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Status and Prospects of Theory

Joe Lykken

Fermilab

Brookhaven Forum,

13 October 2017

This is not a summary talk

But if you insist I can summarize the status of theory on one slide:

Theoretical guidance for experimentalists

- The entire world-wide particle theory community has yet to emerge from a 40 year long drought of successful predictions for BSM phenomena
- While ironically we have built, brick by brick, a golden age of verified precise predictions for amazing complex Standard Model phenomena
- And BSM phenomena **have** appeared, although our theoretical understanding of them is still primitive: neutrino oscillations, dark matter, dark energy, inflation

Theoretical guidance for (young) theorists

1. Just because it is well-trodden ground doesn't mean you cannot find lumps of gold lying around that were missed

2. Just because it is true doesn't mean you are thinking about it in the right way

3. Try to work on things that will either inspire a new experiment, or be used to help an experiment already launched, or provide a fresh perspective (not just a new wrinkle) on a persistent mystery

Doing more with the Higgs

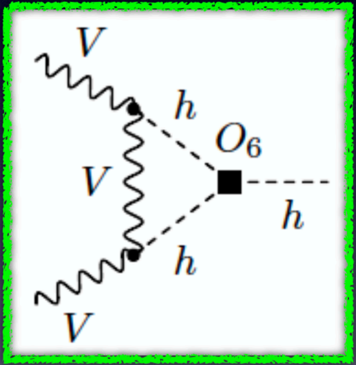
- As we march towards the HL-LHC era, the LHC becomes more and more a precision Higgs factory
- Theorists are already figuring out new ways to extract crucial information about the Higgs sector
- Challenge the experiments and they will respond!

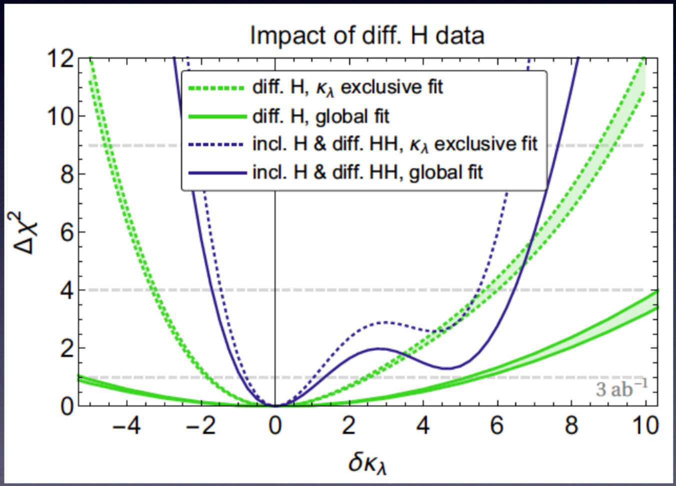
Pinning down the Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

- m_H and v are precisely measured, but a big challenge to constrain $\frac{\lambda_3}{\lambda_3^{SM}}$
- Observing double Higgs production will be tough at HL-LHC, HE-LHC or even a 100 TeV pp collider

S. Homiller, BNL Forum
M. Sullivan, BNL Forum
P. Huang, BNL Forum



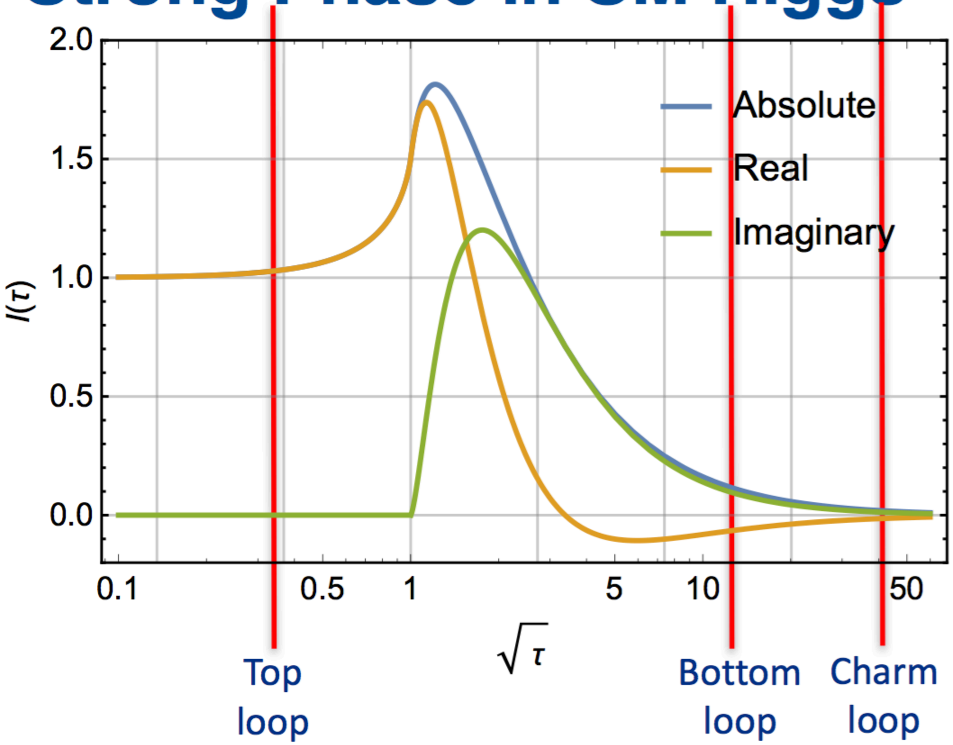


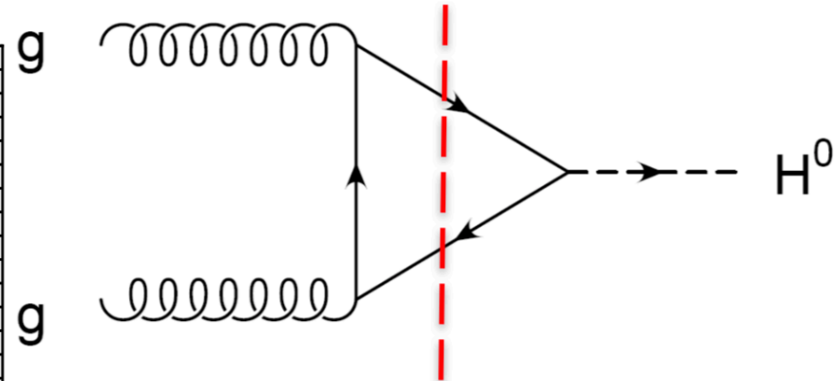
- Do better off-shell ?!

G. Zanderighi, BNL Forum

Bizon, Gorbahn, Haisch, GZ '16
Degrassi, Maltoni, Giardino, Pagani '16
Degrassi, Fedele, Giardino '17
Di Vita, Grojean, Panico, Riembau, Vantalon '17

Strong Phase in SM Higgs





- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

Phase in gluon-gluon-fusion $\mathbf{0.042}$

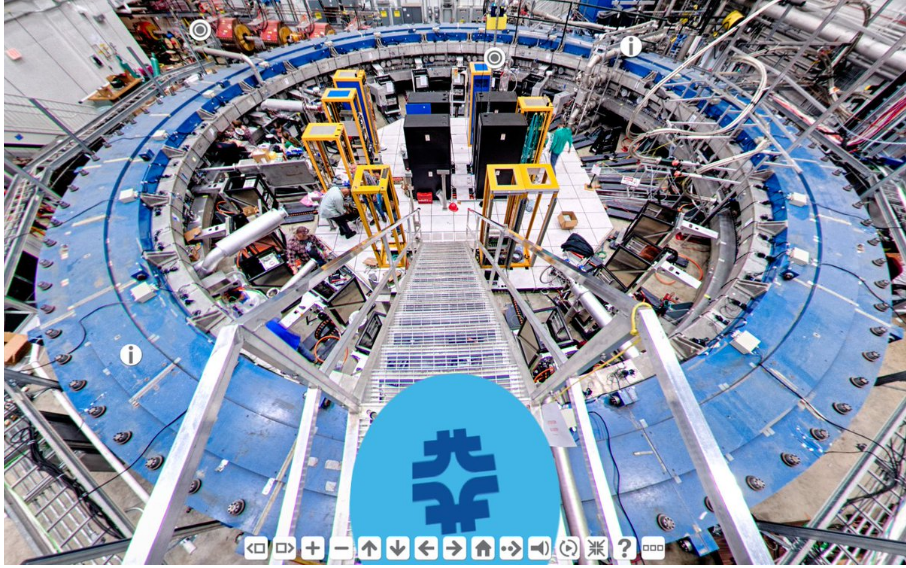
On-shell Higgs production constrains the Higgs width!

