Unitary quantum conformal BMS_3 field theories

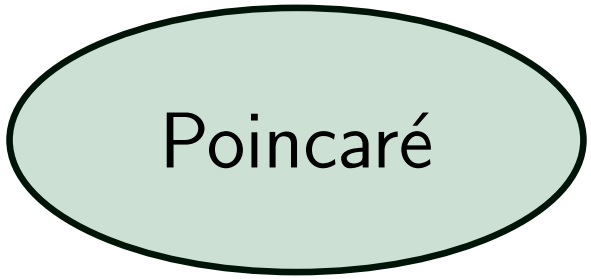
Daniel Grumiller

Institute for Theoretical Physics
TU Wien

Harvard U., Simons Collaboration on Celestial Holography
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FWF

with Iva Lovrekovic 2609.07828


Poincaré

Motivation 1: Extensions of Poincaré symmetries

- symmetries constrain QFTs (Poincaré, conformal, BMS, ...)

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"... the most fundamental equation of relativistic QFT" Schwinger '63

$$[\mathcal{H}(x),\, \mathcal{H}(x')] = \delta^{ij} \left(\mathcal{H}_i(x) + \mathcal{H}_i(x')\right) \partial_j \delta(x - x')$$

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Strominger '13

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BPZ '84; yellow book by Di Francesco, Mathieu, and Sénéchal

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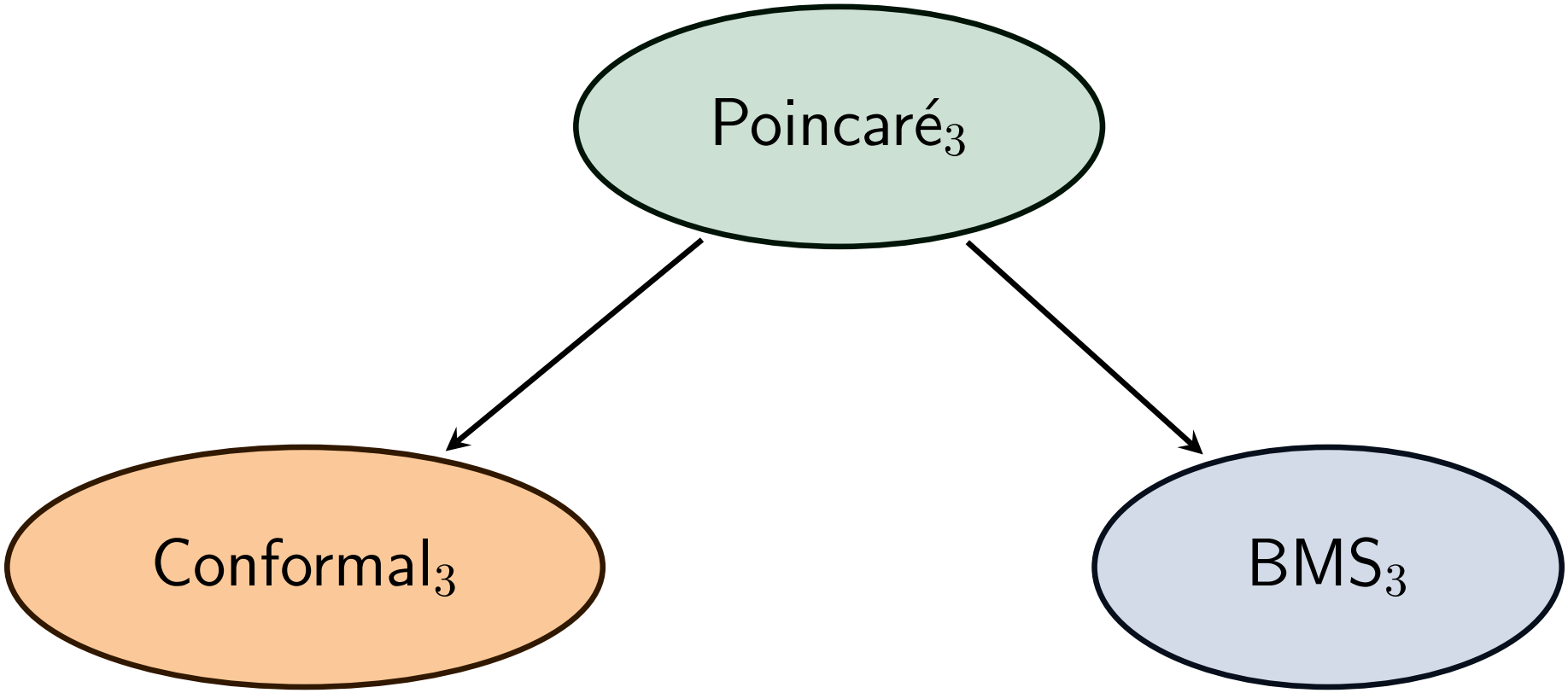
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  $c < 1$: minimal models, $c = 1$: Ginsparg list, $c > 1$: many examples but no classification

see Eberhardt, Livine '26

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Goal: join conformal and asymptotic symmetries to get more constraints on unitary QFTs compatible with these symmetries


Poincaré$_3$
Conformal$_3$
BMS$_3$

Motivation 2: Gravity in 3d as a toy model for holography

Overarching question: how general is holography?

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Gravity in 3d offers

- states with horizons (BTZ, FSC, warped BHs, ...)

Bañados, (Henneaux), Teitelboim, Zanelli '92-'93; Cornalba, Costa '02; Anninos, Li, Padi, Song, Strominger '08; ...

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Brown, Henneaux '86; Barnich, Compere '06; Compere, Song, Strominger '13; Troessaert '13; ...

