Observables of Quantum Gravity at the LHC

Sabine Hossenfelder

Perimeter Institute

Simplify the Complicated

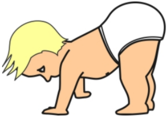
Simplify the Complicated

Top-down 

Simplify the Complicated

Top-down

Bottom-up



Simplify the Complicated

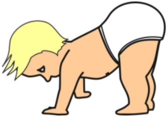
Top-down

Top-down inspired bottom-up approaches

...Extra Dimensions...Minimal Length ...

...DSR ...Holographic Principle ...

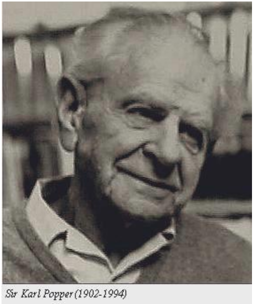
Bottom-up



Simplify the Complicated

Top-down

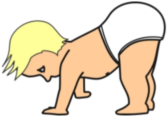
"Science may be described as the art of systematic over-simplification."



Karl Popper (The Observer, August 1982)

Top-down inspired bottom-up approaches
...Extra Dimensions...Minimal Length ...
...DSR ...Holographic Principle ...

Bottom-up



General Relativity

Einstein's field equations couple the stress-energy tensor to the curvature of space-time:

$$\begin{aligned} R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R &= 16\pi G T_{\mu\nu} \\ \left[\frac{1}{\mathrm{Length}^2}\right] &= G \left[\frac{\mathrm{Energy}}{\mathrm{Length}^3}\right] \end{aligned}$$

$\longrightarrow$ G has dimension of Length/Energy

The Planck Scale

The Planck mass m_p is the energy at which a particle causes a significant perturbation of the metric in a volume given by its own Compton wavelength $l_\mathrm{p} = \hbar/m_\mathrm{p}$

$$
\begin{aligned}
1 = \Delta g \quad &\approx \quad \frac{GM}{rc^2} \rightarrow \frac{Gm_\mathrm{p}^2}{c^2\,\hbar} \\
\Rightarrow m_\mathrm{p} \quad &= \quad \sqrt{\frac{\hbar c}{G}} \approx 10^{16}\mathrm{TeV} \quad , \quad l_\mathrm{p} = \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-20}\mathrm{fm}
\end{aligned}
$$

And is far, far off the scale we can reach with earth build accelerators.

The Planck Scale

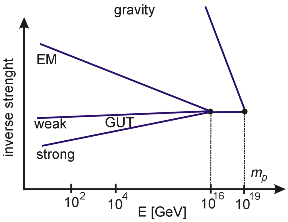
Max Planck,

Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin (1899), p. 479

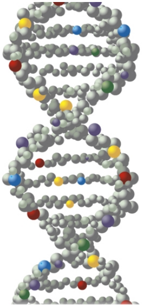
> Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Ausdruck (41) der Strahlungsentropie auftretenden Constanten a und b die Möglichkeit gegeben ist, Einheiten für Länge, Masse, Zeit und Temperatur aufzustellen, welche, unabhängig von speciellen Körpern oder Substanzen, ihre Bedeutung für alle Zeiten und für alle, auch ausserirdische und aussermenschliche Culturen nothwendig behalten und welche daher als »natürliche Maasseinheiten« bezeichnet werden können.

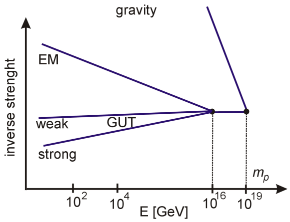
It is interesting to note that with the help of the [above constants] it is possible to introduce units [...] which [...] remain meaningful for all times and also for extraterrestial and non-human cultures, and therefore can be understood as 'natural units'.

Extrapolation over 16 orders of Magnitude



Extrapolation over 16 orders of Magnitude





- How does particle physics look like in the Planckian regime?
- For a lowered Planck scale this is important for collider physics
- Concrete scenario to lower Planck scale: large extra dimensions

General Relativity in Higher Dimensions

With d extra dimensions:

$$\begin{aligned} R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R &= 16\pi G_d T_{\mu\nu} \\ \left[\frac{1}{\mathrm{Length}^2}\right] &= G_d \left[\frac{\mathrm{Energy}}{\mathrm{Length}^{3+d}}\right] \end{aligned}$$

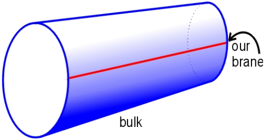
$\longrightarrow$ G_d has dimension of Length^{1+d}/Energy or, with $\hbar = 1$, it has dimension Energy^{-2-d}.

