Quantum Field Theory without Lagrangians

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What is a QFT?

[everyone has a view]

Physically:
macroscopic structure emerging from microscopic dynamics

local action

$$S[\phi]$$

short distance d.o.f.

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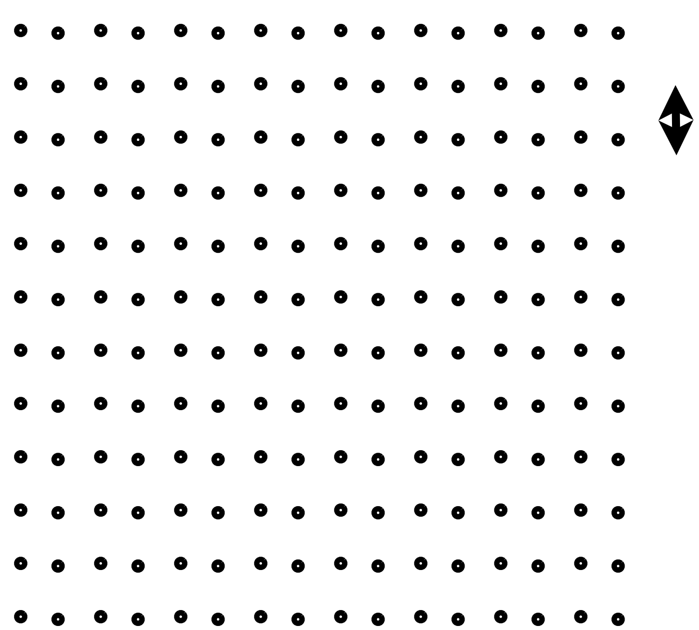

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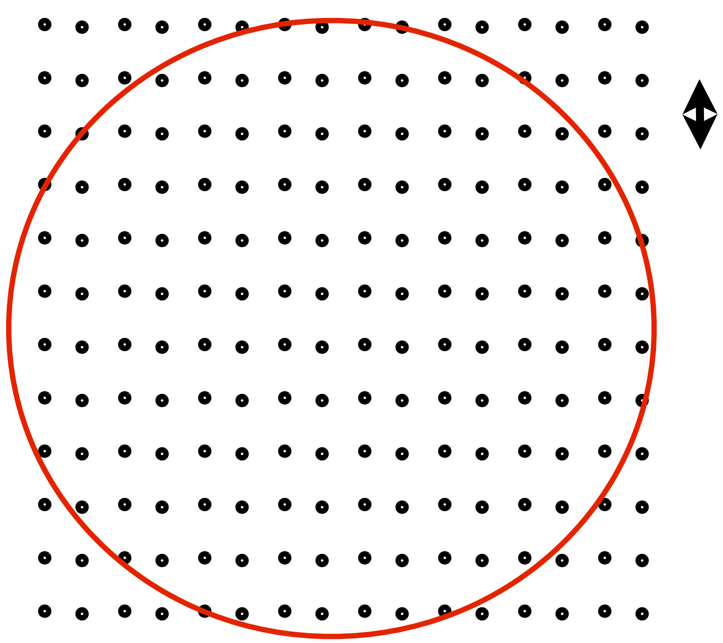

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Look at long distances: x >> a

Main tool: Renormalization Group [Wilson 1971]

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Mathematically: an associative algebra of local operators $\mathcal{O}_i(x)$

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Associativity:

$$\Big(\mathcal{O}_i(x) \times \mathcal{O}_j(y)\Big) \times \mathcal{O}_k(z) = \mathcal{O}_i(x) \times \Big(\mathcal{O}_j(y) \times \mathcal{O}_k(z)\Big)$$

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Follows from demanding well-defined correlation functions:

$$\Big\langle \mathcal{O}_i(x_1)\mathcal{O}_j(x_2)\mathcal{O}_k(x_3)\mathcal{O}_l(x_t) \Big\rangle$$

no Lagrangian, no clear rel. between O's and fund. fields...

Plan of this talk

1. RG picture
2. Conformal fixed points
3. Bootstrap

Renormalization Group

Experiment $\Rightarrow$

long-distance dynamics is universal (finite # of parameters)

[Cf. short-distance arbitrary, unknown,or grossly simplified]

Renormalization Group

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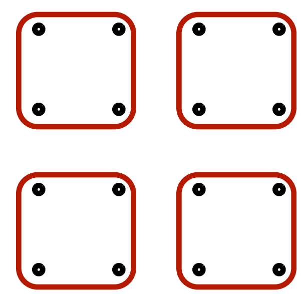
RG "explains" this by the flow: $S_1[\phi_1] \rightarrow S_2[\phi_2] \rightarrow \ldots$



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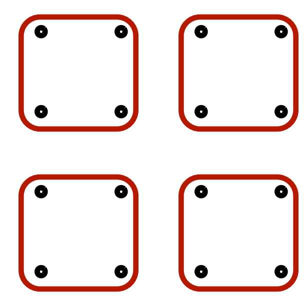
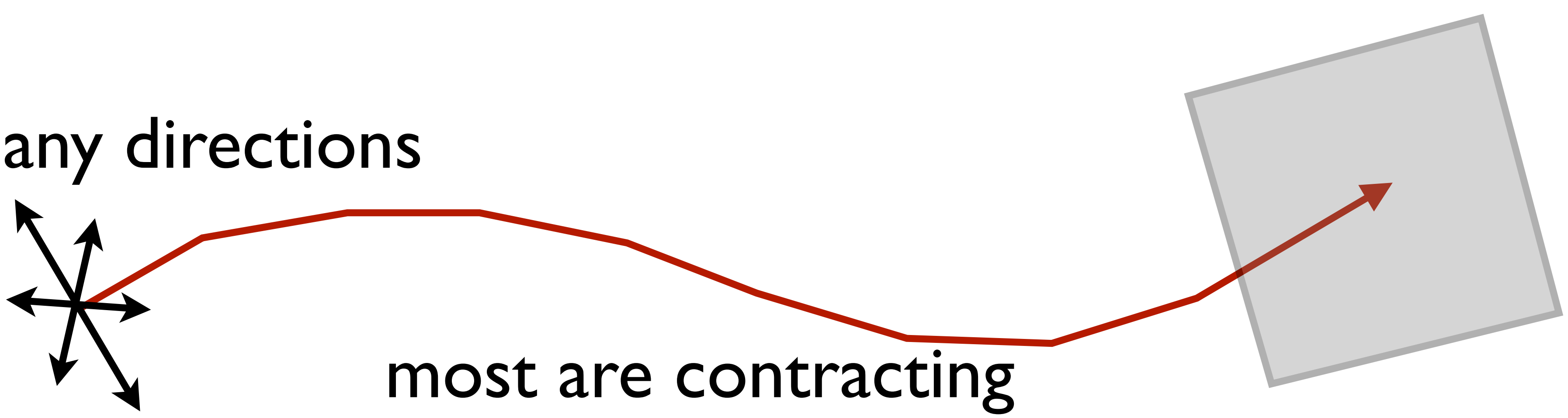
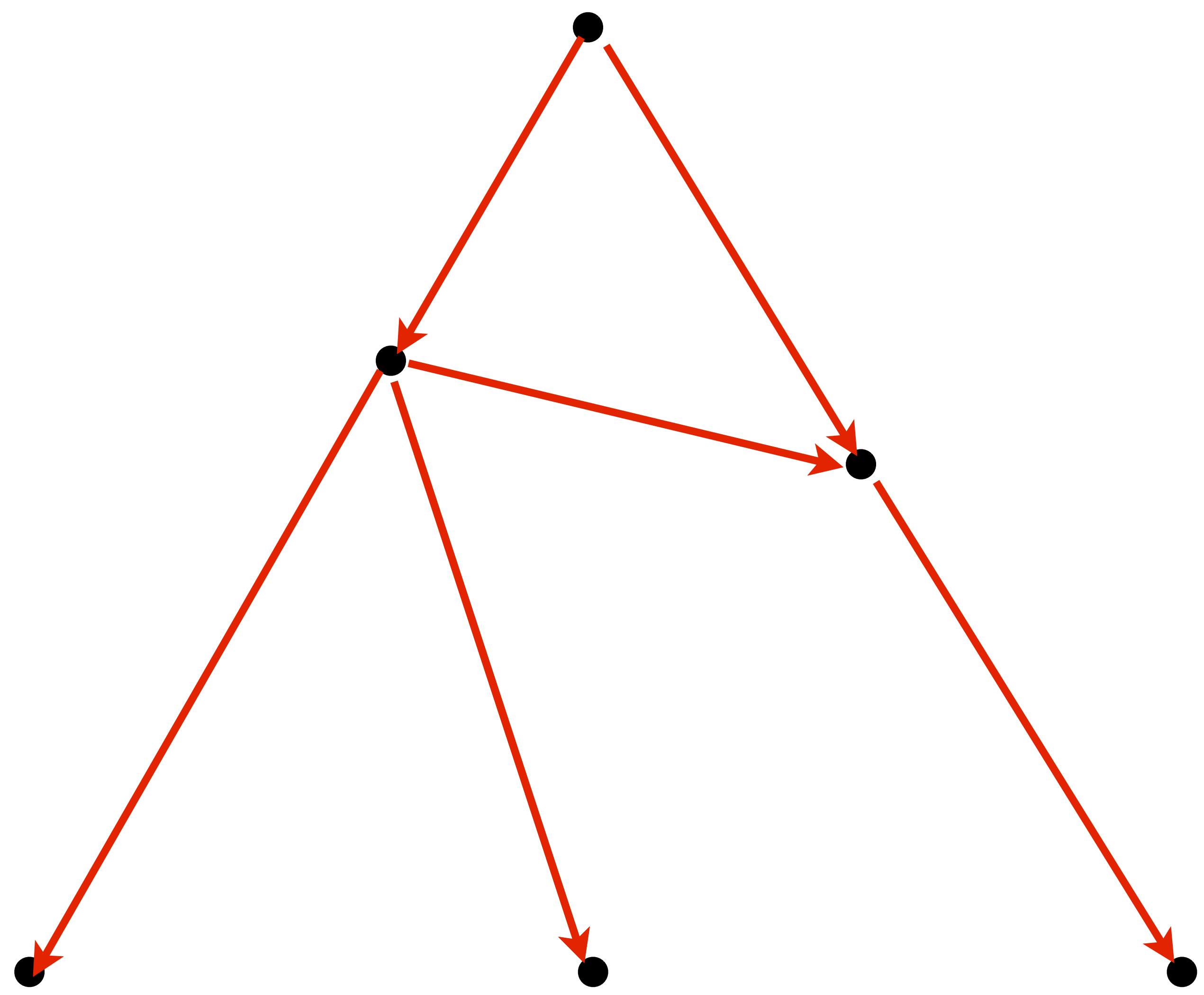




