What have we learned about the quantum theory of gravity

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1 How to unify quantum theory and gravity

Quantum mechanics: (1926)

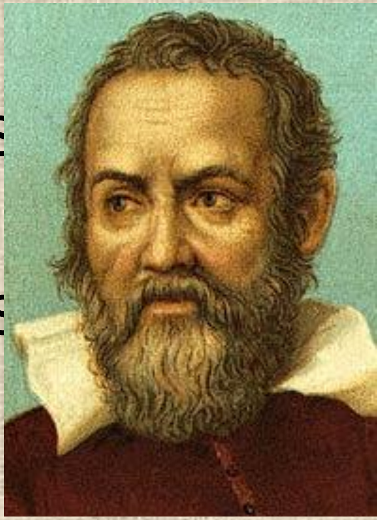
Theory of light, atoms, particles…
Uncertainty principle,
Wave/particle duality

General relativity: (1916)

Einstein‟s theory of space, time and gravity
Gravity is part of the geometry of spacetime
Geometry is dynamical and relational
Dynamic, expanding universe
Black holes, gravity waves….

What is science?

Philosophers and historians tell us there is no universal scientific method that leads necessarily to the truth.



Popper, Feyerabend, Kuhn…

But why does it work so well?

Perhaps because scientists form a community that is bound and governed by ethical principles.

Ethical principles underlying science:

1. If an issue can be decided by people of good faith, applying rational argument to publicly available evidence, then it must be regarded as so decided.

2. If, on the other hand, rational argument from the publicly available evidence does not succeed in bringing people of good faith to agreement on an issue, we must allow and even encourage people to draw diverse conclusions.

Because we don't know the answer, when we confront stubborn hard problems we should encourage people to take risks with big ambitious ideas.

But we should also diversify risk by encouraging different approaches.

Indeed, science moves fastest if we cultivate diverse and conflicting approaches to unsolved problems. Conflict motivates imagination.

Also, premature consensus around a wrong idea could stop the progress of science.

"Certainly, there is no way to establish that any theory describes our world without subjecting its predictions to experimental verification."

Brian Greene, The Elegant Universe, p 210

What is the experimental context for quantum gravity?

$L_{Pl}^2 = hG/c^3 \sim 10^{-33}$ cm $E_{pl} = h/L_{Pl} \sim 10^{19}$ Gev

Where could phenomena at these scales be observed?

•The fate of Poincare invariance: *Is Poincare invariance broken or corrected at order $L_{Pl} E$?*

•Corrections to CMB fluctuations: *Are there corrections to CMB Observations at order $L_{Pl} E_{inflation}$?*

•Unification: *Does quantum gravity imply predictions for particle Physics?*

Quantum gravity changes radically space and time at the Planck scale, which is 10^{-35} of a meter.

We used to think this was impossible to do experiments to probe this scale:

"An accelerator powerful enough to study … Planckian objects would have to be as large as the entire galaxy."

-Leonard Susskind 2006

But in the late 90s we realized we have access to experiments much larger than galaxies… because we detect particles which have traveled across the whole universe for billions of light years.

During this travel tiny effects are amplified, enabling us to probe the geometry on the Planck scale.

Three roads to quantum gravity

Two roads to quantum gravity
come from two competing ideas
about what space and time are:

An absolute unchanging background: Newton

vrs

An ever-changing network of relationships: Leibniz

Two roads to quantum gravity
come from two competing ideas
about what space and time are:

An absolute unchanging background: Newton

"BACKGROUND DEPENDENT"

vrs

An ever-changing network of relationships: Leibniz

"BACKGROUND INDEPENDENT"

BACKGROUND DEPENDENT:

Ordinary quantum mechanics
The standard model

Assume the properties of space and time are fixed and unchanging

BACKGROUND INDEPENDENT:

General relativity

Tells us that space and time are dynamical,
Ever evolving networks of relationships

Julian Barbour

So quantum gravity and unification require bringing together phenomena understood in a background dependent way with gravity which is understood in a background independent way.

From the 1930s people have disagreed about which road to take.

This is due partly to the fact that there are different styles and communities in physics.

The competing approaches foster competing research styles:

Foundational: Einstein, Bohr, Shrodinger, Penrose, Connes…

- Critical perspective on existing theories
- Informed by philosophy and history
- Proceeds by dialogues among independent minds
- Good for making revolutions

Produced quantum mechanics and relativity

Tend to embrace background independence

•***Pragmatic:*** *Fermi, Feynman, Gell-*Mann, Weinberg, Glashow…

- Takes for granted and builds on existing theories
- Disdain of philosophy and history
- Proceeds by teamwork

"Shut up and calculate"

Produced the standard model of particle physics

Tend to resort to background dependent approaches

The first background dependent approach:

Heisenberg and Pauli 1929

"Quantization of the gravitational field, which appears to be necessary for physical reasons, may be carried out without any new difficulties by means of a formalism fully analogous to that applied here."

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The first background independent approach:

Matvei Petrovich Bronstein, 1935

"The elimination of the logical inconsistencies [requires] rejection of our ordinary concepts of space and time, modifying them by some much deeper and non-evident concepts… "

The history of the first road: background dependent.

Failure
Failure
Failure
Failure
Failure
Failure
Hawking radiation from black holes 1974
Failure
Failure
Failure
Failure
Failure
String theory 1984

The history of the second road: background independent

Failure
Failure
Failure
Failure
Failure
Failure
Failure
Failure
Failure
Failure
Failure
Failure

Loop quantum gravity	1986
Spin foam models	1994
Causal dynamical triangulations	1998

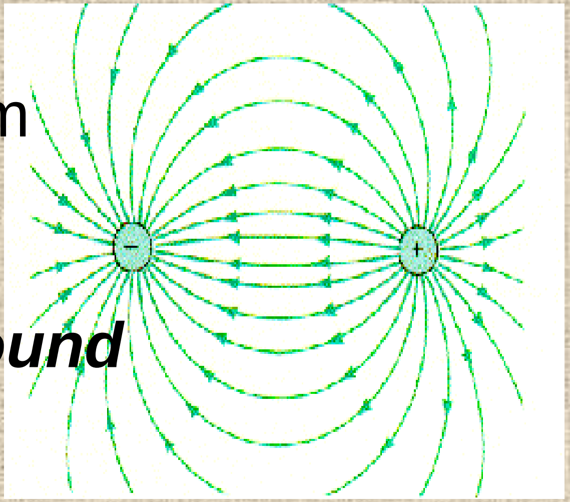
....

Both string theory and loop quantum gravity come from the same idea:

The fundamental things are not points.

They are one dimensional lines extended in space

The electric force is conveyed by field lines (Faraday 1840s)



This idea can be made sense of in quantum theory

String theory develops this in a background dependent context

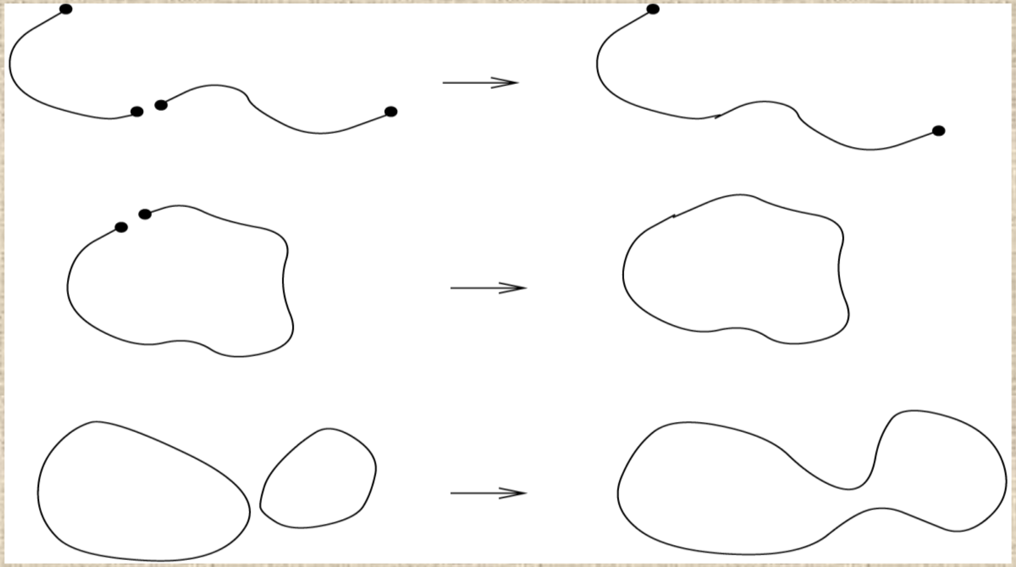
Loop quantum gravity develops this in a background independent context

String theory has compelling features:

•All known kinds of particles and forces can be understood as vibrations of strings stretched in space

•The motion and interactions of strings obey simple laws

•The theory is described in an approximation method familiar from the standard model.



•It gives finite consistent answers to at least the third order of approximation.

