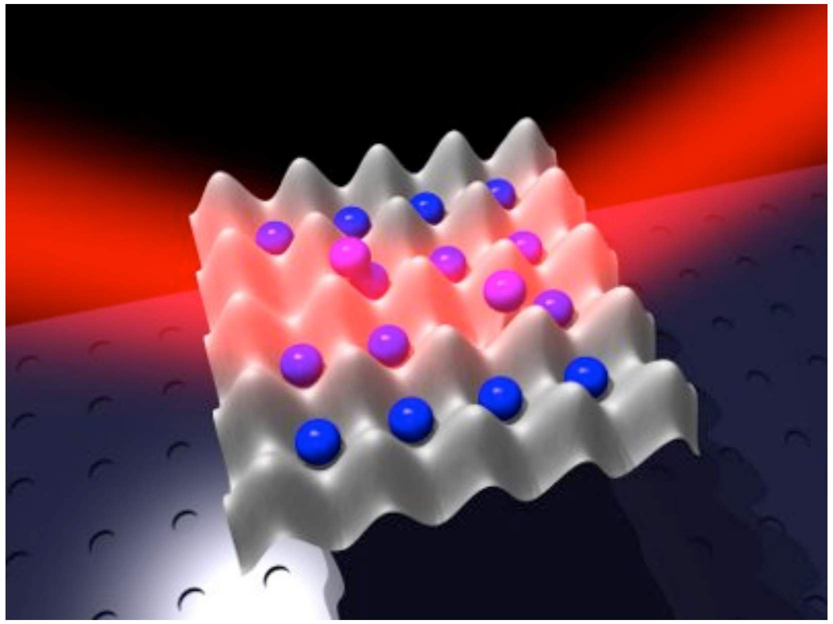
New modes of axion and gravity wave detection have also been proposed, using precision magnetometry and atom interferometry.



According to Savas Dimopoulos (Stanford):

"They provide new tools ... for probing fundamental laws. They are characterized by high precision or high coherence, instead of high energy ... these activities can ... enrich the long periods between consecutive accelerators."

Finally, we have the increasingly impressive ability to manipulate cold atoms in optical lattices:

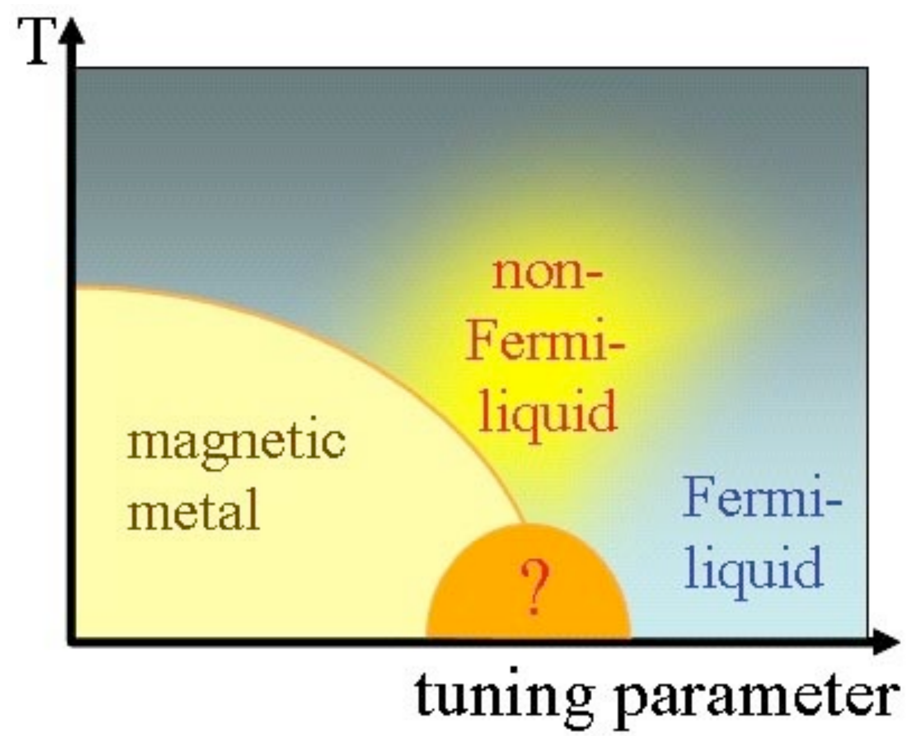


As Subir Sachdev (Harvard) notes:

"Many technical difficulties remain, but we can optimistically hope that there will eventually be realizations of quantum field theories of matter coupled to dynamic gauge field modes."

With Condensed Matter Physics:

A common language, that of quantum many-body theory (or field theory), is shared between the disciplines. Field theory may be useful to attack (at least toy models of):



Here, a variety of technical tools and qualitatively new ideas developed in HEP may prove of use.

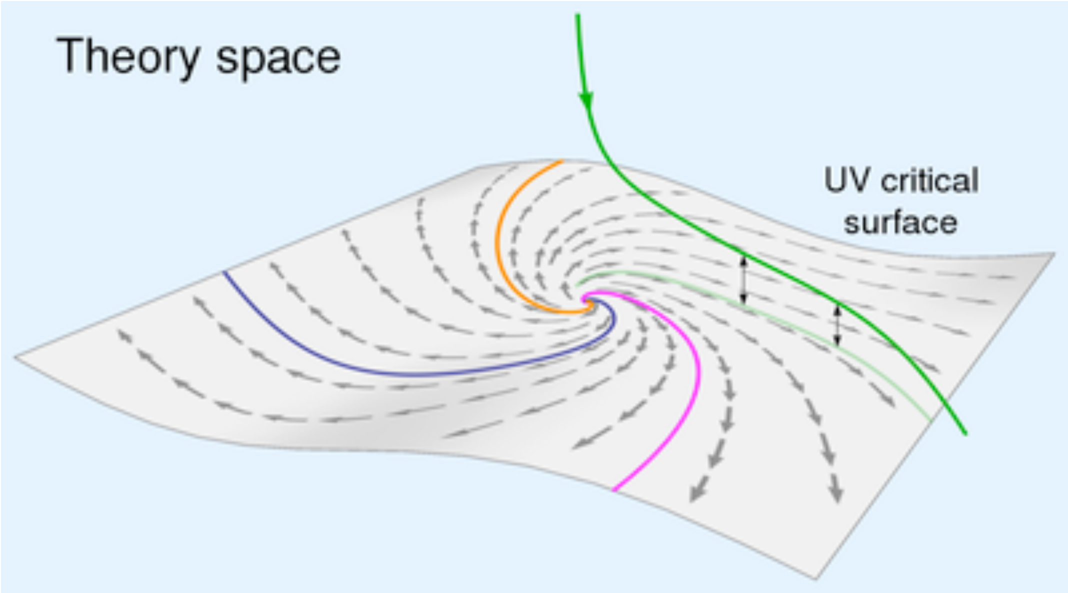
A. Vishwanath (Berkeley) notes:

