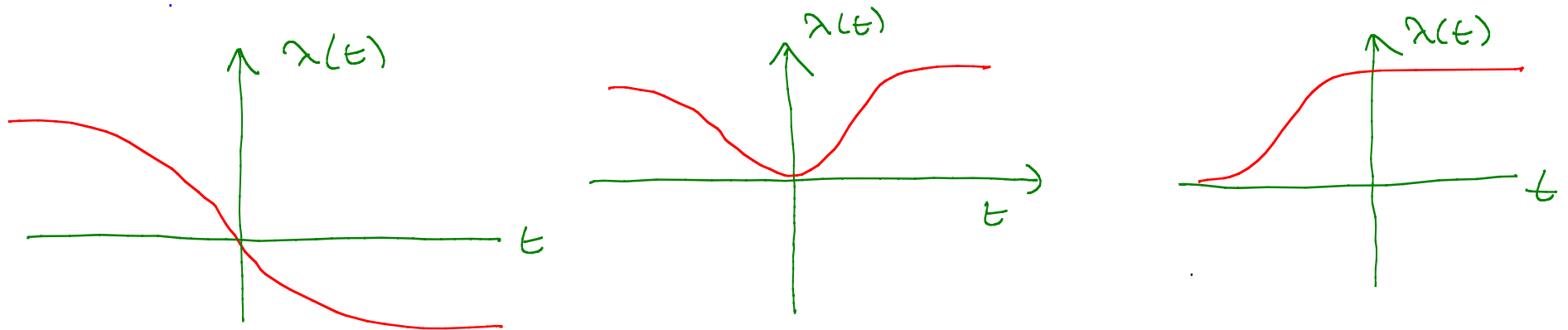


UNIVERSALITY IN QUANTUM
QUENCHES IN FIELD THEORY
AND HOLOGRAPHY

SUMIT R. DAS

CONSIDER SOME HAMILTONIAN WITH A TIME DEP.
PARAMETER $\lambda(t)$ WHICH INTERPOLATES BETWEEN
CONSTANT VALUES



REGARDLESS OF THE SPEED : CALL THIS QUANTUM
QUENCH

QUANTUM QUENCH IS PARTICULARLY INTERESTING
WHEN THE PROTOCOL INVOLVES A CRITICAL
POINT

ONE THEN EXPECTS THAT TIME EVOLUTION
CARRIES UNIVERSAL SIGNATURES OF THE CRITICAL
POINT

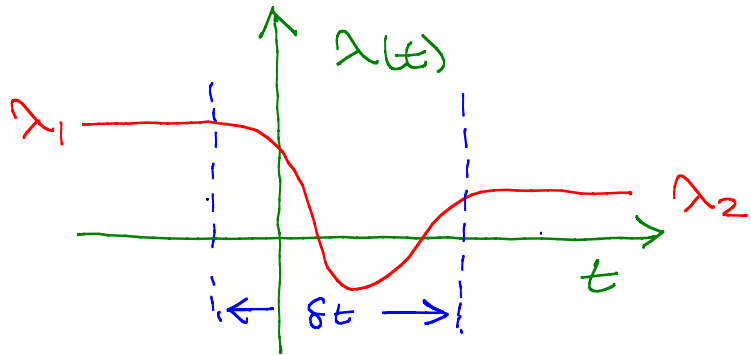
-

OUR SETTING INVOLVES AN ACTION

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

Δ : DIMENSION OF RELEVANT OPERATOR \mathcal{O}_Δ

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



λ_0 : OVERALL SCALE

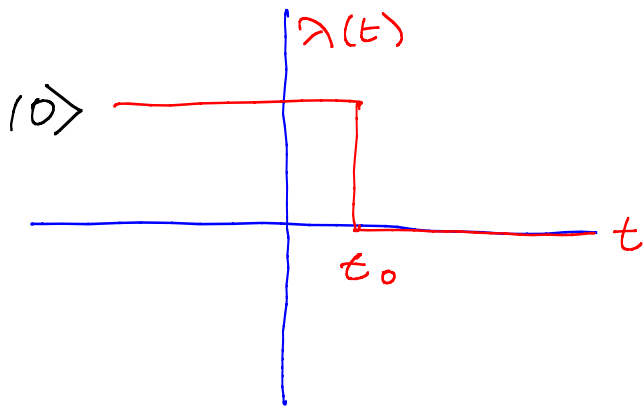
$(\delta t)^{-1}$: QUENCH RATE

$F \sim \mathcal{O}(1)$ VALUES

UNIVERSAL RESULTS HAVE BEEN KNOWN FOR
A WHILE IN TWO EXTREME LIMITS

- SUDDEN QUENCH (CALABRESE & CARDY)
- SLOW QUENCH (KIBBLE - ZUREK)

INSTANTANEOUS QUENCH



STATE AT $t = t_0 - \epsilon$ IS AN
INITIAL CONDITION FOR FURTHER
TIME EVOLUTION

IN $1+1$ DIMENSIONS CALABRESE &
CARDY DERIVED A SET OF
UNIVERSAL RESULTS

e.g. ONE POINT FUNCTION FOR SOME OPERATOR
(WHICH IS NOT CONSERVED)

$$\langle A \rangle_N \exp\left(-\frac{\pi x}{2\tau_0} t\right)$$

x : CONFORMAL DIMENSION

τ_0 : INITIAL LENGTH SCALE

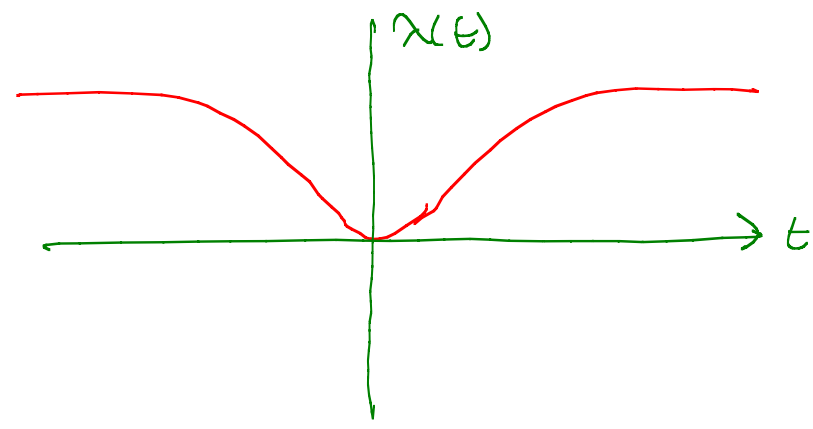
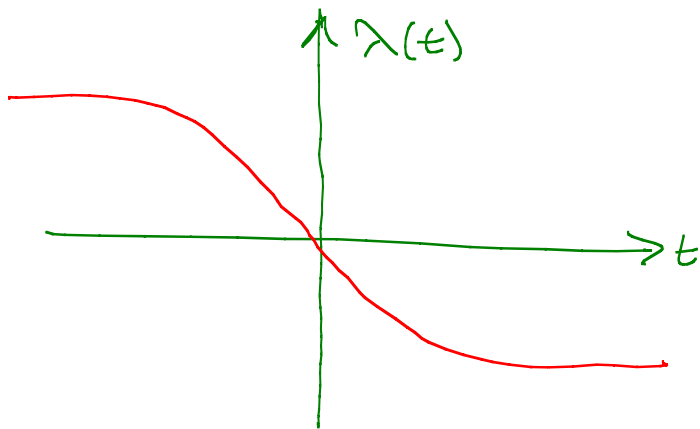
⇒ RATIOS OF RELAXATION TIMES **UNIVERSAL**

