Add extra dimensions (make model more complicated: introduce new fields, structures, degrees of freedom, etc.)

Hope problems go away without introducing new problems.
Proposal of Emergent Dimensions

At the fundamental scales, space becomes lower dimensional.

At less fundamental scales, the dimensionality of space increases.

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

On intermediate scales ($\text{TeV}^{-1} < L < \text{Gpc}$) space is 3D.

On very large scales ($\text{Gpc} < L$) space is higher dimensional.
Outline

• Examples
• Benefits
• Propagation
• Exper. Sigs.
Example

A house of cards is a 3D object, but looking closely reveals that it is made of 2D pieces.
Another Example (From Nature)

Graphene

$L_2$

$L_1$

$L_3$
Big Benefits at Small Scales?

Why would we want fewer dimensions at higher energies?
The Hierarchy Problem

Gauge boson corrections to the Higgs mass:

3D: \[ \frac{g^2}{4} \int_0^\Lambda \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_w^2} \approx \Lambda^2 \frac{g^2}{64\pi^2} \]

2D: \[ \frac{g^2}{4} \int_0^\Lambda \frac{d^3k}{(2\pi)^3} \frac{1}{k^2 - m_w^2} \approx \Lambda \frac{g^2}{8\pi^2} \]

1D: \[ \frac{g^2}{4} \int_0^\Lambda \frac{d^2k}{2\pi} \frac{1}{k^2 - m_w^2} \approx \text{Log} \left( \frac{\Lambda}{m_w} \right) \frac{g^2}{8\pi} \]
Black Holes

In 2+1 D the vacuum solutions of Einstein’s Equations are locally flat

No singularities in 2+1 D

As 3+1D black holes evaporate, they eventually will become 2+1 D and stop being black holes.

No information loss paradox
The problem of nonrenormalizability goes away.

\[ \frac{1}{2} (\partial \phi)^2 - \frac{\lambda}{4!} \phi^4 - \frac{\mu^2}{2} \phi^2 \]

\[ - \frac{1}{6!} \frac{\lambda^2}{m^2} \phi^6 \ldots \]
Benefits?

What do we gain by having more dimensions at large scales?
In 4+1 D, a 3+1 D homogenous and isotropic solution

\[
d s^2 = d t^2 - e^{2 \sqrt{\Lambda/3} t} \left( d r^2 + r^2 d \Omega^2 \right) - d \psi^2
\]

\[
\Lambda = 3/\Psi^2 \quad \text{position dependent cosmological constant}
\]

Vacuum solution to a 3+1 observer \(( G_{MN} = 0 )\)

\[
\rho = (10^{-3} eV)^4 \rightarrow \psi \approx 10^{60} M_{Pl}^{-1} \approx \text{horizon size}
\]

Other large scale puzzles may just be excitations of the lattice.

- Bulk Flow
- Axis of Evil
- Low Power on Large Scales
Between two points there are many possible paths. The lattice determines all possible paths.

Continuous

Discrete

The lattice determines all possible paths.
Geometry of the 2+1 D lattice

- Avoids preferred direction in space
- Avoids systematic violations of Lorentz invariance
- A ‘preferred’ reference system may exist: (the lattice rest frame) (CMB rest frame)
At high energies particles will begin to travel through the lower dimensional spacetime. ($\lambda < \text{Typical lattice scale (TeV}^{-1})$)

**Alignment of high energy secondary particles observed from cosmic rays.**

- **Pamir mountains**
  - 6 out of 14 events
  - $E > 700$ TeV
  - 2 Very Linear Events
    - STRATANA
    - JF2af2
    - $E > 1000$ TeV

- **Mt. Kanbala**
  - 3 out of 6 events
  - $E > 700$ TeV
  - Low Energy Showers
    - No alignment
    - $E < 200$ TeV

Experimental Signatures?

What if the observations of alignment of cosmic ray showers are real?
Experimental Signatures?

In the CM frame, 3 jet events are always coplanar (both 3D and 2D). 4 jet events do not need to be coplanar to conserve momentum in 3D.

Coplanar 4 jet events $\rightarrow$ very strong 2D signature

Other Signatures

• Scattering cross sections will change when $\lambda < L_{2\rightarrow3}$ (reduced phase space)

• High energy jets become elliptical in shape (start out planar than expand spherically)

• Higher order processes at high energies become planar
Experimental Signatures?

In 2+1 D there are no local gravitational degrees of freedom.

- No gravitons
- No gravity waves in 2+1 D

Above the cutoff frequency where space transitions from 3D → 2D, no gravity waves

LISA should see a cutoff above a certain GW frequency

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

Frequency of primordial gravity waves redshifted to today
CONCLUSIONS

Many problems have accumulated.

Reducing (increasing) the dimensionality of space at small (large) causes many of these problems to disappear.

Clear, model independent observation signatures

Work still to be done

Fundamental Model: Lagrangian Inflation
...etc.
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 $E_\ast \geq M_{Pl}$.
- Only one event observed
- Physics of the source poorly understood
- Their conclusion ($E_* \geq M_{Pl}$) is valid only if linear corrections exist
- Both photons $E < \text{TeV}$ (3 and 30 GeV)
- 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
Two different reference frames.

Poison Randomization
Which frame created the sprinkling?
If $\lambda_{2\rightarrow 3} < L_3$ the particle will propagate locally in 2D (instead of in 3D).

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

Particle remembers its group velocity through quantum interference of several paths.