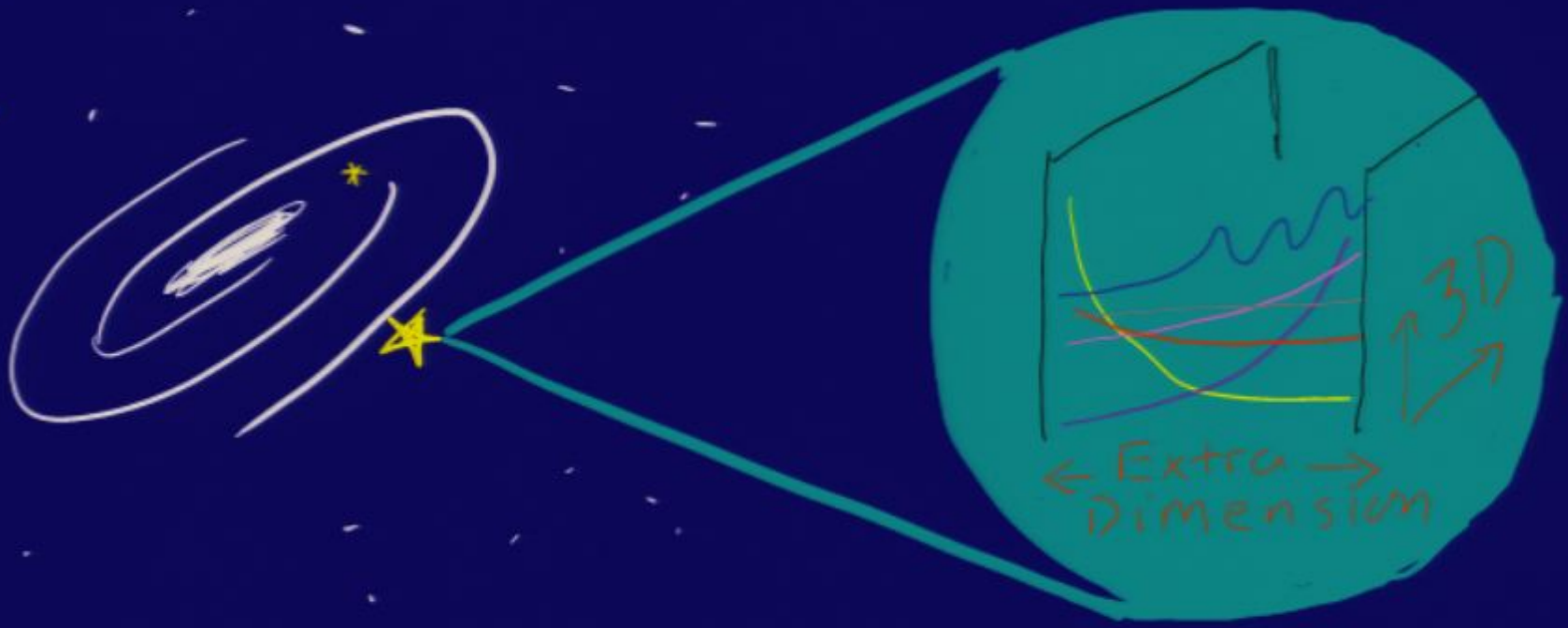
Title: 4D Cosmos from 5D Chaos

Date: May 09, 2007 02:00 PM

URL: http://pirsa.org/07050004

Abstract: Modern motivations for extra spacetime dimensions will be presented, in particular the surprising AdS/CFT connection to particle compositeness. It will be shown how highly curved, "warped", extra-dimensional geometries can naturally address several puzzles of fundamental physics, including the weakness of gravity, particle mass hierarchies, dark matter, and supersymmetry breaking. The possibility of direct discovery of warped dimensions at
particle colliders such as the CERN Large Hadron Collider will be discussed. Some current questions in warped cosmology will also be introduced.

4D COSMOS FROM 5D WARPED CHAOS



Raman Sundrum, Johns Hopkins

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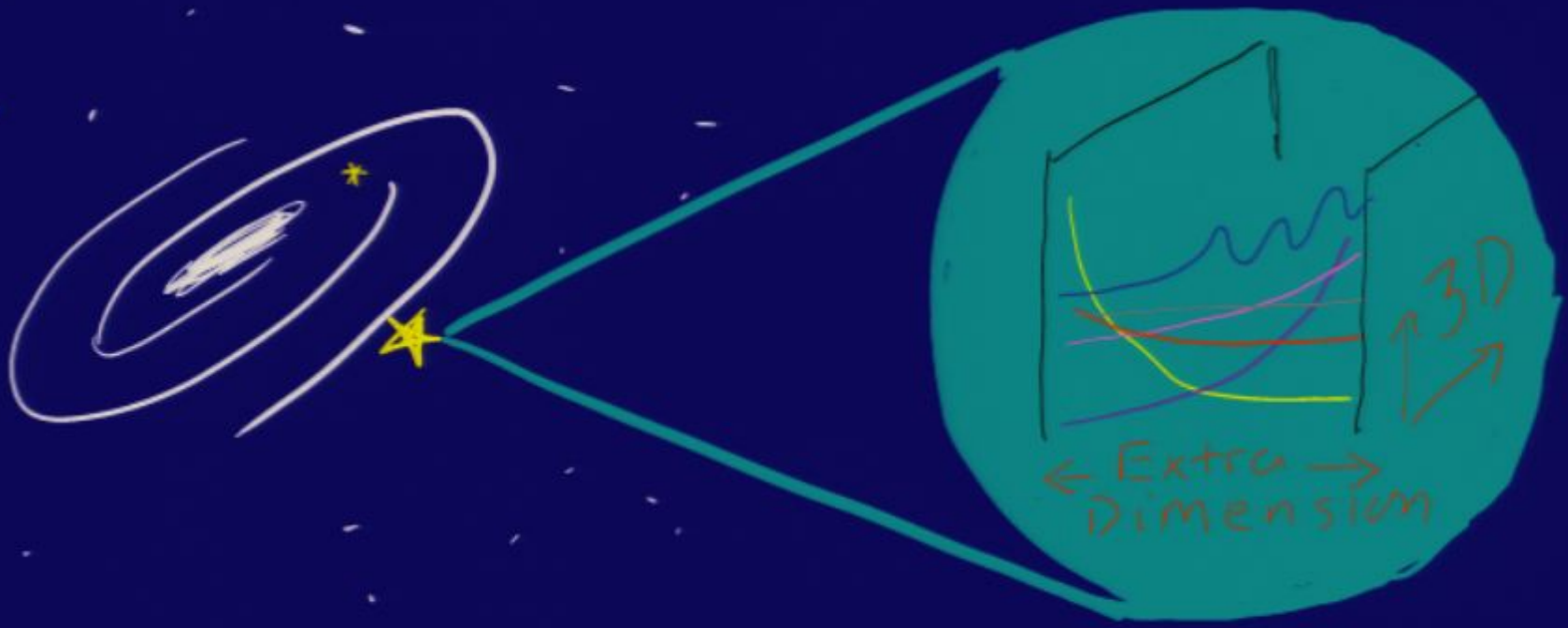

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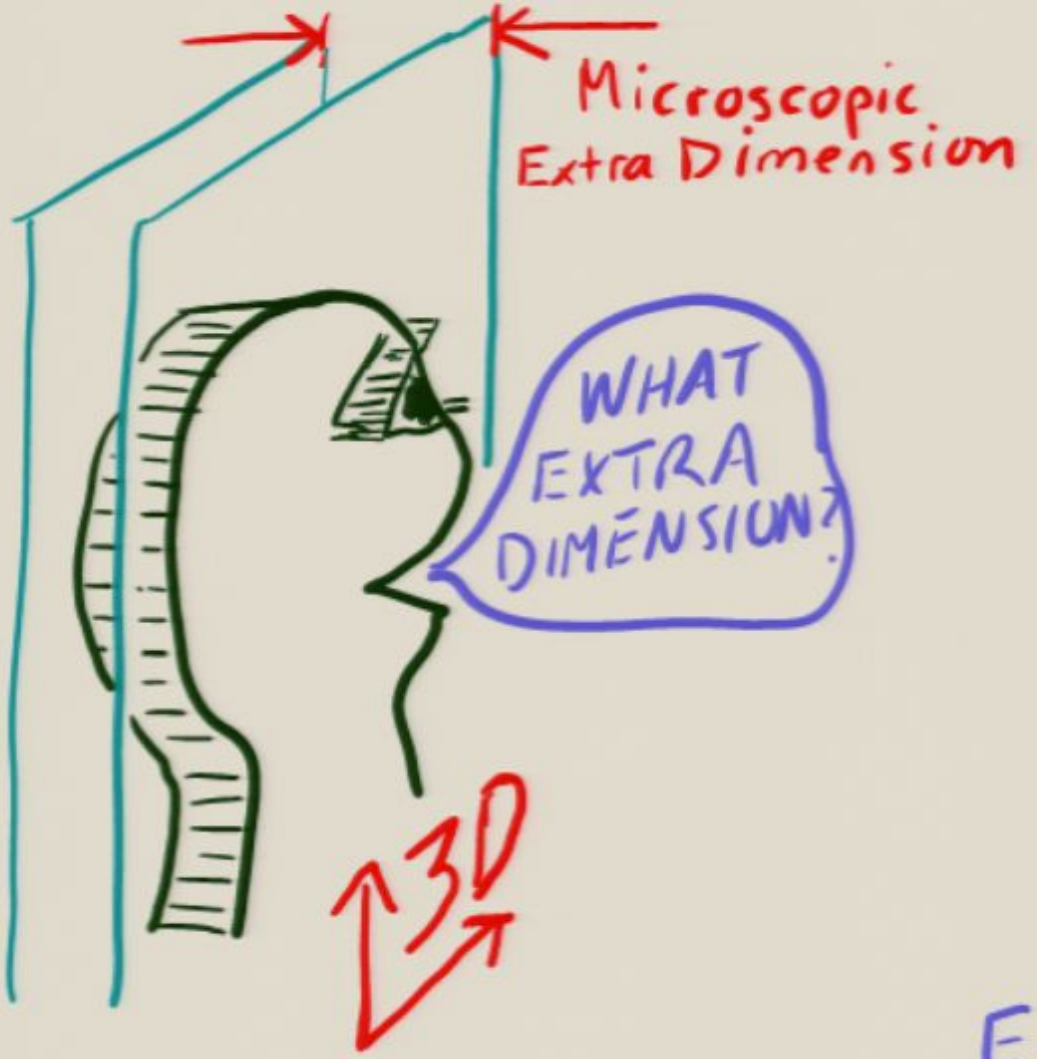
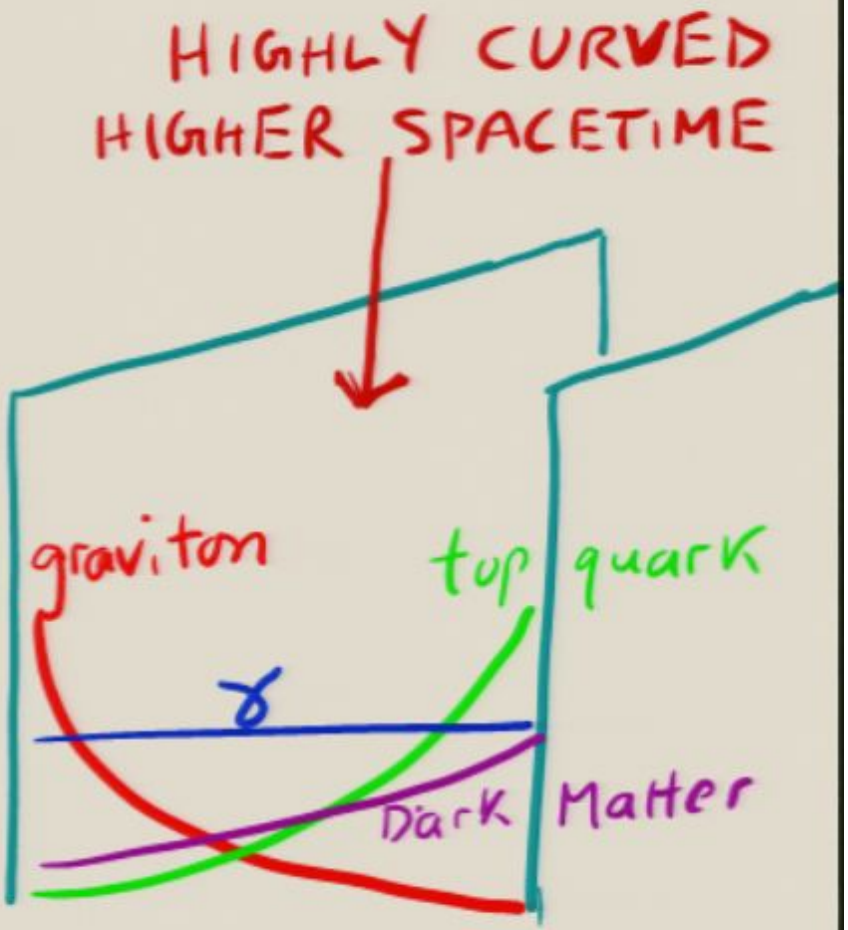
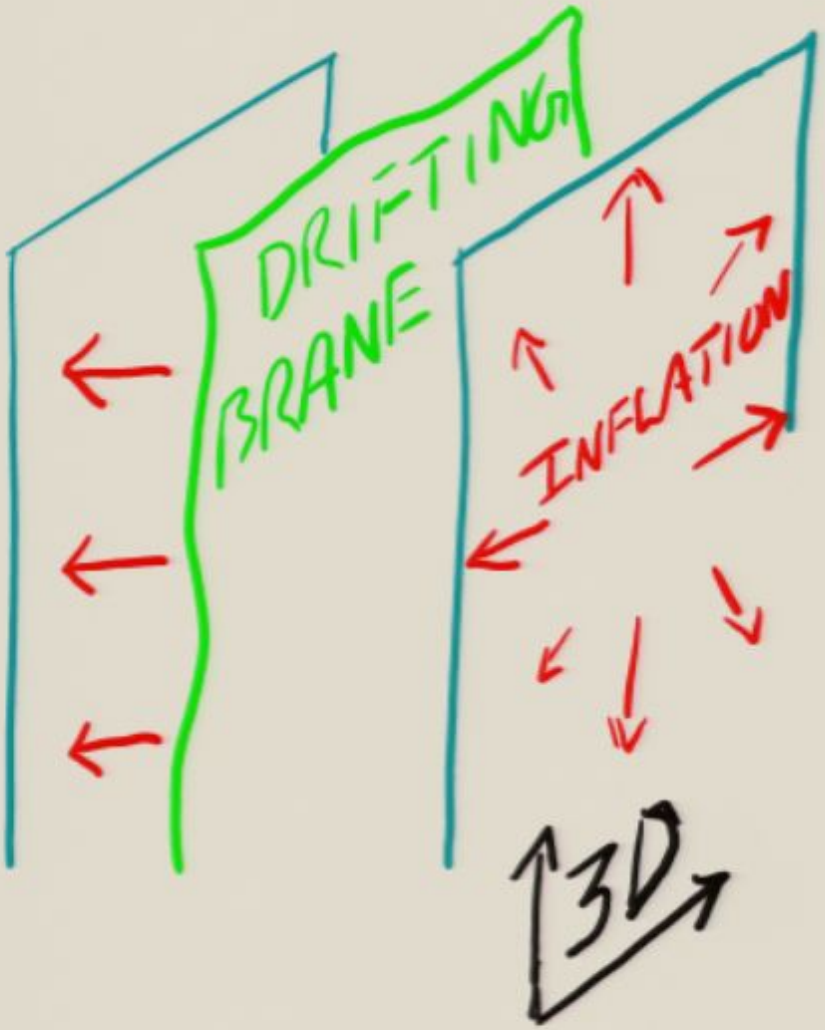
OUTLINE





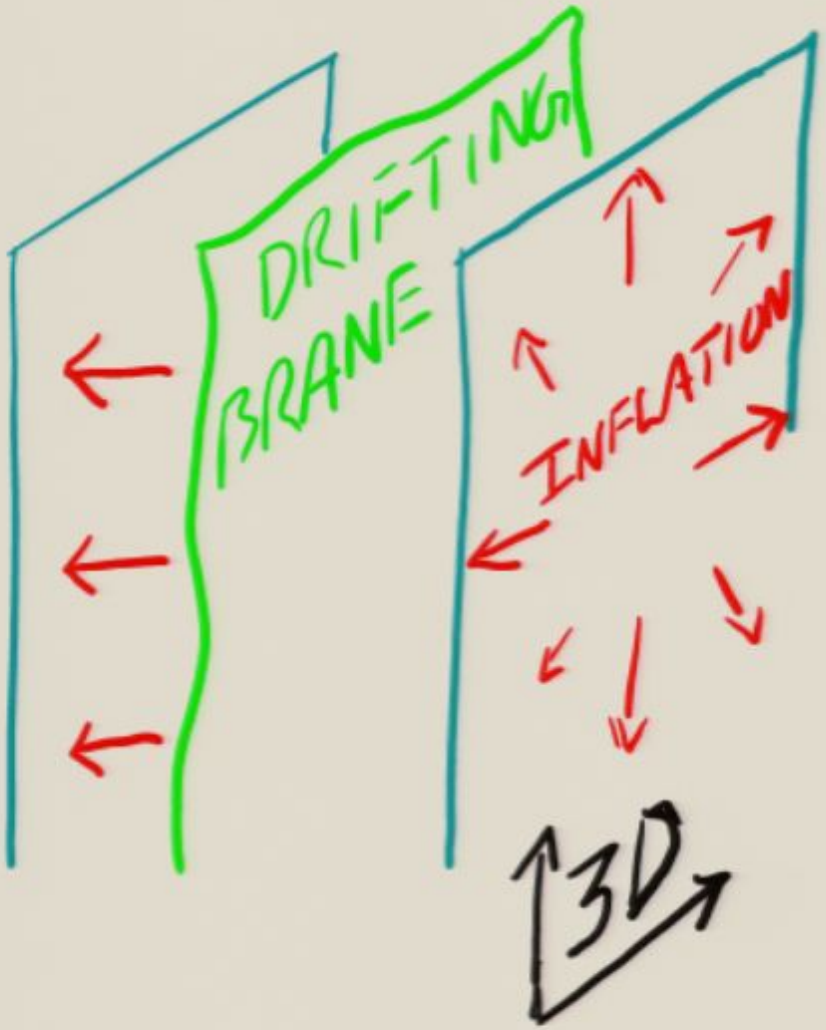
EXTRA-DIMENSIONAL
WAVEFUNCTIONS

⇒ OBSERVED STRUCTURES
OF FUNDAMENTAL



EARLY UNIVERSE

LARGE HADRON COLLIDER



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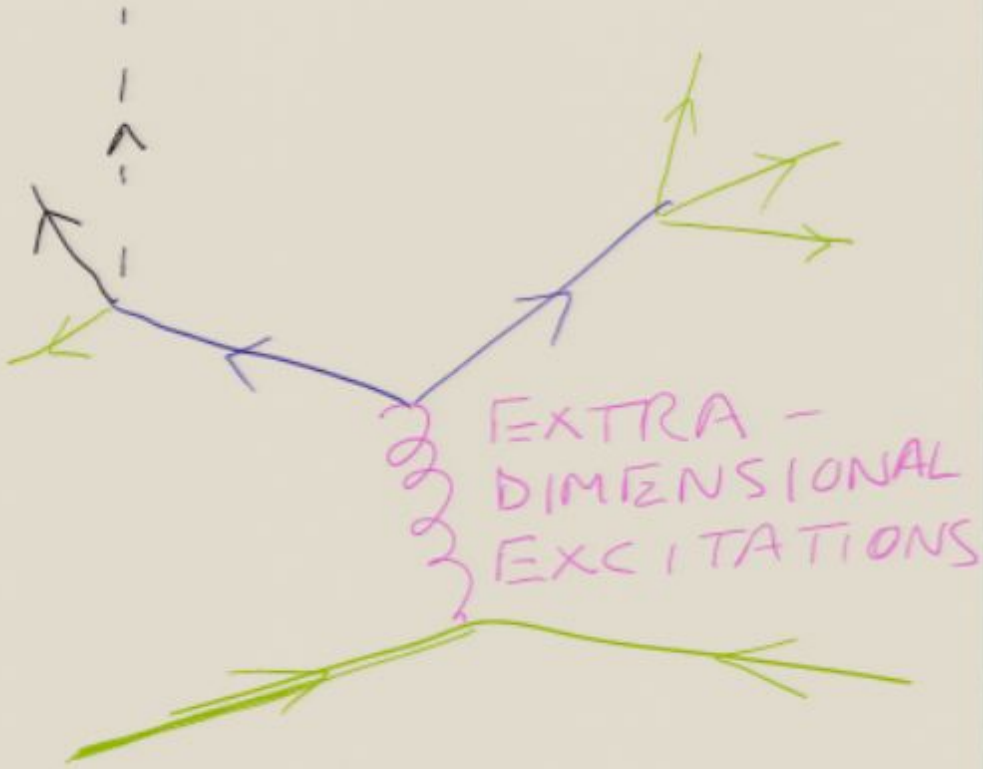

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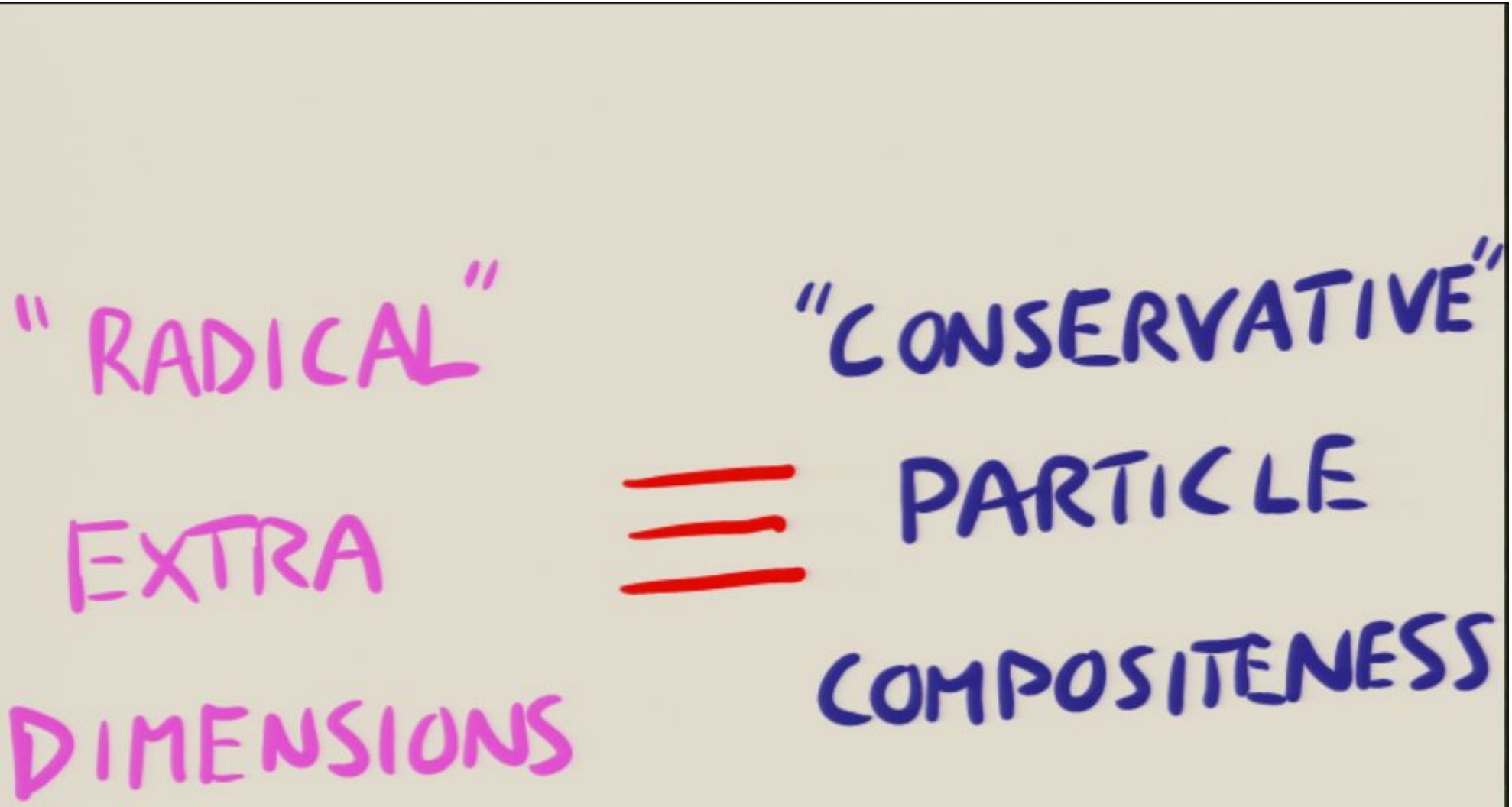
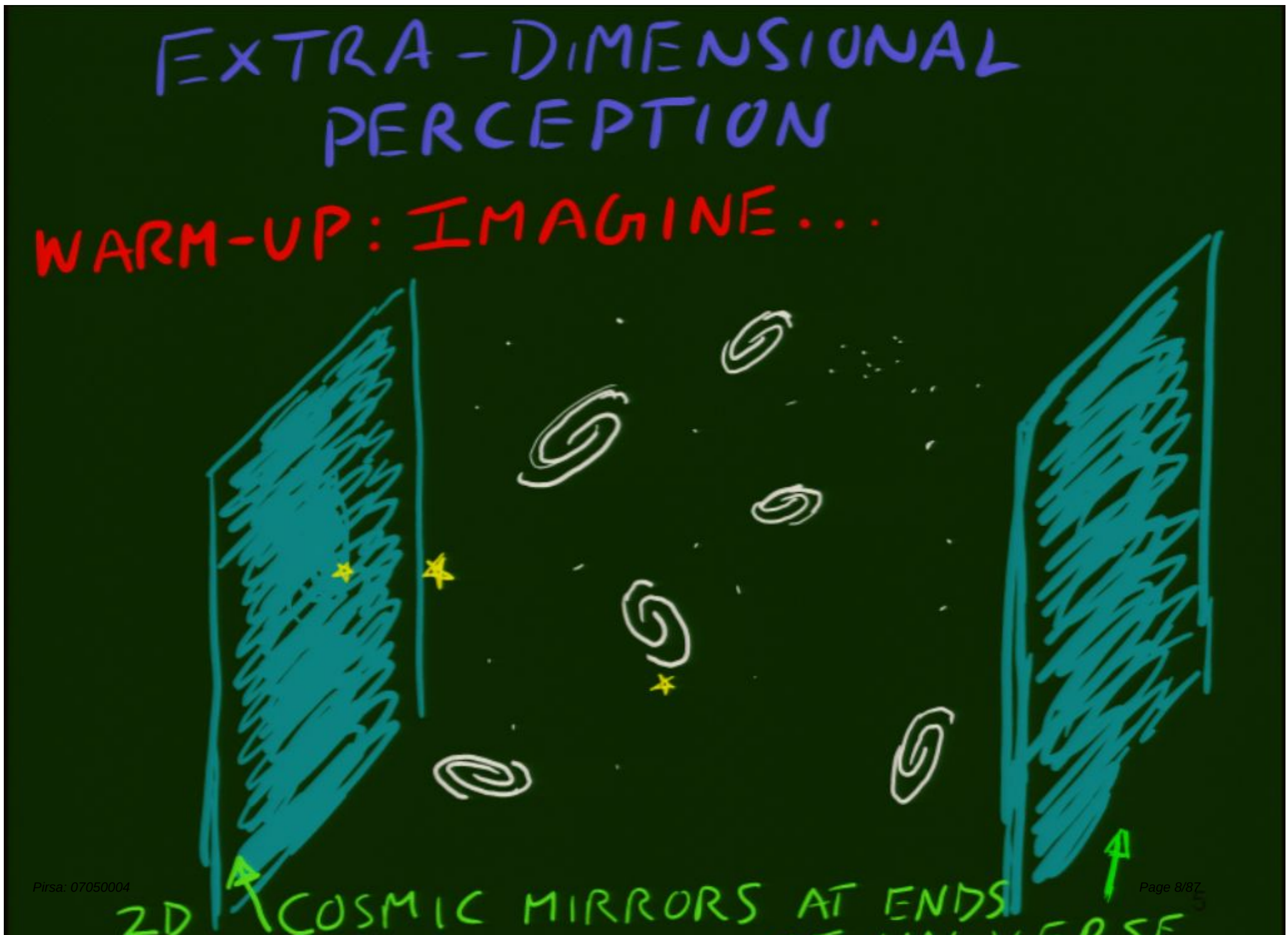
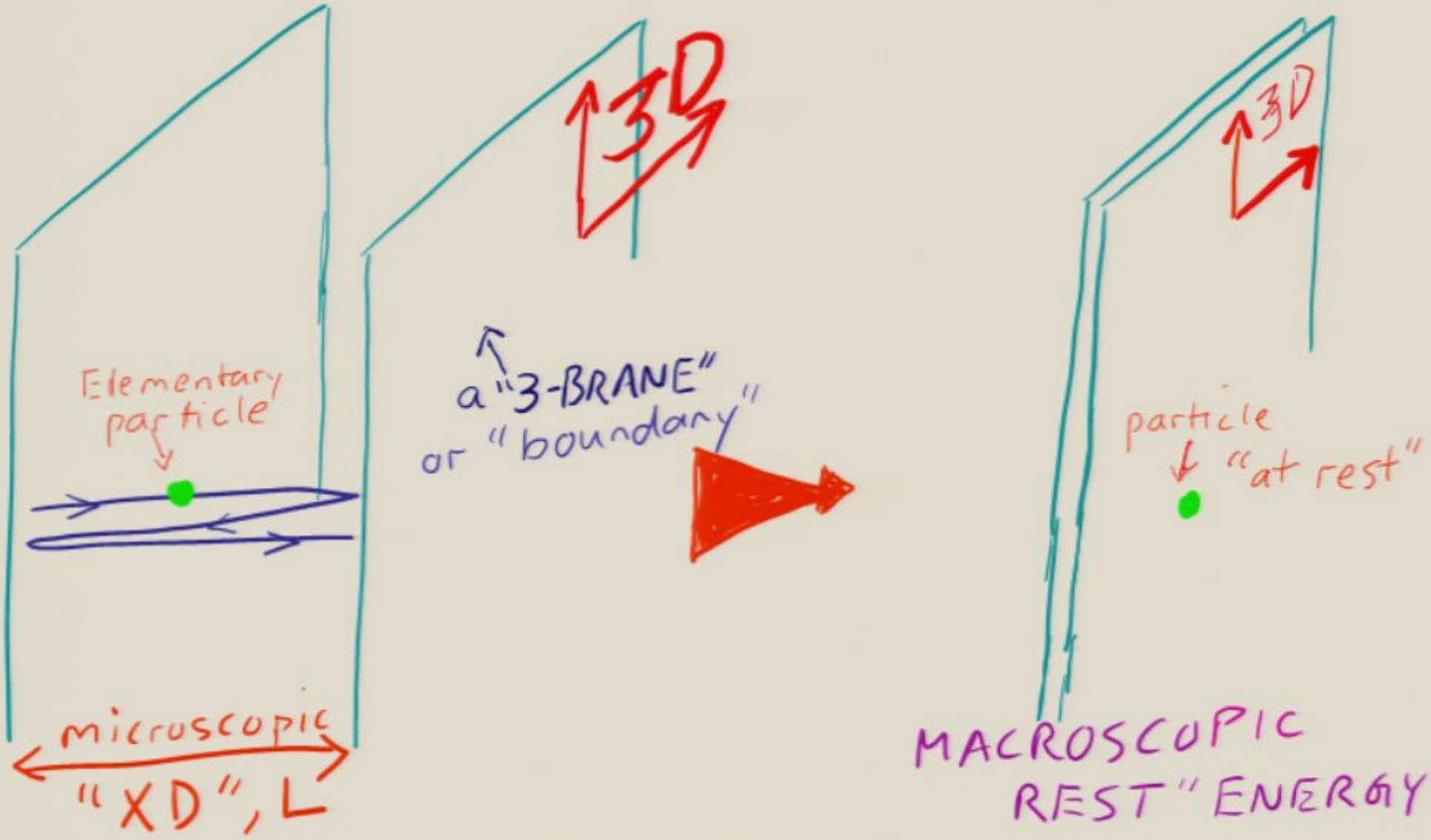

