Strings 2016
Tsinghua University, Beijing

(Super-)Conformal Bootstrap in 2D

Xi Yin
Harvard University

based on work with Scott Collier, Ying-Hsuan Lin, Shu-Heng Shao, David Simmons-Duffin, Yifan Wang

1. Modular bootstrap revisited

   Collier, Lin, XY, 1608.?????

2. (4,4) superconformal bootstrap

   Lin, Shao, Simmons-Duffin, Wang, XY, 1511.04065

3. (2,2) superconformal bootstrap

   Lin, Shao, Wang, XY, 1608.?????

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to "generic" 3d gravity theory in AdS3.

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to “generic” 3d gravity theory in AdS3.

Can we construct such a CFT?

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to “generic” 3d gravity theory in AdS3.

Can we construct such a CFT?

Cannot be rational, because RCFT always contains an extended chiral algebra: extra holomorphic currents that are Virasoro primaries.

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to "generic" 3d gravity theory in AdS3.

Can we construct such a CFT?

Cannot be free orbifolds, because they also contain extra (higher spin) currents.

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to “generic” 3d gravity theory in AdS3.

Can we construct such a CFT?

Use exactly marginal deformations?

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to "generic" 3d gravity theory in AdS3.

Can we construct such a CFT?

Use exactly marginal deformations?

Try (2,2) SCFT, gauge away R-current?
Nope, still have conserved higher spin currents of spin 3 and higher...

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to "generic" 3d gravity theory in AdS3.

Can we construct such a CFT?

Use exactly marginal deformations?

Bosonic NLSM on CY? Perturbatively, need infinitely many fine tunings…existence of fixed point questionable…

Q: What do we know about 2D unitary, $c>1$ compact CFTs with no conserved current primaries (of any spin)?

Expected to be ubiquitous: e.g. holographic dual to “generic” 3d gravity theory in AdS3.

Can we construct such a CFT?

No more tricks in my bag …

A **YUGE** gap in our knowledge of 2d CFTs

A **YUGE** gap in our knowledge of 2d CFTs

Either we are missing important constraints

A **YUGE** gap in our knowledge of 2d CFTs

Either we are missing important constraints

Or we have been ignorant about the vast majority of 2d CFTs…

A **YUGE** gap in our knowledge of 2d CFTs

Either we are missing important constraints

Or we have been ignorant about the vast majority of 2d CFTs... e.g. ones with nonzero twist gap

A **YUGE** gap in our knowledge of 2d CFTs

Either we are missing important constraints

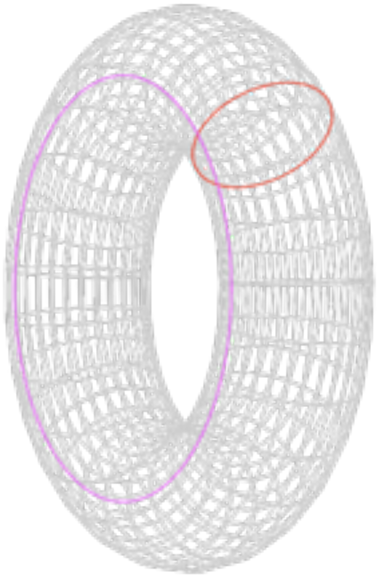
Or we have been ignorant about the vast majority of 2d CFTs…

Most likely the latter.

Conformal Bootstrap in 2D

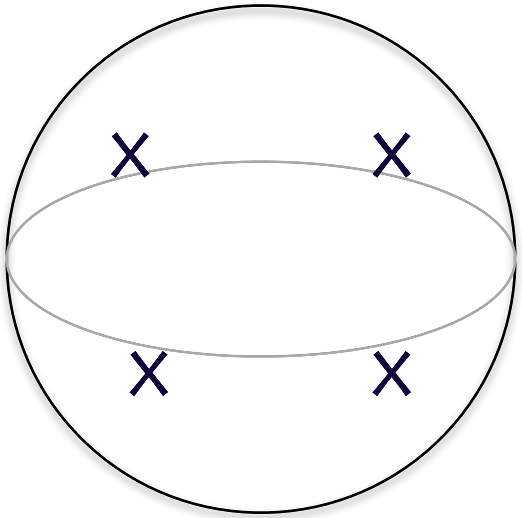
Conformal Bootstrap in 2D

modular invariance



$$\tau \to -\frac{1}{\tau}$$

sphere crossing



$$z \to 1 - z$$

Conformal Bootstrap in 2D

In principle, modular invariance of torus 1-point functions combined with crossing relation of sphere 4-point functions for **all** Virasoro primaries define a consistent CFT. [BPZ,Friedan-Shenker, Segal, Moore-Seiberg]

Conformal Bootstrap in 2D

In principle, modular invariance of torus 1-point functions combined with crossing relation of sphere 4-point functions for **all** Virasoro primaries define a consistent CFT. [BPZ,Friedan-Shenker, Segal, Moore-Seiberg]

For now, we investigate the consequence of modular invariance of the partition function and the crossing relation of 4-point function separately. **Unitarity** will be assumed throughout this talk.

Modular Bootstrap

Modular Bootstrap

[For rational CFT, this is textbook stuff]

Modular Bootstrap

[Modern reboot: Hellerman, Friedan-Keller, Qualls-Shapere]

Modular Bootstrap

[Hellerman, Friedan-Keller, Qualls-Shapere]

Assuming absence of conserved currents and c>1, the torus partition function admits character decomposition:

$$Z(\tau,\bar{\tau}) = \chi_0(\tau)\bar{\chi}_0(\bar{\tau}) + \sum_{h,\bar{h}>0} d(h,\bar{h})\chi_h(\tau)\bar{\chi}_{\bar{h}}(\bar{\tau})$$

Modular Bootstrap

[Hellerman, Friedan-Keller, Qualls-Shapere]

Assuming absence of conserved currents and c>1, the torus partition function admits character decomposition:

$$Z(\tau,\bar{\tau}) = \chi_0(\tau)\bar{\chi}_0(\bar{\tau}) + \sum_{h,\bar{h}>0} d(h,\bar{h})\chi_h(\tau)\bar{\chi}_{\bar{h}}(\bar{\tau})$$

$$\chi_0(\tau) = q^{-\frac{c}{24}} \prod_{n=2}^{\infty} \frac{1}{1-q^n}$$ is the vacuum character

$$\chi_h(\tau) = q^{h-\frac{c}{24}} \prod_{n=1}^{\infty} \frac{1}{1-q^n}$$ is a non-degenerate Virasoro character

Modular Bootstrap

[Hellerman, Friedan-Keller, Qualls-Shapere]

Assuming absence of conserved currents and c>1, the torus partition function admits character decomposition:

$$Z(\tau,\bar{\tau}) = \chi_0(\tau)\bar{\chi}_0(\bar{\tau}) + \sum_{h,\bar{h}>0} d(h,\bar{h})\chi_h(\tau)\bar{\chi}_{\bar{h}}(\bar{\tau})$$

We simply impose the positivity of $d(h,\bar{h})$ and modular invariance of $Z(\tau,\bar{\tau})$, namely,

$$Z(-1/\tau,-1/\bar{\tau}) = Z(\tau,\bar{\tau})$$

and that the spin $s = h - \bar{h}$ takes integer values

Modular Bootstrap

[Hellerman, Friedan-Keller, Qualls-Shapere]

Assuming absence of conserved currents and c>1, the torus partition function admits character decomposition:

$$Z(\tau,\bar{\tau}) = \chi_0(\tau)\bar{\chi}_0(\bar{\tau}) + \sum_{h,\bar{h}>0} d(h,\bar{h})\chi_h(\tau)\bar{\chi}_{\bar{h}}(\bar{\tau})$$

We simply impose the positivity of $d(h,\bar{h})$ and modular invariance of $Z(\tau,\bar{\tau})$, namely,

$$Z(-1/\tau,-1/\bar{\tau}) = Z(\tau,\bar{\tau})$$

and that the spin $s = h - \bar{h}$ takes integer values

What sort of constraints are there on the weights and degeneracy of the primaries?

Modular Bootstrap

Seek linear functionals D with the property that

$$D\left[Z(-1/\tau,-1/\bar{\tau})-Z(\tau,\bar{\tau})\right]\equiv E_0+\sum d(h,\bar{h})E_{h,\bar{h}}$$

(before imposing modular invariance)

$E_0>0$ (say $=1$) and $E_{h,\bar{h}}>0$ for all **sufficiently large** weights $h,\bar{h}$

Modular Bootstrap

Seek linear functionals D with the property that

$$D\left[Z(-1/\tau,-1/\bar{\tau})-Z(\tau,\bar{\tau})\right]\equiv E_0+\sum d(h,\bar{h})E_{h,\bar{h}}$$

(before imposing modular invariance)

$E_0>0$ (say $=1$) and $E_{h,\bar{h}}>0$ for all **sufficiently large** weights $h,\bar{h}$

If such a linear functional is found, we then deduce the existence of a certain low dimension primary, and possibility constraints on the degeneracy of such primaries.

Modular Bootstrap

Seek linear functionals D with the property that

$$D\left[Z(-1/\tau,-1/\bar{\tau})-Z(\tau,\bar{\tau})\right]\equiv E_0+\sum d(h,\bar{h})E_{h,\bar{h}}$$

(before imposing modular invariance)

$E_0>0\ (\text{say}=1)$ and $E_{h,\bar{h}}>0$ for all **sufficiently large** weights $h,\bar{h}$

If such a linear functional is found, we then deduce the existence of a certain low dimension primary, and possibility constraints on the degeneracy of such primaries. And much more...

Modular Bootstrap

Seek linear functionals D with the property that

$$D\left[Z(-1/\tau,-1/\bar{\tau}) - Z(\tau,\bar{\tau})\right] \equiv E_0 + \sum d(h,\bar{h}) E_{h,\bar{h}}$$

(before imposing modular invariance)

$E_0 > 0 \text{ (say } = 1)$ and $E_{h,\bar{h}} > 0$ for all **sufficiently large** weights $h, \bar{h}$

We proceed numerically using semidefinite programming, implemented with SDPB [Simmons-Duffin]

Modular Bootstrap

Seek linear functionals D with the property that

$$D\left[Z(-1/\tau,-1/\bar{\tau})-Z(\tau,\bar{\tau})\right]\equiv E_0+\sum d(h,\bar{h})E_{h,\bar{h}}$$

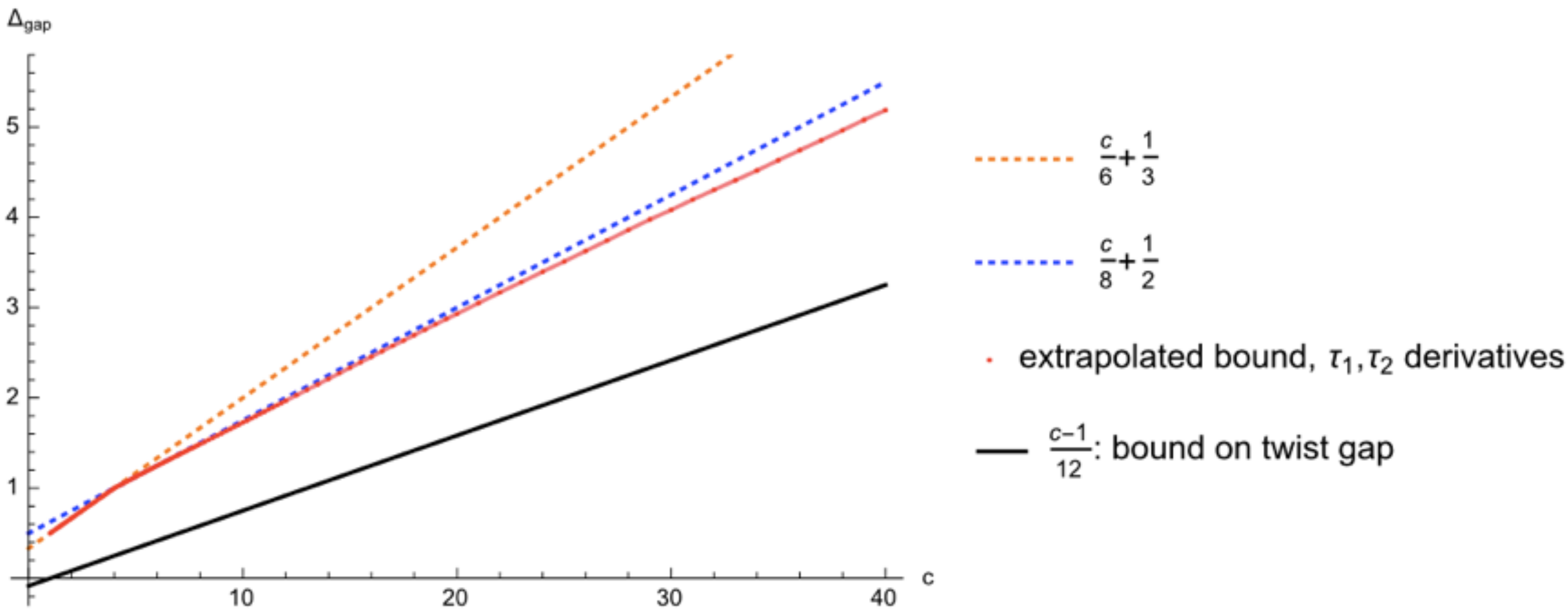
(before imposing modular invariance)

$E_0>0$ (say $=1$) and $E_{h,\bar{h}}>0$ for all **sufficiently large** weights $h,\bar{h}$

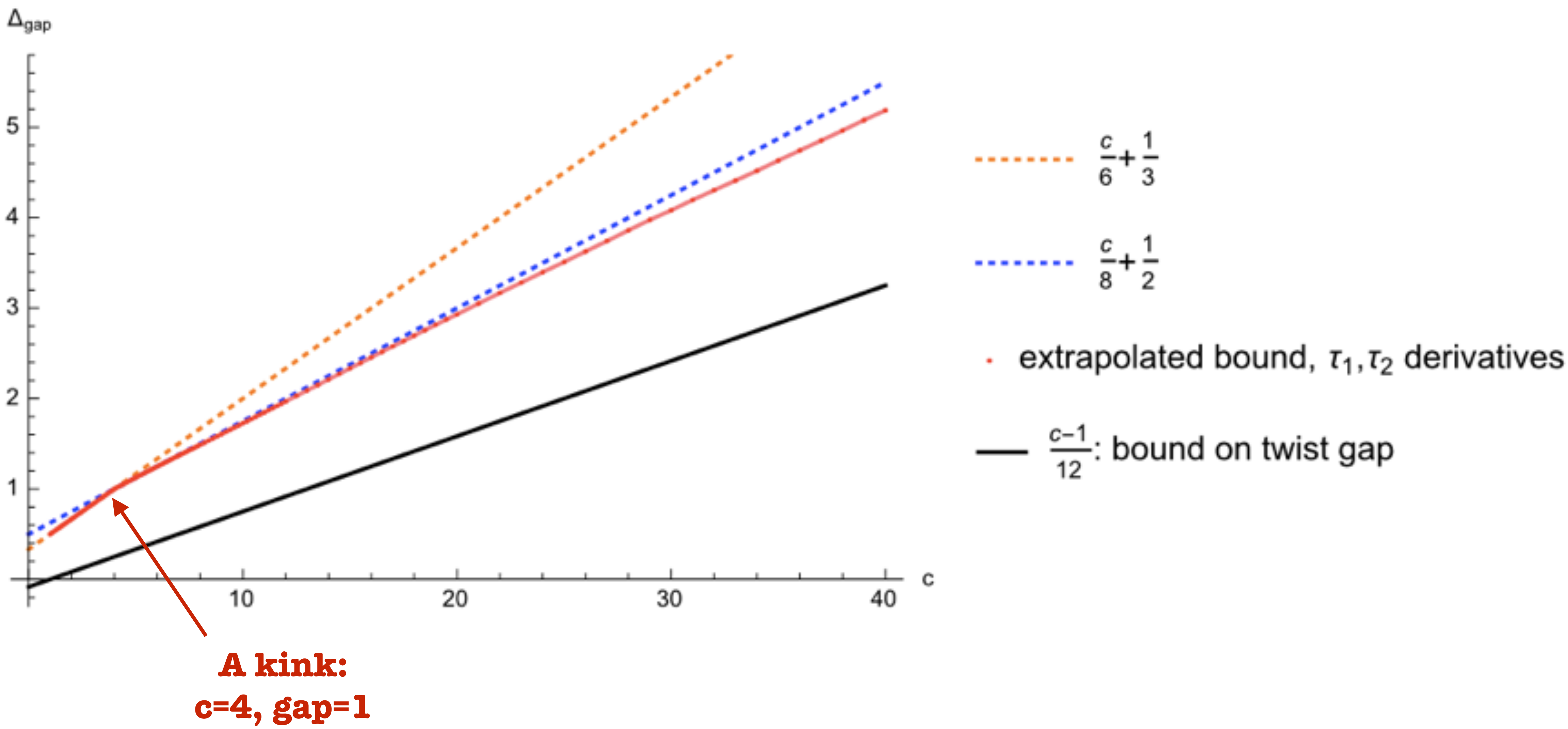
We proceed numerically using semidefinite programming, implemented with SDPB [Simmons-Duffin]

Try $\quad D=\sum_{n+m\leq N} a_{n,m}\partial_z^n\partial_{\bar{z}}^m\Big|_{z=0}, \qquad \tau\equiv ie^z,\ \bar{\tau}=-ie^{\bar{z}}$

