Title: Dual gravity study of the (2+1)D compact U(1) gauge theory coupled with strongly interacting matter fields

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Abstract: Strongly correlated many-body systems are often formulated as gauge theories where gauge field plays a role of Lagrangian multiplier and fundamental matter field represents a fractional degree of freedom which carries only a fractional quantum number of microscopic particle. Although the fractional particles are prone to be confined at high energy owing to an infinite bare gauge coupling, they can emerge as deconfined degrees of freedom at low/intermediate energy scales as the gauge coupling is renormalized to a finite value by fluctuating matter fields. The resulting dynamics of the gauge field crucially depends on the number and the dynamics of the matter fields. In this talk, I will discuss how a change in the dynamics of matter fields affects the dynamics of gauge field. I will consider a field theory where a 2+1D compact U(1) gauge field is coupled to a large number of fundamental matter fields with an infinite bare gauge coupling and the matter fields are, in turn, subject to an additional strong interaction. This field theory can be realized as a low energy theory of a D-brane configuration and nonperturbative effects of the strong interaction can be studied from the AdS/CFT correspondence. Using the dual gravity theory, I will discuss how the strong interaction between matter fields can drastically modify the dynamics of the U(1) gauge field. Our result suggests that even an unstable brane configuration can define a consistent field theory once tachyonic modes are frozen.

Emergent gauge theory in strongly correlated many-body system;

A dual gravity study of the (2+1)D compact U(1) gauge theory

Sung-Sik Lee

MIT

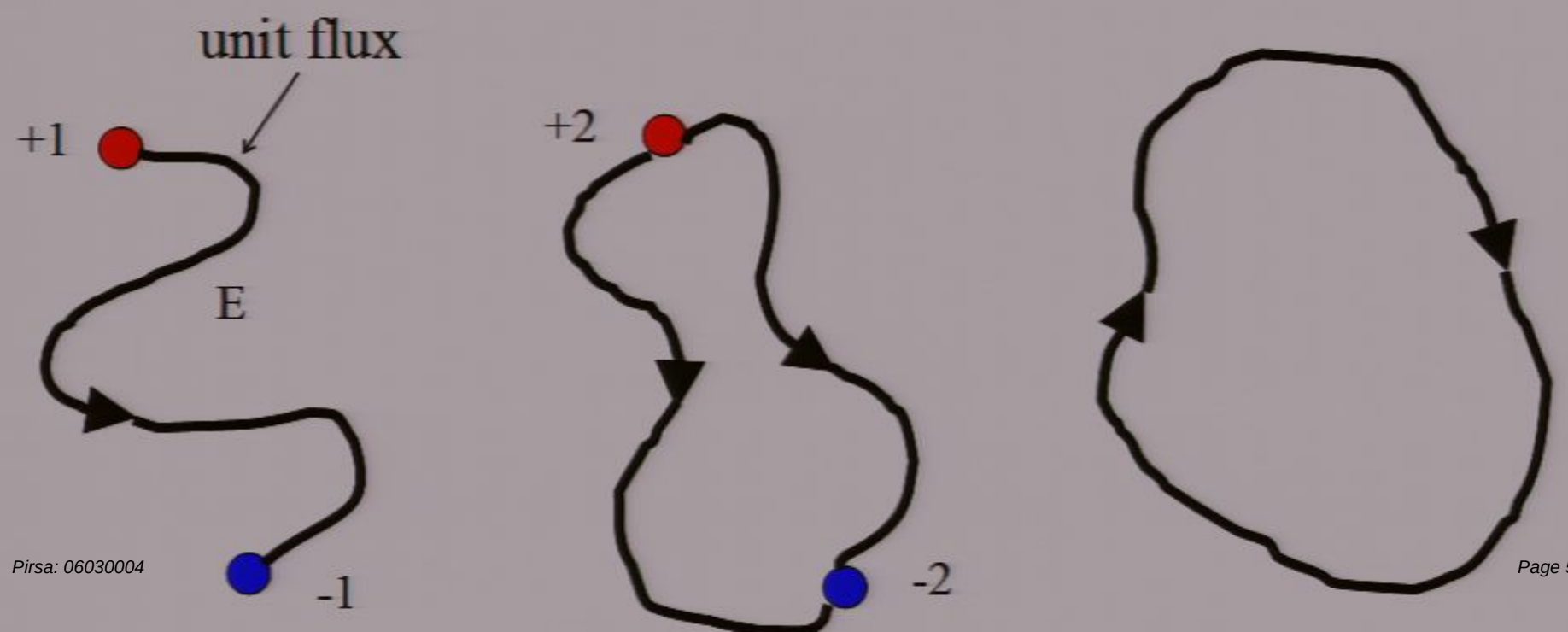
Outline

- Gauge theory
- Emergent gauge theories (fractionalization)
  - Spin model
  - Supersymmetric QCD
  - Exciton('meson') model
- Dual gravity theory of an emergent gauge theory

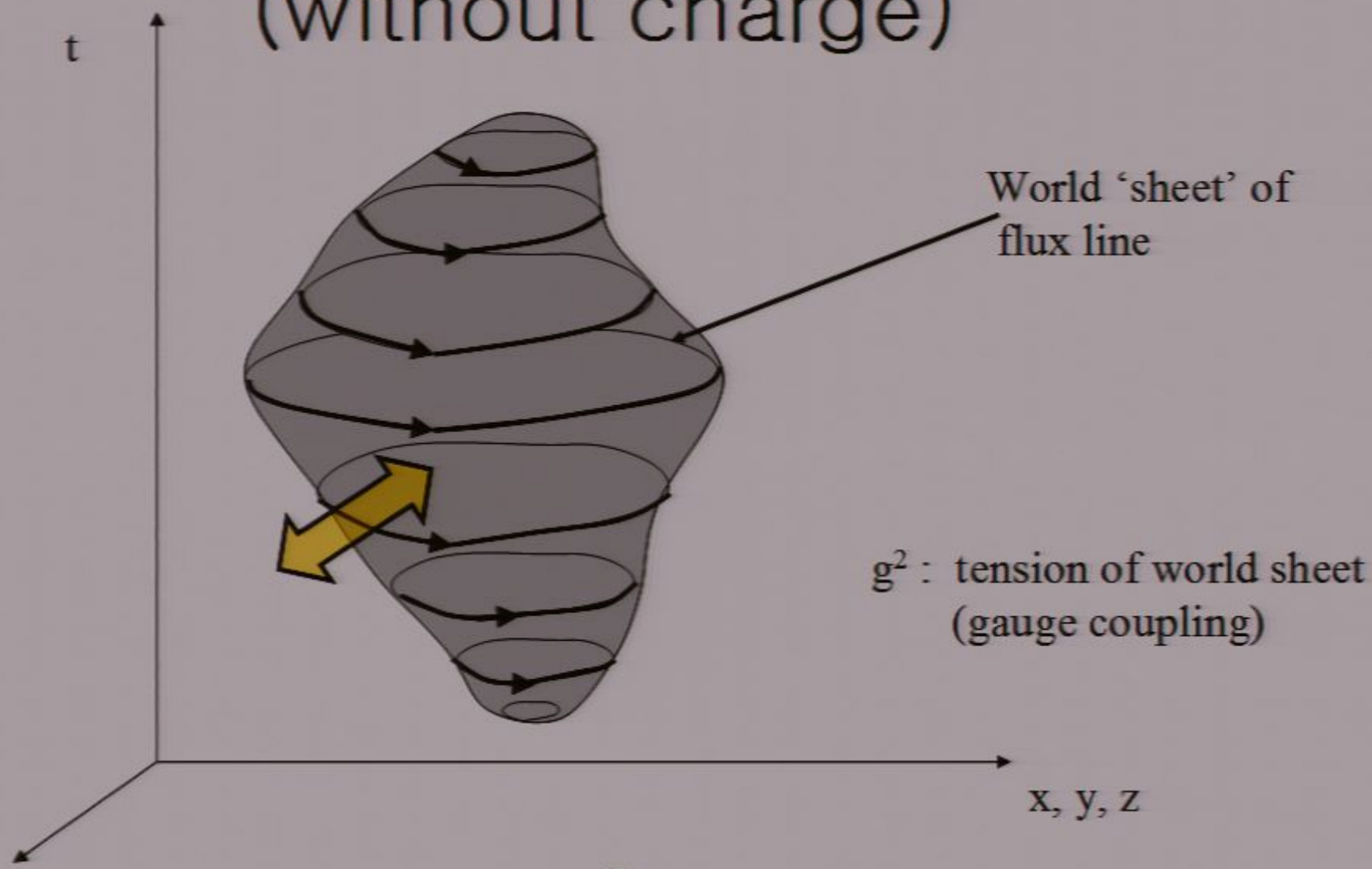
Gauge theory

Gauge theory: guiding principle of interactions between elementary particles

$$\nabla \cdot \mathbf{E} = \rho$$

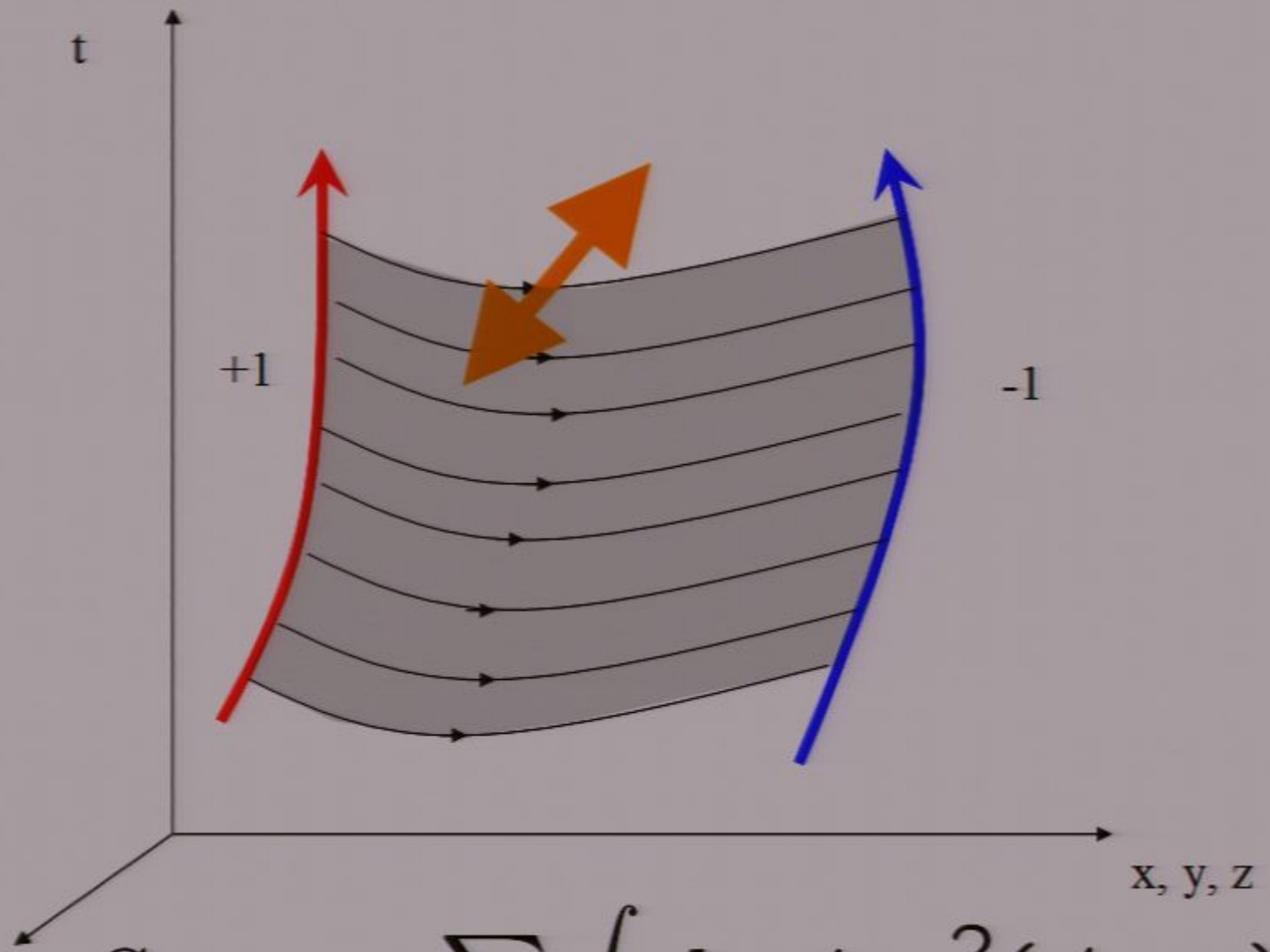


Dynamics of unit flux line (without charge)



$$S_E = g^2(Area)$$

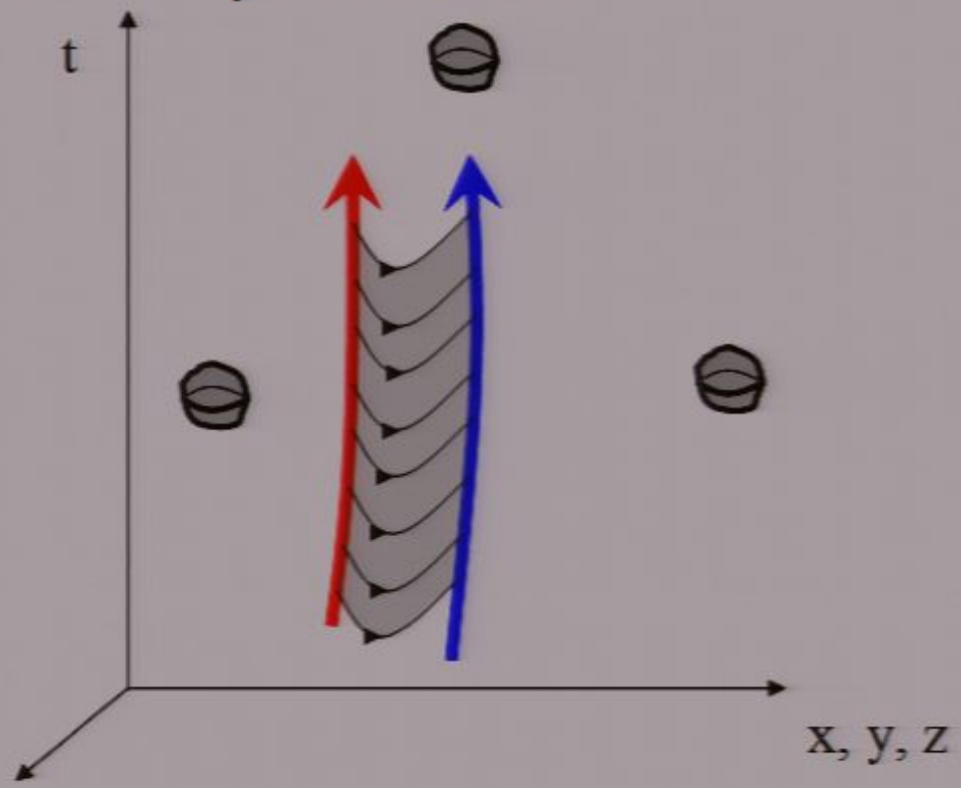
Dynamics of flux line and charge



$$S_E = m \sum_i \int ds_i + g^2 (Area)$$

Confinement phase

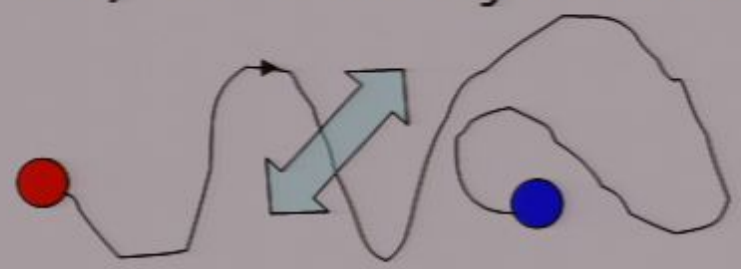
- Strong coupling
- Tension dominate
- Small bubbles of flux
- Linear potential
- Charges confined
- Ex) Chromodynamics



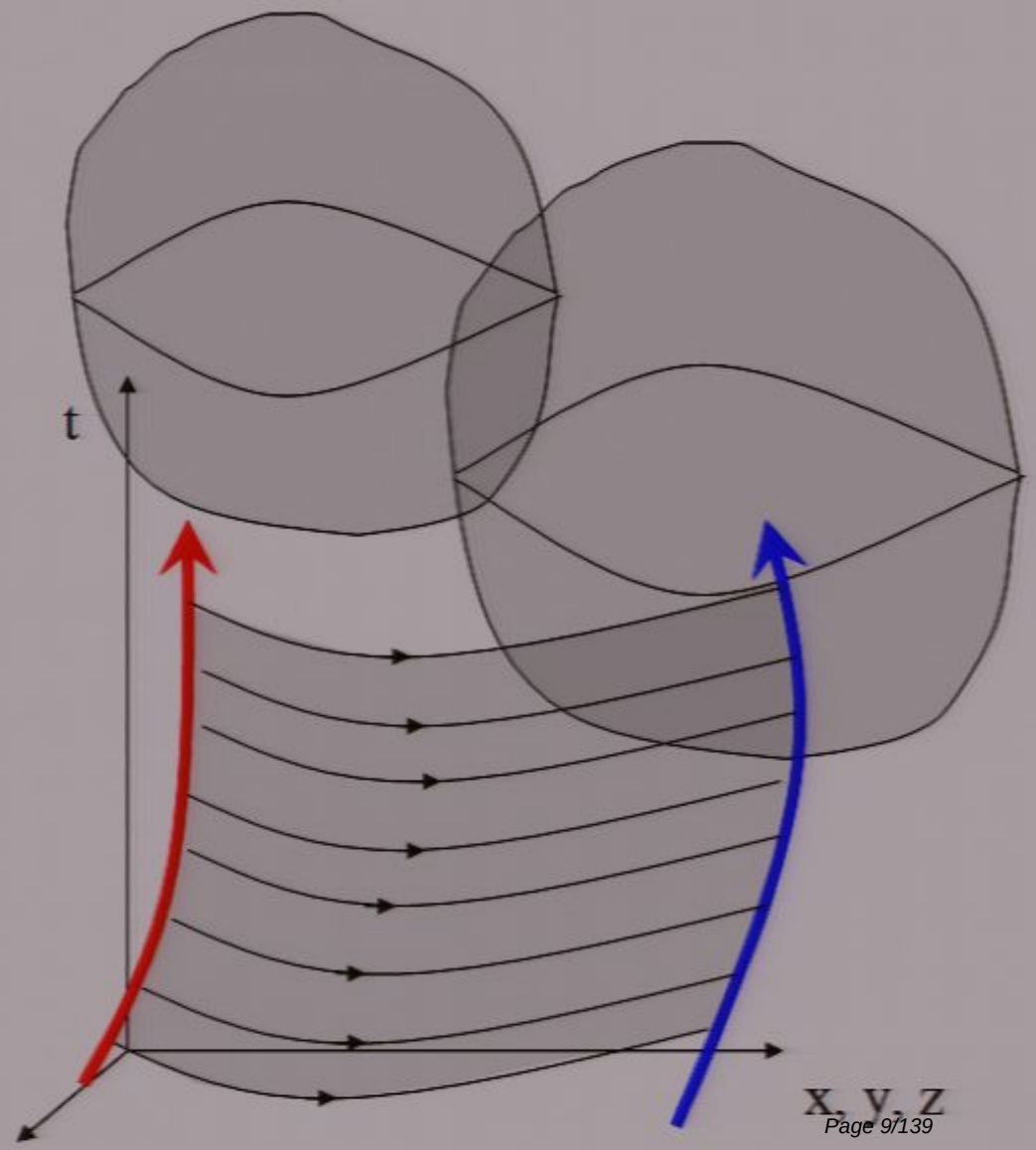
$$V(r) \sim r$$

Deconfinement phase

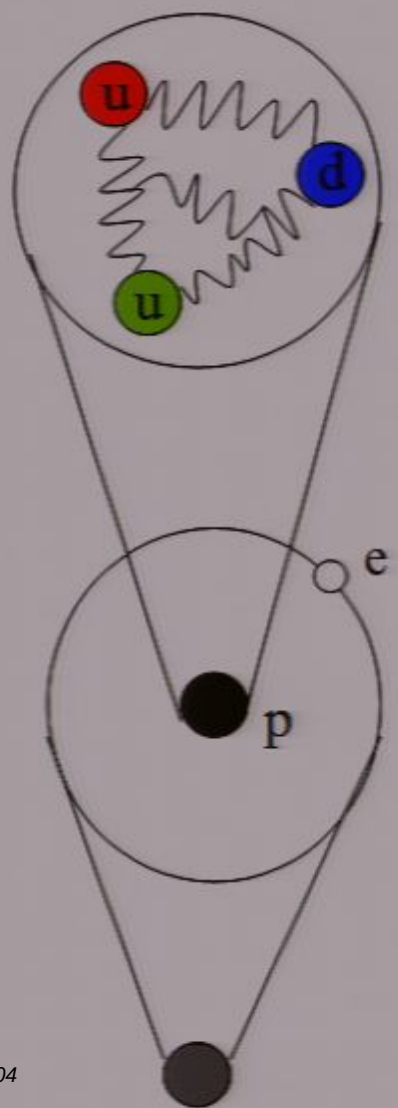
- Weak coupling
- Fluctuation dominate
- Large bubbles of flux
- Coulomb potential
- Charges deconfined
- Ex) Electrodynamics



$$V(r) \sim -1/r$$



Success of gauge principle

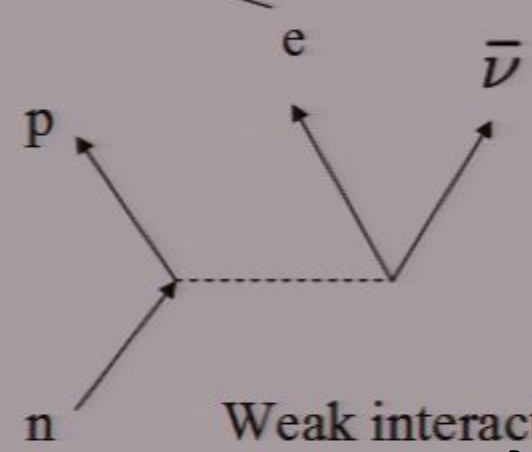


Strong interaction : SU(3)

M_W^{exp}	$= 80.41$ GeV
$M_W^{prediction}$	$= 80.39$ GeV

$SU(2) \times U(1)$

Electro-magnetic interaction



Weak interaction

Emergent gauge theory
example I : spin model

Confining gauge field (Valence Bond solid)

$$H_1 = J \sum_{i,j} \vec{S}_i \cdot \vec{S}_j + \cdots$$

$$= \frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$$

: spin singlet

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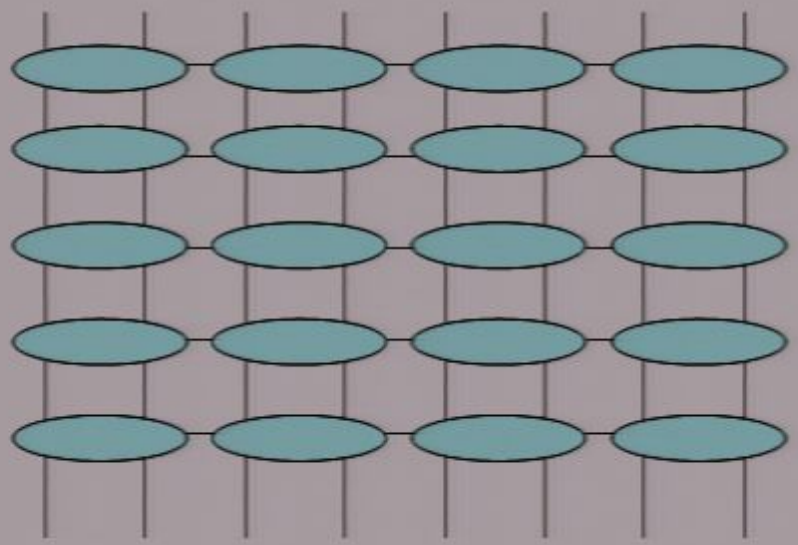

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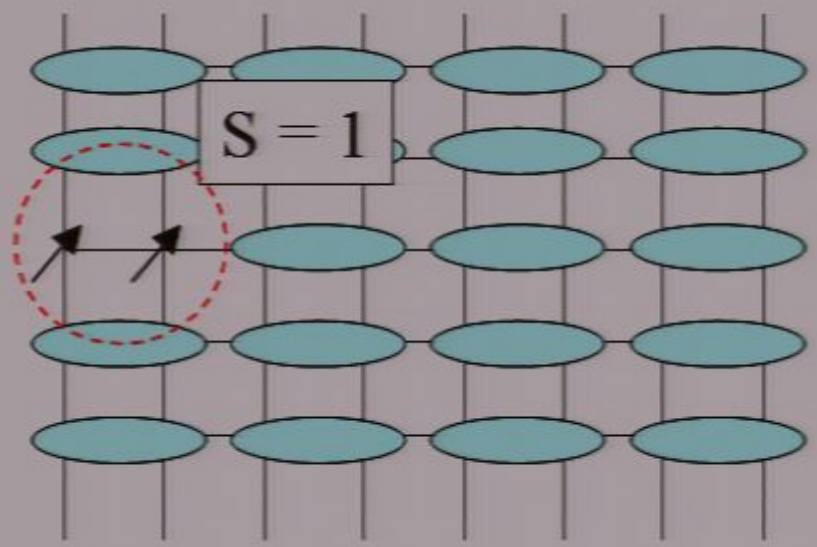

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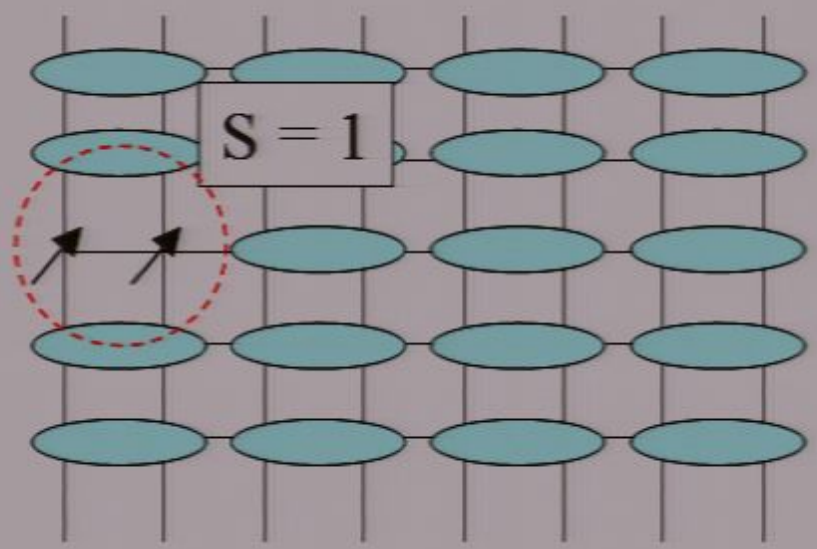

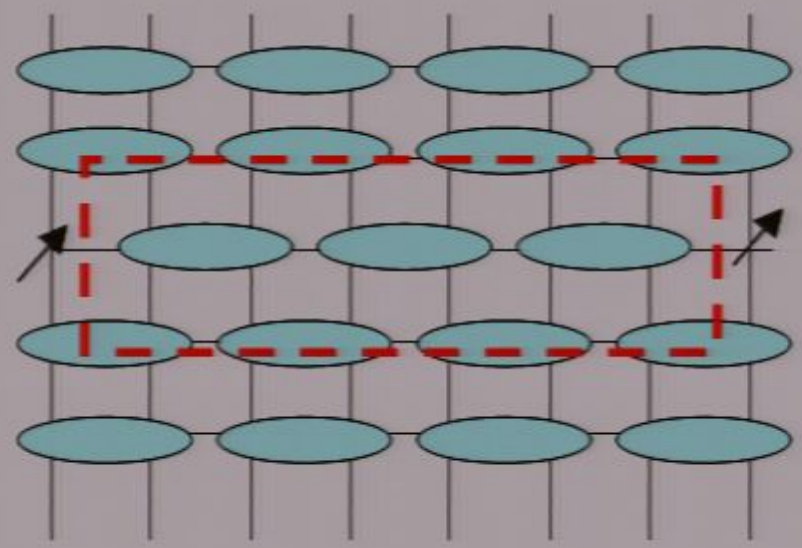

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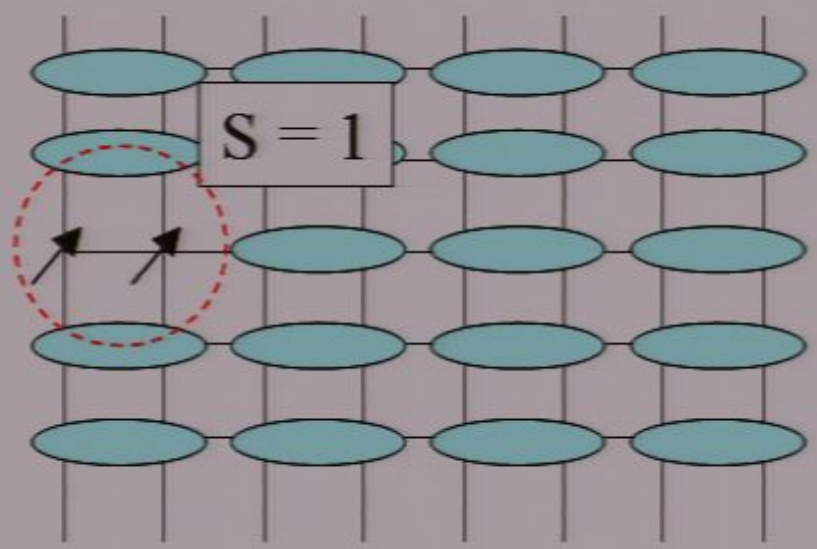

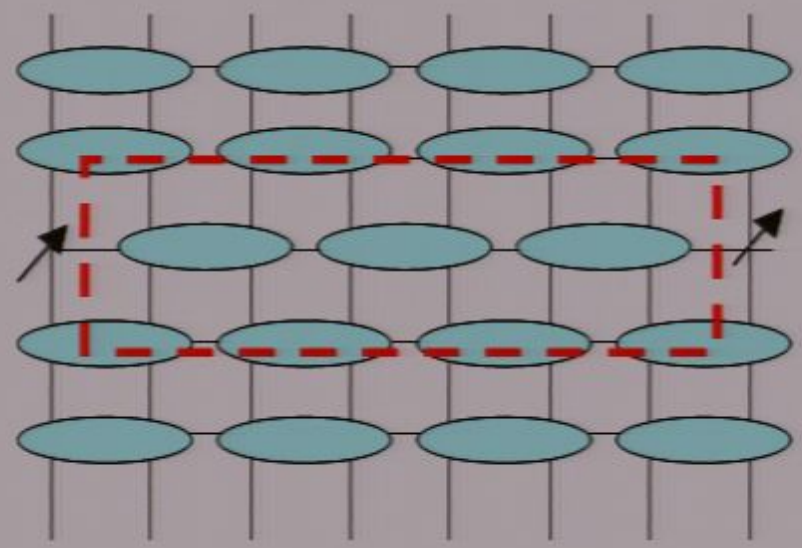

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Deconfinement (fractionalization) I

(Resonating Valence Bond) [P.W. Anderson]

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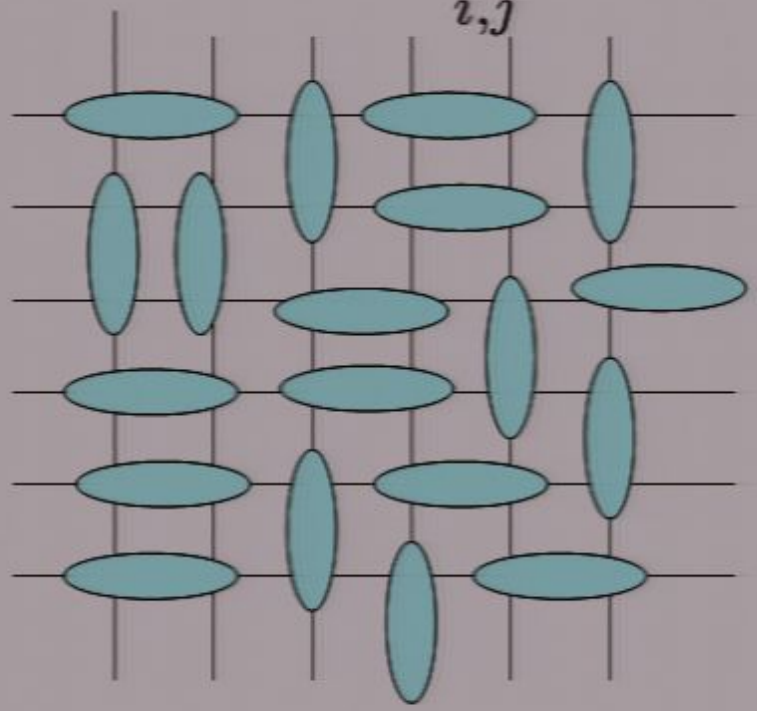

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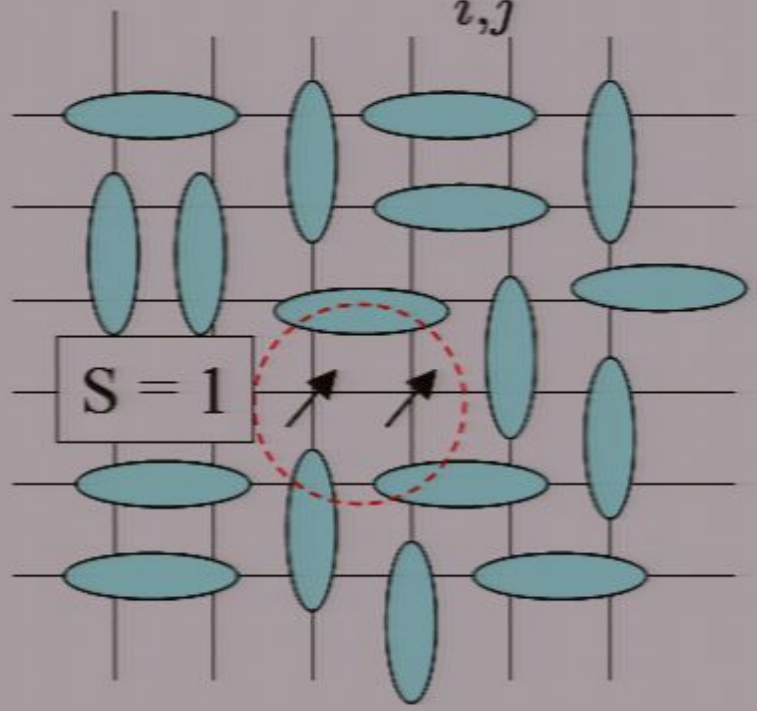

