

The background of the slide is a composite image. It features a central black hole with a bright, glowing accretion disk, surrounded by a field of stars and nebulae. Overlaid on this cosmic scene is a large, semi-transparent puzzle that covers most of the slide. The puzzle pieces are interlocking and have a golden-brown border. The overall color palette is dominated by deep blues, purples, and oranges from the cosmic imagery, contrasted with the white and gold of the puzzle.

# *Higher spins Past, Present, and Puzzles*

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*Puzzles  
in the QG landscape*

Graz  
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*Why higher spins?*

# Particles



Elementary excitations over given vacua are classified according to the irreps of the corresponding symmetry group

For maximally symmetric space-time vacua

|               |                       |                |
|---------------|-----------------------|----------------|
| $\Lambda = 0$ | <i>Minkowski</i>      | $IO(D - 1, 1)$ |
| $\Lambda > 0$ | <i>de Sitter</i>      | $O(D, 1)$      |
| $\Lambda < 0$ | <i>Anti-de Sitter</i> | $O(D - 1, 2)$  |

# Particles



Elementary particles in D=4 labeled by two quantum numbers:

Mass  $m \geq 0$

Spin  $s = 0, 1/2, 1, 3/2, 2, 5/2, 3, \dots$

(The ``spin'' label gets more complicated in D>4)

*Natural to investigate the most general (gauge) theory that  
incorporates all spins*

Majorana 1932

*very first paper on relativistic particles with any spin*



... the electron, positron, neutron, and proton, each have a spin of a half, and thus the work of the present paper will have no immediate physical application. All the same, it is desirable to have the equations ready for a possible future discovery [...] or for approximate application to composite particles. Further, the underlying theory is of considerable mathematical interest."

Dirac 1936

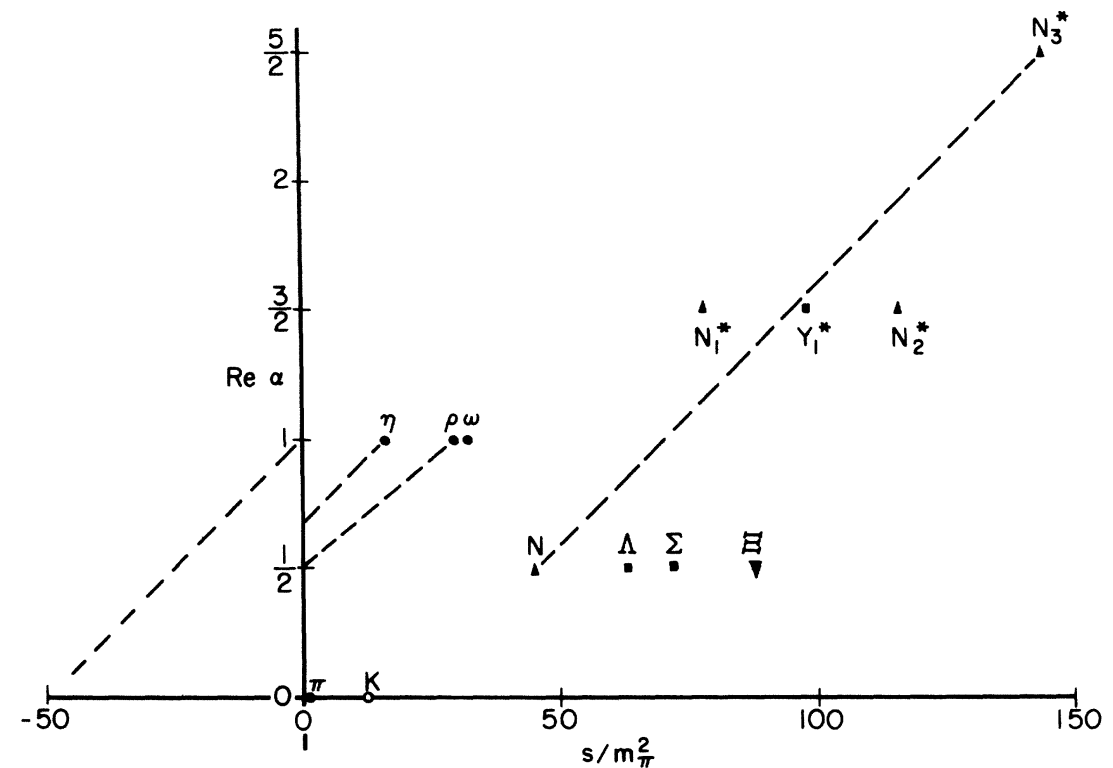


Fierz 1939, Fierz-Pauli 1939, Wigner...

