Note Title 5/22/2014

UNIVERSALITY IN RAPID QUANTUM QUENCH

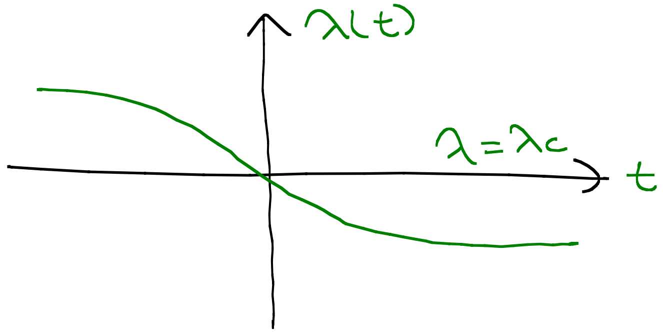
SUMIT R. DAS
UNIVERSITY OF KENTUCKY
YITP, KYOTO

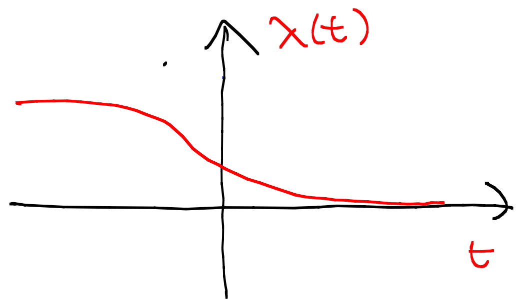
Based on:

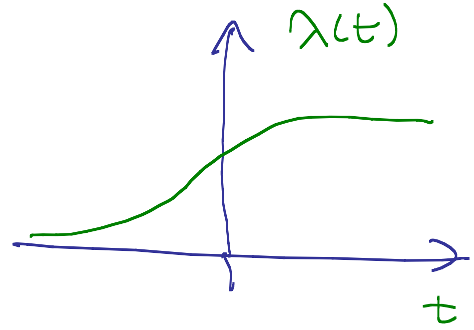
S.R.D, D. Galante & R. Myers, PRL 112 (2014)
" " " — TO APPEAR SOON

QUANTUM QUENCH & CRITICAL POINTS

IN MANY AREAS OF PHYSICS AN INTERESTING PROBLEM CONCERNS HAMILTONIANS WITH TIME DEPENDENT PARAMETERS $\lambda(t)$ WHICH PASSES THROUGH A CRITICAL POINT







STARTING WITH eg THE GROUND STATE, THE SUBSEQUENT TIME EVOLUTION IS EXPECTED TO CARRY UNIVERSAL SIGNATURES OF THE CRITICAL POINT

AN EARLY EXAMPLE IS KIBBLE-ZUREK SCALING CONJECTURE. CONSIDER STARTING IN A GAPPED PHASE WITH THE QUENCH RATE SLOW COMPARED TO THE GAP AND $\lambda(t) - \lambda_c \sim \vartheta t$.

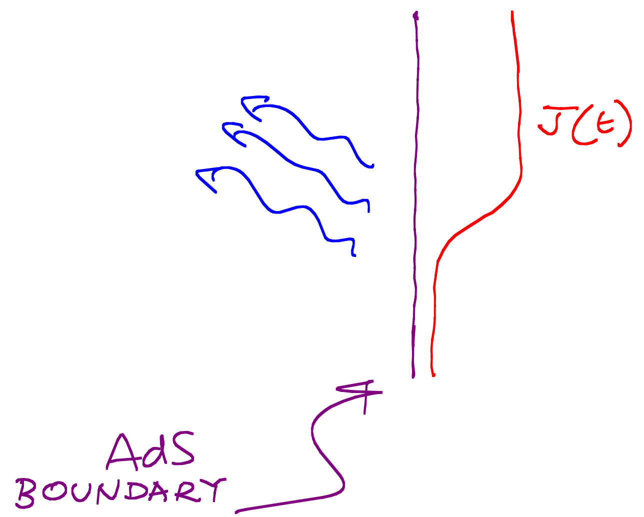
$$\boxed{\langle \mathcal{O}(t) \rangle \sim (\vartheta)^{\frac{x\nu}{z\nu+1}} F\left(t\,\vartheta^{\frac{z\nu}{z\nu+1}}\right)}$$

x : DIMENSION OF $\mathcal{O}$

ν = CORR. LENGTH EXPONENT $\quad z$: DYNAMICAL CRITICAL EXPONENT

THIS CONJECTURE DATES BACK TO 1976 – BUT THERE IS NOT MUCH UNDERSTANDING WHY THIS WORKS

IN RECENT YEARS HOLOGRAPHIC METHODS HAVE PROVIDED SOME INSIGHT INTO THE PROBLEM



- CONSIDER TIME DEPENDENT BOUNDARY CONDITION e.g. FOR A BULK SCALAR ≡ TIME DEPENDENT SOURCE
- ARRANGE $J(t)$ TO CROSS A CRITICAL POINT
- CALCULATE RESPONSE