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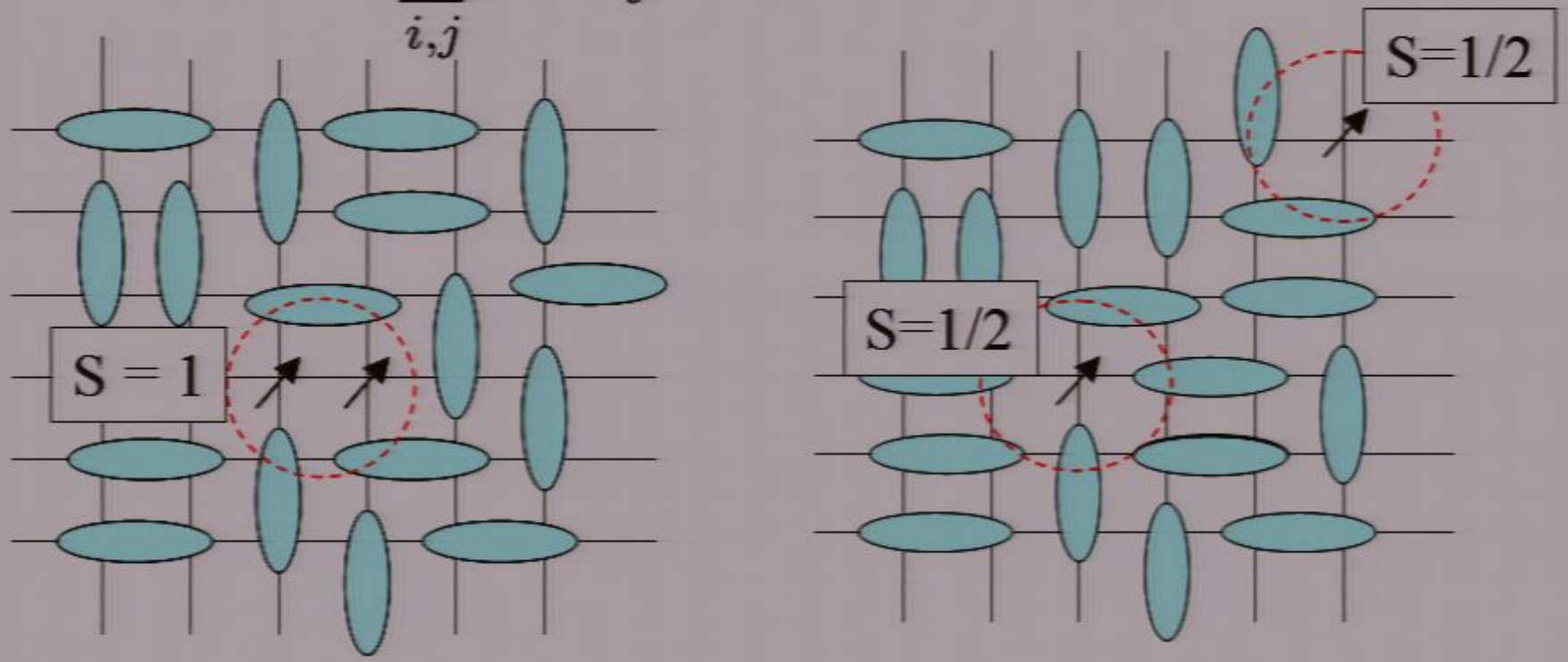

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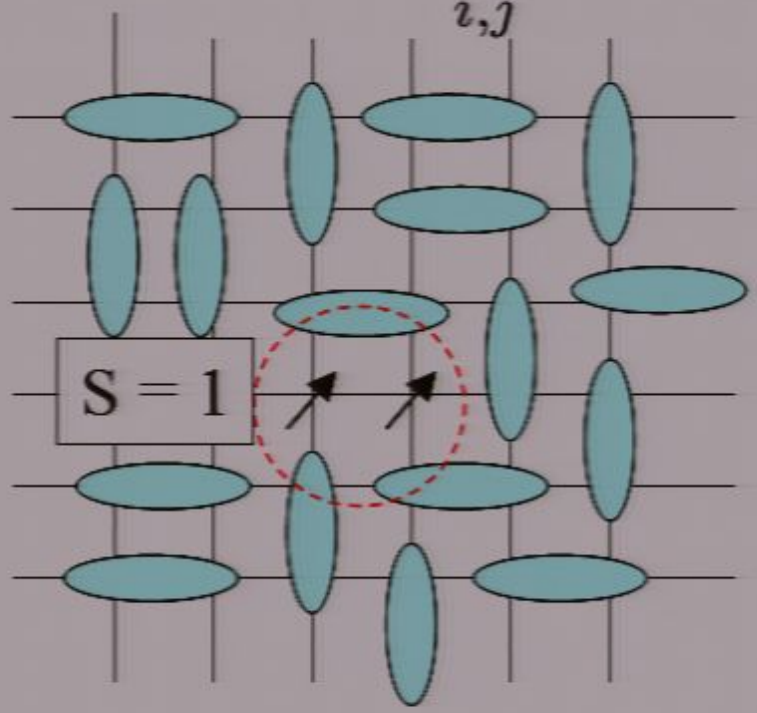

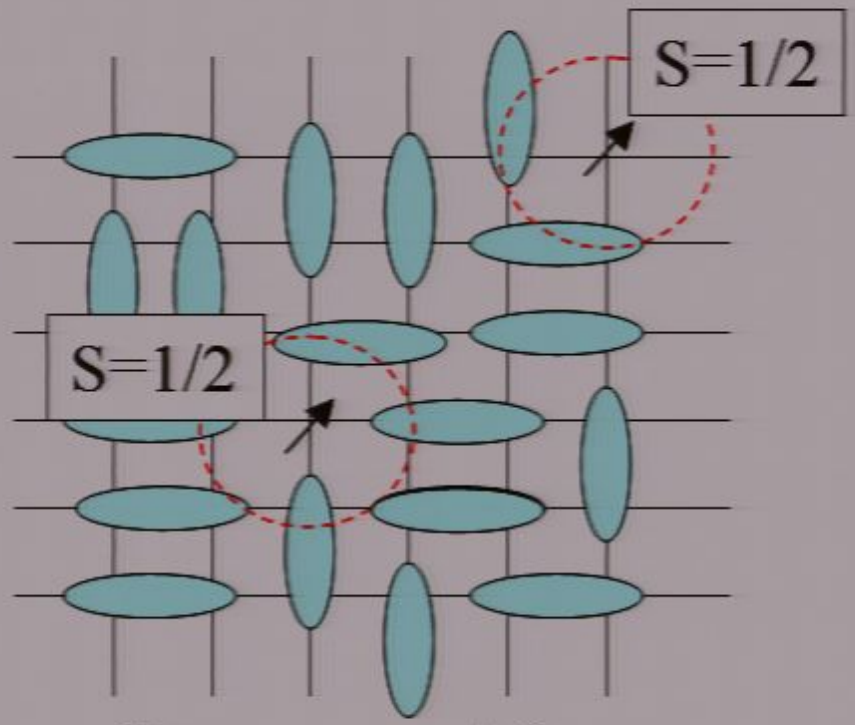

no linear potential :
deconfined (fractionalized)

Emergent gauge theory example II : super QCD

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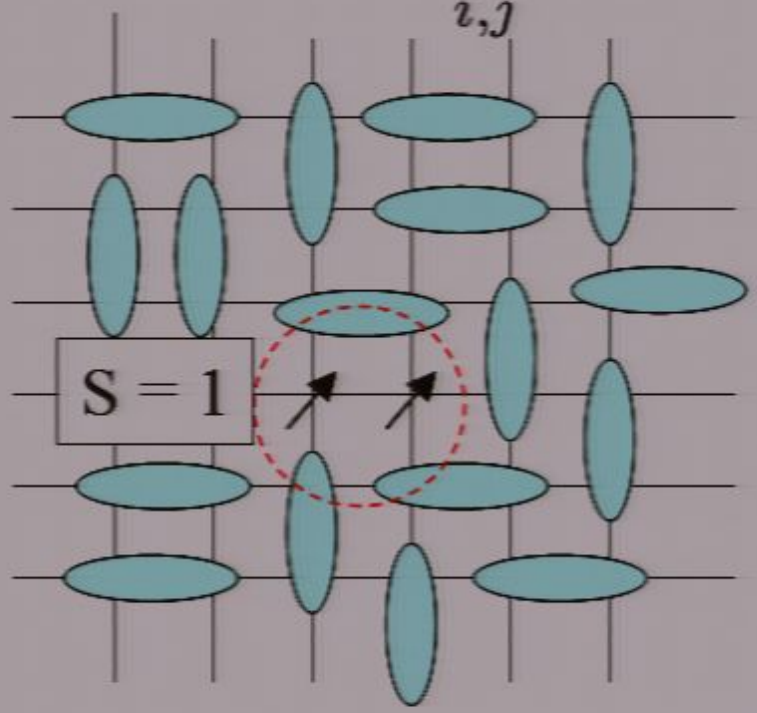

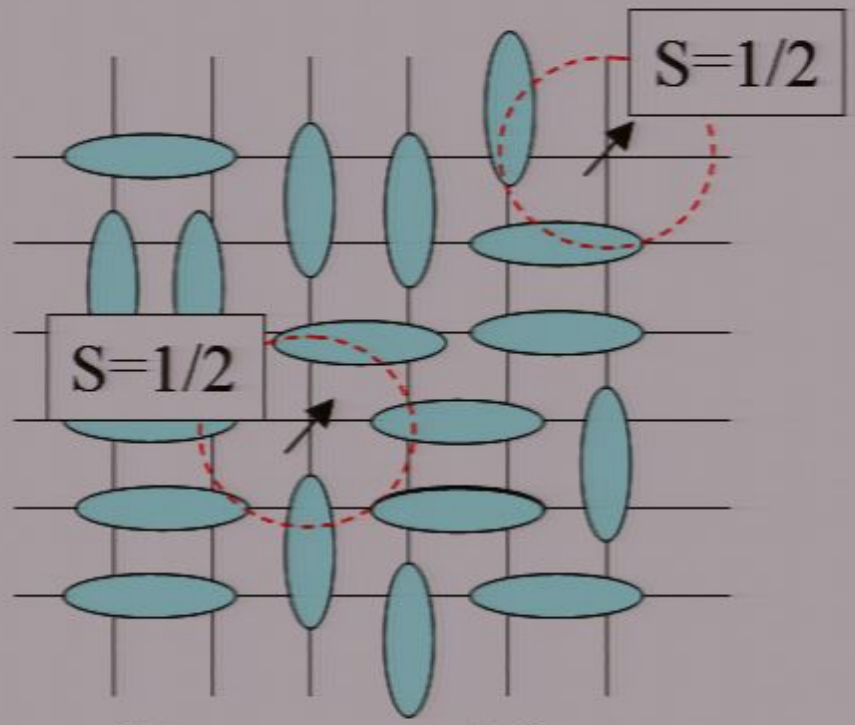

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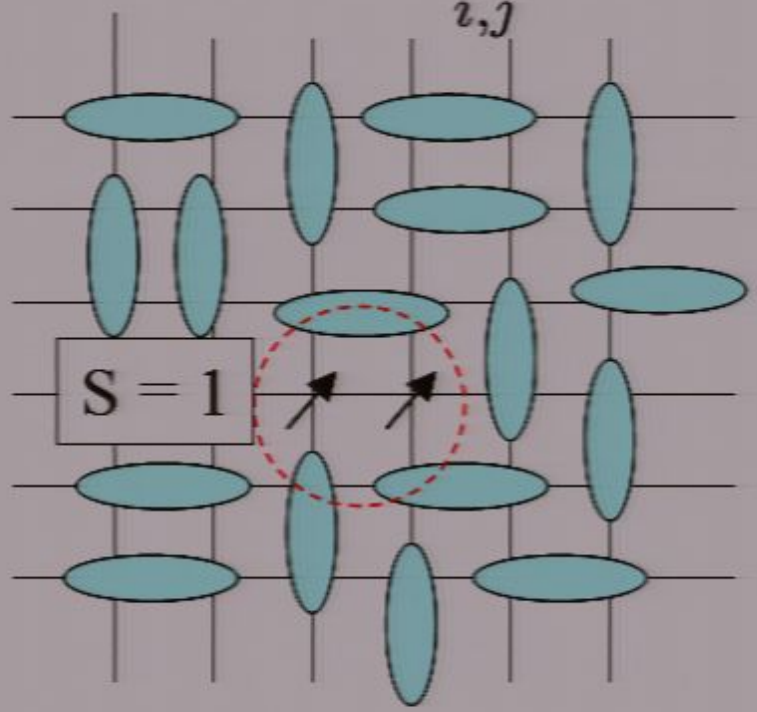

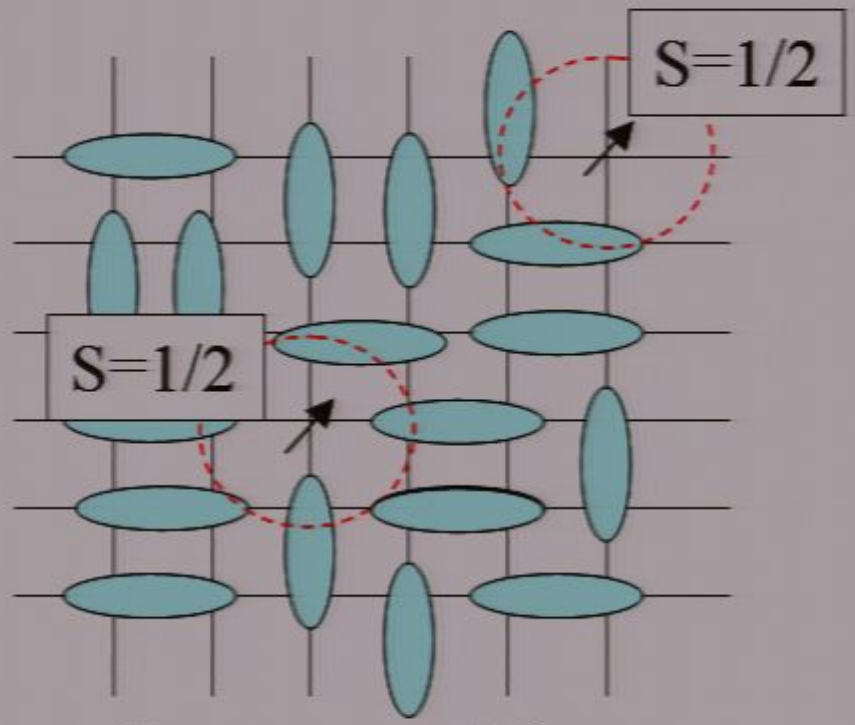

no linear potential :
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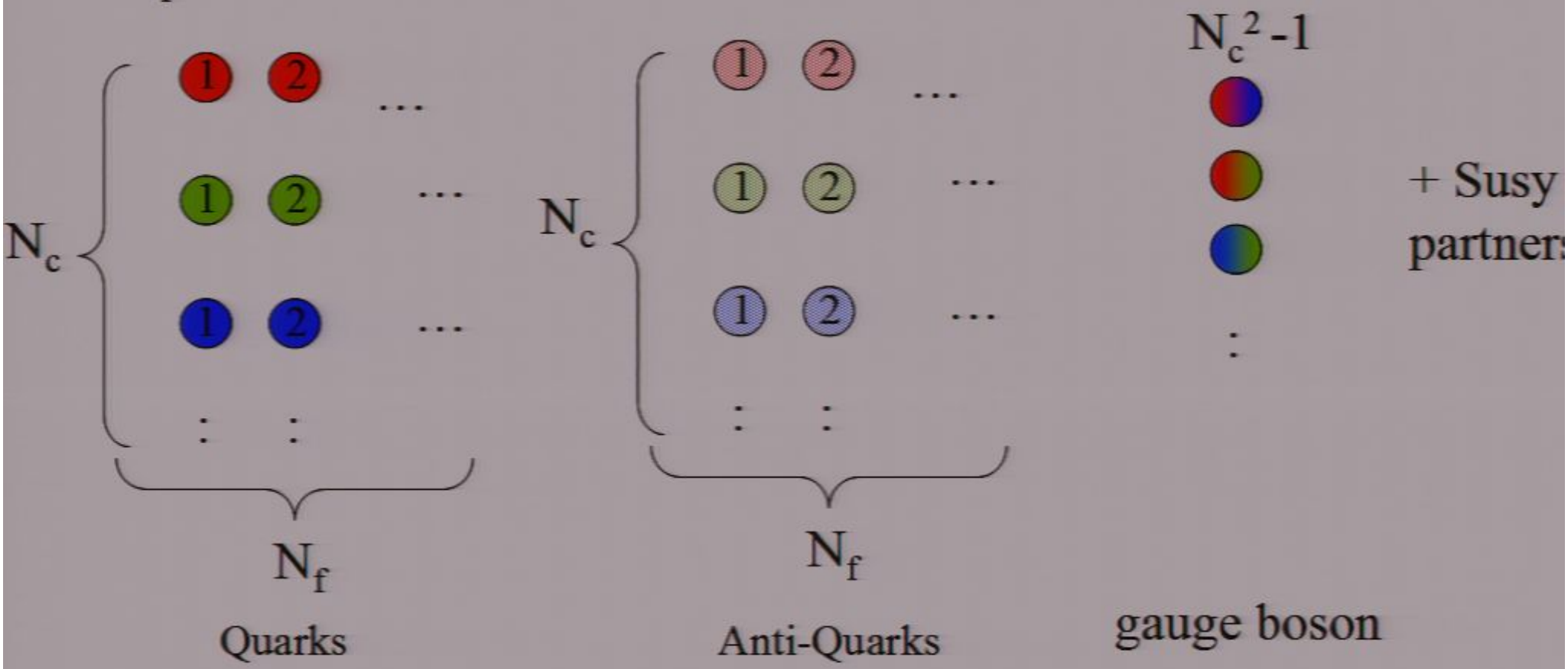
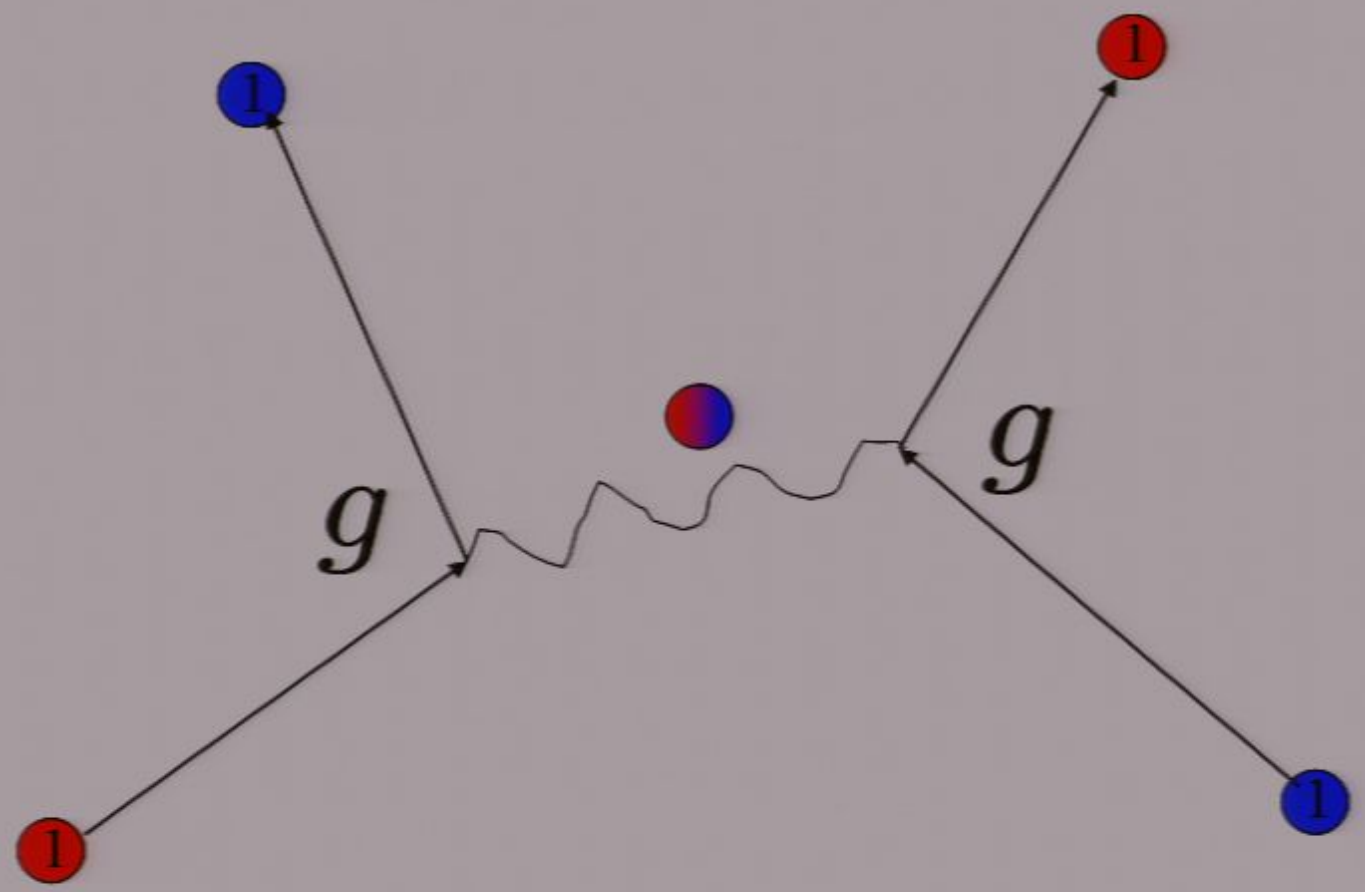
Emergent gauge theory example II : super QCD

Supersymmetric QCD

N=1 supersymmetric $SU(N_c)$ gauge theory coupled with N_f fundamental matter fields



gauge coupling



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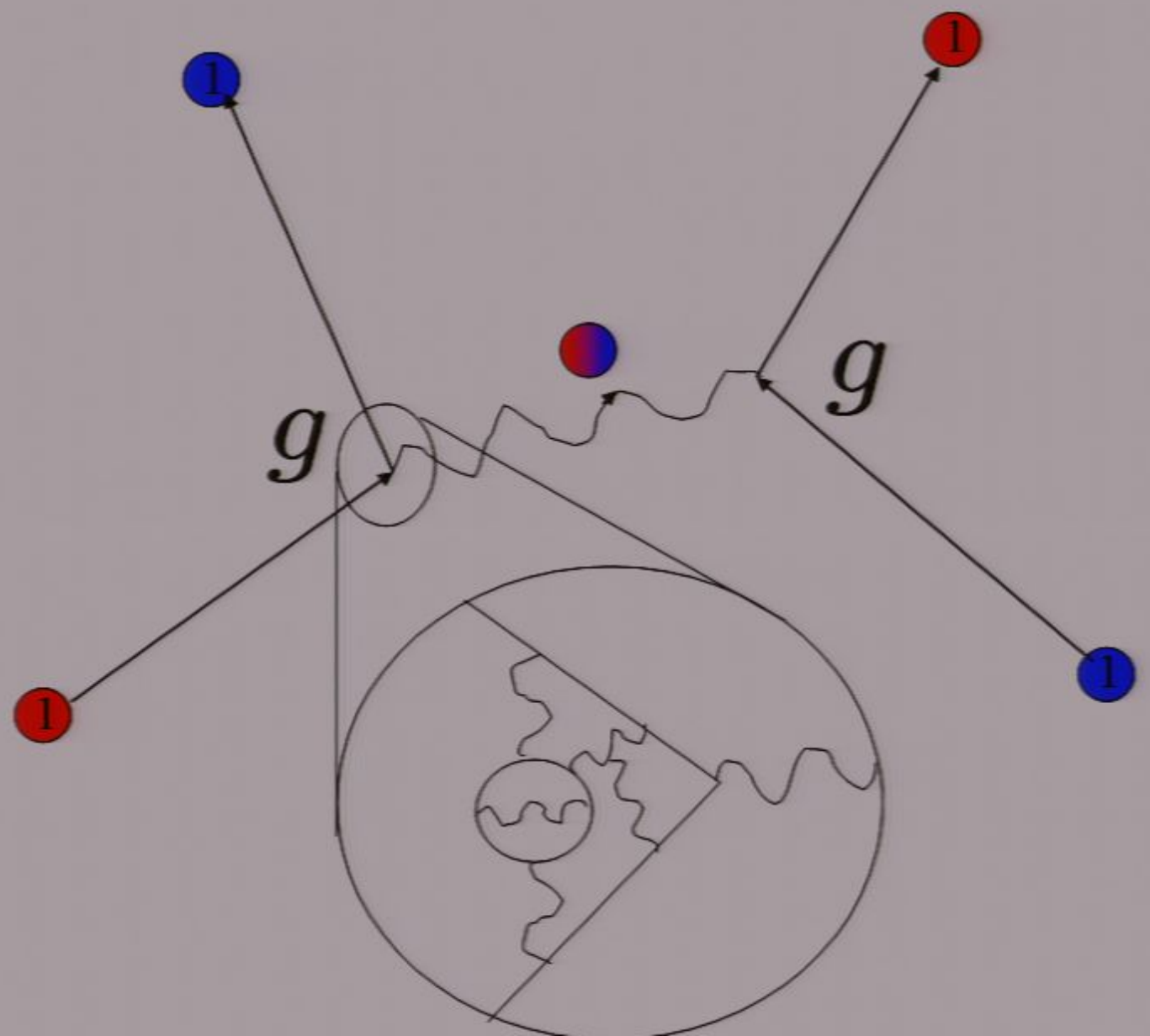
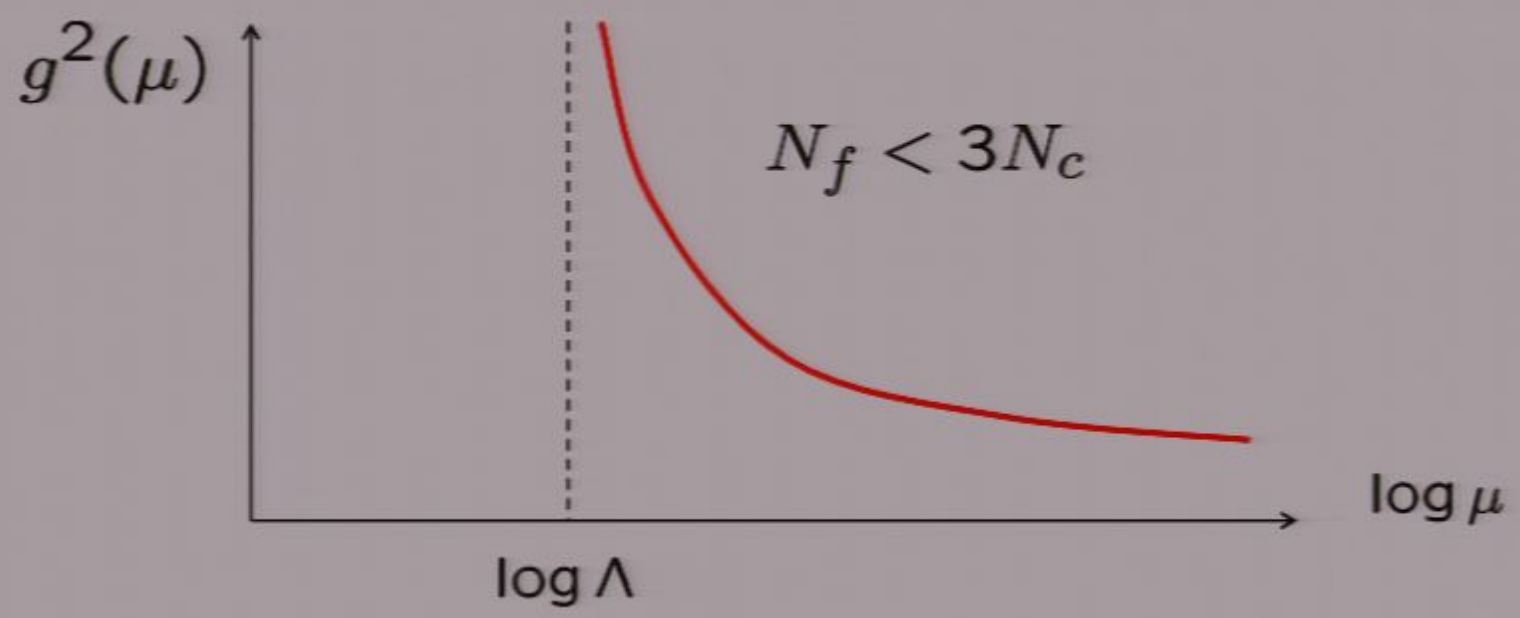


Running gauge coupling

Change of gauge coupling with energy scale μ



Fractionalization

[N. Seiberg]

$$N_c + 2 < N_f < \frac{3}{2} N_c < 3 N_c$$

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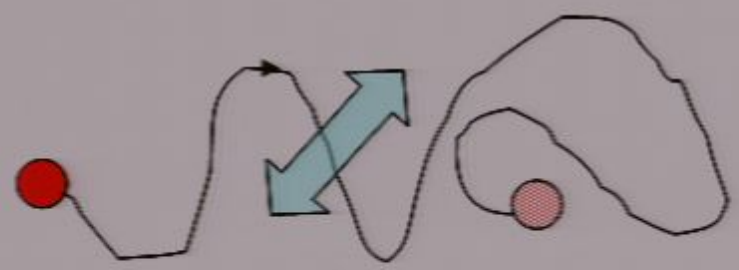

high energy

Λ

SU(N_c) gauge theory
(gluons, N_f matters)

Fractionalization

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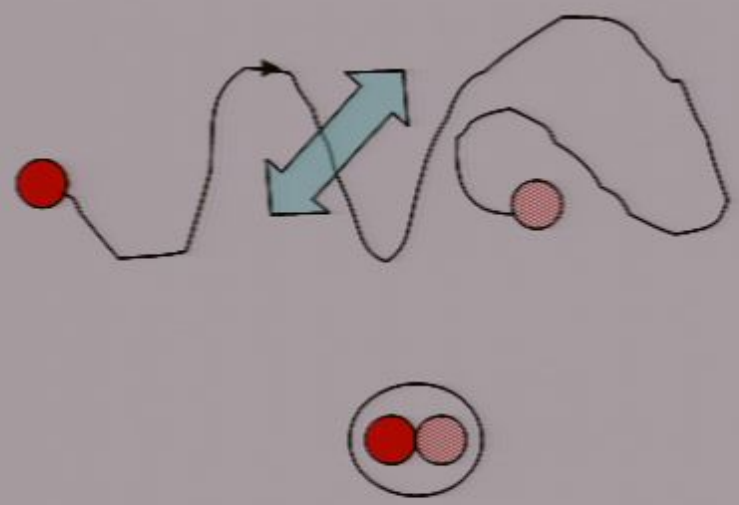

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SU(N_c) gauge theory
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Non-linear sigma model
(mesons, baryons)

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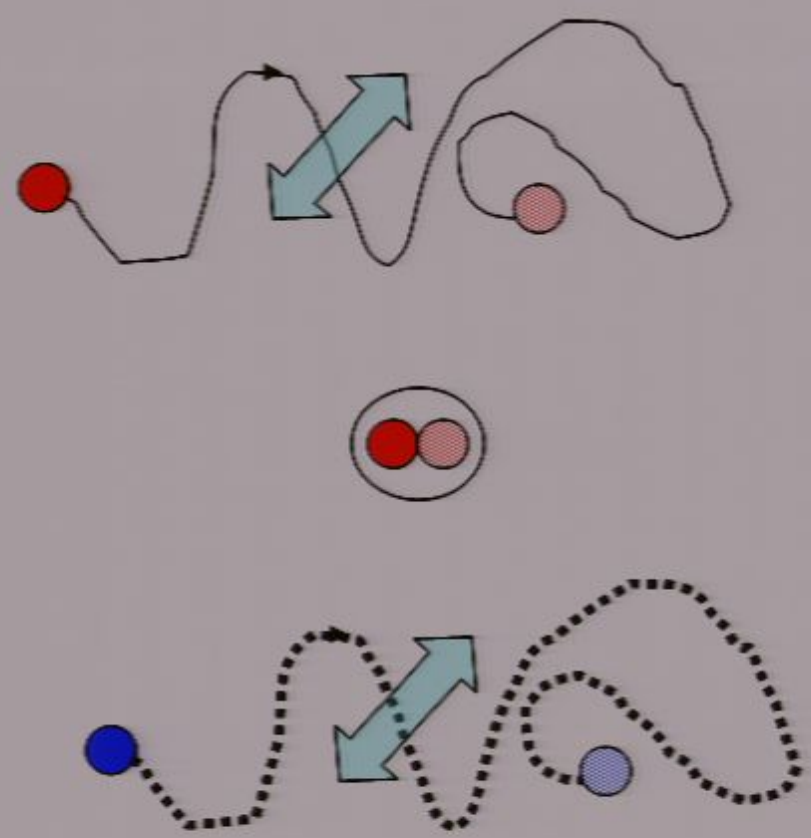


high energy

Λ

$SU(N_c)$ gauge theory
(gluons, N_f matters)

Non-linear sigma model
(mesons, baryons)

$SU(N_f\text{-}N_c)$ gauge theory
("gluons", N_f "matters")

Emergent gauge theory
example III : exciton (meson) model

Model

a,b=1,2,…,N

(U(1) gauge theory)

Model

+ -

a b a,b=1,2,…,N

(U(1) gauge theory)

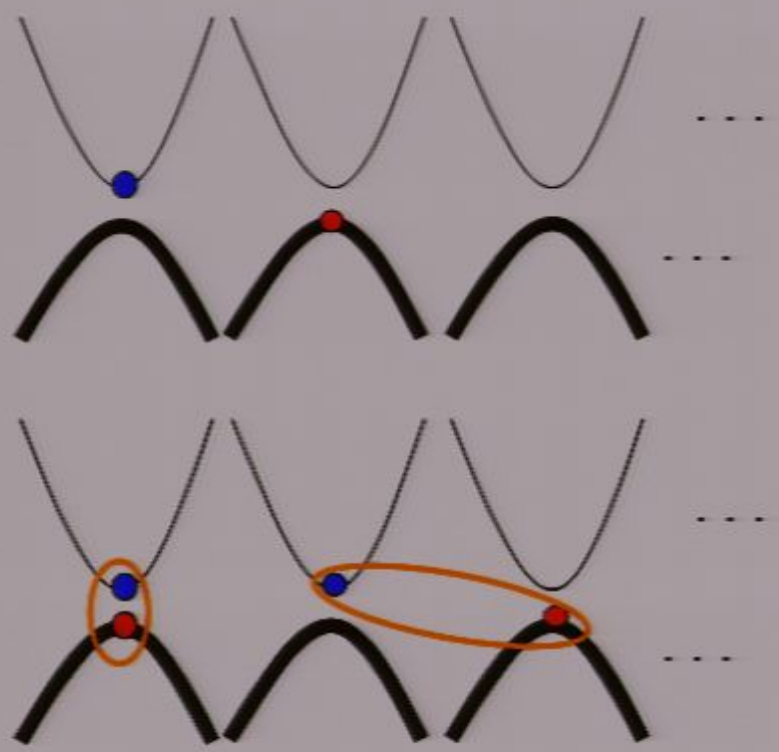
ab N^2 composite particles

(non-linear sigma model)

