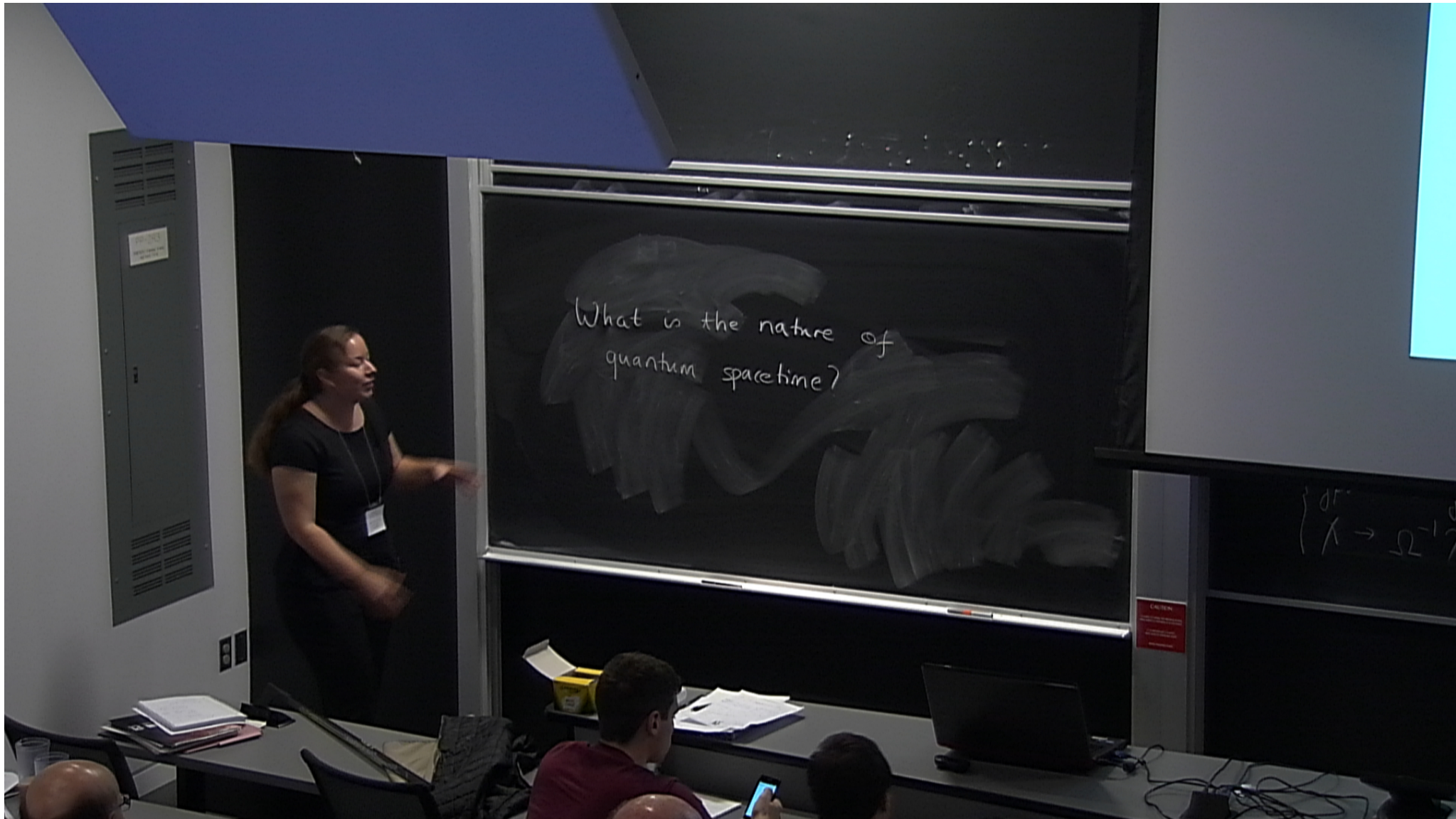


Title: Dynamical Dimensional Reduction

Date: Oct 24, 2012 11:30 AM

URL: <http://pirsa.org/12100104>

Abstract: ***Dynamical dimensional reduction and Asymptotic Safety***
The effective average action approach to Quantum Einstein Gravity (QEG) is discussed as a natural framework for exploring the scale dependent Riemannian geometry and multifractal micro-structure of the effective spacetimes predicted by QEG. Their fractal properties are related to the functional RG flow on theory space, and the special role of the running cosmological constant is emphasized. The prospects of an experimental verification will also be discussed.
Vanishing dimension: theory and phenomenology
Lower-dimensionality at higher energies has manifold theoretical advantages as recently pointed out. Moreover, it appears that experimental evidence may already exists for it - a statistically significant planar alignment of events with energies higher than TeV has been observed in some earlier cosmic ray experiments. If this alignment is not a fluke, then the LHC should be able to see effects associated with the dimensional crossover. Further, (2+1)-dimensional spacetimes have no gravitational degrees of freedom, and gravity waves cannot be produced in that epoch in the early universe. This places a universal maximum frequency at which primordial gravity waves can propagate, which may be accessible to future gravitational wave detectors such as LISA. In this talk, the theoretical motivation for "vanishing dimensions" as well as generic experimental and observational signature will be discussed



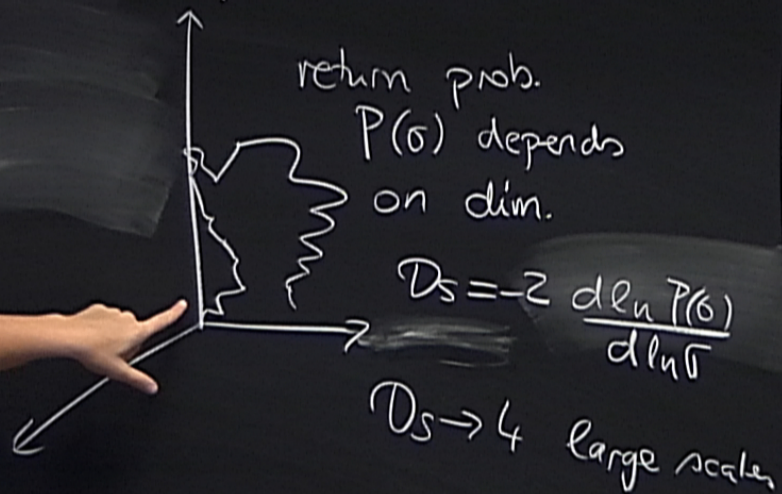
Common result: dynamical dimensional reduction

dim. of our universe: • at large scales
4 (3+1)

• at small scales
→ extra dim?
→ reduction to $d \rightarrow 2$

notions of dim.

- top. dim. d
- spectral dim D_S



• $D_S \rightarrow 2$ at small scales

- AS
(interacting FP)
- Causal Dyn. Triangulation

• LQG
 $\langle A \rangle \sim \sqrt{l^2(l^2 + l_{Pl}^2)}$
 $\sim l^2, l \gg l_{Pl}$
 $l, l \ll l_{Pl}$

- Hořava-Lifshitz
(anisotropic scaling of
space and time)

- Is dim. red. generic?
 - singularity resolution?
 - early universe?
 - matter propagation on qm spacetime?
- experimental evidence?

Dynamical
Dimensional Reduction
and
Asymptotic Safety

Martin Reuter

- Describe asymptotically safe (non-perturbatively renormalized) Quantum Einstein Gravity (QEG) in terms of effective average action:

scale dependent effective field theory:

$$\{\Gamma_k[g_{\mu\nu}], 0 \leq k < \infty\}$$

MR, 1996

metric exp.-value:

$$\frac{\delta \Gamma_k}{\delta g_{\mu\nu}} [\langle g_{\mu\nu} \rangle_k] = 0 \quad \Rightarrow$$

- QEG spacetimes $(\mathcal{M}, \{\langle g_{\mu\nu} \rangle_k, 0 \leq k < \infty\})$ equipped with "scale-dependent Riemannian structure".

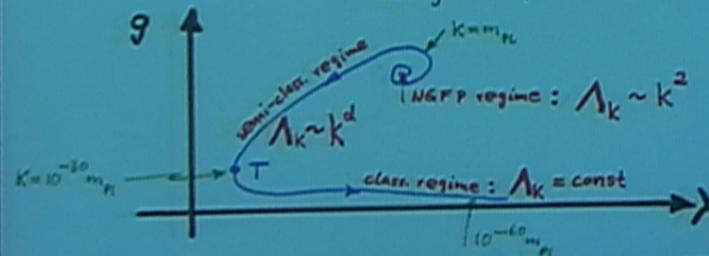
MR, J. Schwinn, 2006

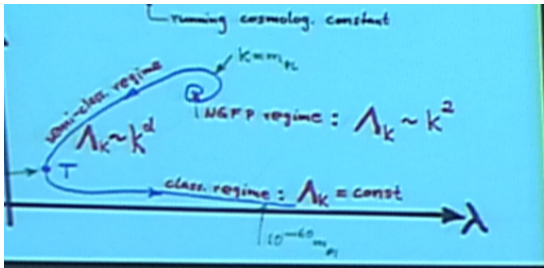
Scale-dependence is driven by quantum fluctuations.

- Example: Einstein-Hilbert truncation

$$G_{\mu\nu}(\langle g \rangle_k) = -\Lambda_k \langle g_{\mu\nu} \rangle_k, \quad \Lambda_k \equiv k^2 \lambda_k$$

↑
running cosmolog. constant





- 15 dim. red. gen
- singularity resolution?
- early universe?
- matter propagation on
- experimental evid

$$\frac{2\Lambda}{k\pi G} = \lambda Z^c X^y$$

$$\lambda = \bar{g}^{1/4}$$

Fractal Properties of Quantum Spacetimes

In the NGFP regime solutions to $\frac{\delta \Gamma_k}{\delta g_{\mu\nu}} = 0$
scale as $\langle g_{\mu\nu} \rangle \sim \frac{1}{k^2}$.