# Massive particles of high spin do exist

Moreover, (strongly interacting) particles of spin higher than 2 are observed since the early 60's, arranging themselves in (approximately) straight lines (*Regge trajectories*) with

$$m^2(s) \sim \frac{1}{\alpha'} s$$



[from *Chew-Frautschi* Phys Rev. Lett. 8 (1962)]

However: they are *not elementary* excitations

# Forces



## *Yang-Mills from Maxwell*

$$\mathcal{L}_{YM} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} = \sum \mathcal{L}_{Maxwell} + \mathcal{O}(A^3) + \mathcal{O}(A^4)$$

$$\delta A_\mu = \partial_\mu \Lambda + \mathcal{O}(A, \Lambda)$$

## *Einstein-Hilbert from Fierz-Pauli*

$$\mathcal{L}_{EH} = \frac{1}{2k} \sqrt{g} R = \mathcal{L}_{Fierz-Pauli} + \mathcal{O}(h^3) + \mathcal{O}(h^4) + \dots$$

$$\delta h_{\mu\nu} = \partial_\mu \Lambda_\nu + \partial_\nu \Lambda_\mu + \mathcal{O}(h, \Lambda)$$

*Abelian gauge symmetries ``know'' about non-Abelian forces*

# Forces ~

*All Abelian gauge symmetries look alike*

*spin 1:*  $\delta A_\mu = \partial_\mu \Lambda$

*spin 2:*  $\delta h_{\mu\nu} = \partial_\mu \Lambda_\nu + \partial_\nu \Lambda_\mu$

*spin 3:*  $\delta \varphi_{\mu\nu\rho} = \partial_\mu \Lambda_{\nu\rho} + \partial_\rho \Lambda_{\mu\nu} + \partial_\nu \Lambda_{\rho\mu}$

$\vdots$

$\vdots$

*spin s:*  $\delta \varphi_{\mu_1 \dots \mu_s} = \partial_{\mu_1} \Lambda_{\mu_2 \dots \mu_s} + \dots$

*What about “high-spin forces”?*

# Plan

I. *Basics*

II. *Higher-spin gravity*

III. *Higher spins and QG*

IV. *Challenges*

V. *Directions*

# Disclaimer:

Too many references... ➡ no references!

*see:*

*Snowmass White Paper:*

*Higher Spin Gravity and Higher Spin Symmetry*

X Bekaert, N Boulanger, A Campoleoni, M Chiodaroli, D F, M Grigoriev, E Sezgin, E Skvortsov

2205.01567 [hep-th]

*Basics*

# *Free theory: the Fierz system*

Fierz 1939

Covariant conditions for massless particles:

$$\delta \varphi_{\mu_1 \cdots \mu_s} = \partial_{(\mu_1} \Lambda_{\mu_2 \cdots \mu_s)}$$

$$\square \varphi_{\mu_1 \cdots \mu_s} = 0$$

$$\partial^a \varphi_{a \mu_2 \cdots \mu_s} = 0$$

$$\varphi^a_{a \mu_3 \cdots \mu_s} = 0$$

$$\square \Lambda_{\mu_1 \cdots \mu_{s-1}} = 0$$

$$\partial^a \Lambda_{a \mu_2 \cdots \mu_{s-1}} = 0$$

$$\Lambda^a_{a \mu_3 \cdots \mu_{s-1}} = 0$$

*single-particle, massless, spin-s degrees of freedom*

# Off the mass shell

spin  $s$ : gauge potential  $\longrightarrow$  symmetric tensor of rank  $s$

$$\delta \varphi_{\mu_1 \dots \mu_s} = \partial_{\mu_1} \Lambda_{\mu_2 \dots \mu_s} + \dots$$