$\longrightarrow$ We will therefore write the coupling as the $d+2$nd power of a higher-dimensional Planck mass , which is the new fundamental scale M_{f}, such that $1/G_d = M_{\mathrm{f}}^{d+2}$

Models with Extra Dimensions

Arkani-Hamed - Dimopoulos - Dvali

- *d* extra space like dimensions (bulk) compactified to radius R



Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B **429**, 263 (1998)
Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B **436**, 257 (1998)
Arkani-Hamed, Dimopoulos and Dvali, Phys. Rev. D **59**, 086004 (1999)

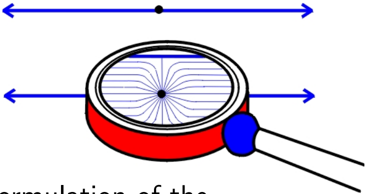
- Gravitons are allowed into all dimensions,
- SM particles are bound to 3-dimensional submanifold (brane)

Arkani-Hamed - Dimopoulos - Dvali

+ Removes hierarchy problem by diluting gravity stronger than other interactions: $m_p^2 = R^d M_f^{d+2}$

$$V \sim \frac{1}{m_p^2}\frac{1}{r}$$

$$V \sim \frac{1}{M_f^{d+2}}\frac{1}{r^{d+1}} \to \frac{1}{M_f^{d+2}}\frac{1}{R^d}\frac{1}{r}$$



- R is not a natural scale, so just a reformulation of the hierarchy problem

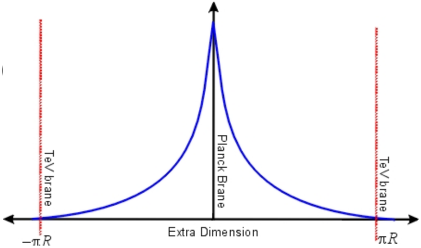
⇒ Results in large radii $1/R \sim$ eV .. 10 MeV

Randall - Sundrum

- 'Warped' geometry in 5 dimensions
  metric on brane depends on 5th coordinate

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

Randall and Sundrum, Phys. Rev. Lett. **83**, 4690 (1999)
Randall and Sundrum, Phys. Rev. Lett. **83**, 3370 (1999)



- Strong curvature into 5th dimension, volume stays finite

\+ Important because of AdS-CFT correspondence

\+ Curvature scale can be natural because of exponential factor.

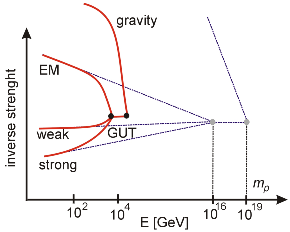
Universal Extra Dimensions

- Also adds *d* extra spacelike dimensions which are compactified

  Appelquist, Cheng and Dobrescu,Phys. Rev. D **64**, 035002 (2001)
  Rizzo, Phys. Rev. D **64**, 095010 (2001)
  Macesanu, McMullen and Nandi, Phys. Rev. D **66**, 015009 (2002)

- Gauge, Higgs, (Fermions) propagate into all of them
- Radius $\sim 1/\text{TeV}$
- Can be embedded into ADD as substructure (fat brane)

\+ Accelerated running of coupling $\rightarrow$ early unification

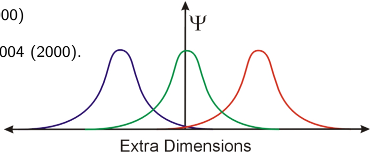


Dienes, Dudas and Gherghetta, Nucl. Phys. B **537**, 47 (1999)

Split Fermion Scenario

- Localization of fermions at different positions inside 'fat' brane

  Arkani-Hamed and Schmaltz, Phys. Rev. D **61**, 033005 (2000)
  Mirabelli and Schmaltz, Phys. Rev. D **61**, 113011 (2000)
  Arkani-Hamed, Grossman, Schmaltz, Phys. Rev. D **61**, 115004 (2000).



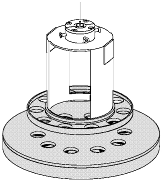
⇒ Couplings on brane depend on overlap: can be very small

- Quick-fix for several problems
  - Solves proton decay problem with lowered fundamental scale
  - Explains hierarchies in Yukawa couplings
  - Suppresses flavor changing decays

Direct Measurements

- Deviations from Newton's law (stronger at small distances)
- Cavendish-like experiments