A. Lauscher, M.R.

~ fractal features,
self-similarity,

2002

$$d_{\text{eff}} = d + \gamma_N^* = 2$$

2002

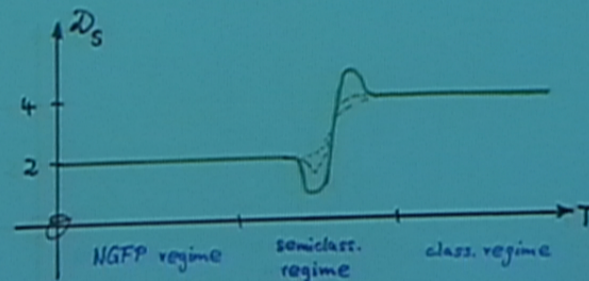
$$\mathcal{D}_S = \frac{d}{2}$$

2005

Spectral dimension:

$$\langle \text{Tr}(e^{T \Delta_{g_{\mu\nu}}}) \rangle \sim T^{-\frac{\mathcal{D}_S}{2}}$$

~ Dynamical dimensional reduction $4 \rightarrow 2$:



Fractal Properties of Quantum Spacetimes

In the NGFP regime solutions to $\frac{\delta \Gamma_k}{\delta g_{\mu\nu}} = 0$
scale as $\langle g_{\mu\nu} \rangle \sim \frac{1}{k^2}$.

A. Lauscher, M.R.

~ fractal features,
self-similarity,

2002

$$d_{\text{eff}} = d + \gamma_N^* = 2$$

2002

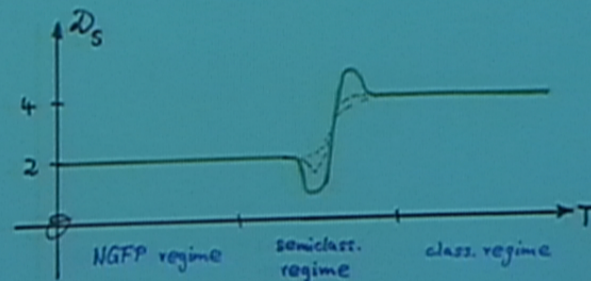
$$\mathcal{D}_S = \frac{d}{2}$$

2005

Spectral dimension:

$$\langle \text{Tr}(e^{T \Delta_{g_{\mu\nu}}}) \rangle \sim T^{-\frac{\mathcal{D}_S}{2}}$$

~ Dynamical dimensional reduction $4 \rightarrow 2$:



• CDT simulations:

$$\mathcal{D}_S = (4.02 \pm 0.01) \longrightarrow (1.80 \pm 0.25)$$

Ambjørn,
Junkewicz,
Loll; 2005

$$\mathcal{D}_S = (3.05 \pm 0.04) \longrightarrow (2.04 \pm 0.10)$$

Benedetti,
Henson;
2009

• EDT simulation:

$$\mathcal{D}_S = (4.04 \pm 0.26) \longrightarrow (1.457 \pm 0.064)$$

Laiho,
Counbe,
2011

• LQG (spatial section) and Spin-Foams:

$$\mathcal{D}_S = 3 \longrightarrow 1.5 \longrightarrow (1.5 \text{ or } 2)$$

$$\mathcal{D}_S = 4 \longrightarrow 2$$

Modesto,
2008

3D Spin-Foams (P.R. / T.V.):

$$\mathcal{D}_S = 3 \longrightarrow 1.5 \longrightarrow 2$$

Modesto,
Caravelli,
2009

• Strong Coupling limit of W-dW. eq.: $4 \rightarrow 2$

Carlip,
2009

• Models: Quantum sphere, $\mathcal{X}$ -Hinkowski:

Benedetti,
2008

$$\mathcal{D}_S = 4 \longrightarrow (<4)$$

QFT on given fractal

Calcagni,
2009

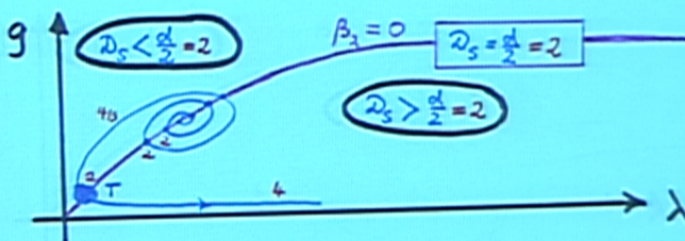
How is it possible that numerical simulations,
still far from the continuum limit,
do already observe a dimensional reduction ?

MR, F. Saueressig (2011)

Scale dependent spectral dimension

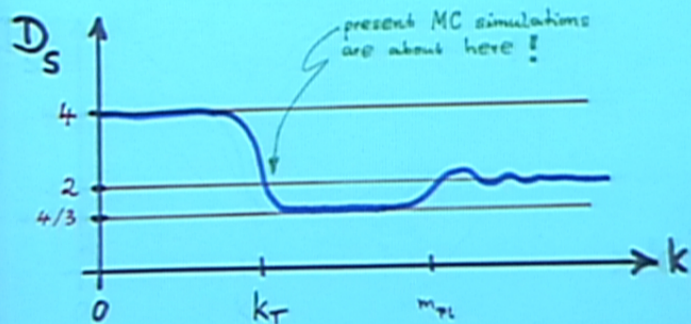
$$\Lambda_k \sim k^{\delta(k)} \Rightarrow \mathcal{D}_S = \frac{2d}{2+\delta}$$

classical	semiclass.	NGFP
$\delta = 0$	$\delta = d = 4$	$\delta = 2$
$\mathcal{D}_S = d = 4$	$\mathcal{D}_S = \frac{2d}{2+d} = \frac{4}{3}$	$\mathcal{D}_S = \frac{d}{2} = 2$



~ infinitely many points with $\mathcal{D}_S = \frac{d}{2}$!

When $T \rightarrow$ origin, 3 plateaus arise:



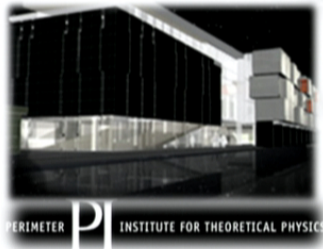
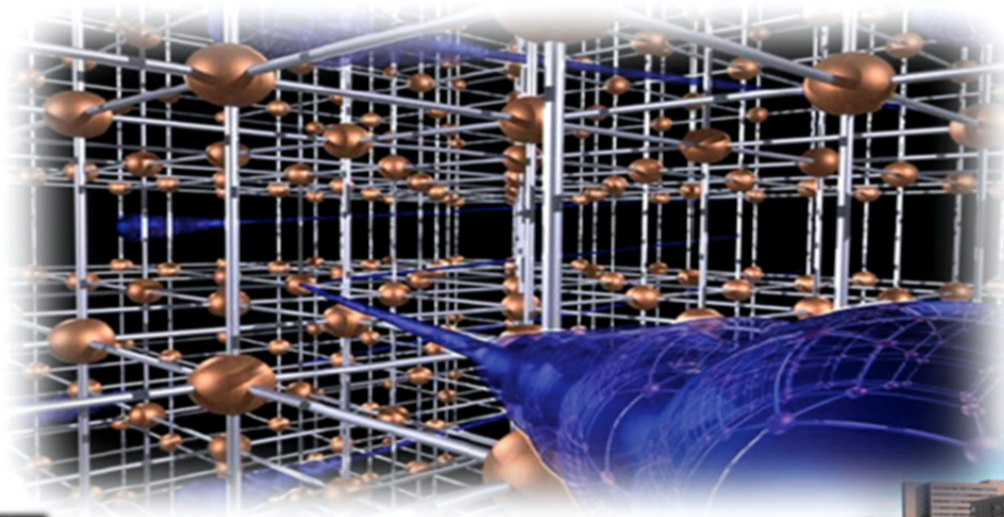
Conclusion

- The scale dependent spectral dimension seems to be an ideal diagnostic tool in order to monitor the approach to the continuum limit in numerical simulations.
- Its observation in real Nature seems extremely difficult though:
 - D_s refers to diffusion of test particles!
idealization: should include backreaction
 - Pure and matter coupled gravity are different;
fractal features require
$$\Lambda_K g_{\mu\nu} \gg 8\pi G T_{\mu\nu}^{\text{Matter}}$$
or strongly K -dependent $T_{\mu\nu}^{\text{Matter}}$
 - Related to (highly nonperturbative) problem of vacuum structure (cf. QCD)
 - Needed: fully dressed inv. graviton / photon propagator

Vanishing Dimensions

Dejan Stojkovic

SUNY at Buffalo



Experimental Search for Quantum Gravity

PI, Oct 22 - 25, 2012



UB University at Buffalo
The State University of New York

Based on:

Detecting Vanishing Dimensions Via Primordial Gravitational Wave Astronomy

J. Mureika, D. Stojkovic,

Phys. Rev. Lett. **106**, 101101 (2011).

Searching for the Layered Structure of Space at the LHC.

L. Anchordoqui, D. Dai, H. Goldberg, G. Landsberg, G. Shaughnessy, D. Stojkovic, T. Weiler,

Phys. Rev. D **83**, 114046 (2011)

Vanishing Dimensions and Planar Events at the LHC.