New Directions in Lattice Gauge Theory

- muon g-2 C. Lehner, BNL Forum
- neutrino-nucleon interactions A. Meyer, BNL Forum
- BSM strong interactions O. Witzel, BNL Forum
- Composite and axion dark matter E. Rinaldi, BNL Forum
- Extra credit: asymptotically safe quantum gravity

J. Laiho et al, J. Ambjorn et al

Muon g-2:
the moment of truth is near



Theory status for a_μ – summary

Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED (5 loops)	11 658 471.895	0.008
EW	15.4	0.1
HVP LO	692.3	**4.2**
HVP NLO	-9.84	0.06
HVP NNLO	1.24	0.01
Hadronic light-by-light	10.5	**2.6**
Total SM prediction	11 659 181.5	4.9
BNL E821 result	11 659 209.1	6.3
FNAL E989/J-PARC E34 goal		$\approx$ **1.6**

C. Lehner, BNL Forum

Trivia Question:

Who is the most-cited Fermilab theorist [86,131 cites], also having the most-cited single paper [8,959 cites]?

Answer:

Trivia Question:

Who is the most-cited Fermilab theorist [86,131 cites], also having the most-cited single paper [8,959 cites]?

Answer:

hep-ph/0603175
LU TP 06–13
FERMILAB-PUB-06-052-CD-T
March 2006

PYTHIA 6.4
Physics and Manual

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E-mail: skands@fnal.gov

Trivia Question:

What will the answer to this same question be in 2030? (my prediction)

Answer:

Trivia Question:

What will the answer to this same question be in 2030? (my prediction)

Answer:

The GENIE Neutrino Monte Carlo Generator

PHYSICS & USER MANUAL

(version 2.10.0)

Costas Andreopoulos[2, 5], Christopher Barry[2], Steve Dytman[3], Hugh Gallagher[6], Tomasz Golan[1, 4], Robert Hatcher[1], Gabriel Perdue[1], and Julia Yarba[1]

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[6] Tufts University, Dept. of Physics and Astronomy, Medford MA, 02155, USA

October 20, 2015

(caveat: technically Gabe is an experimentalist)

The challenge of neutrino – nuclear interactions

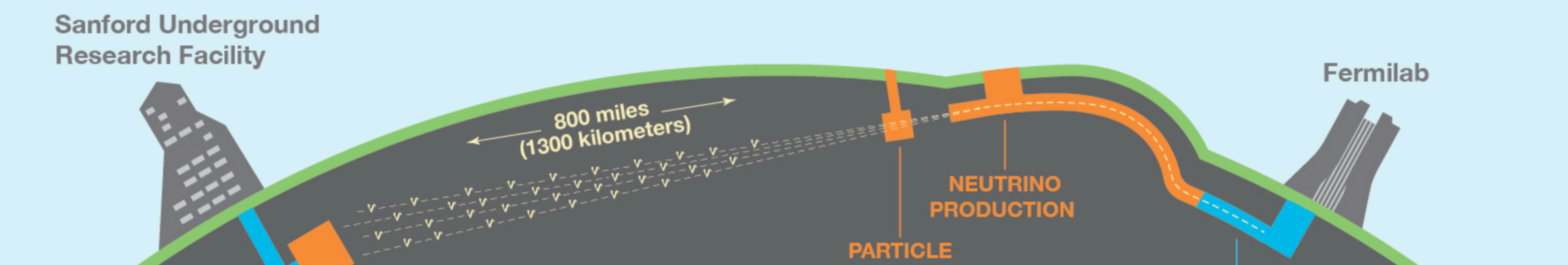
Questions with billion dollar scale impact

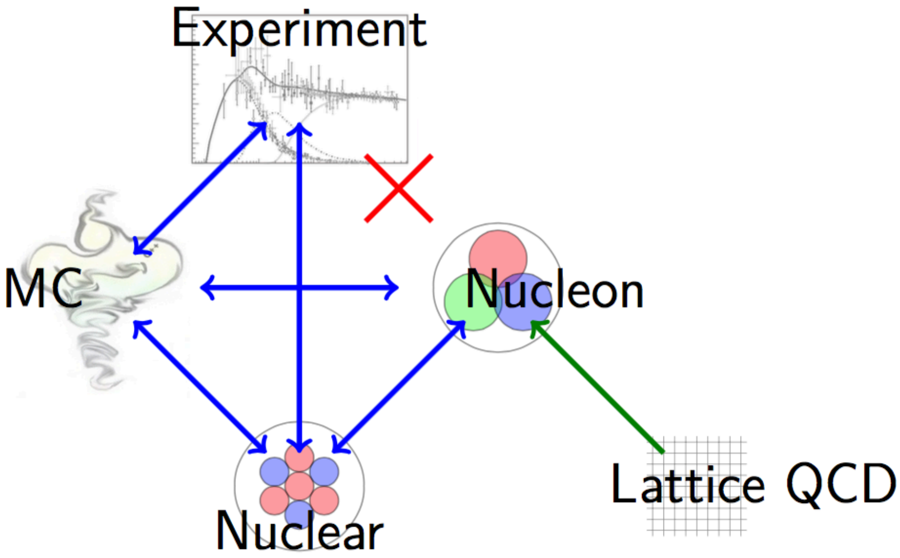
Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this…

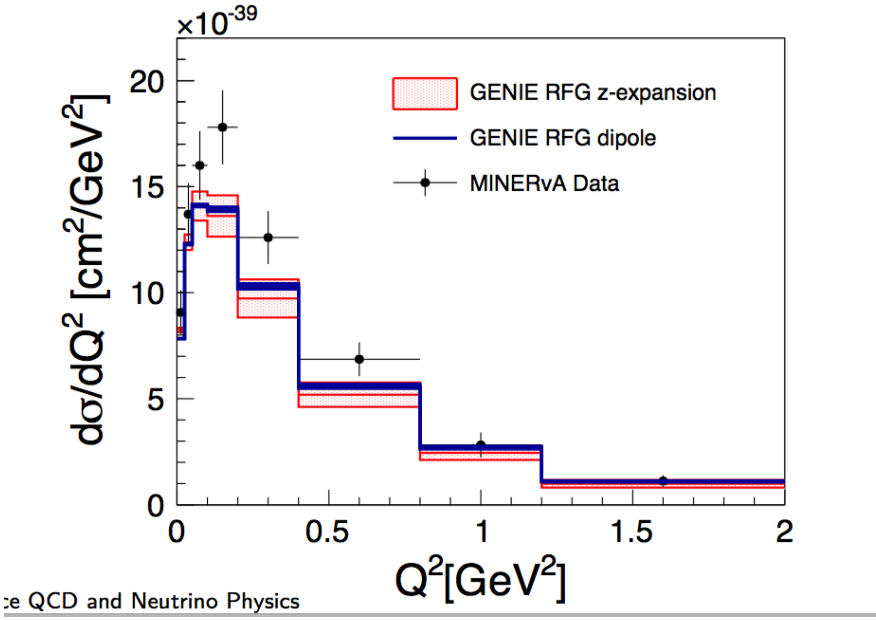
Any result will be based on assumptions and not on controlled approximation.

P. Huber, BNL Forum

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT







Ideally, lots of redundancy and checks between elements of analysis

F_A not well determined by experiment,

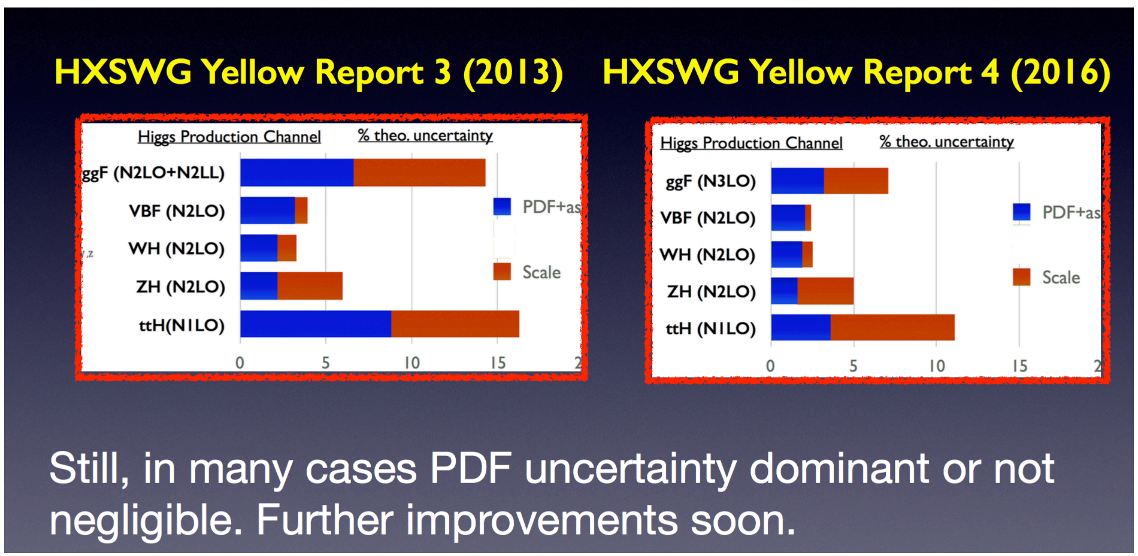
$\Longrightarrow$ nucleon amplitudes constrained by/used to constrain nuclear models