- OTHER RESULTS FOR CORR. FUNCTIONS
- TIME EVOLUTION OF ENTANGLEMENT ENTROPY

HOLOGRAPHIC REALIZATION : HARTMAN & MALDACENA

"SLOW" QUENCH

COUPLING STARTS FROM GAPPED PHASE SLOWLY
AND CROSSES A CRITICAL POINT

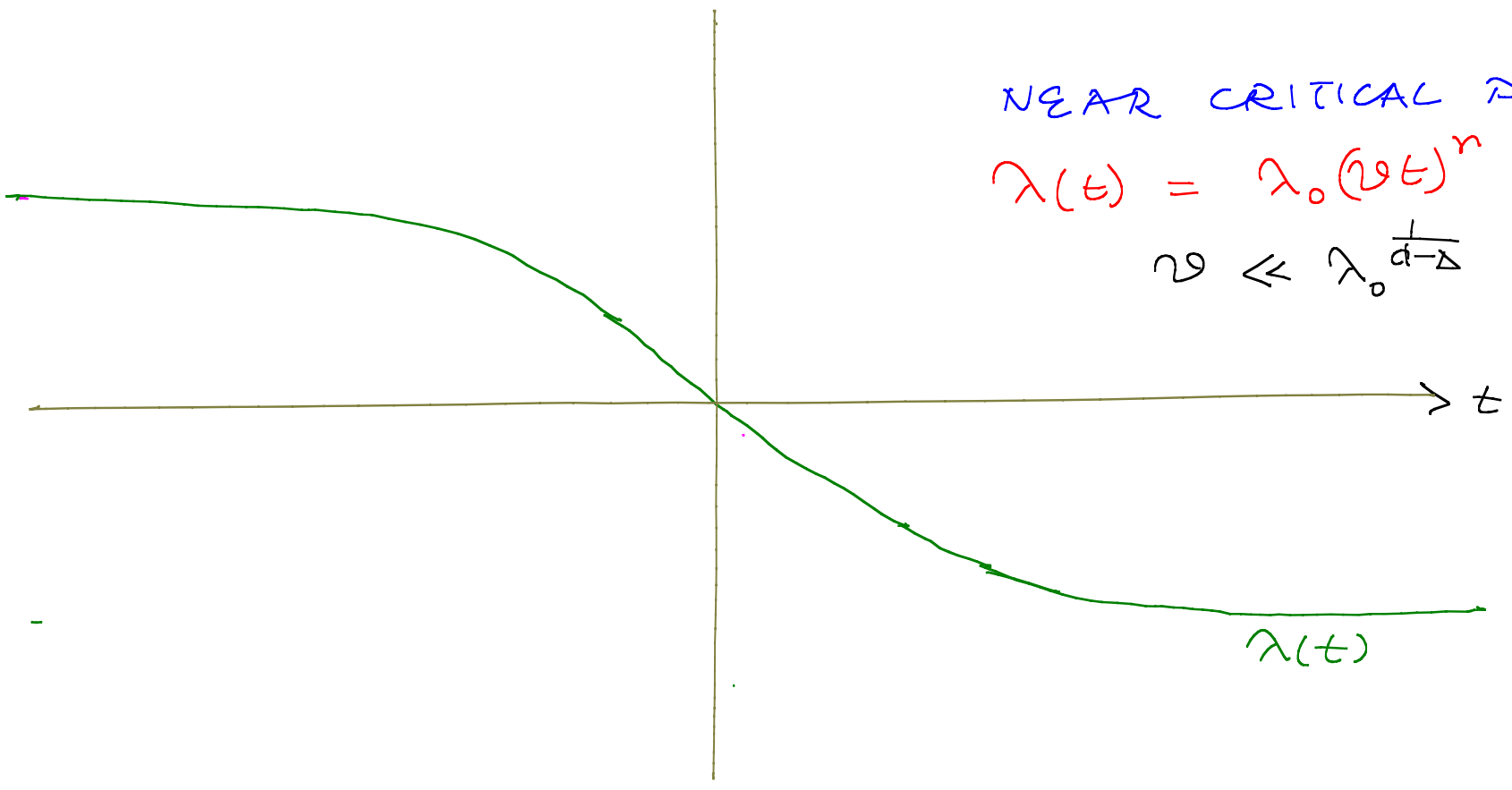


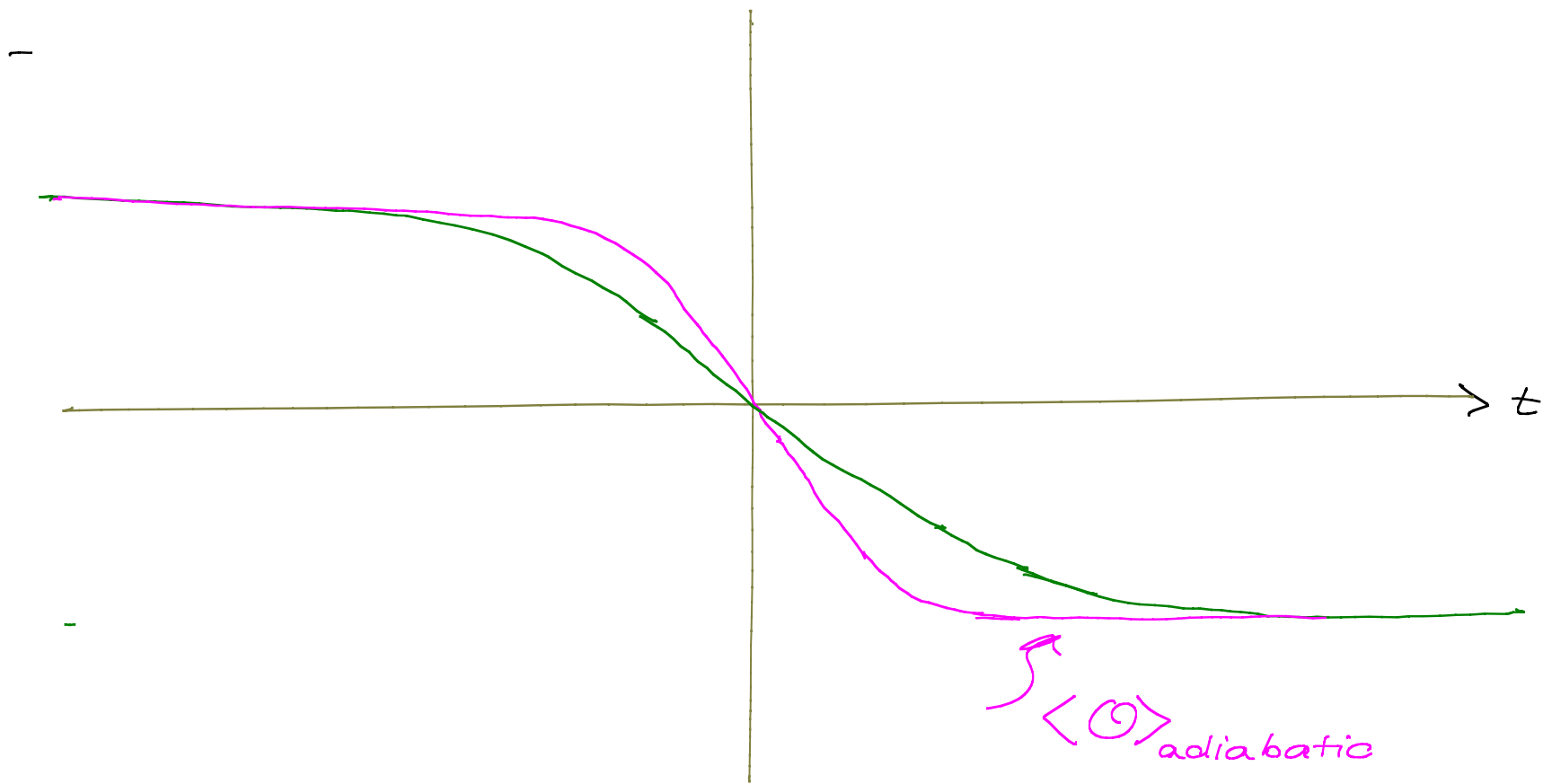
$\lambda = 0$ IS A CRITICAL THEORY

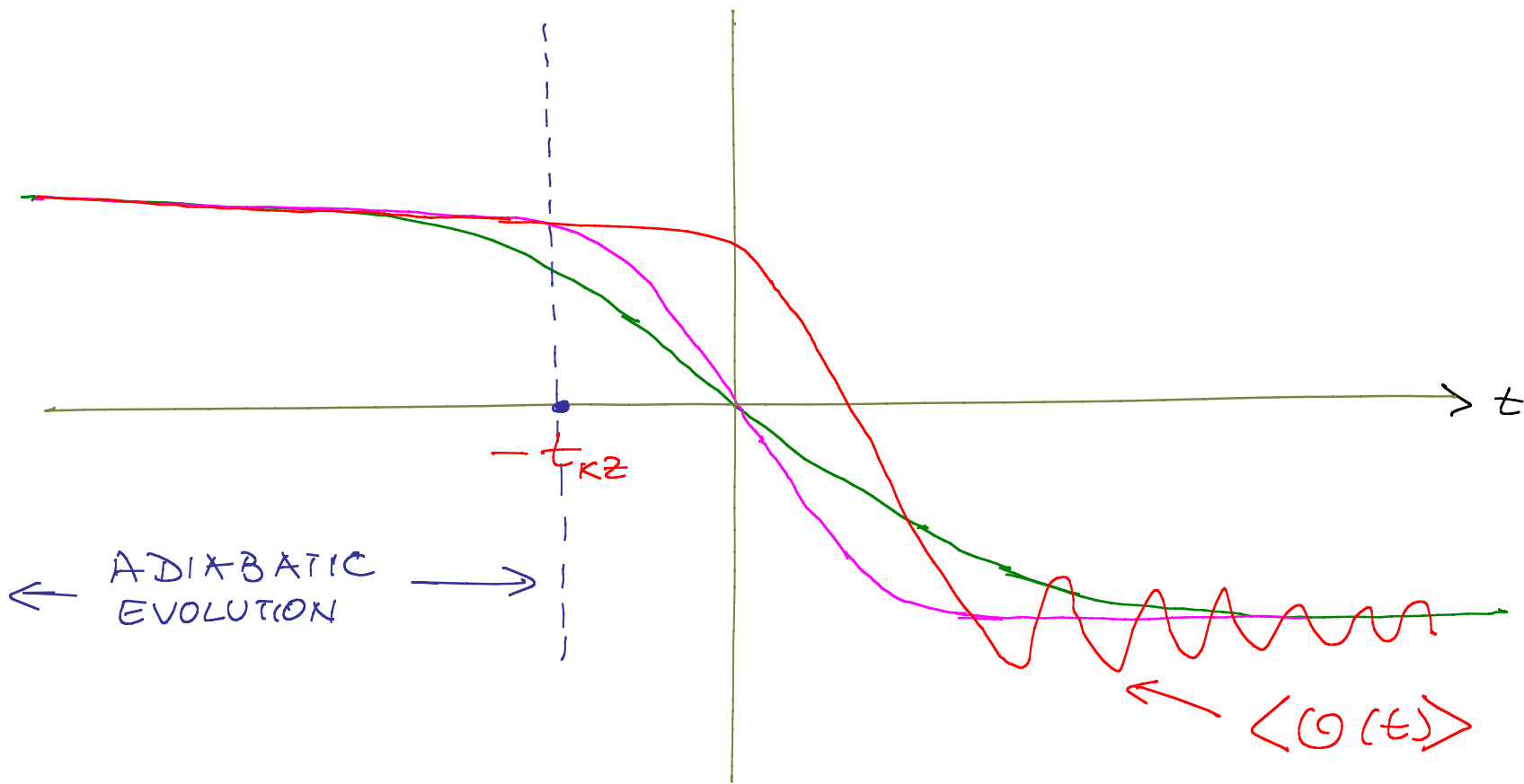
NEAR CRITICAL POINT

$$\lambda(t) = \lambda_0 (\omega t)^n$$

$$\omega \ll \lambda_0^{\frac{1}{d-\Delta}}$$







$$\langle \mathcal{O} \rangle \sim (\lambda_0 v^r)^{\frac{\Delta}{r+d-\Delta}}$$

$$\lambda(t) \sim \lambda_0 (vt)^r$$

Δ : CONF. DIMENSION

THIS IS A SPECIAL CASE OF KIBBLE-ZUREK SCALING
 UNDERLYING ASSUMPTIONS NOT EASY TO UNDERSTAND
 FOR STRONGLY COUPLED THEORIES

USING HOLOGRAPHY WE CAN GET SOME INSIGHT

P. BASU & S.R.D -	JHEP 1201 (2012)103
P. BASU, D. DAS, S.R.D & T. NISHIOKA -	JHEP 1303 (2013)146
P. BASU, D. DAS, S.R.D & K. SENGUPTA -	JHEP 1312 (2013)070
S.R.D & T. MORITA -	JHEP 1501 (2015)084

HOLOGRAPHIC KIBBLE ZUREK

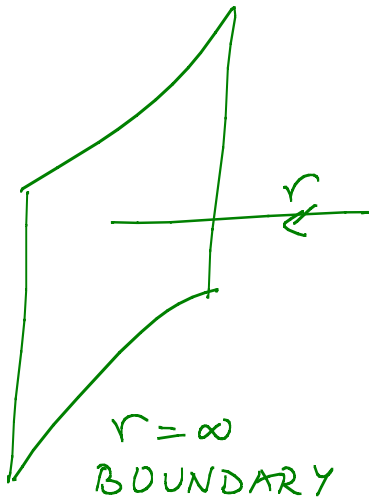
$$S = S_{\text{EFT}} + \int dt d^{d-1} \vec{x} \lambda(t) \mathcal{O}_{\Delta}(\vec{x}, t)$$

SCALAR OPERATOR \mathcal{O}_{Δ} DUAL TO $\phi(r, \vec{x}, t)$

$$\phi(\vec{x}, r, t) \xrightarrow{r \rightarrow \infty} r^{\Delta-d} [\lambda(t) + o(1/r^2)] + r^{\Delta} [A(t) + o(1/r^2)]$$

$$\langle \mathcal{O}_{\Delta}(\vec{x}, t) \rangle = A(t)$$

