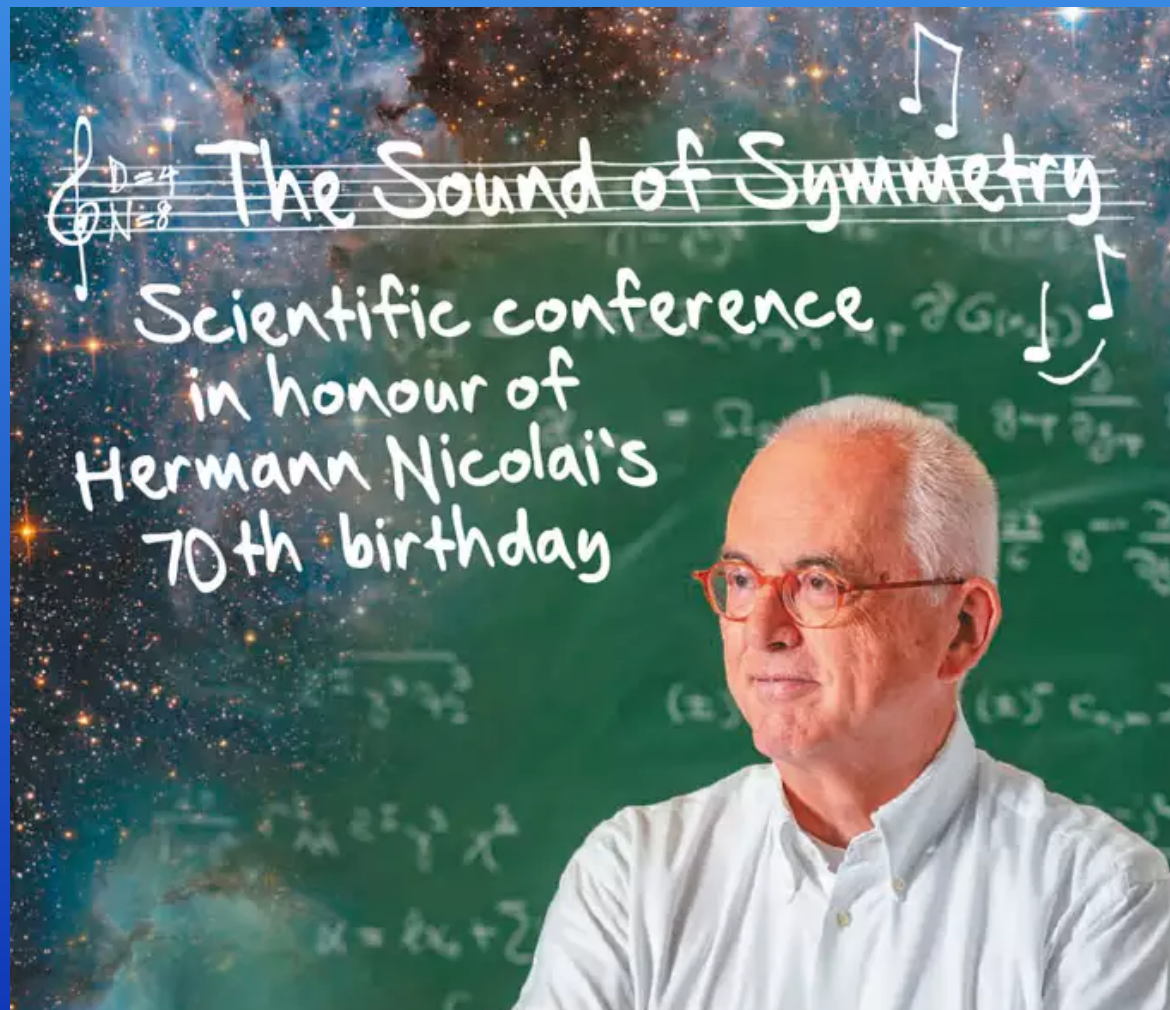
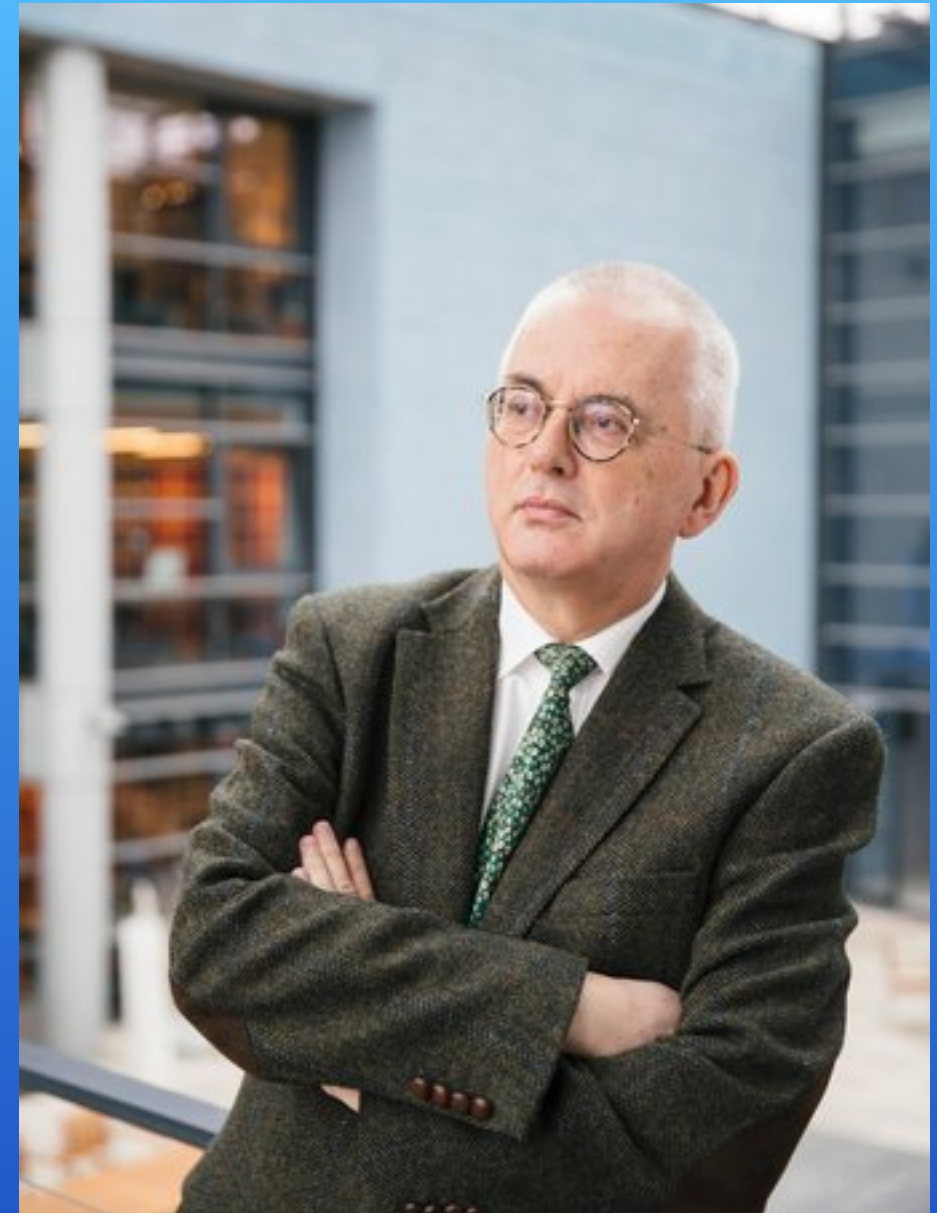


Gauged Supergravity and Black-Hole Microstructure

HermannFest



Friday September 15, 2022



Nick Warner

Research supported
supported in part by:
ERC Grant number: 787320 -
QBH Structure and DOE
grant DE- SC0011687



European Research Council
Established by the European Commission

Gauged Supergravity

Nuclear Physics B208 (1982) 323–364
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$N = 8$ SUPERGRAVITY

B. DE WIT

NIKHEF-H, Amsterdam, The Netherlands

H. NICOLAI

CERN, Geneva, Switzerland

Received 27 May 1982

The complete structure of $N = 8$ supergravity is presented with an optional local $SO(8)$ invariance. The $SO(8)$ gauge interactions break E_7 invariance, but leave the local $SU(8)$ unaffected. Exploiting $E_7 \times SU(8)$ invariance and using explicit lowest order results, we first derive the complete action and transformation laws. Subsequently, we introduce local $SO(8)$ invariance and prove the consistency of the theory. Possible implications of our results are discussed.

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Bernard's bad influence:

To establish our notation and for the purpose of convenience we list a number of γ -matrix identities, as well as some relations for self-dual tensors. We use local Lorentz indices $a, b, \dots = 1, \dots, 4$, and the Pauli metric $\eta^{ab} = \text{diag}(+, +, +, +)$. All our results

Gauged Supergravity

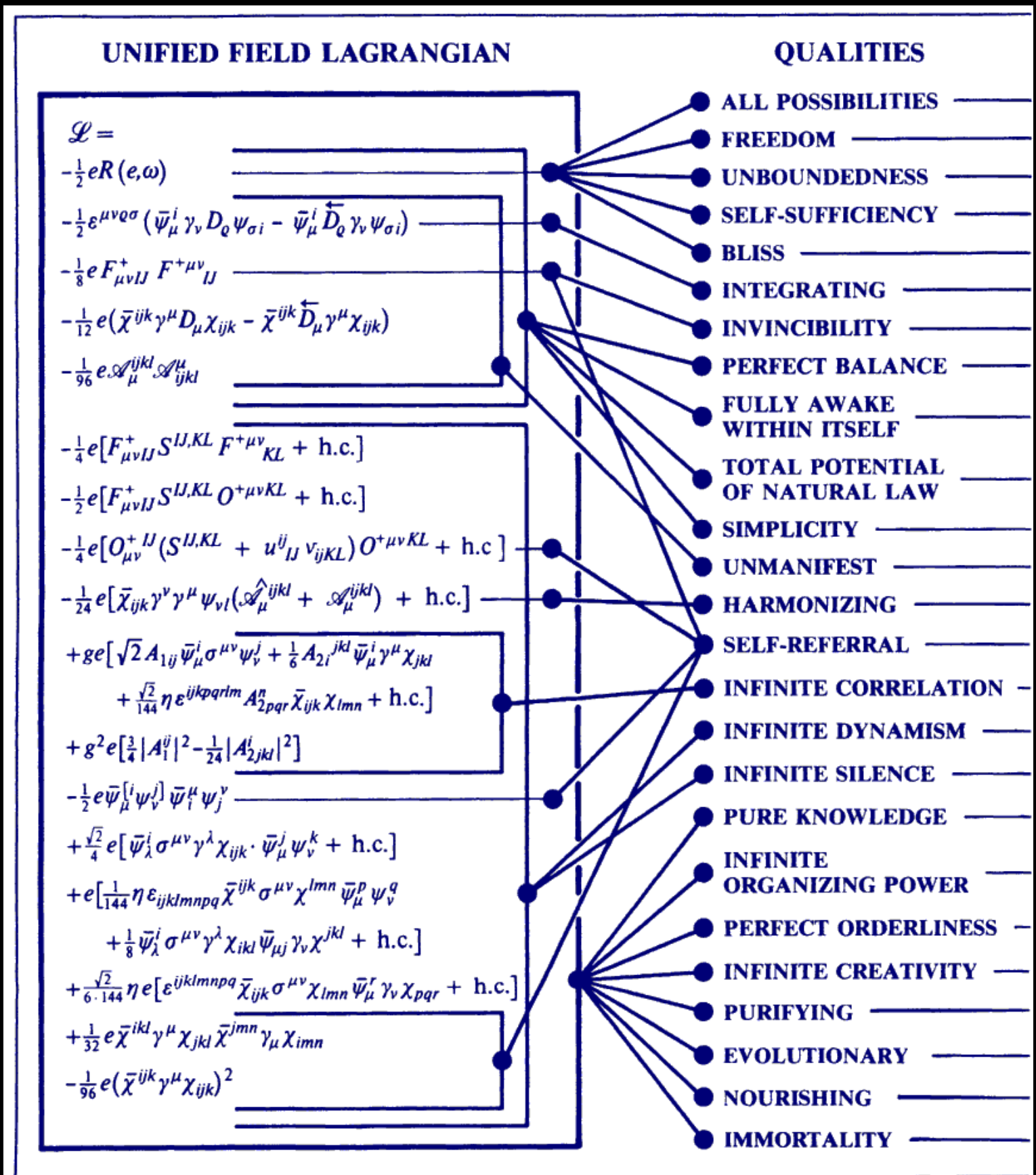


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Gauged Supergravity

GAUGED $N = 8$ SUPERGRAVITY AND ITS BREAKING FROM SPONTANEOUS COMPACTIFICATION

B. BIRAN¹, F. ENGLERT

Faculté des Sciences, Université Libre de Bruxelles², Brussels, Belgium

B. de WIT

NIKHEF-H, Amsterdam, The Netherlands

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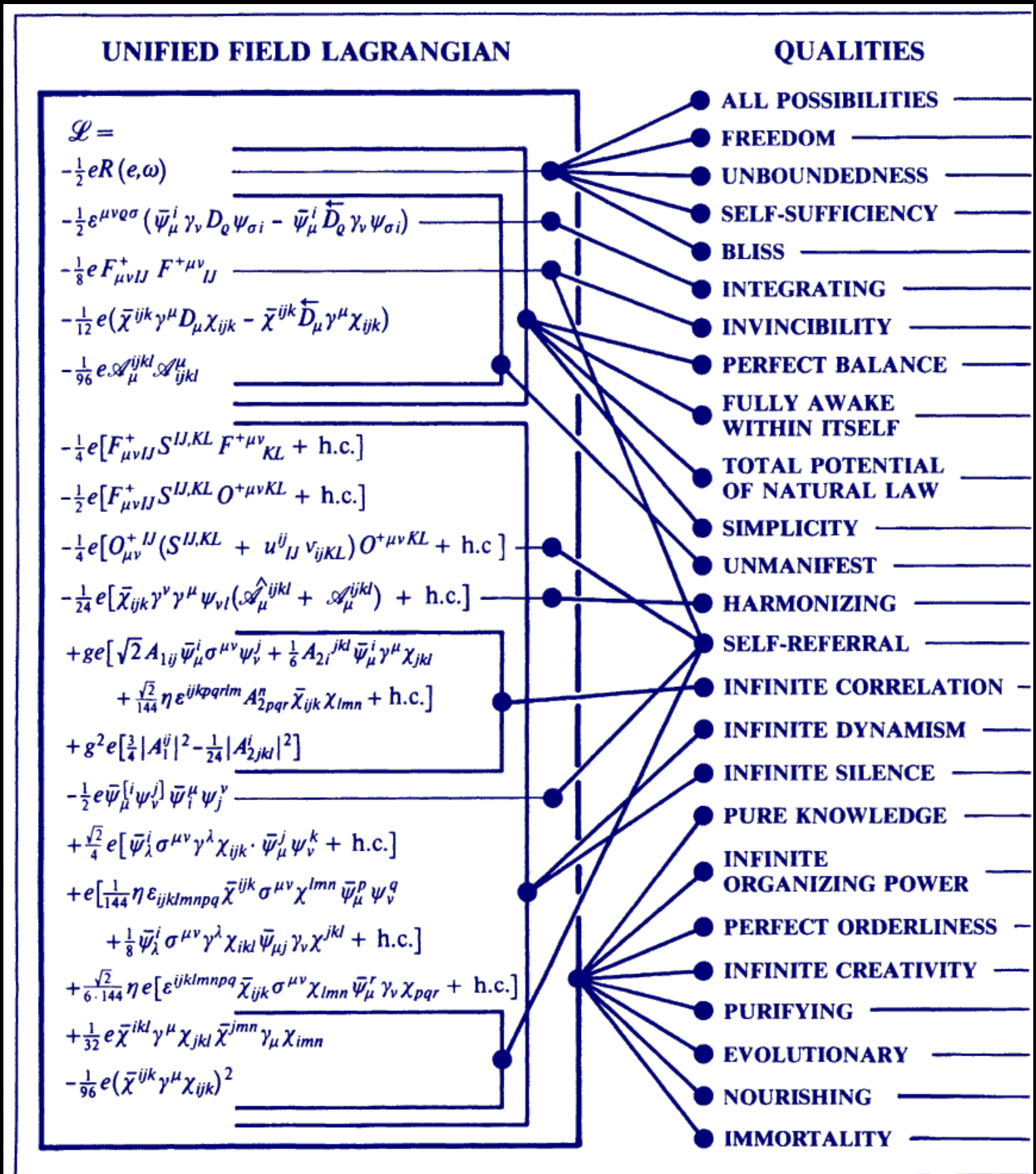


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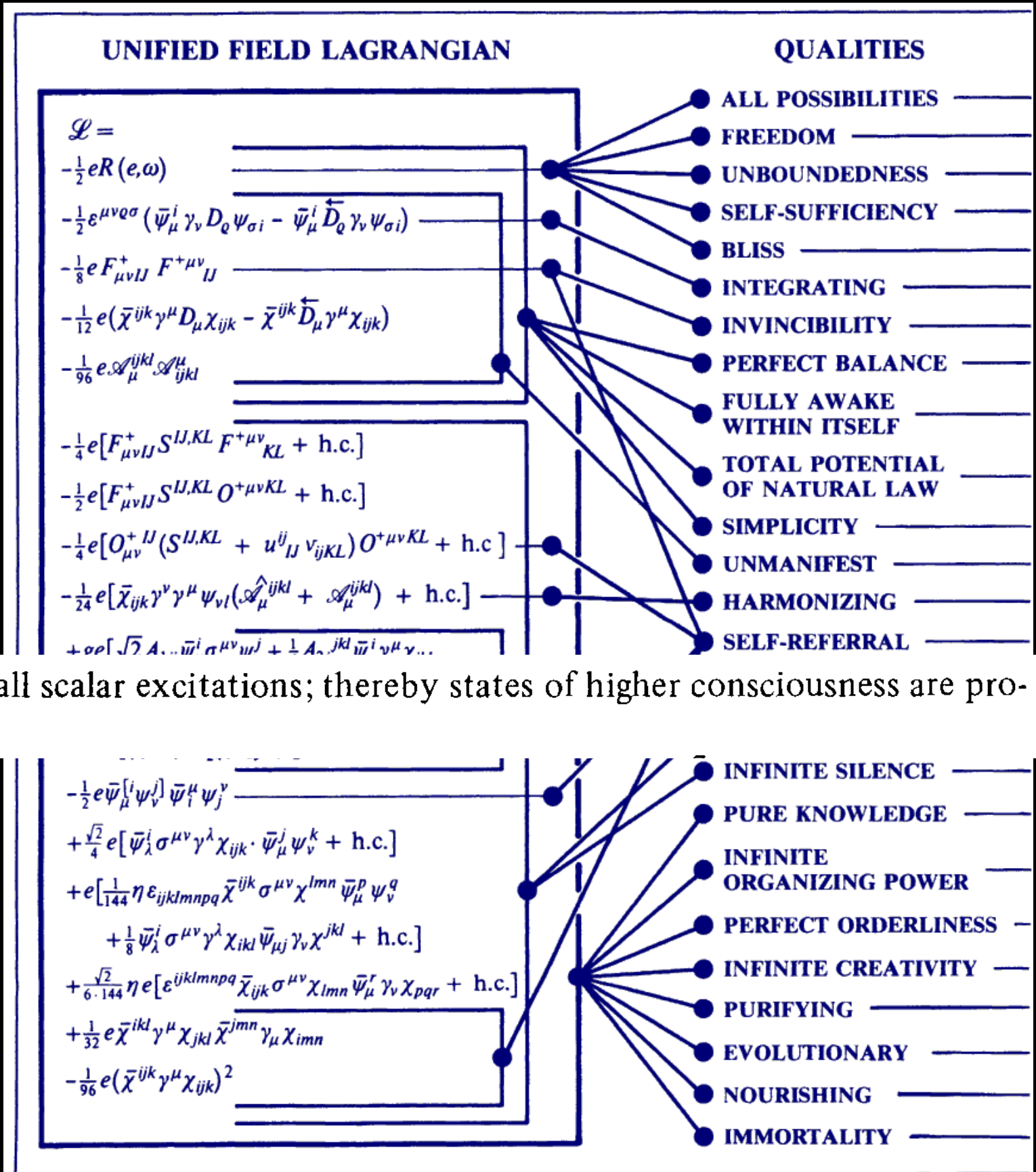


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Gauged supergravity, symmetry breaking and dimensional reduction

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THE $SU(3) \times U(1)$ INVARIANT BREAKING OF GAUGED $N=8$ SUPERGRAVITY

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Commun. Math. Phys. 125, 369–384 (1989)

**Communications in
Mathematical
Physics**

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The Structure Of $N=16$ Supergravity in Two Dimensions

H. Nicolai¹ and N. P. Warner²★

¹ II. Institut für Theoretische Physik, Universität Hamburg, D-2000 Hamburg 50, Federal Republic of Germany

² CERN, CH-1211 Geneva 23, Switzerland

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THE EMBEDDING OF GAUGED $N=8$ SUPERGRAVITY INTO $d=11$ SUPERGRAVITY

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Institute for Theoretical Physics, University of Utrecht, Utrecht, The Netherlands

H. NICOLAI

CERN, Geneva, Switzerland

N.P. WARNER*

California Institute of Technology, Pasadena, CA 91125, USA

Received 11 December 1984

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Nicolai¹ and N. P. Warner^{2*}

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²CERN, CH-1211 Geneva 23, Switzerland

Gauged supergravity in five dimensions

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North-Holland, Amsterdam

COMPACT AND NON-COMPACT GAUGED SUPERGRAVITY THEORIES IN FIVE DIMENSIONS*

M. GÜNAYDIN

*University of California, Lawrence Livermore Laboratory, Livermore, CA 94450, USA and
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L.J. ROMANS¹ and N.P. WARNER²

California Institute of Technology, Pasadena, CA 91125, USA

Received 3 December 1985

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The Faustian Bargain of Consistent Truncations

Miracles of gauged supergravity and consistent truncations on spheres

Dynamics in low dimensions is very, very much simpler: *uplift 10 or 11 dimensions is often very complicated....*

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Scalars in low dimensions encode:

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However:

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⇒ *The lower-dimensional consistent truncation may only capture a limited sector of the essential physics*

Early 2000's: Gauged Supergravity in Three Dimensions

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Maximal gauged supergravity in three-dimensions

H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Ecole Normale Superieure) (Oct, 2000)

Published in: *Phys.Rev.Lett.* 86 (2001) 1686-1689 • e-Print: [hep-th/0010076](#) [hep-th]

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Compact and noncompact gauged maximal supergravities in three-dimensions

H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Ecole Normale Superieure) (Mar, 2001)

Published in: *JHEP* 04 (2001) 022 • e-Print: [hep-th/0103032](#) [hep-th]

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N=8 matter coupled AdS(3) supergravities

H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Ecole Normale Superieure) (Jun, 2001)

Published in: *Phys.Lett.B* 514 (2001) 165-172 • e-Print: [hep-th/0106153](#) [hep-th]

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Vacua of maximal gauged D = 3 supergravities

T. Fischbacher (Potsdam, Max Planck Inst.), H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Utrecht U.) (Jul, 2002)

Published in: *Class.Quant.Grav.* 19 (2002) 5297-5334 • e-Print: [hep-th/0207206](#) [hep-th]

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Gauged supergravities in three-dimensions: A Panoramic overview

B. de Wit (Utrecht U.), H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Hamburg U., Inst. Theor. Phys. II) (2003)

Published in: *PoS jhw2003* (2003) 016, *PoS jhw2003* (2003) 018 • Contribution to: [27th Johns Hopkins Workshop on Current Problems in Particle Theory](#), [27th Johns Hopkins Workshop on Current Problems in Particle Theory](#), 016, [27th Johns Hopkins Workshop on Current Problems in Particle Theory](#), 018 • e-Print: [hep-th/0403014](#) [hep-th]

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Chern-Simons versus Yang-Mills gaugings in three-dimensions

Hermann Nicolai (Potsdam, Max Planck Inst.), Henning Samtleben (Utrecht U.) (Mar, 2003)

Published in: *Nucl.Phys.B* 668 (2003) 167-178 • e-Print: [hep-th/0303213](#) [hep-th]

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Kaluza-Klein supergravity on AdS(3) x S**3

Hermann Nicolai (Potsdam, Max Planck Inst.), Henning Samtleben (Utrecht U.) (Jun, 2003)

Published in: *JHEP* 09 (2003) 036 • e-Print: [hep-th/0306202](#) [hep-th]

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An effective field theory description for Kaluza-Klein supergravity on AdS(3) x S**3

H. Nicolai (Potsdam, Max Planck Inst.), H. Samtleben (Hamburg U.) (Apr, 2004)

Contribution to: [Deserfest: A Celebration of the Life and Works of Stanley Deser](#), 217-232

 cite  claim

Uplifting to Six Dimensions

M. Cvetič, H. Lu, and C. Pope, “Consistent Kaluza-Klein sphere reductions,” Phys. Rev. D 62 (2000) 064028, arXiv:hep-th/0003286.

