Title: Introduction to String Theory

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Abstract:

Introduction to String Theory

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Outline

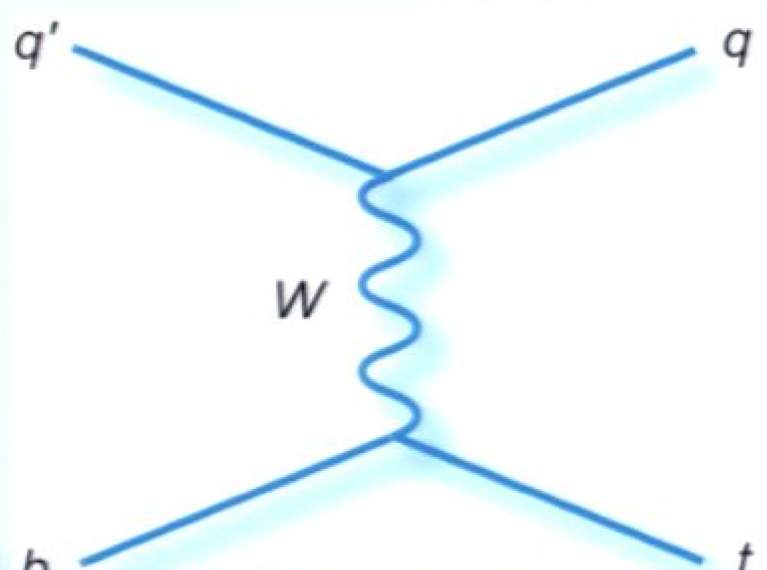
I. String Theory as a (possible) high energy description of Nature.

II. The Gauge/Gravity duality

Our Current Model of Nature

1. Standard Model of Particle Physics:
   - Describes all ***known*** particles and their interactions using the framework of relativistic Quantum Field Theory. In this language, all possible interactions (the ***Lagrangian***) can be deduced only by knowing the fundamental gauge symmetries (SU(3) x SU(2) x U(1)).
   - Fields are local in space-time: $A_\mu(t,\mathbf{x})$, $\Psi_i(t,\mathbf{x})$, $\phi(t,\mathbf{x})$,…
   - They obey Dirac quantization conditions: e.g.

$$[\phi(t,\mathbf{x}), \partial\phi(t,\mathbf{x}')/\partial t] = i\delta^{(3)}(\mathbf{x} - \mathbf{x}')$$



http://www-d0.fnal.gov/

Parameter	Meaning	Measured value
	Weak coupling constant at m_Z	0.6520 ± 0.0001
$_W$	Weinberg angle	0.48290 ± 0.00005
$_s$	Strong coupling constant at m_Z	1.221 ± 0.022
^{2}	Quadratic Higgs coefficient	$\sim -10^{-33}$
	Quartic Higgs coefficient	$\sim 1?$
$_e$	Electron Yukawa coupling	2.94×10^{-6}
$_\mu$	Muon Yukawa coupling	0.000607
$_\tau$	Tauon Yukawa coupling	0.0102156233
$_u$	Up quark Yukawa coupling	0.000016 ± 0.000007
$_d$	Down quark Yukawa coupling	0.00003 ± 0.00002
$_c$	Charm quark Yukawa coupling	0.0072 ± 0.0006
$_s$	Strange quark Yukawa coupling	0.0006 ± 0.0002
$_t$	Top quark Yukawa coupling	1.002 ± 0.029
$_b$	Bottom quark Yukawa coupling	0.026 ± 0.003
in θ_{12}	Quark CKM matrix angle	0.2243 ± 0.0016
in θ_{23}	Quark CKM matrix angle	0.0413 ± 0.0015
in θ_{13}	Quark CKM matrix angle	0.0037 ± 0.0005
$_{13}$	Quark CKM matrix phase	1.05 ± 0.24
θ_{qcd}	CP-violating QCD vacuum phase	$< 10^{-9}$
G_{ν_e}	Electron neutrino Yukawa coupling	$< 1.7 \times 10^{-11}$
G_{ν_μ}	Muon neutrino Yukawa coupling	$< 1.1 \times 10^{-6}$
G_{ν_τ}	Tau neutrino Yukawa coupling	< 0.10
$\sin \theta'_{12}$	Neutrino MNS matrix angle	0.55 ± 0.06
$\sin 2\theta'_{23}$	Neutrino MNS matrix angle	≥ 0.94
$\sin \theta'_{13}$	Neutrino MNS matrix angle	≤ 0.22
δ'_{13}	Neutrino MNS matrix phase	?

From Max Tegmark, Anthony Aguirre, Martin J Rees, Frank Wilczek, Phys.Rev.D73:023505,2006 (astro-ph/0511774)

Inputs from (scattering) experiments

Use to predict any other scattering processes

2. Gravity:

- Also described by a local field theory for the "metric" $g_{\mu\nu}(x)$ that measures distances in space-time.

$$\Delta s^2 = \sum_{\mu\nu = 0,\ldots 3} g_{\mu\nu} \Delta x^\mu \Delta x^\nu$$

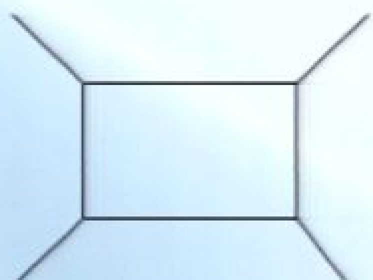
- The theory is, however, classical: Einstein's General Relativity.
- It is also derivable from a Lagrangian formulation:

$$S \sim \int_{\mathcal{M}} d^4x \sqrt{-g} R(g, \partial g)$$

Determinant of metric

Ricci Curvature

- Quantization leads to a ***non-renormalizable*** Quantum Field Theory for $g_{\mu\nu}(x)$ (need infinite number of counter terms to absorb divergences)

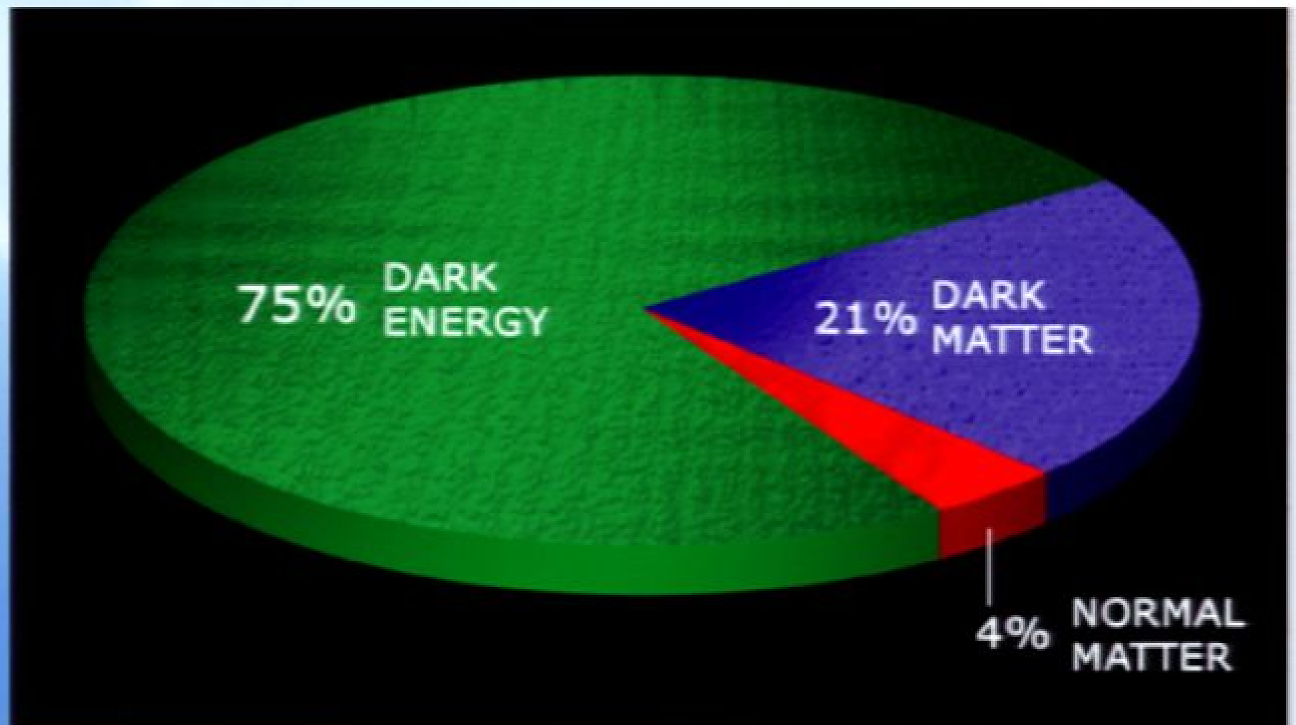


$= \infty$

Problems with Standard Model

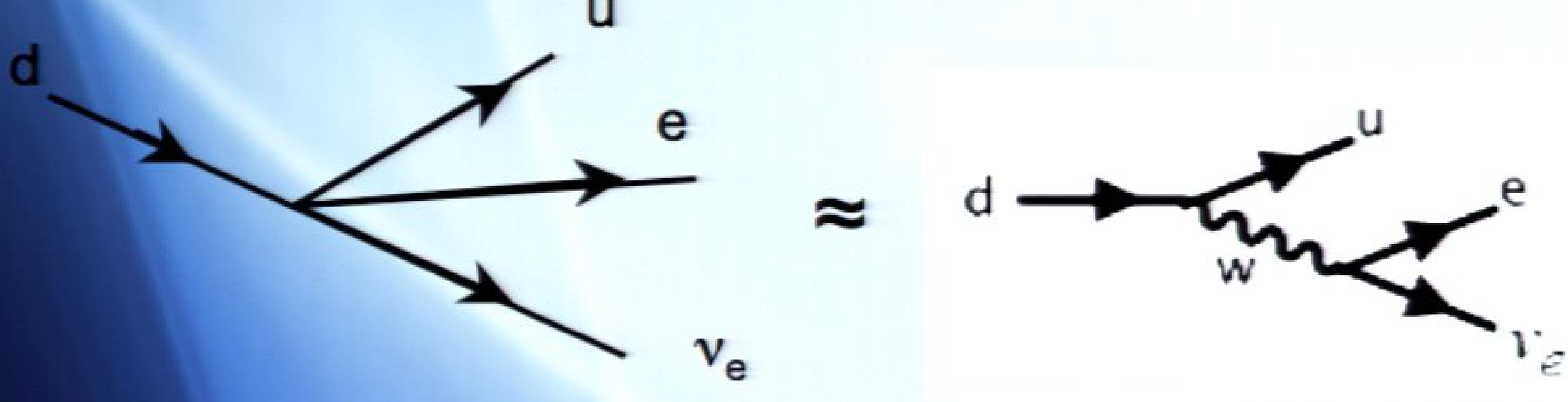
1. Quantum Gravity

2. Astrophysics and Cosmology tells us that…



String Theory and Unification

1. Non-renormalizable field theories can sometimes be "fixed" by adding extra degrees of freedom
   - o Example: Fermi's four-fermion interaction for beta-decay



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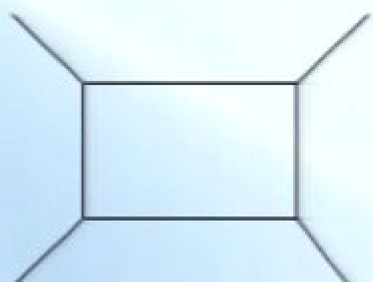

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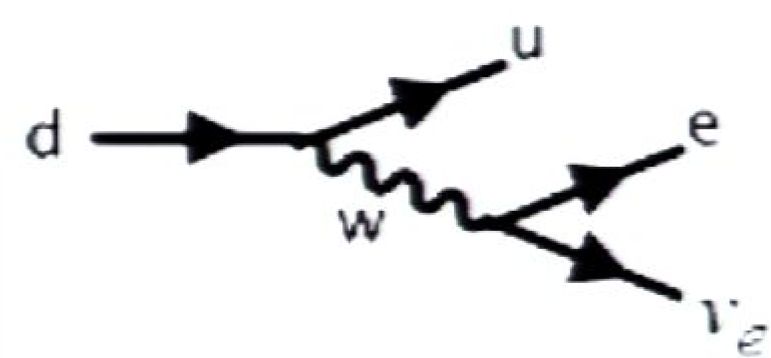