"RADICAL"
EXTRA
DIMENSIONS
≡
"CONSERVATIVE"
PARTICLE
COMPOSITENESS

EXTRA-DIMENSIONAL PERCEPTION

WARM-UP: IMAGINE...



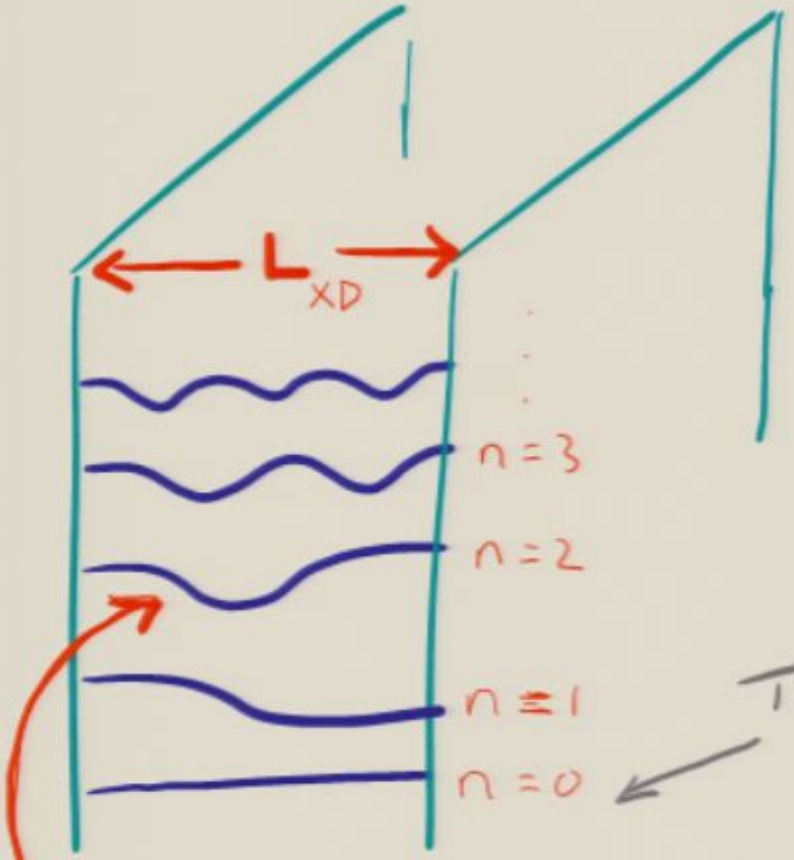
ADDING A DIMENSION



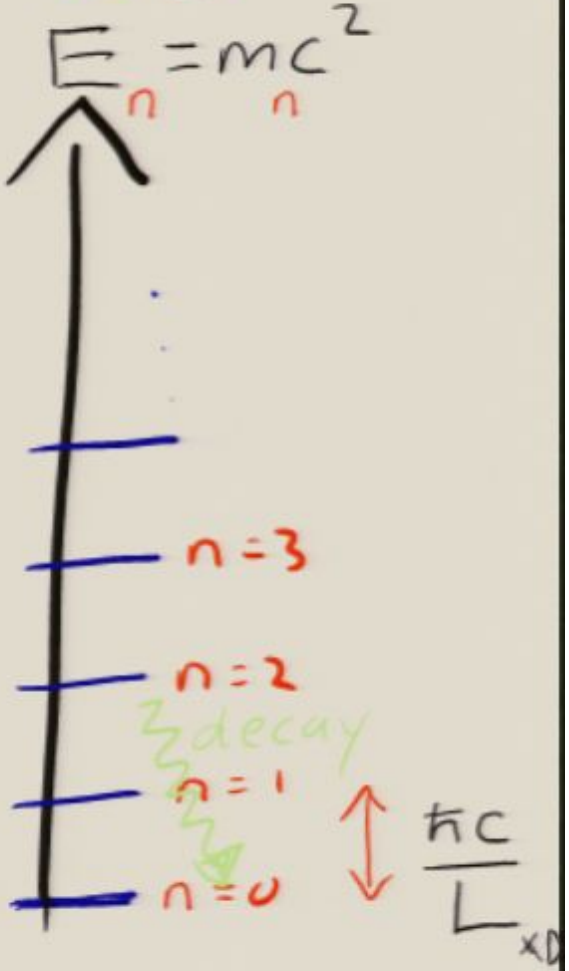
XD KINETIC ENERGY

RELATIVITY $\Rightarrow E = mc^2$

QUANTUM MECHANICS



This is you.

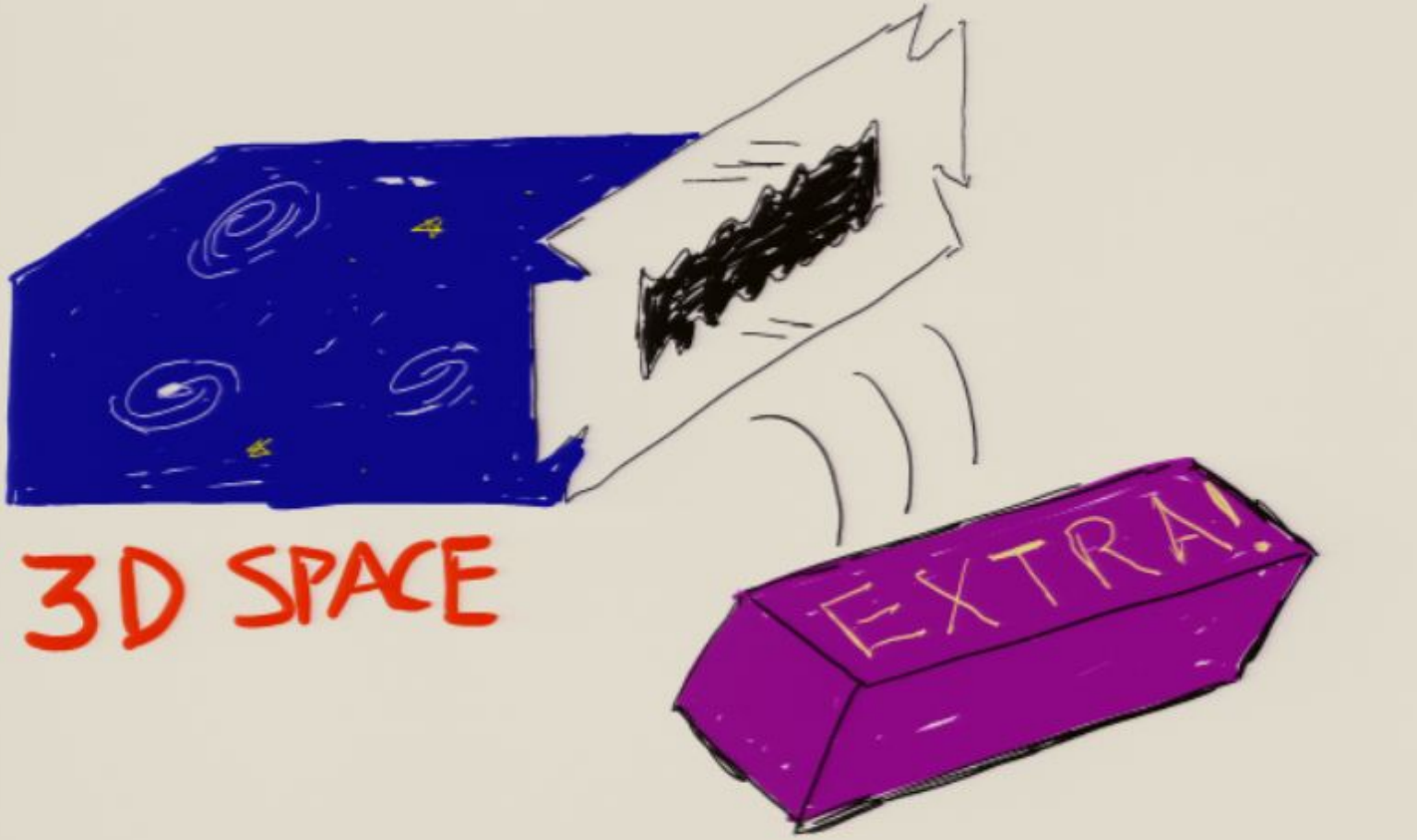


XD WAVEFUNCTIONS, E_{XD} DISCRETIZED

"KALUZA-KLEIN" XD SPECTRUM

(XD Thumbprint)

OCCAM'S RAZOR ?



UNIFICATION

GRAVITY

QUARKS

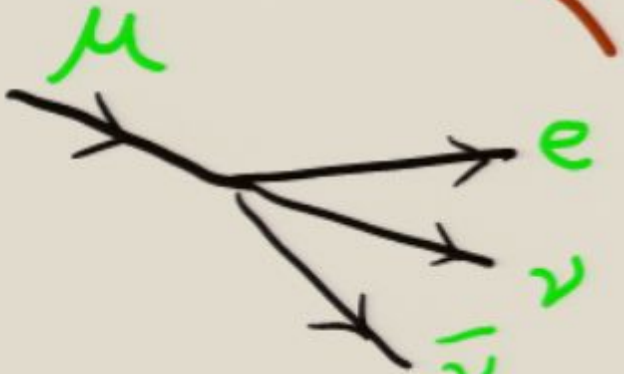
Proton Pion

STRONG INTERACTIONS

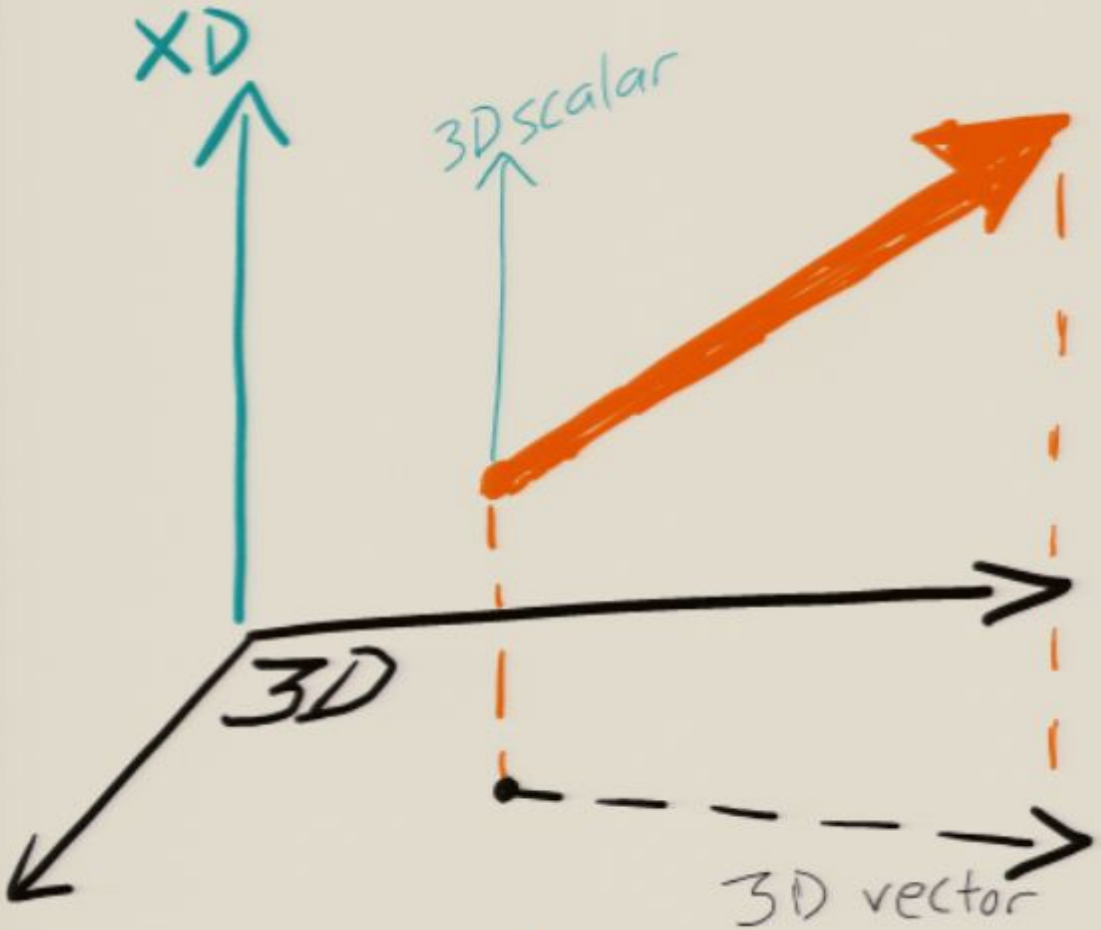
?

ELECTROWEAK INTERACTIONS

ELECTRO-MAGNETISM



HIGHER-DIMENSIONAL VECTORS



Higher Dimensional Electromagnetism

↙ 3D EM

↓ 3D scalar

Nordstrom 1910's = Higgs Boson Hosotani 1983

Higher Dimensional General Relativity

(Cylinder World)

→ 3D General Relativity

→ 3D EM Klein 1930's

BUT ~~DETAILS~~

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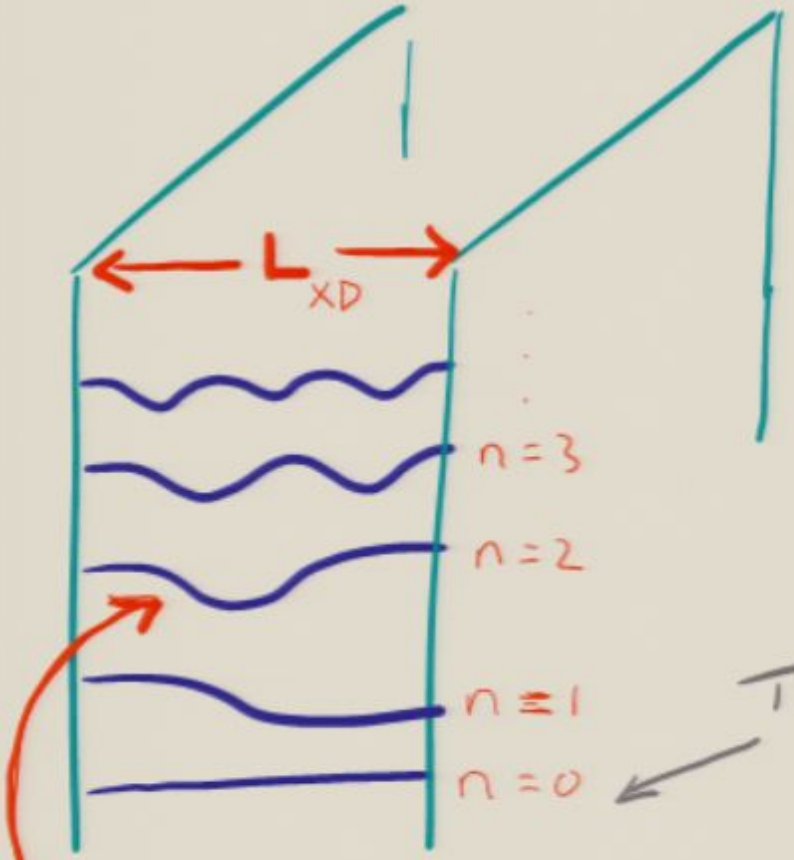

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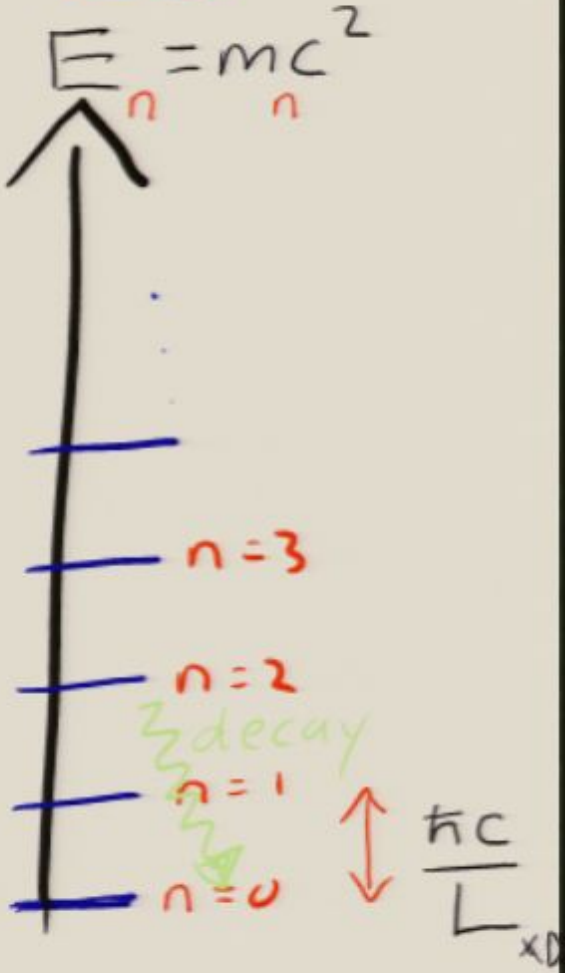

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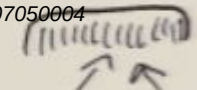

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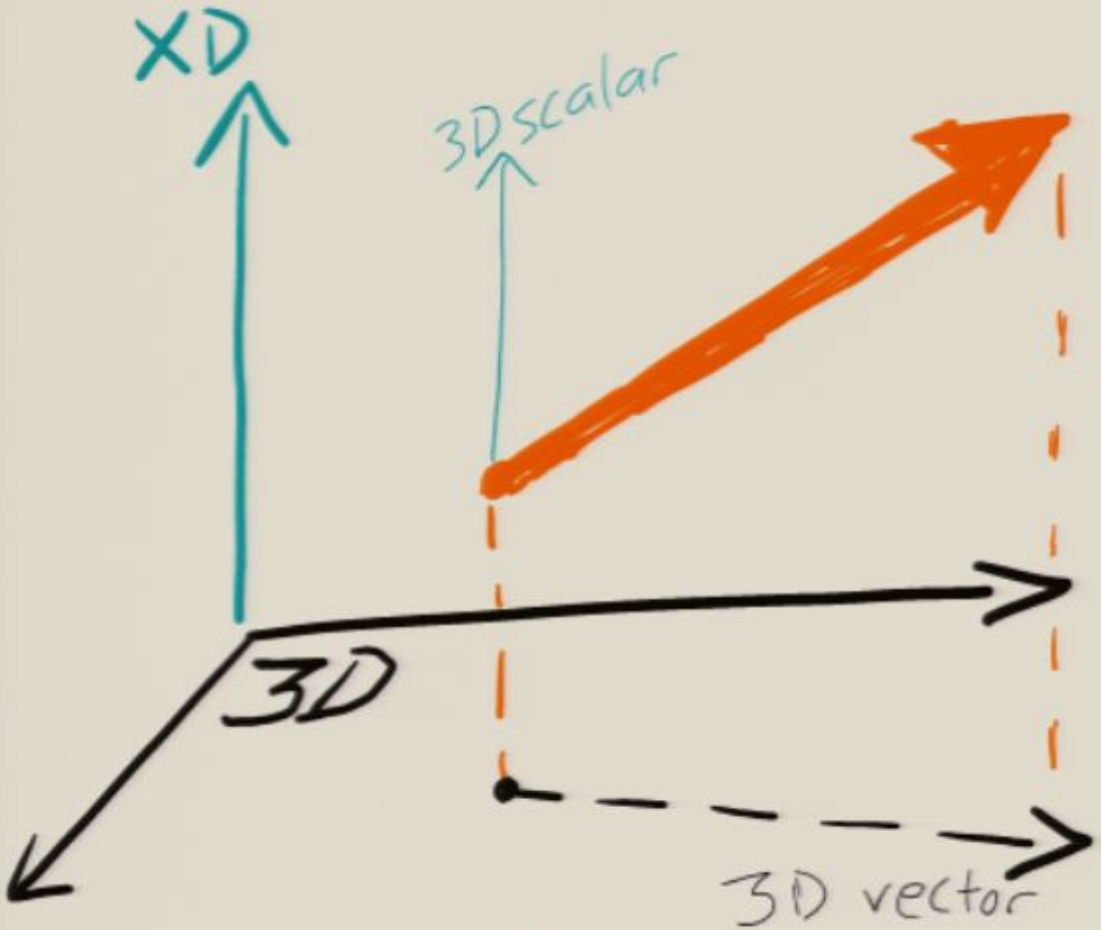

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BUT ~~DETAILS~~

Higher Dimensional General Relativity

(Cylinder World)

→ 3D General Relativity

→ 3D EM

GRAND UNIFICATION...

