Evolving Dimensions

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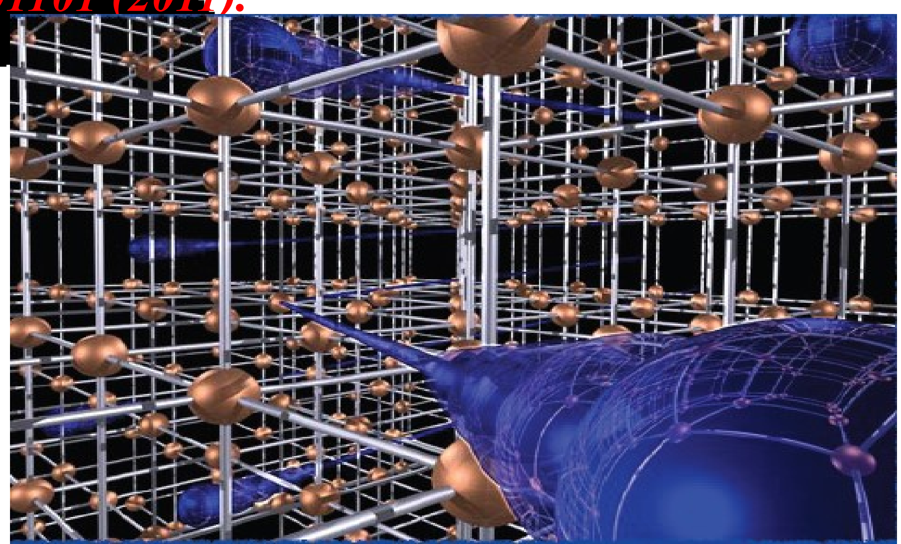
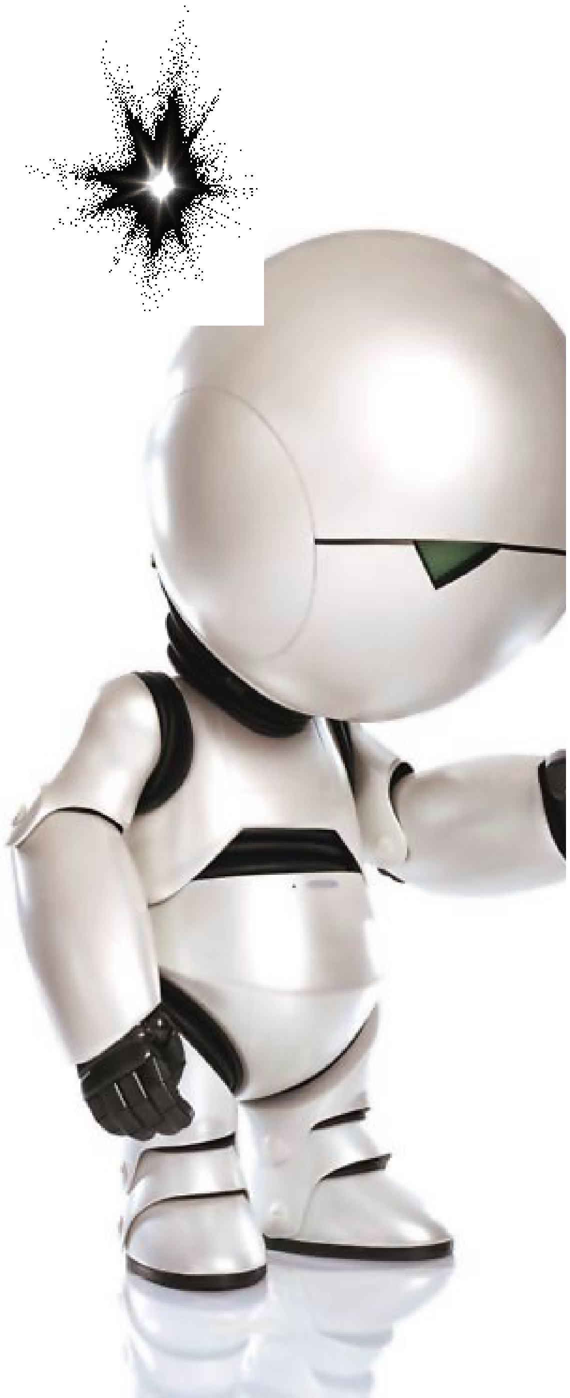
Based on:

Vanishing Dimensions and Planar Events at the LHC.
L. Anchordoqui, D. Dai, M. Fairbairn, G. Landsberg, **D. Stojkovic**,
Submitted to PRD

Searching for the Layered Structure of Space at the LHC.
L. Anchordoqui, D. Dai, H. Goldberg, G. Landsberg, G. Shaughnessy, **D. Stojkovic**, T. Weiler,
Submitted to PRD

Detecting Vanishing Dimensions Via Primordial Gravitational Wave Astronomy
J. Mureika, **D. Stojkovic**,
Phys. Rev. Lett. 106, 101101 (2011).





Outline

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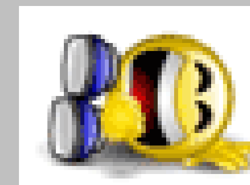
Our universe is lower dim on short scales and higher dim on large scales!

- Motivation for this proposal
- Possible evidence

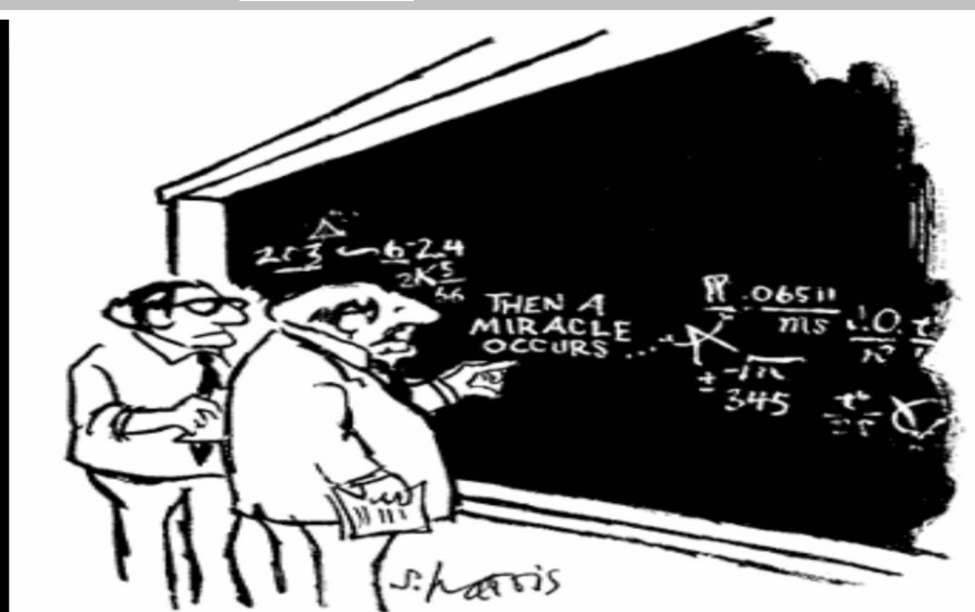
Potential problems

Experimental signature

The current wisdom



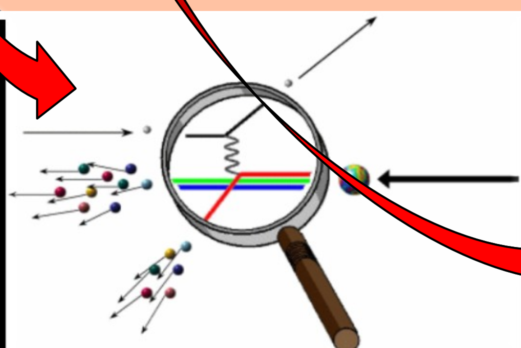
- Let’s make the things more complicated
- Introduce extra di[illegible]ons, new particles, new structures…
- And hope that th[illegible]ems will miraculously disappear

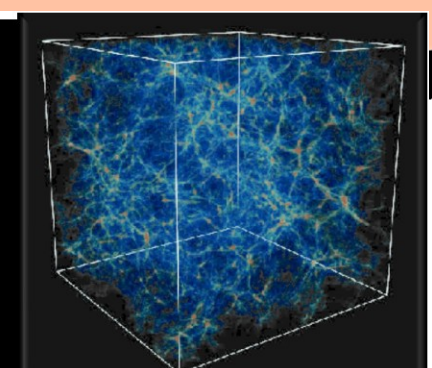


“I think you should be more explicit here in step two.”