"...in recent times, we have been confronted with strongly coupled problems ... where non-perturbative techniques are sorely required ... [a] promising topic is SUSY as a tool and its realization in condensed matter."

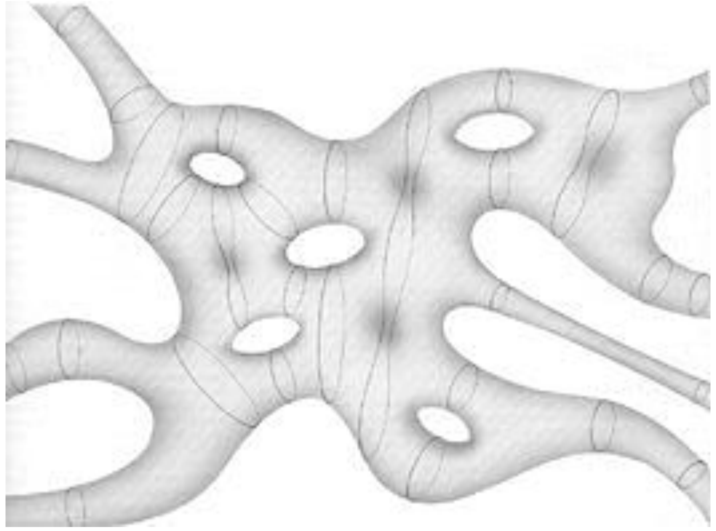
S. Sachdev (Harvard) adds:

"Many important correlated electron materials display strange metal regimes where a description based on quasiparticle excitations breaks down. Here, much insight has been gained from ... the AdS/CFT correspondence."

It is important to emphasize that what is suggested is not a one way street -- the ideas of condensed matter physics have greatly enriched understanding of field theory historically, in a way that had significant impact on high energy physics.

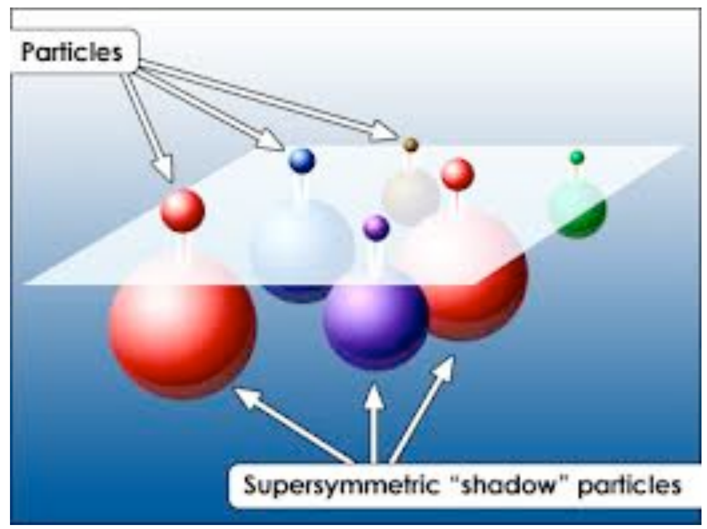


For instance, the ideas of RG flow developed in both communities...



... and CFT techniques developed for 2d statistical models play a crucial role in string theory.

In fact, it is possible that condensed matter ideas will allow us to finally realize some theories long discussed in HEP circles, in condensed matter labs:



Emergent Space-time Supersymmetry at the Boundary of a Topological Phase

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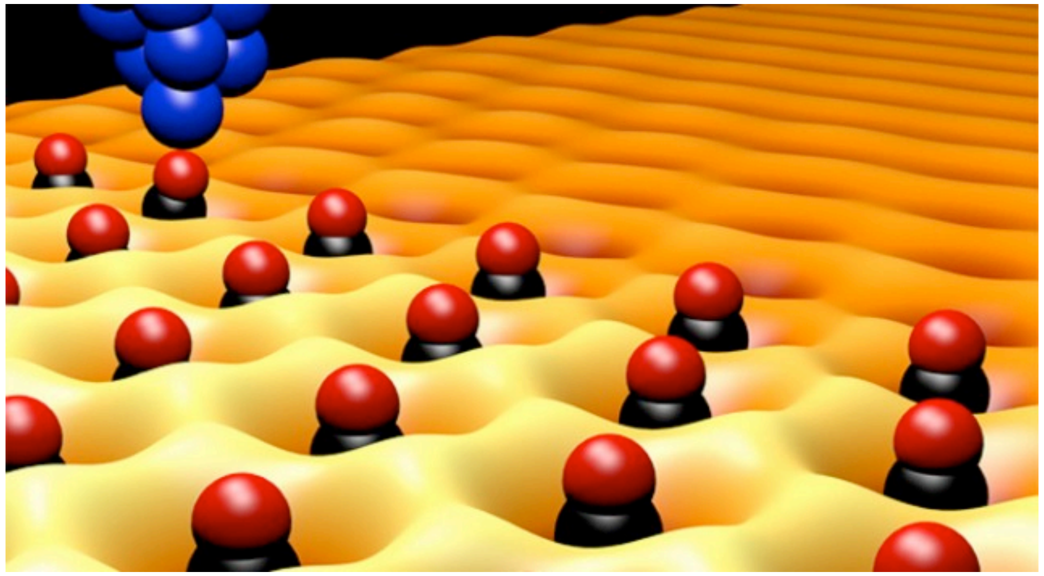
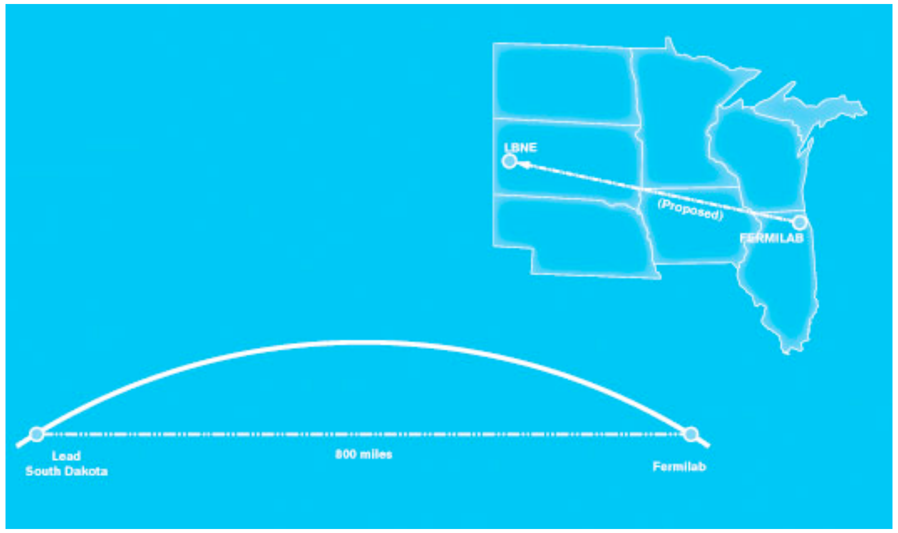
In contrast to ordinary symmetries, supersymmetry interchanges bosons and fermions. Originally proposed as a symmetry of our universe, it still awaits experimental verification. Here we theoretically show that supersymmetry emerges naturally in topological superconductors, which are well-known condensed matter systems. Specifically, we argue that the quantum phase transitions at the boundary of topological superconductors in both two and three dimensions display supersymmetry when probed at long distances and times. Supersymmetry entails several experimental consequences for these systems, such as, exact relations between quantities measured in disparate experiments, and in some cases, exact knowledge of the universal critical exponents. The topological surface states themselves may be interpreted as arising from spontaneously broken supersymmetry, indicating a deep relation between topological phases and SUSY. We discuss prospects for experimental realization in films of superfluid He_3-B.



Finally, P. Steinhardt (Princeton) emphasizes a completely new set of opportunities at the interface with condensed matter physics:

"For the first time in human history, we are developing the capability of controlling the formation of materials, rather than having to coax Nature into self-organizing them ... The control capabilities have just emerged and I think we have not even scratched the surface in terms of figuring out what we can do ... I think it is natural ... to seed creative work in these areas."

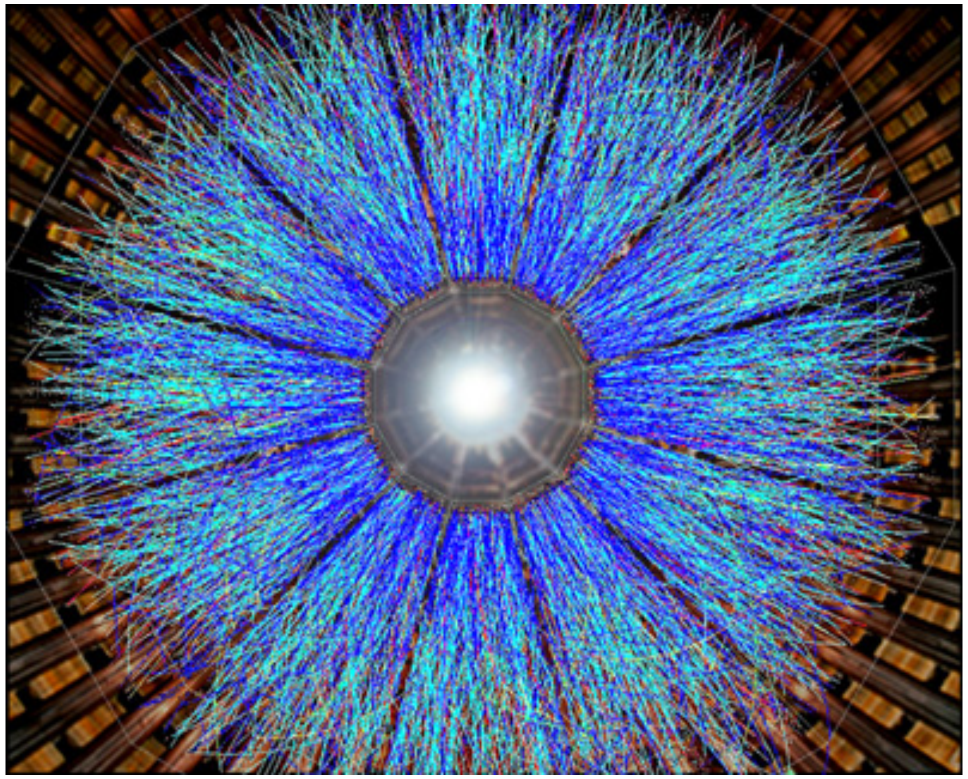
With Nuclear Physics, there are some specific important connections to be explored in the near future:

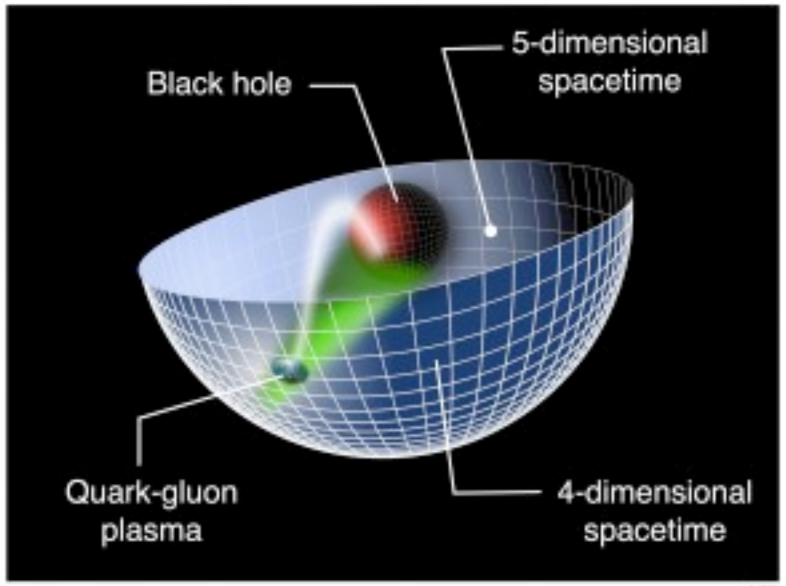


M. Ramsey-Musolf (U Mass, Amherst):

"[knowledge of neutrino/nuclear cross sections] is a huge issue for LBNE and other oscillation studies. The nuclear targets are complicated many body systems, and the way neutrino cross sections are modeled ... is rather simple-minded. Dedicated resources need to be invested..."

In addition, there is strong synergy in the investigation of field theories - starting with lattice QCD and more recently, in the investigation of QGP.

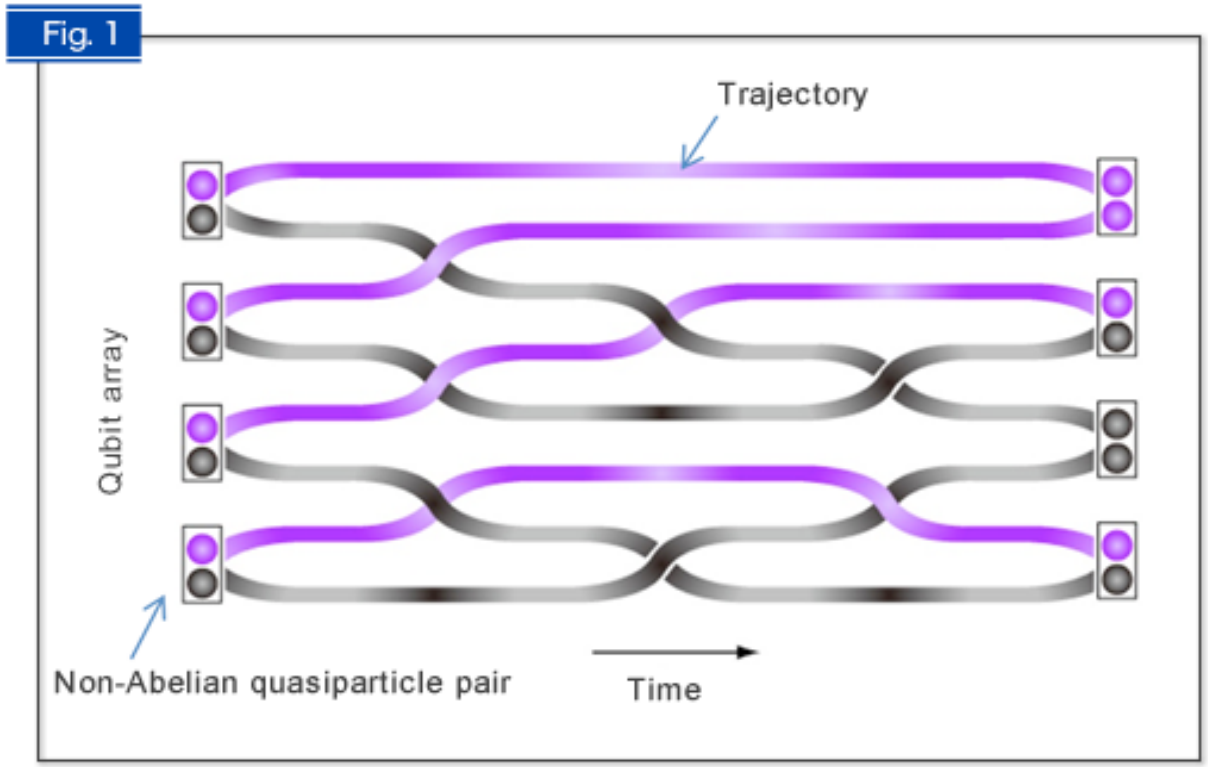


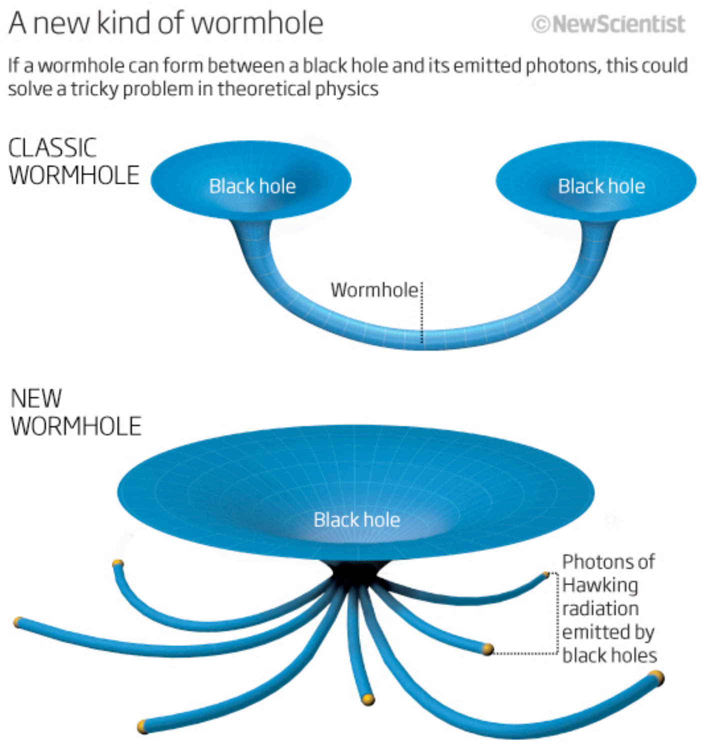


"The analysis of dynamics of strongly coupled liquids without quasiparticles poses a great challenge to theoretical physics ... Over the past decade, theoretical physicists have gained substantial qualitative insights into these dynamical questions ... by using holography, or AdS/CFT ..."