M. Cvetič, H. Lu, and C. Pope, “Consistent sphere reductions and universality of the Coulomb branch in the domain wall / QFT correspondence,” Nucl. Phys. B 590 (2000) 213–232, arXiv:hep-th/0004201.

M. Cvetič, H. Lu, C. Pope, A. Sadrzadeh, and T. A. Tran, “S³ and S⁴ reductions of type IIA supergravity,” Nucl. Phys. B 590 (2000) 233–251, arXiv:hep-th/0005137.

N. S. Deger, H. Samtleben, O. Sarioğlu, and D. Van den Bleeken, “A supersymmetric reduction on the three-sphere,” Nucl. Phys. B 890 (2014) 350–362, arXiv:1410.7168 [hep-th].

H. Samtleben and O. Sarioğlu, “Consistent S³ reductions of six-dimensional supergravity,” Phys. Rev. D 100 no. 8, (2019) 086002, arXiv:1907.08413 [hep-th].

Early 2020's: Gauged Supergravity in Three Dimensions

Microstate Geometries from Gauged Supergravity in Three Dimensions

#13

[Daniel R. Mayerson](#) (IPhT, Saclay), [Robert A. Walker](#) (IPhT, Saclay and Stanford U., Phys. Dept.), [Nicholas P. Warner](#) (IPhT, Saclay and Stanford U., Phys. Dept. and Southern California U.) (Apr 27, 2020)

Published in: *JHEP* 10 (2020) 030 • e-Print: [2004.13031](#) [hep-th]

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Supersymmetry and superstrata in three dimensions

[Anthony Houppe](#) (IPhT, Saclay), [Nicholas P. Warner](#) (IPhT, Saclay and Southern California U.) (Dec 14, 2020)

Published in: *JHEP* 08 (2021) 133 • e-Print: [2012.07850](#) [hep-th]

New superstrata from three-dimensional supergravity

#6

[Bogdan Ganchev](#) (IPhT, Saclay), [Anthony Houppe](#) (IPhT, Saclay), [Nicholas P. Warner](#) (IPhT, Saclay and Southern California U.) (Oct 6, 2021)

Published in: *JHEP* 04 (2022) 065 • e-Print: [2110.02961](#) [hep-th]

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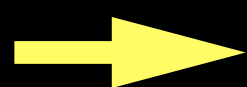
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The three-dimensional gauged supergravity needed for black-hole microstructure: requires hypermultiplet scalars

Complete with **new** uplift formulae for:

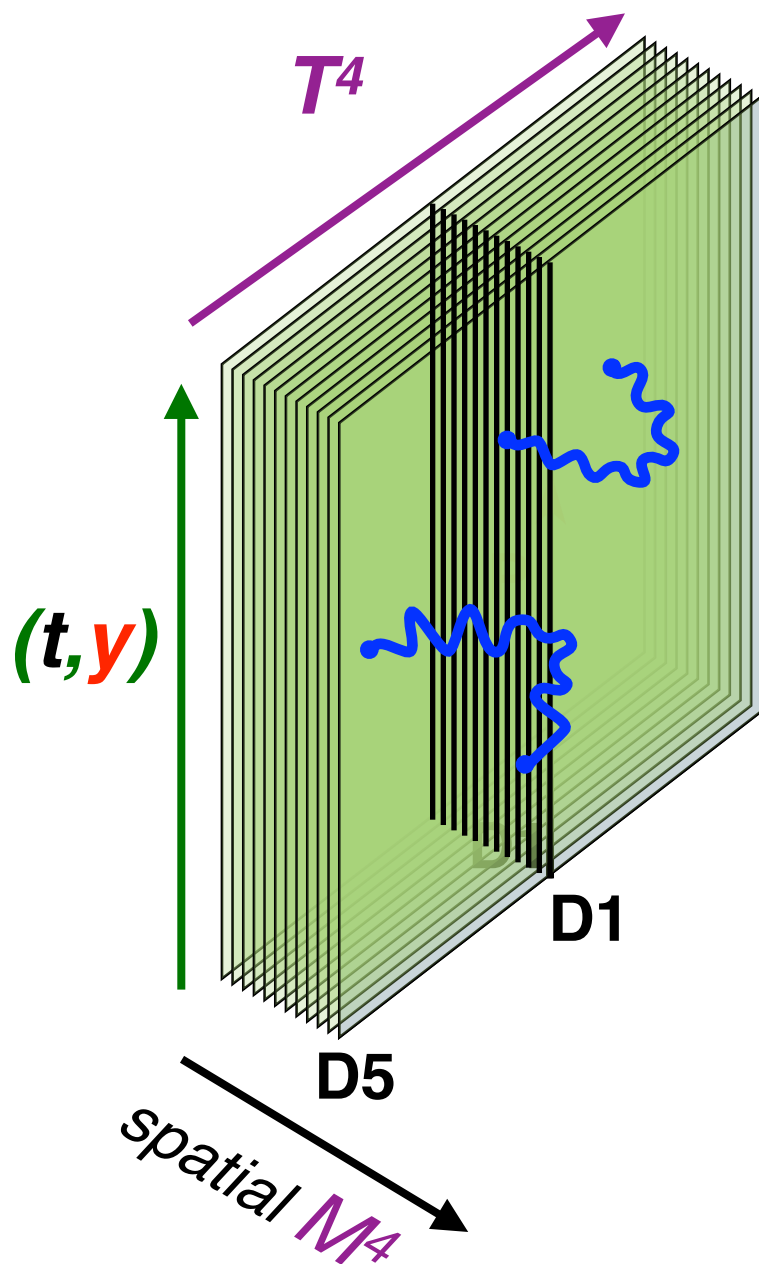
Three-dimensional hypermultiplets



Six-dimensional tensor gauge fields

Black-Hole Microstructure

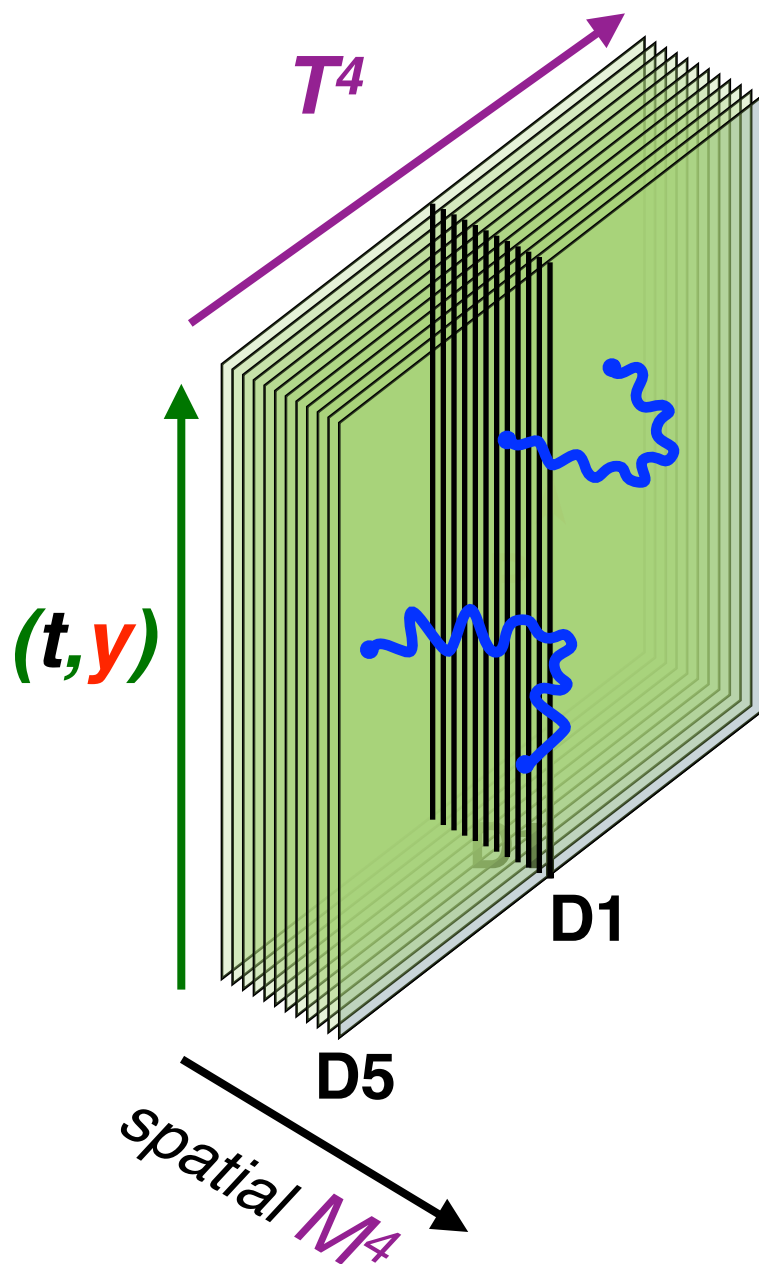
The D1-D5 system wrapped on $T^4 \times S^1(y)$



D5 branes wrapped on $T^4 \times S^1(y)$

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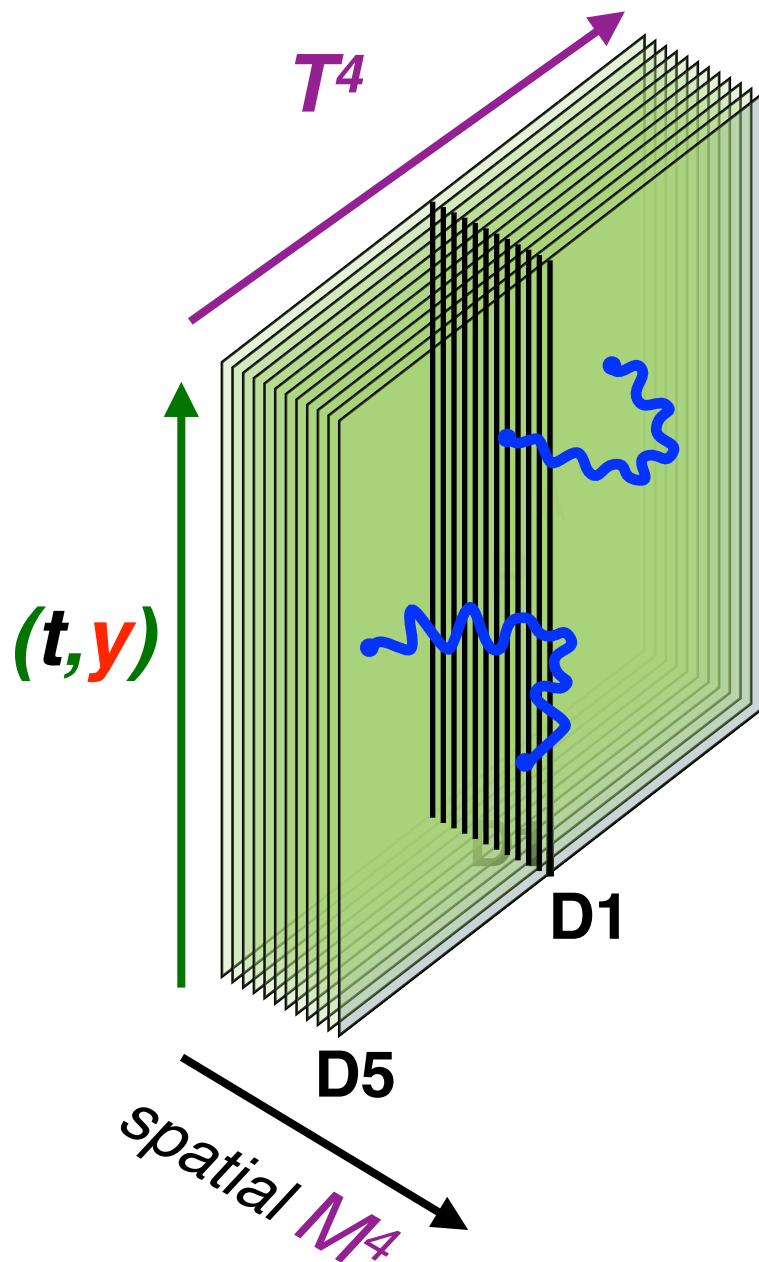


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32 supersymmetries $\Rightarrow$ 8 supersymmetries

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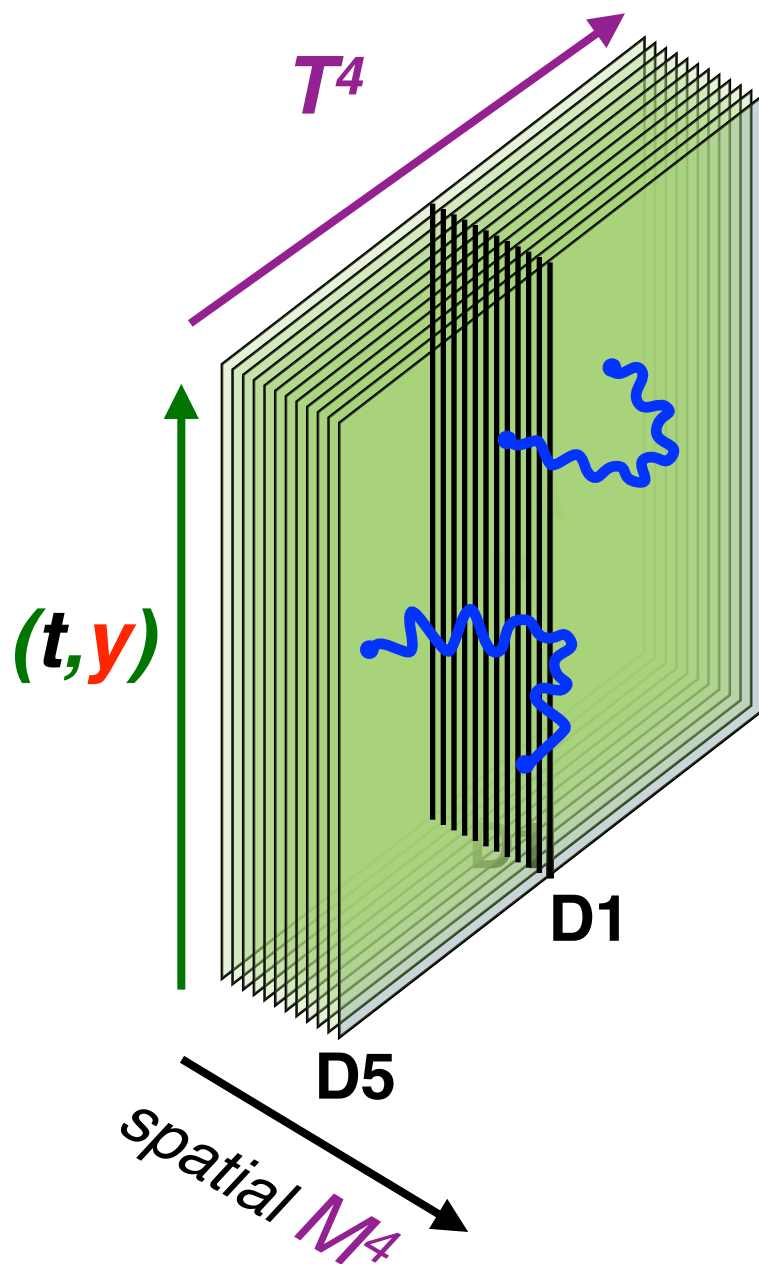
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Open D1-D5 superstrings moving in T^4
with $\mathbf{N} \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^{\mathbf{N}}/S_{\mathbf{N}}$

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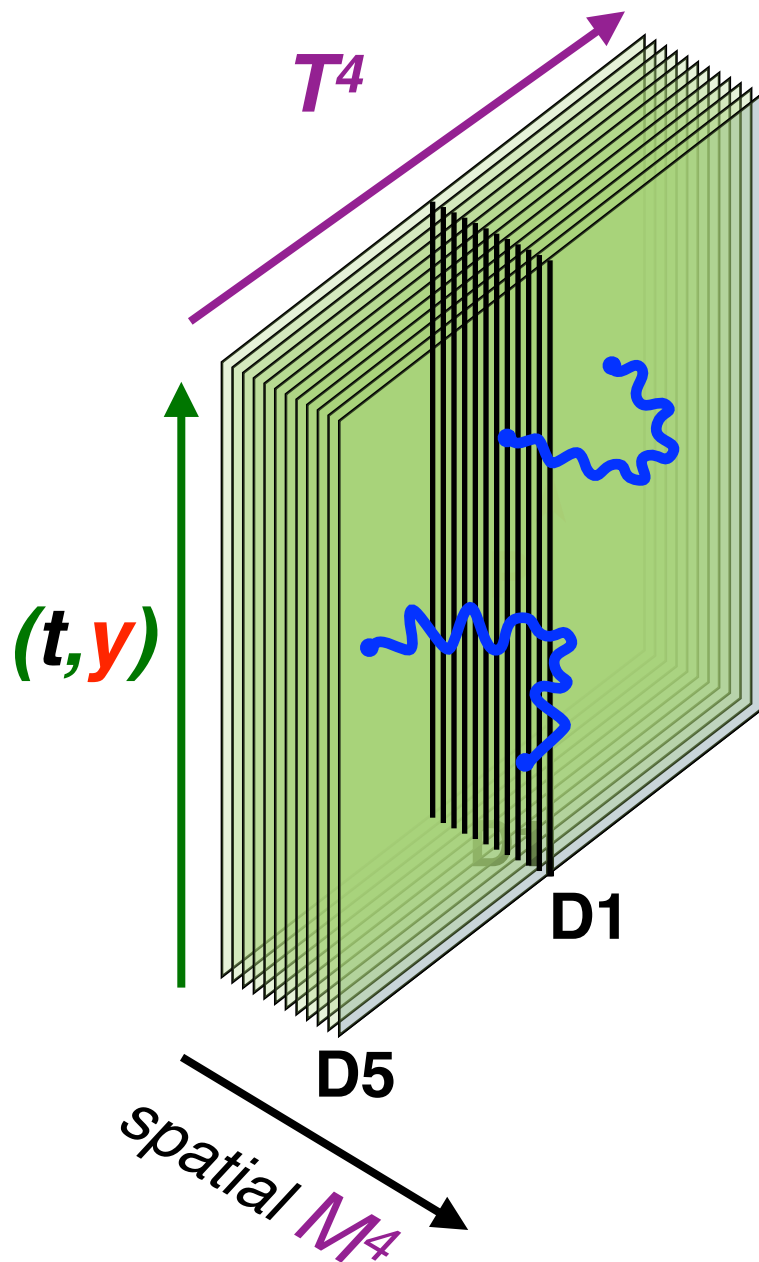
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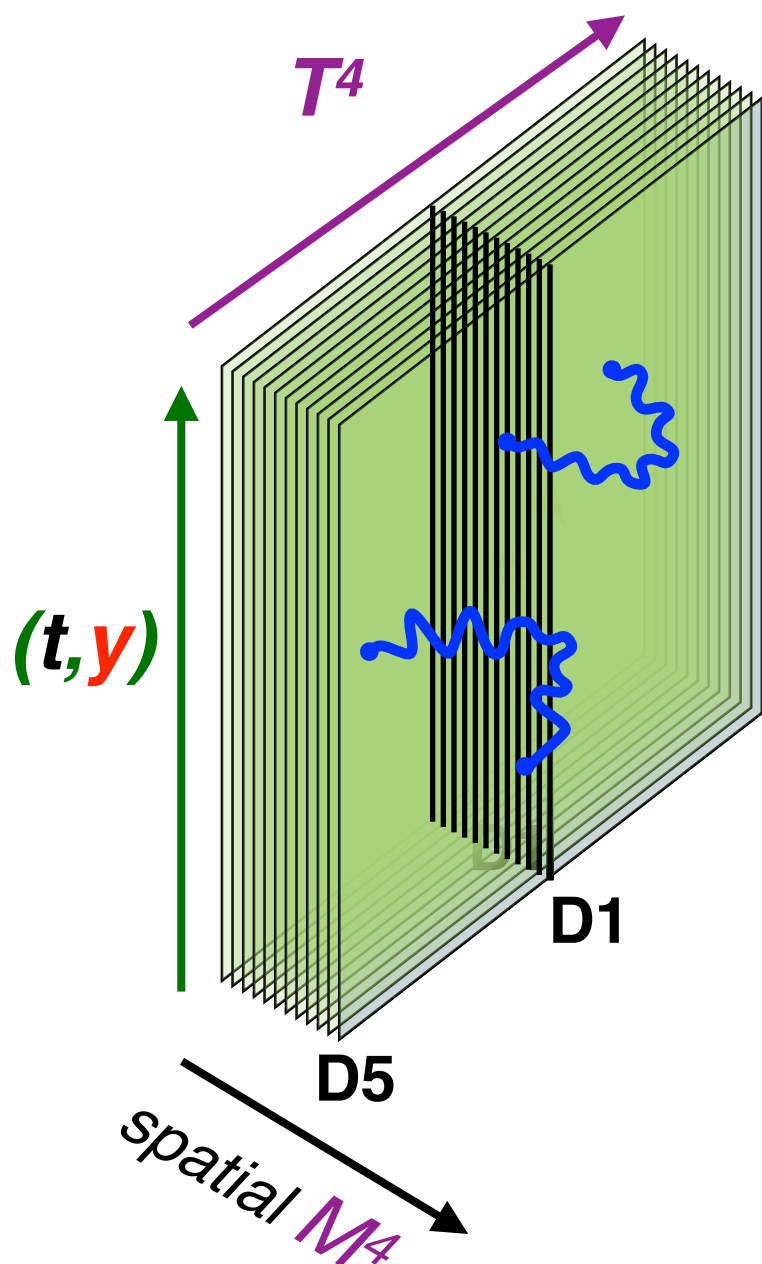
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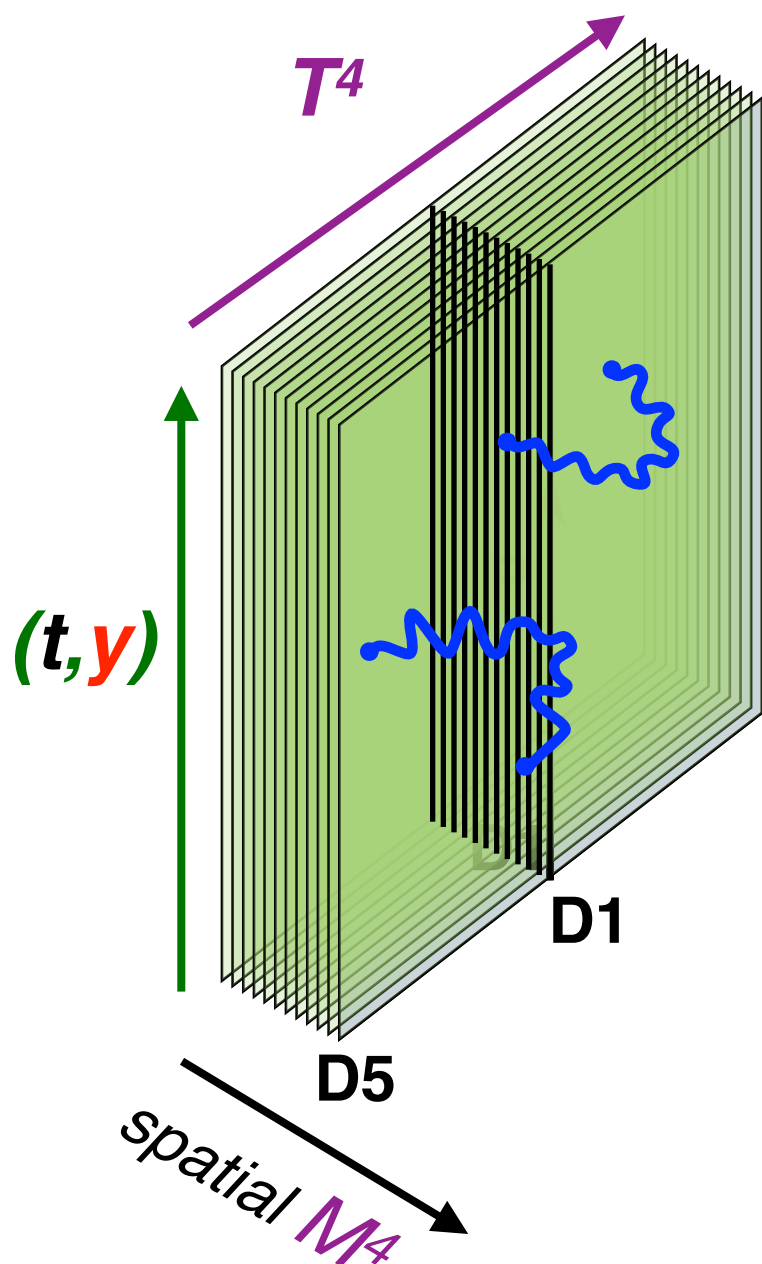
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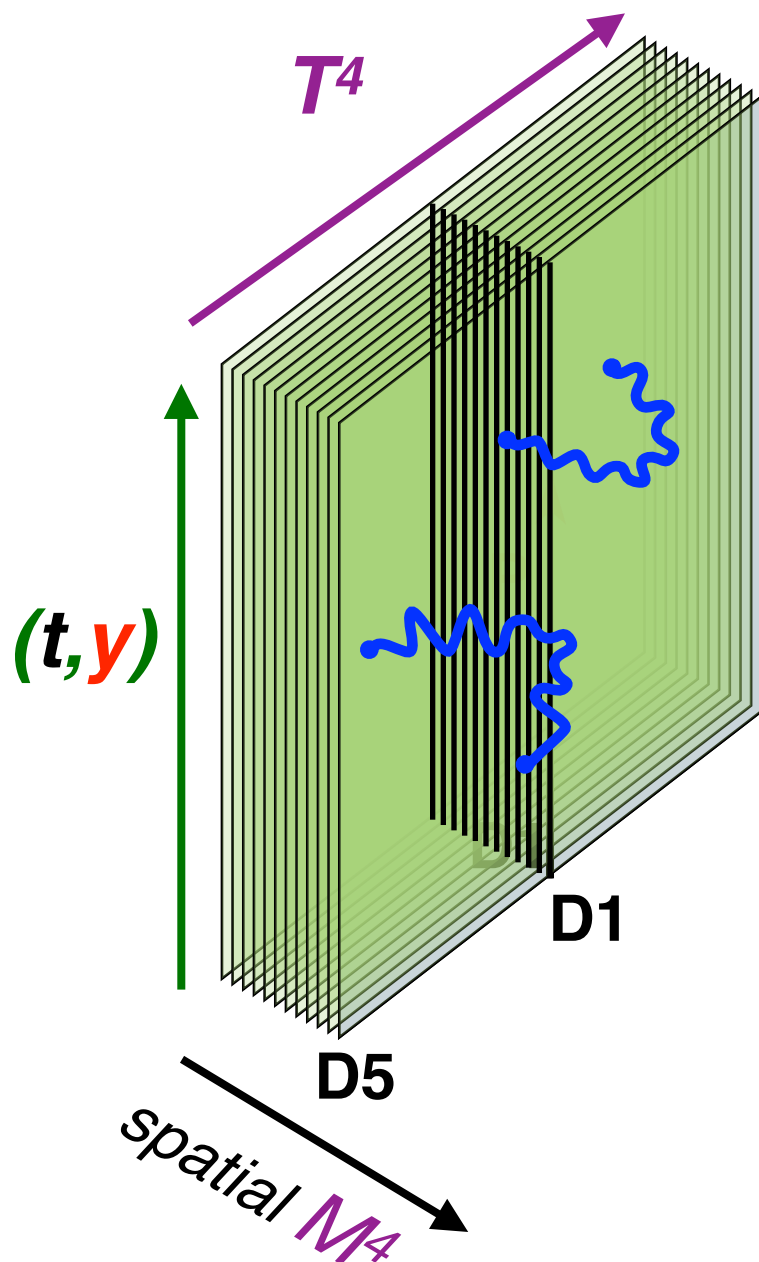
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D1 + D5 branes source generic $C_{\mu\nu}$ in 10 dimensions