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Strominger '97; Carlip '98; Bagchi, Detournay, Fareghbal, Simon '12; Barnich '12; Shaghoulian '15; ...

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Maldacena, Ooguri '00-'01; Bagchi, Detournay, Grumiller '12; Detournay, Hartman, Hofman '12; ...

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- graviton excitations (at least off-shell)

Maloney, Witten '07; Barnich, Gonzalez, Maloney, Oblak '15; Cotler, Jensen '18; ...

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- scattering when coupled to matter fields (Maxwell, Klein-Gordon, ...)

Bosma, Geiller,Majumdar, Oblak '23; Hao, Shinmyo, Suzuki, Takahashi, Takayanagi '25

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  prime example: Brown–Henneaux '86 as precursor of $\text{AdS}_3/\text{CFT}_2$

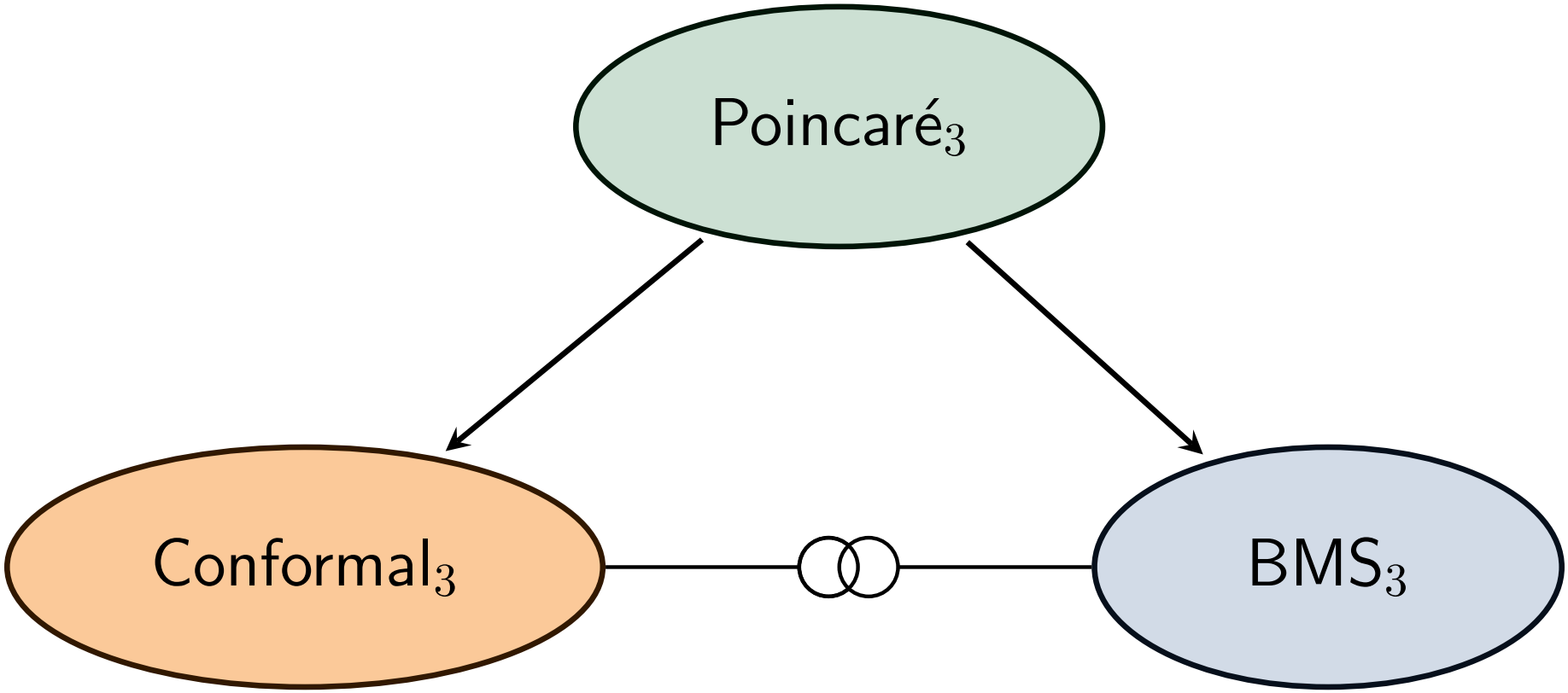
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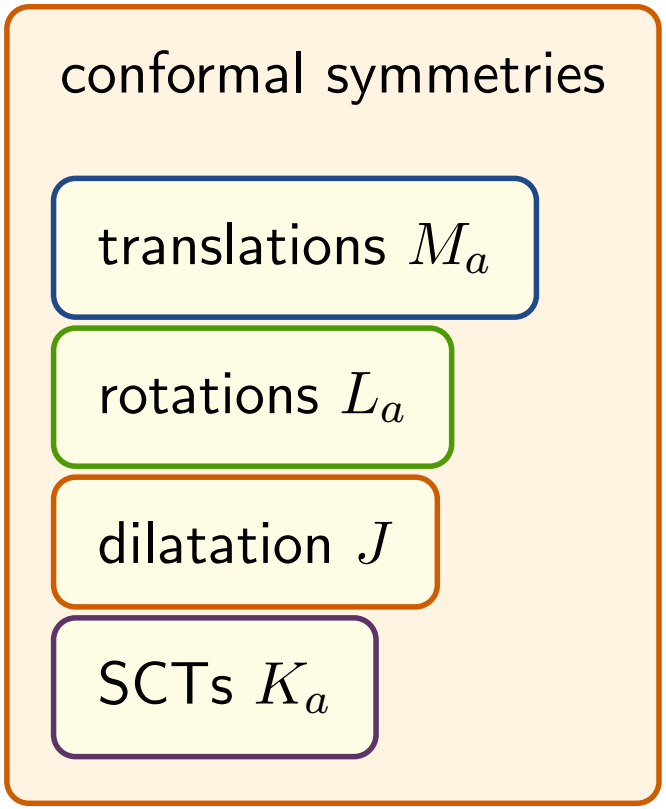
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Goal: join conformal and asymptotic symmetries in 3d gravity