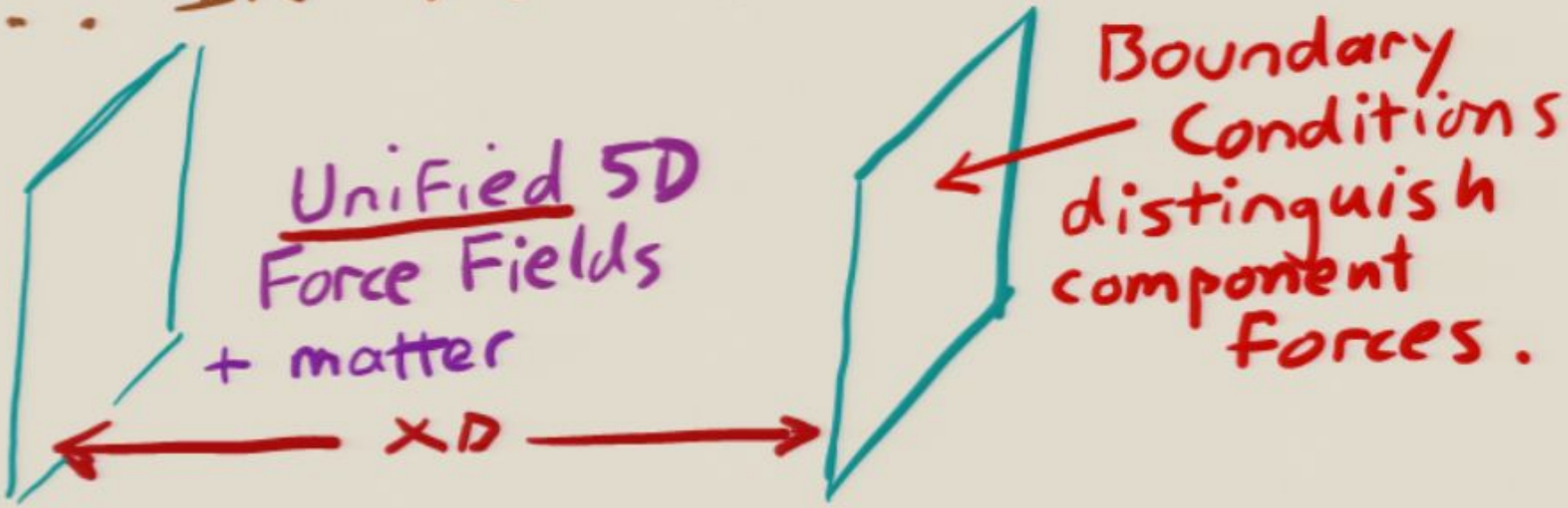
Electromagnetism → ElectroWeak Interactions ← Weak Interactions

Standard Model strong hints

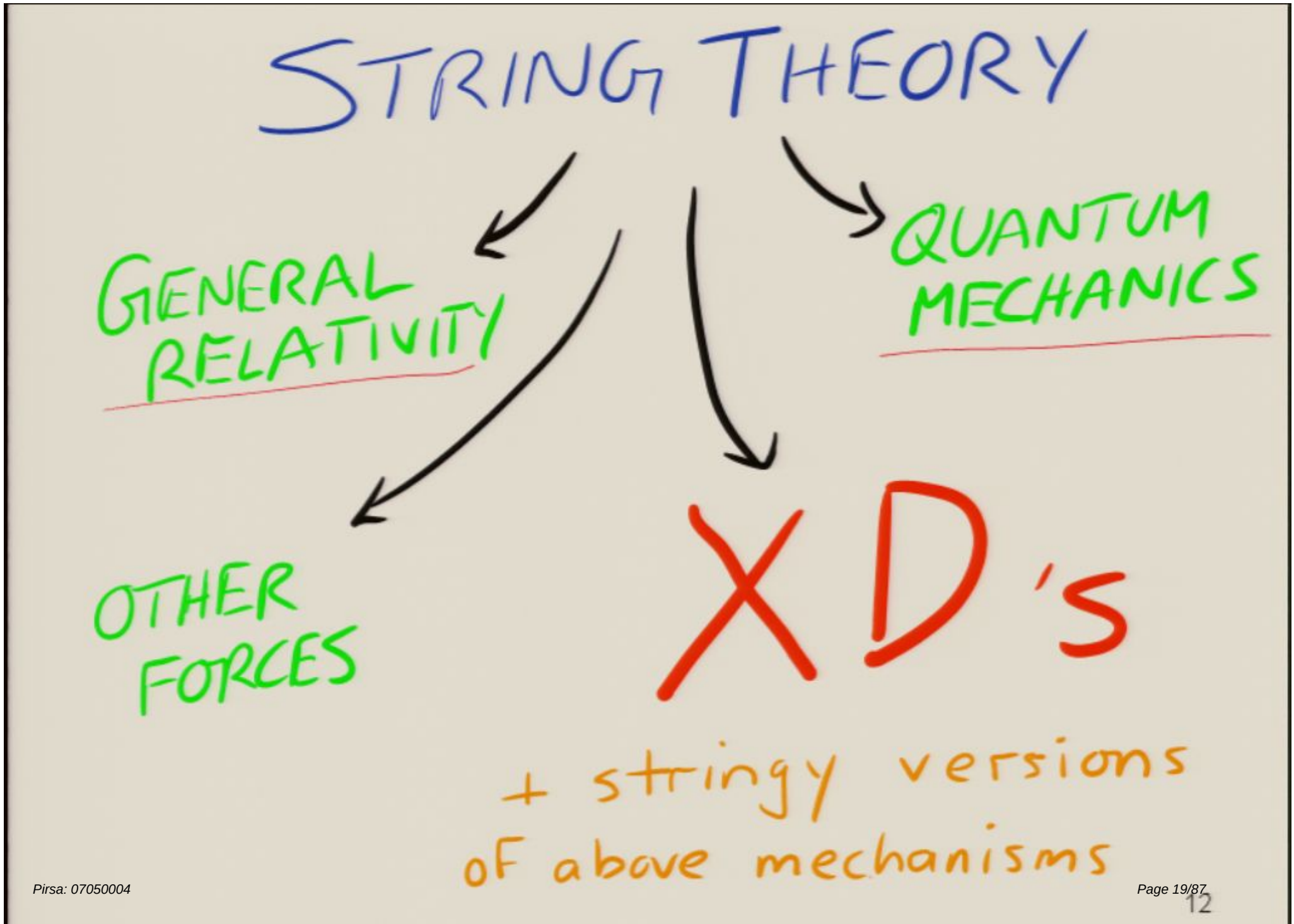
Strong Interactions → Unified Mother Force ← ElectroWeak Interactions

Georgi, Glashow '74

... IN XD "BULK"

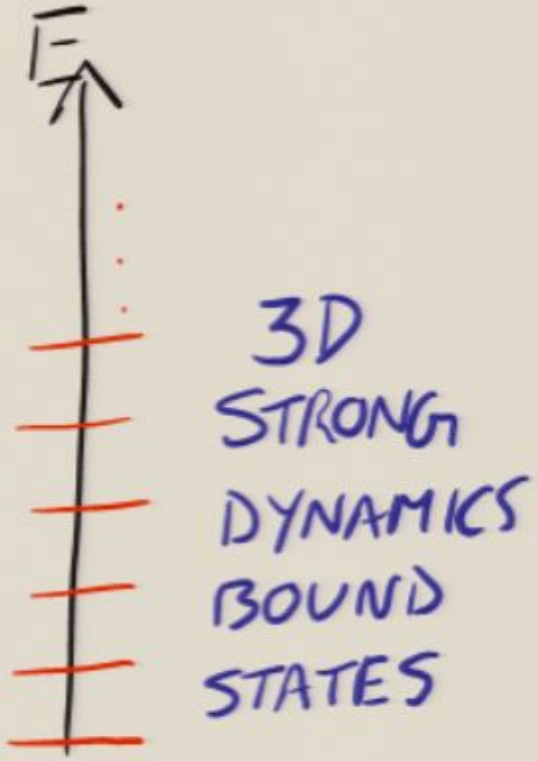


"Orbifold Unification": Kawamura '00; Hall, Nomura '01


STRING THEORY
GENERAL RELATIVITY
QUANTUM MECHANICS
OTHER FORCES
XD's
+ stringy versions
of above mechanisms

EMERGENT XD's

("AdS/CFT"; "Holography")



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XD KALUZA-KLEIN STATES

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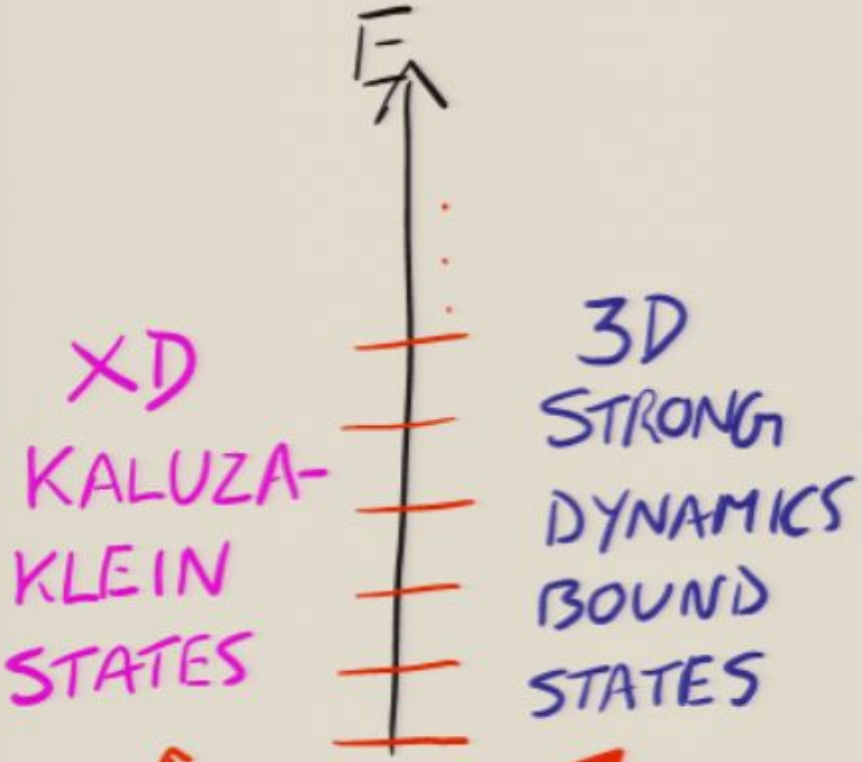

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↳ 't Hooft '93
Susskind '94

XD KALUZA-KLEIN STATES

3D STRONG DYNAMICS BOUND STATES

SOMETIMES EQUIVALENT PHYSICS!

"MOTHER & CHILD" or "SISTERS"?

ILLUSION OF DEPTH DIMENSION

PRIME EXAMPLE

"N = 4 Supersymmetric Yang-Mills Theory"
of many-colored quarks & gluons in (3+1)D

[Cousin of QCD]

is SCALE-INVARIANT

= QUANTUM GRAVITY
(string theory) IN INFINITE
5D CURVED SPACETIME

Maldacena '98
Gubser, Klebanov, Polyakov '98
Witten '98

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ILLUSION OF DEPTH DIMENSION CREATED BY FLAT, SCALE-INVARIANT

$T_{\mu\nu} | 0 \rangle$

5D. spin-2 particle

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CONFORMAL FIELD THEORY

Lorentz invariance $x^\mu \to \Lambda^\mu{}_\nu x^\nu$

Translation inv. $x^\mu \longrightarrow x^\mu + a^\mu$

Scale invariance $x^\mu \longrightarrow \lambda x^\mu$

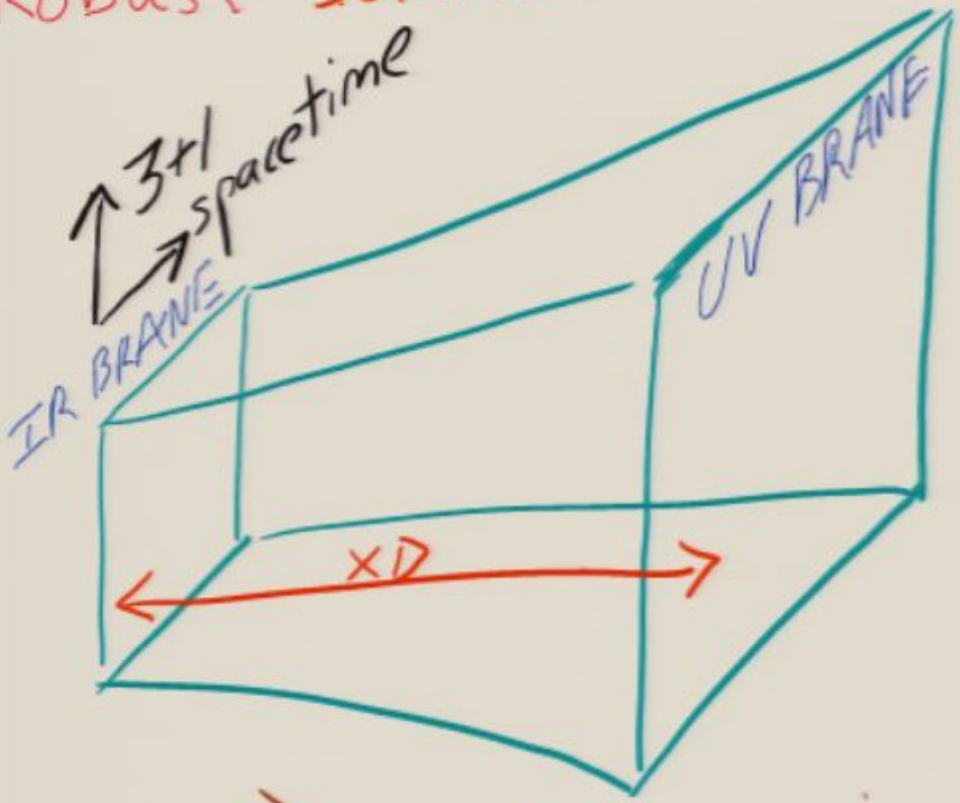
+ Locality $\Longrightarrow$ conjecture

Inversion inv. $x^\mu \longrightarrow x^\mu / x^2$!

$\Rightarrow$ 5D "Lorentz" invariance

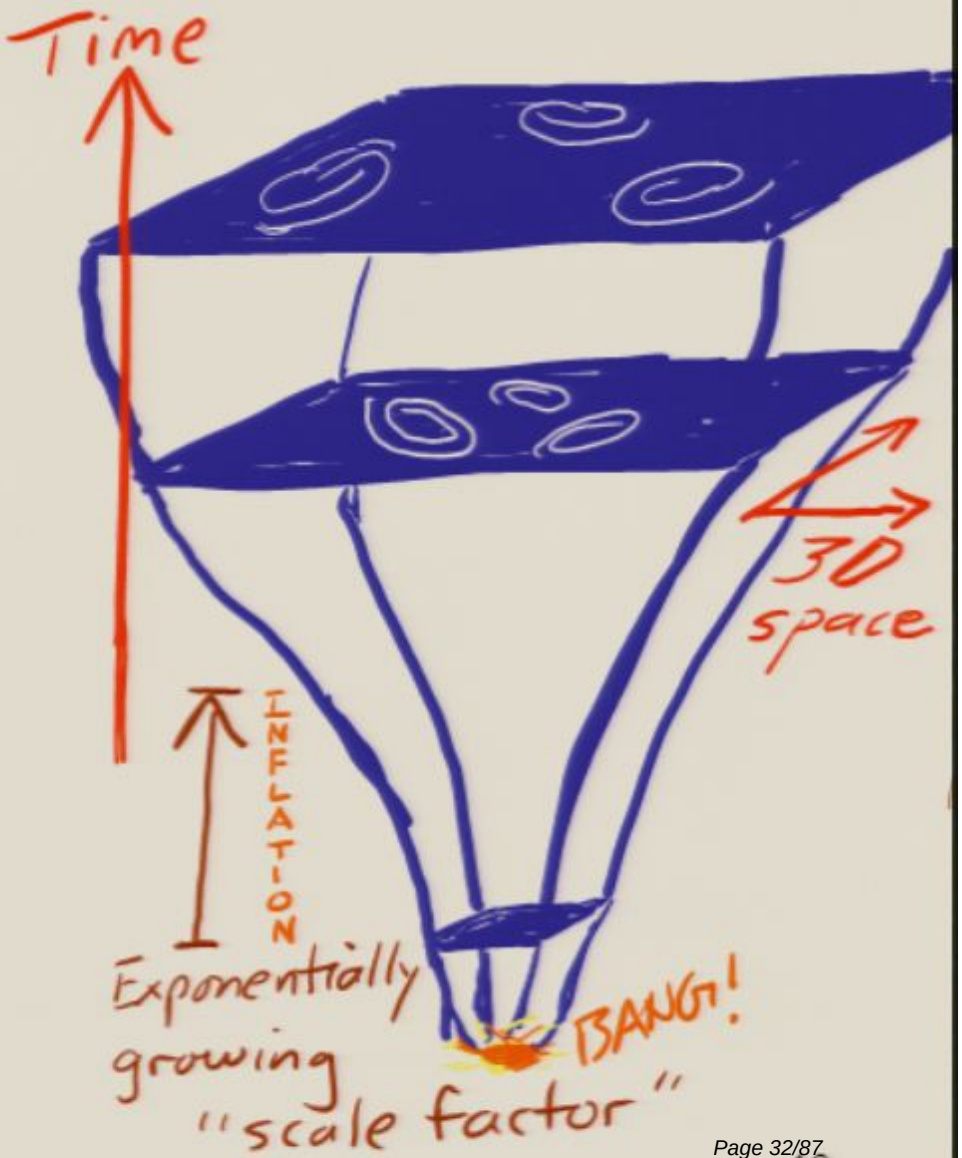
WARPED COMPACTIFICATION

General Relativity
"Parallel Plate Capacitor"
Robust Solution:



Exponentially growing
"Warp factor"

compare with . . .



GEOMETRY

constant radius of curvature

$$ds^2_{|0>} = e^{-2y/R} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

"Warp factor"

Minkowski 4D metric

XD distance

$0 \leq y \leq L_{xD}$

Low-Frequency gravitational modes:

$<< c/R \, , \, c/L_{xD}$

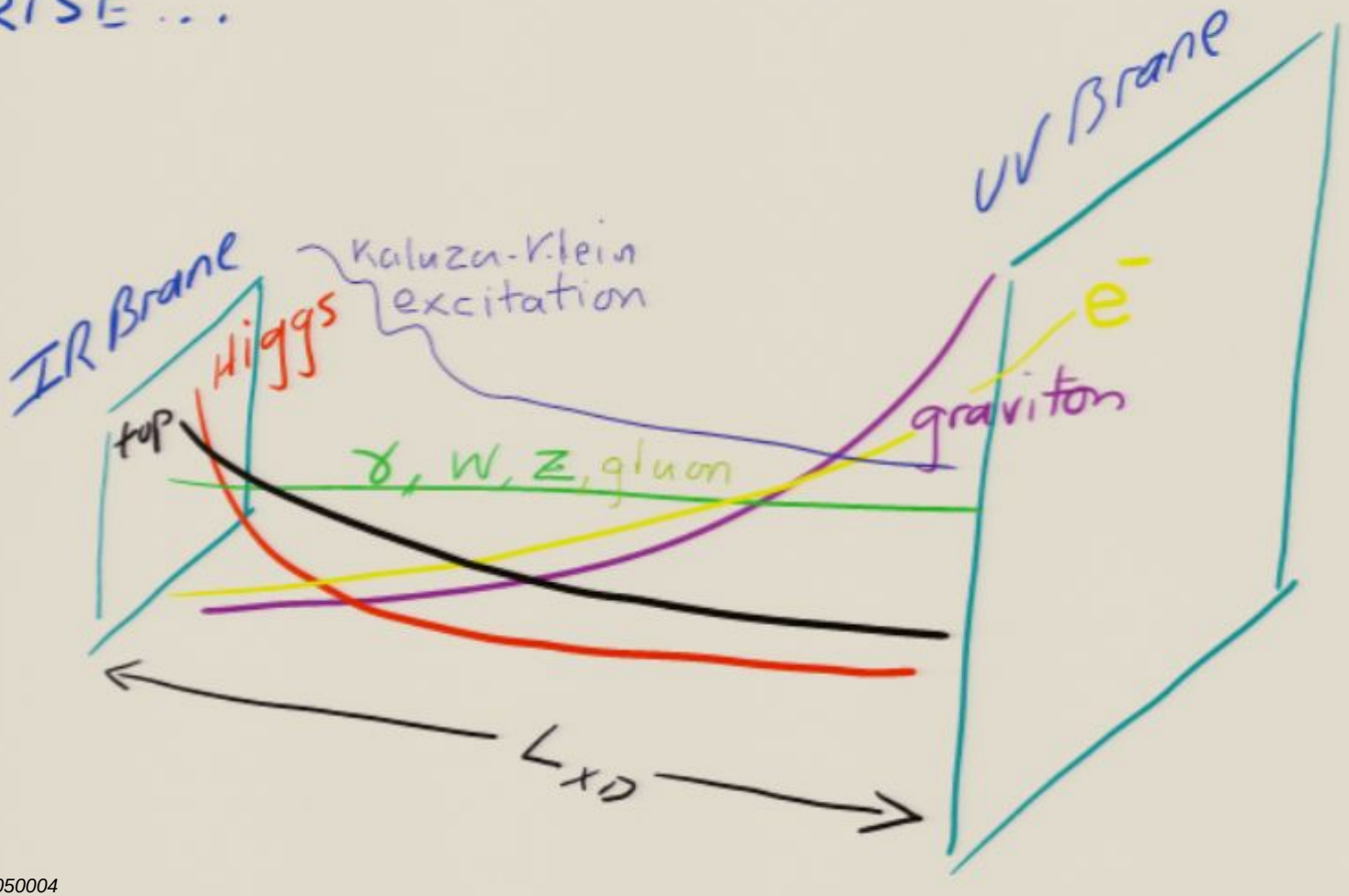
$$ds^2 = e^{-2y/R} g_{\mu\nu}(x) dx^\mu dx^\nu + dy^2$$

locally, Equivalence

WARPED HIERARCHIES

VERY DIFFERENT XD WAVEFUNCTIONS ARISE . . .

⇒ EXPONENTIAL HIERARCHIES IN MASSES & INTERACTIONS FROM WAVEFUNCTION OVERLAPS



GRAVITY'S WEAKNESS

$\frac{F_{gravity}}{F_{electric}} < 10^{-30}$ for known elementary charges

but $\sim O(1)$ "messy" quantum corrections in Standard Model

$\equiv$ "Hierarchy Problem"

Higgs condensate of vacuum = Lorentz-invariant "aether" slows elementary charges < light-speed

$\Longrightarrow$ Masses $\propto_{\text{Warped XD}} e^{-L_{XD}/R}$ by length rescaling

$F \propto G_{mm} \propto e^{-2L_{XD}/R} \ll 1$ hierarchy

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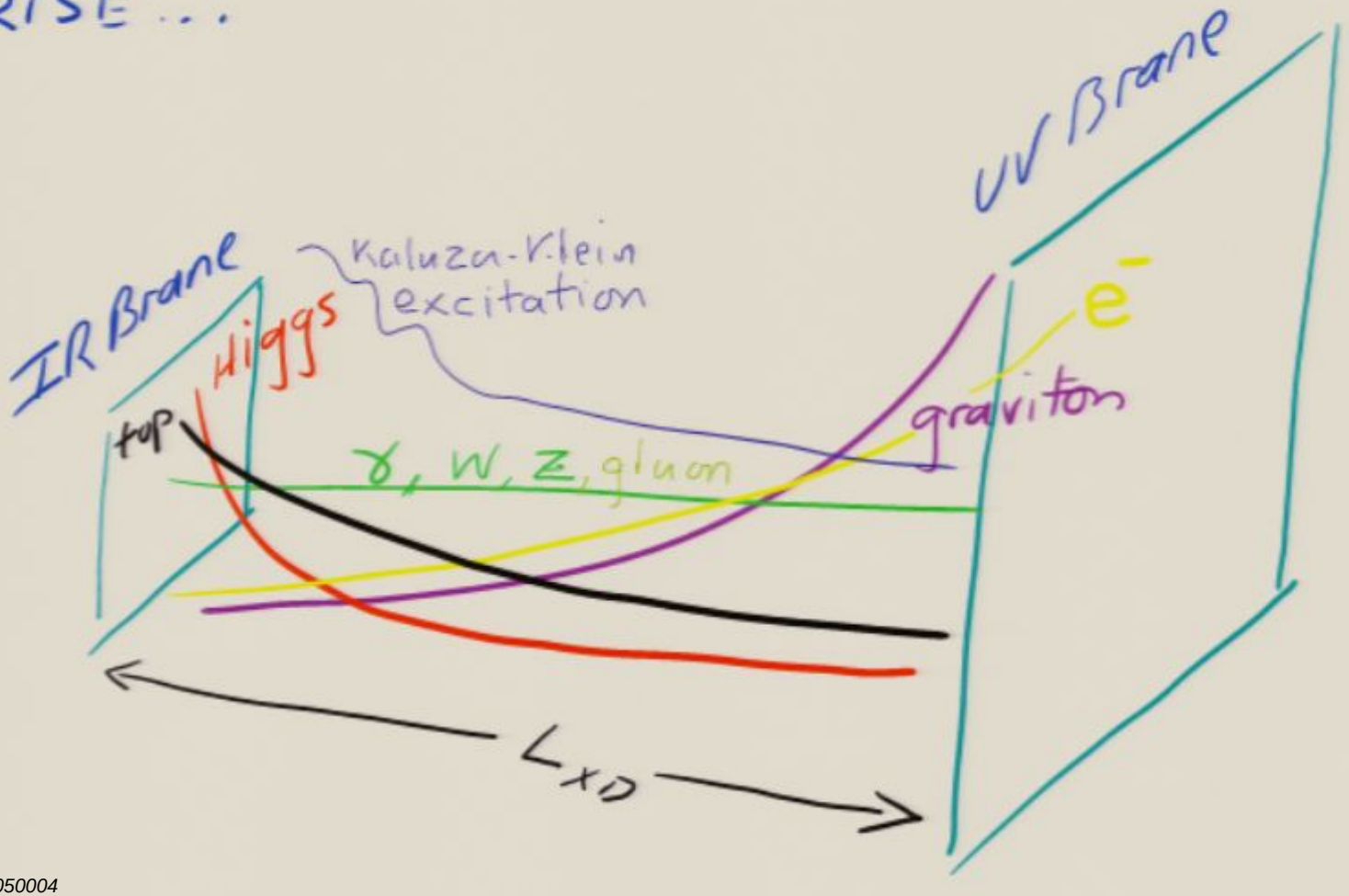

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WEAKNESS OF GRAVITY

$\frac{F_{gravity}}{F_{electric}} < 10^{-30}$ between known elementary charges

Standard Model $\Rightarrow O(1)$ quantum corrections

EXPLAINED BY $\sim e^{-L_{xD}}$

HIGGS-GRAVITON WAVEFUNCTION OVERLAP

$\Downarrow$ Elementary Particle Masses

+ Hidden ElectroWeak Unification

via Bose-Einstein condensate of Higgs particles in "vacuum".

[Distinct from, but partly motivated by "Large Extra Dimensions" Arkani-Hamed Dimopoulos, Dvali '98]

CHAOS ON THE BORDERS

NON-GRAVITATIONAL FORCE FIELDS:

Boundary Conditions

Neumann Neumann ⟶ Long-Range Forces

Dirichlet Dirichlet ⟶ Nambu-Goldstone Bosons, axions, ...