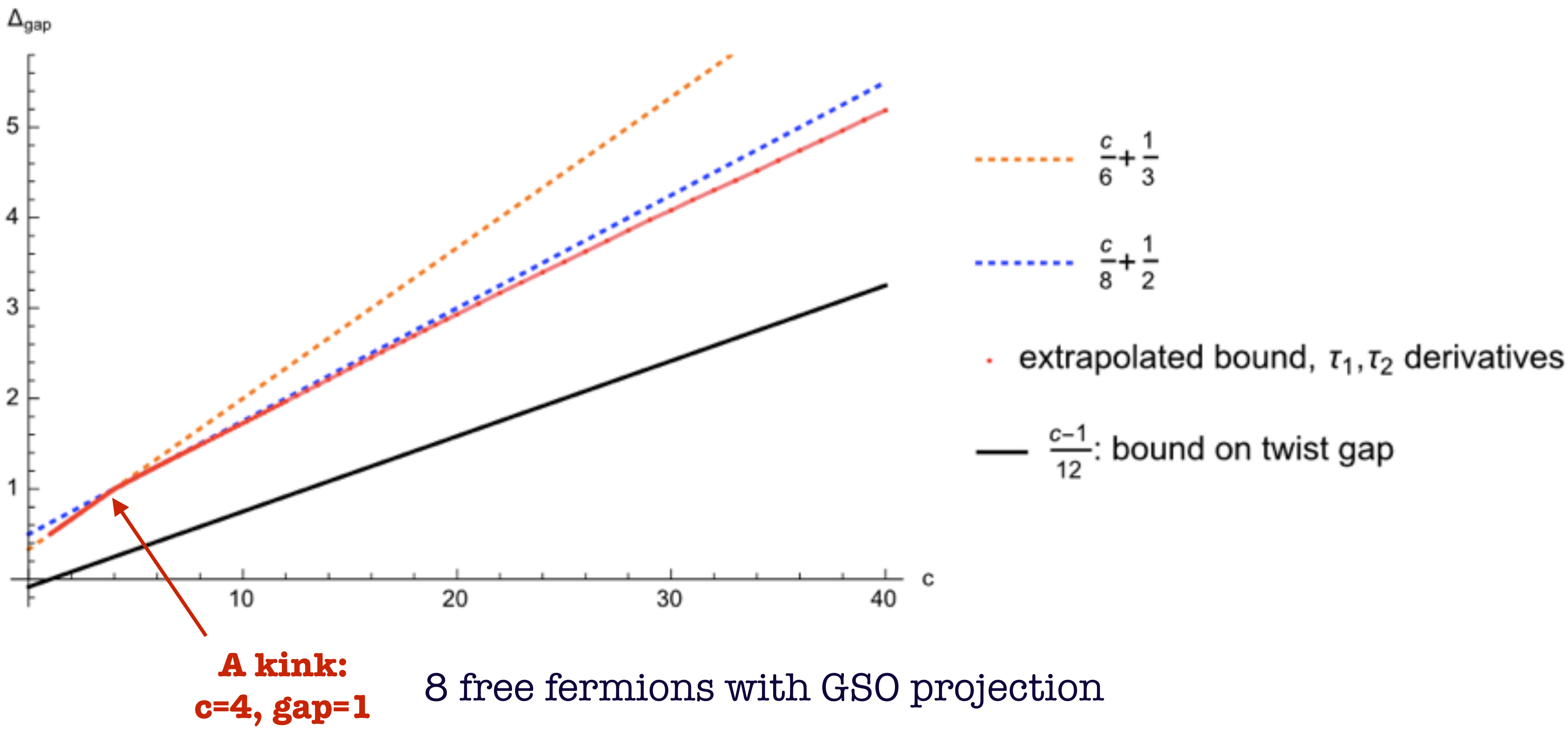
Bounds on the gap in scaling dimension



Bounds on the gap in scaling dimension



Bounds on the gap in scaling dimension

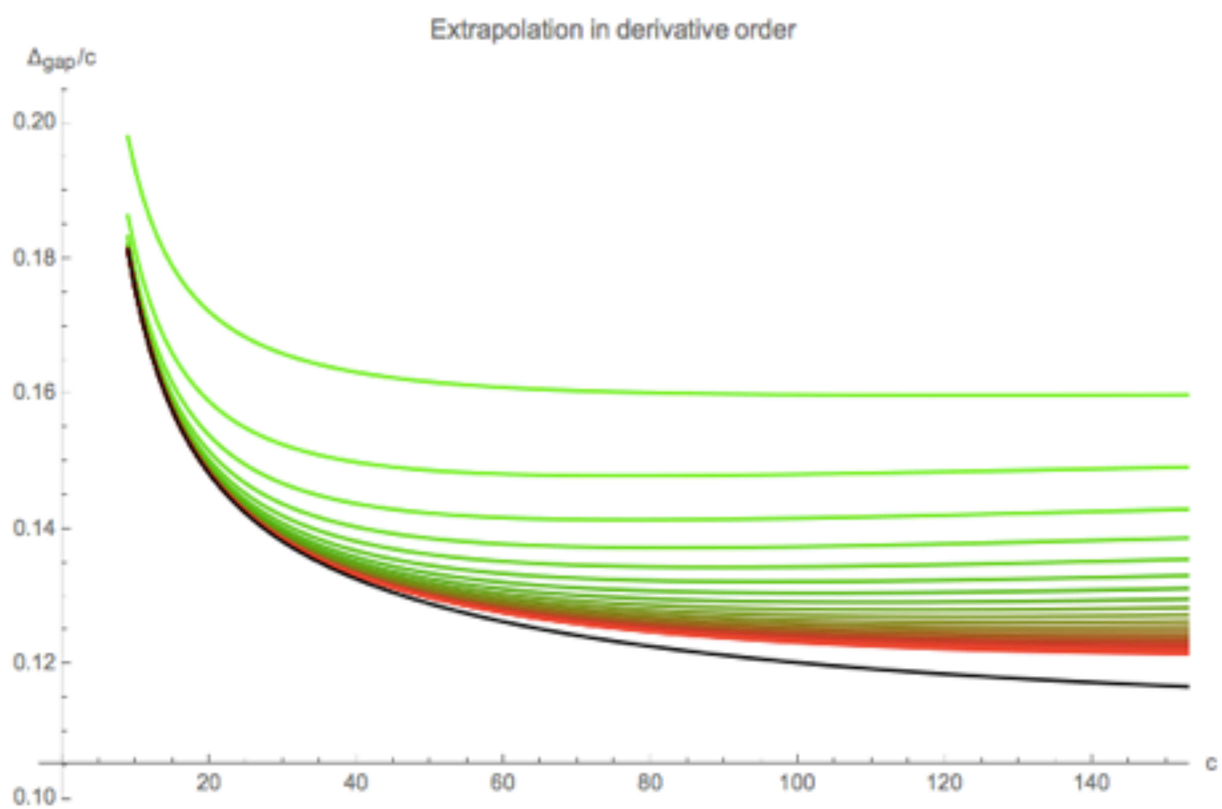


8 free fermions with GSO projection

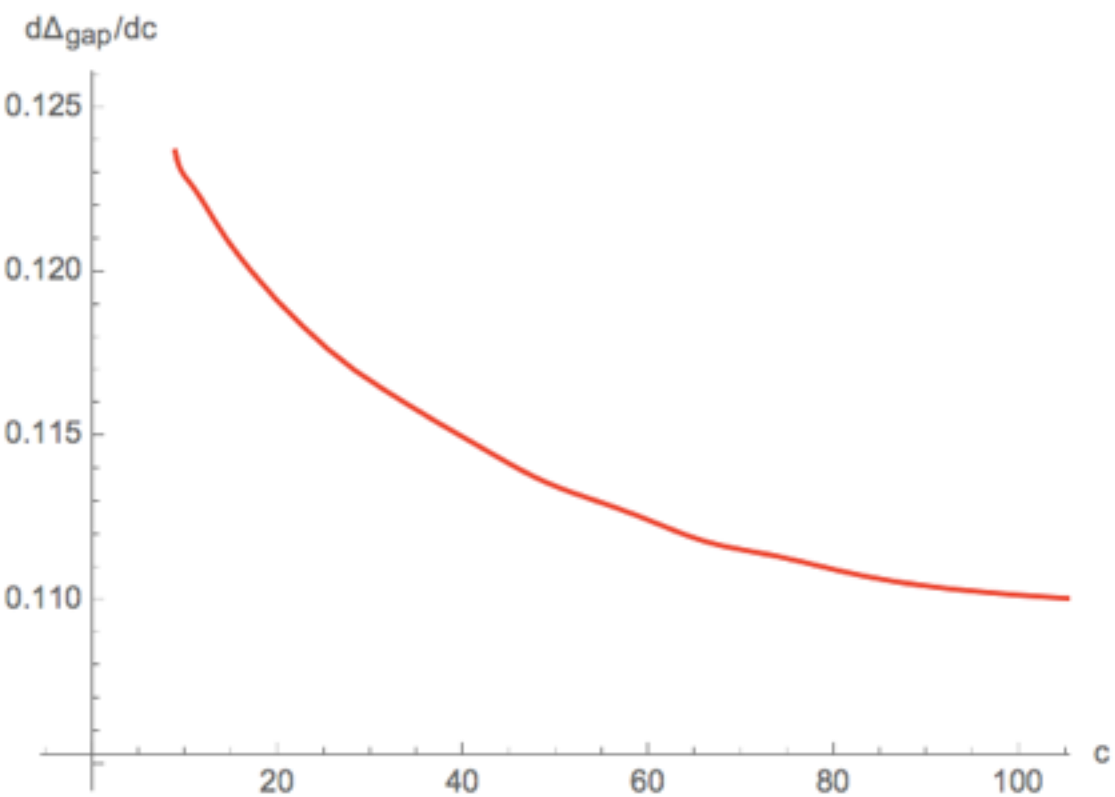
(despite conserved currents, partition function can be formally decomposed into non-degenerate characters with positive coefficients, due to twist-1 primaries)

Asymptotics at large c?

Δ_{gap}/c

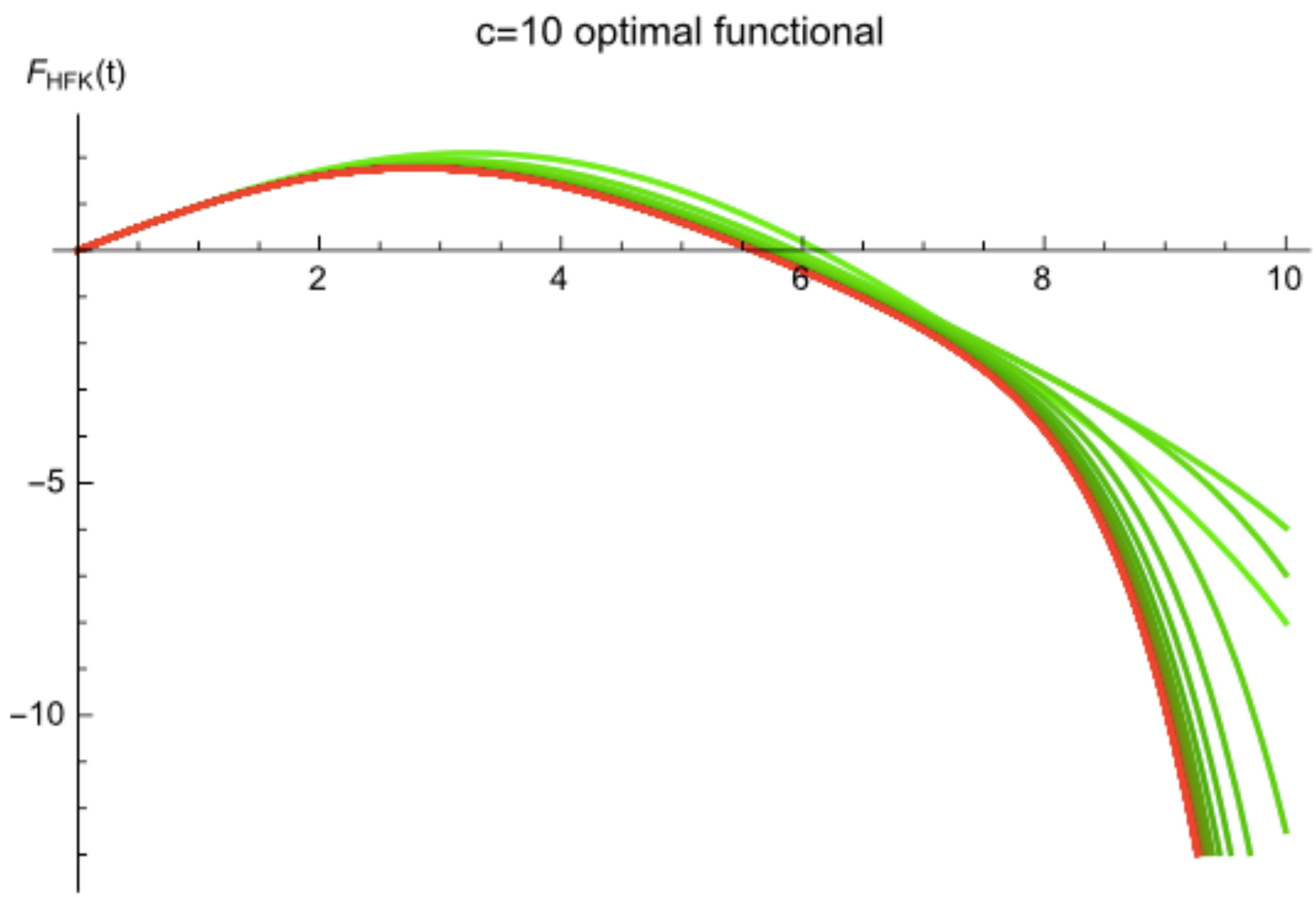


slope of $\Delta_{gap}(c)$



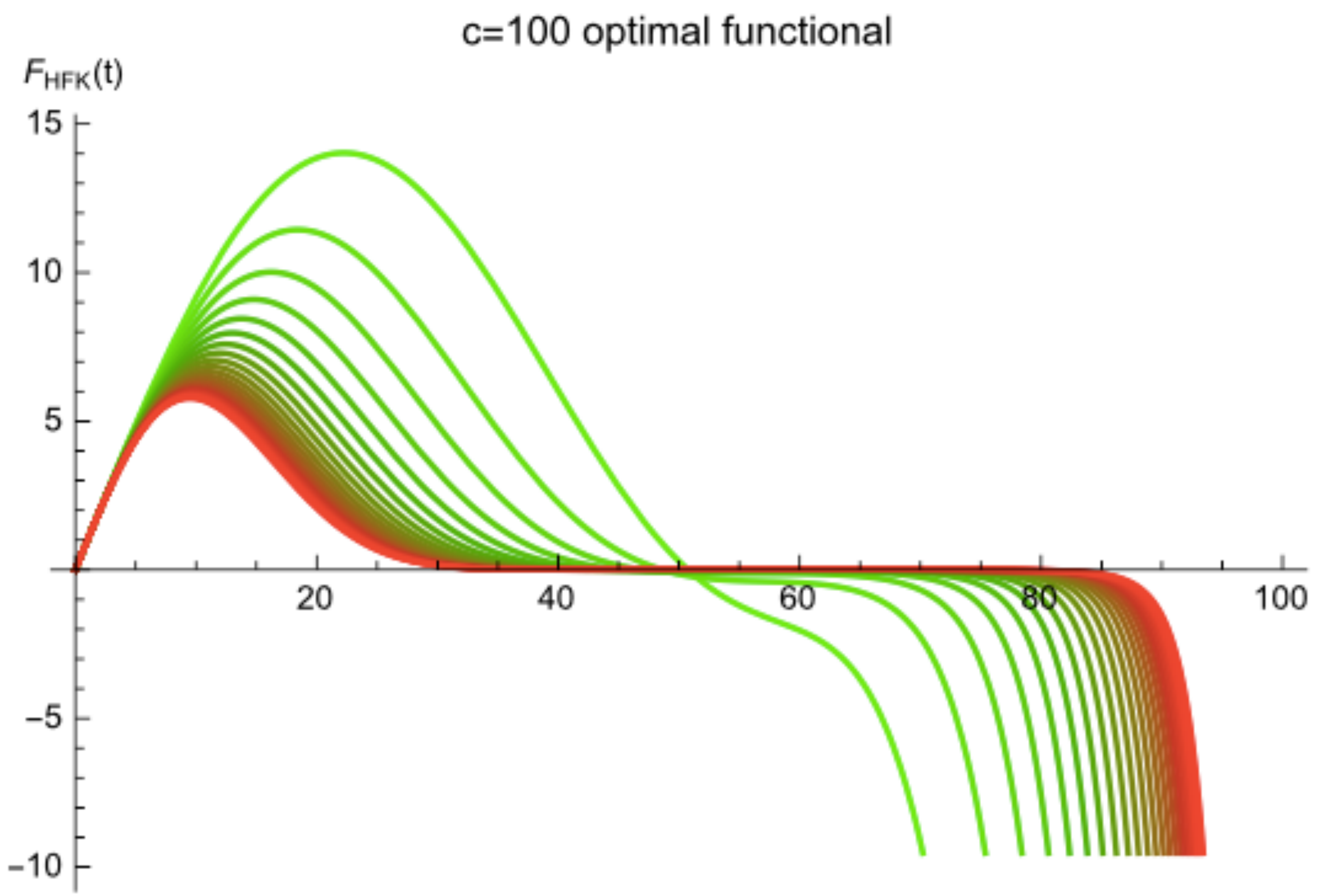
Why is it hard at large c?

The optimal linear functional as a function of $\beta\partial_\beta$ (evaluated at $\beta = 1$)

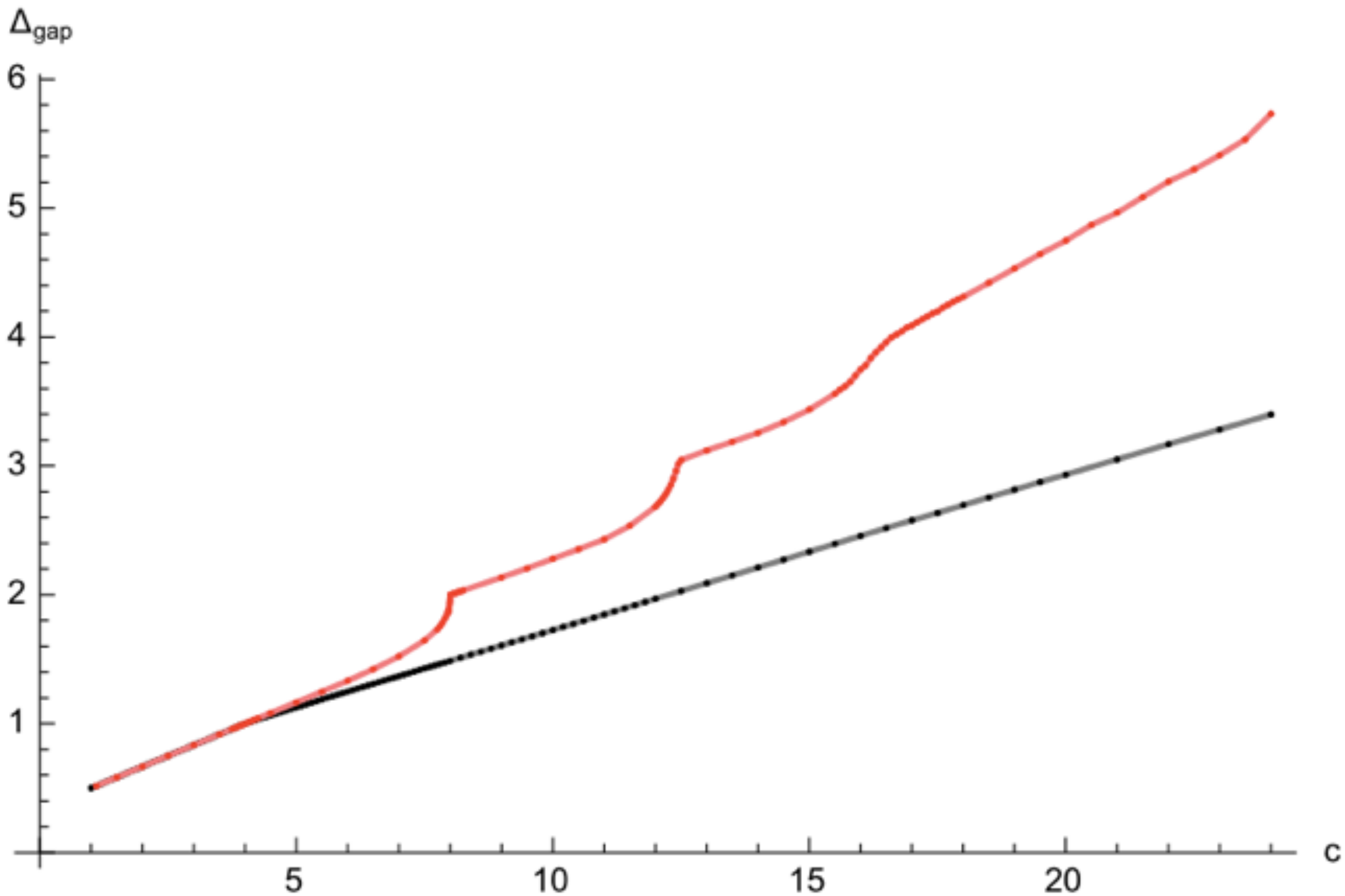


Why is it hard at large c?

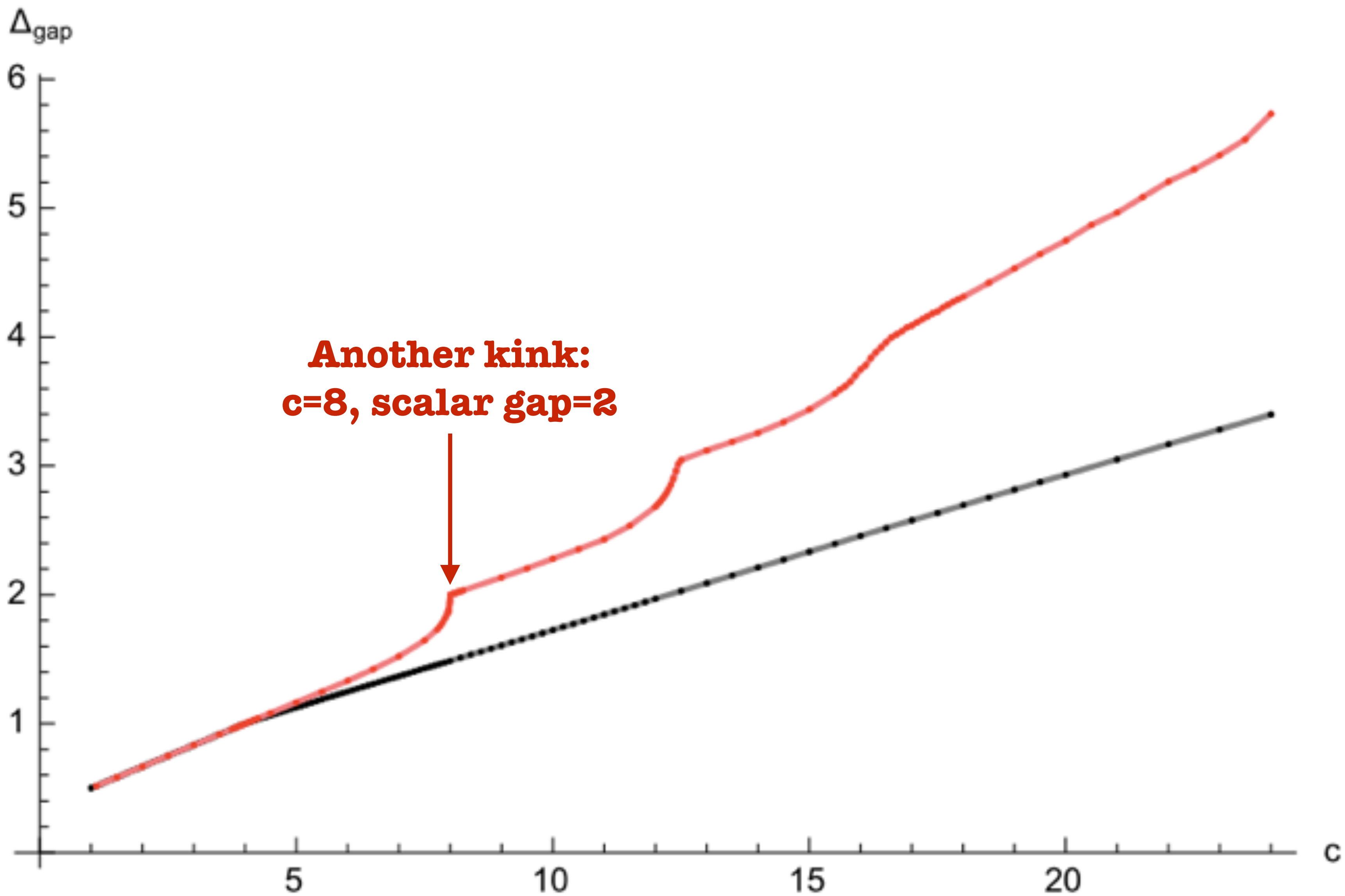
The optimal linear functional as a function of $\beta\partial_\beta$ (evaluated at $\beta = 1$)