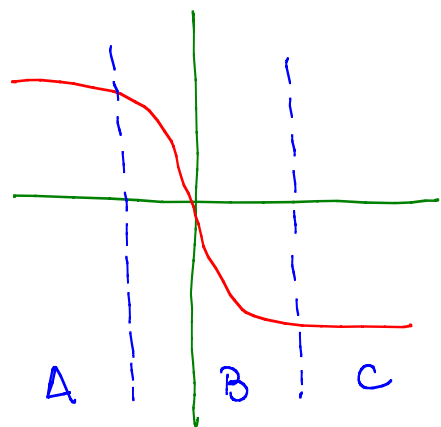
\Rightarrow SOLVE BULK EQUATIONS WITH A TIME DEP. BOUNDARY CONDITION



STRATEGY

- CONSIDER A BULK THEORY SUCH THAT THE BOUNDARY FIELD THEORY HAS AN ISOLATED CRITICAL POINT (e.g. HOLOGRAPHIC SUPERCONDUCTOR)
- INTRODUCE A TIME DEPENDENT SOURCE FOR THE CORRESPONDING ORDER PARAMETER WHICH CROSSES THIS CRITICAL POINT
- CALCULATE THE RESPONSE

THE RESULT FROM SEVERAL MODELS WITH HOLOGRAPHIC CRITICAL POINTS



$$\nu \ll \lambda_0^{\frac{1}{d_1 - \Delta}}$$

REGION A : ADIABATIC EXPANSION VALID
- POWER SERIES EXPANSION
IN ν

REGION B : A DIFFERENT EXPANSION IN
FRACTIONAL POWERS OF ν , ν^α
- POWER DETERMINED BY
CRITICAL EXPONENTS

IN REGION B THE BULK SCALAR CAN BE EXPANDED
IN EIGENMODES OF THE LINEAR FLUCTUATION
OPERATOR \mathcal{D}

$$\phi(r, t) = \sum_n \phi_n(r) \xi_n(t).$$

$$\mathcal{D} \phi_n = \lambda_n \phi_n$$

AT THE CRITICAL POINT $\lambda = 0$ THE OPERATOR \mathcal{D}
HAS A ZERO MODE \Rightarrow ADIABATICITY BREAKDOWN

TO LOWEST ORDER IN THE v^α EXPANSION THE
ZERO MODE DOMINATES THE DYNAMICS

TO LEADING ORDER IN ν^α EXPANSION THE BULK EQUATIONS HAVE SCALING SOLUTIONS

$$\mathcal{O}_\Delta(t, \nu) = \nu^\alpha f(t \nu^\beta)$$

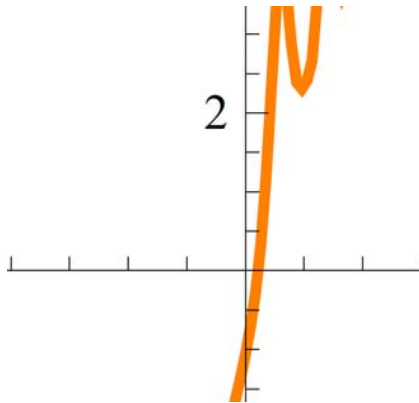
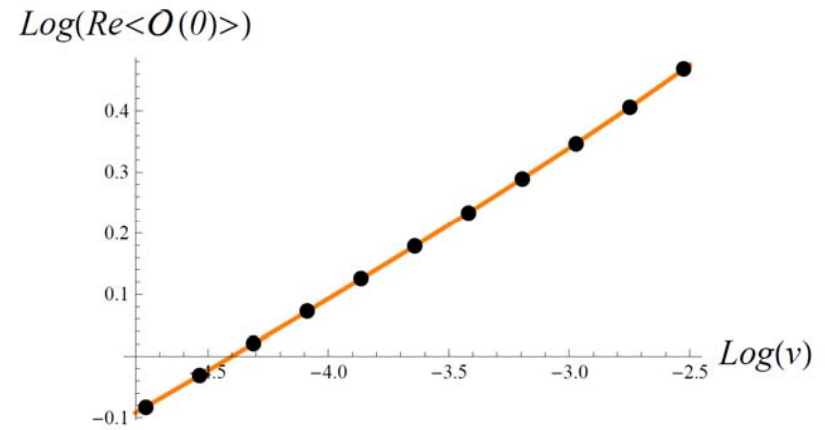
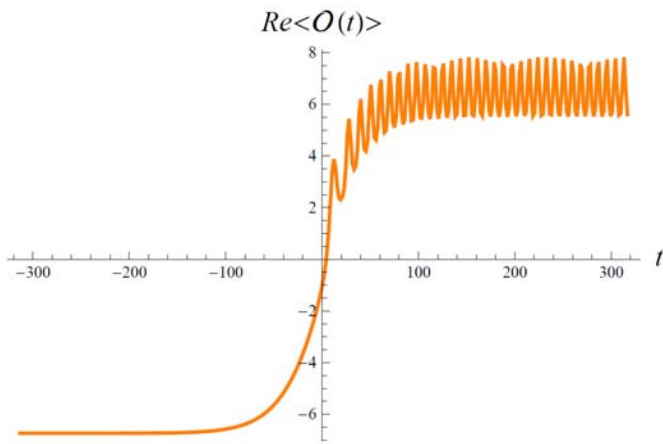
SIMILARLY FOR $\langle T_{\mu\nu} \rangle$ & $\langle J_\mu \rangle$