Dirichlet Neumann ⟶ Higgs mechanism, Short-Range forces

Neumann Dirichlet ⟶ Conservation Laws, Baryon No., Custodial Isospin ...

FERMION WAVEFUNCTIONS ⟹ HIERARCHICAL MASSES CORRELATED WITH FLAVOR-CHANGING TRANSITIONS

Grossman, Neubert '00
Pomarol, Gherghetta '00

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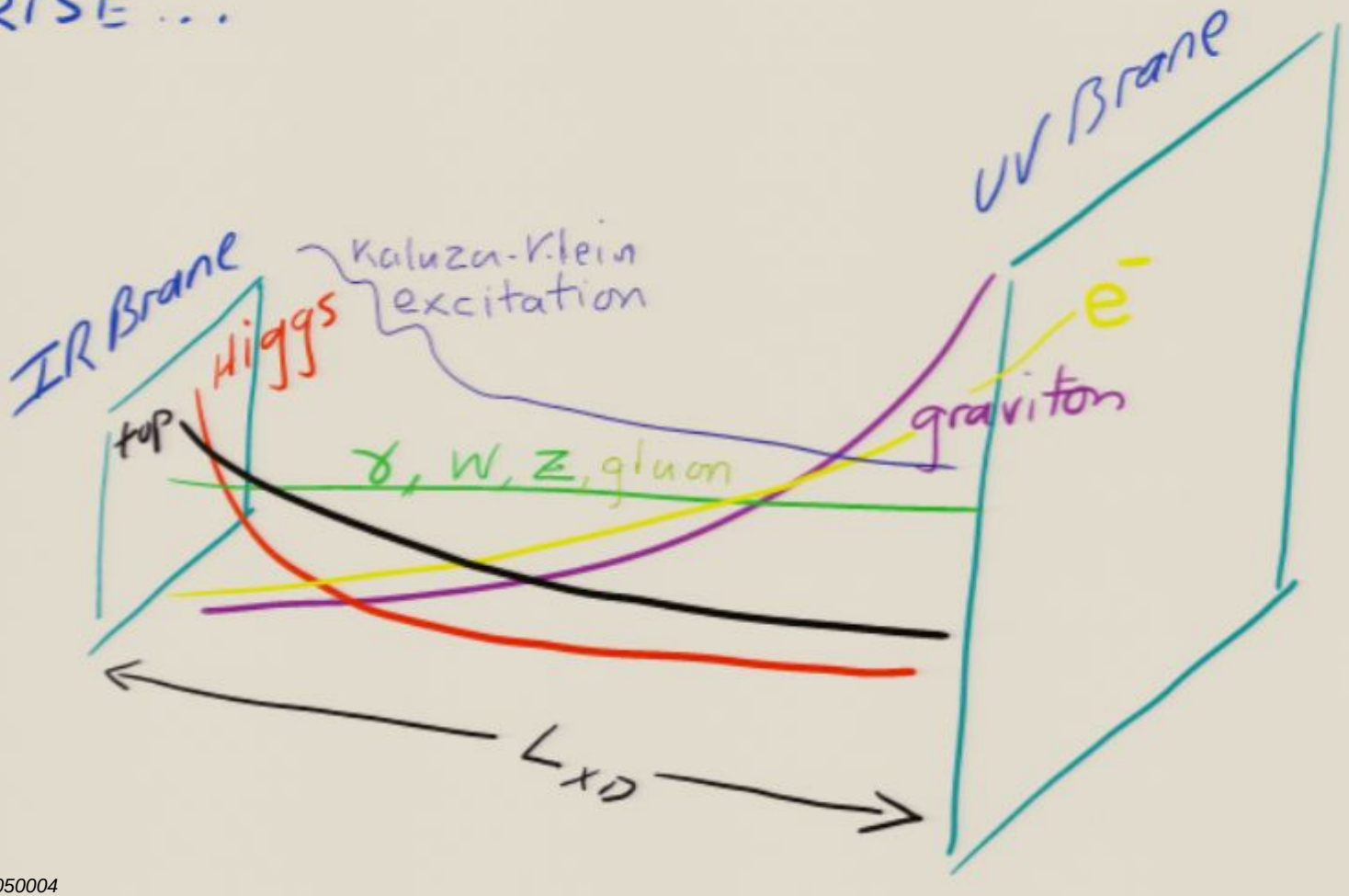

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Grossman, Neubert '00
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$T_{\mu\nu} |0\rangle$

$\updownarrow$

G_N 5D. spin-2 particle

$m_{5D} = 0_1$

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M_{Pl} G_N 5D spin-2 particle

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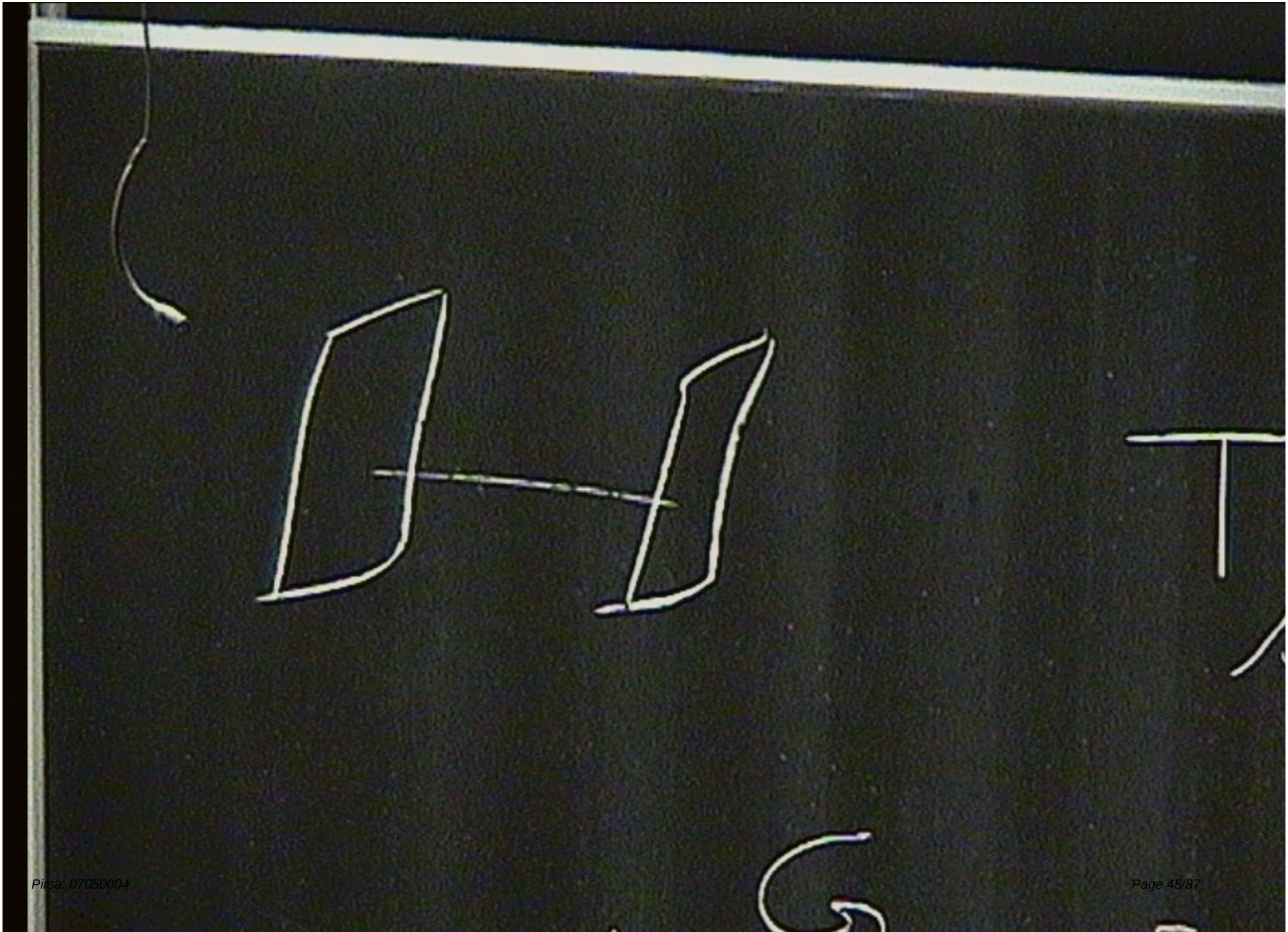

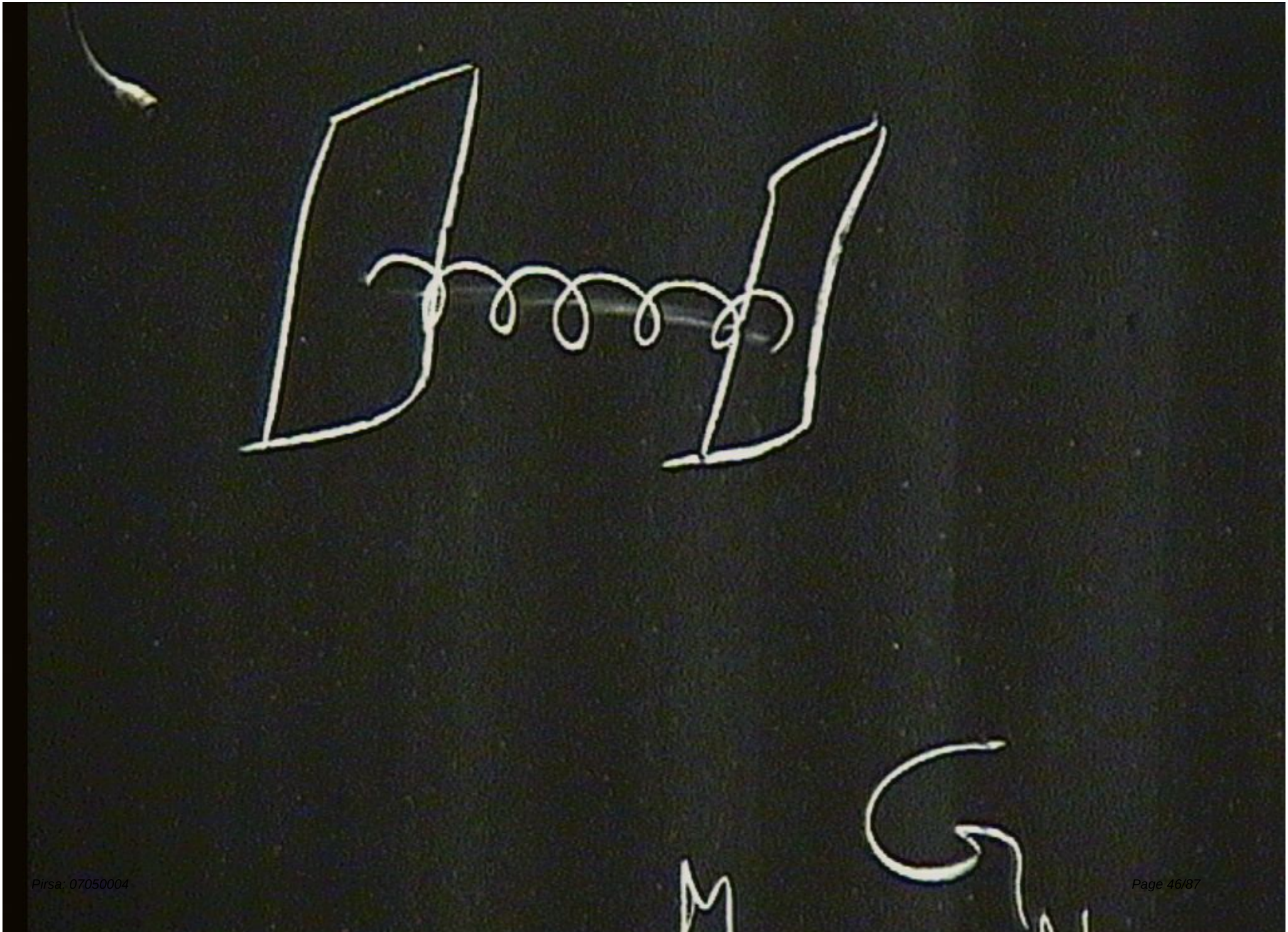

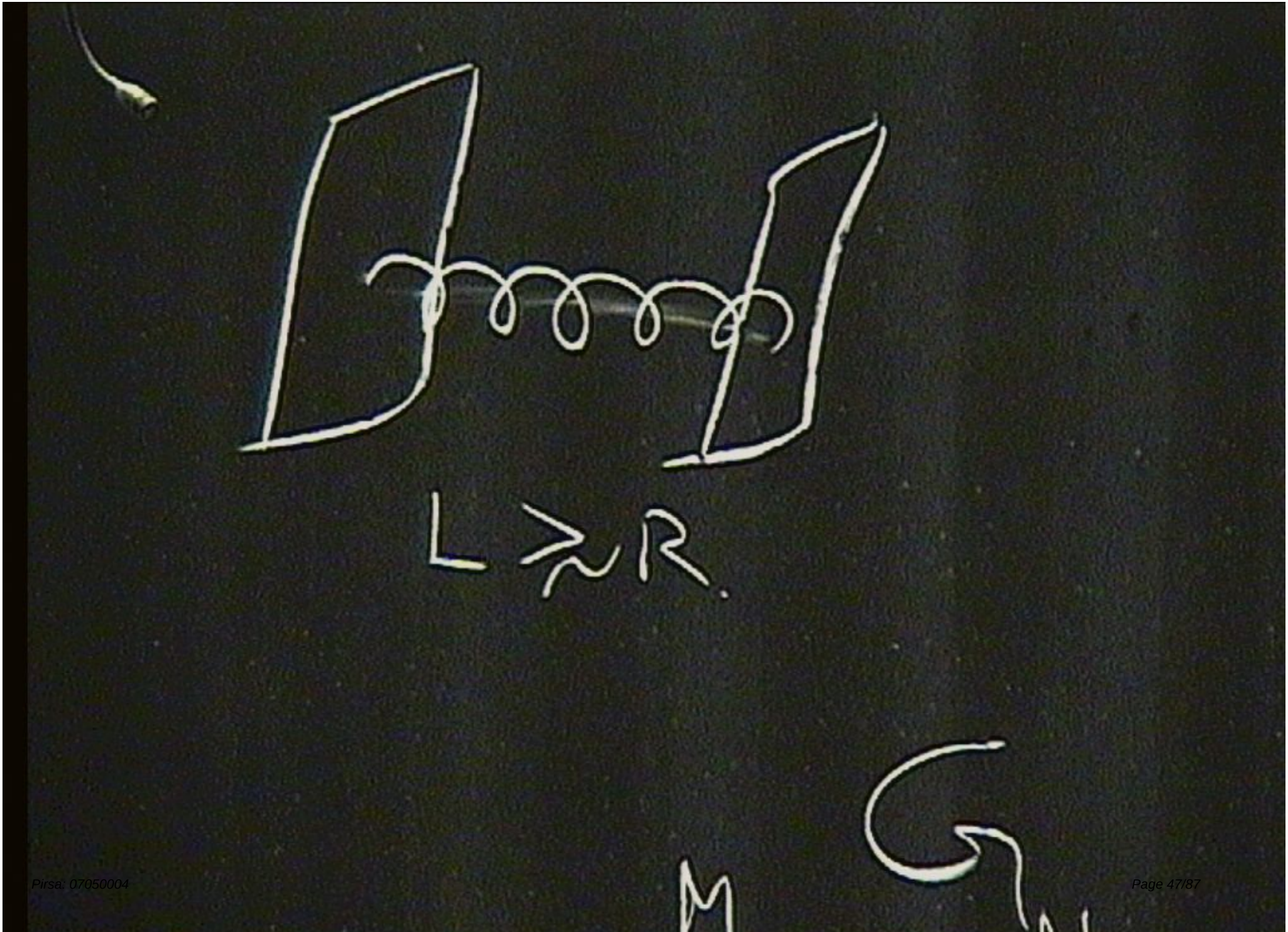
L ≥ R.

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Grossman, Neubert '00
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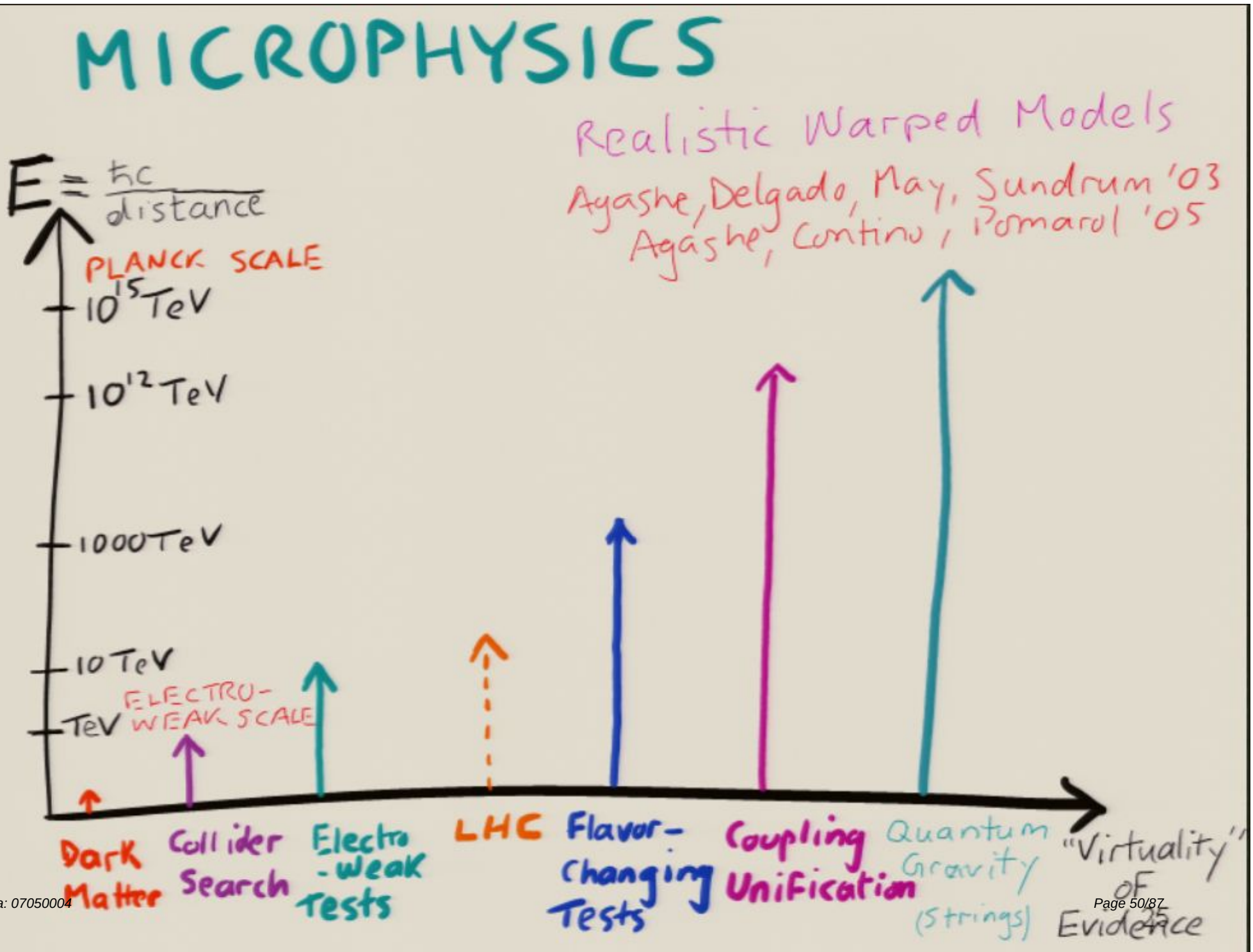

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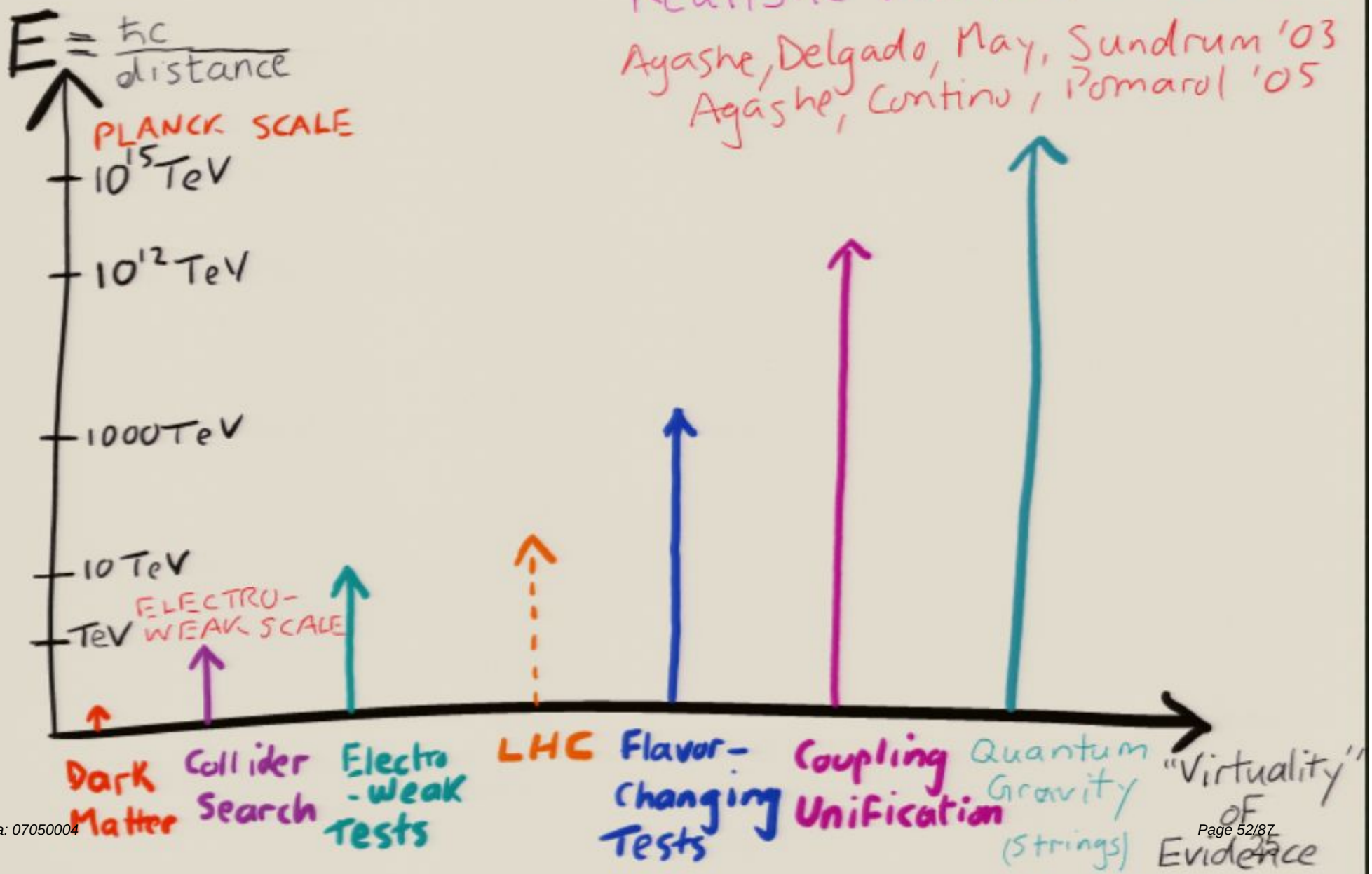
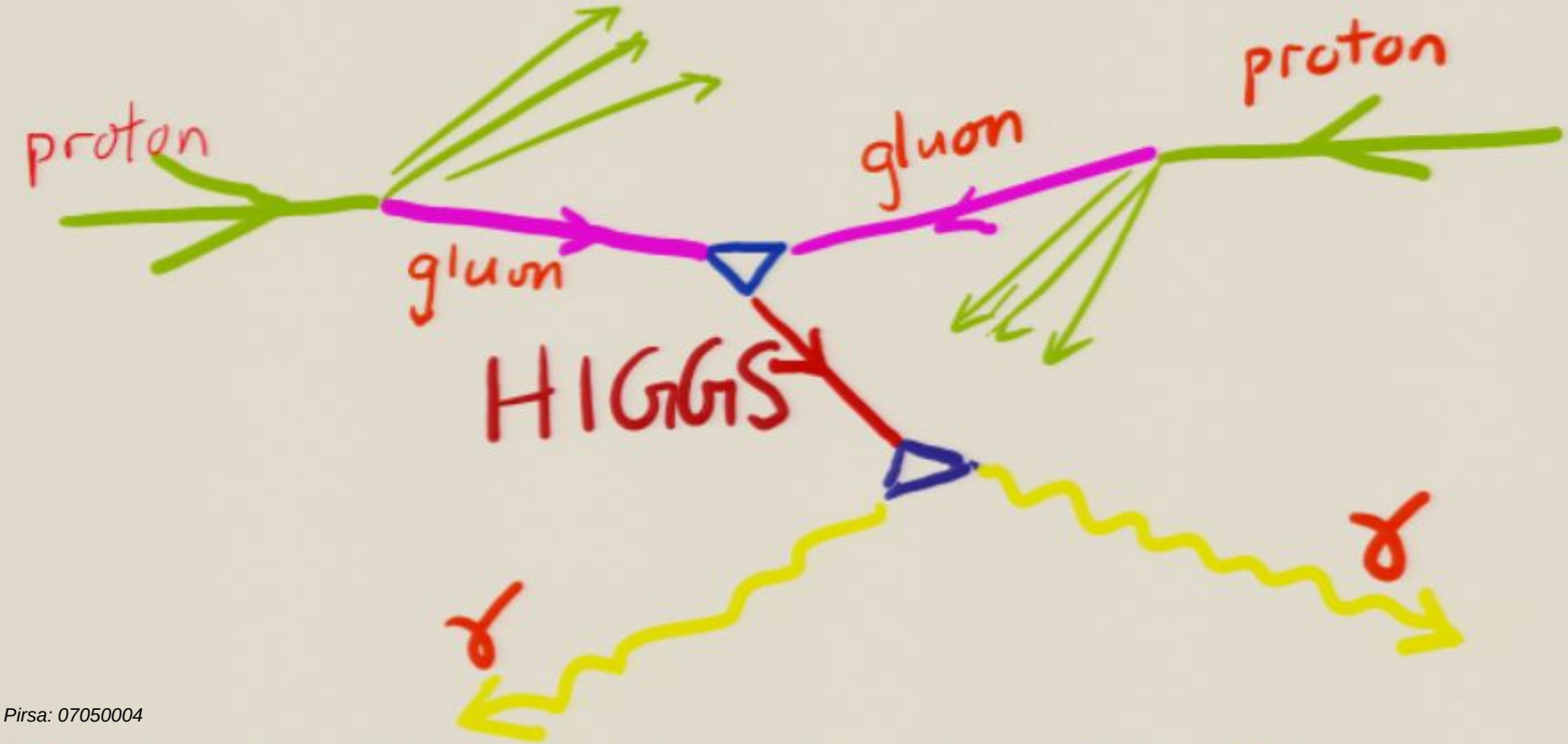


TeV-SCALE COLLIDER SEARCH FOR MISSING LINK OF ELECTRO-WEAK UNIFICATION

@ FERMILAB TEVATRON, CERN LARGE HADRON COLLIDER



SHOULD THEN BE ACCOMPANIED BY ...