Low
Energy

Model

exciton



Low
Energy

+ -

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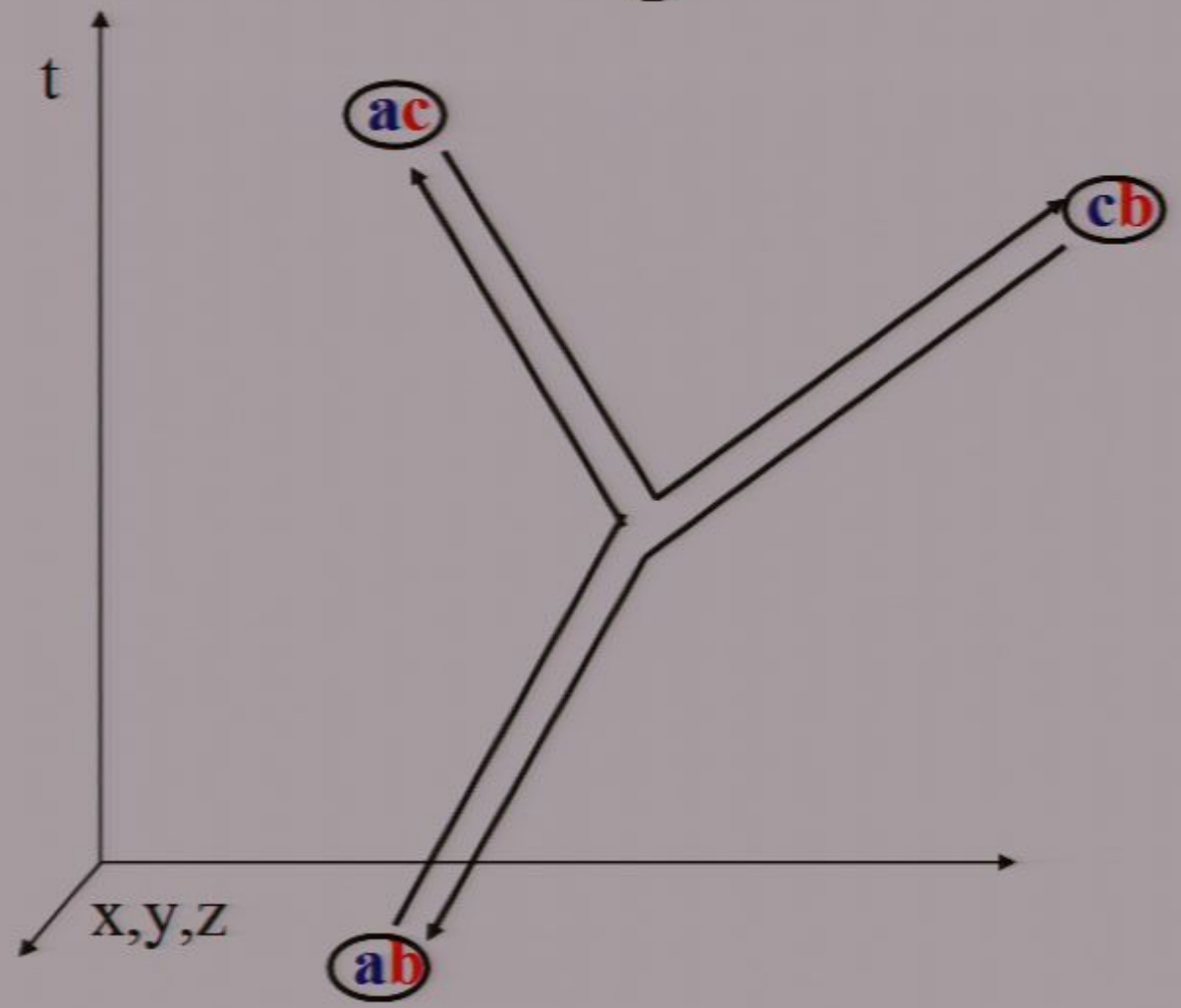
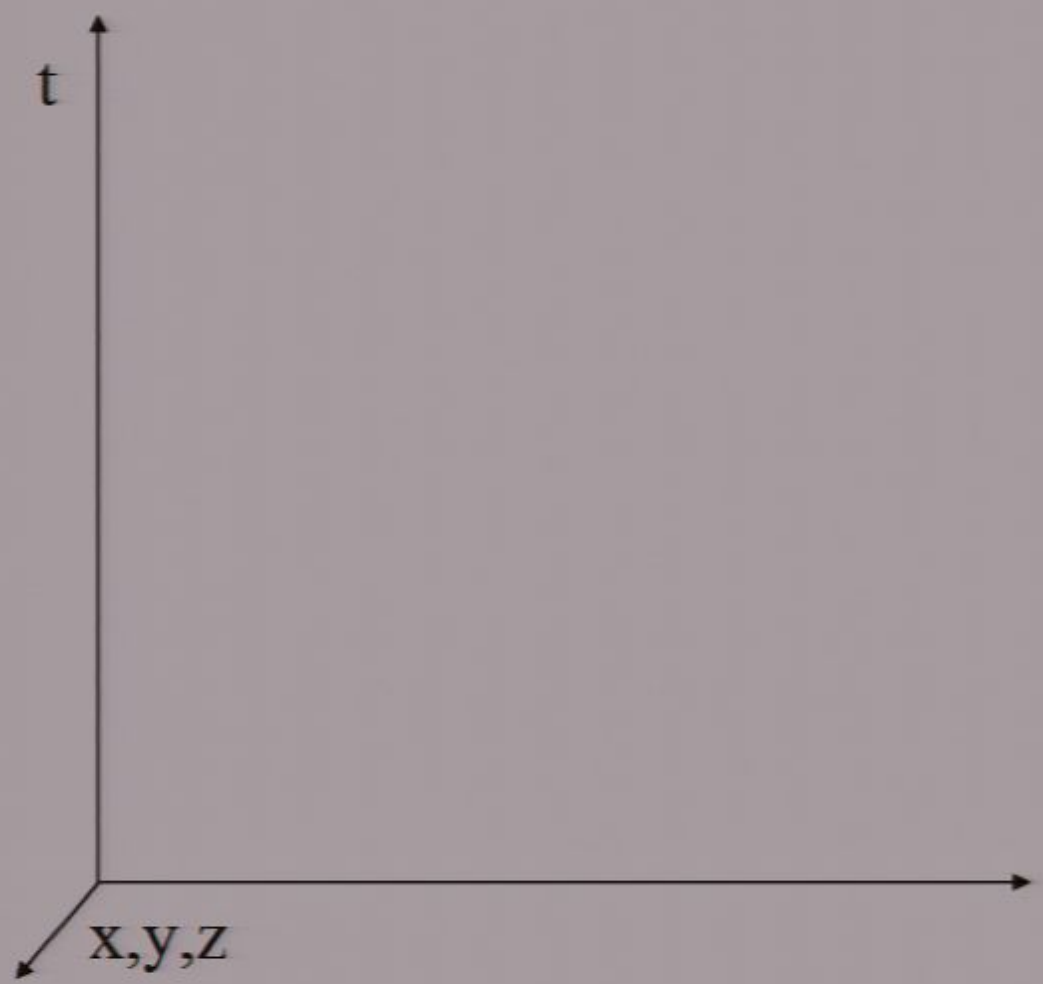
Scattering



Dynamics in a strong coupling limit



Frequent exchange
of partner

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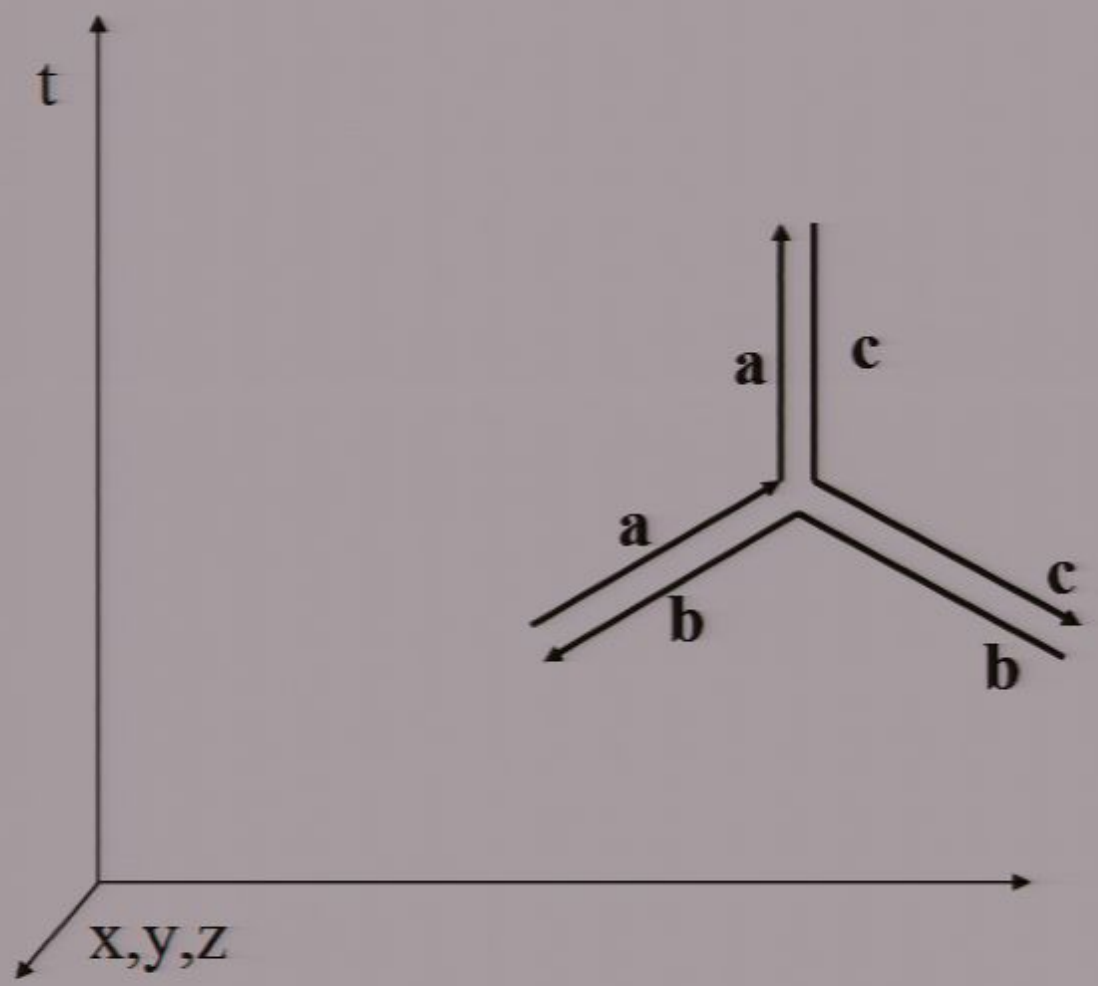

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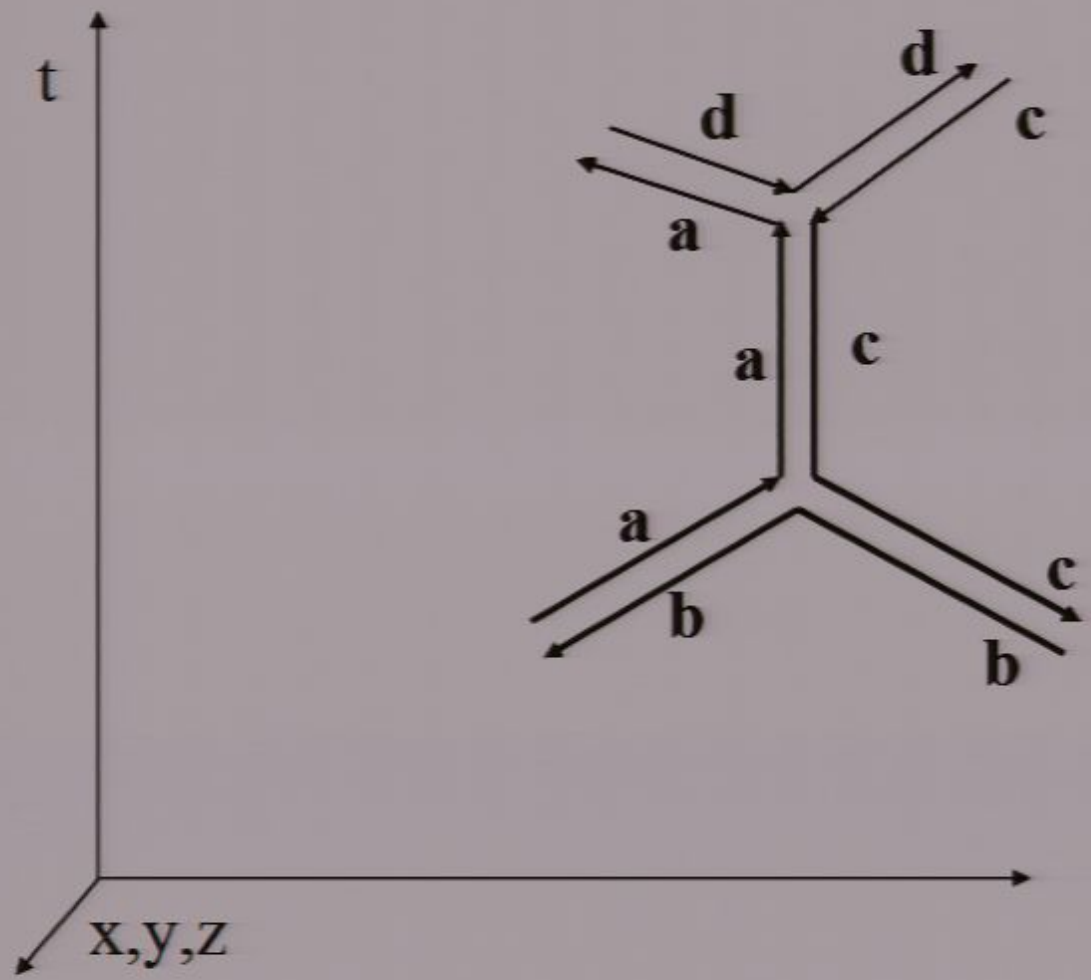

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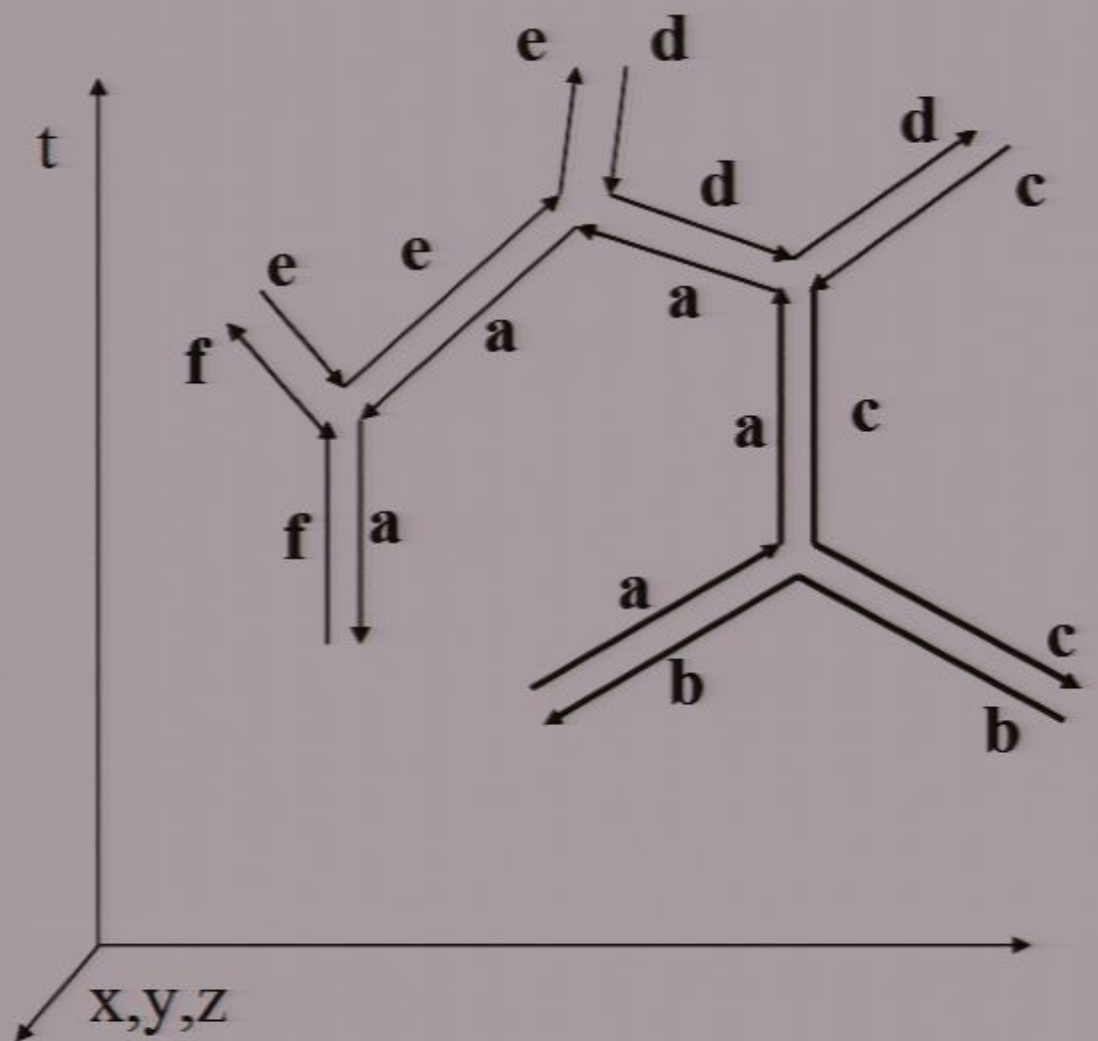

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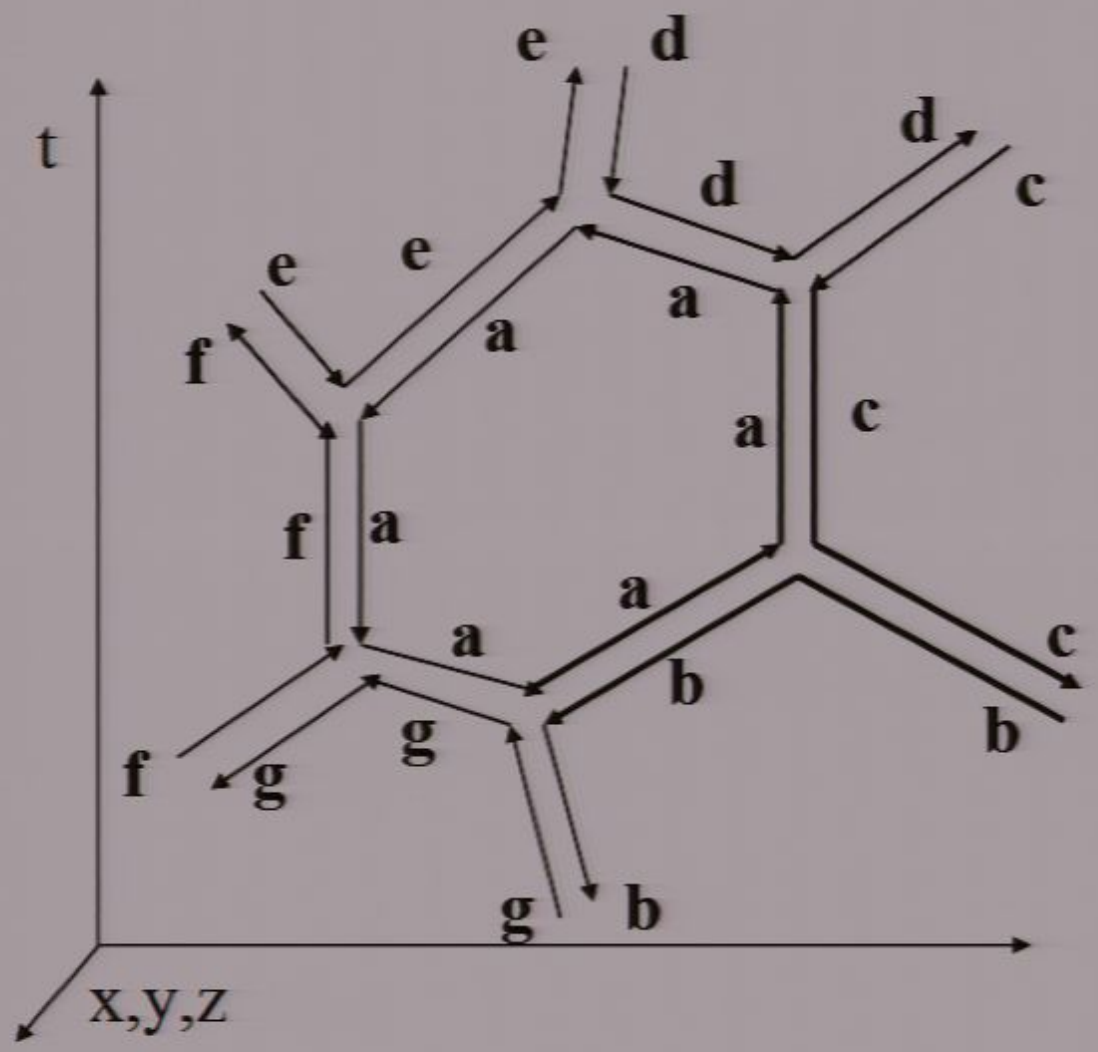
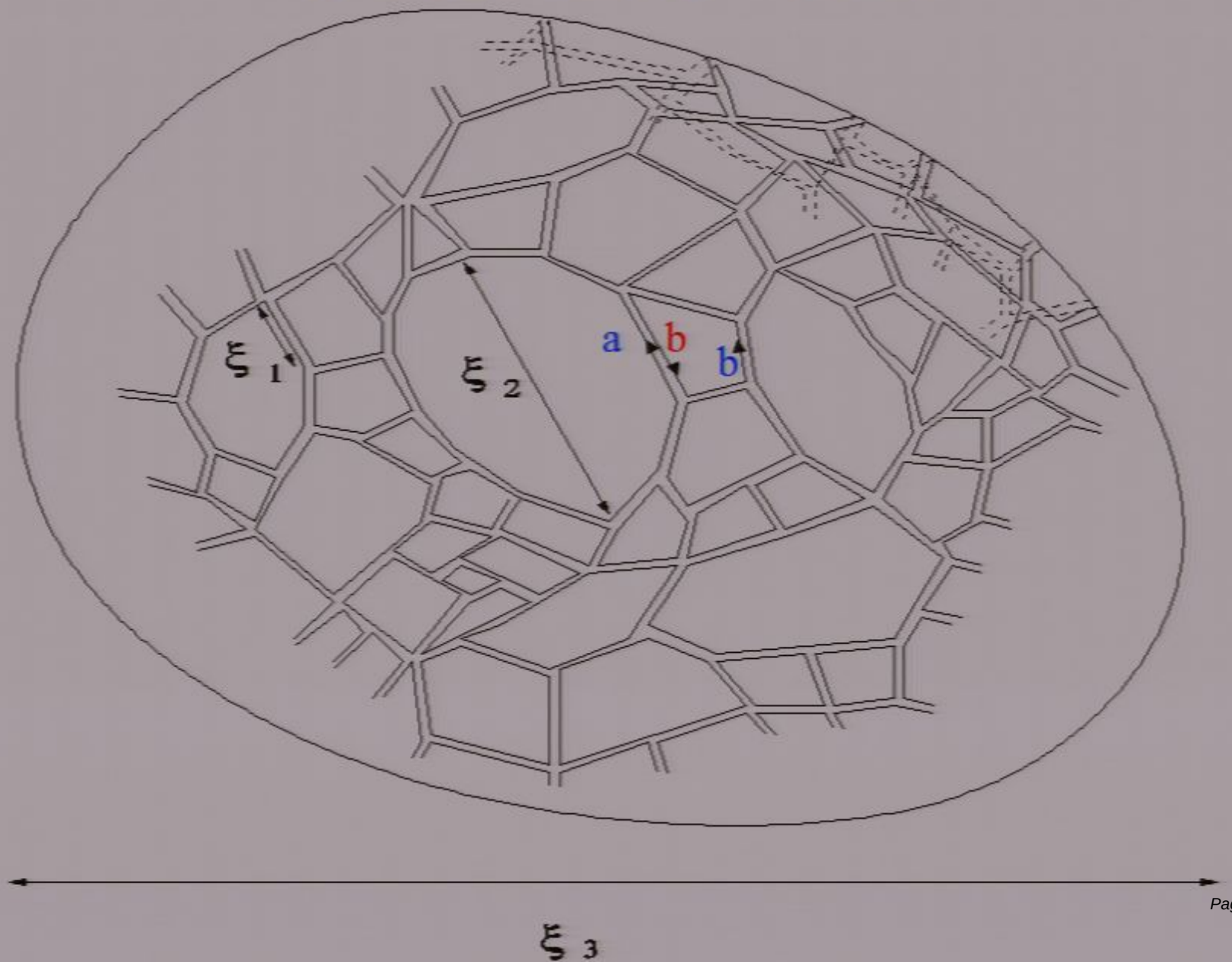


Frequent exchange of partner

World Line Web



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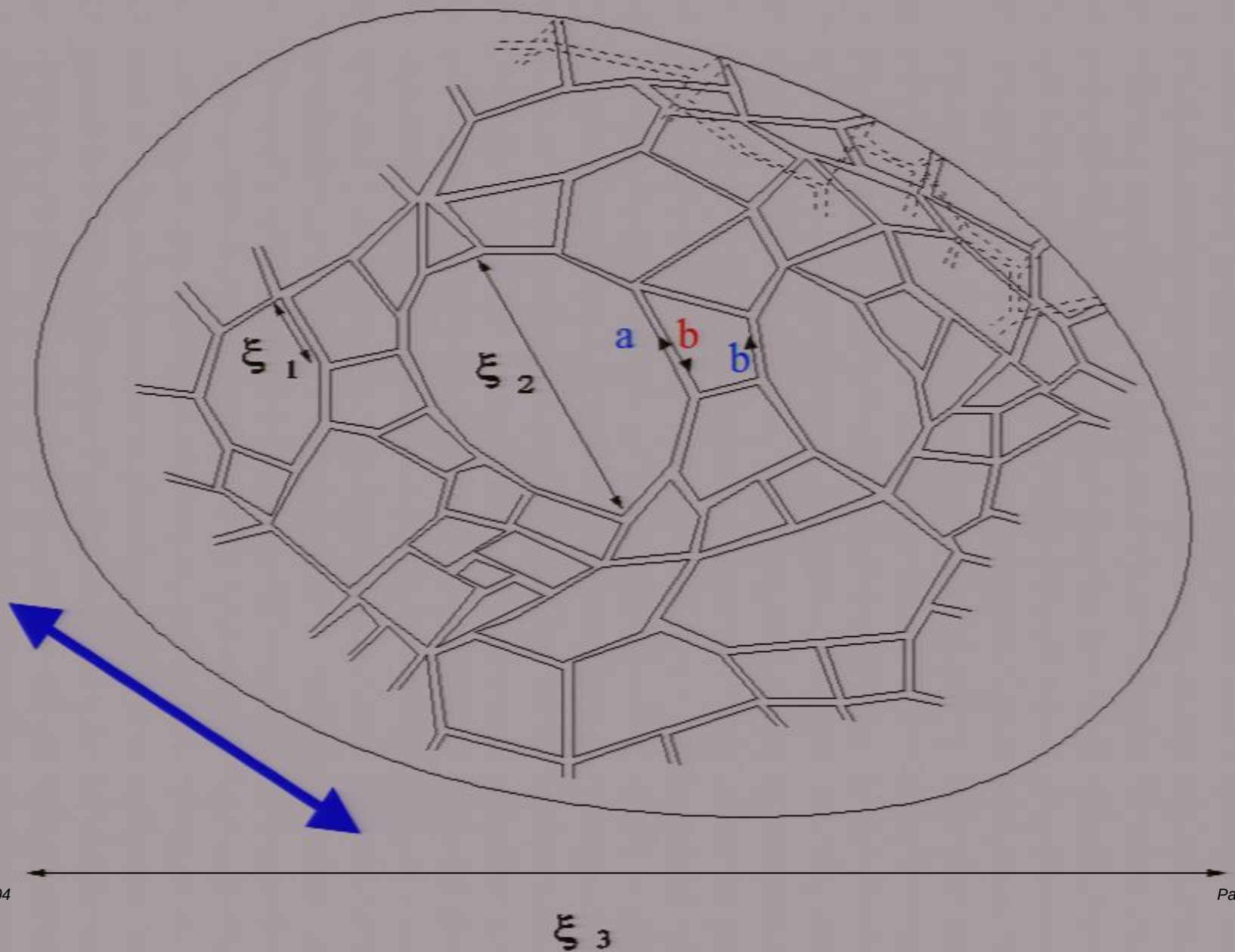
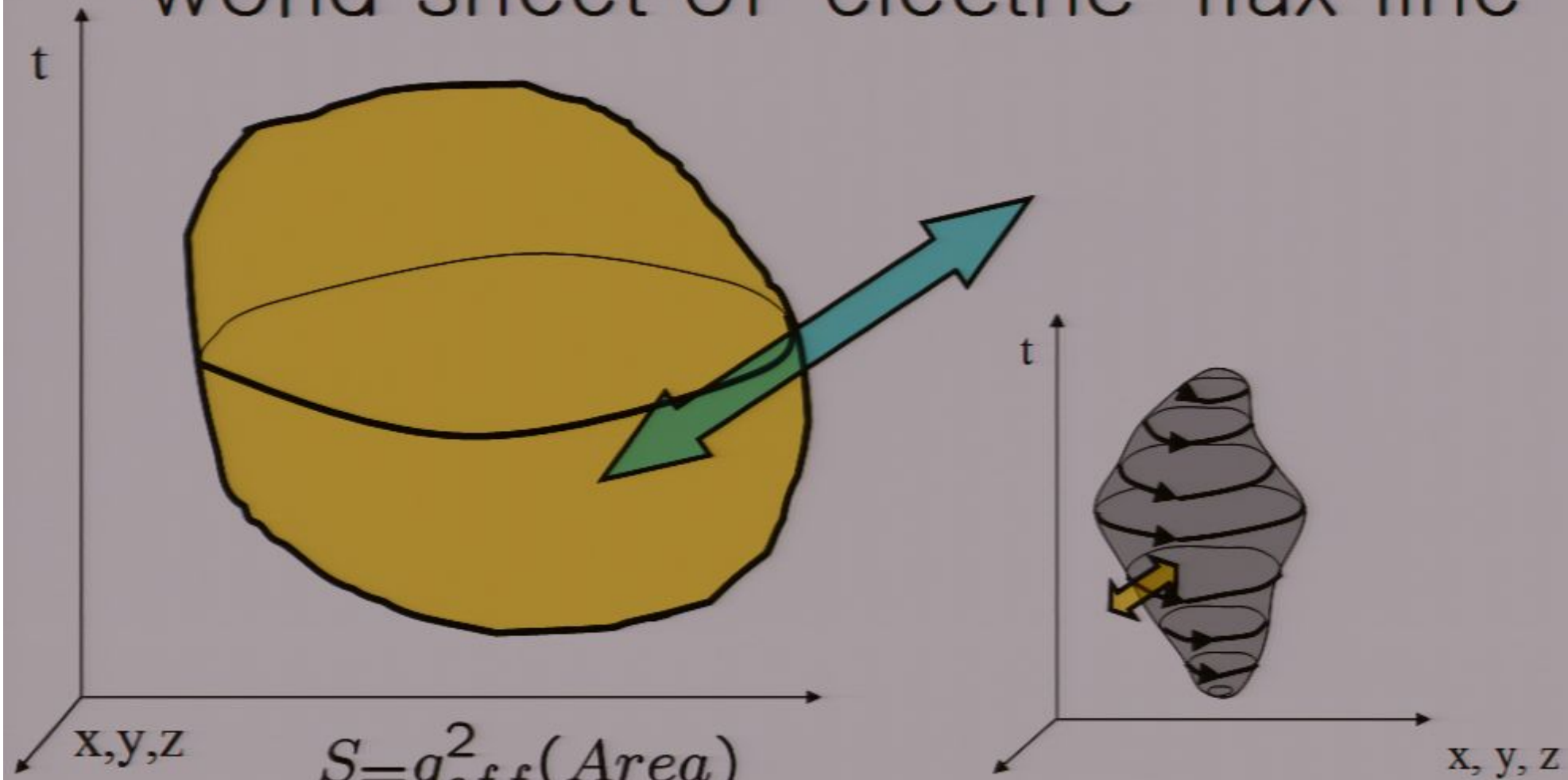