The mathematics is very beautiful.
There are beautiful connections to the math of the standard model

The package deal:

The consistency of string theory requires extra features:

- 6 extra dimensions of space

- An extra constraint called supersymmetry

There no observational evidence for either of these

The troubles with extra dimensions

•They must be curled up very small to hide them.

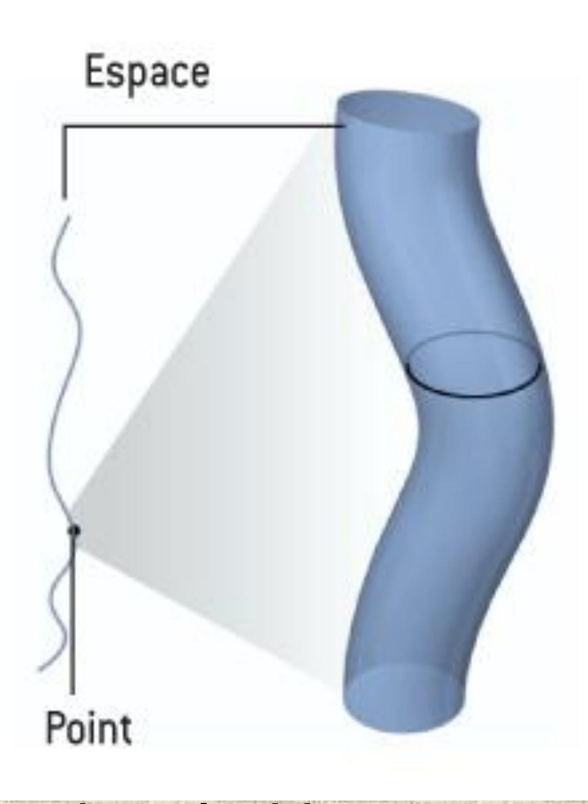
•There are an infinite number of ways to do this

•This leads to an infinite number of different
string theories

•The properties of the elementary particles and forces depend on the choices made for the geometry of the extra dimensions

Hence the theory makes no predictions for the elementary particles, dark matter, dark energy… !

More troubles with extra dimensions



•If they are like the three dimensions we know they are dynamical.

•If they are not like them there is no unification

•Hence the properties of particles should chan in time -but experiment shows they don't!

•The new dimensions can get big or collapse to singularities -but this has never been observed!

Einstein understood the problem already by 1923:

“It is anomalous to replace the four-dimensional continuum by a five-dimensional one and then subsequently to tie up artificially one of those five dimensions in order to account for the fact that it does not manifest itself… ”

The troubles with supersymmetry:

It requires that for each particle there is another particle of the same mass and charges but with spin different by 1/2 unit.

This is not observed in nature.

It implies the cosmological constant is not positive

But it is observed to be positive

It implies the geometry of space does not evolve in time.

But it is observed to evolve

Hence the supersymmetry must be broken or hidden.

Many properties of string theory have only been studied assuming supersymmetry is not broken.

We know very little about the theory in the case required to describe our world.

Basic conjectures of string theory:

- **Perturbative finiteness:** *demonstrated through second order in the string coupling constant (d'Hoker and Phong, 2001)*

- **S (strong-weak) duality:** Shown for states with maximal supersymmetry, some evidence beyond that.

- **M-theory:** *There is a unification of all the different string theories in an 11 dimensional theory.* Some properties and limits of the conjectured theory are known, but no proposal for basic principles or equations.

•**The weak Maldacena conjecture:** There is a mappying between some states and observables of supergravity on asymptotically $AdS^5 XS^5$ and some observables of N=4 Super-Yang-Mills (SYM). *There is lots of evidence.*

•**The strong Maldacena conjecture:** There is an isomorphism between string theory on asymptotically $AdS^5 XS^5$ and N=4 Super-Yang-Mills (SYM). *Open*

- No definition for string theory on $AdS^5 XS^5$ beyond supergravity and certain extremal limits.
- No nonperturbative definition of N=4 SYM.
- Thus there is no detailed proposal for the conjecture.

The strange story of the string landscape:

1984: “String theory is unique”

1985: 100,000s of ways to curl up the extra dimensions

1986: Actually, a vast number of ways

“***All predictive power seems to have been lost*.”

-Andrew Strominger

1992: In this situation we must find new ways to make predictions (ls)

1995: There could be unique unification of all the string theories, theory to be called M theory (but it has not so far been found.)

1998 The cosmological constant observed to be positive, ruling out all known versions

2003 Evidence for string theories with positive cosmological constant…..10^{500} of them

2005: Evidence for infinite families of string theories

THE PRESENT SITUATION:

- ***The unification that was originally compelling is still compelling***
- ***Several key conjectures remain open.***
- ***Up till now string theory makes no predictions at all***
- ***It has no cogent formulation in terms of simple principles and equations.***
- ***We have only partial descriptions of an infinite number of different versions.***
- ***Most properties are only understood in detail for the unphysical case of exact supersymmetry. It is not known which extend to the real situation where supersymmetry is absent or broken.***

A possible approach is the (weak) anthropic principle:

- There are an infinite number of universes, each governed by a randomly chosen version of string theory

- We live in one where life is possible, otherwise random.

- We can only make predictions that are consequences of our own existence.

Detailed arguments show there are very few such predictions, because any attempt depends on details of the statistics of the other, unobservable universes.

Some then proposed **changing the rules of science:**

"Most advances in the history of science have been marked by discoveries about nature, but at certain turning points we have made discoveries about science itself… Now we may be at a new turning point, a radical change in what we accept as a legitimate foundation for a physical theory….The larger the number of possible values of physical parameters provided by the string landscape, the more string theory legitimates anthropic reasoning as a new basis for physical theories: Any scientists who study nature must live in a part of the landscape where physical parameters take values suitable for the appearance of life and its evolution into scientists.

-Steven Weinberg,

"It would be very foolish to throw away the right answer on the basis that it doesn"t conform to some criteria for what is or isn"t science"

— Leonard Susskind

Some disagree:

:"...nothing is a substitute for definitive, testable predictions that can determine whether string theory has truly lifted the veil of mystery hiding the deepest truths of our universe."

Brian Greene, The Elegant Universe, p 18

"Certainly, there is no way to establish that any theory describes our world without subjecting its predictions to experimental verification." **ibid p 210**

"No one should believe string theory until it makes predictions that are verified in the laboratory."

- James S Gates NOVA, Elegant Universe

"Even today, more than three decades after its initial articulation, most string practitioners believe we still don't have a comprehensive answer to the rudimentary question, What is string theory? . . . [M]ost researchers feel that our current formulation of string theory still lacks the kind of core principle we find at the heart of other major advances."

Brian Greene, The Fabric of Reality

"Actually, I would not even be prepared to call string theory a „theory," rather a „model," or not even that: just a hunch. After all, a theory should come with instructions on how to deal with it to identify the things one wishes to describe, in our case the elementary particles, and one should, at least in principle, be able to formulate the rules for calculating the properties of these particles, and how to make new predictions for them. Imagine that I give you a chair, while explaining that the legs are still missing, and that the seat, back and armrest will perhaps be delivered soon. Whatever I did give you, can I still call it a chair?"

Gerard „t Hooft

What about the other two roads?

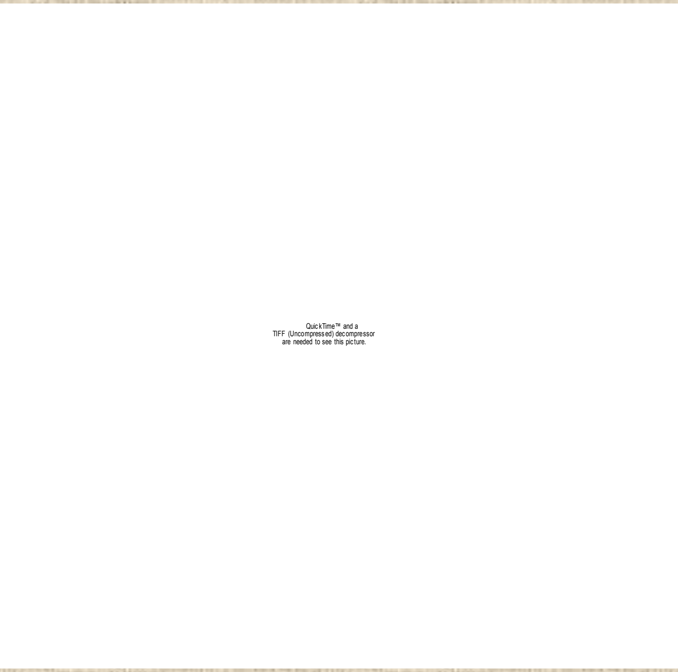
Meanwhile a lot of progress has been made on background independent approaches...

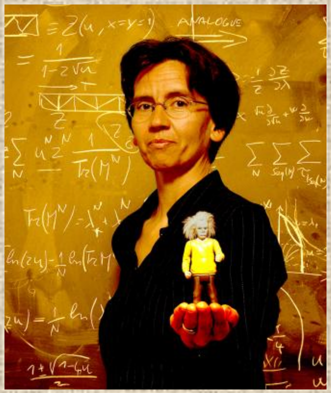
And we have discovered that we can do experiments to probe quantum gravity

Causal dynamical triangulations

Models quantum geometry in terms of discrete elements

Calculations show space looks smooth and three dimensional at macroscopic scales





Renate Loll

A key observational question for quantum gravity is:

What is the symmetry of the ground state?