CHAOS ON THE BORDERS

NON-GRAVITATIONAL FORCE FIELDS:

Boundary Conditions

Neumann Neumann ⟶ Long-Range Forces

Dirichlet Dirichlet ⟶ Nambu-Goldstone Bosons, axions, ...

Dirichlet Neumann ⟶ Higgs mechanism, Short-Range forces

Neumann Dirichlet ⟶ Conservation Laws, Baryon No., Custodial Isospin ...

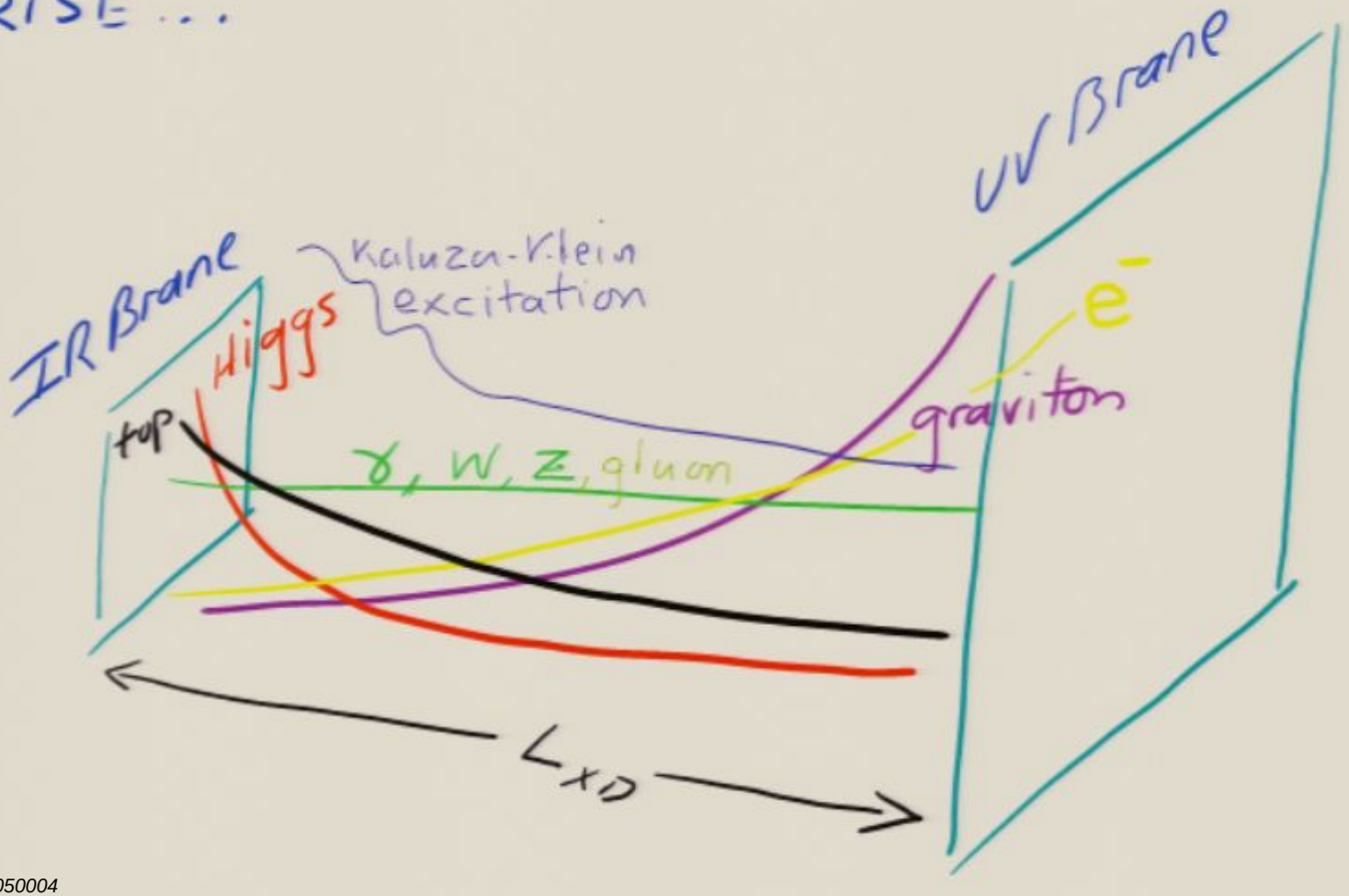
FERMION WAVEFUNCTIONS ⟹ HIERARCHICAL MASSES CORRELATED WITH FLAVOR-CHANGING TRANSITIONS

Grossman, Neubert '00
Pomarol, Gherghetta '00

WARPED HIERARCHIES

VERY DIFFERENT XD WAVEFUNCTIONS ARISE . . .

⇒ EXPONENTIAL HIERARCHIES IN MASSES & INTERACTIONS FROM WAVEFUNCTION OVERLAPS



GRAVITY'S WEAKNESS

$\frac{F_{gravity}}{F_{electric}} < 10^{-30}$ for known elementary charges

but $\sim O(1)$ "messy" quantum corrections in Standard Model

$\equiv$ "Hierarchy Problem"

Higgs condensate of vacuum = Lorentz-invariant "aether" slows elementary charges < light-speed

$\Longrightarrow$ Masses $\propto_{\text{Warped XD}} e^{-L_{XD}/R}$ by length rescaling

$F \propto G_{mm} \propto e^{-2L_{XD}/R} \ll 1$ hierarchy

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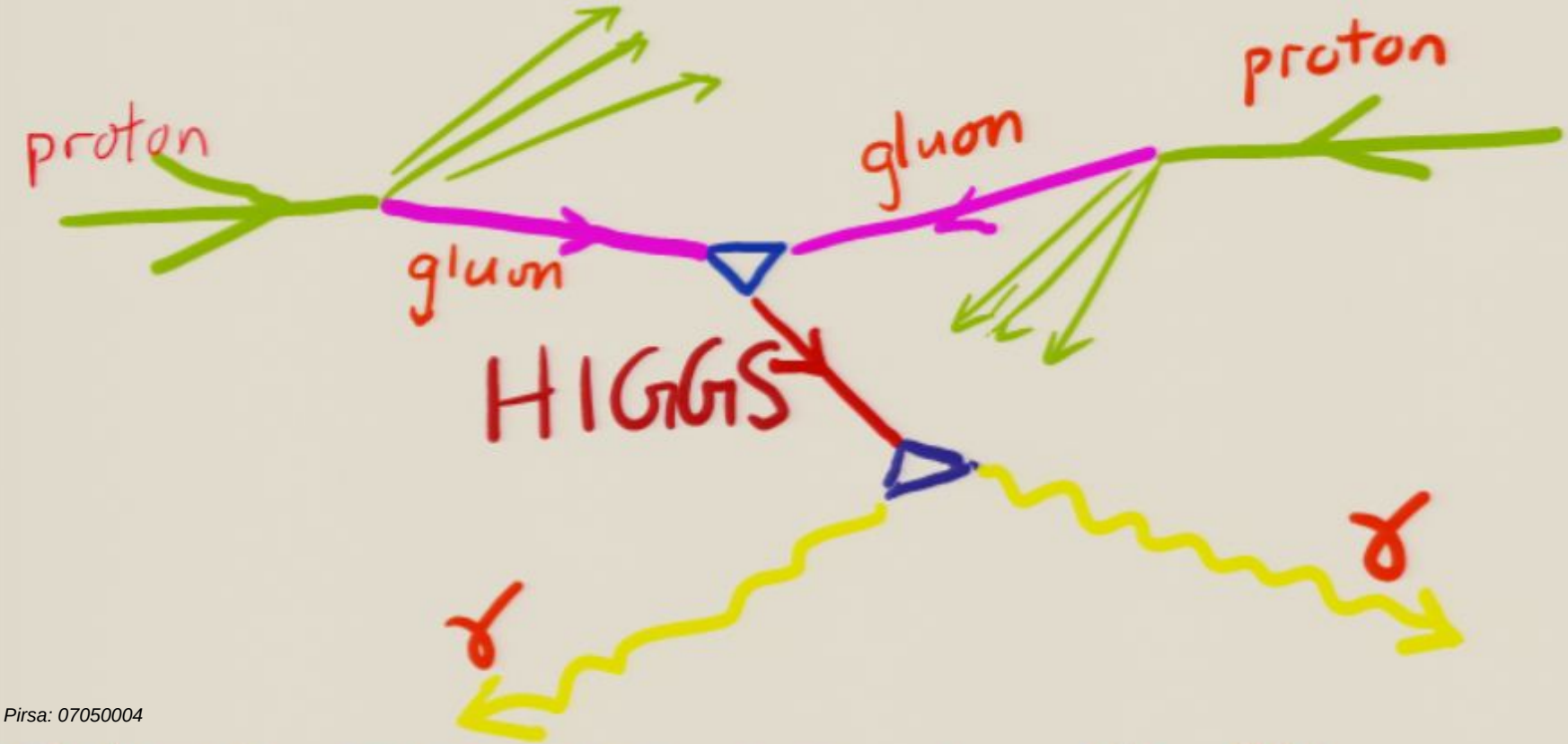

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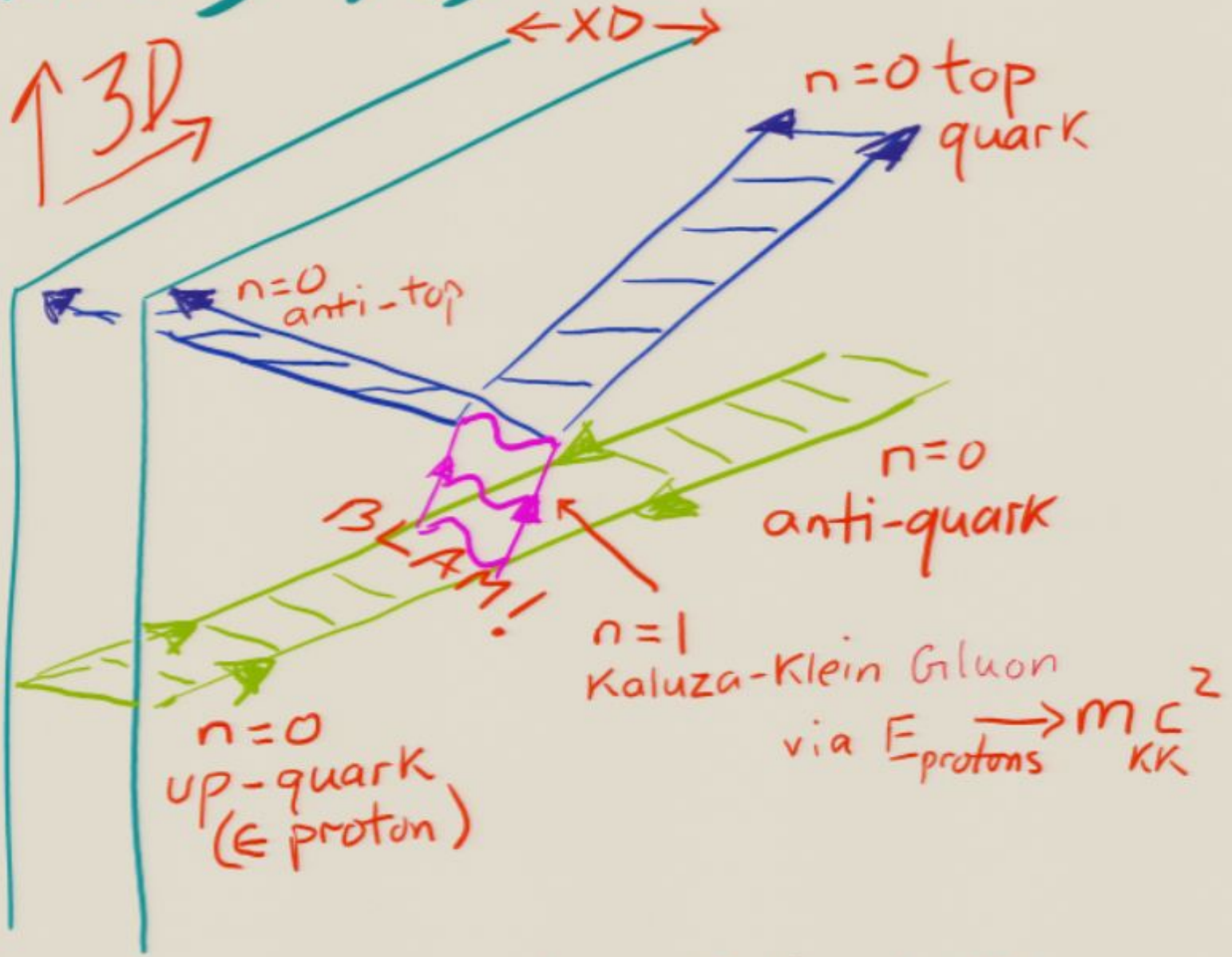
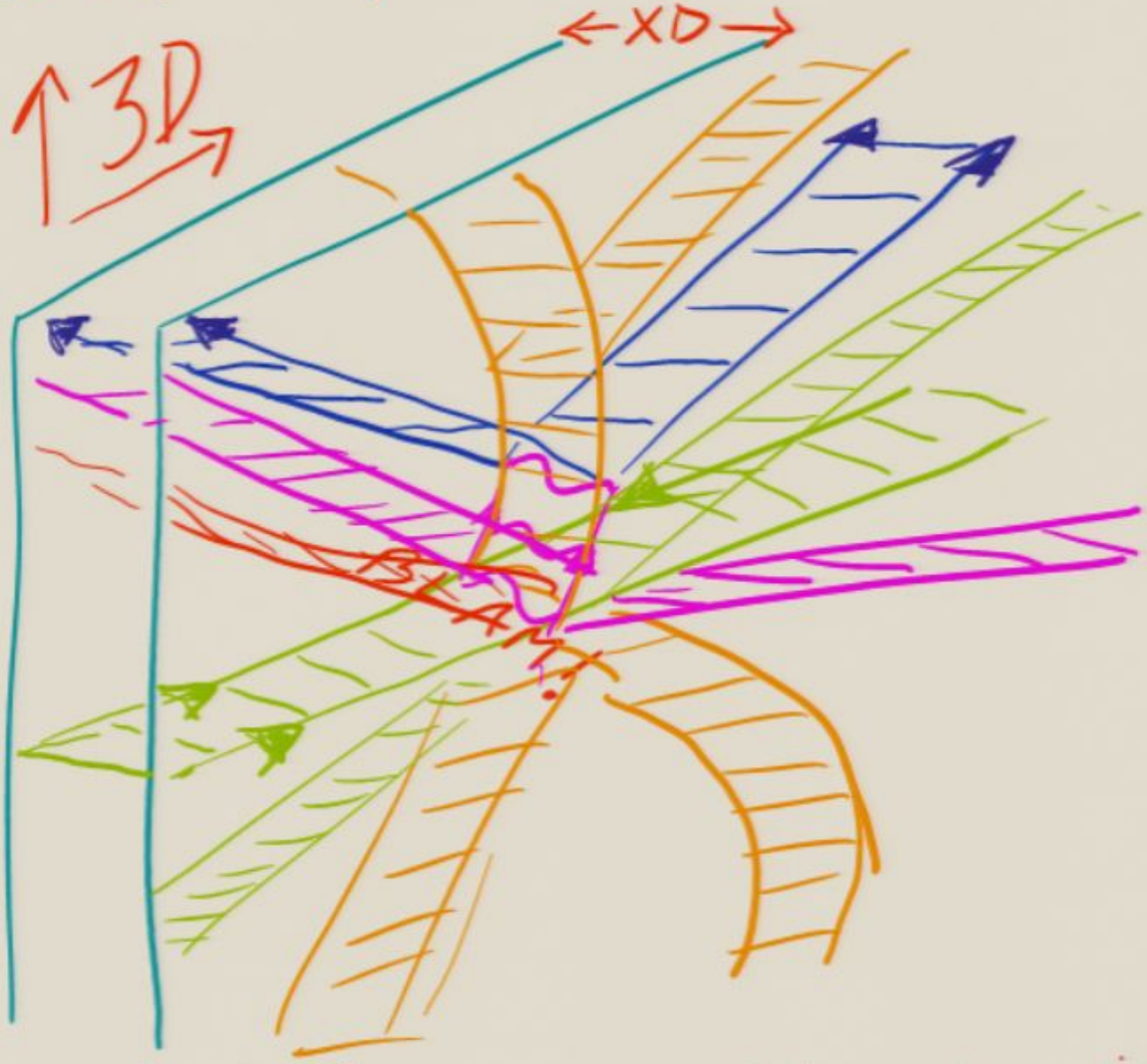
. . . WARPED XDs @ LHC



Simplified description of LHC

MESSIER, IN PRACTICE ...



KK Gluon Search Strategy

Agashe, Belyaev, Krupovnickas
Perez, Virzi '06

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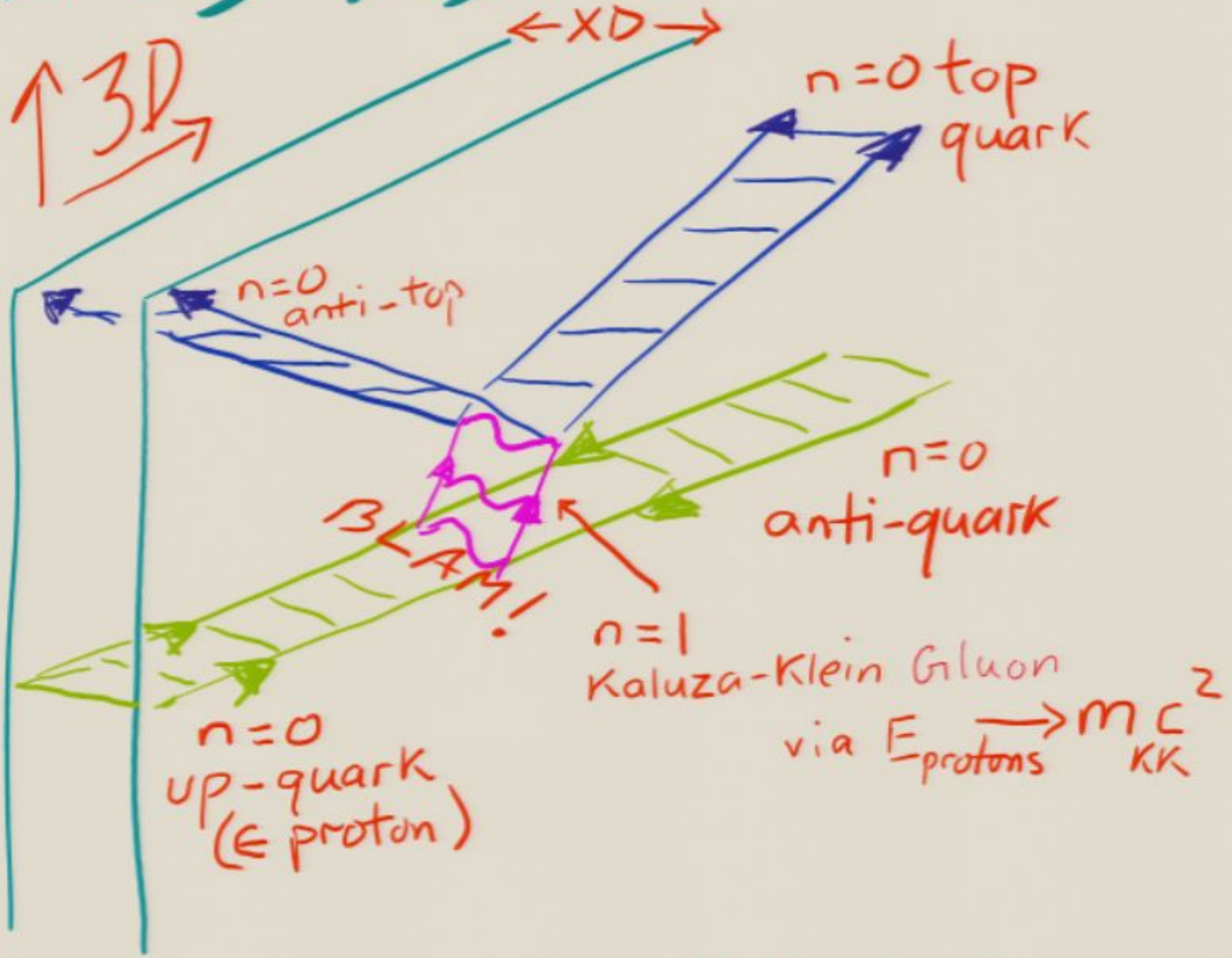

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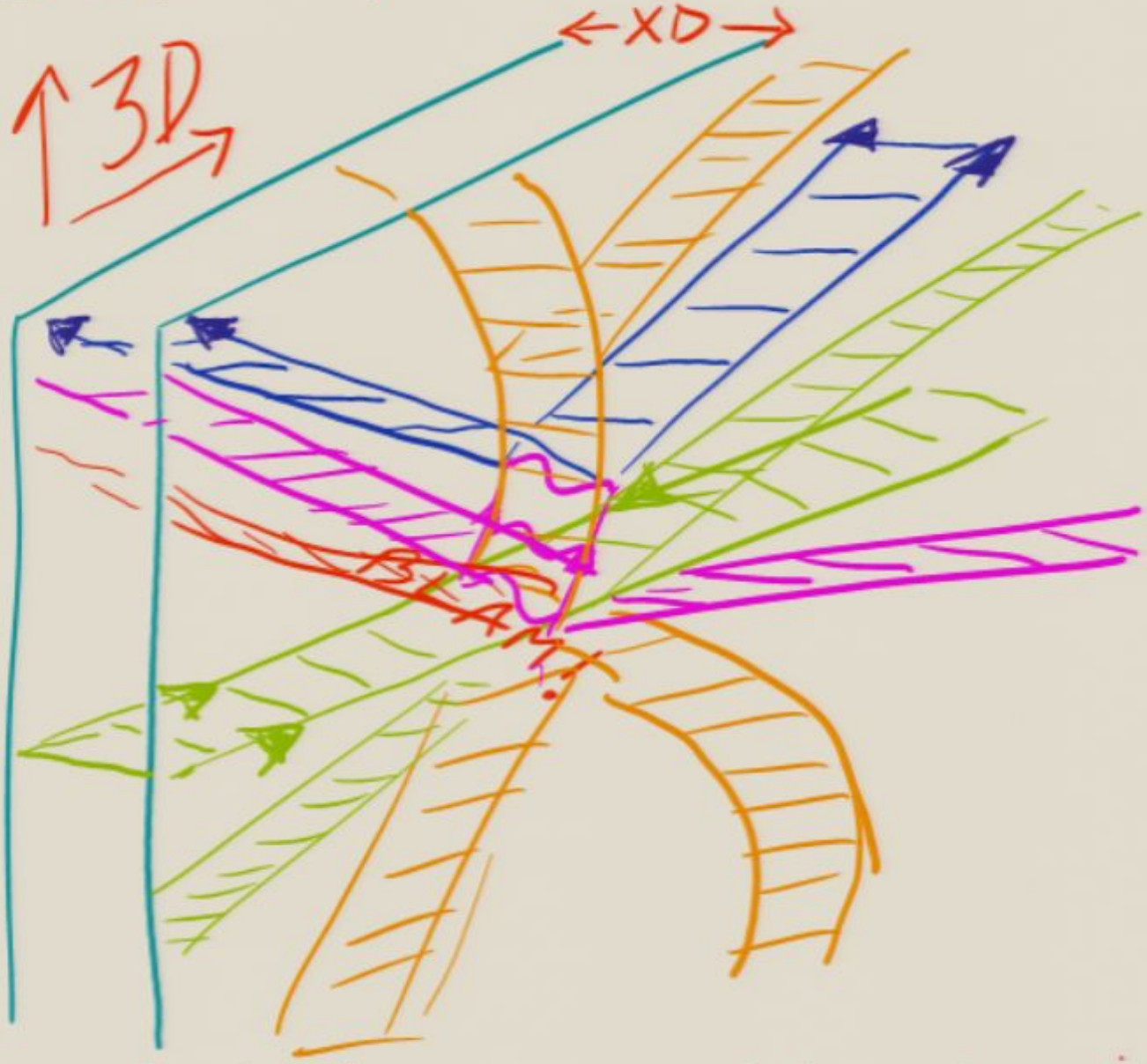

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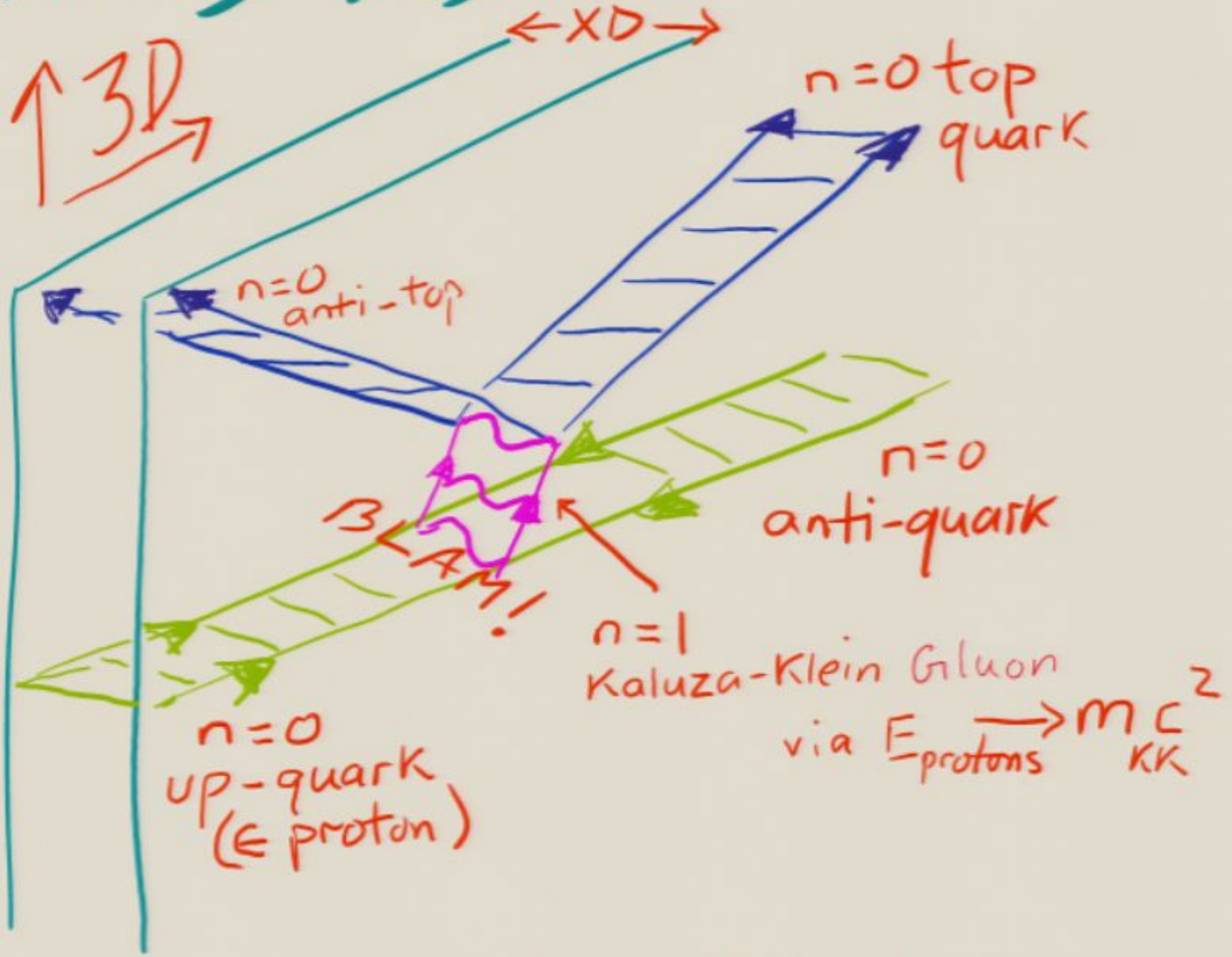