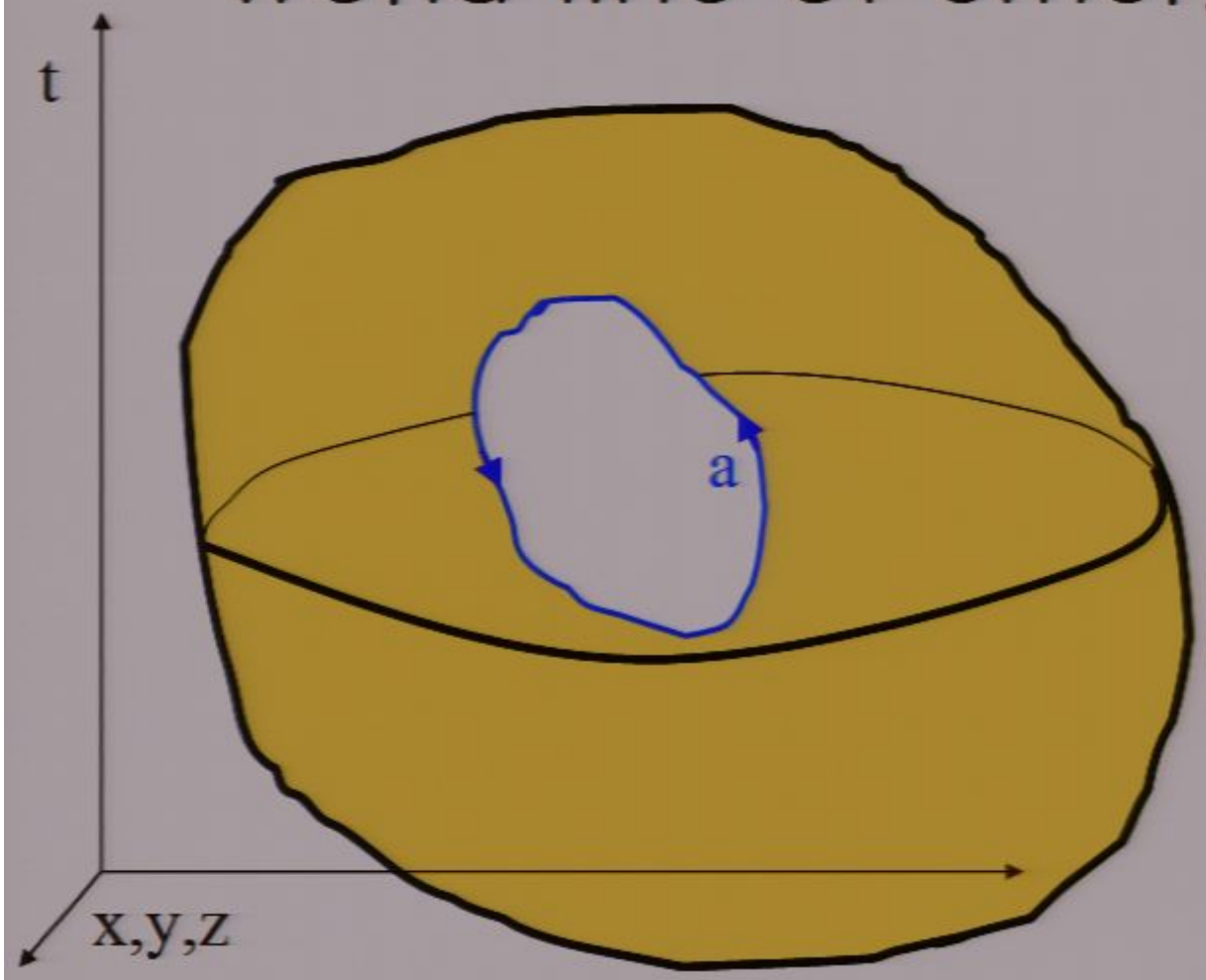
Membrane :
world sheet of 'electric' flux line



$$S = g_{eff}^2 (Area)$$

World line web looks like a smooth membrane
which fluctuate wildly

Boundary of big hole : world line of emergent matter

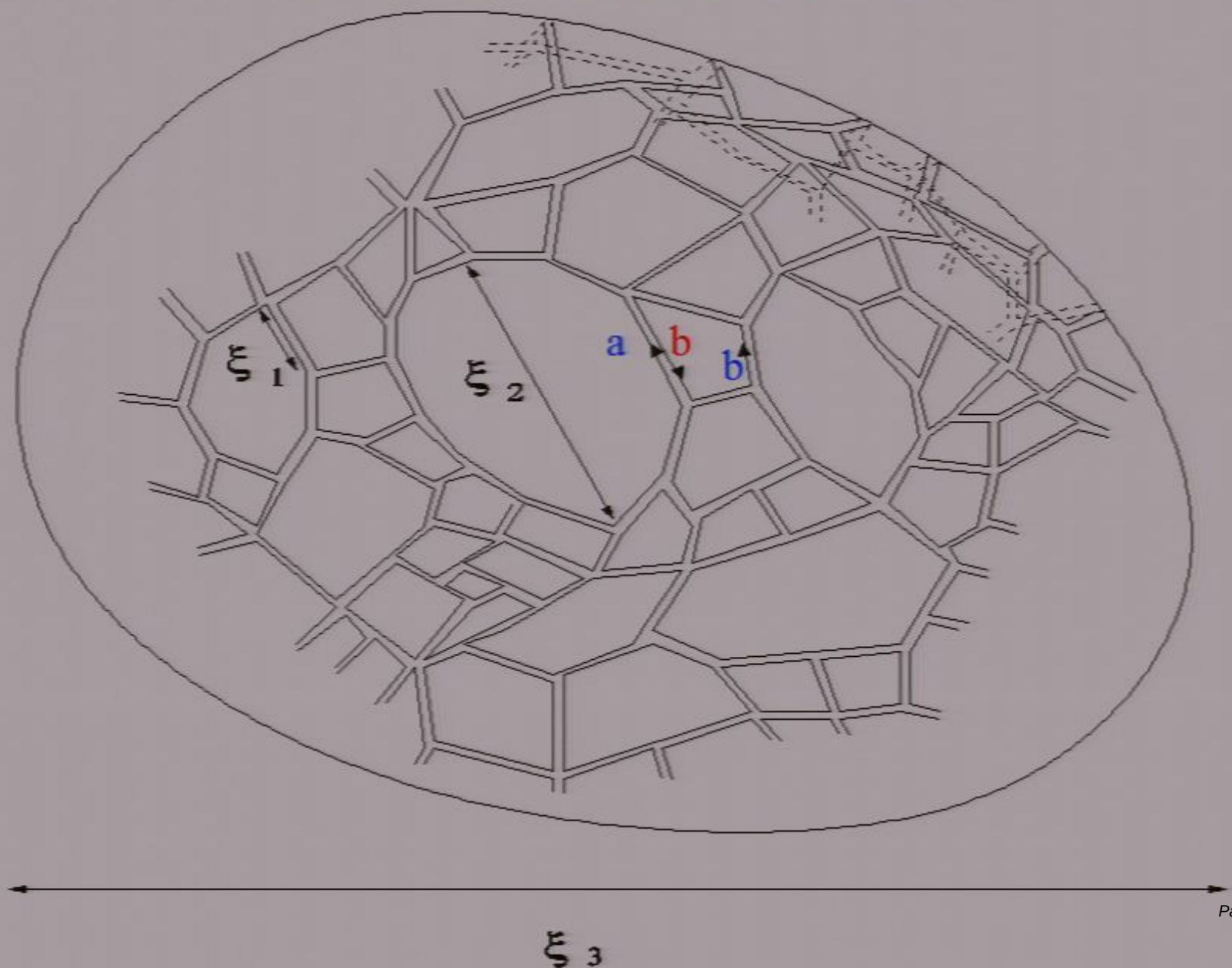


U(1) gauge theory coupled with N fractionalized particles

Boundary of puncture looks like a world line of particle

World line web looks like world sheet of an electric flux line

World Line Web



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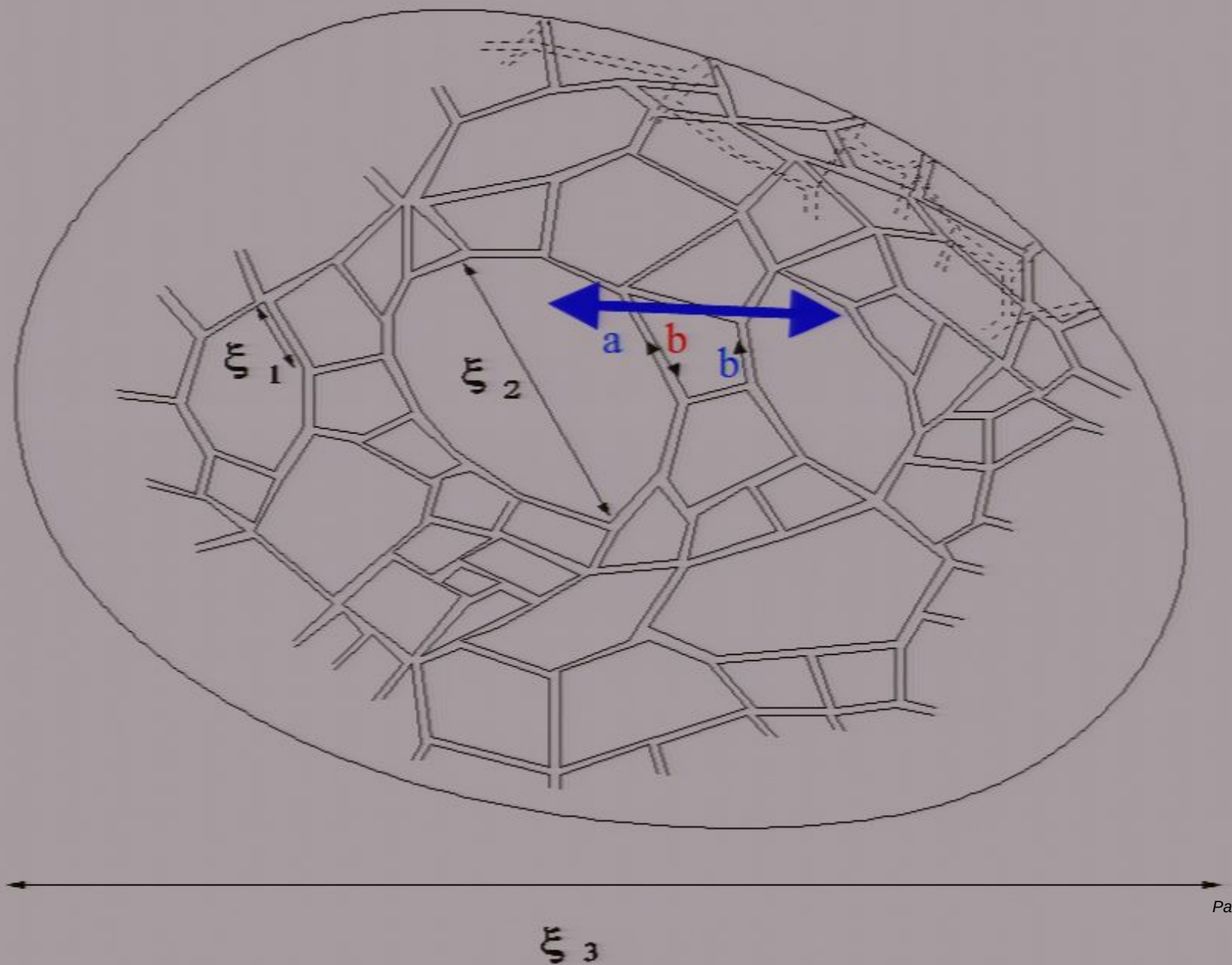

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Low Energy

(a new U(1) gauge theory)*U(1)

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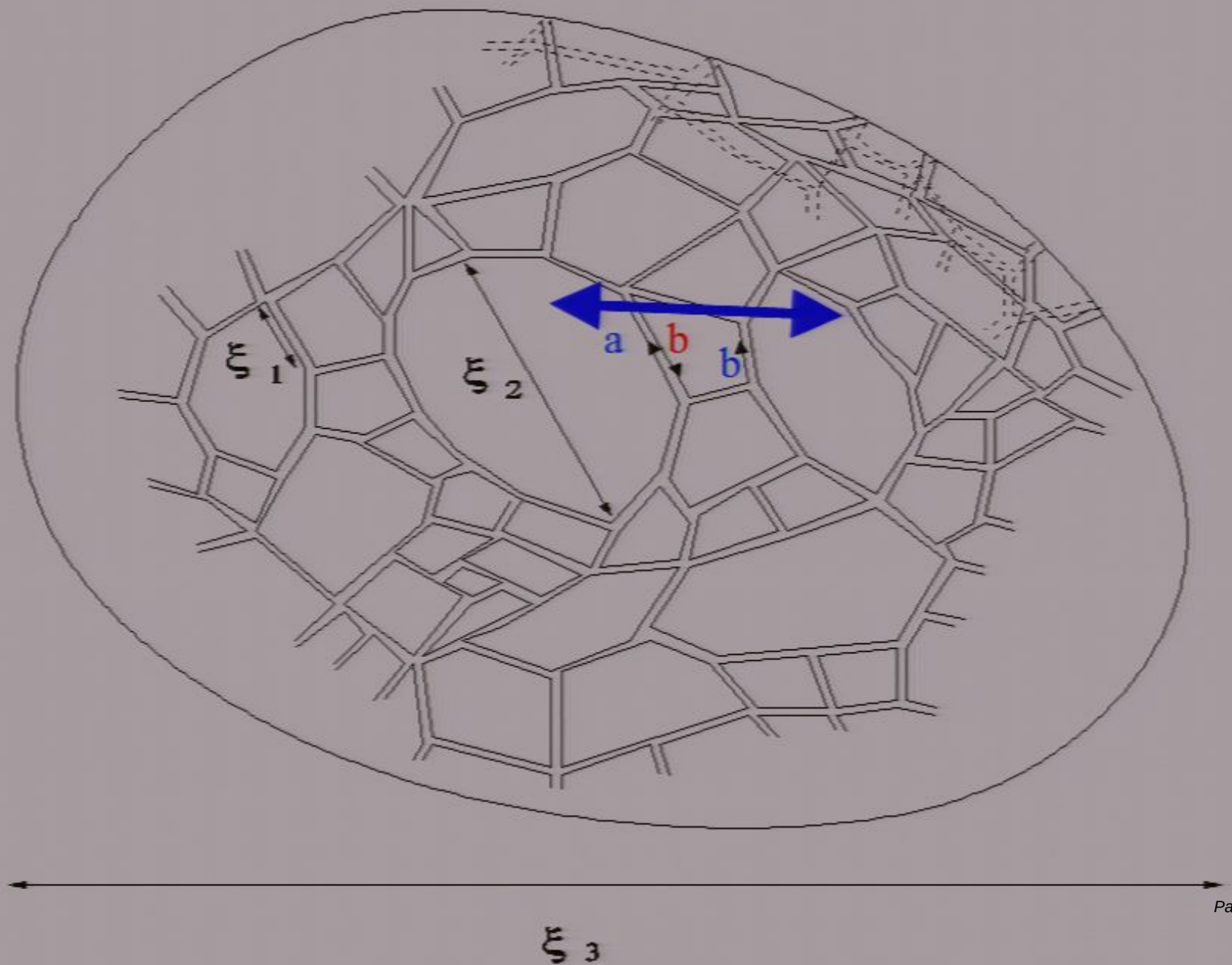

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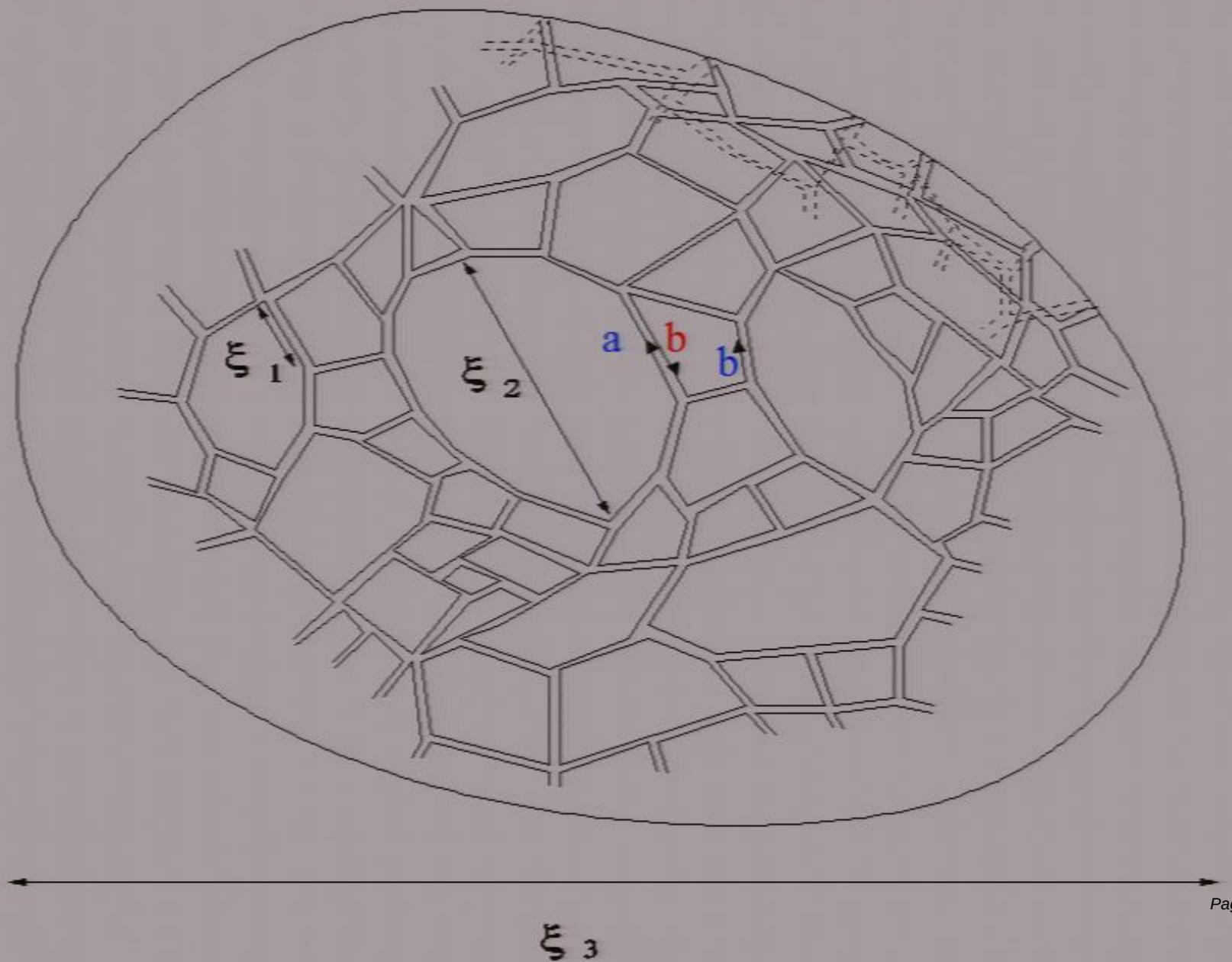
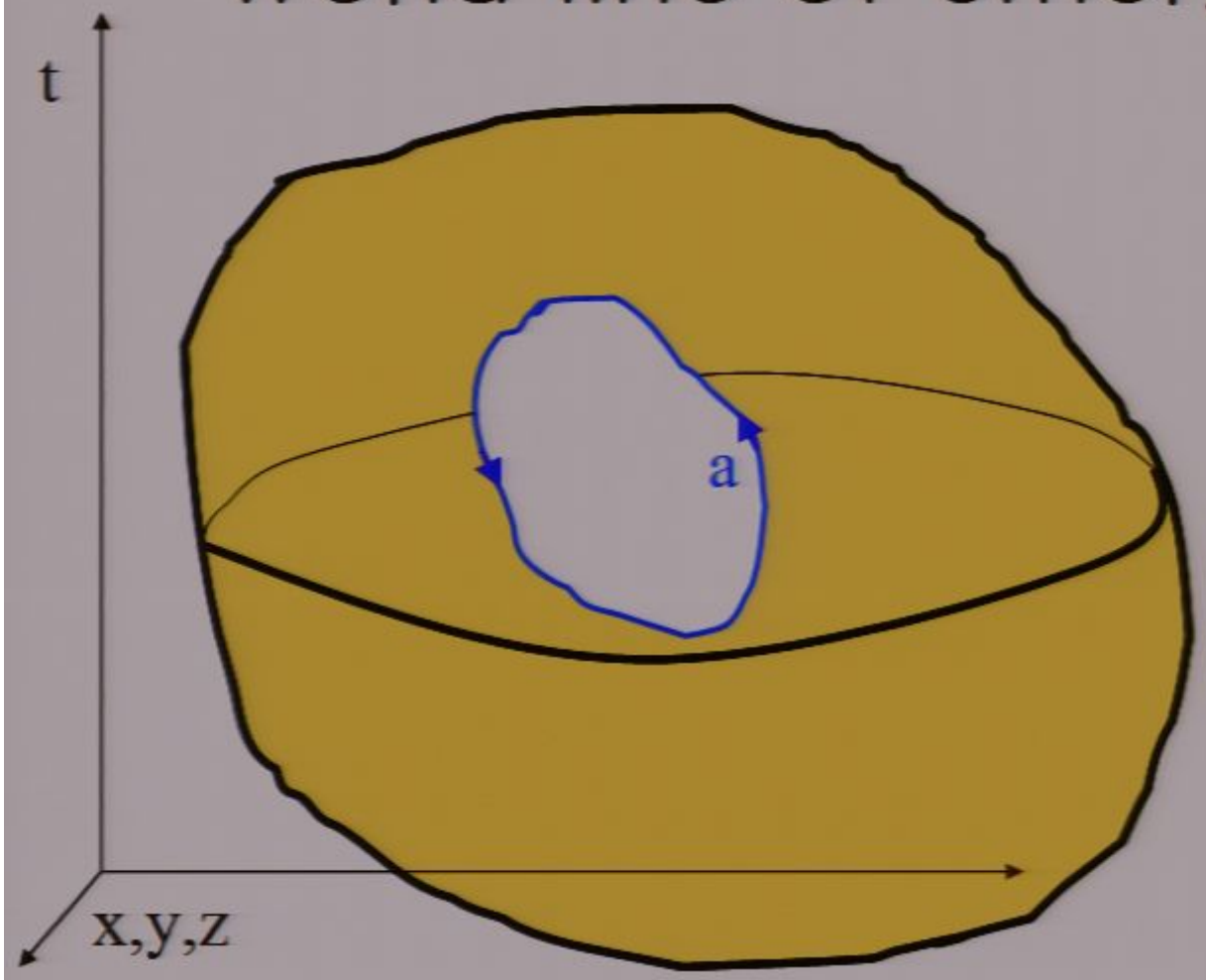


Boundary of big hole : world line of emergent matter



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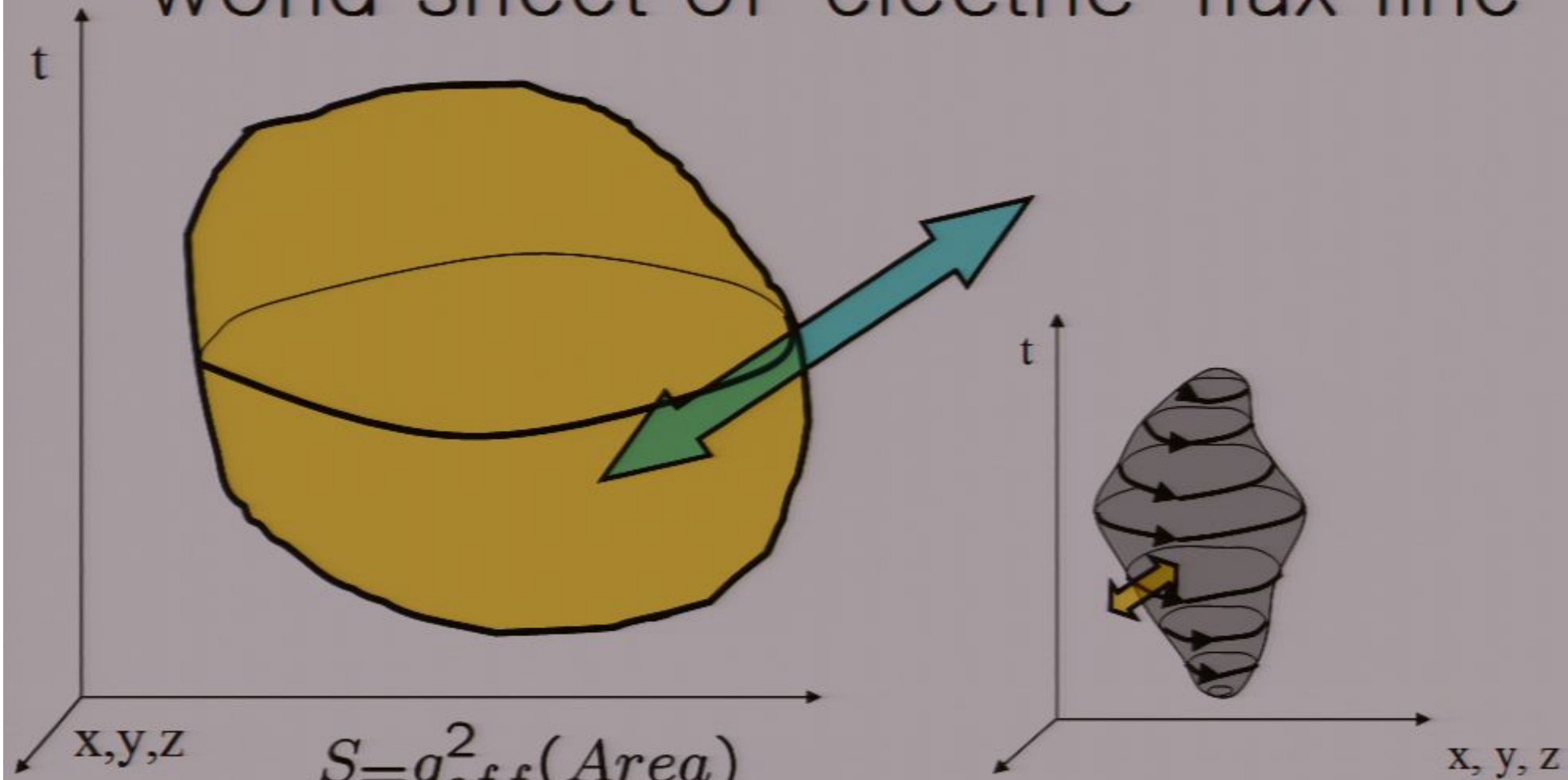
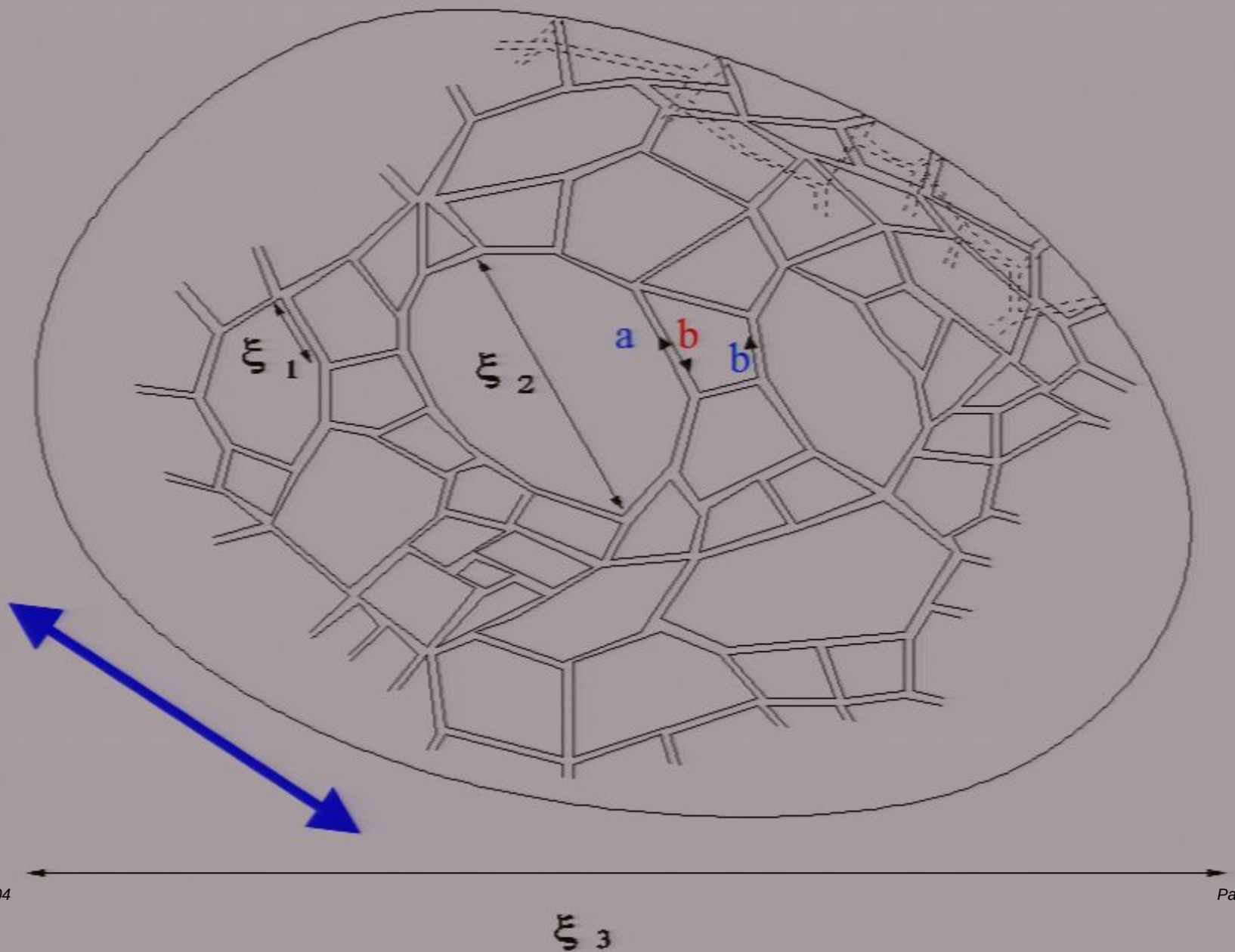
world sheet of 'electric' flux line



$$S = g_{eff}^2 (Area)$$

World line web looks like a smooth membrane
which fluctuate wildly

World Line Web



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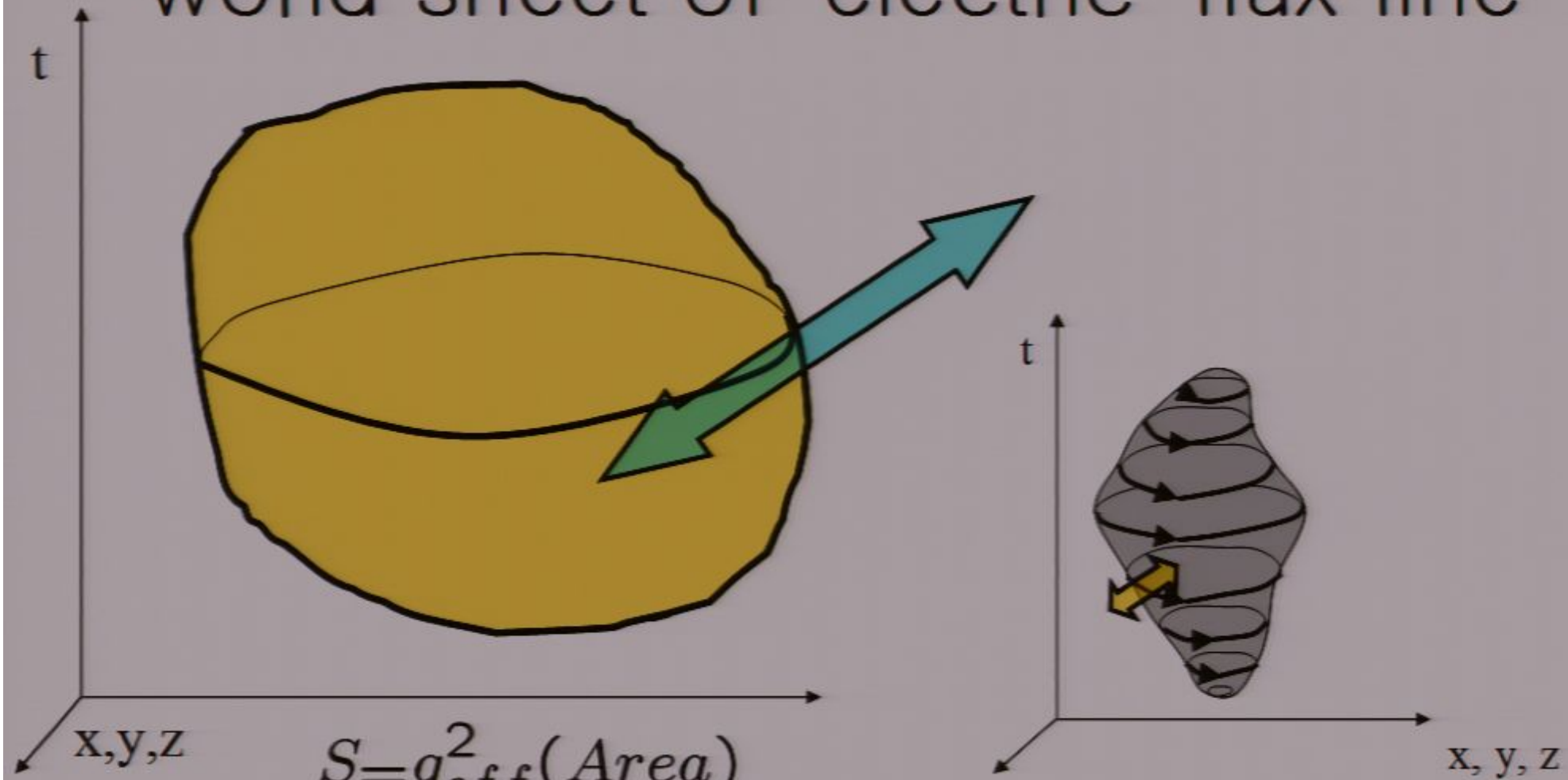

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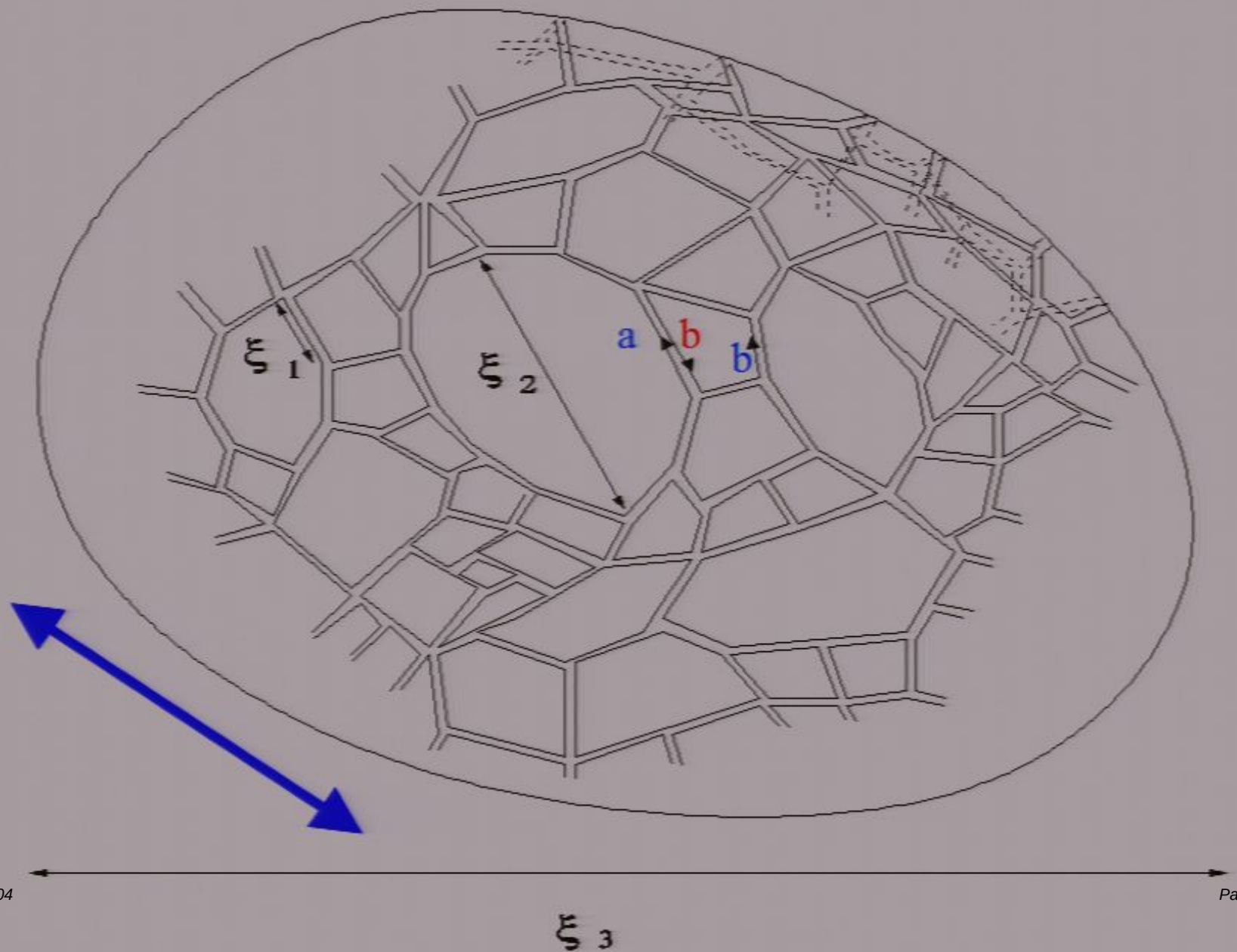

