Unification? It's Only a Matter of Time

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Rutherford Appleton Lab, PPD Seminar

The Nature of Unification

1 Simple, Unique, Minimal Assumptions for some
basic Entity, Concept and/or Maths Structure
as Foundation for…

2 Standard Model: Multiplet Structure of Leptons and Quarks under
Lorentz x Gauge symmetries, with masses and couplings
[Understand Higgs and Neutrino Sectors]

3 Quantum + Gravity: Framework uniformly valid on ALL scales
Amalgamating Quantum Theory with General Relativity
[Measurement Problem…, Black Hole Singularities]

4 Cosmology: Large Scale Observations associated with
Dark Matter, Dark Energy and Early Universe
[Modifications to ΛCDM to address tensions]

5 Big picture, 'Before the Big Bang', Origins in General

Outline

1 Simple, Unique, Minimal Assumptions:

Time, rather than Matter or Space, as the Basic Entity in the Mathematical Form of 'Generalised Proper Time'

2 Standard Model:

Direct Link with Groups E_6 and E_7 and SM-like multiplet properties, and connections with the Higgs and Neutrino Sectors

3 Quantum + Gravity:

Construction of 4D spacetime from local temporal elements as basis for 'Quantum Gravity' addressing known issues

4 Cosmology:

Candidates for Dark Matter and Dark Energy, with differences from ΛCDM, and Early Universe Structure Formation

5 Big picture, 'Before the Big Bang':

'Origins of Time'?... Summary

Historical Run-up: Relations between Space, Time and Matter

Classical Physics

Absolute Time: x^0

3D Space: $x^1, \; x^2, \; x^3$

Matter: particles

Special Relativity

Proper Time — 4D Spacetime

$$(\Delta s)^2 = (\Delta x^0)^2 - (\Delta x^1)^2 - (\Delta x^2)^2 - (\Delta x^3)^2$$

Matter: particles, fields

Lorentz Symmetry

General Relativity

Local Proper Time — 4D Spacetime

$$(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2$$

Matter: particles, fields

Extra Space Dimensions

Augmented *n*D Spacetime form — Matter

$$(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2 - (\delta x^4)^2 \ldots$$

Symmetry $\mathrm{SO}^+(1, n-1) \supset$ Lorentz

Generalised Proper Time

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$$

$p = 2,3,4,\ldots \quad \alpha_{abc\ldots} = -1,0,1$

$a, b, c \ldots$ sum over 0 to $n-1$

$$(\delta s)^2 = \tilde{\eta}_{ab}\delta x^a \delta x^b \quad a, b, \text{sum over 0 to } n-1$$

$$\tilde{\eta}_{ab} = \begin{pmatrix} +1 & 0 & 0 & 0 & 0 & \cdots \\ 0 & -1 & 0 & 0 & 0 & \cdots \\ 0 & 0 & -1 & 0 & 0 & \cdots \\ 0 & 0 & 0 & -1 & 0 & \cdots \\ 0 & 0 & 0 & 0 & -1 & \ddots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots \end{pmatrix}$$

Historical Run-up: Relations between Space, Time and Matter

Classical Physics

Absolute Time x^0 — 3D Space x^1, x^2, x^3 — Matter: particles

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Proper Time — 4D Spacetime — Matter: particles, fields

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Local Proper Time — 4D Spacetime — Matter: particles, fields

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Symmetry $\mathrm{SO}^+(1, n-1) \supset$ Lorentz

Generalised Proper Time

Basis for 4D Spacetime — Basis for Matter

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots = \left(\eta_{ab}\delta x^a \delta x^b\right) \times (\delta x \ldots)^{p-2} + (\delta x \ldots)^p$$

Symmetry $\hat{G} \supset$ Lorentz $\times$ Gauge

External x Internal Symmetry for Physics

Historical Run-up: Relations between Space, Time and Matter

Classical Physics

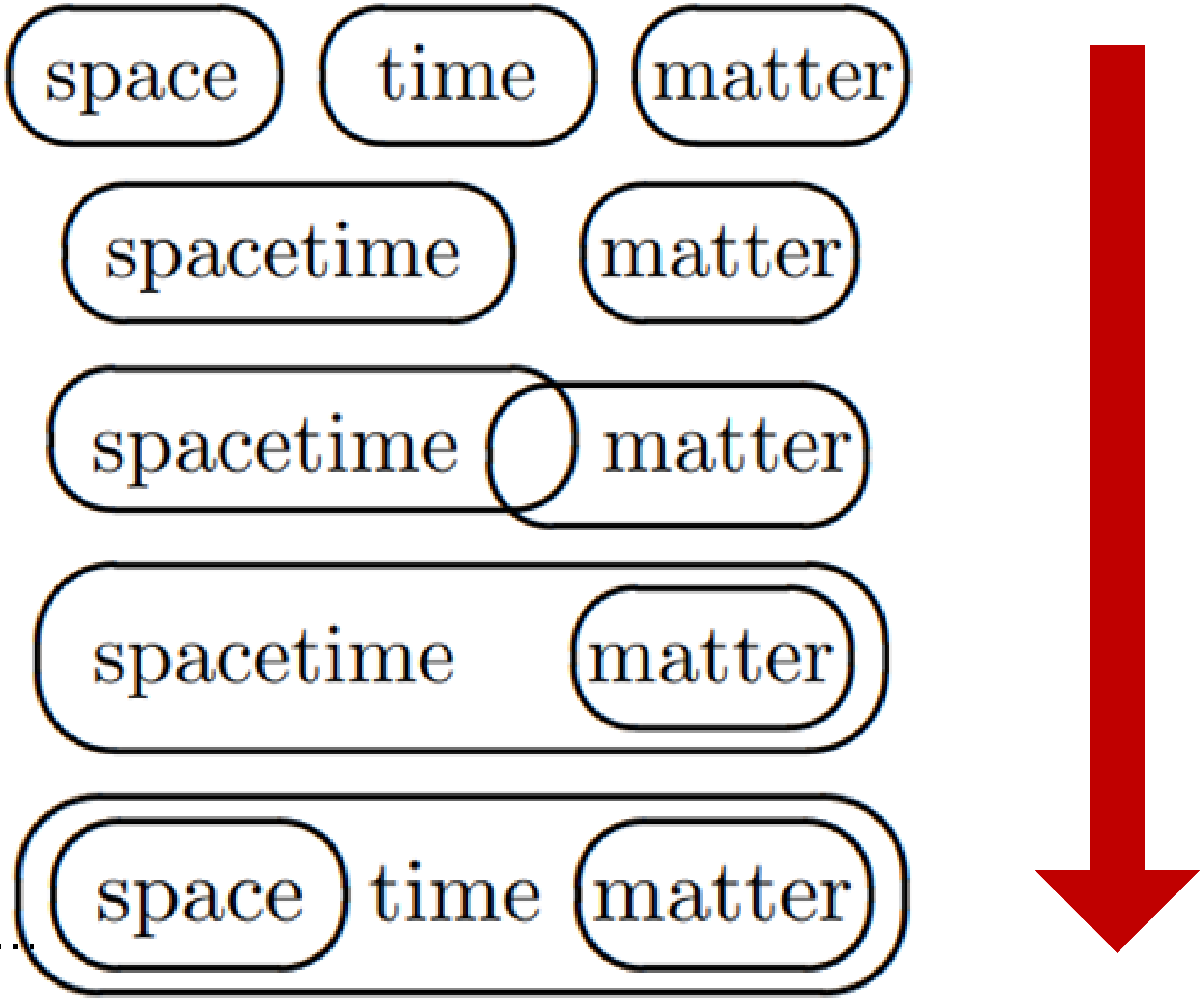
Special Relativity

General Relativity

Extra Space Dimensions

Generalised Proper Time

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$



Generalised proper time is a natural further step along this trajectory

Re-examine basic motivation: cf. ESD do not need a quadratic form for matter!

Basis in time is: simpler, more unique, more unifying, more conservative, more direct

Represents the simplest possible unifying relation between Space, Time, Matter

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

from:

Write as determinant of a complex 2x2 Hermitian matrix $\boldsymbol{\delta x}_4 \in \mathrm{h}_2\mathbb{C}$:

$$(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2 = \det\begin{pmatrix} \delta x^0 + \delta x^3 & \delta x^1 - \delta x^2 i \\ \delta x^1 + \delta x^2 i & \delta x^0 - \delta x^3 \end{pmatrix} = \det(\boldsymbol{\delta x}_4)$$

with Lorentz group $\mathrm{SO}^+(1,3) \rightarrow \mathrm{SL}(2,\mathbb{C})$ symmetry

$2 \times 2 \rightarrow 3 \times 3$ matrix

Extend to determinant of a 3x3 matrix $\boldsymbol{\delta x}_9 \in \mathrm{h}_3\mathbb{C}$:

$$(\delta s)^3 = \det\left(\begin{array}{cc|c} \delta x^0 + \delta x^3 & \delta x^1 - \delta x^2 i & \delta x^4 + \delta x^5 i \\ \delta x^1 + \delta x^2 i & \delta x^0 - \delta x^3 & \delta x^6 + \delta x^7 i \\ \hline \delta x^4 - \delta x^5 i & \delta x^6 - \delta x^7 i & \delta x^8 \end{array}\right) = \det(\boldsymbol{\delta x}_9)$$

with symmetry $\mathrm{SL}(3,\mathbb{C})$

$$= \det\begin{pmatrix} \delta x^0 + \delta x^3 & \delta x^1 - \delta x^2 i \\ \delta x^1 + \delta x^2 i & \delta x^0 - \delta x^3 \end{pmatrix} \delta x^8 + (\delta x \ldots)^3$$

As an example of:

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots = \left(\eta_{ab}\delta x^a \delta x^b\right) \times (\delta x \ldots)^{p-2} + (\delta x \ldots)^p$$

generalised proper time — nD form, $\hat{G}$ sym.

basis for 4D spacetime

basis for matter

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

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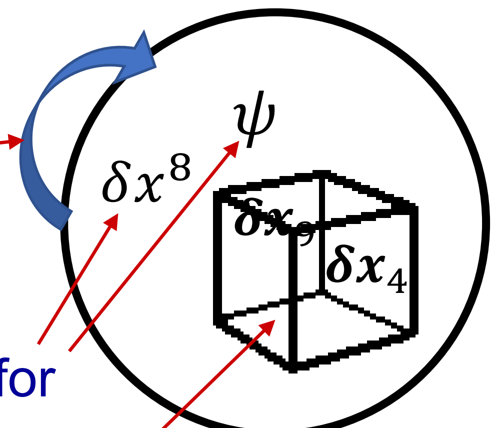
with symmetry ~~$\mathrm{SL}(3,\mathbb{C})$~~

$$(\delta s)^3 = \det\left(\begin{array}{c|c} \boldsymbol{\delta x}_4 & \psi \\ \hline \psi^\dagger & \delta x^8 \end{array}\right)$$



external × internal

'Small piece of the SM'

$\mathrm{SL}(3,\mathbb{C}) \rightarrow \mathrm{SL}(2,\mathbb{C}) \times \mathrm{U}(1)$

Original 9 components $\boldsymbol{\delta x}_9 \in \mathrm{h}_3\mathbb{C}$ →

4	ψ	Weyl spinor	1
1	δx^8	scalar	0
4	$\boldsymbol{\delta x}_4$	vector	0

Basis for matter

Symmetry broken on extracting 4D spacetime part $\boldsymbol{\delta x}_4 \in \mathrm{h}_2\mathbb{C}$

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

Write as determinant of a complex 2x2 Hermitian matrix $\boldsymbol{\delta x}_4 \in h_2\mathbb{C}$:

from:

$$(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2 = \det\begin{pmatrix} \delta x^0 + \delta x^3 & \delta x^1 - \delta x^2 i \\ \delta x^1 + \delta x^2 i & \delta x^0 - \delta x^3 \end{pmatrix} = \det(\boldsymbol{\delta x}_4)$$

with Lorentz group $SO^+(1,3) \rightarrow SL(2,\mathbb{C})$ symmetry

$2\times 2 \rightarrow 3\times 3$ matrix

Extend to determinant of a 3x3 matrix $\boldsymbol{\delta x}_9 \in h_3\mathbb{C}$:

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with symmetry $SL(3,\mathbb{C})$

$(\delta s)^3 = \det(\boldsymbol{\delta x}_{27})$ 27D cubic with $E_6 \equiv SL(3,\mathbb{O})$ on $\boldsymbol{\delta x}_{27} \in h_3\mathbb{O}$

$\mathbb{C} \rightarrow \mathbb{O}$ algebra

The Octonions $\mathbb{O}$ are generalisation of the complex numbers $\mathbb{C}$ with 7 imaginary units

Octonion: $a = a_1 + a_2\, i + a_3\, j + a_4\, k + a_5\, kl + a_6\, jl + a_7\, il + a_8\, l$

Real norm: $|a|$ defined by: $|a|^2 = a\bar{a}$ and inverse: $a^{-1} = \frac{\bar{a}}{|a|^2}$ for any $a \in \mathbb{O}$

with: $|ab| = |a||b|$ for any $a, b \in \mathbb{O}$ $\Rightarrow$ describe symmetry transformations

however: $(ab)c \neq a(bc)$ for many $a, b, c \in \mathbb{O}$ $\Rightarrow$ non−associative algebra