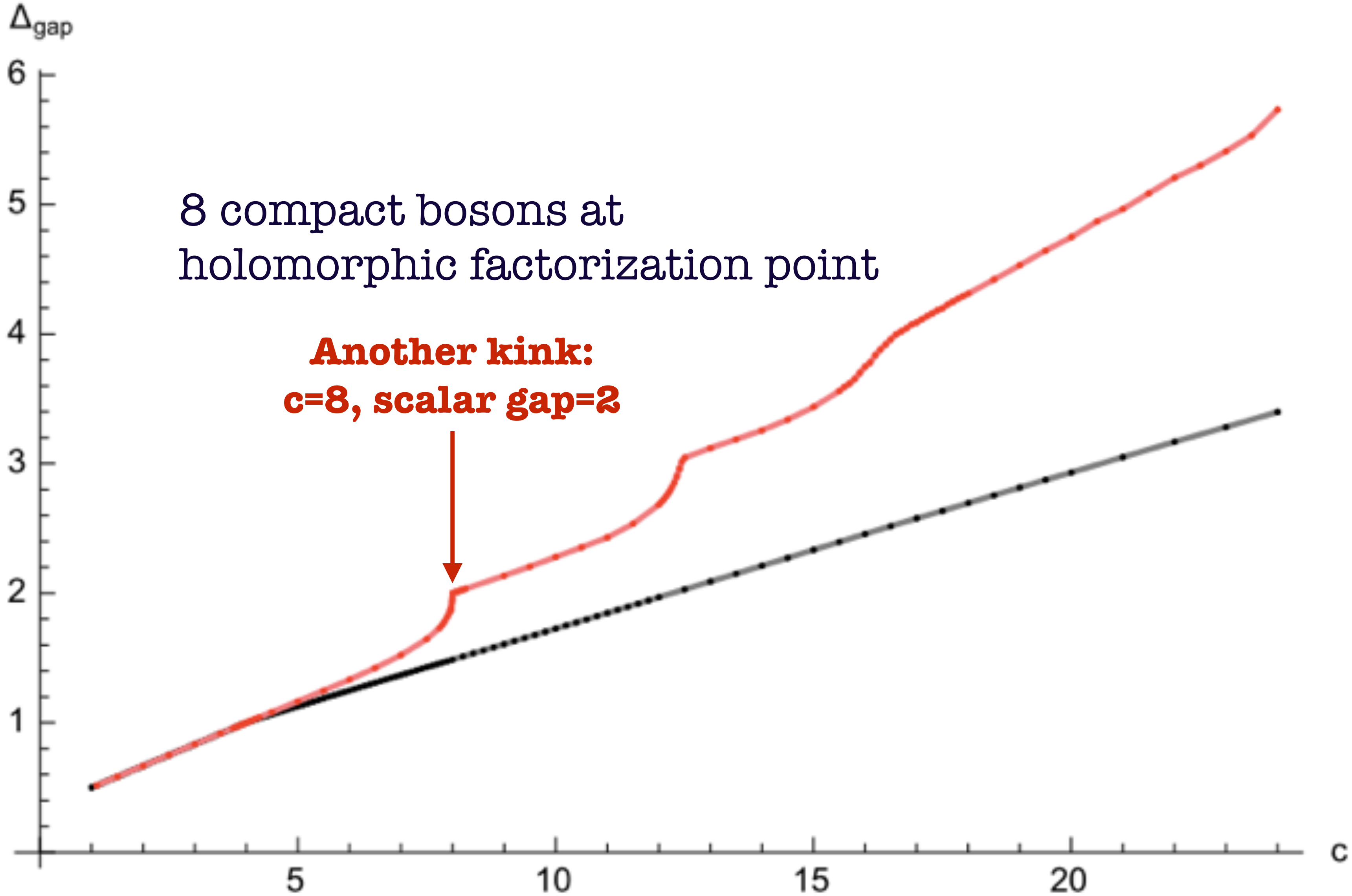
Bounds on the gap of scalar primaries



Bounds on the gap of scalar primaries

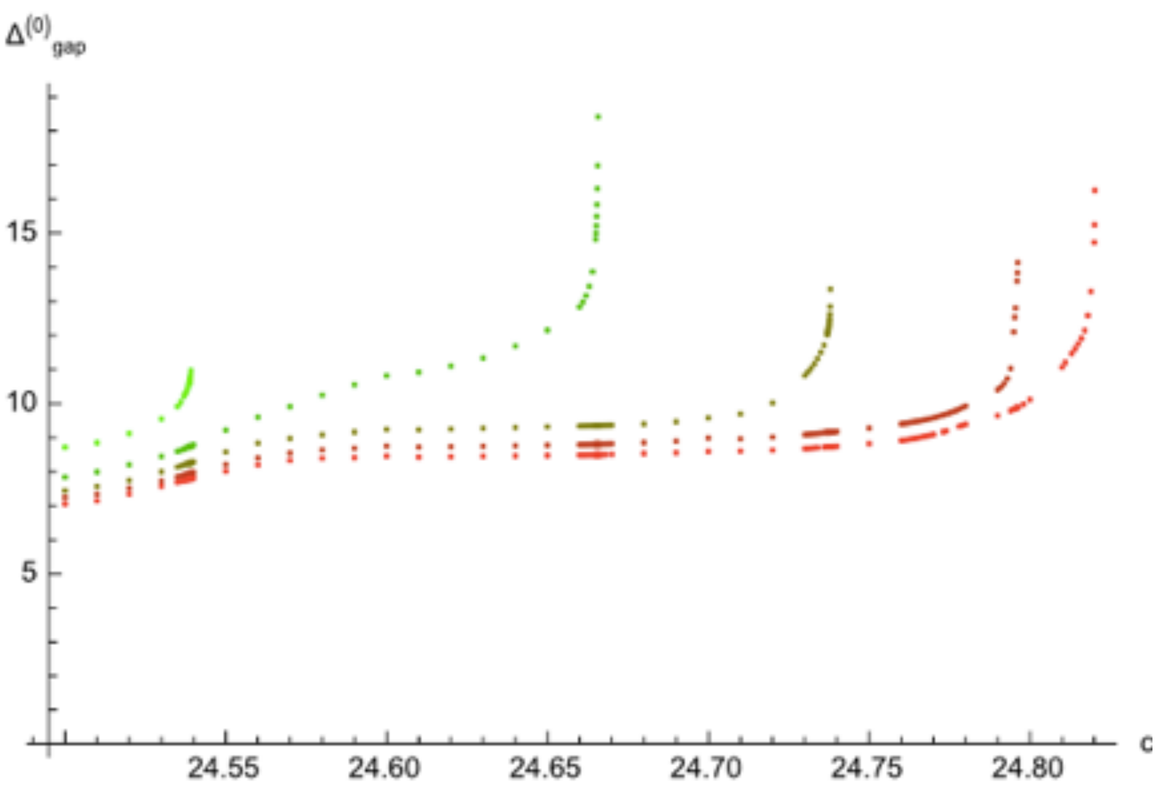


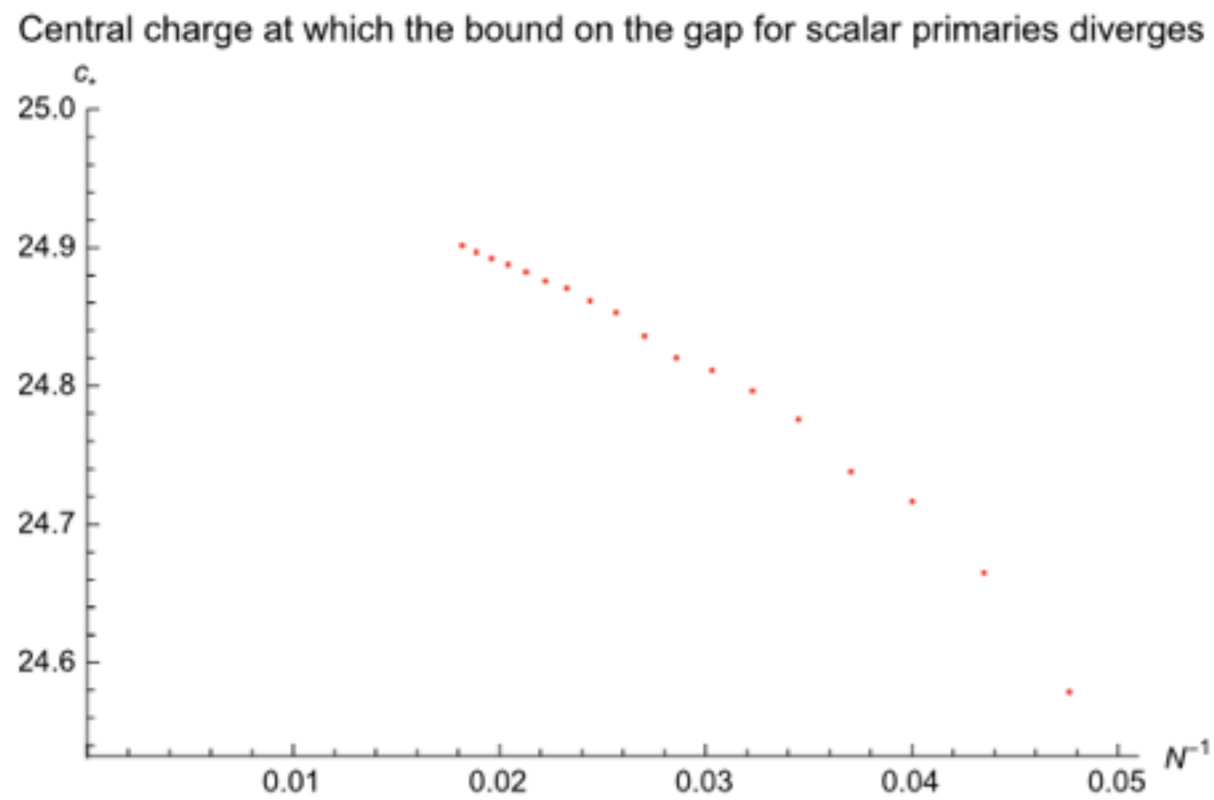
Bounds on the gap of scalar primaries



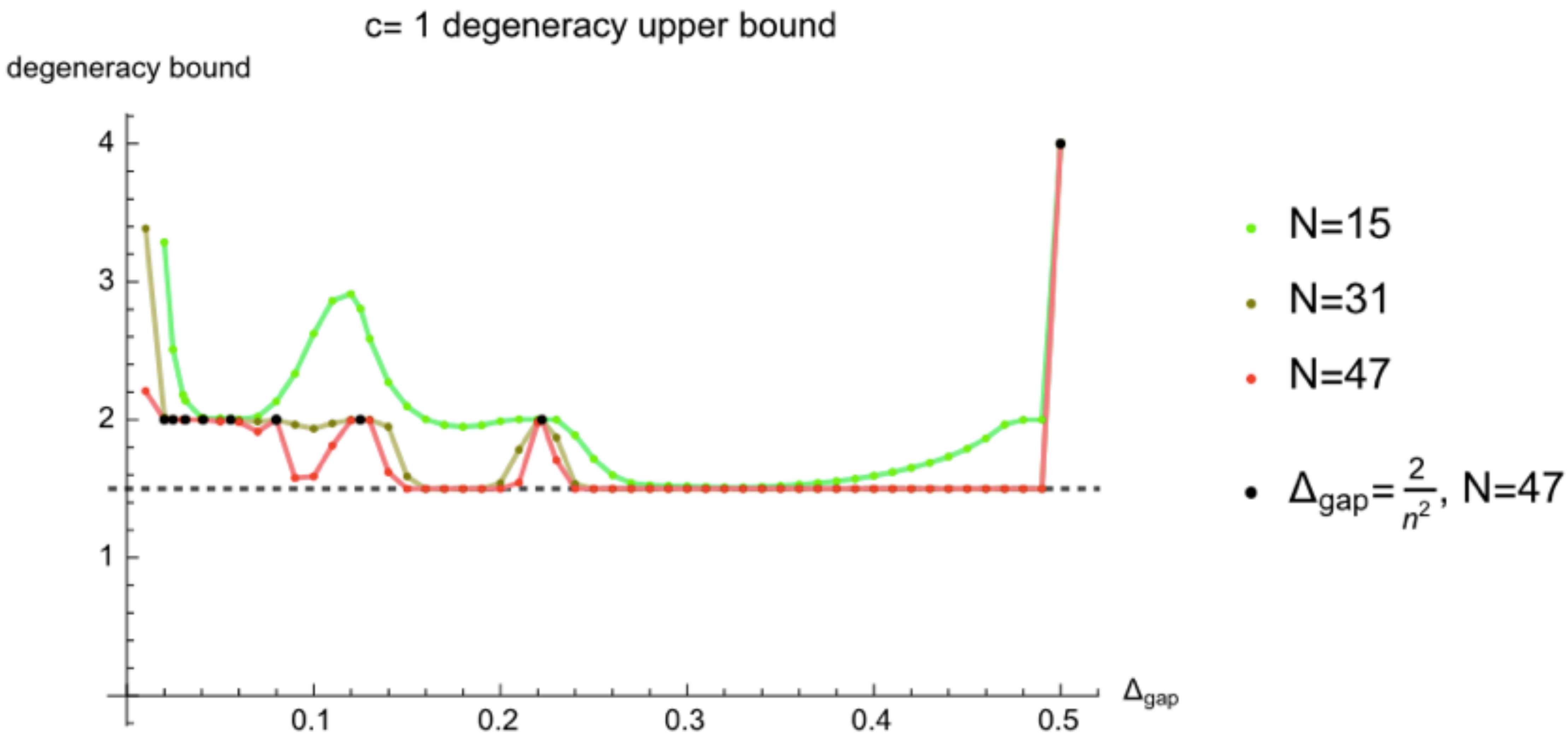
Bounds on the gap of scalar primaries

… that disappear at c=25 !?

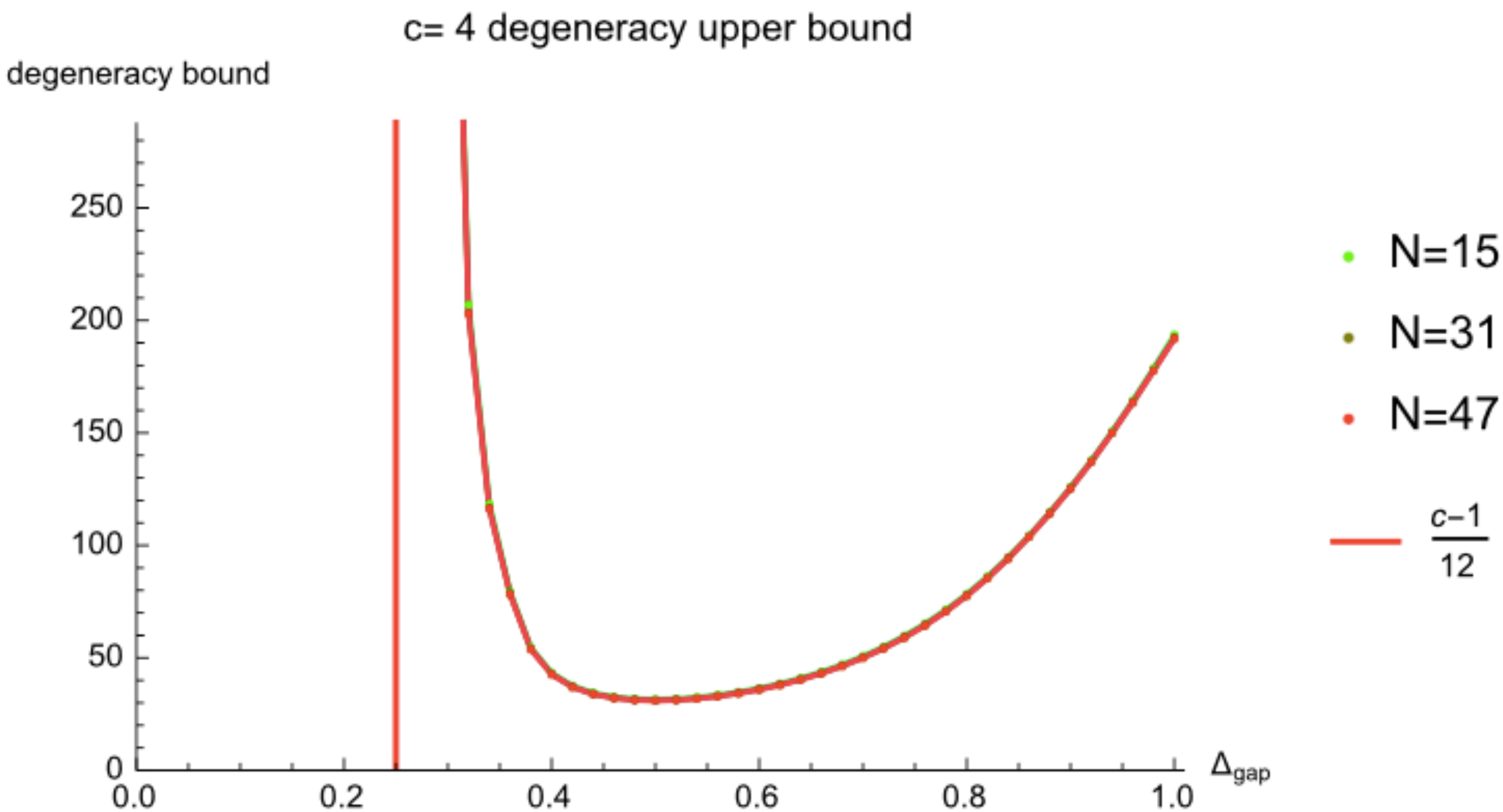




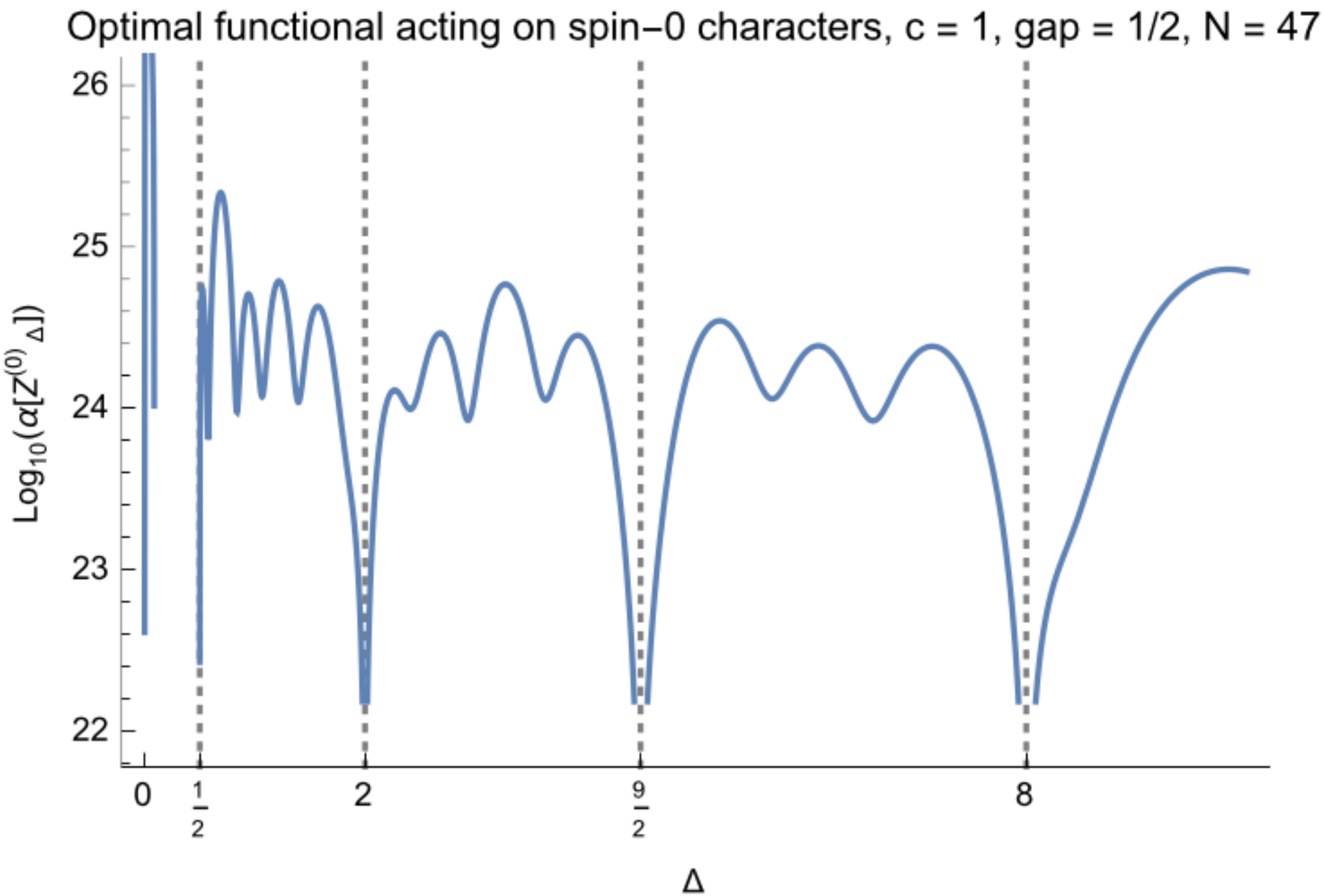
Upper bound on the degeneracy at the gap



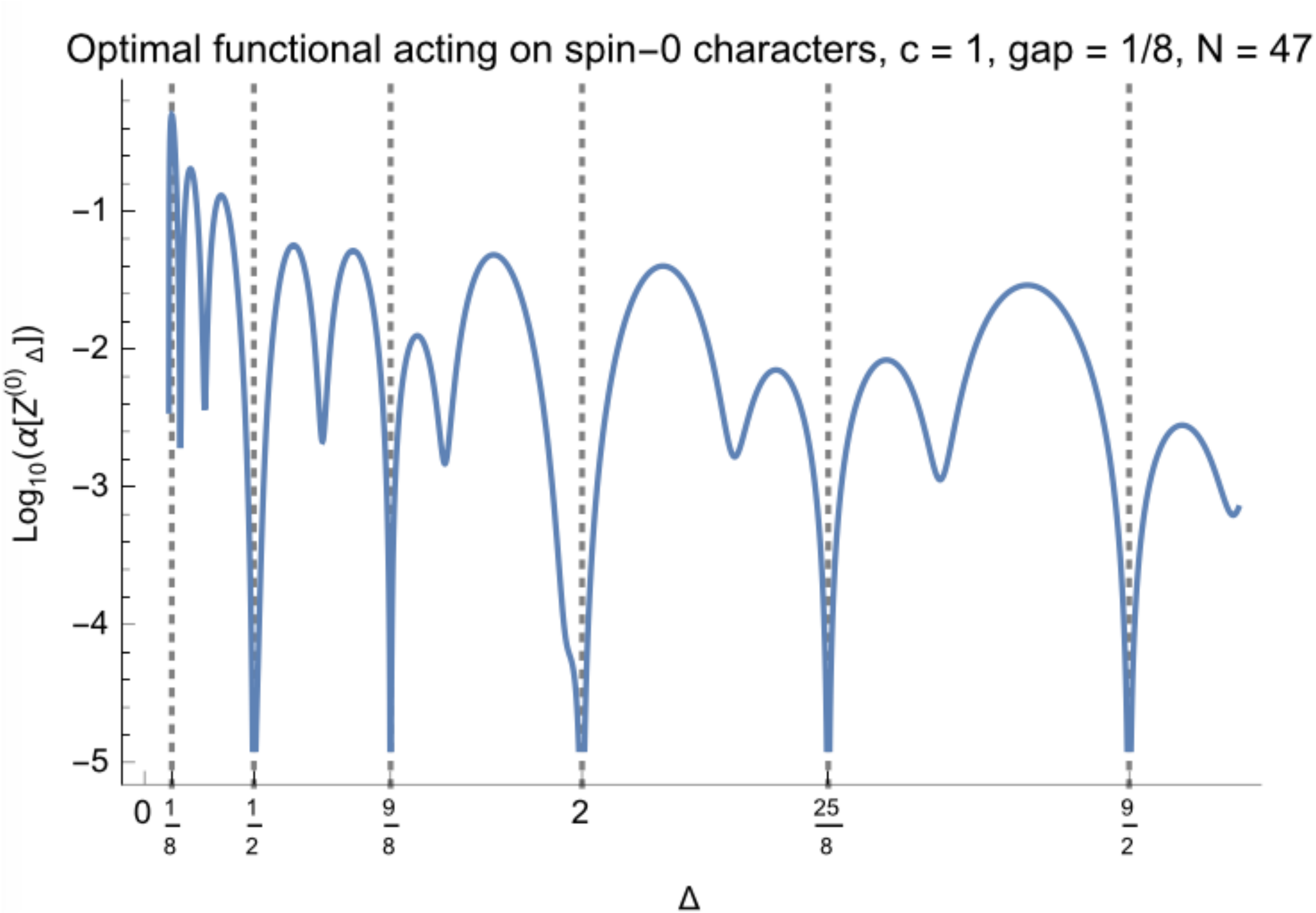
Upper bound on the degeneracy at the gap