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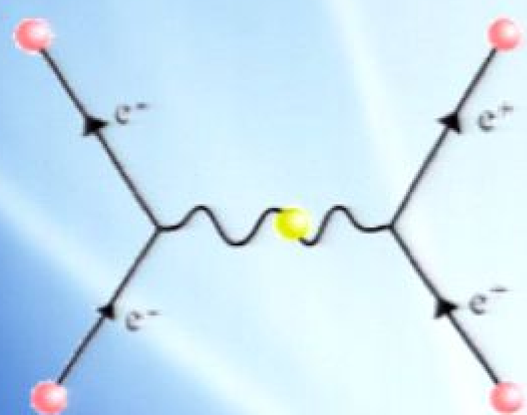

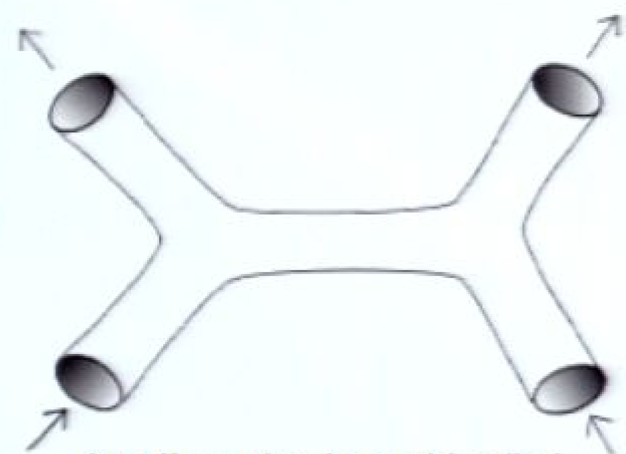

http://www.ipod.org.uk/reality/

2. The basic object of ***perturbative*** string theory is a two-dimensional Quantum Field Theory

$$S = -\frac{1}{4\pi\alpha'}\int d^2\sigma\sqrt{-\gamma}\left[(\gamma^{ab}G_{\mu\nu}(X) + i\epsilon^{ab}B_{\mu\nu}(X))\partial_a X^\mu \partial_b X^\nu + \alpha'\Phi R\right]$$

World sheet metric

Target space-time metric

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1. Classically, the theory has conformal invariance (= diffeo + weyl rescaling)

$$\gamma_{ab}(\tau,\sigma) \rightarrow \Omega(\tau,\sigma)\gamma_{ab}(\tau\sigma)$$

2. Quantization proceeds as usual by imposing commutation relations between the fields $X^\mu(\tau,\sigma)$. Consider the example of bosonic string in flat target space. (after choosing coordinates in world-sheet)

$$S = -\frac{1}{4\pi\alpha'}\int d^2\sigma \partial_a X^\mu \partial^a X_\mu \Longrightarrow \left(\frac{\partial^2}{\partial\tau^2} - \frac{\partial^2}{\partial\sigma^2}\right) X^\mu(\tau,\sigma) = 0$$

Expand in Fourier modes

$$X^\mu(\tau,\sigma) = X^\mu_R(\sigma^-) + X^\mu_L(\sigma^+) \qquad \sigma^\pm = \tau \pm \sigma$$

$$X^\mu_R(\sigma^-) = \frac{1}{2}x^\mu + \alpha' p^\mu \sigma^- + i\left(\frac{\alpha'}{2}\right)^{1/2}\sum_{n\neq 0}\frac{1}{n}\alpha^\mu_n e^{-2in\sigma^-}$$

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2. Because of conformal invariance on the world-sheet, the stress energy tensor has to be zero $T_{ab} = 0$ (as a constraint acting on states $T_{ab}|\psi\rangle = 0$). The zeroth mode of this constraint gives

$$\boxed{M^2 = \frac{2}{\alpha'}\left[\sum_{n=1}^{\infty}(\alpha^\mu_{-n}\alpha_{n\mu} + \tilde{\alpha}^\mu_{-n}\tilde{\alpha}_{n\mu}) - 2\right]}$$

where $M^2 = p_\mu p^\mu$ is mass of string state as seen in target spacetime.

3. Lowest energy states:

$$|0, k\rangle \qquad \epsilon_{\mu\nu}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0, k\rangle$$

Vacuum $M^2 = -4/\alpha'$ (tachyonic)

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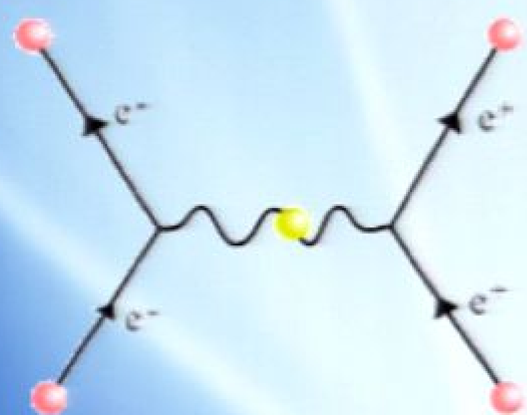

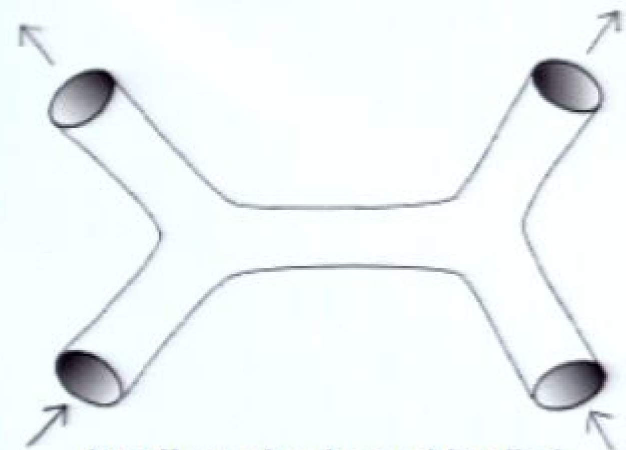

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World sheet metric

Target space-time metric

[redacted]

$\sum_{\eta} e^{-\Phi_{\eta}}$

$C_2^{(-1)} W(g\eta)$ w^{i}

$\mathcal{O}\left((\sqrt{N})^{4n}\right)$

$\mathbb{Q}[x^4 + x^2$

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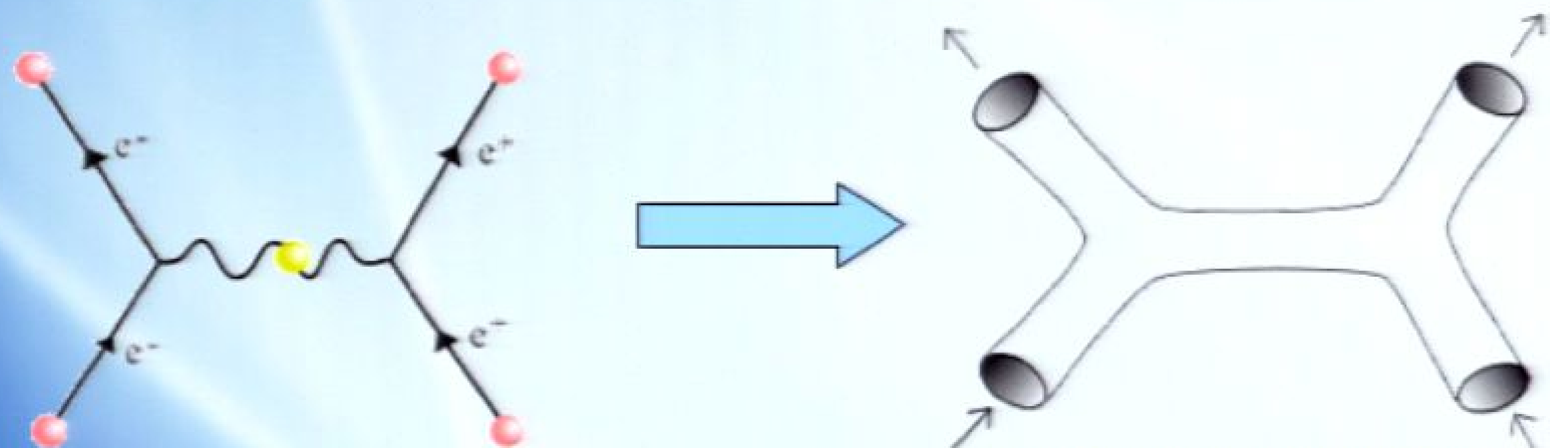

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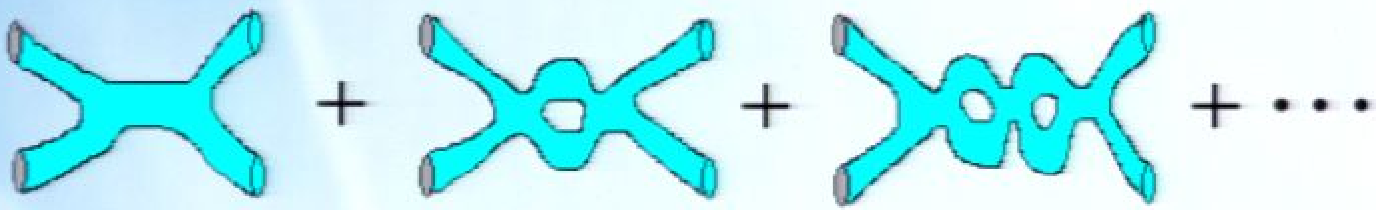
1. Conformal invariance is very powerful: can define S-matrix to scatter string states (gravitons, etc.). From it can construct effective field theory that looks exactly like Einstein's gravity to lowest order in α'.



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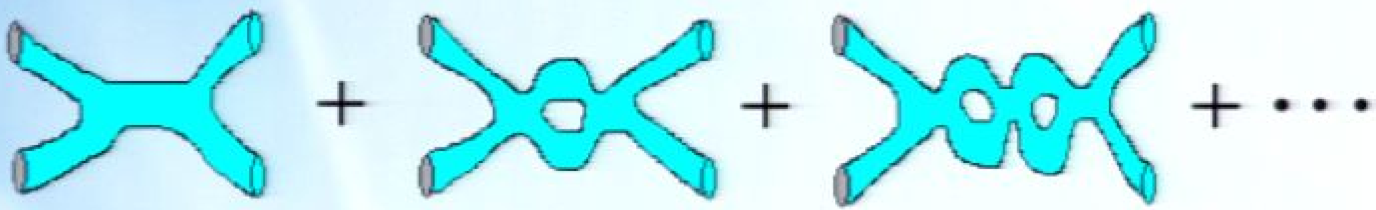