L. Anchordoqui, D. Dai, M. Fairbairn, G. Landsberg, D. Stojkovic,

Mod. Phys. Lett. A **27** (2012) 1250021

Nature Editorial: *Nature* **466**, 426 (2010)

“Collider gets yet more exotic 'to-do' list”

Outline

~~• Brief overview~~

- ~~• Dimensionality of space-time~~
- ~~• Extra dimensions~~

• Evolving dimensions:

*Our universe is lower dim on short scales
and higher dim on large scales!*





Outline

Experimental signature

• ~~Brief overview~~

- Dimensionality of space-time
- Extra dimensions

• Evolving dimensions:

*Our universe is lower dim on short scales
and higher dim on large scales!*

- Motivation for this proposal
- Possible evidence

Potential problems

Outline

~~• Brief overview~~

- ~~• Dimensionality of space-time~~
- ~~• Extra dimensions~~

• Evolving dimensions:

*Our universe is lower dim on short scales
and higher dim on large scales!!*

- Motivation for this proposal
- Possible evidence

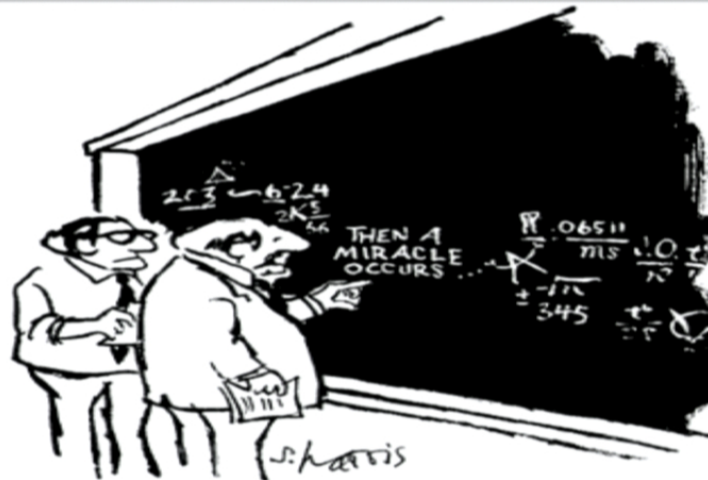
Potential problems

Experimental signature



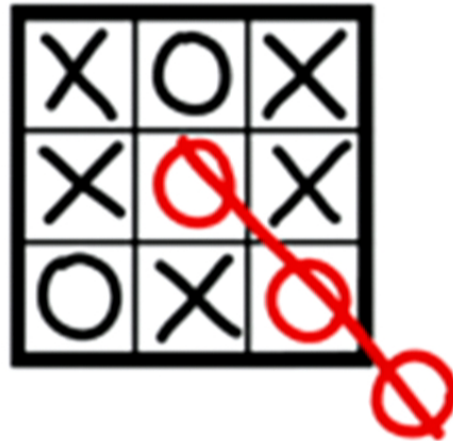
The current wisdom

- Let's make the things more complicated
- Introduce extra dimensions, new particles, new structures...
- And hope that the problems will miraculously disappear



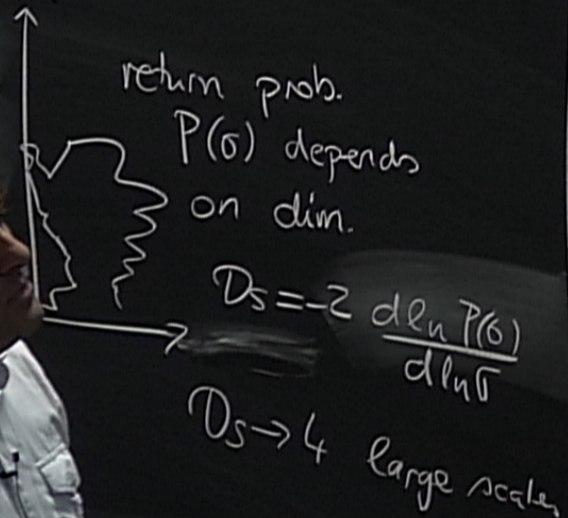
"I think you should be more explicit here in step two."

**THINK
OUTSIDE
THE BOX**



notions of dim.

- top. dim. d
- spectral dim D_S



• $D_S \rightarrow 2$ at small scales

- AS
(interacting FP)
- Causal Dyn. Triangulation

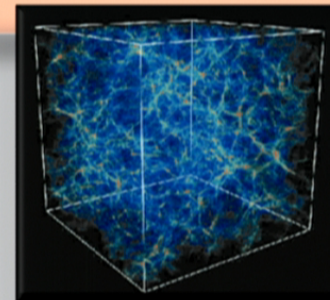
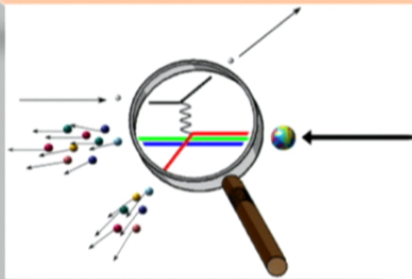
• LQG
 $\langle A \rangle \sim \sqrt{l^2(l^2 + l_{Pl}^2)}$
 $\sim l^2, l \gg l_{Pl}$
 $l, l \ll l_{Pl}$

- Hořava-Lifshitz
(anisotropic scaling of
space and time)



Proposal

- **Number of dim depends on scale which we are probing**
 - Short scales ($L < \text{TeV}^{-1}$) space is lower dimensional
 - Medium scales ($\text{TeV}^{-1} < L < \text{Gpc}$) space is 3-dim
 - Large scales ($L > \text{Gpc}$) space is higher dimensional





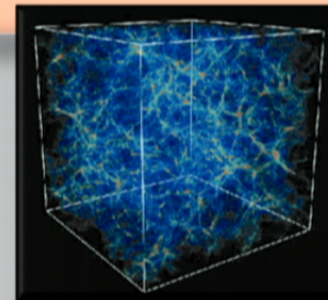
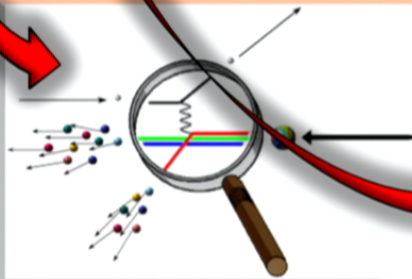
Proposal

- **Number of dim depends on scale which we are probing**

- Short scales ($L < \text{TeV}^{-1}$) space is lower dimensional

- Medium scales ($\text{TeV}^{-1} < L < \text{Gpc}$) space is 3-dim

- Large scales ($L > \text{Gpc}$) space is higher dimensional



Example

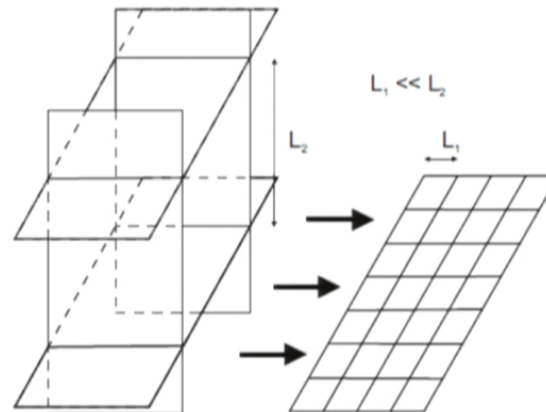
An example of a structure which is 1d on short scales while it appears effectively 2d on large scales.



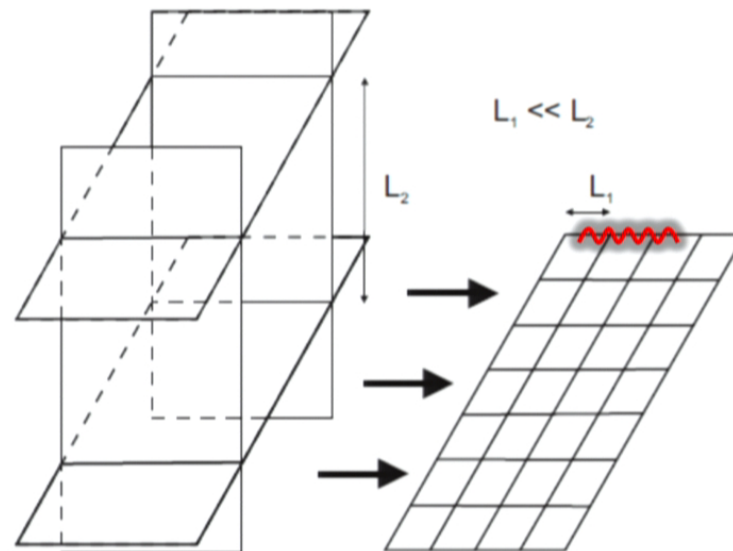
Ordered Lattice

Ordered Lattice. This structure is

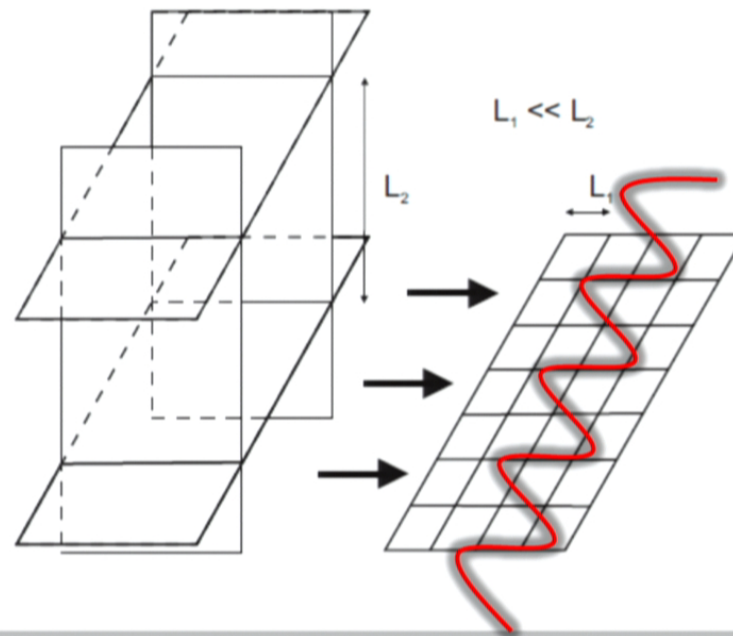
- 1d on scales $0 < L < L_1$,
- 2d on scales $L_1 < L < L_2$
- 3d on scales $L_2 < L < L_3$
-