P. Basu & S.R.D. — HOLOGRAPHIC MAGNETS

P. Basu, D. Das, S.R.D & T. Nishioka — HOLOGRAPHIC SUPERFLUID

P. Basu, D. Das, S.R.D & K. Sengupta — DOUBLE TRACE QUANTUM CRITICAL POINT

THESE WORKS HAVE REVEALED A SIMPLE MECHANISM OF DECOUPLING OF SCALES IN THE CRITICAL REGION

— THIS RESULTS IN KIBBLE-ZUREK SCALING

FURTHERMORE, PROVIDES A SYSTEMATIC WAY TO CALCULATE CORRECTIONS TO THE LEADING SCALING BEHAVIOR

RAPID QUANTUM QUENCH

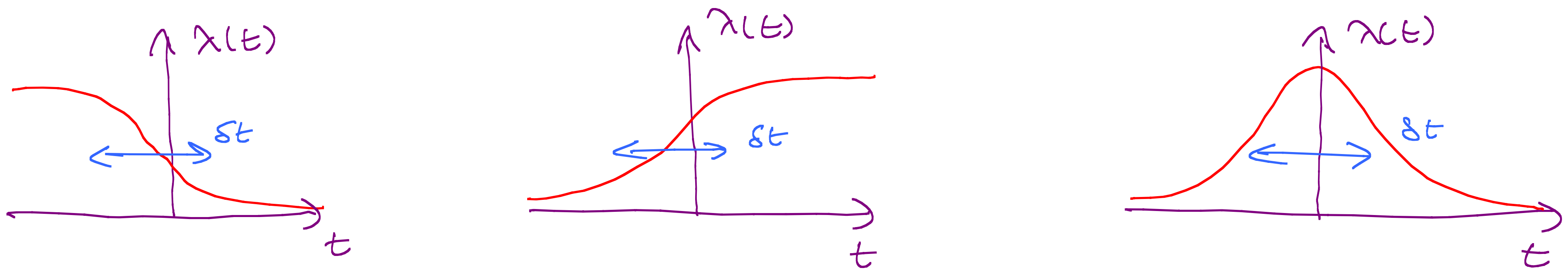
THIS TALK WILL DEAL WITH THE OPPOSITE LIMIT — WHEN THE QUENCH RATE IS FAST COMPARED TO GAP.

CONSIDER A DEFORMATION OF A CFT BY A RELEVANT OPERATOR

$$S = S_{CFT} + \int dt\, d^{d-1}x \;\lambda(t)\, \mathcal{O}_{\Delta}(t)$$

THE TIME DEPENDENT COUPLING $\lambda(t)$ HAS THE FORM

$$\lambda(t) = \lambda_0\, f(t/\delta t)$$



IN THE REGIME

$$\lambda_0 (\delta t)^{d-\Delta} \ll 1$$

WE WILL ARGUE THAT THERE IS A UNIVERSAL SCALING

$$\langle \mathcal{O}_\Delta \rangle \sim (\delta t)^{d-2\Delta}$$

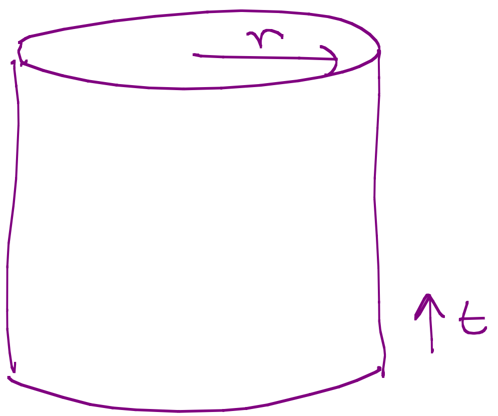
WHILE THE RATE OF PRODUCTION OF ENERGY DENSITY

$$\frac{dE}{dt} = -\dot{\lambda}(t) \langle \mathcal{O} \rangle \sim (\delta t)^{d-2\Delta-1}$$

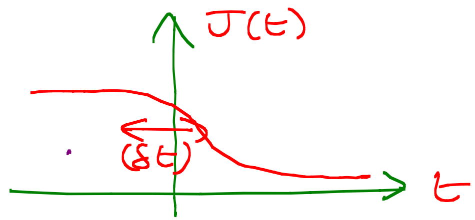
THIS SCALING WAS FIRST FOUND IN A HOLOGRAPHIC CALCULATION (Buchel, Myers & van Niekerk)

$$S = \frac{1}{2\kappa^2}\int d^{d+1}x\,\sqrt{g}\left\{ R + \frac{d(d-1)}{L^2} - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 \right\}$$

TURN ON A NON-TRIVIAL BOUNDARY CONDITION



$$\phi(r,t) \longrightarrow r^{-(d-\Delta)}\left[J(t) + O(1/r^2)\right] + r^{-\Delta}\left[A(t) + O(1/r^2)\right]$$

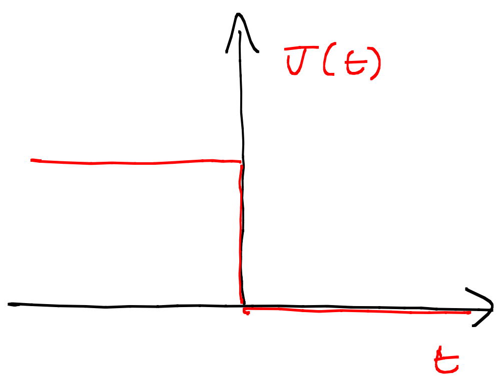


$$\langle \mathcal{O} \rangle \sim (\delta t)^{d-2\Delta}$$

SAME FOR REVERSE QUENCH

THE RESULT MAY APPEAR TROUBLESOME.
FOR $\Delta < d/2$ IT APPEARS THAT THERE IS NO SMOOTH LIMIT $\delta t \to 0$

HOWEVER $\delta t \to 0$ SHOULD LEAD TO KNOWN RESULTS FOR ABRUPT QUENCH – e.g. Calabrese & Cardy.