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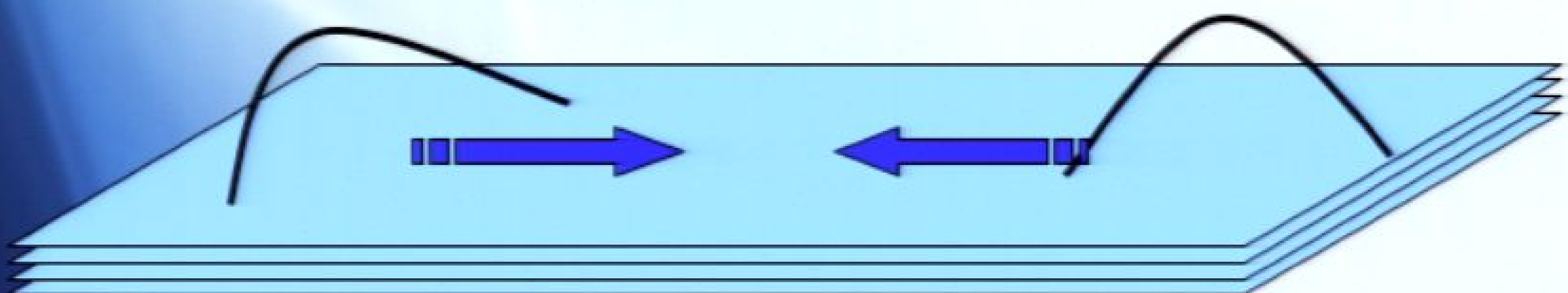
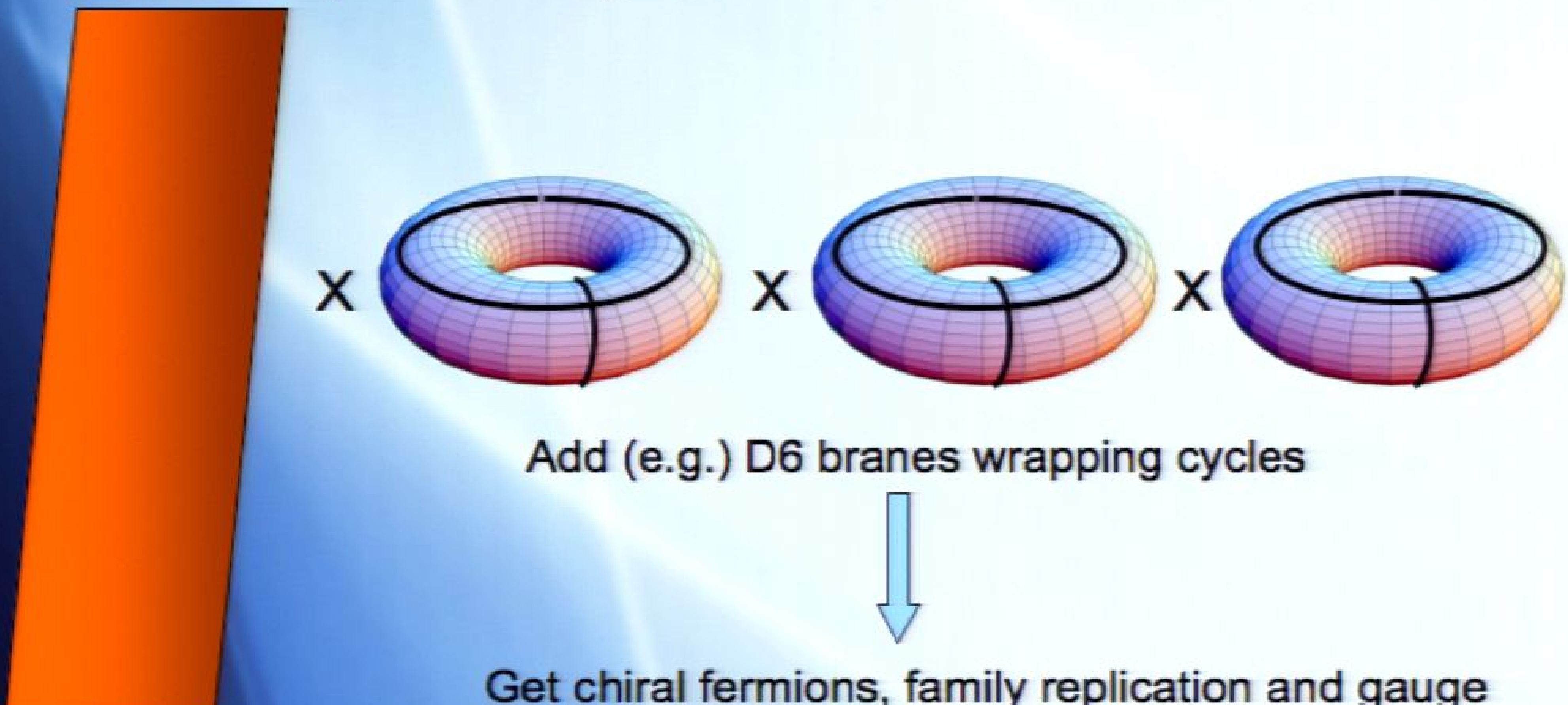
Gauge Interactions: Open Strings and D-branes

1. String Theory has non-perturbative solitonic objects called D(richlet)-branes.
   - o Open Strings correspond to small "vibrations" of D-branes
2. Open strings carry extra indices indicating in which D-brane they are ending. (Chan-Paton indices)
3. When the D-branes overlap, they give rise to U(N) gauge groups
   - o One shows this by studying scattering of open strings on D-brane.



Constructing Semi-Realistic Models

1. Need to compactify 6 dimensions for super-strings.
   - Example: intersecting D6 branes



Add (e.g.) D6 branes wrapping cycles

Get chiral fermions, family replication and gauge groups of type $U(n_1) \times U(n_2) \times \ldots$

Flat 4 dim. space

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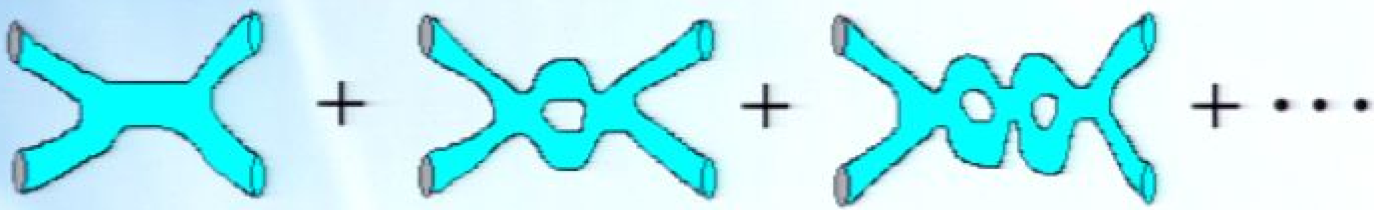

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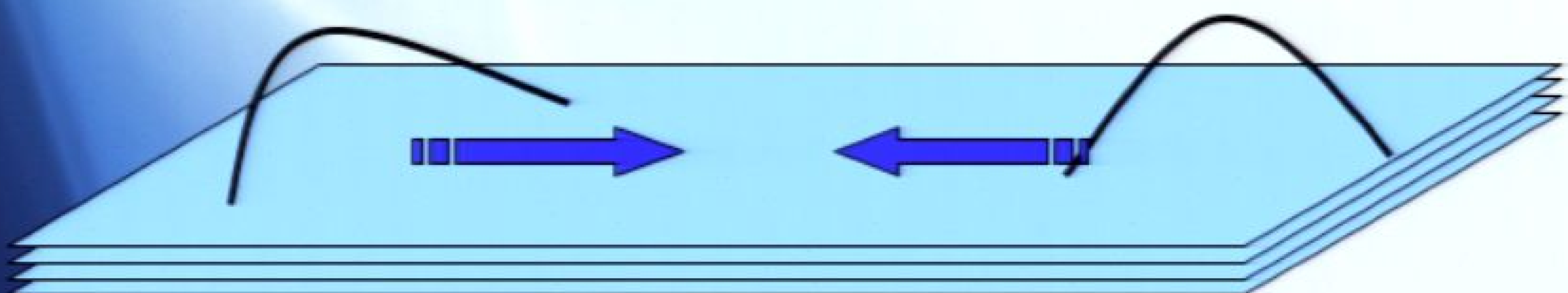

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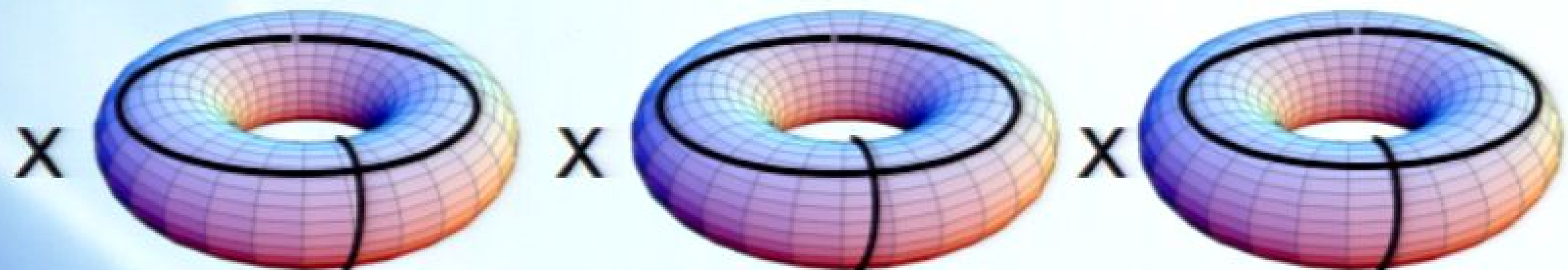

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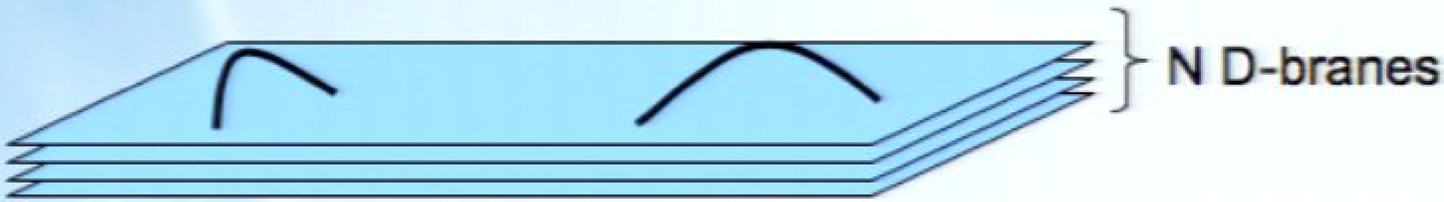
The Gauge/Gravity Duality

A Closer Look at D-branes

1. There are two equivalent descriptions of D-branes:
   - Open Strings = Gauge Theory on world-volume



   - Closed Strings = replace D-branes by their back-reacted geometry

(asymptotically) Anti-de-Sitter Geometry

U(N) gauge theory ~ gravity on asymptotically AdS spacetime

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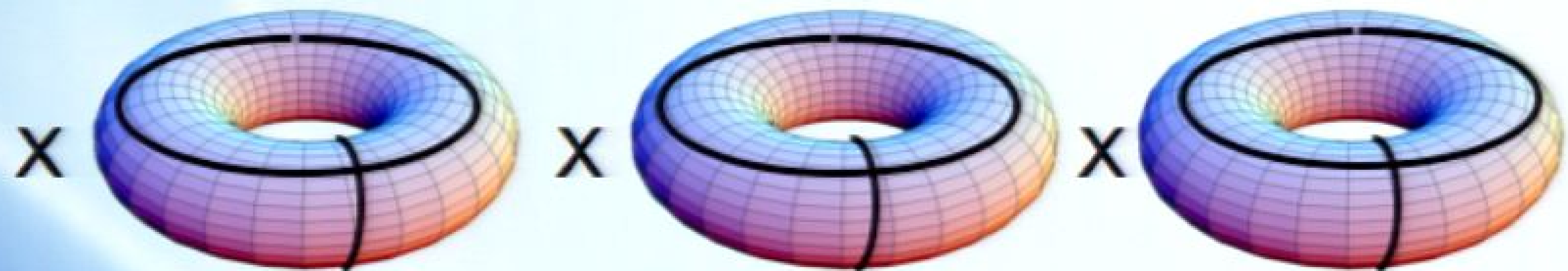

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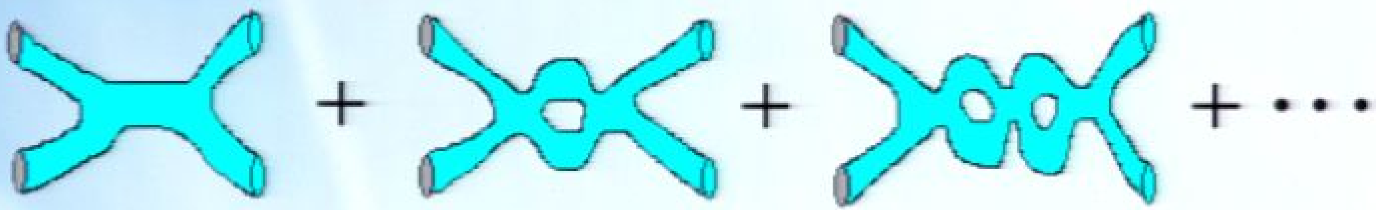