Proposal

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





Example

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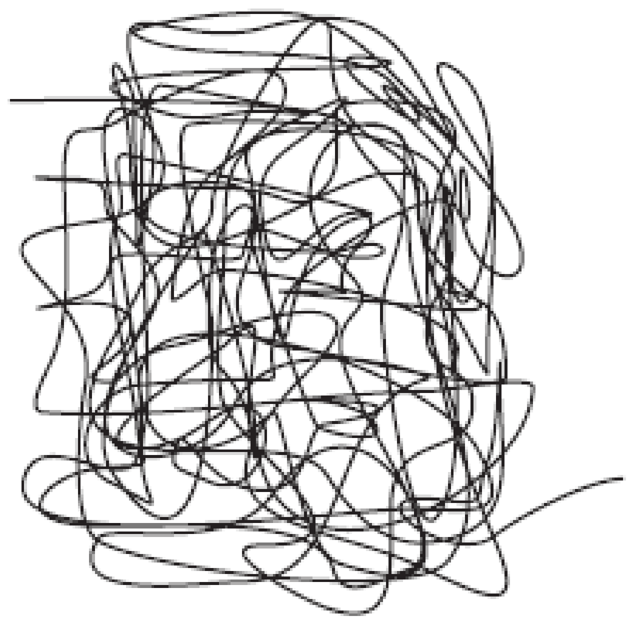
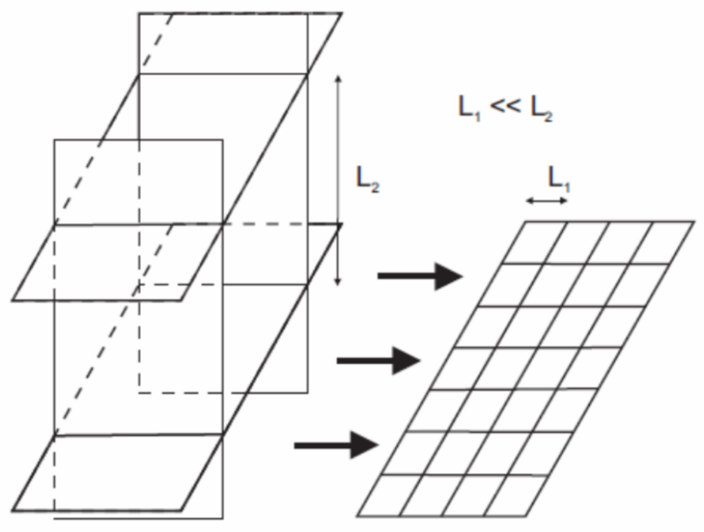


Ordered Lattice

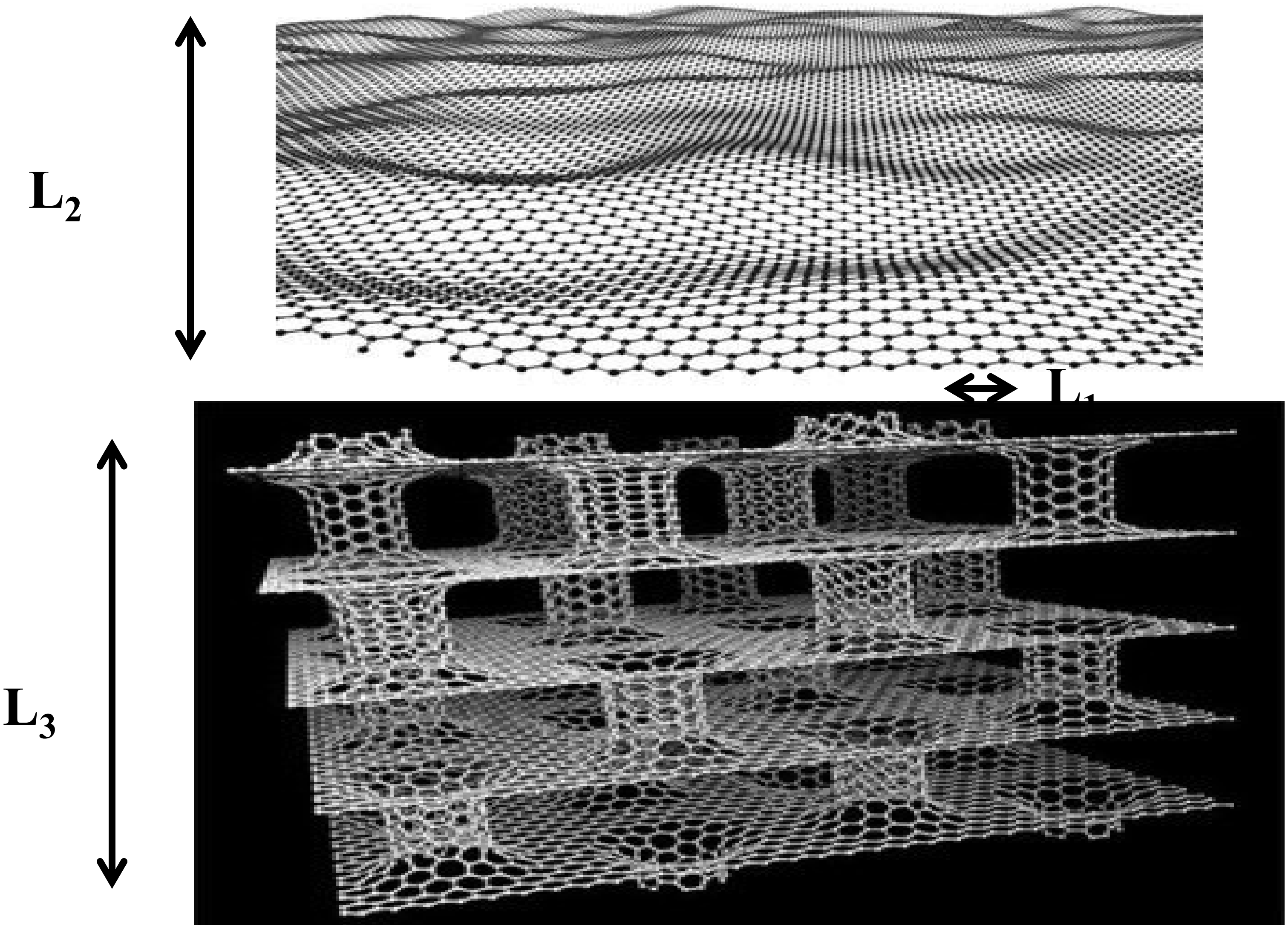
Ordered Lattice. This structure is

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



Graphene

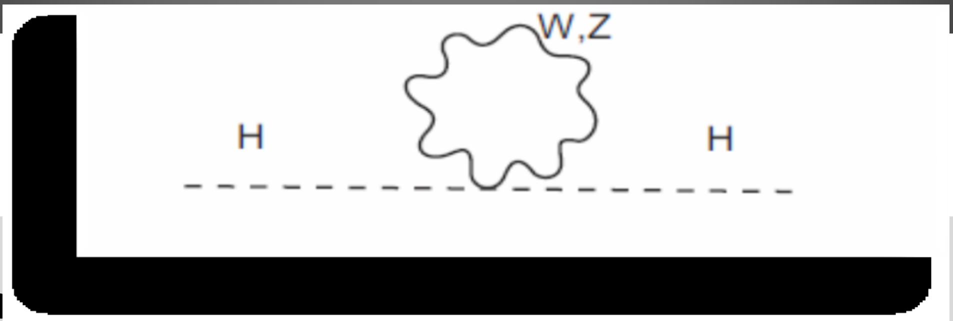
Nature already builds these structures



Benefits?