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Conformal$_3$
BMS$_3$

Merging conformal and asymptotic symmetries

Conformal BMS_3 symmetries



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Conformal BMS_3 symmetries

conformal symmetries

- translations M_a
- rotations L_a
- dilatation J
- SCTs K_a

asymptotic symmetries (3d)

- super-translations M_n

BMS '62

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More specific goal: study unitary field theories with symmetries L_n, J_n, M_n, K_n dubbed "conformal BMS_3 symmetries"

Interlude: Chern–Simons formulation

Many 3d gravity theories have classical formulations as CS theories

$$I_{\rm CS}[A] = \frac{k}{4\pi} \int \langle A \wedge {\rm d}A + \tfrac{2}{3}\, A \wedge A \wedge A \rangle$$

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Choice of gauge group determines which gravity theory:

- $\mathrm{SO}(3,1)$ [$\mathrm{SO}(2,2)$]: [A]dS$_3$ Einstein gravity

  Achucarro, Townsend '86; Witten '88

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Horne, Witten '89

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- $\mathrm{SL}(N) \times \mathrm{SL}(N)$: AdS$_3$ higher spin gravity

  Henneaux, Rey '10; Campoleoni, Fredenhagen, Pfenninger, Theisen '10

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Afshar, Bagchi, Fareghbal, Grumiller, Rosseel '13; Gonzalez, Matulich, Pino, Troncoso '13

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Choice of boundary conditions determines symmetries of dual QFT:

- typical setup: $A = b^{-1}(\mathrm{d}+a)b$, $\delta b = 0$, $\delta a \neq 0$, $b = b(r)$,
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  see e.g. Bañados '99

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- soft Heisenberg: $a = J^+(\varphi)L_0\;\mathrm{d}\varphi + \ldots$
- general: $a = (\mathcal{L}^+(x^+,x^-)L_+ + \mathcal{L}^0(x^+,x^-)L_0 + \mathcal{L}^-(x^+,x^-)L_-)\,\mathrm{d}x^+ + \ldots$

see Grumiller, Riegler '16

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Focus on conformal gravity in this talk

Classical conformal BMS_3 as asymptotic symmetries of conformal gravity

- Fuentealba–Gonzalez–Perez–Tempo–Troncoso boundary conditions:

$$a_\varphi = L_+ - \big(\mathcal{L}(t,\varphi) - \mathcal{J}^2(t,\varphi)\big)\, L_- - \mathcal{M}(t,\varphi)\, M_- - \mathcal{K}(t,\varphi)\, K_- - \mathcal{J}(t,\varphi)\, J_0$$

- generators of $so(3,2)$: rotations/boosts L_+, L_0, L_-, translations M_+, M_0, M_-, SCTs K_+, K_0, K_-, dilatations J_0 $\qquad a, b \in \{-1, 0, 1\}$

$$\begin{aligned}
[L_a,\, L_b] &= (a-b)\, L_{a+b} \\
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- asymptotic symmetry algebra $\qquad n, m \in \mathbb{Z}$

$$\begin{aligned}
[L_n,\, L_m] &= (n-m)\, L_{n+m} + \frac{c}{12}\,\big(n^3 - n\big)\,\delta_{n+m,\,0} \\
[L_n,\, J_m] &= -m\, J_{n+m} \\
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  also: $|c| = \infty$ eliminates all nonlinear terms