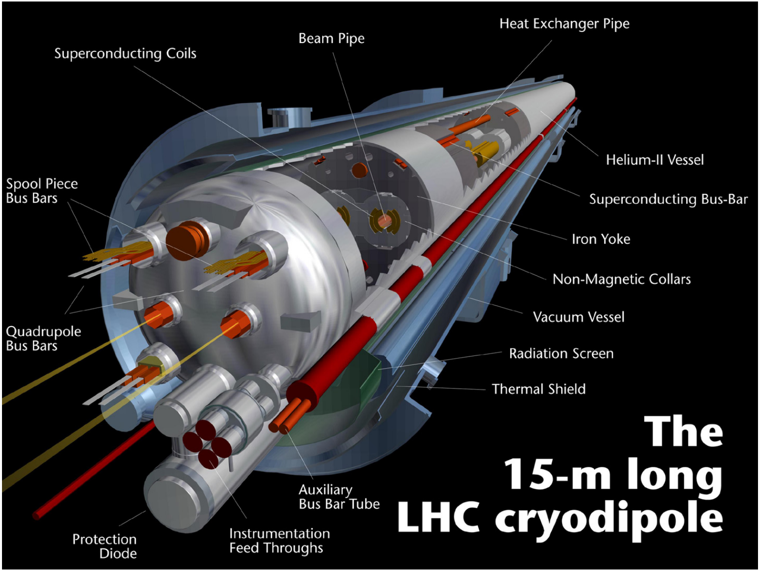
Chiaverini *et al*, Phys. Rev. Lett. **90**, 151101 (2003)
Long and Price, Comptes Rendus Physique **4**, 337 (2003)
Hoyle *et al*, Phys. Rev. D **70**, 042004 (2004)



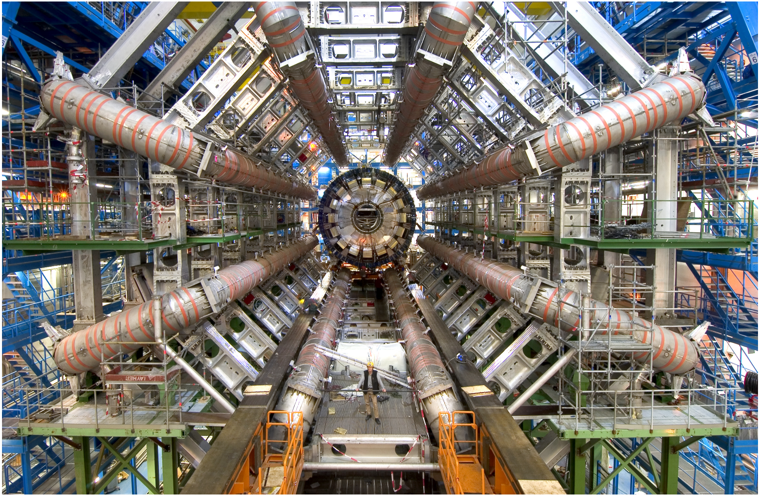
- Current constraint (important for $d = 2$ in ADD-scenario):
  $\longrightarrow R < 0.18$ mm

The Large Hadron Collider

The Large Hadron Collider

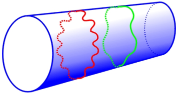


The Large Hadron Collider



Theory of KK-Excitations

- Compactification leads to quantized momenta



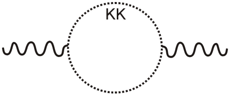
$$\psi(x,y) = \sum_{n=-\infty}^{+\infty} \psi^{(n)}(x) \exp(iny/R)$$

- Presence of extra dimensions leads to apparent mass-term:

$$\left[\partial_x \partial^x - \left(\frac{n}{R}\right)^2\right] \psi^{(n)}(x) = 0$$

- Results in tower of apparently massive particles on brane
  - * In UXD and RS: KK-excitations of every SM particle in bulk
  - * In RS: not equally spaced
  - * In ADD: gravitons, right handed ν's
- Virtual exchange divergent for $d > 1$:

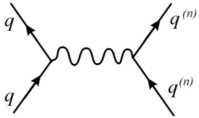
$$\sum_n \int d^4p \frac{1}{[p^2 + (n/R)^2]^2} \to \infty$$



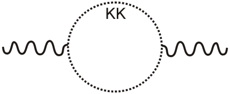
Observables of KK-excitations

- Real production of exitations in UXDs: pair production only

Rizzo and Wells, Phys. Rev. **D61**, 016007 (2000)
Appelquist, Cheng and Dobrescu, Phys. Rev. D **64**, 035002 (2001)



- Modifications due to virtual contributions



- Tightest constraints on UXDs from precision electroweak $1/R > 4$ TeV (for $d = 1$, depends on precise scenario).
- Spacing of excitations distinguishes scenario.