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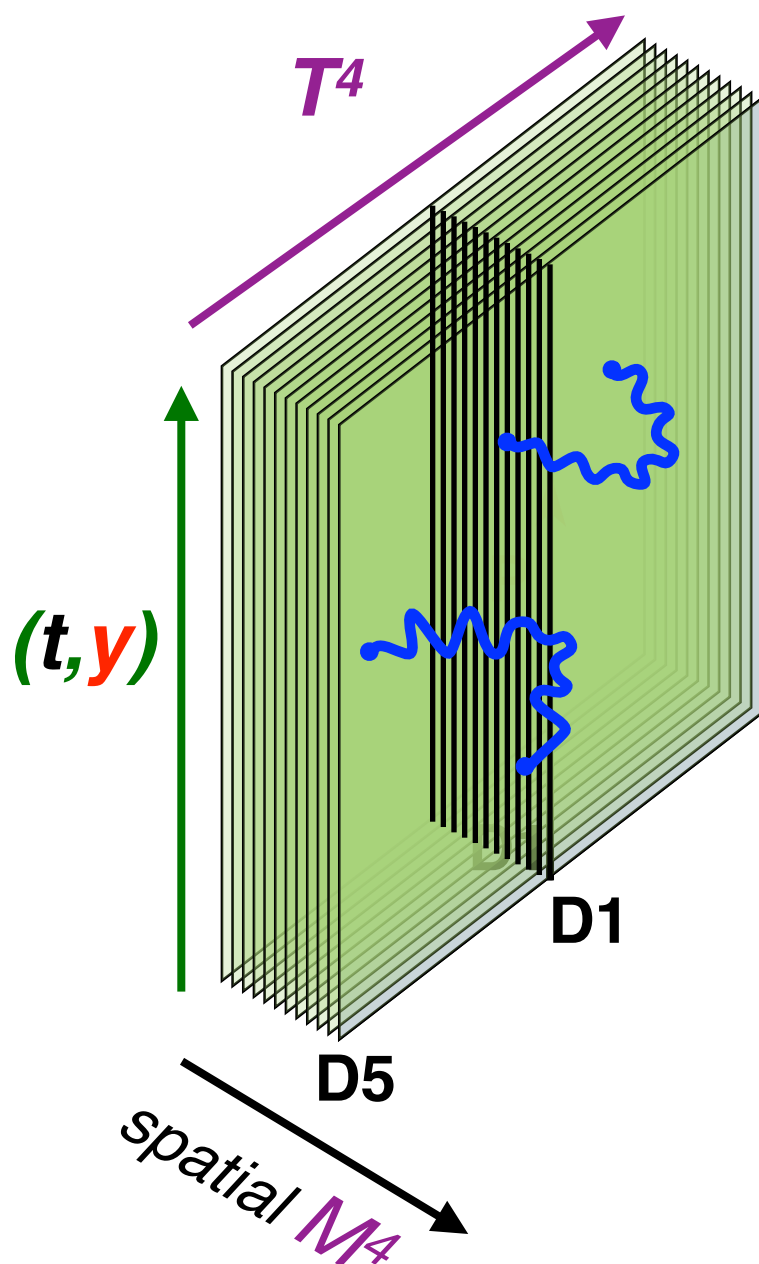
$\Rightarrow$ *Six-dimensional (1,0) supergravity*

+ what matter multiplets?

D1 + D5 branes source generic $C_{\mu\nu}$ in 10 dimensions

... coherent open string excitations source $B_{\mu\nu}$

The D1-D5 system wrapped on $T^4 \times S^1(y)$



D5 branes wrapped on $T^4 \times S^1(y)$

D1 branes wrapped on $S^1(y)$

32 supersymmetries $\Rightarrow$ 8 supersymmetries

Open D1-D5 superstrings moving in T^4
with $\mathbf{N} \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^{\mathbf{N}}/S_{\mathbf{N}}$

Dual Supersymmetric CFT with
(4,4) supersymmetry and $c = 6 \mathbf{N} = 6 N_1 N_5$

First Compactification: Reduce on the T^4

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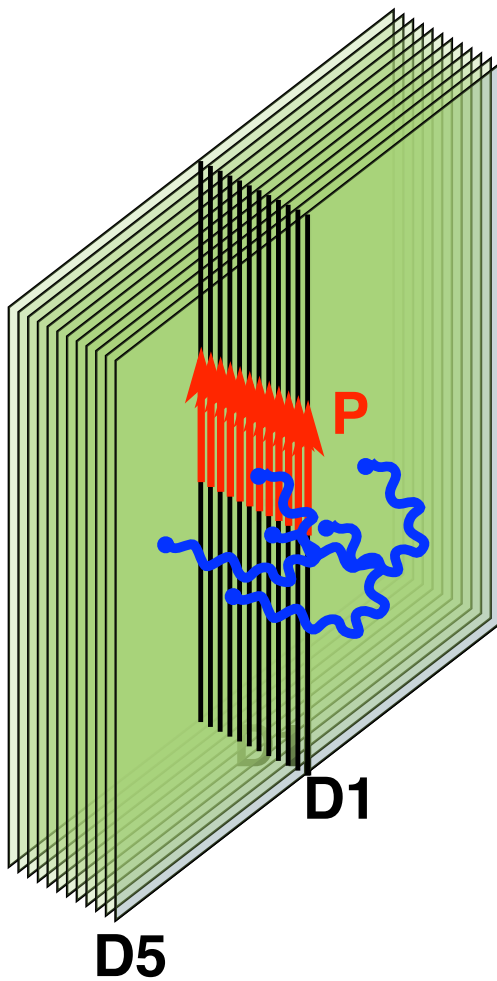
Supersymmetric Microstructure: Momentum Excitations

Add purely **left-moving** momentum:

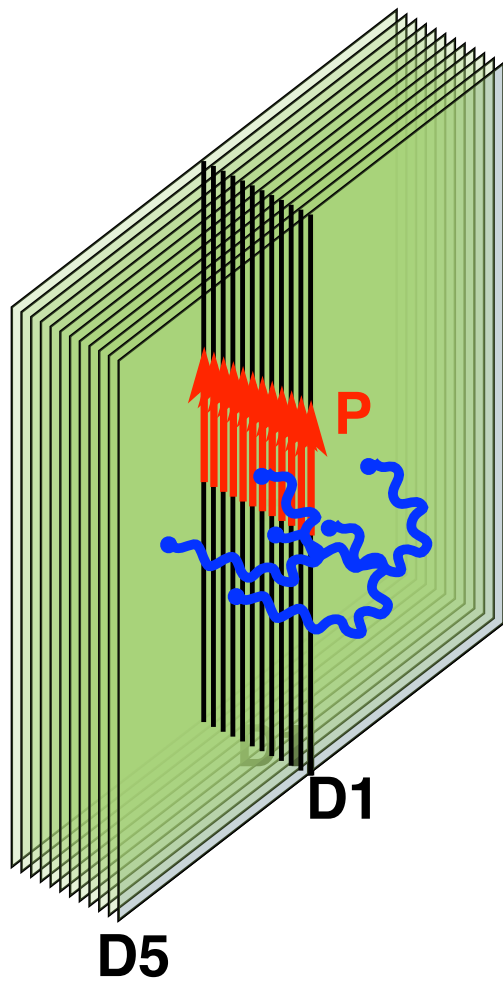
$$Q_P \sim N_P = L_{0,\text{left}} \neq 0$$

Right moving sector: **Ramond ground state**

$\Rightarrow$ **$1/8$** BPS states



Supersymmetric Microstructure: Momentum Excitations



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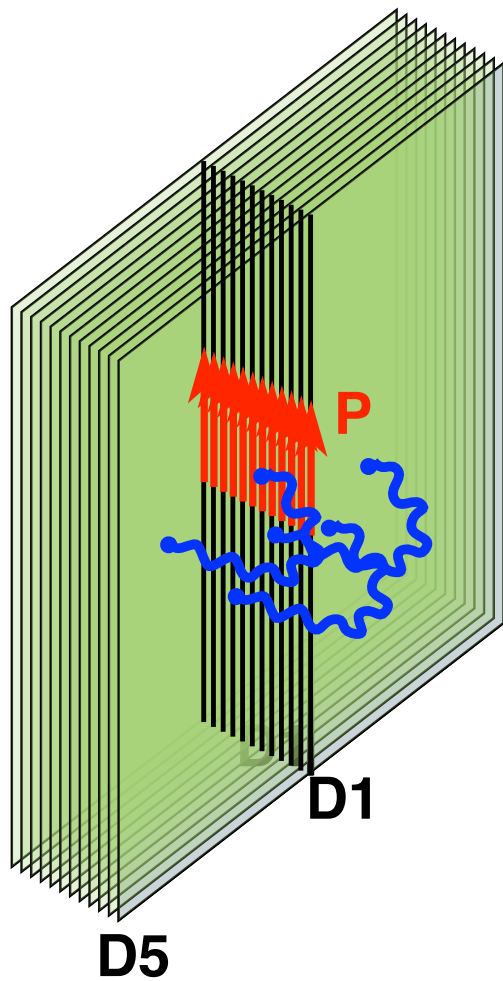
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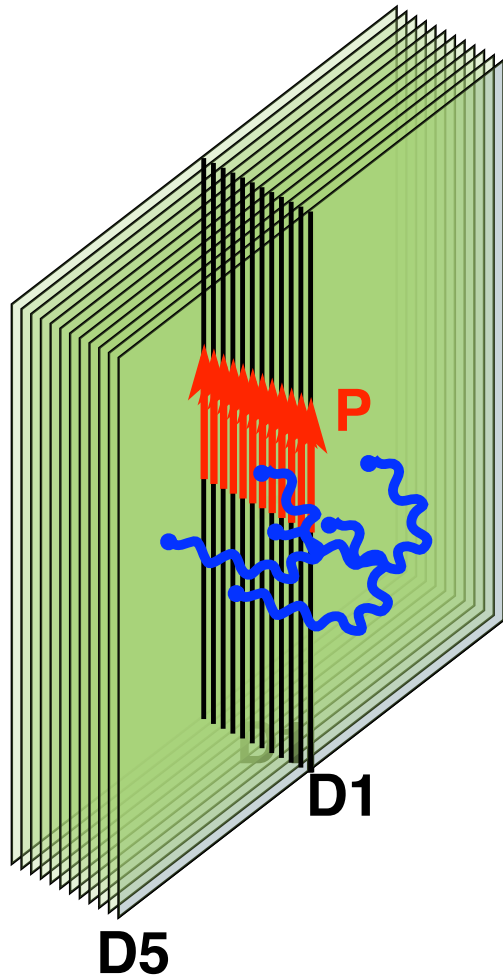
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Back-reacted geometry + *imposing spherical symmetry*

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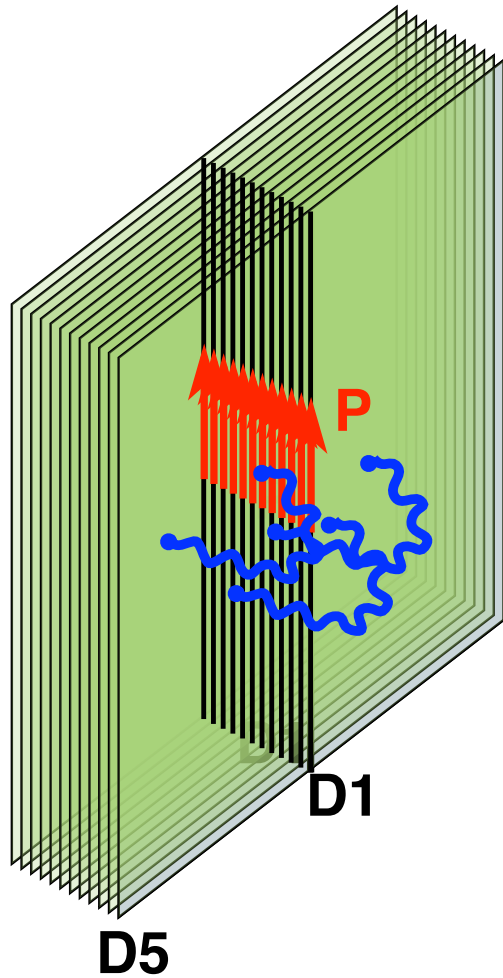
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Strominger, Vafa 1996 Perfect match! Declare victory

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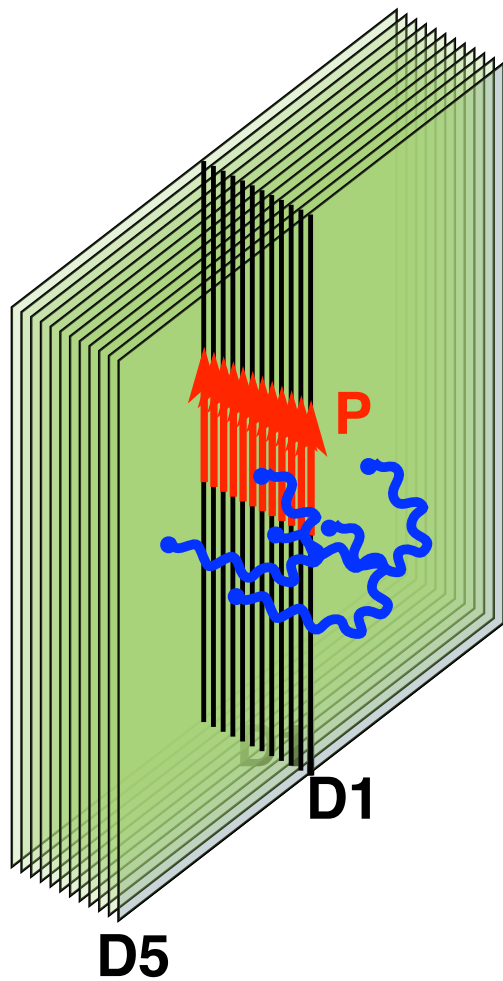
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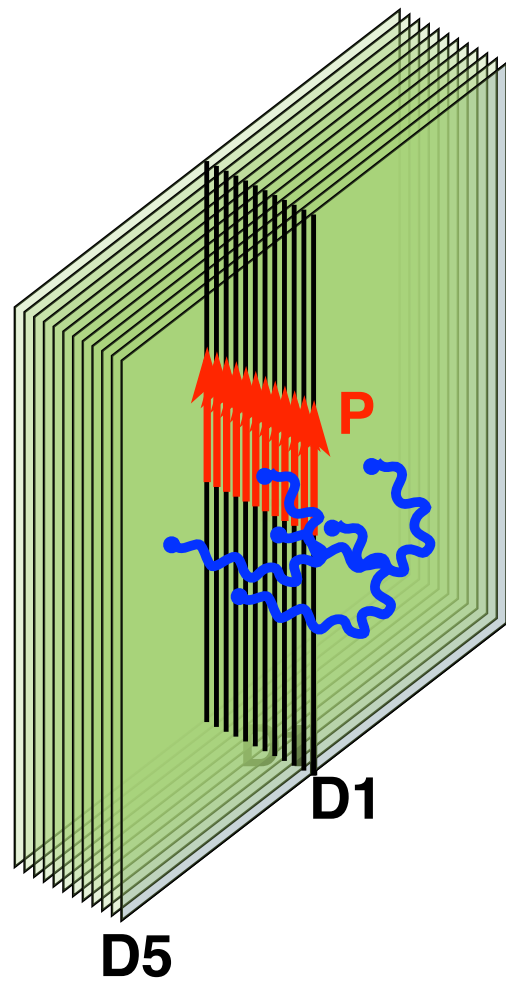
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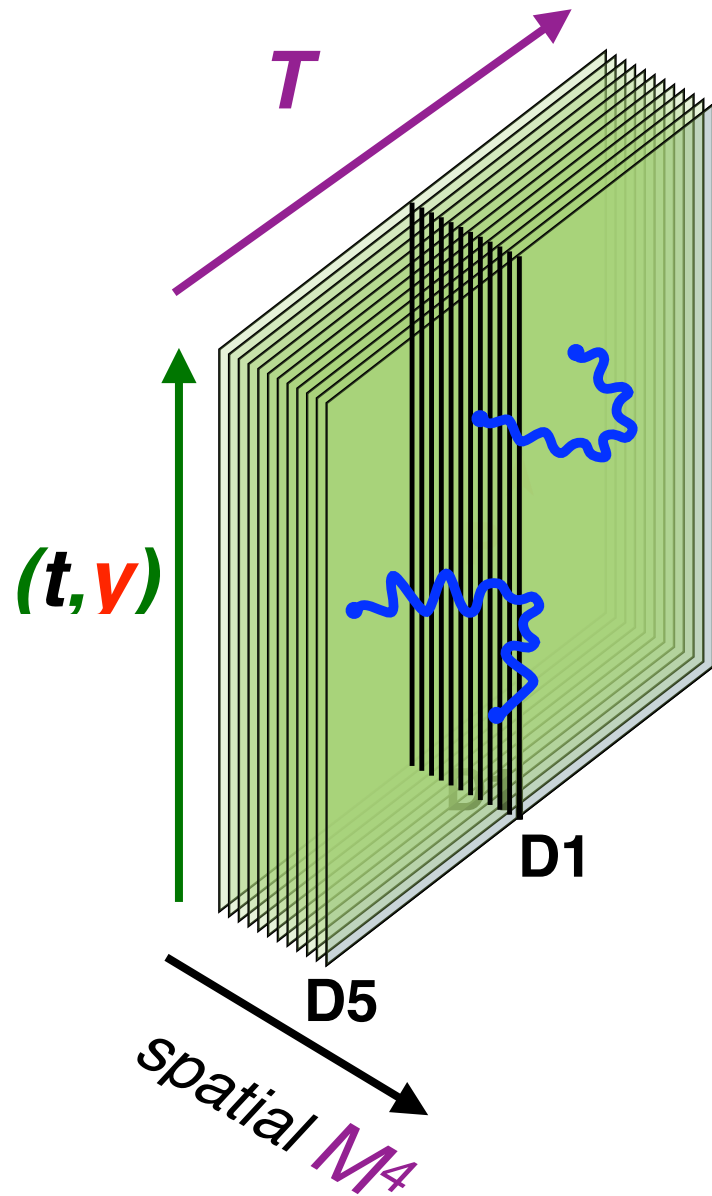
Coherent states of open strings carrying **left-moving** momentum

$\Rightarrow$ **Six-dimensional (1,0) supergravity** coupled to **anti-self-dual tensor multiplets**.