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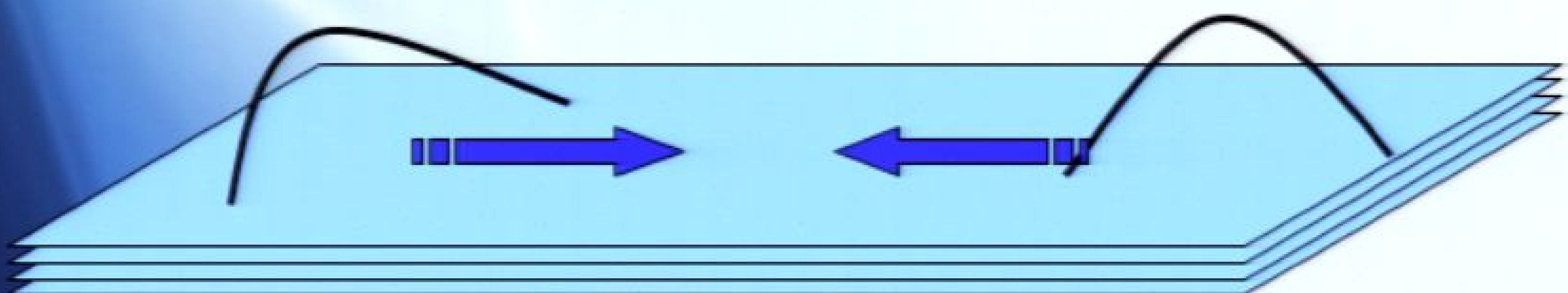

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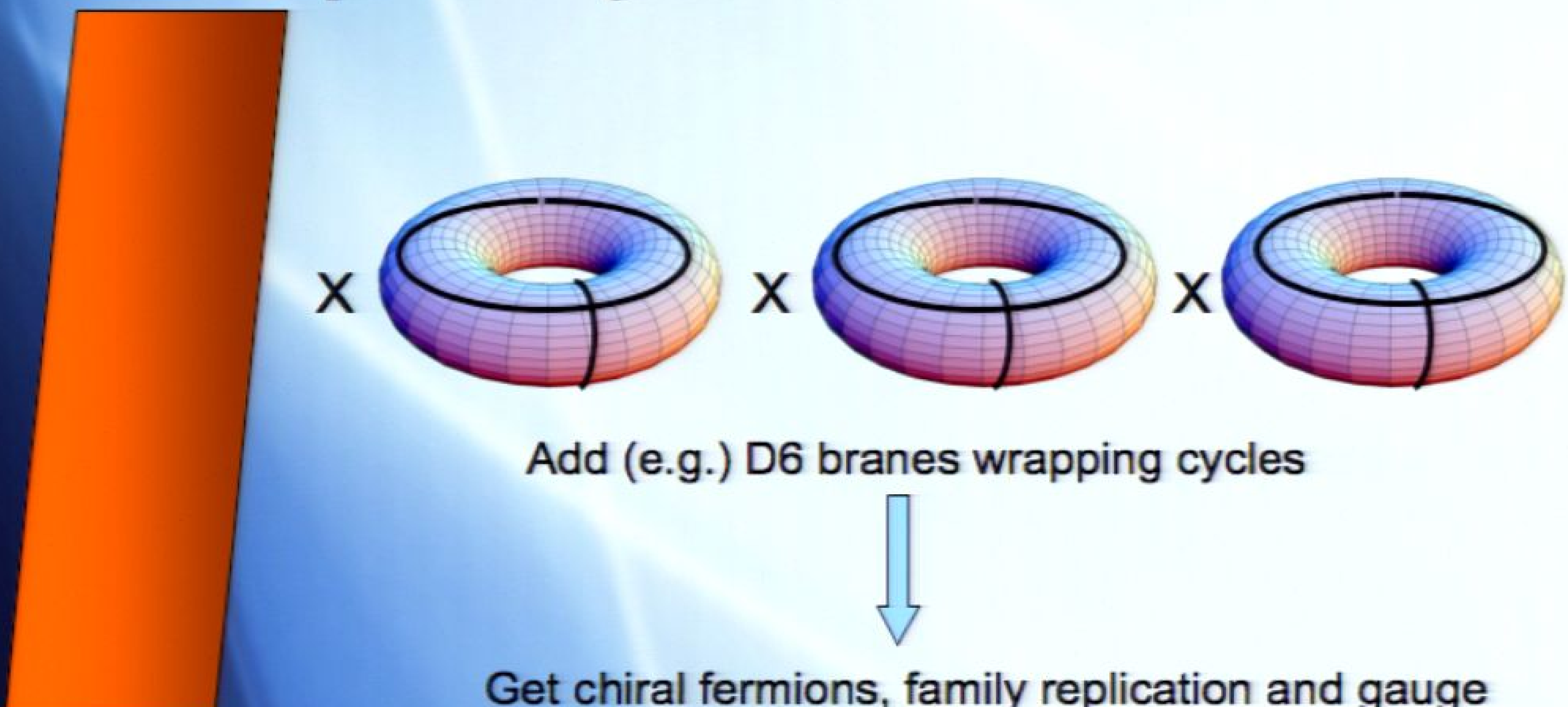
   - Example: intersecting D6 branes



Add (e.g.) D6 branes wrapping cycles

Get chiral fermions, family replication and gauge groups of type $U(n_1) \times U(n_2) \times \ldots$

Flat 4 dim. space

The Gauge/Gravity Duality

A Closer Look at D-branes

1. There are two equivalent descriptions of D-branes:
   - Open Strings = Gauge Theory on world-volume

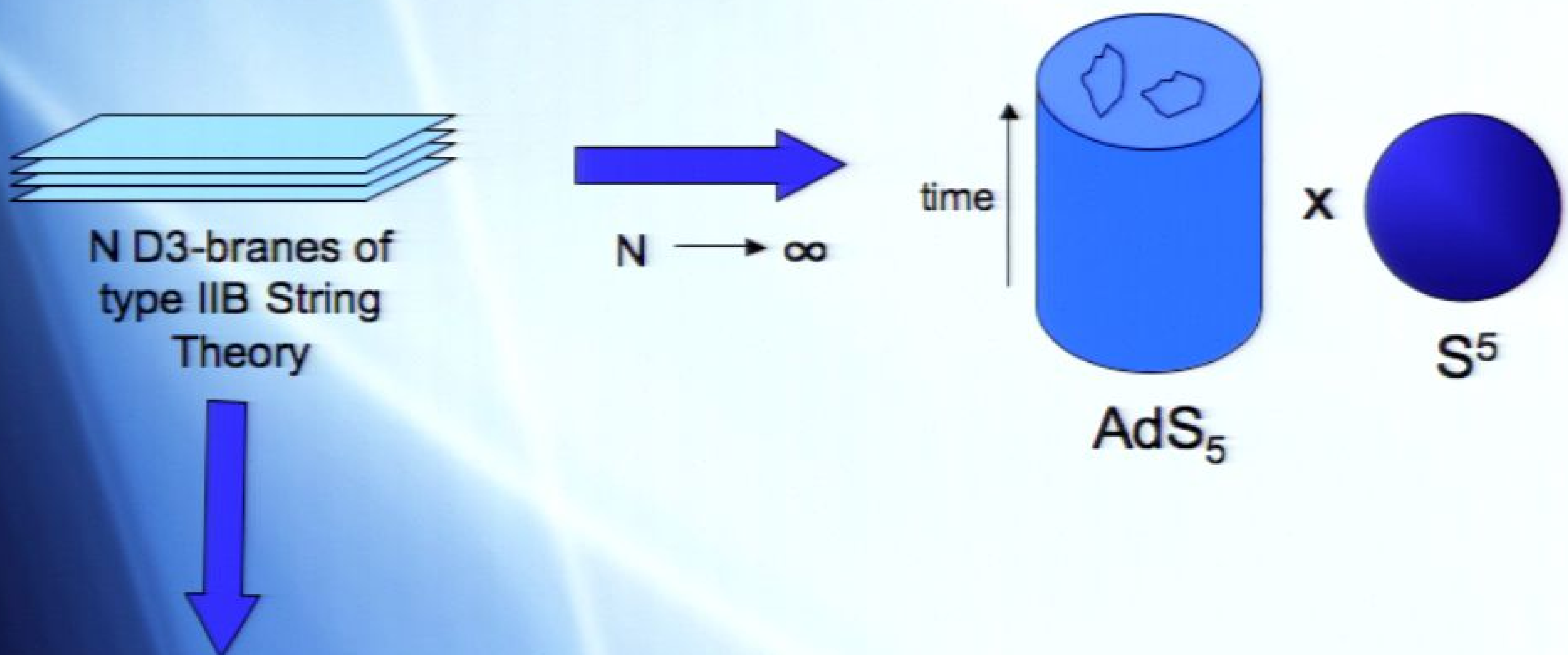
   - Closed Strings = replace D-branes by their back-reacted geometry

(asymptotically) Anti-de-Sitter Geometry

U(N) gauge theory ~ gravity on asymptotically AdS spacetime

The AdS/CFT Correspondence

1. In 1997, Maldacena gave the first concrete example of the AdS/CFT duality (Adv.Theor.Math.Phys. 2 (1998) 231-252 and hep-th/9711200)



$\mathcal{N} = 4$ Supersymmetric Yang-Mills theory in R x S^3 with gauge group U(N) ← scale invariant theory (conformal field theory)

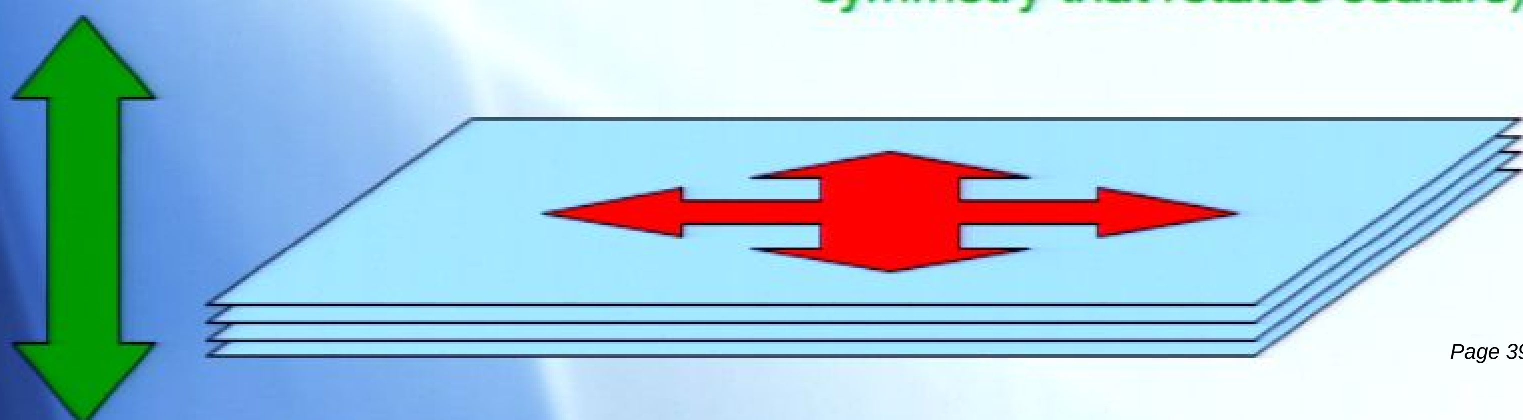
$\mathcal{N}=4$ Supersymmetric Yang-Mills Theory

1. The Lagrangian:

$$\mathcal{L} = \mathrm{Tr}\Bigg(-\frac{1}{2g_{YM}^2}F_{\mu\nu}F^{\mu\nu} + \frac{\theta_I}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} - \sum_a i\bar{\lambda}^a\bar{\sigma}^\mu D_\mu\lambda_a - \sum_i D_\mu X^i D^\mu X^i - \sum_i \frac{R}{6}X^i X^i$$
$$+\sum_{a,b,i} g_{YM}C_i^{ab}\lambda_a[X^i,\lambda_b] + \sum_{a,b,i} g_{YM}\bar{C}_{iab}\bar{\lambda}^a[X^i,\bar{\lambda}^b] + \frac{g_{YM}^2}{2}\sum_{i,j}[X^i,X^j]^2\Bigg) ,$$

From strings moving tangent to D3-branes

Scalars come from motion of D3-branes transverse to their 4-volume (note SO(6) global symmetry that rotates scalars)



$\mathcal{N}=4$ Supersymmetric Yang-Mills Theory

1. An IR/UV duality

String scale

10 dimensional
Plank length

$$\frac{\alpha'}{R^2} = \frac{1}{\sqrt{\lambda}}, \quad \frac{1}{N} = \left(\frac{l_P}{R}\right)^4, \quad g_{YM}^2 = 2\pi g_s$$

Radius of
AdS_5 and S^5

$$\lambda = g_{YM}^2 N$$

Yang-Mills
coupling

String coupling
(string loops)

2. ***A strongly coupled CFT in the large N limit can be described by classical gravity!!!***
   1. N large gives classical geometry
   2. Large λ suppresses stringy correction to geometry.