Gravitation as Effective Theory (ADD)

Philosophy: use naively quantized gravity in perturbative limit

T. Han, J. D. Lykken and R. J. Zhang, Phys. Rev. D **59** (1999) 105006
S. Cullen, M. Perelstein and M. E. Peskin, Phys. Rev. D **62**, 055012 (2000)
T. G. Rizzo, Phys. Rev. D **64**, 095010 (2001)
J. Hewett and M. Spiropulu, Ann. Rev. Nucl. Part. Sci. **52**, 397 (2002)

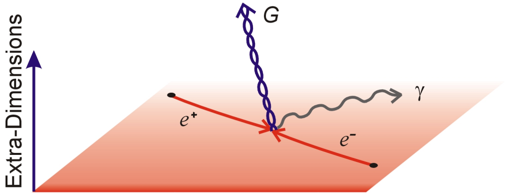
- Perturbation of metric: $g_{AB} = \eta_{AB} + \Psi_{AB}$
- Decompose: spin-2 $h_{\mu\nu}$, vector $V_{\mu i}$, scalar ϕ_{ij} (trace $\phi^i{}_i = \phi$)
- Coupling to matter $\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_M$
- Energy momentum tensor on brane $T_{AB} = \eta^\mu{}_A \eta^\nu{}_B T_{\mu\nu}(x)\delta(y)$
- Yields coupling terms: $\mathcal{L}_{int} = -\frac{1}{2} T\phi - T^{\mu\nu} h_{\mu\nu}$

Massive Gravitons (ADD)

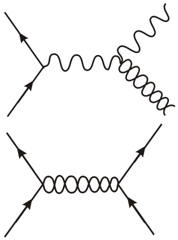
- Yields tower of massive gravitons with tiny spacing
- Large phase space makes contributions important at $\sqrt{s} \sim M_f$
- # of excitations with energy E is $N(E) \sim (ER)^d$

$$\text{E.g.} \quad e^+e^- \to \gamma G : \quad \sigma \sim \frac{\alpha}{m_p^2} N(\sqrt{s}) \sim \frac{\alpha}{s} \left(\frac{\sqrt{s}}{M_f} \right)^{d+2}$$

- Brane breaks Poincaré invariance and momentum conservation on brane



Signatures of Gravitons



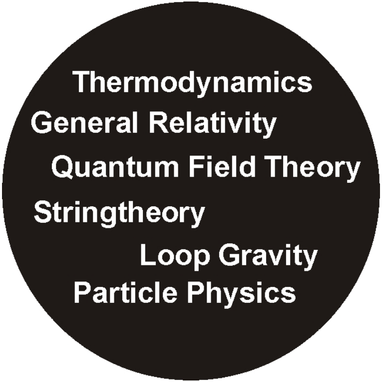
Collider physics (current bounds on M_f in TeV-range):

- Real gravitons lead to missing energy
- Virtual exchange modifies cross sections

Astrophysics (bounds weak for $d > 4$, strong for $d \leq 4$):

- Enhanced cooling of supernovae/red giants from graviton emmission
- Cooling in early universe and contributions to background from decay of bulk excitations
- Anomalous re-heating of neutron stars by decay of gravitationally trapped massive gravitons

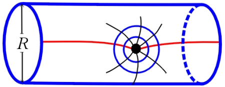
Information content of Black Holes



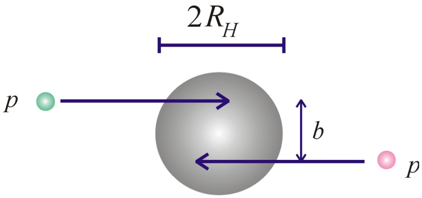
Black Holes in Extra Dimensions

In large extra dimensions (ADD)

- Gravity stronger at small distances $\Rightarrow$ horizon radius R_H larger
- For $M \sim 1$ TeV , R_H increases from $\sim 10^{-38}$ fm to 10^{-4} fm!
- For these black holes it is $R_H \ll R$ and they have approx higher dimensional spherical symmetry

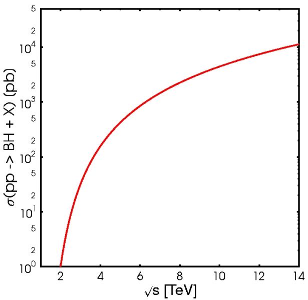


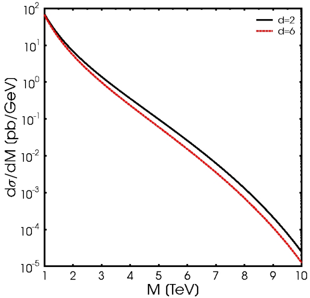
- At the LHC partons can come closer than their Schwarzschild horizon $\longrightarrow$ a black hole can be created!



Production of Black Holes

- Semi-classical cross-section $\sigma \sim \pi R_H^2$
- Can be improved by modelling colliding wave packets
- Yields $\sim 10^8$ black holes per year for LHC pp-collisions
- Numerical tools available for event simulation

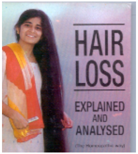




Evaporation of Black Holes

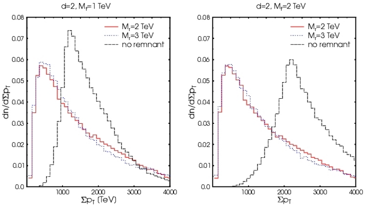
Evaporation proceeds in 3 stages:

1. Balding phase: hair loss – the black holes radiates off angular momentum and multipole moments
2. Hawking phase: thermal radiation into all particles of the standard model as well as gravitons
3. Final decay or remaining black hole relic



Black hole thermodynamics: $T = \kappa/2\pi$ and $dS/dM = 1/T$

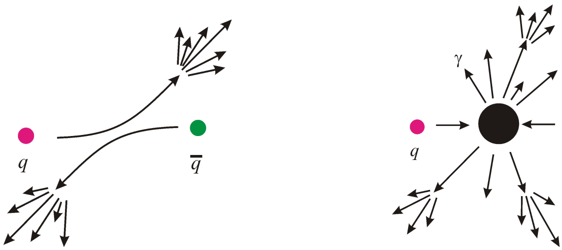
Numerical investigation:
black hole event generators
CHARYBDIS, CATFISH, BlackMax



Tanaka *et al*, Eur. Phys. J. C **41**, 19 (2005) [arXiv:hep-ph/0411095].
Harris *et al*, JHEP **0505**, 053 (2005) [arXiv:hep-ph/0411022]
Cavaglia *et al*, Comput. Phys. Commun. **177**, 506 (2007) [arXiv:hep-ph/0609001].
Dai *et al*, Phys. Rev. D **77**, 076007 (2008) [arXiv:0711.3012 [hep-ph]].

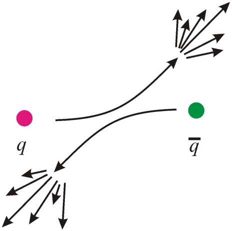
Observables of Black Holes

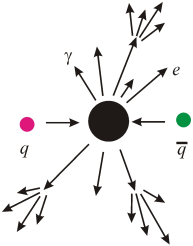
- Multi-jet like events, spherical, typical temperature $\sim$ 200 GeV



Observables of Black Holes

- Multi-jet like events, spherical, typical temperature ~ 200 GeV
- Momentum cut-off at $\sim M_f$ (hard to observe)
- Thermal spectrum $\rightarrow$ allows to reconstruct d and M_f
- Virtual black holes: baryon/flavor non-conservation

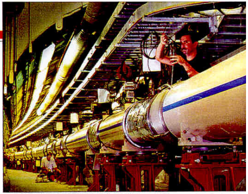




TEILCHENPHYSIK

Angst vor dem großen Knall

Physiker wollen bei New York den Anfang des Universums erforschen und lösen Endzeitstimmung aus

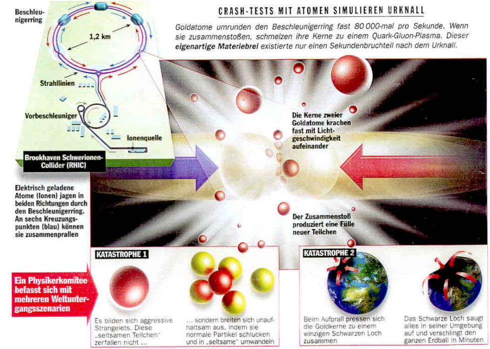


VOR DEM ERSTEN STOSS Seit Juli flitzen Goldatome durch den unterirdischen Ringtunnel. Ab Herbst gehen sie auf Kollisionskurs

In der „Unendlichen Geschichte" von Michael Ende breitet sich das Nichts unaufhaltsam aus. Es reißt Tiere und Pflanzen fort, verschlingt Berge und Seen – und lässt von ganz Phantásien nicht mehr als ein Sandkorn übrig.

Solch ein Schicksal steht vielleicht der Erde bevor, fürchten jetzt viele Amerikaner, wenn ein neuer Teilchenbeschleuniger bei New York ab Herbst schwere Atome aufeinander hetzt. Der Relativistische Schwerionen-Collider (RHIC) in Brookhaven lässt die Teilchen so heftig zusammenkrachen, dass sie 10 000-mal heißer als die Sonne werden. Damit wollen die Physiker Bedingungen schaffen, wie sie direkt nach dem Urknall herrschten.

„Eine Kettenreaktion könnte den Planeten verschlingen", warnte im Juli Walter Wagner, ein weithin unbekannter Physiker auf Hawaii. Die angesehene „Sunday Times" meldete daraufhin: „Urknall-Maschine könnte Erde zerstören." Seitdem versuchen die RHIC-Forscher verzweifelt, besorgte Bürger zu beruhigen. Forschungsleiter John Marburger hat sogar ein Physikerkomitee einberufen, das diesen Monat zu den Katastrophenszenarien Stellung nimmt.



Big Bang Machine: Will it destroy Earth?

The London Times July 18, 1999

Creation of a black hole on Long Island?

A NUCLEAR accelerator designed to replicate the Big Bang is under investigation by international physicists because of fears that it might cause 'perturbations of the universe' that could destroy the Earth. One theory even suggests that it could create a black hole. [...]