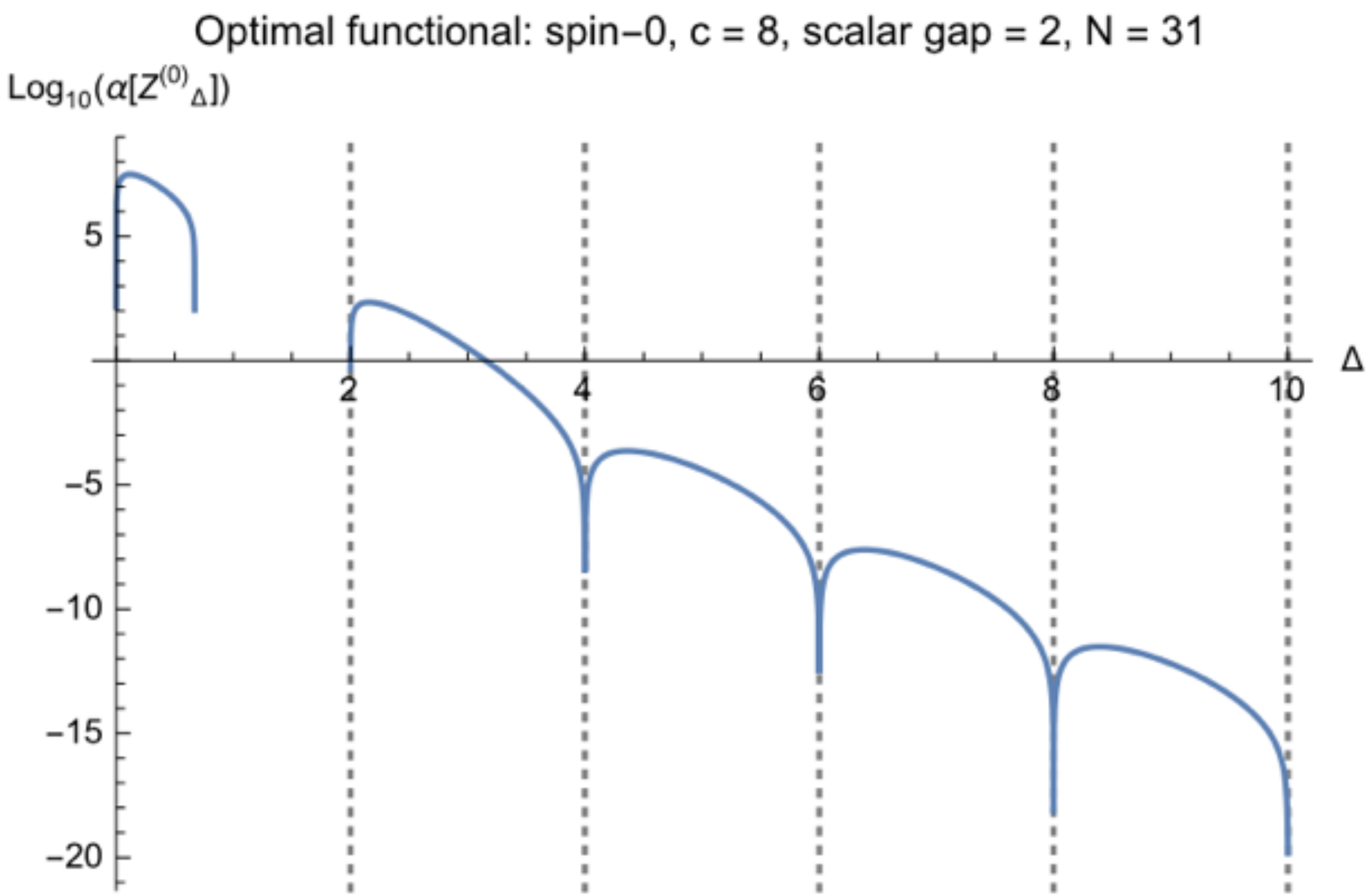
Extremal spectrum



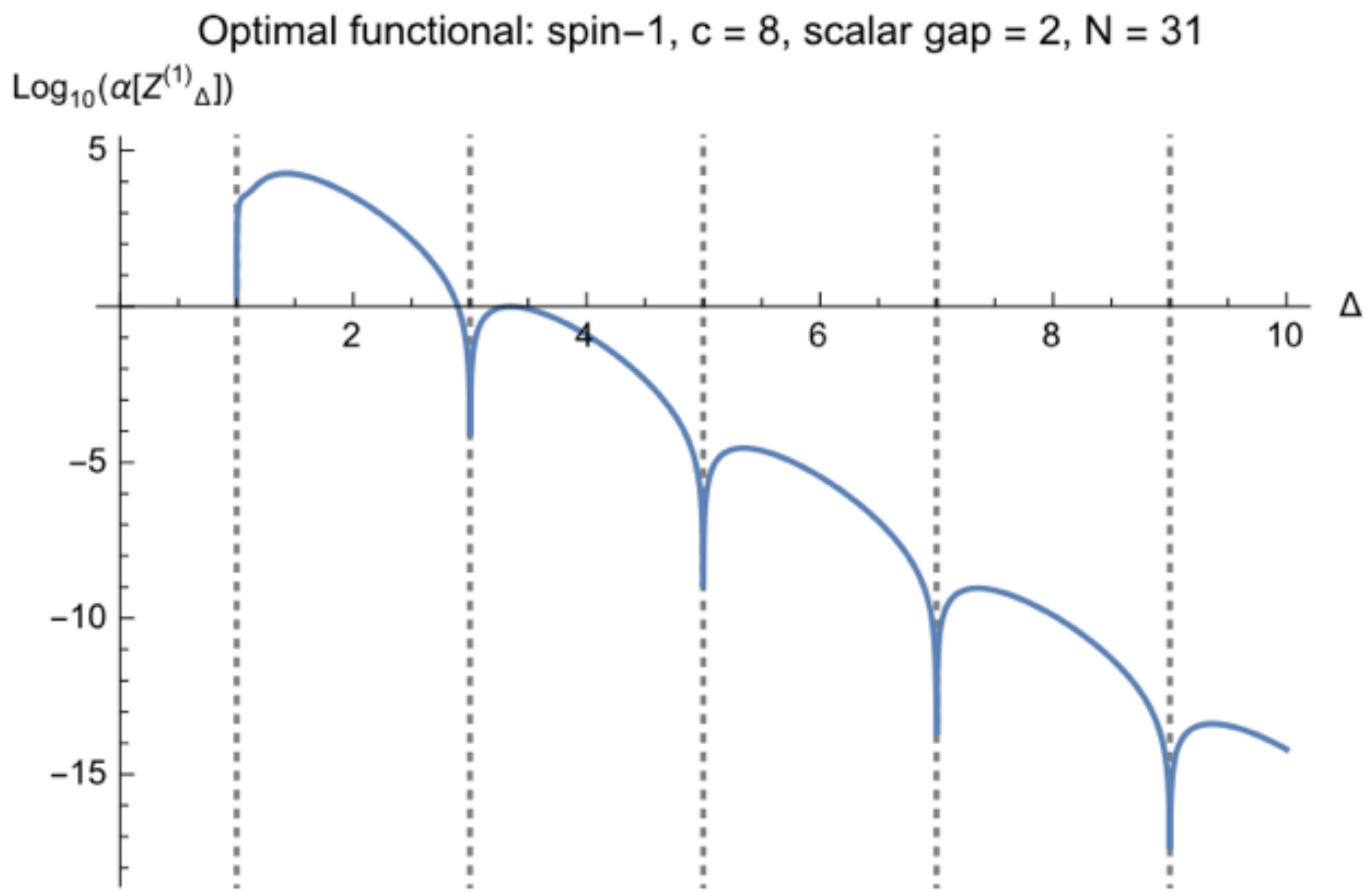
Extremal spectrum



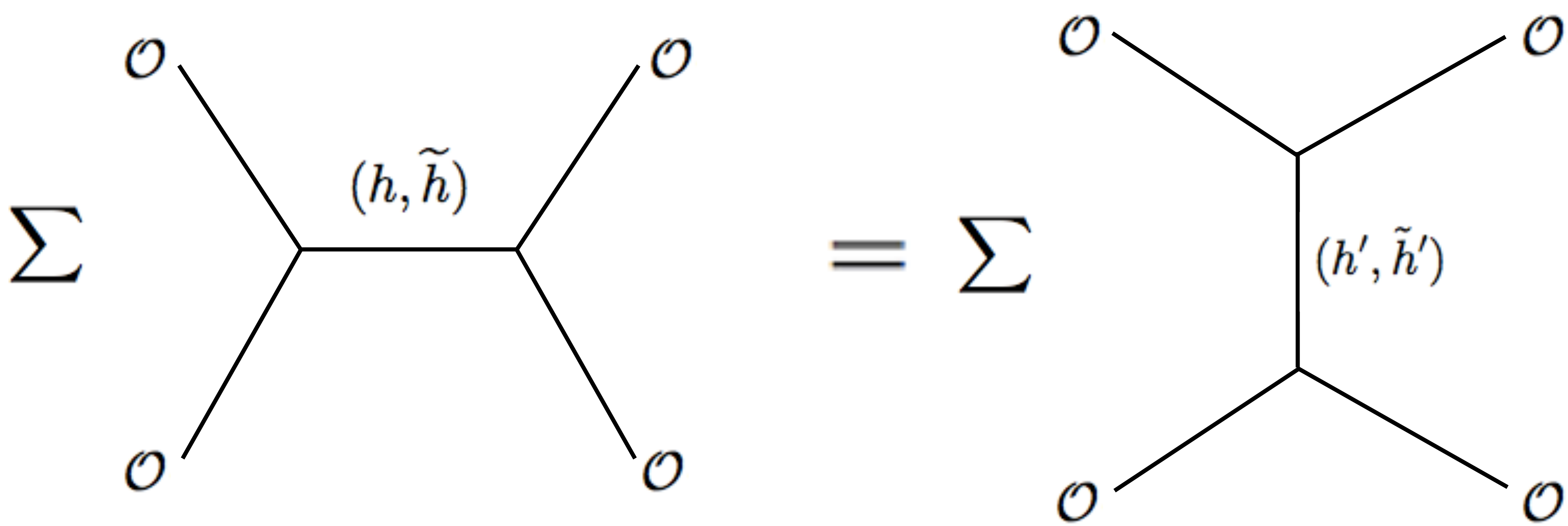
Extremal spectrum



Extremal spectrum

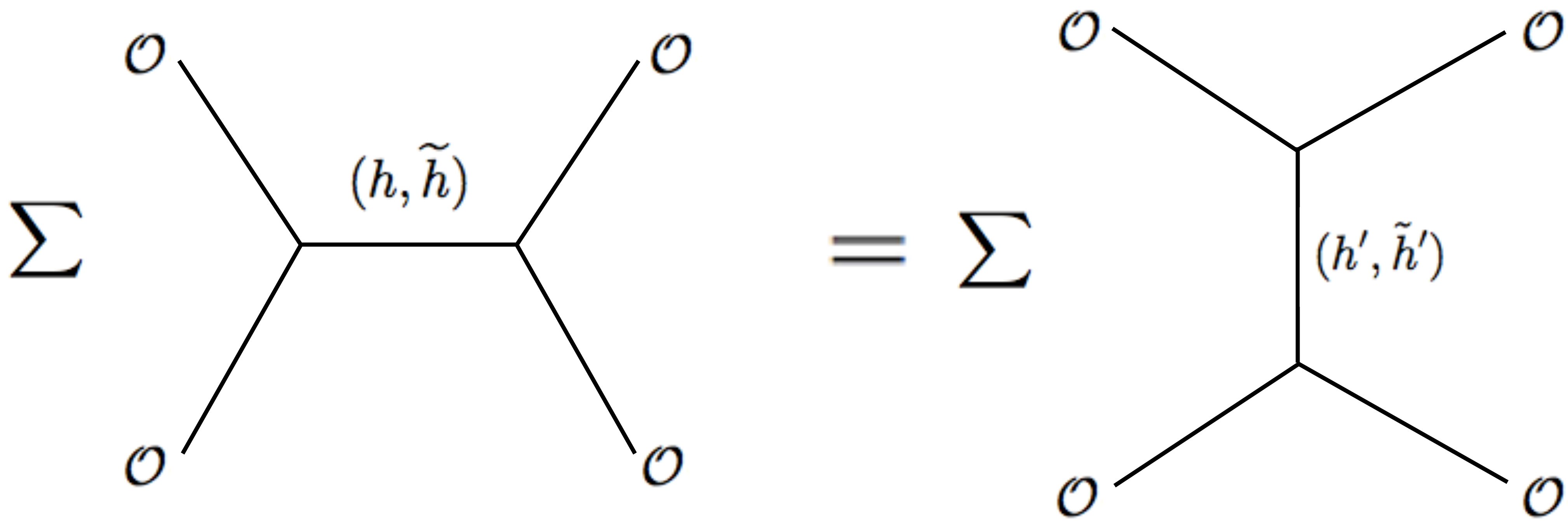


Conformal bootstrap: the crossing equation



[Belavin, Polyakov, Zamolodchikov, Rattazzi, Rychkov, Vichi, Tonni, Poland, Simmons-Duffin, El-Showk, Paulos, ...]

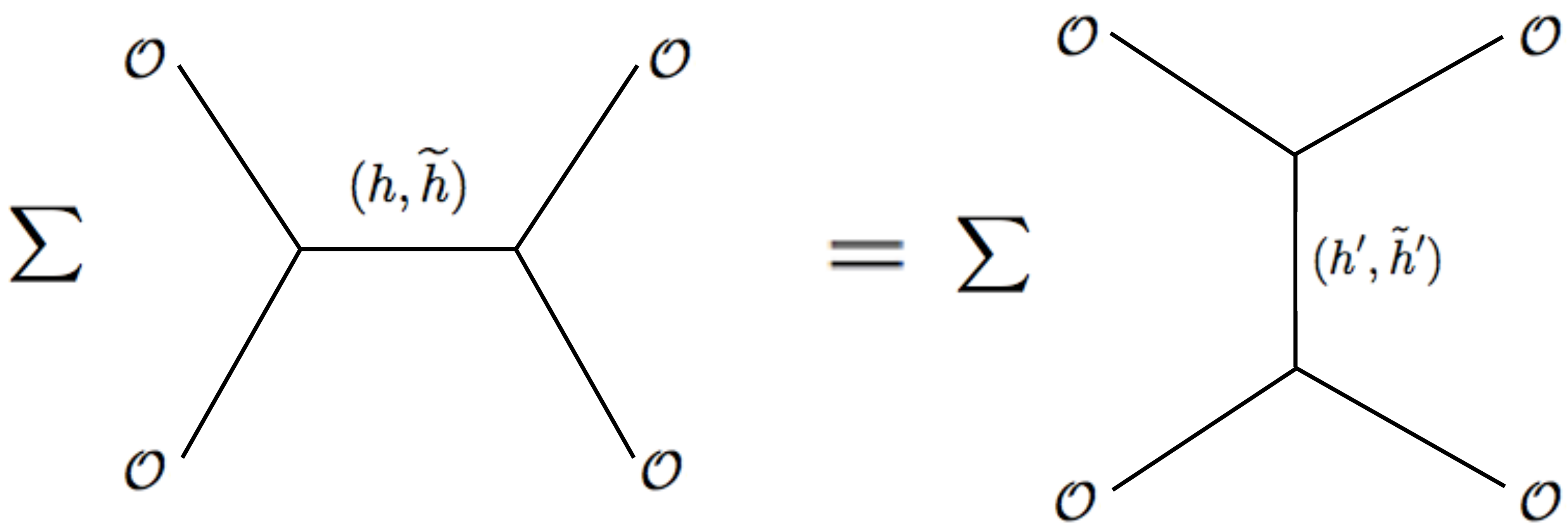
Conformal bootstrap: the crossing equation



[Belavin, Polyakov, Zamolodchikov, Rattazzi, Rychkov, Vichi, Tonni, Poland, Simmons-Duffin, El-Showk, Paulos, ...]

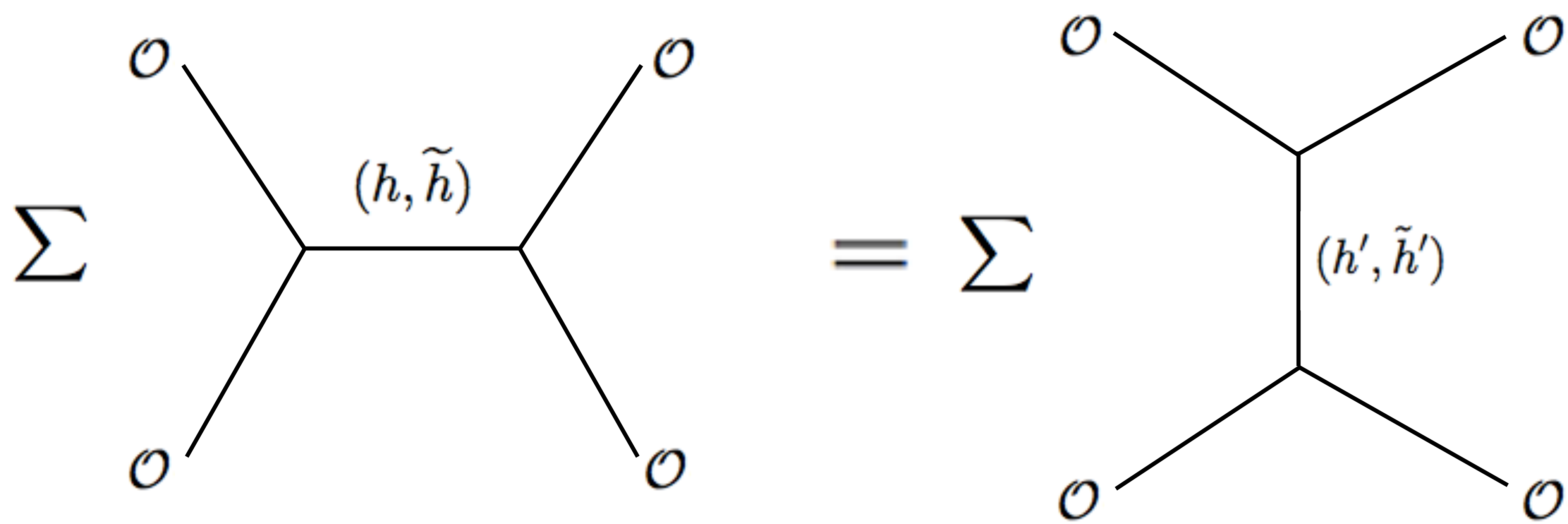
We revisit this problem in 2D, using modern numerical methods.

Conformal bootstrap: the crossing equation



We will consider "simple" external primaries

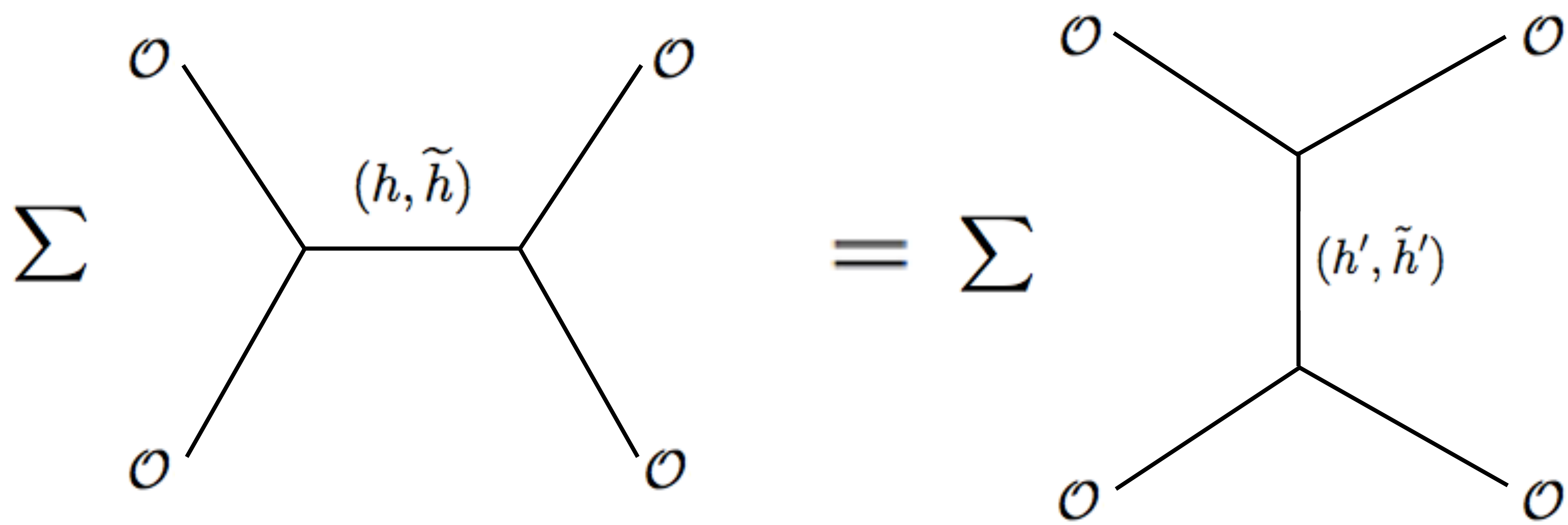
Conformal bootstrap: the crossing equation



We will consider "simple" external primaries

e.g. low dimension, marginal, BPS, ...

Conformal bootstrap: the crossing equation



We will consider "simple" external primaries

e.g. low dimension, marginal, BPS, …

and constrain the content of OPE from unitarity

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6 e.g. K3 CFT

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6 e.g. K3 CFT

2. (2,2) SCFT, $3 \leq c \leq 9$

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6 e.g. K3 CFT

2. (2,2) SCFT, $3 \leq c \leq 9$ including CY_3 models

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6 e.g. K3 CFT

2. (2,2) SCFT, $3 \leq c \leq 9$ including CY_3 models

Our goal is to constrain the spectrum of non-BPS operators in the OPE.

I will present concrete results on the OPE of BPS operators in superconformal theories

1. (4,4) SCFT, c=6 e.g. K3 CFT

2. (2,2) SCFT, $3 \leq c \leq 9$ including CY_3 models

Our goal is to constrain the spectrum of non-BPS operators in the OPE.

When there is a conformal manifold, we would like to understand the moduli dependence of the spectrum.

(4,4) superconformal bootstrap

1. c=6k small N=4 superconformal algebra

(4,4) superconformal bootstrap

1. c=6k small N=4 superconformal algebra
2. focus on the simplest nontrivial case k=1

(4,4) superconformal bootstrap

1. $c=6k$ small N=4 superconformal algebra

2. focus on the simplest nontrivial case $k=1$

3. consider OPE of a pair of marginal BPS primaries (weight h = $SU(2)_R$ spin $j = 1/2$)

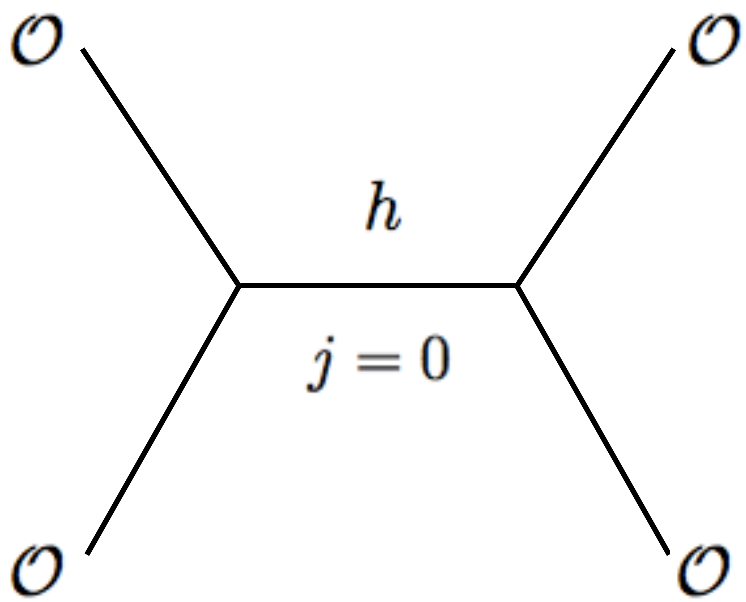
(4,4) superconformal bootstrap

1. c=6k small N=4 superconformal algebra
2. focus on the simplest nontrivial case k=1
3. consider OPE of a pair of marginal BPS primaries (weight h = $SU(2)_R$ spin j = 1/2)
4. study superconformal block decomposition of BPS 4-point function

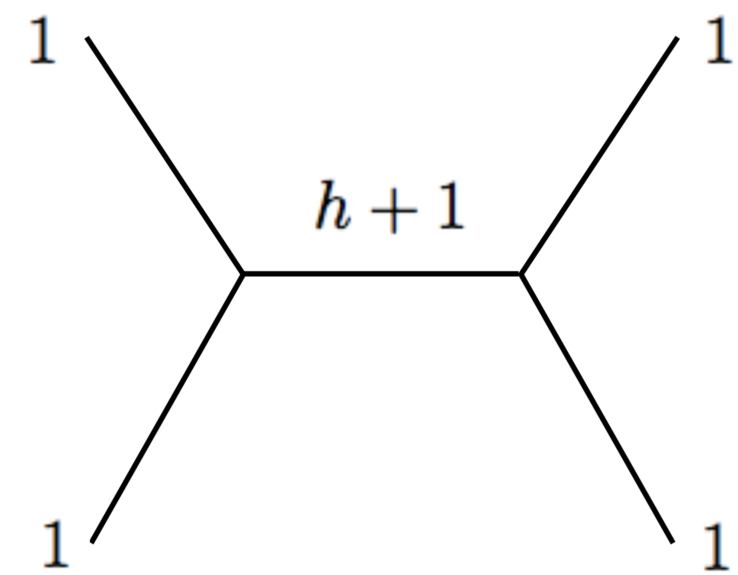
Key ingredient 1: N=4 BPS superconformal block

(c=6, k=1 case)

Key ingredient 1: N=4 BPS superconformal block
(c=6, k=1 case)



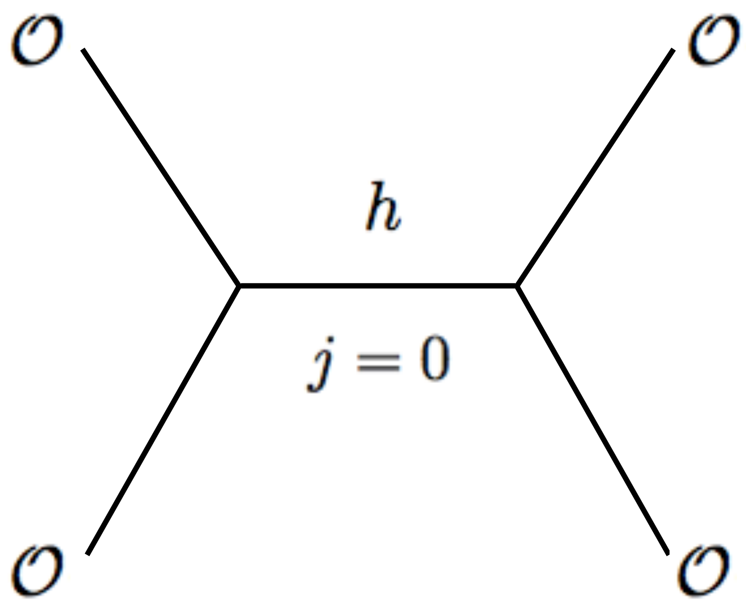
$$= \quad z^{\frac{1}{2}}(1-z)^{\frac{1}{2}}$$



$\mathcal{N}=4, \quad c=6$

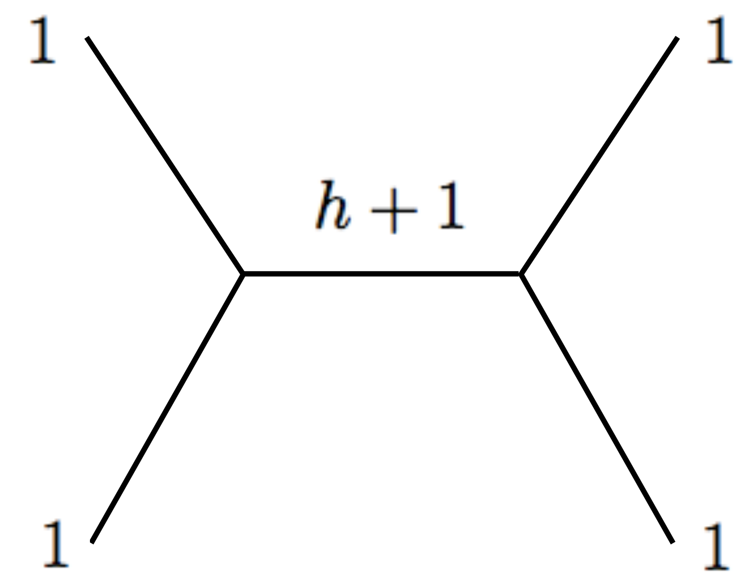
Virasoro, $\quad c=28$

Key ingredient 1: N=4 BPS superconformal block (c=6, k=1 case)



$\mathcal{N}=4, \quad c=6$

$$= \quad z^{\frac{1}{2}}(1-z)^{\frac{1}{2}}$$



Virasoro, $\quad c=28$

Comes from analyzing the N=2 cigar coset SL(2)/U(1), combined with Ribault-Teschner relation between SL(2) WZW and bosonic Liouville.