Lattice QCD acts as a disruptive technology to break degeneracy

A. Meyer, BNL Forum

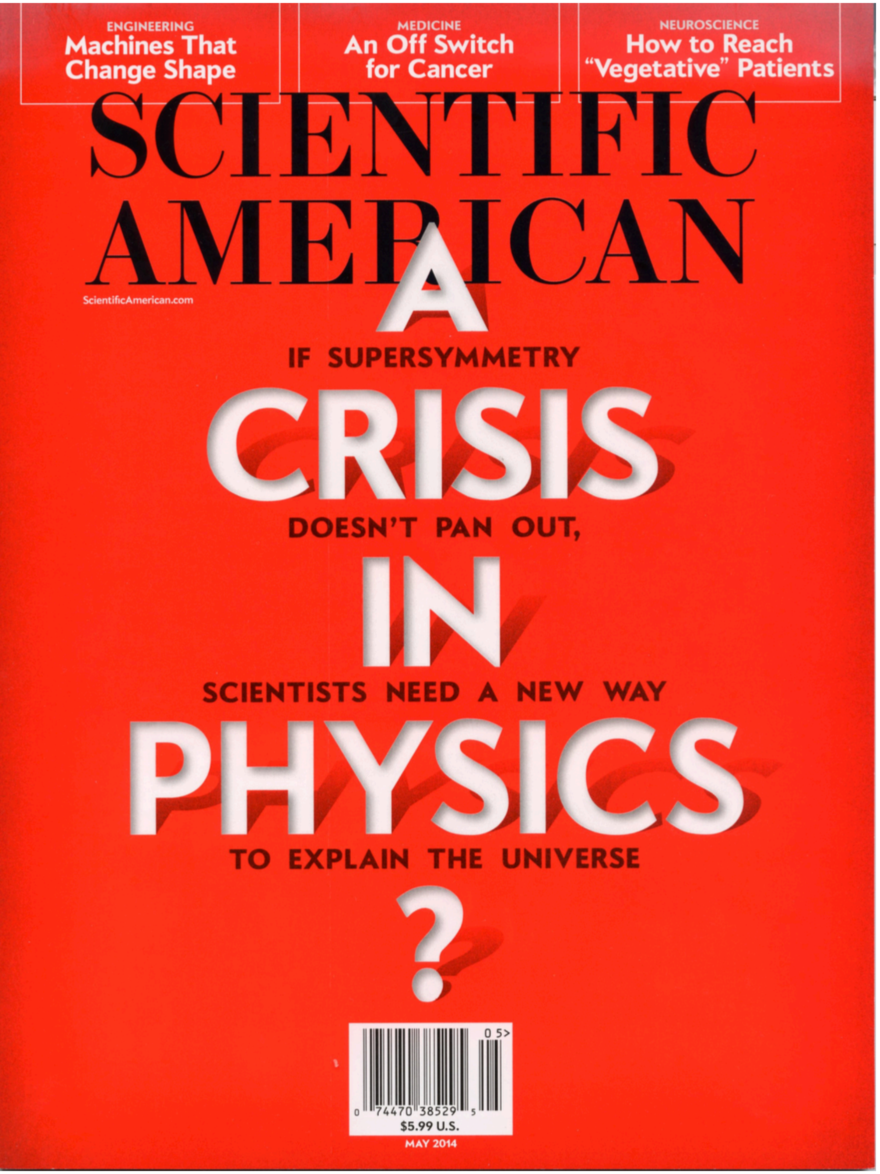
Analogy with the challenges of PYTHIA (and other generators) for LHC:

- Parton distributions are fit from data, not computed from first principles – how to assign meaningful uncertainities?
- Hadronization and fragmentation into hadrons comes from a model – how to assign meaningful uncertainities?
- Underlying event from a model – same question

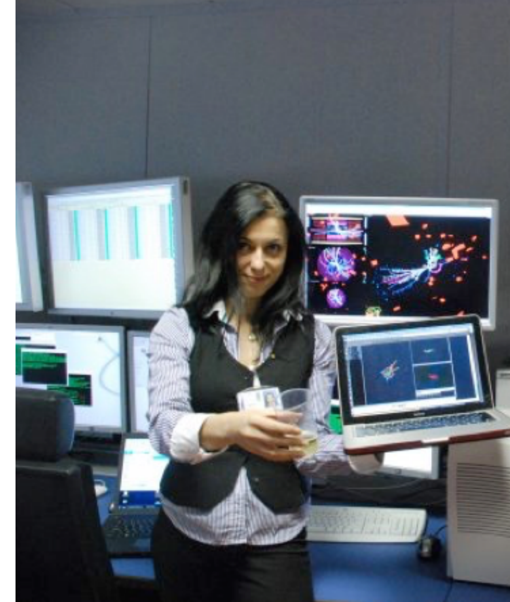


G. Zanderighi, BNL Forum

Where is SUSY?



Trouble makers:
May 2014



Maria Spiropulu with the first CMS collision, 2009

My one and only visit to LHC tunnel, with a magnet built at Fermilab

SUSY SUSY SUSY

- Supersymmetry is a **very powerful idea and theory tool**
- There are **good reasons** to suppose that it is part of our quantum world
- However searches at the LHC and elsewhere have **not yet detected** the superpartner particles that are predicted
- This has created a **mini-crisis** that is stimulating **new thinking** by particle theorists and **creative approaches** by particle experimenters
- Meanwhile new ideas in condensed matter physics are connecting to supersymmetry **in a completely different way**

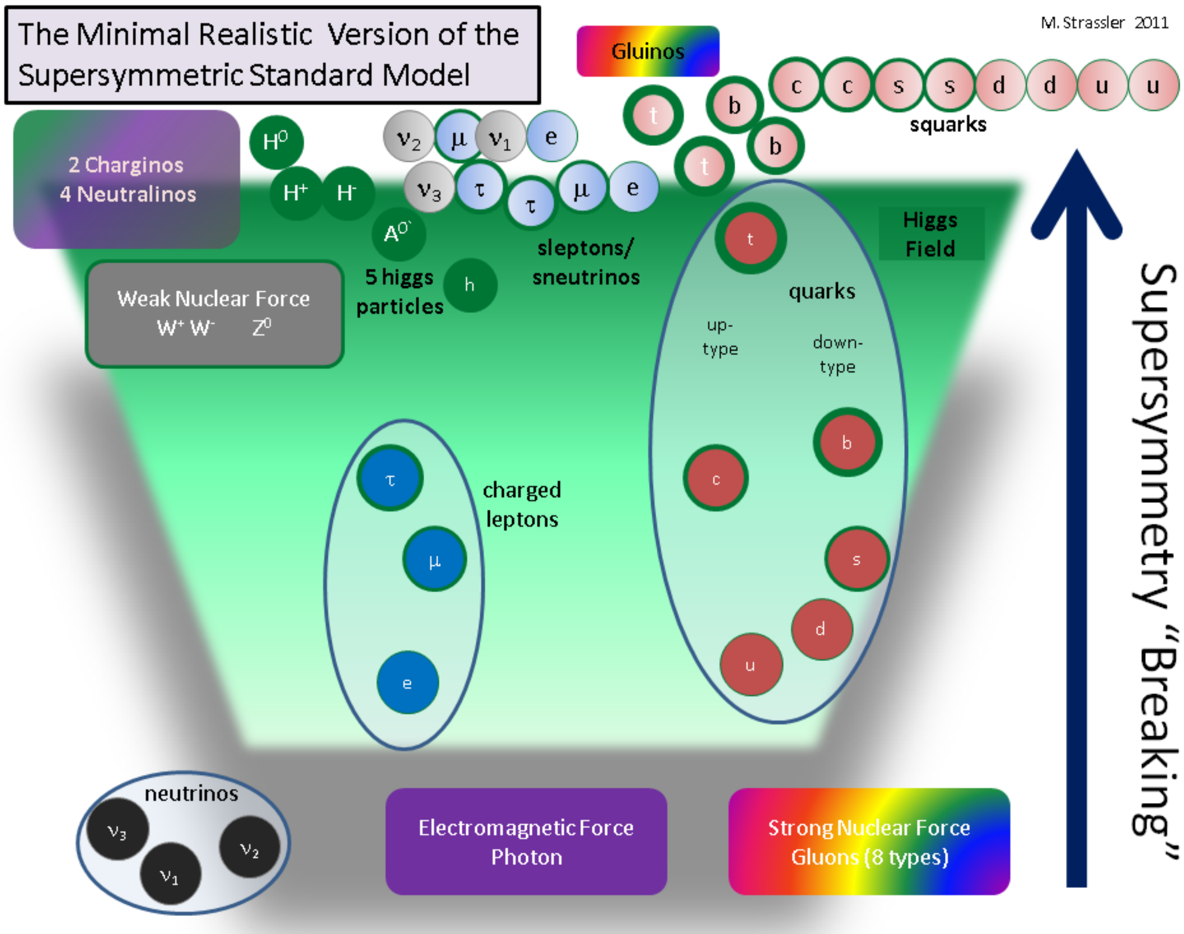
Maximal supersymmetry: SUSY as a theory tool