The committee will also consider an alternative, although less likely, possibility that the colliding particles could achieve such a high density that they would form a mini black hole. In space, black holes are believed to generate intense gravita-tional fields that suck in all surrounding matter. The creation of one on Earth could be disastrous. [...]

John Nelson, professor of nuclear physics at Birmingham University who is leading the British scientific team at RHIC, said the chances of an accident were infinitesimally small - but Brookhaven had a duty to assess them. "The big question is whether the planet will disappear in the twinkling of an eye. It is astonishingly unlikely that there is any risk - but I could not prove it," he said.

FORSCHUNG & TECHNIK

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CRASH-TESTS MIT ATOMEN SIMULIEREN URKNALL

Goldatome umrunden den Beschleunigerring fast 80 000-mal pro Sekunde. Wenn sie zusammenstoßen, schmelzen ihre Kerne zu einem Quark-Gluon-Plasma. Dieser ***eigenartige Materiebrei*** *existierte nur einen Sekundenbruchteil nach dem Urknall.*

Beschleunigerring

1,2 km

Strahllinien

Vorbeschleuniger

Ionenquelle

Brookhaven Schwerionen-Collider (RHIC)

Elektrisch geladene Atome (Ionen) jagen in beiden Richtungen durch den Beschleunigerring. An sechs Kreuzungspunkten (blau) können sie zusammenprallen

Die Kerne zweier Goldatome krachen fast mit Lichtgeschwindigkeit aufeinander

Der Zusammenstoß produziert eine Fülle neuer Teilchen

Ein Physikerkomitee befasst sich mit mehreren Weltuntergangsszenarien

KATASTROPHE 1

Es bilden sich aggressive Strangelets. Diese „seltsamen Teilchen" zerfallen nicht ...

... sondern breiten sich unaufhaltsam aus, indem sie normale Partikel schlucken und in „seltsame" umwandeln

KATASTROPHE 2

Beim Aufprall pressen sich die Goldkerne zu einem winzigen Schwarzen Loch zusammen

Das Schwarze Loch saugt alles in seiner Umgebung auf und verschlingt den ganzen Erdball in Minuten

112 FOCUS 32/1999

Big Bang Machine: Will it destroy Earth?

The London Times July 18, 1999

Creation of a black hole on Long Island?

A NUCLEAR accelerator designed to replicate the Big Bang is under investigation by international physicists because of fears that it might cause 'perturbations of the universe' that could destroy the Earth. One theory even suggests that it could create a black hole. [...]

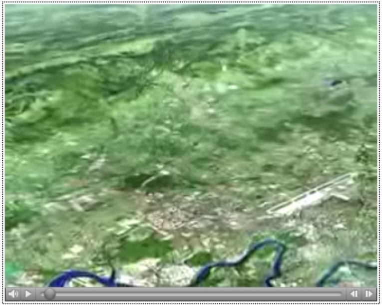
The committee will also consider an alternative, although less likely, possibility that the colliding particles could achieve such a high density that they would form a mini black hole. In space, black holes are believed to generate intense gravita-tional fields that suck in all surrounding matter. The creation of one on Earth could be disastrous. [...]

John Nelson, professor of nuclear physics at Birmingham University who is leading the British scientific team at RHIC, said the chances of an accident were infinitesimally small - but Brookhaven had a duty to assess them. "The big question is whether the planet will disappear in the twinkling of an eye. It is astonishingly unlikely that there is any risk - but I could not prove it," he said.

Catastrophe Scenario - Remake

The New York Times March 29, 2008

Asking a Judge to Save the World, and Maybe a Whole Lot More



More fighting in Iraq. Somalia in chaos. People in this country can't afford their mortgages and in some places now they can't even afford rice.

None of this nor the rest of the grimness on the front page today will matter a bit, though, if two men pursuing a lawsuit in federal court in Hawaii turn out to be right. They think a giant particle accelerator that will begin smashing protons together outside Geneva this summer might produce a black hole or something else that will spell the end of the Earth and maybe the universe.

Scientists say that is very unlikely - though they have done some checking just to make sure.

(Video: Misunderstood Universe/YouTube)

The world's physicists have spent 14 years and $8 billion building the Large Hadron Collider, in which the colliding protons will recreate energies and conditions last seen a trillionth of a second after the Big Bang. Researchers will sift the debris from these primordial recreations for clues to the nature of mass and new forces and symmetries of nature. But Walter L. Wagner and Luis Sancho contend that scientists at the European Center for Nuclear Research, or CERN, have played down the chances that the collider could produce, among other horrors, a tiny black hole ...

Dr. Arkani-Hamed said concerning worries about the death of the Earth or universe, "Neither has any merit." He pointed out that because of the dice-throwing nature of quantum physics, there was some probability of almost anything happening. There is some minuscule probability, he said, "the Large Hadron Collider might make dragons that might eat us up."