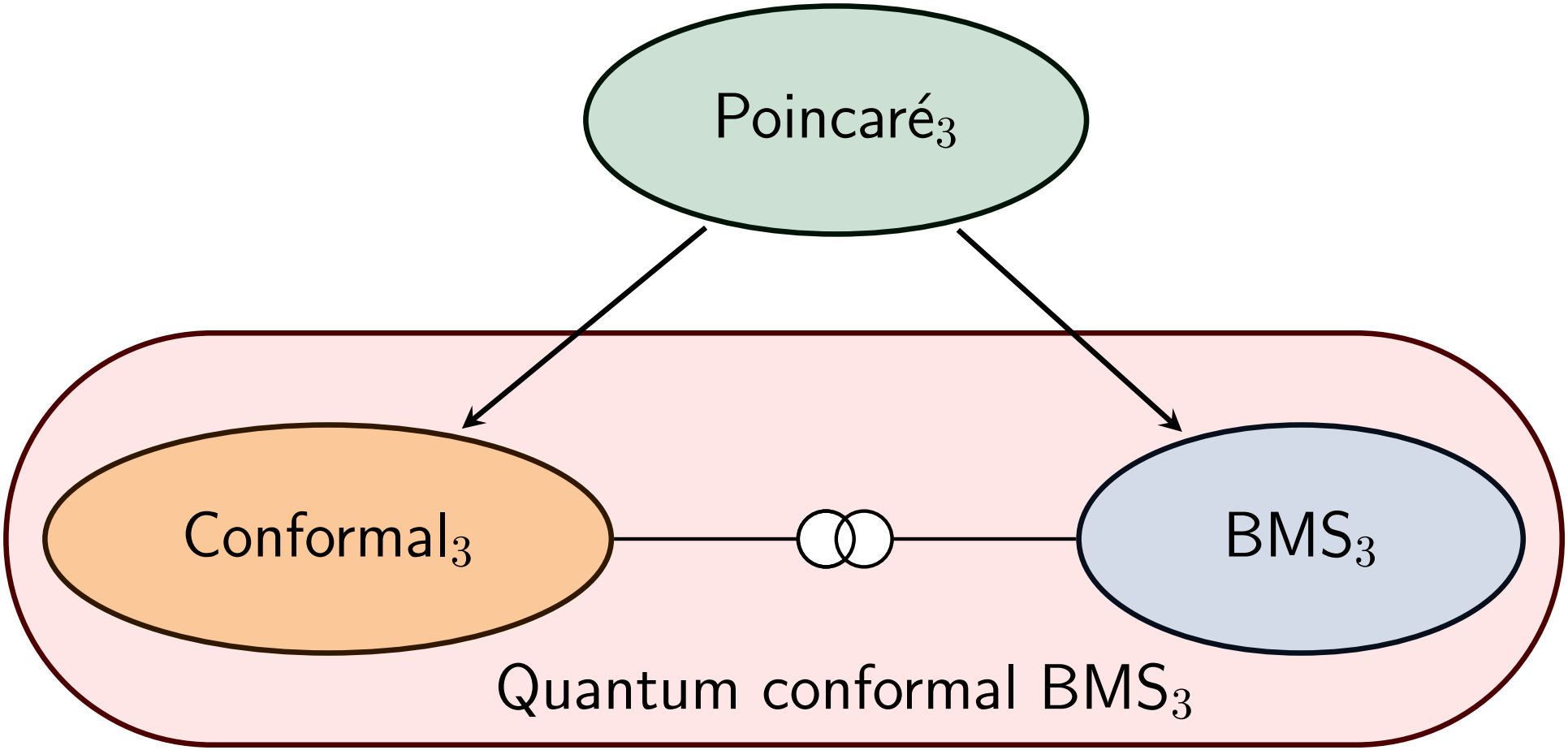
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Consider finite c and quantum version of conformal BMS_3


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Quantum conformal BMS$_3$

Quantum conformal BMS_3 algebra (aka $W_{(2,2,2,1)}$) Fasquel '20

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&\quad + \frac{c}{12k}\left(n^2 + m^2 - nm - 1\right) J_{n+m} + \text{nonlinear terms}
\end{aligned}
$$

c: Virasoro central charge; k: $\hat{u}(1)$ level

Chiral CFT subalgebra

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BMS$_3$/Carroll CFT$_2$ subalgebra

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Quantum conformal BMS_3 algebra (aka $W_{(2,2,2,1)}$) Fasquel '20

warped conformal subalgebra

$$
\begin{aligned}
[L_n,\, L_m] &= (n-m)\, L_{n+m} + \frac{c}{12}\left(n^3 - n\right)\delta_{n+m,\,0} \\
[L_n,\, J_m] &= -m\, J_{n+m} \\
[L_n,\, M_m] &= (n-m)\, M_{n+m} \\
[L_n,\, K_m] &= (n-m)\, K_{n+m} \\
[J_n,\, J_m] &= k\, n\, \delta_{n+m,\,0} \\
[J_n,\, M_m] &= M_{n+m} \\
[J_n,\, K_m] &= -K_{n+m} \\
[M_n,\, M_m] &= [K_n,\, K_m] = 0 \\
[M_n,\, K_m] &= \frac{c}{12}\left(n^3 - n\right)\delta_{n+m,\,0} + (n-m)\, L_{n+m} \\
&\quad + \frac{c}{12k}\left(n^2 + m^2 - nm - 1\right) J_{n+m} + \text{nonlinear terms}
\end{aligned}
$$

c: Virasoro central charge; k: $\hat{u}(1)$ level

Quantum conformal BMS$_3$ algebra (aka $W_{(2,2,2,1)}$) Fasquel '20

wedge algebra is conformal algebra $so(3,\,2) \simeq \mathfrak{sp}(4)$ $a, b \in \{-1,\,0,\,1\}$

$$
\begin{aligned}
[L_a,\,L_b] &= (a-b)\,L_{a+b} \\
[L_a,\,J_0] &= 0 \\
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[M_a,\,M_b] &= [K_a,\,K_b] = 0 \\
[M_a,\,K_b] &= (a-b)\,L_{a+b} - \left(a^2+b^2-ab-1\right) J_0
\end{aligned}
$$

commutator with all nonlinear terms:

$$[M_n,\, K_m] = \frac{c}{12}\left(n^3 - n\right)\delta_{n+m,\,0} + (n-m)\, L_{n+m}$$
$$+ \frac{c}{12k}\left(n^2 + m^2 - nm - 1\right) J_{n+m} + \frac{1 - \frac{c}{4k}}{c-1}\,(n-m)\,\Lambda^{(2)}_{n+m}$$
$$+ \frac{c\,(4k-1)}{2k^2\,(c-1)}\,\Lambda^{(3,p)}_{n+m} + \frac{c}{3k^2}\,\Lambda^{(3,q)}_{n+m}\,.$$

with composite operators

weight-2 primary: $\Lambda^{(2)}_n = L_n - \frac{c}{2k}\sum_r :J_{n-r}\,J_r:$

weight-3 primary: $\Lambda^{(3,p)}_n = \sum_r :L_{n-r}\,J_r: \; - \frac{c+2}{6k}\sum_{r,s} :J_{n-r-s}\,J_r\,J_s:$