HERE THE SYSTEM HAS TO BE TREATED IN A SUDDEN APPROXIMATION – THE STATE AT $t=0$ SERVES AS INITIAL CONDITION FOR FURTHER TIME EVOLUTION BY THE NEW CONSTANT HAMILTONIAN

THE HOLOGRAPHIC RESULTS RELATE TO A STRONGLY COUPLED FIELD THEORY — MAYBE SUCH SPECIAL THEORIES DO NOT HAVE A SMOOTH SUDDEN QUENCH LIMIT.

HOW ABOUT WEAKLY COUPLED THEORIES ?

- WE DECIDED TO LOOK AT SOLVABLE FREE FIELD THEORIES WITH TIME-DEPENDENT MASSES

- USE THE LESSON TO FORMULATE AN ARGUMENT FOR ANY DEFORMED CONFORMAL FIELD THEORY

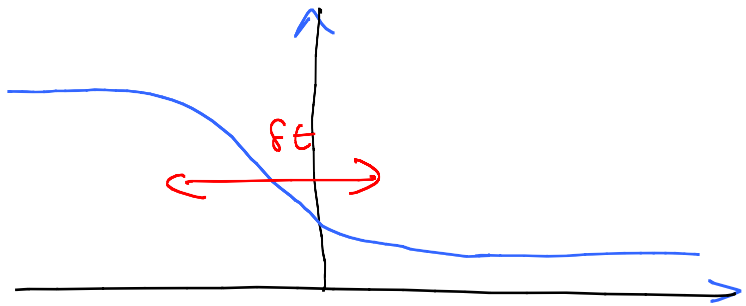
BOSONIC FREE FIELDS

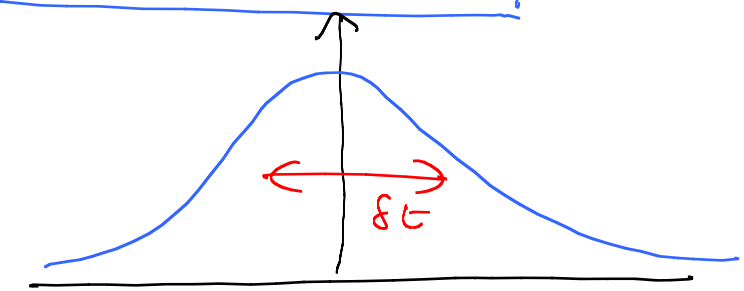
$$S = \int d^d x \left[\frac{1}{2}(\partial\phi)^2 - m^2(t)\,\phi^2 \right]$$

WORK WITH A $m^2(t)$ SO THAT THE CORRELATORS CAN BE FOUND ANALYTICALLY

$$\boxed{m^2(t) = A - B\tanh\left(\frac{t}{\delta t}\right)}$$

$$\boxed{m^2(t) = \frac{m_0^2}{\cosh^2(t/\delta t)}}$$





FOR $m^2(t) = A - B\tanh(\nu t)$ A CHOICE $A = B = m^2/2$ BRINGS US SMOOTHLY FROM A GAPPED THEORY TO A CONFORMAL FIELD THEORY

THE MODE EXPANSION IS

$$\Phi(\vec{x},t) = \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \left[a_k^{in} u_k^{in} + a_k^{in\dagger} u_k^{in*} \right]$$

$$\boxed{u_k^{in} = \frac{1}{\sqrt{2\omega_{in}}} e^{i(\vec{k}\cdot\vec{x} - \omega_{in} t - i\omega_- \delta t \log(2\cosh t/\delta t))} \, {}_2F_1\left(a,b,c;\tfrac{1}{2}\left(1+\tanh\tfrac{t}{\delta t}\right)\right)}$$

$$a = 1 + i\omega_- \delta t \qquad \omega_{in}^2 = k^2 + (A+B)$$

$$b = i\omega_- \delta t \qquad \omega_{out}^2 = k^2 + (A-B)$$

$$c = 1 - i\omega_{in} \delta t \qquad \omega_\pm = \frac{1}{2}(\omega_{out} \pm \omega_{in}),$$

THESE ARE THE IN MODES

$$u_k^{in} \xrightarrow[t\to-\infty]{} \frac{1}{\sqrt{2\omega_{in}}} \exp\left[i(\vec{k}\cdot\vec{x} - \omega_{in} t)\right]$$

SIMILARLY THERE ARE OUT MODES WHICH ASYMPTOTE TO APPROPRIATE PLANE WAVES AT LATE TIMES

WE WANT TO CALCULATE

$${}_{in}\langle 0 | \phi^2 | 0 \rangle_{in} = \int \frac{d^{d-1}k}{(2\pi)^d} \frac{1}{2\omega_{in}} \left| {}_2F_1 \right|^2$$

PRETTY MUCH AS IN THE HOLOGRAPHIC CALCULATION

THIS QUANTITY IS OF COURSE UV DIVERGENT

THE HOLOGRAPHIC CALCULATION WAS ALSO UV DIVERGENT – THIS WAS HANDLED BY STANDARD HOLOGRAPHIC RENORMALIZATION

IN OUR CASE WE OF COURSE NEED THE STANDARD FIELD THEORETIC RENORMALIZATION

SINCE THE MASS IS TIME DEPENDENT, THE COUNTERTERMS SHOULD INVOLVE $\partial_t m^2$, $\partial_t^2 m^2$ – AS FOR FIELD THEORIES IN CURVED SPACE-TIME WHOSE COUNTERTERMS DEPEND ON R, $R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta}$ ...