- K. Rajagopal (MIT)

With Quantum Information Science:

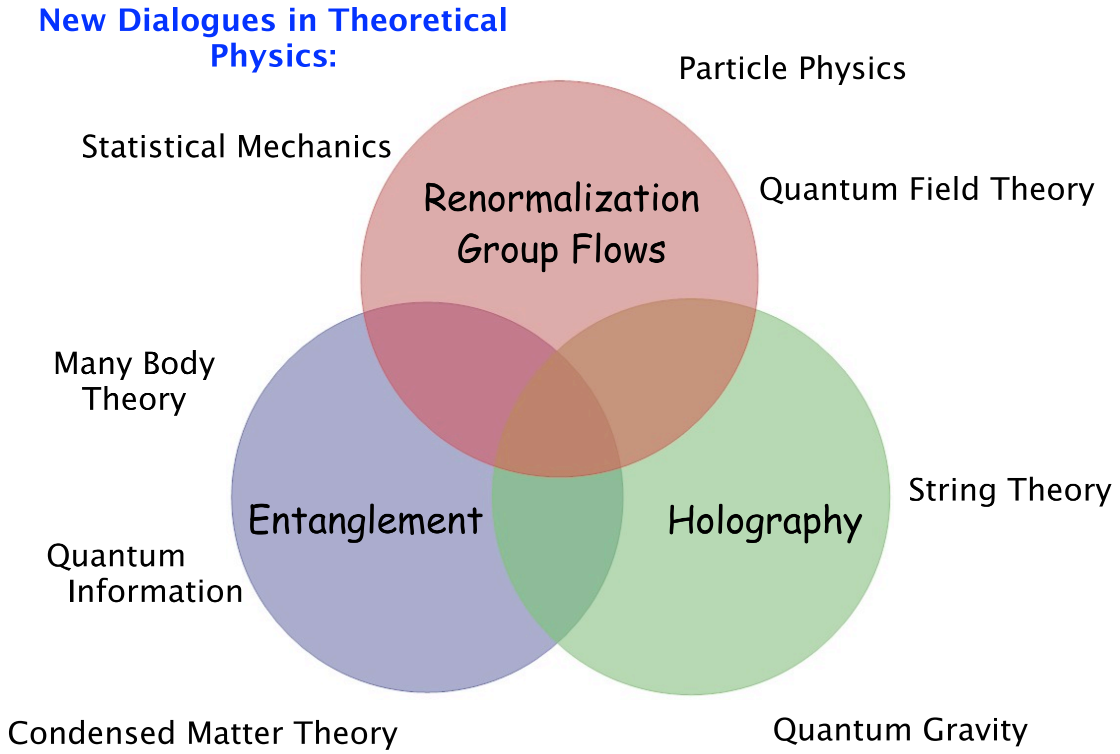




"A particularly deep connection involves the emergence of topological quantum field theory, originally developed by particle physicists, as an especially elegant ... approach to achieve error-resistant quantum computing...Meanwhile, ideas generated by the QI community are exerting an expanding influence on particle physics and string theory."

- J. Preskill (Caltech)

I close this discussion of the "inner circle" subfields by pointing to a broad theme that seems to unify some of the new, highly inter-disciplinary research directions:



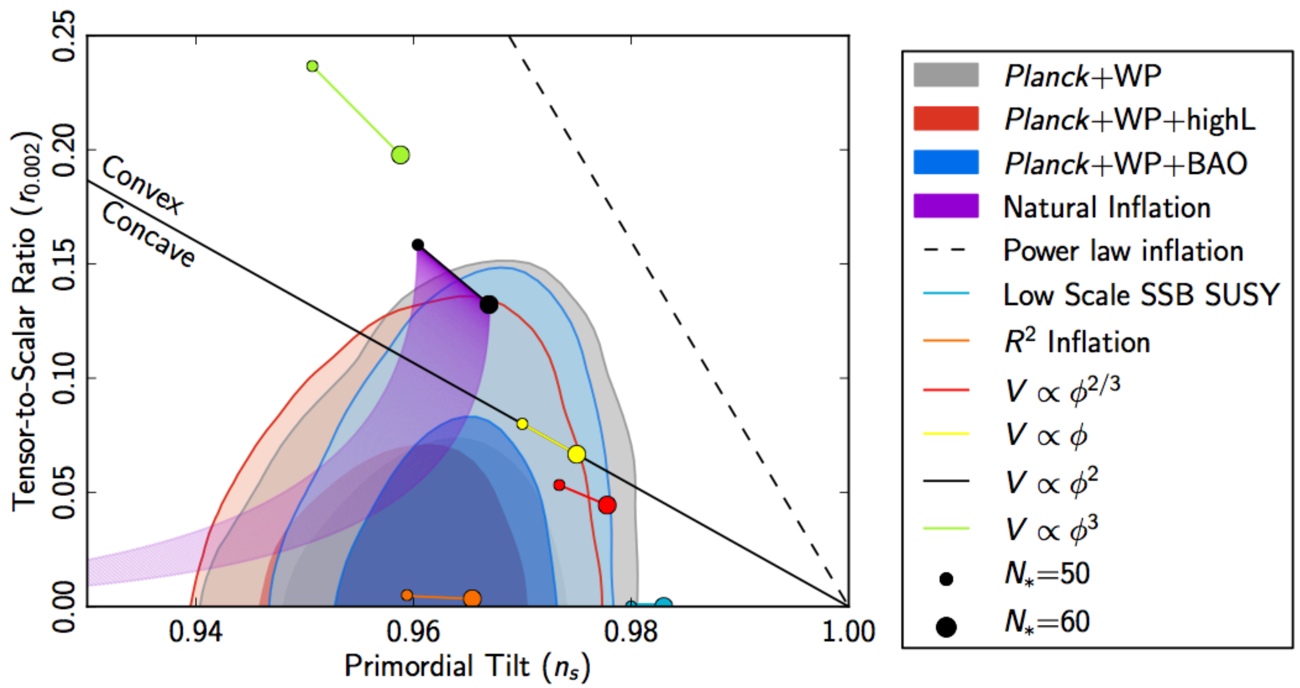
Renaissance using modern tools of QFT, together with entanglement, to provide new windows on issues ranging from novel topological states of condensed matter to emergence of space-time