weight-3 quasi-primary: $\Lambda^{(3,q)} = \sum_{r,s} :J_{n-r-s}\,J_r\,J_s:$

and usual normal order prescription for any operator $\mathcal{O}_n \in \{L_n, J_n, M_n, K_n\}$

$$:\mathcal{O}_{n-r}\,J_r: \;= \begin{cases} \mathcal{O}_{n-r}\,J_r \text{ if } r \geq 0 \\ J_r\,\mathcal{O}_{n-r} \text{ if } r < 0 \end{cases} \qquad :\mathcal{O}_{n-r-s}\,J_r\,J_s: \;= \begin{cases} :\mathcal{O}_{n-r-s}\,J_r:\; J_s \text{ if } s \geq 0 \\ J_s\,:\mathcal{O}_{n-r-s}\,J_r:\; \text{ if } s < 0 \end{cases}$$

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- also central charged fixed by Jacobi id's but literature somewhat confusing
  1. Fasquel '20: $c = -12k + 4 - 30/(k+3)$
  2. Fuentealba et al '20: $c = k + \mathcal{O}(1)$
  3. Yu, Chen '22: $c = -12k + 4$
  4. Gupta, Suryanarayan '23: $c = -12k + 28 - 30/(k+1)$

1,2,4 correct but use different conventions for c and k, e.g., $k_{\text{Fasquel}} + 2 = k_{\text{GS}}$

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- correct result

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features level duality

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Consider next automorphisms of quantum conformal BMS_3

Three automorphisms of quantum conformal BMS_3

1. Rescaling: $M_n \to \lambda M_n$, $K_n \to K_n/\lambda$
   important lesson: M_0 eigenvalues not good quantum numbers

   unlike Carroll CFT_2

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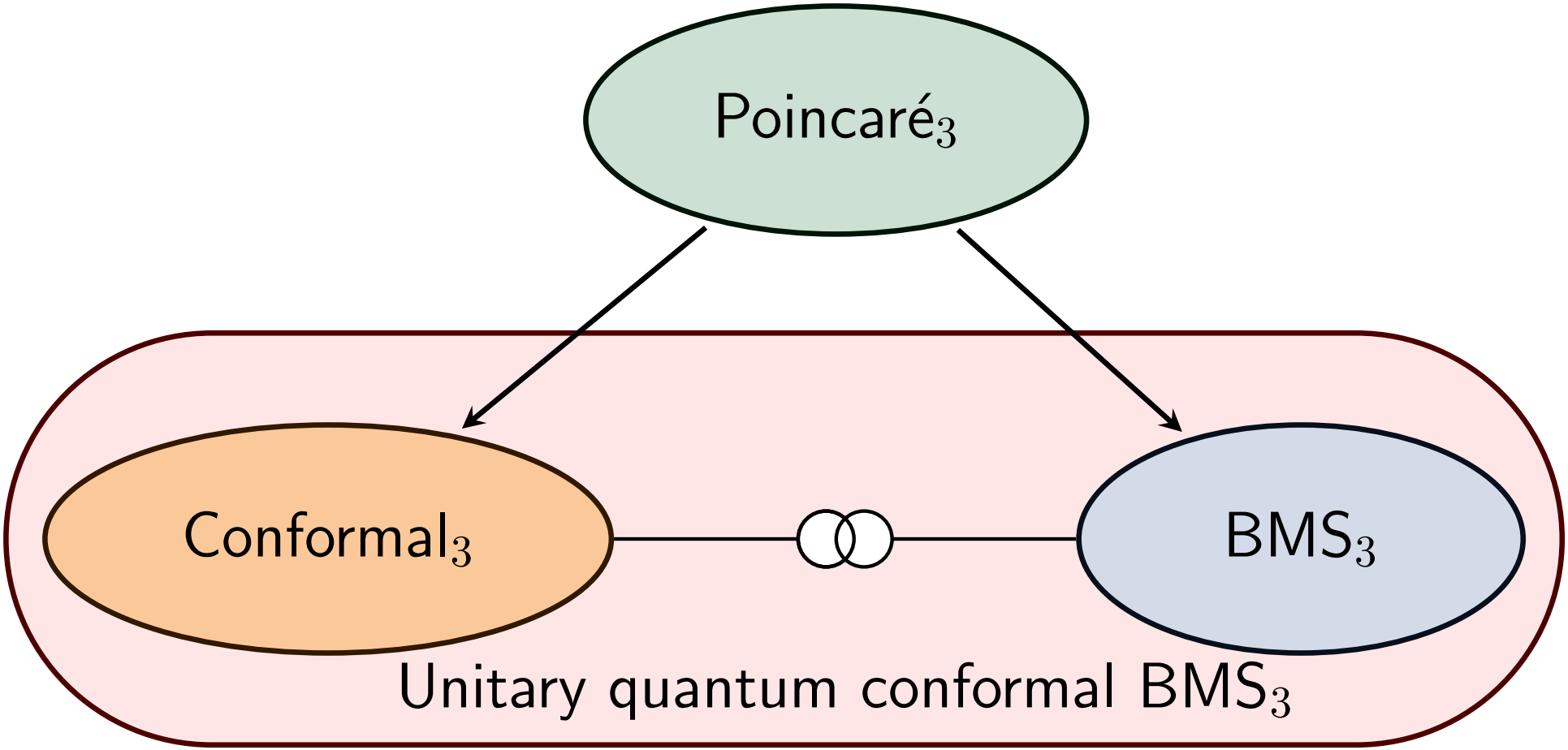
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physical states labeled like in warped CFT:

$$J_0\,|\psi\rangle = q\,|\psi\rangle \qquad L_0\,|\psi\rangle = h\,|\psi\rangle$$

primary conditions: $L_n|q,\,h\rangle = J_n|q,\,h\rangle = M_n|q,\,h\rangle = K_n|q,\,h\rangle = 0 \quad \forall n \geq 1$
spectral flow (naively): $h \to h - q + \frac{k}{2} \qquad q \to q - k$