TO ISOLATE THE DIVERGENT TERMS EXPAND THE INTEGRAND FOR LARGE k. FOR $A = B = \frac{1}{2} m^2$

$$\frac{k^{d-2}\,dk}{\omega_{in}} |{}_2F_1|^2 = k^{d-3} + \frac{1}{2} k^{d-5} \left(-m^2 + m^2 G^2\right)$$
$$+ \frac{1}{8} k^{d-7} \left(3m^4 - 6m^4 G^2 + 3m^4 G^4 - \frac{4m^2 G^2}{\delta t^2} + \frac{12 m^2 G^4}{\delta t^2} - \frac{8 m^2 G^6}{\delta t^2}\right) + \cdots\cdots$$

$$G^2(t) \equiv \frac{1}{2}\left(1 + \tanh \frac{t}{\delta t}\right)$$

THIS EXPRESSION CAN BE IN FACT EXPRESSED ENTIRELY IN TERMS OF $m^2(t)$ AND ITS DERIVATIVES

$$m^2(t) = m^2\left(1 - G^2(t)\right)$$

$$\partial_t^2 m^2(t) = \frac{m^2}{(\delta t)^2}\left(4G^2 - 12G^4 + 8G^6\right)$$

USING TRIGNOMETRIC IDENTITIES THE DIVERGENT PIECES NOW BECOME

$$k^{d-3} - \frac{1}{2}k^{d-5}m^2(t) + \frac{1}{8}k^{d-7}\left(3m^4(t) + \partial_t^2 m^2(t)\right) + \ldots\ldots$$

IF WE WERE DEALING WITH A QFT IN CURVED SPACE-TIME THE COUNTER TERMS ARE DETERMINED BY GENERAL COVARIANCE — THEY HAVE TO BE CONSTRUCTED OUT OF CURVATURE INVARIANTS

WHAT IS THE PRINCIPLE WHICH DETERMINES THE FORM OF THESE COUNTERTERMS IN OUR CASE ?

$$\boxed{\text{ADIABATIC EXPANSION \& COUNTERTERMS}}$$

THE NECESSARY COUNTERTERMS ARE IN FACT GIVEN PRECISELY BY AN ADIABATIC EXPANSION OF THE ANSWER, – WITH EXACT COEFFICIENTS

TO DO THIS WRITE

$$u_k = \frac{1}{\sqrt{2\Omega_k(t)}} \exp\left[i\vec{k}\cdot\vec{x} - i\int^t \Omega_k(t')\,dt' \right]$$

$$\Rightarrow \quad \Omega_k^2 = \omega_k^2 - \frac{1}{2}\frac{\partial_t^2 \Omega_k}{\Omega_k} + \frac{3}{4}\left(\frac{\partial_t \Omega_k}{\Omega_k}\right)^2$$

$$\omega_k^2(t) = k^2 + m^2(t)$$

SOLVE THIS IN A DERIVATIVE EXPANSION

$$\Omega_k(t) = \omega_k(t) - \frac{1}{4\omega_k(t)}\left[\frac{\partial_t^2 \omega_k}{\omega_k} - \frac{3}{2}\left(\frac{\partial_t \omega_k}{\omega_k}\right)^2\right] + \cdots$$