- Since supersymmetry relates particles of different spin, there is a maximum amount of supersymmetry that you can build into a field theory if you want spins no higher than spin 1 (gauge boson) or spin 2 (graviton)

- In 4-dimensions these maximally supersymmetric field theories are essentially unique: they are called **N=4 super-Yang-Mills theory** and **N=8 supergravity** (N is the number of supersymmetry generators $\mathbf{Q}^{\mathbf{i}}_{\alpha}$)

- **They have very special interesting properties**

Why might we imagine that the Standard Model should be replaced by a softly broken supersymmetric version?



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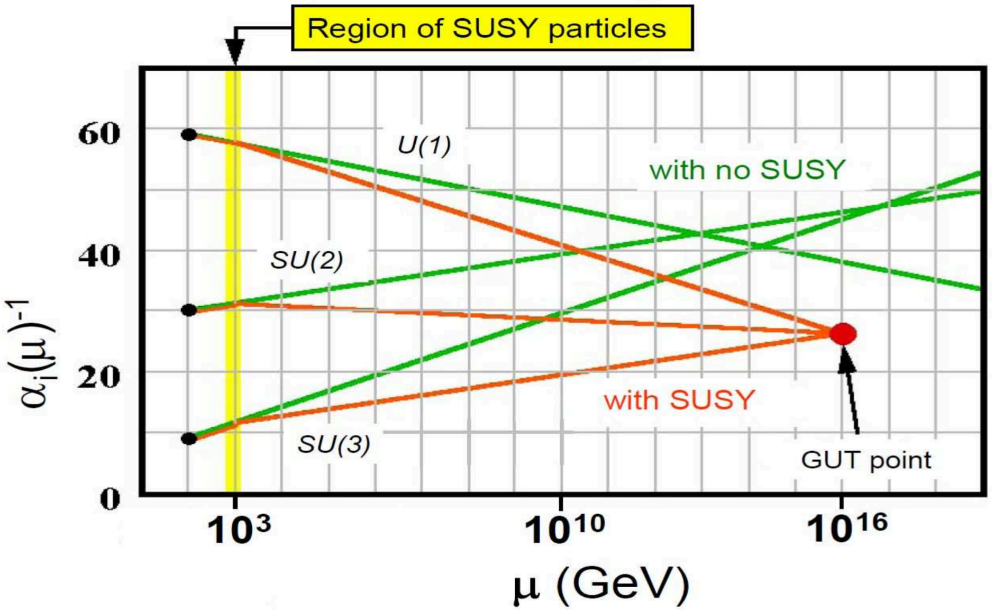
What is SUSY good for? ---- Grand Unification

It is striking that the assumption of SUSY with superpartners very roughly in the TeV mass range implies that the SM gauge forces all have the same strength at an energy scale around 10^{16} GeV



What is SUSY good for? ---- Solving the Hierarchy Problem

What is SUSY good for? ---- Proton decay and dark matter

- A general supersymmetrization of the Standard Model gives instantaneous proton decay (oops)
- A partial fix to this bad prediction is to assume an additional discrete symmetry, called R-parity
- This then also implies that the lightest superpartner particle is stable
- If the lightest superpartner is also uncharged it then provides a good candidate to explain dark matter with a correct thermal relic abundance from the Big Bang

It is striking that the assumption of SUSY with superpartners very roughly in the TeV mass range gives a viable explanation of dark matter almost for free (there are some caveats)

What is SUSY good for? ---- prediction of electroweak symmetry breaking, and estimate of Higgs boson mass

- The Standard Model predicts neither the scale of electroweak symmetry breaking, nor the mass of the Higgs boson, and electroweak symmetry breaking is put in by hand

- With softly broken supersymmetry added, electroweak symmetry breaking is automatic, and the mass of the Higgs boson is predicted up to quantum corrections involving logarithms of the (unknown) superpartner masses

- Assuming superpartners lighters than a few TeV, the Higgs boson mass was predicted to be less than about 130 to 140 GeV

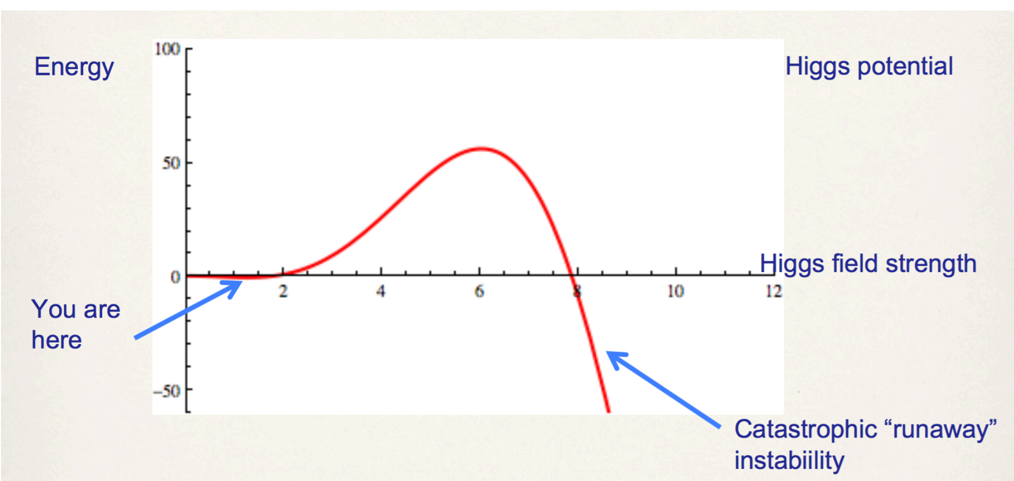
It is striking that the assumption of SUSY with superpartners very roughly in the TeV mass range **predicted** an upper bound on the Higgs boson mass only slightly higher than the actual value; without SUSY the Higgs boson mass could have been 1000 GeV

What is SUSY good for? ---- making the universe stable

- We can do a Standard Model calculation to determine if the Higgs vacuum state that we find ourselves in now is stable or merely long-lived; The answer is that the vacuum is unstable

- Eventually a spontaneous bubble of a lower energy state will appear as a quantum fluctuation somewhere in the universe, and expand to destroy us all