Poincaré$_3$
Conformal$_3$
BMS$_3$
Unitary quantum conformal BMS$_3$

Restrictions from unitarity

- $c \geq 1$

$$\frac{1}{4} \leq k \leq 1 \qquad \text{or} \qquad k < -1$$

Restrictions from unitarity

- $c \geq 1$ and $k \geq 0$

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  no semi-classical values of c compatible with unitarity

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Only four candidates for unitary quantum conformal BMS_3 field theories

Spectral flow of modules $L(q,\, h)$

- modules $L(q,\, h)$ labeled by labels of primary with additional lowest-charge condition

$$K_0|q,\, h\rangle = 0$$

modules contain at least one primary and all their descendents

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- top space of module contains i primaries given by

$$M_0^j|q,\, h\rangle \qquad j = 0, 1, \ldots, i-1$$

dimension of top space i given by lowest positive integer $i_\pm, i_0$:

$$i_\pm = \tfrac{1}{2} - q \pm \sqrt{\tfrac{1}{4} + k(k-1) - q(q-1) + 2h(k+1)} \qquad i_0 = 1 - 2q$$

restricts k, q, h to certain rational values

also, if $i = 1$ and q is known (and not half-integer) we deduce the weight

$$h = \frac{q^2 - \frac{1}{2}k(k-1)}{k+1}$$

similar formulas work for other values of i

Spectral flow of modules $L(q,\, h)$

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- action of spectral flow on module $L(q,h)$:

$$\psi\big(L(q,\, h)\big) = L(q+i-1-k,\, h-q-i+1+\tfrac{k}{2})$$

where $i =$ dimension of top space of $L(q,h)$

Spectrally flowing from the vacuum — all primaries of CFT I

- applying spectral flow successively to vacuum module $L(0,0)$ yields

$$L(0,\,0) \xrightarrow{\psi} L(-k,\,\tfrac{k}{2}) \xrightarrow{\psi} L(-2k,\,2k) \xrightarrow{\psi} ?$$

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  we get three non-vacuum modules, two with $i = 1$, $L(\pm\frac{1}{4}, \frac{1}{8})$, and one with $i = 2$, $L(-\frac{1}{2}, \frac{1}{2})$

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- thus, we obtain four non-vacuum primaries on the vacuum orbit of spectral flow:

$$\text{CFT I:}\quad |\pm\tfrac{1}{4},\,\tfrac{1}{8}\rangle \qquad\qquad |\pm\tfrac{1}{2},\,\tfrac{1}{2}\rangle$$

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Fasquel '20

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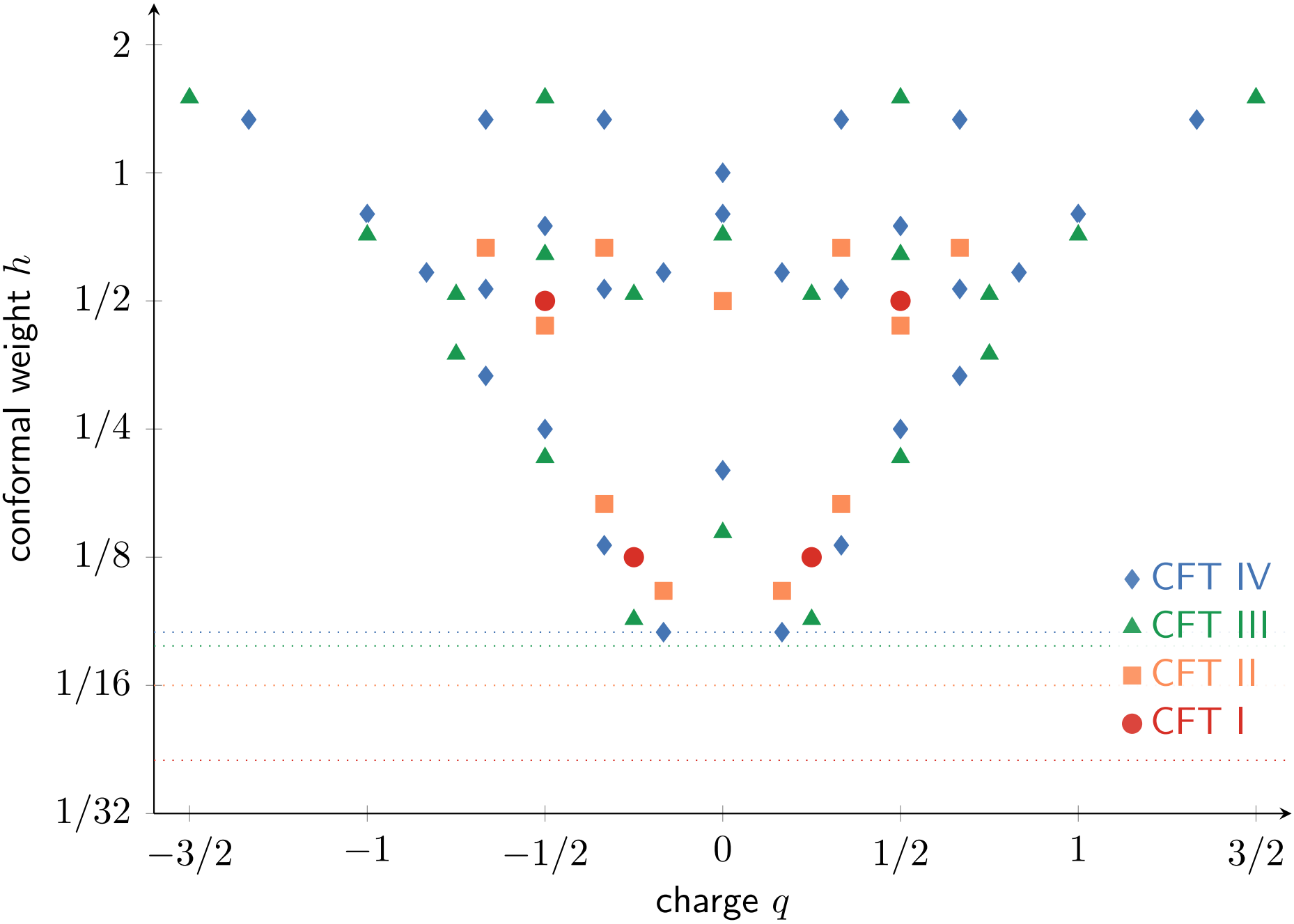
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- for CFT II, III, IV get 2, 3, 4 spectral flow orbits Fasquel '20
- obtain all primary states from spectral flow