[Chang-Lin-Shao-Wang-XY, ‘14]

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20) \times SO(4)$

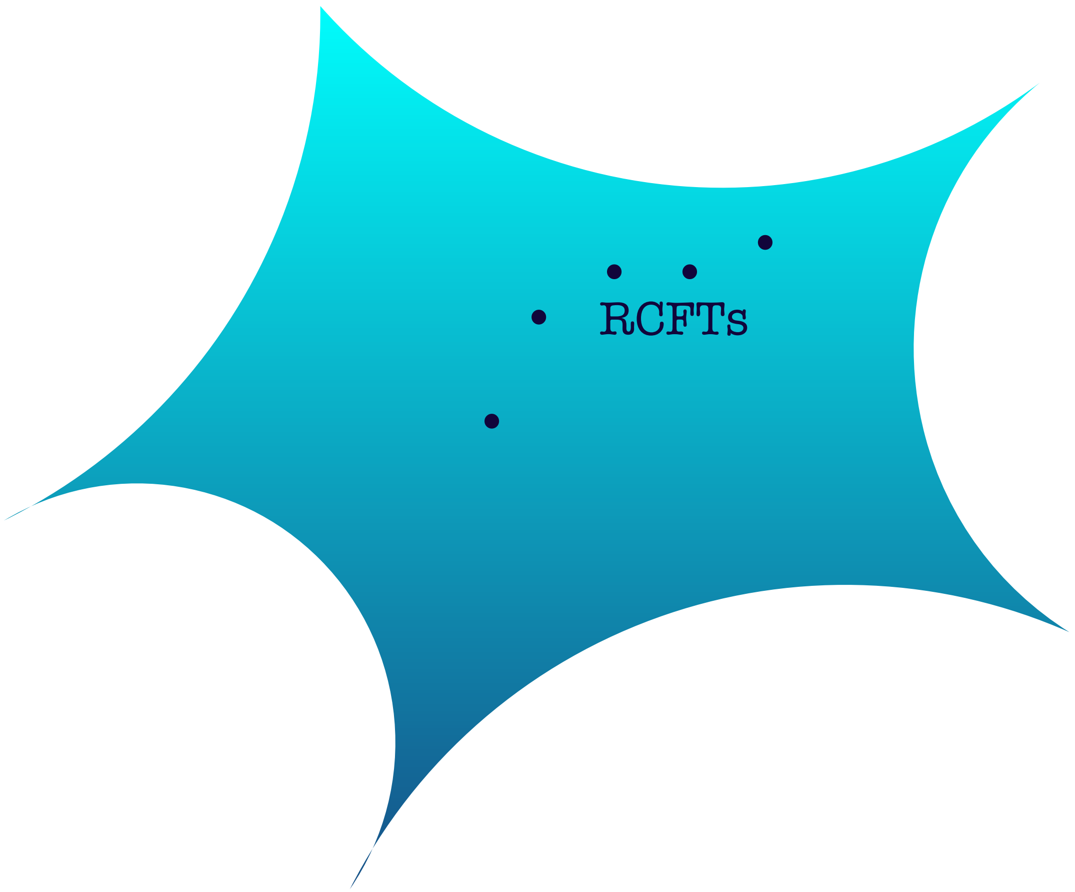
parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$

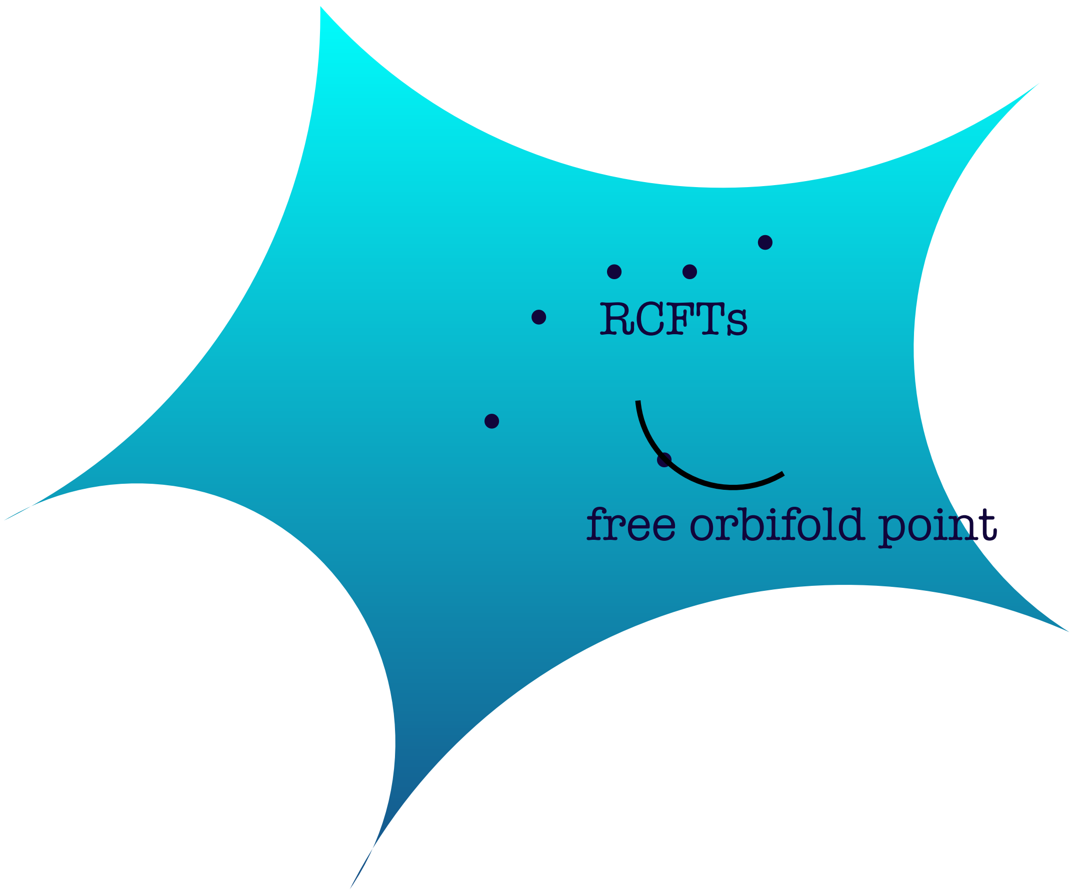


Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$

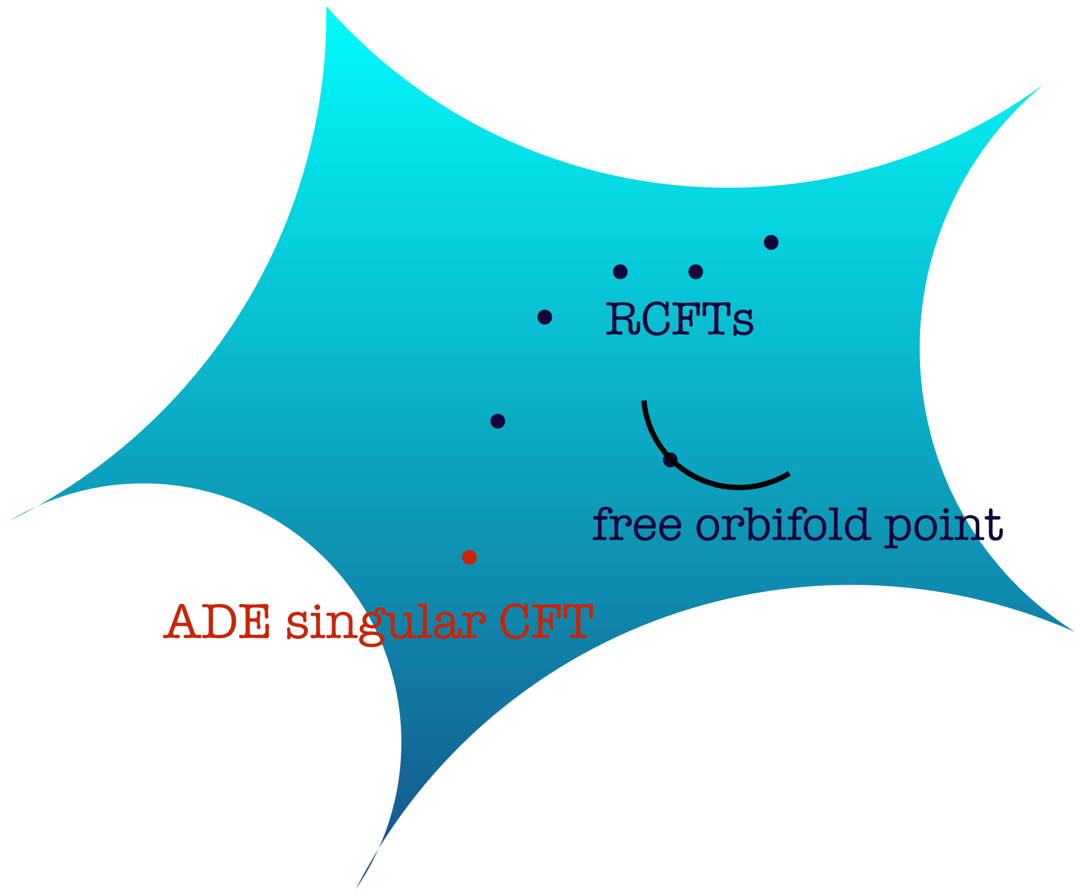


Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$

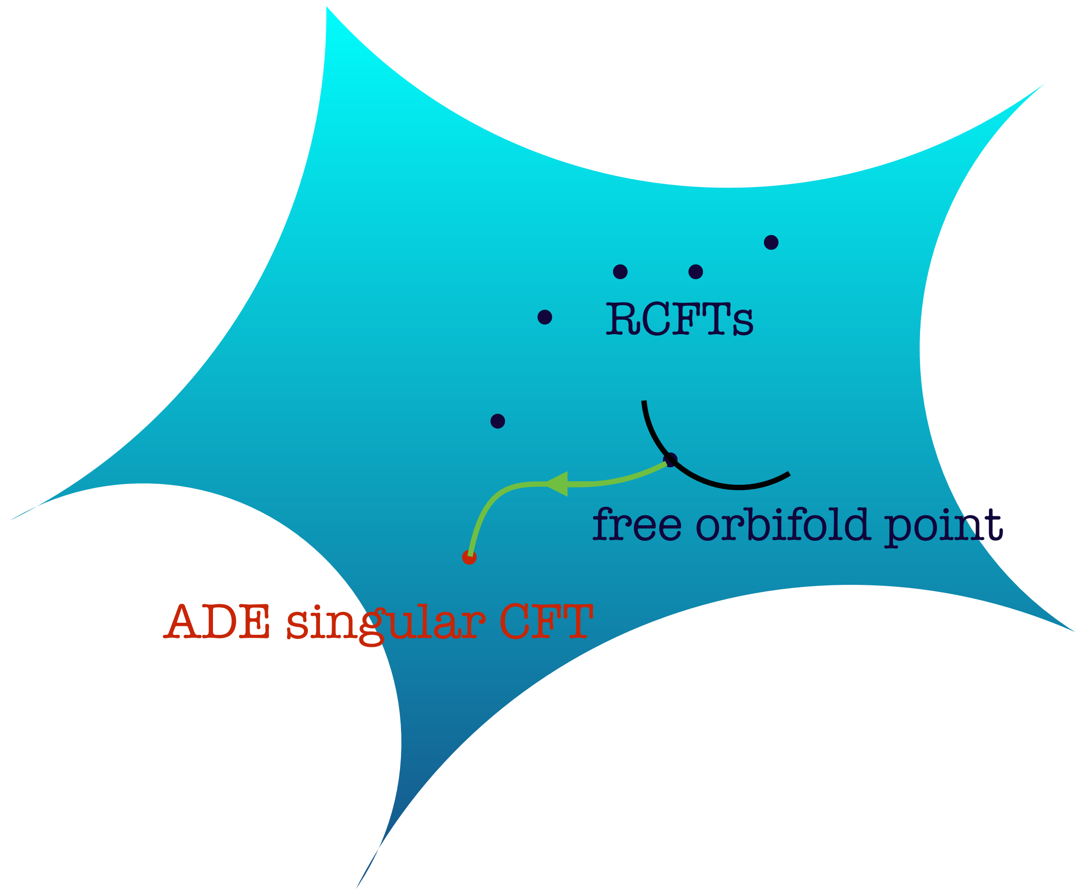


Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$

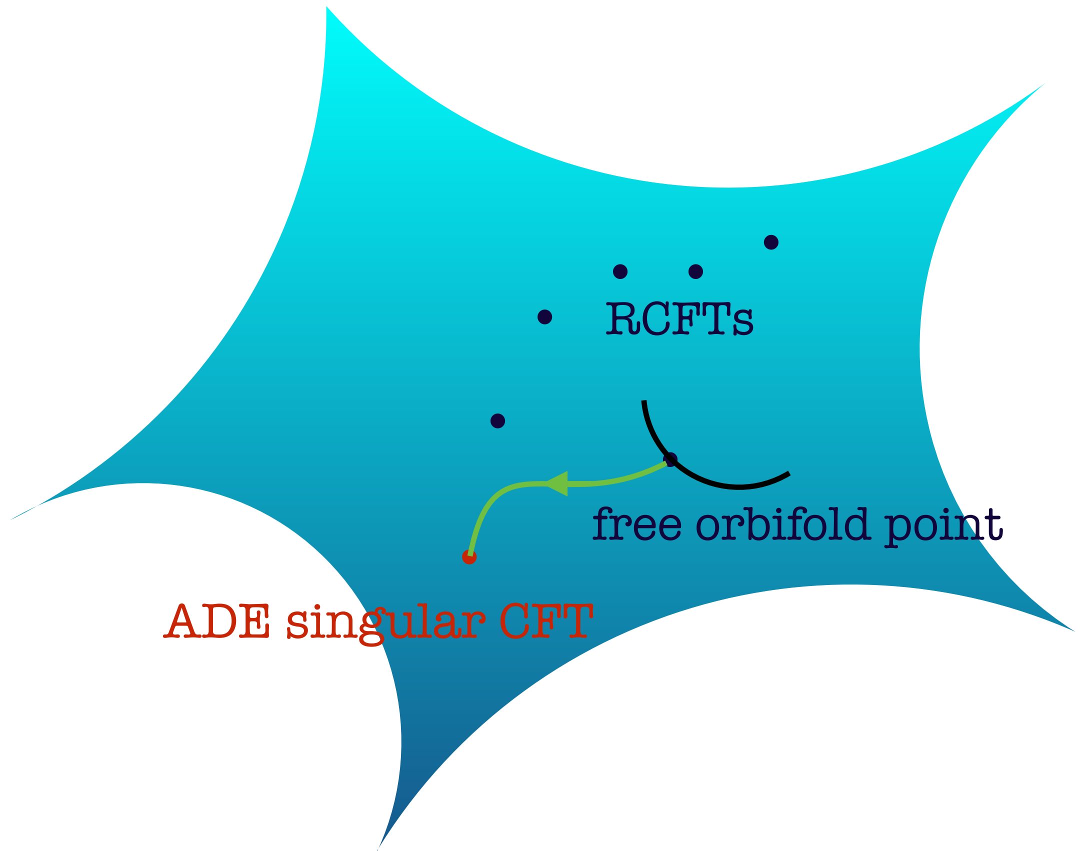


Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$



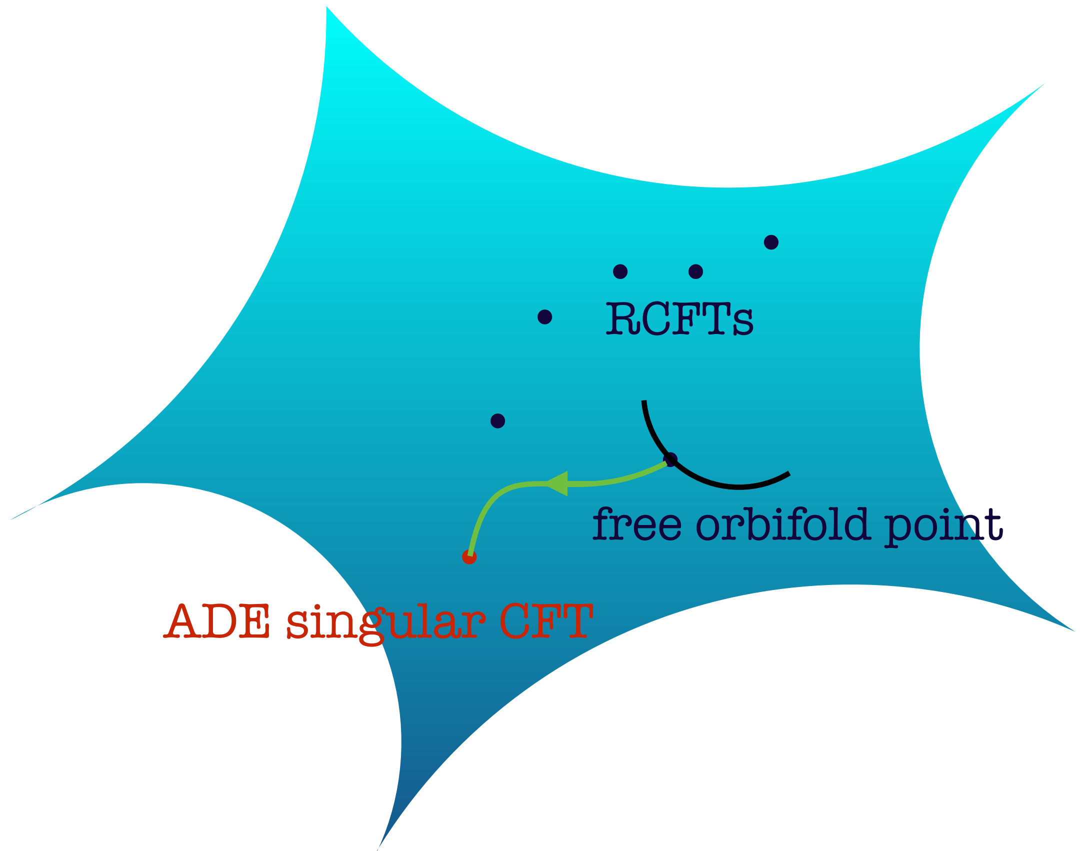
$$\int \frac{d^2 z}{|z(1-z)|}\langle \mathcal{O}_i(z,\bar{z})\mathcal{O}_j(0)\mathcal{O}_k(1)\mathcal{O}_\ell(\infty)\rangle = \frac{\partial^4}{\partial y^i \partial y^j \partial y^k \partial y^\ell}\bigg|_{y=0} \int_{\mathcal{F}} d^2\tau \frac{\Theta_\Lambda(y|\tau,\bar{\tau})}{\eta(\tau)^{24}}$$

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20) \times SO(4)$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$



$$\int \frac{d^2 z}{|z(1-z)|} \langle \mathcal{O}_i(z,\bar{z}) \mathcal{O}_j(0) \mathcal{O}_k(1) \mathcal{O}_\ell(\infty) \rangle = \frac{\partial^4}{\partial y^i \partial y^j \partial y^k \partial y^\ell}\bigg|_{y=0} \int_{\mathcal{F}} d^2\tau \frac{\Theta_\Lambda(y|\tau,\bar{\tau})}{\eta(\tau)^{24}}$$

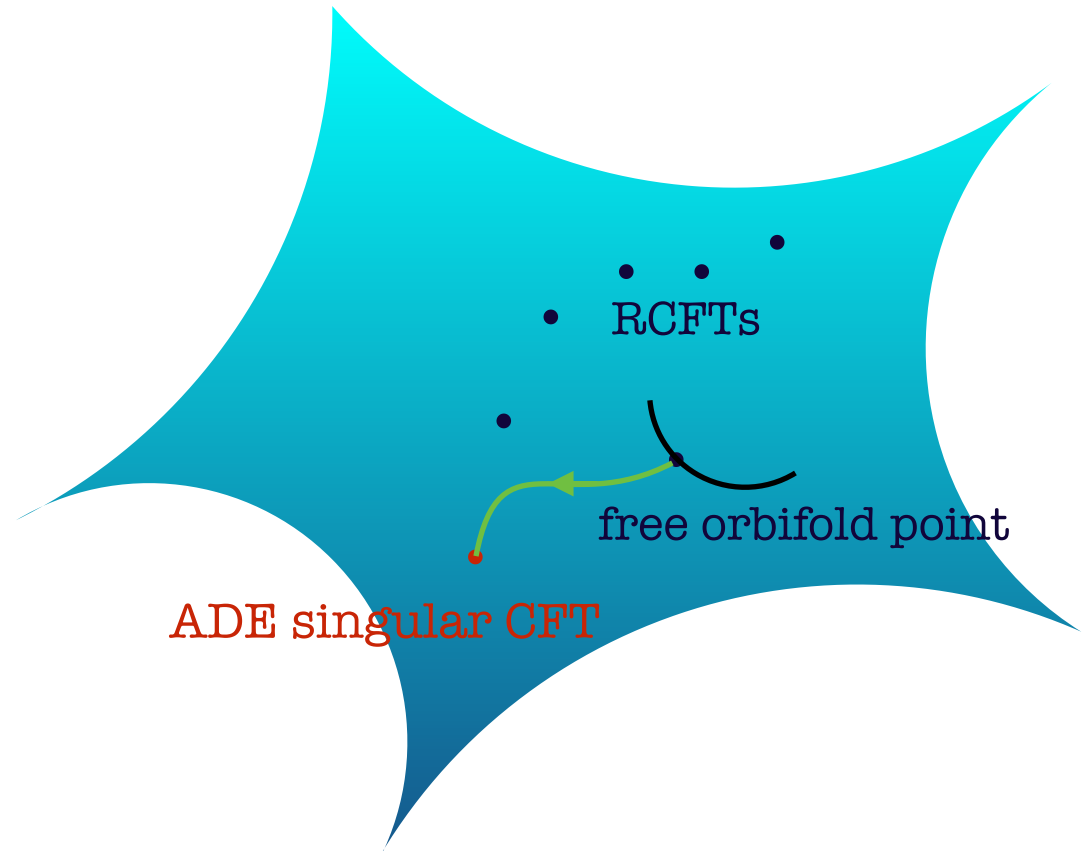
LHS = effective coupling of type IIB string on K3 at tree level