RG view of theory space



● = fixed point

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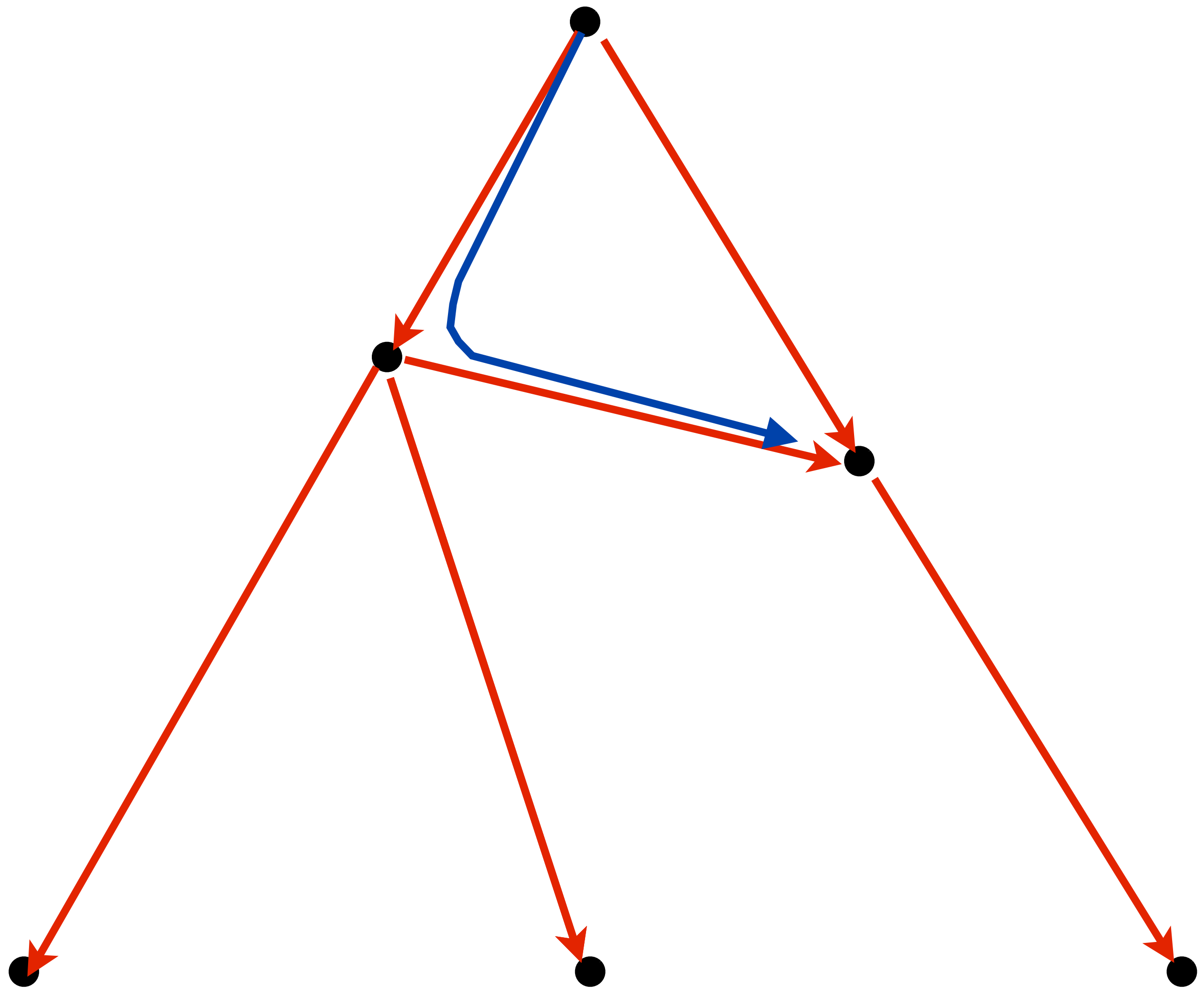

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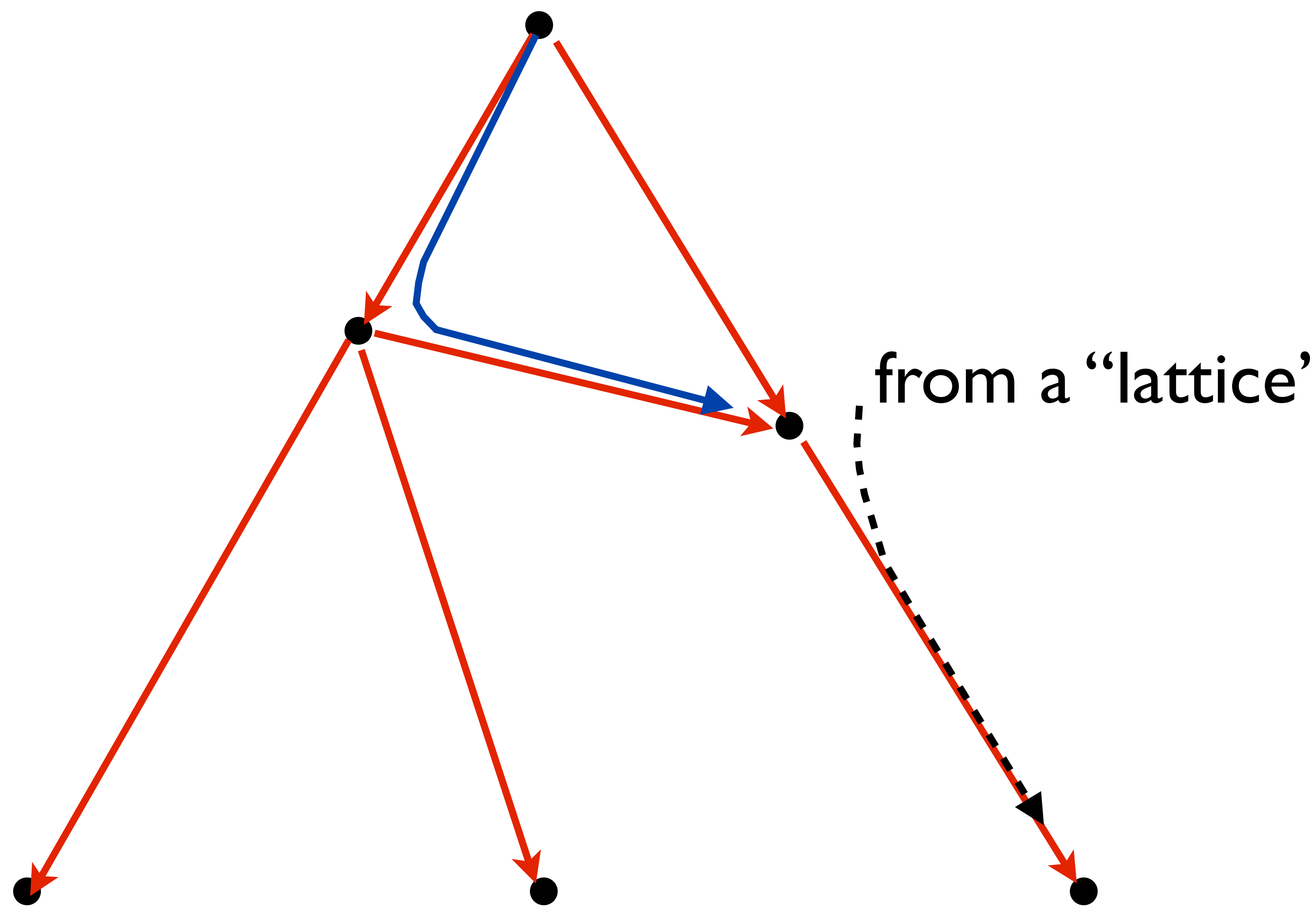

• = fixed point

Lagrangian field theories

= flows starting from the Gaussian fixed points

$(\partial\phi)^2$ $\qquad\qquad$ $\bar{\psi}\gamma.\partial\psi$ $\qquad\qquad$ $(F_{\mu\nu})^2$

Possibilities for the IR dynamics

1. no massless modes (mass gap)

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[Effective Field Theory techniques]

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[Effective Field Theory techniques]

3. (CFT) scale-invariant fixed point with a continuous spectrum

$$0 < p^2 < \infty$$

[no S-matrix, just correlation functions with "anomalous dimensions"]