Applications: many!

I. Understand emergence of space-time and strings from gauge theory variables.

- o Basic Dictionary:

Expand fields of SYM in spherical harmonics on S^3:

$$Z(t,\Omega) = \sum_A Z_A(t) Y_A(\Omega)$$

where $A = (n,m,l),\ n \geq l \geq 0,\ l \geq m \geq -l$ labels irreps. of SO(4).

$$\Delta_{S^3} Y_A(\Omega) = -n(n+2)\,, \quad \int d\Omega_3 Y_A^*(\Omega) Y_B(\Omega) = \delta_{AB}$$

Get interacting harmonic oscillators

$$S = \sum_A \int dt\ \mathrm{Tr}\left[|\dot{Z}_A|^2 - (n+1)^2 |Z_A|^2\right] + \textit{\textbf{interactions}}$$

Classify states by their quantum numbers SO(4) x SO(6)

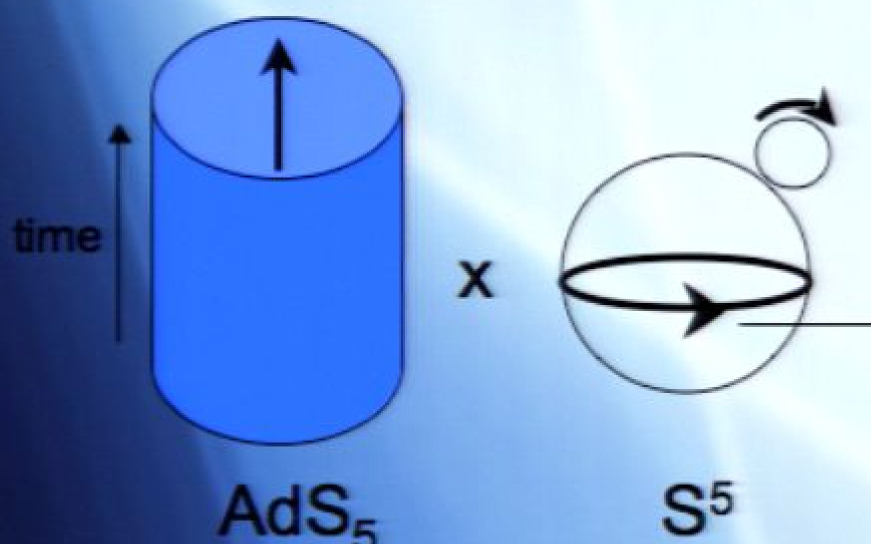
Emergent Strings

- o This is the same classification as quantum states on $AdS_5 \times S^5$
- o Example: take the ***zero mode*** (on S^3) of two of the complex scalars of SYM

SO(4) x SO(6)

Rotation on $S^3 \subset AdS_5$

Rotation on S^5



Closed string with two angular momenta on S^5

$$\mathrm{Tr}\left(\hat{A}^\dagger_Z \hat{A}^\dagger_Y \cdots\right)|0\rangle$$

$$[(\hat{A}_Z)^j_i, (\hat{A}^\dagger_Z)^l_k] = \delta^l_i \delta^l_k$$

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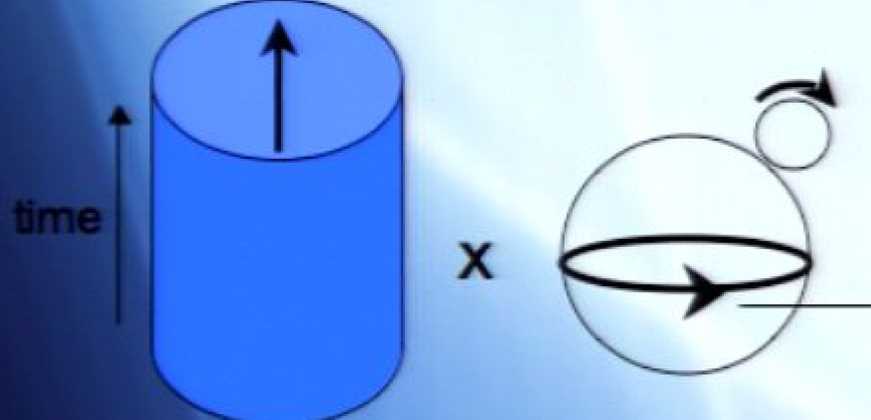

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- The Hamiltonian of SYM theory at weak coupling acts on these single trace states as a spin chain!

$$\mathrm{Tr}\left(\hat{A}^\dagger_Z \hat{A}^\dagger_Y \cdots\right)|0\rangle \simeq |\uparrow\downarrow\cdots\rangle$$

- The one-loop Hamiltonian is precisely the $XXX_{1/2}$ spin chain (in the large N limit)

$$\hat{H} = \lambda \sum_{l=1}^{J} \left(1 - 4\vec{S}_l \cdot \vec{S}_{l+1}\right) \qquad \lambda = g_{YM}^2 N$$

acts on nearest-neighbor "spins"

$$|\uparrow\downarrow\cdots\rangle$$

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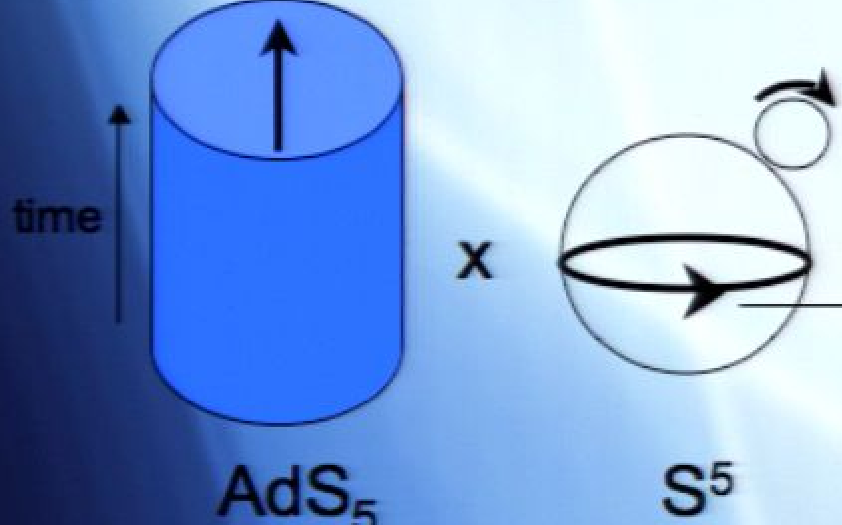

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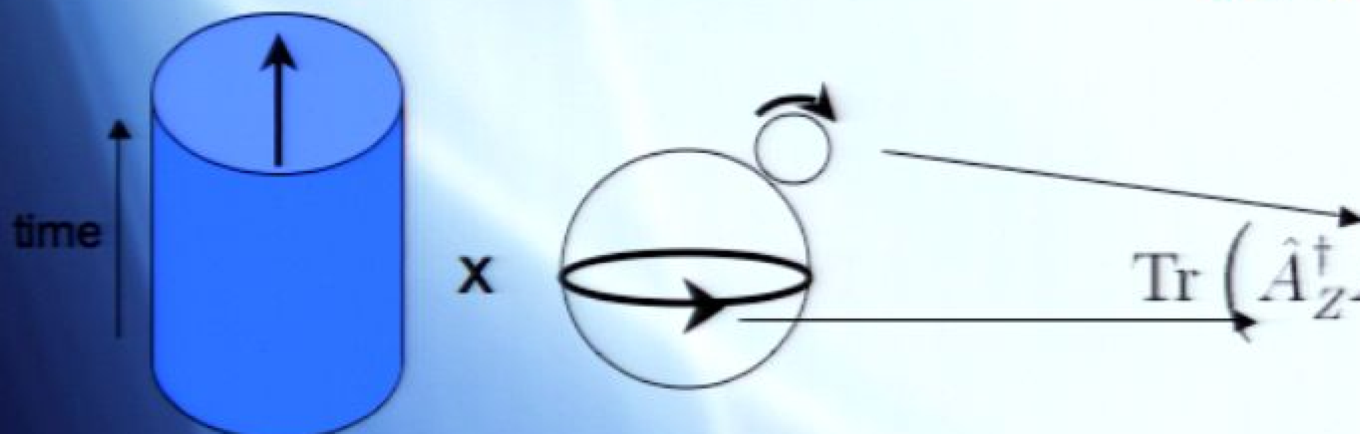

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- It is well known that for J →∞ (many "spins") the XXX spin chain has a classical description as a non-linear sigma model (Landau-Lifshitz model)

Build coherent states: $\langle\vec{n}|\vec{S}|\vec{n}\rangle = \frac{1}{2}\vec{n}.\quad |CS\rangle = |\vec{n}_1, \vec{n}_2, \ldots\rangle$

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$$= \int dt \sum_{l=1}^{J} \left[\vec{C}(n_l)\cdot\vec{n}_l - \frac{\lambda}{2(4\pi)^2}(\vec{n}_{l+1} - \vec{n}_l)^2 \right]$$

Take large J limit $\approx J \int dt \int_0^{2\pi} \frac{d\sigma}{2\pi} \left[\vec{C}\cdot\partial_t\vec{n} - \frac{1}{8}\tilde{\lambda}(\partial_\sigma\vec{n})^2 + \ldots \right]$

$\tilde{\lambda} = \frac{\lambda}{J^2}$ $\quad (dC = \epsilon^{ijk} n_i dn_j \wedge dn_k)$

Emergent Strings

- It was first shown by Kruczenski (2003) that one can obtain same sigma model for a string rotating with angular momentum $J >> 1$ along the S^5.
- Note that the effective expansion parameter for such a string is

$$\tilde{\lambda} = \frac{\lambda}{J^2}$$

  This "miracle" allows a comparison with the weakly coupled SYM theory.

- This effective expansion parameter was first discovered by **B**erenstein, **M**aldacena and **N**astase (hep-th/0202021) and the limit of taking $\lambda \to \infty$ with λ/J^2 = fixed is known as the **BMN** limit.

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Emergent Spacetime at Strong Coupling

- Supersymmetric states saturate a "minimum" energy condition called the BPS bound: **(H - J)|ψ⟩ = 0**, where H is Hamiltonian and J is the R-charge generator (the SO(6) symmetry of SYM).