The Emergence of Three-Dimensional Gauged Supergravity

D5 branes wrapped on $T^4 \times S^1(y)$

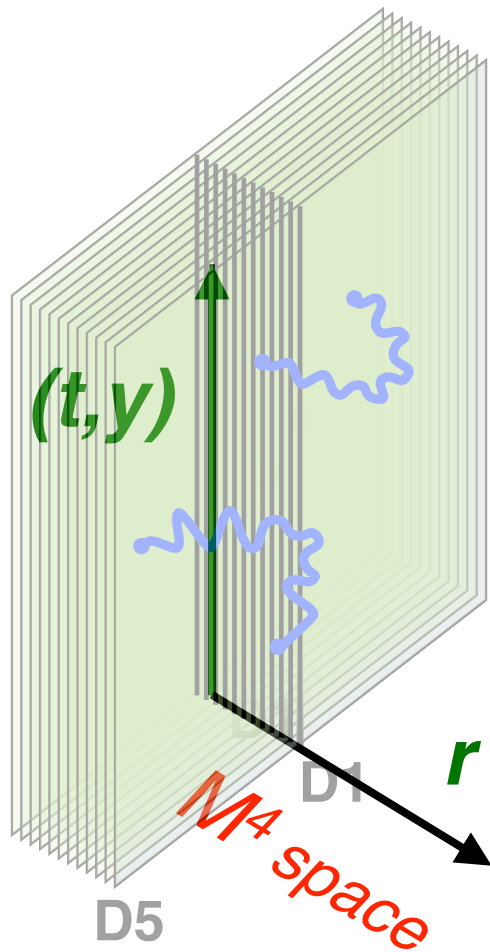
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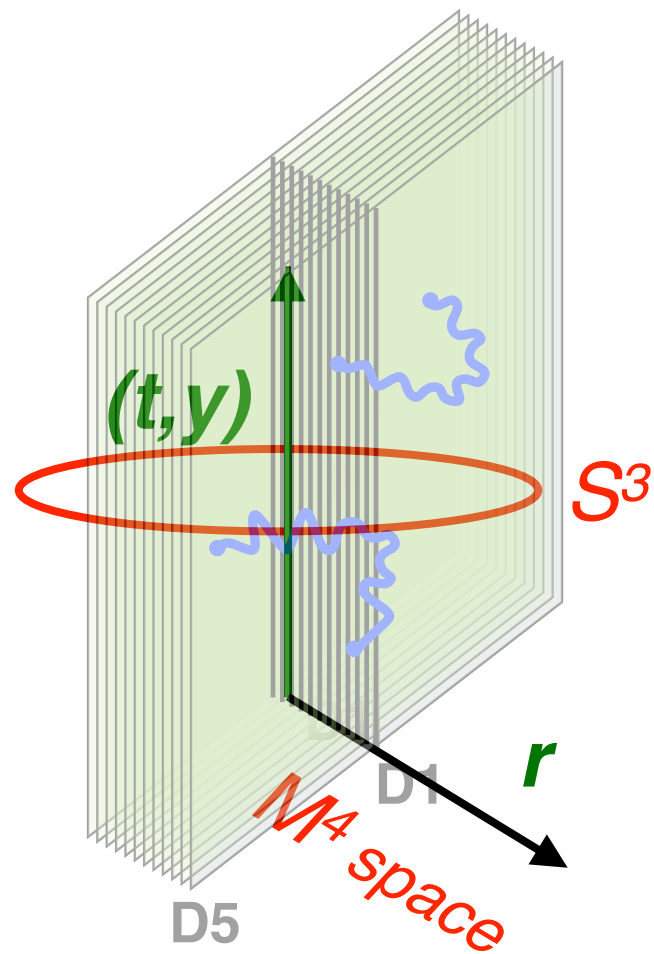
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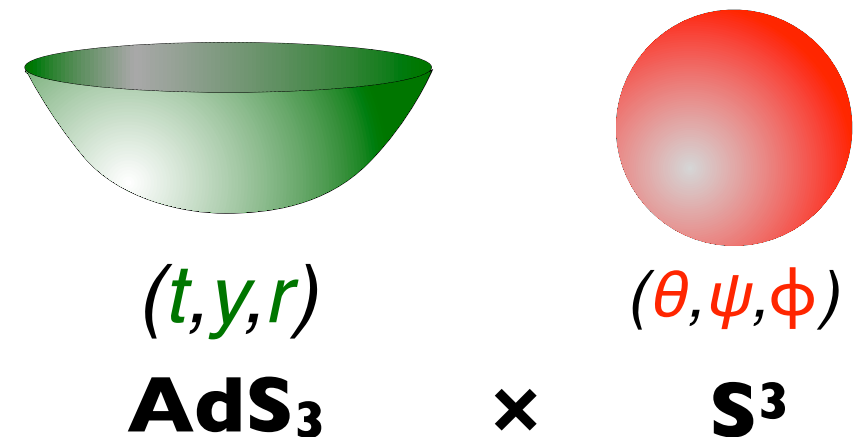
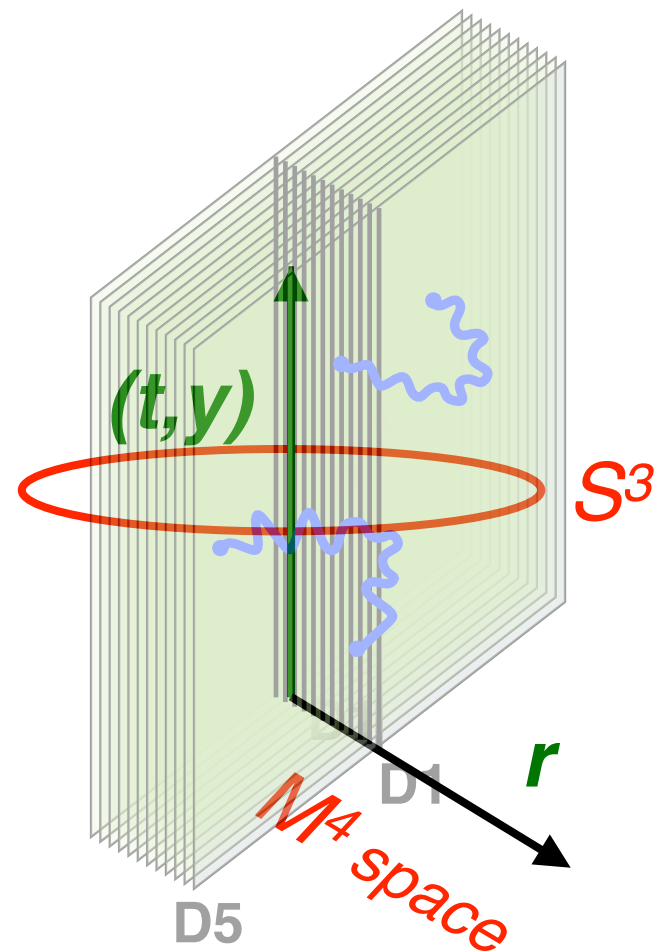


The Emergence of Three-Dimensional Gauged Supergravity

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The maximally supersymmetric supergravity ground state

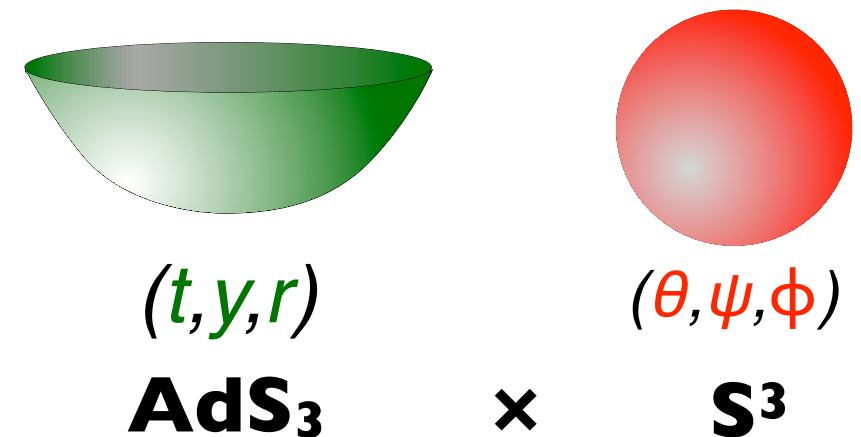
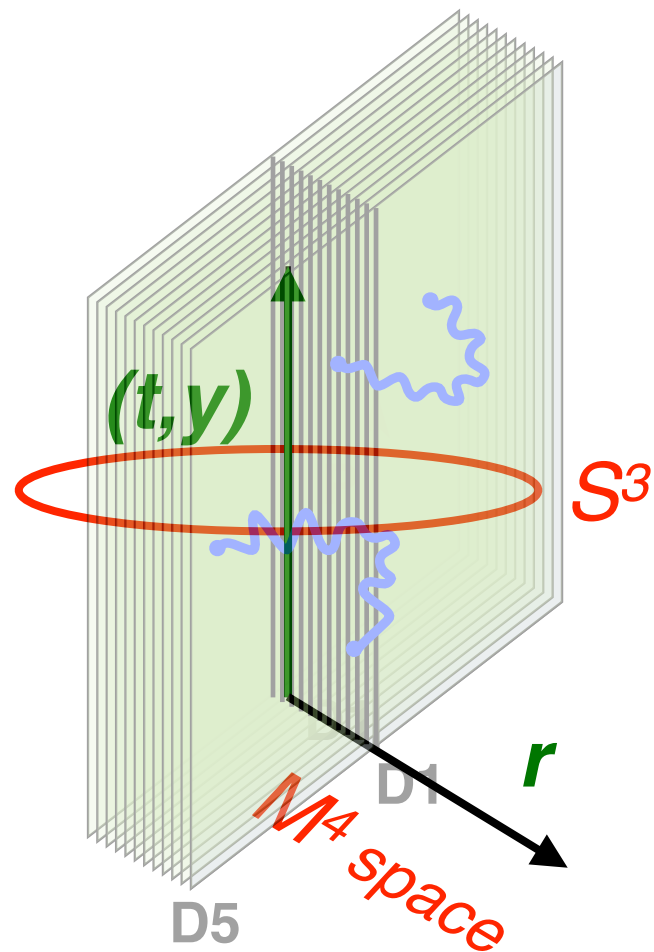


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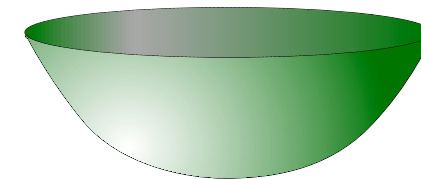
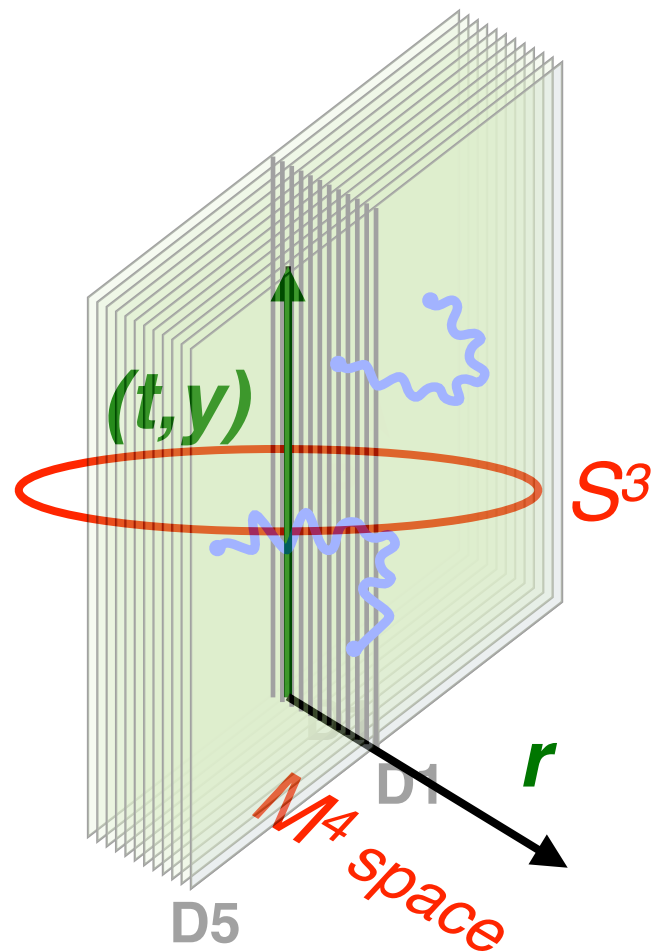
$\Rightarrow$ *Three-dimensional $SO(4)$ gauged $N=4$ supergravity*

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(t, y, r)

AdS_3

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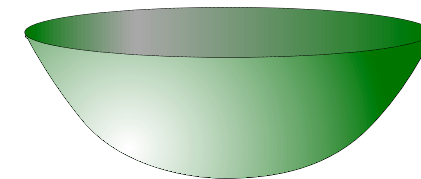
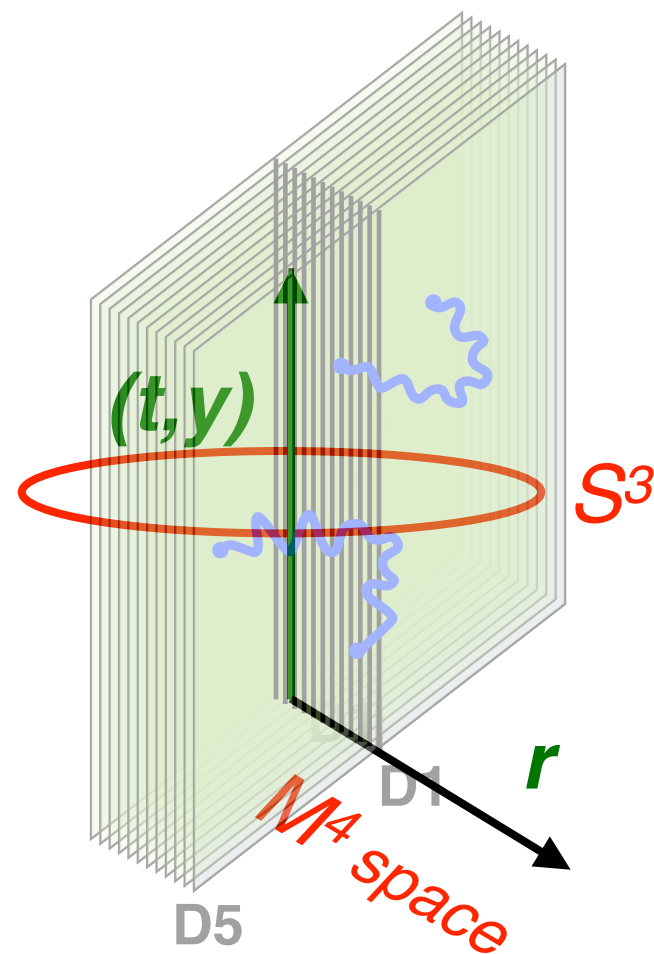
Which theory?

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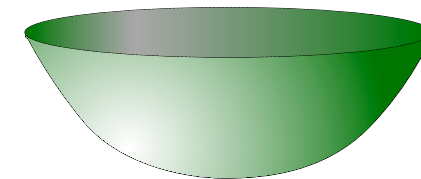
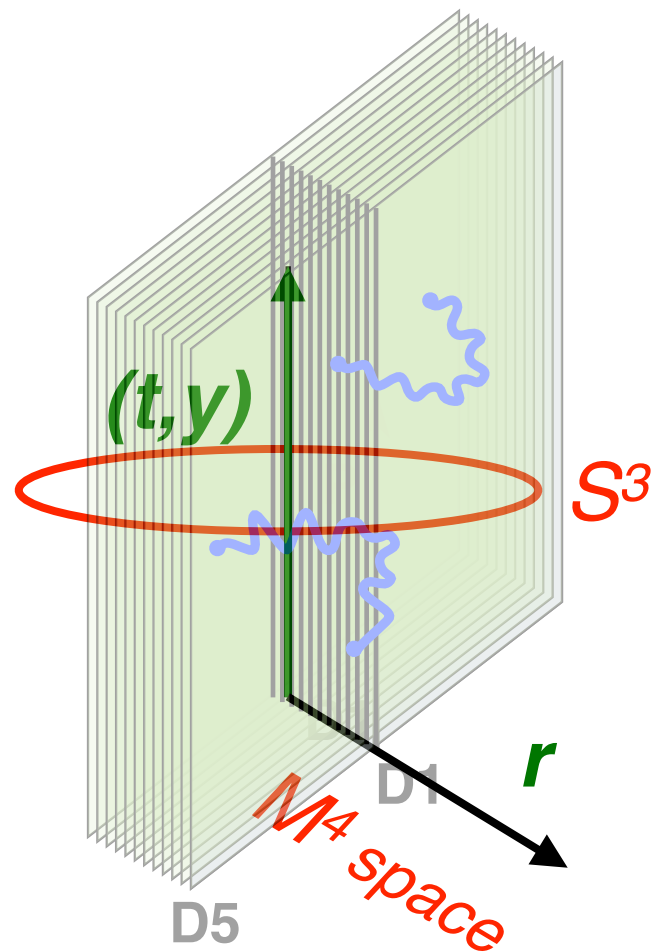
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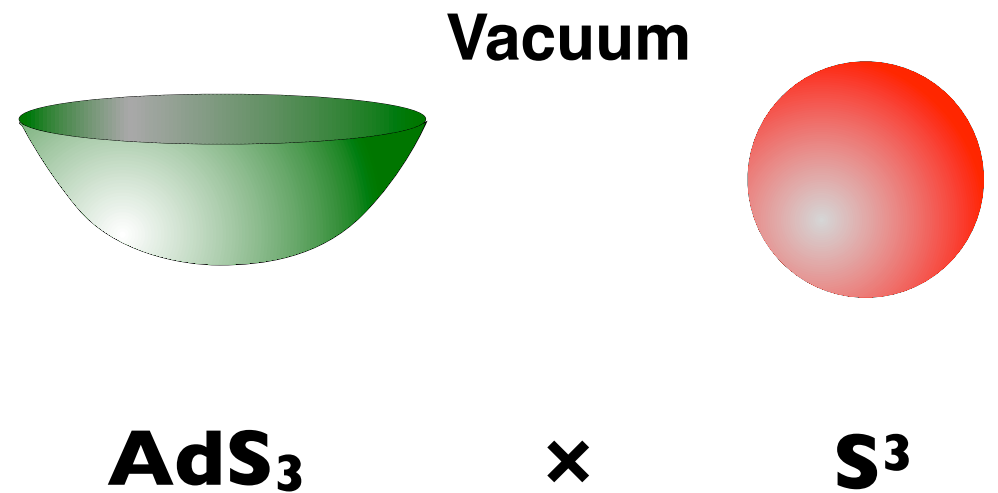
$\rightarrow$ *Three-dimensional hypermultiplets*

The BMPV black hole

Following Strominger, Vafa

Add pure momentum, Q_P to the vacuum state ...

Ignore details of how the momentum is actually carried by supergravity fields



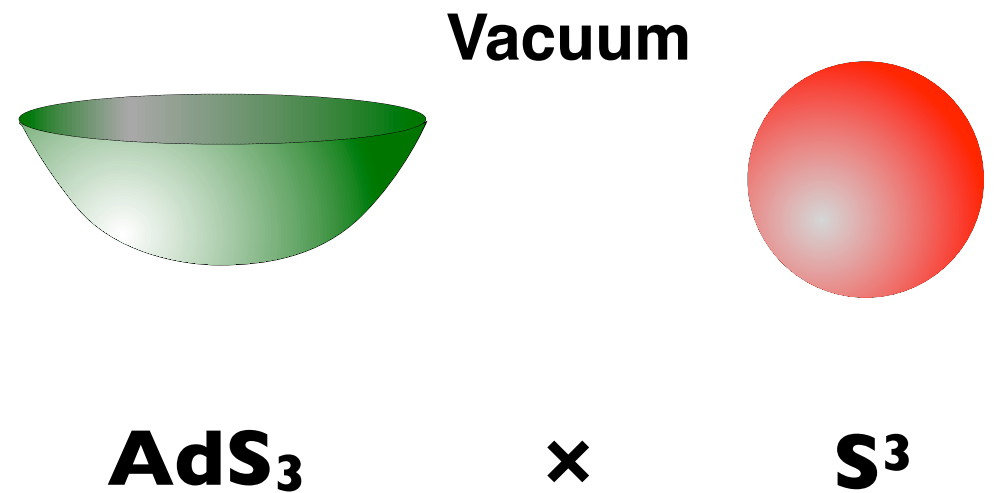
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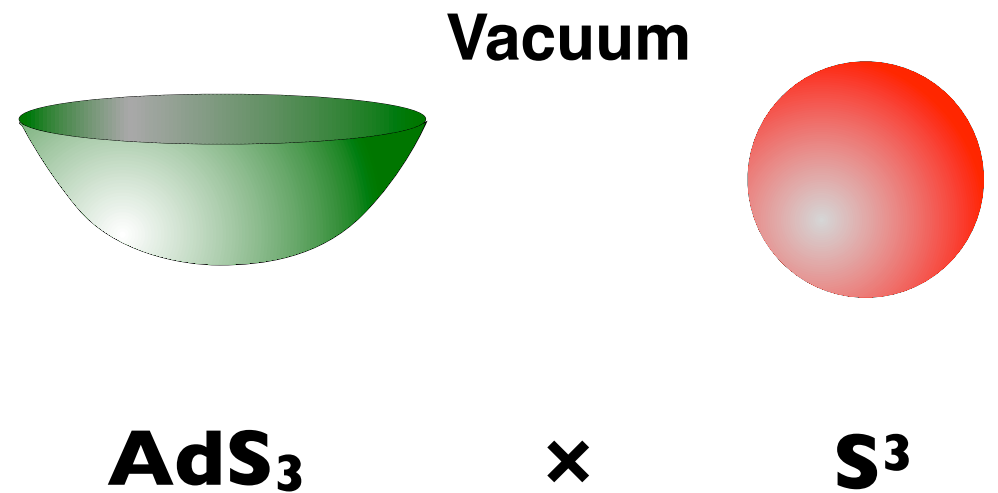
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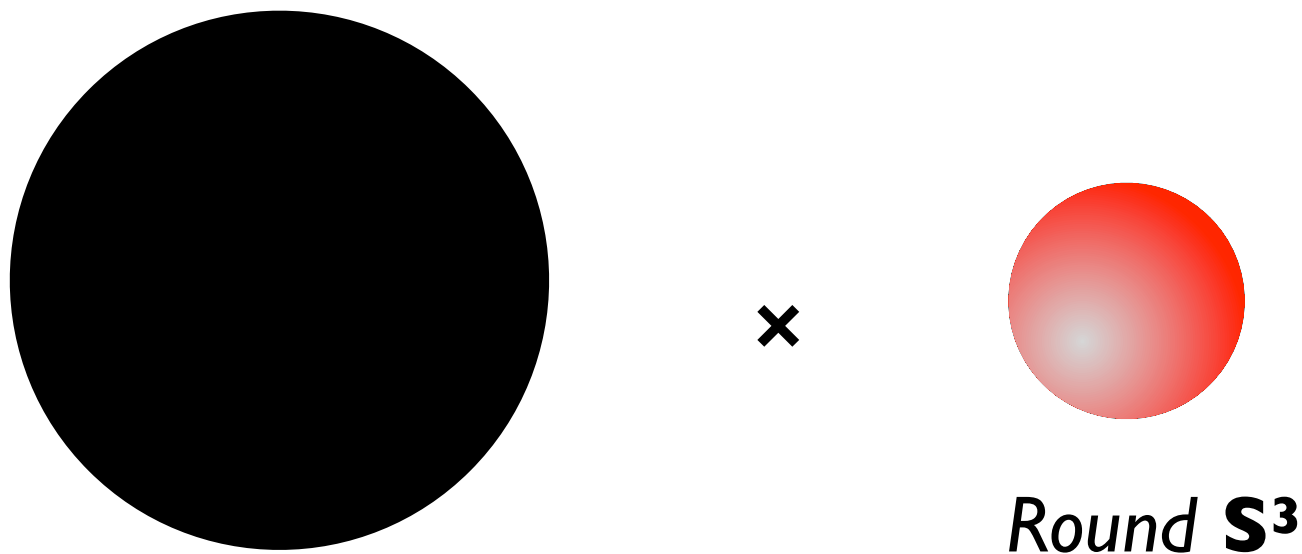
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Back-reacted Geometry