Example

$$\mathcal{L} = (\partial\phi)^2 + m^2\phi^2 + \lambda\phi^4$$ in d=3

UV fixed point

relevant perturbations

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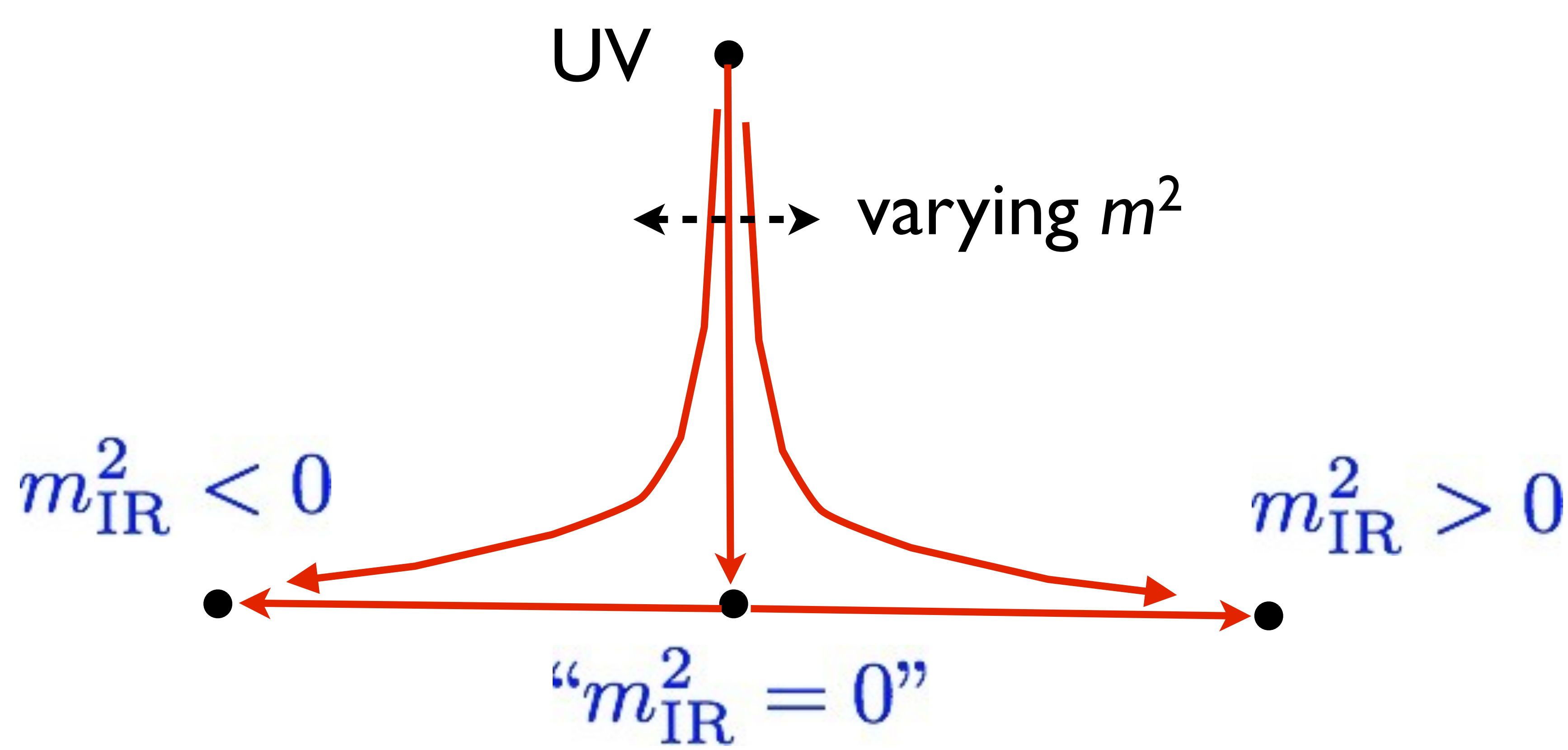

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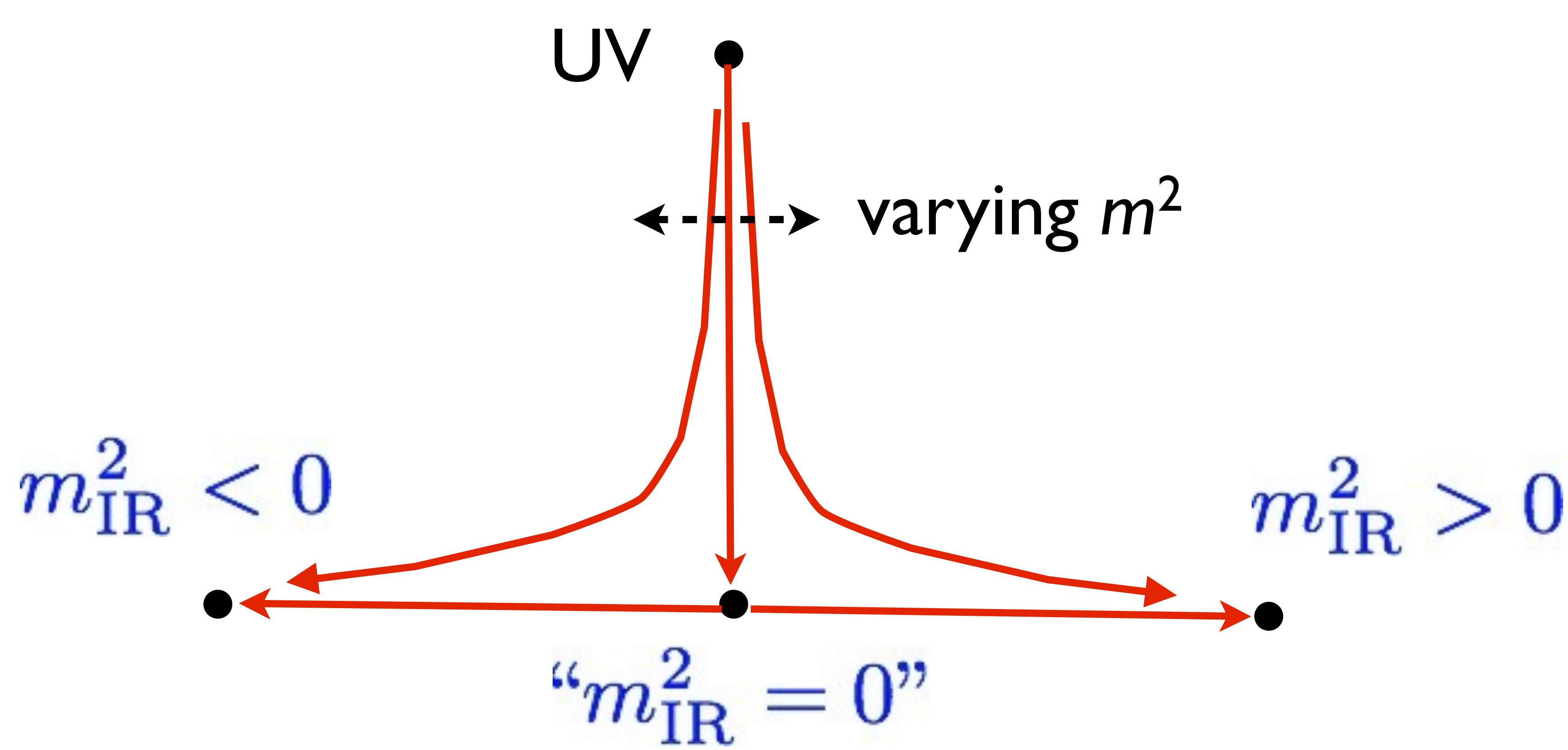

a CFT

(same universality class as the critical point of the 3d Ising model)

Main idea of conformal bootstrap

CFTs are universal, "rigid" structures.
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Using the "algebra of local operators" definition...

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Proposed in 1970's by:

Raoul Gatto

Sergio Ferrara

Aurelio Grillo

Alexander Polyakov

Why conformal?

In a **scale-inv** theory, correlators covariant under Poincaré+dilatations:

$$\langle \mathcal{O}_1(\lambda x_1)\mathcal{O}_2(\lambda x_2)\dots\rangle = \frac{1}{\lambda^{\Delta_1+\Delta_2+\dots}}\langle \mathcal{O}_1(x_1)\mathcal{O}_2(x_2)\dots\rangle$$

In a **conformal** theory, Poincaré+dilatations+special conf.transformations:

$$\vec{x}' = \lambda(x)[\vec{x} - \vec{a}x^2] \qquad \lambda(x) = [1 - 2\vec{a}.\vec{x} + a^2x^2]^{-1}$$

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[For non-derivative (aka primary) operators]

Scale inv + locality ⇒ conformal invariance

In a theory with a local stress tensor $T_{\mu\nu}$

scale invariance ⇔ $$T^{\mu}_{\mu} = \partial_{\mu} J^{\mu}$$

conformal invariance ⇔ $$T^{\mu}_{\mu} = 0$$

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Generically

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[Technical part begins]

Conf. invariant correlators

Constraints on correlation functions [Polyakov 1971]:

$$\langle O_i(x) O_j(y) \rangle = \frac{\delta_{ij}}{|x|^{\Delta}}$$

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Starting from 4-point functions more difficult:

$$\langle O(x_1) O(x_2) O(x_3) O(x_4) \rangle = \frac{g(u,v)}{x_{12}^{2\Delta} x_{34}^{2\Delta}}$$

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$$v = u_{2\leftrightarrow 4}$$

[cross ratios]

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BUT: g(u,v) not independent, can be computed in terms of Δ's and f_{ijk}'s

Conf. invariant Operator Product Expansion

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structure constants
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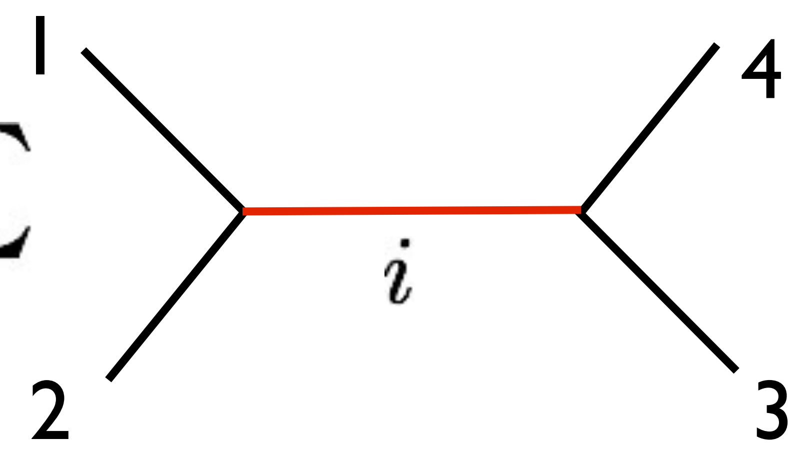
coefficients fixed by conformal symmetry