IN THE ADIABATIC EXPANSION

$$\langle \phi^2 \rangle = \int \frac{d^{d-1}k}{(2\pi)^d} \frac{1}{2\Omega_k}$$

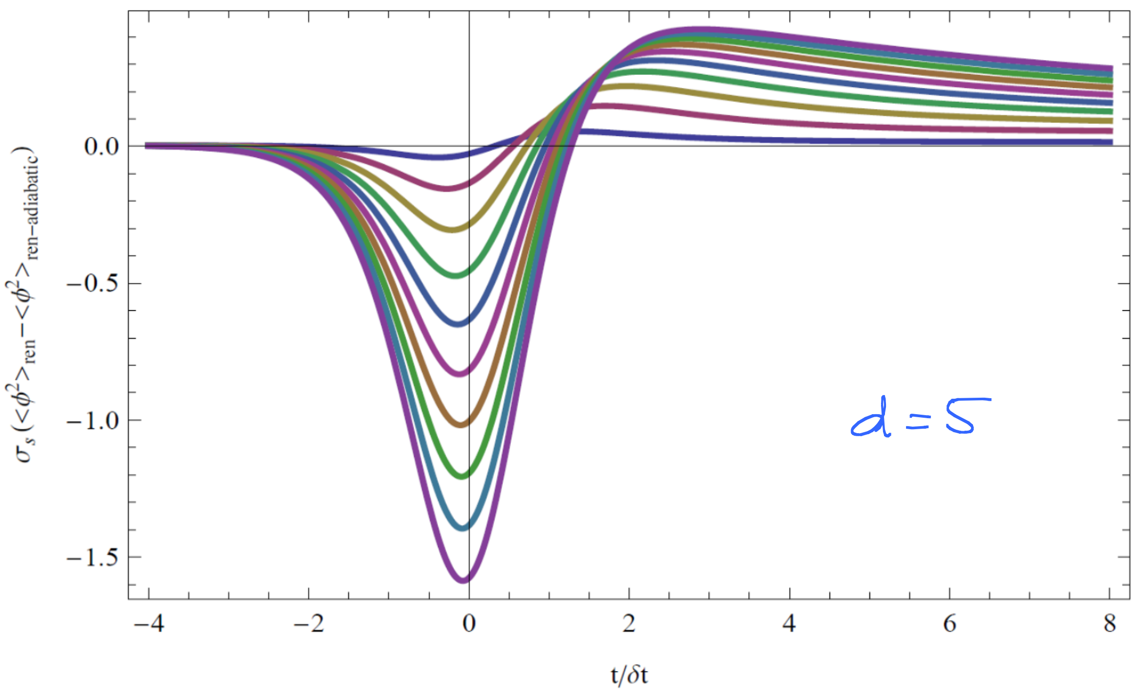
THE DIVERGENT PIECES OF THIS ARE NOW OBTAINED BY EXPANDING THE ARGUMENT IN LARGE k

THE RESULT IS PRECISELY THE SAME AS OBTAINED FROM LARGE-K EXPANSION OF THE EXACT ANSWER

THE BASIC REASON IS THE FOLLOWING

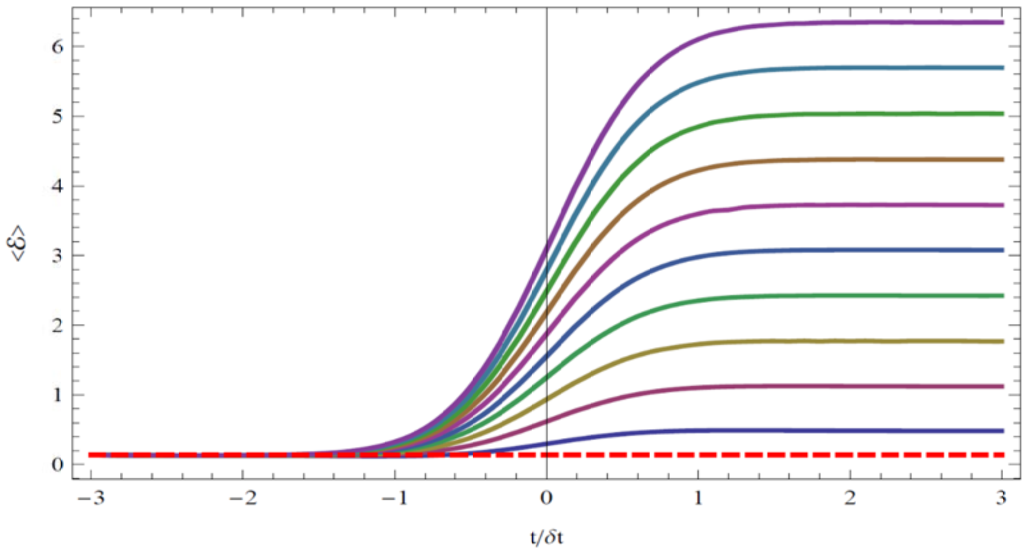
- WE ARE ALWAYS CONSIDERING A QUENCH RATE WHICH IS SLOW COMPARED TO THE UV CUTOFF

- THUS THE HIGH MOMENTUM BEHAVIOR IS FAITHFULLY REPRODUCED BY THE ADIABATIC EXPANSION



PROFILE OF $\langle\phi^2\rangle_{ren} - \langle\phi^2\rangle_{adiabatic}$ AS FUNCTION OF TIME

CURVES WITH HIGHER PEAKS IN ABSOLUTE VALUE HAVE SMALLER (δt)



BEHAVIOR OF THE ENERGY DENSITY $\langle \varepsilon \rangle$ AS A FUNCTION OF TIME

THE RAPID QUENCH LIMIT

SO FAR OUR RESULTS ARE FOR ARBITRARY δt

WE NOW CONSIDER THE RAPID QUENCH REGIME

$$\frac{1}{\Lambda_{UV}} \ll \delta t \ll \frac{1}{m}$$

THE EXPRESSIONS CAN BE NOW EXPANDED IN POWERS OF THE DIMENSIONLESS PARAMETER

$$k = m(\delta t)$$

— THE SAME EXPANSION FOR COUNTERTERMS

FINALLY PERFORM THE INTEGRALS

THE LEADING ORDER RESULTS ARE

$$\langle \phi^2 \rangle_{ren} - \langle \phi^2 \rangle_{adiabatic} = \begin{cases} (-1)^{\frac{d-1}{2}} \dfrac{\pi}{2^{d-2}} \partial_t^{d-4} m^2(t) & \text{odd } d \geq 5 \\ \dfrac{(-1)^{d/2}}{2^{d-3}} \log(k_0 \delta t)\, \partial_t^{d-4} m^2(t) & \text{even } d \geq 6 \\ \dfrac{1}{2} m^2 G^2(t) \log(k_0 \delta t) & d = 4 \\ -\dfrac{\pi m^2}{4}(\delta t) \log\left[\frac{1}{2}\left(1 - \tanh\frac{t}{\delta t}\right)\right] & d = 3 \end{cases}$$