B. Slightly more distant disciplines

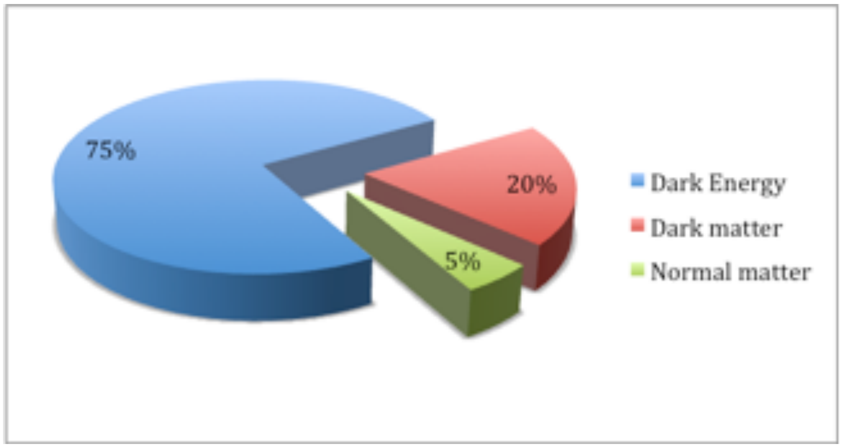
Next, we come to the "middle circle" of disciplines which still sometimes share significant intersections with particle physics - these would include astrophysics, plasma physics, climate research,...

With astrophysics, the synergy is particularly strong: particle physics and astrophysics meet at the HEP Cosmic Frontier. There are several important astrophysical research goals that are equally interesting for high energy physicists.

* Ground-based CMB observations are now probing a very interesting parameter space in the hunt for primordial gravitational waves (from inflation).



This is a probe of physics at the very highest energies, and could yield hints of GUT-scale inflation (and of super-Planckian inflaton excursions in field space).



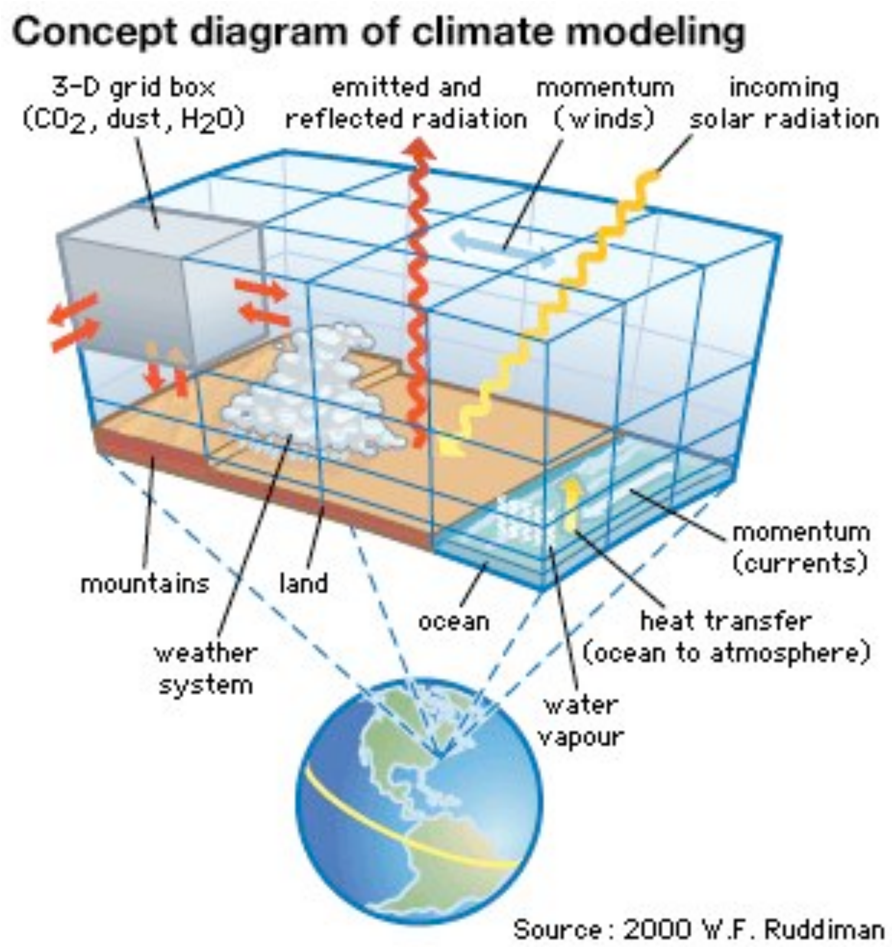
* A variety of observations (beyond just optical) are relevant to the Cosmic Frontier goal of investigating the nature of dark matter and dark energy. All of these are central to the interests of high energy physicists.

Finally, echoing comments in other fields (e.g. - could we help develop a culture of larger experiments in CM?):

"The largest unexplored synergy seems to lie in using the human, organizational and physical infrastructure (of particle physics) to advance the most interesting science around."