- One can show from the SYM action that, at the ***classical*** level. Such states can only be composed of the scalar zero-modes, subject to the extra condition,

$$[X^i, X^j] = 0$$

minimizes energy

$$S_{se} = \int dt \, \mathrm{tr} \left(\sum_{a=1}^{6} \frac{1}{2}(D_t X^a)^2 - \frac{1}{2}(X^a)^2 - \boxed{\sum_{a,b=1}^{6} \frac{1}{8\pi^2} g_{YM}^2 [X^a, X^b][X^b, X^a]} \right)$$

Does not contribute to J

Emergent Spacetime at Strong Coupling

- Berenstein (hep-th/0507203, 0403110) proposed that we should expand around commuting matrices at strong coupling. (since commutators give biggest contribution to energy as $\lambda >>1$)
- Quantum Mechanics of commuting matrices

$$H = \frac{1}{2}\mathrm{tr}(\Pi_a^2) + \frac{1}{2}\mathrm{tr}[(X^a)^2]$$

Momentum

- But need to take into account constraint: $[X^i, X^j] = 0$
  - Go to eigenvalue basis

$$\mu^2 = \prod_{i<j} |\vec{x}_i - \vec{x}_j|^2$$

Jacobian

$$\boxed{H = \sum_i \left(-\frac{1}{2\mu}\nabla_i \mu^2 \nabla_i \frac{1}{\mu} + \frac{1}{2}|\vec{x}_i|^2 \right)}$$

Emergent Spacetime at Strong Coupling

- Ground State wave function:

$$|\hat{\psi}_0^2| \sim \mu^2 \exp(-\sum x_i^2) = \exp\left(-\sum \vec{x}_i^2 + 2\sum_{i<j} \log|\vec{x}_i - \vec{x}_j|\right)$$

- In the large N limit can replace sums by integral over eigenvalue distribution and use Saddle Point approximation

$$|\hat{\psi}_0^2| \sim \exp\left(-\int d^{2d}x\rho(x)\vec{x}^2 + \int d^{2d}x d^{2d}y \rho(x)\rho(y) \log|\vec{x} - \vec{y}|\right)$$

- Saddle point equation with constraint $\int \rho = N$

$$\vec{x}^2 + C = 2\int d^{2d}y \rho_0(y) \log|\vec{x} - \vec{y}|$$

Emergent Spacetime at Strong Coupling

- Find singular distribution on an $S^5 \subset R^6$

$$\rho_0 = N \frac{\delta(|\vec{x}| - r_0)}{r_0^{2d-1} \mathrm{Vol}(S^{2d-1})}$$

where $r_0 = \sqrt{\frac{N}{2}}$

- ***This is the S^5 of AdS_5 x S^5 !!***
- One can also study off-diagonal excitations around the commuting matrix background. The Hamiltonian is

$$H_{offdiag} = \sum_{i \neq j} \frac{1}{2} (\Pi_a)_i^j (\Pi_a)_j^i + \frac{1}{2} \omega_{ij}^2 (X^a)_i^j (X^a)_j^i$$

$$\omega_{ij}^2 = 1 + \frac{g_{YM}^2}{2\pi^2} |\vec{x}_i - \vec{x}_j|^2$$

From commutator

Emergent Spacetime at Strong Coupling

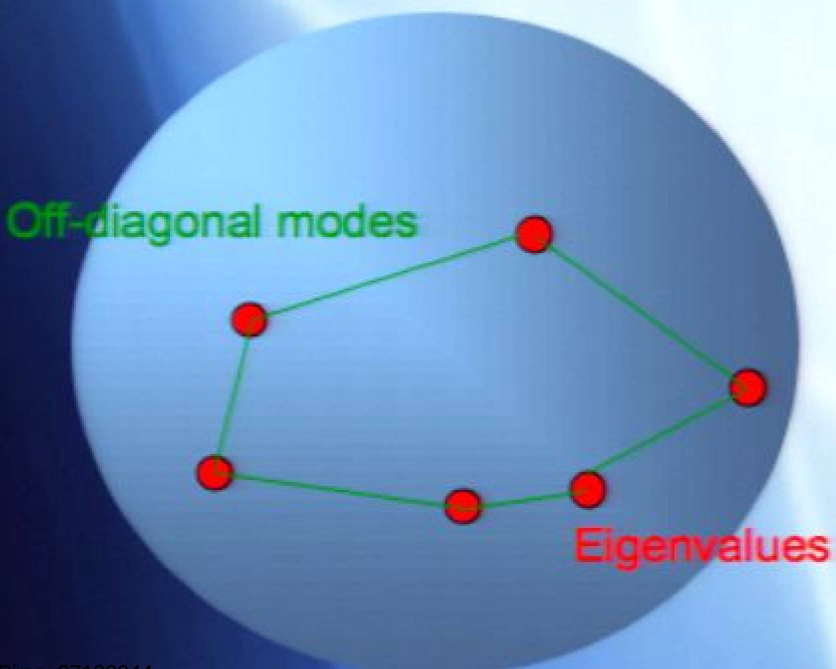
- Consider the state

$$|\psi_k\rangle \sim \sum_{l=0}^{J} \exp(ipl) \sum_{j,j'} z_j^l Y_{j'}^{\dagger j} z_{j'}^{J-l} X_j^{\dagger j'} \hat{\psi}_0 |0\rangle_{od}$$

Commuting background

$(z = x_1 + i\, x_2)$

Off-diagonal excitations



Emergent Spacetime at Strong Coupling

- The energy of such a state can be written as an integral over sphere: (Berenstein, Correa, Vazquez hep-th/0509015)

$$\langle H_{offdiag}\rangle = \frac{\boxed{\int \prod dx^i |\hat{\psi}_0|^2 \sum_{j,j'}} \left| \sum_l \exp(ipl) z_j^l z_{j'}^{J-l}\right|^2 2\sqrt{1+\frac{g_{YM}^2}{2\pi^2}|\vec{x}_j - \vec{x}_{j'}|^2}}{\boxed{\int \prod dx^i |\psi_0|^2 \sum_{j,j'}} \left| \sum_l \exp(ipl) z_j^l z_{j'}^{J-l}\right|^2}$$

$$\approx \frac{\int d\Omega_5 d\Omega'_5 \boxed{\left| \sum_l \exp(ipl) z^l z'^{J-l}\right|^2} 2\sqrt{1+\frac{g_{YM}^2}{2\pi^2}|\vec{x} - \vec{x}'|^2}}{\int d\Omega_5 d\Omega'_5 \boxed{\left| \sum_l \exp(ipl) z^l z'^{J-l}\right|^2}}$$

$$\boxed{\sum_{l=0}^{J}\sum_{l'=0}^{J} (\cos\theta)^{l+l'} (\cos\theta')^{2J-l-l'} e^{i(l-l')(p+\phi'-\phi)}}$$

In the large J limit, the sums localize integral at

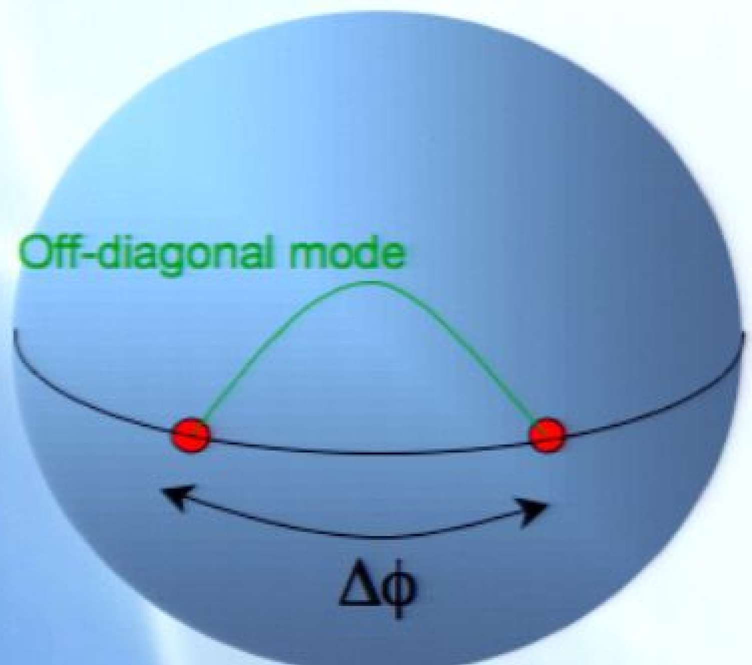
$$\theta = \theta' = 0 \qquad \phi - \phi' = p$$

Emergent Spacetime at Strong Coupling

- Energy:

$$E \approx 2\sqrt{1 + \frac{g_{YM}^2 N}{\pi^2}\sin\left(\frac{\Delta\phi}{2}\right)} \approx \frac{2}{\pi}\sqrt{g_{YM}^2 N}\left|\sin\left(\frac{\Delta\phi}{2}\right)\right|$$

- Geometrical Interpretation



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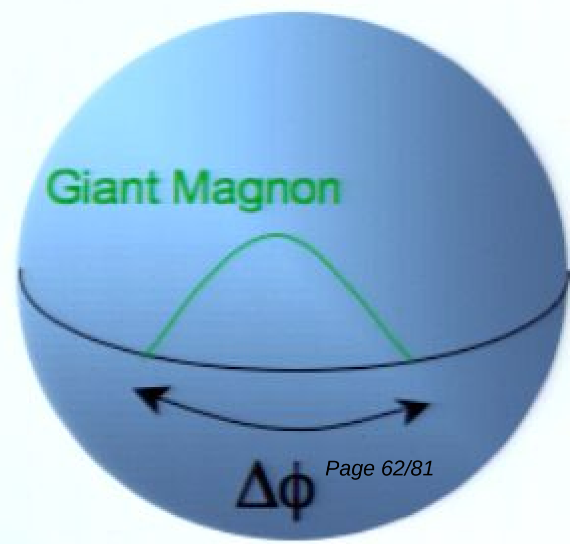
- In hep-th/0604135 Maldacena and Hofman found ***classical*** strings solutions on the sphere that, in the limit of infinite J, have their "ends" localized at equator of S^5.

- These were called "Giant Magnons" and have energy

$$E = \frac{2}{\pi}\sqrt{g_{YM}^2 N}\left|\sin\left(\frac{\Delta\phi}{2}\right)\right|$$

- This matches our SYM calculation!!



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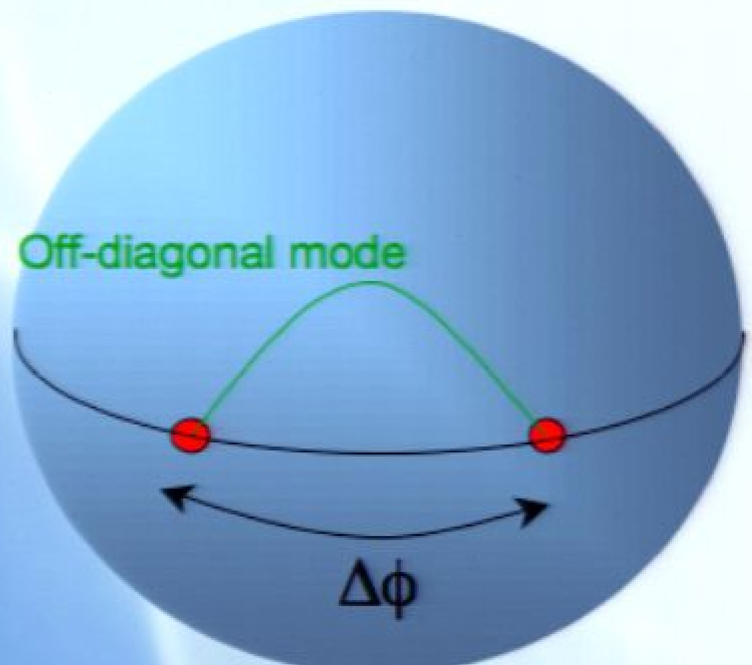