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

The hierarchy problem



• **Gauge boson**

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

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

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

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.**

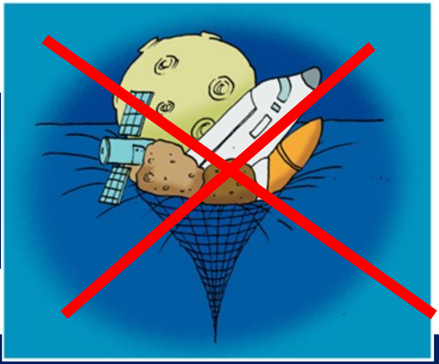
What about gravity?

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
- number of degrees of freedom in finite
- quantum field theory reduces to quantum mechanics
- 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

↓

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

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

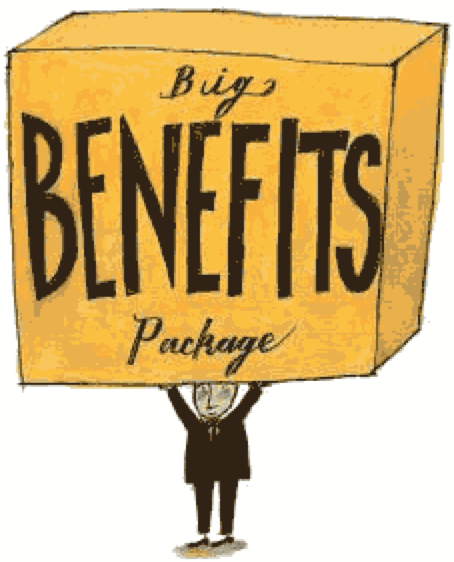
Unless augmented by some scalar field

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

Fully integrable and quantizable

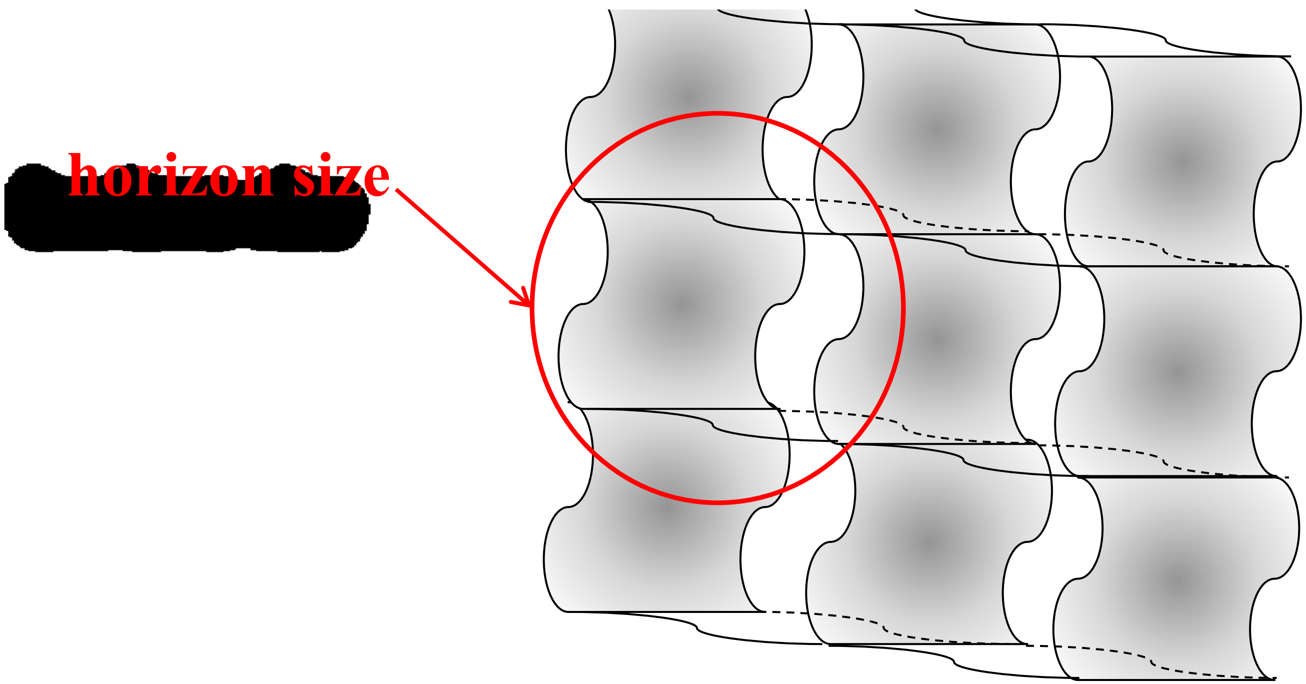
Benefits?

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



Our Universe may be 4+1 dim on large scales

- Many 3d sheets comprise 4d space
- Stars and galaxies are on 3d sheets
- Universe becomes 4d on scales comparable to the horizon radius



Cosmological constant

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

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

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

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

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

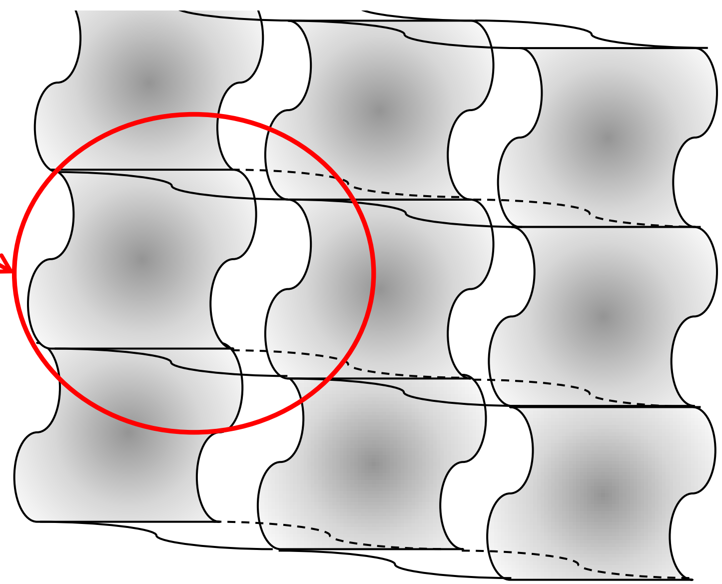
where $T_{\mu\nu}$ is induced matter with $p = -\rho$, $\rho = \Lambda/(8\pi G)$

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

Other large scale puzzles

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

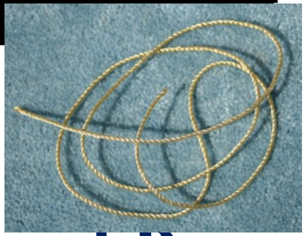
horizon size



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

How to describe this evolving background?