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Catastrophe Scenario - Remake

Evaporation is faster than Mass Gain

The mass loss of the black hole from the evaporation

$$\frac{dM_-}{dt} \sim 10^3 \mathrm{GeV/fm}$$

is much larger than any possible mass gain even in a very dense medium (QGP, neutron star),

$$\frac{dM_+}{dt} \sim R_H^2 T^4 \sim 10^{-9} \mathrm{GeV/fm}$$

(even with high γ-factor $\sim 10^8$).

$\longrightarrow$ the black hole decays and can not grow.

Paper Inflation

One can make things more complicated:

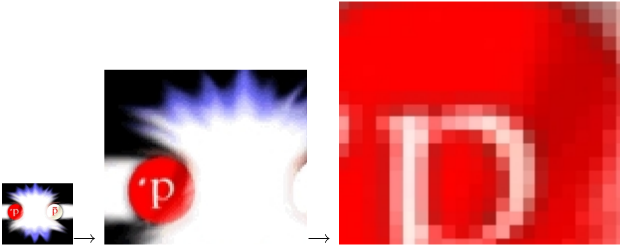
... embed UXD into ADD... different radii of extra dimensions... compactification on various topologies... splits... twists... shapes...black strings, rings, things, black saturns etc... various brane configurations and trapping in such... oszillations of branes... recoil effect... potentials to stabilize dimensions...

- Be aware of a model's limitations
- It was never meant to more than a qualitative discription of the first effects of quantum gravity in particle interactions.
- Working out details of models without any experimental evidence whatsoever does little else than increasing the number of published papers.

The Minimal Length Scale

The Minimal Length Scale

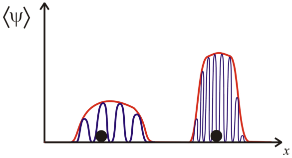
- Very general expectation for quantum gravity: fluctuations of spacetime itself disable resolution of small distances
- Can be found e.g. in string theory, Loop Gravity, NCG, etc.
- Minimal length scales acts as UV cutoff
- Lowering the Planck mass means raising the Planck length



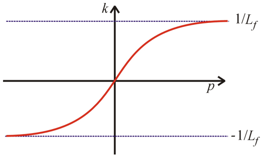
...is there a fundamental limit to the resolution of structures?

An Effective Model for the Minimal Length*

- For large momenta, p, Compton-wavelength $\lambda = 1/k$ can not get arbitrarily small $\lambda > L_\mathrm{f} = 1/M_\mathrm{f}$



- Model by modifing relation between wave-vector k and momentum p. Results in modified commutation relations
$k = k(p) = \hbar p + a_1 p^3 + a_2 p^5 \ldots \Rightarrow [p_i, x_j] = i \partial p_i / \partial k_j$



* SH *et al*, Phys. Lett. B598 (2004) 92-98; SH, Phys. Rev. D **73**, 105013 (2006)

Consequences of the Minimal Length

- Implies a generalized uncertainty principle, first correction

$$\Delta x \Delta p \geq \frac{1}{2}\hbar\left(1 + b_1 \frac{\Delta p^2}{M_{\rm f}^2}\right) \quad ,$$

- A squeezed phase space at high energies

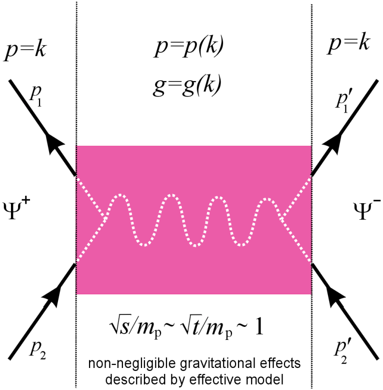
$$\langle p|p'\rangle = \frac{\partial p}{\partial k}\delta(p-p') \Rightarrow dk \rightarrow \frac{dp}{\hbar}\frac{\partial k}{\partial p} = \frac{dk}{\hbar} e^{-p^2 L_{\rm min}^2} \quad ,$$

- And a modified dispersion relation

$$\omega^2 - k^2 - \mu^2 = \Pi(k,\omega)$$

- Can but need not have a energy dependent speed of light $d\omega/dk \neq 1$.