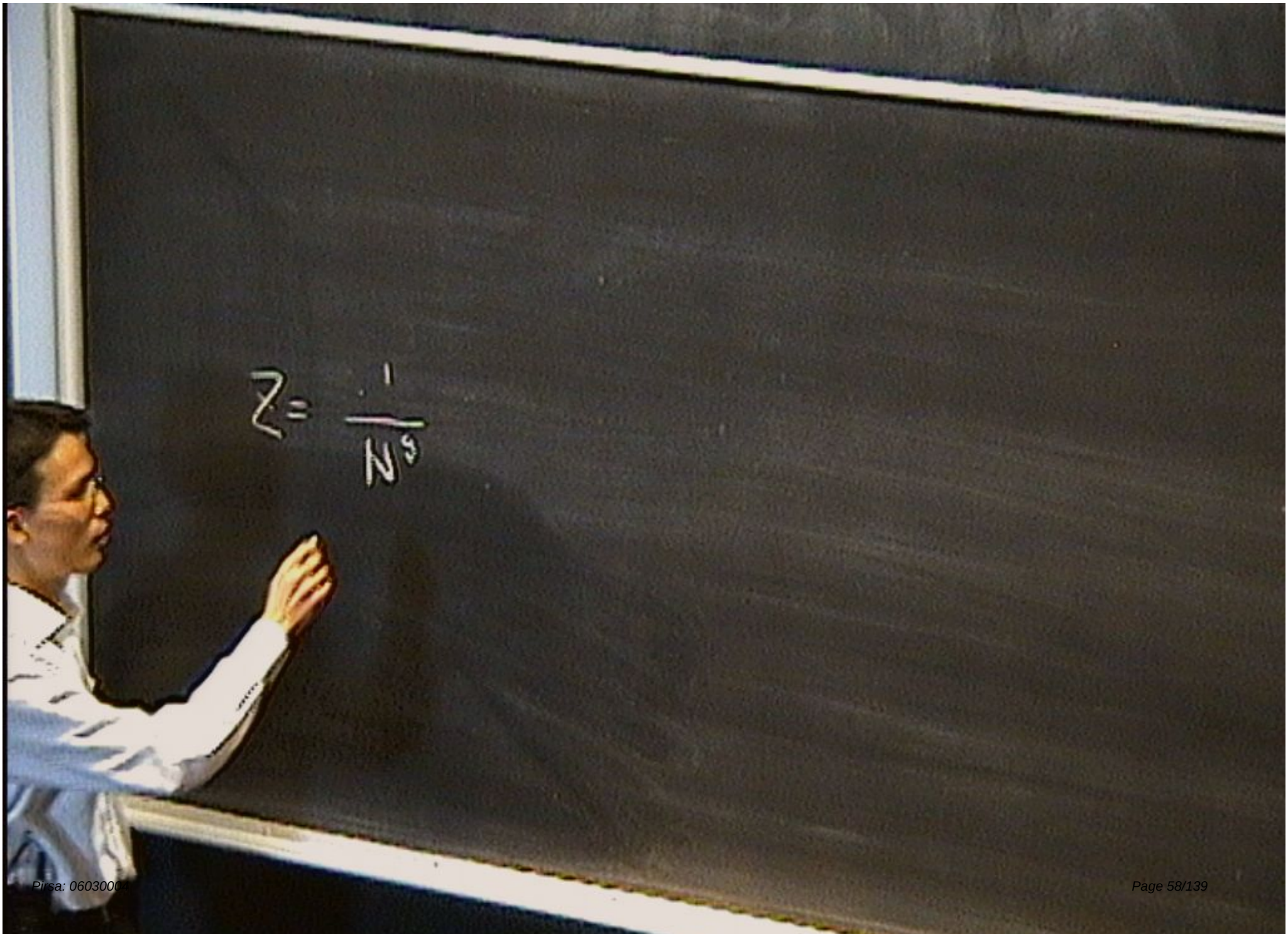
$Z = \frac{1}{N^s}$

$$Z = N^{\alpha}$$

$SU(N)$

$Z = N^{\chi}$

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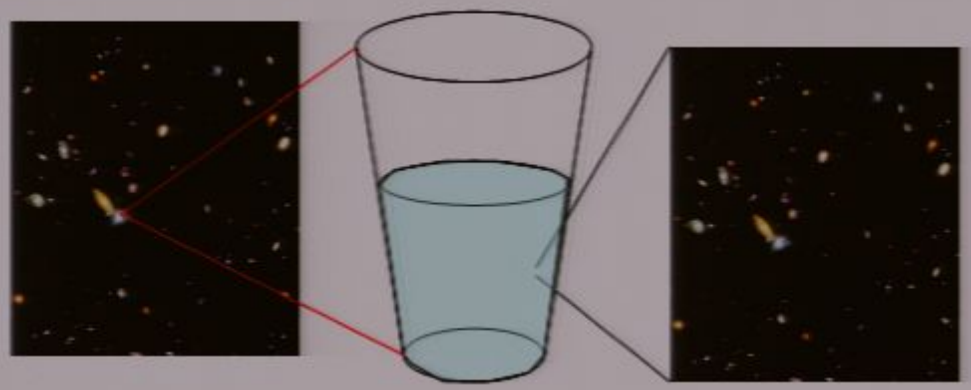

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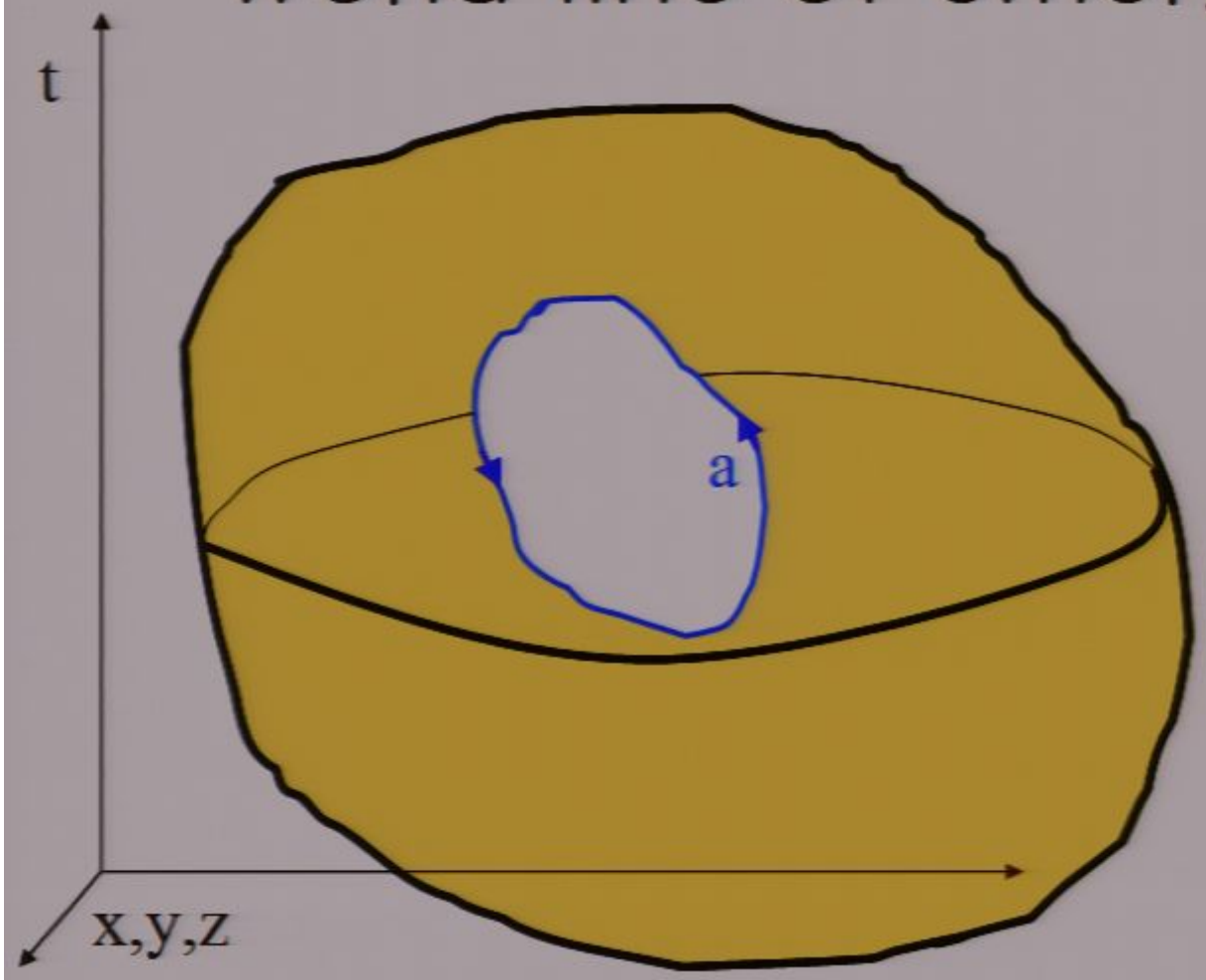

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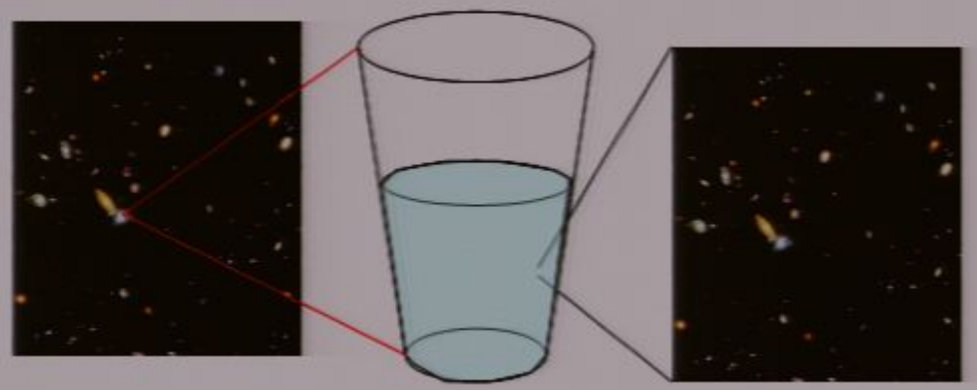

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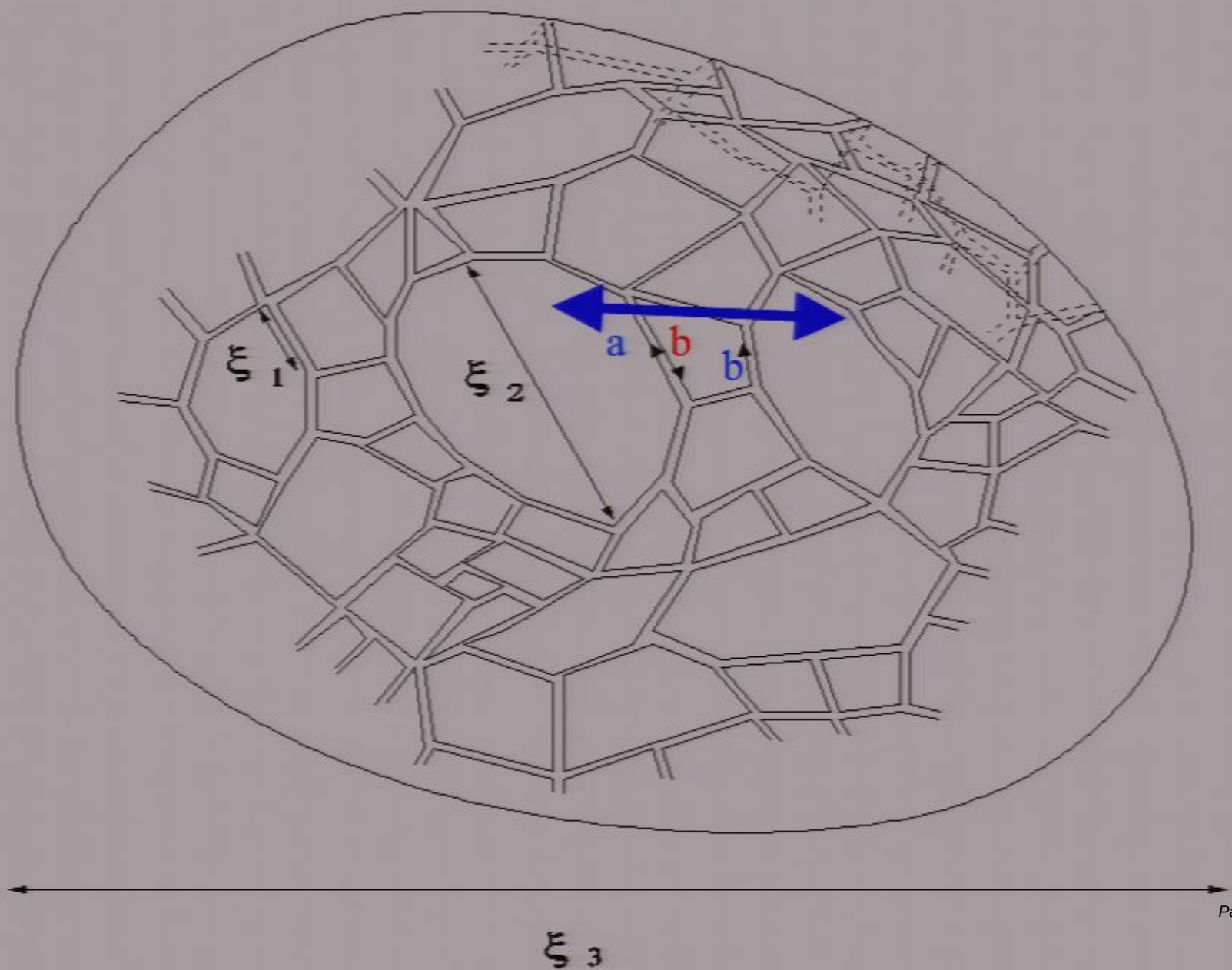

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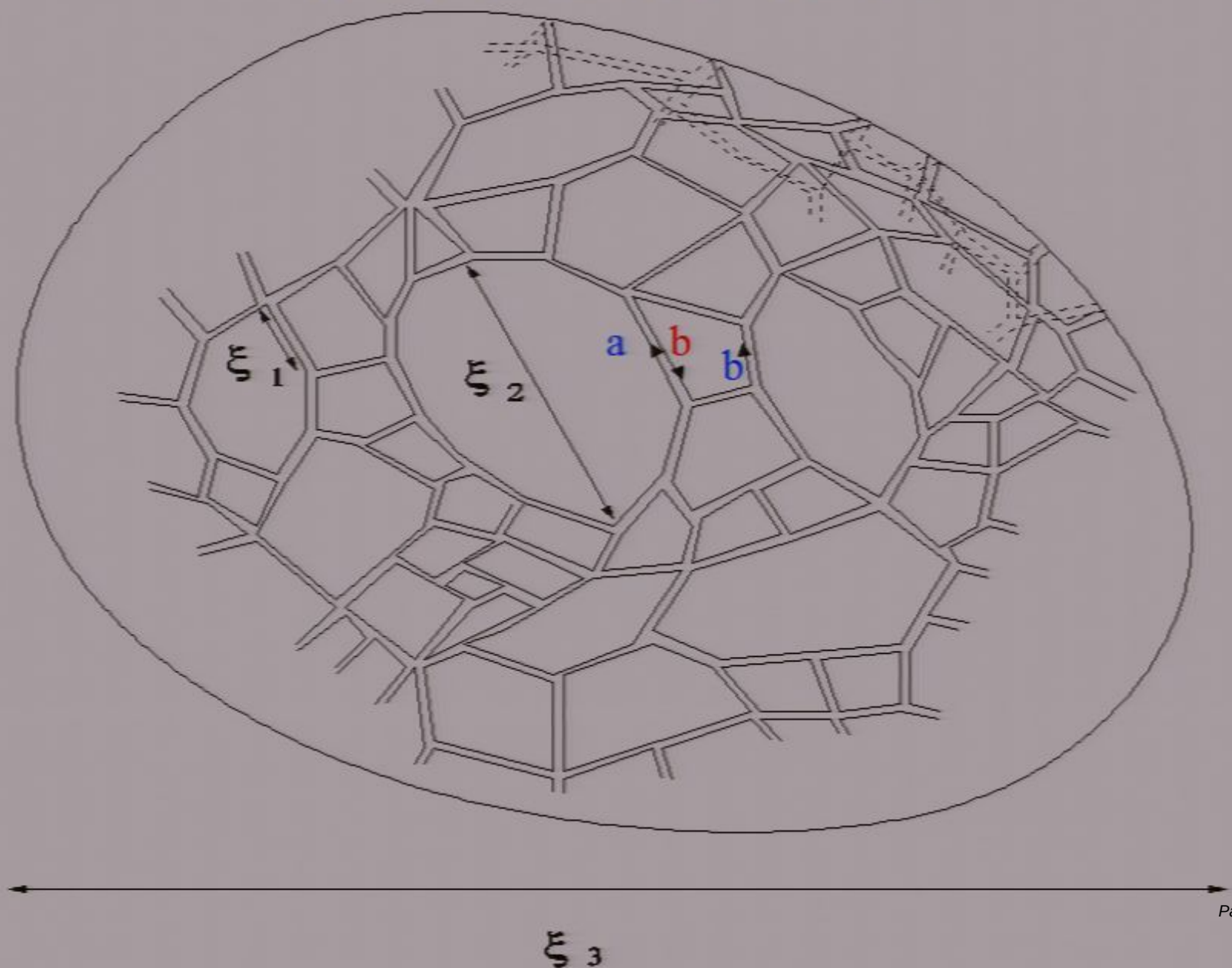

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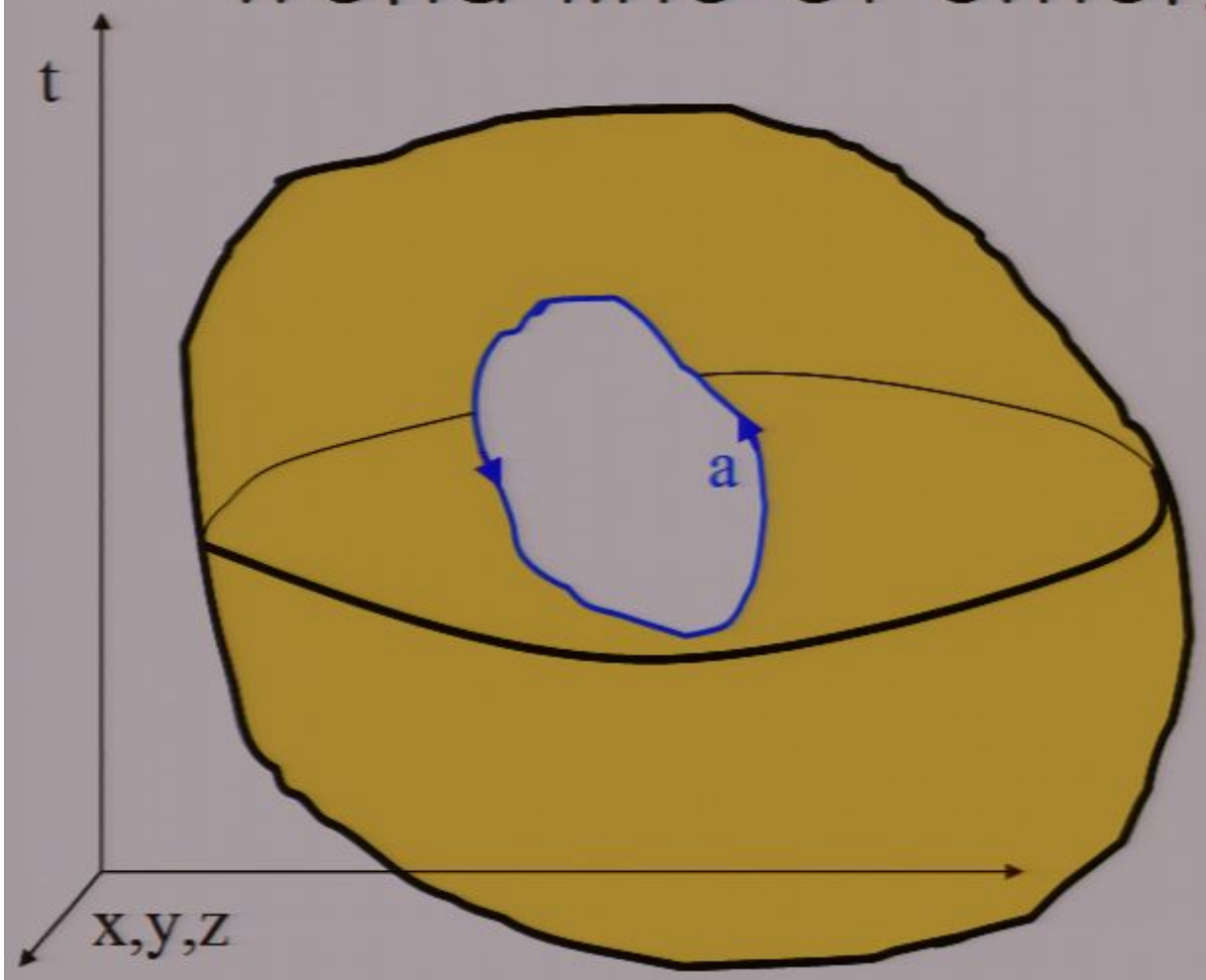

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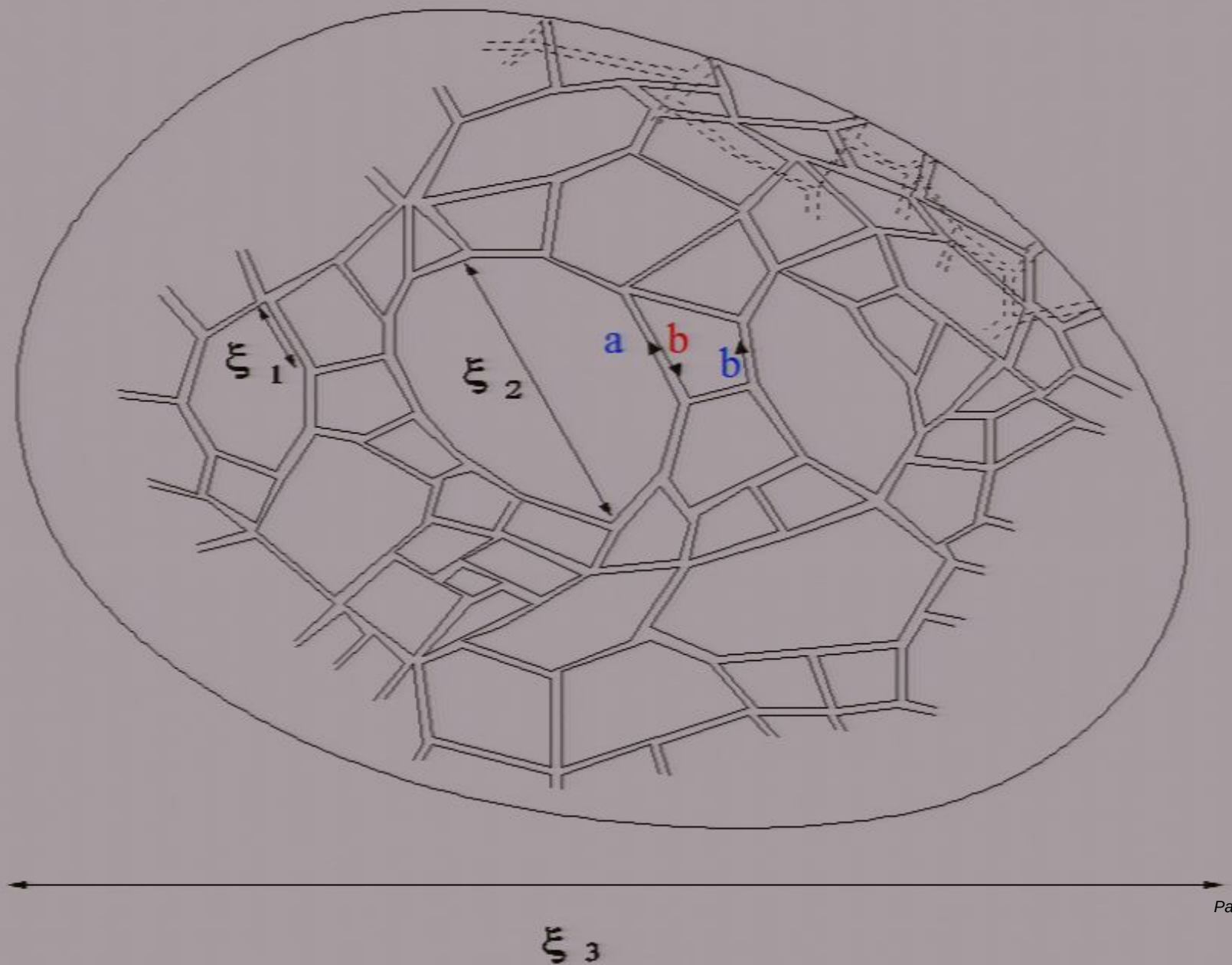
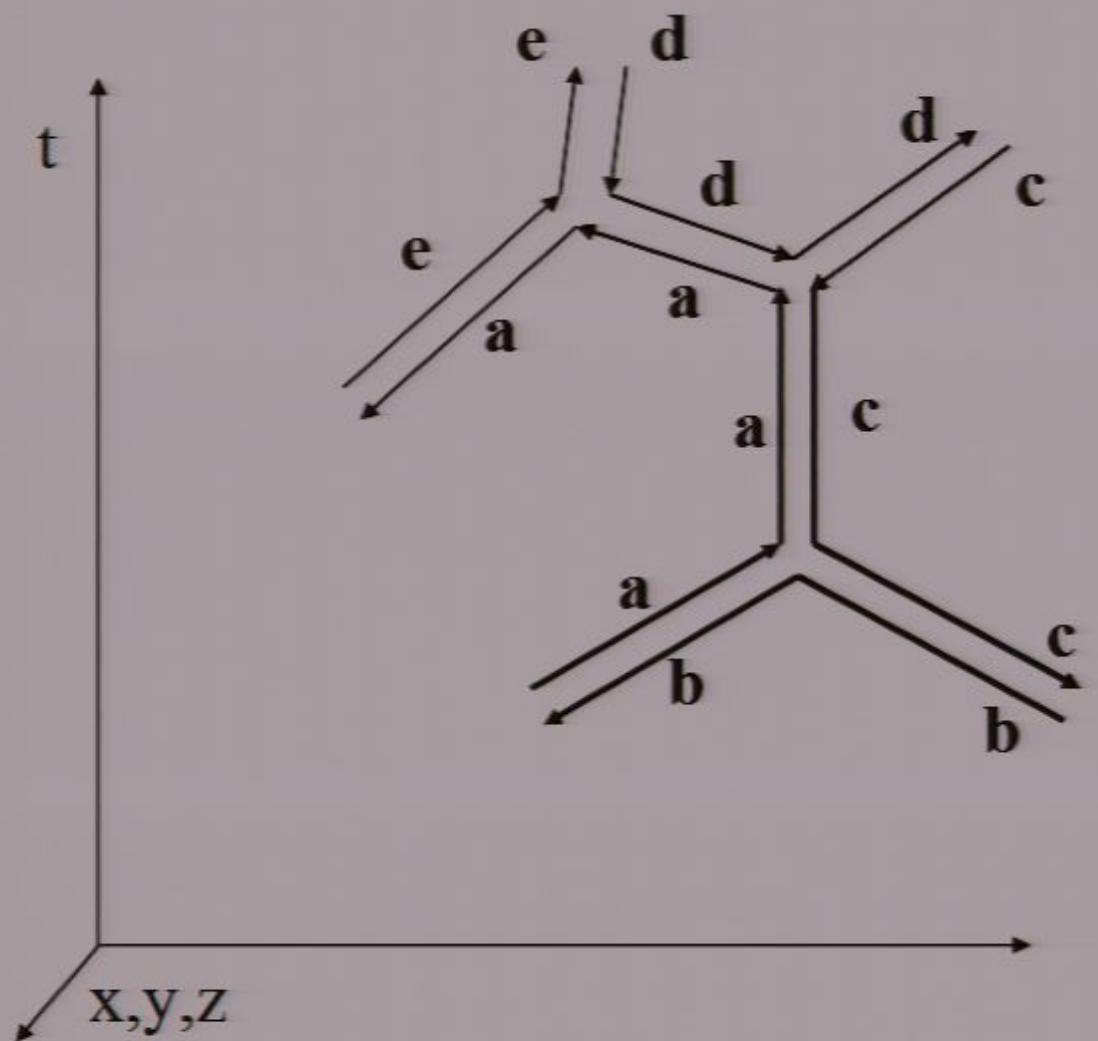


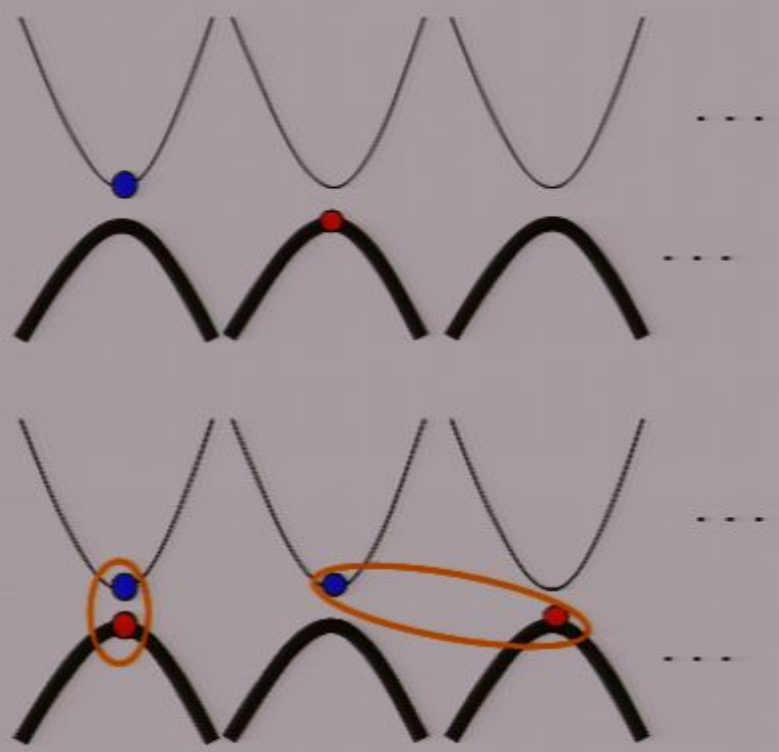
Dynamics in a strong coupling limit



Frequent exchange of partner

Model

exciton



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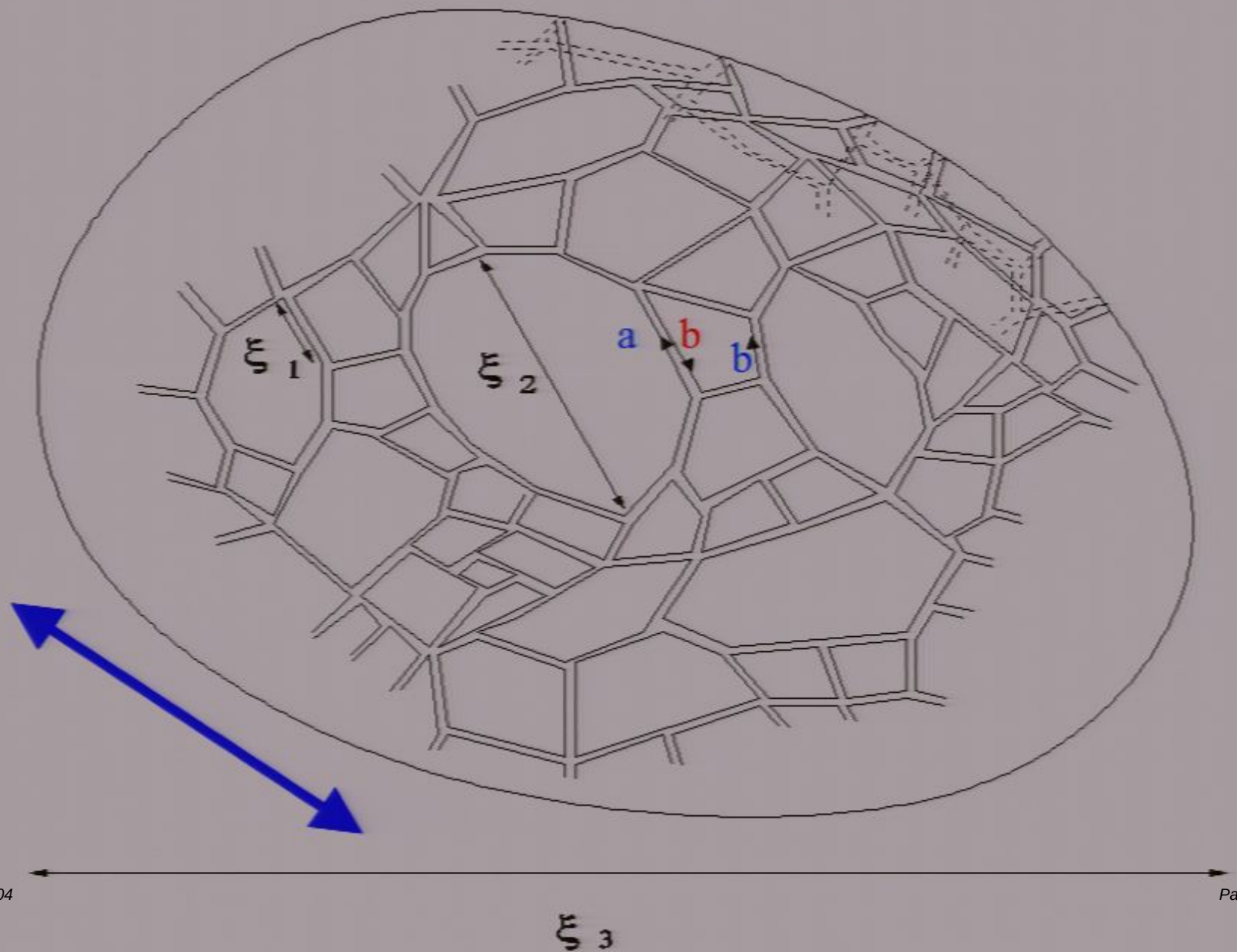
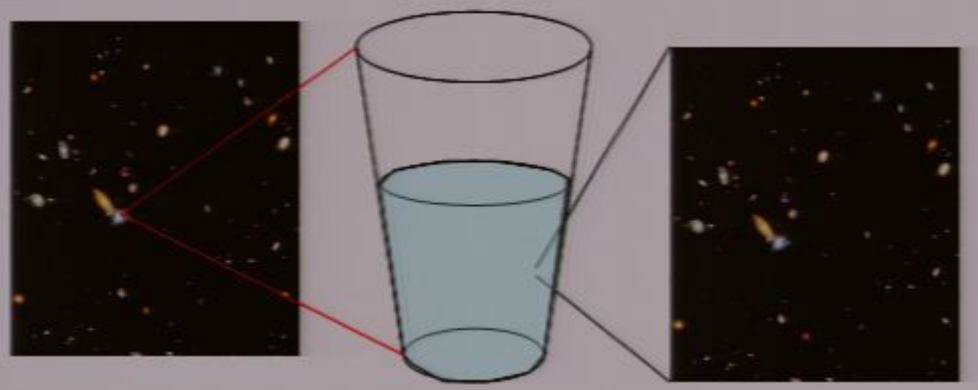