Global Lorentz and Poincare invariance are not symmetries of classical GR, they are only symmetries of the ground state with $L=0$.

Hence, the symmetry of the quantum ground state is a dynamical question.

Three possibilities

1 Poincare invariant

2 Broken Lorentz invariance

3 Deformed Poincare invariance (DSR)

Doubly special relativity

Giovanni Amelino
-Camelia

Joao Magueijo

Consistent modification of special relativity which captures effects of quantum gravity.

Implies predictions for real Experiments

Sabine
Hossenfelder

Snyder 1947, Fock 50s, Lukierski et al 91, Majid et al 93
Amelino-Camelia 2000, Magueijo + Smolin 2001

Principles of deformed special relativity (DSR):

1) Relativity of inertial frames
2) The constancy of c, a velocity
3) The constancy of an energy E_p
4) c is the universal speed of photons for $E \ll E_{p.}$

Principles of deformed special relativity (DSR):

1) Relativity of inertial frames

2) The constancy of c, a velocity

3) The constancy of an energy E_p

4) c is the universal speed of photons for $E << E_p$.

Consequences:

- Modified energy-momentum relations
- Momentum space has constant curvature given by E_p
- Spacetime geometry is non-commutative.
- metric becomes scale dependent: $g_{ab}(E)$
- Usual energy-momentum conservation non-linear
- Linear conservation of new 5d momentum. (Girelli-Livine)

DSR is realized precisely in 2+1 gravity with matter hep-th/0307085

There are two basic low energy QG effects:

1) Corrections to energy momentum relations:

$$E^2 = p^2 + m^2 + a\, lp\, E^3 + b\, lp^2\, E^4 + \ldots$$

$$v = c(1 + a\, lp\, E + \ldots)$$

2) Modifications in the conservation laws.

Some basic consequences:

- Modifications of thresholds such as in GZK
- Energy dependence of the speed of light, neutrinos …

Are they sufficient to distinguish the three possibilities of exact, broken or deformed Poincare invariance (DSR)?

The GZK threshold

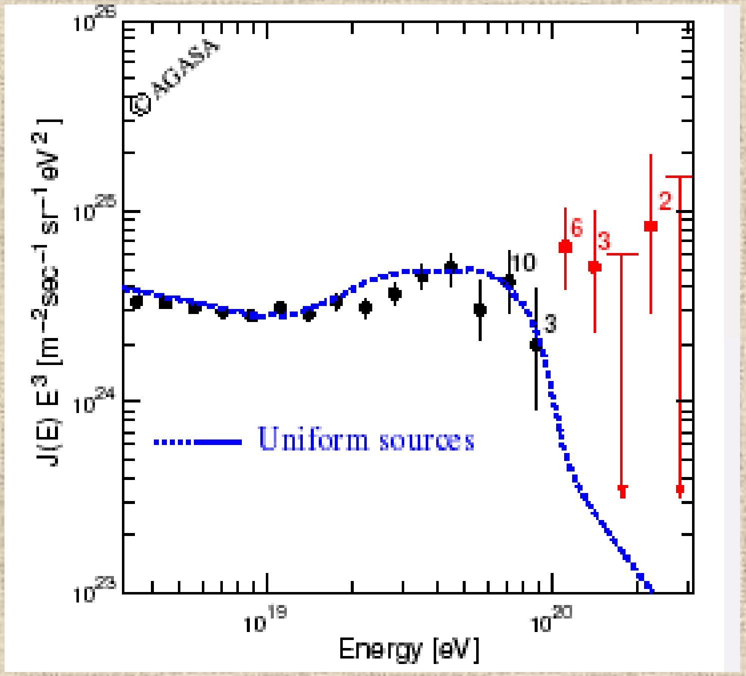
An effect of a modified energy momentum relation alone

$$E^2 = p^2 + m^2 + a\, lp\, E^3 + b\, lp^2\, E^4 + \ldots$$

This moves the threshold for pion production from protons scattering from microwave photons. The threshold is predicted to be at 3 10^{19} ev.

Prediction from Lorentz Inv
+ uniform sources

AGASA reported events over the GZK threshold!



Energy dependent speed of light. $v=c(1+ a\, lp\, E + b\, lp^2 E^2 + ...)$

- Accumulates for long distances
- Observable in Gamma Ray bursts.
- present limits have $a < 1000$
- *GLAST will put limits $a < 1$*

- **Could be parity even or odd**

- A parity odd v(E) has been ruled out at $O(l_P)$

  by observations of distant polarized radio galaxies

  Also, by polarization observed in Gamma Ray Bursts

  Colburn, Boggs, Nature ***423,*** *415–417 (2003). Mitrofanov, Nature, VOL 426 13 Nov 2003*

- ***GLAST could see $O(l_{PL})$ parity-even v(E)***

Broken lorentz invariance gives modified dispersion relations but unmodified conservation laws

- *GZK threshold moves appreciably*
- *helicity dependent energy dependent speed of light*

Deformed lorentz invariance gives both.

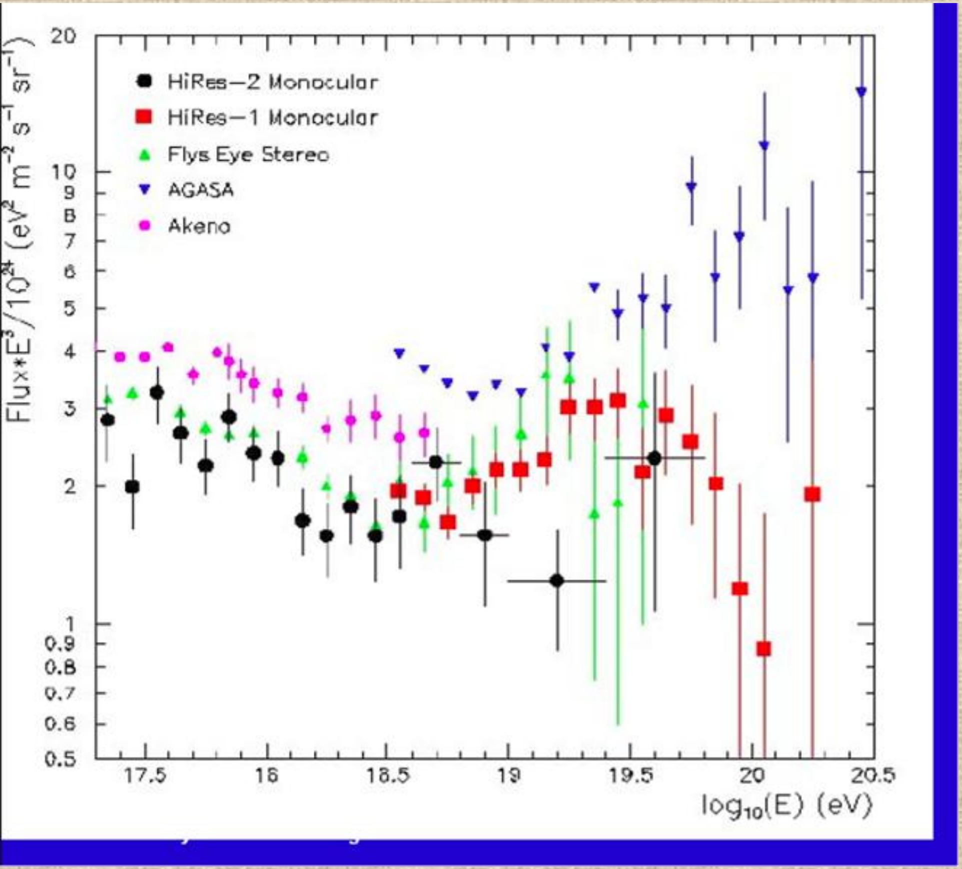
- *GZK threshold as in ordinary special relativity*
- *helicity independent energy dependent speed of light*

To distinguish the three possibilities we need three experiments:

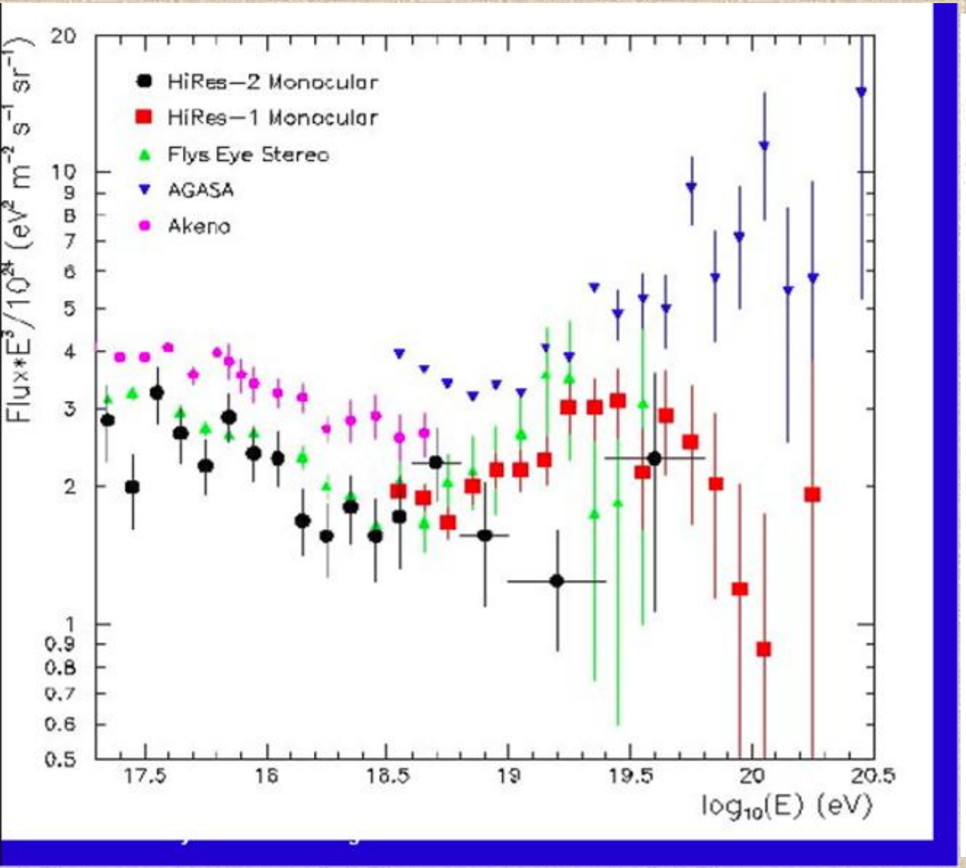
- *AUGER tests GZK*
- *GLAST tests energy dependence of photons*
- *Detection of polarized photons from distant sources tests helicity dependence*

GZK: AGASA, Sugar saw anomalous events

HIRES didn't



AUGER last report: Astro-ph/0608136



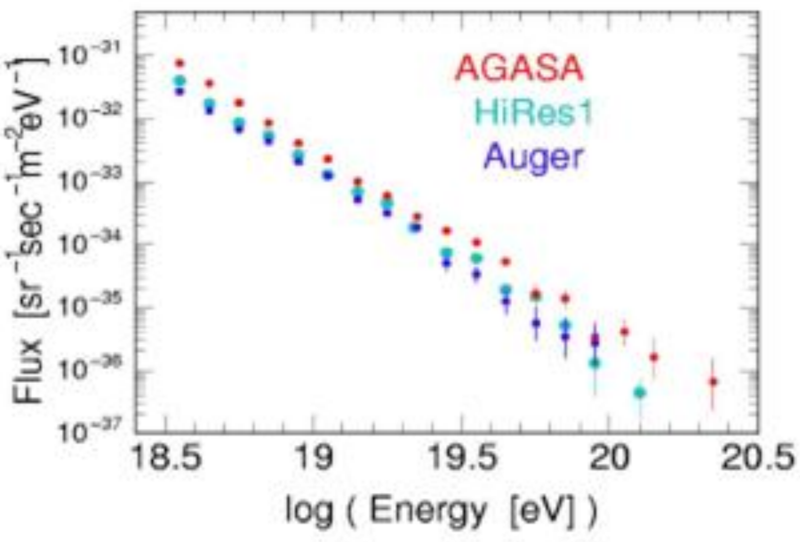


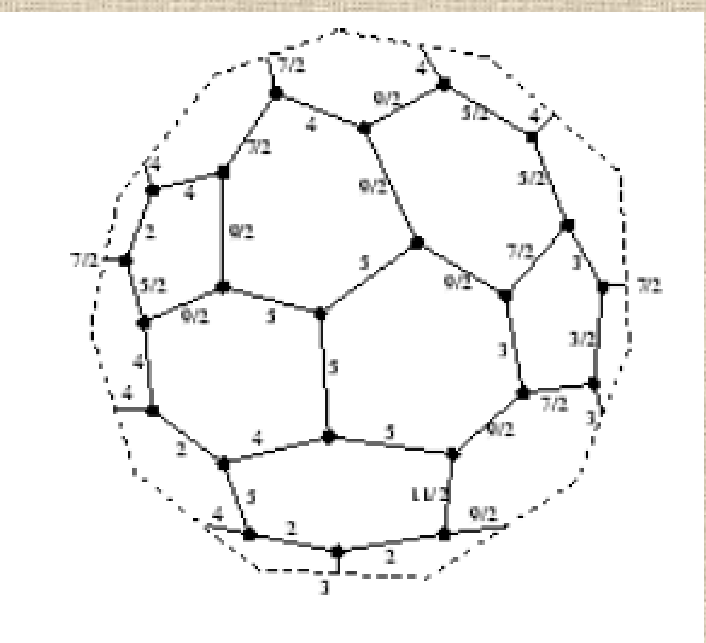
Fig. 6. The energy spectrum of EHECRs measured by the Pierre Auger experiment compared with the AGASA [38] and HiRes-I [39] results.

Loop quantum gravity

Rigorously consistent unification of general relativity and quantum theory

Laurent Freidel

Etera Livine



LQG is **not** , so far, a candidate for the fundamental theory.

LQG is **not** , so far, a candidate for the fundamental theory.

It ***is***:

A well defined and consistent framework for defining and studying a large class of diffeomorphism invariant gauge theories.

These include GR, SUGRA, in any spatial dimension, d>1,
with varied matter fields.

There is a large body of results of different kinds, some rigorous, some heuristic, some from study of related models of black holes and quantum cosmologies.

It is a well developed framework for approaching background independent quantum theories… .including perhaps string/M theory.

It is based on 4 principles:

Four principles:

1) The Gauge principle: All forces are described by gauge fields

- Gauge fields: A_a valued in an algebra G
- Gravity: A_a valued in the lorentz group of SU(2) subgroup
- p form gauge fields
- Supergravity: Y_m is a component of a connection.

2) Duality: equivalence of gauge and loopy (stringy) descriptions

observables of gauge degrees of freedom are non-local: described by measuring parallel transport around loops

Wilson loop $T[g, A] = Tr \exp \int_g A$

3)

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Developed on a background with fixed metric, this leads to string theory!

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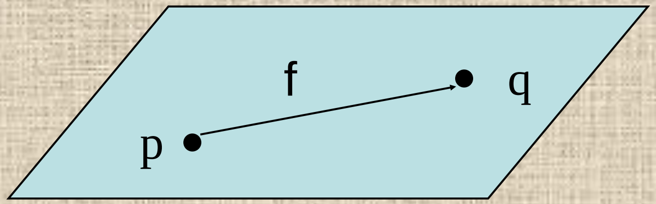
3) ***Diffeomorphism invariance and background independence***

3) Background independence (partial)

Means that are no fixed, non-dynamical fields and no global symmetries. Topology, differential structure and boundary conditions are fixed.

gauge invariance of general relativity includes ACTIVE diffeomorphism invariance of the spacetime manifold.



spacetime is NOT modeled by a manifold and metric, but by the equivalence class of manifolds and metrics, which are equivalent under any diffeomorphism !! Points are only distinguished by values of fields.

Realizes the basic principle that space and time are not fixed but reflect only dynamically evolving relationships

The gravitational field can be described as a gauge theory:

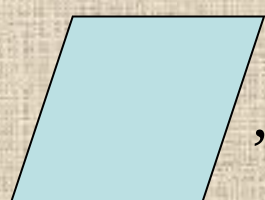
Spacetime connection = Gauge field = configuration variable
Spacetime metric = Electric field = momentum

•Quantum gauge fields can be described in terms of operators that correspond to Wilson loops and electric flux. These have a natural algebra that can be quantized:

The loop/surface algebra.

$T[g,A] = Tr\exp \int_g A$ 

$E[S] = \int_S E$ 

[ , ] = h G Int 

The fundamental theorem: **Consider a background independent gauge theory, compact Lie group G on a spatial manifold S of dim >1. No metric!!** **(G=SU(2) for 3+1 gravity)**

> **There is a unique representation of the loop/surface algebra in which the Hilbert space carries a unitary rep of the diffeomorphism group of S, called H^{kin}.**

Lewandowski, Okolo, Sahlmann, Thiemann+ Fleishhack (LOST theorem)

This means that there is a unique diffeomorphism invariant quantum quantum theory for each G and S.

The Hilbert space of diffeo invariant states, H, is a subspace of $\mathbf{H}^{kin*}$

Ashtekar: GR is a diffeomorphism invariant gauge theory!!

The dynamics of GR have been expressed in closed form in terms of finite operators and evolution amplitudes on H.