conformal weight h
2
1
1/2
1/4
1/8
1/16
1/32
$-3/2$
-1
$-1/2$
0
1/2
1
3/2
charge q
CFT IV
CFT III
CFT II
CFT I

Inequalities obeyed by all spectra

1. BPS inequality

$$h \geq \frac{q^2}{2k}$$

implied by unitarity, so not surprising

a bit suprising: each CFT has four non-vacuum-primaries that saturate BPS inequality

explanation: generated from spectral flow of vacuum module plus charge conjugation:

$$L(0,\,0) \xrightarrow{\psi} L(-k,\,\tfrac{k}{2}) \xrightarrow{\psi} L(-2k,\,2k)$$

see plot of normalized spectra on next page!

Inequalities obeyed by all spectra

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2. gap inequality

$$h \geq \frac{c}{24}$$

   a bit surprising but plausible from holographic arguments

   assuming lowest-lying nonvacuum state has weights q_0, h_0 and $i = 1$ yields inequality on level such that gap inequality holds

$$-1 < k \leq 6q_0^2 + \frac{1}{2}$$

   saturates for CFT IV! ($q_0 = \frac{1}{6}$, $k = \frac{2}{3}$)

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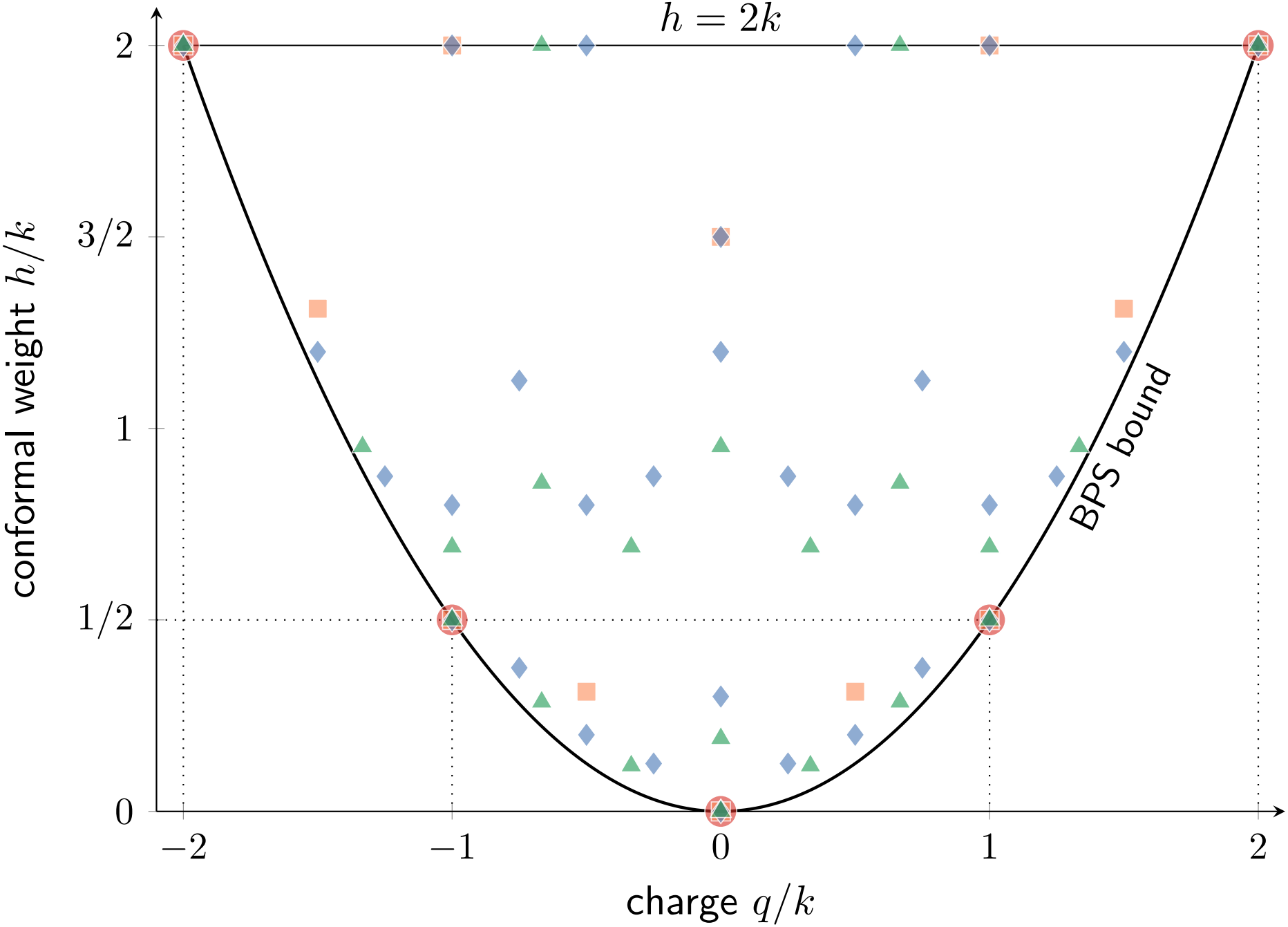
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3. upper bound