Can still construct $SL(3,\mathbb{O})$ actions on $h_3\mathbb{O}$ (with $(\delta s)^3 = \det(\boldsymbol{\delta x}_{27})$ invariant)

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

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with symmetry $\mathrm{SL}(3,\mathbb{C})$

$\mathbb{C} \rightarrow \mathbb{O}$ algebra

$(\delta s)^3 = \det(\boldsymbol{\delta x}_{27})$ 27D cubic with $\mathrm{E}_6 \equiv \mathrm{SL}(3,\mathbb{O})$ on $\boldsymbol{\delta x}_{27} \in \mathrm{h}_3\mathbb{O}$

$(\delta s)^4 = q(\boldsymbol{\delta x}_{56})$ 56D quartic form with E_7 on $\boldsymbol{\delta x}_{56} \in F(\mathrm{h}_3\mathbb{O})$

Freudenthal triple system

Generalised proper time, directly connects with Exceptional Lie Groups

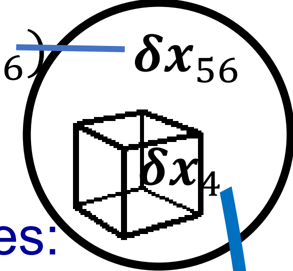
Since 1970s: 'Grand Unified Theory', for internal gauge symmetry only

Sequence of unifying groups: $\mathrm{SU}(5) \subset \mathrm{SO}(10) \subset \mathrm{E}_6 \subset \mathrm{E}_7 \subset \mathrm{E}_8$

(largest exceptional Lie group)

Well-known connections with SM structure
(as also for the Octonions $\mathbb{O}$)

For all physics in 4D spacetime full E_7 symmetry of $(\delta s)^4 = q(\boldsymbol{\delta x}_{56})$ broken to external × internal form:



56 \ $\mathrm{E}_7 \supset$	$\mathrm{SL}(2,\mathbb{C})$ Lorentz	× $\mathrm{SU}(3)_c$	× $\mathrm{U}(1)_Q$	matter
4	vector	**1**	0	'ν_L'
8	Dirac	**1**	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	scalar	**3**	$\frac{2}{3}$	$\begin{pmatrix} `u_L\text{'} \\ `u_R\text{'} \end{pmatrix}$
24	Dirac	**3**	$\frac{1}{3}$	$\begin{pmatrix} d_L \\ d_R \end{pmatrix}$
4	vector	**1**	0	'Higgs' $\boldsymbol{\delta x}_4$
4	scalar	**1**	0	Yukawa

Rich in SM properties:

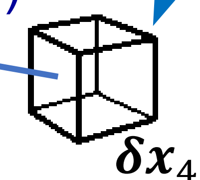
Lorentz spinor structures

Colour $\mathrm{SU}(3)_c$ singlets and triplets

Electromagnetic $\mathrm{U}(1)_Q$ fractional charges

elements of Electroweak theory (incl. L-R asym.)

$$h^2(x) = \frac{\eta_{ab}\delta x^a \delta x^b}{(\delta s)^2}$$



Norm ~ SM scalar Higgs

While incomplete, and with discrepancies seen as underlined, uncover significant structures of SM, far more directly and closely to than with ESD, and little redundancy.

If treat as GUT (drop Lorentz factor):

$$\mathrm{E}_7 \supset \mathrm{SU}(3)_c \times \text{`}\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y\text{'}$$

breaks to the above…

$$\mathrm{E}_7 \supset \mathrm{SU}(3)_c \times \mathrm{U}(1)_Q$$

…by action on $\boldsymbol{\delta x}_4$ 'Higgs'

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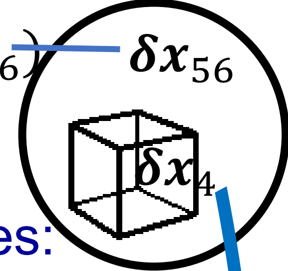

$56 \backslash \mathrm{E}_7 \supset$	Lorentz ×	$\mathrm{SU}(3)_c$ ×	$\mathrm{U}(1)_Q$	matter
4	vector	$\mathbf{1}$	0	'ν_L'
8	Dirac	$\mathbf{1}$	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	scalar	$\mathbf{3}$	$\frac{2}{3}$	$\begin{pmatrix} \text{'}u_L\text{'} \\ \text{'}u_R\text{'} \end{pmatrix}$
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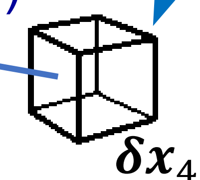

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Still needed:
- u,v as spinors
- full electroweak theory
- three generations

Propose: E_8 on $(\delta s)^{p>4} = Q(\boldsymbol{\delta x}_{248})$ octonionic construction, for full SM

Three comments on the status of Standard Model identification:

1) The E_7 stage does not give exactly one SM generation

No such thing as a single pristine isolated 'generation of the Standard Model' in nature. Significant mismatch between weak / mass eigenstate, in both quark and lepton sectors, as associated with mixing between the three generations of the SM, which is 'one thing'. Extracting something from full E_8, expect a bit ragged at the edges (as for E_6 and E_7)

2) Known that E_8 does not quite work for SM

Standard breaking 248 rep. $E_8 \supset$ Lorentz x SU(3) x SU(2) x U(1) does NOT give SM.

Standard analysis of Lie Groups E_6, E_7, E_8 built upon 4 group theory axioms:

- Closure: $g_1 \cdot g_2 \in G$ for all $g_1, g_2 \in G$
- Identity: $e \cdot g_1 = g_1$ for all $g_1 \in G$
- Inverse: $g_1^{-1} \cdot g_1 = e$ for all $g_1 \in G$
- Associativity: $(g_1 \cdot g_2) \cdot g_3 = g_1 \cdot (g_2 \cdot g_3)$ for all $g_1, g_2, g_3 \in G$

Here symmetry, for GPT, more fundamental than standard group structure and axioms In particular can describe symmetries based on octonions which are non-associative.

that is: $(ab)c \neq a(bc)$ for many $a, b, c \in \mathbb{O}$ $\Rightarrow$ non−associative algebra

Lie groups and representations based on $\mathbb{C}$ maths. $\mathbb{O}$ can give non-standard reps.

3) Coleman-Mandula Theorem?

Symmetry for All Physics is Lorentz x Gauge

Is the theory predictive?

First prediction of the theory is that an '$\mathbb{O}$ -based E_8' symmetry of GPT should exist, a 'mathematical puzzle' to complete the three generation SM multiplet structure

DJJ, `Time, E_8, and the Standard Model', arXiv:1709.03877

For Beyond-SM physics will likely need $E_6 \rightarrow E_7 \rightarrow E_8$ symmetry on full form of GPT

Possibility of new gauge symmetry or states identified in full symmetry breaking.

Already for E_7 have basis for L-R asymmetry, as particularly marked in neutrino sector:

E_6 on $(\delta s)^3 = \det(\boldsymbol{\delta x}_{27})$ — $\nu \equiv \boldsymbol{h}$ — 4D spacetime external $\boldsymbol{\delta x}_4$ — 27 representation

E_7 on $(\delta s)^4 = q(\boldsymbol{\delta x}_{56})$ — ν — $\boldsymbol{h}$ — 27 and $\overline{27}$ (L and R)

E_8 on $(\delta s)^8 = Q(\boldsymbol{\delta x}_{248})$ — $\nu_L \quad \nu_L \quad \nu_L$ — $\boldsymbol{h} \quad \nu_R \quad \nu_R$ — $\sim$ '(27 and $\overline{27}$) $\times$ 3' ?

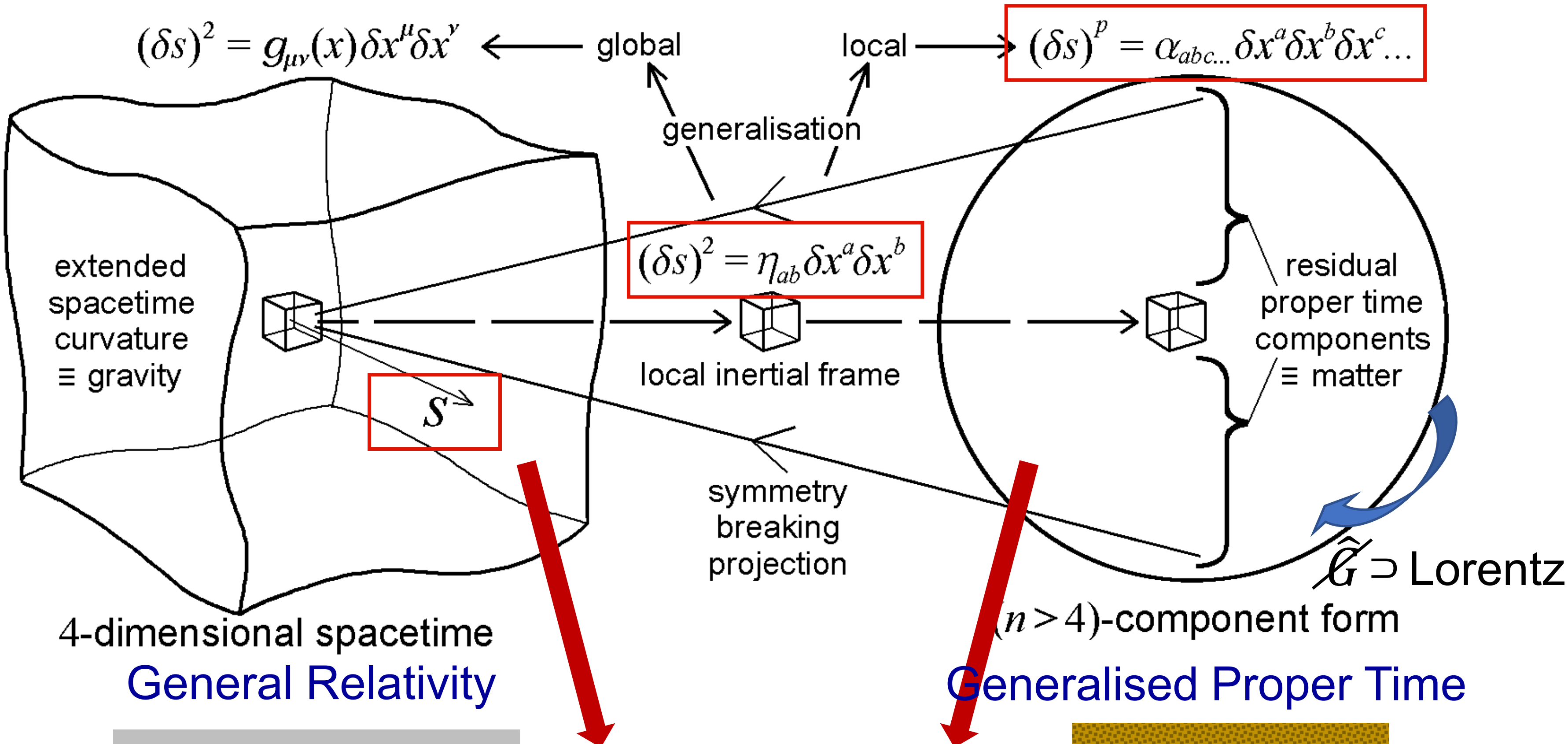
Strong hint that 'Higgs' $\boldsymbol{\delta x}_4$ may be a composite of 'right-handed neutrino' components.

Accounting for the very different empirical properties of left and right-handed neutrinos

DJJ, 'GPT as a Unifying Basis for Models with Two Right-Handed Neutrinos', arXiv:1905.12419

...all of above is for local Standard Model$^+$ properties, what about Gravity?