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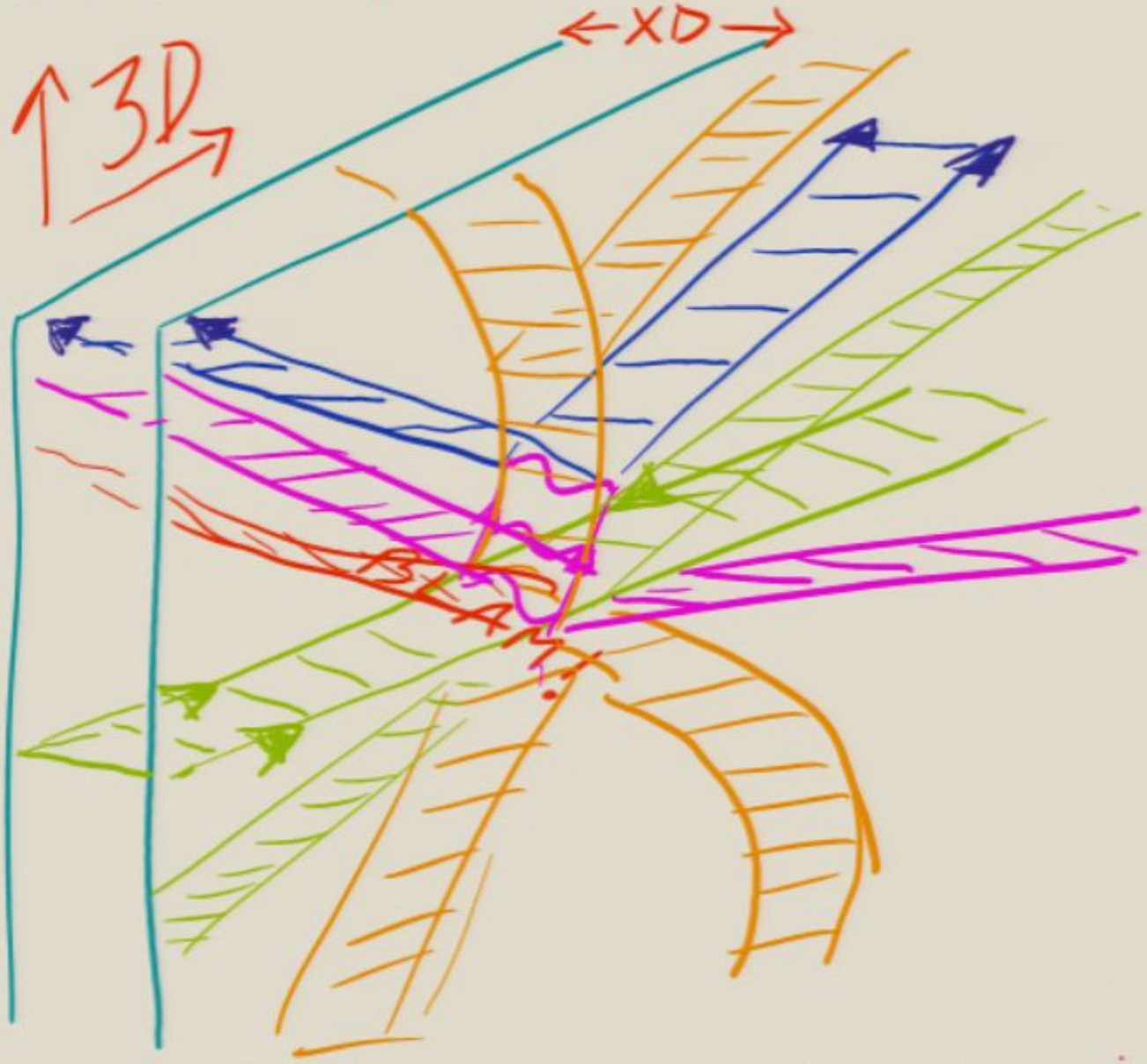

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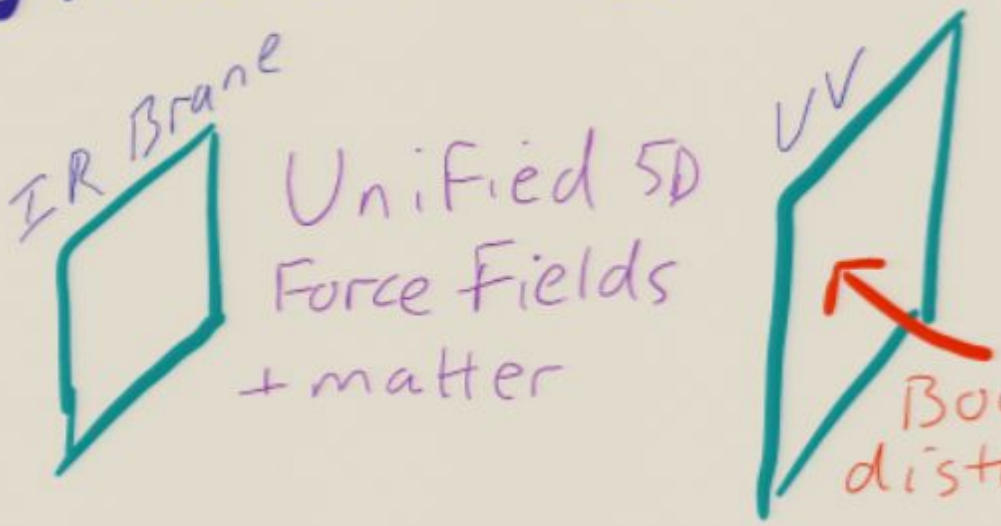
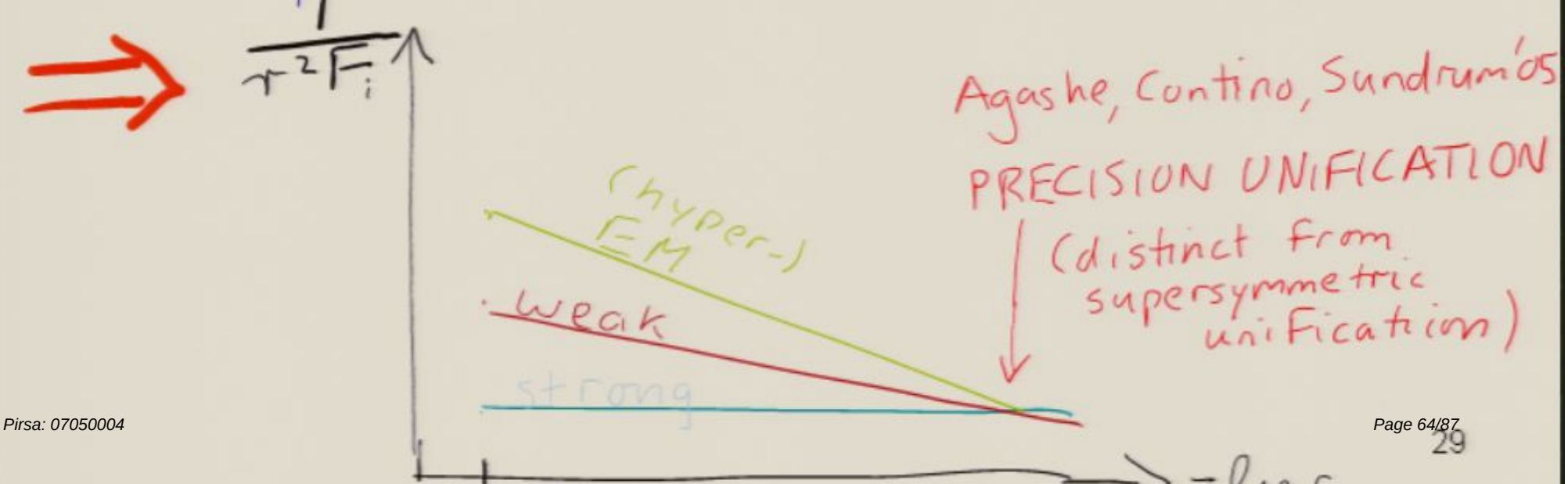


Pomarol '00

⋮

Fit to precision electroweak data



Agashe, Contino, Sundrum '05

PRECISION UNIFICATION

(distinct from supersymmetric unification)

⇒ DARK MATTER

Baryon No. conservation naturally stabilizes exotic particles eg. ~100 GeV ↔ top quark.
unification

RELIC ABUNDANCE of such WIMPs naturally accounts for Dark Matter. Agashe, Servant '04

COLLIDER SYNTHESIS

DIRECT DETECTION

INDIRECT DETECTION(?)

Dark Matter annihilation

LHC, Precision study

≡ PARTIAL COMPOSITENESS

AdS/CFT

D.B. Kaplan '91

Standard quarks, $e^-, \mu, \gamma, W^+, Z^0 \ldots$

$= \alpha |\ ; \rangle + \beta |$  $\rangle$

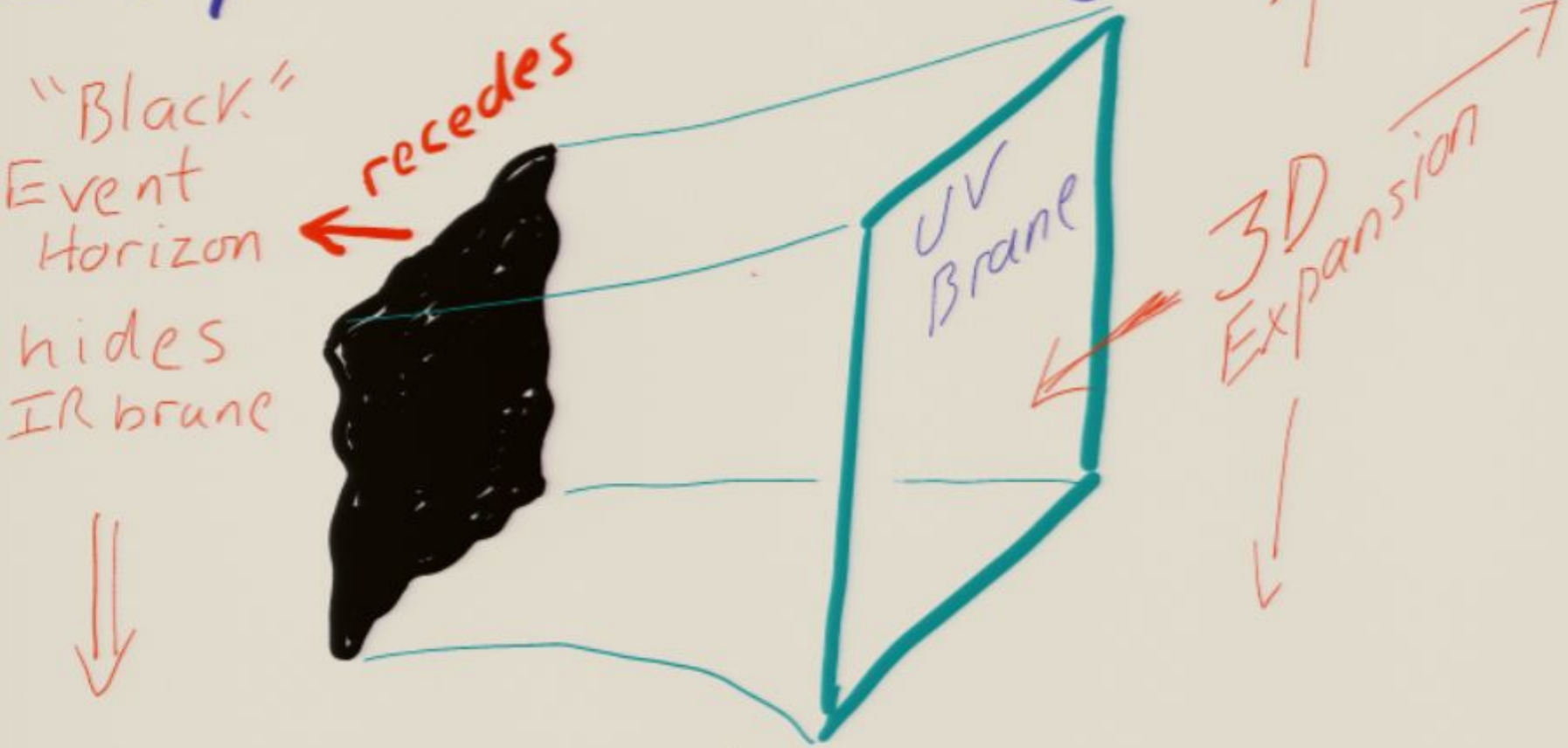
Point-Particle

Composite Particle of NEW STRONG DYNAMICS

ELECTROWEAK PHASE TRANSITION

(Baryogenisis?)

Early Universe at high T



ElectroWeak Unification manifest

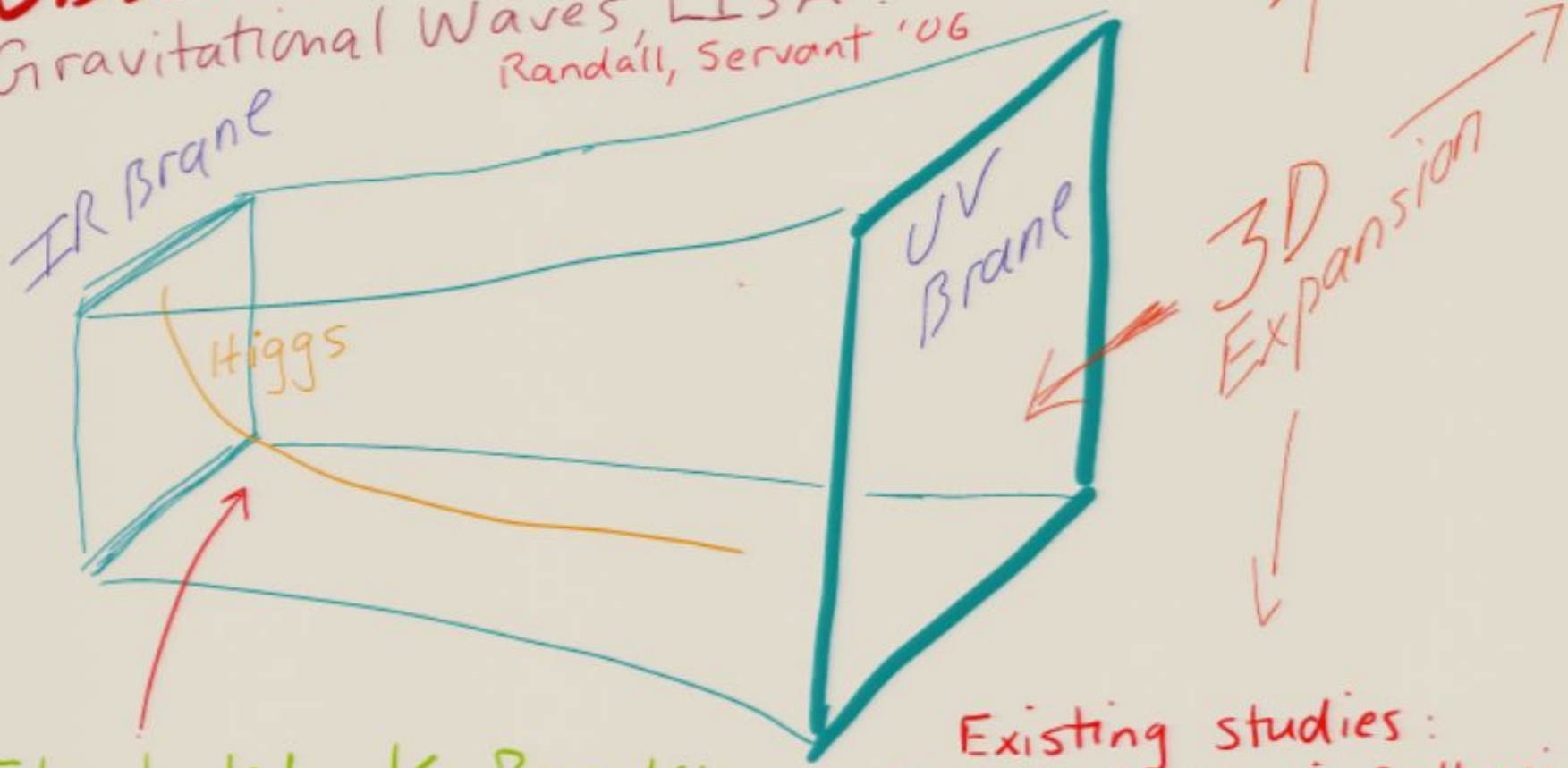
Universe cools.

Quantum processes → IR brane emergence

Details?

Observable implications?

Gravitational Waves, LISA?
Randall, Servant '06



ElectroWeak Breaking

Existing studies:
Creminelli, Nicolis, Rattazzi '02

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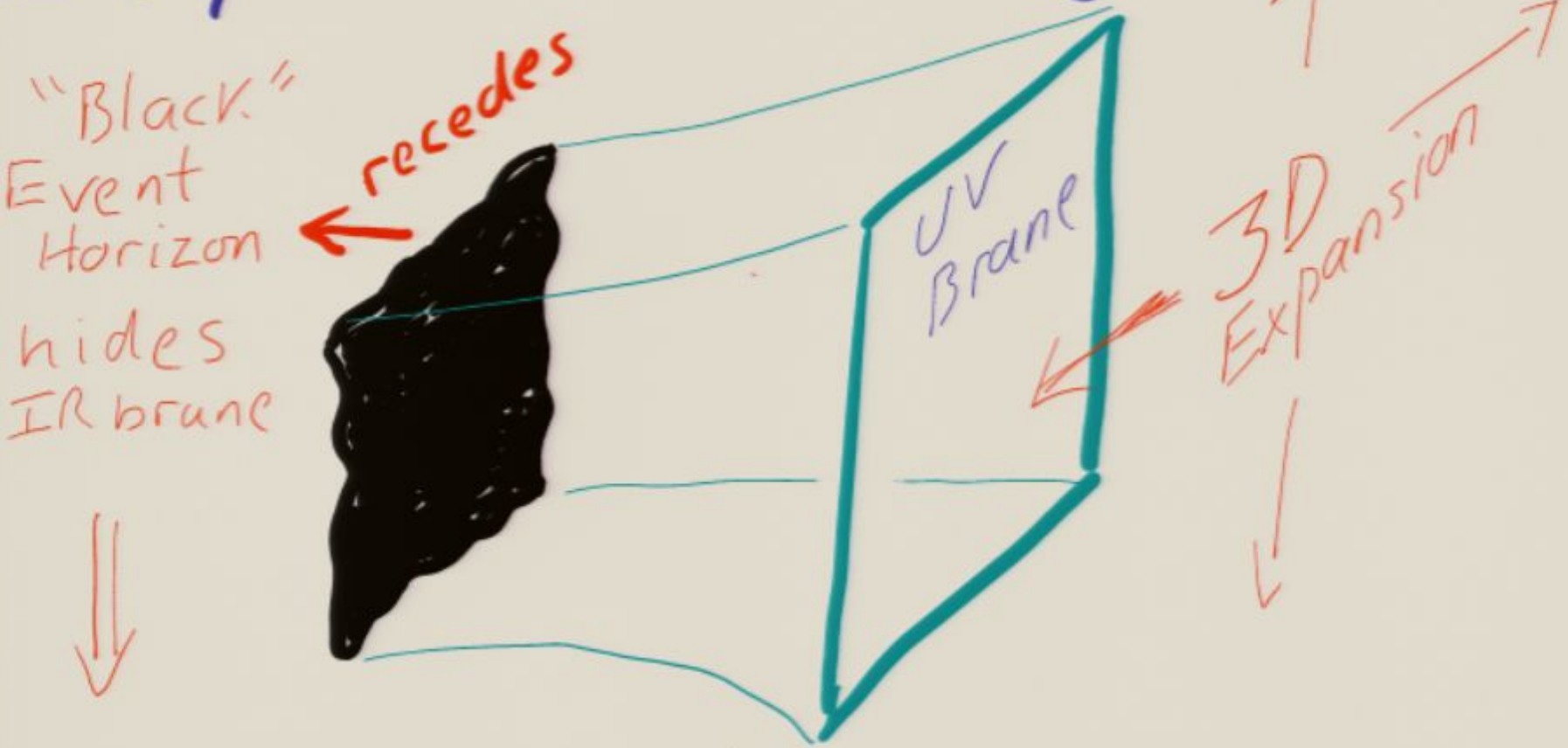

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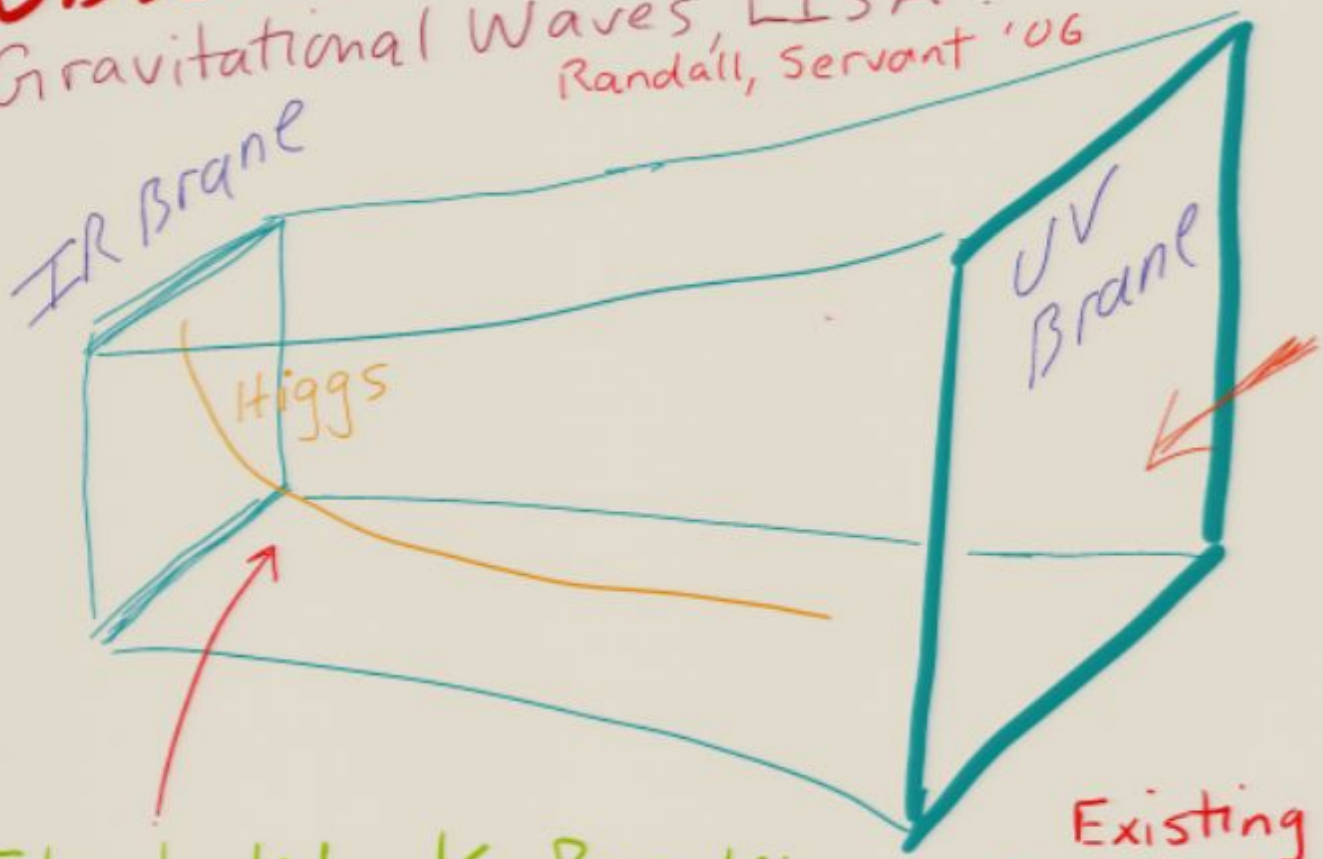

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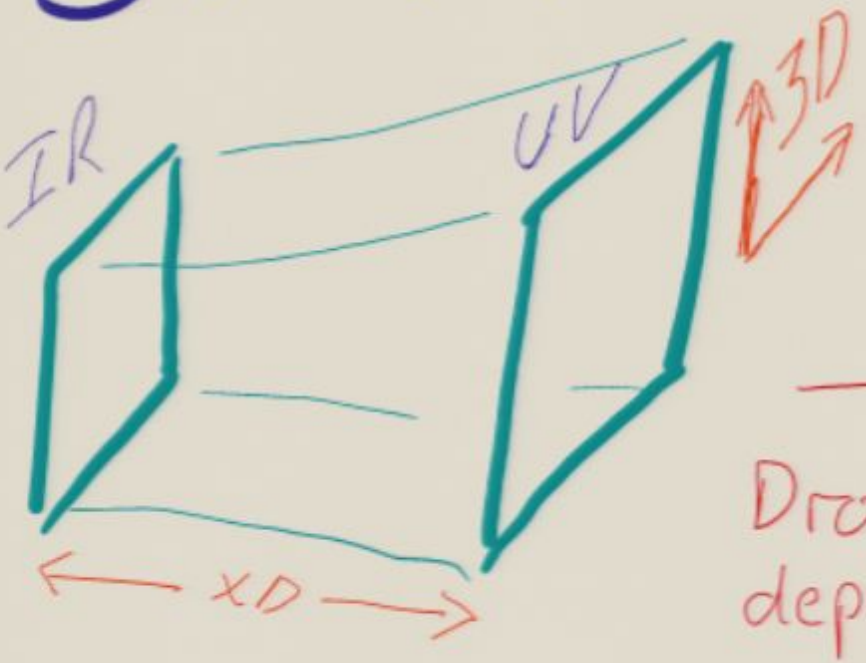
STRING THEORY exploits Warped Hierarchies