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$



$$\int \frac{d^2 z}{|z(1-z)|}\langle \mathcal{O}_i(z,\bar{z})\mathcal{O}_j(0)\mathcal{O}_k(1)\mathcal{O}_\ell(\infty)\rangle = \frac{\partial^4}{\partial y^i \partial y^j \partial y^k \partial y^\ell}\bigg|_{y=0} \int_{\mathcal{F}} d^2\tau \frac{\Theta_\Lambda(y|\tau,\bar{\tau})}{\eta(\tau)^{24}}$$

LHS = effective coupling of type IIB string on K3 at tree level

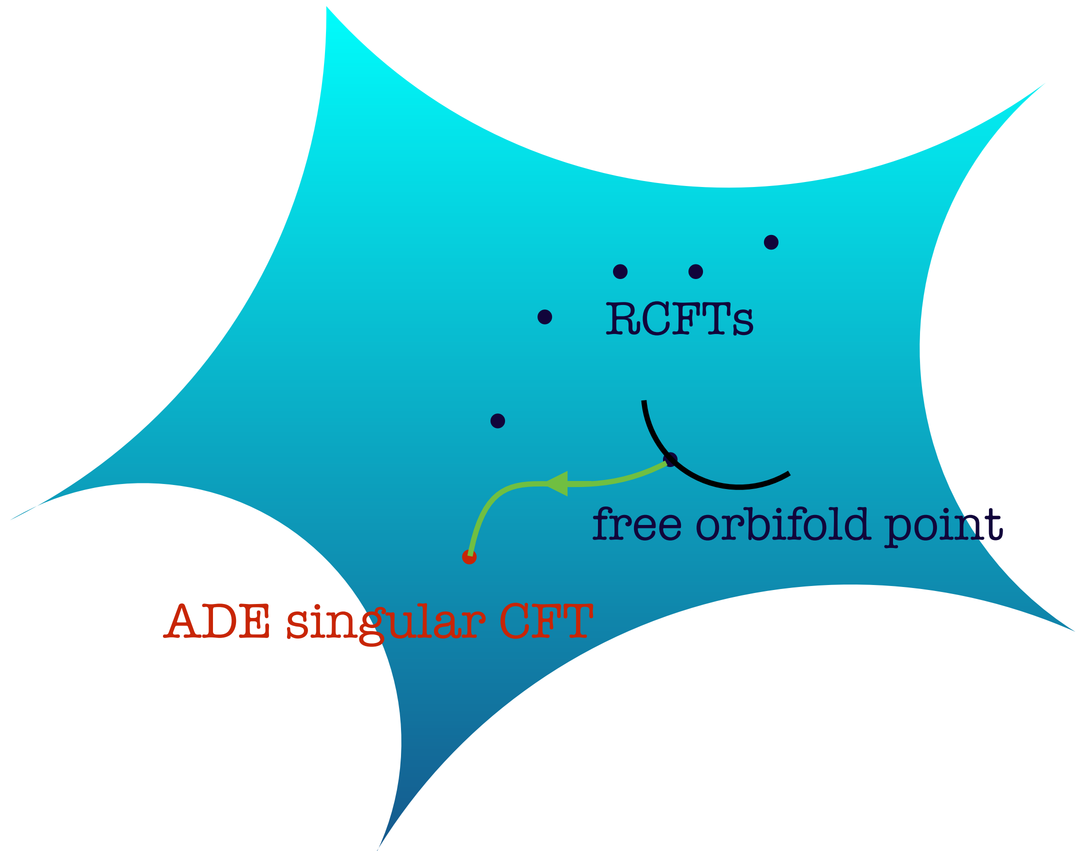
RHS = solution to a set of second order differential equations on the moduli space that follow from 6D supersymmetry Ward identities

Key ingredient 2: An exact result on the integrated BPS 4-point function (as function of moduli)

The moduli space of K3 CFT

$\mathrm{Aut}(\Gamma_{20,4})\backslash SO(20,4)/SO(20)\times SO(4)$

parameterized by lattice embedding $\Gamma_{20,4} \subset \mathbb{R}^{20,4}$



$$\int \frac{d^2 z}{|z(1-z)|}\langle \mathcal{O}_i(z,\bar{z})\mathcal{O}_j(0)\mathcal{O}_k(1)\mathcal{O}_\ell(\infty)\rangle = \left.\frac{\partial^4}{\partial y^i \partial y^j \partial y^k \partial y^\ell}\right|_{y=0} \int_{\mathcal{F}} d^2\tau \frac{\Theta_\Lambda(y|\tau,\bar{\tau})}{\eta(\tau)^{24}}$$

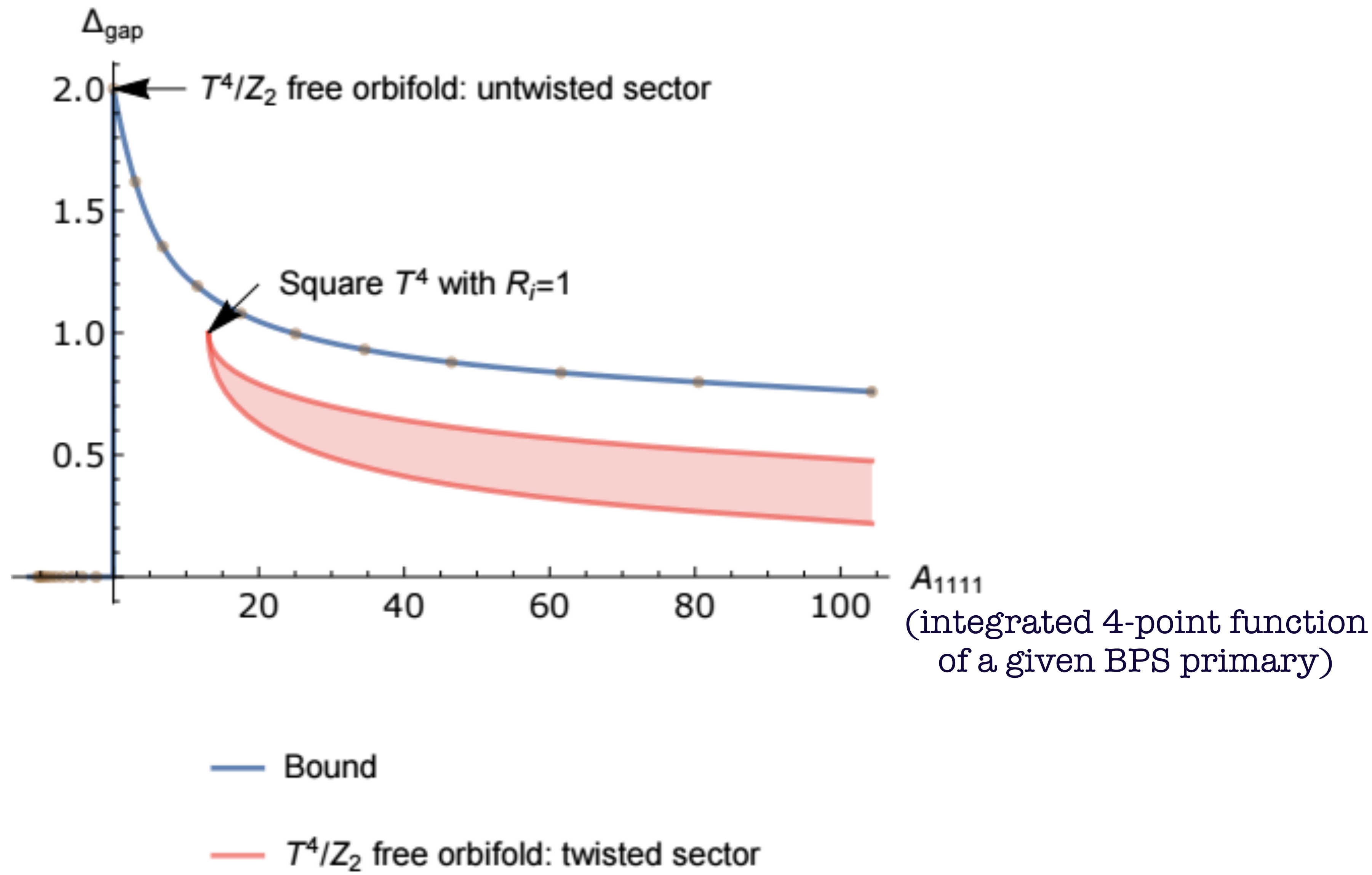
LHS = effective coupling of type IIB string on K3 at tree level

RHS = solution to a set of second order differential equations on the moduli space that follow from 6D supersymmetry Ward identities

[Kiritsis-Obers-Pioline, '00, Lin-Shao-Wang-XY, '15]

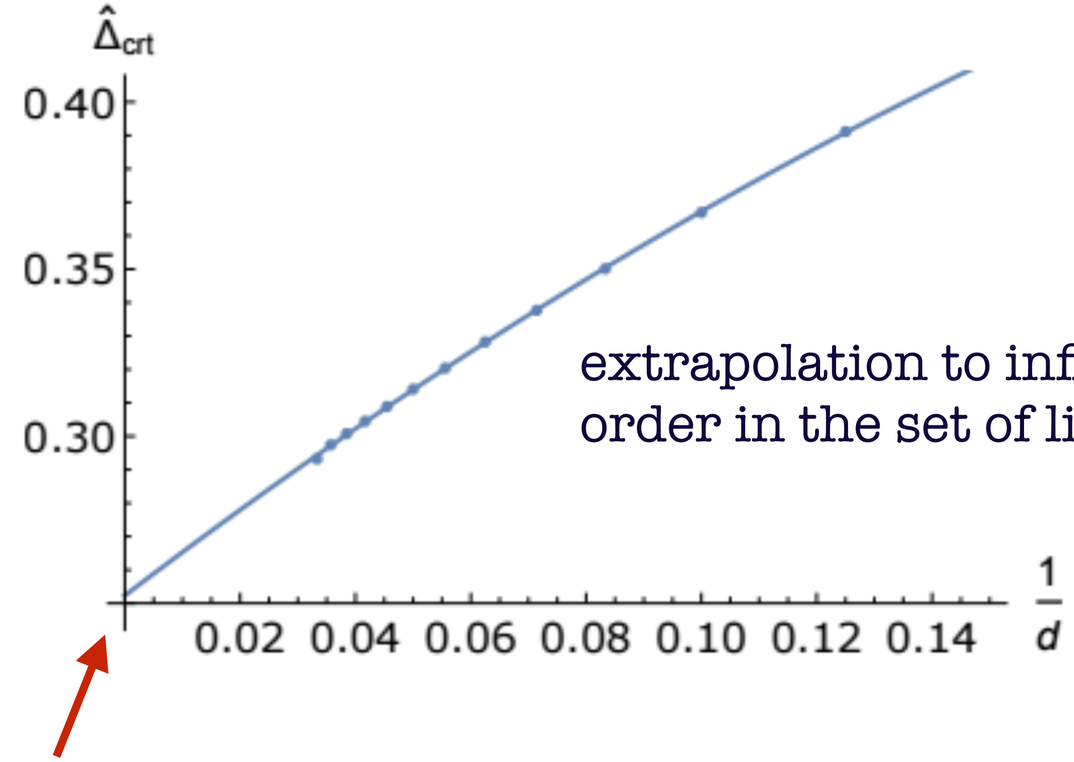
Feed into the bootstrap machine...

The gap in the non-BPS operator spectrum of the K3 CFT



The development of continuum

(when the integrated BPS 4-point function diverges)



extrapolation to infinite derivative
order in the set of linear functionals

quadratic fit	0.252
A_1 cigar	0.25

A taste of $\mathcal{N}=2$ superconformal bootstrap…

A taste of N=2 superconformal bootstrap...

Let us study the OPE of a conjugate pair of BPS operators (chiral primary $h=q/2$ and anti-chiral primary $h=-q/2$), and bound the gap in terms of chiral ring coefficients.

A taste of N=2 superconformal bootstrap...

Let us study the OPE of a conjugate pair of BPS operators (chiral primary $h=q/2$ and anti-chiral primary $h=-q/2$), and bound the gap in terms of chiral ring coefficients.

A warm up: $c=3$, $q=1/3$

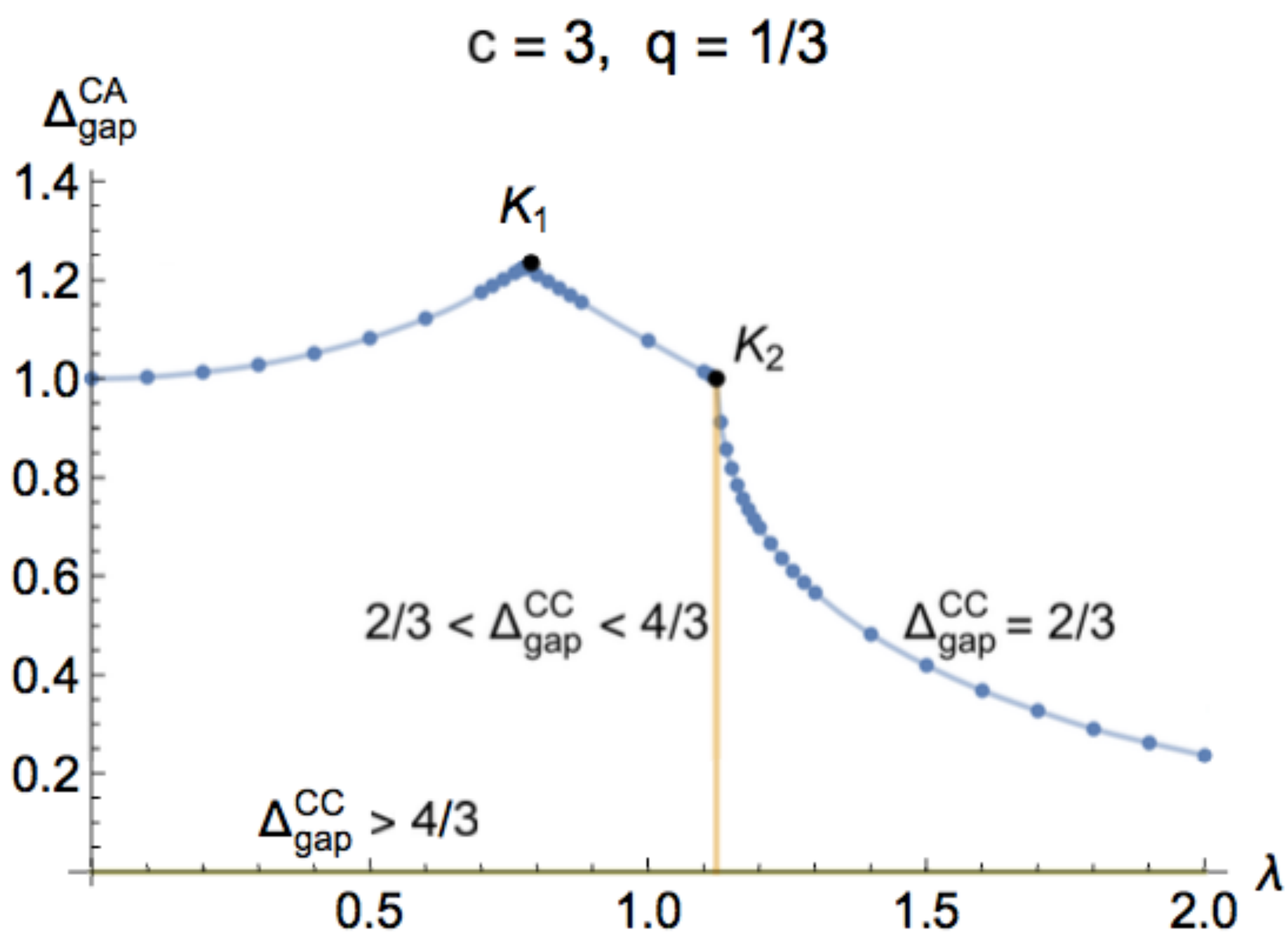
A taste of N=2 superconformal bootstrap...

Let us study the OPE of a conjugate pair of BPS operators (chiral primary $h=q/2$ and anti-chiral primary $h=-q/2$), and bound the gap in terms of chiral ring coefficients.

A warm up: $c=3$, $q=1/3$ (realized by twist fields of T^2/Z_3)