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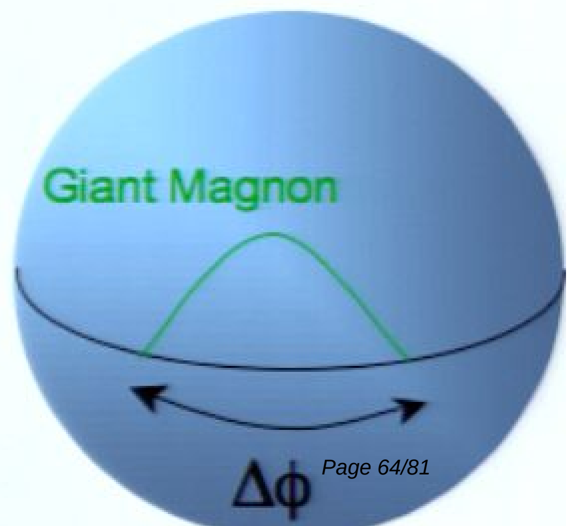


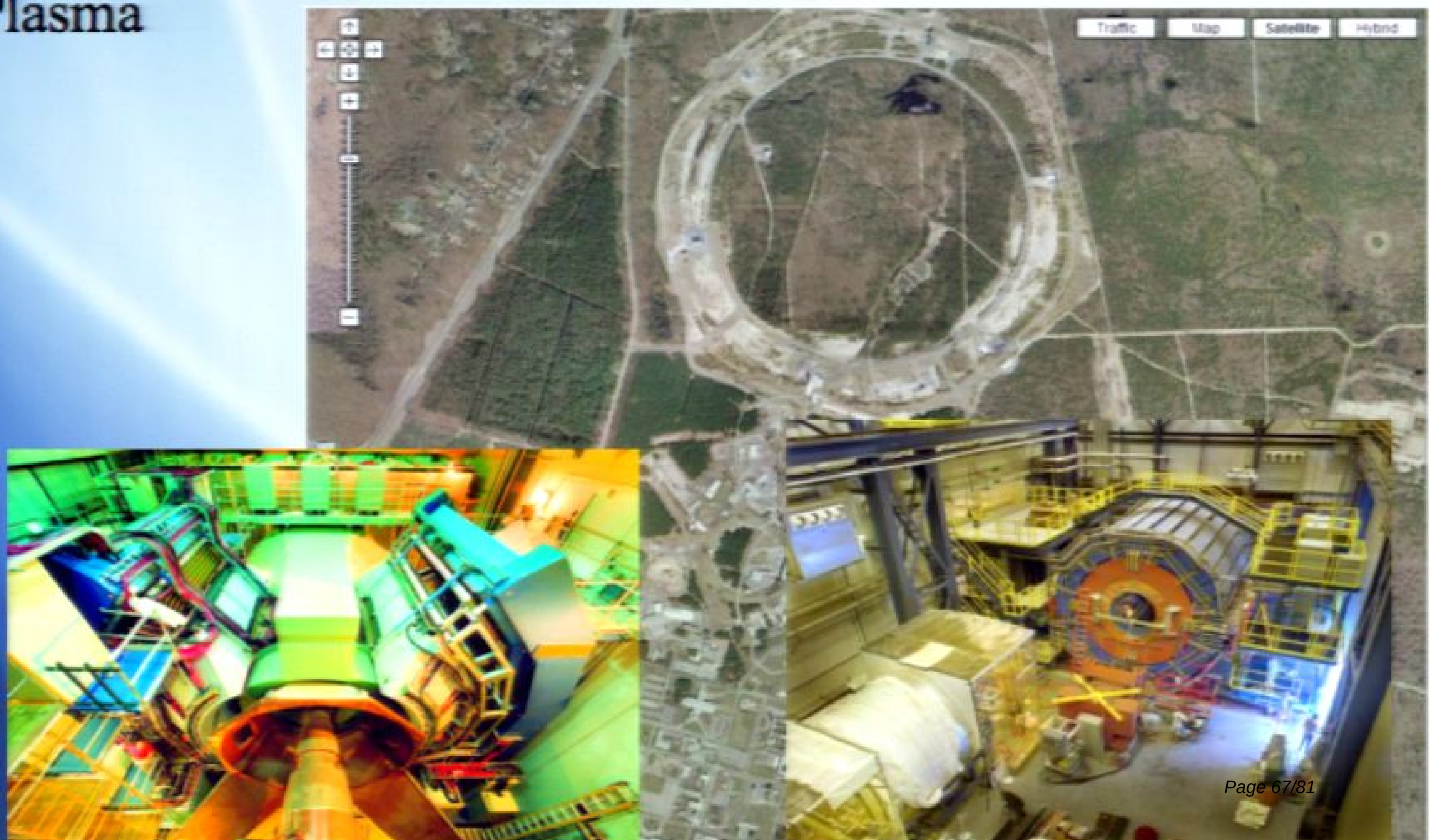
Lessons so far…

- AdS/CFT is hard to check because of strong/weak coupling duality.
- One can already see emergence of semi-classical strings at weak coupling by studying certain single trace operators and taking large spin limits (the SO(6) R-charge in SYM).
- At strong coupling it seems that correct expansion is around commuting matrices for the scalar zero-modes.
  - Eigenvalues play the role of "space-time"
  - Off-diagonal excitations are the strings

String Theory and Strongly Coupled Plasmas

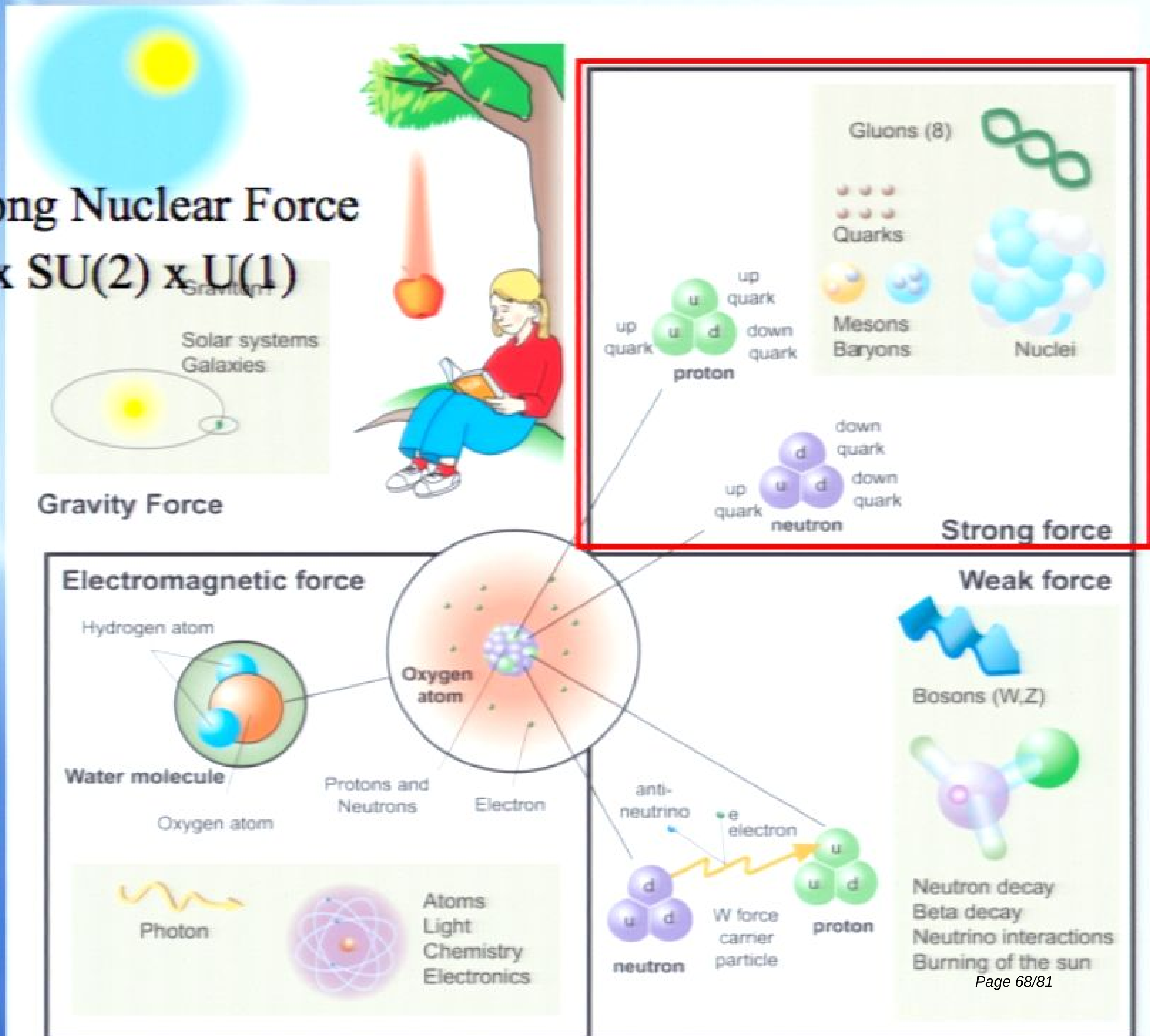
Motivations

- o RHIC (Relativistic Heavy Ion Collider) physics
  - Seeks to understand new phase of matter: Quark Gluon Plasma



- The Strong Nuclear Force

SU(3) x SU(2) x U(1)



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- Quantum Chromodynamics (QCD) is the theory of the strong interactions
  - It is a matrix version of Electromagnetism ($i,j = 1,2,3$ (colors))

$$(A_\mu)^i{}_j \qquad\qquad \Psi^i$$

Gluons: force carriers

Quarks: matter

- Important difference with E&M: ***Asymptotic freedom!***

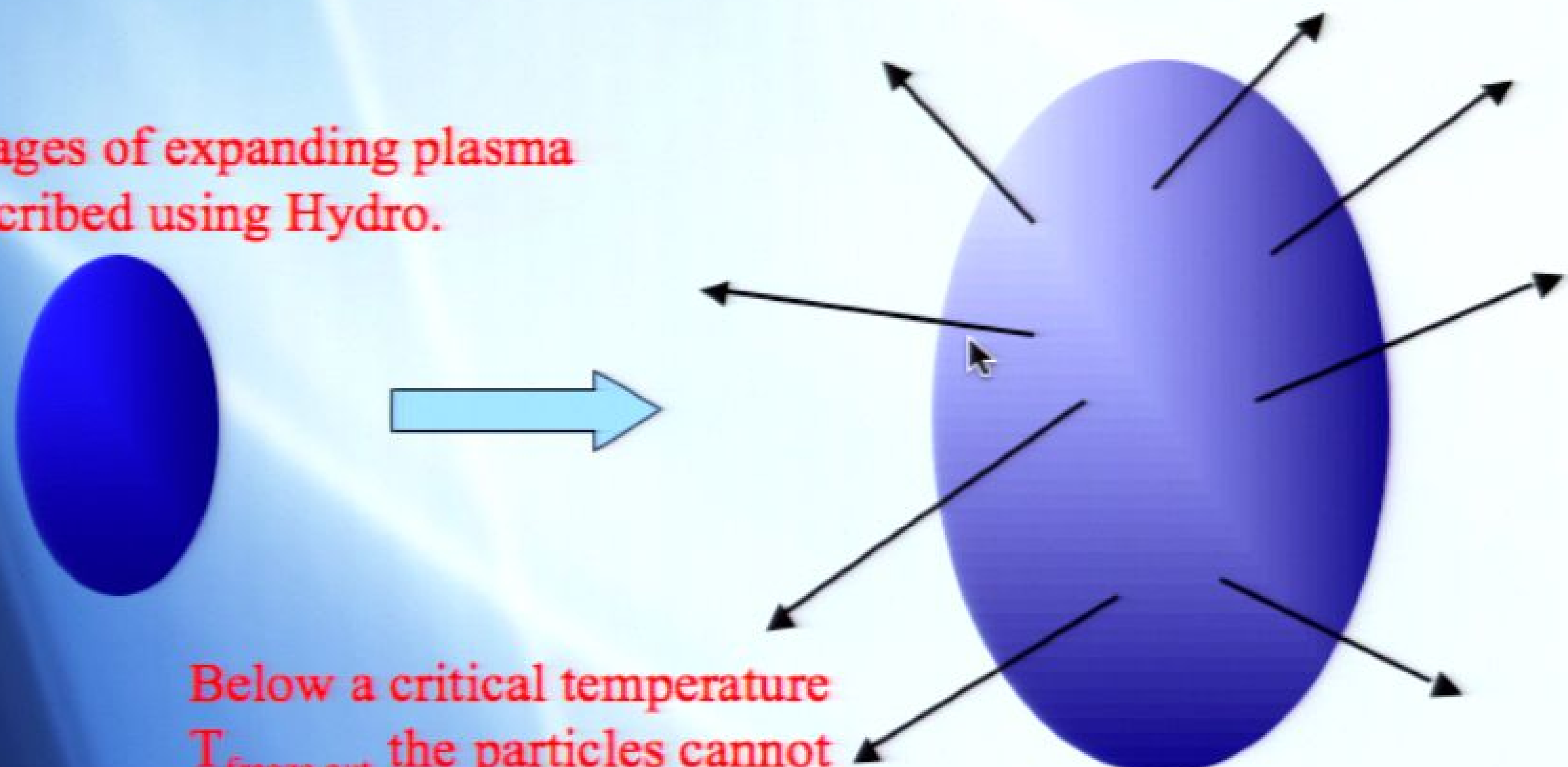
Coupling

Anatomy of RHIC Collision

RHIC and Relativistic Hydrodynamics

- It turns out that the expanding plasma at RHIC can be well described using ***dissipative relativistic hydrodynamics***.