THUS THE GENERAL SCALING LAW IS

$$\langle \phi^2 \rangle_{ren} \sim m^2 (\delta t)^{4-d} \qquad \text{odd}$$

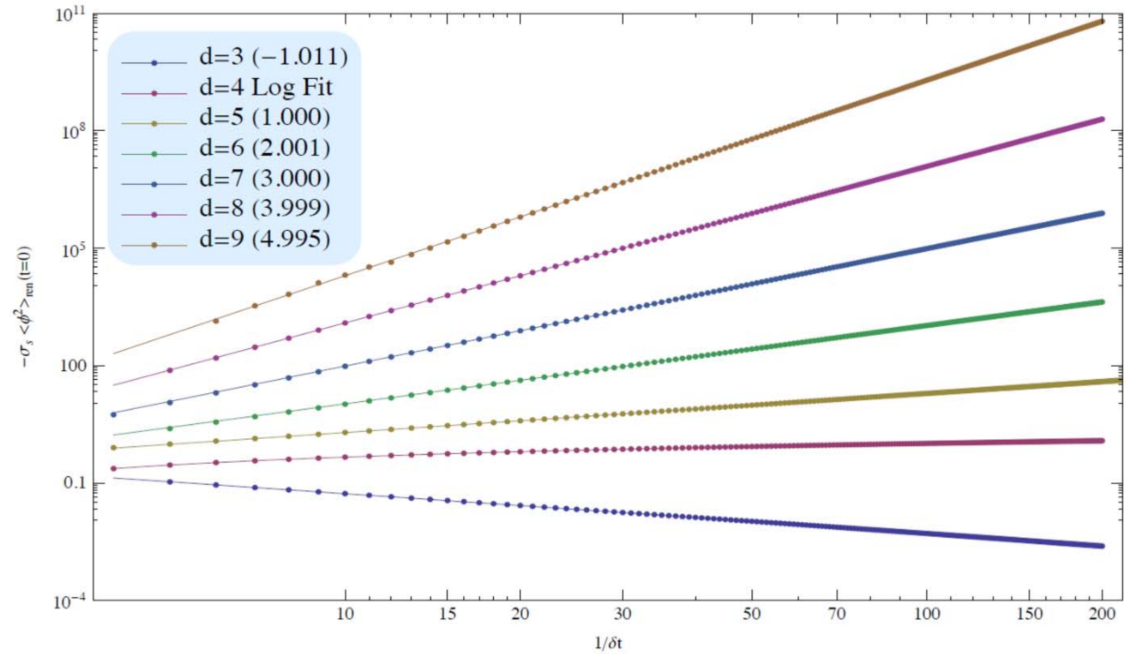
$$\sim m^2 (\delta t)^{4-d} \log(\delta t) \qquad \text{even.}$$

THIS IS CONSISTENT WITH THE FINDING

$$\langle \mathcal{O} \rangle \sim (\delta t)^{d-2\Delta}$$

SINCE FOR FREE FIELDS $\Delta = d-2$

LOG ENHANCEMENT FOR EVEN DIMENSIONS WAS ALSO FOUND IN THE HOLOGRAPHIC CALCULATION



LOG-LOG PLOT OF $\langle \phi^2(0) \rangle_{ren.}$ AS A FUNCTION OF $(\delta t)^{-1}$

(LEADING ORDER ADIABATIC ANSWER SUBTRACTED)

CONSISTENT WITH $(\delta t)^{4-d}$ + log ENHANCEMENT FOR EVEN d.

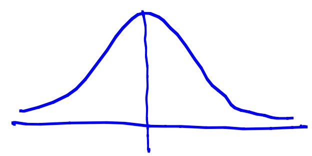
$\boxed{\text{CFT} \to \text{CFT QUENCHES}}$

THE SCALING FORM IS NOT SPECIAL TO QUENCH FROM A MASSIVE → CFT

SAME RESULT HOLDS FOR CFT → MASSIVE QUENCH

SAME RESULT ALSO HOLDS FOR A CFT → CFT QUENCH

$$\widetilde{m}^2(t) = \frac{m^2}{\cosh^2(t/\delta t)}$$



THIS CASE CAN ALSO BE SOLVED ANALYTICALLY AND EVERYTHING GOES THROUGH AS BEFORE

FERMIONIC QUENCHES

ANOTHER FREE FIELD THEORY WHICH CAN BE SOLVED IS DIRAC FERMION

$$\bar{\psi}\left[i\gamma^\mu \partial_\mu - m\left(A + B \tanh t/\delta t\right)\right]\psi$$