From OPE to 4-point functions

$$\langle \underbrace{O_1 O_2}_{} \underbrace{O_3 O_4}_{} \rangle = \sum_i f_{12i} f_{34i} P(x_{12}, \partial_2) P(x_{34}, \partial_4) \langle O_i(x_2) O_i(x_4) \rangle$$

$$\sum_i$$



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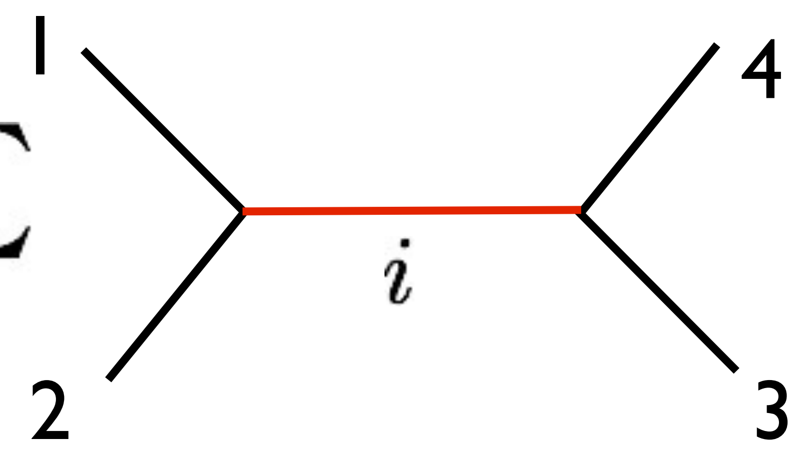

⇒ Representation for the function g(u,v):

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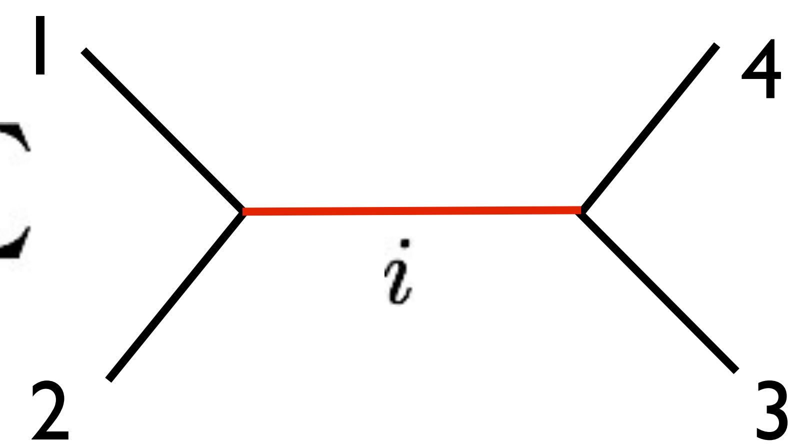

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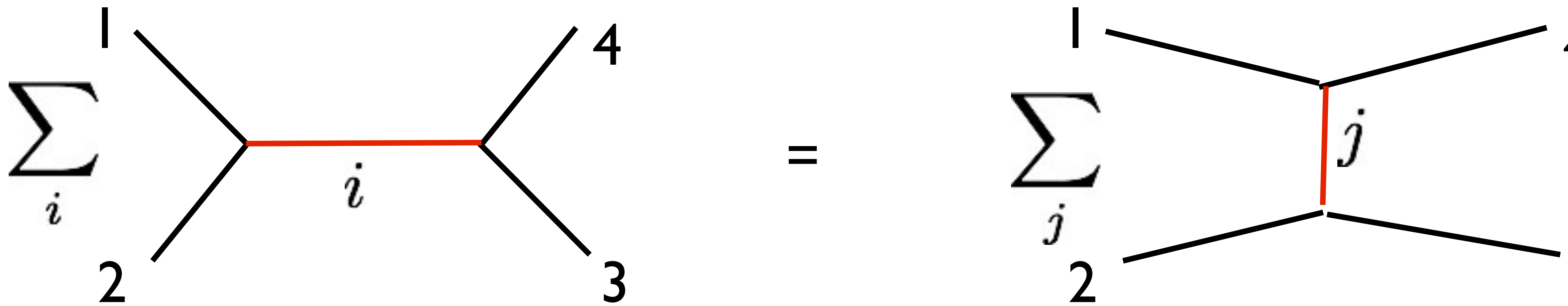
conformal blocks

[Complicated but known functions, depend on the dimension and spin of Oi]

Conformal bootstrap

[Ferrara,Grillo,Gatto, 1973], [Polyakov, 1974]

For any four operators O_i



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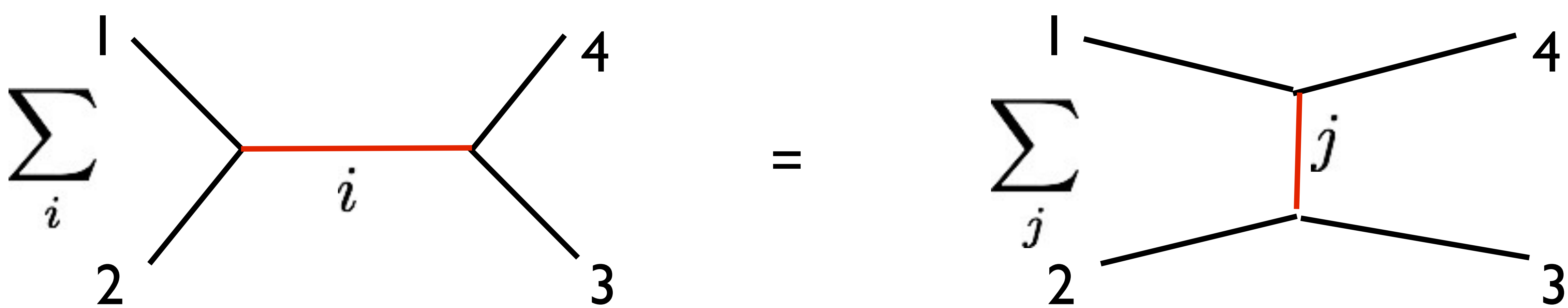

Schematically:

$$\sum_i f_{12i} f_{34i} G_{\Delta_i,\ell_i}(u,v) = \sum_j f_{14j} f_{23j} G_{\Delta_j,\ell_j}(v,u)$$

[i.e. 2↔ 4, u↔ v]

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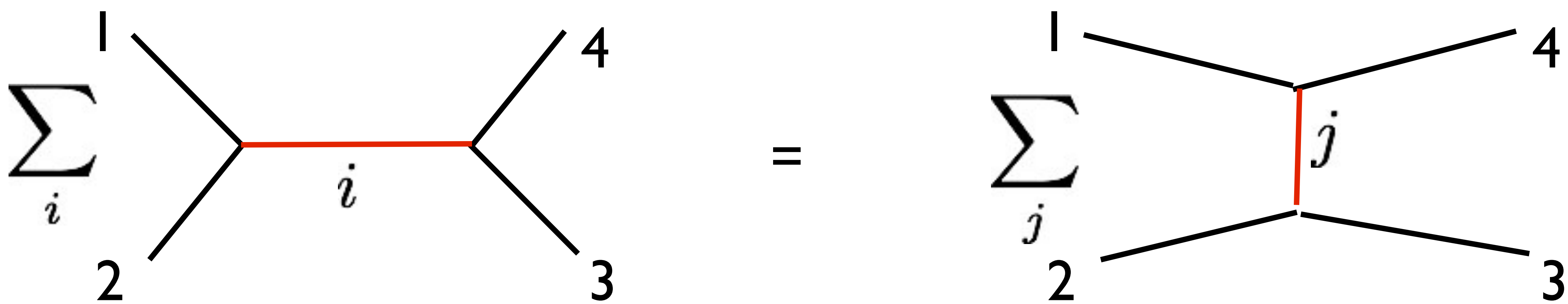

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∞ equations for ∞ unknowns. Hopeless?

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- resurrected in **d≥3** in [Rattazzi, S.R., Tonni, Vichi, 2008] and many valuable subsequent works by various people

Example: critical 3d Ising model (IR fixed point of φ^4 theory)

CFT with Z$_2$ global symmetry

From RG:

from [Pelissetto,Vicari, 2000]

Operator	Spin l	$\mathbb{Z}_2$	Δ	Exponent
σ	0	$-$	0.5182(3)	$\Delta = 1/2 + \eta/2$
σ'	0	$-$	$\gtrsim 4.5$	$\Delta = 3 + \omega_A$
ε	0	$+$	1.413(1)	$\Delta = 3 - 1/\nu$
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ε''	0	$+$	4.67(11)	$\Delta = 3 + \omega_2$
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[*infinitely many primaries per each spin*]

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lowest lying Z_2 odd/even scalars

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OPEs:

$$\sigma \times \sigma = 1 + (\epsilon + \epsilon' + \ldots) + (T_{\mu\nu} + \ldots) + (C_{\mu\nu\kappa\lambda} + \ldots) + \ldots$$