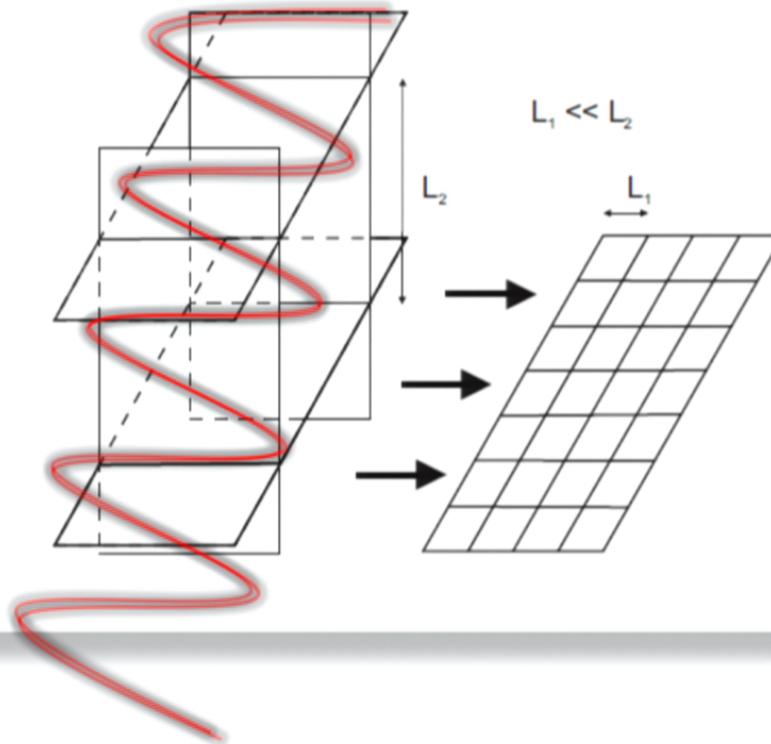
Ordered Lattice



Ordered Lattice

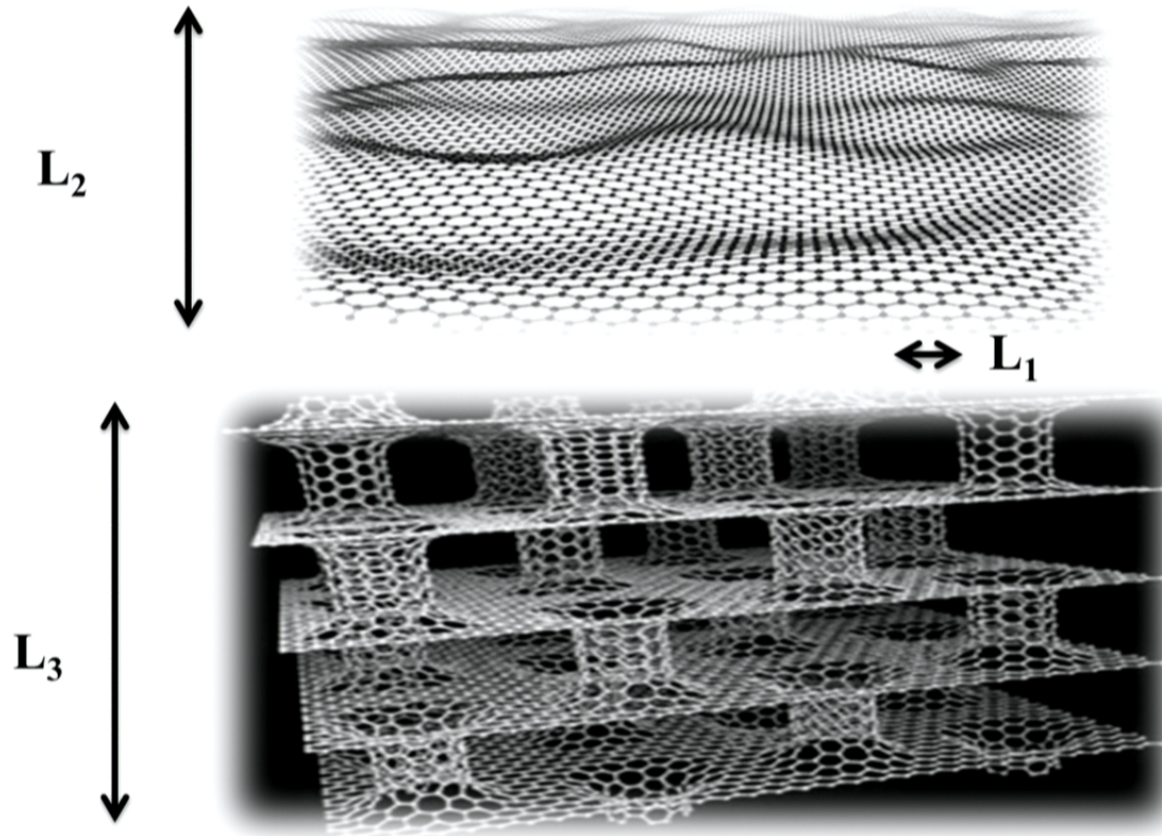


Ordered Lattice



Graphene

Nature already builds these structures



Benefits?

What do we gain by having less dimensions at high energies?



The hierarchy problem



- Gauge boson corrections to the Higgs mass:

$$\text{In 3 dim : } \frac{g^2}{4} \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2 - m_W^2} \approx \Lambda^2 \frac{g^2}{64\pi^2}$$

$$\text{In 2 dim : } \frac{g^2}{4} \int \frac{d^3 k}{(2\pi)^3} \frac{1}{k^2 - m_W^2} \approx \Lambda \frac{g^2}{8\pi^2}$$

$$\text{In 1 dim : } \frac{g^2}{4} \int \frac{d^2 k}{2\pi} \frac{1}{k^2 - m_W^2} \approx \text{Log} \left(\frac{\Lambda}{m_W} \right) \frac{g^2}{8\pi}$$



The hierarchy problem

If $3d \rightarrow 2d$ crossover happens at 1 TeV
 $2d \rightarrow 1d$ crossover happens at 10-100 TeV



- **The hierarchy problem disappears!**
- **No need for new physics – just The Standard Model.**

What about gravity?

In 2+1 dim any solution of the vacuum Einstein's eq. is locally flat

$$R_{\mu\nu\rho\sigma} = \varepsilon_{\mu\nu\alpha} \varepsilon_{\rho\sigma\beta} G^{\alpha\beta}$$

- no local gravitational degrees of freedom
- problem of non-renormalizability disappears

No Black Holes in 2+1 dim



In 2+1 dim any solution of the vacuum Einstein's eq. is locally flat



No real singularities – NO BLACK HOLES

(unless we add negative cosmological constant – BZT black hole)



As 3d BH evaporates, it becomes 2d, where it stops being a BH



NO INFORMATION LOSS PARADOX

Gravity stops being GR?

In 1+1 dim

$$\int d^2x \sqrt{-g} R = \text{Euler's characteristic of the manifold}$$

Unless augmented by some scalar field

$$\int d^2x \sqrt{-g} [\phi R + V(\phi)] \quad - \text{dilaton gravity}$$

Fully integrable and quantizable

Benefits?

What do we gain by having more dimensions at large scales?



Cosmological constant

In 4+1 dim, 3d homogeneous and isotropic solution

$$ds^2 = dt^2 - e^{2\sqrt{\Lambda/3}t} (dr^2 + r^2 d\Omega^2) - d\psi^2$$

$\Lambda = 3 / \Psi^2$ – position dependent cosmological constant

Vacuum equations $G_{AB} = 0$, for a 3d observer at $\psi = \text{const}$, look like

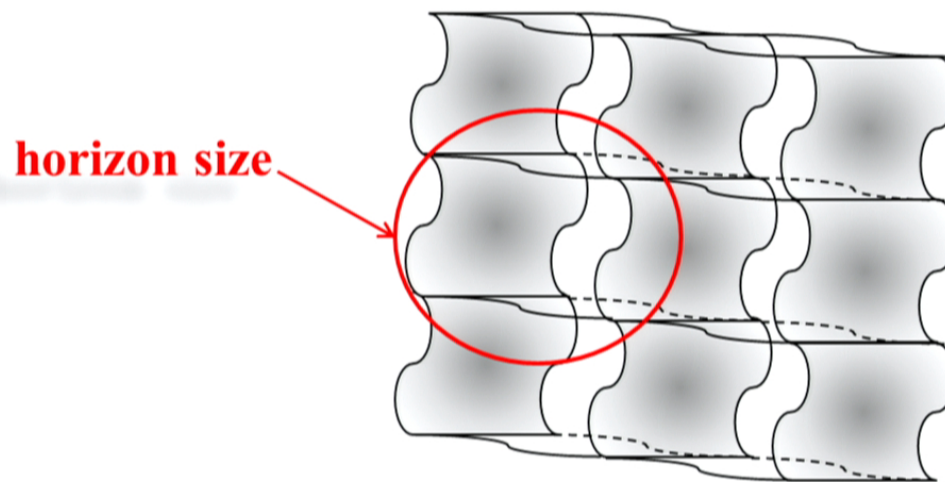
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

where $T_{\mu\nu}$ is induced matter with $p = -\rho$, $\rho = \Lambda/(8\pi G)$

$\rho = (10^{-3} \text{ eV})^4$ corresponds to $\psi \approx 10^{60} M_{Pl}^{-1} \approx \text{horizon size}$