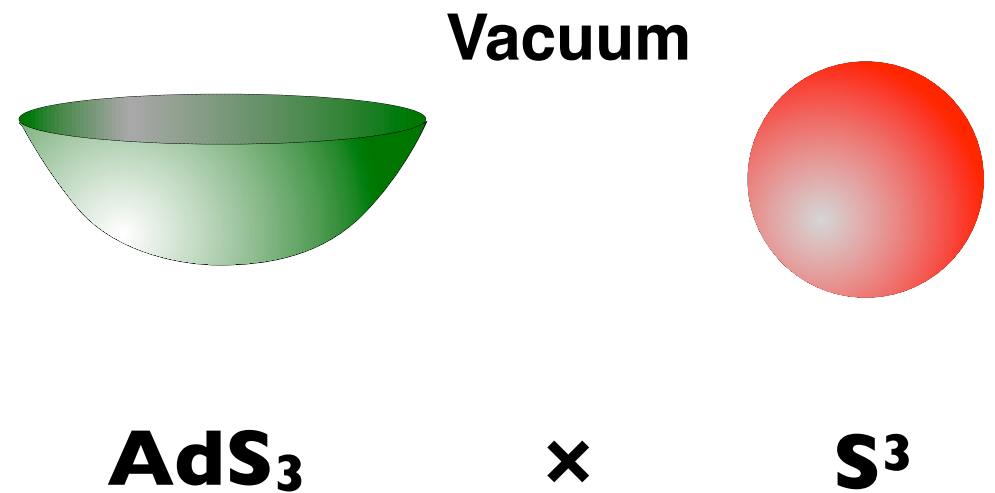
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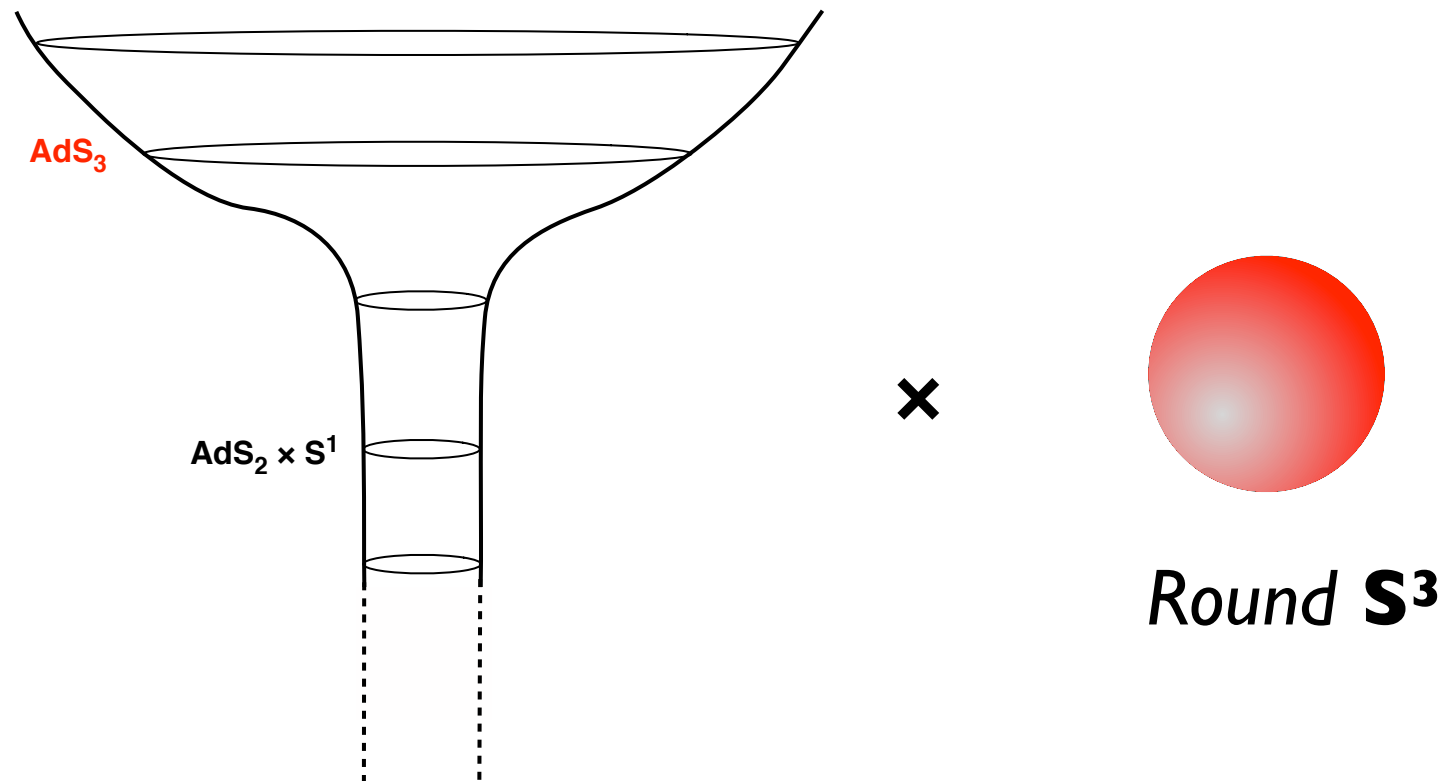
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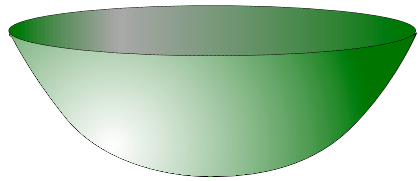


Back-reacted Geometry

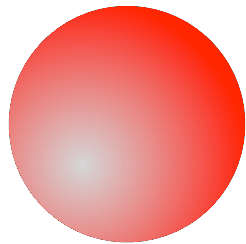
The Black hole - BTZ geometry



Precision Holography



Vacuum



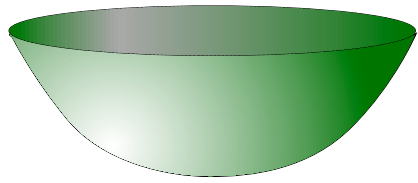
AdS₃

×

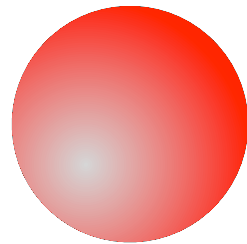
S³

Back-reacted BPS Geometry + Momentum Excitations

Precision Holography



Vacuum

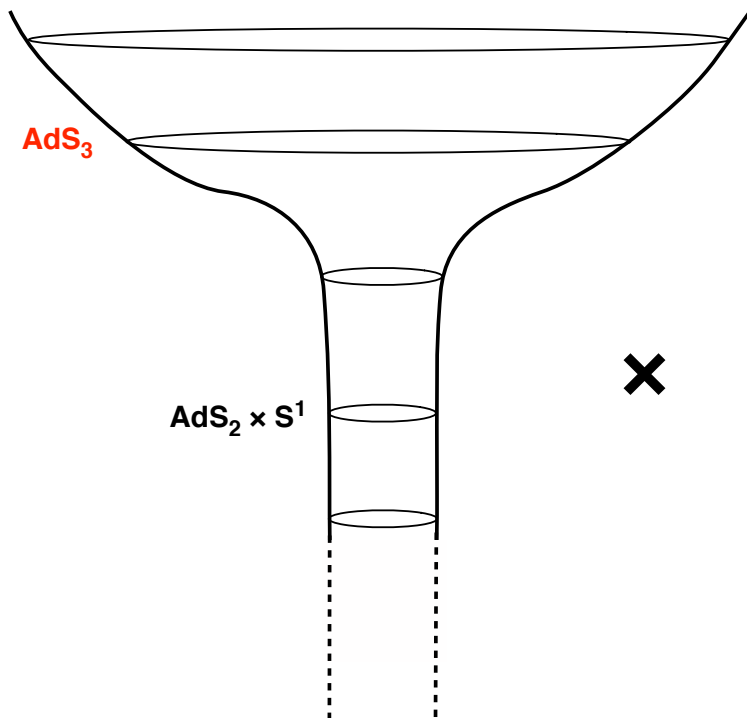


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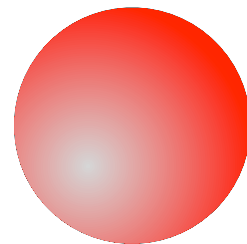
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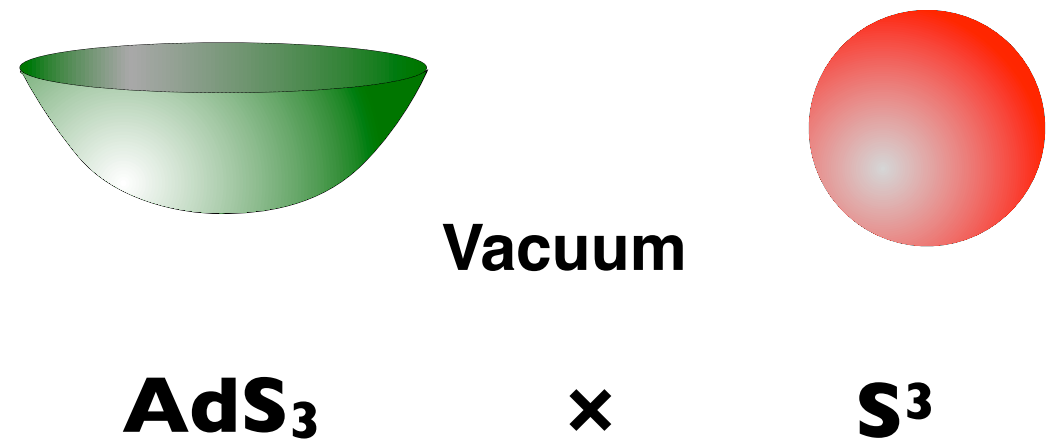


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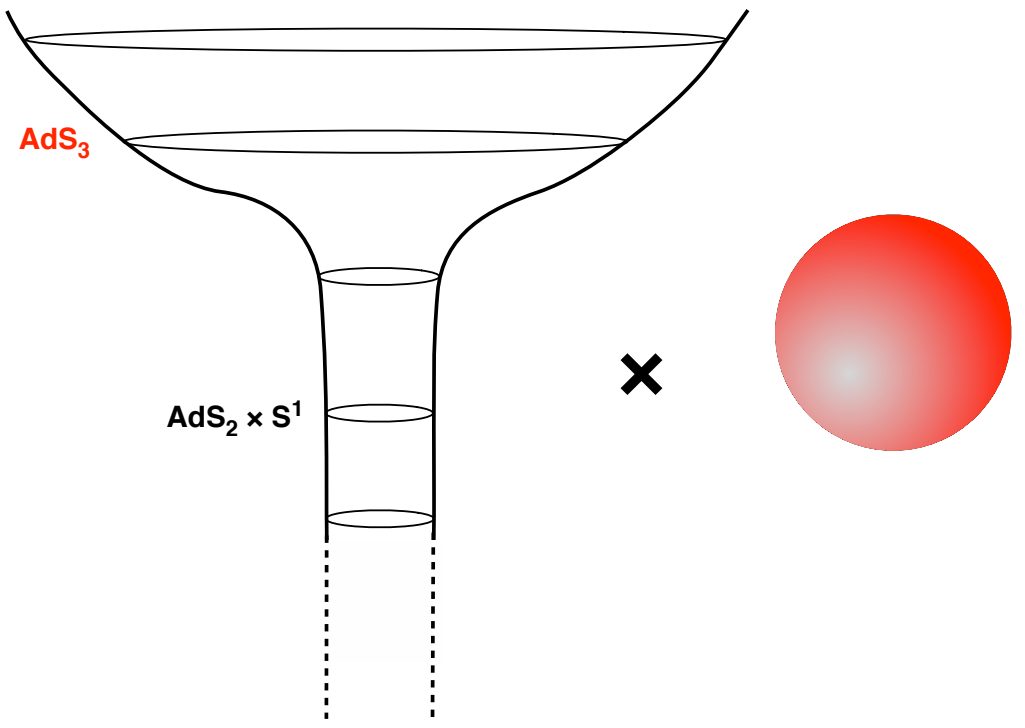
Precision Holography

Encode details of Momentum carriers



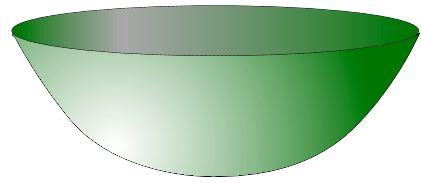
Six dimensions
Anti-self-dual tensor fields
Three dimensions
Hypermultiplet scalars

Back-reacted BPS Geometry + Momentum Excitations



Precision Holography

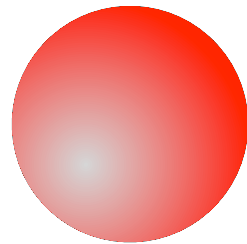
Encode details of Momentum carriers



Vacuum

AdS₃

×



S³

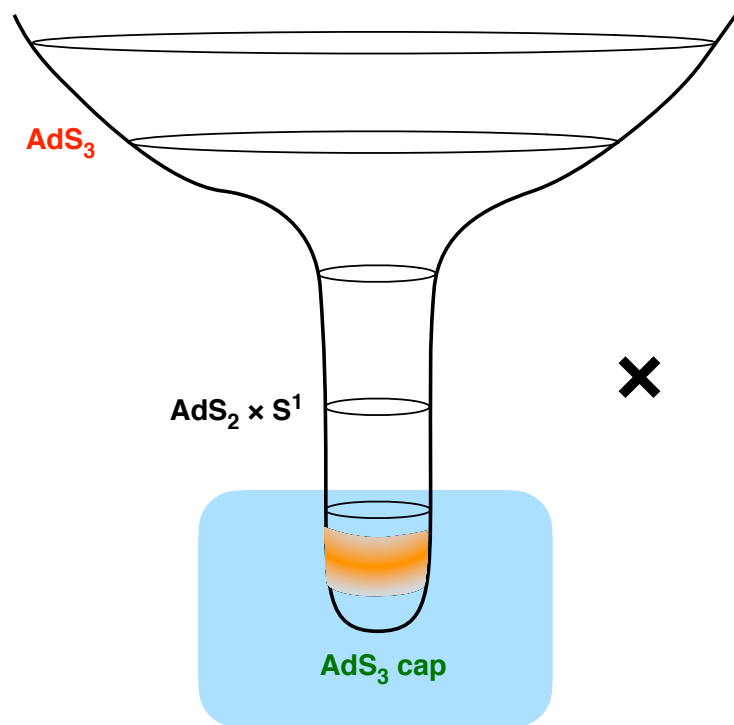
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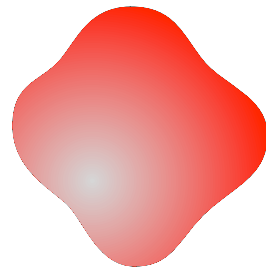
Three dimensions

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Back-reacted BPS Geometry + Momentum Excitations



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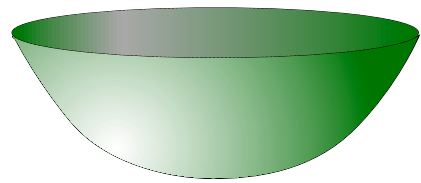
Deformed **S³**

The superstratum:

Black-hole-like throat looks like
a capped BTZ geometry

Precision Holography

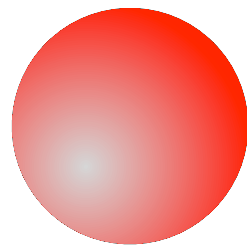
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Vacuum

AdS₃

×



S³

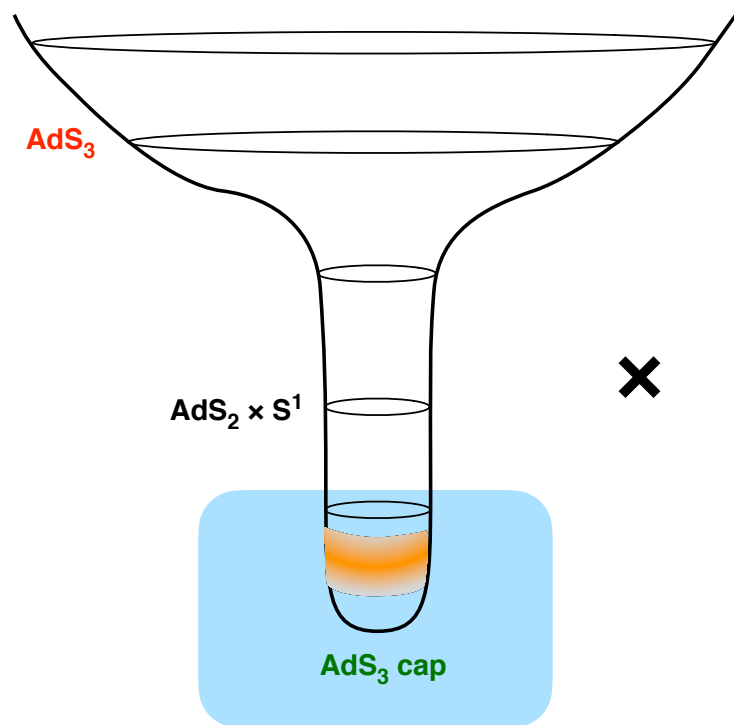
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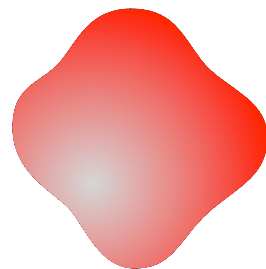
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×



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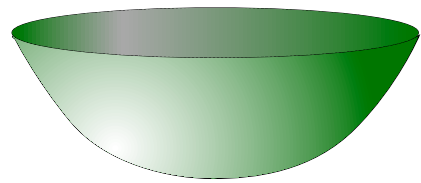
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Holographic dictionary with states of the *D1- D5* CFT verified to high precision

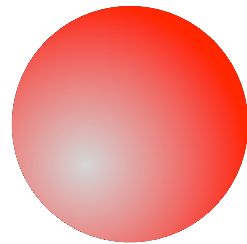
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Precision Holography

Encode details of Momentum carriers



Vacuum



AdS₃

×

S³

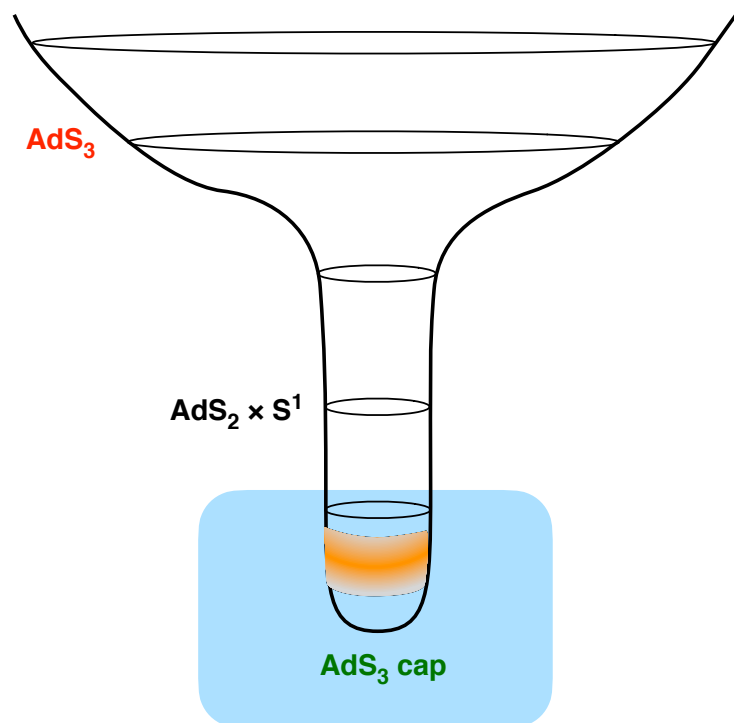
Six dimensions

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Back-reacted BPS Geometry + Momentum Excitations



The superstratum:

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For the simplest superstrata the
Deformed S³ is handled by the
magic of consistent truncation ...