- With SUSY this generically cannot happen



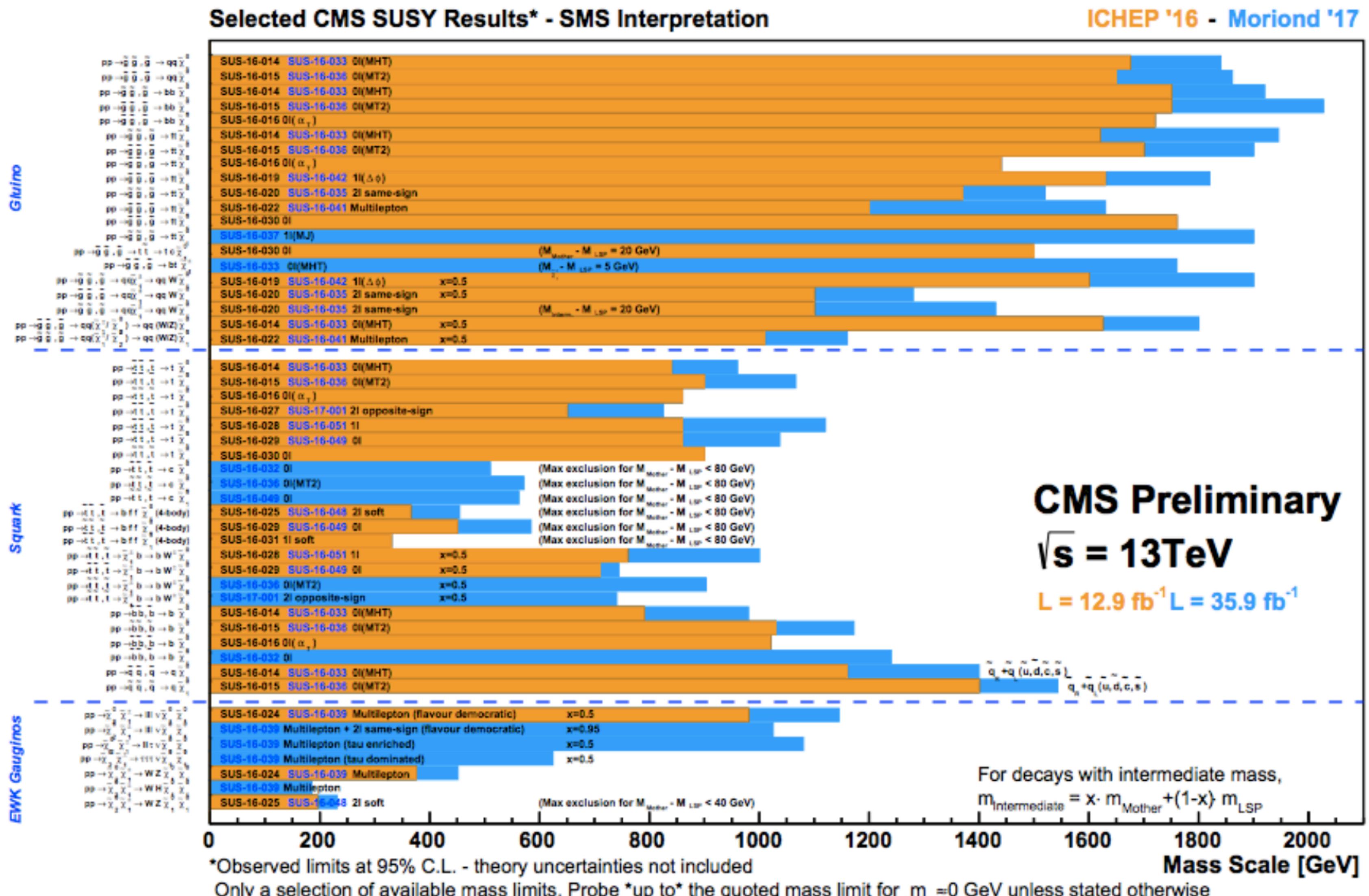
Experimental status of supersymmetry

Two obvious experimental approaches have been pursued for a long time now:

- Try to produce superpartner particles at high energy particle colliders like the LHC
- Try to detect dark matter particles streaming in from space

How are we doing?

Superpartners @ LHC? Ummmm not yet…

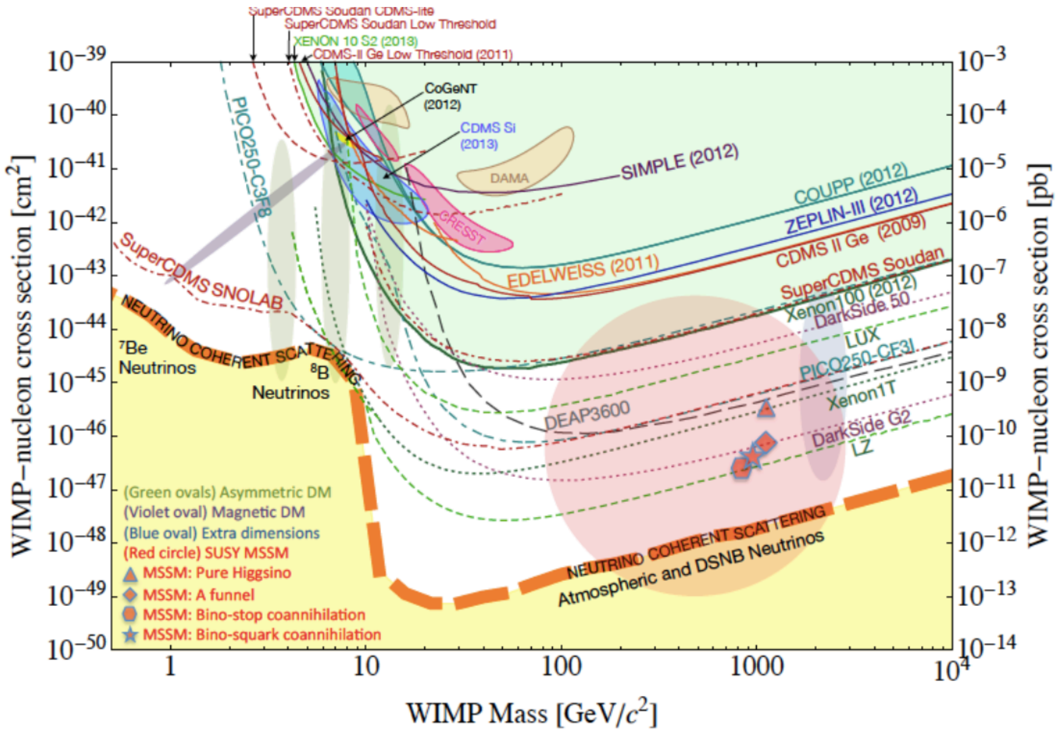


Unnatural SUSY?

$$\begin{aligned} M_Z^2 &= -1.8\mu^2(\text{UV}) + 5.9M_3^2(\text{UV}) - 0.4M_2^2(\text{UV}) - 1.2m_{H_U}^2(\text{UV}) \\ &+0.9m_{Q_3}^2(\text{UV}) + 0.7m_{U_3}^2(\text{UV}) - 0.6A_t(\text{UV})M_3(\text{UV}) \\ &-0.1A_t(\text{UV})M_2(\text{UV}) + 0.2A_t^2(\text{UV}) + 0.4M_2(\text{UV})M_3(\text{UV}) + \ldots \end{aligned}$$

- **This is disturbing**, since in softly broken SUSY these masses are directly related to the Z boson mass (91 GeV) by model parameters of order ~1
- This would imply that the parameters are **fine-tuned** to get a smaller Z mass from larger superpartner masses by an accidental cancellation

Direct searches for WIMP dark matter



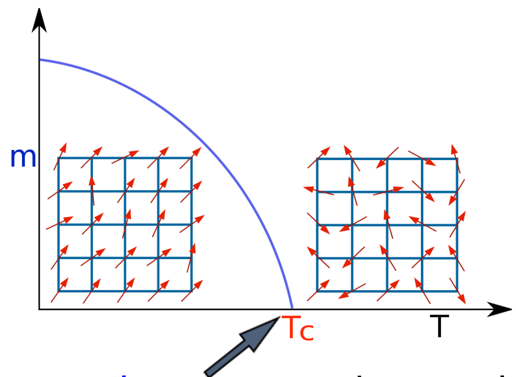
- **This is not yet disturbing**, since a large fraction of the SUSY-preferred parameter space in mass versus WIMP-nucleon cross section has still not been probed
- **But no signals yet**, need to get serious about other DM options

Is there some other way to look for supersymmetry in the real world?

Emergent symmetry in condensed matter

- The microscopic degrees of freedom of condensed matter systems break symmetries that we take for granted in particle theory (boost invariance, rotation invariance) and have lots of short-range complexity

- Not surprisingly, as you approach a critical point broken symmetries can be restored, since e.g. an order parameter vanishes

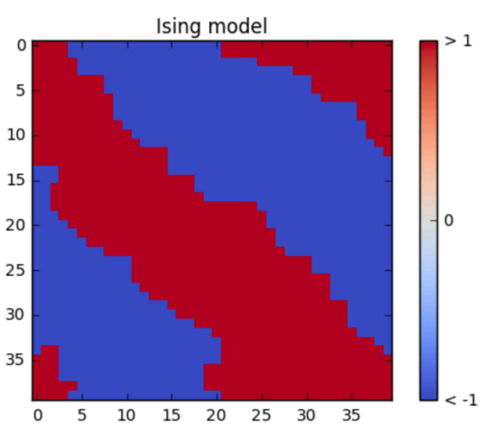


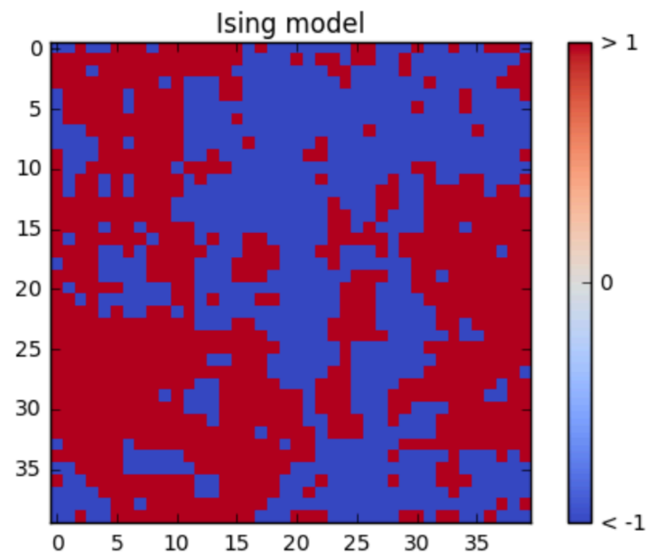
Full rotational symmetry at the critical point