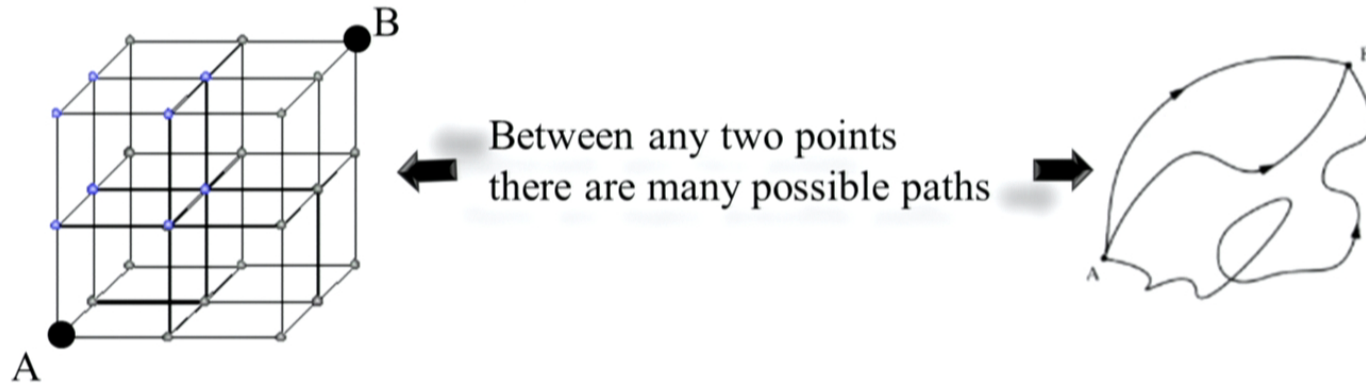
Other large scale puzzles

- Bulk flow
- “Axes of Evil”
- Lack of CMB power on large scales



Could be just the physics of large wavelength excitations of the lattice

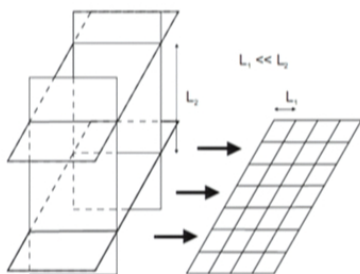
How do particles propagate on this background?



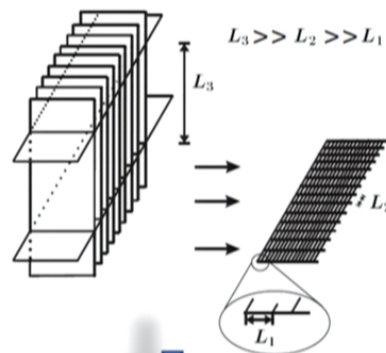
Feynman Path Integral

- Due to quantum fluctuations particle follows a jagged path
- Straight classical trajectory and paths nearest to it give the highest contribution
- Interference of many possible paths gives a straight propagation on average
- Our case: geometry of the lattice dictates the jaggedness of the path

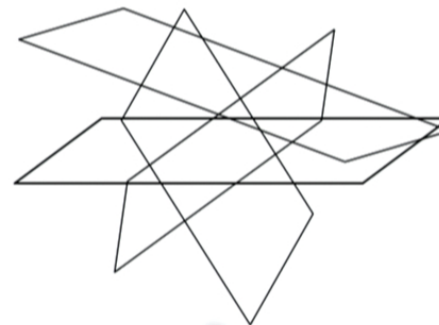
Geometry of the lattice



“Natural” Lattice



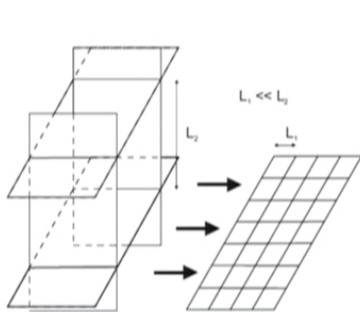
Stack of branes



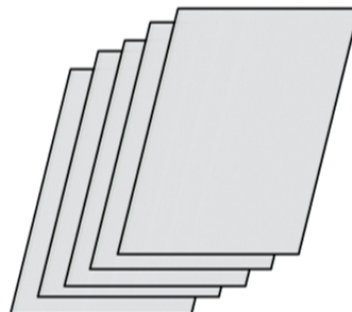
Random Lattice

- In all cases short distance physics is 2d (1d)
- But the way one recovers 3d space at large distances is not the same

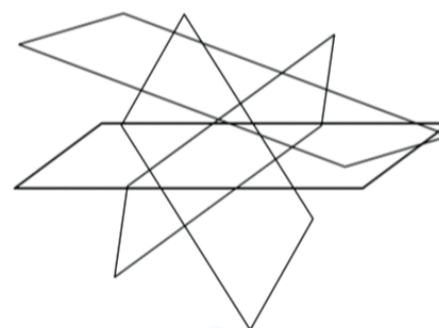
Geometry of the lattice



“Natural” Lattice



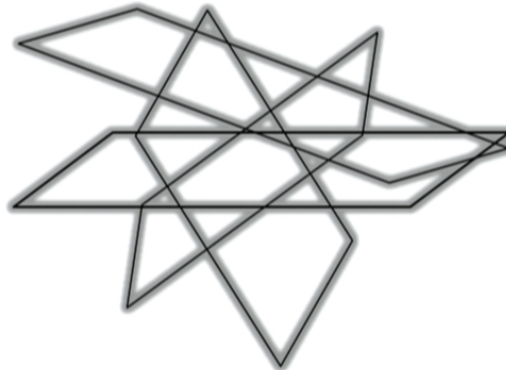
Stack of branes



Random Lattice

- In all cases short distance physics is 2d (1d)
- But the way one recovers 3d space at large distances is not the same

Geometry of the lattice



Random Lattice



- Avoids preferred direction in space
- Avoids systematic violations of Lorentz invariance
- The preferred reference system may exist: **the rest frame of the lattice** (no more problematic than the preferred rest frame of the CMB)

Lorentz symmetry violation

- Lorentz invariance is restored on average on large distances
- However, small fluctuations of the path can have measurable effects for light propagating over large cosmological distances

The effective speed of light **might** change

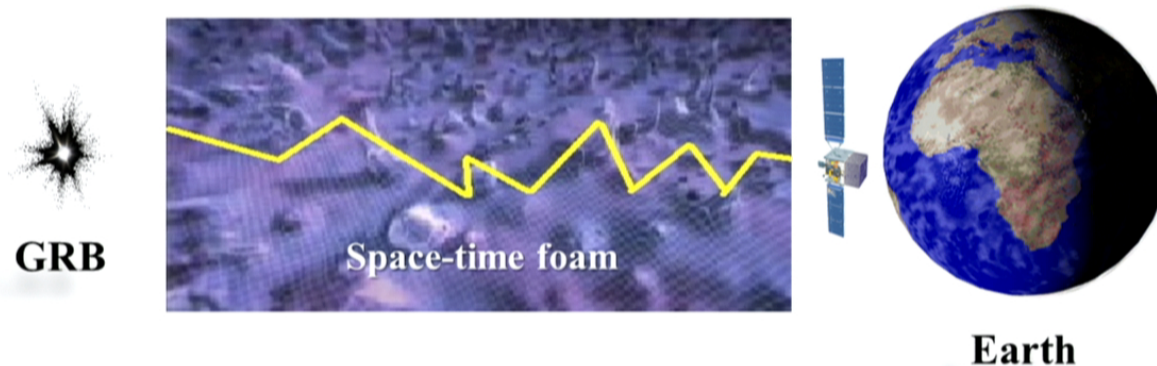
$$c_{eff} = c \left(1 + \xi \frac{E}{E_*} + \eta \frac{E^2}{E_*^2} \right)$$

Two simultaneously emitted photons of energy difference $\Delta E = E_1 - E_2$ will arrive at the observer with a time delay $\Delta t = t_1 - t_2$

$$\left| \frac{c_{eff}}{c} - 1 \right| \approx \left(\frac{E_\gamma}{E_* c^2} \right)^n \quad n = 1, 2, 3$$

$$\Delta t \approx \left(\frac{\Delta E_\gamma}{E_* c^2} \right)^n \frac{D}{c}$$

Gamma rays and Fermi satellite

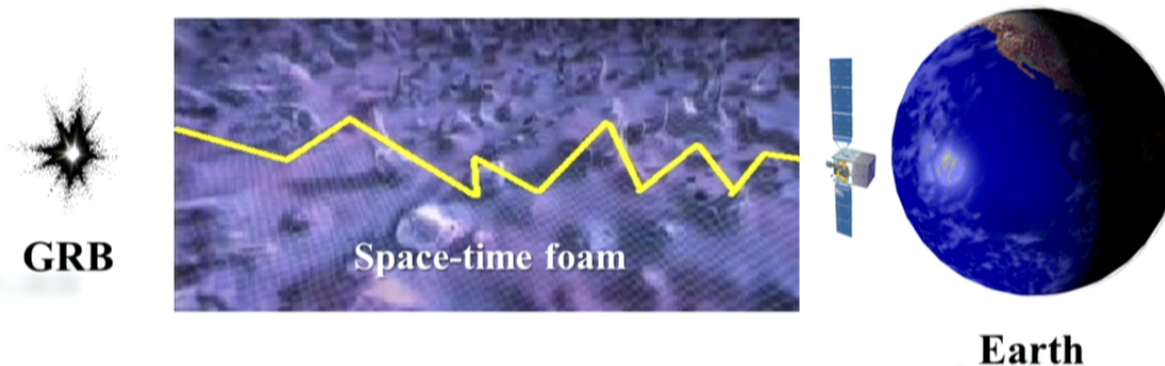


Fermi observed one 31-GeV and one 3-GeV photon arriving with the time delay of less than 1 sec