Complementary metric generalisations, but invariance of proper time central



$$G^{\mu\nu} = -\kappa T^{\mu\nu}$$

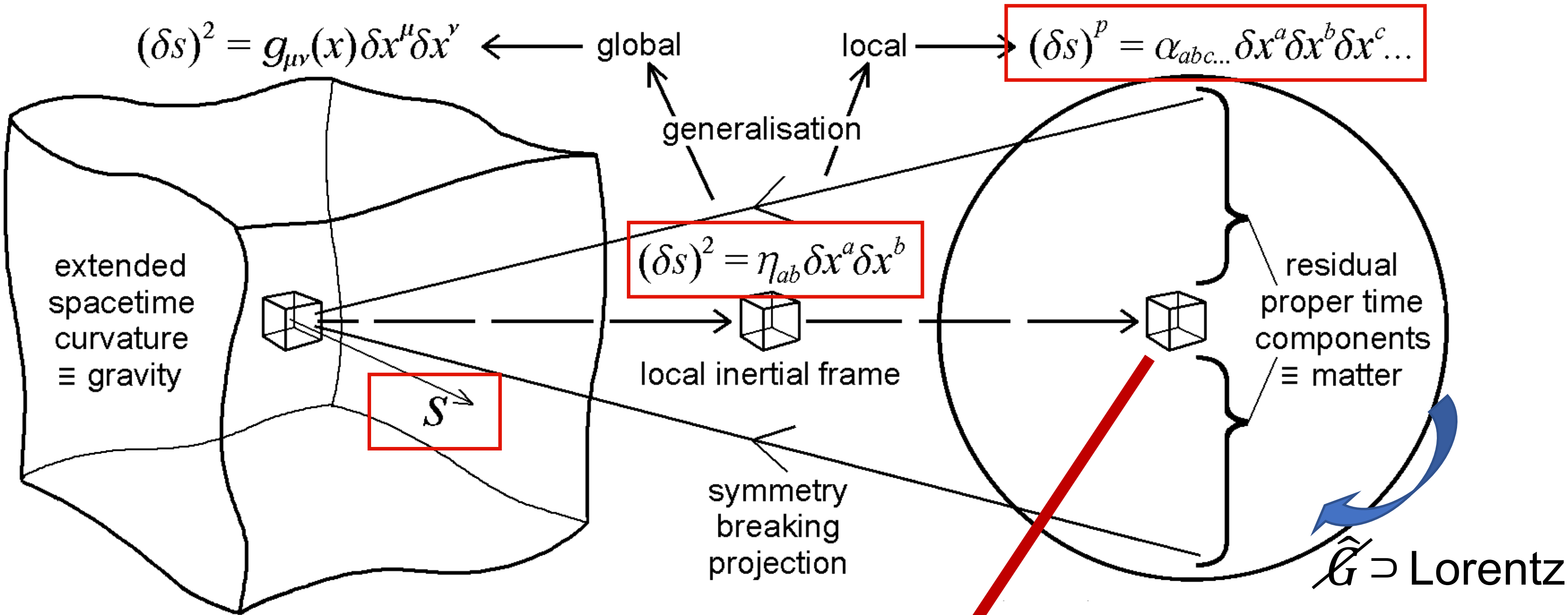
Aim of Unified Field Theory to incorporate the 'wood' into an augmented GR

Progression from 1D time s to 4D spacetime $(\delta s)^2$ to nD space-time-matter $(\delta s)^p$ form

Extend from 4D spacetime to incorporate matter, not more space,

hence can drop quadratic assumption and generalise $(n > 4$ and $p > 2)$

Complementary metric generalisations, but invariance of proper time central



$\boldsymbol{\delta x_4}$ closely connected with the Higgs in the Standard Model

effective metric function:

$$(\delta s)^2 = g_{ab}(x)\delta x^a \delta x^b$$

perturb from flat:

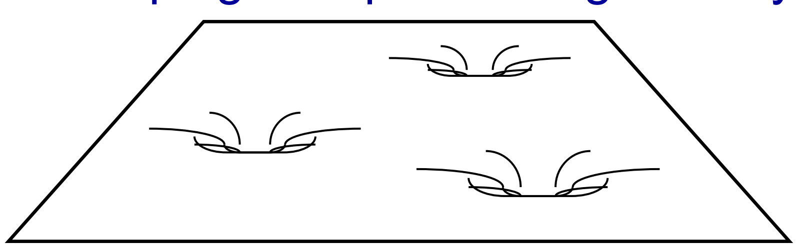
$$g_{ab}(x) = \frac{\eta_{ab}}{h^2(x)}$$

with scalar field:

$$h^2(x) = \frac{\eta_{ab}\delta x^a \delta x^b}{(\delta s)^2}$$

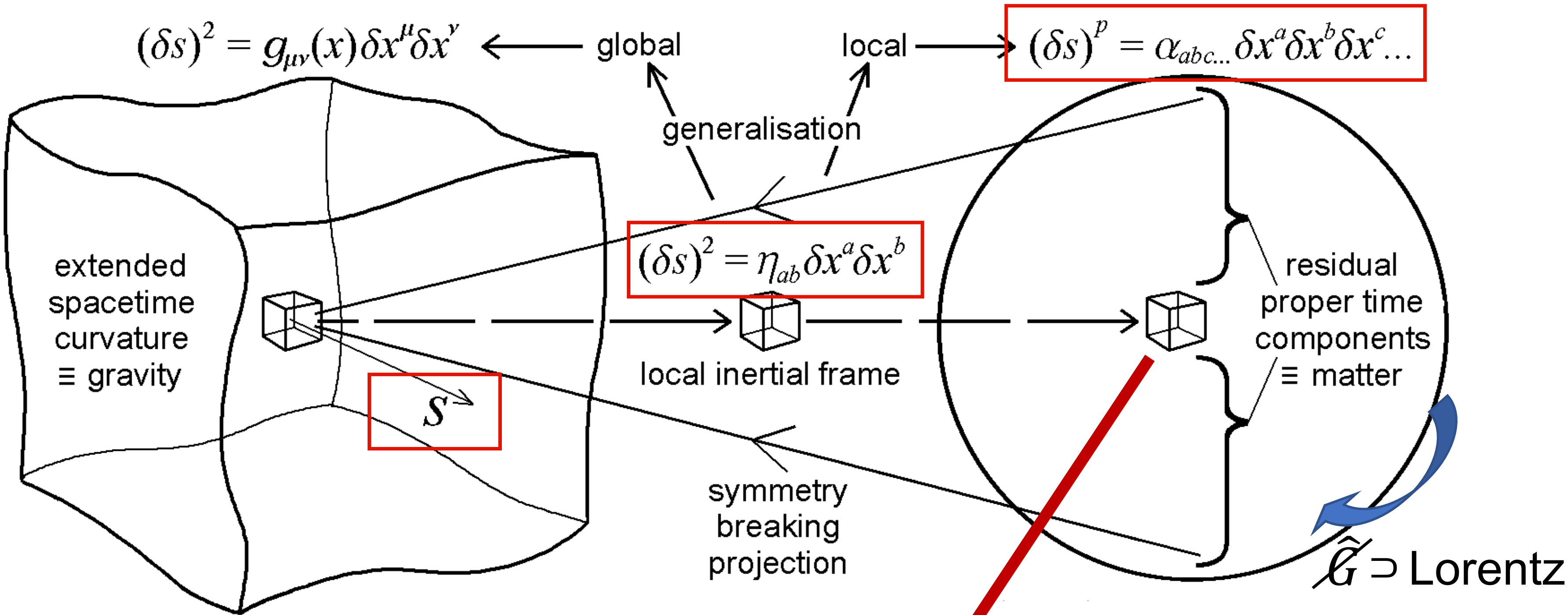
$$(\delta s)^2 = \frac{\eta_{ab}\delta x^a \delta x^b}{h^2(x)}$$

Variations in $h^2(x)$: local time dilations ≡ warping 4D spacetime geometry



project 4D spacetime part

Complementary metric generalisations, but invariance of proper time central



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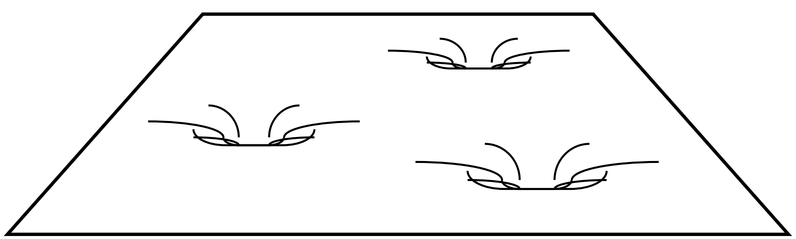


$\boldsymbol{\delta x_4}$ closely connected with the Higgs in the Standard Model

Here <u>Source</u> of mass
via Einstein field equation:

$$G^{\mu\nu} = f^{\mu\nu}(h^2) \rightarrow -\kappa T^{\mu\nu}$$

In turn fields that interact with $\boldsymbol{\delta x_4}$ will perturb geometry and gain mass

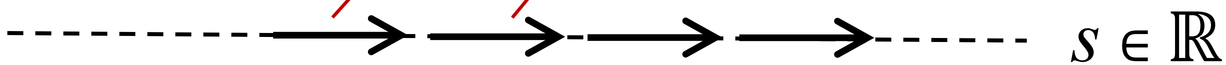
Connects mass in General Relativity with that in the Standard Model

The theory based on Generalised Proper Time fits very well with General Relativity

However, in starting with GPT, with time the basic entity, how to build GR framework?

Can express $\underline{\delta s \in \mathbb{R}}$ as: $\delta s = \delta x^1 + \delta x^2$

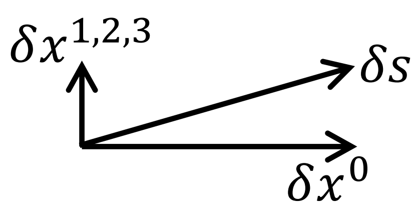
These intervals 'fit together' composing the 'real line' $\mathbb{R}$

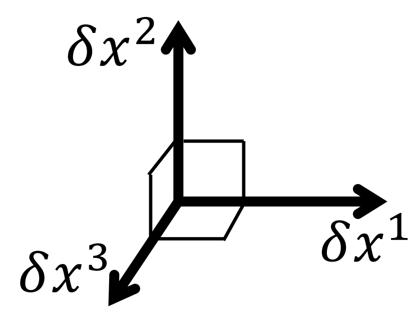


Can express $\underline{\delta s \in \mathbb{R}}$ as: $(\delta s)^2 \rightarrow (\delta x^0)^2 - \left[(\delta x^1)^2 + (\delta x^2)^2 + (\delta x^3)^2\right]$

with: $\{\delta x^0, \delta x^1, \delta x^2, \delta x^3\} \in \mathbb{R}^4$

This arithmetic substructure has an implicit geometric interpretation as form of 3D space itself





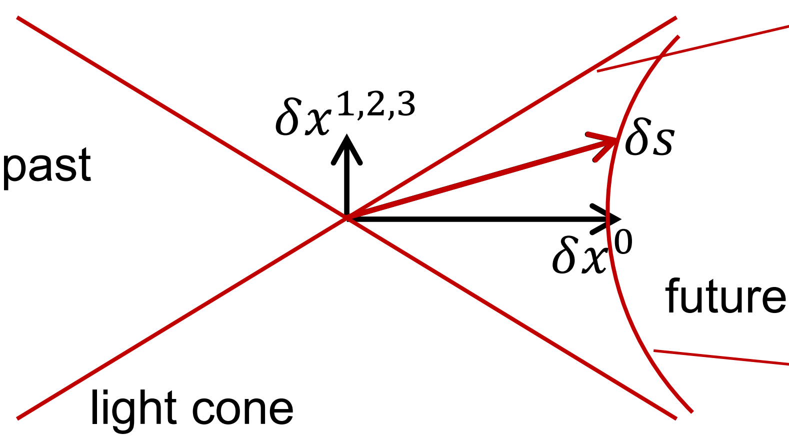
full quadratic form describes a local 4D spacetime element

Can express $\underline{\delta s \in \mathbb{R}}$ as: $\delta s = \delta x^1 + \delta x^2$

These intervals 'fit together' composing the 'real line' $\mathbb{R}$

Can express $\underline{\delta s \in \mathbb{R}}$ as: $(\delta s)^2 = (\delta x^0)^2 - \left[(\delta x^1)^2 + (\delta x^2)^2 + (\delta x^3)^2\right]$

with: $\{\delta x^0, \delta x^1, \delta x^2, \delta x^3\} \in \mathbb{R}^4$



With the $\mathrm{SO}^+(1,3)$ symmetry mapping out light cone geometry of 4D spacetime (passive coord. transformations)

And flow of time δs represented by forward light cone (active hyperbolic rotations)

full quadratic form describes a local 4D spacetime element

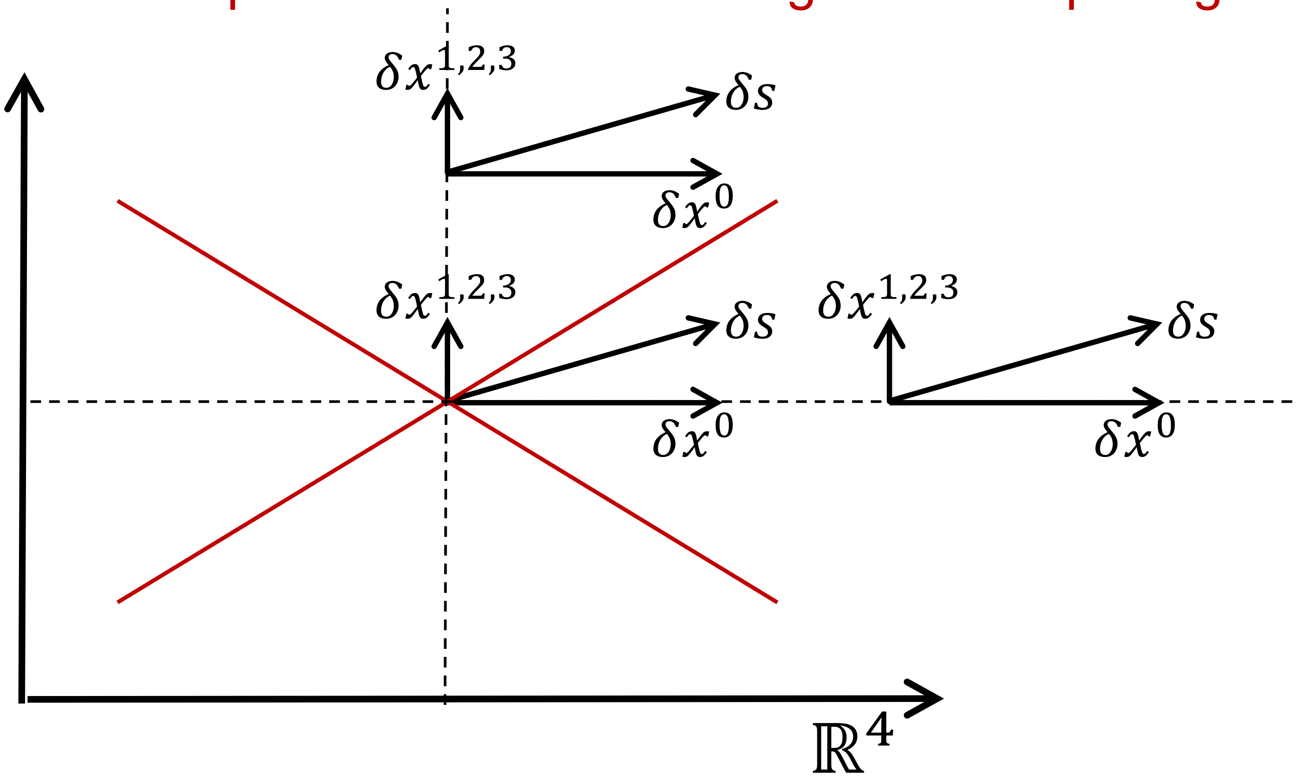
Causal order of time represented

Can express $\underline{\delta s \in \mathbb{R}}$ as: $\delta s = \delta x^1 + \delta x^2$