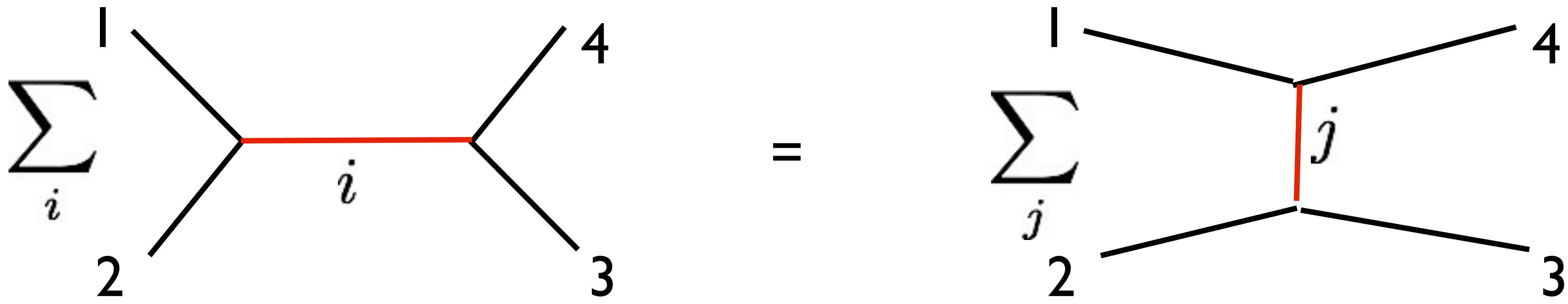
even spins only

$$\sigma \times \epsilon = \sigma + \sigma' + \ldots + \ldots$$

all spins

Bootstrap analysis

focus on the 4-point function <σσσσ>, σ = lowest Z_2-odd operator



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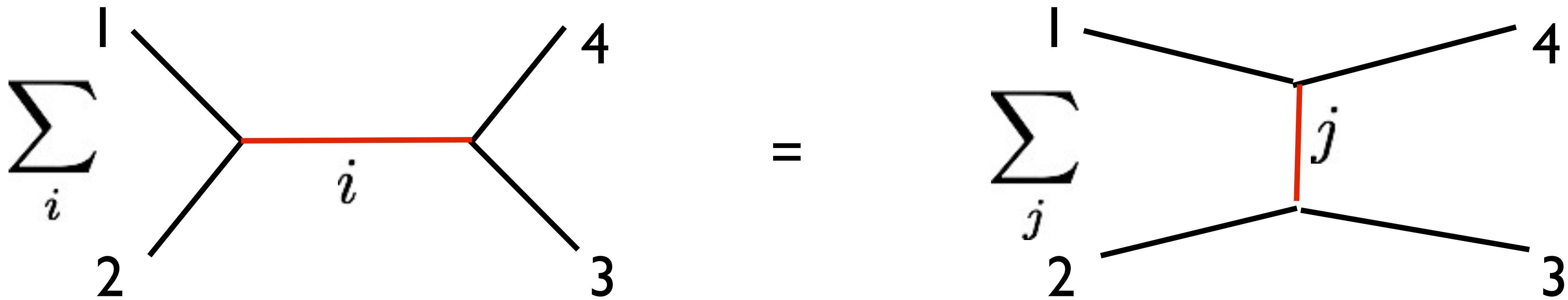

$$u^{\Delta_\sigma}[1+\sum_i p_i G_{\Delta_i,\ell_i}(u,v)] = u \leftrightarrow v \quad \text{[crossing]}$$

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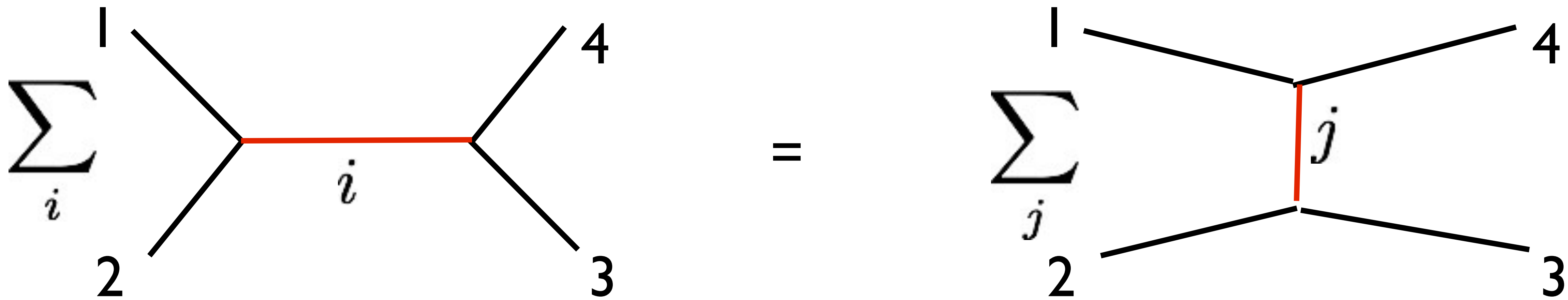

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contribution of unit operator in the OPE

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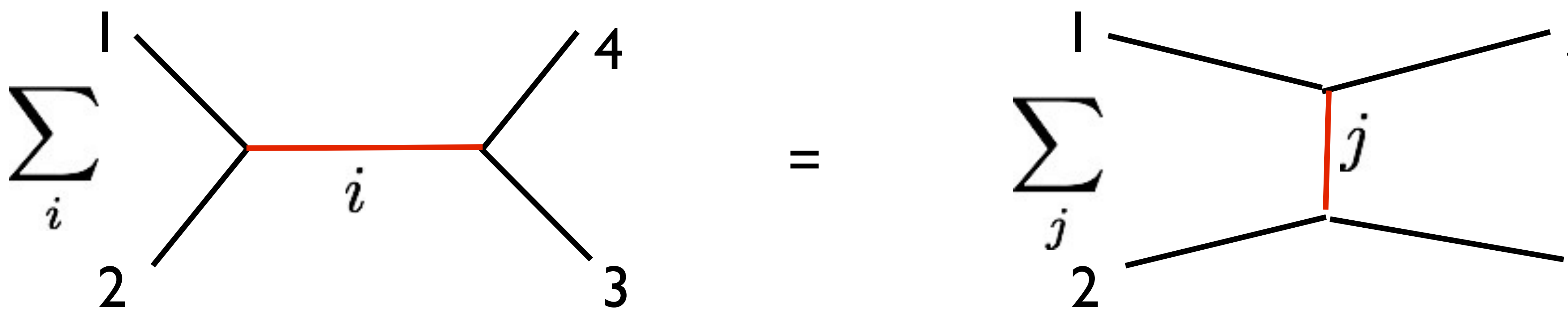


$$u^{\Delta_\sigma}[1+\sum_i p_i G_{\Delta_i,\ell_i}(u,v)] = u \leftrightarrow v$$ [crossing]

contribution of unit operator in the OPE

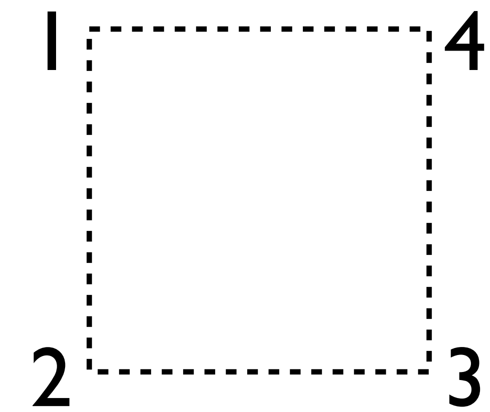
$$p_i = f^2_{\sigma\sigma i} \geq 0$$

Limits possible cancellations

How to impose the equation?

$$u^{\Delta_\sigma}[1+\sum_i p_i G_{\Delta_i,\ell_i}(u,v)] = u \leftrightarrow v$$

- Work near the crossing-democratic configuration:
  square $u = v = 1/4$



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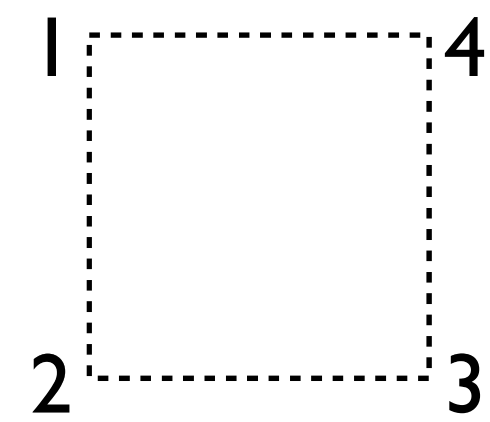

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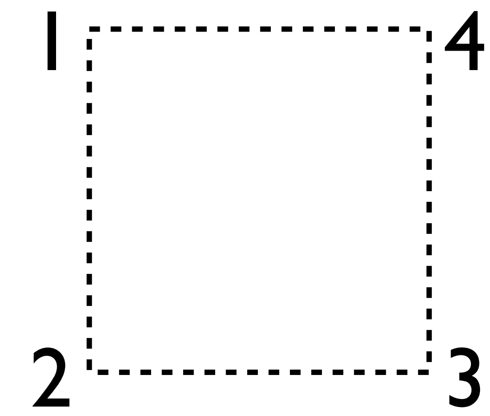

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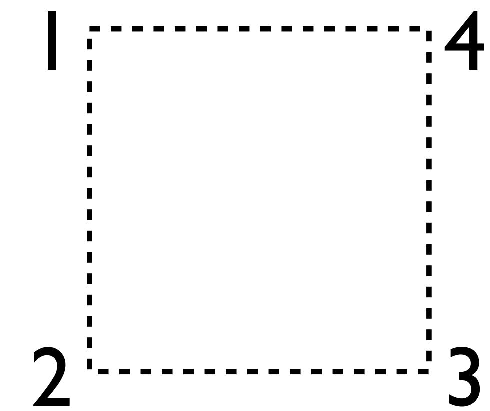

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- However only interested in solutions with all $p_i \geq 0$

A sharp question

Lowest Z_2-odd and even scalars **σ** and **ε** = most important operators

Can we use conformal bootstrap to relate their dimensions?