EXPONENTS CONSISTENT WITH KIBBLE ZUREK

FRAMEWORK FOR CORRECTIONS - POWERS OF ν^α

INHOMOGENITIES & DEFECTS

- SONNER, del CAMPO, ZUREK
- CHESLER, GARCIA-GARCIA & LIU

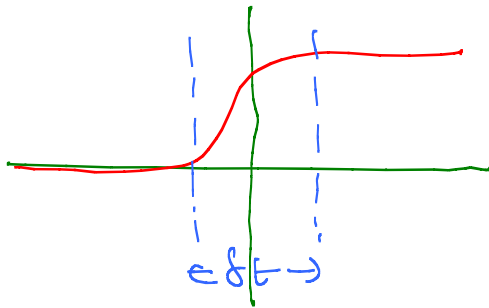


PROBE APPROXIMATION RESULTS
 FOR A $T=0$ HOLOGRAPHIC
 SUPERCONDUCTOR OF NISHIOKA-RYU-
 TAKAYANGI
 (P. BASU, D. DAS, S. R. DAS &
 T. NISHIOKA)

HOLOGRAPHIC FAST QUENCH

BUCHTEL, LEHNER, MYERS & VAN NIEKERK
STUDIED QUENCHES HOLOGRAPHICALLY

$$S = S_{\text{CFT}} - \int \lambda(t) \mathcal{O}_{\Delta}(x, t)$$



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

USING STANDARD TECHNIQUES OF HOLOGRAPHIC
RENORMALIZATION : NUMERICAL RESULT

$$\begin{aligned} \langle \mathcal{O}_\Delta \rangle_{\text{ren}} &\sim (\delta t)^{d-2\Delta} \\ \langle E \rangle_{\text{ren}} &\sim (\delta t)^{d-2\Delta} \end{aligned}$$

AT TIMES
SOON
AFTER THE
QUENCH

CONSISTENT WITH WARD IDENTITY

$$\frac{d\langle E \rangle}{dt} = \frac{d\lambda}{dt} \langle \mathcal{O}_\Delta \rangle$$

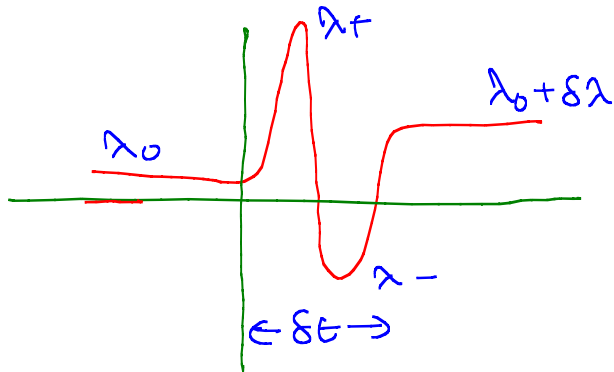
THESE RESULTS ARE SOMEWHAT PUZZLING.

$\langle \mathcal{O}_\Delta \rangle \sim (\delta t)^{d-2\Delta} \Rightarrow$ NO SMOOTH LIMIT $\delta t \rightarrow 0$ WHEN
 $d > \Delta > d/2$

NEVERTHELESS THERE IS A PERFECTLY WELL DEFINED
ABRUPT QUENCH

COULD THIS BE A SPECIAL FEATURE OF STRONGLY
COUPLED FIELD THEORIES WHICH HAVE GRAVITY
DUALS ?

WE WILL ARGUE THAT THIS IS A GENERAL RESULT FOR ANY DEFORMED CFT IN ANY NUMBER OF DIMENSIONS



$$\delta t \ll \lambda_{\pm}^{\frac{1}{d-d}}, (\lambda_0 + \delta\lambda)^{\frac{1}{d-d}}$$

FOR TIMES $t \lesssim \delta t$

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

FOR TIMES AFTER QUENCH IS OVER

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

S.R.D, D.GALANTE & R.MYERS

PRL 112 (2014) 171601

JHEP 1502 (2015) 167

arXiv 1505.05224

WE WILL ALSO DISCUSS IN SOME DETAIL HOW THE
 $\epsilon \rightarrow 0$ RESULTS RELATE TO THOSE OF
INSTANTANEOUS QUENCH

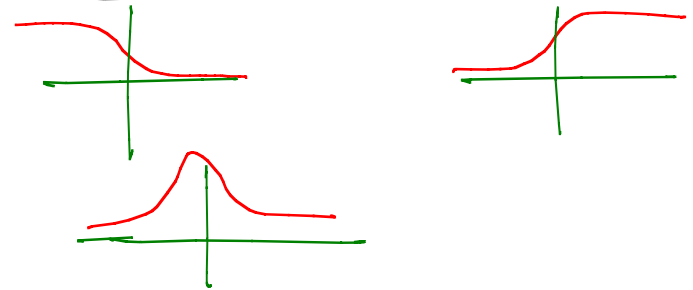
FAST QUENCH IN FREE FIELDS

SMOOTH QUENCHES IN SOLVABLE FREE FIELD THEORY WITH
TIME DEPENDENT MASS

$$S = \int d^d x dt [(\partial \phi)^2 - m^2(t) \phi^2]$$

$$(I) \quad m^2(t) = A + B \tanh(t/\delta t)$$

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



PROBLEM CAN BE EXACTLY SOLVED FOR ALL δt FOR
THESE MASS PROFILES

THE (HEISENBERG PICTURE) STATE IS THE "IN" VACUUM

$$\Phi(\vec{x}, t) = \int \frac{d^d k}{(2\pi)^d} [a(k) u_k(x, t) + h.c.]$$

$$a(k)|0\rangle = 0$$

THE (HEISENBERG PICTURE) STATE IS THE "IN" VACUUM

$$\Phi(\vec{x}, t) = \int \frac{d^{d-1}k}{(2\pi)^{d-1}} [a(k)u_k(x, t) + h.c.]$$

$$a(k)|0\rangle = 0$$

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

$$a = 1 + i\omega_- \delta t, \quad b = i\omega_- \delta t, \quad c = 1 - i\omega_{in} \delta t$$

$$\omega_{in} = \sqrt{k^2 + m_{in}^2} \quad \omega_{out} = \sqrt{k^2 + m_{out}^2} \quad \omega_{\pm} = \frac{1}{2}(\omega_{out} \pm \omega_{in})$$

$$u_k \rightarrow \frac{1}{\sqrt{2\omega_{in}}} \exp[i(\vec{k} \cdot \vec{x} - \omega_{in} t)] \quad \text{as } t \rightarrow -\infty$$

THERE IS ALSO A SET OF "OUT" MODES

$$\phi = \int \frac{d^d k}{(2\pi)^{d+1}} [b_k \psi_k + h.c.]$$

BOGOLIUBOV : $u_k = \alpha_k \psi_k + \beta_k \psi_{-k}^*$

$$\alpha_k = \sqrt{\frac{\omega_{out}}{\omega_{in}}} \frac{\Gamma(1 - i\omega_{in}\delta t) \Gamma(-i\omega_{out}\delta t)}{\Gamma(-i\omega_{+}\delta t) \Gamma(1 - i\omega_{+}\delta t)}$$

$$\beta_k = \sqrt{\frac{\omega_{out}}{\omega_{in}}} \frac{\Gamma(1 - i\omega_{in}\delta t) \Gamma(i\omega_{out}\delta t)}{\Gamma(i\omega_{-}\delta t) \Gamma(1 + i\omega_{-}\delta t)}$$

THIS KIND OF SETUP IS RELEVANT IN
INFLATIONARY COSMOLOGY - SIMILAR
CALCULATIONS PERFORMED EARLIER
(e.g.: BRANDENBERGER & TRASCHEN)

THESE STUDIES OF COURSE INVOLVED $d=4$

THE ONE POINT FUNCTION OF QUENCHED OPERATOR

$$\langle 0 | \phi^2(x, t) | 0 \rangle_{in} = \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \frac{1}{2\omega_{in}} |2F_1|^2$$

THIS QUANTITY IS OF COURSE UV DIVERGENT
AN EFFICIENT WAY TO RENORMALIZE THIS IS
TO REGARD $m^2(t)$ AS A BACKGROUND FIELD

$$S \rightarrow S_0(\phi, m^2, g_{\mu\nu}) - S_{ct}(m^2, g_{\mu\nu}, \Lambda)$$

$g_{\mu\nu}$ IS A BACKGROUND METRIC

EXPECTATION VALUES MAY BE COMPUTED FROM

$$Z(m^2, g_{\mu\nu}) = \int \mathcal{D}\phi_x \exp[-iS].$$

$$\langle \phi^2 \rangle_{\text{ren}} = -2i \left(\frac{1}{\sqrt{g}} \frac{\delta}{\delta m^2} \log Z \right)_{\substack{g_{\mu\nu} = \eta_{\mu\nu} \\ \Lambda \rightarrow \infty}}$$

$$\langle T_{\mu\nu} \rangle_{\text{ren}} = -2i \left(\frac{1}{\sqrt{g}} \frac{\delta}{\delta g^{\mu\nu}} \log Z \right)_{\substack{g_{\mu\nu} = \eta_{\mu\nu} \\ \Lambda \rightarrow \infty}}$$

COUNTERTERMS GENERALLY DEPEND ON
 $\partial_\epsilon m^2, \partial_\epsilon^2 m^2 \dots$ IN ADDITION TO m^2

IT TURNS OUT THAT THE COUNTERTERM ACTION MAY BE OBTAINED FROM AN **ADIABATIC EXPANSION**

eg. $\langle 0 | \phi^2 | 0 \rangle_{\text{adiabatic}} = \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \frac{1}{2\Omega_k}$