Usually interpreted as the limit $E_* \geq M_{\text{Pl}}$

Gamma rays and Fermi satellite



Fermi observed one 31-GeV and one 3-GeV photon arriving with the time delay of less than 1 sec



Usually interpreted as the limit $E_* \geq M_{\text{Pl}}$

Fermi result and vanishing dimensions

- **Caveats:**

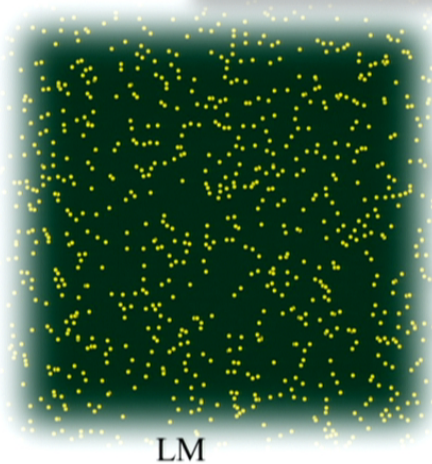
- i. Only one event observed
- ii. Physics of the source poorly understood
- iii. Limit $E_* \geq M_{\text{Pl}}$ valid only if linear corrections exist
- iv. Both photons $E_\gamma < \text{TeV} \rightarrow \text{no } c_{\text{eff}}(\Delta E)$
- v. High interaction probability for high energy gamma rays with CMB and infrared background photons ($e^+ e^-$)

Regular vs. random lattice

F. Dowker, J. Henson, R. Sorkin, gr-qc/0311055



Regular lattice in two different Lorentz frames (a) and (b)



(Poison) Randomization is crucial:

- One can't tell what frame was used to produce sprinkling
- Approximation is equally good in any frame

LIV and vanishing dimensions

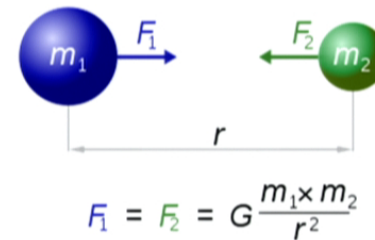
We can't take limits on LIV face value ($E_* \geq M_{Pl}$)

We simply do not understand how particles interact with the space-time structure at the fundamental level

$M_{Pl} = 10^{19} \text{ GeV}$ doesn't even make sense in 2d

$$M_{Pl}^{(3d)} = \sqrt{\frac{c\hbar}{G^{(3d)}}}$$

$$M_{Pl}^{(2d)} = \frac{c^2}{G^{(2d)}}$$



There is no $\hbar$ in M_{Pl} in 2d

No quantum gravity in 2d? Classical gravity sufficient?

Concrete Model?



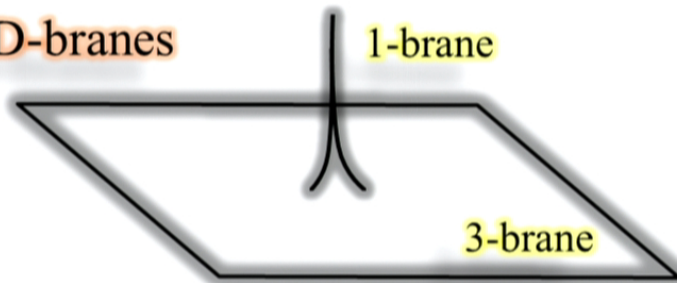
String theory solutions



C. Callan, J. Maldacena, Nucl.Phys. B513, 198 (1998)

N. Constable, R. Myers, O. Tafjord, Phys.Rev. D61 (2000) 106009

D-branes

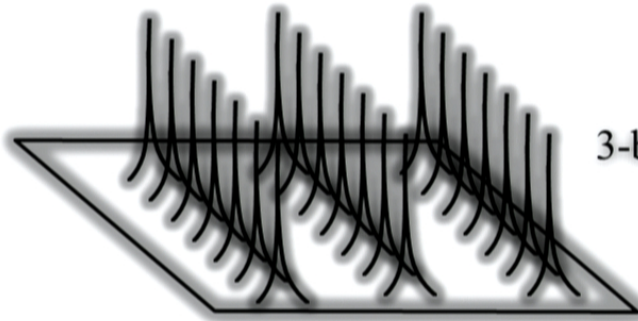


1-brane smoothly matching 3-brane

$$ds^2 = -dt^2 + f(r)dr^2 + g(r)d\Omega^2$$

$\downarrow r \rightarrow 0$
 dz^2

$\downarrow r \rightarrow 0$
 0



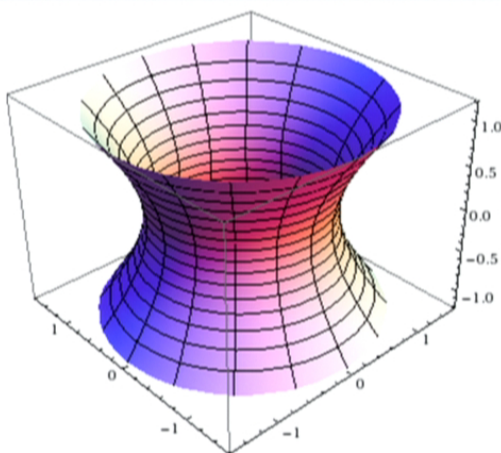
3-brane that looks like 1-brane around every point

$$\sum_i \frac{1}{|x - x_i|^n}$$

How to describe this evolving background?

$g_{\mu\nu}$ - metric on a higher dimensional manifold

γ_{ab} - metric on a sub-manifold (e.g. string worldsheet)



$$\gamma_{ab} = g_{\mu\nu} \partial_a X^\mu \partial_b X^\nu$$

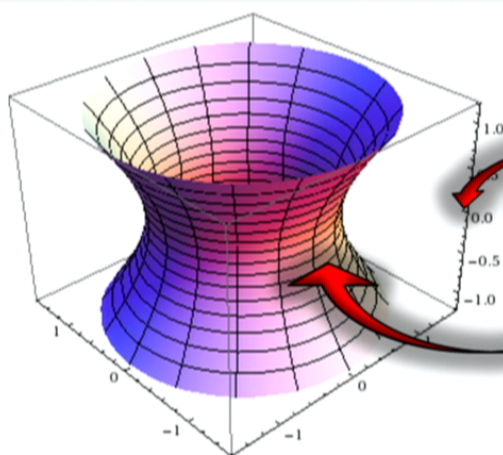
X^μ are dimensions that we observe in our world

But they are also (dynamical) fields on a worldsheet

How to describe this evolving background?

$g_{\mu\nu}$ - metric on a higher dimensional manifold

γ_{ab} - metric on a sub-manifold (e.g. string worldsheet)



$$\gamma_{ab} = g_{\mu\nu} \partial_a X^\mu \partial_b X^\nu$$

X^μ are dimensions that we observe in our world

But they are also (dynamical) fields on a worldsheet

Concrete stringy model



with N. Afshordi

$$I_{free} = -\frac{1}{4\pi\alpha'} \int d^2\xi \sqrt{-\gamma}$$

$$\gamma_{ab} = g_{\mu\nu} \partial_a X^\mu \partial_b X^\nu$$

$$L_{mass} = \sum_{i=1}^n m(E_i, E)^2 X_i X^i =$$

$$= m_0^2 e^{-E_1/E} X_1 X^1 + m_0^2 e^{-E_2/E} X_2 X^2 + \dots + m_0^2 e^{-E_n/E} X_n X^n$$

$$E_1 \gg E_2 \gg, \dots, \gg E_n$$

Hot Big Bang, $E \gg E_1, E_2, \dots, E_n$

When E drops to $E \ll E_1$

.....

Today, $E \sim 10^{-3} \text{ eV}$,



X^i are not excited

only X^1 is excited



X^1, X^2, X^3 are excited

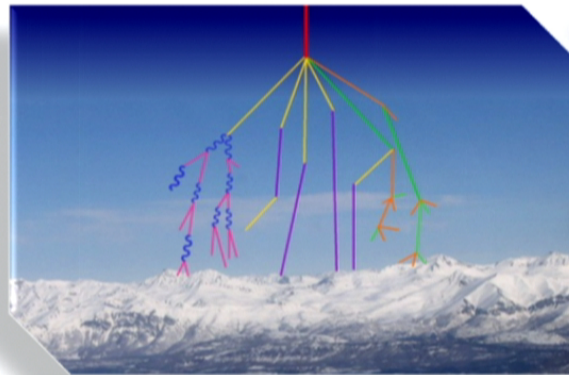
Experimental evidence?