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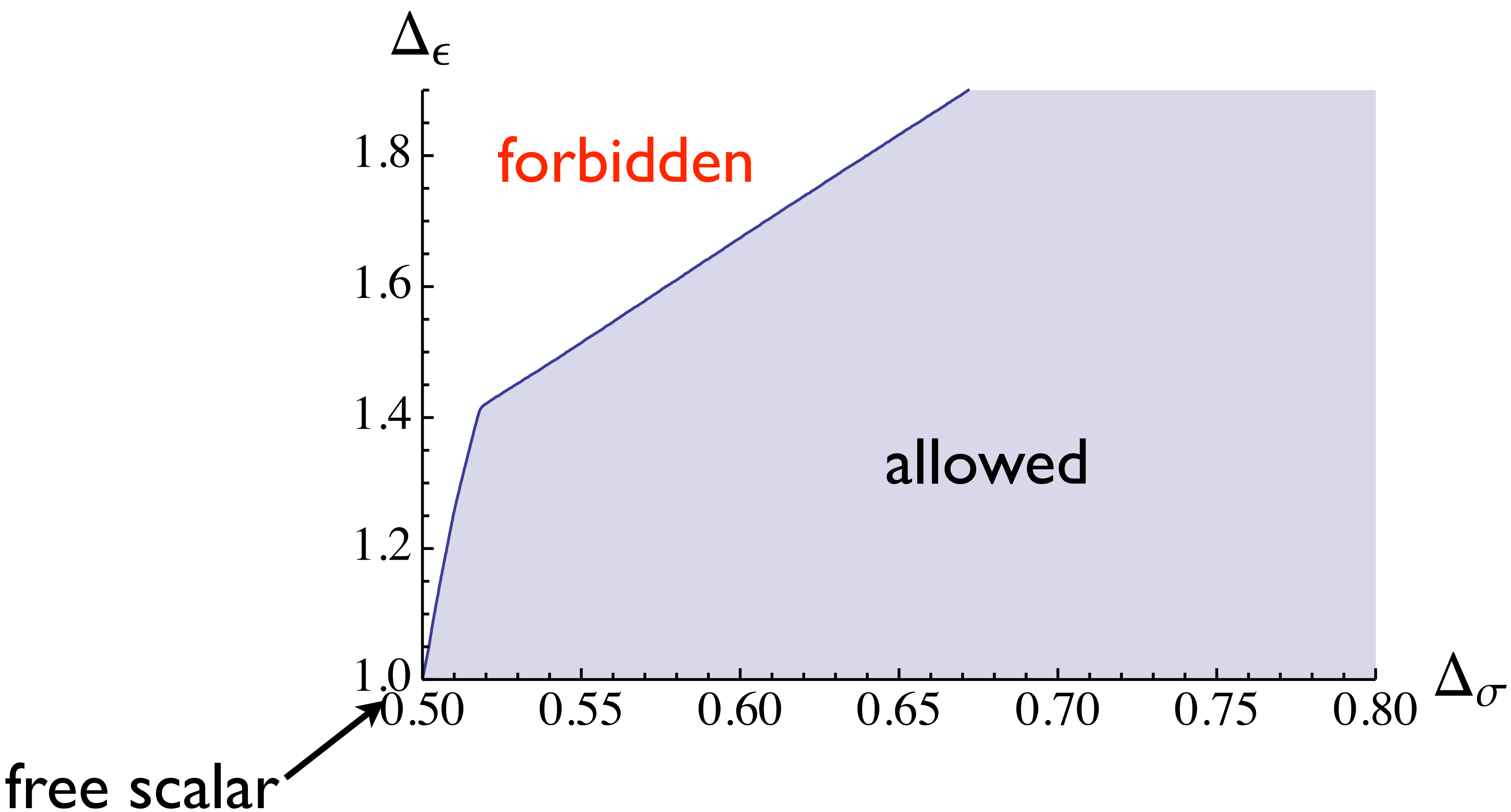
Can we use conformal bootstrap to relate their dimensions?

May be possible since ε appears in σ x σ OPE:

$$\begin{aligned}\sigma \times \sigma = 1 + (\epsilon + \epsilon' + \ldots) \\ +(T_{\mu\nu} + \ldots) \\ +(C_{\mu\nu\kappa\lambda} + \ldots) \\ + \ldots\end{aligned}$$

Bootstrap ⇒ $\Delta_\varepsilon \leq f(\Delta_\sigma)$

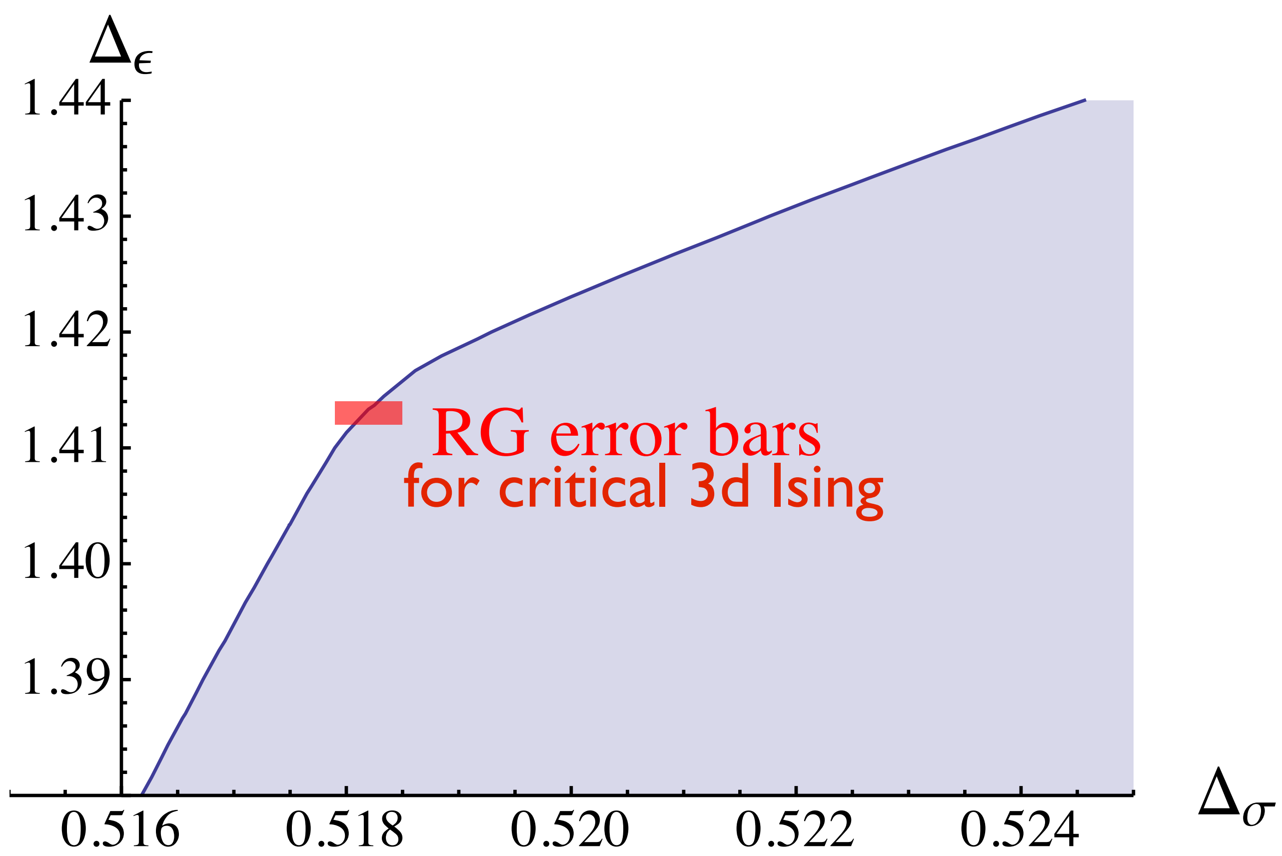
El-Showk, Paulos, Poland, Simmons-Duffin, S.R., Vichi 2012



[A rigorous nonperturbative constraint on any Conformal QFT, derived without any ref. to Lagrangians]

Zoom on the kink

El-Showk, Paulos, Poland, Simmons-Duffin, S.R., Vichi 2012+ work in progress



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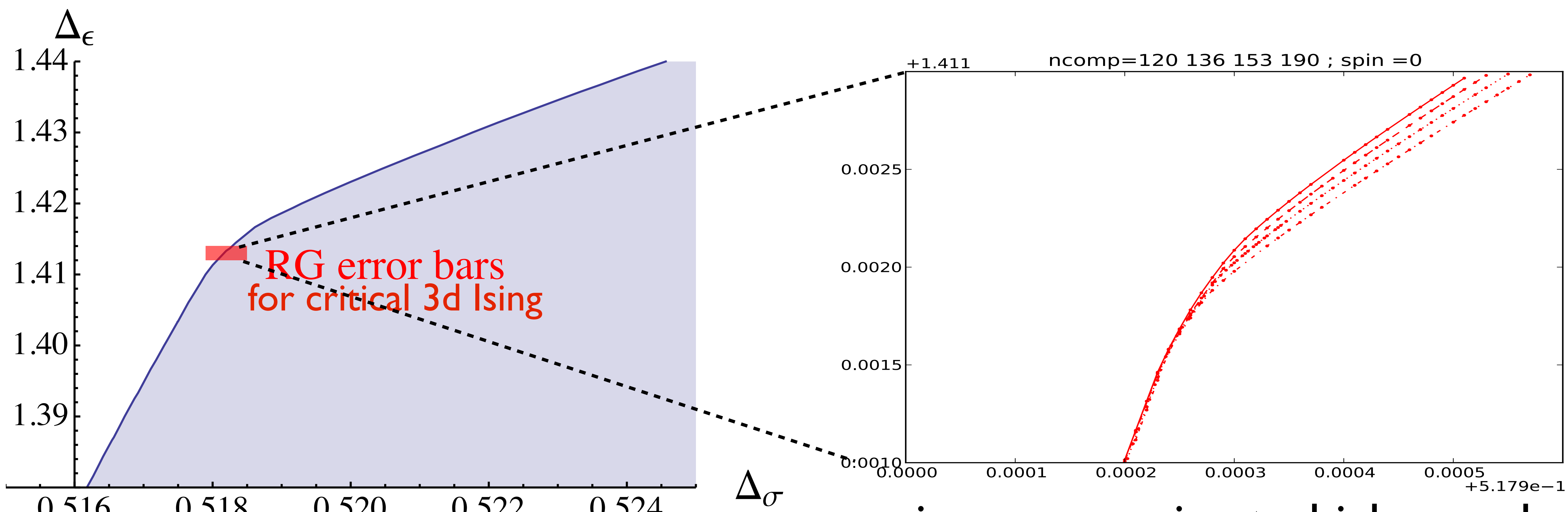