The Collision Region



Applications of the Model

The model is useful to examine effects of a minimal length scale

- Modified quantum mechanics:

$\longrightarrow$ Schrödinger's equation, levels in hydrogen atom, g-2, Casimir-effect

- Derivation of modified Feynman-rules:

$\longrightarrow$ General prescription for calculations

- Tree-level cross-sections (e.g. $e^+e^- \rightarrow f^+f^-$):

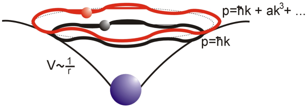
$\longrightarrow$ Show overall suppression relative to SM-result

- Loop-contributions (e.g. running coupling):

$\longrightarrow$ Finite, minimal length acts as UV-regulator

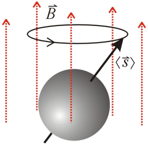
Observables of a Minimal Length - High Precision

- Hydrogen atom: shift of energy levels



SH, M. Bleicher, S. Hofmann, S. Scherer, J. Ruppert and H. Stöcker, Phys. Lett. B598 (2004) 92-98

- g-2

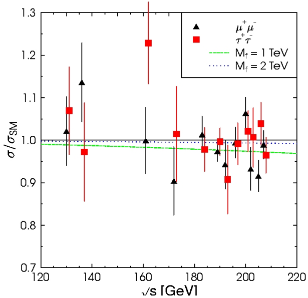


U. Harbach, SH, M. Bleicher and H. Stöcker Phys. Lett. B 584 (2004) 109-113

Observables of a Minimal Length - High Energy

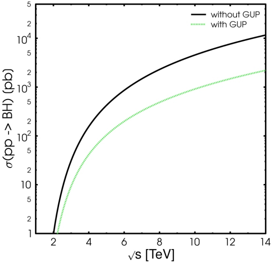
- Suppression of cross-section from $\sqrt{s} \sim M_f$ on.

  SH, M. Bleicher, S. Hofmann, S. Scherer, J. Ruppert
  and H. Stöcker, Phys. Lett. B598 (2004) 92-98



- Black hole production becomes more difficult

  SH, Phys. Lett. B598 (2004) 92-98



- Loop corrections regularized
  Modified running of gauge couplings

  SH, Phys. Rev. D 70 (2004) 105003

$$\int d^4p \frac{1}{p^2(p-q)^2} \sim \ln\frac{\Lambda}{\mu_0} \quad \text{for} \quad d=0$$

$$\int d^{4+d}p \frac{1}{p^2(p-q)^2} \sim \left(\frac{\Lambda}{\mu_0}\right)^d \quad \text{for} \quad d>1?$$

$$\rightarrow \int d^{4+d}p \left|\frac{\partial k}{\partial p}\right| \frac{1}{p^2(p-q)^2} < \infty$$

Deformed Special Relativity

- Minimal length L_{min} requires new Lorentz-transformations
- New transformations have 2 invariants: c and L_{min}
- Generalized Uncertainty $\Longleftrightarrow$ Deformed Special Relativity
    * When relation $k(p)$ is known and p's (usual) transformation, then also the transformation of k is known.
    * When the new transformation on k is known, then one gets $k(p)$ by boosting in and out of the restframe where $k = p$.

SH, Class. Quantum Grav. 23 (2006) 1815.

Interpretation of an Invariant Minimal Length

Besides c there is a second invariant L_{min} for all observers

- DSR approach
  - * DSR applies for each observer to agree on minimal-ness ... ?
  - * Therefore deformed transformation applies to free particles
  - * If caused by quantum gravity effects what sets the scale?
- GUP approach
  - * Two observers can not compare lengths without interaction
  - * The strength of gravitational effects sets the scale for the importance of quantum gravity
  - * Free particles do not experience any quantum gravity or DSR
  - * Effects apply for virtual particles in the interaction region only

$\longrightarrow$ Propagator of exchange particles is modified

Summary

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? Do I believe, that gravitons, black holes and a minimal length describe nature ?

! Yes !

$\longrightarrow$ Black holes and a minimal length scale are such general expectations for a TOE that they are very likeley to become important at *some* high energy scale.

backreaction.blogspot.com

BackRe(Action)

Events on the world lines of two theoretical physicists, from the horizon to timelike infinity. A scientifically minded blog with varying amounts of entertainment, distractions, and every day trivialities.

BY BEE ON SUNDAY, AUGUST 26, 2007

MAGIC's observation of Gamma Ray bursts

A couple of days ago, the MAGIC collaboration posted a paper on the arXiv:

Probing Quantum Gravity using Photons from a Mkn 501 Flare Observed by MAGIC

which I didn't mean to comment on, but it seems it has caused quite an astonishing amount of discussion. The SciAm blog sees hints of a breakdown of General Relativity, Lubos Motl expresses his skepticism, Slashdot proclaims it is a test of String Theory, which then causes Buffy Woit to fight against the living dead predictions, thereby unfortunately claiming to be in agreement with Lubos, who returns the favor with a second post denying any agreement with *"the critique of science"*, fading out in a characteristic rant about 'aggressive imbeciles'. Even the more reasonable article by Chris Lee on Ars Technica which cautions that quantum gravity has probably not *"made a sudden leap forward"* proclaims that *"this is the first real data against which such a theory can be tested"*, the caution of which however leads the SciAm bloggers to nag that those *"who have been loudly complaining about the lack of [observations that probe string theory] have gone silent."*

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