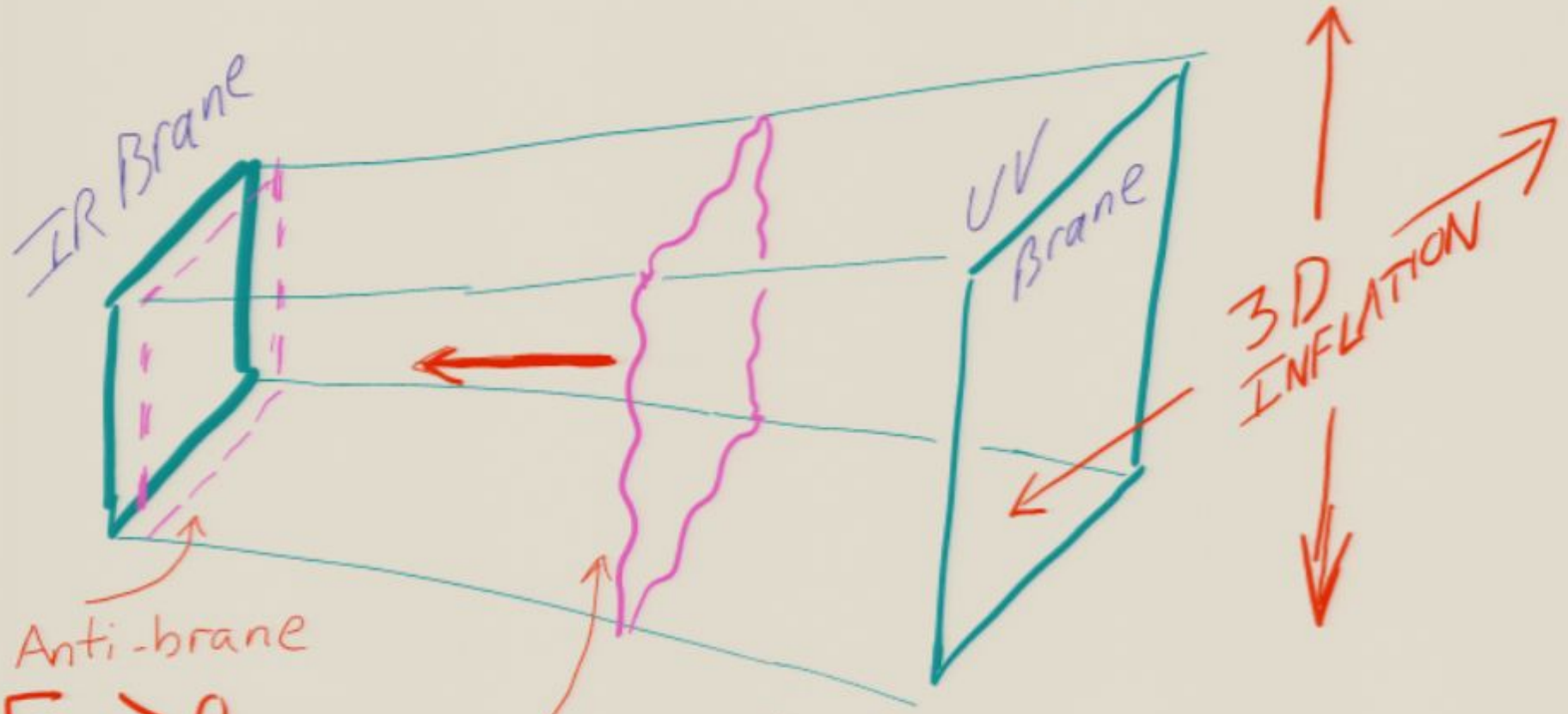
Drop 3D depiction

H. Verlinde '99
Giddings, Kachru, Polchinski '02
Kachru, Kallosh, Linde, Trivedi '03
⋮

6D xD Manifold

WARPED BRANE INFLATION

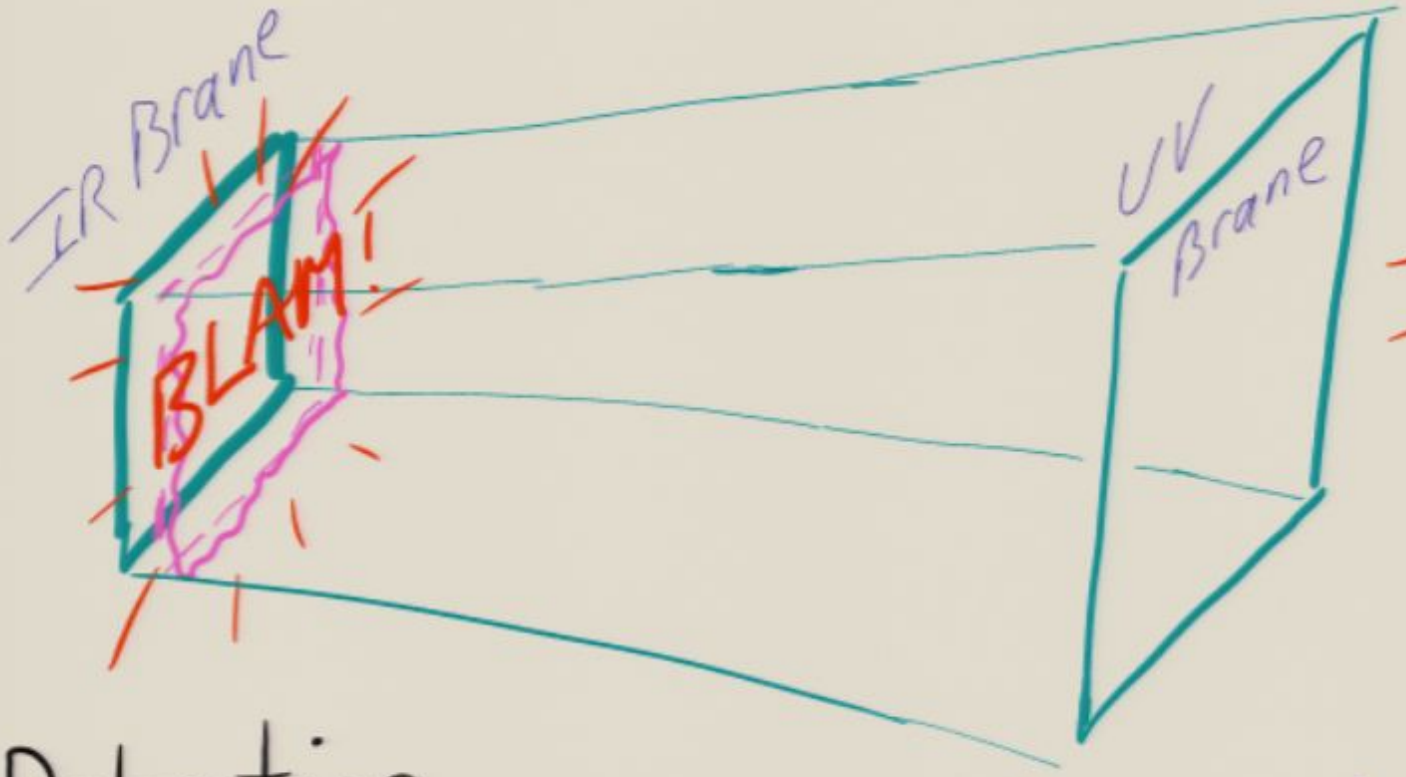
Dvali, Tye '98



IN STRING THEORY

Kachru, Kallosh, Linde, Maldacena, McAllister,

WARPED BRANE INFLATION



Reheating Universe

Specific CMB signatures ?
Structure formation

CONCLUSIONS

WARPED HIGHER-DIMENSIONAL SPACETIMES CAN ELEGANTLY →

OBSERVED STRUCTURES OF MICROPHYSICAL LAWS

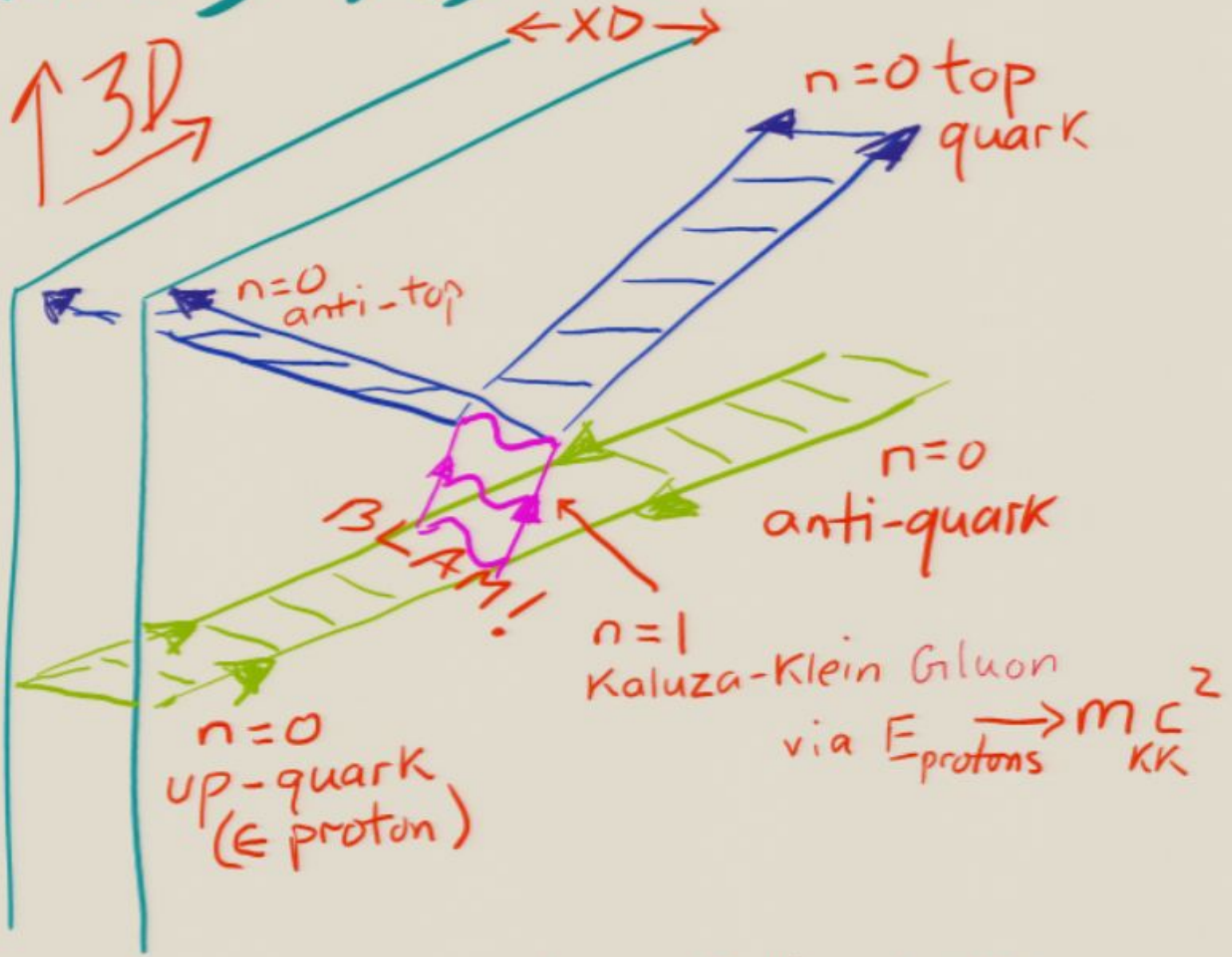
THEY HAVE TRANSFORMED

PUZZLES → puzzles under active research

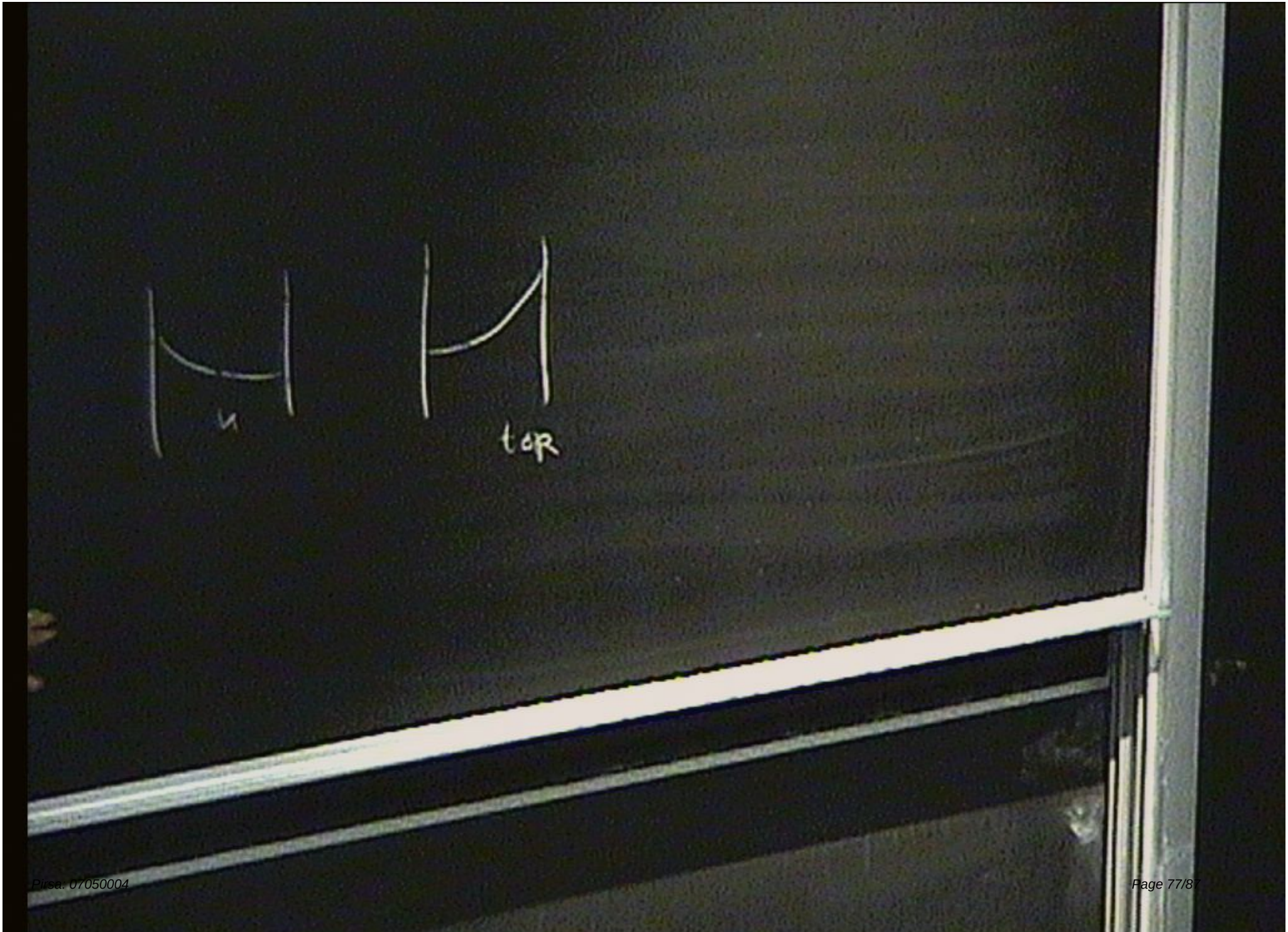
THEY HAVE TESTABLE IMPLICATIONS FOR DIVERSE RANGE OF EXPERIMENTS,

End of slide show, click to exit.