Experimental evidence for vanishing dimensions may already exists

Alignment of high energy secondary particles was observed in families of cosmic ray particles detected in the Pamir mountains

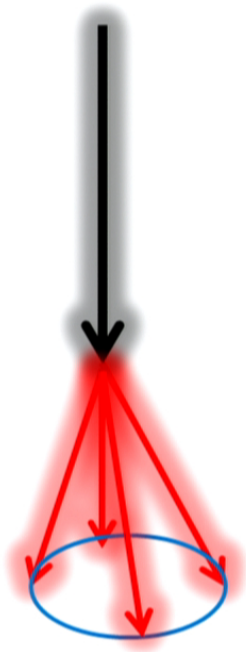
(Russia and Tajikistan)

6 out of 14 events

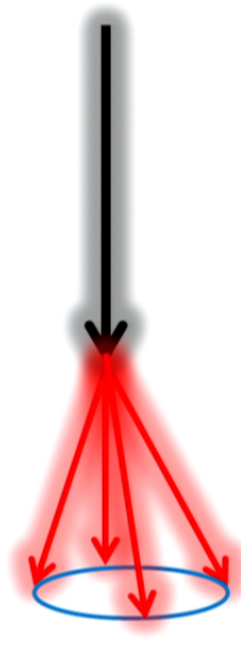


Altitude 4400 m

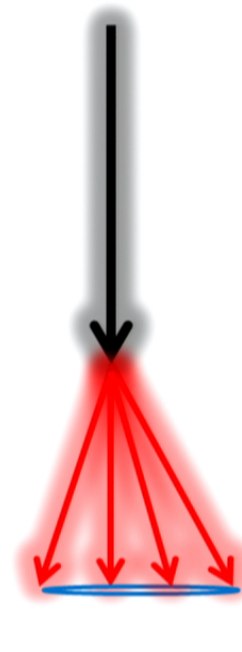
Alignment is statistically significant for families with high energies
 $E > 700 \text{ TeV}$ which corresponds to **$E_{\text{COM}} > 4 \text{ TeV}$**



Circle:
3d event
 $\lambda = 0$



Ellipse:
Somewhat planar
 $\lambda > 0.5$



Line:
Pure 2d event
 $\lambda = 1$

Parameter λ measures the degree of alignment

Experimental evidence?

- Most of the aligned events originate just above the chamber
- Thus, sea/ground level experiments can't see the effect

Mt. Kanbala (in China)

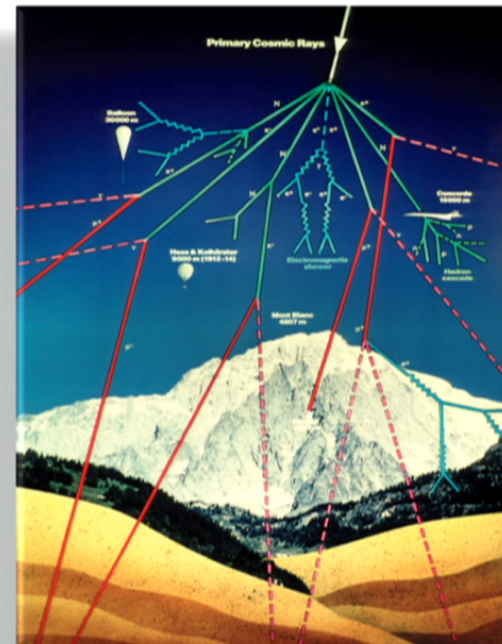
$E > 700 \text{ TeV}$, 3 out of 6 events

Two stratospheric experiments

$E > 1000 \text{ TeV}$

$$\lambda = 0.99$$

- *STRANA* superfamily, detected on board of a Russian stratospheric balloon
- *JF2af2* superfamily, detected on a high-altitude flight of the aircraft Concord

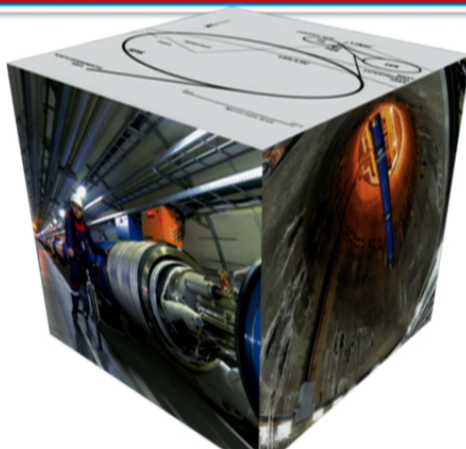


Possible LHC signature

If the alignment in cosmic rays at $E_{\text{COM}} > 4 \text{ TeV}$ is not a fluke



LHC might observe similar alignment



LHC signature

If the fundamental high energy physics is 2d , the following must be true regardless of the exact underlying model:

- **Cross section changes due to the reduced phase space**

LHC signature

If the fundamental high energy physics is 2d , the following must be true regardless of the exact underlying model:

- **Cross section changes due to the reduced phase space**
- **Higher order scattering processes at high energies become planar**

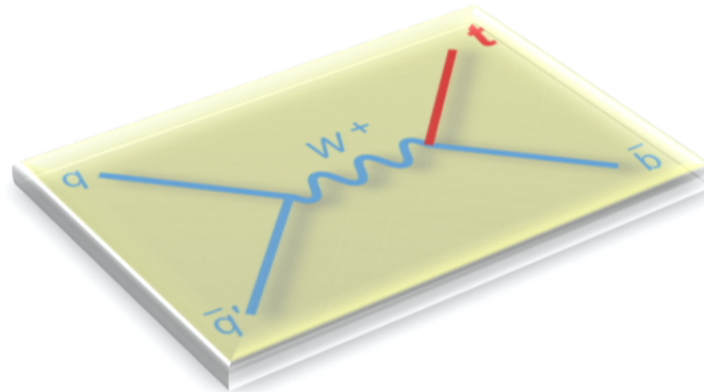
LHC signature

If the fundamental high energy physics is 2d , the following must be true regardless of the exact underlying model:

- Cross section changes due to the reduced phase space
- Higher order scattering processes at high energies become planar
- Jets of sufficiently high energy may become elliptic in shape

2d scattering

For scattering to be 2d , wavelength of the mediator must be $< L_3$

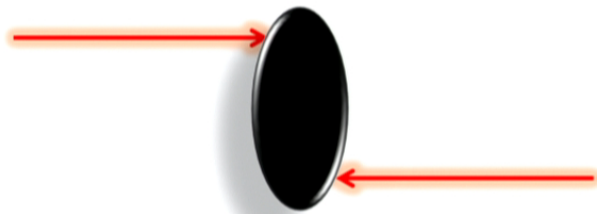


Momentum transfer
 $Q^2 > \Lambda_3^2$

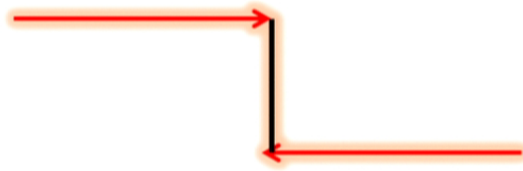
Thus, only hard scattering can probe 2d structure of space

2d vs 3d scattering

Cross-section in 2d is a **line** (not a **disk** as in 3d)



3d cross section



2d cross section

Phase space $\sim d\Omega_d$: total cross-section reduced by a factor of 2

2d vs 3d scattering

Coulomb Potential:

$$\text{3d} \quad V(r) \propto \alpha / r \quad \longrightarrow \quad \alpha \text{ is dimensionless}$$

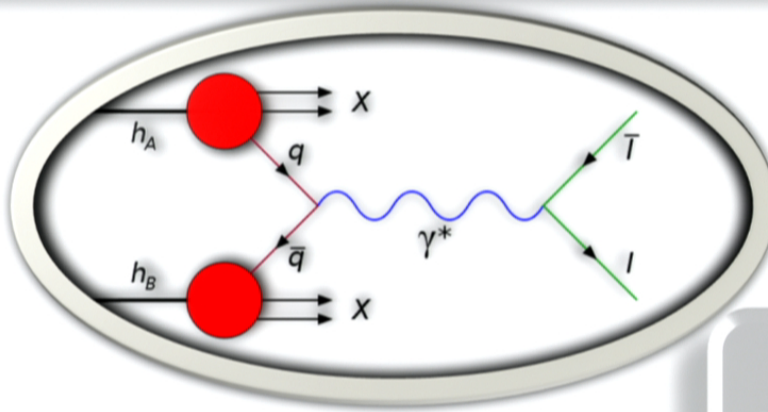
$$\text{2d} \quad V(r) \propto \alpha \text{Ln}\left(\frac{r}{r_0}\right) \quad \longrightarrow \quad \alpha = \text{L}^{-1}$$

$$\text{3d} \quad \sigma = L^2 \Rightarrow \sigma \propto \frac{\alpha^2}{E^2}$$

$$\text{2d} \quad \sigma = L \Rightarrow \sigma \propto \frac{\alpha^2}{E^3}$$

2d vs 3d scattering

Drell-Yan cross section will drop as $1/E^3$ instead of $1/E^2$ once the $3d \rightarrow 2d$ crossover energy is surpassed



Drell-Yan process

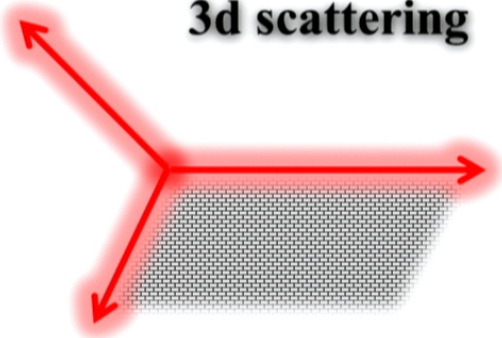
$$\sigma^{DY} = \begin{cases} \sigma_{SM}^{DY} & \text{if } \sqrt{\hat{s}} < \Lambda_3 \\ \sigma_{SM}^{DY} \left(\frac{\Lambda_3}{\sqrt{\hat{s}}} \right) & \text{if } \sqrt{\hat{s}} > \Lambda_3 \end{cases}$$