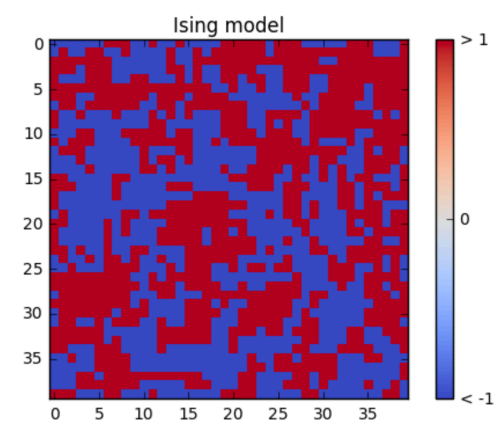
In addition to restoring rotational symmetry, it is possible to see **larger** symmetries emerge…

Emergent space-time symmetry

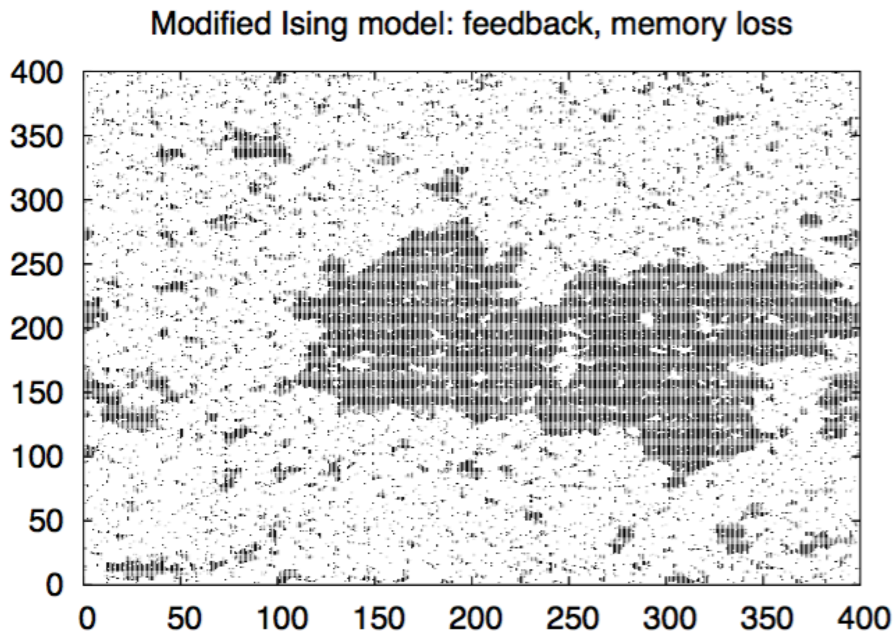
- In fact the critical 2D Ising model can be described by a conformally invariant 2-dimensional relativistic field theory
- This is emergent space-time symmetry
- This CFT is the c=1/2 minimal model of Friedan, Qiu, and Shenker
- The critical behavior of many other systems are also in the this universality class…







Ising model universality class



binary race relations and the development of ghettos

Figure 2: In the same model of the previous figure, a large ghetto is formed if people forget faster their learned tolerance.

We include idiosyncratic preferences or individual biases of stocks, here the willingness to be bullish or not. These Lagrange multipliers h_i can also be interpreted as external influences on entities i induced by the macroeconomic background. By example a company can prosper and make benefits during a crisis period and the associated stock can still fall simultaneously because investors are negatively influenced by the economic background. The stock will have a propensity to fall even if profits are made. If the orientation of the stock satisfies its preference, $h_i s_i$ will be positive. The total conflict of the system is then given by

stock prices closing up or down

$$\mathcal{H}(\mathbf{s}) = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} J_{ij} s_i s_j - \sum_{i=1}^{N} h_i s_i \quad (5)$$

Ising model universality class

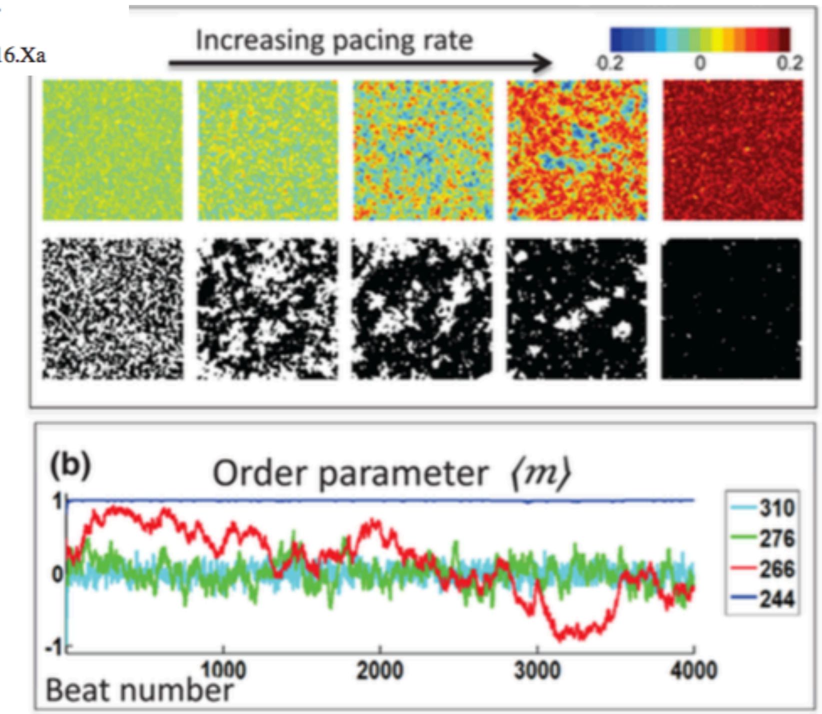
Calcium Alternans is Due to an Order-Disorder Phase Transition in Cardiac Cells

Enrique Alvarez-Lacalle,[1] Blas Echebarria,[1] Jon Spalding,[2] and Yohannes Shiferaw[2]
[1]*Departament de Física Aplicada, Universitat Politècnica de Catalunya-BarcelonaTech, 08028 Barcelona, Spain*
[2]*Department of Physics and Astronomy, California State University, Northridge, California 91330, USA*
(Received 23 July 2014; revised manuscript received 18 October 2014; published 12 March 2015)

Electromechanical alternans is a beat-to-beat alternation in the strength of contraction of a cardiac cell, which can be caused by an instability of calcium cycling. Using a distributed model of subcellular calcium we show that alternans occurs via an order-disorder phase transition which exhibits critical slowing down and a diverging correlation length. We apply finite size scaling along with a mapping to a stochastic coupled map model, to show that this transition in two dimensions is characterized by critical exponents consistent with the Ising universality class. These findings highlight the important role of cooperativity in biological cells, and suggest novel approaches to investigate the onset of the alternans instability in the heart.

DOI: 10.1103/PhysRevLett.114.108101 PACS numbers: 87.19.Hh, 05.70.Fh, 87.16.Xa

e.g. cardiac instabilities



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Ising model universality class?

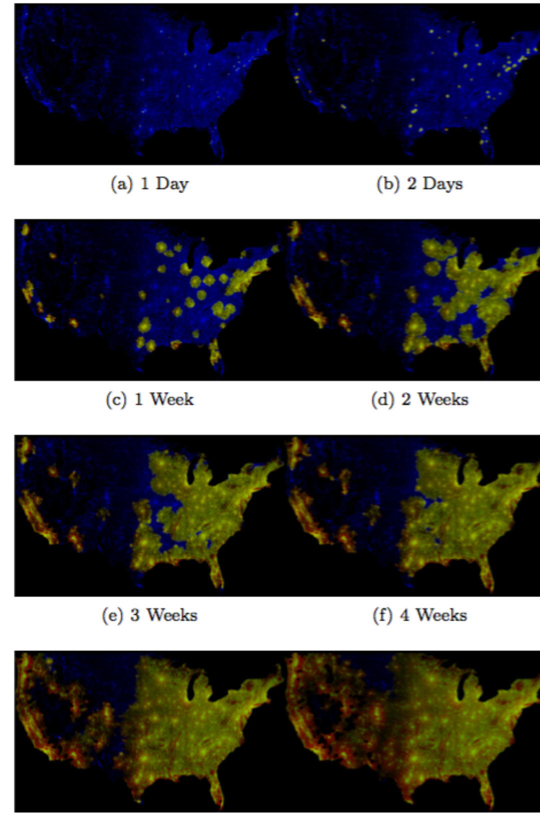
You Can Run, You Can Hide:
The Epidemiology and Statistical Mechanics of Zombies

Alexander A. Alemi,[1,*] Matthew Bierbaum,[1,†] Christopher R. Myers,[1,2,‡] and James P. Sethna[1,§]
[1] *Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY 14853*
[2] *Institute of Biotechnology, Cornell University, Ithaca, New York*
(Dated: June 5, 2015)

We use a popular fictional disease, zombies, in order to introduce techniques used in modern epidemiology modelling, and ideas and techniques used in the numerical study of critical phenomena. We consider variants of zombie models, from fully connected continuous time dynamics to a full scale exact stochastic dynamic simulation of a zombie outbreak on the continental United States. Along the way, we offer a closed form analytical expression for the fully connected differential equation, and demonstrate that the single person per site two dimensional square lattice version of zombies lies in the percolation universality class. We end with a quantitative study of the full scale US outbreak, including the average susceptibility of different geographical regions.