. . . WARPED XDs @ LHC



Simplified description of LHC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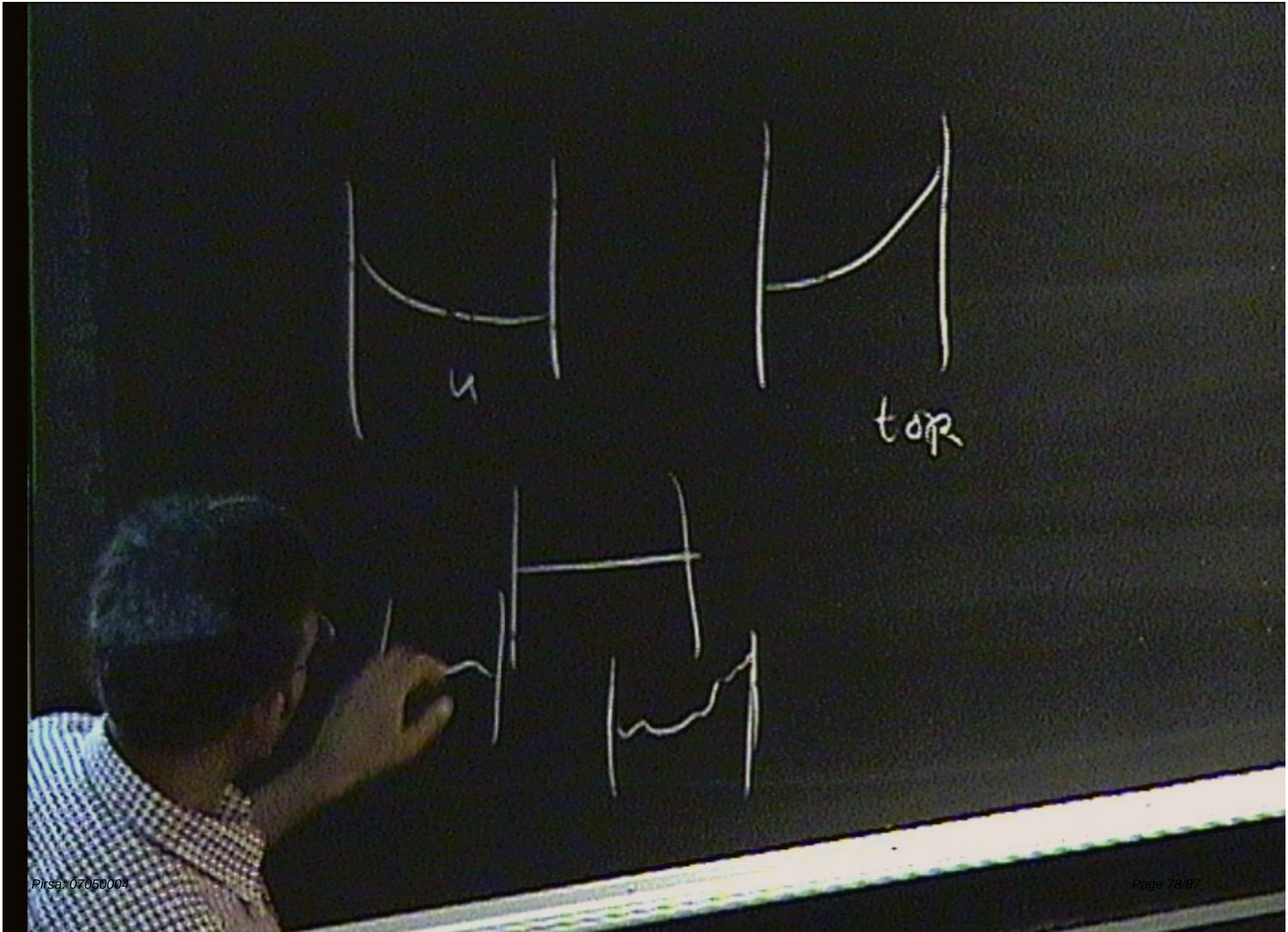
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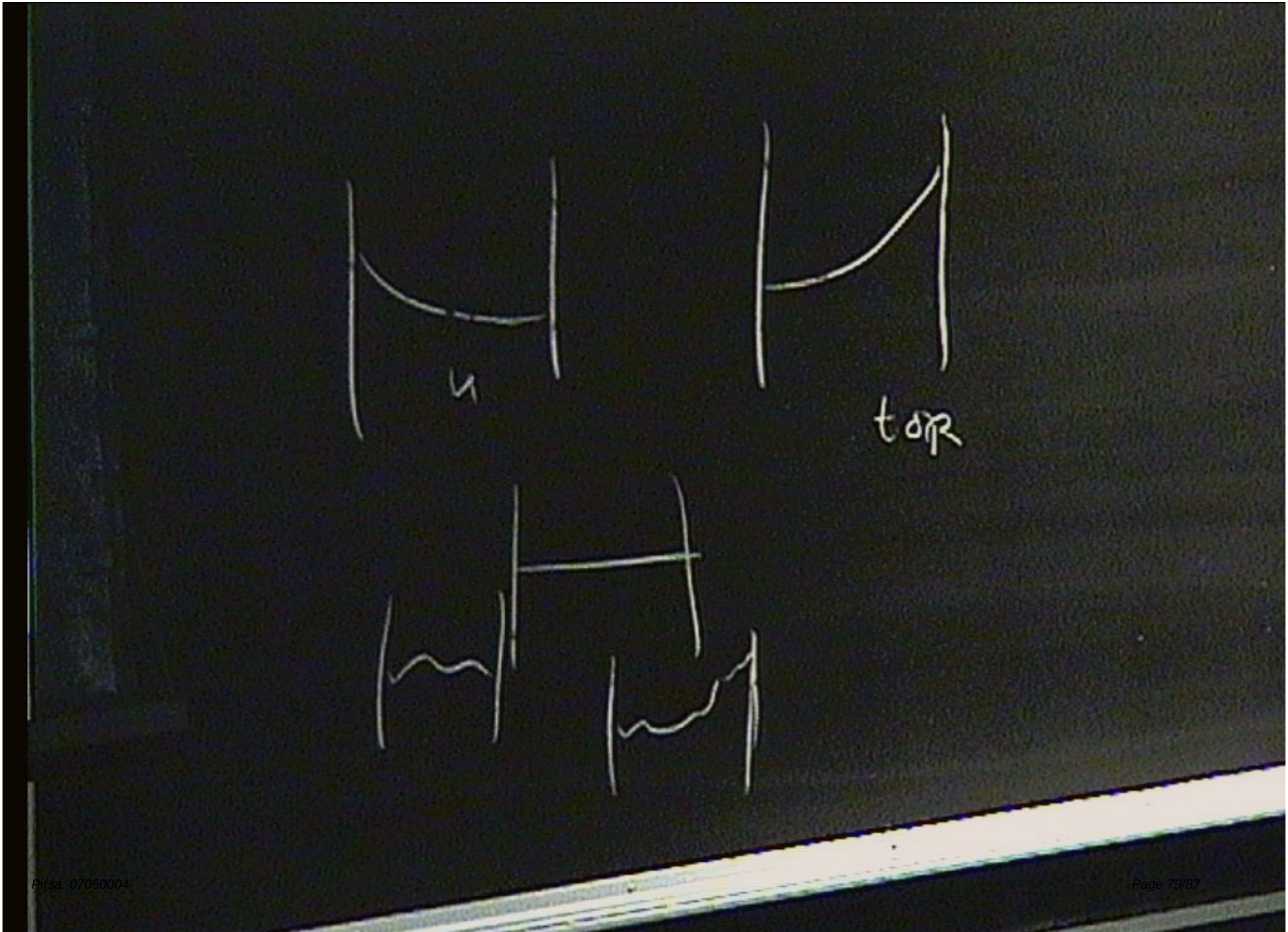
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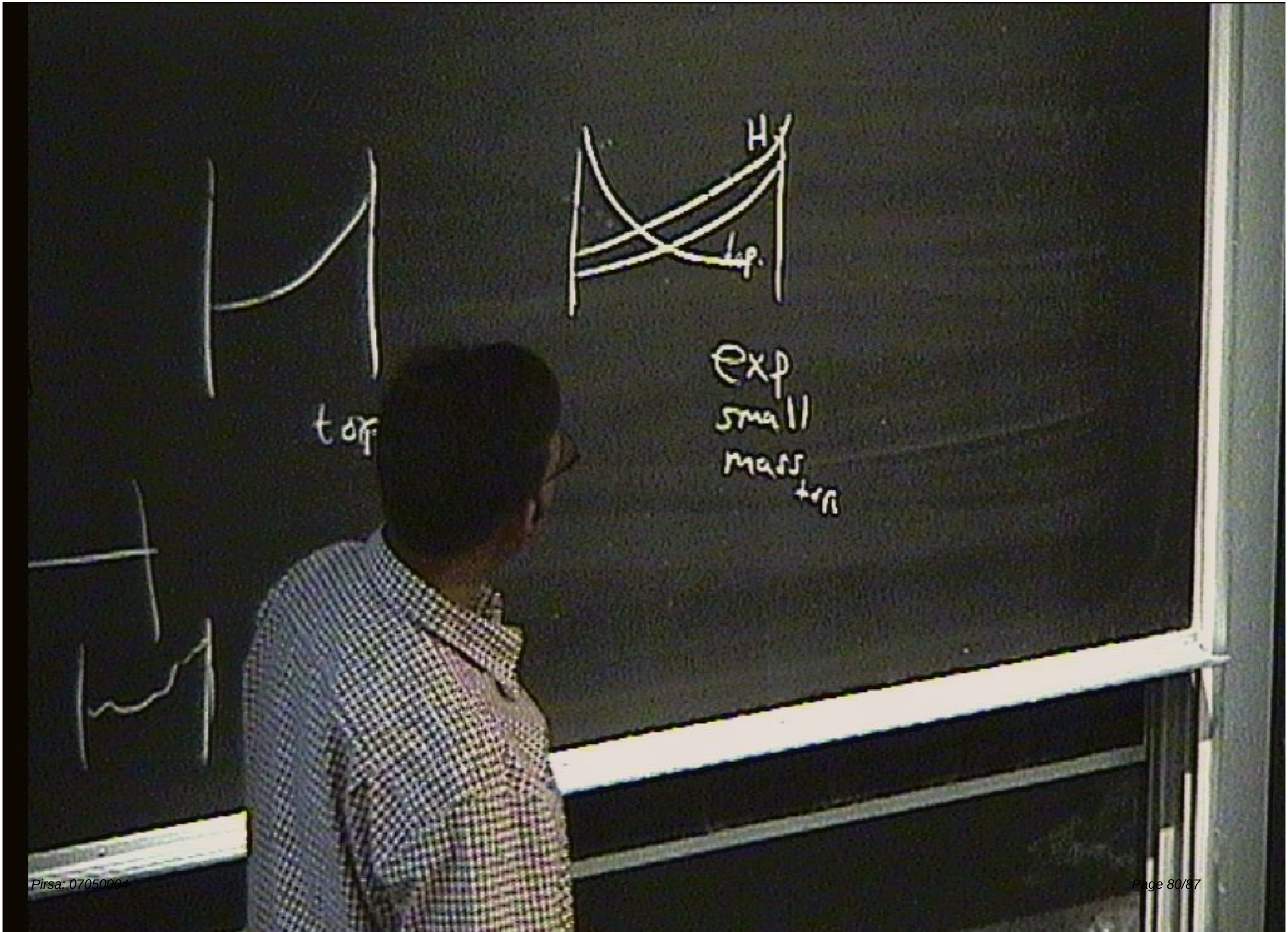
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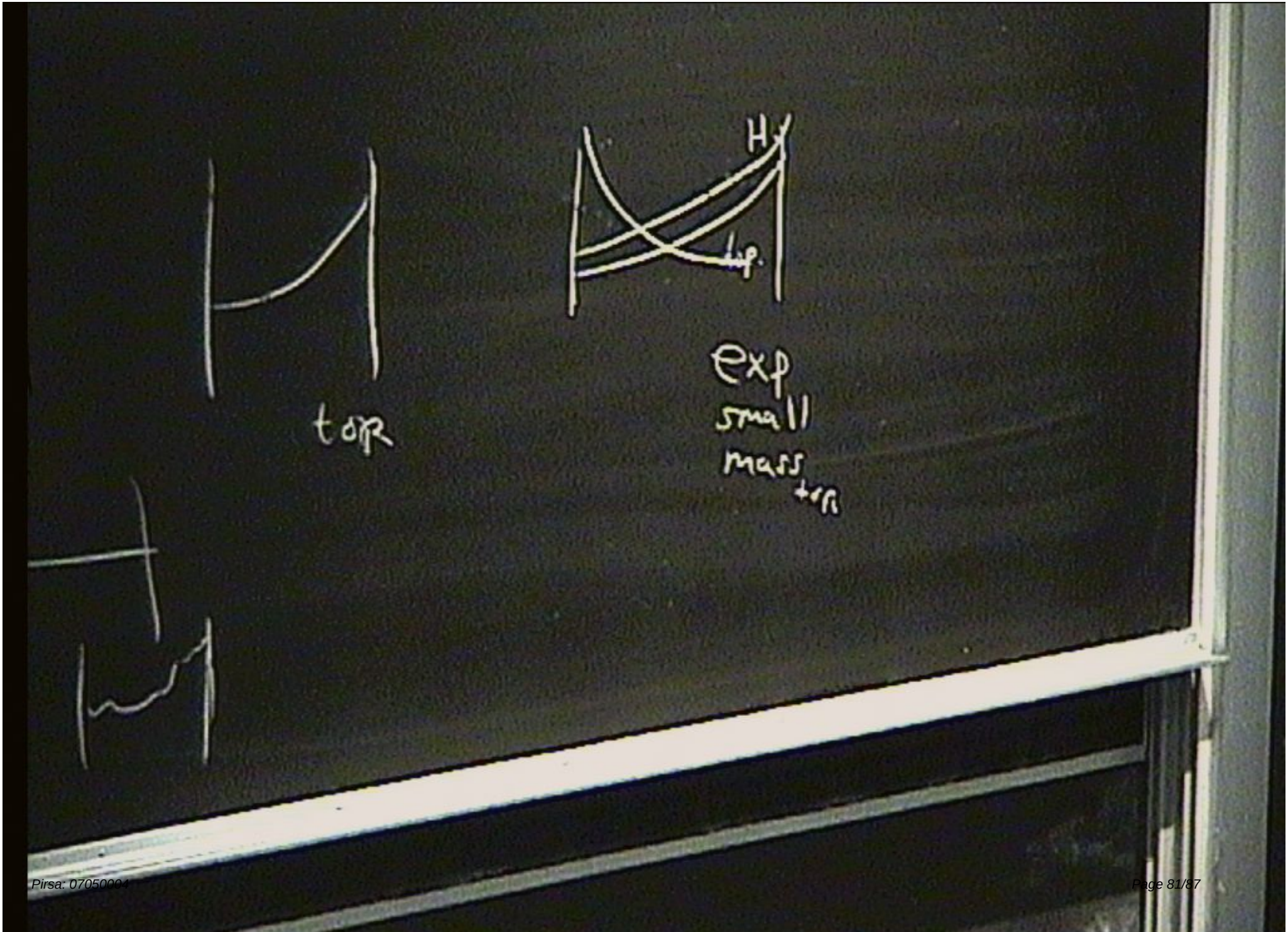
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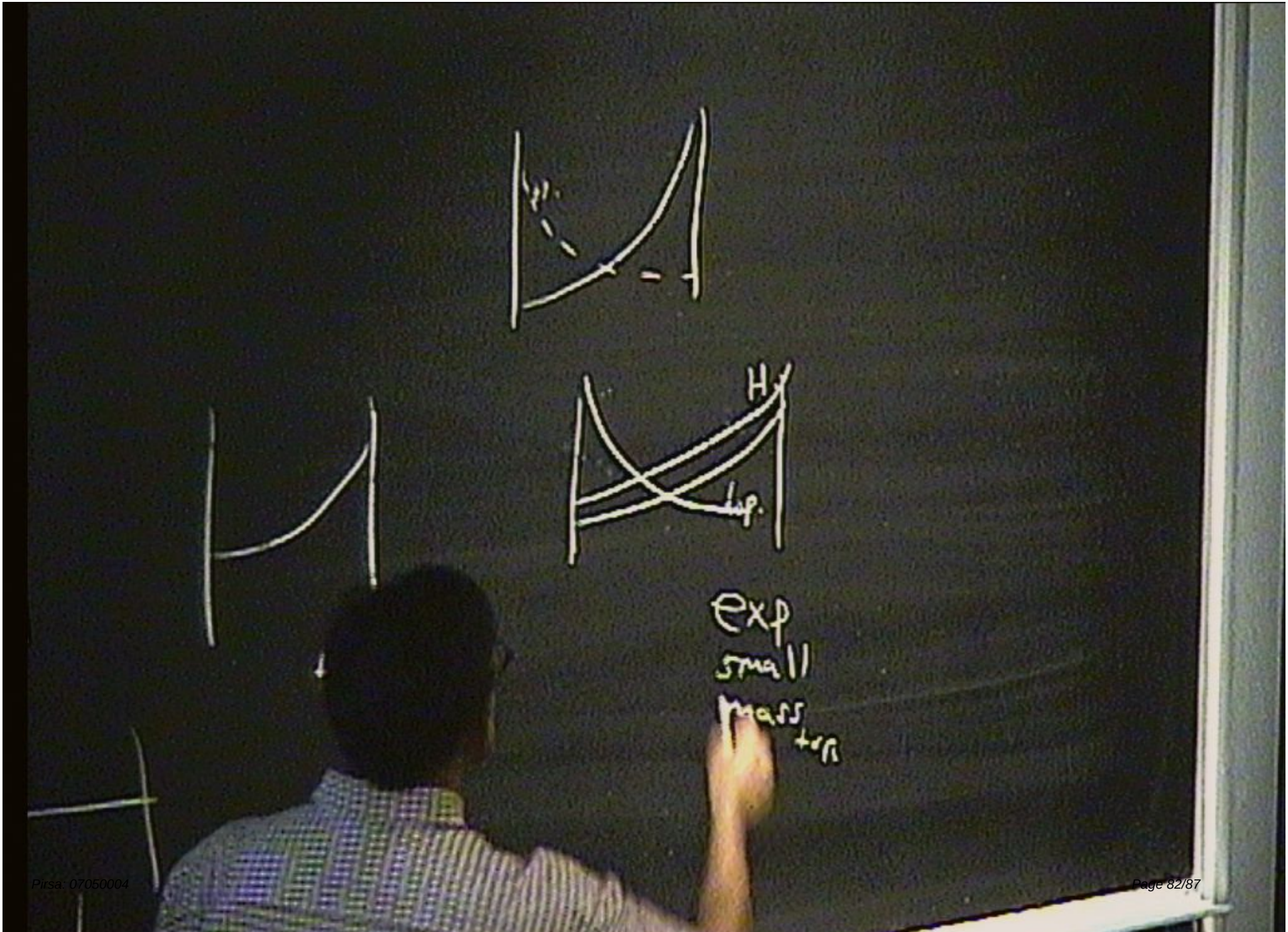
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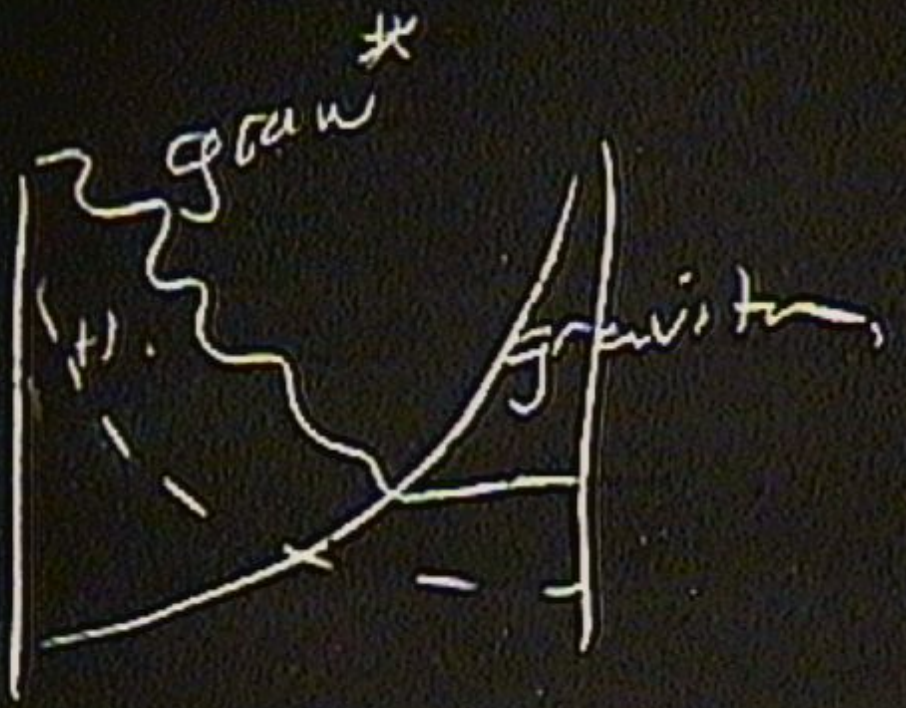
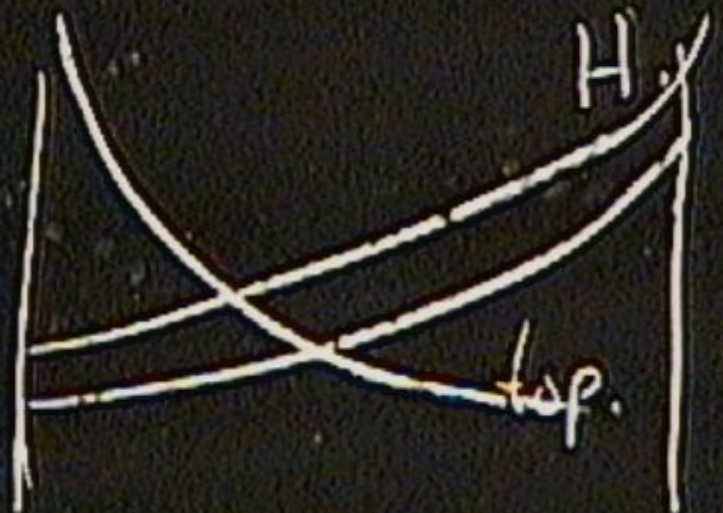

graw
gravitons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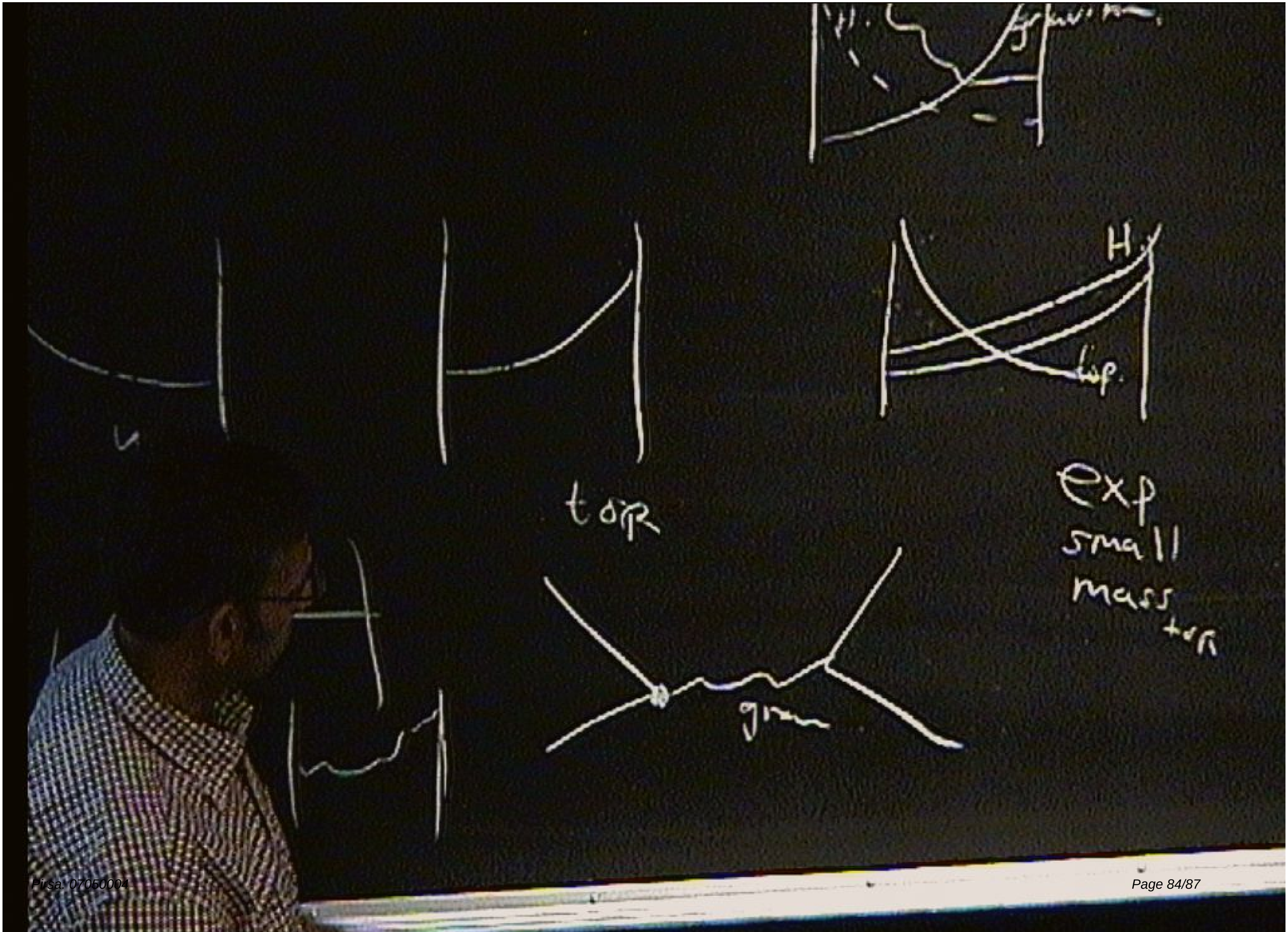
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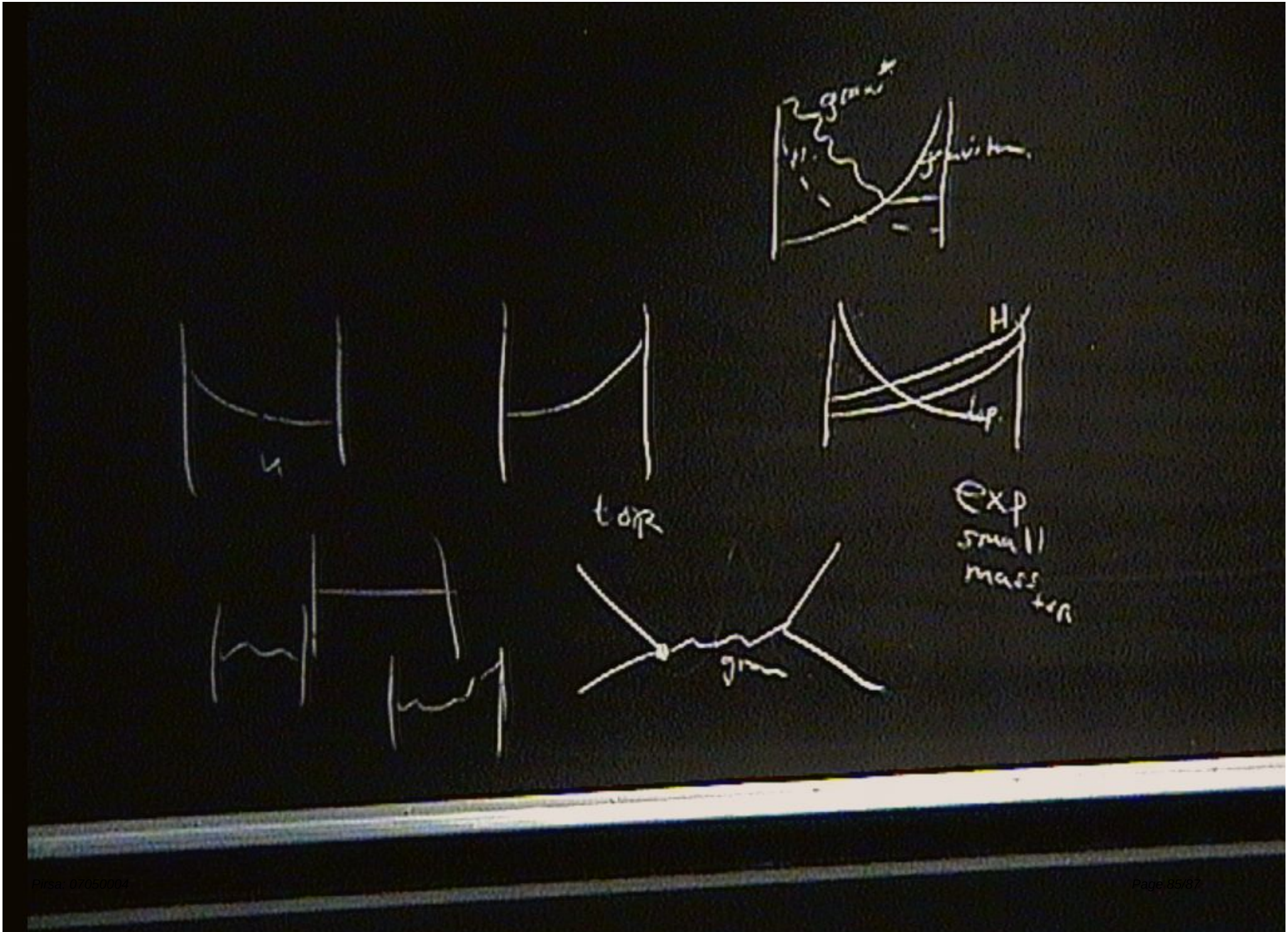
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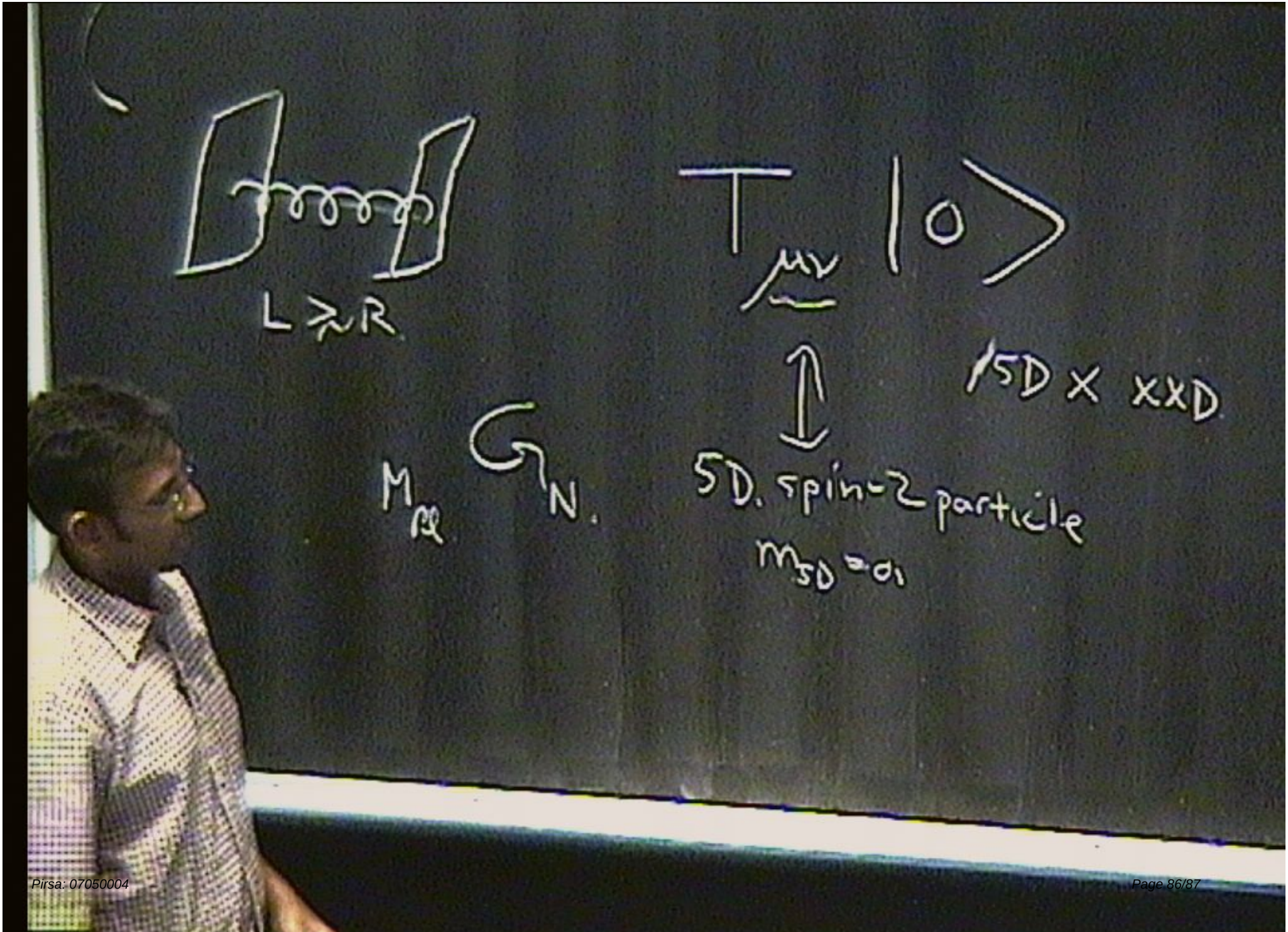
L ≳ R
$T_{\mu\nu}|0\rangle$
5D × XXD
M_{Pl}
G_N.
5D. spin-2 particle
$m_{5D} = 0$.

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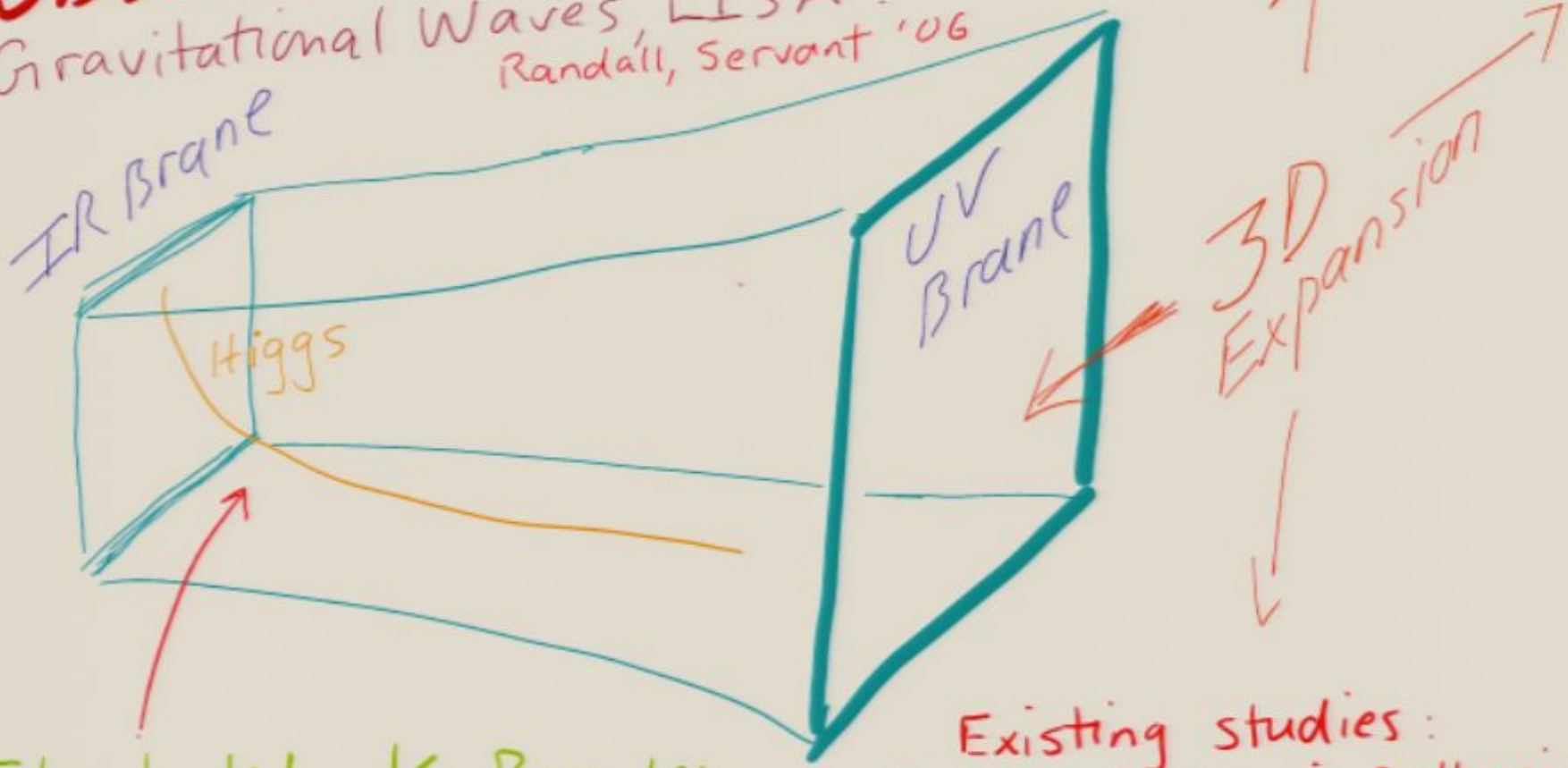

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