*kinetic ("Ricci") tensor: gauge invariant completion of  $\square \varphi$*

$$\rightarrow \mathcal{F}_{\mu\nu} = \square h_{\mu\nu} - (\partial_\mu \partial^\alpha h_{\alpha\nu} + \partial_\nu \partial^\alpha h_{\alpha\mu}) + \partial_\mu \partial_\nu h^\alpha{}_\alpha$$

$$\mathcal{F}_{\mu\nu\rho} = \square \varphi_{\mu\nu\rho} - (\partial_\mu \partial^\alpha \varphi_{\alpha\nu\rho} + \dots) + (\partial_\mu \partial_\nu \varphi^\alpha{}_{\alpha\rho} + \dots)$$

Fronsdal – single particle

$$\rightarrow M_\mu = \square A_\mu - \partial_\mu \partial^\alpha A_\alpha$$

$$M_{\mu_1 \dots \mu_s} = \square \varphi_{\mu_1 \dots \mu_s} - \partial_{(\mu_1} \partial^\alpha \varphi_{\alpha \mu_2 \dots \mu_s)}$$

Maxwell-like – multi particle

# *The Noether procedure*

Basic idea: construct interactions perturbatively  
while keeping

*locality*

*number of independent  
gauge symmetries*

$$\begin{aligned} S[\varphi] &= S_0[\varphi] + g S_1[\varphi] + g^2 S_2[\varphi] \dots, \\ \delta\varphi &= \delta_0\varphi + g\delta_1\varphi + g^2\delta_2\varphi \dots, \end{aligned}$$

Solving order by order

$$\begin{aligned} \delta_0 S_0[\varphi] &= 0, \\ \delta_1 S_0[\varphi] + \delta_0 S_1[\varphi] &= 0, \\ \delta_2 S_0[\varphi] + \delta_1 S_1[\varphi] + \delta_0 S_2[\varphi] &= 0, \\ \dots \end{aligned}$$

# *The cubic vertex*

General scheme:

- select three fields:  $\varphi^{(s_1)}, \varphi^{(s_2)}, \varphi^{(s_3)}$
- select a total number of derivatives  $n = n_1 + n_2 + n_3$
- impose that the theory keeps the same number of gauge symmetries as in the free case
- compute the consistent vertices  $V_3 \sim \partial^n \varphi_1 \varphi_2 \varphi_3$   
together with the first correction to the gauge transformation

Proceeding this way  
*full classification of allowed cubic vertices*  
for covariant massless fields in D=4;

on flat background:

$$s_1 + s_2 - s_3 \leq \# \partial \leq s_1 + s_2 + s_3$$

$$(s_1 \geq s_2 \geq s_3)$$

Beyond cubic order our knowledge is far less complete

Bottom line: massless higher spins admit a Lagrangian description

- In full generality up to cubic order on  $D=4$ , Minkowski and (A)dS space-time
- In full generality at the free level on  $D>4$  Minkowski space-time  
*(the general free fermionic Lagrangian in any  $D$  first written in 2009)*
- only for simple classes of massless particles in  $D>4$  (A)dS space-time

*What's next?*

*Higher-spin gravity*

# *Building interacting theories*

Schematically, three options



Geometric intuition

GR 1915



Perturbative construction

SUGRA 1976



Gauge theory of an assigned  
non-Abelian algebra

YM 1954

# Vasiliev's higher-spin theory ( $\mathcal{D}=4$ )

➔ Based on non-abelian gauge algebras with tensorial generators:

$$\textit{spin } 1: \quad T^a \qquad \qquad \textit{spin } 2: \quad T^a_{\mu} \qquad \qquad \textit{spin } s: \quad T^a_{\mu_1 \dots \mu_s}$$