improves going to higher order

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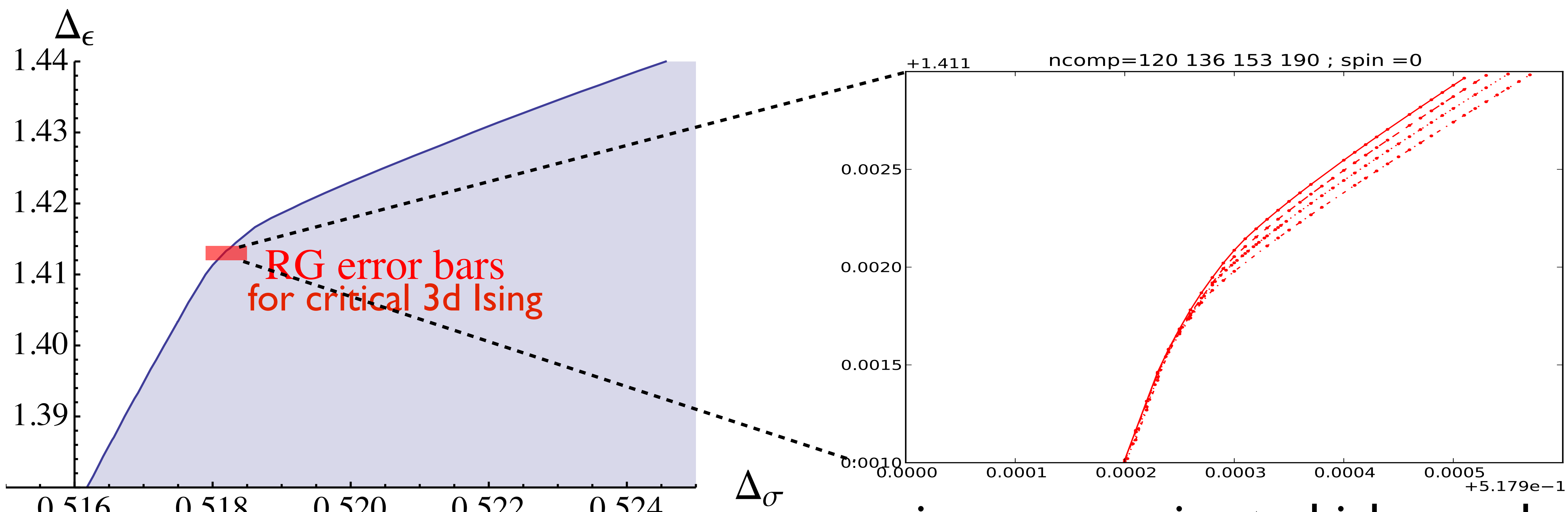
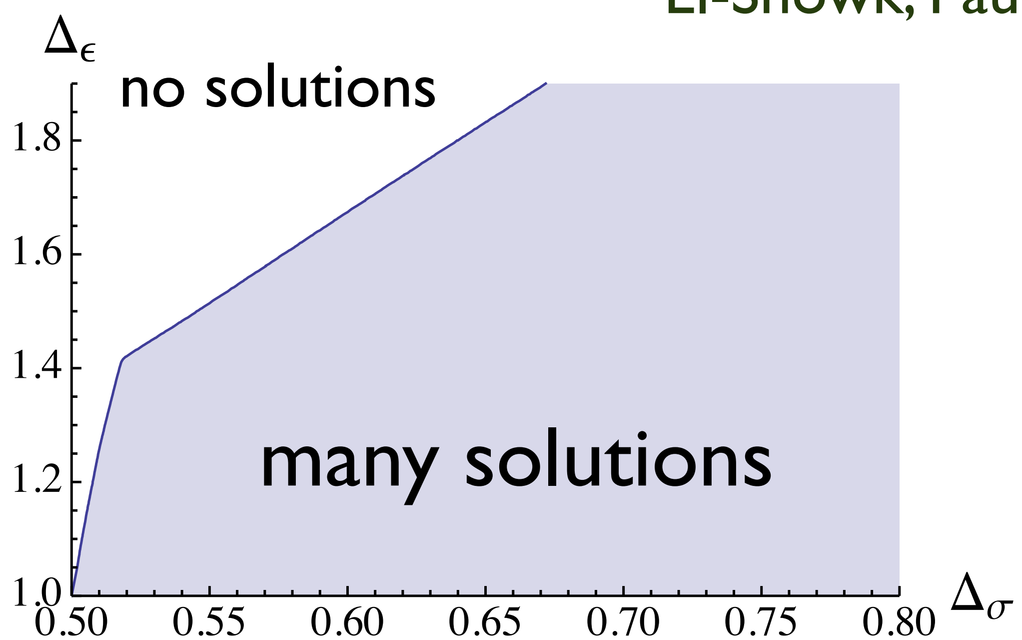


improves going to higher order

Conjecture: critical 3d Ising lies at the limiting kink

Full spectrum determination

El-Showk, Paulos, Poland, Simmons-Duffin, S.R., Vichi, work in progress



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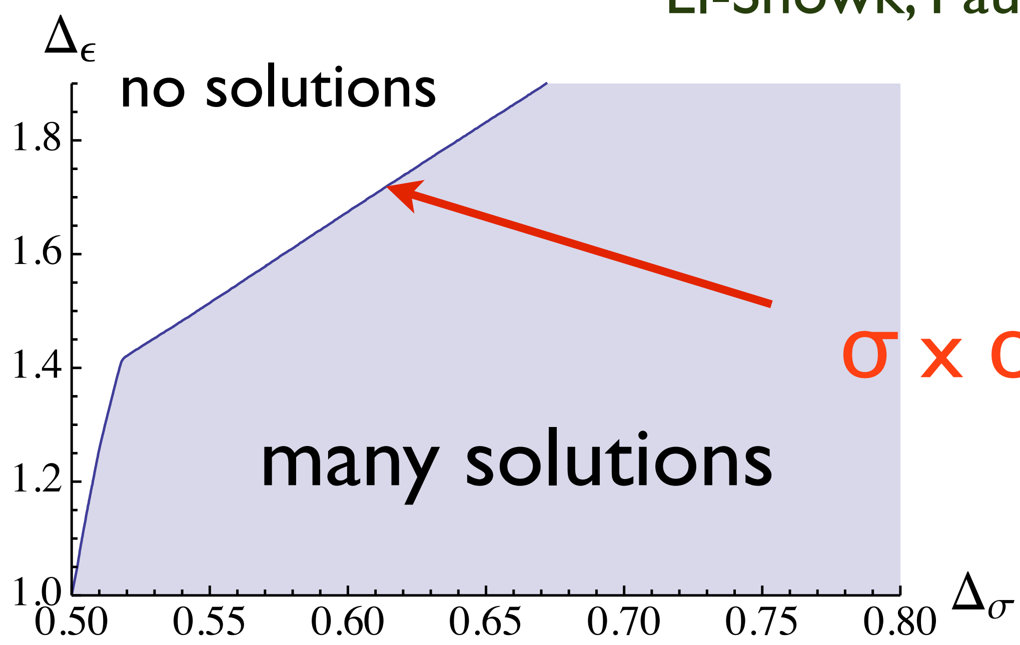

on the bdry: unique solution

σ x σ fixed (all operators and OPE coeffs)

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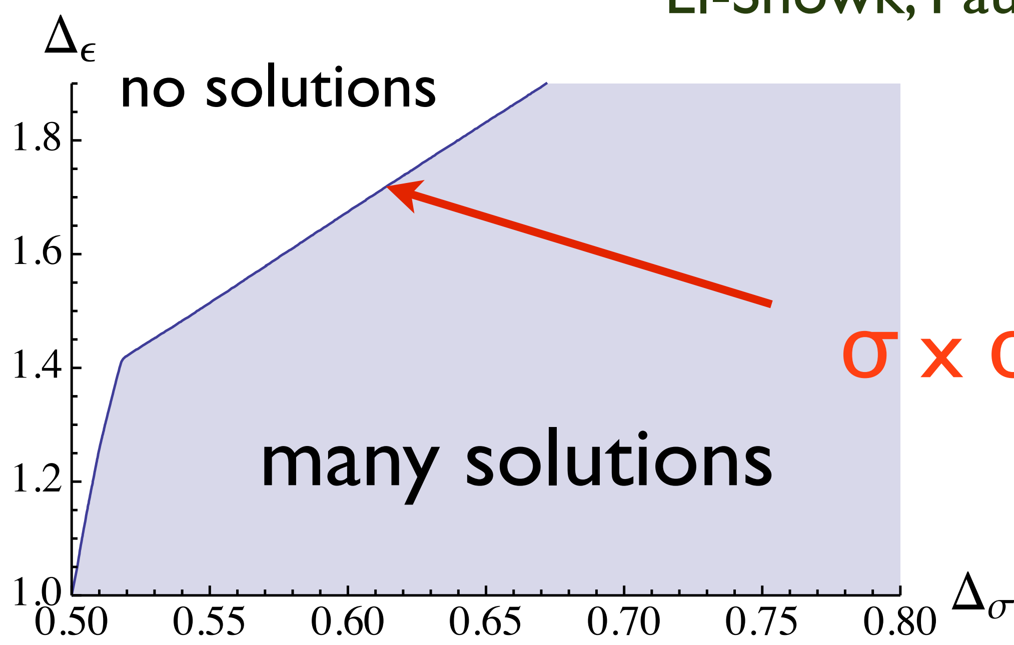