N=(2,2) Bootstrap

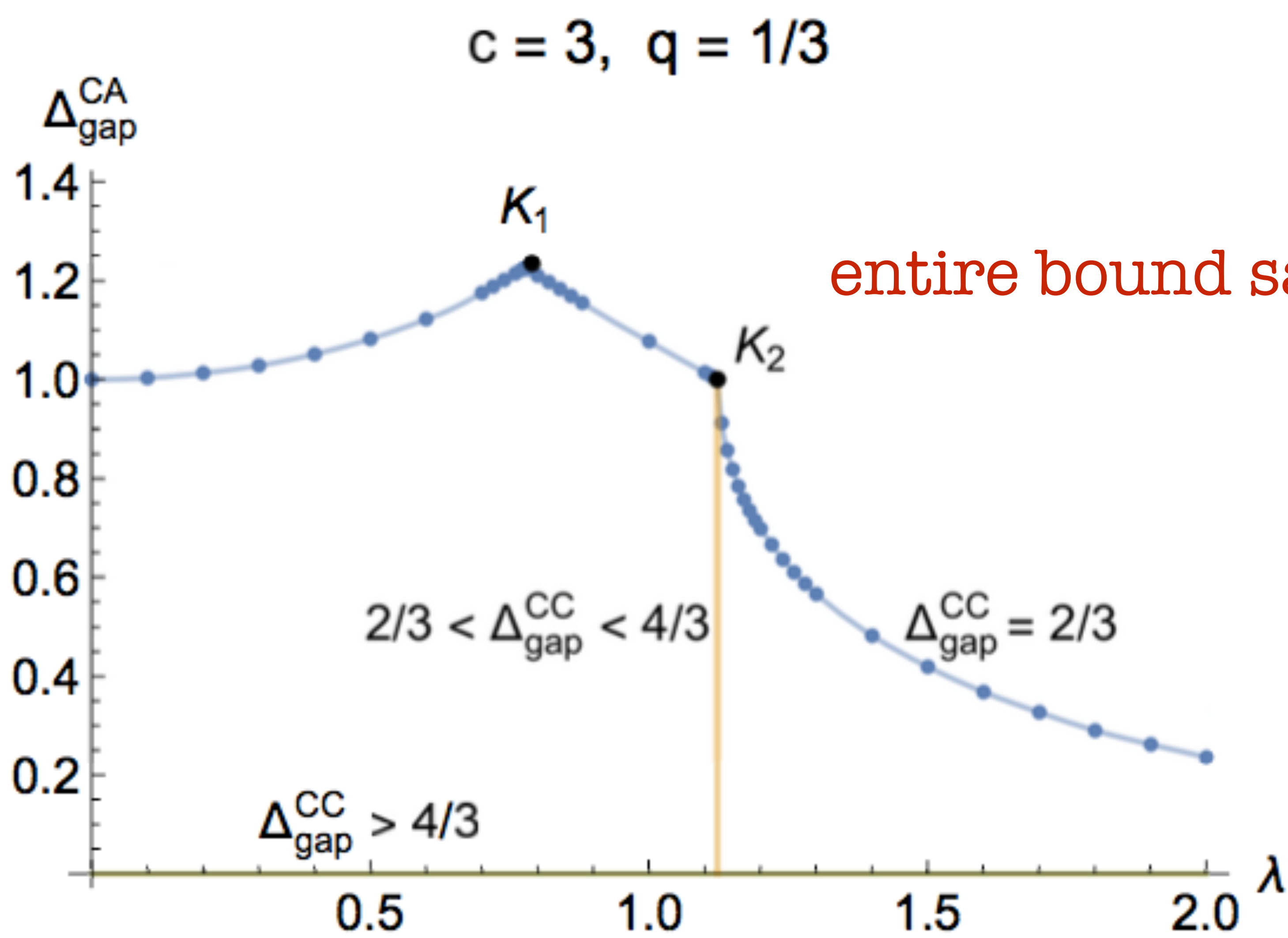
c=3, chiral-anti-chiral OPE, q=1/3



OPE coefficient of q=2/3 BPS primary

N=(2,2) Bootstrap

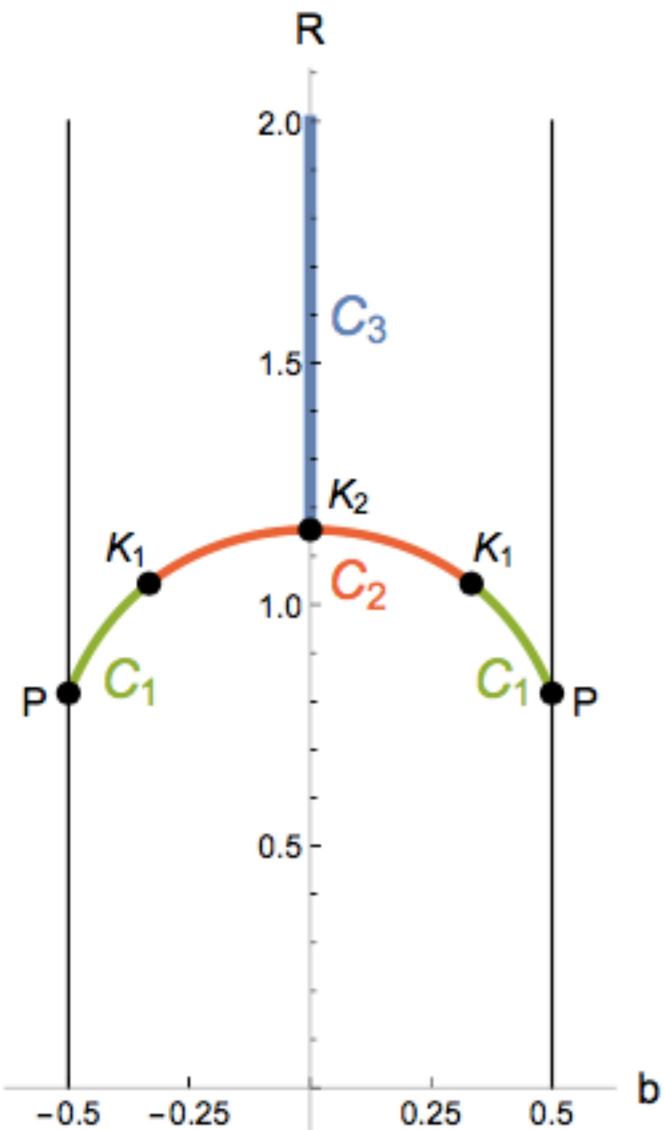
c=3, chiral-anti-chiral OPE, q=1/3



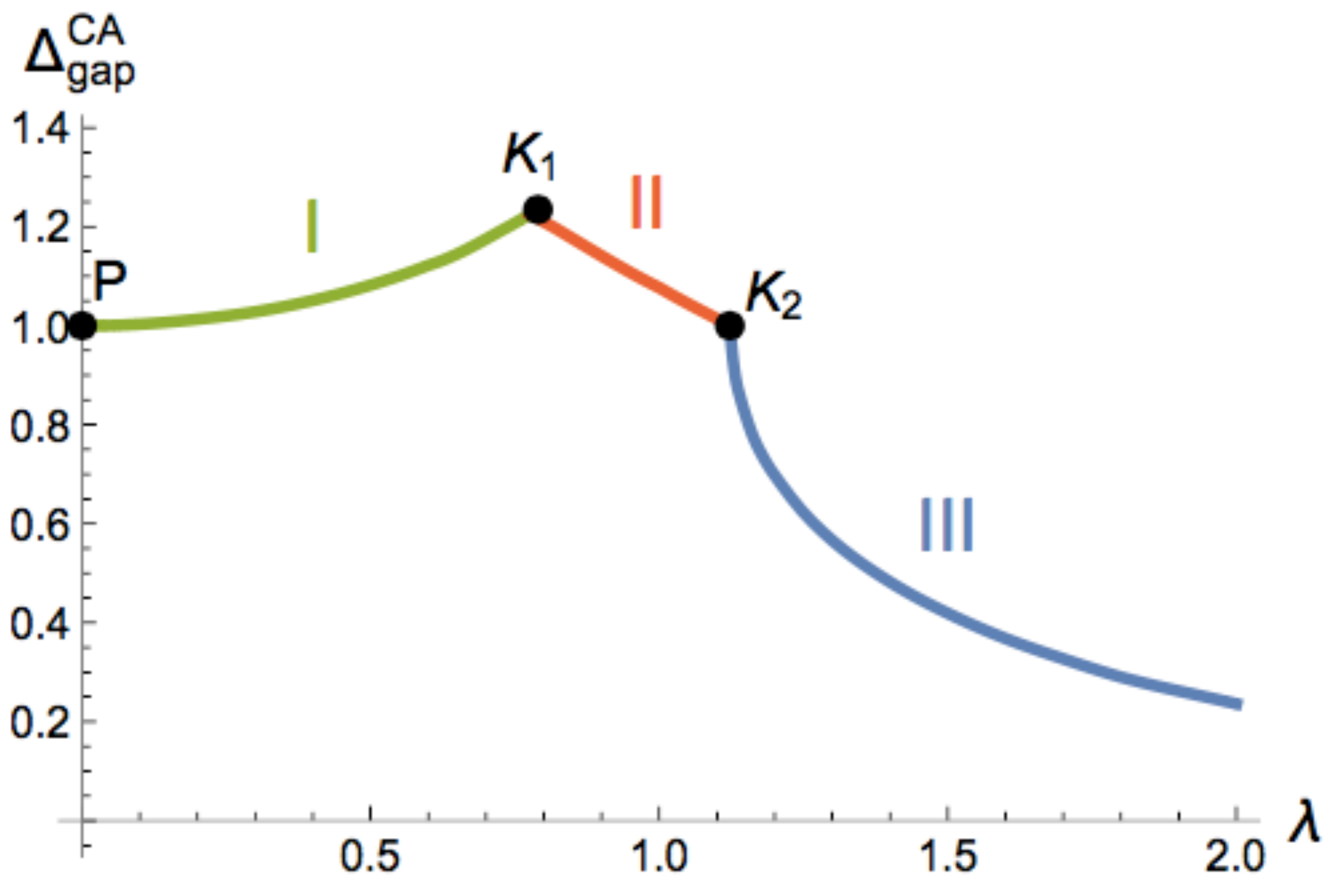
entire bound saturated!

OPE coefficient of q=2/3 BPS primary

N=(2,2) Bootstrap



moduli space of T^2/Z_3



bootstrap bound

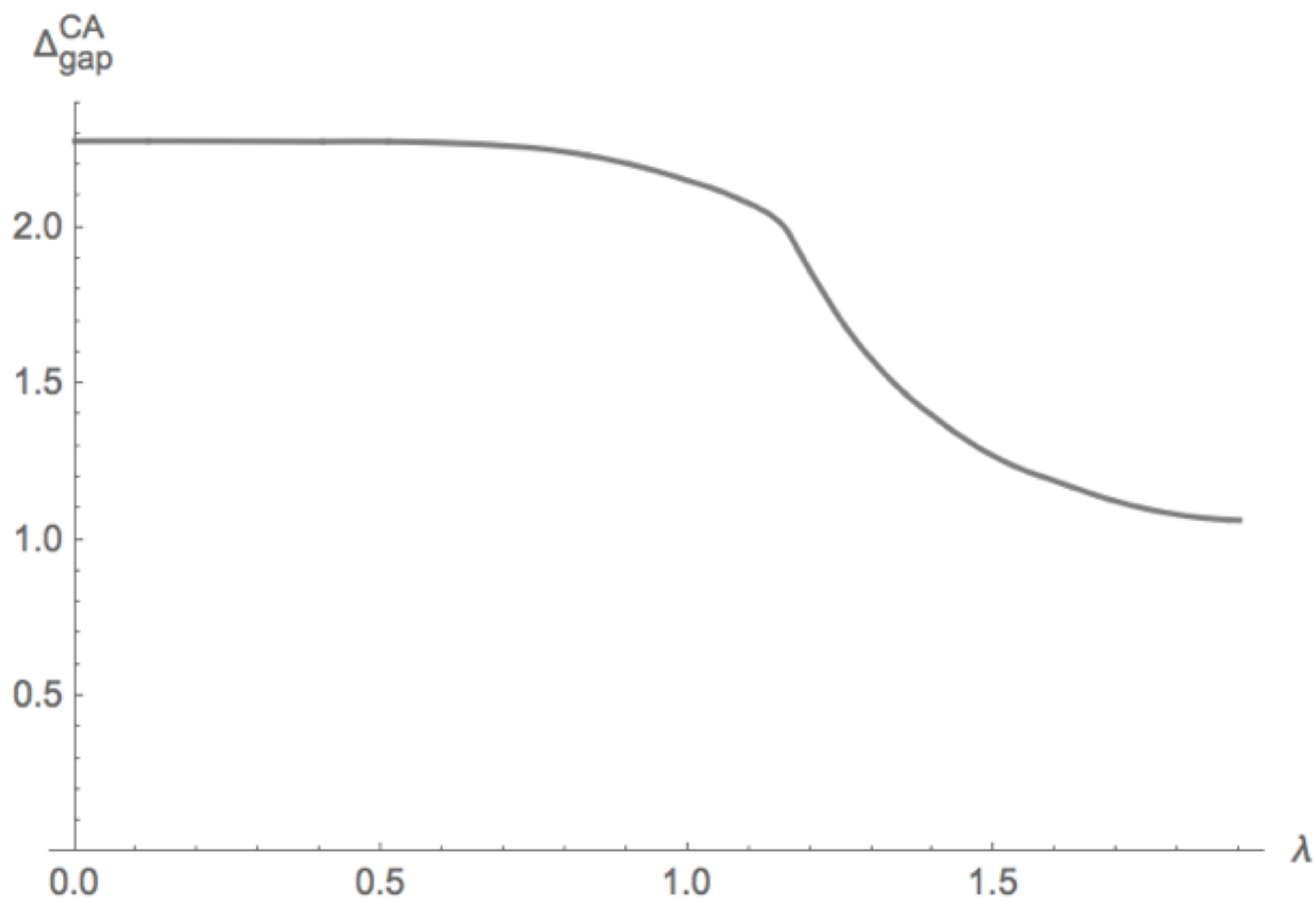
Now for Calabi-Yau 3-fold model...

Now for Calabi-Yau 3-fold model…

c=9, chiral-anti-chiral OPE, q=1

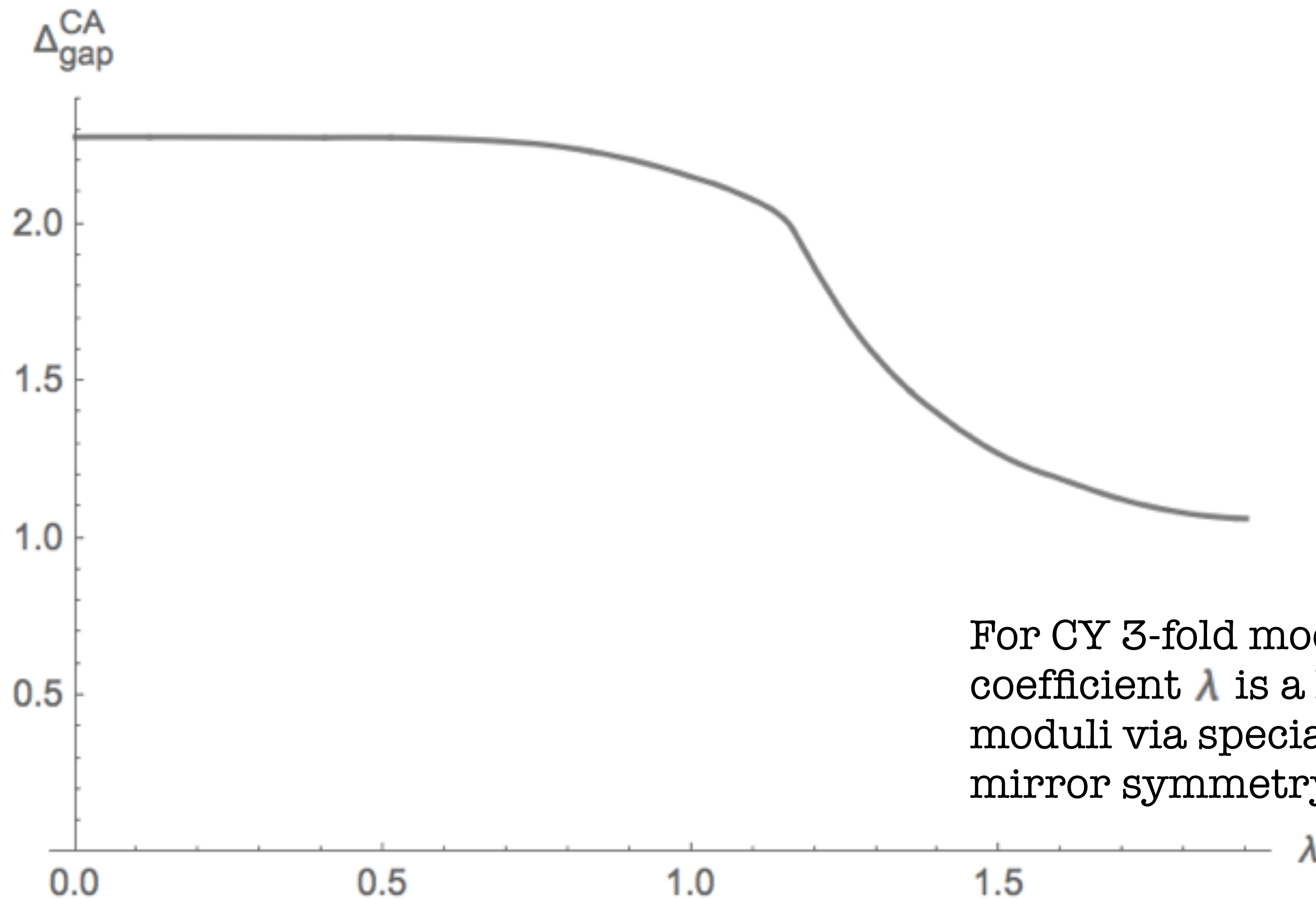
N=(2,2) Bootstrap

c=9, chiral-anti-chiral OPE, q=1



N=(2,2) Bootstrap

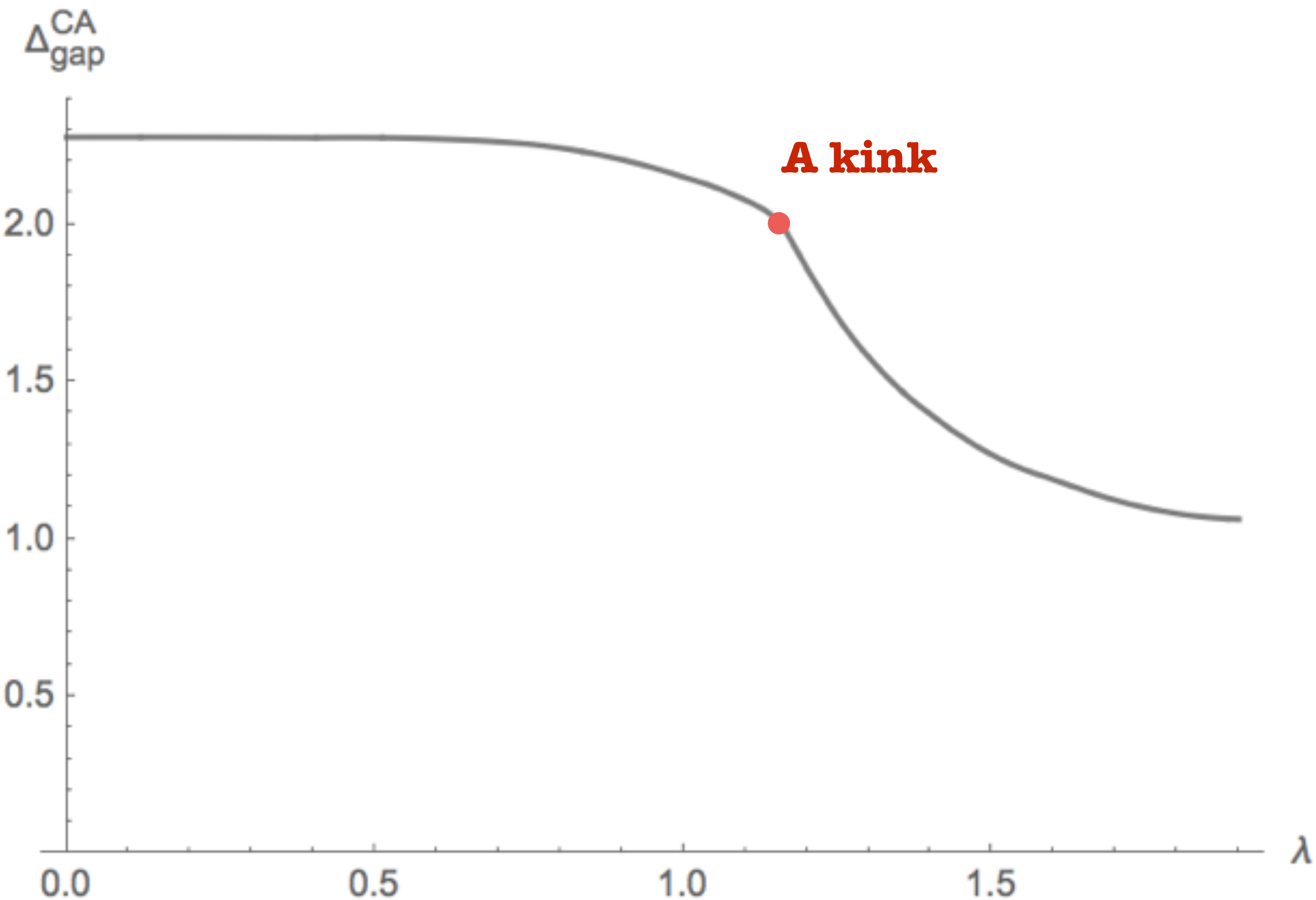
c=9, chiral-anti-chiral OPE, q=1



For CY 3-fold models, the BPS OPE coefficient λ is a known function of moduli via special geometry and mirror symmetry.