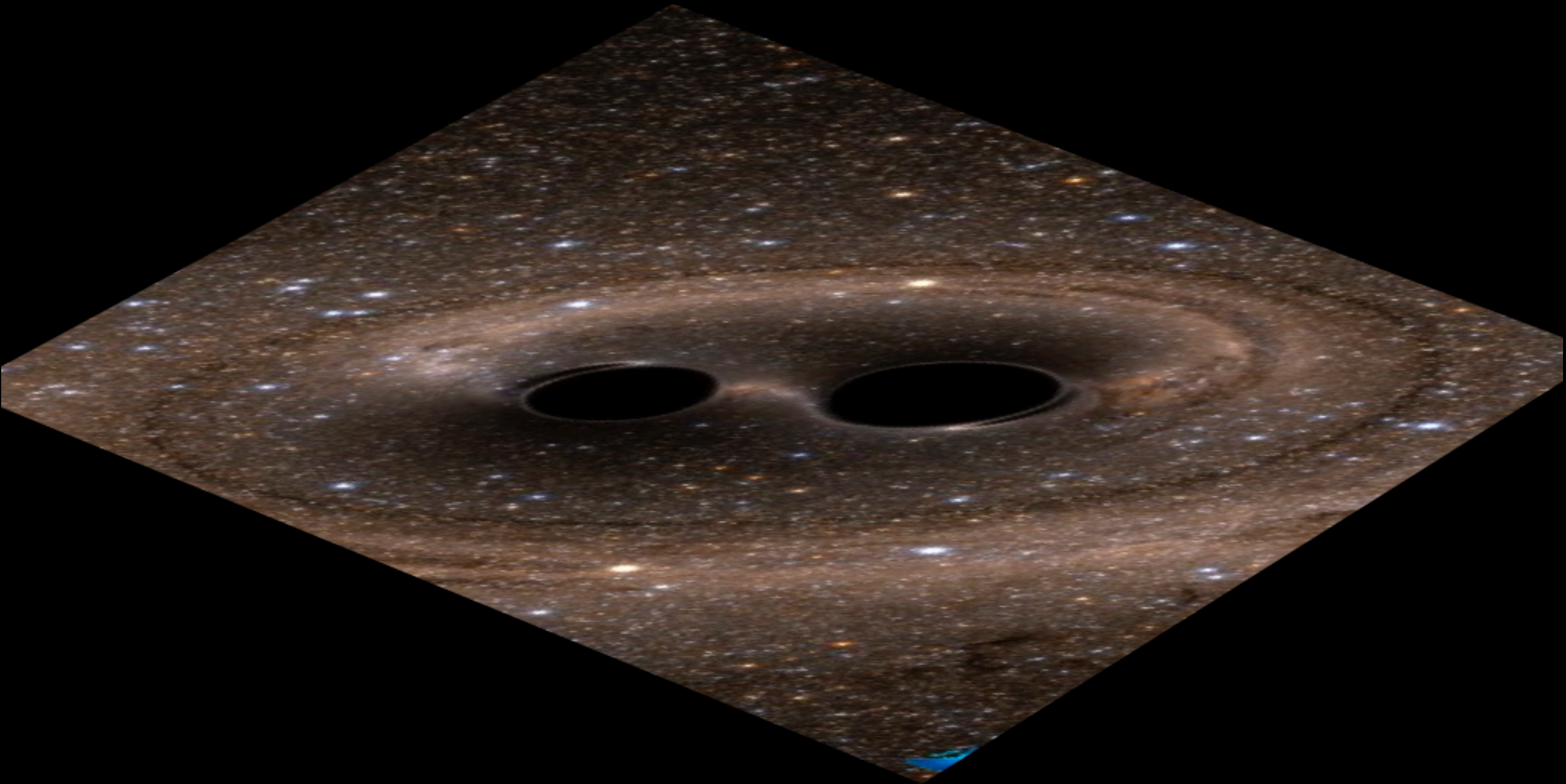
⇒ *Three-dimensional gauged supergravity*

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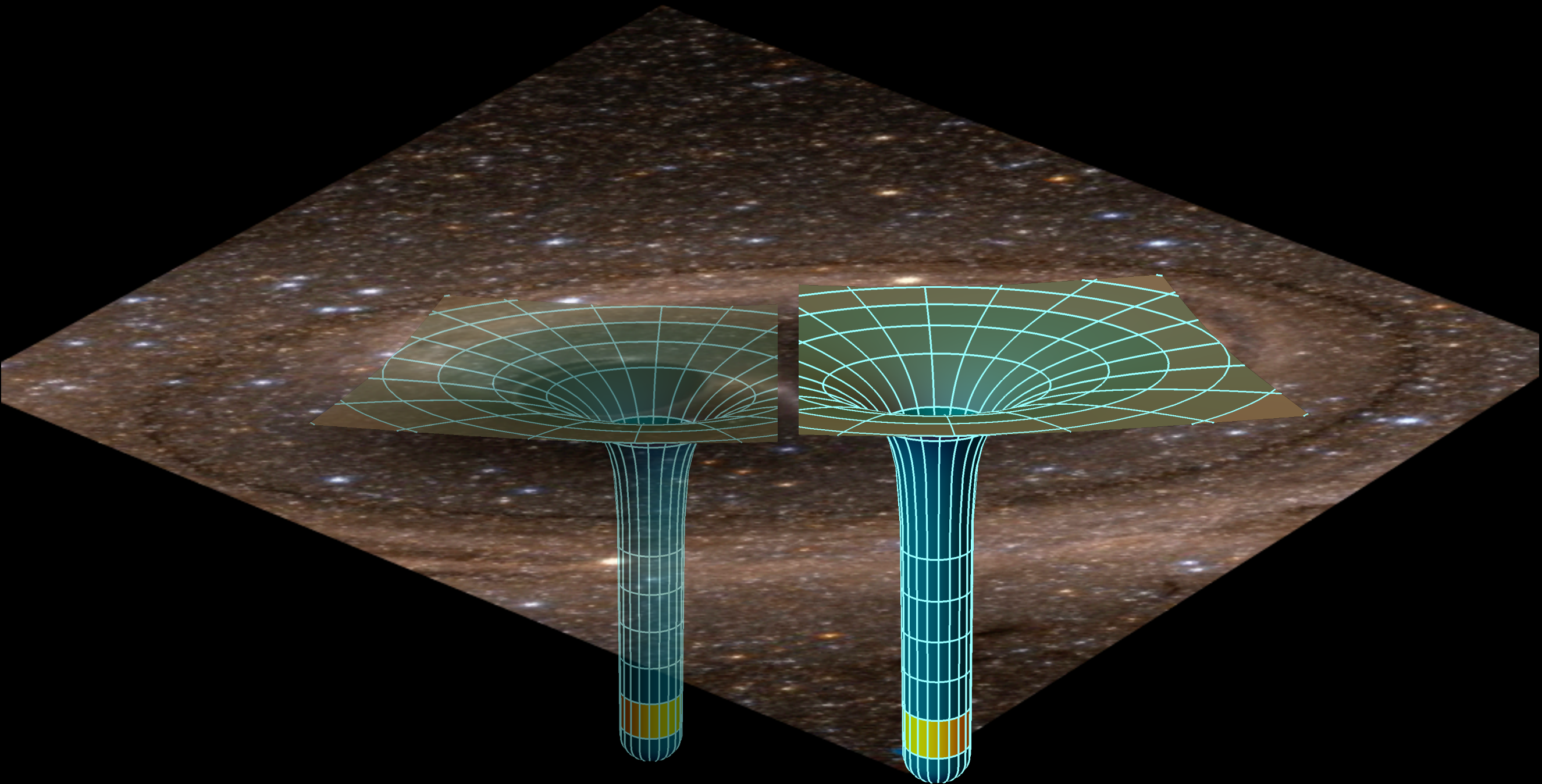
Microstate geometries:

Smooth, horizonless solutions of the supergravity equations with the same macroscopic behavior as a black-hole



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Smooth, horizonless solutions of the supergravity equations with the same macroscopic behavior as a black-hole



Gauged Supergravity in Three Dimensions

Microstate Geometries from Gauged Supergravity in Three Dimensions

#13

[Daniel R. Mayerson](#) (IPhT, Saclay), [Robert A. Walker](#) (IPhT, Saclay and Stanford U., Phys. Dept.), [Nicholas P. Warner](#) (IPhT, Saclay and Stanford U., Phys. Dept. and Southern California U.) (Apr 27, 2020)

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- ❖ *Determined exactly which gauged $SO(4)$ $N = 4$ supergravity is the correct one for black-hole microstructure*
- ❖ *Included the extra anti-self-dual tensor multiplets*
 - $\Leftrightarrow$ *extra hypermultiplets in three dimensions*
 - $=$ *Momentum wave carriers*

Gauged Supergravity in Three Dimensions

Microstate Geometries from Gauged Supergravity in Three Dimensions

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 - $\Leftrightarrow$ *extra hypermultiplets in three dimensions*
 - $=$ *Momentum wave carriers*
- ❖ *Uplift formulae for hypermultiplet scalars*
 - $\Leftrightarrow$ *tensor gauge field fluxes*

Gauged Supergravity in Three Dimensions

Microstate Geometries from Gauged Supergravity in Three Dimensions

#13

Daniel R. Mayerson (IPhT, Saclay), Robert A. Walker (IPhT, Saclay and Stanford U., Phys. Dept.), Nicholas P. Warner (IPhT, Saclay and Stanford U., Phys. Dept. and Southern California U.) (Apr 27, 2020)

Published in: *JHEP* 10 (2020) 030 • e-Print: [2004.13031](#) [hep-th]

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*Vast families of superstrata can be constructed directly in six dimensions
... why do we need this (very restricted) three-dimensional formulation?*

Finding Non-Extremal Microstrata

Mayerson, Walker and Warner, *arXiv:2004.13031*

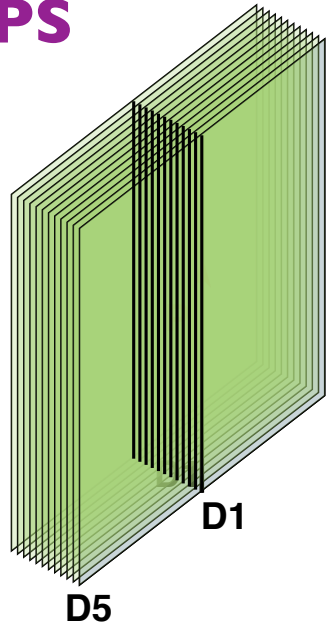
Ganchev, Houppe and Warner, *arXiv:2107.09677*

Ganchev, Houppe, Giusto and Russo, *arXiv:2112.03287*

Ganchev, Houppe, Giusto, Russo and Warner, *to appear*

Supersymmetry breaking

$\frac{1}{4}$ BPS

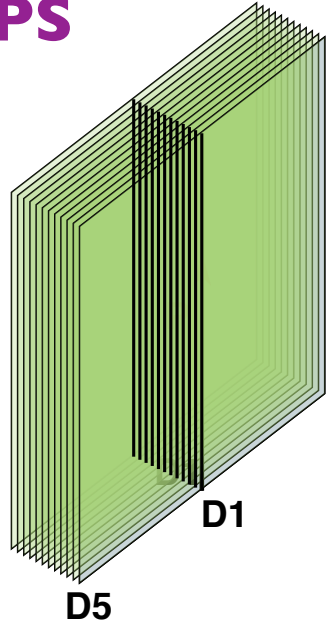


Vacuum for Left/Right Movers

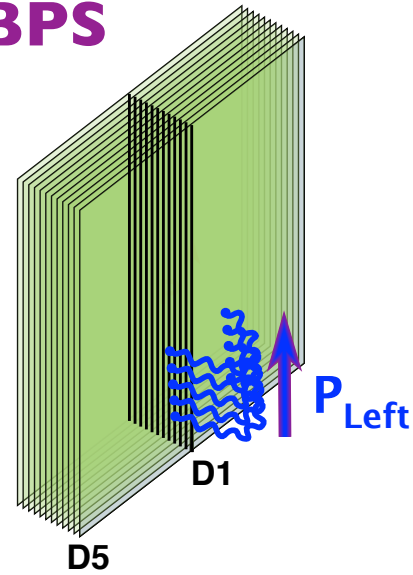
**$(4,4)$
supersymmetry**

Supersymmetry breaking

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$\frac{1}{8}$ BPS

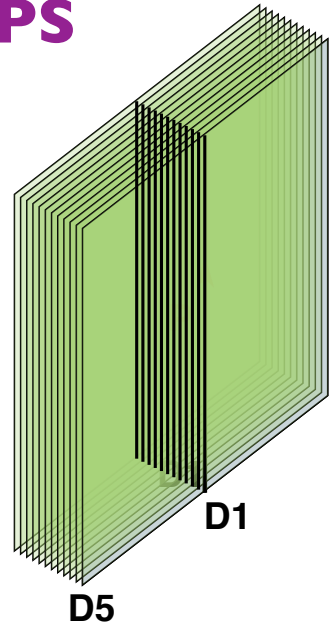


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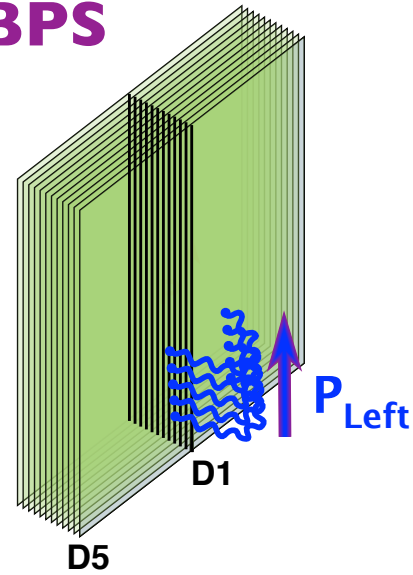
Vacuum for Right Movers only
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supersymmetry

Supersymmetry breaking

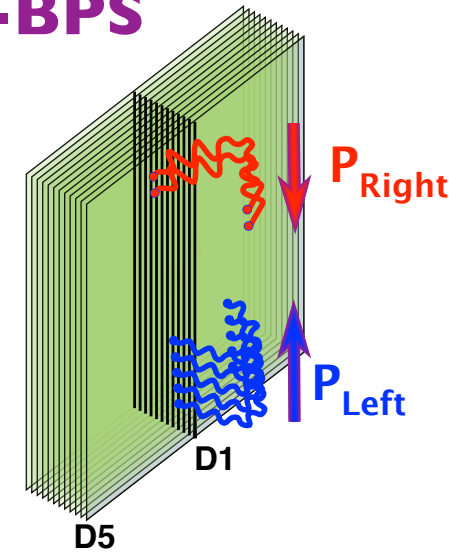
$\frac{1}{4}$ BPS



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Non-BPS



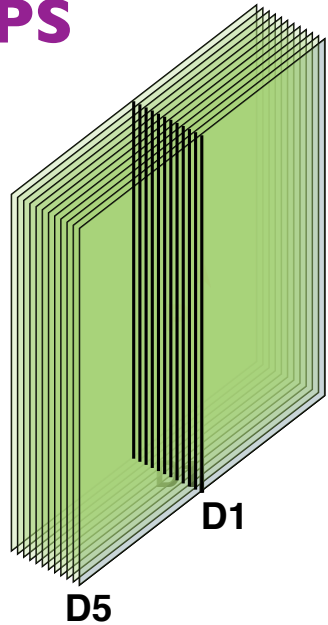
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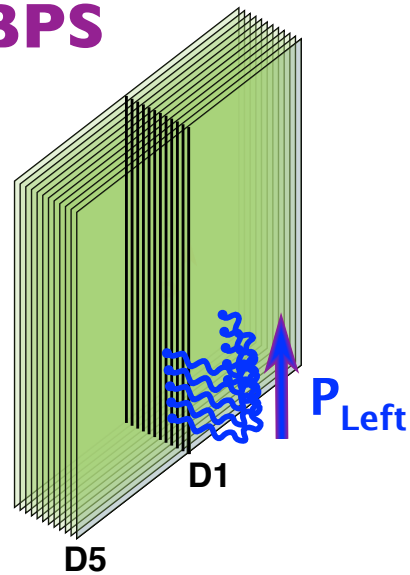
Left/Right excited states
 $(0,0)$
supersymmetry

Supersymmetry breaking

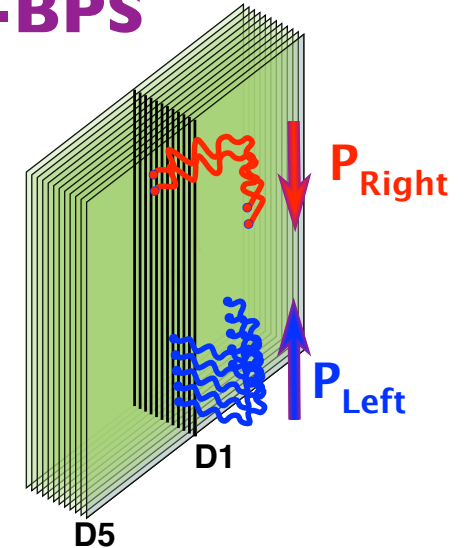
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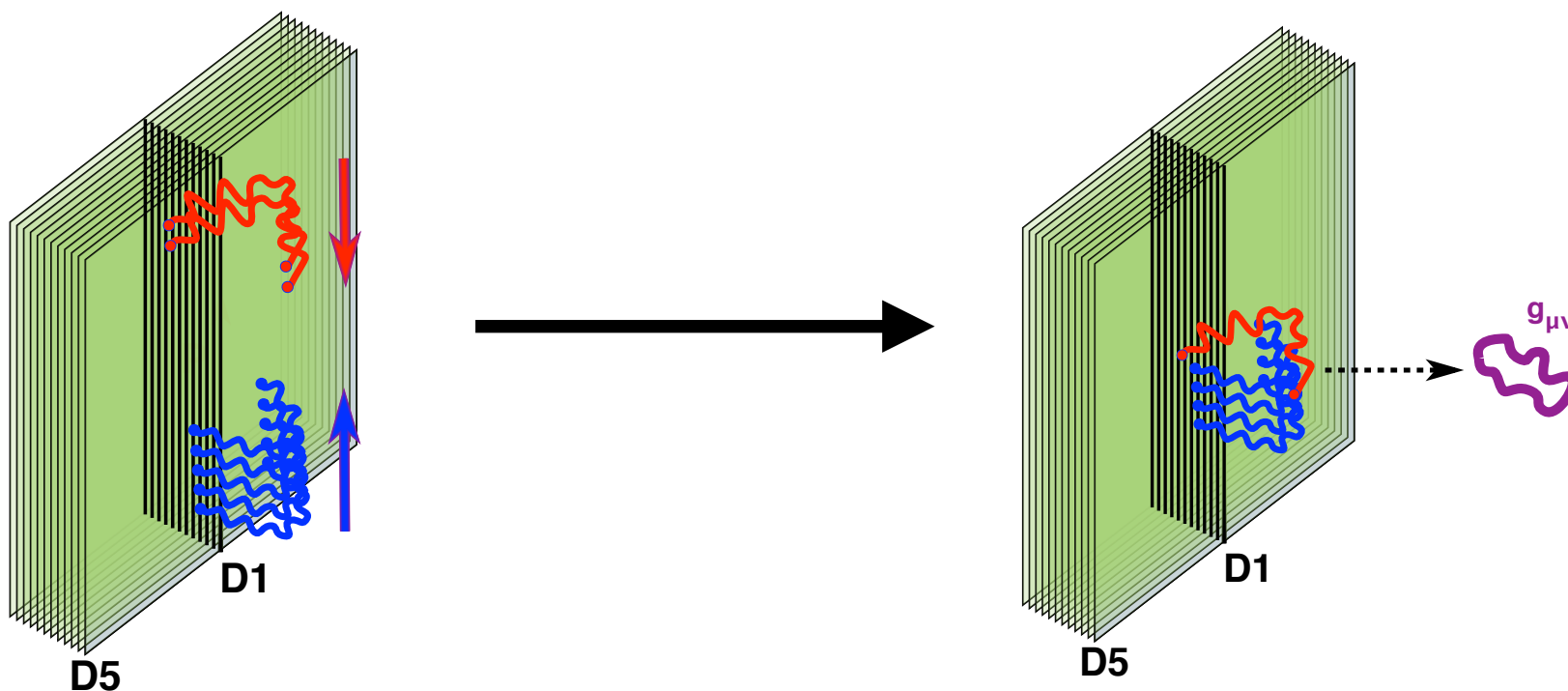


Vacuum for Left/Right Movers
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supersymmetry

Vacuum for Right Movers only
 $(0,4)$
supersymmetry

Left/Right excited states
 $(0,0)$
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Such a non-BPS state has finite analogue of Hawking temperature:



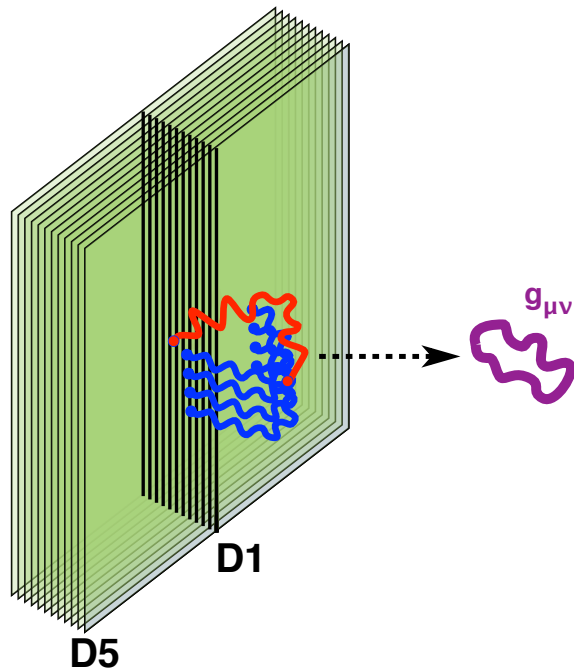
Hawking radiation from
scattering into closed
string modes

Huge Advantages of Gauged Supergravity in Three Dimensions

- ★ We have to solve the equations of motion numerically/perturbatively:
Much easier in (t,y,r) than in (t,y,r,θ,ψ,ϕ) *all together*

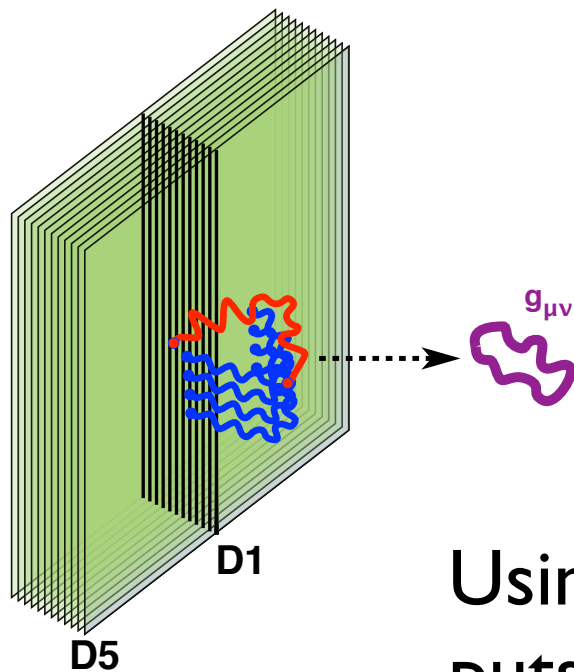
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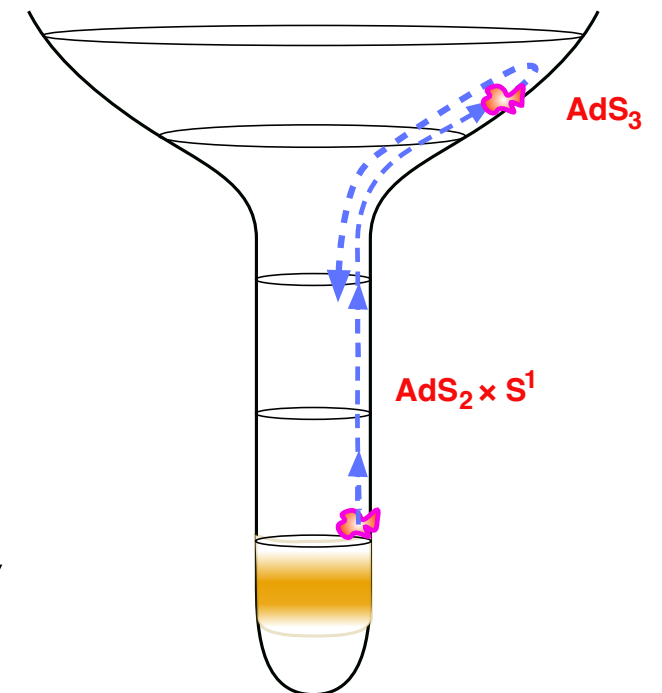


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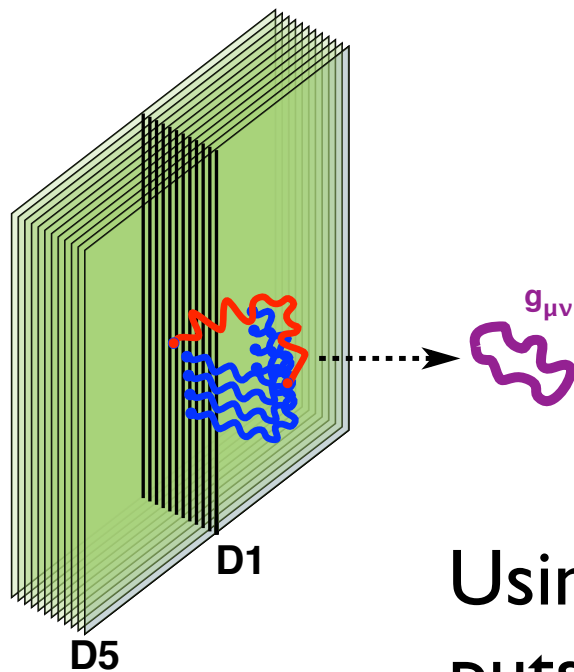


Using AdS_3 boundary conditions effectively puts it in a box and stabilizes against decay

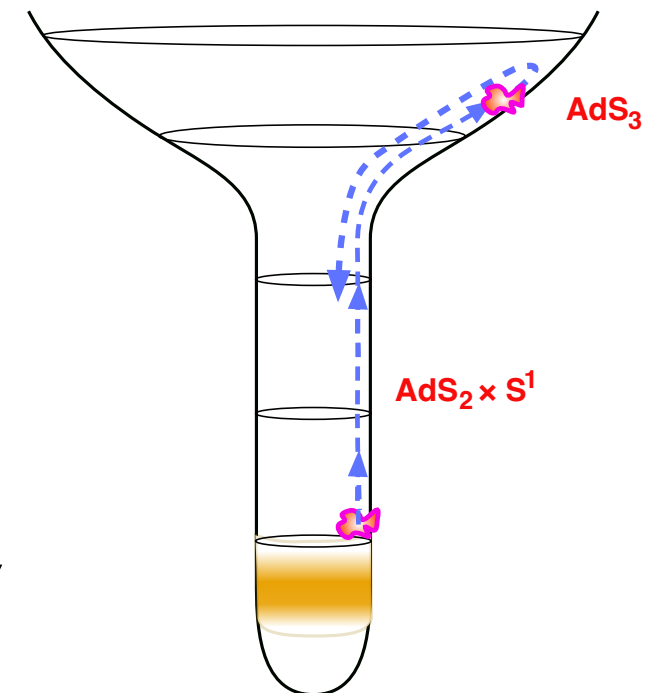


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AdS_3 microstrata can be made time-independent:

Non-extremal microstates in equilibrium with their “Hawking radiation”

Scalar fields, m_{AB} (inverse m^{AB}) and χ_A , coupled to gravity and $SO(4)$ KK
Maxwell fields, $A^{AB} = -A^{BA}$, from the S^3 fibration

$$\begin{aligned}\mathcal{L} = & \frac{1}{4} R - \frac{1}{16} \text{Tr}[(\mathcal{D}_\mu m) m^{-1} (\mathcal{D}^\mu m) m^{-1}] - \frac{1}{8} m^{AB} (\mathcal{D}_\mu \chi_A) (\mathcal{D}^\mu \chi_B) - V \\ & - \frac{1}{8} m_{AC} m_{BD} F_{\mu\nu}^{AB} F^{\mu\nu CD} - \frac{1}{2} g_0 \varepsilon^{\mu\nu\rho} (A_\mu^{AB} \partial_\nu \tilde{A}_\rho^{BA} - \frac{4}{3} g_0 A_\mu^{AB} A_\nu^{BC} A_\rho^{CA}) \\ & + \frac{1}{16} \varepsilon^{\mu\nu\rho} Y_{\mu AB} F_{\nu\rho}^{AB} \\ & Y_{\mu AB} \equiv \chi_B \mathcal{D}_\mu \chi_A - \chi_A \mathcal{D}_\mu \chi_B\end{aligned}$$

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$\rightarrow$ Many new non-extremal/non-BPS solutions

The Simplest Family of Solutions

Ganchev, Houppe and Warner, 2107.09677

Six-dimensions

- The hypermultiplets: $\chi_1 + i\chi_2 = \nu(\bar{\xi}) e^{i(\omega \tau + n \psi)}$

Tensor Gauge Fields

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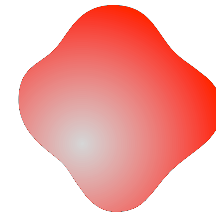
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S³ Shape

The Simplest Family of Solutions

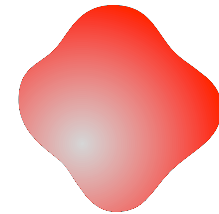
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S³ Shape

- Maxwell fields

$$\tilde{A}^{12} = \frac{1}{g_0} [\Phi_1(\xi) d\tau + \Psi_1(\xi) d\psi]$$
$$\tilde{A}^{34} = \frac{1}{g_0} [\Phi_2(\xi) d\tau + \Psi_2(\xi) d\psi]$$

Fibering of the S³ over the space-time

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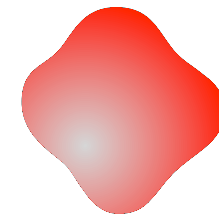
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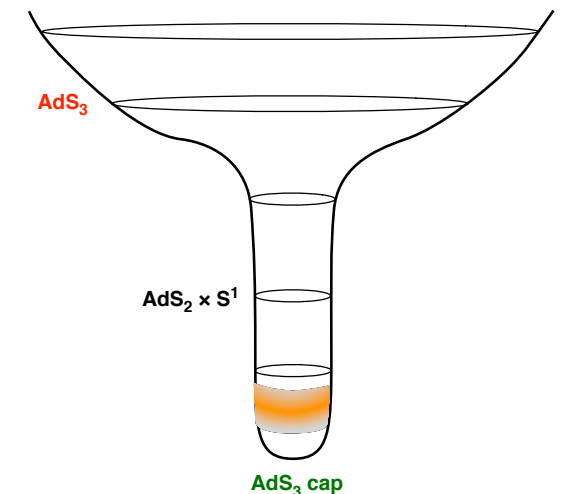
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$$ds_3^2 = g_0^{-2} \left[-\Omega_1^2 \left(d\tau + \frac{k}{(1-\xi^2)} d\psi \right)^2 + \frac{\Omega_0^2}{(1-\xi^2)^2} (d\xi^2 + \xi^2 d\psi^2) \right]$$

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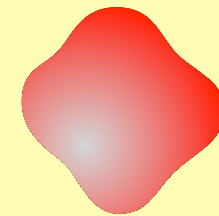
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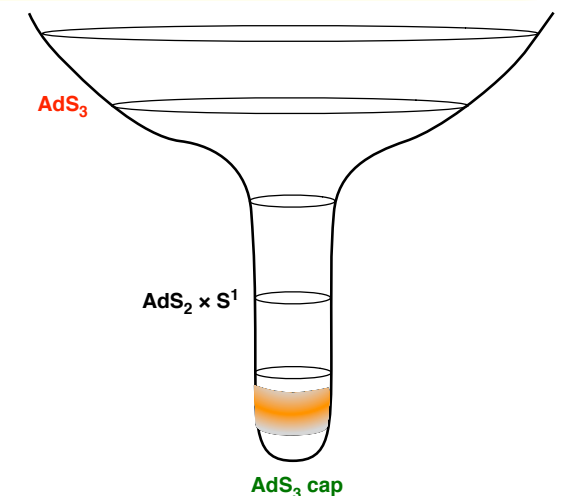
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The Ansatz: Eleven functions of one variable, ξ :

ν, μ_0, μ_1, μ_2

Scalars

Ω_0, Ω_1, k

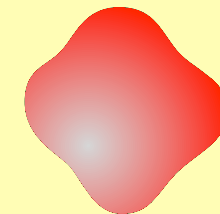
3D Geometry

$\Phi_1, \Psi_1, \Phi_2, \Psi_2$

Electromagnetic KK Fields

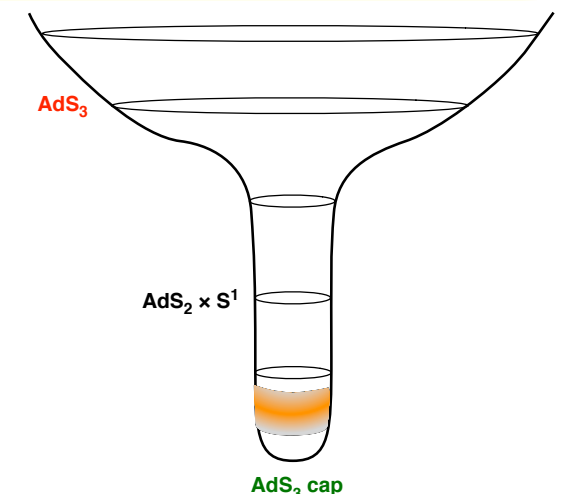
Six-dimensions

Tensor Gauge Fields



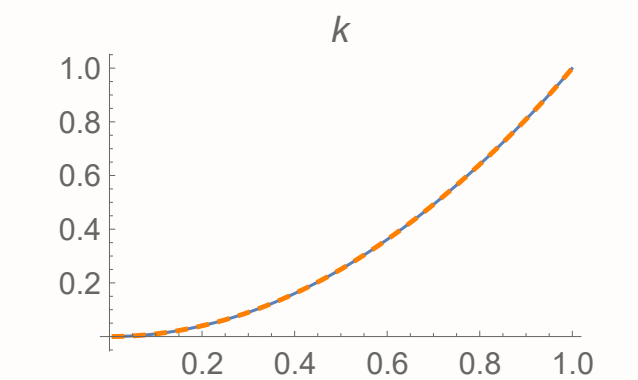
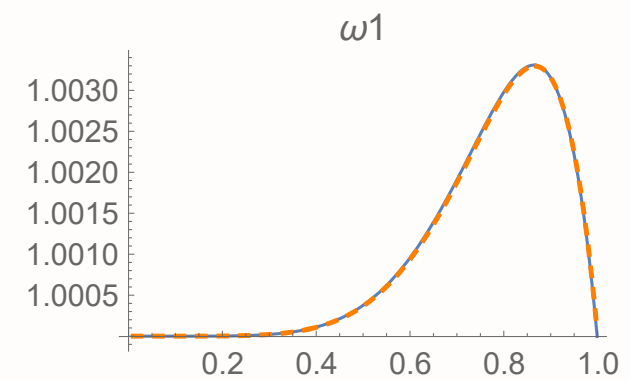
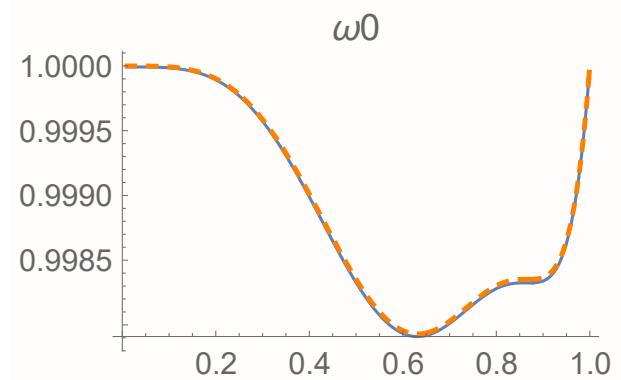
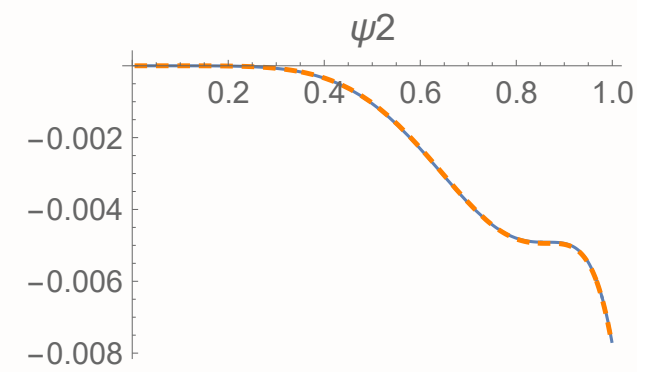
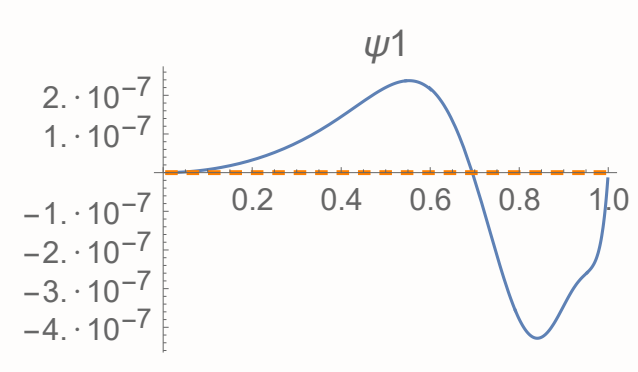
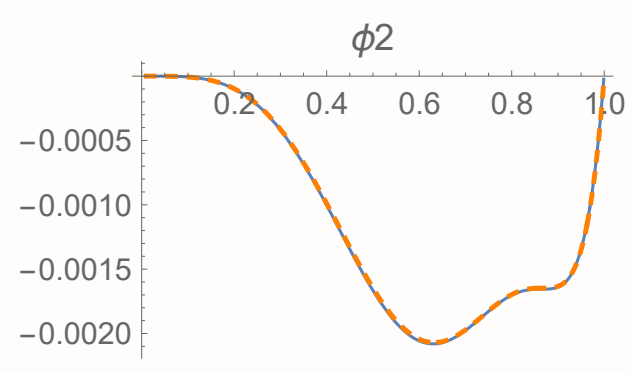
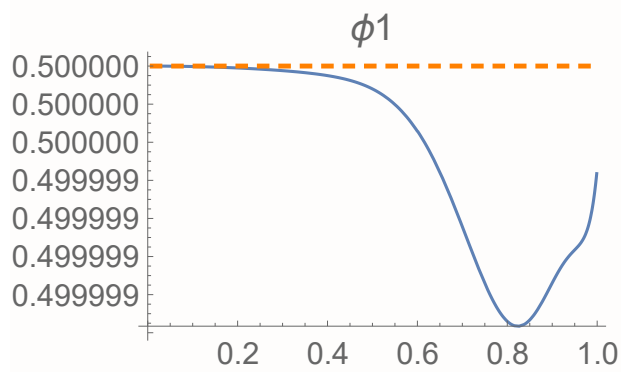
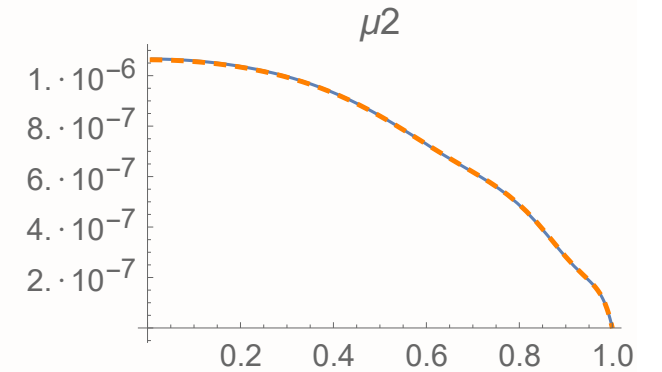
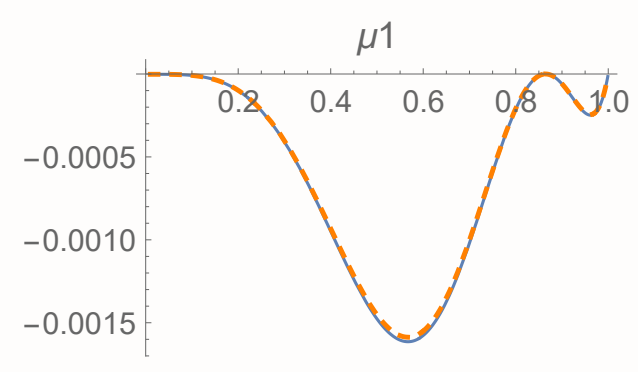
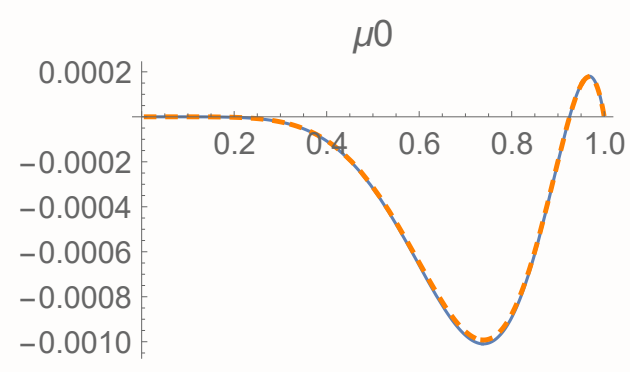
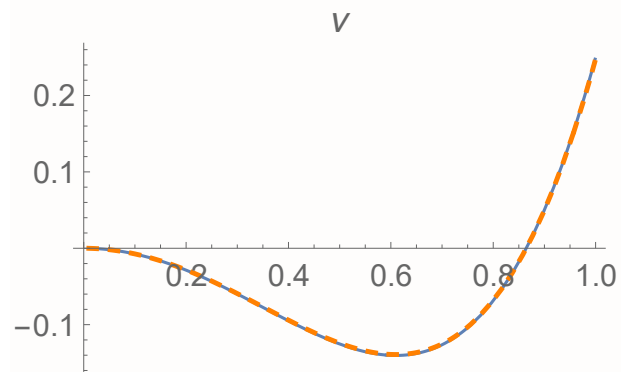
S³ Shape

Fibering of the S³ over the space-time



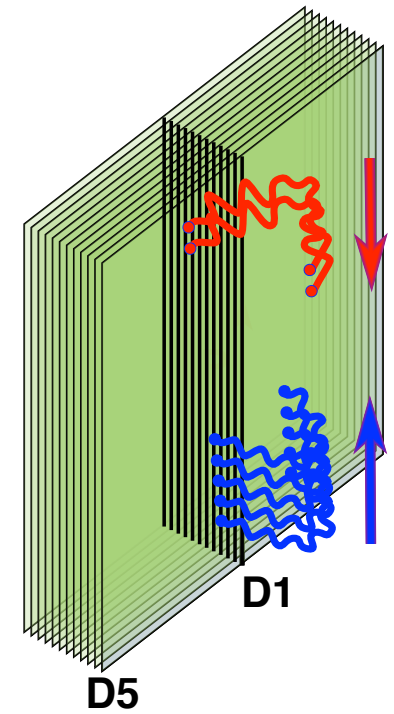
Solve: Perturbation theory and Numerics

Comparison of numerical and perturbation theory results at $\alpha=1/4$, $\beta=0$, $\omega_0=2$



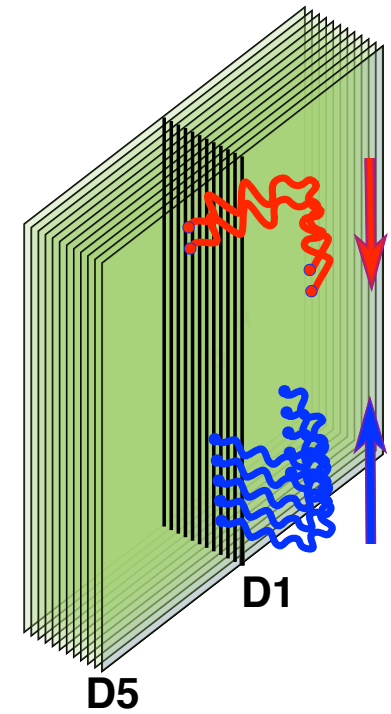
Important results

- Non-extremal microstate geometries exist as stable gravitational solitons ... and examples can be constructed



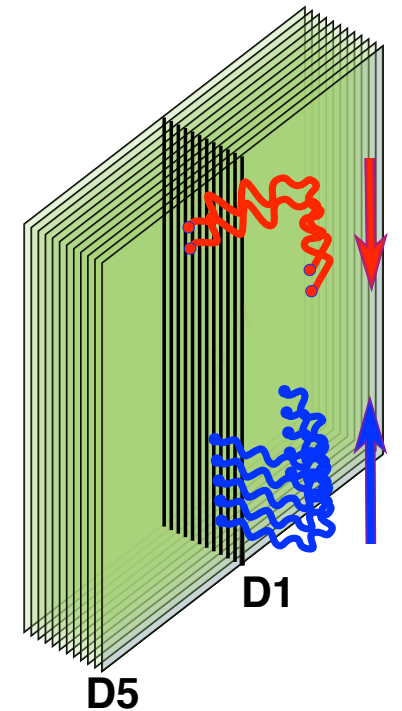
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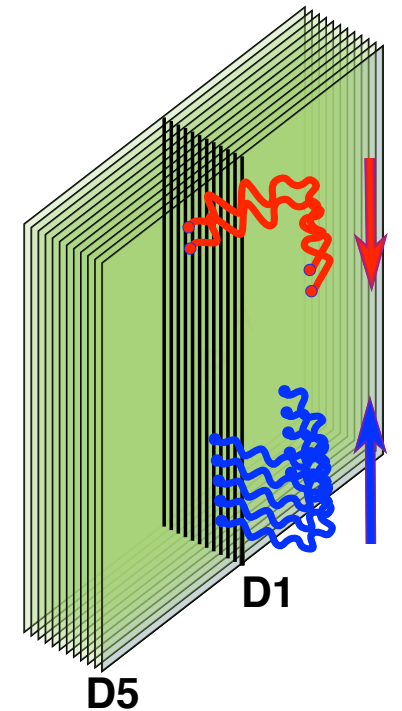
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$$\omega_{non-BPS} = \omega_{BPS} + \delta\omega, \quad \delta\omega \sim -(\textit{Amplitude})^2 + \dots$$

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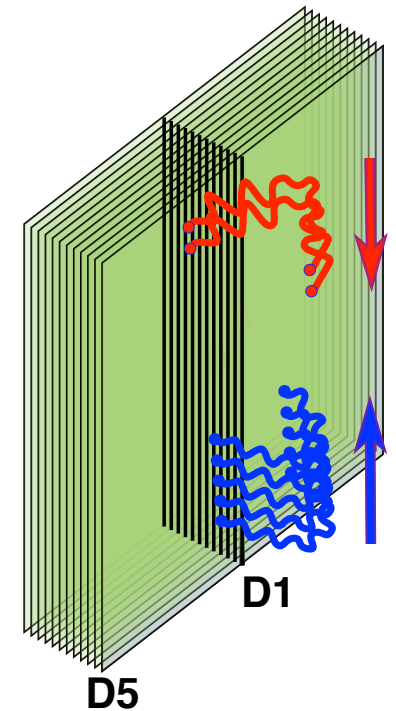


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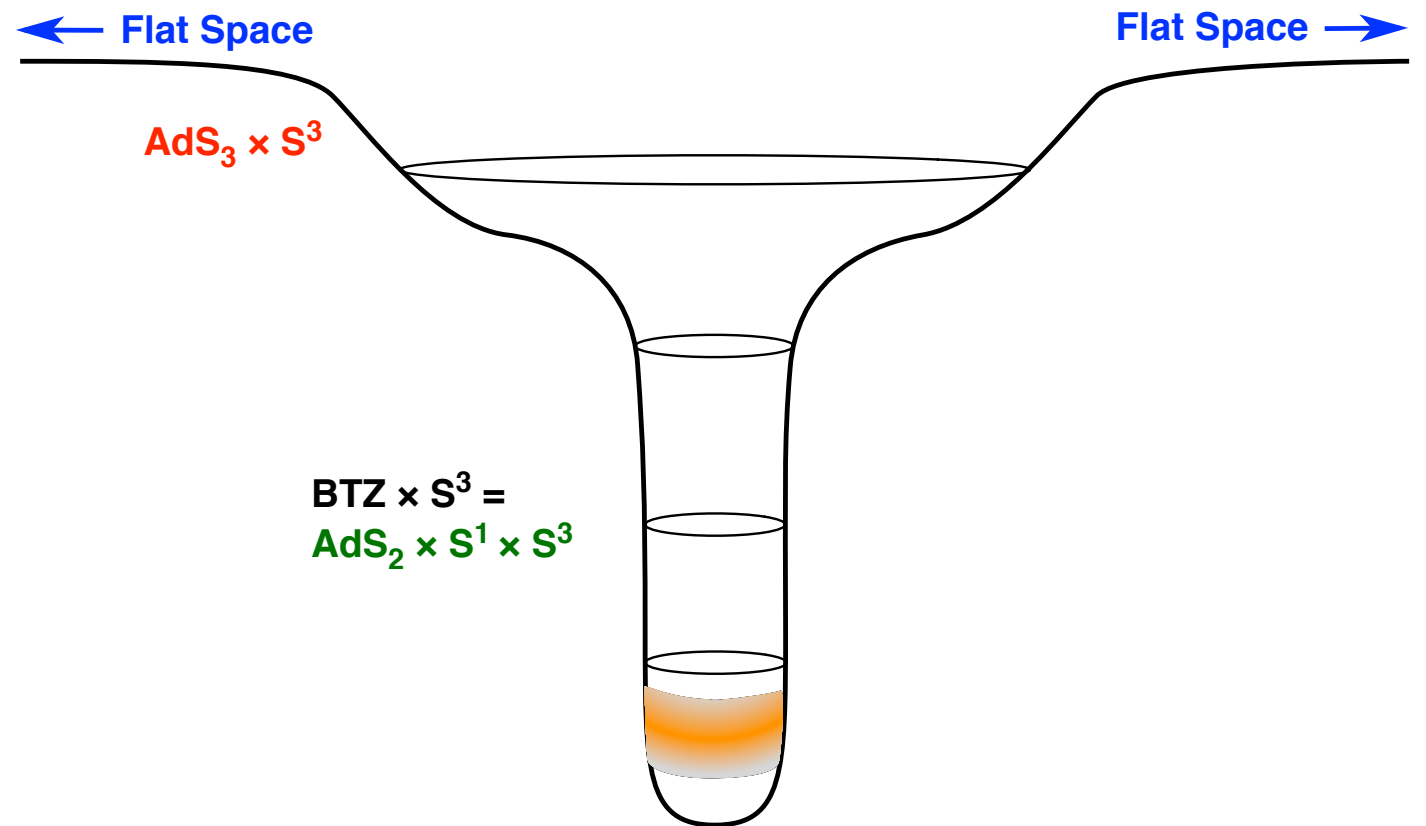
- Frequencies of modes of oscillation of microstrata decrease monotonically below supersymmetric values: Binding energy increases as supersymmetry breaking becomes larger ...