UV & IR similarity



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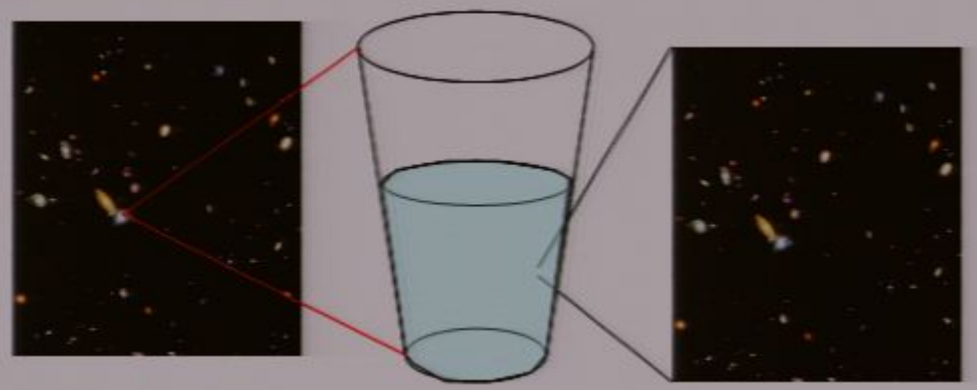

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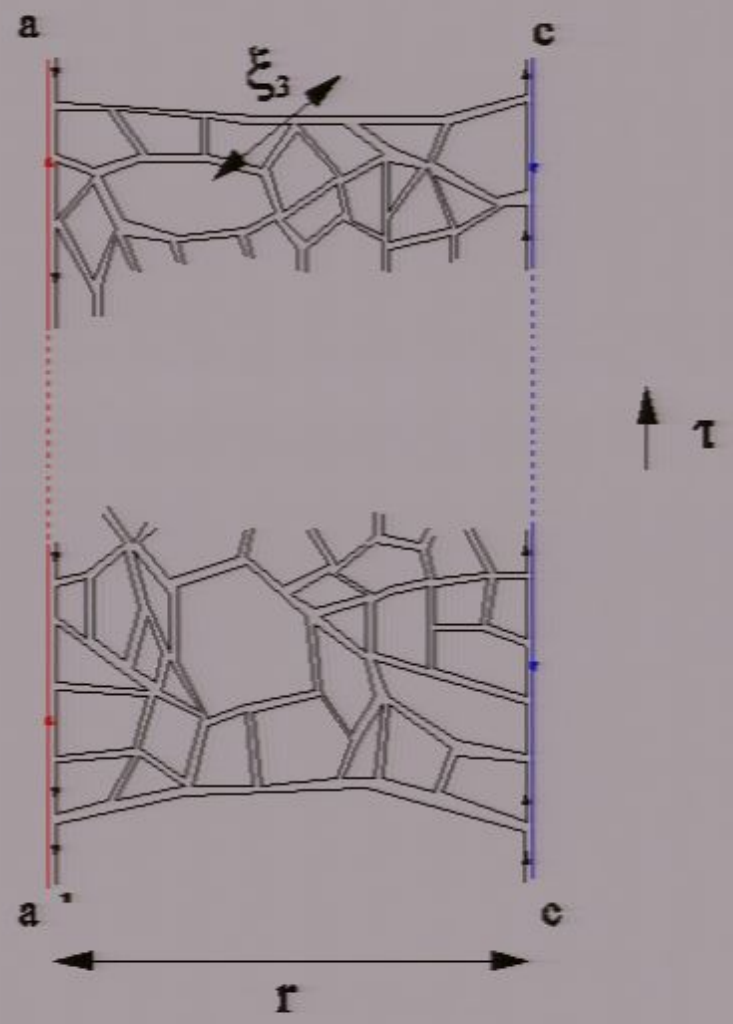
Cascade of fractionalization



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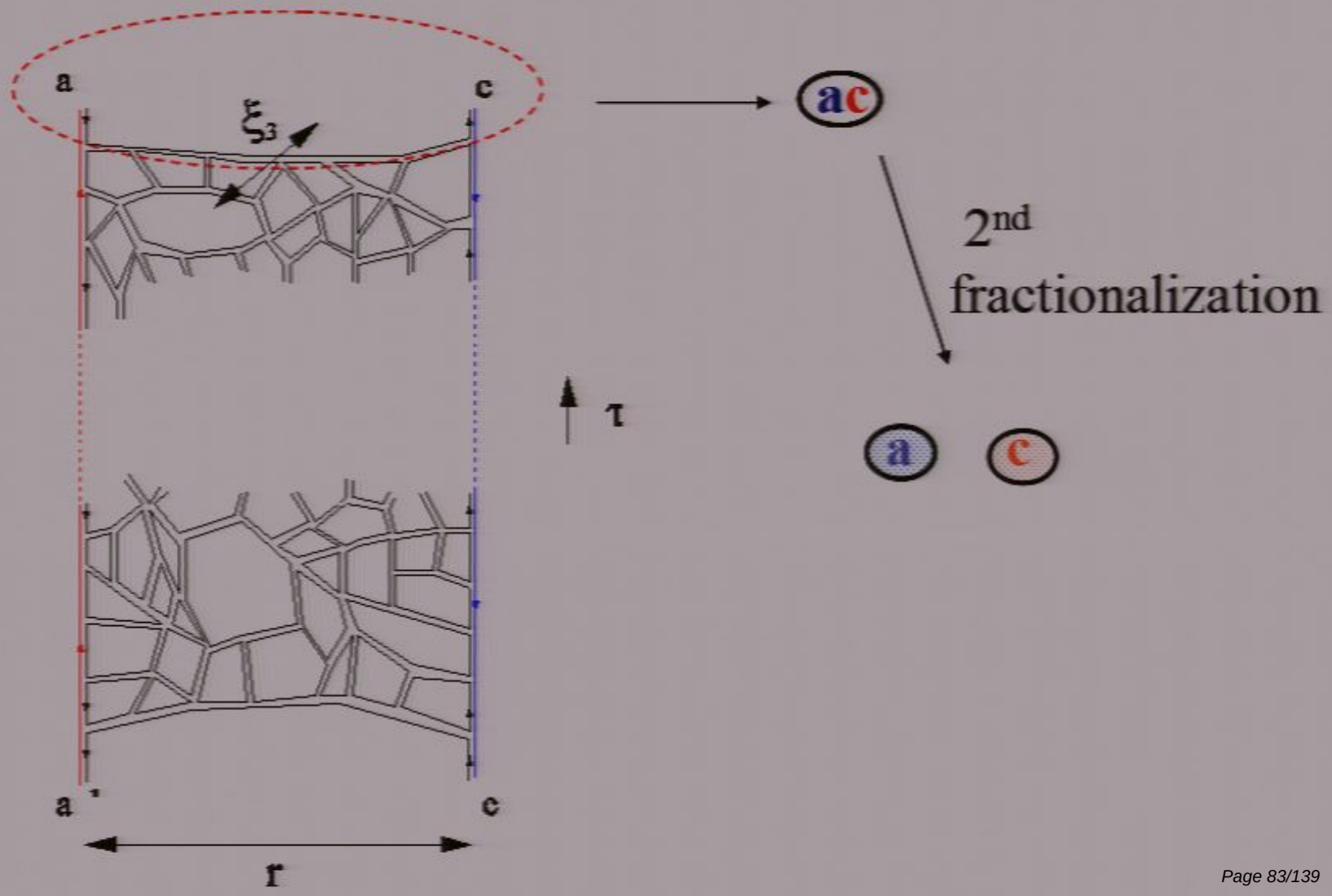
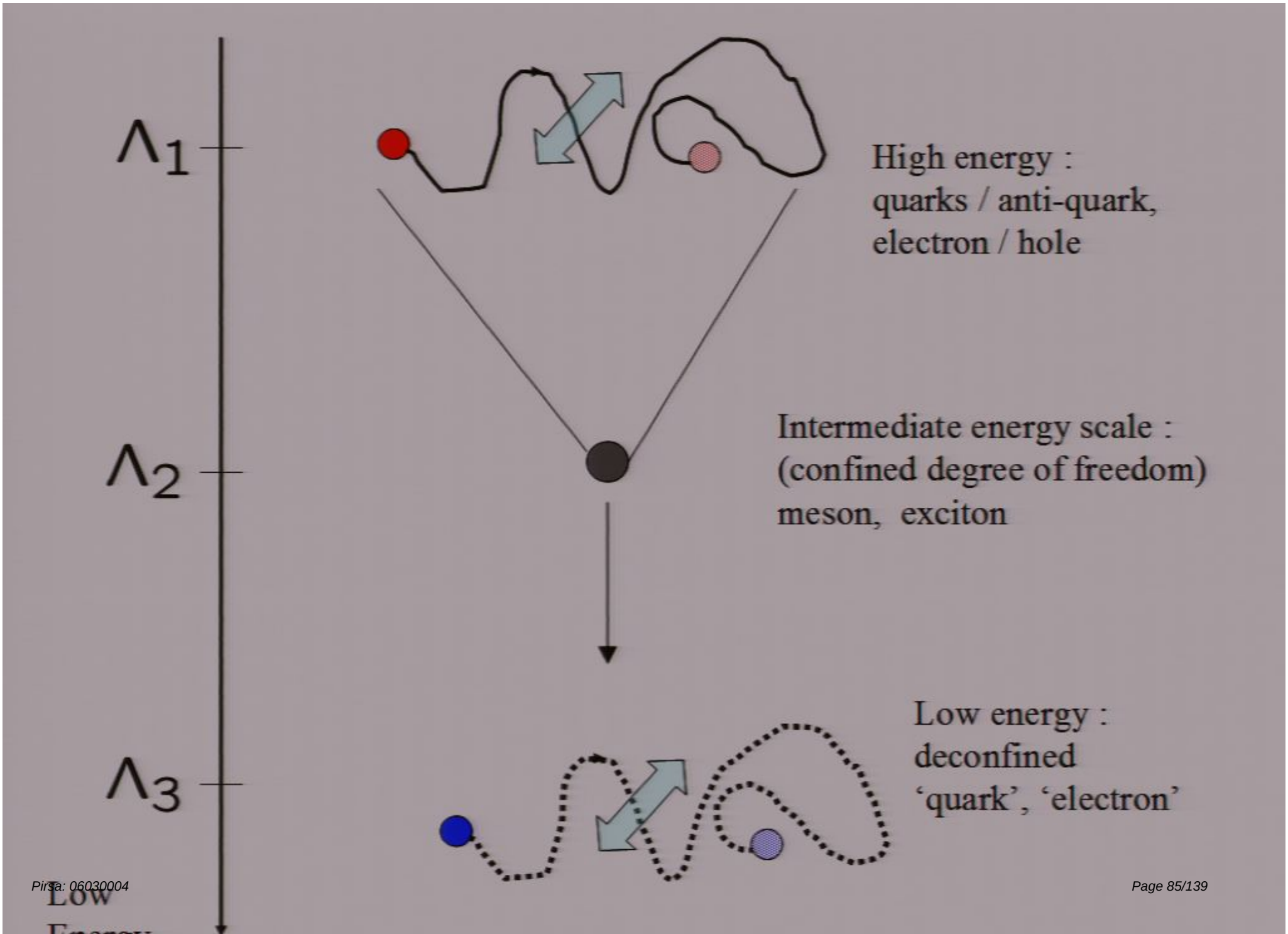


Dual gravity description of an emergent gauge theory with strong interactions


Λ_1
Λ_2
Λ_3
High energy :
quarks / anti-quark,
electron / hole
Intermediate energy scale :
(confined degree of freedom)
meson, exciton
Low energy :
deconfined
'quark', 'electron'
Low
Energy

Gauge theory formalism for fractionalization

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$$M \longrightarrow \qquad M = \phi^* \phi$$

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local symmetry : $\quad \phi \to e^{i\alpha}\phi \Rightarrow M \to M$

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Strong self interaction

Field theory, where condensed matter physics and string theory can meet

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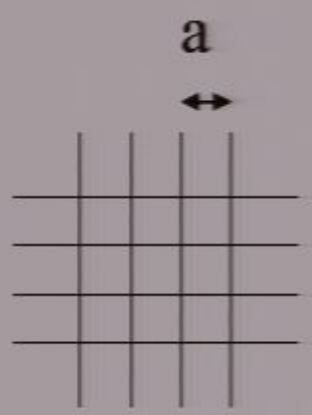

$L >> a$

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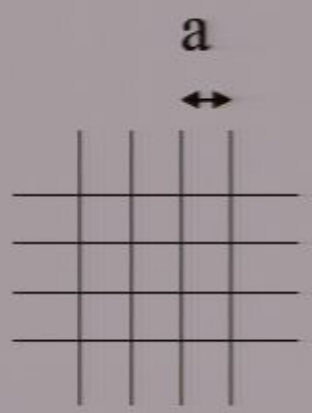

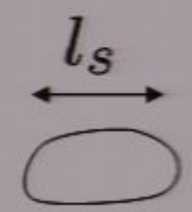

$L >> a$

$L >> l_s$

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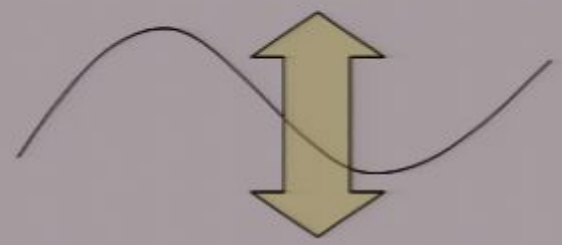
String theory includes both gauge theory and gravity

Open string :

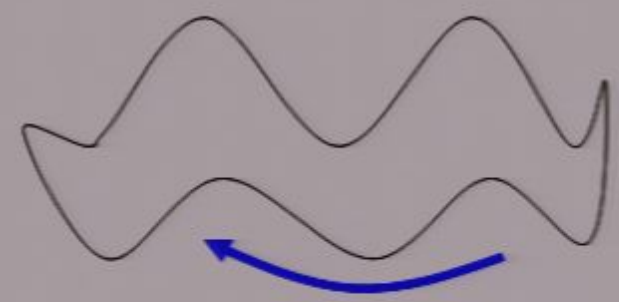


gauge field A_μ

D-2 transverse direction

Closed string :

$\times$



D-2 right moving modes

D-2 left moving modes

graviton $h_{\mu\nu}$

Closed string propagating in 10D

10D

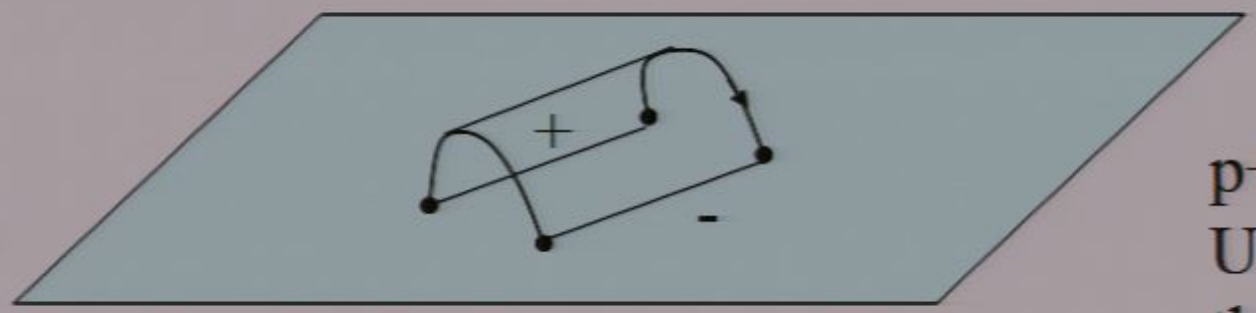
graviton

Space-time

open string can end on D-brane

10D

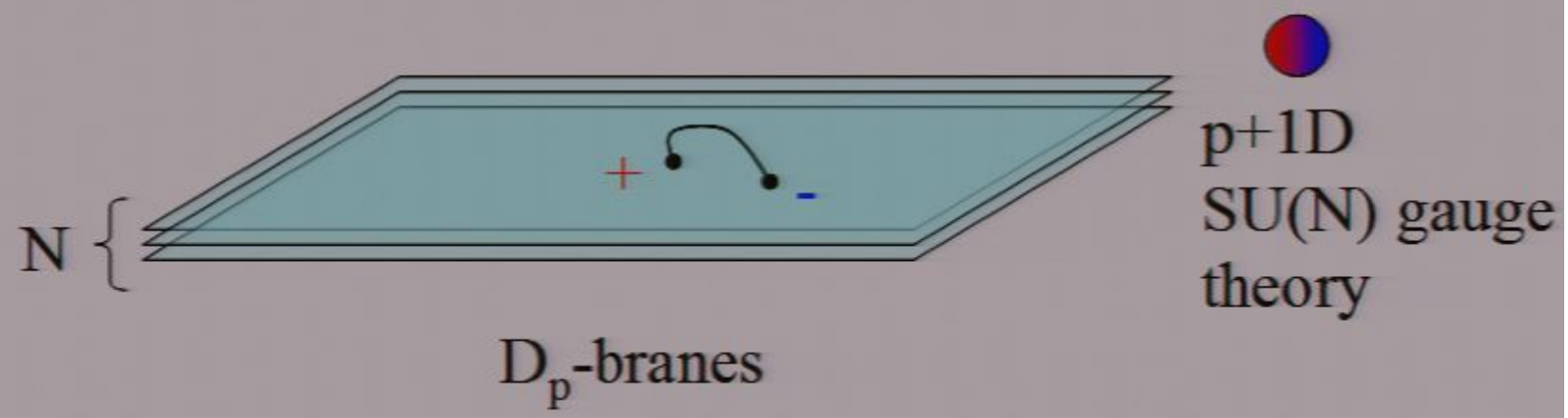
0,1,2,..,p



p+1D
U(1) gauge
theory

D_p-branes

open string can end on D-brane



D-branes

D_2-brane

D_p-branes

D−branes

D_2-brane

2+1D U(1) gauge theory

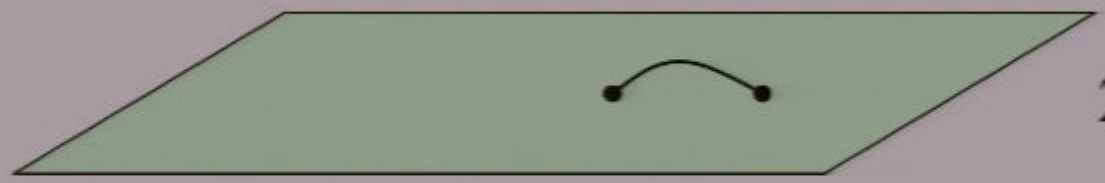
D_p-branes

N

$$S = \frac{1}{g^2}\int d^3x F_{\mu\nu}^2$$

D−branes

D_2-brane



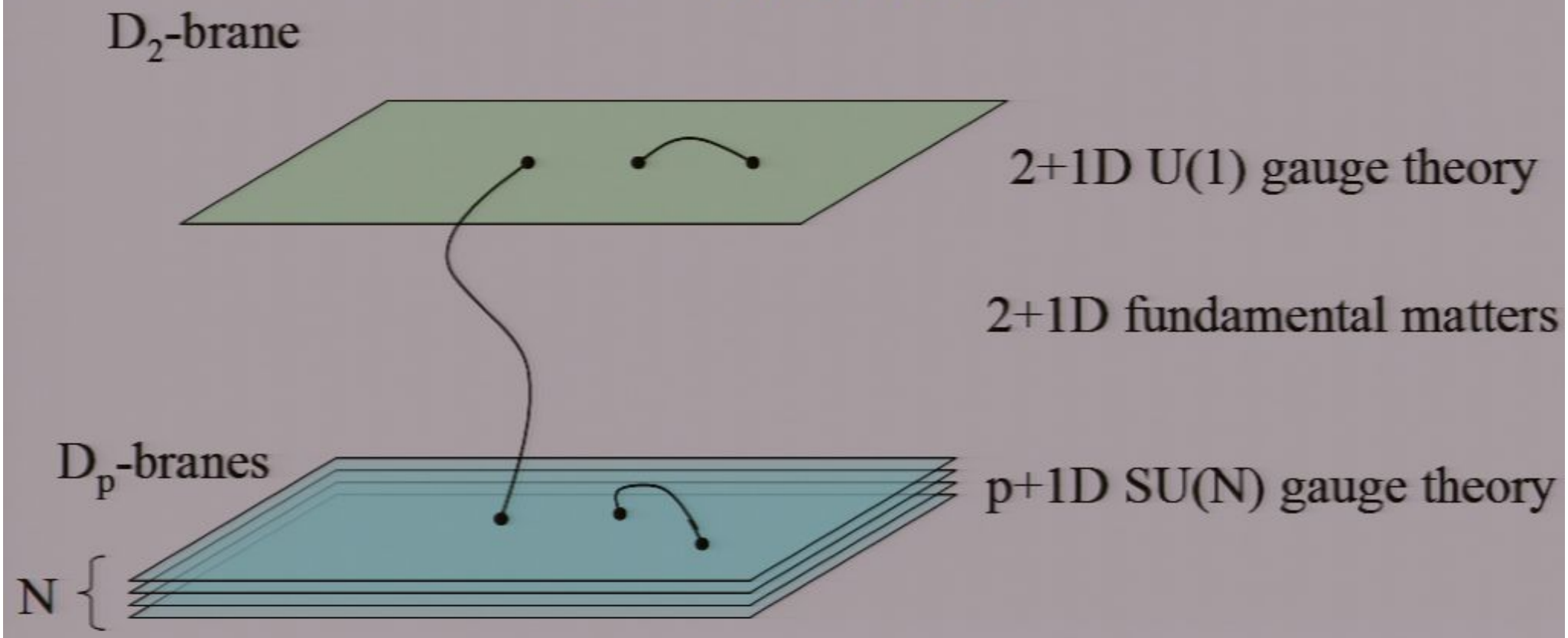
2+1D U(1) gauge theory

D_p-branes

p+1D SU(N) gauge theory

$$S = \frac{1}{g^2}\int d^3x F_{\mu\nu}^2 + \frac{1}{g_{YM}^2} tr \int d^{p+1}x \mathcal{F}_{\mu\nu}^2$$

D−branes



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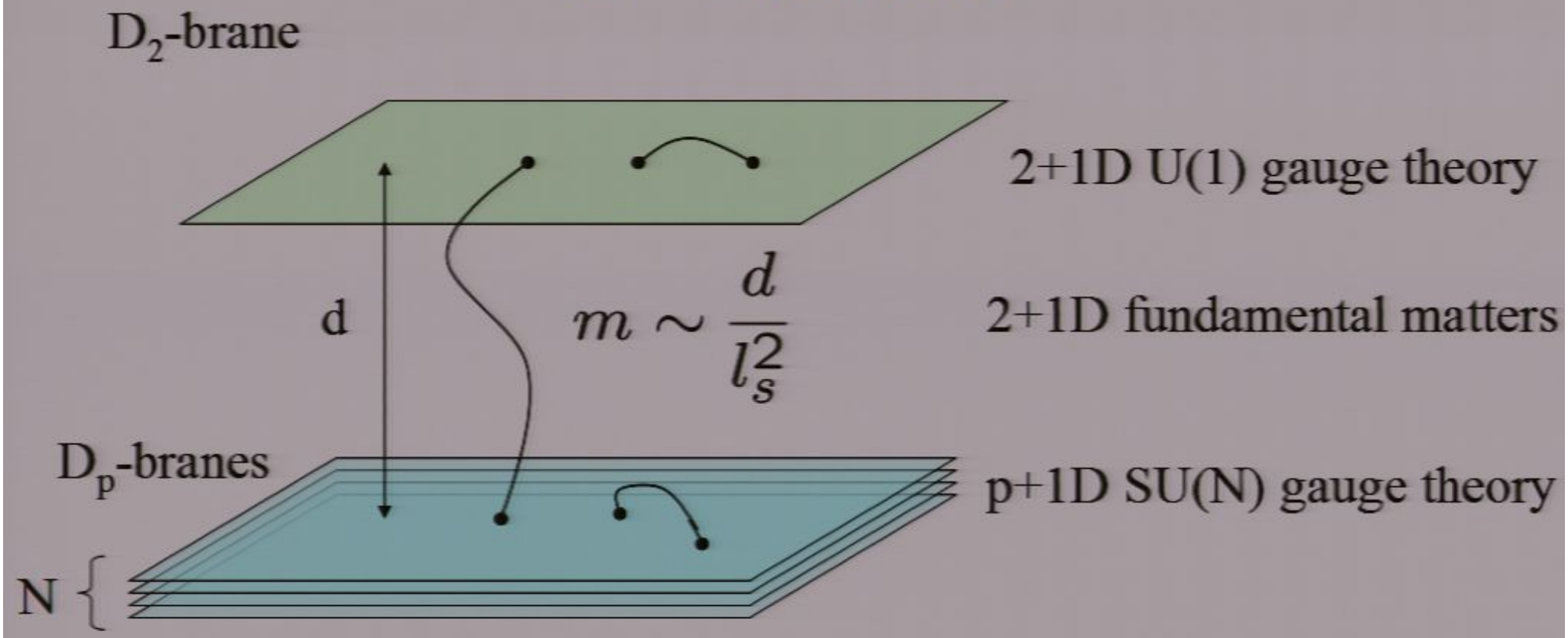
$$+ \int d^3x |(\partial_\mu - iA_\mu + i\mathcal{A}_\mu)\Phi|^2$$

D−branes



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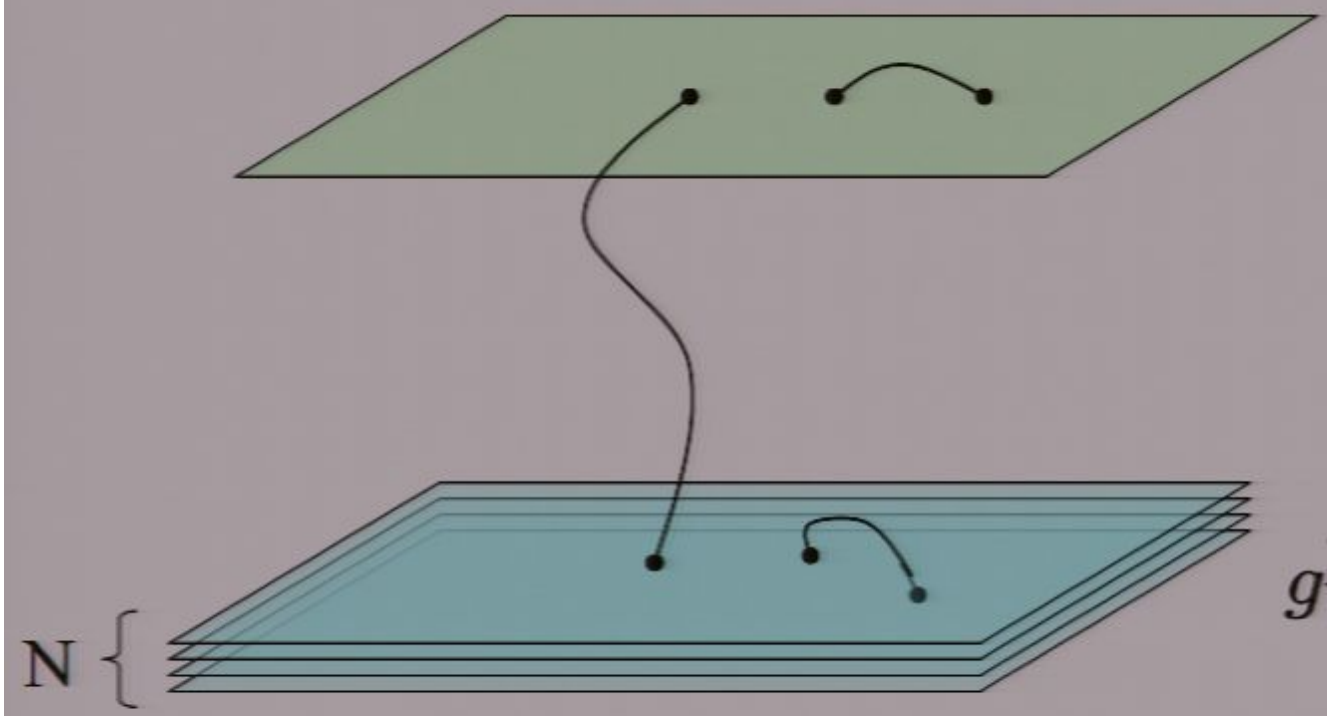
Infinite bare gauge coupling



$$g^2 \sim \frac{g_s}{l_s}$$

$$g_{YM}^2 \sim g_s l_s^{p-3}$$

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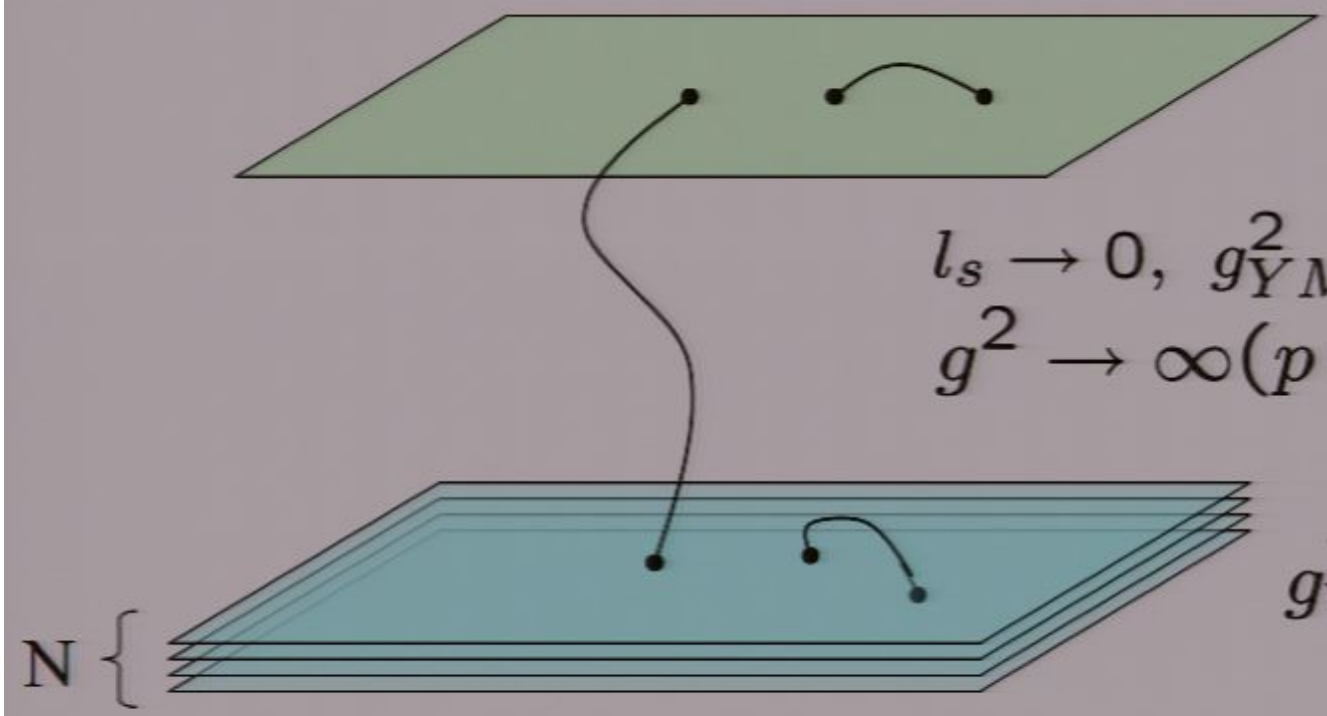
Infinite bare gauge coupling



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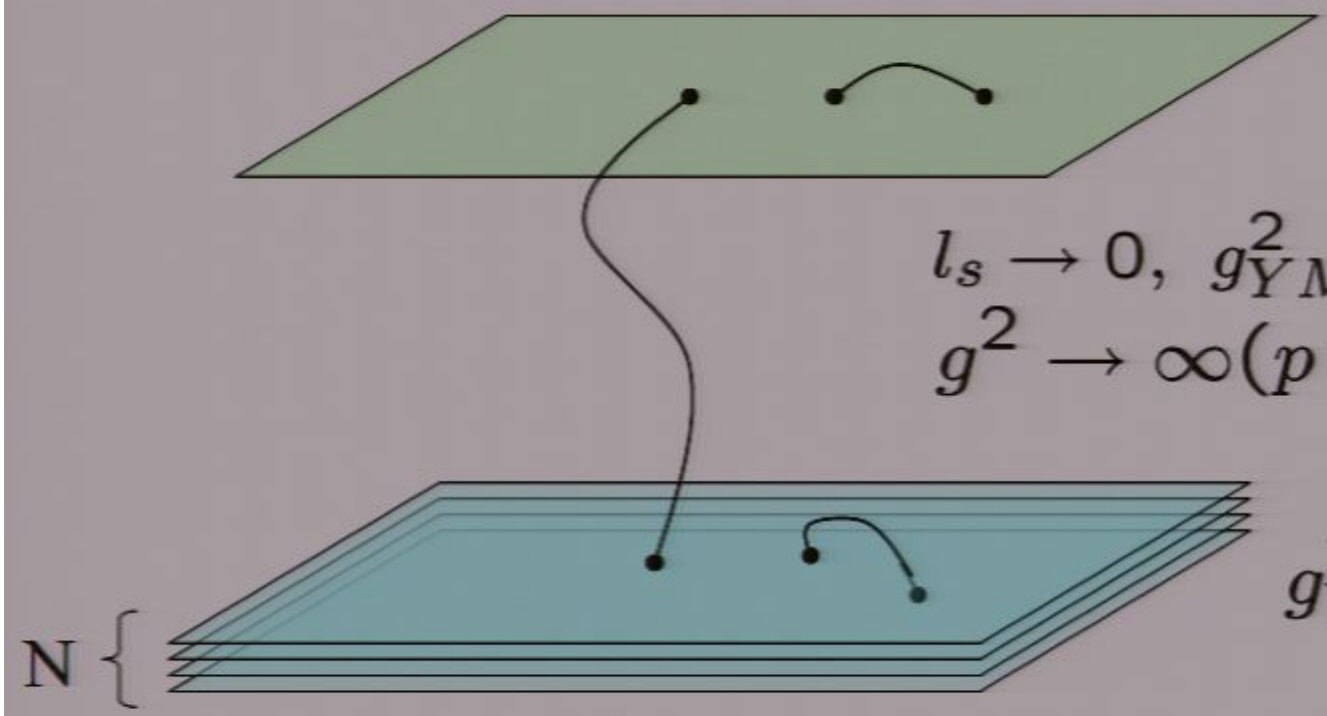