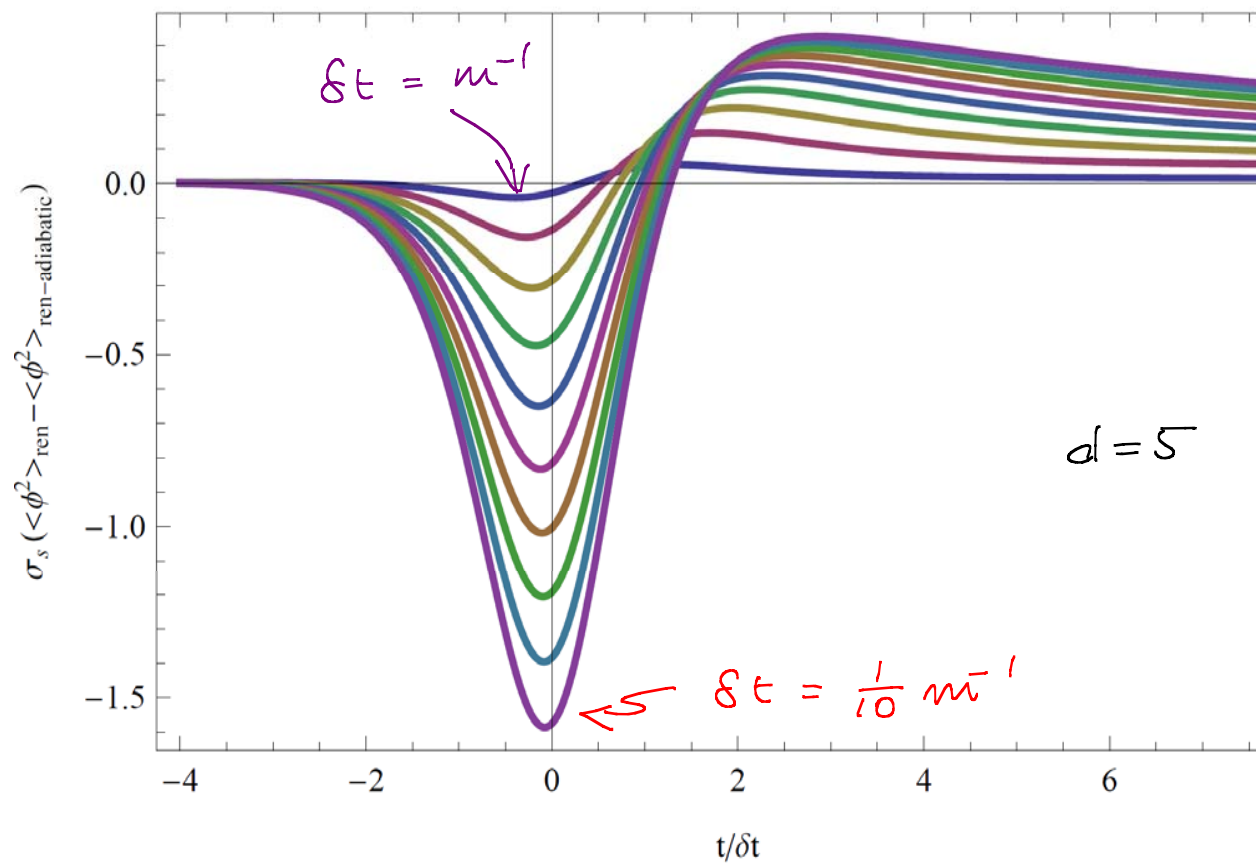
$$\Omega_k(t) = \omega_k(t) - \frac{1}{4\omega_k} \left(\frac{\dot{\omega}_k}{\omega_k} - \frac{3}{2} \left(\frac{\dot{\omega}_k}{\omega_k} \right)^2 \right) + \dots$$

$$\omega_k(t) \equiv \sqrt{k^2 + m^2(t)}$$

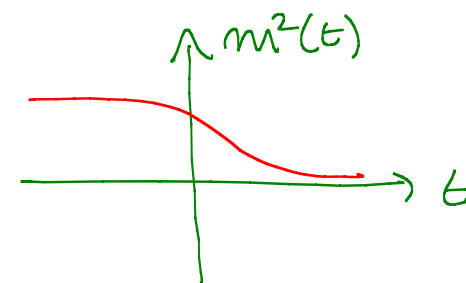
THIS MAY APPEAR PUZZLING AT FIRST
ADIABATIC EXPANSIONS ARE GOOD WHEN THE RATE
OF CHANGE IS SLOW — BUT WE ARE INTERESTED
IN FAST QUENCHES

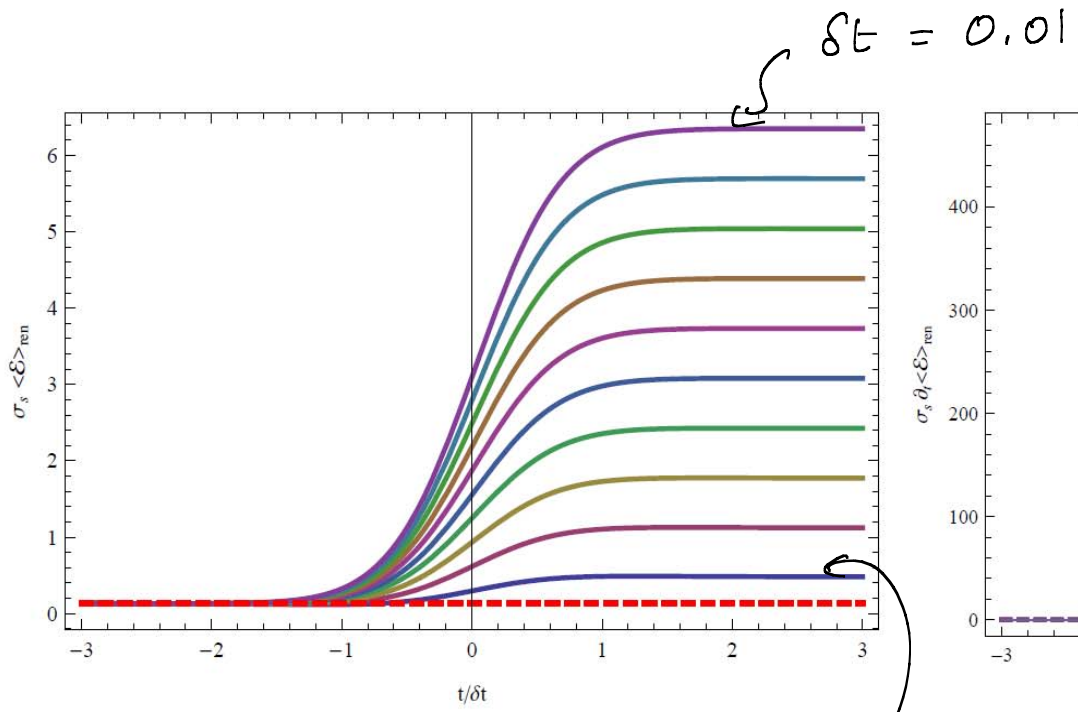
THE POINT IS THAT OUR QUENCH RATE IS FAST
COMPARED TO PHYSICAL SCALES BUT SLOW COMPARED
TO THE CUTOFF SCALE

⇒ ADIABATIC EXPANSION IS GOOD FOR THE UV
CONTRIBUTION

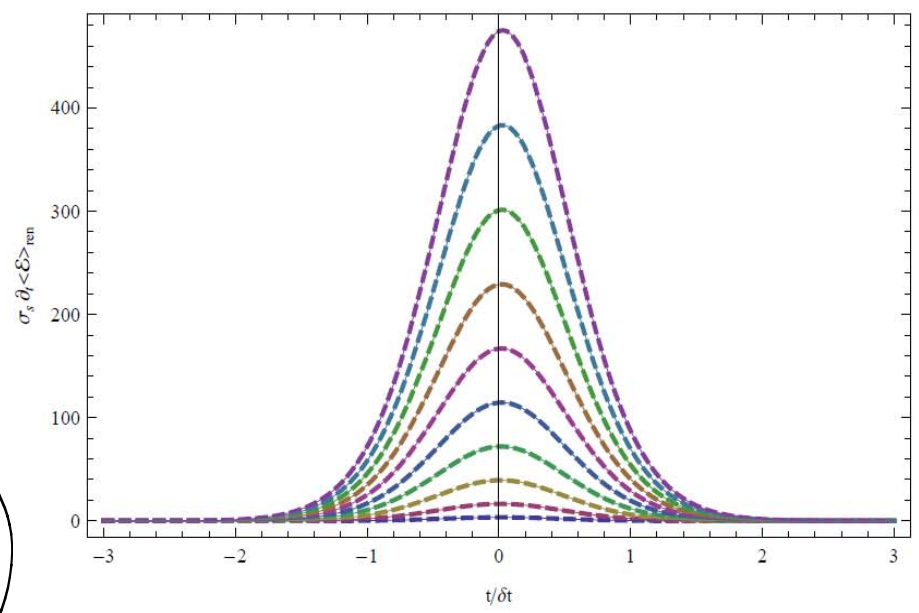


$$m^2(t) = \frac{1}{2} m_0^2 (1 - \tanh \frac{t}{\delta t})$$





$\langle \mathcal{E} \rangle$ AS FUNCTION OF $t/\delta t$
 $\delta t = 0.1$



$\partial_t \langle \mathcal{E} \rangle$ AS FUNCTION OF $t/\delta t$

WE CAN NOW CONSIDER FAST QUENCH LIMIT

$$m_0 \delta t \ll 1$$

IN THIS LIMIT ONE RECOVERS ANALYTIC EXPRESSIONS

ODD d
 $d \geq 5$

$$\langle \phi^2 \rangle_{\text{ren}} = (-1)^{\frac{d-1}{2}} \frac{\pi}{2^{d-2}} \partial_t^{d-4} m^2 + O(\delta t^{6-d})$$