I. R. Klebanov and L. Susskind, Nucl.Phys. B 309, 175 (1988)



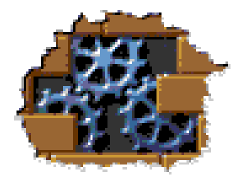
- Take a string and chop it into N segments
- Let each segment carry non-vanishing P^+ and $P_\perp$

$$H = \sum_i^N \frac{1}{2P^+(i)} \left\{ \vec{P}_\perp^2(i) + \left[\vec{X}(i+1) - \vec{X}(i) \right]^2 \right\}$$

- P^+ makes the string grow in length
- $P_\perp$ is the source of the extrinsic curvature

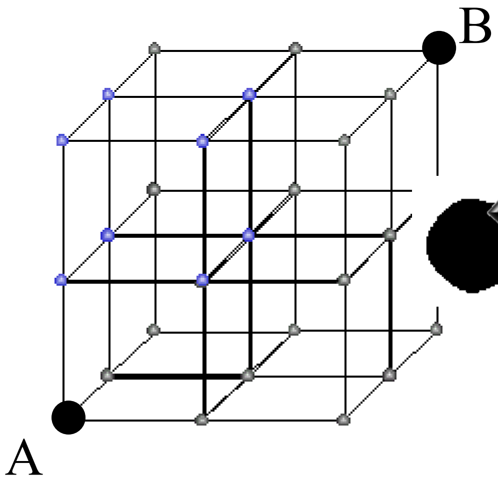
Result

- [redacted]



- [redacted]
- [redacted]
- [redacted]

How do particles propagate on this background?



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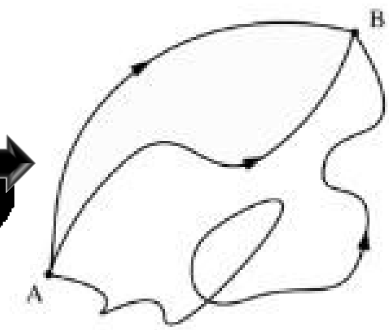

Feynman Path Integral

- [redacted]
- [redacted]
- [redacted]
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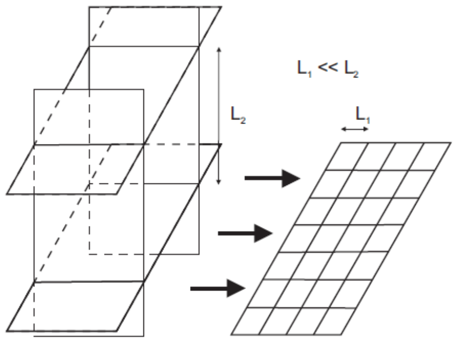
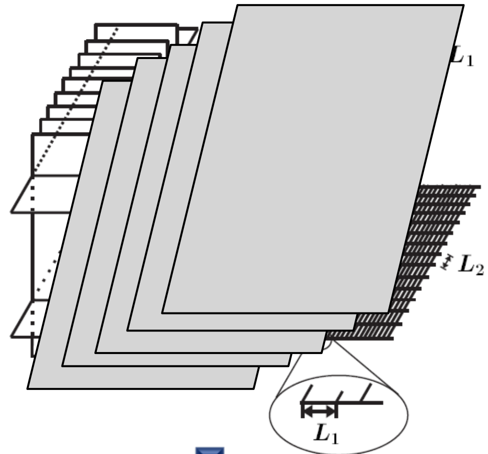
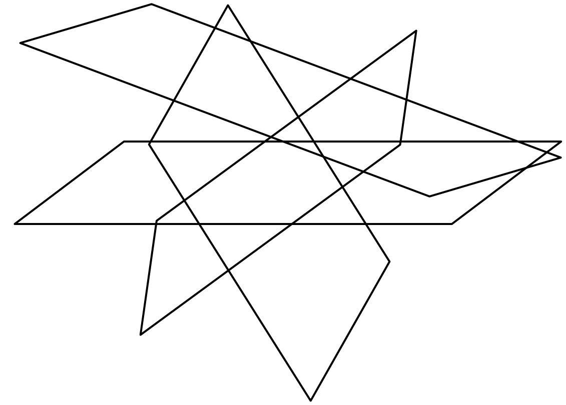
Geometry of the lattice





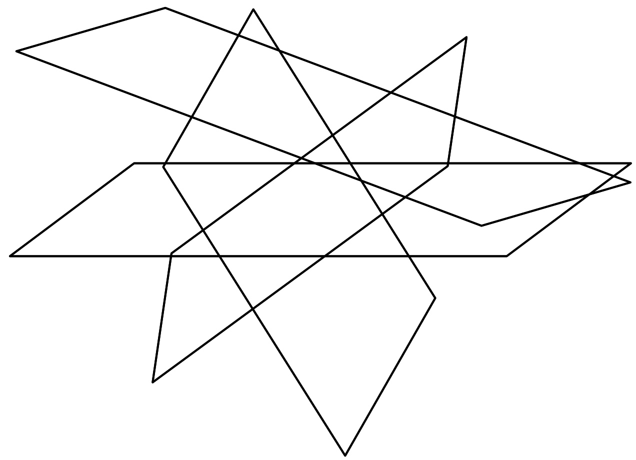


“Natural” Lattice

Stack of branes

Random Lattice

Geometry of the lattice



Random Lattice

- Avoids prefer[illegible]
- Avoids syste[illegible] ariance
- The preferred [illegible] he 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

[redacted] might [redacted]

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

[redacted]

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

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

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 $E_* \geq M_{Pl}$

Fermi result and vanishing dimensions

- **Caveats:**

i. Only one event observed

ii. Physics of the source poorly understood

iii. Limit $E_* \geq M_{Pl}$ valid only if linear corrections exist (LQG)

iv. Both photons $E_\gamma <$ TeV $\rightarrow$ no $c_{eff}(\Delta E)$

v. High interaction probability for high energy gamma rays with CMB and infrared background photons ($e^+ e^-$)

Regular vs. random lattice

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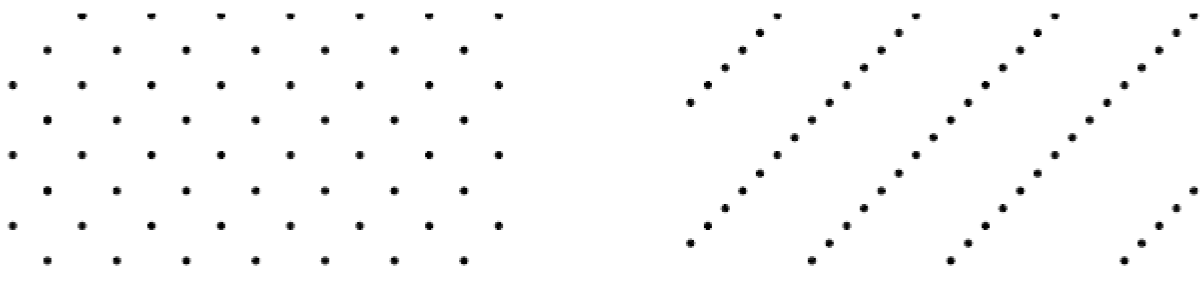
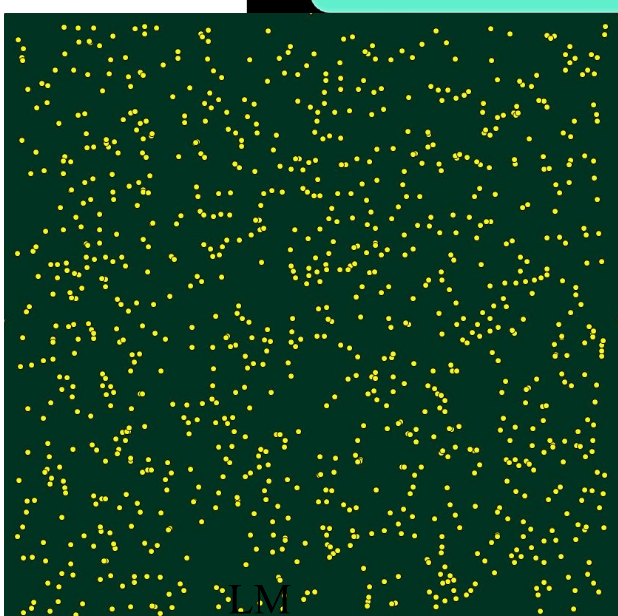


(a) (b)

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

[redacted]