Next Steps ...

- More complicated multi-mode states: transition to chaos in detail

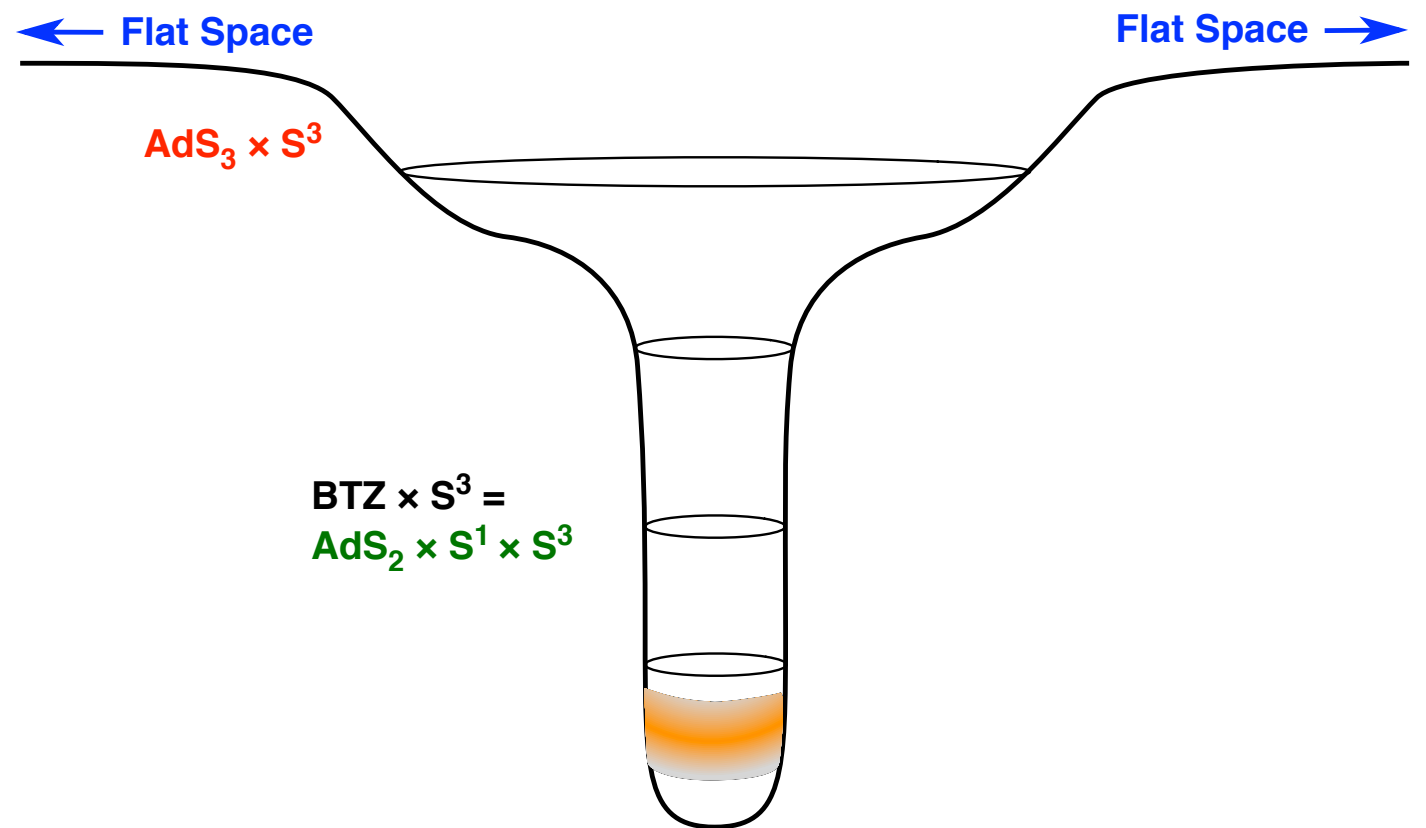
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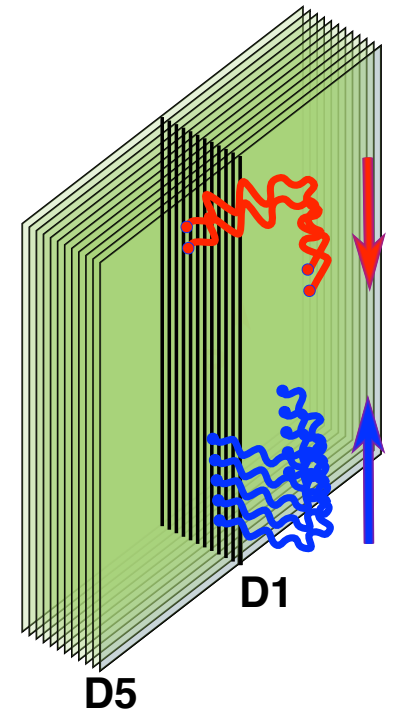
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and compute Decay/“Hawking radiation” as a tunneling process ...

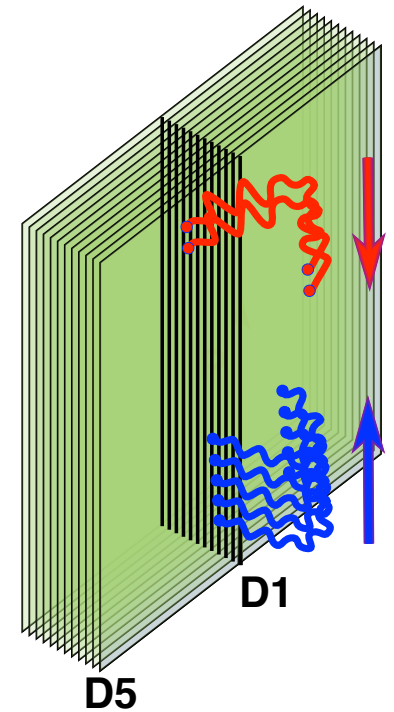
Final comments

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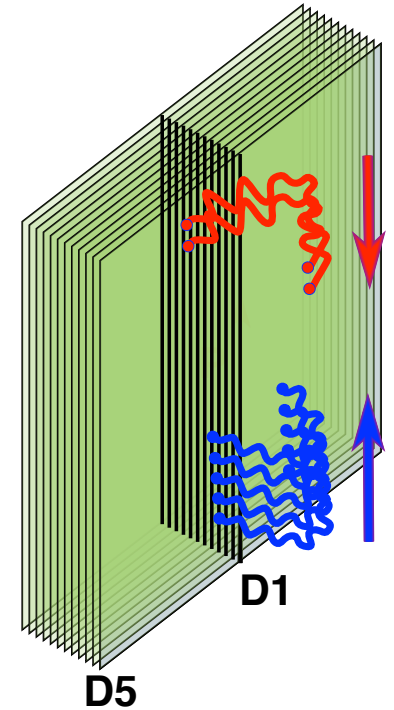
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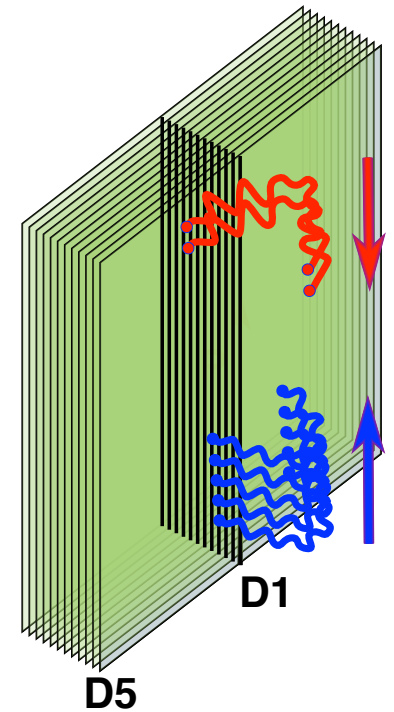
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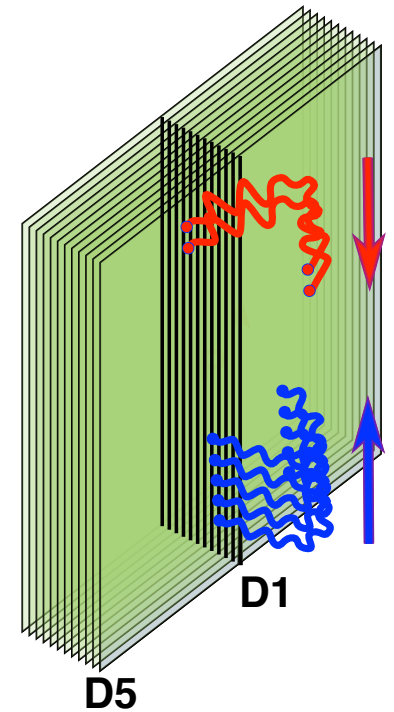
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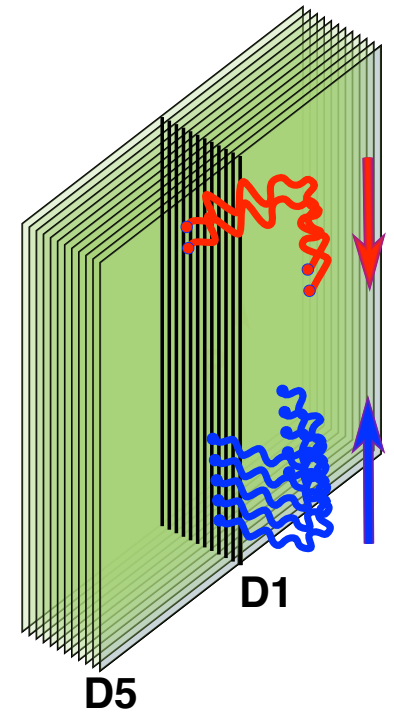
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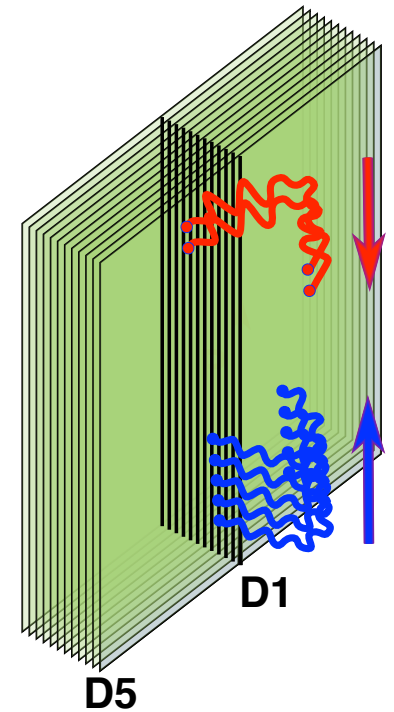
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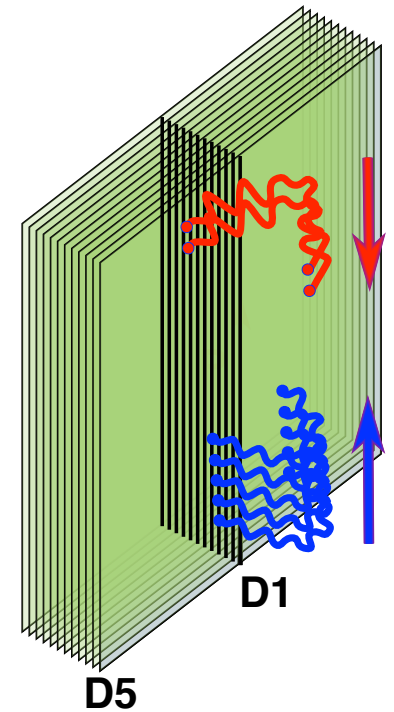
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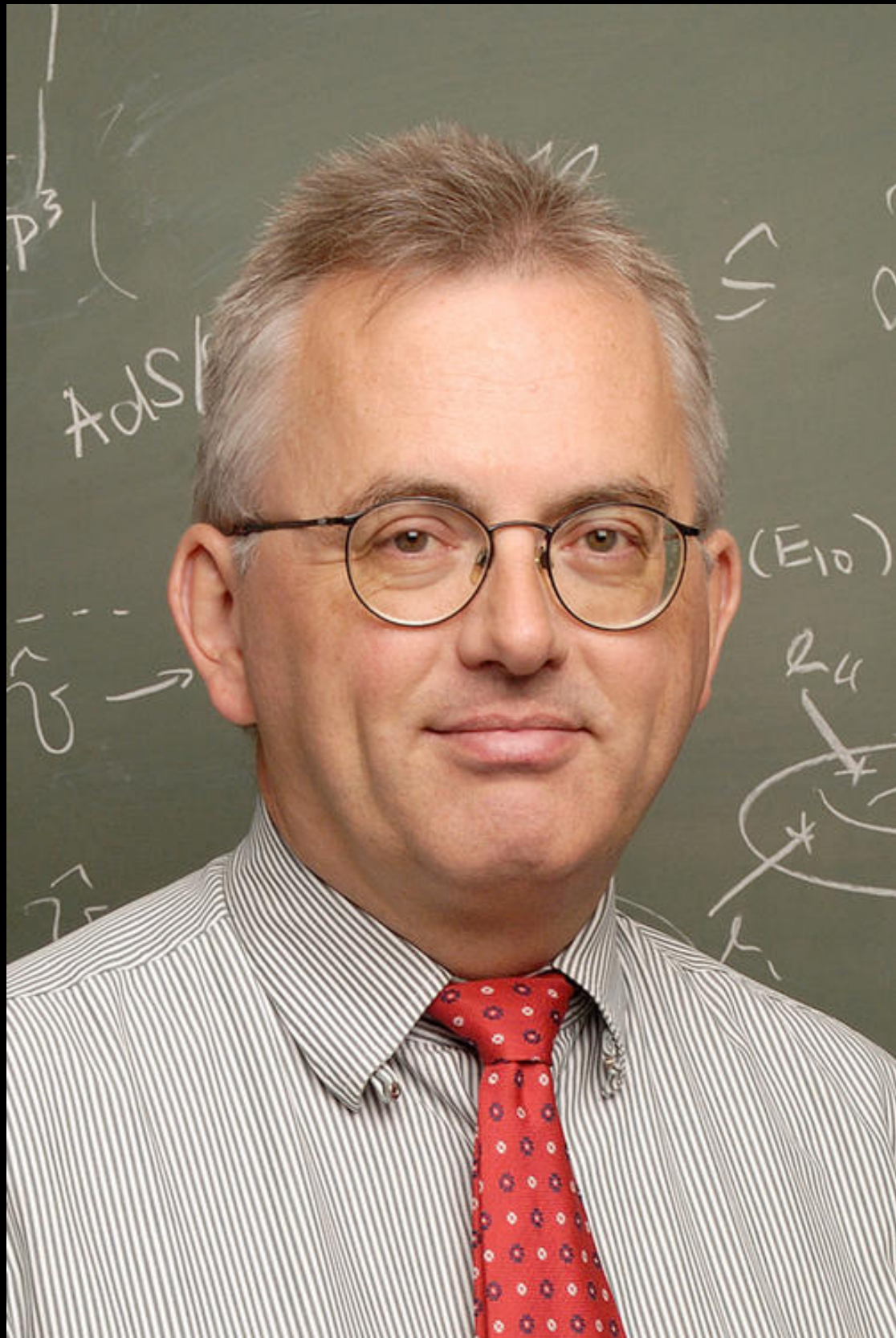
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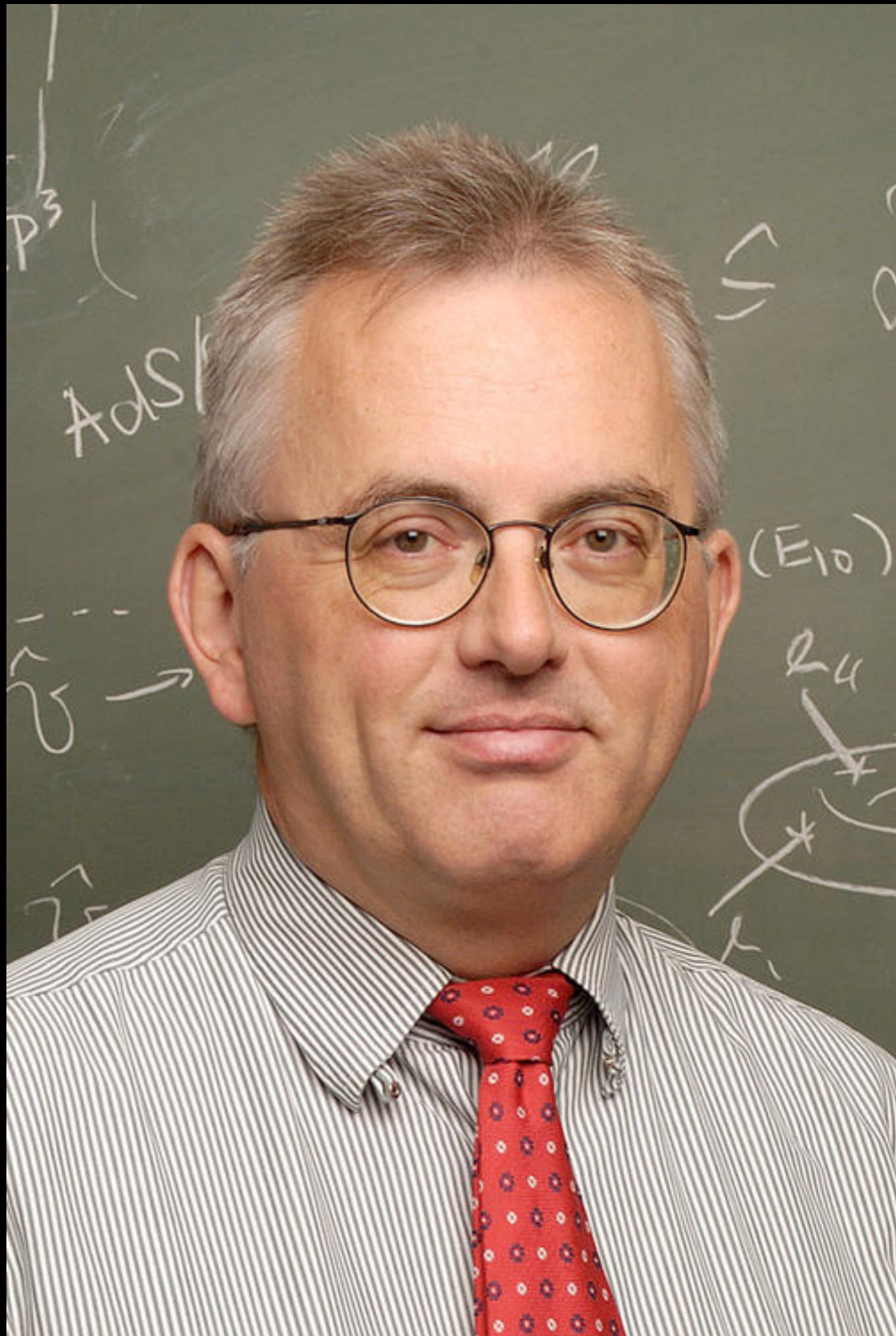
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providing a route to computing the decay as “Hawking Radiation” into flat space



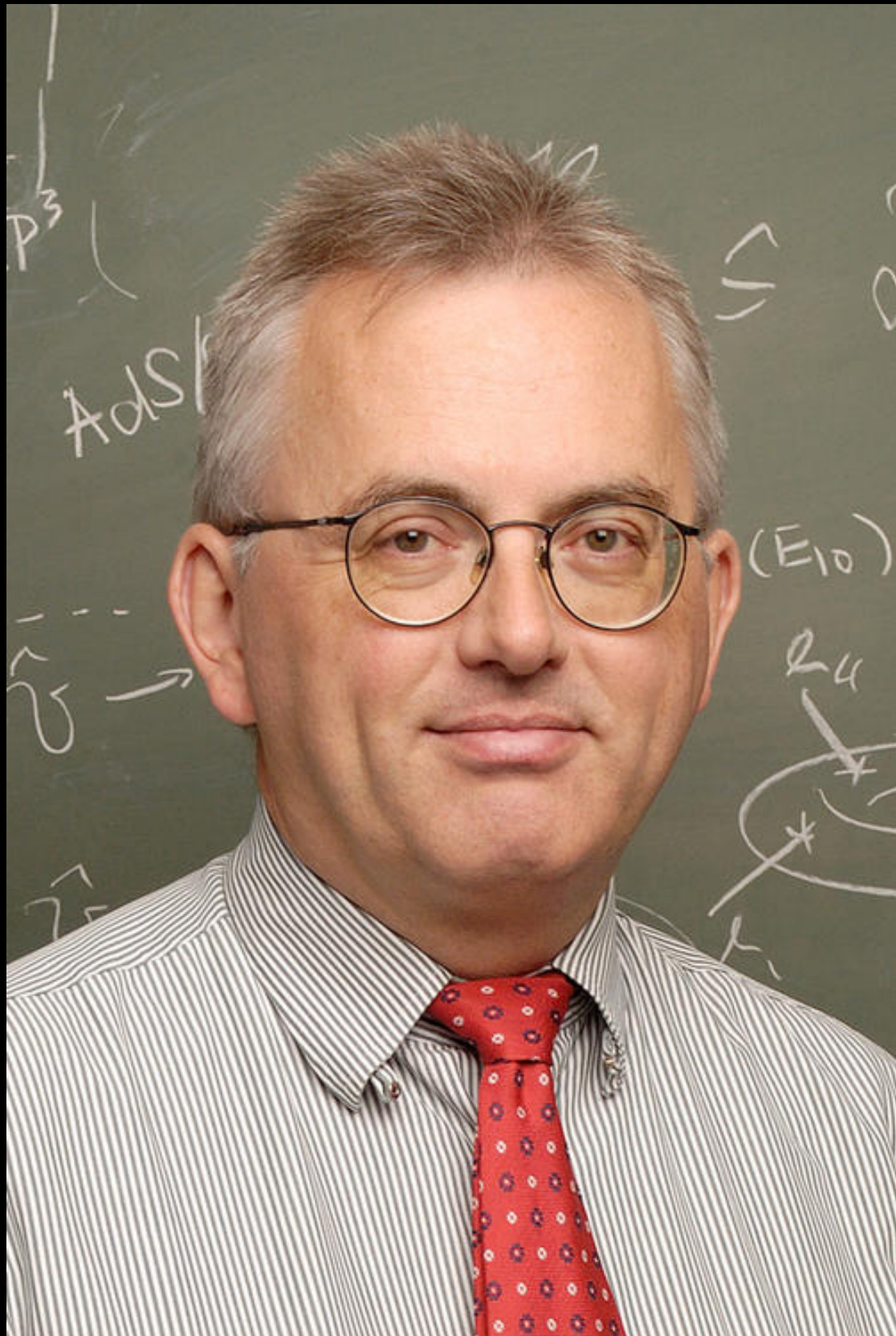


Happy Birthday Hermann!



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*And thank you for your
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