PACS numbers: 87.23.Cc, 87.23.Ge, 87.10.Mn, 87.15.Zg

Sorry this one is in the universality class of the percolation model, not the Ising model



(a) 1 Day (b) 2 Days (c) 1 Week (d) 2 Weeks (e) 3 Weeks (f) 4 Weeks (g) 2 Months (h) 4 Months

FIG. 11. Simulation of a zombie outbreak in the continental United States. Initially one in every million individuals was infected at random. Results are shown above at (a) one day, (b) two days, (c) one week, (d) two weeks, (e) three weeks, (f) four weeks, and (g) two months after the outbreak begins. Shown here are the population of susceptible individuals (S) in blue, scaled logarithmically, zombies in red and removed in green (color online). All three channels are superimposed. A movie version of this outbreak is available in the supplemental materials online.

Emergent supersymmetry?

- This example certainly suggests the possibility that some 2D condensed matter systems might demonstrate **emergent supersymmetry** close to a critical point

- Indeed the next-simplest of the minimal 2D conformal field theories, with c=7/10, is in fact a 2D superconformal theory!

- Furthermore the Tri-critical Ising model is described by this superconformal field theory near its tri-critical point

Emergent supersymmetry?

SUPERSYMMETRY, TWO-DIMENSIONAL CRITICAL PHENOMENA AND THE TRICRITICAL ISING MODEL*†

Zongan QIU[1,2]

Enrico Fermi and James Franck Institutes and Department of Physics, University of Chicago, Chicago, IL 60637, USA

Received 22 October 1986

We discuss the general properties of supersymmetrical two-dimensional critical phenomena, i.e. superconformal field theory. We first review the consequences of ordinary conformal invariance. We then discuss general features of superconformal invariance and the superdifferential equation that correlation functions in certain theories obey. We give the explicit form of this differential equation in the even sector of the tricritical Ising model at its tricritical point. We find the solution of this equation. The physical realizations of this model, e.g. helium adsorbed on krypton-plated graphite, are the first observable supersymmetric field theories in nature.

Seems to imply that emergent supersymmetry was first observed in a real physical system more than 30 years ago…

PHYSICAL REVIEW LETTERS

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Possible Ising Transition in a ^{4}He Monolayer Adsorbed on Kr-Plated Graphite

M. J. Tejwani, O. Ferreira, and O. E. Vilches
Phys. Rev. Lett. **44**, 152 – Published 21 January 1980

ABSTRACT

The specific heat of ^{4}He adsorbed on Kr-plated graphite indicates the existence of an order-disorder transition from a (1×1) [½] triangular structure on a honeycomb lattice of adsorption sites. The specific heat singularity is logarithmic, as predicted from universality considerations, different from the power law observed in the $(\sqrt{3} \times \sqrt{3})R30°$ order-disorder transition of ^{4}He on the bare graphite.

Received 24 October 1979

"Despite extensive searches the Tri-critical Ising quantum criticality and the associated supersymmetry has yet to be observed experimentally in spin models" – X. Zhu and M. Franz arXiv:1602.08172

The New York Times

January 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

The specific heat of ^{4}He adsorbed on Kr-plated graphite indicates the existence of an order-disorder transition from a (1×1) [½] triangular structure on a honeycomb lattice of adsorption sites. The specific heat singularity is logarithmic, as predicted from universality considerations, different from the power law observed in the $(\sqrt{3}\times\sqrt{3})R30°$ order-disorder transition of ^{4}He on the bare graphite.

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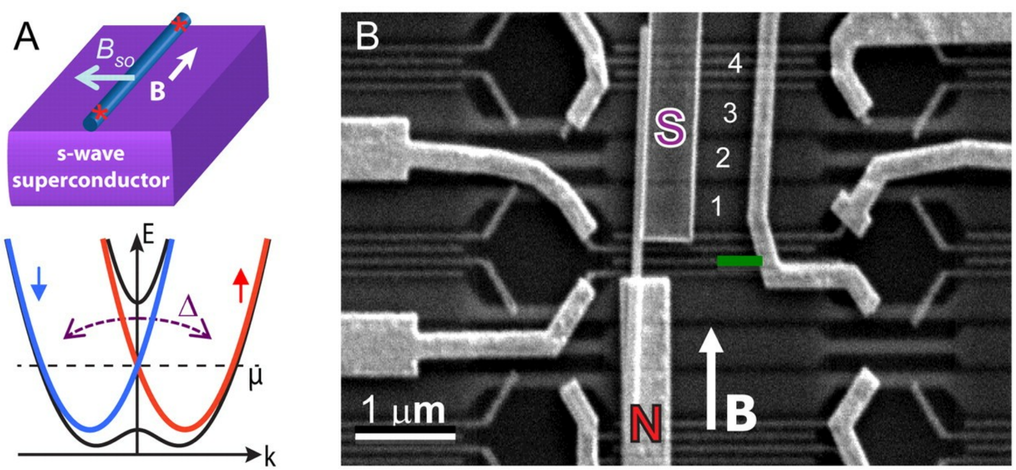
Majorana fermions as qubits

- In the past few years there has a been a lot of activity, both theory and experiment, related to realizing **Majorana fermions as quasiparticle modes in condensed matter systems**
- The motivation for this is **quantum computing**, i.e. the ability to construct robust qubits
- This progress may also lead to the first explicit demonstrations of **supersymmetry** in condensed matter

Majorana zero modes in real systems

- The most progress so far is by using semiconductor nanowires, proximity coupled to ordinary (s-wave) superconductors
- Since 2012 at least six groups have presented evidence for unpaired Majorana quasiparticles at the ends of nanowires



Mourik et al., Science 2012 (Kouwenhoven's group, Delft) following proposals by Lutchyn, Sau & Das Sarma, 2010; Oreg, Refael & von Oppen, 2010.

Emergent supersymmetry redux?

- Recently several groups have tried to revive the idea of demonstrating emergent SUSY in a condensed matter system, now focusing on the various setups thought to give topological superconductors with Majorana quasiparticles

T. Grover et al, arXiv:1301.7449
I. Affleck et al, arXiv:1504.05192
X. Zhu, arXiv:1602.08172

- They show that this can be done if we assume that one can also engineer a strong attractive 4-fermion interaction

The Entanglement Frontier

Long-range quantum entanglement is relevant to a number of situations in particle physics:

- Black holes
- Neutrino oscillations
- Possibly the decoupling of dark sectors [Y. Nakai, Brookhaven Forum]

There may be fundamental insights to be gained here

ER = EPR: down the wormhole

J. Maldacena and L. Susskind, arXiv:1306.0533:

- General Relativity contains solutions in which two distant black holes are connected through the interior via a wormhole (“Einstein-Rosen bridge”)
- These solutions can be interpreted as maximally entangled states of two black holes that form an EPR (Einstein-Podolsky-Rosen) pair

- Propose that this is true in general: any EPR pair can be regarded as physically connected via some sort of “quantum” wormhole

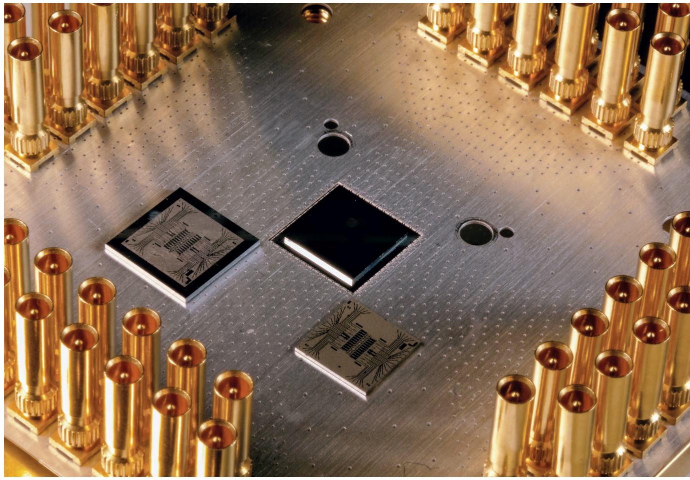
- Since EPR pairs are the basis for quantum communications, this is not idle speculation…

Teleportation through wormholes in the laboratory?