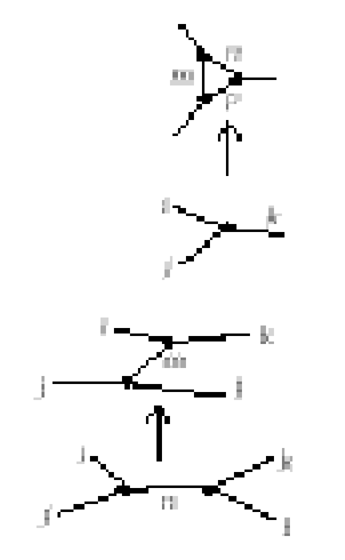
General structure: *causal spin network theories*

•Pick an algebra G

Def: G-spin network is a graph G with edges labeled by representations of G and vertices labeled by invariants.

• Pick a differential manifold S.

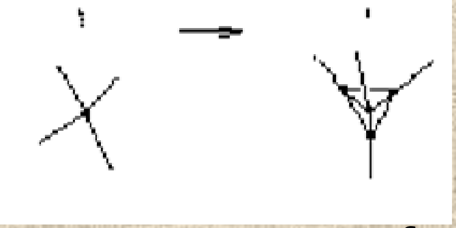
{G} an embedding of G in S, up to diffeomorphism

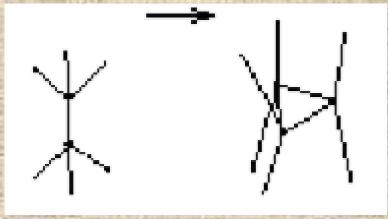


•Define a Hilbert space H:

|{G}> Orthonormal basis element for each {G}

•Define a set of local moves and give each an amplitude





•A history is a sequence of moves from an in state to an out state

•Each history has a causal structure

4) Gravitational theories are <u>constrained or perturbed topological field theories</u>

We are familiar with gauge theories in which not all components of a field are physically meaningful.

The rest are called pure gauge. $dA_a \sim {}_a f$

A topological field theory is a theory whose local fields are entirely pure gauge.

All the physical degrees of freedom and observables live on the boundaries of spacetime.

Their quantum observables define topological invariants of space.

4) Gravitational theories are <u>constrained</u> topological field theories

The dynamics is given by

S= Topological theory + quadratic constraints

All the derivatives are in the topological term

So commutators, path integral measure and boundary terms are those of the topological theory.

On top of these we just impose quadratic operator equations.

This is true of GR and supergravity in all dimensions, including 11.

LQG: What has and has not been done?

•A well defined, and unique framework for formulating and studying diffeomorphism invariant gauge theories in any dim, with or without susy. → Discreteness of area and volume operators.

•In d=3,4 the hamiltonian constraint for quantum GR is known on H in closed form and is uv finite, including all usual matter fields.

•In d=3 the theory coupled to interacting scalar fields has been solved and gives an effective QFT on κ-Minkowski spacetime.

•In d=4 the path integral involves a sum over diagrams and on each a sum over labels. The latter are known to be uv finite.

•In d=4 there is evidence, not yet proof, for a good low energy limit which recovers GR + QFT.

- •Semiclassical states exist, excitations are low energy gravitons.

- •Propagator has been computed from a spin foam model and agrees at low energes with GR

•Indications of novel and testible $O(l_{Pl})$ effects including deformation of Poincare symmetry leading to an energy dependent speed of light. This is shown precisely in 2+1 but only semiclassically in 3+1.

Thus DSR is a consequence in 2+1 dimensions.

Is this also true in 3+1 dimensions?

So far there is a semiclassical argument, but no proof.

Loop quantum cosmology

Applications of the methods of loop quantum gravity to quantum cosmological models.

Martin Bojowald

Stephon Alexander

Applications to cosmology

Loop quantum cosmology: (M Bojowald + many others) ***R***

•Based on a reduction to a quantum theory with finite degrees of freedom.

The basic principle: *Normalizable states go to normalizable states.*

Wilson loops are normalizable in the full quantum field theory.
In the reduction, Wilson loops become plane waves e^{ika}.
So plane waves (in scale factor, a) become normalizable states.

$$< e^{ika} | e^{ila} > = d_{kl}$$

•This is *inequivalent* to the usual mini-superspace quantization.

•It preserves the result that volume is represented by an operator with a discrete spectrum.

Basic cosmological results:

- The ***exact*** evolution by the Hamiltonian constraint solved. Coupling to matter, including inflaton fields can be easily incorporated exactly.
- The volume (hence time) is discrete.
- At large volumes (in planck units) FRW classical cosmology is recovered
- At small volumes the singularity is absent, and replaced by a bounce, before which the universe was contracting.
- At small volume leading corrections can be modeled by an effective dynamics

Basic mechanism of singularity removal:

- The operator, ***$V \sim a^3$***, that represents the volume of space has a discrete spectrum with a minimum non-zero lowest eigenvalue.

- It is naive and wrong to write the density operator as 1/a.

- The operator that represents density is a ***commutator:***

$$r \sim e^{-ika} \, [V, e^{ika}] \, .$$

Both are finite and e^{ika} has bounded spectra.

⇒ r has a discrete spectrum, bounded above.

Hence there is a finite upper limit to density and a bounce.

Cosmological singularities replaced by bounces:

Big Crunch Avoidance in k = 1 Semi-Classical Loop Quantum Cosmology

Parampreet Singh*, Alexey Toporensky†

gr-qc/0312110

Gravity coupled to a massive scalar field:

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 \,.$$

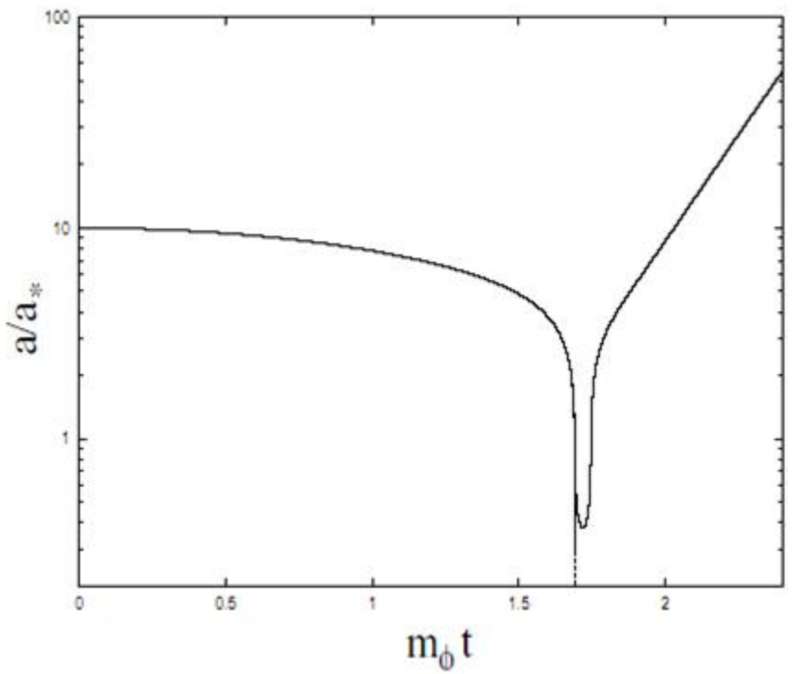


FIG. 1: Evolution of scale factor for a closed universe in classical cosmology is shown by the dashed curve and in loop quantum cosmology is shown by the solid curve for the quadratic potential with $j = 100$, $m_\phi = 0.1 M_{\rm pl}$ and initial conditions $a_i = 10\, a_*$, $H_i = 0$, $\phi_i = 0$ and $\dot{\phi}_i$ determined from eq.(5). A collapsing closed universe in classical cosmology encounters a big crunch whereas in loop quantum cosmology it bounces into an expanding phase when $a = 0.38\, a_*$ and avoids big crunch.

Singularity removal is non-negotiable in this class of model quantum cosmologies!!

No dependence on initial conditions, matter content, fine tuning etc.

The same appears to be true for black holes.

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Presently under investigation. (Brunnemann + Thiemann)

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Are there consequences for cosmological observations?

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•Inflation can be recovered by coupling to scalar field.

•***Corrections to the power spectrum for inflation derived*** Hofman +Winkler astro-ph/0411124, Hossain gr-qc/04110124

There is an order L_p term!!