*s.t.*

$$[T_{s_1}, T_{s_2}] = T_{s_1+s_2-1} + T_{s_1+s_2-3} + \dots + T_{|s_1-s_2|+1}$$

➔ Maximal finite subalgebra contains up to spin 2; beyond that, unbounded spin

➔ If higher spins are present, spin 2 is unavoidable; e.g.  $[T_2, T_2] = T_3 + T_1$

*higher-spin gravity*

# Vasiliev's higher-spin theory ( $\mathcal{D}=4$ )

→ Extends the Cartan formulation of GR

$$e^a \longrightarrow e^{a_1 \dots a_{s-1}}$$

including generalised spin connections and torsion constraints

→ Non-linear, non-Lagrangian, gauge-invariant equations are provided. In the free limit they do describe free massless higher spins (unbounded spectrum)

However, fields are generating functions in an **extended** space that includes

→ spacetime together with two sets of **auxiliary commuting spinor variables**:  
*not easy nor fully clear how to read off couplings among physical fields*

# Other higher-spin gravities

## → *Chiral models*

Higher-spin analogues of self-dual YM and gravity, giving up parity and unitarity. Non-trivial vertices to all orders; tree-level amplitudes vanish for real momenta

## → *Conformal higher-spin theories*

Higher-spin generalisations of conformal gravity, non-unitary due to higher derivatives. Non-trivial local interactions coexist with cancellations of on-shell amplitudes

## → *Bilocal higher-spin model*

Higher-spin fields emerge as collective variables of a free large-N vector model. Bilocal boundary degrees of freedom reconstruct an interacting higher-spin theory in the bulk

*Higher spins & QG*

Higher-spin gravity is governed by infinite-dimensional gauge algebras involving tensorial generators of arbitrarily high rank. Invariance under such a large symmetry is extremely constraining

✧ *downside:* *too many constraints may forbid nontrivial dynamics*

✧ *upside:* *conceivable that the same symmetries may tame the UV divergences of gravity*

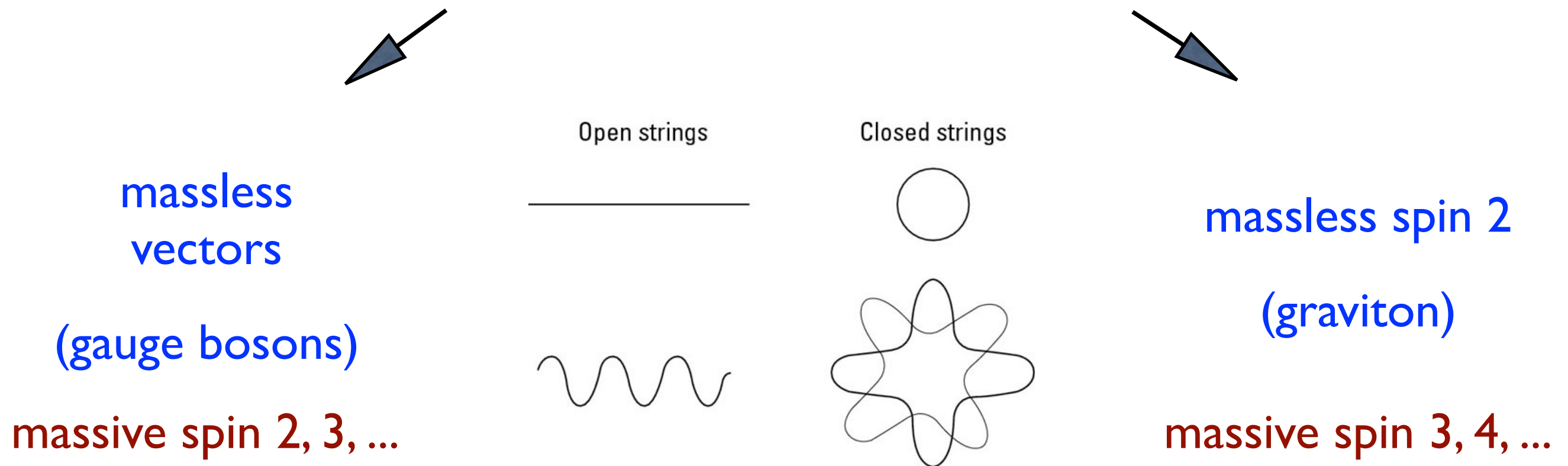


This (unresolved) tension lies at the heart of higher spin theory

What we do know is that both String Theory and Holography  
provide remarkable indications of the  
relevance of higher spins to quantum gravity