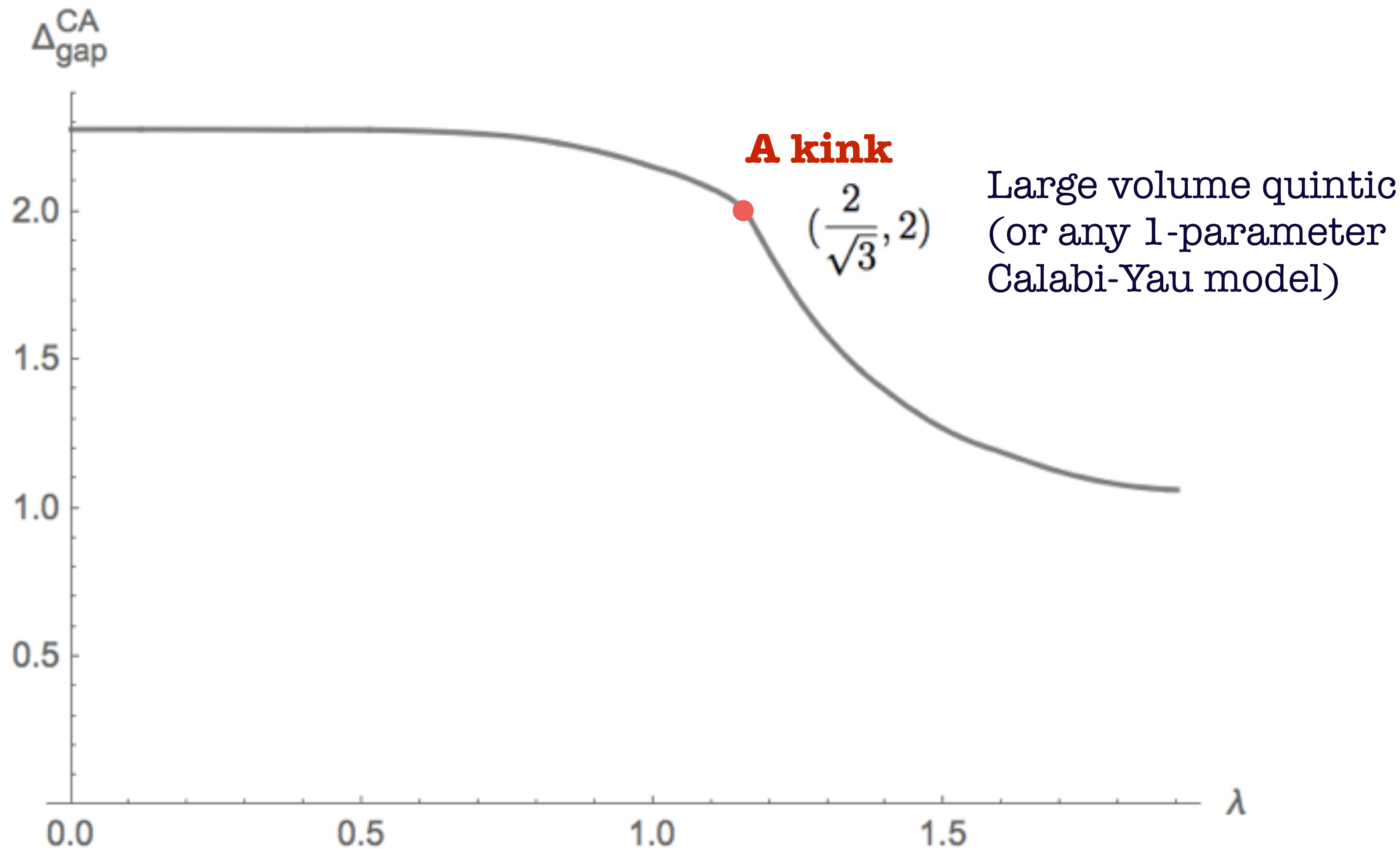
N=(2,2) Bootstrap

c=9, chiral-anti-chiral OPE, q=1



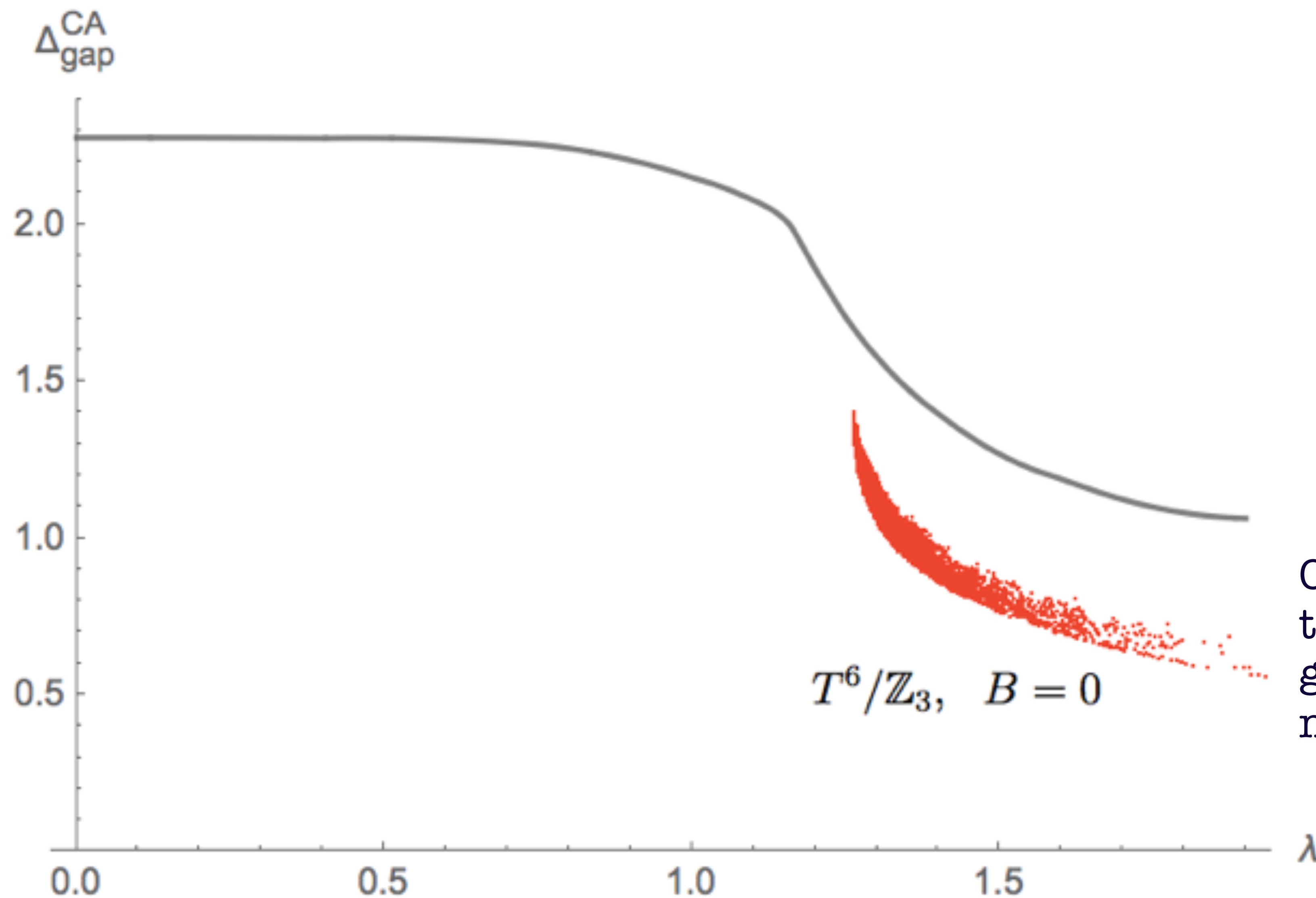
N=(2,2) Bootstrap

c=9, chiral-anti-chiral OPE, q=1



N=(2,2) Bootstrap

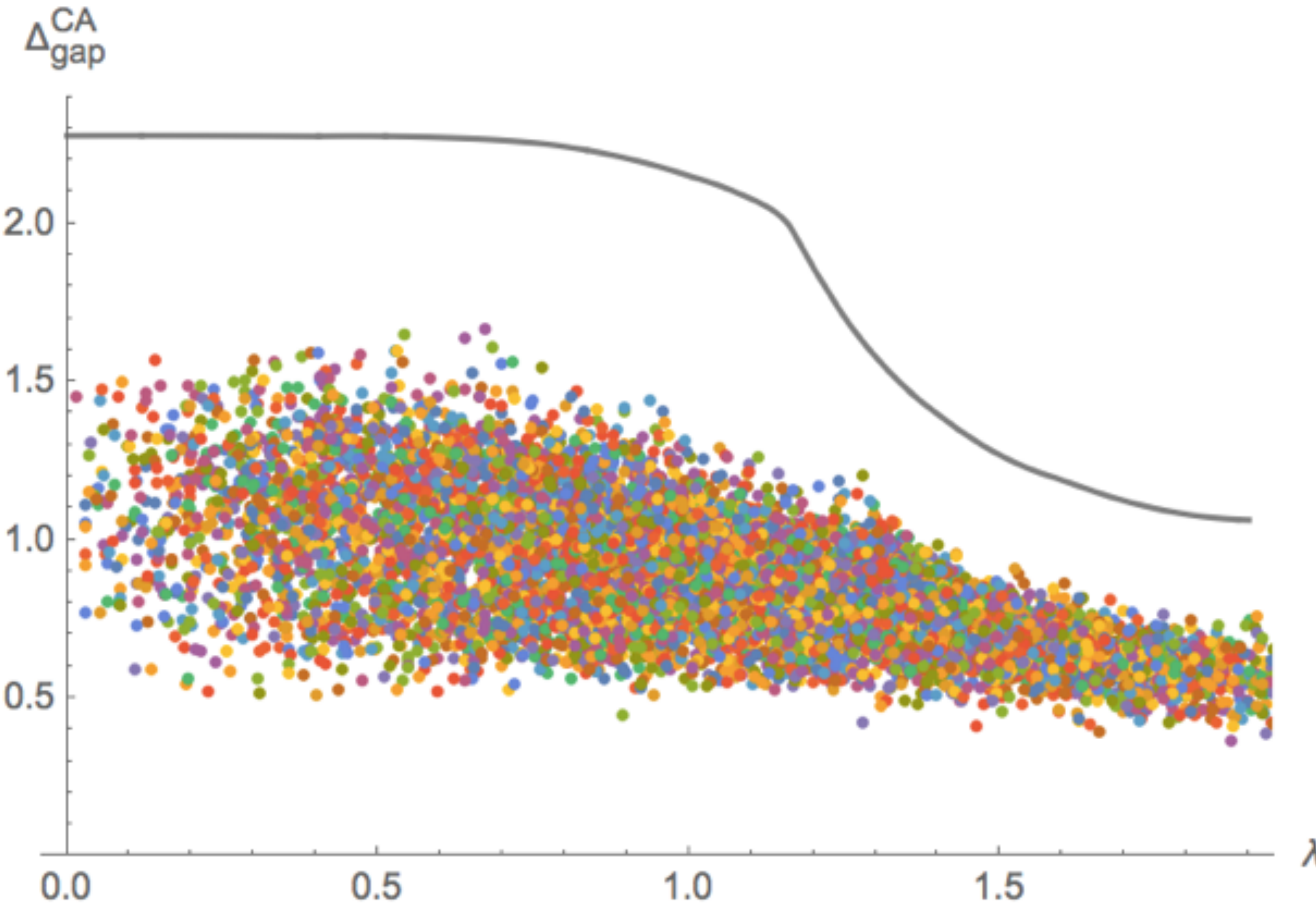
c=9, chiral-anti-chiral OPE, q=1



OPE of twist fields of the Z-manifold CFT: general tilting, but no B-field

N=(2,2) Bootstrap

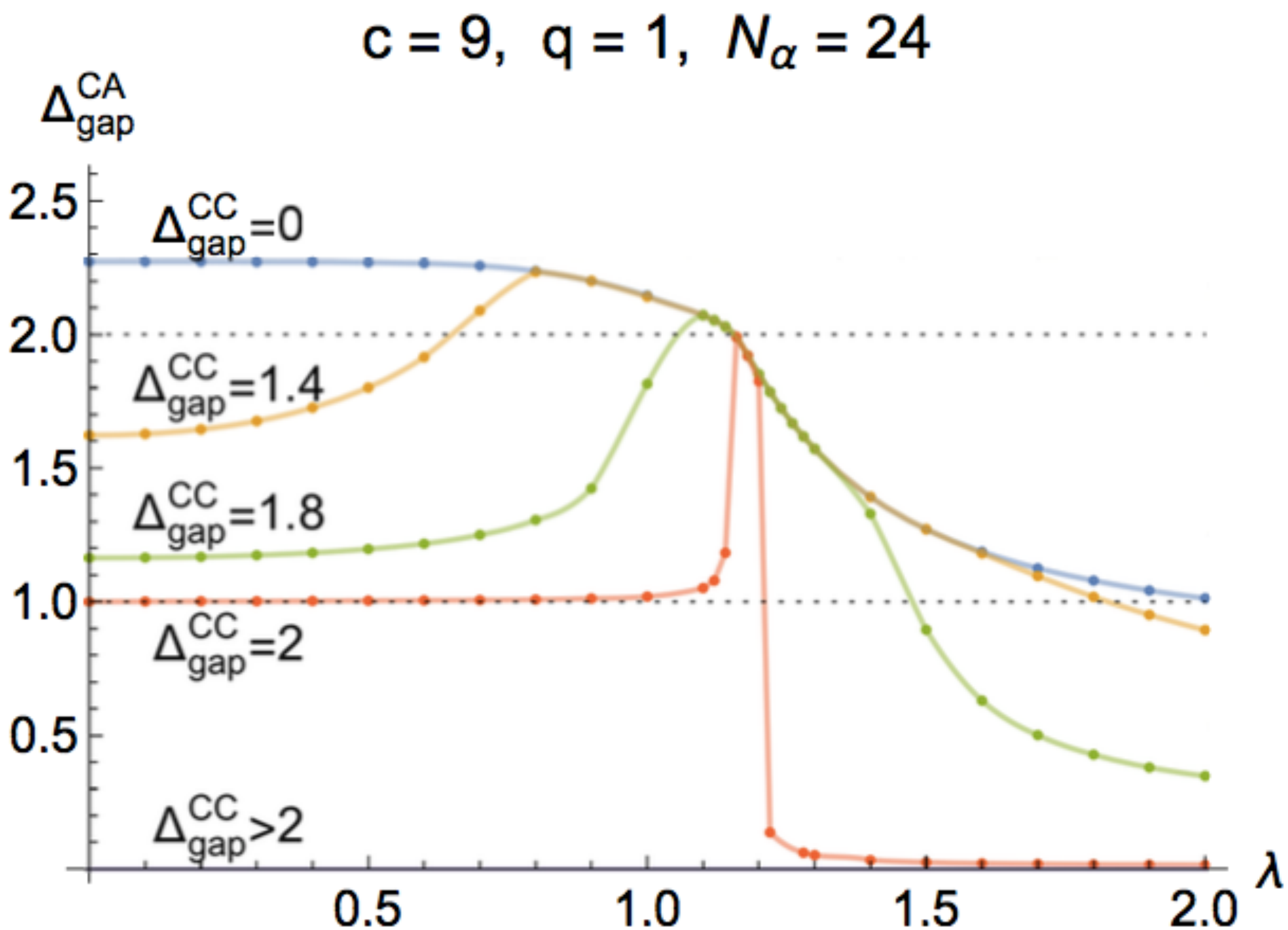
c=9, chiral-anti-chiral OPE, q=1



OPE of twist fields of the Z-manifold CFT: a sampling over general tilting and flat B-field

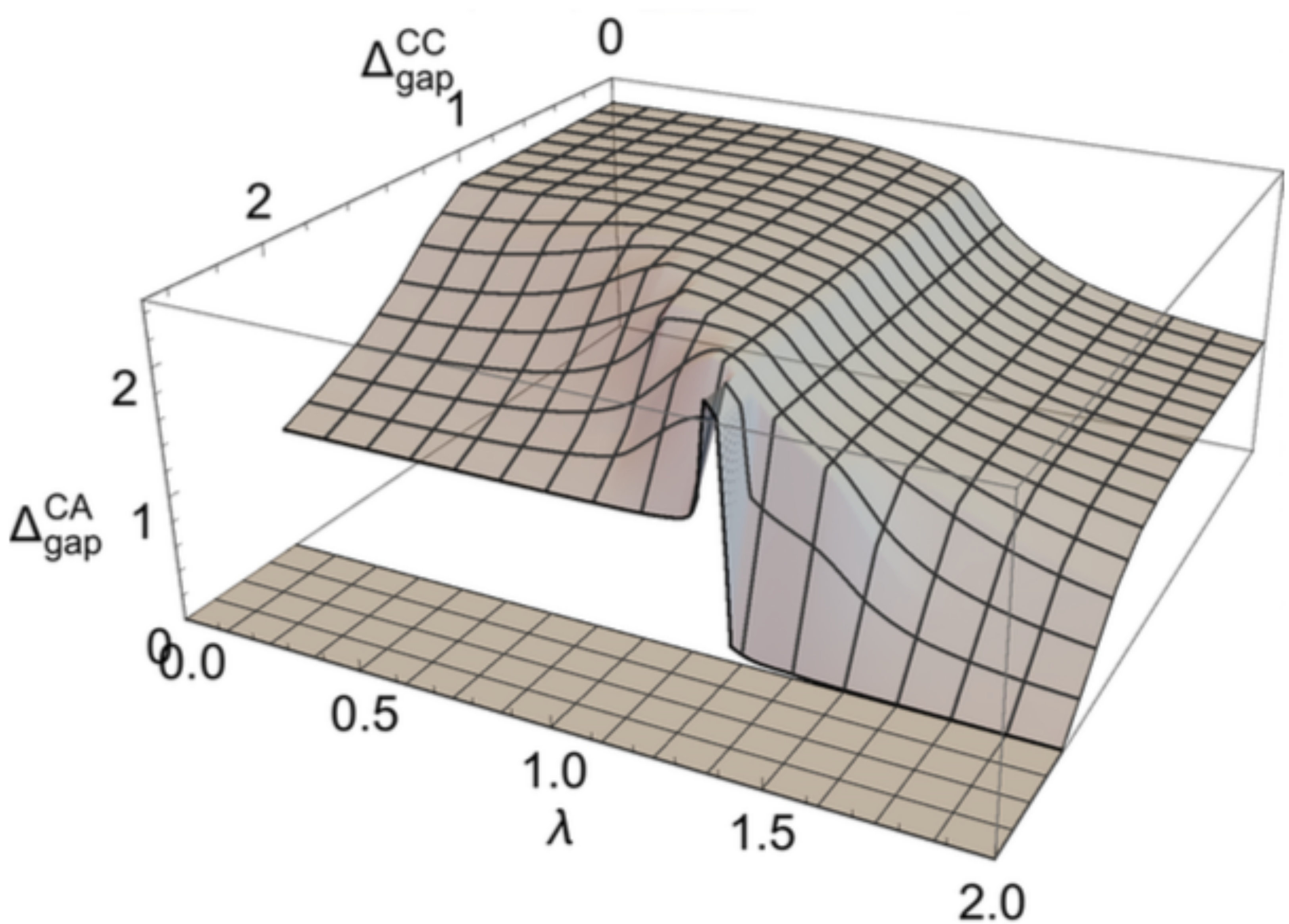
N=(2,2) Bootstrap

c=9, chiral-anti-chiral OPE, q=1



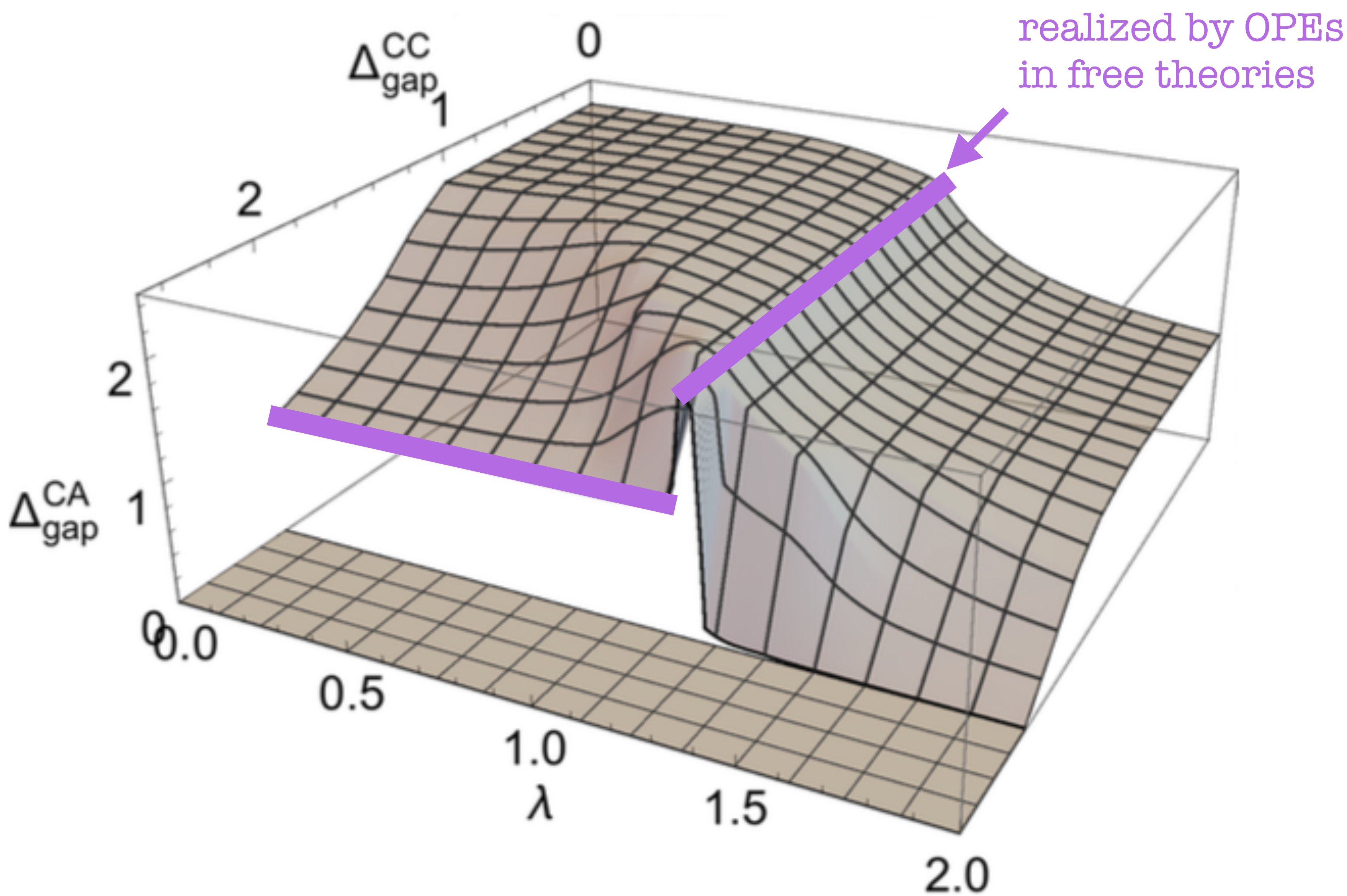
N=(2,2) Bootstrap

c=9, gaps in chiral-anti-chiral (CA) vs chiral-chiral (CC) channels, q=1



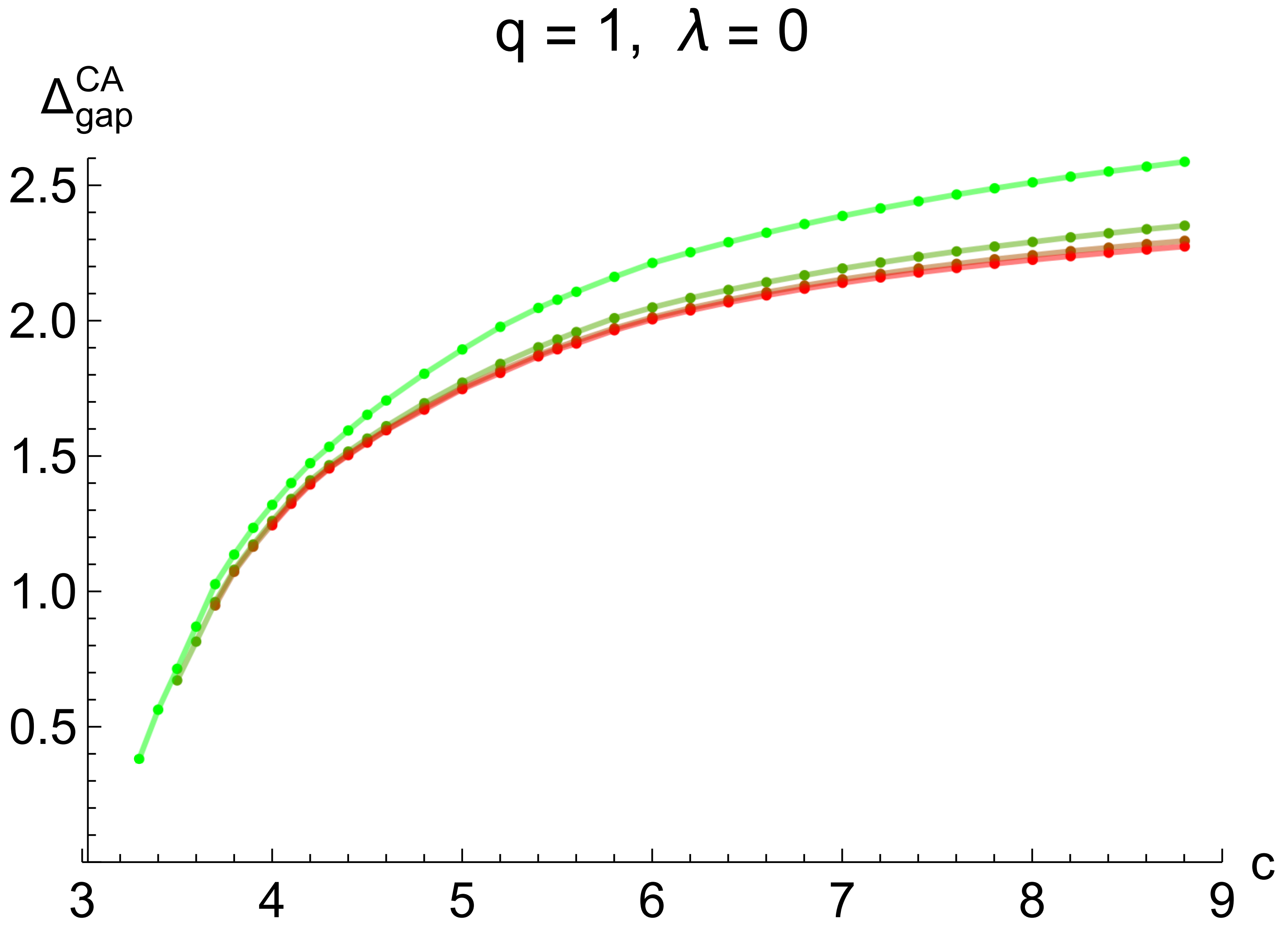
N=(2,2) Bootstrap

c=9, gaps in chiral-anti-chiral (CA) vs chiral-chiral (CC) channels, q=1



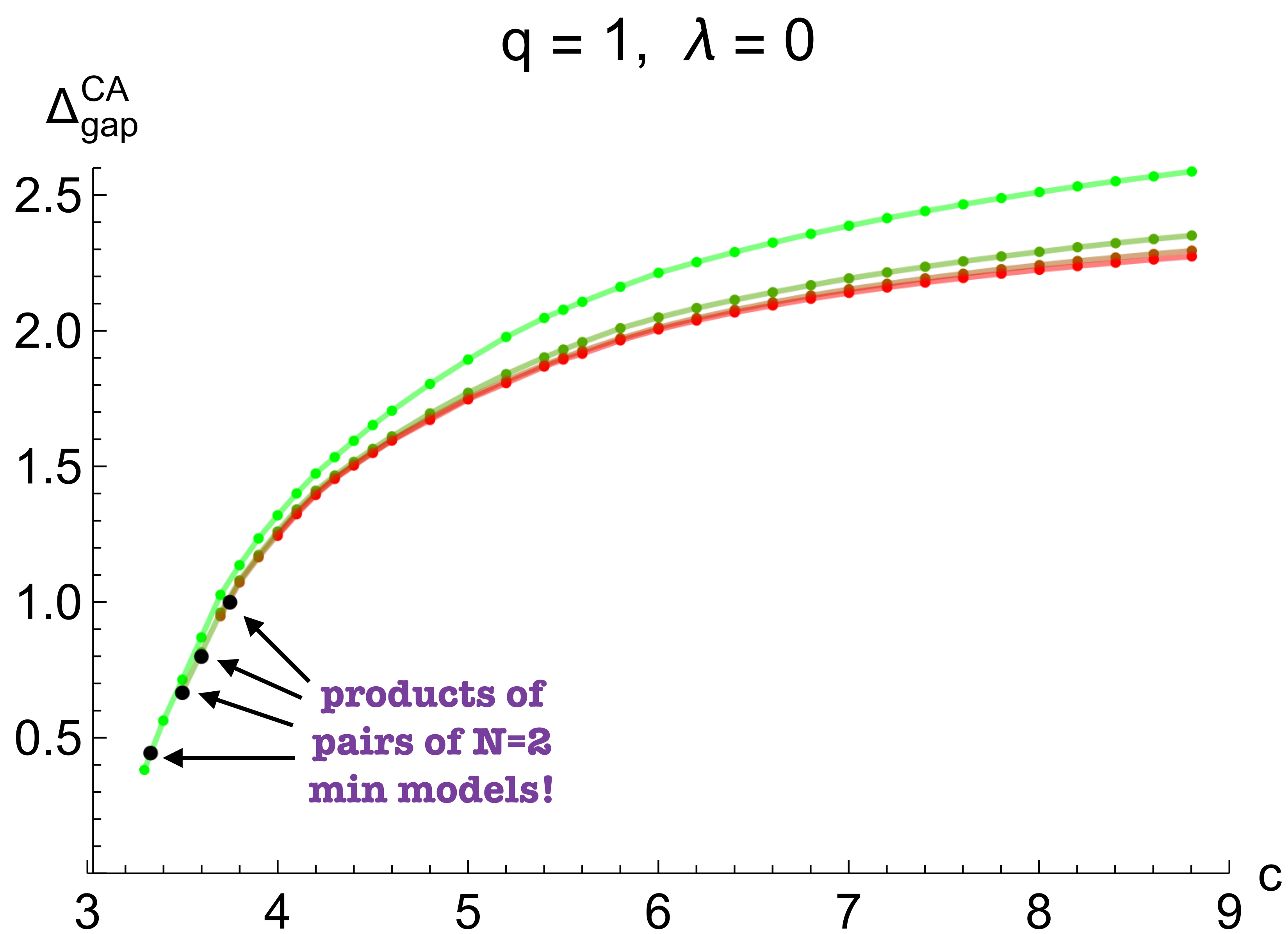
(2,2) with marginal deformation

3<c<9, OPE of marginal chiral and anti-chiral primaries



(2,2) with marginal deformation

3<c<9, OPE of marginal chiral and anti-chiral primaries



To be continued…