These intervals 'fit together' composing the 'real line' $\mathbb{R}$

Can express $\underline{\delta s \in \mathbb{R}}$ as: $(\delta s)^2 = (\delta x^0)^2 - \left[(\delta x^1)^2 + (\delta x^2)^2 + (\delta x^3)^2\right]$

These quadratic elements 'fit together' composing extended patch of $\mathbb{R}^4$:

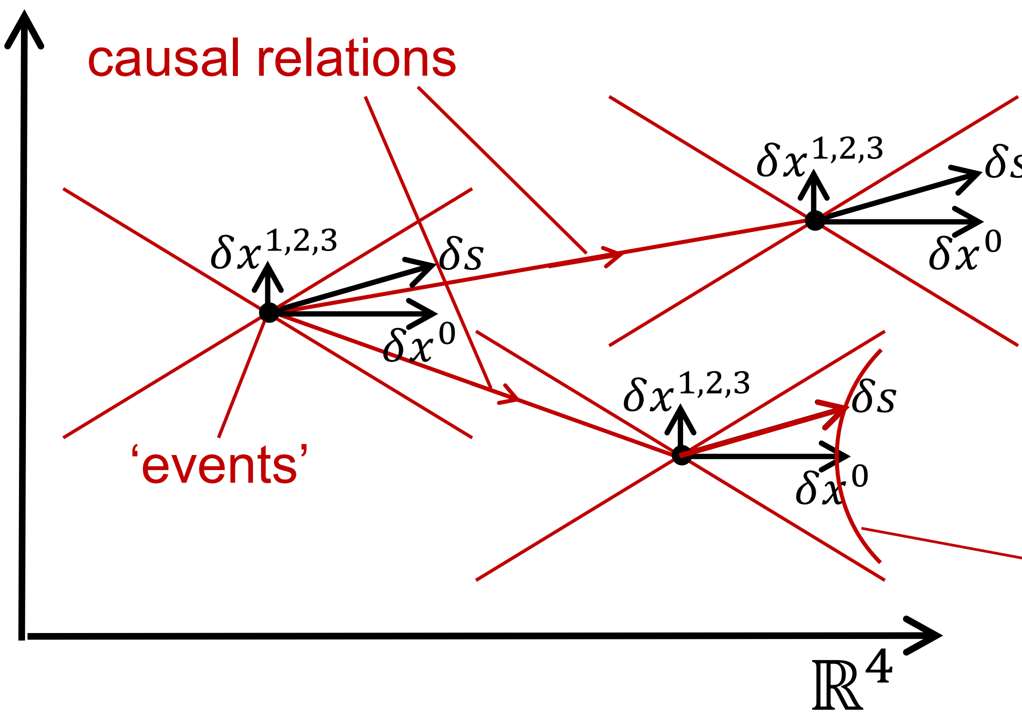


Can express $\underline{\delta s \in \mathbb{R}}$ as: $\delta s = \delta x^1 + \delta x^2$

These intervals 'fit together' composing the 'real line' $\mathbb{R}$

Can express $\underline{\delta s \in \mathbb{R}}$ as: $(\delta s)^2 = (\delta x^0)^2 - \left[(\delta x^1)^2 + (\delta x^2)^2 + (\delta x^3)^2\right]$

These quadratic elements 'fit together' composing extended patch of $\mathbb{R}^4$:



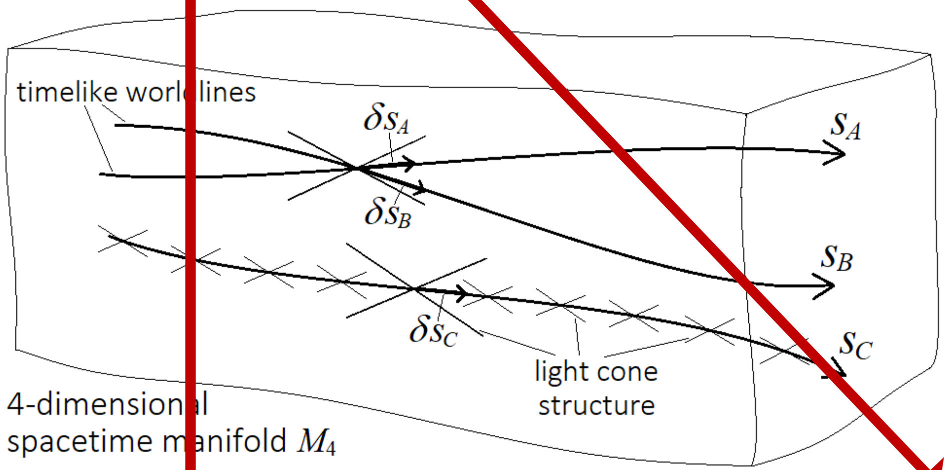
Construction taken to the spacetime continuum limit

Arithmetic substructure of time accommodates the Geometric form through which it propagates

Any trajectory with $s \in \mathbb{R}$ has above local quadratic form

Via $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2$ elements

can construct a continuous extended 4-dimensional spacetime manifold:

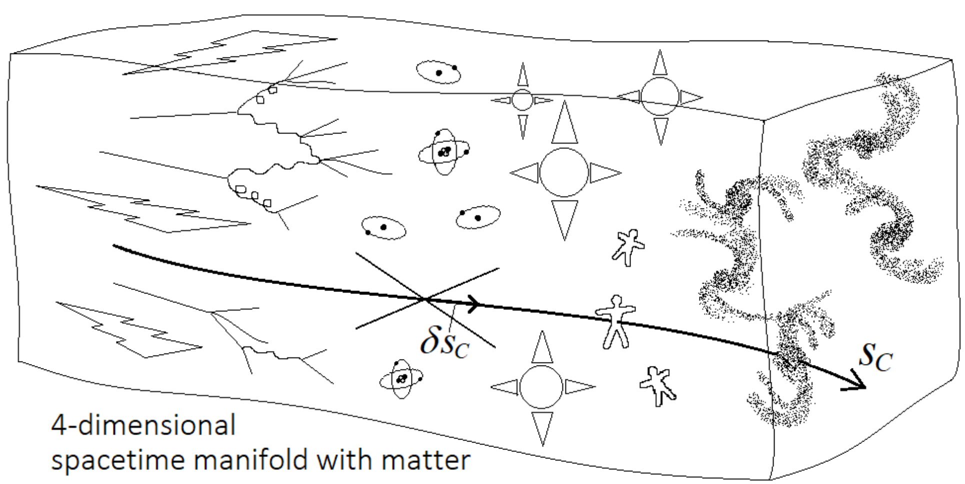


With timelike worldlines $s_A, s_B, s_C, \ldots$ passing through any location

(as elements within full temporal structure)

Via $(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$ $= \underbrace{\left(\eta_{ab}\delta x^a \delta x^b\right)} \times \underbrace{(\delta x \ldots)^{p-2} + (\delta x \ldots)^p}$

direct arithmetic generalisation of proper time, fill out matter content



Construct full 4D spacetime block containing everywhere a flow of time underlying matter evolution dynamics

With direct connection to Standard Model of PP

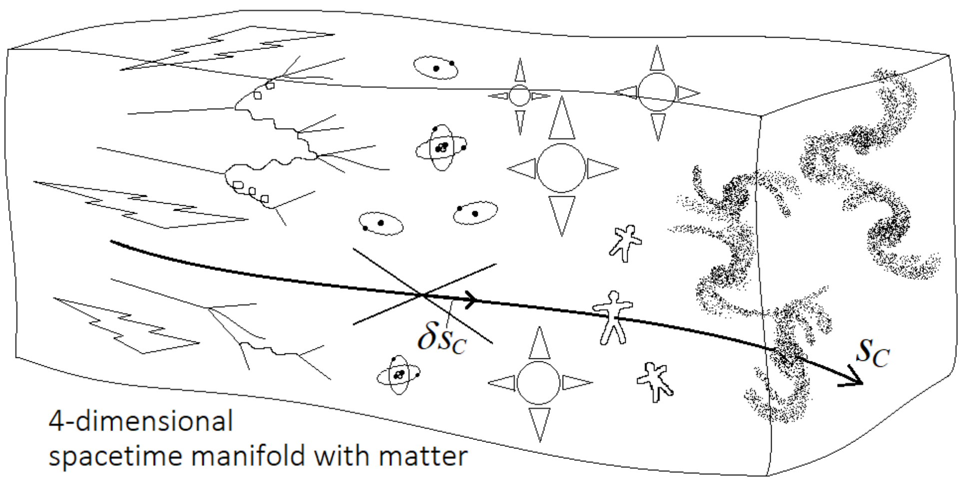
Generalised proper time as basis for 4D spacetime and its matter content

Analogy with river: fixed geological bed and banks containing everywhere a flow of water

4D block - as associated with general relativity

dynamic - as associated with quantum theory

Basis for unifying GR+QM framework

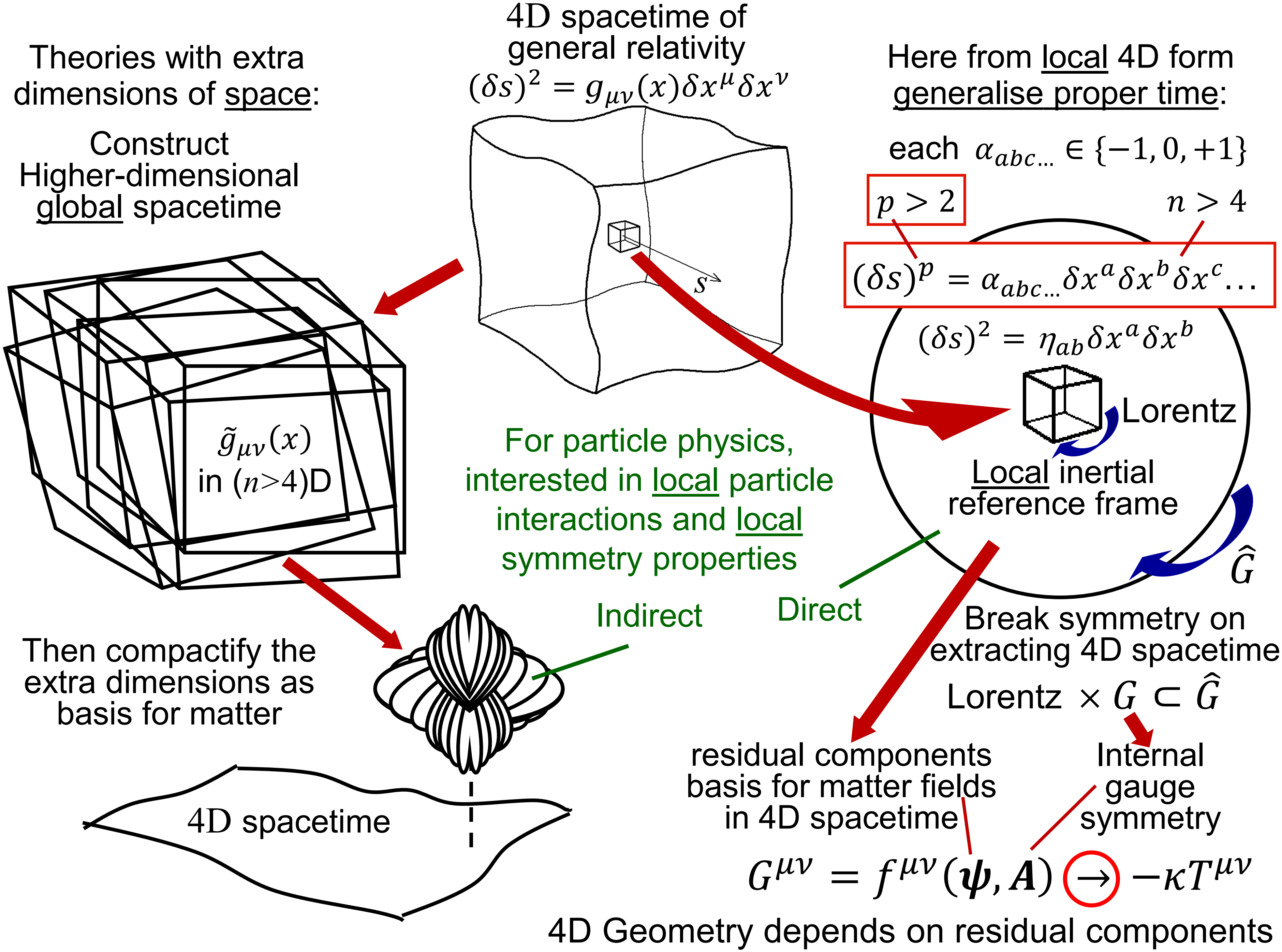


4-dimensional spacetime manifold with matter

Construct full 4D spacetime block containing everywhere a flow of time underlying matter evolution dynamics