# *String theory “predicts” higher spins*

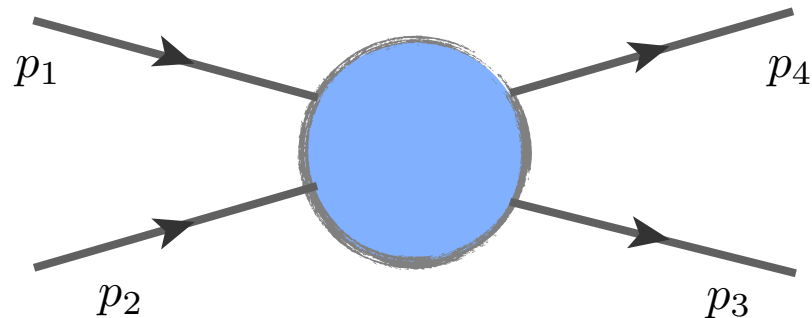
1st quantisation of its vibrating modes  $\rightarrow$  relativistic particles



string solution to unification of interactions and UV finiteness  
involves particles with all possible spins

# Higher-spins & UV behaviour

Taking seriously into account the possibility of exchanging particles of arbitrary spin  $J$ :



$$s = -(p_1 + p_2)^2$$

$$t = -(p_2 + p_3)^2$$

$$\mathcal{A}(s, t) \sim \sum_J g_J^2 \frac{(-s)^J}{t - m_J^2}$$

*tree level, large  $s$  and fixed  $t$*

- \* **UV finiteness:** the sum of infinitely many worse and worse behaved propagators might lead to soft UV result!
- \* **planar duality:** only if infinitely many spins are present one may have singularities in the s-channel s.t.  $\mathcal{A}(s, t) \sim \hat{\mathcal{A}}(t, s)$ ,

explicit realisation: Veneziano formula

There are a number of relevant differences with higher-spin gravities: background (flat vs AdS), spacetime dimension, spectrum...

*Two central questions:*



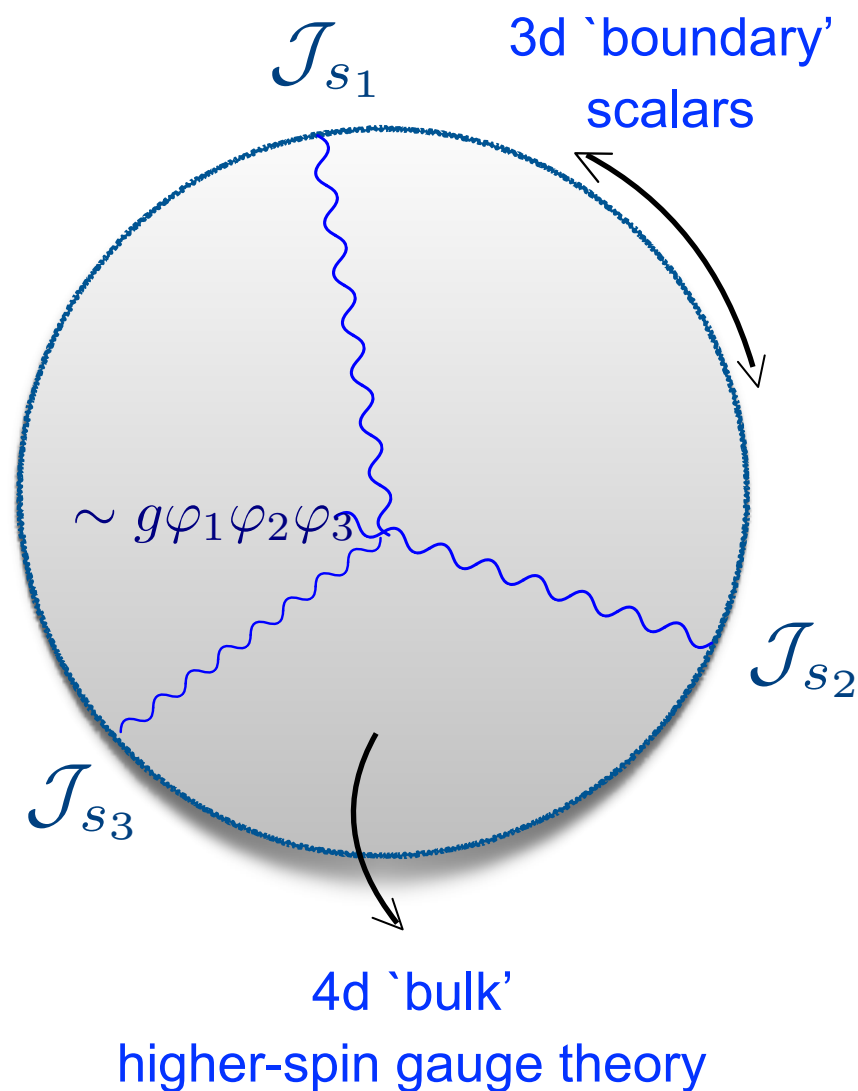
*is ST a higher-spin gauge theory with spontaneously broken higher-spin symmetry?*