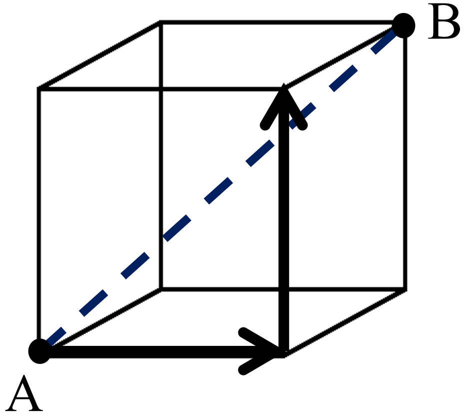
[redacted]

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

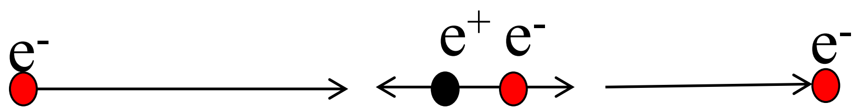
[redacted]

Effective speed of light

- To propagate from A to B with **c** on a straight line
- It must move with $\mathbf{c_{eff}} = \sqrt{3}\ \mathbf{c}$ along the sides



No problem in the Feynman path integral picture



In a short time (TeV^{-1}) particle can move with $v > c$ due to quantum effects

Discrete structures don't need to change an effective speed of light

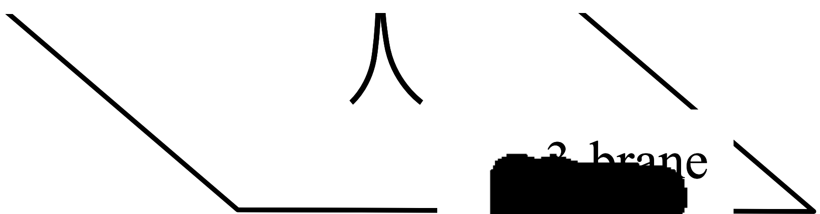
String theory solutions

[redacted]

[redacted]

[redacted]

[redacted]

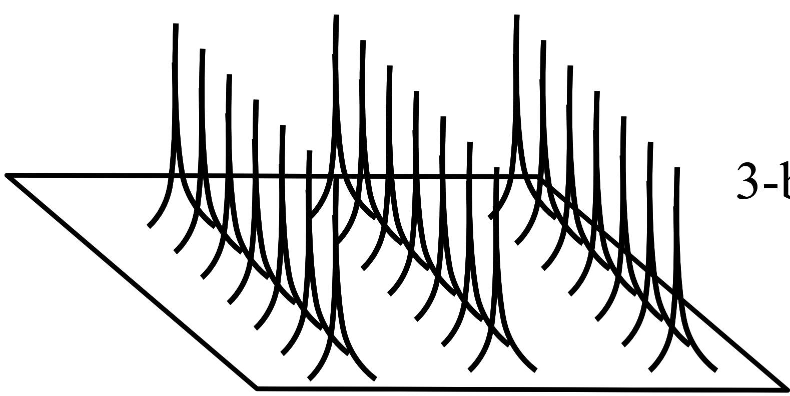


[redacted]

[redacted]

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

$$f(r)dr^2 \xrightarrow{r \to 0} dz^2 \qquad g(r)d\Omega^2 \xrightarrow{r \to 0} 0$$



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

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

Experimental evidence?

Experimental evidence for vanishing dimensions may already exists.

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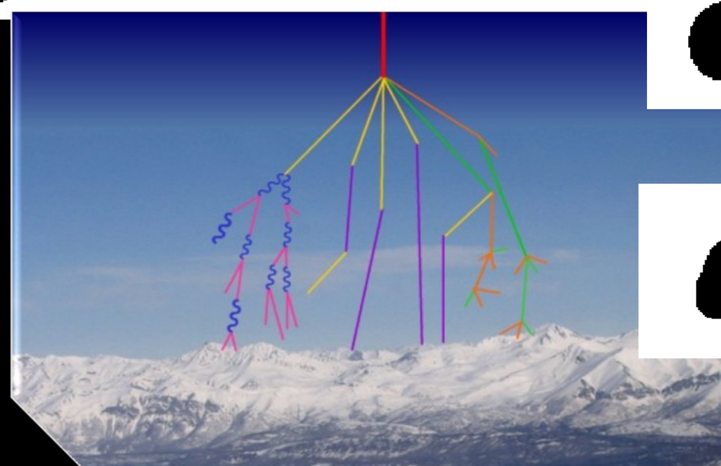
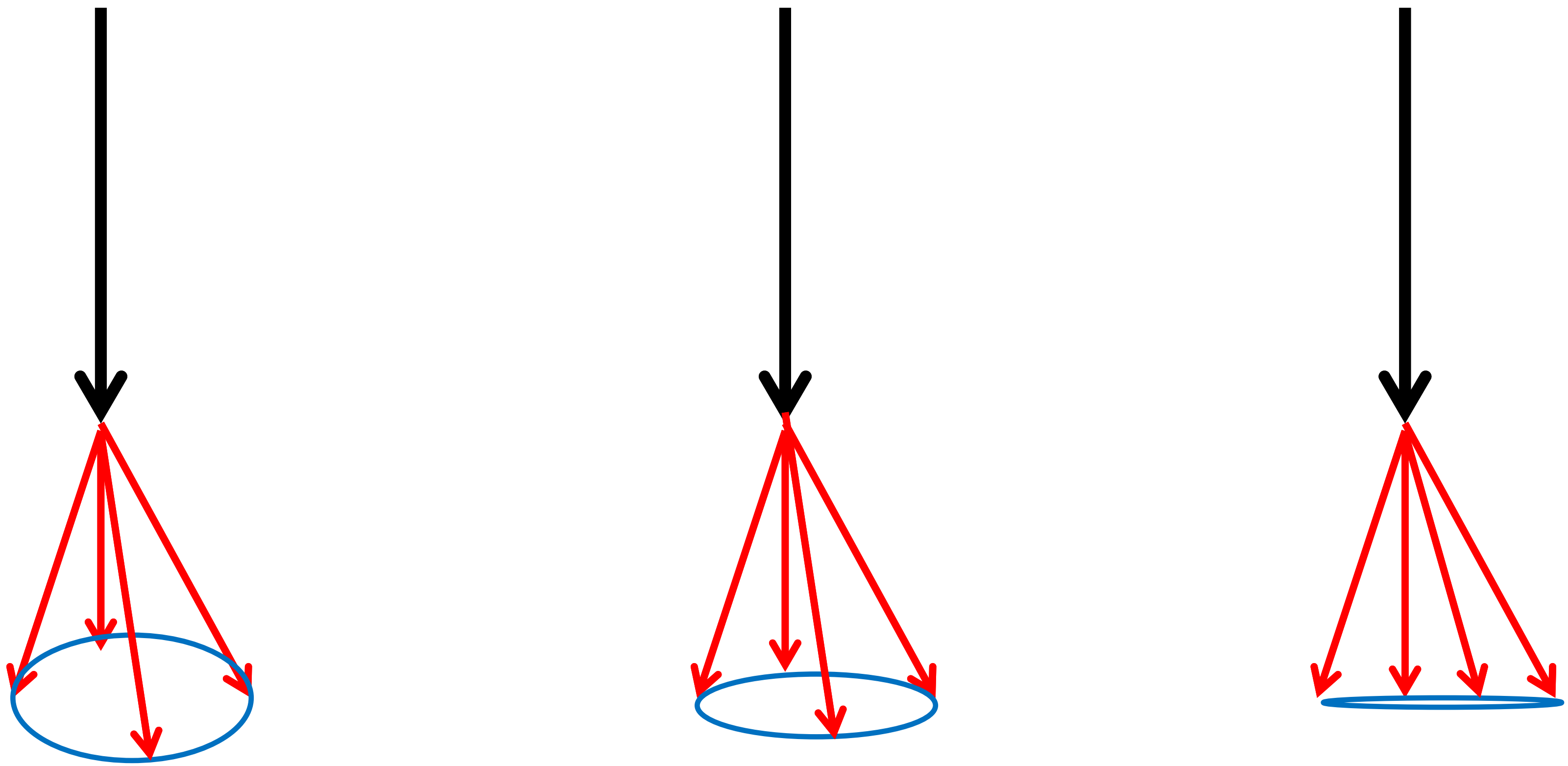


[redacted]

E > 700 TeV [redacted] **$E_{COM} > 4$ TeV**



[redacted]

[redacted]

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

Parameter λ measures the degree of alignment

[redacted]

Experimental evidence?