L. Susskind and Y. Zhao, arXiv:1707.04354

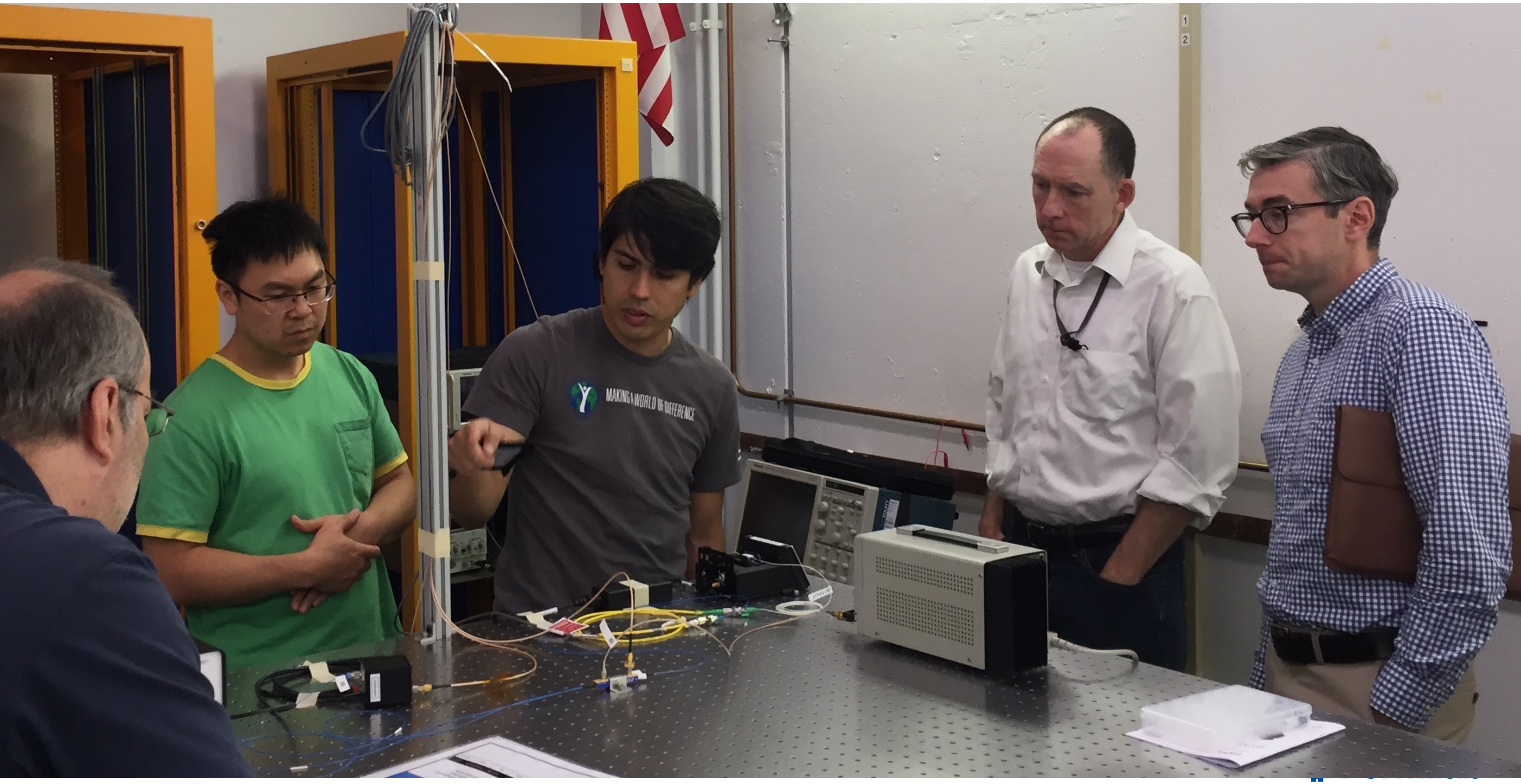
More practical than physical shells, two entangled quantum computers can simulate the CFTs. Of course to allow the teleportation of a real sentient being, the numbers of qubits in each computer would have to be enormous, but with a pair of hundred-qubit computers a ten-qubit teleportee could be teleported. By allowing small variations of the initial state it should be possible to confirm that the teleportee's final state responds to conditions in the wormhole, thereby giving operational significance to ER=EPR.

Speculative, but perhaps testable in the near future

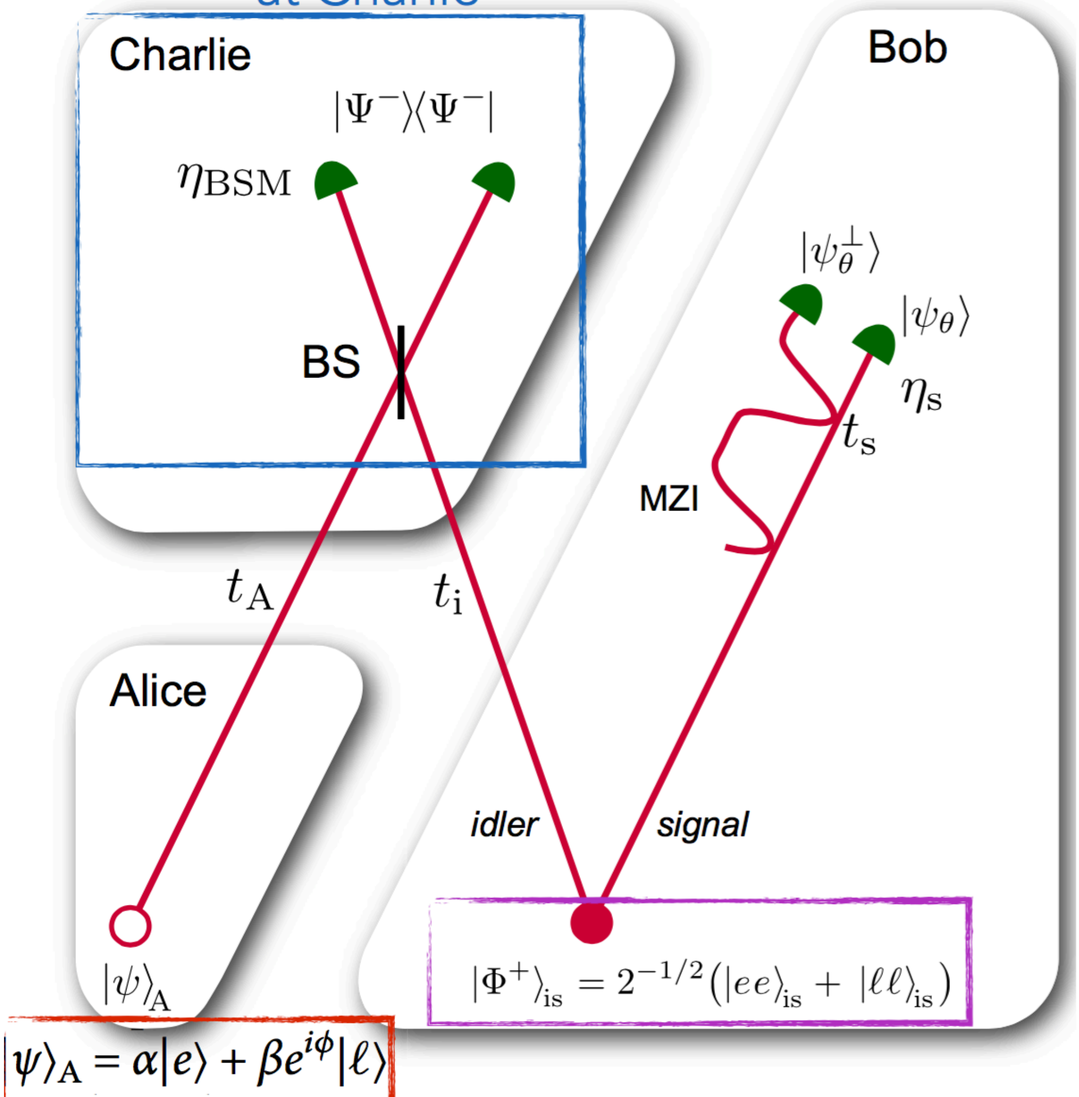


inqnet

Pilot quantum teleportation experiment at Fermilab, partnership with Caltech and AT&T



Bell State Measurement (BSM) at Charlie



Bob creates an entangled pair (one of the four Bell States)

1) He keeps the "signal" photon
2) He send the "idler" photon to Charlie

Alice sends her qubit to Charlie

Charlie performs a BSM by using the beam splitter and the two SNPSDs

$|e\rangle$: *early* photon state

$|l\rangle$: *late* photon state

Conclusion