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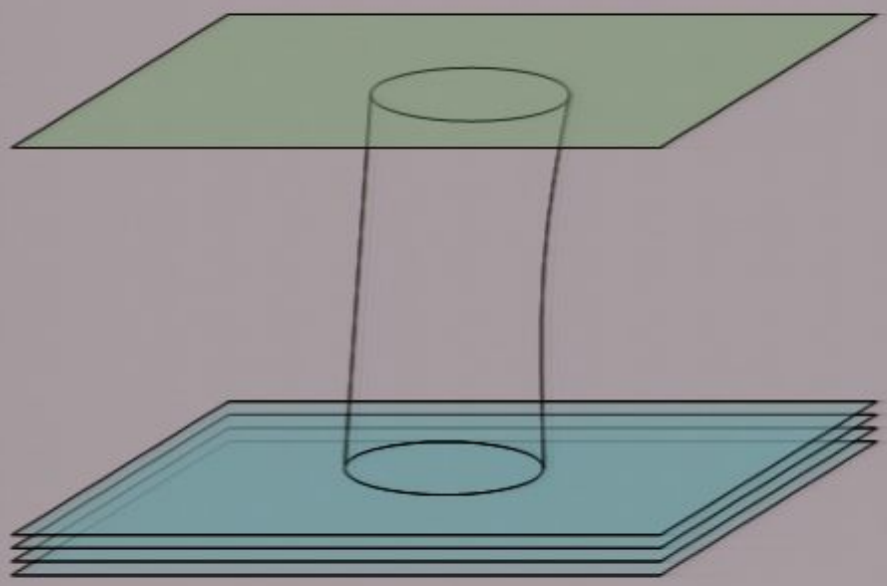
Open/closed string duality

Space-time



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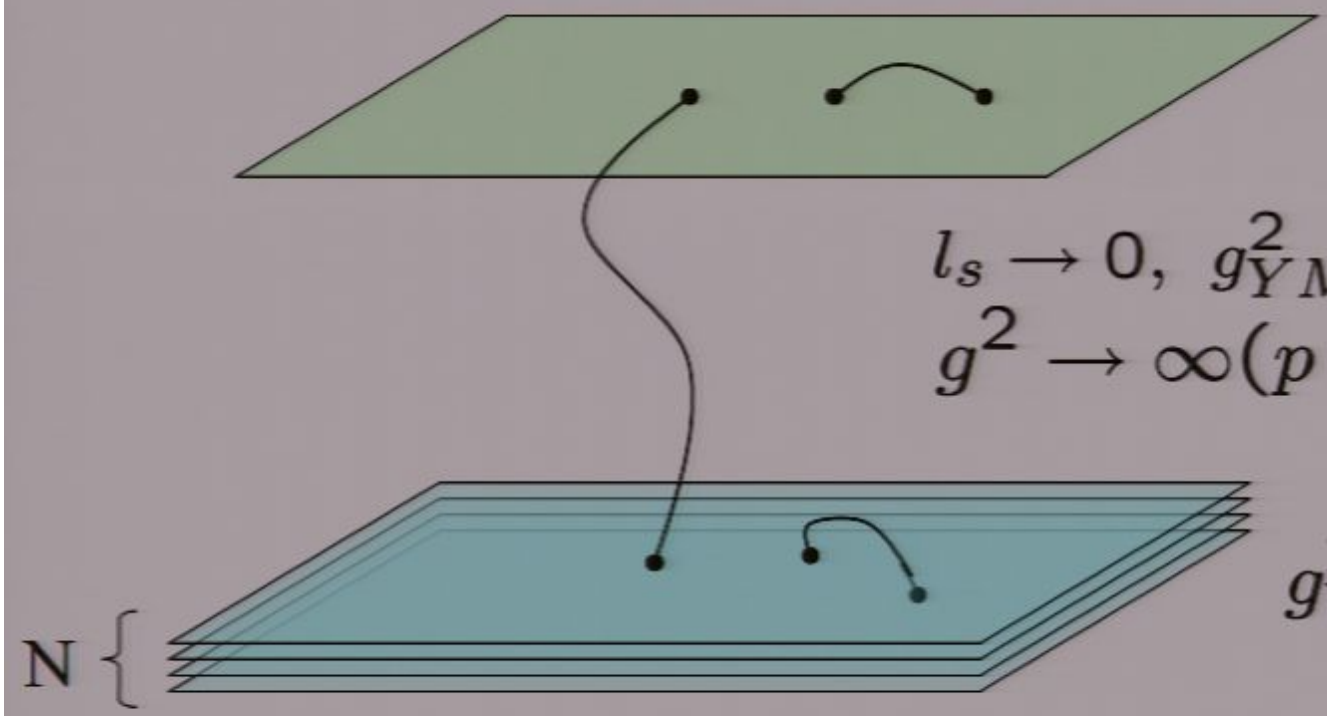

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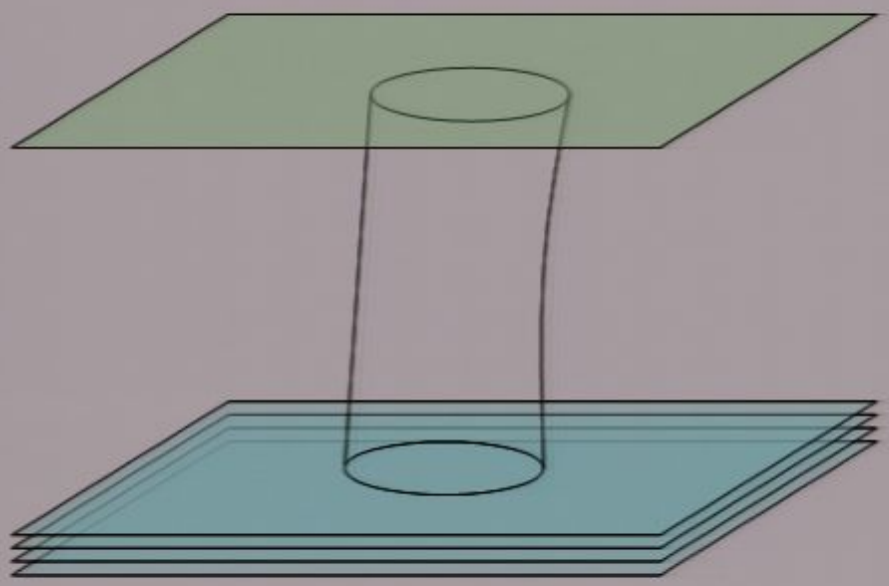

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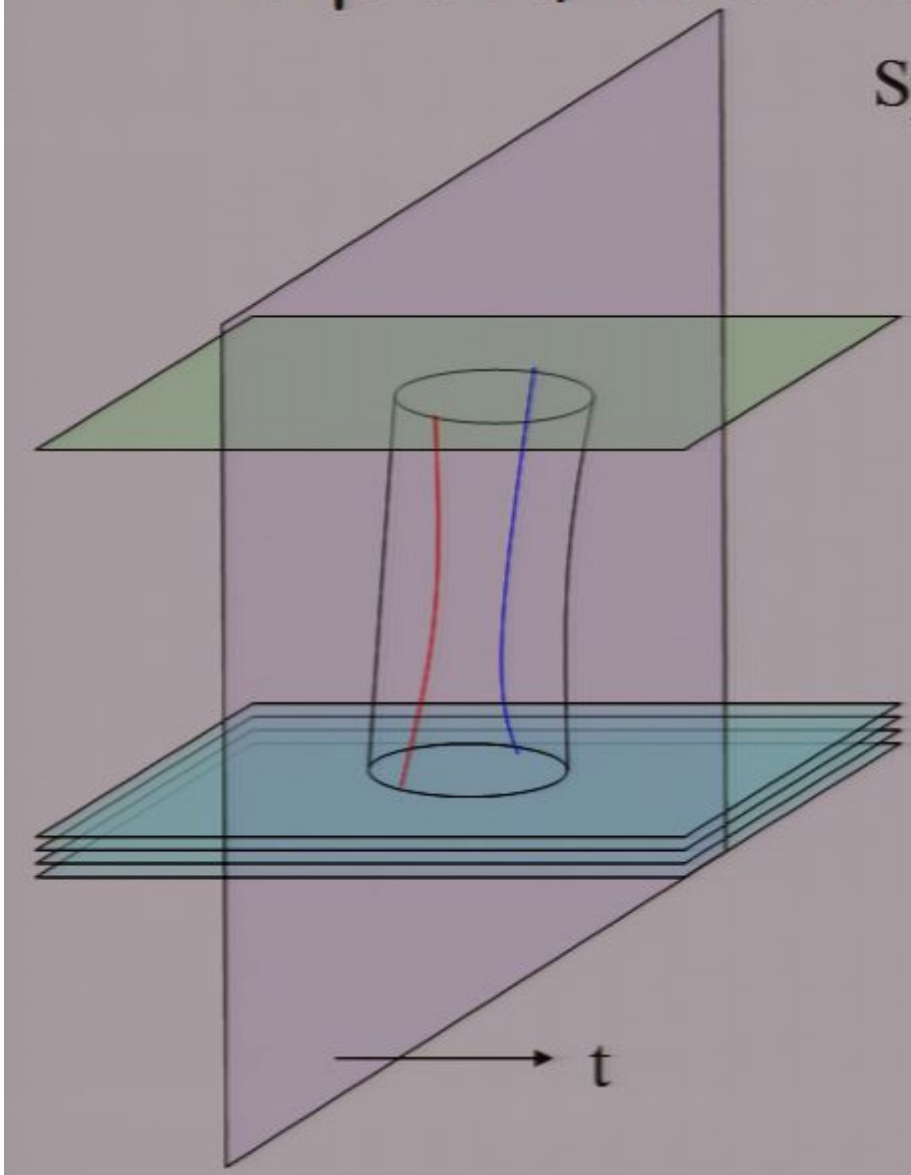

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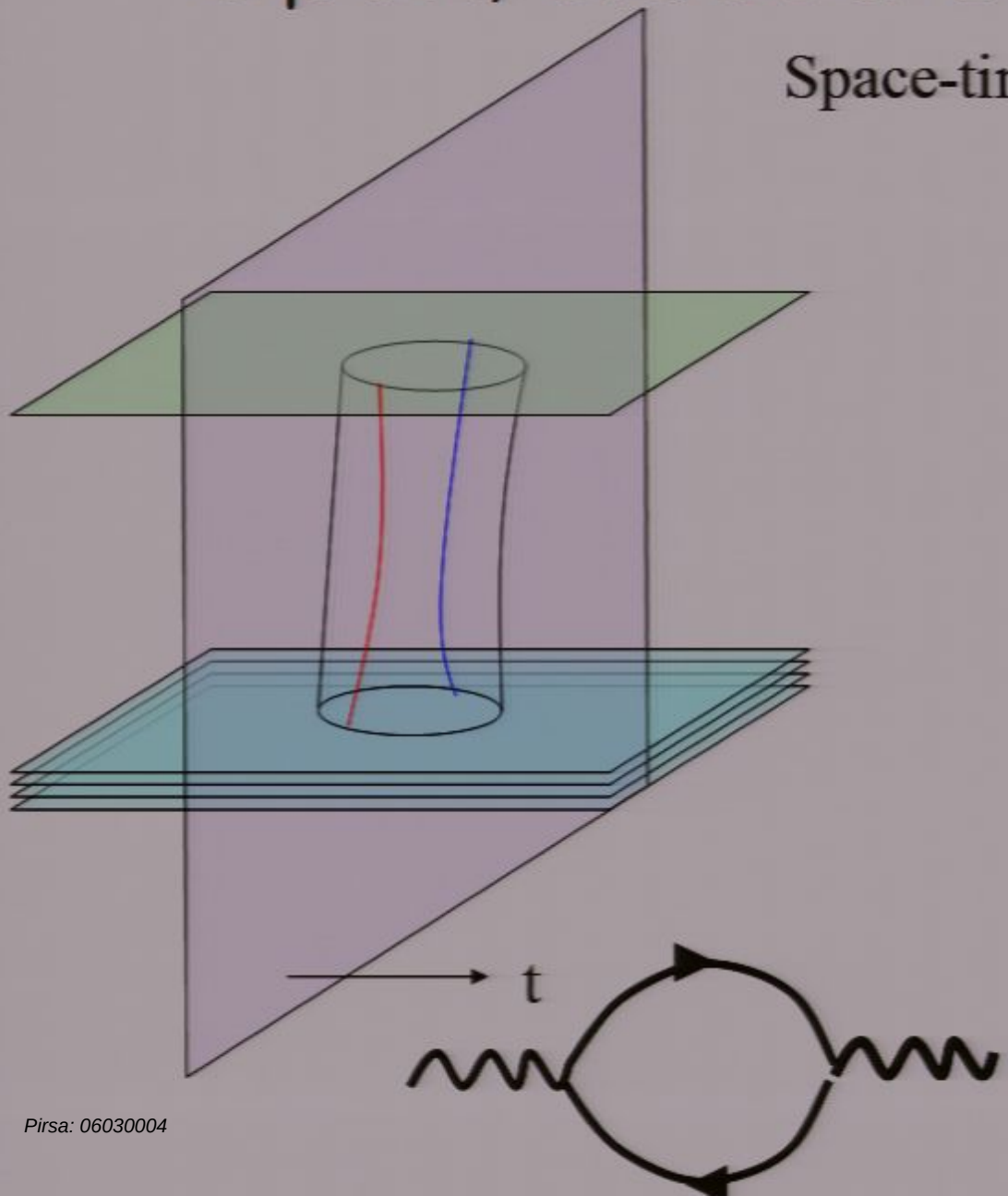

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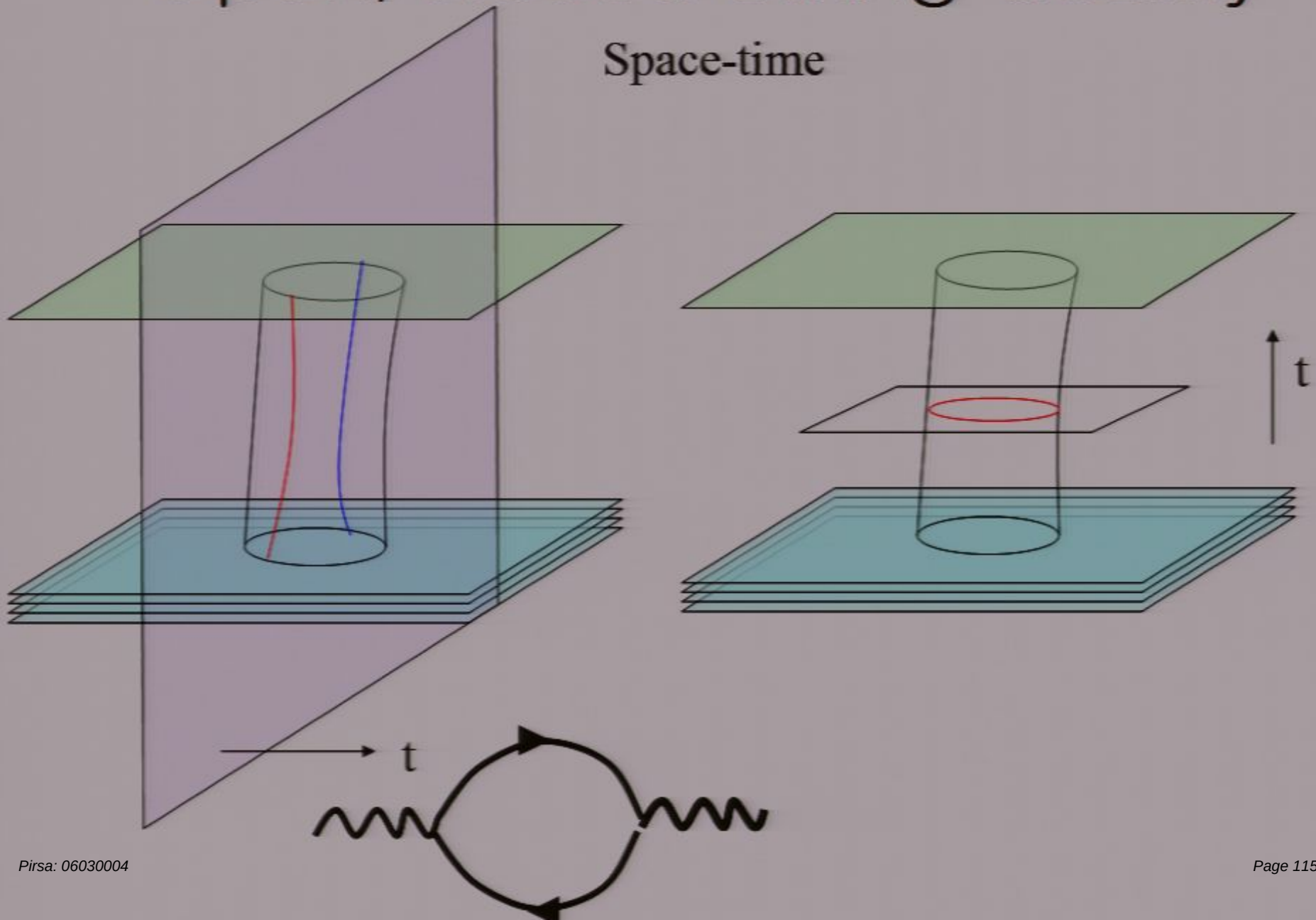

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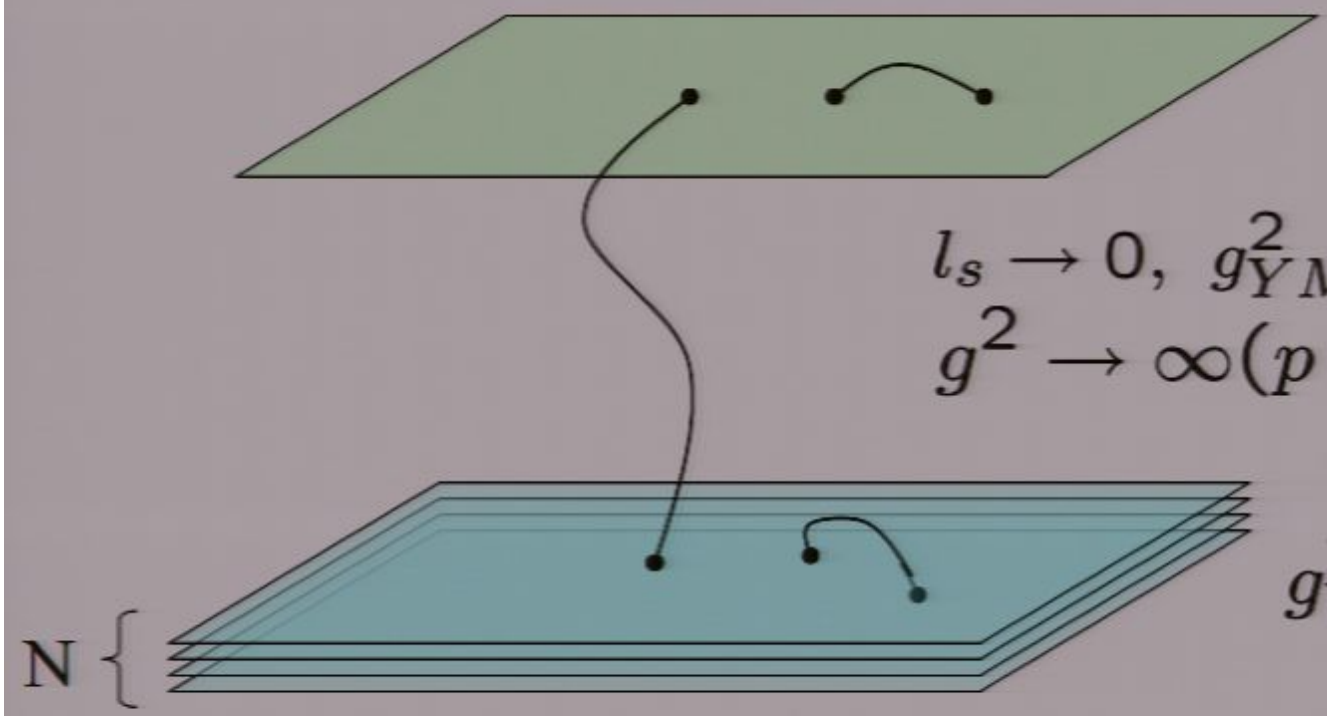

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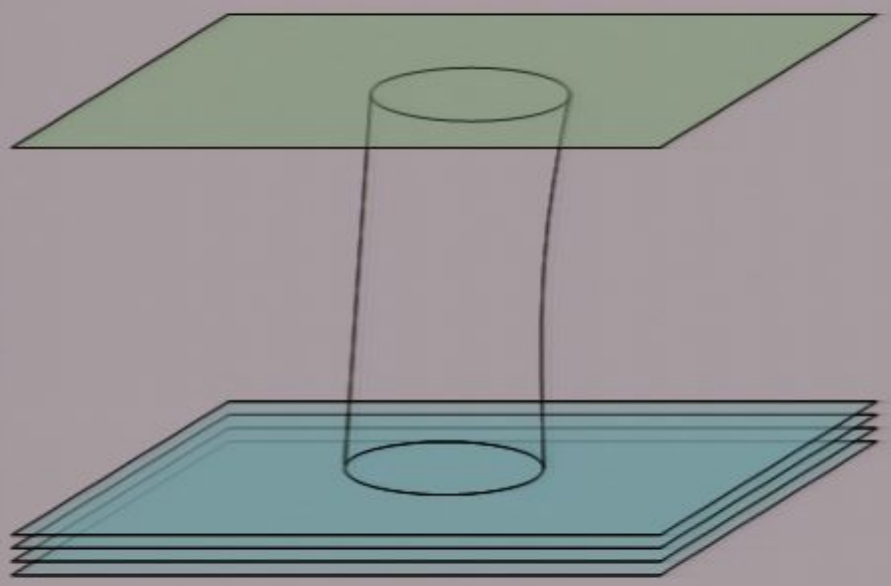

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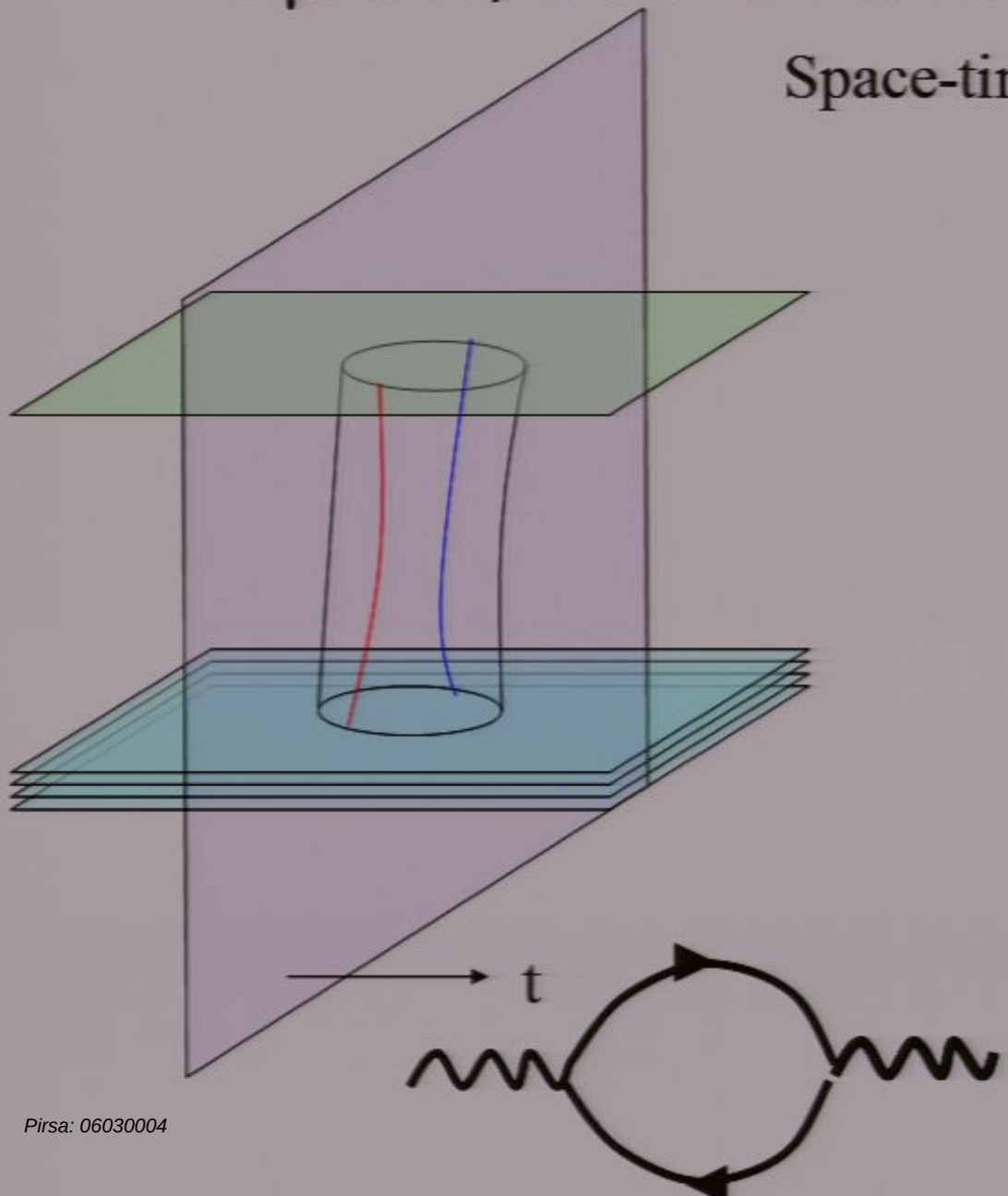

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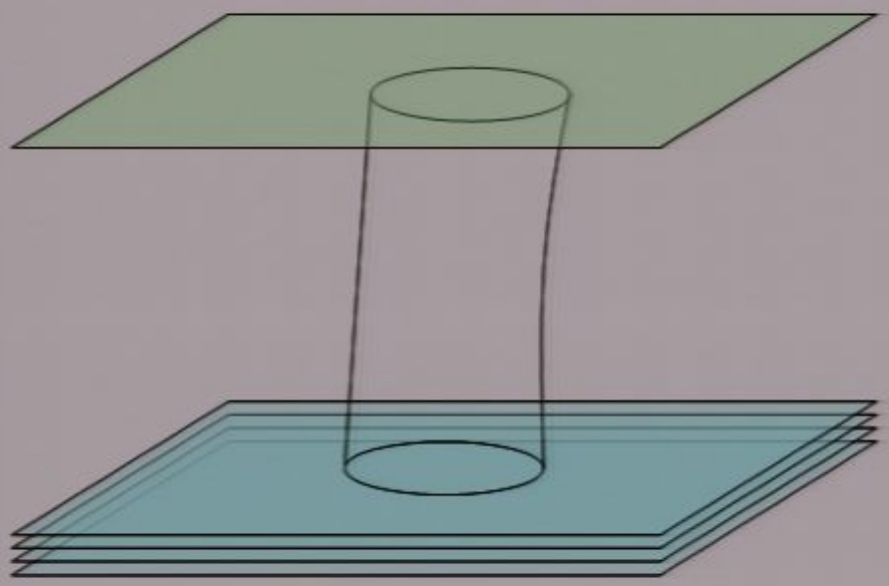

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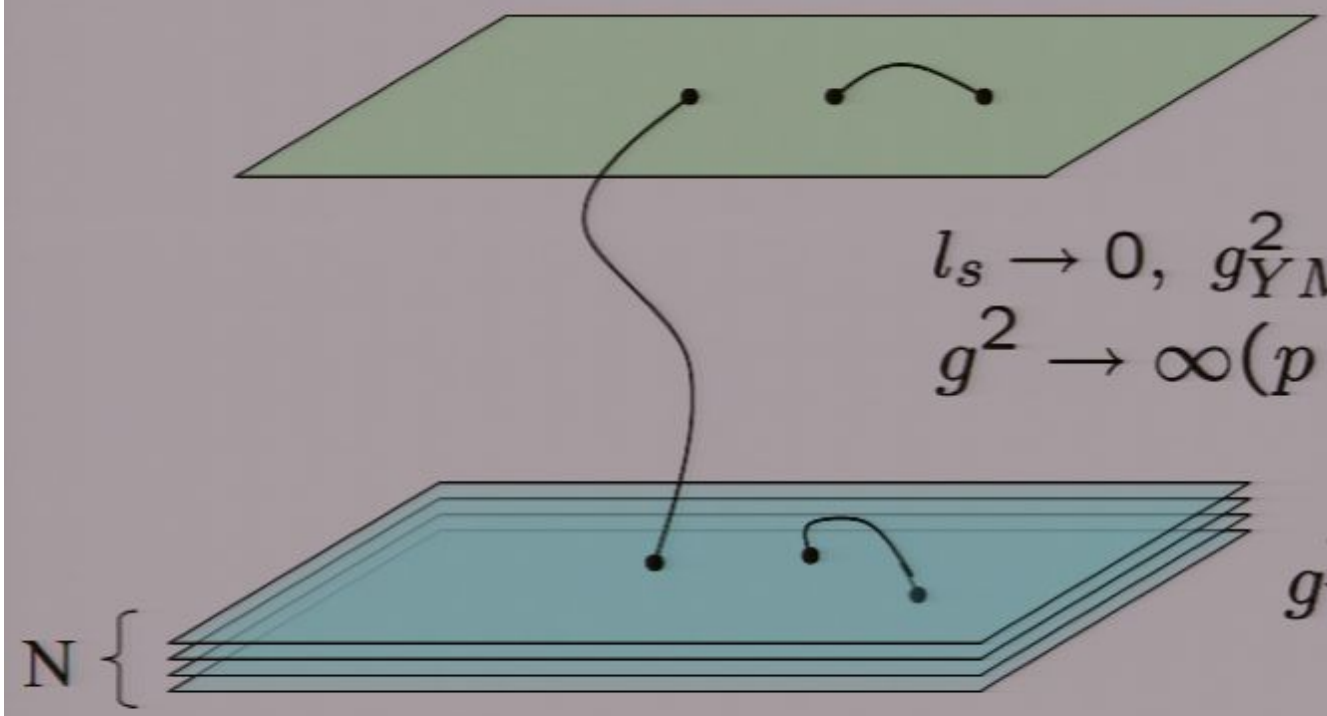

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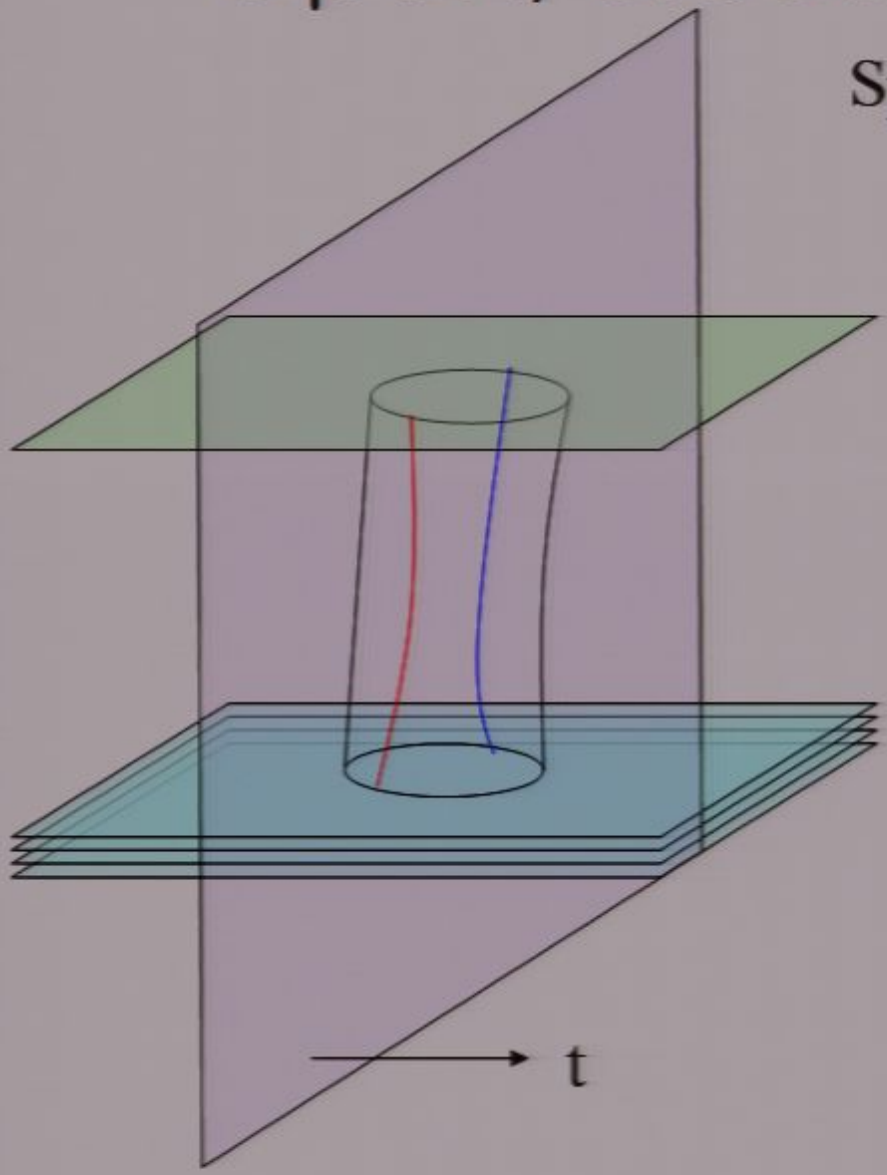