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

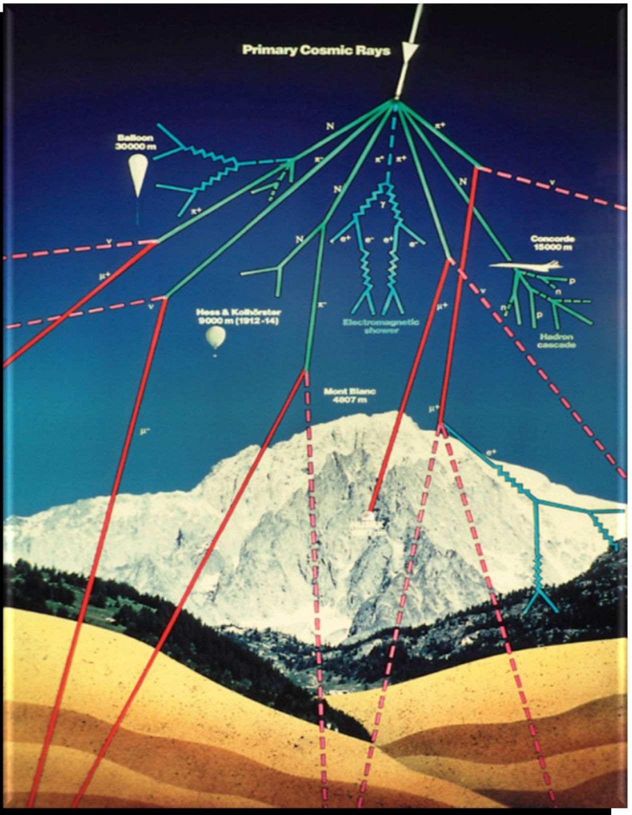
[redacted]

E > 700 TeV , 3 out of 6 events

[redacted]

E > 1000 TeV [redacted]

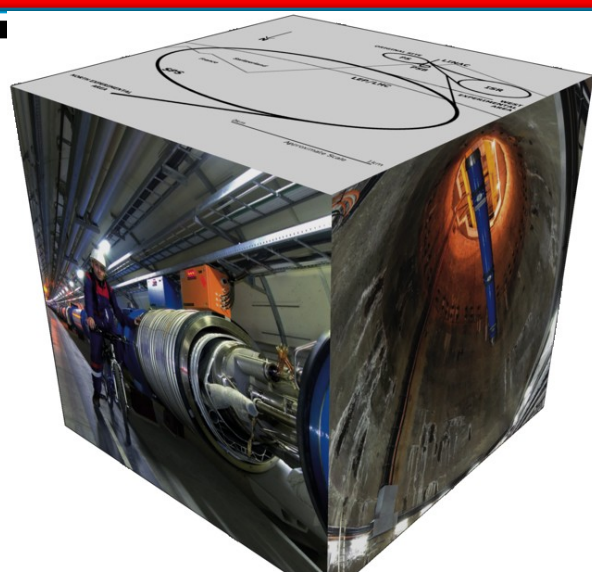
[redacted]



Possible LHC signature

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

LHC might observe similar alignment



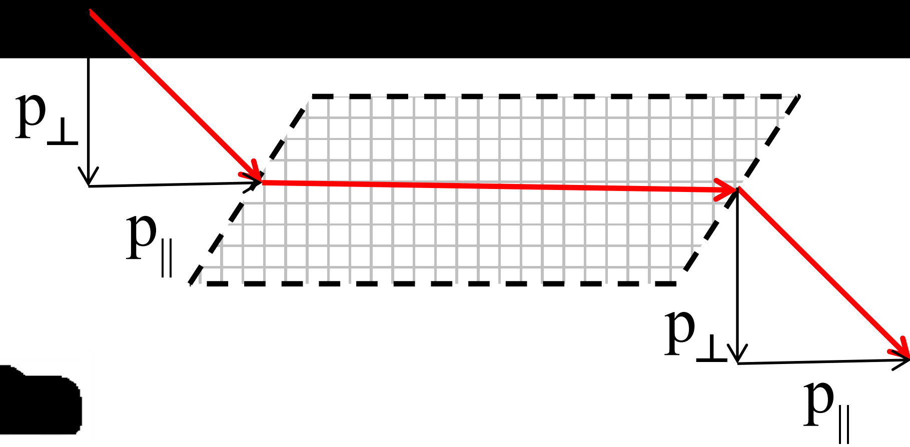
LHC signature

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**
- **Higher order scattering processes at high energies become planar**
- **Jets of sufficiently high energy may become elliptic in shape**

3d momentum conservation

If $\lambda_{\text{de Broglie}} < L_3$ ⇒
particle propagates locally in 2d, rather than 3d



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[redacted]

To preserve 3d momentum of particles propagating over $L \gg L_3$
lattice absorbs $p_\perp$ and then re-emits it by the lattice back-reaction

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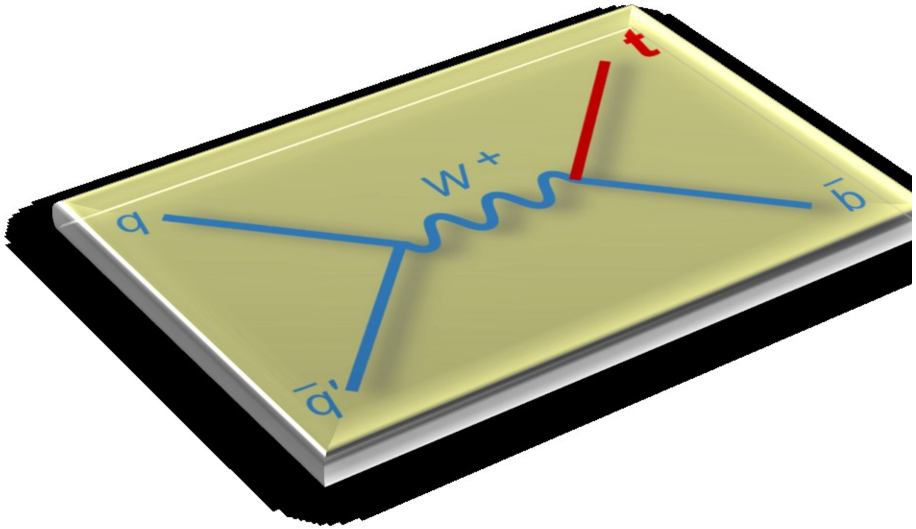
Particle remembers its group velocity through quantum interference of several paths