RESULTS SIMILAR TO SCALAR FIELDS

RESULT FOR GENERIC CFT

OUR STUDIES OF SOLVABLE FREE FIELDS IN FACT SUGGESTS A COMPLETELY GENERAL ARGUMENT FOR A RELEVANT DEFORMATION OF ANY CFT

THE KEY POINT IS THAT WE NEED TO CONSIDER RENORMALIZED QUANTITIES — THIS IS THE RIGHT THING TO DO IF WE CONSIDER QUENCH RATES

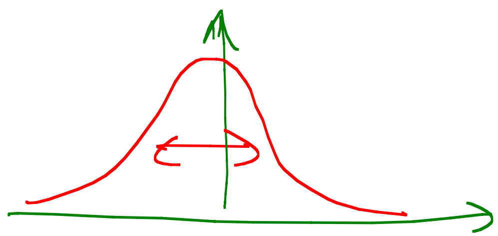
SLOW COMPARED TO UV SCALE

FAST COMPARED TO SCALE OF COUPLING

CONSIDER A PERTURBED CFT

$$S = S_{CFT} + \int d^d x \, \lambda(t) \, \mathcal{O}_\Delta(\vec{x}, t)$$

THE PROFILE OF THE COUPLING $\lambda(t)$ IS SIMILAR TO THE PULSED PROFILE CONSIDERED EARLIER



$$\lambda(t) = \lambda_0 f(t/\delta t)$$

NOW CONSIDER COMPUTING $\langle \mathcal{O}_\Delta \rangle$ USING PERTURBATION THEORY

— PERFORM RENORMALISATION TO GET RID OF CUTOFF

$$\langle \mathcal{O}_\Delta \rangle = \langle \mathcal{O}_\Delta \rangle_{\lambda_0 = 0} + \lambda_0 \int d^{d-1}x' \, dt' \, f(t'/\delta t) \, G_R(\vec{x}, t; \vec{x}', t')$$
$$+ \frac{\lambda_0^2}{2} \int d^d x' \, d^d x'' \, dt \, dt'' \, f(t'/\delta t) \, f(t''/\delta t) \, K(x, t; x', t'; x'', t'')$$
$$+ \cdots\cdots$$

THE SECOND TERM IS THE USUAL LINEAR RESPONSE

$$G_R = \theta(t-t') \langle 0 | [\mathcal{O}_\Delta(\vec{x}, t), \mathcal{O}_\Delta(\vec{x}', t')] | 0 \rangle_{CFT}$$

SINCE $\mathcal{O}_\Delta$ IS RELEVANT WE HAVE $\langle \mathcal{O}_\Delta \rangle_{CFT} = 0$

THE CORRELATORS WHICH APPEAR ARE ALL CORRELATORS IN THE CFT

THUS THE INTEGRALS IN THE RENORMALIZED QUANTITY MUST SCALE AS APPROPRIATE POWERS OF (δt)

$$\langle \mathcal{O}_\Delta \rangle = (\delta t)^{-\Delta} \left[a_1 g + a_2 g^2 + \cdots \right]$$

WHERE g IS THE DIMENSIONLESS COUPLING

$$\boxed{g = \lambda_0 (\delta t)^{d-\Delta}}$$

FOR A RAPID QUENCH $g \ll 1$

EXPECT : COUNTERTERMS DETERMINED BY AN ADIABATIC EXPANSION

THIS GIVES THE LEADING ORDER RESULT

$$\boxed{\langle \mathcal{O}_\Delta \rangle \sim \lambda_0 (\delta t)^{d-2\Delta}}$$

NOETHER'S THEOREM $\Rightarrow$ ENERGY DENSITY E

$$\frac{dE}{dt} = - \frac{d\lambda(t)}{dt} \langle \mathcal{O}_\Delta \rangle$$

SINCE THE ENERGY IS BASICALLY PRODUCED DURING THE INTERVAL δt

$$E \sim \lambda_0^2 (\delta t)^{d-2\Delta}$$

CONNECTION TO ABRUPT QUENCH

AN ABRUPT QUENCH INVOLVES A SUDDEN CHANGE FROM ONE TIME INDEPENDENT HAMILTONIAN H_{in} TO ANOTHER TIME INDEPENDENT HAMILTONIAN H_{out}

OUR RESULTS MIGHT APPEAR TO IMPLY THAT THIS DOES NOT CORRESPOND TO THE $\delta t \to 0$ LIMIT OF SMOOTH QUENCHES!

THIS, OF COURSE, CANNOT BE TRUE.

THE KEY POINT IS THAT WE HAVE CONSIDERED QUENCH TIME SCALES δt

$$\Lambda_{UV}^{-1} \ll \delta t \ll \lambda_0^{-\frac{1}{d-\Delta}}$$

THIS IS WHY WE HAVE CONSIDERED RENORMALIZED QUANTITIES

A TRULY ABRUPT QUENCH NECESSARILY MEANS THAT THE RATE IS FAST COMPARED TO ALL SCALES — INCLUDING THE CUTOFF SCALE

QUANTITIES LIKE $\langle O_\Delta \rangle$ OR $\langle E \rangle$ REQUIRES A SUM OVER ALL MOMENTA

LET US LOOK AT THIS IN DETAIL FOR THE SCALAR FIELD WITH

$$m^2(t) = A - B \tanh(t/\delta t)$$

AND COMPUTE THE 2-POINT FUNCTION

WE EXPRESS THIS IN TERMS OF THE OUT MODES

$$v^{out}_{\vec{k}}(\vec{x},t) \xrightarrow[t \gg \delta t]{} \frac{1}{\sqrt{4\pi\omega_{out}}} \exp\left[i(\vec{k}\cdot\vec{x} - \omega_{out} t)\right]$$