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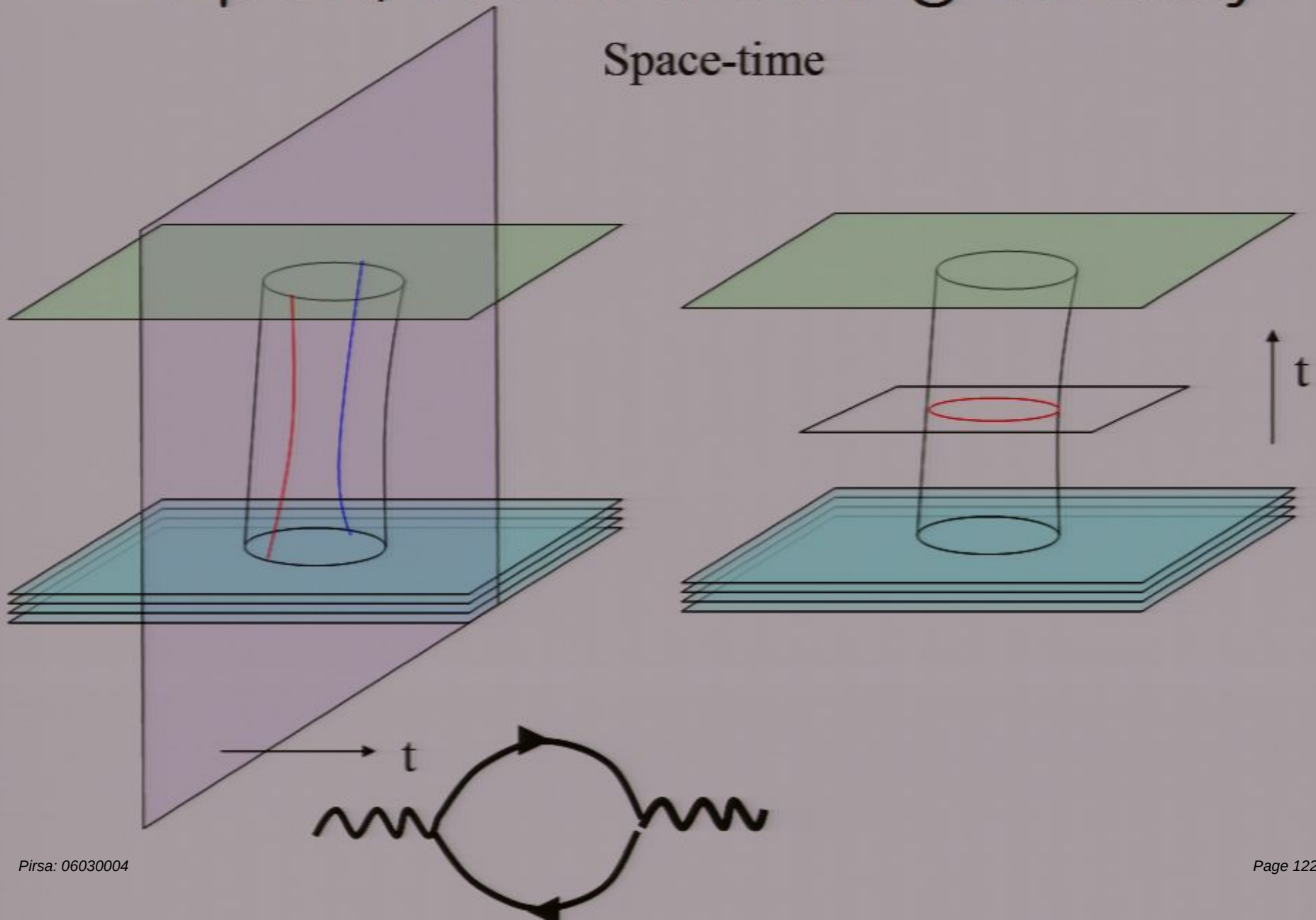

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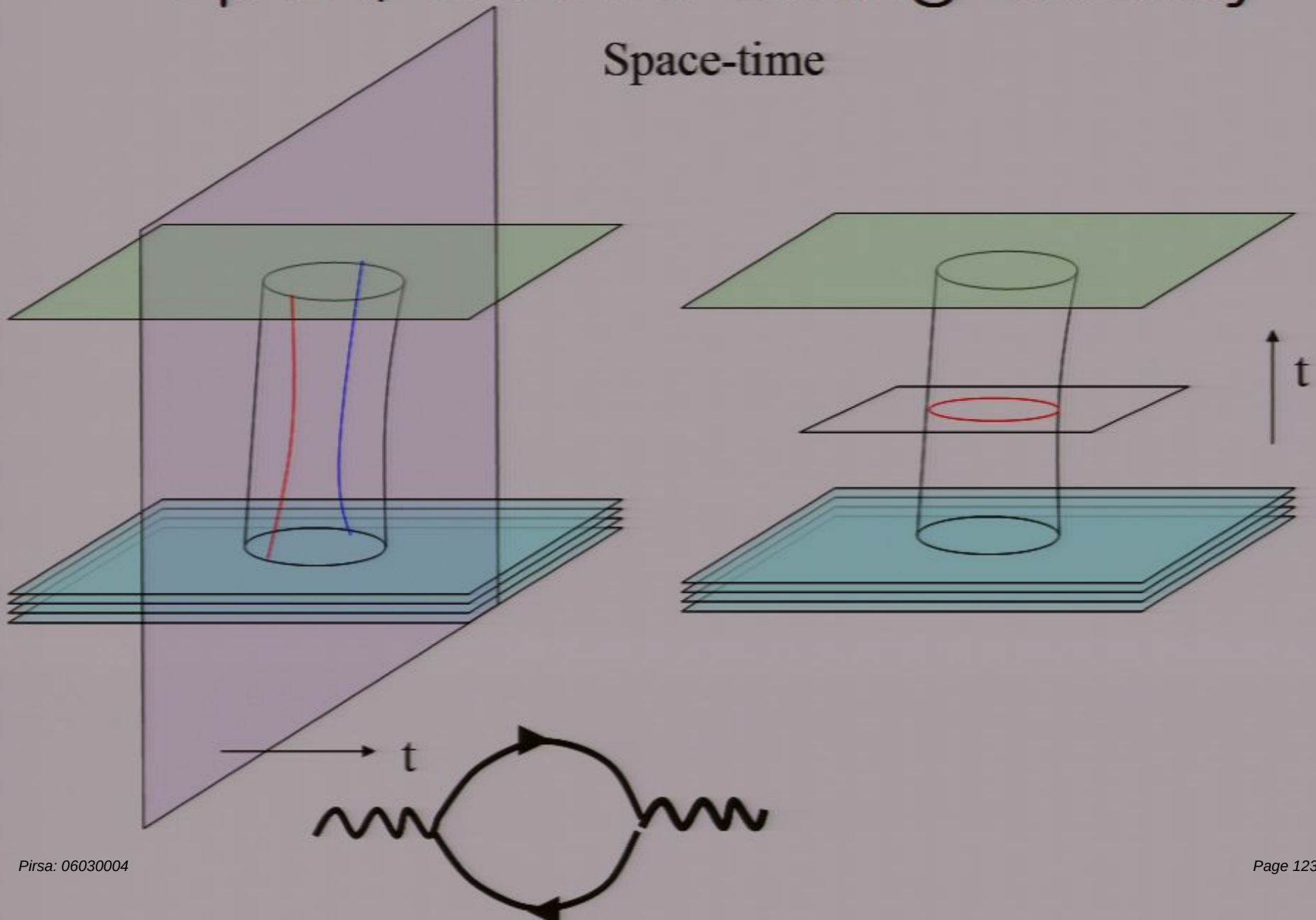

Renormalization of gauge coupling

$$G_{\mu\nu}(x), \phi(x)$$

AdS background
[Maldacena]

$$\Gamma = \frac{1}{(2\pi)^2 l_s^3} \int dx^3 e^{-\phi} \sqrt{det(G^{ind}_{\mu\nu} + 2\pi l_s^2 F_{\mu\nu})}$$

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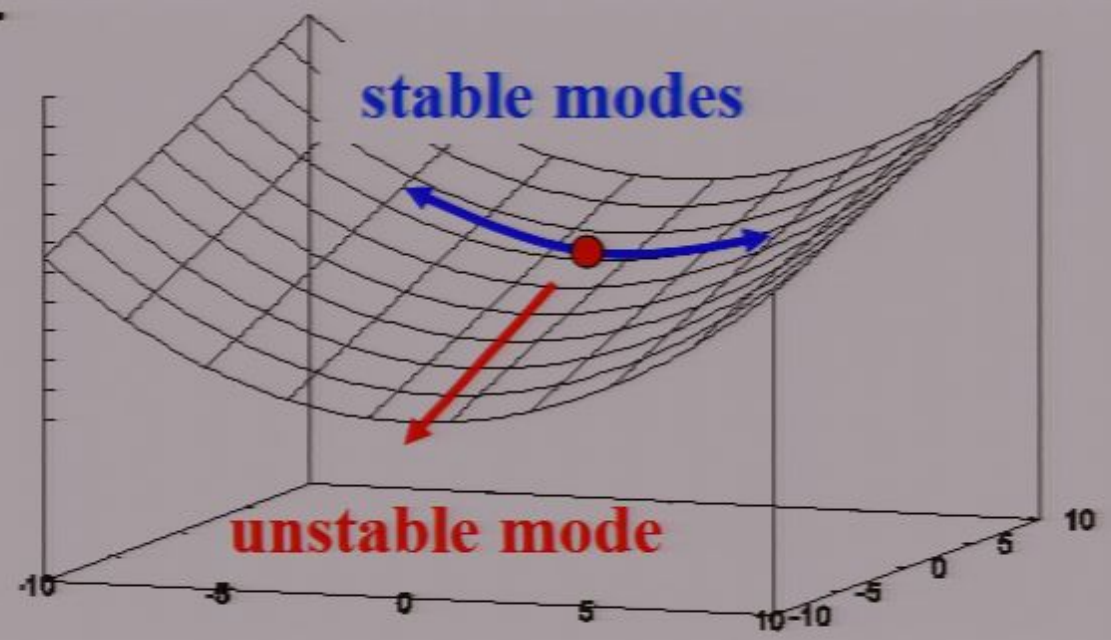
P=4 : no supersymmetry

D_2-brane

unstable due to
gravitational attraction
: tachyonic mode in field theory!

D_p-branes

Stable field theory out of unstable field theory



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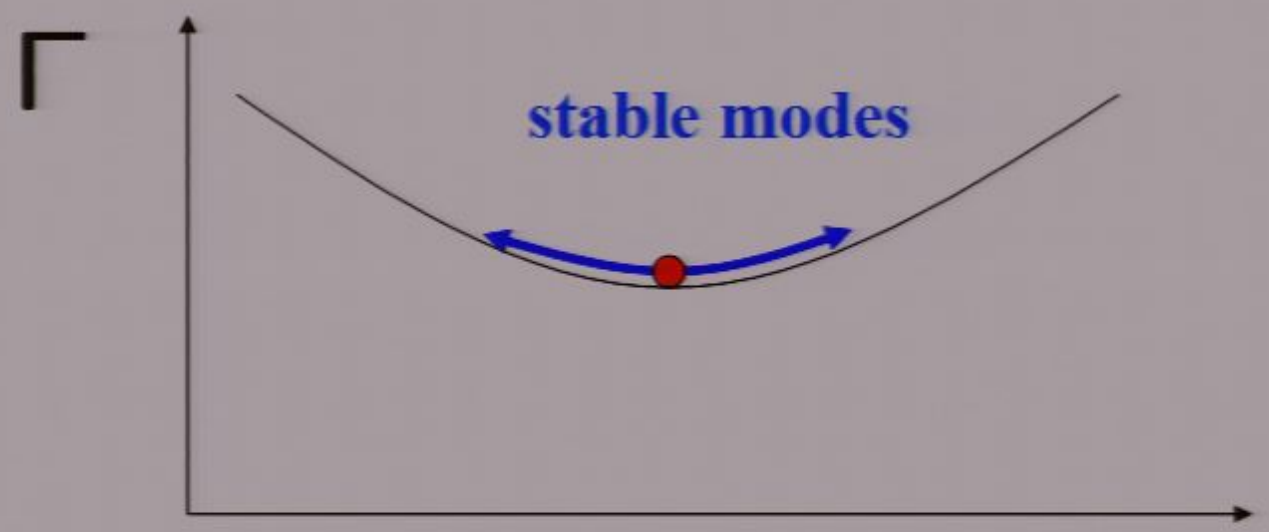

Freeze the unstable mode

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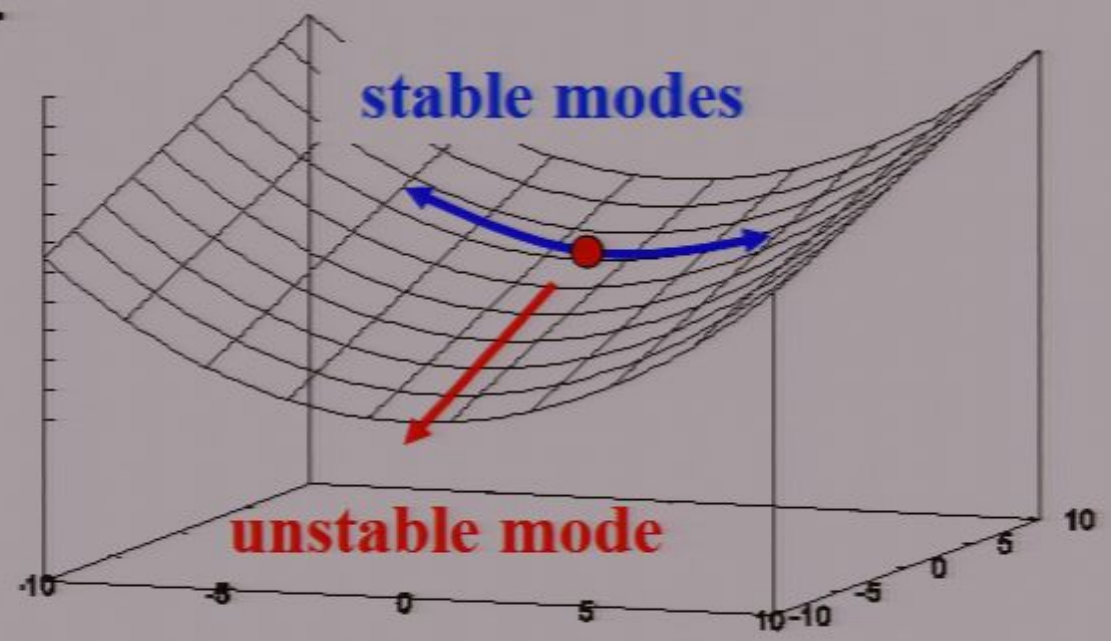

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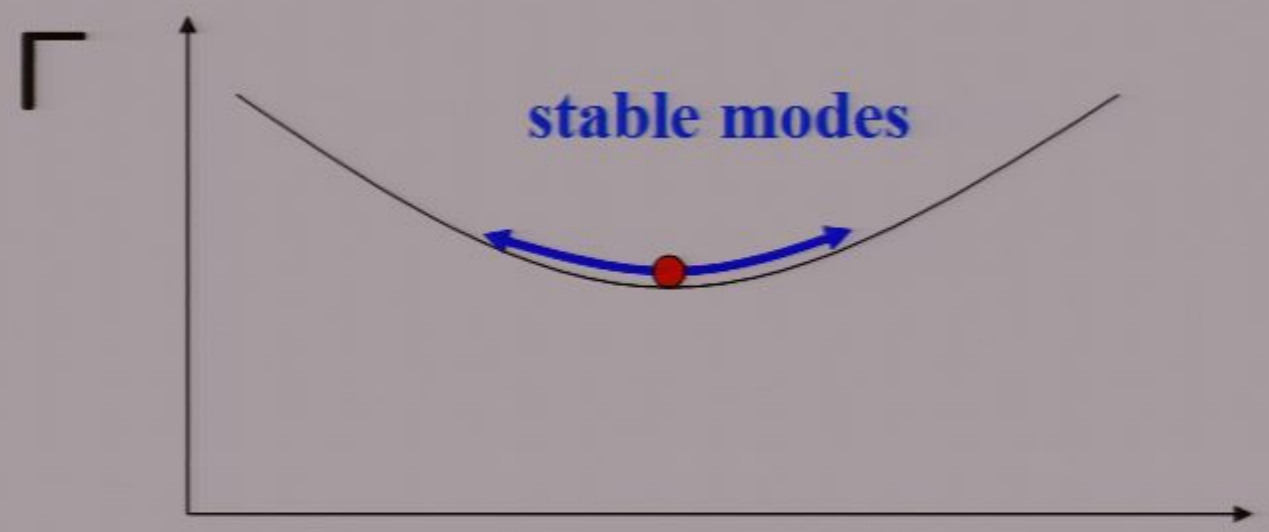

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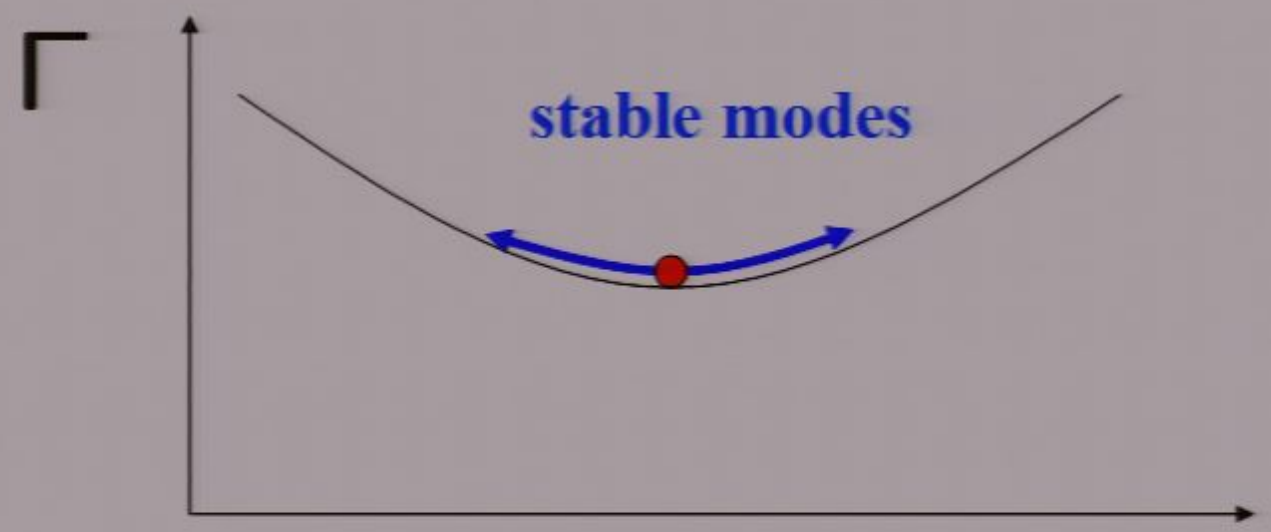

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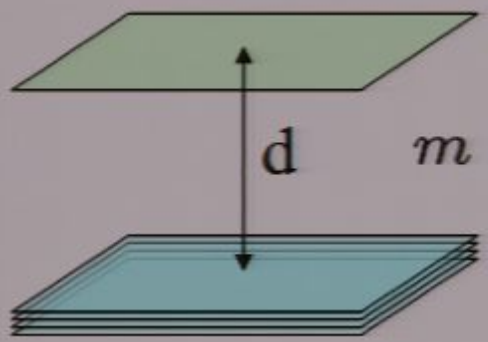
Renormalized gauge coupling



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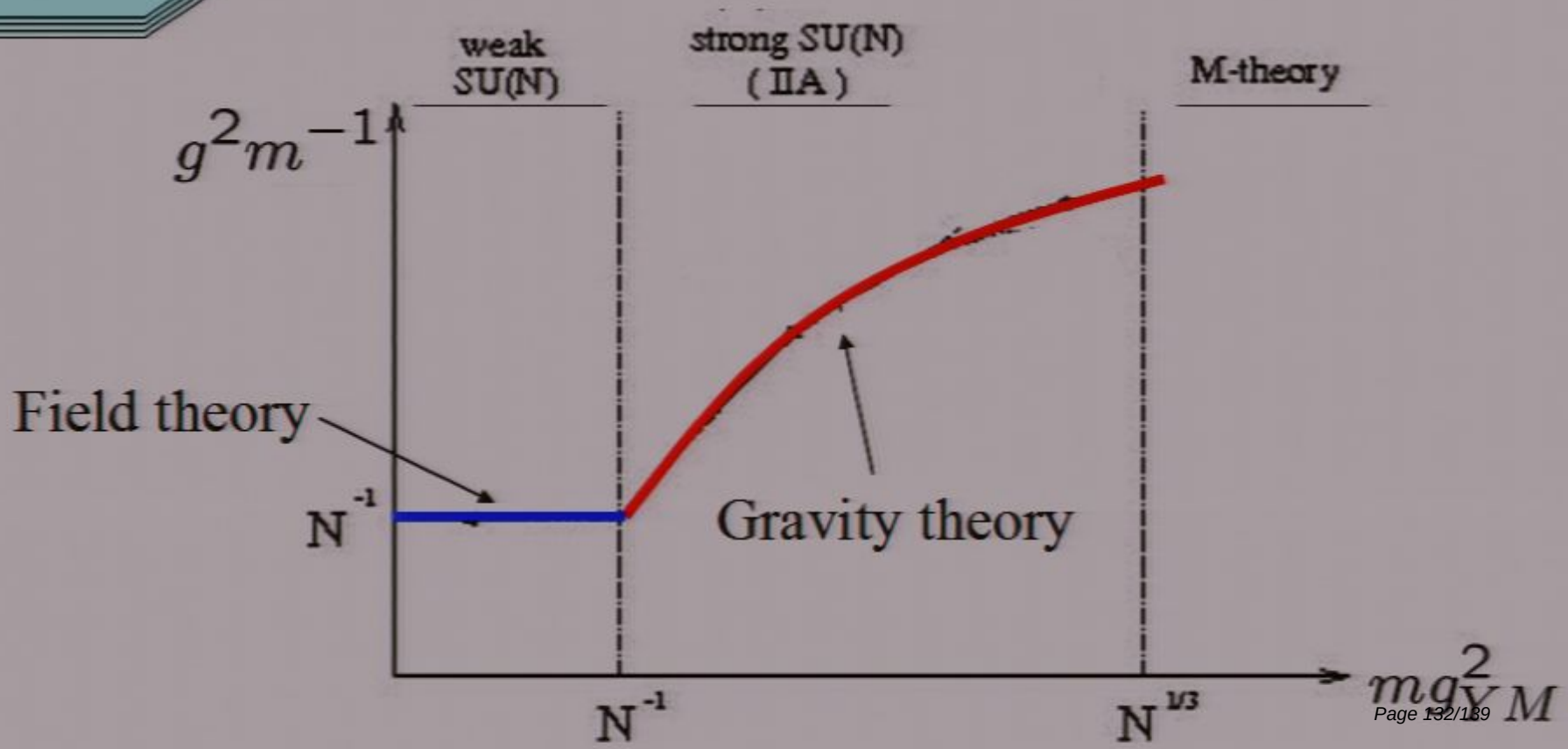

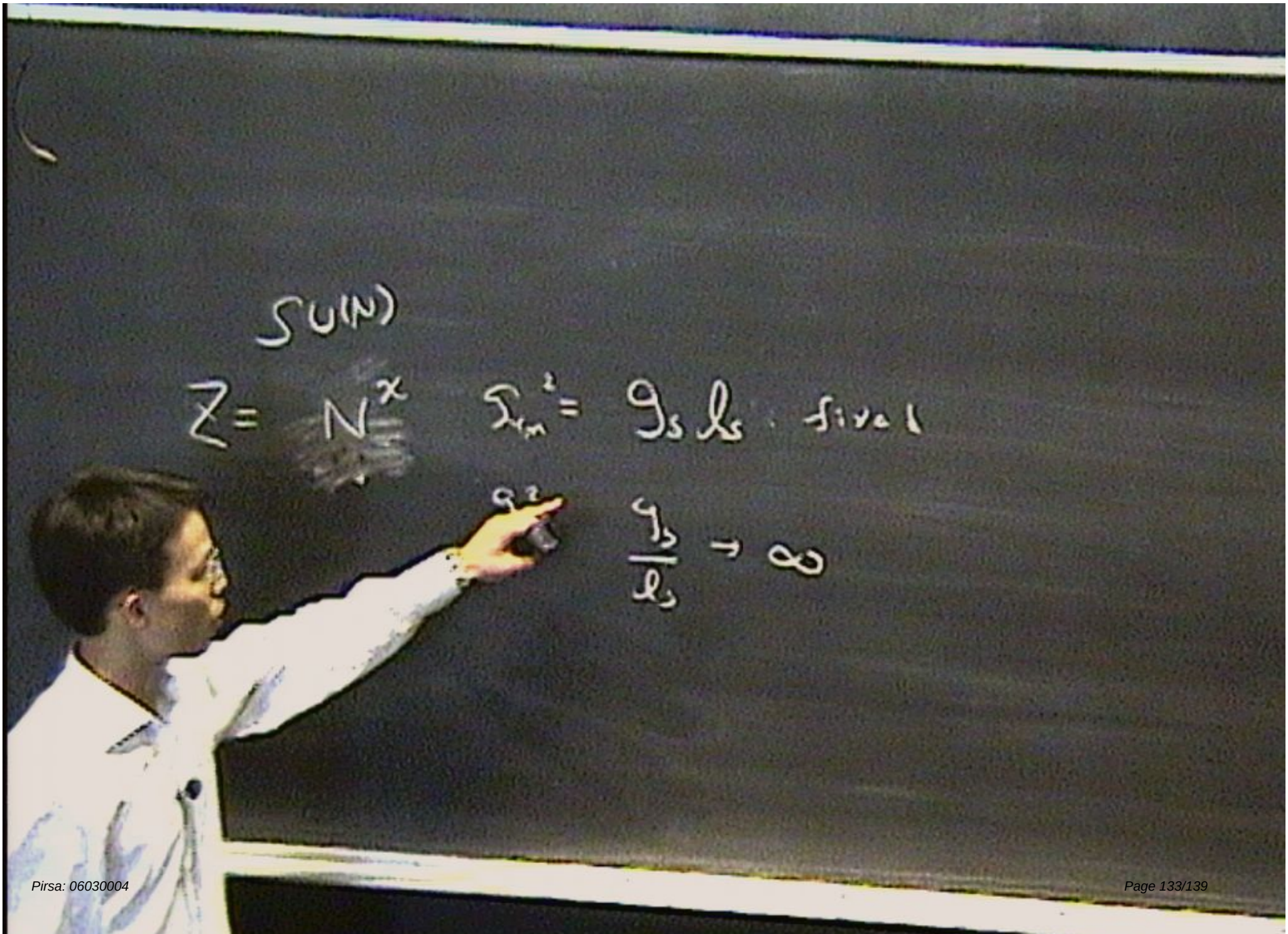
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g^2
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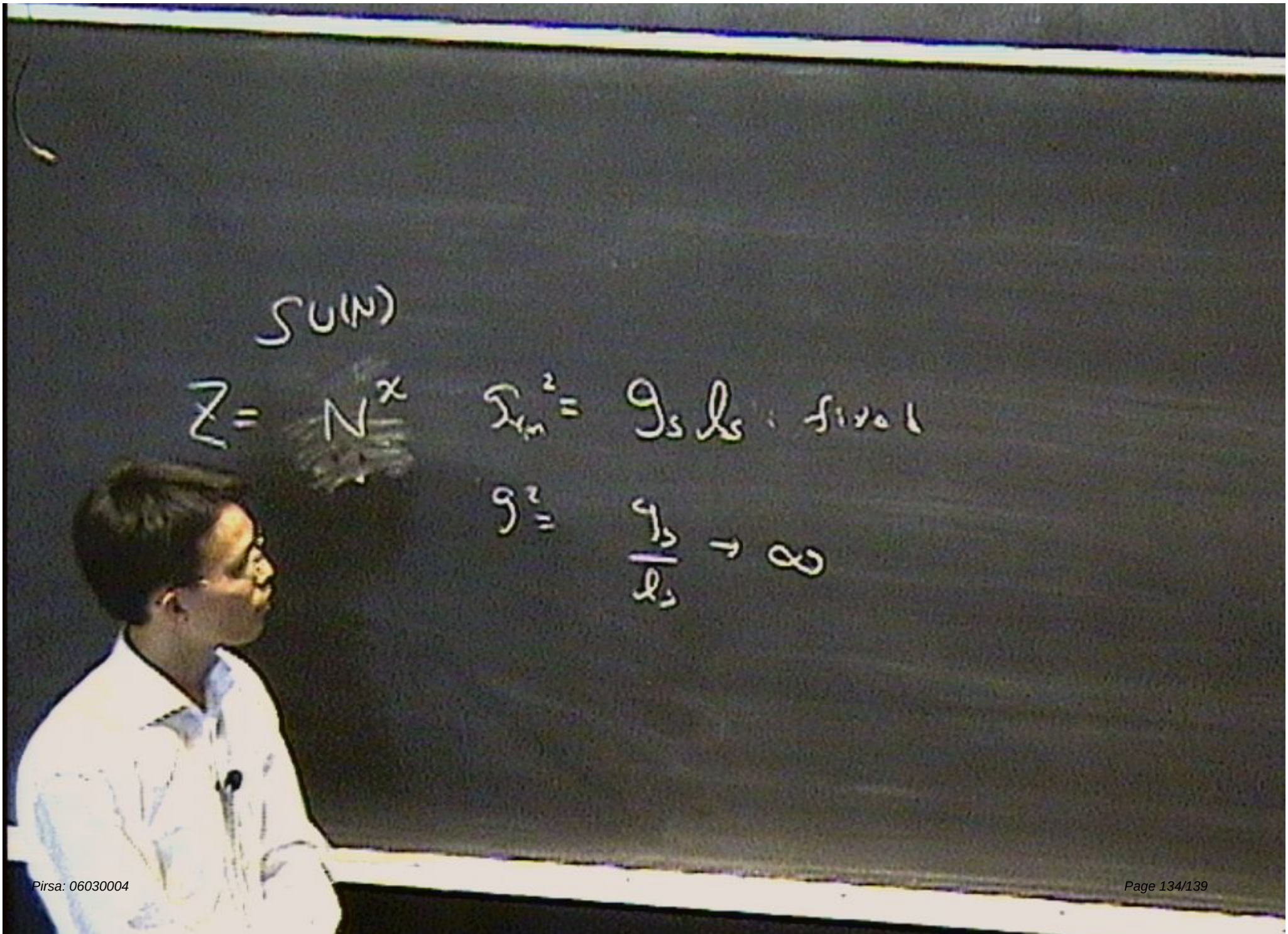
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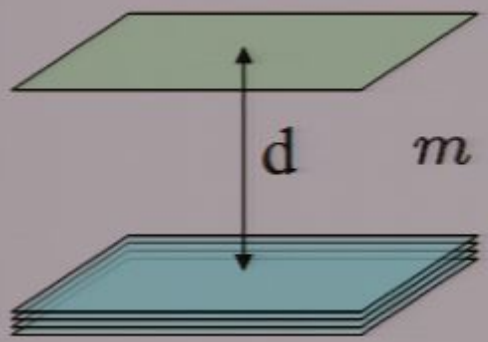
Renormalized gauge coupling



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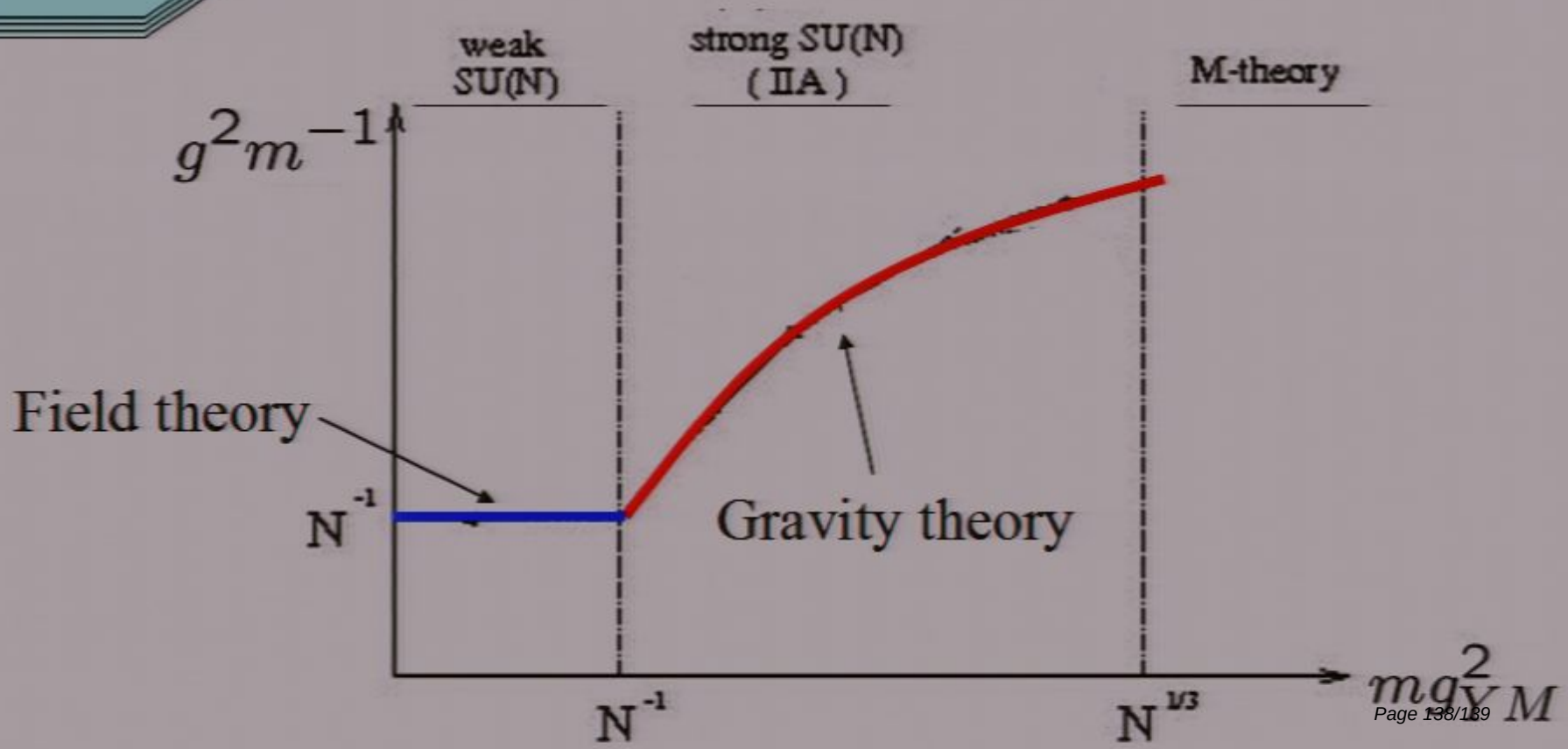

Conclusion

- Emergence of gauge theories/fractionalization
  - World line web
  - New state of matter
  - New insight into gauge theory
- Strongly coupled gauge theory
  - Gravity description
  - Non-supersymmetric (unstable) D-brane