2d scattering

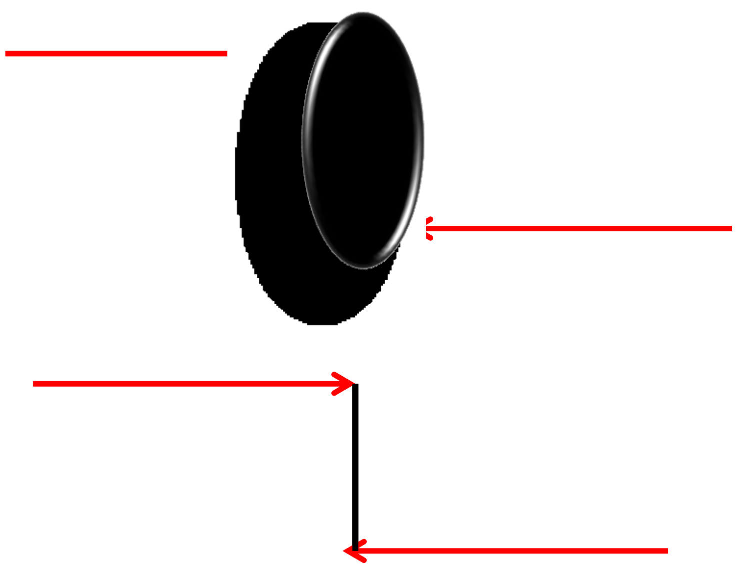
For scattering to be 2d , wavelength of the mediator must be < L_3



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)



[redacted]

[redacted]

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

2d vs 3d scattering

Coulomb Potential:

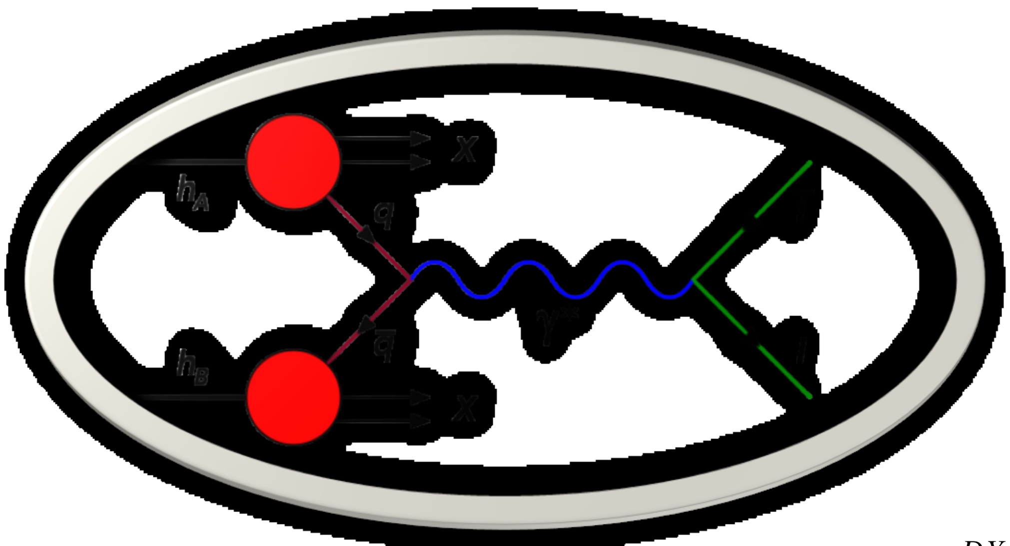
[redacted]d [redacted] → [redacted]

[redacted]d $\sigma = L^2 \Rightarrow \sigma \propto \frac{\alpha^2}{E^2}$

[redacted]d $\sigma = L \Rightarrow \sigma \propto \frac{\alpha^2}{E^3}$

2d vs 3d scattering

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



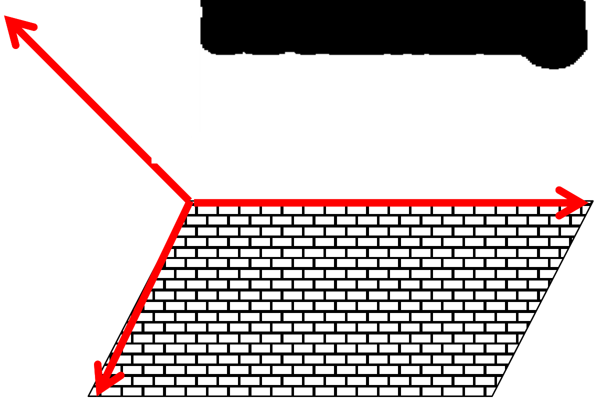
$$\sigma^{DY} = \begin{cases} \sigma_{SM}^{DY} & if\ \sqrt{\hat{s}} < \Lambda_3 \\ \sigma_{SM}^{DY}\left(\dfrac{\Lambda_3}{\sqrt{\hat{s}}}\right) & if\ \sqrt{\hat{s}} > \Lambda_3 \end{cases}$$

Limits from Tevatron data $\Lambda_3 > 800$ 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

[redacted]



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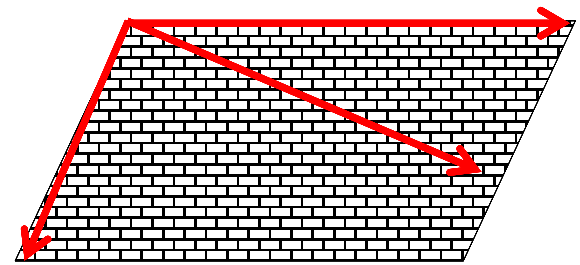
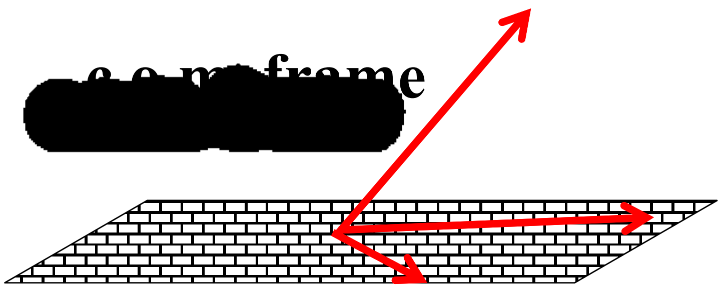


Thus, outgoing partons must be in the same plane in the c.o.m. frame of the collision, thus drastically different from the 3d scattering

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

[redacted]



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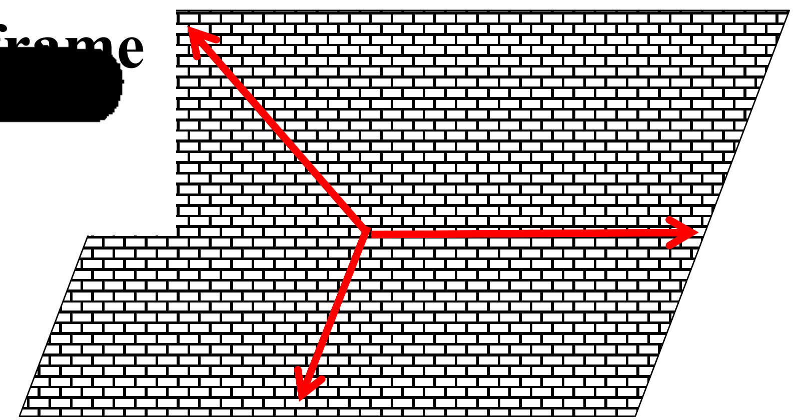
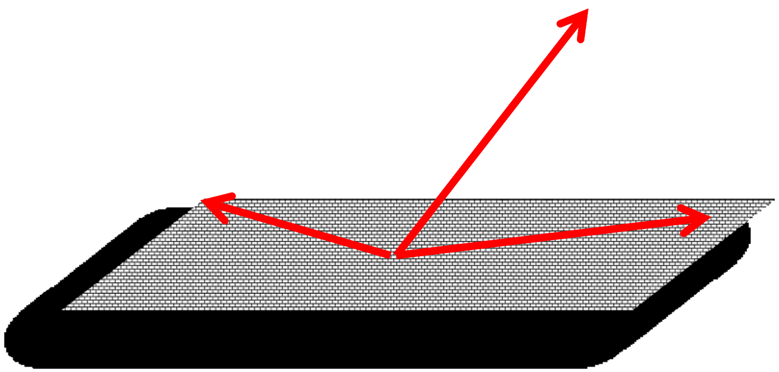