Gives a 10% effect for quadrapole mode

Loop quantum gravity effects on inflation and the CMB

Shinji Tsujikawa[1], Parampreet Singh[2], and Roy Maartens[1]

astro-ph/ 0311015

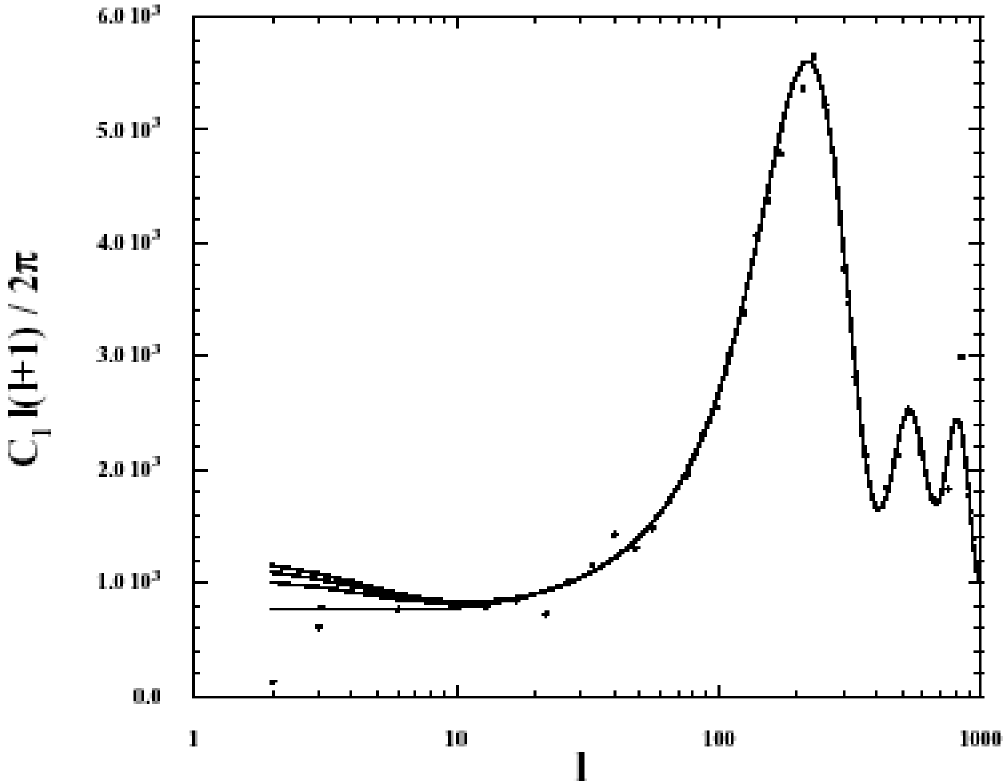


FIG. 3: The CMB angular power spectrum with loop quantum inflation effects. From top to bottom, the curves correspond to (i) no loop quantum era (standard slow-roll chaotic inflation), (ii) $\bar{\alpha} = -0.04$ for $k \leq k_0 = 2 \times 10^{-3}\,\mathrm{Mpc}^{-1}$, (iii) $\bar{\alpha} = -0.1$ for $k \leq k_0$, and (iv) $\bar{\alpha} = -0.3$ for $k \leq k_0$. There is some suppression of power on large scales due to the running of the spectral index.

Results on black holes and horizons:

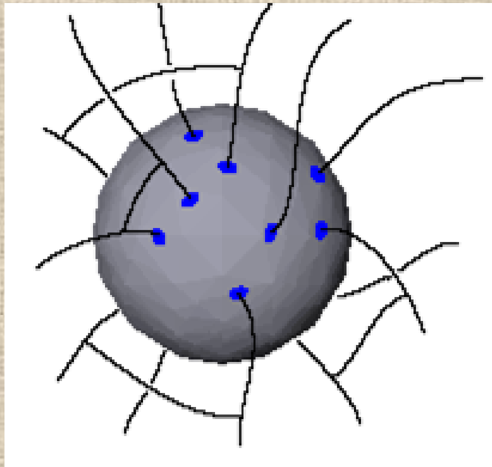
•We have exact results for boundary conditions of the form

E (s.d. 2-form of metric) = constant F (left-handed curvature)

•This includes all black hole and cosmological horizons

•The horizon state space is described in terms of Chern-Simons theory
It can be decomposed into eigenstates of area

•For each area the horizon state space is finite dimensional-gives the exact quantum geometry of the horizon.



•The Bekenstein Hawking relation holds exactly

S (entropy) = Area / 4Gh

S ***(Ling and Zhang)***

The (finite) renormalization of G required is fixed independently by matching to the quasi normal mode spectrum of bh's (Dreyer)

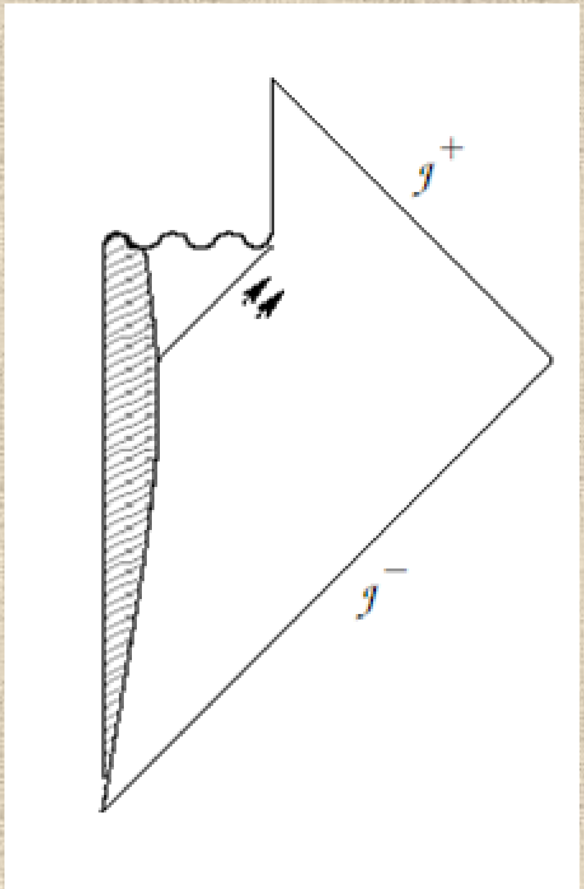
Black hole singularities removed

Modesto gr-qc/0407097, 0504043
Husain & Winkler gr-qc/0410125
Ashtekar & Bojowald gr-qc/0504029

Same mechanism as works in cosmology.

Unitarity, information loss and all that???

The standard scenario
(Hawking...)

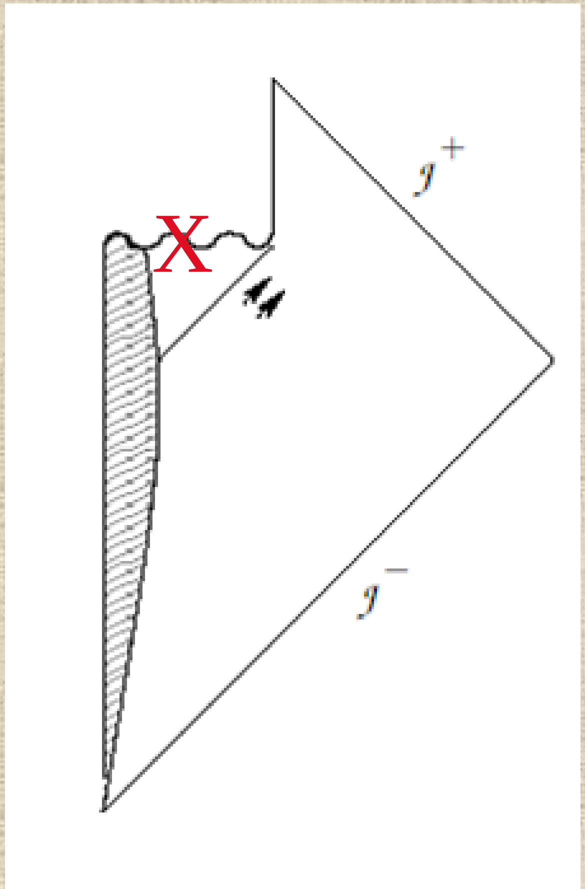


There seems to be a paradox.

Where can the information go?

Unitarity, information loss and all that?

The standard scenario
(Hawking...)



There seems to be a paradox.

Where can the information go?

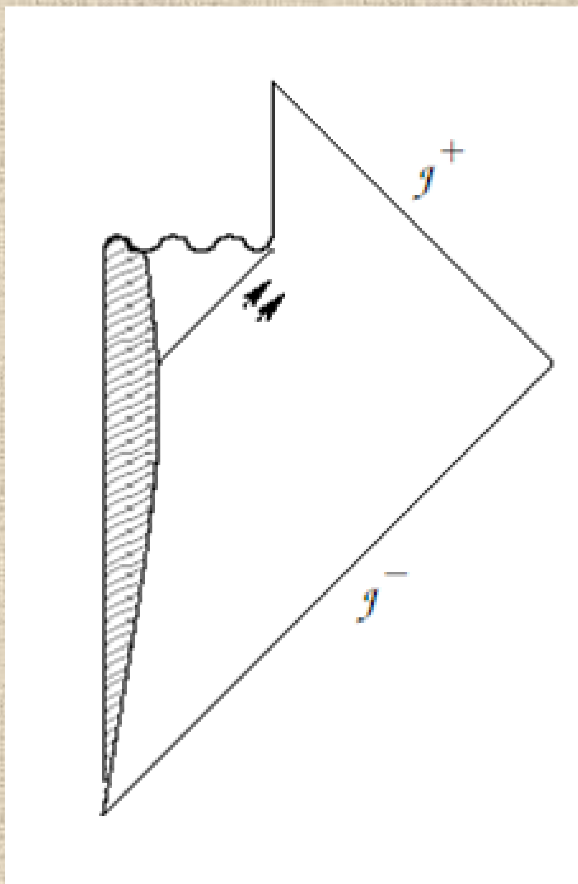
But quantum gravity effects are shown to eliminate the singularity