First stages of expanding plasma are described using Hydro.



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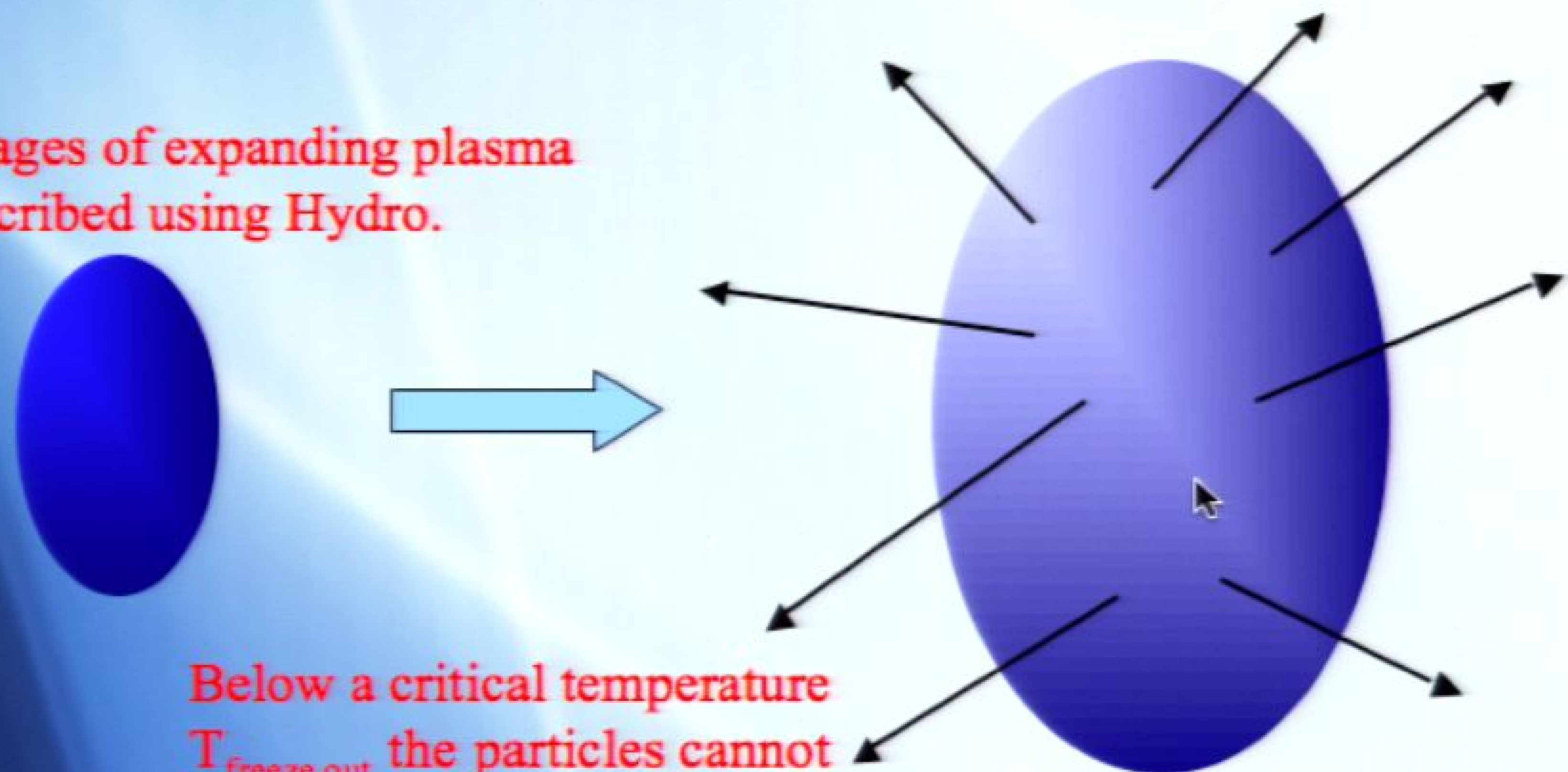

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Can predict particle distribution using end-point of Hydro simulation (Cooper Frye mechanism)

Anatomy of RHIC Collision

Hydrodynamics from String Theory

- Metric perturbation in bulk obeys linearized Einstein's equations.
- Induced stress energy tensor in SYM can be calculated from the asymptotic fall off of the metric as u → 0 (Haro, Skenderis and Solodukhin hep-th/0002230)
- Example: ***String Theory*** predicts (in units of p = 1)

$$\boxed{G^{tx}_{xz}(k) = -\frac{4\tilde{k}\tilde{w}}{2i\tilde{w}+\tilde{k}^2} - \frac{8\tilde{k}\tilde{w}^3}{(2i\tilde{w}+\tilde{k}^2)^2}(1-\log 2)+\cdots}$$

- ***Hydro*** predicts:

$$\tilde{w} = \frac{w}{2\pi T} \qquad \tilde{k} = \frac{k}{2\pi T}$$

$$\boxed{G^{tx}_{xz}(k) = -\frac{2\pi T\eta}{p}\frac{2\tilde{k}\tilde{w}}{2i\tilde{w}+\tilde{k}^2} - \frac{8\tilde{k}\tilde{w}^3}{(2i\tilde{w}+\tilde{k}^2)^2}(2\pi T)\tau_{\Pi}+\cdots}$$

Hydrodynamics from String Theory

- Use AdS/CFT to test equations and measure transport coefficients (relaxation time and shear viscosity).

- Imagine perturbing BH metric $g = g_{BH} + h$.
  - This produces also a perturbation in metric of SYM.
  - Produces perturbation on $T_{\mu\nu}$ in SYM from the homogeneous plasma.
  - Compare from prediction of Hydro theory.

- Look at response of $T_{\mu\nu}$ to metric perturbation around flat space.

$$h_{\mu\nu} = \int d^4k \tilde{h}_{\mu\nu}(k) e^{ik\cdot x}$$

Compare bewteen gravity and Hydro theory

$$\delta\tilde{T}_{\mu\nu}(k) = G^{\alpha\beta}_{\mu\nu}(k)\tilde{h}_{\alpha\beta}(k)$$

Linear response

Hydrodynamics from String Theory

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Hydrodynamics from String Theory

- We see matching and we measure:

$$\boxed{\eta = \frac{p}{\pi T} = \frac{s}{4} \qquad \tau_{\Pi} = \frac{1 - \log 2}{2\pi T}}$$

where $p = \frac{\pi^2}{8} N^2 T^4 \qquad s = \frac{\partial p}{\partial T}$

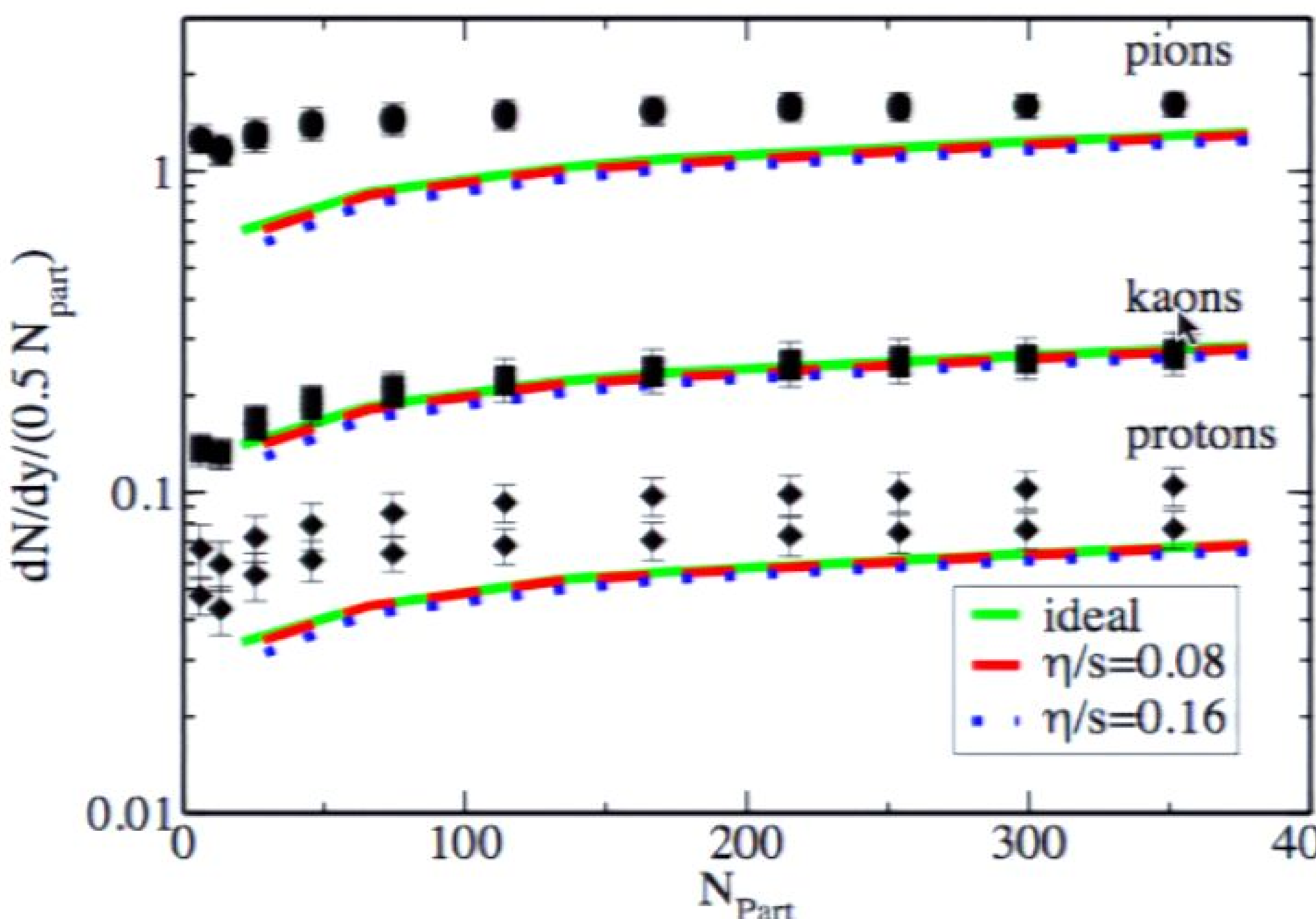
First measured by Policastro, Starinets and Son hep-th/0104066

•Conjectured to be lowest possible value of η/s for any gauge theory.

- How close to QCD??

Hydrodynamics from String Theory

- Fits to data using Hydro theory (Romatschke and Romatschke 0706.1522 [nucl-th]) (η/s for SYM is 0.25)

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