THESE MODES ARE RELATED TO THE IN MODES WE CONSIDERED BY A BOGOLIUBOV TRANSFORMATION WHICH CAN BE COMPUTED (Birell & Davies)

$$u_k^{in} = \alpha_k v_k + \beta_k v_{-k}^*$$

THIS LEADS TO

$$\left\langle \phi(\vec{x},t)\,\phi(\vec{x}',t')\right\rangle = \int \frac{d^{d-1}k}{(2\pi)^d}\Big[\, v_k(x,t)\,v_k^*(x',t') + |\beta_k|^2 \left\{ v_k(x)\,v_k^*(x') + v_{-k}^*(x)\,v_{-k}(x') \right\} + \alpha_k \beta_k^*\, v_k(x)\,v_{-k}(x') + \alpha_k^* \beta_k\, v_{-k}^*(x)\,v_k^*(x') \Big]$$

THE COEFFICIENTS HAVE COMPLICATED FORMS

THIS LEADS TO

$$\langle \phi(\vec{x},t)\,\phi(\vec{x}',t')\rangle = \int \frac{d^{d-1}k}{(2\pi)^d}\Big[\, \vartheta_k(x,t)\,\vartheta_k^*(x',t') + |\beta_k|^2 \{ \vartheta_k(x)\,\vartheta_k^*(x') + \vartheta_{-k}^*(x)\,\vartheta_{-k}(x') \} + \alpha_k \beta_k^* \; \vartheta_k(x)\,\vartheta_{-k}(x') + \alpha_k^* \beta_k \; \vartheta_{-k}^*(x)\,\vartheta_k^*(x') \Big]$$

THE COEFFICIENTS HAVE COMPLICATED FORMS

$$|\alpha|^2 = 1 + |\beta|^2 = \frac{\sinh^2(\pi\omega_+\delta t)}{\sinh(\pi\omega_{in}\delta t)\,\sinh(\pi\omega_{out}\delta t)}$$

$$\beta\alpha^* = \frac{\omega_{out}}{\omega_{in}}\;\frac{\pi\omega_{in}\delta t}{\sinh(\pi\omega_{in}\delta t)}\;\frac{[\Gamma(i\omega_{out}\delta t)]^2}{(-i\omega_+\omega_-\delta t^2)\,[\Gamma(i\omega_-\delta t)]^2\,[\Gamma(i\omega_+\delta t)]^2}$$

HOWEVER IN THE LIMIT

$$\omega_{in}\,\delta t \ll 1\,, \quad \omega_{out}\,\delta t \ll 1\,, \quad t, t' \gg \delta t$$

FOR EVERY MOMENTUM WHICH APPEARS IN THE INTEGRAL δt DROPS OUT COMPLETELY AND WE GET

$$\langle \phi(x,t)\phi(x',t')\rangle = \int \frac{d^{d-1}_k}{(2\pi)^{d-1}} e^{ik(x-x')} \Big\{ \frac{1}{2\omega_{out}} e^{-i\omega_{out}(t-t')} + \frac{(\omega_{out}-\omega_{in})^2}{4\omega_{out}^2\omega_{in}} \cos\left(\omega_{out}(t-t')\right) + \frac{\omega_{out}^2-\omega_{in}^2}{4\omega_{out}^2\omega_{in}} \cos\left(\omega_{out}(t+t')\right) \Big\}$$

INTEGRAND – EXACTLY WHAT ONE GETS IF ONE PERFORMS A SUDDEN QUENCH

$$\omega_{in} \to \omega_{out}$$

(Cardy & Sotiriadis)

THIS LIMIT REQUIRES, IN PARTICULAR

$$\delta t \ll \Lambda_{UV}^{-1}$$

WHICH IS NOT THE REGIME OF OUR INTEREST

FOR A THEORY WITH A FINITE CUTOFF THIS MEANS

- FOR VERY HIGH QUENCH RATES DEPENDENCE ON THE RATE DROPS OFF

- HOWEVER THERE IS AN INTERMEDIATE REGIME WHERE THE UNIVERSAL SCALING HOLDS

IT WOULD BE INTERESTING TO STUDY THIS IN SOME SOLVABLE MODEL

MAYBE EVEN MEASURABLE

FINALLY, FOR FINITE DISTANCE CORRELATORS

$$\Delta x \gg \delta t$$

ONLY LOW MOMENTUM MODES CONTRIBUTE — THE RESULTS OF RAPID, SMOOTH QUENCH AND THOSE OF ABRUPT QUENCH SHOULD AGREE

WE HAVE TALKED ABOUT A UNIVERSAL SCALING RESULT FOR RAPID QUANTUM QUENCHES

INTERESTINGLY, THIS RESULT WAS FIRST DISCOVERED IN A HOLOGRAPHIC CALCULATION

HOWEVER OUR WORK INDICATES THAT THE RESULT IS IN FACT A GENERIC PROPERTY OF A CFT DEFORMED BY A RELEVANT OPERATOR WITH A TIME-DEPENDENT COEFFICIENT

THANK YOU !