Modesto gr-qc/0407097, 0504043
Husain & Winkler gr-qc/0410125
Ashtekar & Varadarajan
Ashtekar & Bojowald gr-qc/0504029

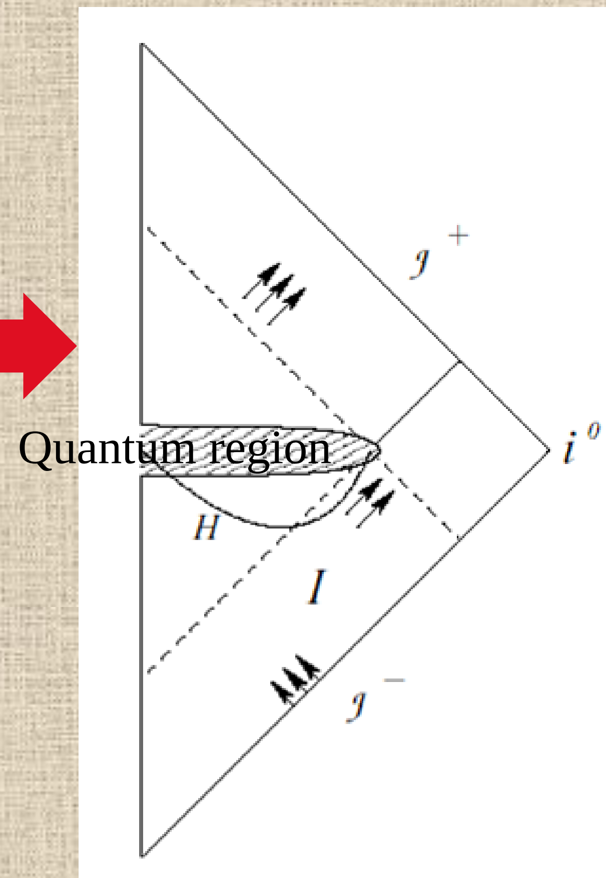
What then??

Unitarity, information loss and all that?

The standard scenario
(Hawking...)



Quantum singularity resolution:
(assuming no permanent baby universe
and finite evaporation time)



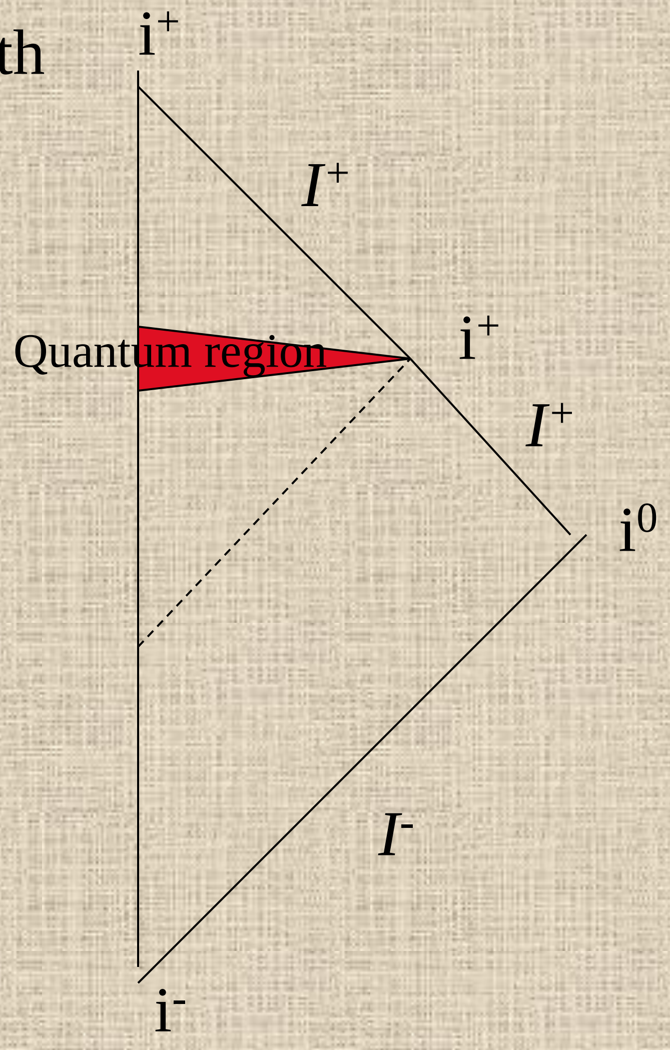
Unitarity restored!

What if the black hole doesn't evaporate in finite time?

We get a permanent "baby universe"

But no problem with basic principles.

Information is conserved,
so long as all of
I^+ is taken into account.



If LQG really unifies gravity and QM, shouldn't it automatically tell us about unifying the rest of physics?

The universe as a quantum computer

Fotini Markopoulou

A quantum spacetime is mathematically the same as the circuit of a quantum computer.

A particle traveling through quantum spacetime is like a bit of quantum information.

Seth Lloyd

This led to the discovery that many quantum theories of gravity are automatically unified theories because they automatically contain matter.

In one theory, the simplest such conserved excitations map to a preon model of the elementary particles., hep-th/0603022

The universe as a superconductor

Xiao-Gang Wen

The particles of the standard Model could be like phonons (quantum sound waves) or vibrations of a solid-they are not fundamental, they emerge from a more fundamental theory.

Olaf Dreyer

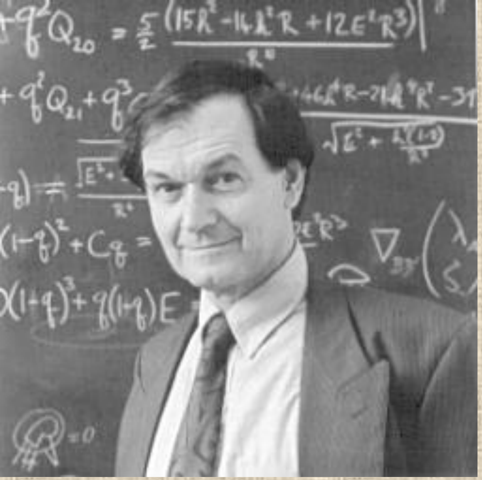
Non-commutative geometry

Alain Connes

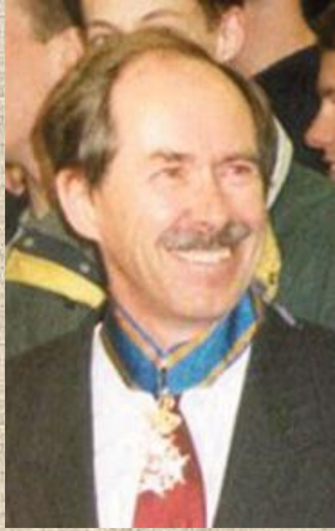
A unification of geometry and quantum theory at the level of their deepest mathematical structures.

Gives a new notion of space which is relational-and background independent.

Leads directly to the standard model of particle physics.



The Third Road:



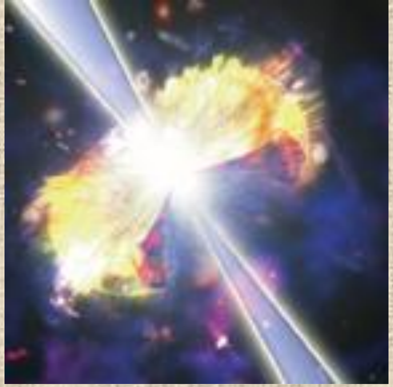
There is no quantum gravity… quantum theory breaks down and is replaced by something deeper.

This road is embraced by two of the greatest living scientists, Roger Penrose and Gerard „t Hooft.
Also brave souls such as Steve Adler and Antony Valentini.

If they are right we may all have been wasting our time.

How can we tell if we are wasting our time?

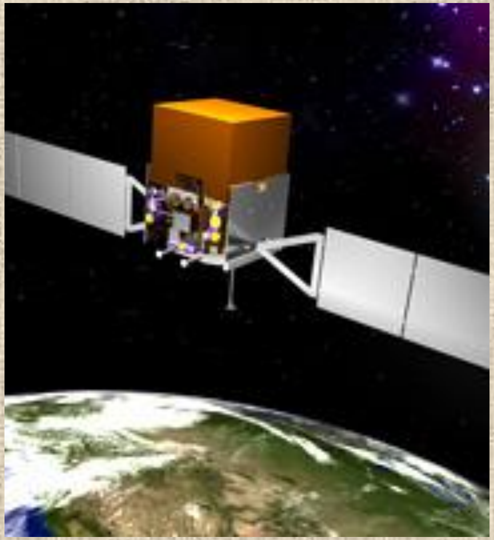
The most important thing is to do experiments that test these different ideas and theories.



Some quantum gravity theories predict special relativity is violated or modified at the Planck length.

This turns out to imply the speed of light increases very slightly with energy.