- R. Blandford (Stanford & SLAC)

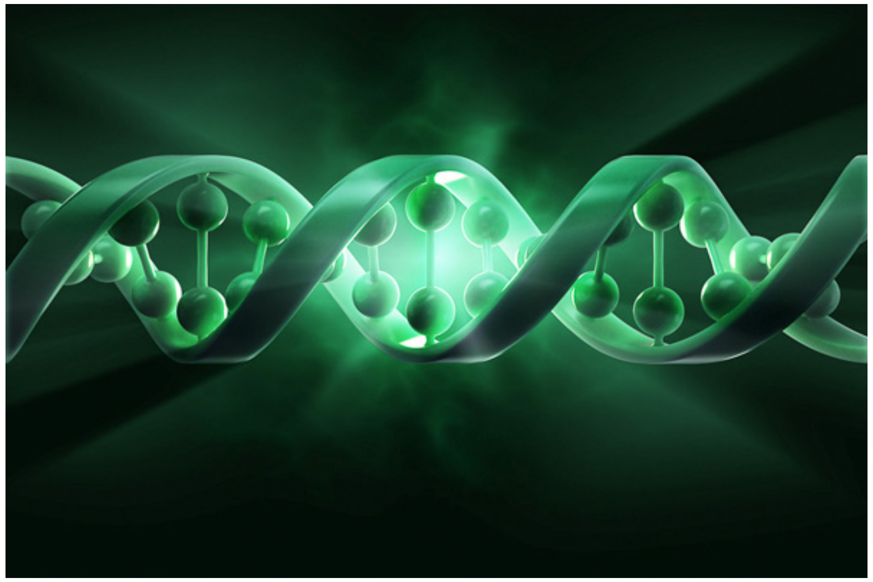
With plasma physics and climate science, the primary connection is the interest in understanding thorny multi-scale dynamical problems



- They believe that, in addition to brute force computation, conceptual advances will be needed to reach the ambitious goals of these fields (the prediction, with quantifiable uncertainty, of future climate statistics as an example of such a goal).
- While there is no direct map of HEP resources onto these problems, there are growing, very promising, intellectual overlaps between HEP and these disciplines (field theories of turbulence, lattice simulation of multi-scale QCD physics, AdS/CFT insights into fluid dynamics, ...).

C. The outer circle

This includes fields like cell biology, neurobiology, and "social sciences" - all with traditionally weak connections to physics.



In all of these areas, consultants agreed that a central issue is the need to develop mathematical frameworks to organize and comprehend large volumes of data that are accumulating.

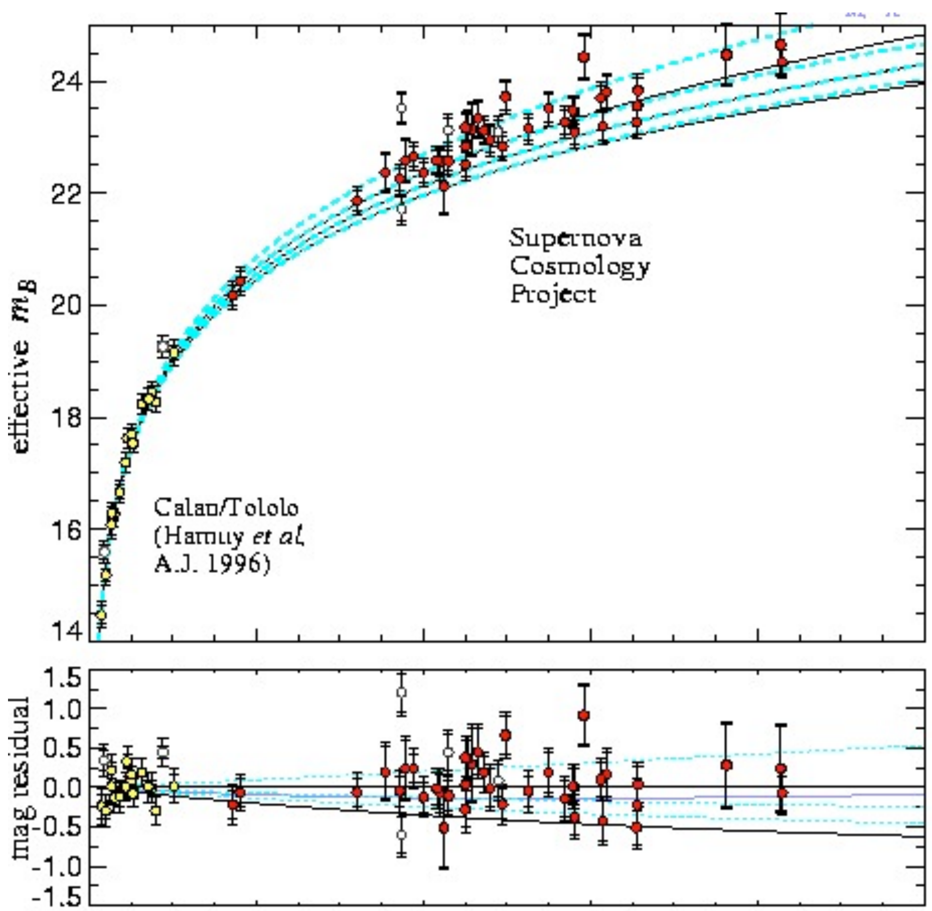
In addition, the HEP community has significant experience successfully pulling off large-scale, complicated projects. This could be useful in other fields:

"Neuroscience is poised to join genomics, astronomy and physics in developing big science projects. High Energy Physics could have a major impact on the way signals are sensed and data collected by neuroscientists... To enable progress in theory and data collection, we must foster collaboration between experimentalists and scientists from statistics, physics, mathematics,..."