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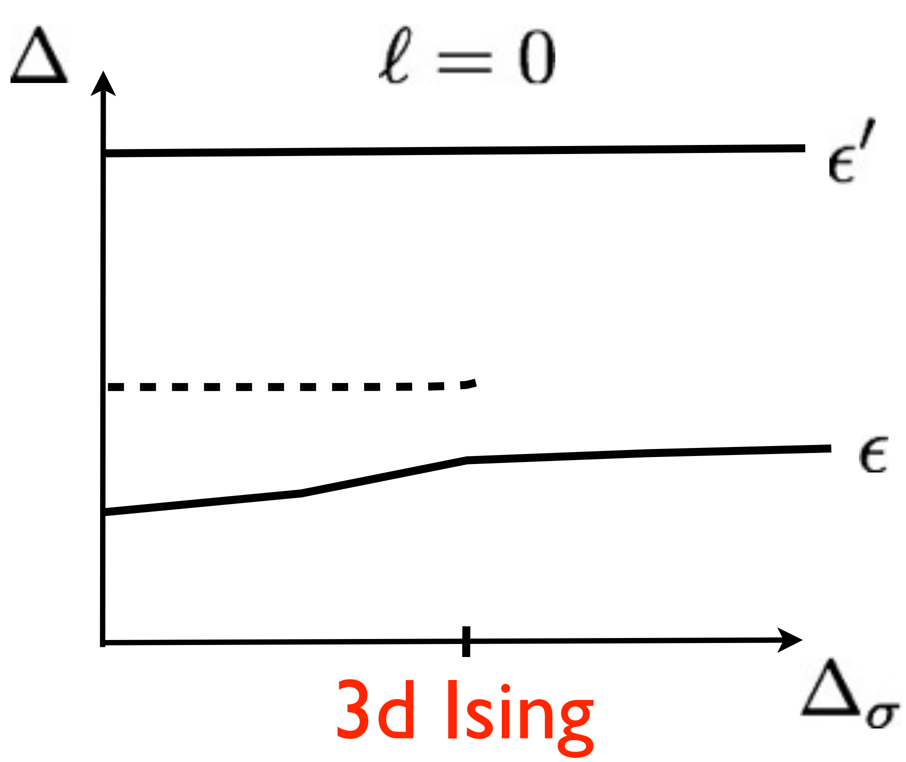
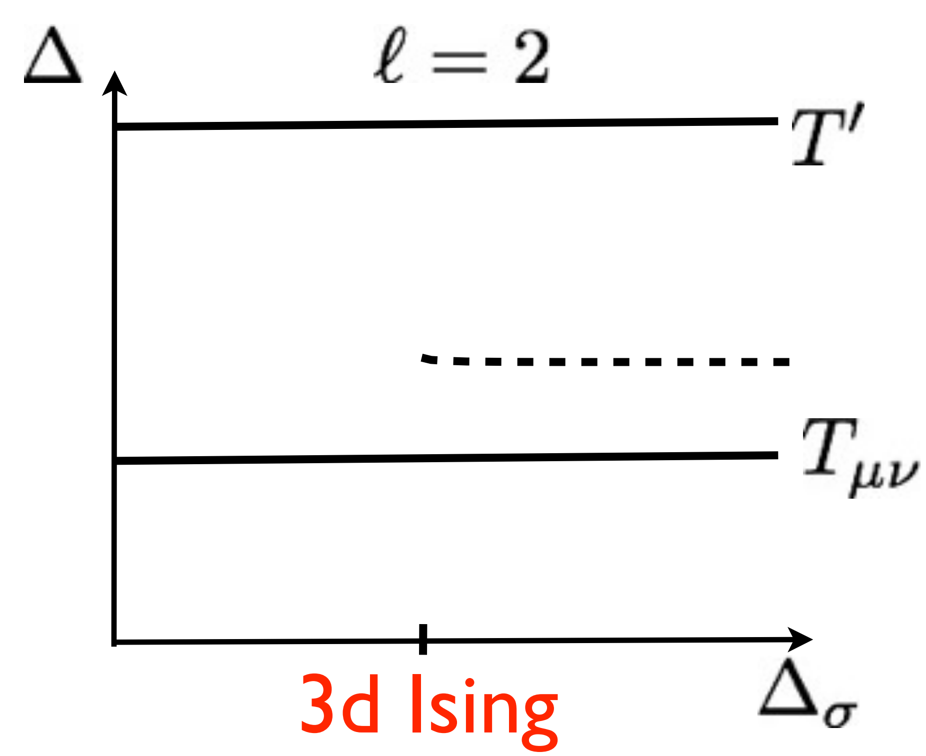
Instructive to compute and plot spectrum as f(Δ_σ):





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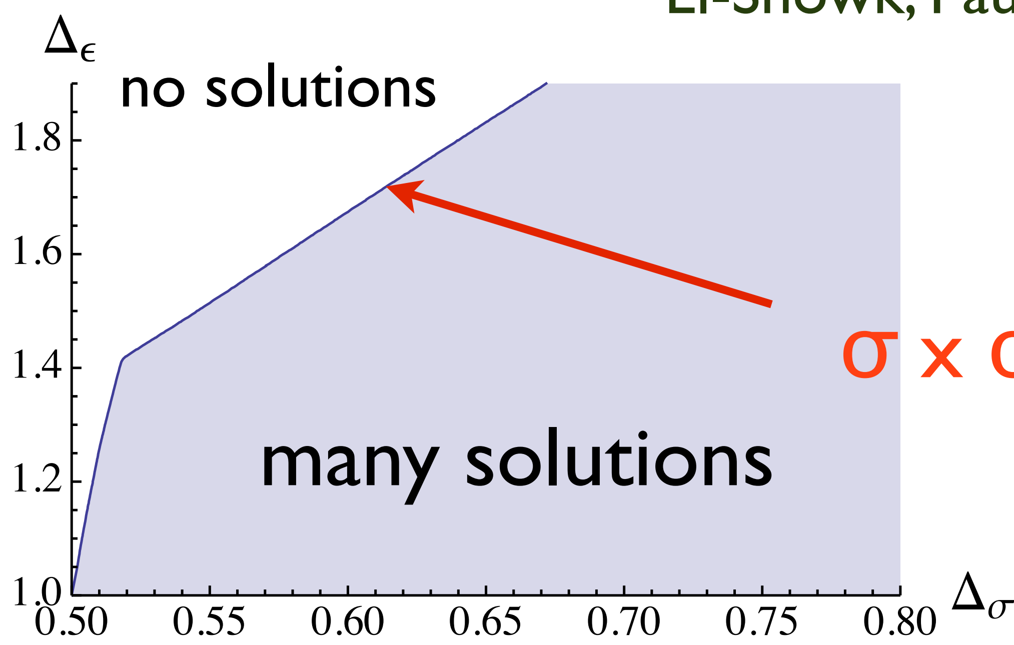

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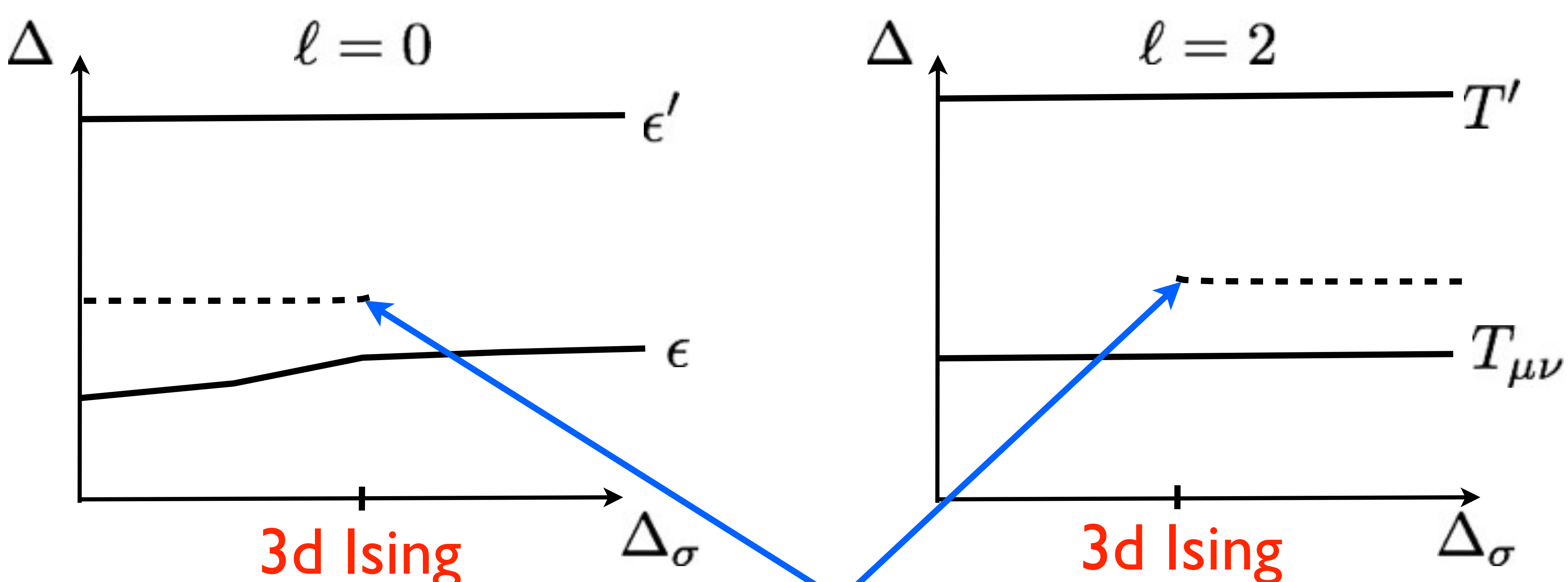

extra op's decouple at Ising point
(OPE coeffs → 0)