$d=3$

$$\langle \phi^2 \rangle_{\text{ren}} = -\frac{m_0}{4} - \frac{m_0^2 \delta t}{16} \log \left[\frac{1}{2} \left(1 - \tanh \frac{t}{\delta t} \right) \right]$$

$$\left(m^2(t) = \frac{1}{2} m_0^2 \left(1 - \tanh \frac{t}{\delta t} \right) \right)$$

FOR EVERY d THE RESULTS ARE

$$d > 4$$

$$\langle \phi^2 \rangle_{\text{ren}} = \frac{(-1)^{d/2}}{2^{d-3}} \log(\mu \delta t) \partial_t^{d-4} m^2(t) + \dots$$

$$d = 4$$

$$\langle \phi^2 \rangle_{\text{ren}} = \frac{m_0^2}{4} \left(1 + \tanh \frac{b}{\delta t}\right) \log(\mu \delta t) + \dots$$

THESE RESULTS IMPLY THAT, UP TO LOGS

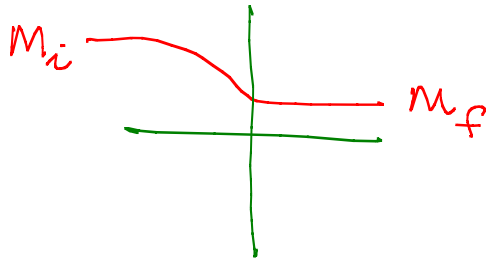
$$\langle \phi^2 \rangle \sim m_0^2 (\delta t)^{4-d}$$

SINCE FOR THIS OPERATOR $\Delta = d-2$

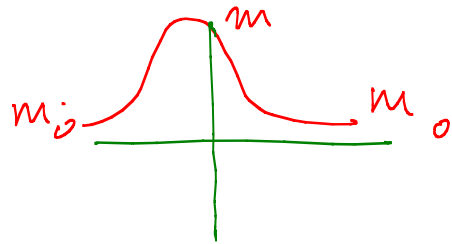
$$\langle \phi^2 \rangle \sim m_0^2 (\delta t)^{d-2\Delta}$$

THIS IS EXACTLY AS FOUND IN HOLOGRAPHY
- LOG CORRECTIONS ALSO FOUND THERE

RESULTS GENERALIZE TO GENERIC MASS PROFILES



$$m_i \delta \epsilon \ll 1 \quad m_f \delta \epsilon \ll 1$$



$$m_o \delta \epsilon \ll 1 \quad m \delta \epsilon \ll 1$$

SIMILAR RESULTS FOR
DIRAC FERMIONS

THIS SCALING BEHAVIOR FOR FAST QUENCH SEEMS TO HOLD FOR

- STRONGLY COUPLED THEORIES WITH GRAVITY DUALS
- FREE FIELD THEORIES

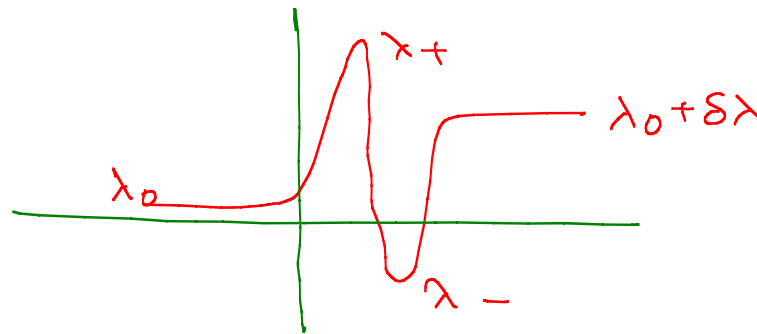
COULD THIS BE A GENERAL RESULT?

THE GENERAL RESULT

CONSIDER NOW A GENERAL INTERACTING THEORY

$$S = S_{\text{CF}} - \int d^d x dt \lambda(t) \mathcal{O}_\Delta(x, t)$$

LET US NOW COMPUTE $\langle \mathcal{O}_\Delta \rangle$ PERTURBATIVELY FOR



QUENCH
STARTS
AT $t=0$

$$\langle \mathcal{O}_\Delta \rangle = \langle \mathcal{O}_\Delta \rangle_{\lambda_0} + \int_0^t dt' \int d^d x' \lambda(t') G_R(x-x'; t-t') \\ + \int dt' dt'' dx' dx'' \lambda(t') \lambda(t'') K(x, x', x''; t, t', t'')$$

FIRST TERM IS STANDARD **LINEAR RESPONSE**

$$G_R(x-x', t-t') \equiv \Theta(t-t') \langle 0 | [\mathcal{O}_\Delta(x, t), \mathcal{O}_\Delta(x', t')] | 0 \rangle_{\lambda_0}$$

WE NOW EXAMINE THIS TERM IN SOME DETAIL

$$\int_0^t dt' \int d^{d-1}x' \lambda(t') G_R(x-x'; t-t')$$

- (x', t') LIES IN PAST LIGHT CONE OF (x, t)
- IF $t \lesssim \delta t$ THE SPATIAL SEPARATION
 $|x-x'| \lesssim \delta t$
- HOWEVER IF δt IS MUCH SMALLER THAN ALL OTHER LENGTH SCALES, INCL. $(\lambda_0)^{-\frac{1}{d-\Delta}}$ CORRELATORS AT DISTANCES SHORTER THAN δt ARE BASICALLY CFT CORRELATORS

THUS RENORMALIZED $\langle \mathcal{O}_\Delta \rangle$ DEPENDS ONLY ON $\delta\lambda$ AND δt

IN TERMS OF A DIMENSIONLESS COUPLING

$$g \equiv (\delta\lambda) (\delta t)^{d-\Delta}$$

WE HAVE AN EXPANSION

$$\langle \mathcal{O} \rangle - \langle \mathcal{O} \rangle_{\lambda_0} = (\delta t)^{-\Delta} \left[a_1\left(\frac{t}{\delta t}\right) \cdot g + a_2\left(\frac{t}{\delta t}\right) g^2 + \dots \right]$$

HOWEVER FAST QUENCH MEANS

$$g \ll 1$$

THUS THE LEADING ANSWER IS

$$\delta \langle \mathcal{O}_\Delta \rangle \sim (\delta t)^{-\Delta} g a_1\left(\frac{t}{\delta t}\right) = (\delta \lambda) (\delta t)^{d-2\Delta} a_1\left(\frac{t}{\delta t}\right)$$

⇒ "EARLY TIME" QUANTITY HAS THIS UNIVERSAL FORM IN ANY THEORY

— SIMILAR ARGUMENT FOR $\langle \mathcal{E} \rangle_{\text{ren}}$

THE ABRUPT LIMIT

- DOES $\delta t \rightarrow 0$ LIMIT REPRODUCE ABRUPT QUENCH?
- TO INVESTIGATE THIS CONSIDER THE EXPLICIT RESULTS FOR FREE BOSONIC FIELDS
- OUR RESULTS ARE FOR RENORMALIZED QUANTITIES
 - THESE ARE RELEVANT ONLY IF THE QUENCH RATE IS MUCH BELOW THE CUTOFF

$$\Lambda_{UV}^{-1} \ll \delta t \ll (\delta\lambda)^{-\frac{1}{d-\Delta}}$$

THIS IS WHY ADIABATIC EXPN. GIVES COUNTERTERMS

AN ABRUPT QUENCH HAS A RATE FASTER THAN ALL SCALES - HAS TO BE OF CUTOFF SCALE

⇒ CLEARLY LOCAL OBSERVABLES IN FAST QUENCH WOULD BE, IN GENERAL, DIFFERENT FROM THOSE IN ABRUPT QUENCH

TO EXAMINE THIS IN MORE DETAIL, LOOK AT UU.FINITE QUANTITIES -

EXCESS ENERGY

ONE SUCH QUANTITY IS THE EXCESS ENERGY DENSITY AT LATE TIMES

$$\Delta E = E - E_{\text{ground}}$$

WHERE E_{ground} IS THE GROUND STATE ENERGY OF THE FINAL HAMILTONIAN

$$E_{\text{ground}} = \frac{1}{2} \int \frac{d^{d-1}k}{(2\pi)^{d-1}} (\omega_{\text{out}})$$

THIS IS IN FACT THE LEADING ADIABATIC RESULT

THE EXPRESSION FOR THIS IS

$$\Delta E = \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \omega_{out} |\beta_k|^2$$