With direct connection to Standard Model of PP

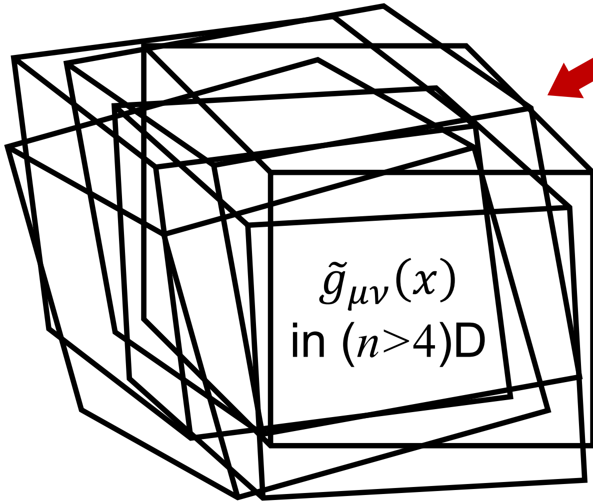
Generalised proper time as basis for 4D spacetime and its matter content



Theories with extra dimensions of space:
Construct Higher-dimensional global spacetime
4D spacetime of general relativity
$(\delta s)^2 = g_{\mu\nu}(x)\delta x^\mu \delta x^\nu$
s
Here from local 4D form generalise proper time:
each $\alpha_{abc\ldots} \in \{-1, 0, +1\}$
$p > 2$
$n > 4$
$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$
$(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$
Lorentz
Local inertial reference frame
$\hat{G}$
$\tilde{g}_{\mu\nu}(x)$ in (n>4)D
For particle physics, interested in local particle interactions and local symmetry properties
Indirect
Direct
Then compactify the extra dimensions as basis for matter
4D spacetime
Break symmetry on extracting 4D spacetime
Lorentz $\times\, G \subset \hat{G}$
residual components basis for matter fields in 4D spacetime
Internal gauge symmetry
$G^{\mu\nu} = f^{\mu\nu}(\boldsymbol{\psi}, \boldsymbol{A}) \rightarrow -\kappa T^{\mu\nu}$
4D Geometry depends on residual components

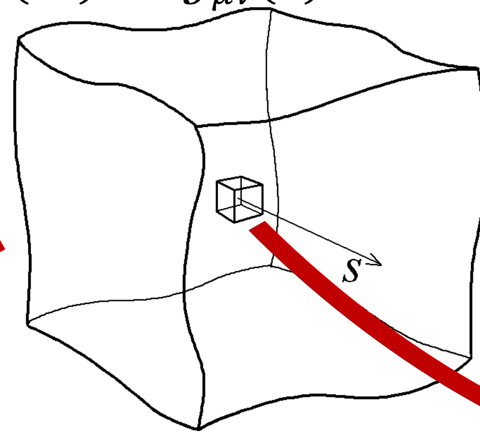
Theories with extra dimensions of <u>space</u>:

Construct Higher-dimensional <u>global</u> spacetime



4D spacetime of general relativity

$$(\delta s)^2 = g_{\mu\nu}(x)\delta x^\mu \delta x^\nu$$



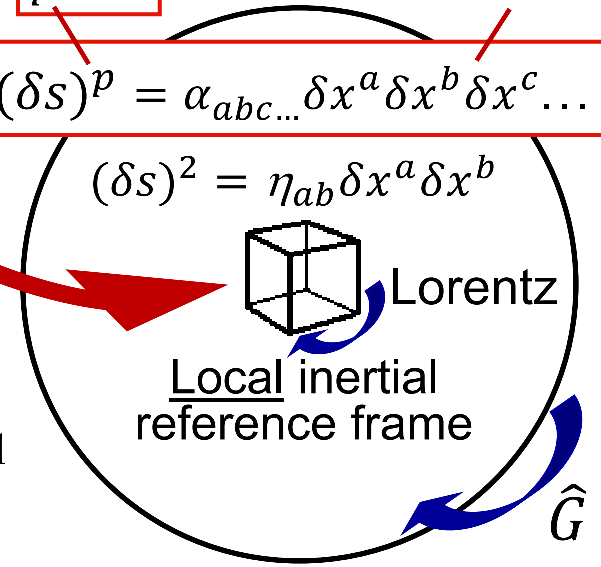
DJJ, `Quantum Gravity from the Composition of Spacetime Constructed through Generalised Proper Time', arXiv:2010.02703

Here from <u>local</u> 4D form <u>generalise proper time</u>:

each $\alpha_{abc\ldots} \in \{-1, 0, +1\}$

$p > 2$ $\qquad$ $n > 4$

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$$



Begin with <u>global</u> nD spacetime from which compactify to 4D spacetime

typically vast ambiguity in matter types
'landscape problem' in string theory

A 'bad' form of non-uniqueness

Basic structure of matter~SM at <u>local</u> level from which build extended 4D spacetime

vast degeneracy in matter contributions
provides basis of QM indeterminacy

$$G^{\mu\nu} = f^{\mu\nu}(\boldsymbol{\psi}, \boldsymbol{A}) =: -\kappa T^{\mu\nu}$$

A 'good' form of non-uniqueness

Extra space dimensions

From <u>local</u> 4D level

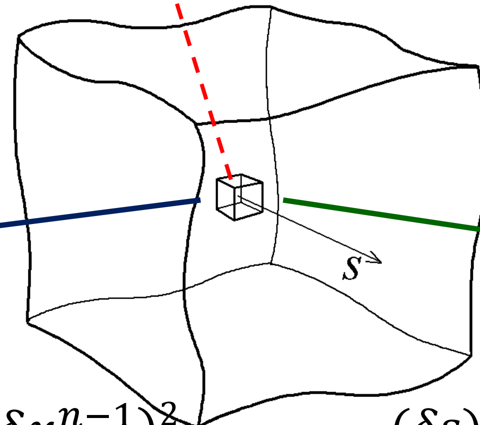
$$(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$$

Generalised proper time

$$\tilde{\eta} = \mathrm{diag}(1, -1, -1, \ldots, -1)$$

$$a, b = 0, \ldots, n-1; \quad n > 4$$

$$(\delta s)^2 = \tilde{\eta}_{ab}\delta x^a \delta x^b$$



each $\alpha_{abc\ldots} \in \{-1, 0, +1\}$

$p > 2$ and $n > 4$

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$$

$$(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 \ldots - (\delta x^{n-1})^2$$

full $\mathrm{SO}^+(1, n-1)$ symmetry broken:

$n \backslash \mathrm{SO}^+(1, n-1) \supset$	Lorentz	$\times$ SO(m)	matter
$m\ (= n-4)$	scalar	m-vector	'dark quarks' $\boldsymbol{\delta x}_m$
4	4-vector	invariant	$\boldsymbol{\delta x}_4$

SO(m) internal symmetry and scalar matter field, in parallel with, but 'hidden' from, the SM sector.

'hidden QCD', compact non-Abelian gauge group generate 'dark glueball/hadron/pion'-type states

Candidate for Self-Interacting <u>Dark Matter</u>

$$(\delta s)^4 = q(\boldsymbol{\delta x}_{56}) \quad \text{56D quartic form}$$

full $\mathrm{E}_7(\mathbb{O})$ symmetry broken:

$56 \backslash \mathrm{E}_7 \supset$	Lorentz	$\times\ \mathrm{SU}(3)_c$	$\times\ \mathrm{U}(1)_Q$	matter
4	<u>vector</u>	**1**	0	'ν_L'
8	Dirac	**1**	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	<u>scalar</u>	**3**	$\frac{2}{3}$	$\begin{pmatrix} `u_L' \\ `u_R' \end{pmatrix}$
24	Dirac	**3**	$\frac{1}{3}$	$\begin{pmatrix} d_L \\ d_R \end{pmatrix}$
4	<u>vector</u>	**1**	0	'Higgs' $\boldsymbol{\delta x}_4$
4	scalar	**1**	0	Yukawa

<u>Standard Model</u> structures directly

Extra space dimensions

From local 4D level

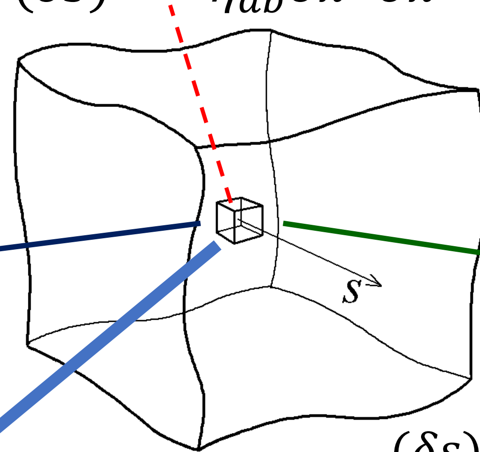
$(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$

Generalised proper time

$\tilde{\eta} = \mathrm{diag}(1,-1,-1,\ldots,-1)$

$a,b = 0,\ldots,n-1;\ n > 4$

$(\delta s)^2 = \tilde{\eta}_{ab}\delta x^a \delta x^b$

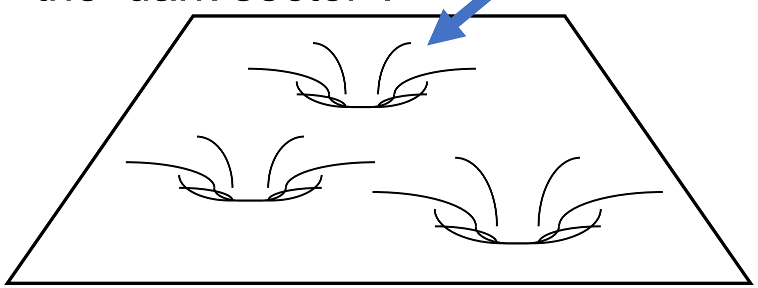


each $\alpha_{abc\ldots} \in \{-1,0,+1\}$

$p > 2$ and $n > 4$

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

But how many ways are there to 'generalise proper time'? And what might they imply for the 'dark sector'?



$(\delta s)^4 = q(\boldsymbol{\delta x}_{56})$ 56D quartic form

full $E_7(\mathbb{O})$ symmetry broken:

56 \ $E_7 \supset$	Lorentz ×	$SU(3)_c$ ×	$U(1)_Q$	matter
4	vector	**1**	0	'ν_L'
8	Dirac	**1**	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	scalar	**3**	$\frac{2}{3}$	$\begin{pmatrix} \text{'}u_L\text{'} \\ \text{'}u_R\text{'} \end{pmatrix}$
24	Dirac	**3**	$\frac{1}{3}$	$\begin{pmatrix} d_L \\ d_R \end{pmatrix}$
4	vector	**1**	0	'Higgs' $\boldsymbol{\delta x}_4$
4	scalar	**1**	0	Yukawa

Full gravitational interaction between DM and SM sectors via common 4D spacetime root

As typical for dark QCD, may be no other interaction with visible matter. (although may be a 'Higgs portal'?)

Candidate for Self-Interacting Dark Matter

Standard Model structures directly

$(\delta s)^2 = \det(\boldsymbol{\delta x}_4)$ 4D quad. form with $\mathrm{SL}(2,\mathbb{C})$ on $\boldsymbol{\delta x}_4 \in \mathrm{h}_2\mathbb{C}$

$2 \times 2 \to 3 \times 3$ matrix

$(\delta s)^3 = \det(\boldsymbol{\delta x}_9)$ 9D cubic form with $\mathrm{SL}(3,\mathbb{C})$ on $\boldsymbol{\delta x}_9 \in \mathrm{h}_3\mathbb{C}$

$\mathbb{C} \to \mathbb{O}$ algebra

$(\delta s)^3 = \det(\boldsymbol{\delta x}_{27})$ 27D cubic with $\mathrm{E}_6 \equiv \mathrm{SL}(3,\mathbb{O})$ on $\boldsymbol{\delta x}_{27} \in \mathrm{h}_3\mathbb{O}$

$(\delta s)^4 = q(\boldsymbol{\delta x}_{56})$ 56D quartic form with E_7 on $\boldsymbol{\delta x}_{56} \in F(\mathrm{h}_3\mathbb{O})$

Freudenthal triple system

$$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$$

A unique sequence of maths structures

full $\mathrm{E}_7(\mathbb{O})$ symmetry broken:

56 \ $\mathrm{E}_7 \supset$	Lorentz $\times$	$\mathrm{SU}(3)_c$ $\times$	$\mathrm{U}(1)_Q$	matter
4	vector	$\mathbf{1}$	0	'ν_L'
8	Dirac	$\mathbf{1}$	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	scalar	$\mathbf{3}$	$\frac{2}{3}$	$\begin{pmatrix} `u_L' \\ `u_R' \end{pmatrix}$
24	Dirac	$\mathbf{3}$	$\frac{1}{3}$	$\begin{pmatrix} d_L \\ d_R \end{pmatrix}$
4	vector	$\mathbf{1}$	0	'Higgs' $\boldsymbol{\delta x}_4$
4	scalar	$\mathbf{1}$	0	Yukawa