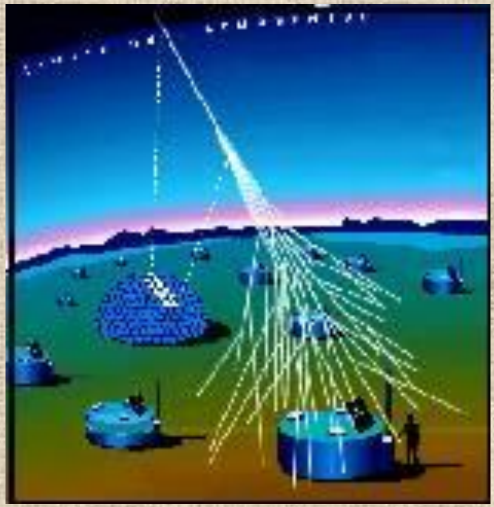
If parity-odd this is already ruled out by astrophysical observations.



DSR predicts a parity-even effect. This to be tested by studying gamma rays from gamma ray bursts, detected by the GLAST satellite.

Experiments which test special relativity at high enough energies are being done for us by the universe, as very high energy cosmic rays interact with the cosmic microwave background.

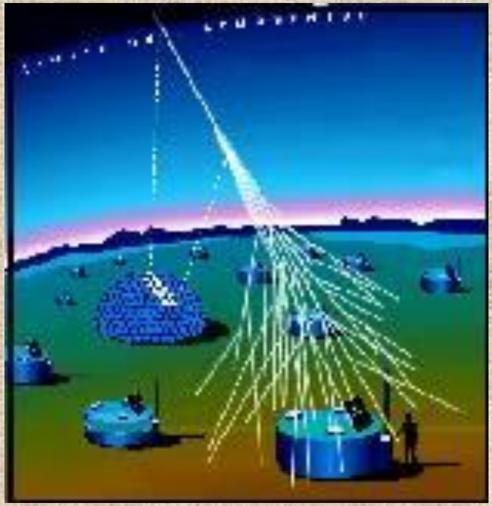
The spectrum of the highest energy cosmic rays is now being studied at AUGER, in Argentina.



AUGER is now taking data that could decide between loop quantum gravity and other approaches to quantum gravity…

So there is no reason to give up on science or change the rules…

Physics is progressing the old fashioned way: by an interaction of theory and experiment.



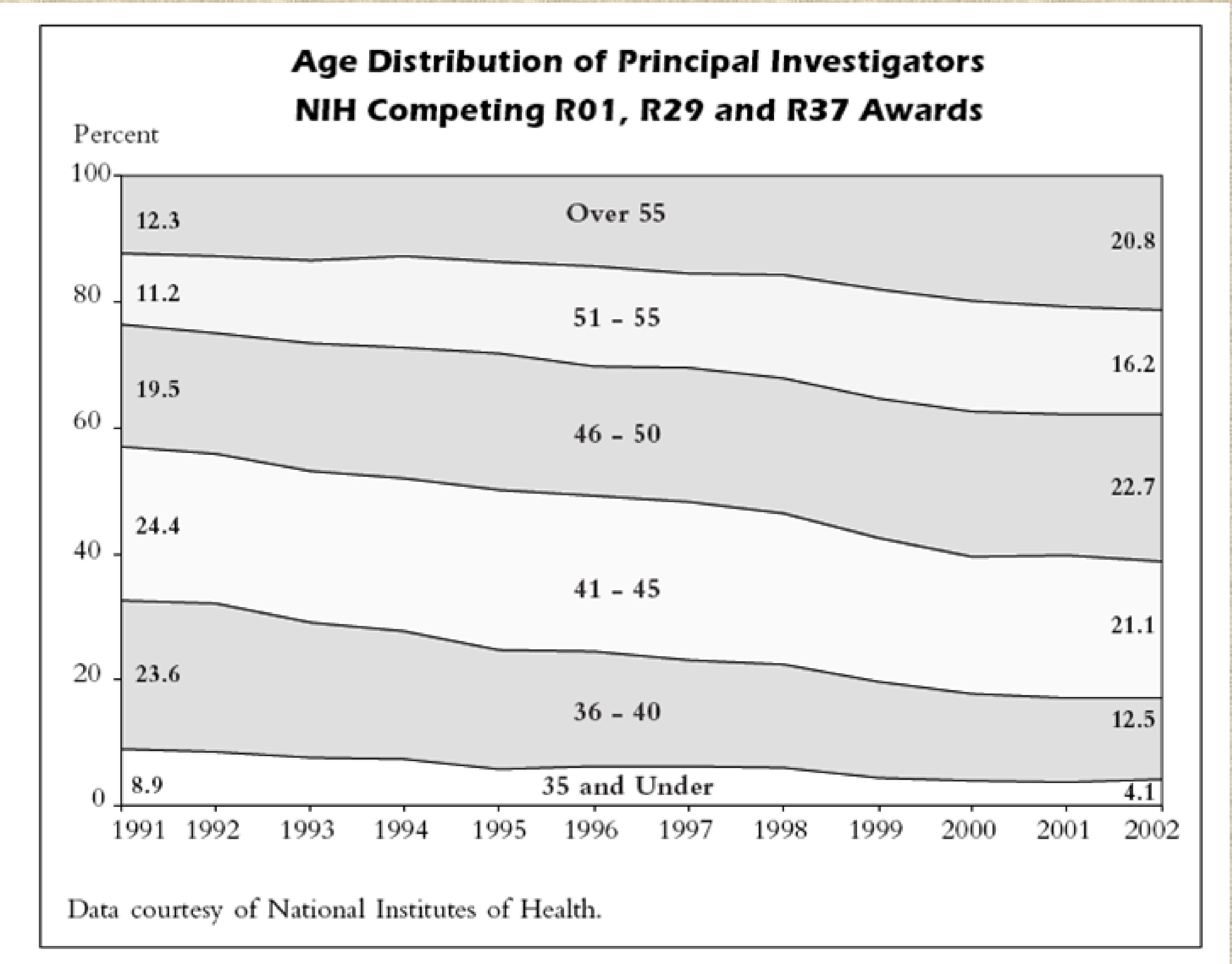
AUGER and GLAST will be able to decide between different approaches to quantum gravity…

What could be done to help speed progress in fundamental physics?

What could be done to help speed progress in fundamental physics?

1) ***Diversify support in frontier areas.*** There are 3 general roads to quantum gravity, and ~10 different approaches. 95% of support has gone to one This makes us very vulnerable to failure of one approach. It also weakens that approach as it closes off good effects from cross-fertilization, criticism and competition. Similar comments apply to other fields.
1) ***We have too many hill climbers, not enough valley crossers.*** Change the questions asked so as to disadvantage people who do "me-too" science and advantage the original, intellectually independent, hard to classify, innovators whose ideas drive the progress of science.
3) ***Have a realistic assessment of risk*.** Reward risk-taking as risky directions must be pursued to make progress. But a premature consensus cannot be allowed to form for sociological rather than scientific reasons. Failure must be expected and allowed, and there must be rewards for admitting failure and moving on to new ideas and projects.
4) ***Weigh the balance towards newer ideas, and younger researchers*,** to counteract the institutional tendency to favor established senior scientists, their students, and large, established research programs.
5) ***Be scientific venture capitalists.*** Seek out and support innovative people with new risky, ambitious ideas and projects.

The issues affect more than physics



“We have developed an incentive system for young scientists that is much to risk averse. In many ways, we are our own worst enemies. The study sections that we establish to review requests for grant funds are composed of peers who claim that they admire scientific risk-taking, but who generally invest in safe science when allocating resources. The damping effect on innovation is enormous, because our research universities look for assistant professors who can be assured of grant funding when they select new faculty appointments. This helps to explain why so many of our best young people are doing “me too” science, working in areas where they compete head-to-head with other scientists who have gone before them — often their mentors or those who have trained in the same laboratory.

Many of my colleagues and I were awarded our first independent funding when we were under 30 years old. We did not have preliminary results, because we were trying something completely new. Almost no one finds it possible to start an independent scientific career under the age of 35. Moreover, whereas in 1991 one-third of the principal investigators with NIH funds were under 40, by the year 2002 this fraction had dropped to one-sixth.”

Bruce Alberts, past president NAS, 2003

Change the criteria used by peer review to advantage valley crossers:

- There must be several single authored papers that propose new ideas or directions that, were they to succeed, would be important.
- There must not be only papers with established senior colleagues.
- There may be papers taking ideas or techniques from one field and applying them to another.
- There may be a record of having asking questions not asked before.
- There will not be evidence of "me-too" science, that is a choice of research directions based on what is popular or trendy in the field.
- There may be evidence of switching directions and abandoning ideas and directions that don‛t succeed.
- There will be evidence that the person aims to solve key fundamental problems in their field.
- As a postdoc, the candidate is unlikely to be working in the same direction as their Ph.d. thesis or Ph.d. mentors.
- The candidate must show evidence of coming up with ideas, results and questions that *surprise* established experts.

In the future we will know more.