WHERE β_k IS THE BOGOLIUBOV COEFFICIENT

THIS IS A UV FINITE QUANTITY

WE SAW THAT COUNTERTERMS WHICH RENDER $E(t)$ FINITE DEPEND ON DERIVATIVES OF m^2 IN ADDITION TO m^2 - BUT DERIVATIVES VANISH AS $t \rightarrow \infty$

THUS SUBTRACTION OF E_{ground} IS SUFFICIENT

$$\begin{aligned}
 d = 2 & \quad \Delta \mathcal{E}^{\delta t \rightarrow 0} = \frac{m^2}{16\pi} + c_1 m^4 (\delta t)^2 + \dots \\
 d = 3 & \quad \Delta \mathcal{E}^{\delta t \rightarrow 0} = \frac{m^3}{24\pi} + c_2 m^4 (\delta t) + \dots \\
 d = 4 & \quad \Delta \mathcal{E}^{\delta t \rightarrow 0} = c_3 m^4 \log(m\delta t) + o(\delta t) \\
 d \geq 5 & \quad \Delta \mathcal{E}^{\delta t \rightarrow 0} \sim m^4 (\delta t)^{4-d} + \dots
 \end{aligned}$$

FOR $d=2,3$ THIS IS FINITE AS $\delta t \rightarrow 0$. THIS FINITE ANSWER IS IN FACT THE RESULT FOR INSTANTANEOUS QUENCH

$$\Delta \mathcal{E}^{\text{inst}} = \frac{\Omega_{d-2}}{(2\pi)^{d-1}} \int dk \cdot k^{d-1} \frac{(\sqrt{k^2+m^2}-k)^2}{4k\sqrt{k^2+m^2}}$$

FOR $d \geq 4$ EXCESS ENERGY DIVERGES AS $\delta t \rightarrow 0$

LIKewise $\Delta \mathcal{E}^{\text{inst}}$ IS UV DIVERGENT

WHILE THESE EXPLICIT RESULTS ARE FOR FREE FIELDS WE EXPECT SIMILAR RESULTS TO HOLD FOR ARBITRARY INTERACTING THEORIES

$\Delta < d/2$ ΔE IS FINITE AS $\delta t \rightarrow 0$
SUBLEADING PIECE DISPLAYS
UNIVERSAL SCALING $\sim (\delta t)^{d-2\Delta}$

$\Delta > d/2$ ΔE DIVERGES AS $(\delta t)^{d-2\Delta}$

CORRELATION FUNCTIONS

ANOTHER CLASS OF UV FINITE QUANTITIES ARE
CORRELATION FUNCTIONS AT FINITE SPATIAL
SEPARATIONS

$$C(\vec{r}, t) \equiv \langle 0 | \phi(\vec{r}, t) \phi(0, t) | 0 \rangle_{in}$$

LATE TIME CORRELATORS

$$C_{\text{smooth}}(t, \vec{r}) = \int \frac{[d\vec{k}]}{2k} e^{i\vec{k} \cdot \vec{r}} \left\{ |\alpha_{\vec{k}}|^2 + |\beta_{\vec{k}}|^2 + \alpha_{\vec{k}} \beta_{\vec{k}}^* e^{2ikt} + \alpha_{\vec{k}}^* \beta_{\vec{k}} e^{-2ikt} \right\}$$

$$C_{\text{abrupt}}(t, \vec{r}) = \int \frac{[d\vec{k}]}{2k} e^{i\vec{k} \cdot \vec{r}} \left\{ \frac{k^2 + m^2 \sin^2(kt)}{k^2 \sqrt{k^2 + m^2}} \right\}$$

(kt) IS CONTAINED IN THE BOGOLIUBOV COEFFICIENTS

$\alpha_{\vec{k}}, \beta_{\vec{k}}$.

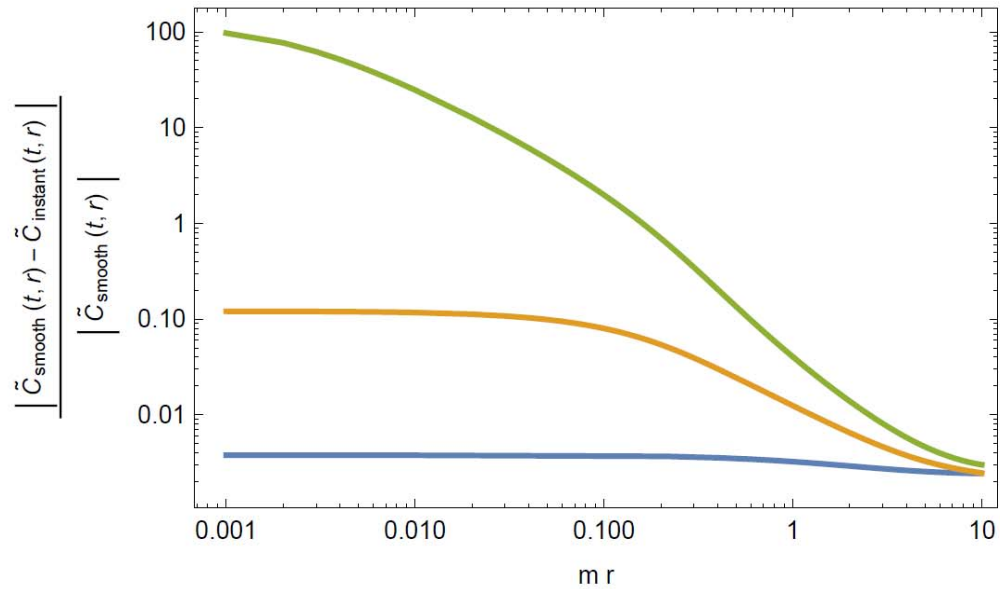


Figure 5. (Colour online) Difference between the late-time correlators for smooth and instantaneous quenches as a function of the separation distance r . The blue line corresponds to the $d = 3$ case while the yellow one belongs to $d = 5$ and $d = 7$ is shown in green. We are using $mt = 10$ with $m\delta t = 1/20$. In $d = 3$ and $d = 5$, the difference remains small for any value of r , while in $d = 7$, it seems to diverge as $r \rightarrow 0$.

CROSSOVER BEHAVIOR

PERHAPS THE MOST INTERESTING BEHAVIOR APPEARS
IN CORRELATORS AT EARLY TIMES.

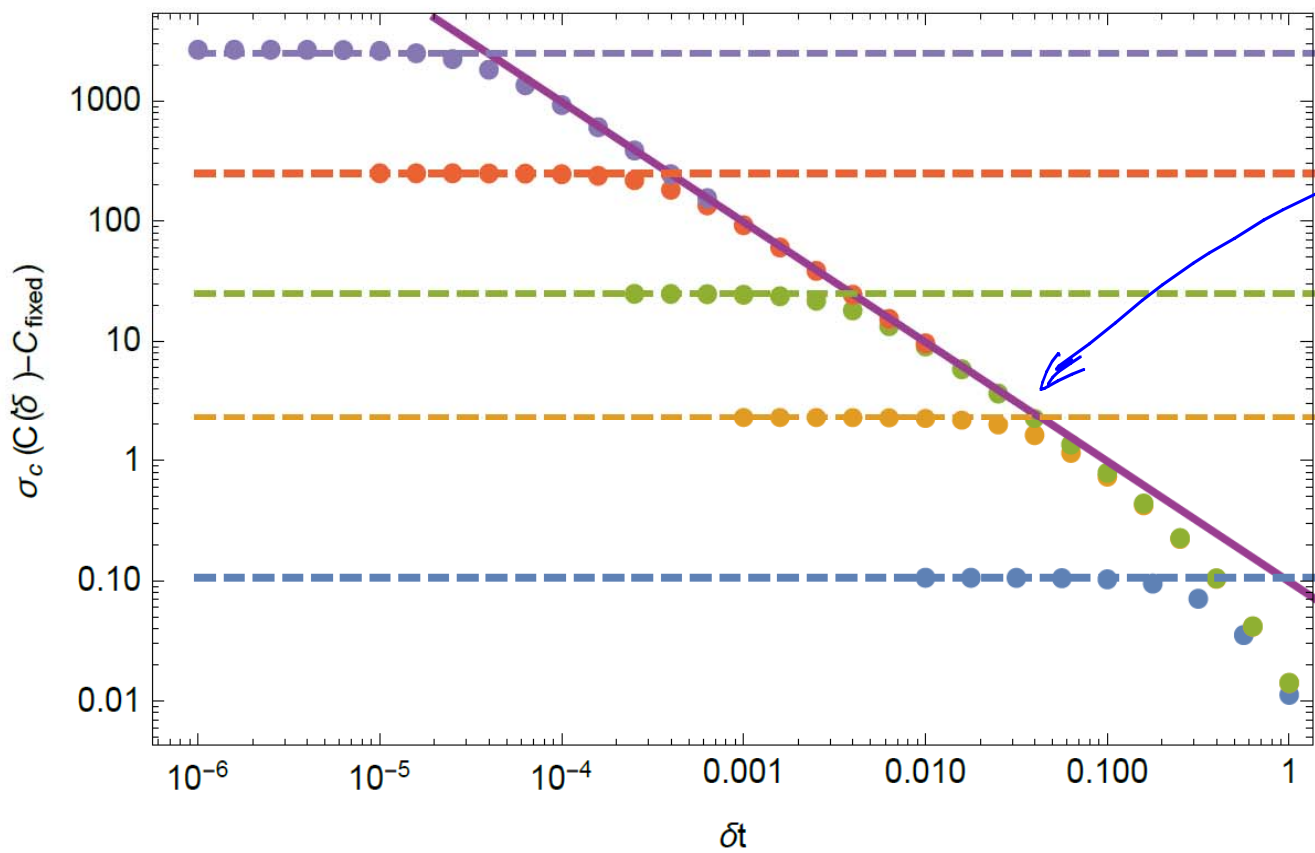
RECALL : THE SCALING OF LOCAL OBSERVABLES
APPEAR AT EARLY TIMES AS WELL.