Standard Model structures directly

$(\delta s)^2 = \det(\boldsymbol{\delta x}_4)$ 4D quad. form with $\mathrm{SL}(2,\mathbb{C})$ on $\boldsymbol{\delta x}_4 \in \mathrm{h}_2\mathbb{C}$

$(\delta s)^3 = \det(\boldsymbol{\delta x}_9)$ 9D cubic form with $\mathrm{SL}(3,\mathbb{C})$ on $\boldsymbol{\delta x}_9 \in \mathrm{h}_3\mathbb{C}$

$(\delta s)^4 = \det(\boldsymbol{\delta x}_{16})$ 16D 4^{th} order form, $\mathrm{SL}(4,\mathbb{C})$ on $\boldsymbol{\delta x}_{16} \in \mathrm{h}_4\mathbb{C}$

$(\delta s)^p = \det(\boldsymbol{\delta x}_{p^2})$ p^2D p^{th} order form, $\mathrm{SL}(p,\mathbb{C})$ on $\boldsymbol{\delta x}_{p^2} \in \mathrm{h}_p\mathbb{C}$

$2\times 2 \to 3\times 3$ matrix

$3\times 3 \to 4\times 4$ matrix

$4\times 4 \to p\times p$ matrix

Alternative sequence of maths structures

Also fully consistent with generalised proper time

$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots$

full $\mathrm{SL}(p,\mathbb{C})$ symmetry broken:

p^2 \ $\mathrm{SL}(p,\mathbb{C}) \supset$	Lorentz $\times$	$\mathrm{SL}(k,\mathbb{C})_D$	$\times$ $\mathrm{U}(1)_D$	matter
4	4-vector	invariant	0	$\boldsymbol{\delta x}_4$ external
k^2 $(k = p-2)$	scalar	$\boldsymbol{\delta x}_{k^2} \to S_k \boldsymbol{\delta x}_{k^2} S_k^\dagger$	0	$\boldsymbol{\delta x}_{k^2}$ dark
$4k$	Weyl	$\boldsymbol{\delta x}_{4k} \to S_k \boldsymbol{\delta x}_{4k}$	1	$\boldsymbol{\delta x}_{4k}$ dark

Symmetry breaking yields gauge interactions independent of visible Standard Model sector.

What are the properties of this contribution to the dark sector?

full $\mathrm{E}_7(\mathbb{O})$ symmetry broken:

56 \ $\mathrm{E}_7 \supset$	Lorentz $\times$	$\mathrm{SU}(3)_c$ $\times$	$\mathrm{U}(1)_Q$	matter
4	vector	**1**	0	'ν_L'
8	Dirac	**1**	1	$\begin{pmatrix} e_L \\ e_R \end{pmatrix}$
12	scalar	**3**	$\frac{2}{3}$	$\begin{pmatrix} 'u_L' \\ 'u_R' \end{pmatrix}$
24	Dirac	**3**	$\frac{1}{3}$	$\begin{pmatrix} d_L \\ d_R \end{pmatrix}$
4	vector	**1**	0	'Higgs' $\boldsymbol{\delta x}_4$
4	scalar	**1**	0	Yukawa

Standard Model structures directly

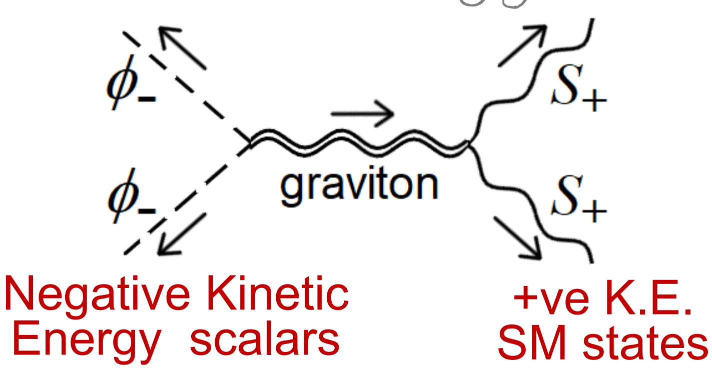
$(\delta s)^p = \det(\boldsymbol{\delta x}_{p^2})$ p^2D p^{th} order form, $\mathrm{SL}(p,\mathbb{C})$ on $\boldsymbol{\delta x}_{p^2} \in \mathrm{h}_p\mathbb{C}$ $p \times p$ matrix

$p^2 \diagdown \mathrm{SL}(p,\mathbb{C}) \supset$	Lorentz $\times$	$\mathrm{SL}(k,\mathbb{C})_D$	$\times$ $\mathrm{U}(1)_D$	matter
4	4-vector	invariant	0	$\boldsymbol{\delta x}_4$ external
k^2 $(k = p-2)$	scalar	$\boldsymbol{\delta x}_{k^2} \to S_k \boldsymbol{\delta x}_{k^2} S_k^\dagger$	0	$\boldsymbol{\delta x}_{k^2}$ dark
$4k$	Weyl	$\boldsymbol{\delta x}_{4k} \to S_k \boldsymbol{\delta x}_{4k}$	1	$\boldsymbol{\delta x}_{4k}$ dark

Independent gauge sector, only (classical) gravitational interaction with SM (i.e. dark)

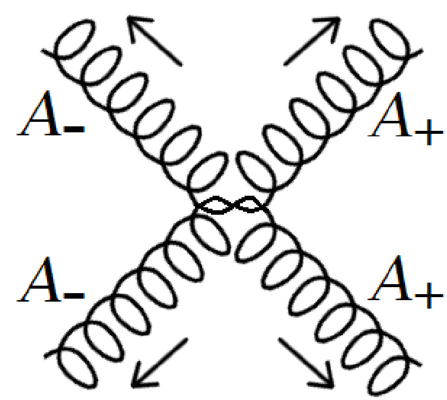
Non-compact gauge group $\mathrm{SL}(k,\mathbb{C})_D$
A_+ positive and A_- negative K.E. states

cf. phantom dark energy?



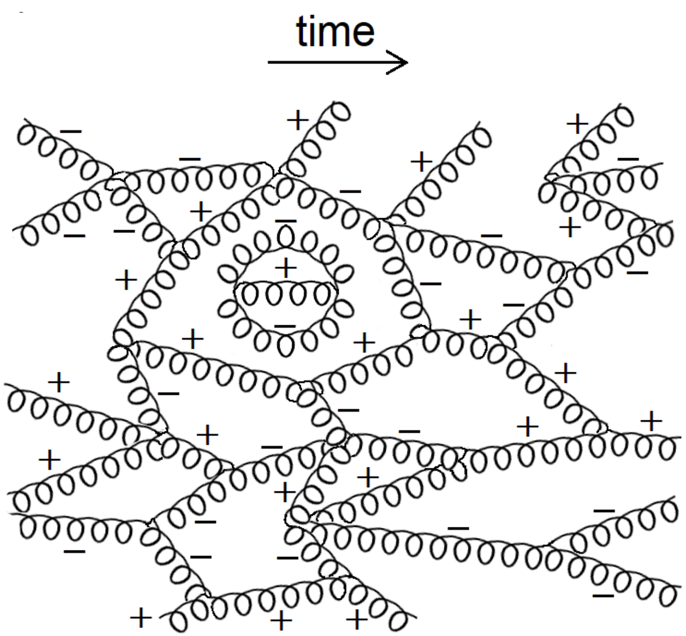
arXiv:9908168
arXiv:1708.06981

create out of vacuum:



$(\delta s)^p = \det(\boldsymbol{\delta x}_{p^2})$ p^2D p^{th} order form, $\mathrm{SL}(p,\mathbb{C})$ on $\boldsymbol{\delta x}_{p^2} \in \mathrm{h}_p\mathbb{C}$ $p \times p$ matrix

p^2 \ $\mathrm{SL}(p,\mathbb{C}) \supset$	Lorentz $\times$	$\mathrm{SL}(k,\mathbb{C})_D$	$\times$ $\mathrm{U}(1)_D$	matter
4	4-vector	invariant	0	$\boldsymbol{\delta x}_4$ external
k^2 $(k = p-2)$	scalar	$\boldsymbol{\delta x}_{k^2} \to S_k \boldsymbol{\delta x}_{k^2} S_k^\dagger$	0	$\boldsymbol{\delta x}_{k^2}$ dark
$4k$	Weyl	$\boldsymbol{\delta x}_{4k} \to S_k \boldsymbol{\delta x}_{4k}$	1	$\boldsymbol{\delta x}_{4k}$ dark



stable equilibrium vacuum state

Raging vacuum sea of $A_\pm$ states can be gravitationally completely benign

energy density: $\rho_V = \rho_{A_+} + \rho_{A_-} = 0$

pressure: $p_V = p_{A_+} + p_{A_-} = 0$

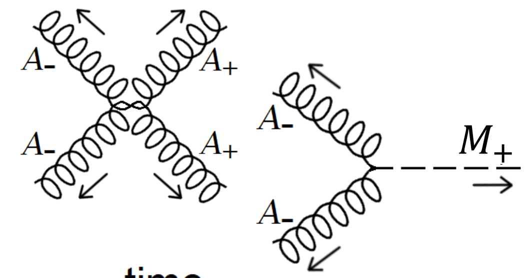
'matter fields' M_+ asymmetrically perturb the equation of state: $p_V = w_V \rho_V$

$\Rightarrow$ parameter $w_V = -1$, with $\rho_V = -p_V > 0$

$$G^{\mu\nu} + \Lambda g^{\mu\nu} = 0$$

GR vacuum, with very small $\Lambda > 0$

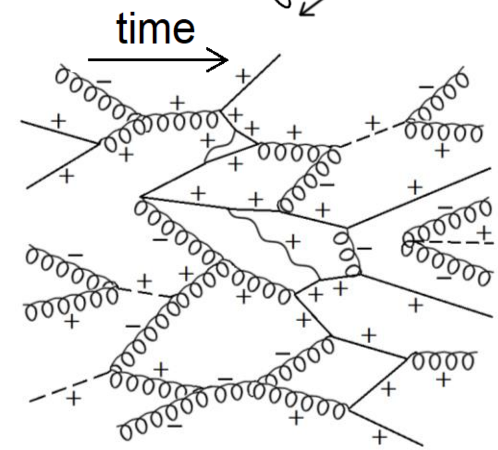
General suitability as a dark energy candidate driving large scale accelerating expansion of the universe



macroscopically: ~uniform in space and time

Created out of the vacuum: equation of state, $w_V = -1$

with A_- part as source of negative pressure $p_V < 0$



Contributions AM_+, and A_- can largely cancel leaving ultra-low net $\rho_V > 0$

(cf. 'QCD quark-gluon plasma' is $\sim 10^{44}\ \times$ too large)

(QFT vacuum energy density is $\sim 10^{120}\ \times$ too large)

Having a source of negative kinetic energy from A_- part is analogous to models of 'phantom dark energy', but here only classical GR with SM, hence stable

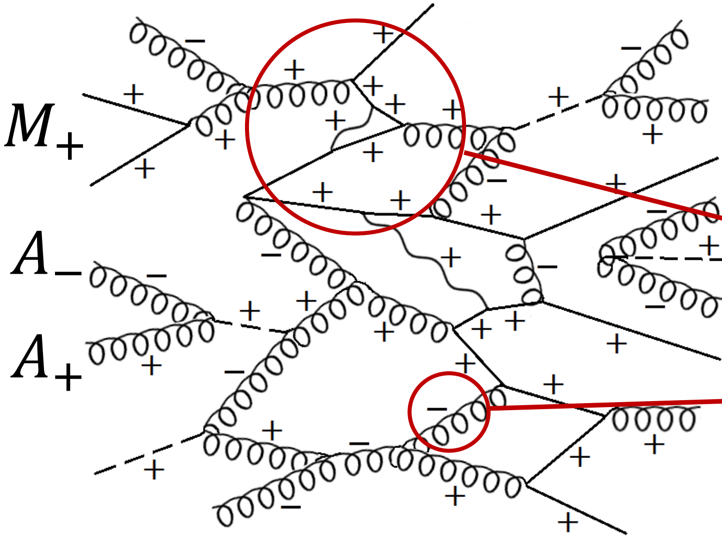
Indeed, no? particle or gauge interactions with the visible sector, hence dark

While such a non-compact non-Abelian sector could be proposed as a model …here such a candidate for dark energy has basis in a fundamental theory

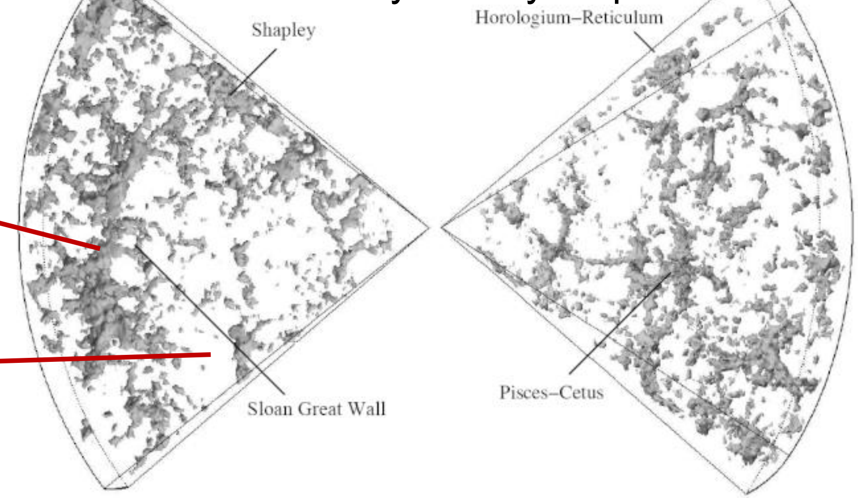
DJJ, `Generalised Local Extra Dimensions as a Basis for the Elementary Structure of Matter', arXiv:2209.06162