Limits from Tevatron data $\Lambda_3 > 800 \text{ GeV}$

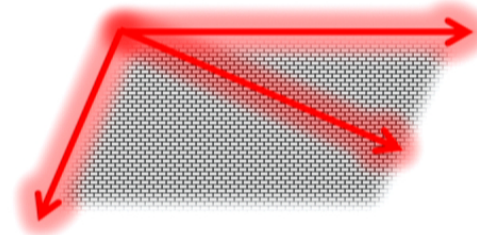
Planar multijet events

In $2 \rightarrow 3$ scattering with $Q^2 > \Lambda_3^2$, all the virtual particles (propagators) must move in the same 2d plane

3d scattering



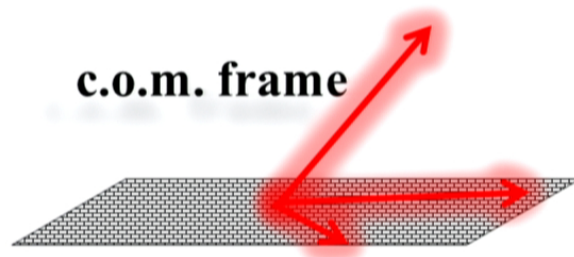
2d scattering



Thus, outgoing partons must be in the same plane in the c.o.m. frame of the collision, thus drastically different from the 3d scattering

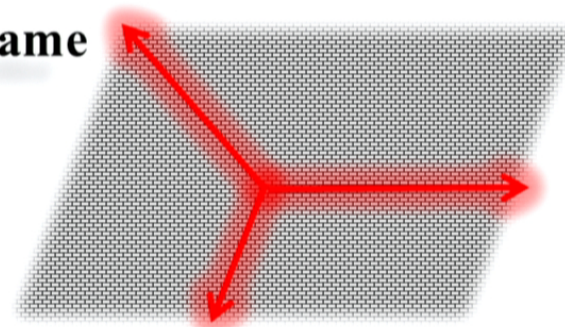
Planar multijet events

- Local plane absorbs the initial $p_{\perp}$ momentum
- Planar scattering happens in **c.o.m.** frame
- Lattice transfers $p_{\perp}$ to the outgoing particles giving them boost
- Planarity is preserved once we boost the particles back



Impossible in com frame even in 3d

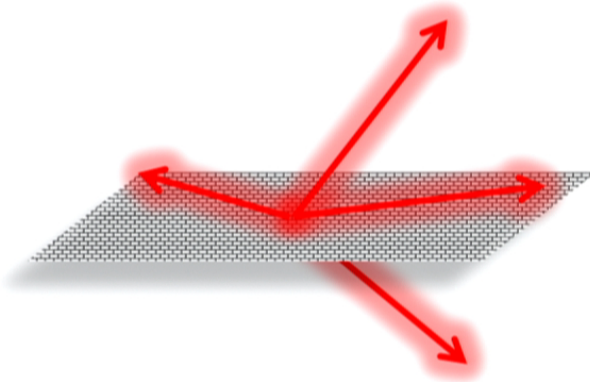
c.o.m. frame



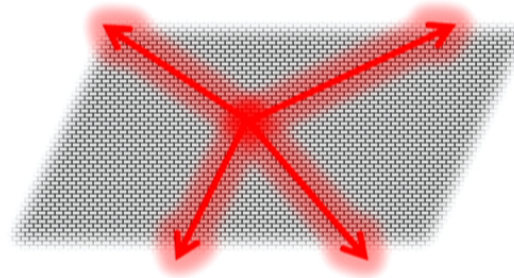
Any three vectors originating from the common point and conserving overall zero momentum will be co-planar even in 3d

Planar multijet events

3d scattering



2d scattering

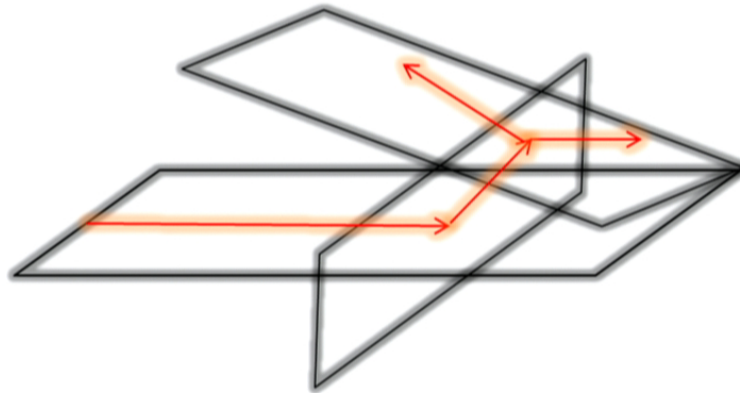
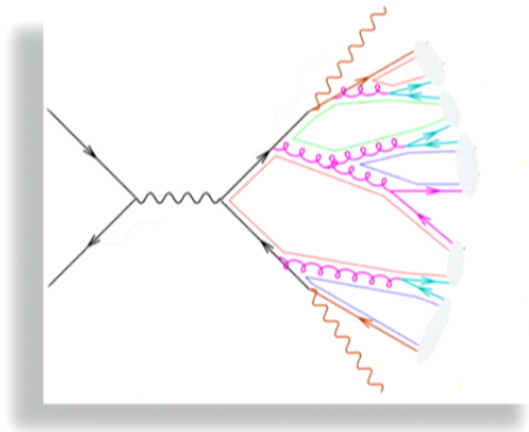


Need 4-jets for acoplanar events in 3d

Co-planar 4-jet events → clear 2d signature

Elliptic Jets

- If the lattice orientation is preserved over distances $\Lambda^{-1}_{\text{QCD}}$ individual jets at very high energy may become elliptic in shape
- Parton showers are ordered in Q^2 : the largest Q^2 happen first



- Showers may not be spherical (start planar then expand in 3d)

Vanishing dimensions at the LHC

Measurement of event shapes at large momentum transfer with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

e-Print: **arXiv:1206.2135**

ATLAS search for “vanishing dimensions”

Gravity waves signature

In 2+1 dim any solution of the vacuum Einstein's eq. is locally flat

$$R_{\mu\nu\rho\sigma} = \varepsilon_{\mu\nu\alpha} \varepsilon_{\rho\sigma\beta} G^{\alpha\beta}$$

- **No local gravitational degrees of freedom**
 - no gravitons in quantum theory
 - no gravity waves in classical theory



Gravity waves signature

The characteristic frequency of gravitational waves produced at some time t in the past is redshifted to its present-day value $f_0 = f_* a(t)/a(t_0)$

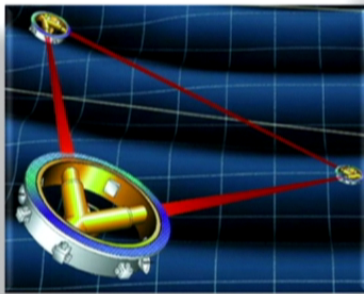
$$f_* \approx H_*^{-1} \quad H_* \approx \frac{8\pi^3 g_* T_*^4}{90 M_{Pl}^2}$$

$$f_0 \approx 1.67 \times 10^{-4} \left(\frac{T_*}{TeV} \right) \text{Hz}$$

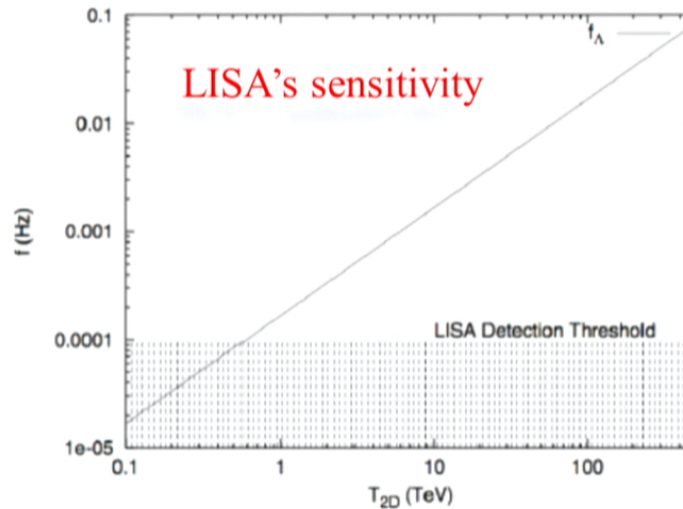
Today's frequency of primordial gravity waves created at $T=T_*$

Gravity waves signature

LISA should be able to see a cut-off in GW frequency



$$f_0 \approx 1.67 \times 10^{-4} \left(\frac{T_*}{\text{TeV}} \right) \text{ Hz}$$



Conclusions

- **Fundamental problems have accumulated**
- **Current ideas do not work**
- **Time for radically new ideas**



We introduced the concept of *evolving dimensions*

- Many problems simply disappear
- Clear model independent observational signature

Remains to be done:

- Concrete Model - Lagrangian

Conclusions

- **Fundamental problems have accumulated**
- **Current ideas do not work**
- **Time for radically new ideas**



We introduced the concept of *evolving dimensions*

- Many problems simply disappear
- Clear model independent observational signature



Remains to be done:

- Concrete Model - Lagrangian

Conclusions

- **Fundamental problems have accumulated**
- **Current ideas do not work**
- **Time for radically new ideas**



We introduced the concept of *evolving dimensions*

- Many problems simply disappear
- Clear model independent observational signature



Remains to be done:

- Concrete Model - Lagrangian





THANK YOU