Gross and Mende 1987, 88



*is ST the only possible higher-spin UV completion of gravity, or are there simpler, UV-finite, higher-spin quantum gravitational theories?*

# Holography ‘predicts’ higher-spin bulk couplings



## Free scalars in $D = 3$

- Conformal invariant
- On top of the conserved energy-momentum tensor, conserved currents of arbitrarily high spin.
- Non-vanishing correlators of conserved currents dual to non-trivial vertices for corresponding gauge fields in 4d AdS bulk

# Higher-spins & holography

Various dualities in D=4, 3 studied in the last fifteen years

- ✧  $AdS_4/CFT_3$  Conformal, 3D theories of N scalars in the fundamental of O(N) (large N) vs massless hsp in  $AdS_4$
- ✧  $AdS_3/CFT_2$  3D higher-spin theories are special:
  - they *admit an action principle*, which is Chern-Simons-like
  - they *admit* consistent truncations to *finite number of spins*
- ✧ For various one-loop quantities, UV divergences cancel after summing over the full higher-spin spectrum with a suitable regularisation

*Challenges*

Noether method, holography, strings....

*a mixed blessing for higher spins*

➔ Noether method: *what happens beyond cubic order?*

➔ Holography: *does exact HS symmetry trivialise the dynamics?*

➔ Strings: *can one really define a sensible tensionless limit?*

## *Two main challenges:*

Generalised symmetry /  
S-Matrix arguments  
(*Coleman-Mandula;*  
*Maldacena-Zhiboedov*)



unbroken higher-spin  
symmetries strongly constrain  
scattering and correlators  
toward trivial/free-theory  
behaviour

Locality of vertices  
beyond cubic order



On both flat and (A)dS  
backgrounds, strong indications  
that preserving higher-spin  
gauge symmetry requires  
non-local vertices

*Ultimate no-go theorems – or glimpses of new rules?*

*Directions*



# *A few perspectives*

- ★ *Rotating black holes*  
higher-spin fields on Kerr backgrounds, superradiance and black-hole spectroscopy
- ★ *Massive higher spins (as EFTs)*  
consistency bounds, scattering amplitudes and the range of validity of the effective theory
- ★ *Early-universe cosmology*  
massive spinning particles as probes of inflation and primordial correlators
- ★ *Deformation quantization*  
star products, higher-spin algebras and the structure of interactions

Personally:

higher-spin gauge symmetry breaking

a central open problem in higher-spin theory



For a broader range of perspectives, see the panel discussion we had in Yerevan two weeks ago!

<https://yerevan2026.yerphi.am/>