Any three vectors originating from the common point and conserving overall zero momentum will be co-planar even in 3d

[redacted]

Planar multijet events

[redacted]



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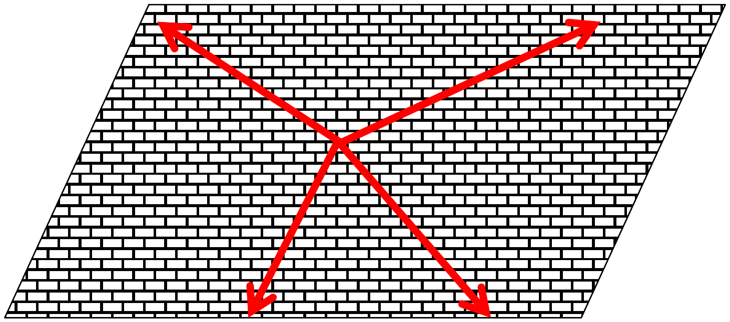
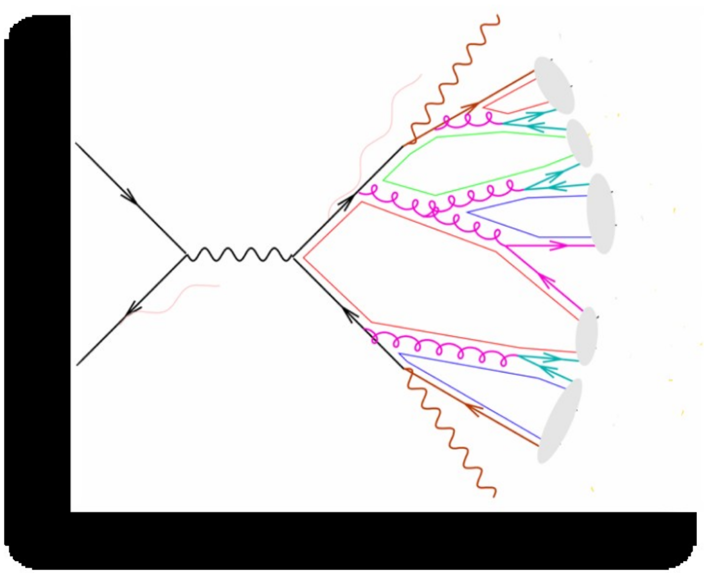


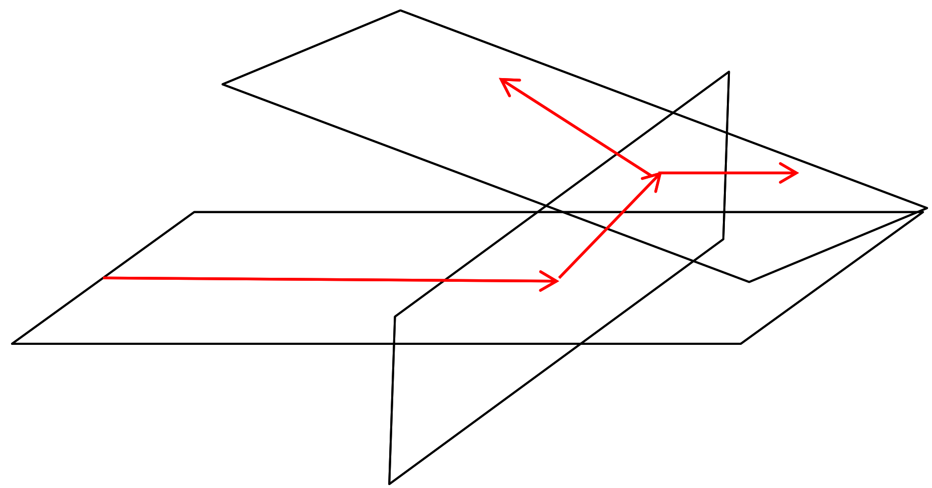
Need 4-jets for acoplanar events in 3d

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

Elliptic Jets

- If the lattice orientation is preserved over distances Λ^{-1}_{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)

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 $f_0 = f_* \, a(t)/a(t_0)$

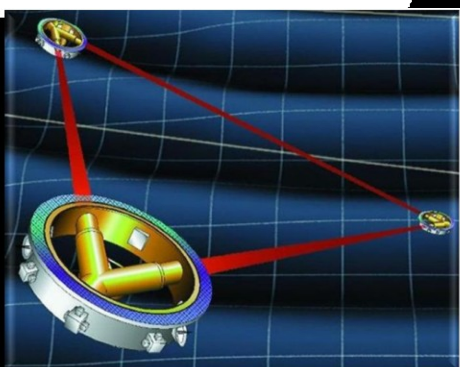
$$f_* \approx H_*^{-1} \qquad H_* \approx \frac{8\pi^3 g_* T_*^4}{90 M_{Pl}^2}$$

$$f_0 \approx 1.67\times10^{-4}\left(\frac{T_*}{TeV}\right)\mathrm{Hz}$$

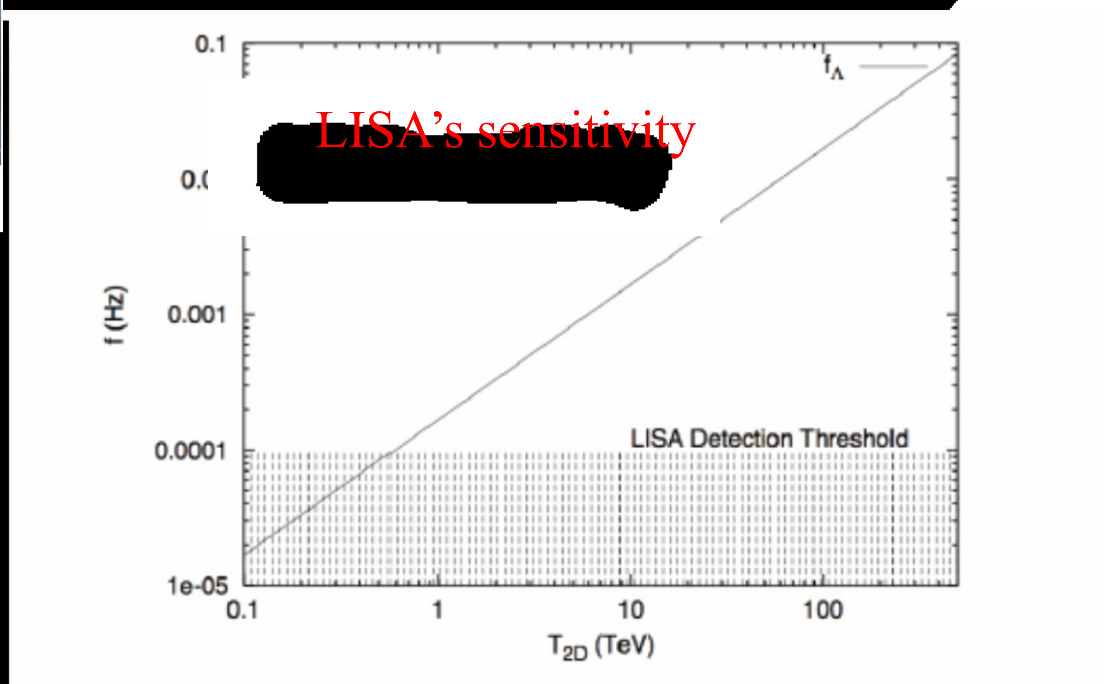
Today's frequency of primordial gravity waves created at $T=T_*$

Gravity waves signature

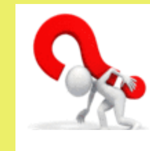
LISA should be able to see a cut-off in GW frequency



$$f_0 \approx 1.67\times10^{-4}\left(\frac{T_*}{TeV}\right)\text{Hz}$$



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 - Lagrang

THANK YOU