SHOULD EXPECT THAT FOR SOME REGIME OF $|\vec{r}|$
WE SHOULD RECOVER SCALING

FOR LARGER $|\vec{r}|$ EXPECT SATURATION

$$m_0 = 1$$

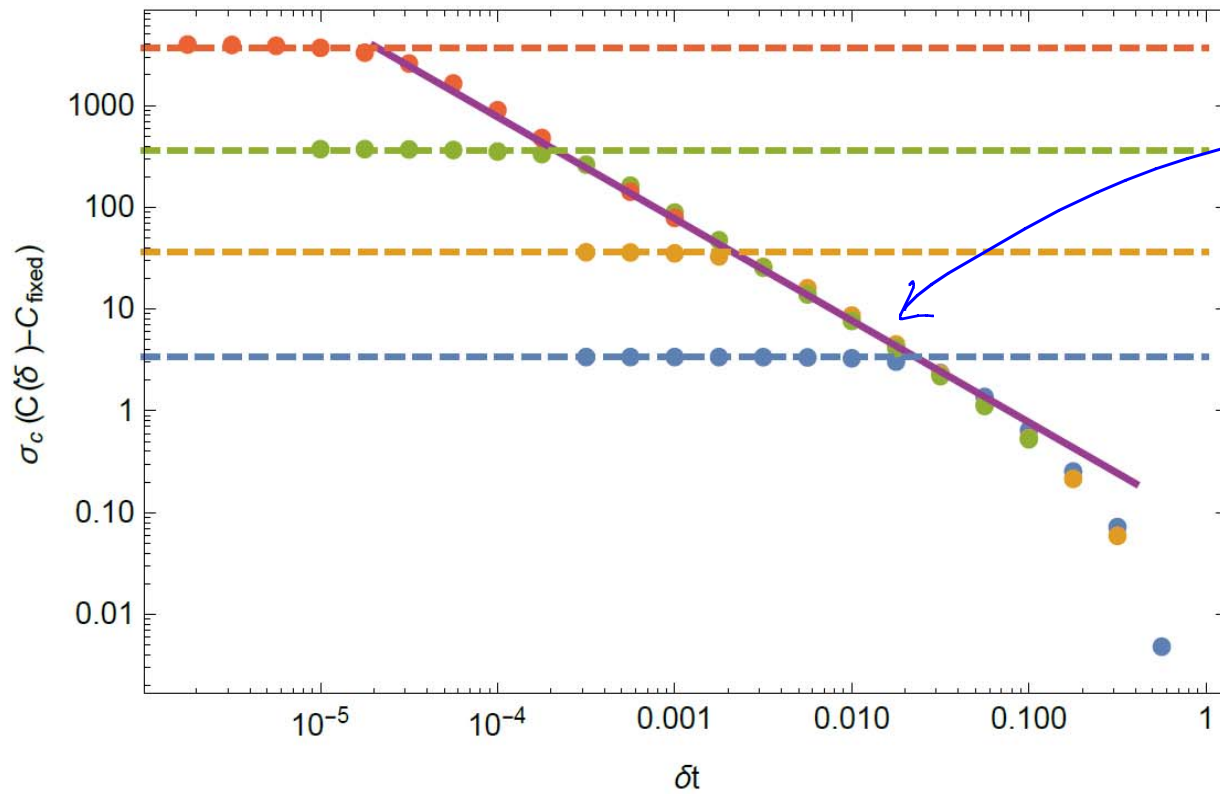
$$\tau = t/\delta t = 0$$



SCALING

- $r = 1$
- $r = \frac{1}{10}$
- $r = \frac{1}{10^2}$
- $r = \frac{1}{10^3}$
- $r = \frac{1}{10^4}$

$m = 1$ $\tau = t/\delta t = 1/2$



SCALING

- $r = \frac{1}{10}$
- $r = \frac{1}{10^2}$
- $r = \frac{1}{10^3}$
- $r = \frac{1}{10^4}$

THUS, FOR AN INTERMEDIATE REGIME OF $|\vec{r}|$ WE
INDEED SEE UNIVERSAL SCALING

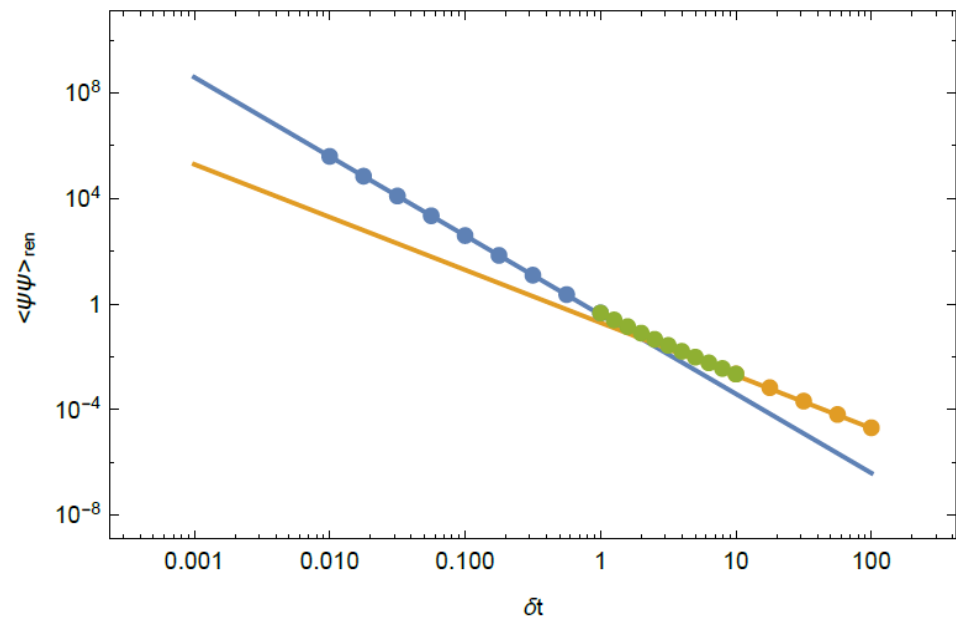
WE EXPECT THE SAME TO HOLD FOR INTERACTING
THEORIES AS WELL

FINITE CUTOFFS ?

FOR THEORIES WITH A FINITE LATTICE SPACING a
OUR RESULTS INDICATE

THERE IS AN INTERMEDIATE QUENCH RATE
FOR WHICH THESE SCALING LAWS HOLD.

FOR APPROPRIATE PROTOCOLS, STUDY OF CROSSOVER
FROM KIBBLE ZUREK TO THIS SCALING CAN
BE STUDIED - COULD BE INTERESTING FOR
EXPERIMENTS !



OUR RESULTS INDICATE THAT **PAST QUENCHES** WITH OPERATORS WITH CONFORMAL DIMENSIONS $\Delta > d/2$ ARE QUALITATIVELY DIFFERENT FROM THOSE WITH $\Delta < d/2$

THIS MAY HAVE IMPLICATIONS FOR USING A **CALABRESE-CARDY STATE**

$$e^{-\tau_0 H} |B\rangle$$

AS A GOOD APPROXIMATION TO A PHYSICAL PAST QUENCH

IMPLICATIONS FOR HOLOGRAPHIC COSMOLOGY

- DEFORMATION OF A BOUNDARY CFT BY A RELEVANT OPERATOR \equiv TIME DEP. BOUNDARY CONDITION FOR A BULK SCALAR WITH $m^2 < 0$
- $\Delta = d/2$ CORRESPONDS TO BF BOUND
- WE SAW THAT WHEN $\Delta > d/2$ IN THE LIMIT $f t \rightarrow 0$ AN INFINITE AMOUNT OF ENERGY DENSITY IS PRODUCED

- IT IS TEMPTING TO CONJECTURE THAT THIS LEADS TO REGIONS OF PLANCK SCALE CURVATURES — SPACELIKE SINGULARITIES

- THERE HAS BEEN A LOT OF WORK IN MODELLING SPACE-LIKE SINGULARITIES IN BULK BY TIME-DEPENDENT COUPLINGS IN THE BOUNDARY THEORY

(S.R.D, J. MICHELSON, K. NARAYAN, A. AWAD, S. TRIVEDI)

- THESE ALSO INVOLVED SOME NON-TRIVIAL INITIAL STATE - NEVER UNDERSTOOD

- ONE SHOULD REVISIT THIS PROBLEM IN THE LIGHT OF THESE FIELD THEORY RESULTS
- POSSIBILITY OF OBTAINING HOLOGRAPHIC COSMOLOGIES STARTING FROM VACUUM IN DISTANT PAST