Role of this dark energy source in very early universe ‘inflationary phase’:

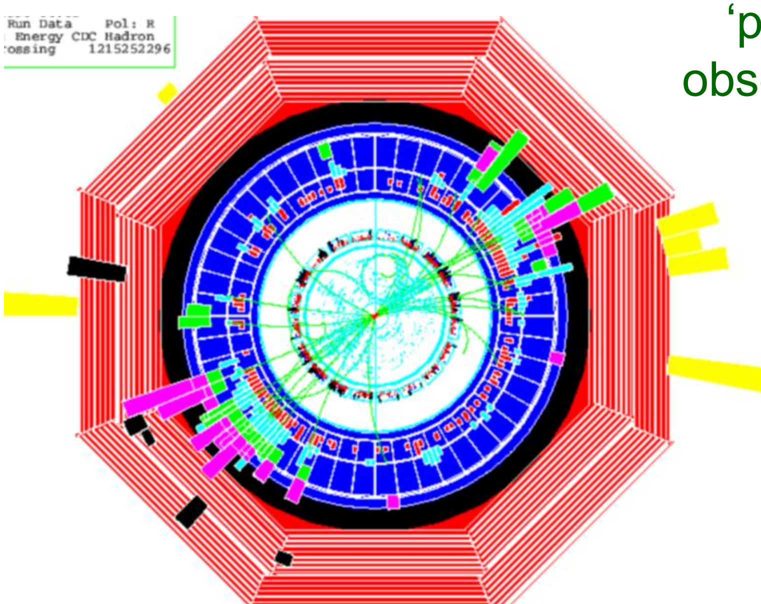
$\rho_V \ggg 0, \;\; p_V \lll 0$ and $p_V = w_V \rho_V$ with $w_V = -1$

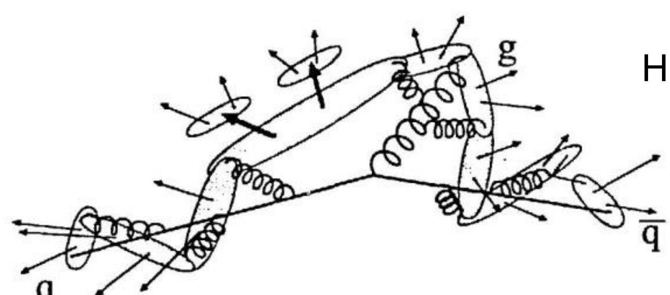


2dF Galaxy Survey Map



Very early dark energy fluctuations preceding ‘phase transition’ to dark matter states may leave observable imprint in cosmic wall/web/void structures





H. Yamamoto
LPHEP85

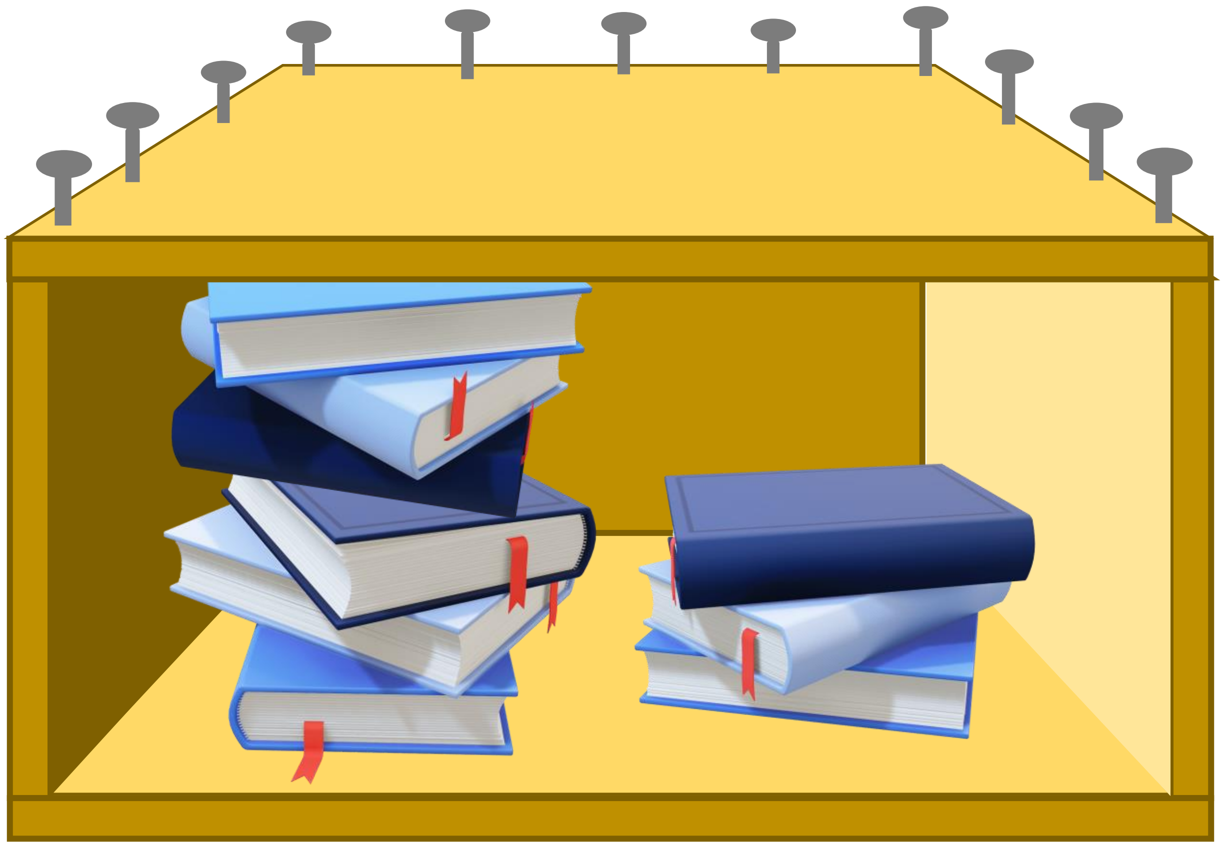
cf. ‘Cosmological Collider’
and ‘Cosmological Bootstrap’

arXiv:1811.00024 arXiv:2203.08121

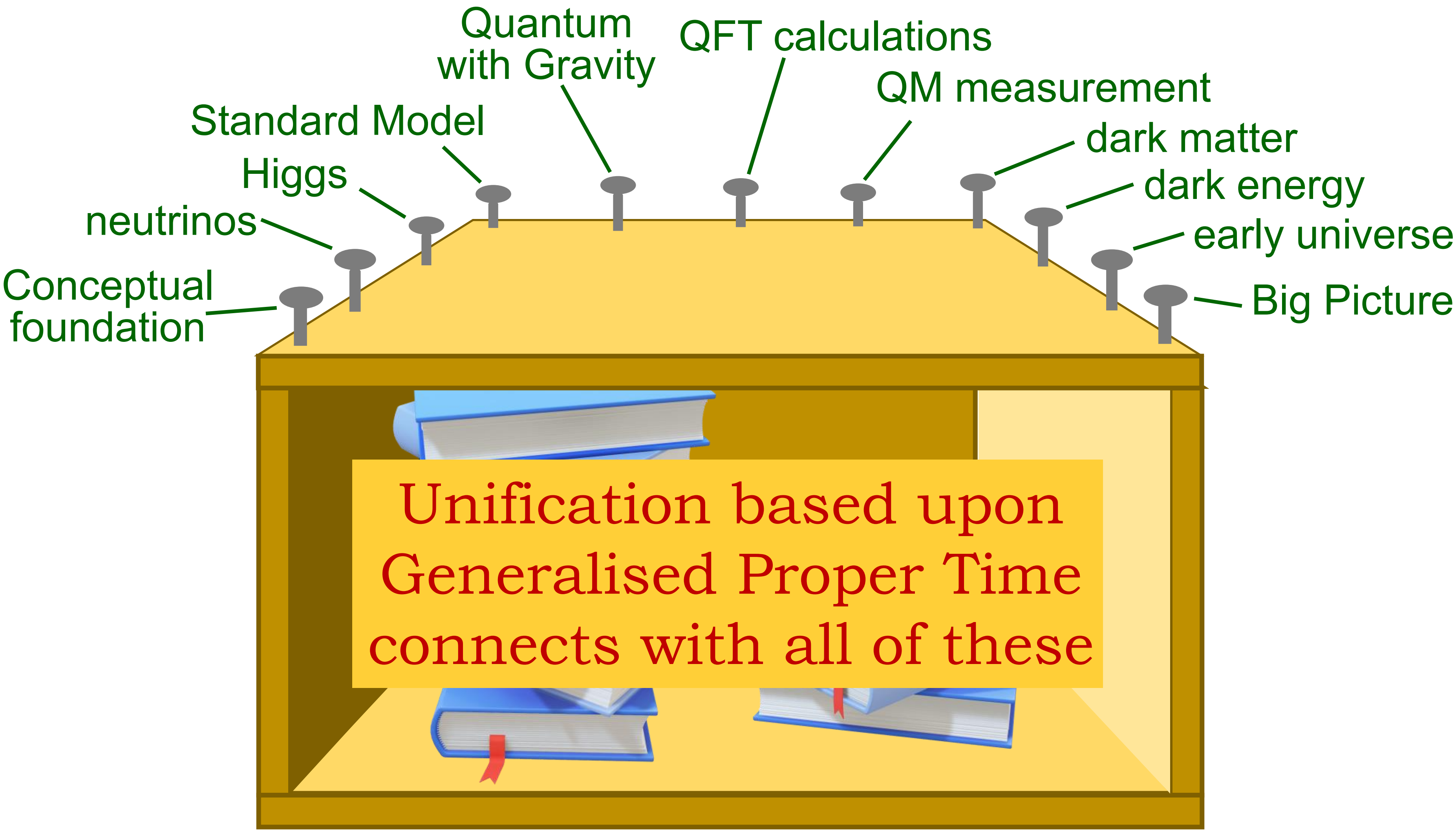
Heisenberg's Box, 'Theory, Criticism and a Philosophy' 1968 lecture, reprinted in 'From a Life of Physics' 1989

"When you try too much for rigorous mathematical methods, you fix your attention on those points which are not important from the physics' point…"

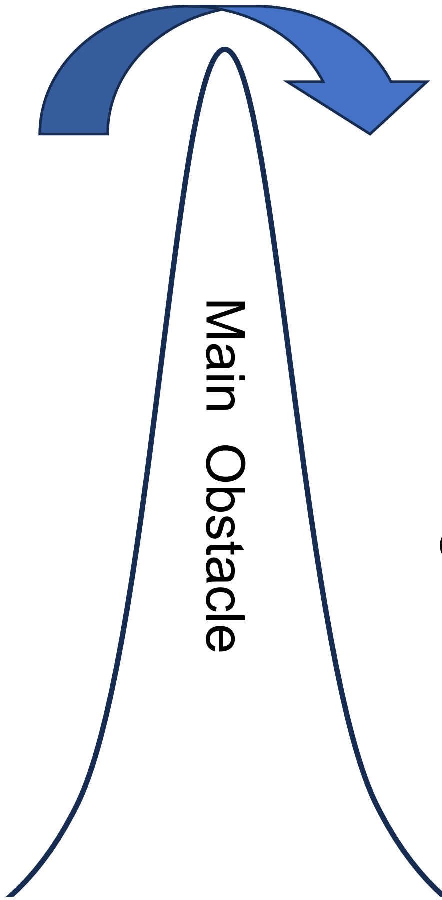
"…one should always have the whole picture in mind before one tries to fix a theory in mathematics…"



For a 21st century Unified Theory would like:



‘Gestalt shift’ in worldview



<u>Obviously</u> can’t construct a theory accounting for complex physical world simply from ‘time’ alone

<u>Obvious</u> ‘time’ provides a natural unifying basis for physical theory since everything ‘happens in time’