$$h \leq 2k$$

no physical interpretation, but technically clear where it comes from

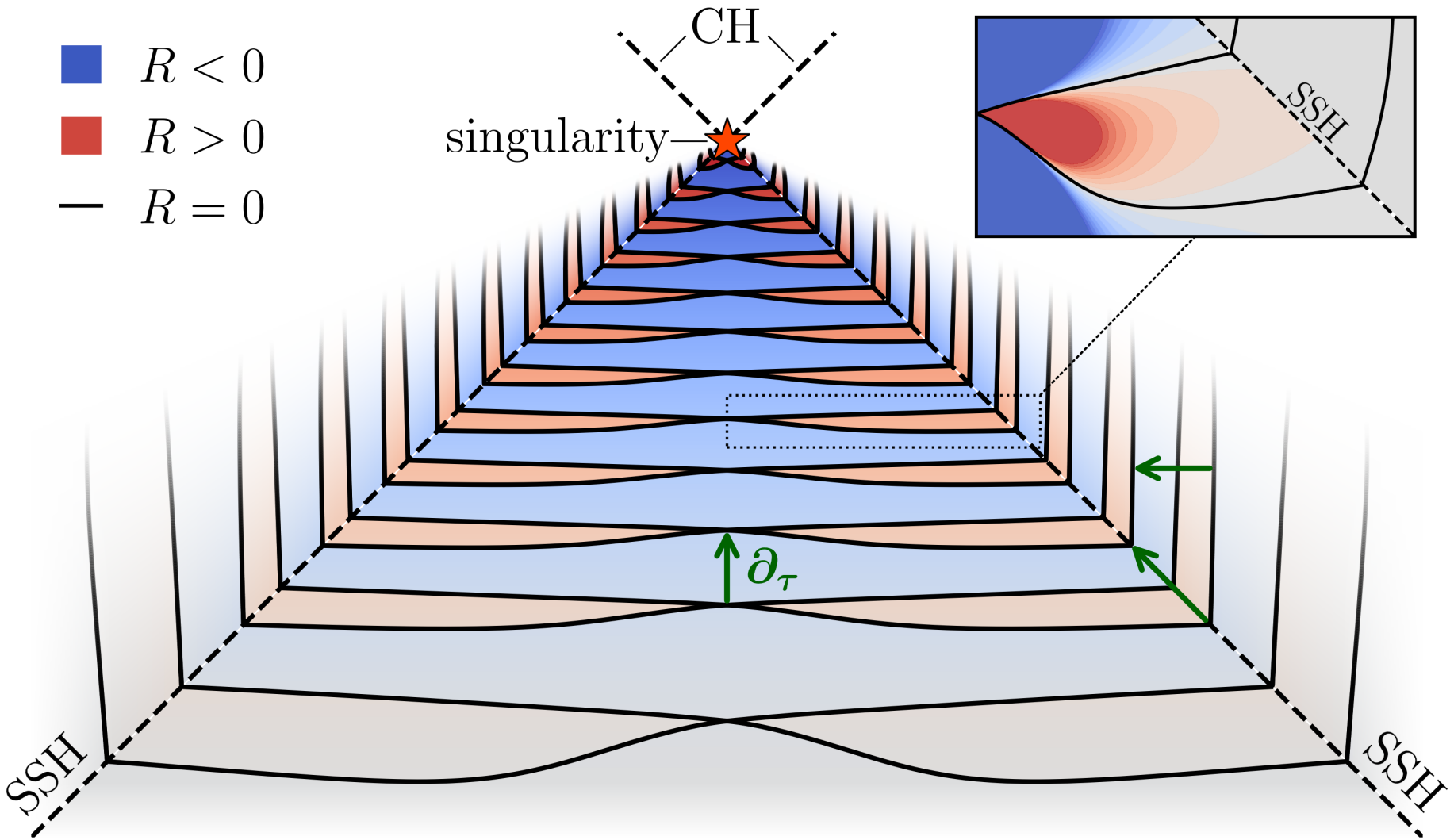
- all modules saturating this bound have either $q = -2k$ or $q = -k$
- top space dimension is either $1 + 3k$ or $1 + 4k$ explains why $k = p/3$ or $k = p/4$
- thus, $i \geq 2$
- spectral flow from such modules always produces modules with $h \leq \frac{3k}{2}$
- spectrally flowing from $h \leq \frac{3k}{2}$ never exceeds $h = 2k$


$h = 2k$
conformal weight h/k
2
3/2
1
1/2
0
−2
−1
0
1
2
charge q/k
BPS bound

Not today: critical collapse at large D

...but I am happy to discuss this in private during the week

work with C. Ecker, F. Ecker



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Thanks for your attention!