- T. Sejnowski (Salk Institute)

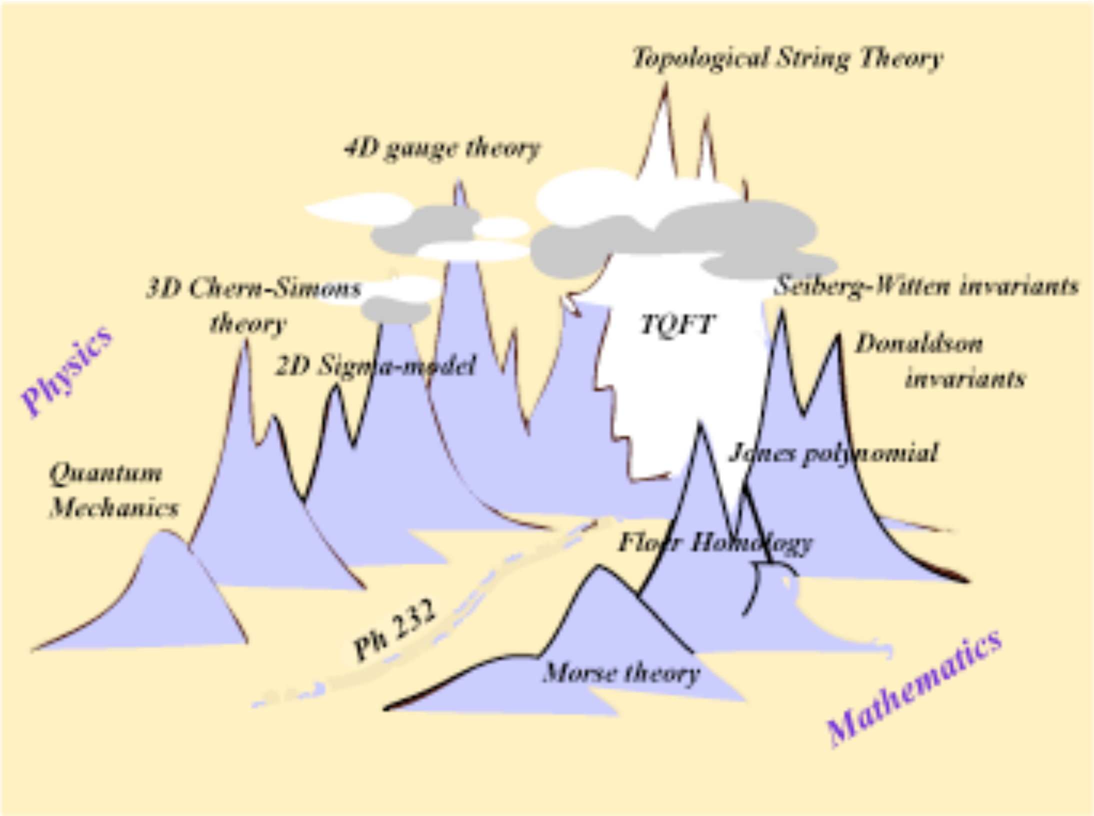
III. Precedents

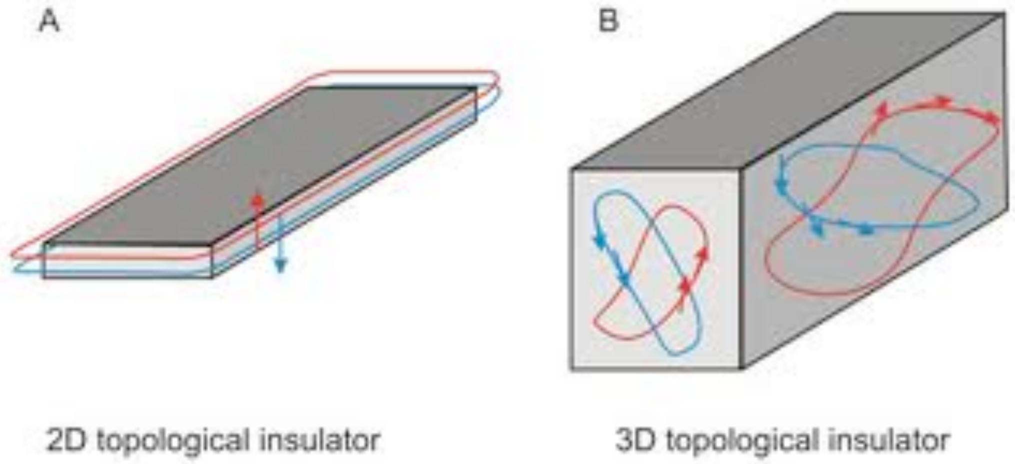
Several well known recent examples serve as clear precedents illustrating very fruitful cross-fertilization between HEP and nearby disciplines.



The Supernova Cosmology Project grew out of the LBNL group of Luis Alvarez. It was incorporated into the mission of the CfPA in the late 1980s; its co-discovery of dark energy drives much of the current excitement at the Cosmic Frontier.

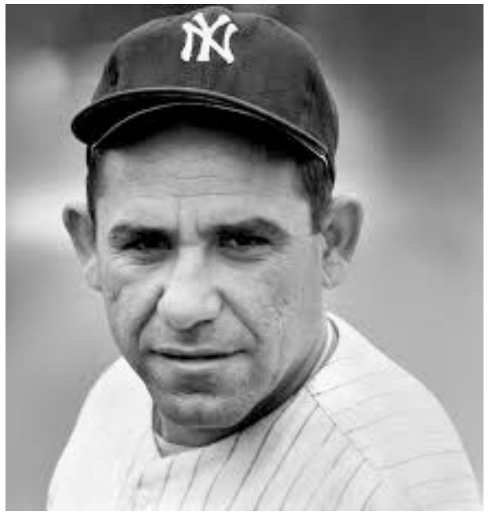
An outstanding example of theoretical cross-fertilization occurred with the development of topological field theory by mathematicians and particle physicists in the 1990s.





Formulated in answer to a challenge posed by Atiyah, such theories have provided startling insights into topology and geometry, and come back to physics with real-world applications in topological insulators and superconductors.

IV. Summary of some present opportunities



"Its tough to make predictions, especially about the future."

Some places we were alerted to exciting opportunities include:

* non-accelerator approaches to fundamental physics, as in multi-lab AMO attacks on EDMs, axion searches or gravity waves

* quantum simulation as a tool to solve strongly interacting systems (with application in many fields)

* Surrounding the current Cosmic Frontier are opportunities in astrophysics that probe dark matter/energy and are of direct interest to particle physicists

* There are deep theoretical issues in climate, plasma, condensed matter that require new techniques; coordinated attacks would also benefit HEP theory if progress occurs

* Could the "big science" culture of HEP be usefully exported to other fields which are beginning to operate in such a mode (as commented upon by our astro, QI, and biology consultants)