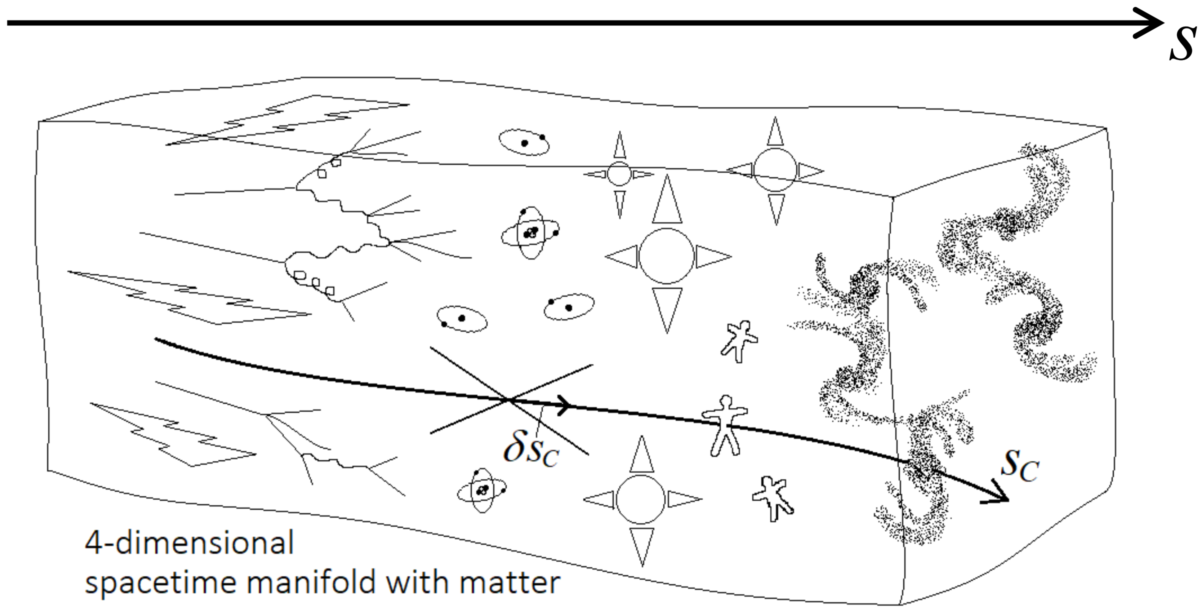
‘Everything should be made as simple as possible, but not simpler’

Much quoted, as paraphrased from:

Einstein, ‘On the Method of Theoretical Physics’ (1933 lecture)

The *trick* is then to see how it is *possible* to construct a theory just from time

A barrier to making this change of perspective may be the common representation of time as a one-dimensional line *in* space (or in spacetime)



However, nothing we know of in the physical world corresponds to a purely 1D vanishingly thin line in space or worldline in spacetime - that is not what time *is*

Rather, taking time to be a real continuum $s \in \mathbb{R}$ says nothing explicit about any relation to spatial extension or properties (does not imply a 'line' in space)

(Like listening to the flow of music in a dark place)

The real numbers $\mathbb{R}$ have basic arithmetic properties of '$\pm$' and '$\times\div$' operations

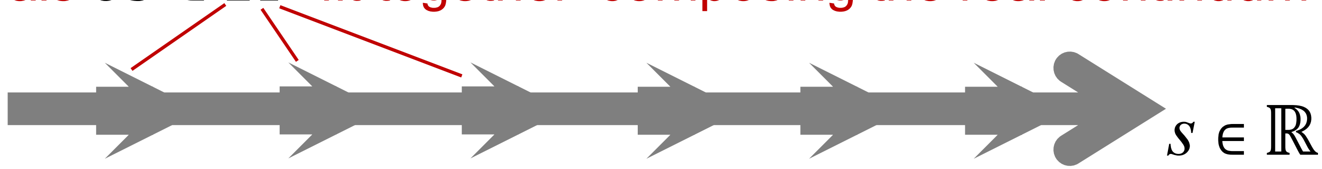
Time as continuum expressed by $\mathbb{R} \Rightarrow$ time itself has these intrinsic properties

The real numbers $\mathbb{R}$ have basic arithmetic properties of '±' and '×÷' operations

Time as continuum expressed by $\mathbb{R}$ ⇒ time itself has these intrinsic properties

Can express $\delta s \in \mathbb{R}$ as: $\delta s = \delta x^1 + \delta x^2 + \delta x^3 \ldots$

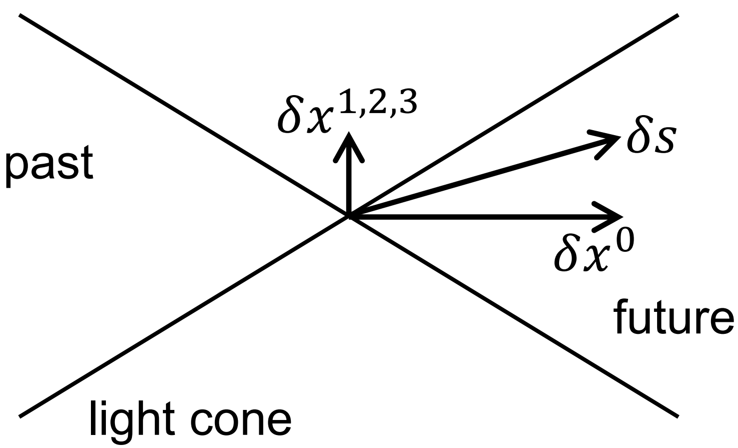
The intervals $\delta s \in \mathbb{R}$ 'fit together' composing the real continuum $\mathbb{R}$



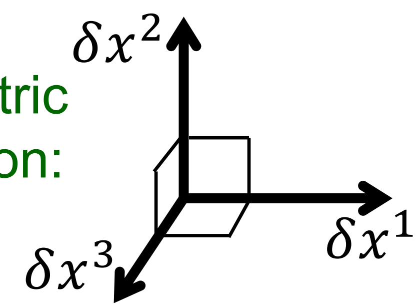
Can express $\delta s \in \mathbb{R}$ as: $(\delta s)^2 = (\delta x^0)^2 - \left[(\delta x^1)^2 + (\delta x^2)^2 + (\delta x^3)^2\right]$

with: $\{\delta x^0, \delta x^1, \delta x^2, \delta x^3\} \in \mathbb{R}^4$

form of space itself identified through an arithmetic substructure of time



has geometric interpretation:



full quadratic form describes a local 4D spacetime element with a causal light cone structure

The real numbers $\mathbb{R}$ have basic arithmetic properties of '$\pm$' and '$\times\div$' operations

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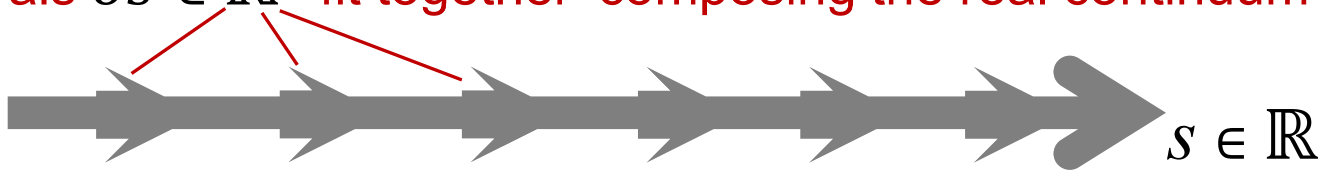
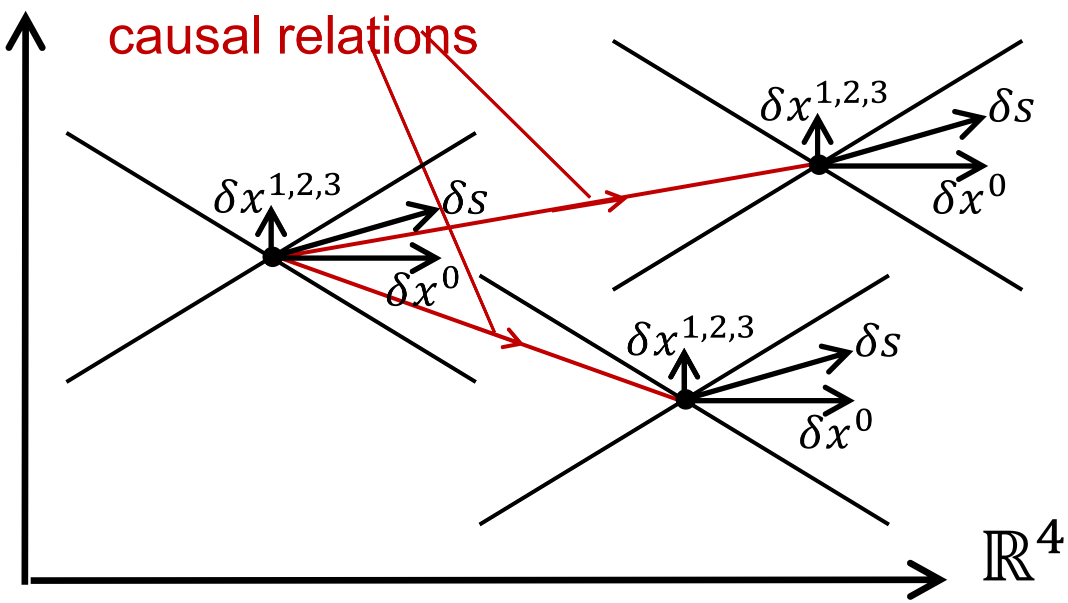


Can express $\delta s \in \mathbb{R}$ as: $(\delta s)^2 = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2$

These quadratic elements 'fit together' composing extended patch of $\mathbb{R}^4$:



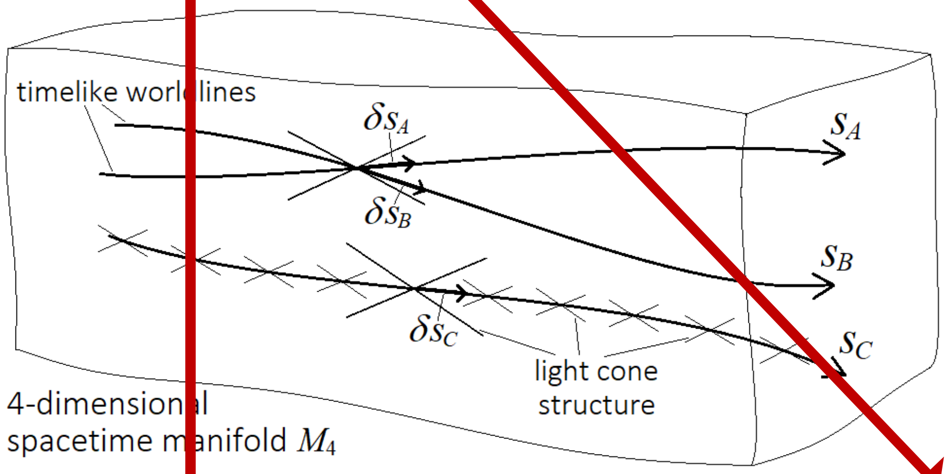
construction of spacetime continuum with no residual discrete structure

local 4D light cone, inertial reference frame at any location

Arithmetic substructure of time contains the Geometric form in which it flows

Via $(\delta s)^2 \rightarrow \eta_{ab}\delta x^a \delta x^b = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2$ elements

can construct a continuous extended 4-dimensional spacetime manifold:



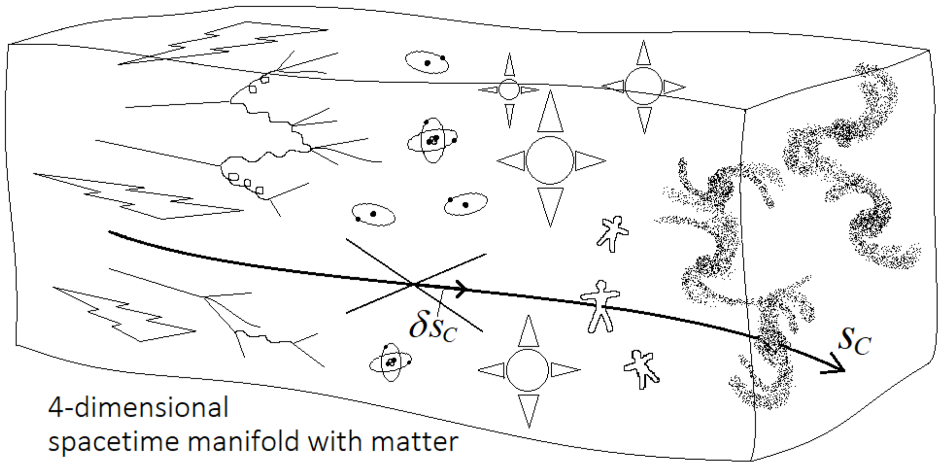
Wholly temporal structure with timelike worldlines $s_A, s_B, s_C, \ldots$

Via $(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots = \left(\eta_{ab}\delta x^a \delta x^b\right) \times (\delta x \ldots)^{p-2} + (\delta x \ldots)^p$

direct arithmetic generalisation of proper time, fill out matter content

Via $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b = (\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2$ elements

can construct a continuous extended 4-dimensional spacetime manifold:



4-dimensional spacetime manifold with matter

Change in perspective from 'time something in world' to 'the world something in time'

Dynamic+Block of GR

Local degeneracy basis for Quantum+Gravity

$$G^{\mu\nu} = f^{\mu\nu}(\boldsymbol{\psi}, \boldsymbol{A}) =: -\kappa T^{\mu\nu}$$

Via $(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots = \left(\eta_{ab}\delta x^a \delta x^b\right) \times (\delta x \ldots)^{p-2} + (\delta x \ldots)^p$

direct arithmetic generalisation of proper time, fill out matter content

Standard Model

$(\delta s)^4 = q(F(\mathrm{h}_3\mathbb{O}))$

E_7 sym. $\Rightarrow \mathrm{E}_8(\mathbb{O})$

$(\delta s)^2 = \hat{\eta}_{ab}\delta x^a \delta x^b$

$\mathrm{SO}^+(1, n-1)$

sym. $n > 4$

Maths rules

GPT over 4D spacetime

Dark Sectors

$(\delta s)^p = \det(\mathrm{h}_p\mathbb{C})$ $p \times p$ matrix

$\mathrm{SL}(p, \mathbb{C})$ sym. $p > 3$

Unifying picture:

All based upon 'one simple equation':

Generalised Proper Time, as basis for

4D spacetime and its matter content

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